THEORETICAL STUDIES ON Ξ PRODUCTION

Yongseok Oh
(Kyungpook National University)

2014.11.30 - 2014.12.2
WORKSHOP ON PROGRESS ON J-PARC HADRON PHYSICS IN 2014
IBARAKI QUANTUM BEAM RESEARCH CENTER, JAPAN

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- ✳ Model-dependent study on the reaction of $\bar{K}N \to K\Xi$
- ✳ Summary & Outlook

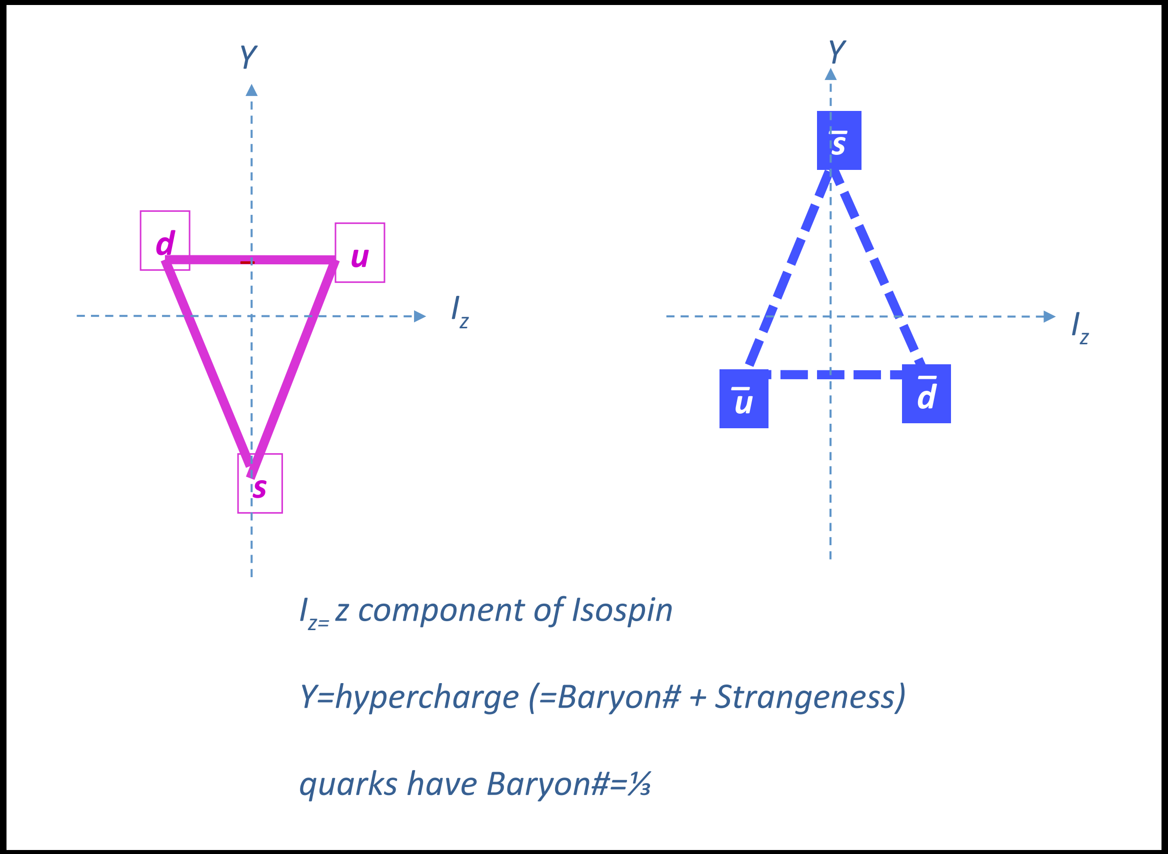
References:
Nakayama, YO, Haberzettl, PRC **74** (2006) 035205
YO, PRD **75** (2007) 074002
Man, YO, Nakayama, PRC **83** (2011) 055201
Nakayama, YO, Haberzettl, PRC **85** (2012) 042201(R)
Jackson, YO, Haberzettl, Nakayama, PRC **89** (2014) 025206
Jackson, YO, Haberzettl, Nakayama, in preparation

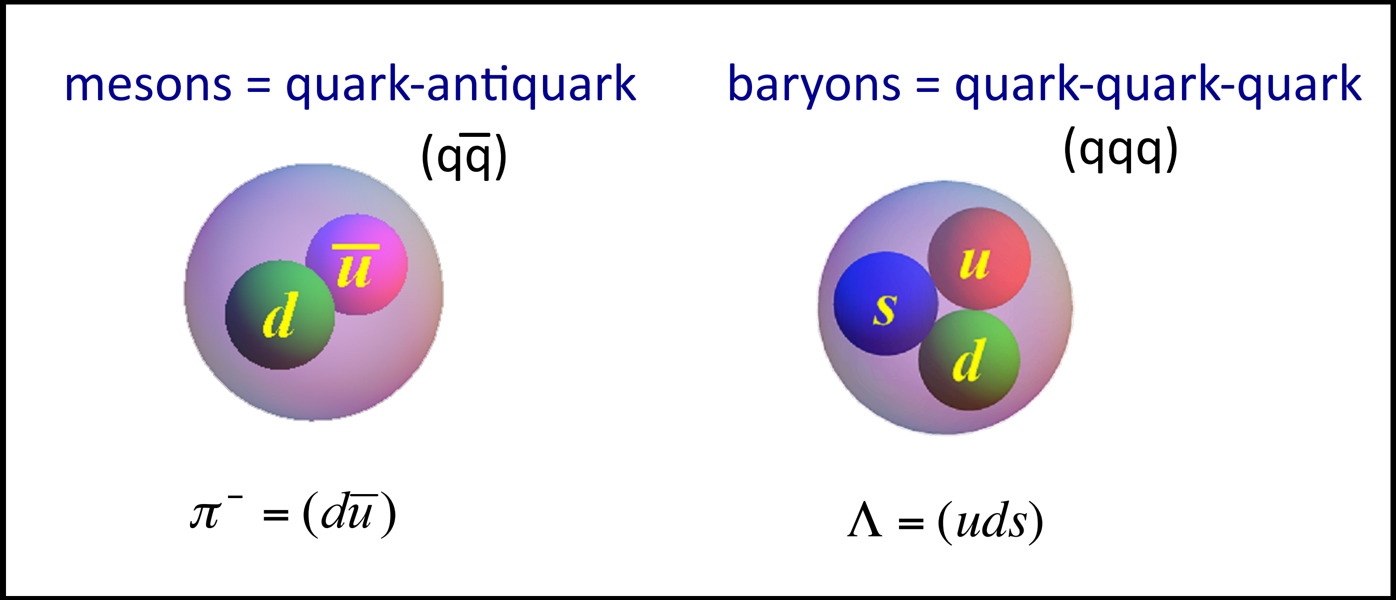
MOTIVATION

QUARK MODEL

M. Gell-Mann (1929-)

G. Zweig (1937-)





A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

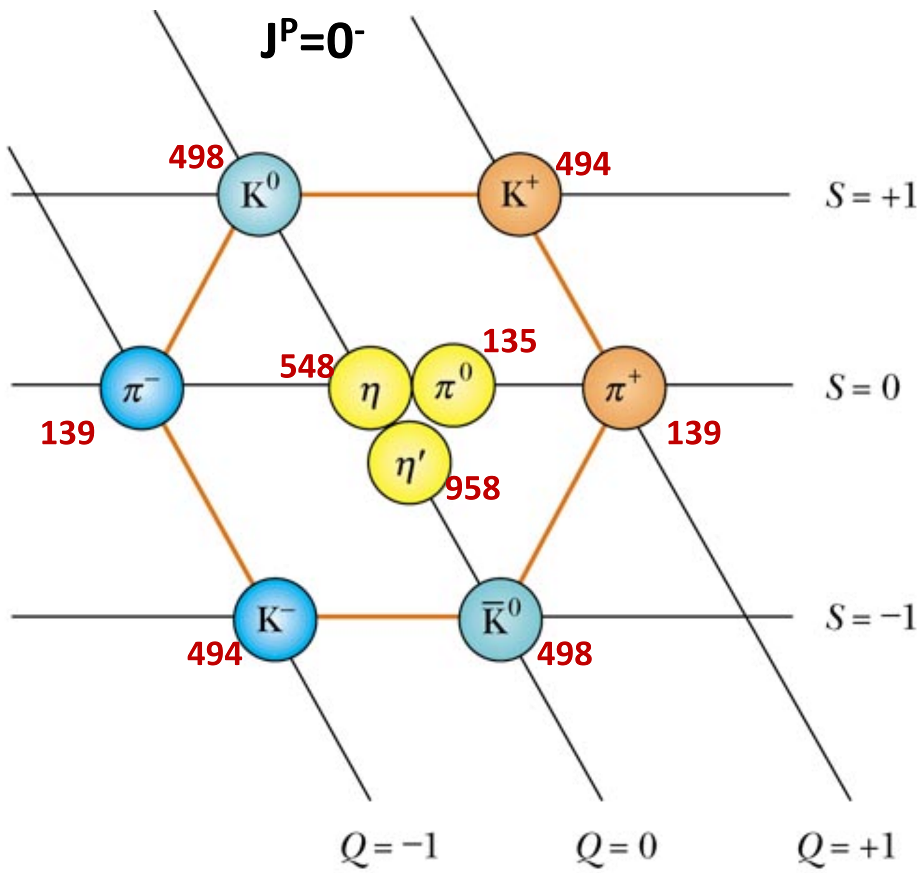
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means of dispersion theory, there are still meaningful and important questions regarding the algebraic properties of these interactions that have so far been discussed only by abstracting the properties from a formal field theory model based on fundamental entities [3] from which the baryons and mesons are built up.

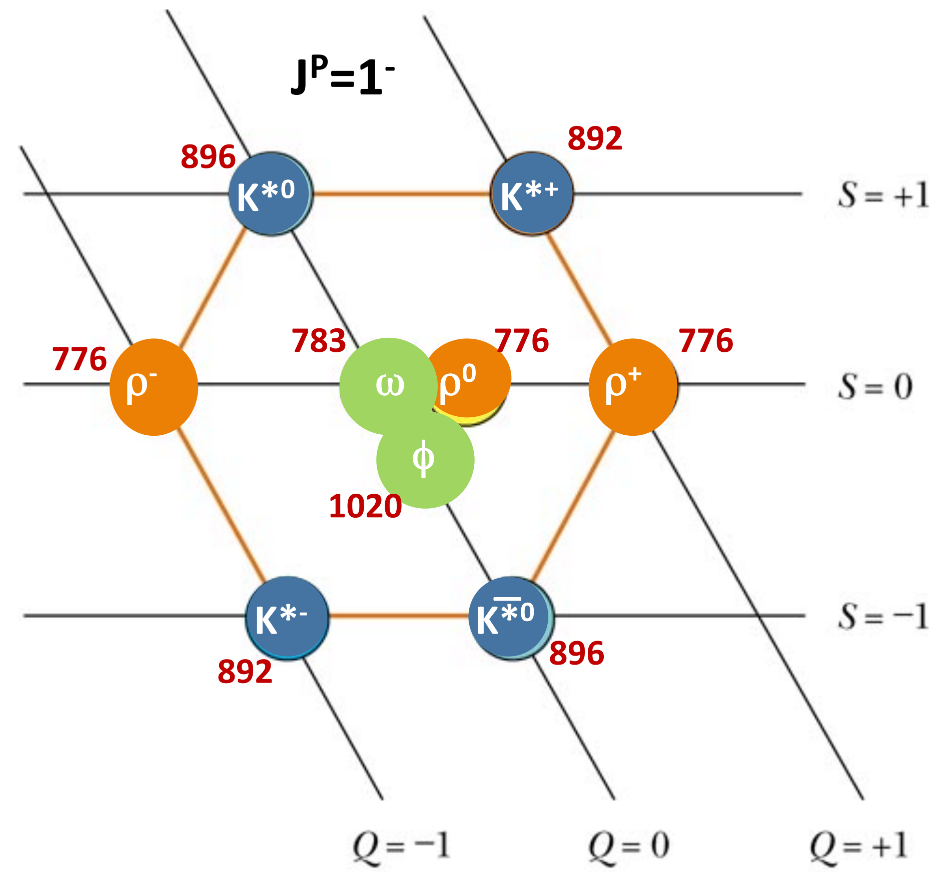
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

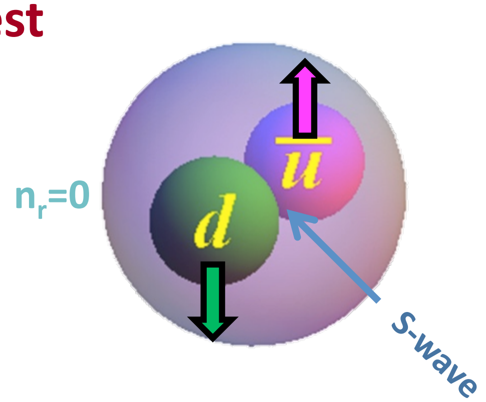
MESONS

Ground state mesons

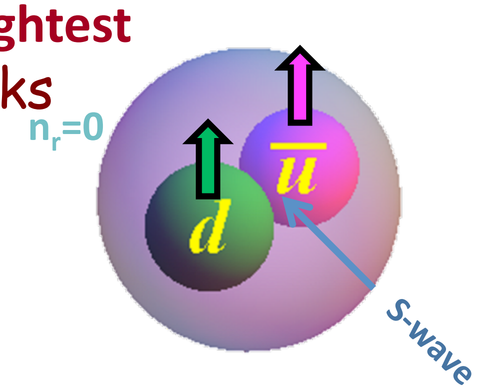




(π^+,π^0,π^-)=lightest
no s-quarks

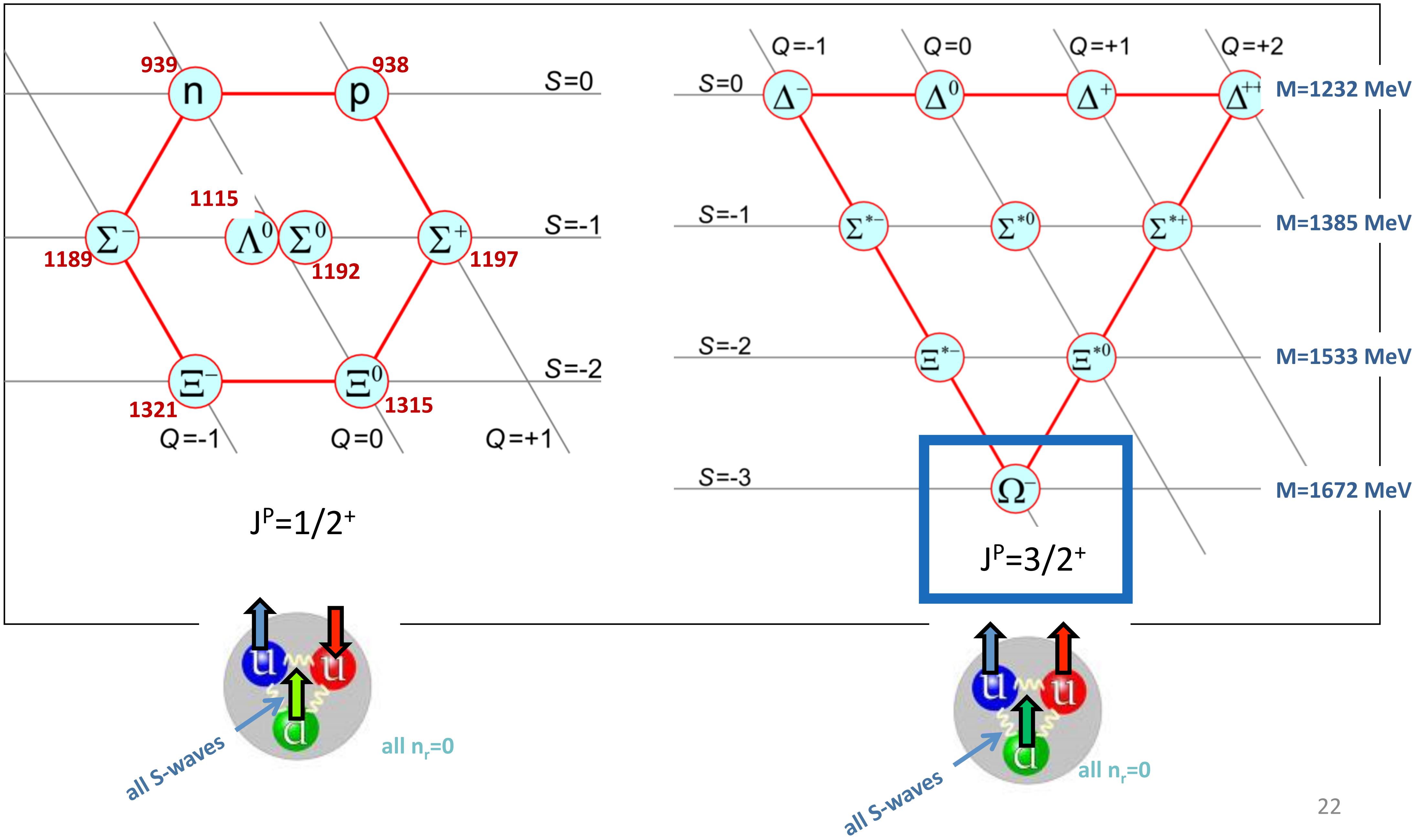


(ρ^+,ρ^0,ρ^-)=lightest
no s-quarks



BARYONS

Ground state Baryons



THE DISCOVERY OF Ω^-

spin-3/2 Ω^-

crucial prediction of the QM

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

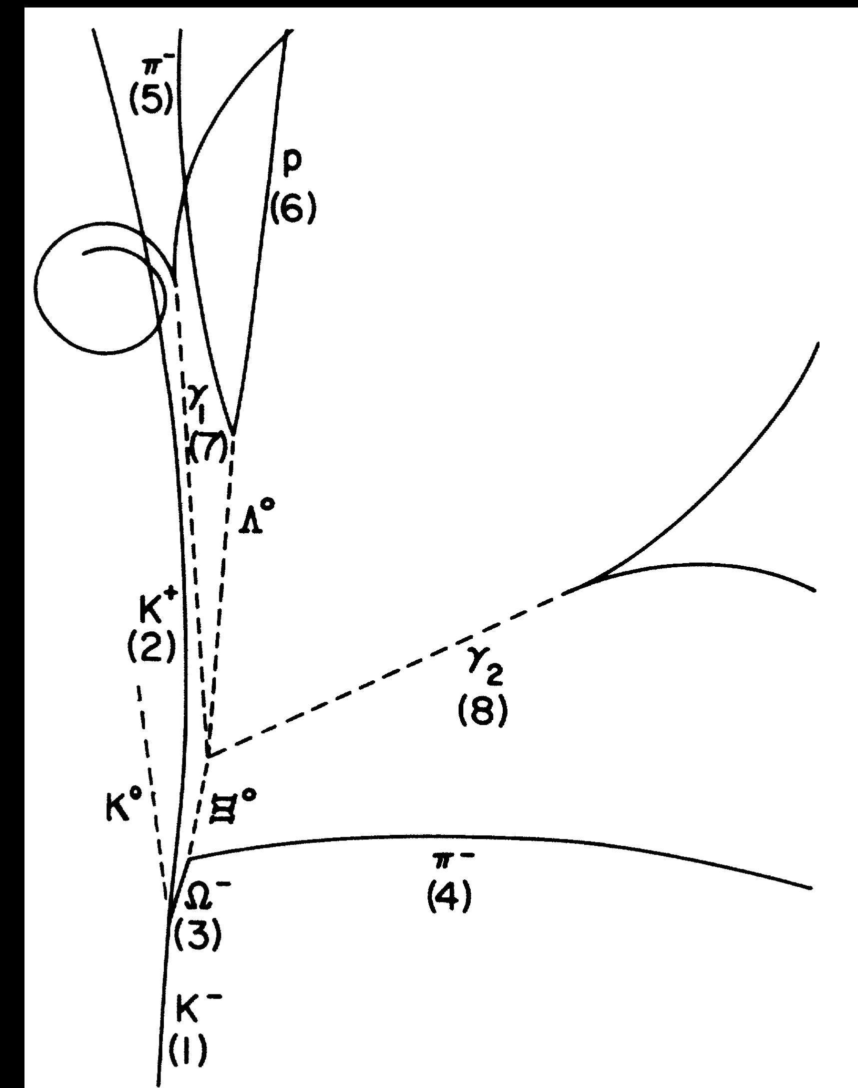
V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios, J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike, M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York

(Received 11 February 1964)

It has been pointed out[1] that among the multitude of resonances which have been discovered recently, the $N_{3/2}^*(1238)$, $Y_1^*(1385)$, and $\Xi_{1/2}^*(1532)$ can be arranged as a decuplet with one member still missing. Figure 1 illustrates the position

length of ~10^6 feet. These pictures have been partially analyzed to search for the more characteristic decay modes of the Ω^-.

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in



In view of the properties of charge ($Q = -1$), strangeness ($S = -3$), and mass ($M = 1686 \pm 12$ MeV/c^2) established for particle 3, we feel justified in identifying it with the sought-for Ω^-. Of course, it is expected that the Ω^- will have other observable decay modes, and we are continuing to search for them. We defer a detailed discussion of the mass of the Ω^- until we have analyzed further examples and have a better understanding of the systematic errors.

1964: the discovery of Ω^-

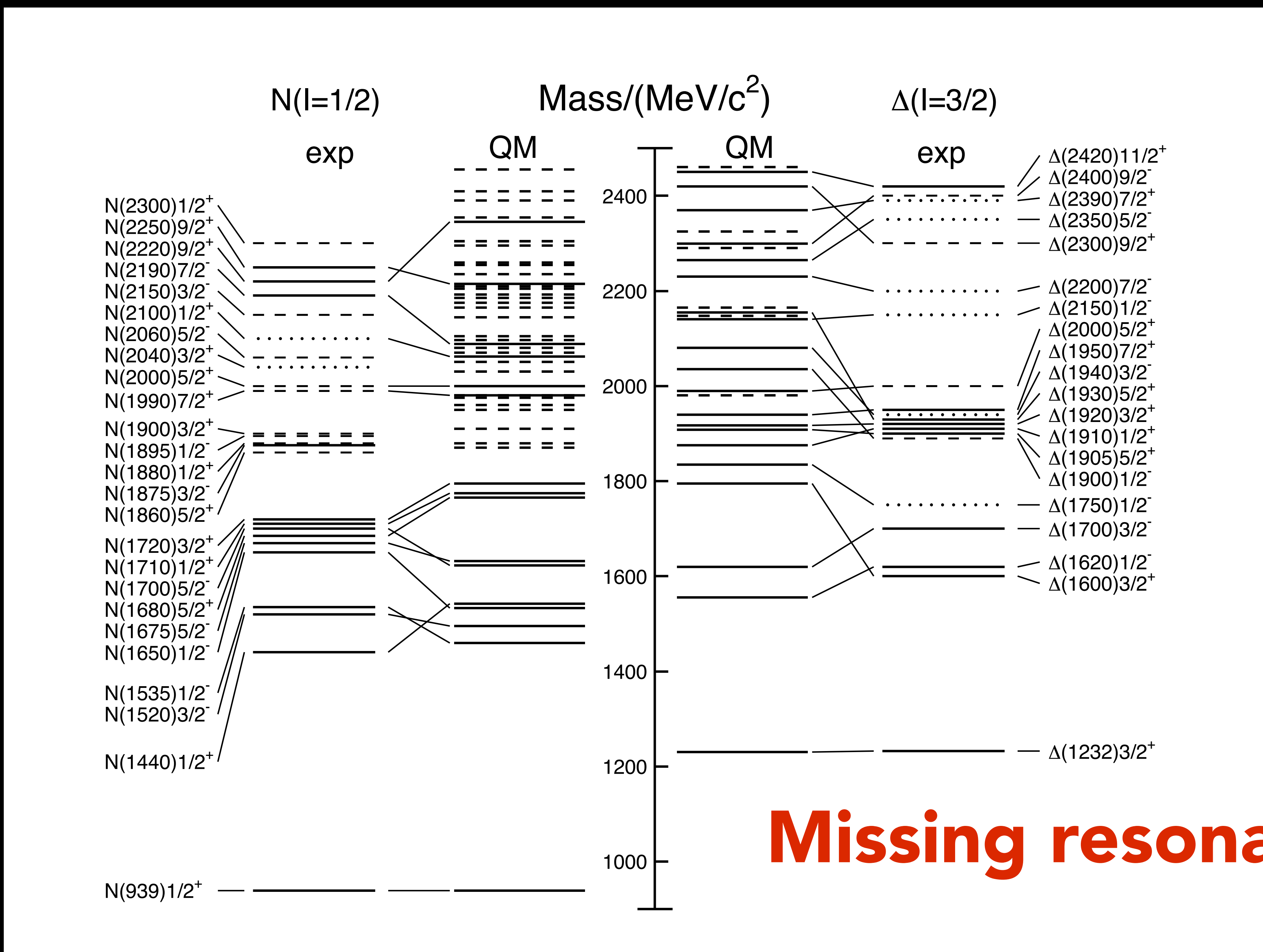
1969: Nobel prize to Gell-Mann "for his contributions and discoveries concerning the classification of elementary particles and their interactions"

BARYON SPECTRUM

orbital excitations, radial excitations

$$J = S + L$$

Excitation Spectrum of the nucleon



Missing resonances problem

QUANTUM NUMBERS OF HYPERONS

2006

PRL **97,** 112001 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Measurement of the Spin of the Ω^- Hyperon

B. Aubert,[1] R. Barate,[1] M. Bona,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges,[2] A. Palano,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] M. Battaglia,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] M. S. Gill,[6] Y. Groysman,[6] R. G. Jacobsen,[6] J. A. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] P. J. Oddone,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] P. del Amo Sanchez,[7] M. Barrett,[7] K. E. Ford,[7]

1964 The discovery of Ω^-
1969 Nobel prize

spin of Ω^-
BABAR Collab. (2006)

2014

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Ξ^0

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

The parity has not actually been measured, but + is of course expected.

1952 The discovery of Ξ (cosmic ray)
1959 The discovery of Ξ (LBNL)
The parity of Ξ?

Hyperons: another way to understand strong interactions

PDG (2012)

PDG List for Ξ baryons

Particle	J^P	Overall status	Status as seen in —				
			$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	1/2+	****					Decays weakly
Ξ(1530)	3/2+	****	****				
Ξ(1620)		*	*				
Ξ(1690)		***		***	**		
Ξ(1820)	3/2−	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)		***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)		**					3-body decays
Ξ(2500)		*		*	*		3-body decays

Parity is not directly measured, but assigned by the quark model

spin-parity known

Current Status

- Only $\Xi(1318)$ and $\Xi(1530)$ are four-star rated.
- Only three states with known spin-parity: those of other states should be explored.

Advantages

- small decay widths : identifiable in missing mass plots
- isospin = ½ only
- no flavor singlet like Λ

Difficulties

- non-strangeness initial state in most cases
- 3-body final states at least
- small cross sections ~ nb

PDG 2012

Ξ RESONANCES

The accompanying table gives our evaluation of the present status of the Ξ resonances. Not much is known about Ξ resonances. This is because (1) they can only be produced as a part of a final state, and so the analysis is more complicated than if direct formation were possible, (2) the production cross sections are small (typically a few μb), and (3) the final states are topologically complicated and difficult to study with electronic techniques. Thus early information about Ξ resonances came entirely from bubble chamber experiments, where the numbers of events are small, and only in the 1980's did electronic experiments make any significant contributions. However, nothing of significance on Ξ resonances has been added since our 1988 edition.

For the case of Ω, it is even worse!

Questions

Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

- Where are the other resonances?
  - only 2 resonances are four-star rated
- Their quantum numbers?
  - The spin-parity quantum numbers are assigned only to 3 states

The 3rd lowest state

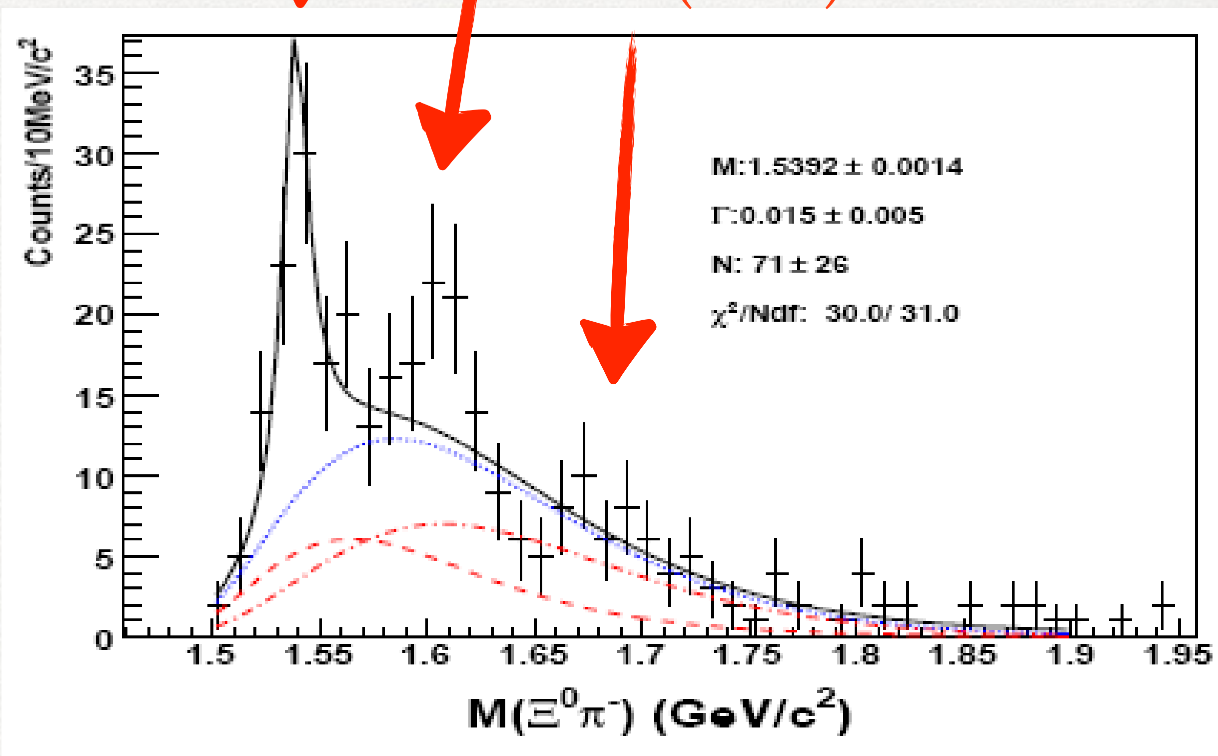
1. Does Ξ(1620) really exist?
   Most recent report on Ξ(1620): **NPB 189 (1981)**
2. The 3rd lowest state: Ξ(1620) vs. Ξ(1690)
3. What are their spin-parity quantum numbers?
   comparison with theoretical predictions

BaBar Collab.: J^P of Ξ(1690) is 1/2-
PRD 78 (2008)

Ξ(1530)

Ξ(1620)?

Ξ(1690)?



CLAS: PRC 76 (2007)

Ξ (1620) vs Ξ (1690)

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

$\Xi(1620)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $*$

J, P need confirmation.

OMITTED FROM SUMMARY TABLE

What little evidence there is consists of weak signals in the $\Xi\pi$ channel. A number of other experiments (e.g., BORENSTEIN 72 and HASSALL 81) have looked for but not seen any effect.

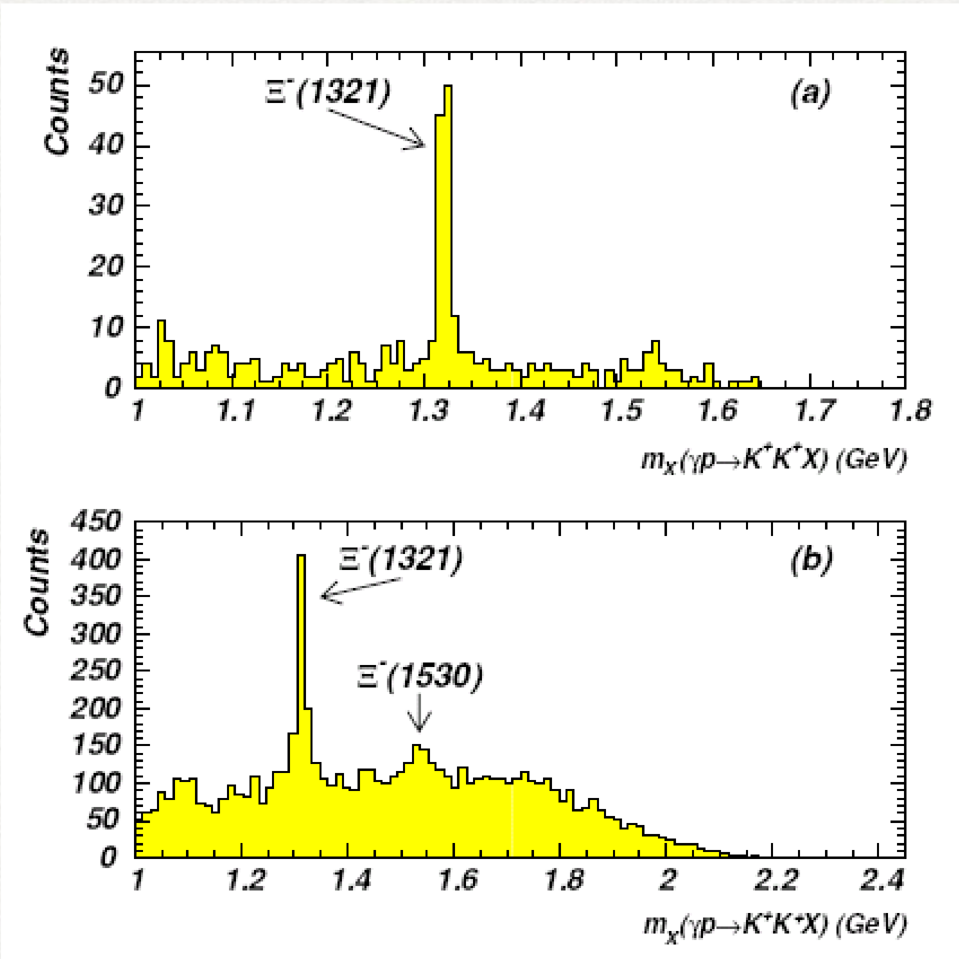
Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) (URL: http://pdg.lbl.gov)

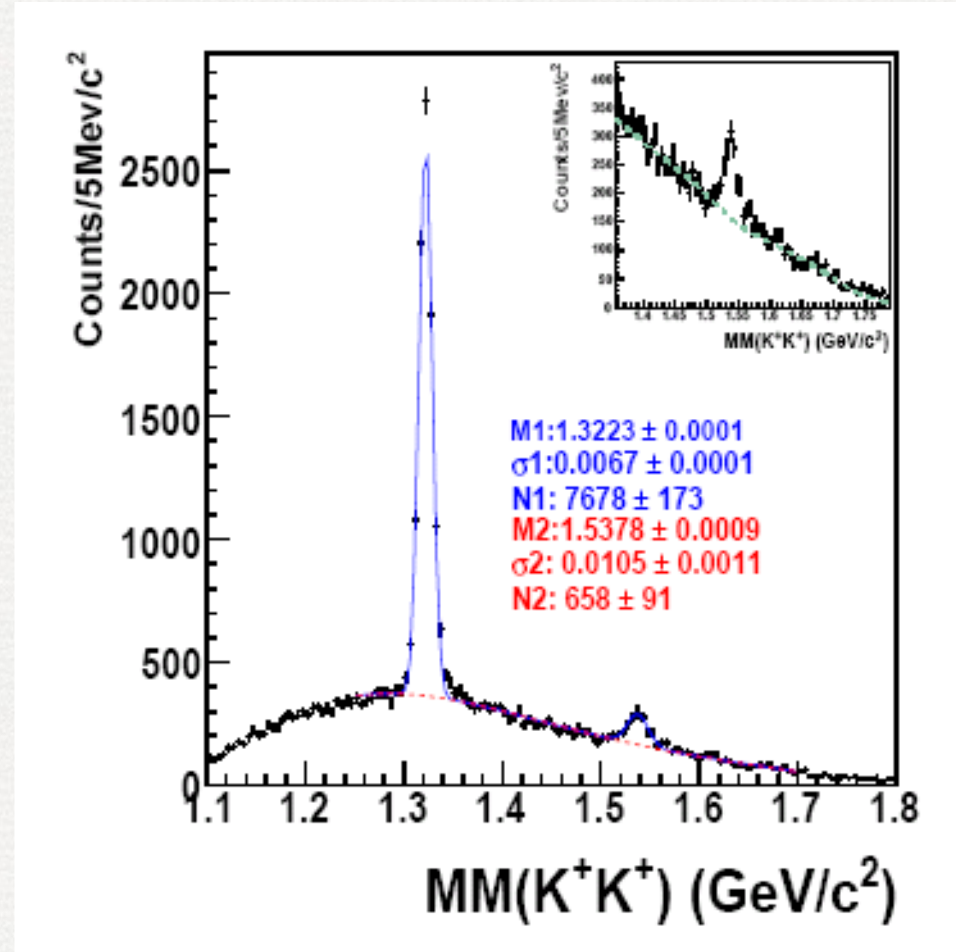
$\Xi(1690)$

$I(J^P) = \frac{1}{2}(?^?)$ Status: $***$

AUBERT 08AK, in a study of $\Lambda_c^+ \to \Xi^-\pi^+K^+$, finds some evidence that the $\Xi(1690)$ has $J^P = 1/2^-$.

CLAS@JLab





PRC 71 (2005)

PRC 76 (2007)

More data sets are under analysis!

CLAS12 proposal

Photoproduction of the Very Strangest Baryons on a Proton Target in CLAS12

(The Very Strange Collaboration)

A. Afanasev, W.J. Briscoe, H. Haberzettl, I.I. Strakovsky*, R.L. Workman, M.J. Amaryan, G. Gavalian, M.C. Kunkel, Ya.I. Azimov, N. Baltzell, M. Battaglieri, A. Celentano, R. De Vita, M. Osipenko, M. Ripani, M. Taiuti, V.N. Baturin, S. Boyarinov, D.S. Carman, V. Kubarovsky, V. Mokeev, E. Pasyuk*, S. Stepanyan, D.P. Weygand, V. Ziegler*, W. Boeglin, J. Bono, L. Guo*,**, P. Khetarpel, P. Markowitz, B. Raue, S. Capstick, V. Crede, W. Roberts, M. Dugger, B.G. Ritchie, G. Fedotov, J. Goetz*, B.M.K. Nefkens, D.I. Glazier, D.P. Watts*, S. Hasegawa, H. Sako, S. Sato, K. Shirotori, K. Hicks, D.G. Ireland, K. Livingston, B. McKinnon, F.J. Klein, N. Walford, A. Kubarovsky, H. Lu, P. Mattione, K. Nakayama, ***Y. Oh***, M. Paolone, J.W. Price, F. Sabatie, C. Salgado, V. Shklyar

** Contact person, * Spokesperson

The George Washington Univ., Old Dominion Univ., Petersburg Nuclear Physics Inst., Argonne Nat'l Lab., INFN Genova, TJNAF, Florida International Univ., Florida State Univ., Arizona State Univ., Univ. of South Carolina, UCLA, Edinburgh Univ., JAEA, Ohio Univ., Univ. of Glasgow, The Catholic Univ. of America, Rensselaer Poly. Inst., Carnegie Mellon Univ., Univ. of Georgia, ***Kyungpook Nat'l Univ.***, Temple Univ., California State Univ., Saclay, Norfolk State Univ., Giessen Univ.

HYPERON SPECTRUM

Baryon structure and Ξ/Ω spectra

Table 1. Low-lying Ξ and Ω baryon spectrum of spin 1/2 and 3/2 predicted by the non-relativistic quark model of Chao *et al.* (CIK), relativized quark model of Capstick and Isgur (CI), Glozman-Riska model (GR), large N_c analysis, algebraic model (BIL), and QCD sum rules (SR). The recent quark model prediction (QM) and the Skyrme model results (SK) are given as well. The mass is given in the unit of MeV.

State	CIK [4]	CI [5]	GR [6]	Large-N_c [7–11]	BIL [12]	SR [13, 14]	QM [15]	SK [1]
$\Xi(\frac{1}{2}^+)$	1325	1305	1320		1334	1320 (1320)	1325	1318
	1695	1840	1798	1825	1727		1891	1932
	1950	2040	1947	1839	1932		2014	
$\Xi(\frac{3}{2}^+)$	1530	1505	1516		1524		1520	1539
	1930	2045	1886	1854	1878		1934	2120
	1965	2065	1947	1859	1979		2020	
$\Xi(\frac{1}{2}^-)$	1785	1755	1758	1780	1869	1550 (1630)	1725	1614
	1890	1810	1849	1922	1932		1811	1660
	1925	1835	1889	1927	2076			
$\Xi(\frac{3}{2}^-)$	1800	1785	1758	1815	1828	1840	1759	1820
	1910	1880	1849	1973	1869		1826	
	1970	1895	1889	1980	1932			
$\Omega(\frac{1}{2}^+)$	2190	2220	2068	2408	2085		2175	2140
	2210	2255	2166		2219		2191	
$\Omega(\frac{3}{2}^+)$	1675	1635	1651		1670		1656	1694
	2065	2165	2020	1922	1998		2170	2282
	2215	2280	2068	2120	2219		2182	
$\Omega(\frac{1}{2}^-)$	2020	1950	1991	2061	1989		1923	1837
$\Omega(\frac{3}{2}^-)$	2020	2000	1991	2100	1989		1953	1978

Exp.

Particle	J^P
$\Xi(1318)$	1/2+
$\Xi(1530)$	3/2+
$\Xi(1620)$	
$\Xi(1690)$	1/2− ?
$\Xi(1820)$	3/2−
$\Xi(1950)$	
$\Xi(2030)$	
$\Xi(2120)$	
$\Xi(2250)$	
$\Xi(2370)$	
$\Xi(2500)$	

The 3rd lowest state

Highly model-dependent !

- The predicted masses for the third lowest state are higher than 1690 MeV (except NRQM)
    - How to describe $\Xi(1690)$?
- The presence of $\Xi(1620)$ is puzzling, if it exits.

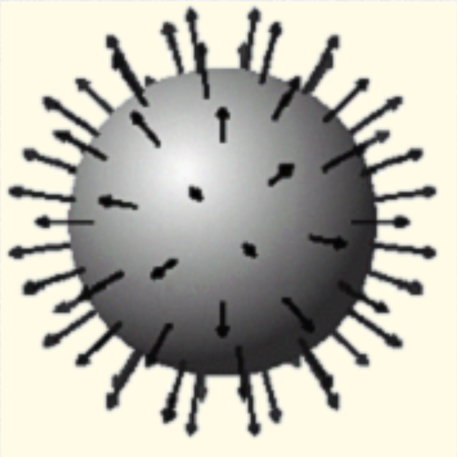
Cf. similar problem in QM: $\Lambda(1405)$

Skyrme Model

- 1960s, T.H.R. Skyrme

- Baryons are topological solitons within a nonlinear theory of pions.

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) + \frac{1}{32e^2}\mathrm{Tr}\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]^2$$



Topological soliton
winding number = integer
↑
interpret as baryon number

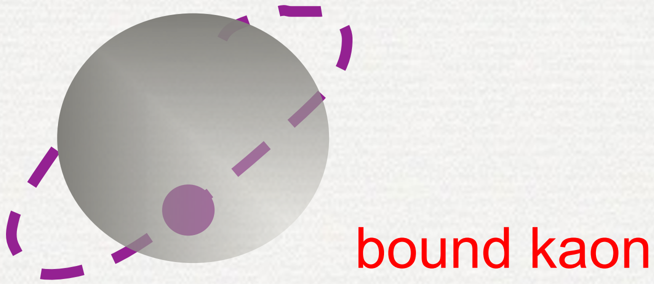
Bound State Model

- Starting point: flavor SU(3) symmetry is badly broken
  - treats light flavors and strangeness on a different footing

    $\mathrm{SU}(3) \to \mathrm{SU}(2) \times \mathrm{U}(1)$

  - Lagrangian $\mathcal{L} = \mathcal{L}_{\mathrm{SU}(2)} + \mathcal{L}_{K/K^*}$

  - The soliton provides a background potential that traps K/K* (or heavy) mesons.



Callan, Klebanov, NPB **262** (1985)

Bound State Model

- Anomalous Lagrangian
  - Pushes up the S = +1 states to the continuum → no bound state
  - Pulls down the S = -1 states below the threshold → allows bound state → description of hyperons
- Renders two bound states with S = -1

after quantization

  - the lowest state: p-wave → gives (+)-ve parity Λ(1116)

270 MeV energy difference

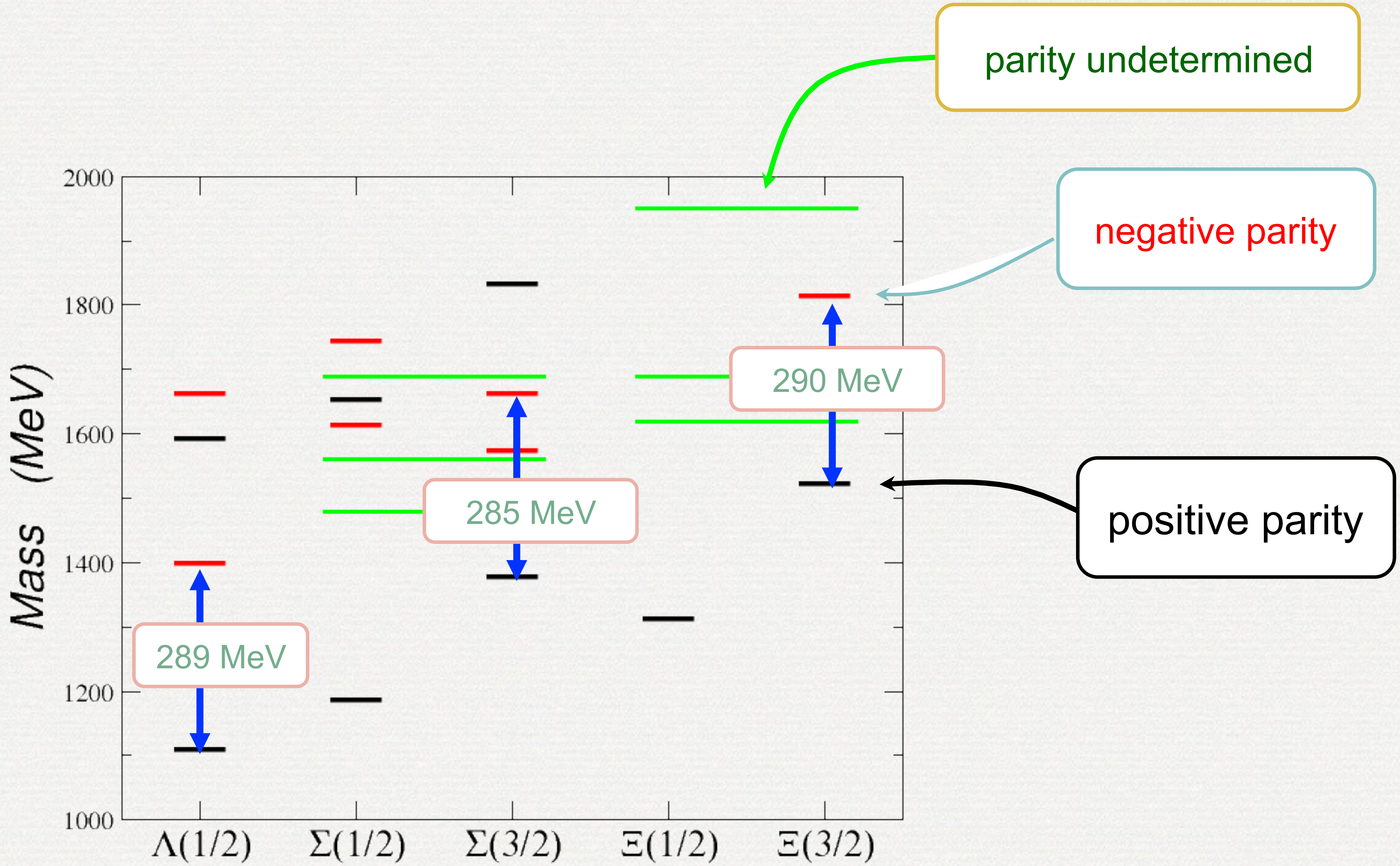
  - excited state: s-wave → gives (-)-ve parity Λ(1405)

- Mass formula includes parameters: depends on dynamics

we fix them to known masses and then predict

Experimental Data

- Experimental Data



MASS FORMULA

$$M(i,j,j_m) = M_{sol} + n_1\omega_1 + n_2\omega_2 + \frac{1}{2I}\Big\{ i(i+1) + c_1c_2 j_m(j_m+1) + (\bar{c}_1 - c_1c_2) j_1(j_1+1) + (\bar{c}_2 - c_1c_2) j_2(j_2+1)$$
$$+ \frac{c_1+c_2}{2}\left[j(j+1) - j_m(j_m+1) - i(i+1) \right] + \frac{c_1-c_2}{2} \vec{R}\cdot(\vec{J}_1 - \vec{J}_2) \Big\}$$

$\mathbf{\Theta}^2 = \bar{c}\boldsymbol{J}_K^2,$

causes mixing

8 parameters: fit to the available data
→ give predictions to the other resonances
The last term gives a mixing between the states which have same
i, j, j_m but different R, J_1, J_2

Fitted values

$M_{sol} = 866$ MeV, $\quad I = 1.01$ fm
$\omega_1 = 211$ MeV, $\quad c_1 = 0.754, \quad \bar{c}_1 = 0.532$
$\omega_2 = 479$ MeV, $\quad c_2 = 0.641, \quad \bar{c}_2 = 0.821$

cf. $\bar{c}_1 = c_1^2, \quad \bar{c}_2 = c_2^2$ in Kaplan, Klebanov, NPB **335** (1990)

Bound State Model

- Best-fitted results based on the derived mass formula

Particle	Prediction (MeV)	Expt
N	939*	$N(939)$
Δ	1232*	$\Delta(1232)$
$\Lambda(1/2^+)$	1116*	$\Lambda(1116)$
$\Lambda(1/2^-)$	1405*	$\Lambda(1405)$
$\Sigma(1/2^+)$	1164	$\Sigma(1193)$
$\Sigma(3/2^+)$	1385	$\Sigma(1385)$
$\Sigma(1/2^-)$	1475	$\Sigma(1480)$?
$\Sigma(3/2^-)$	1663	$\Sigma(1670)$
$\Xi(1/2^+)$	1318*	$\Xi(1318)$
$\Xi(3/2^+)$	1539	$\Xi(1530)$
$\Xi(1/2^-)$	1658 (1660)	$\Xi(1690)$?
$\Xi(1/2^-)$	1616 (1614)	$\Xi(1620)$?
$\Xi(3/2^-)$	1820	$\Xi(1820)$
$\Xi(1/2^+)$	1932	$\Xi(1950)$?
$\Xi(3/2^+)$	2120*	$\Xi(2120)$
$\Omega(3/2^+)$	1694	$\Omega(1672)$
$\Omega(1/2^-)$	1837	
$\Omega(3/2^-)$	1978	
$\Omega(1/2^+)$	2140	
$\Omega(3/2^+)$	2282	$\Omega(2250)$?
$\Omega(3/2^-)$	2604	

Recently confirmed by COSY
PRL ***96*** *(2006)*

BaBar : the spin-parity of
$\Xi(1690)$ is $1/2^-$
PRD ***78*** *(2008)*
NRQM predicts $1/2^+$

puzzle in QM

Unique prediction of this model.
The $\Xi(1620)$ should be there.
still one-star resonance

Ω's would be discovered in future.

YO, PRD **75** (2007)

경북대학교

More Comments

Two Ξ states

Kaons: one in p-wave and one in s-wave

$\Rightarrow \vec{J} = \vec{J}_{sol} + \vec{J}_m \qquad (\vec{J}_m = \vec{J}_1 + \vec{J}_2)$

$\vec{J}_{sol}$: soliton spin $(=1/2)$, $\vec{J}_1(\vec{J}_2)$: spin of the p(s)-wave kaon $(=1/2)$

$J_m = 0$ or 1: both of them can lead to $J^P = 1/2^-$ Ξ states

Therefore, two $J^P = 1/2^-$ Ξ states and one $J^P = 3/2^-$ Ξ states

In this model, it is natural to have two $J^P = 1/2^-$ Ξ states at 1616 MeV & 1658 MeV

Clearly, different from quark models

Other approaches

Unitary extension of chiral perturbation theory

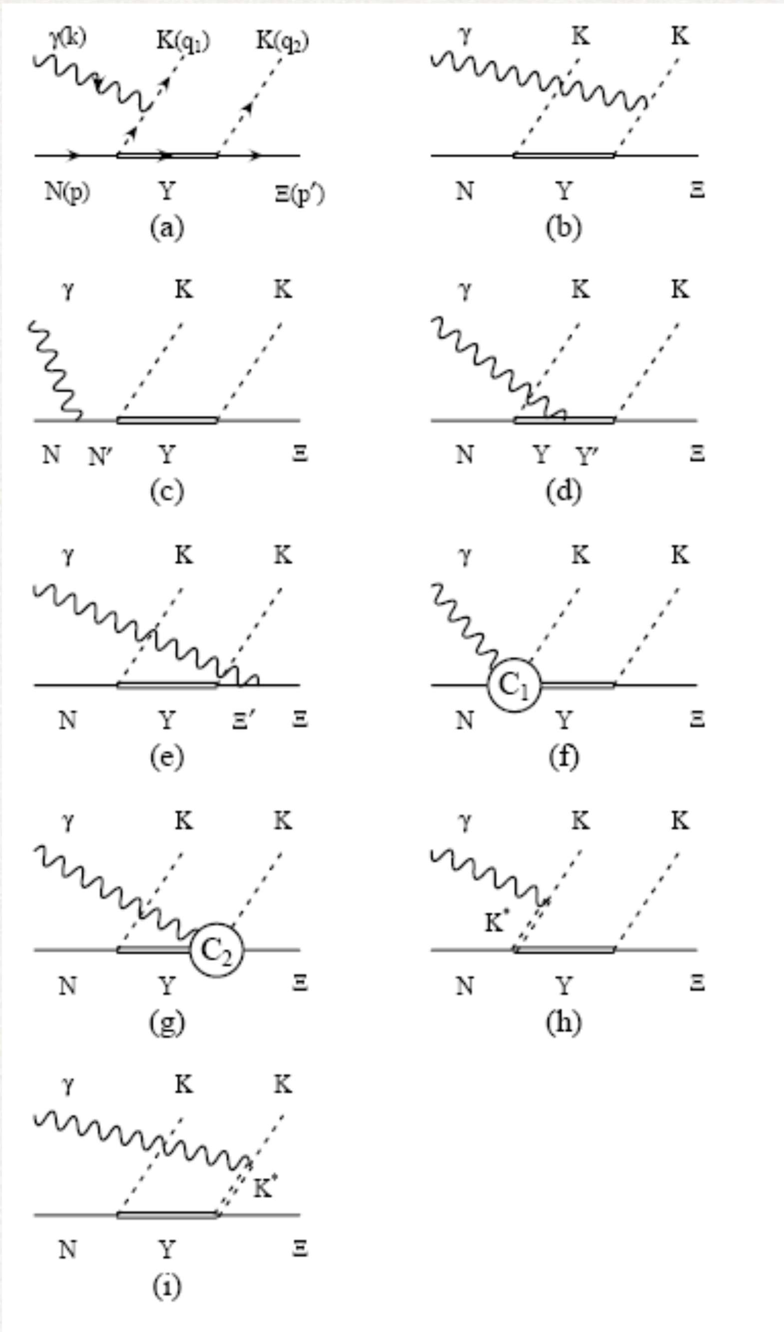
Ramos, Oset, Bennhold, PRL 89 (2002): $1/2^-$state at 1606 MeV

Garcia-Recio, Lutz, Nieves, PLB 582 (2004): claim tht the $\Xi(1620)$ and $\Xi(1690)$ are $1/2^-$states

PRODUCTION PROCESSES

Photoproduction

- photoproduction $\gamma N \to K K \Xi$

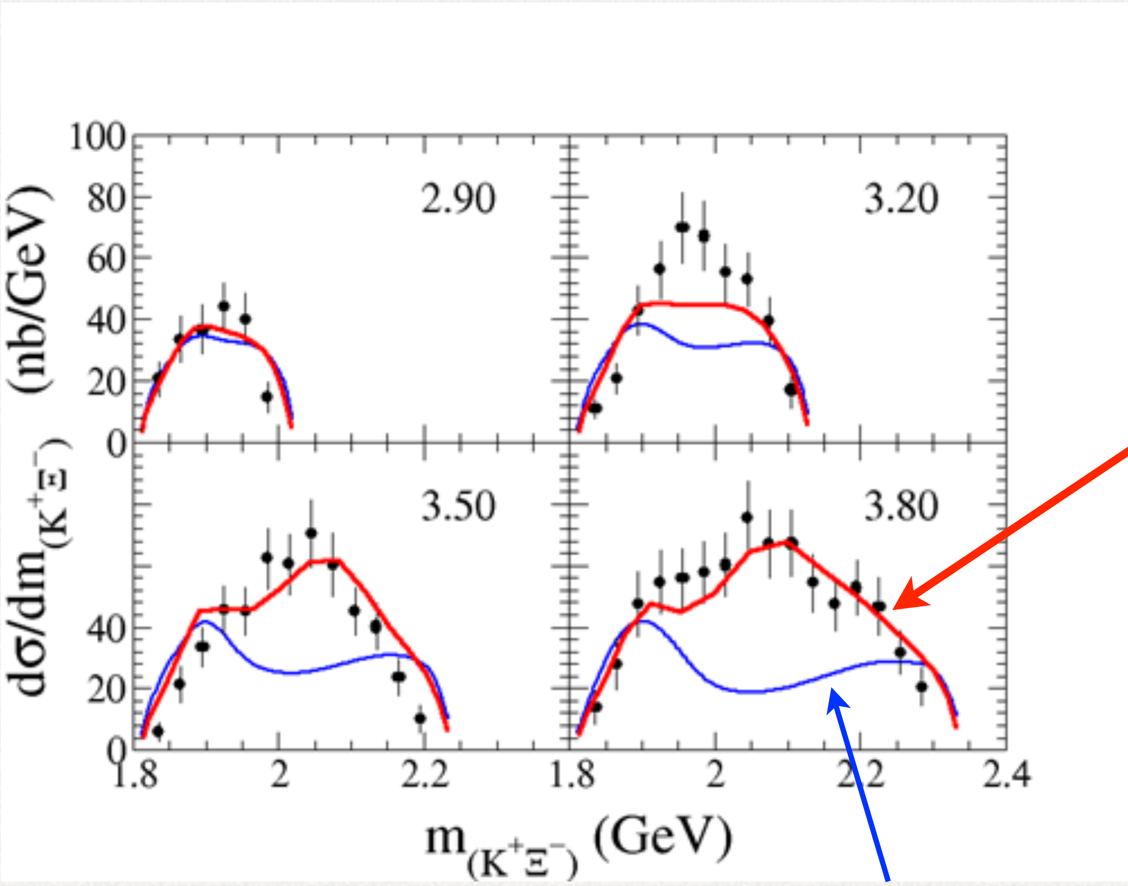


Λ states					Σ states				
State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Lambda K}\rvert$	State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Sigma K}\rvert$
Λ(1116)	$1/2^+$		****		Σ(1193)	$1/2^+$		****	
Λ(1405)	$1/2^-$	≈ 50	****		Σ(1385)	$3/2^+$	≈ 37	****	
Λ(1520)	$3/2^-$	≈ 16	****						
Λ(1600)	$1/2^+$	≈ 150	***	4.2	Σ(1660)	$1/2^+$	≈ 100	***	2.5
Λ(1670)	$1/2^-$	≈ 35	****	0.3	Σ(1670)	$3/2^-$	≈ 60	****	2.8
Λ(1690)	$3/2^-$	≈ 60	****	4.0	Σ(1750)	$1/2^-$	≈ 90	***	0.5
Λ(1800)	$1/2^-$	≈ 300	***	1.0	Σ(1775)	$5/2^-$	≈ 120	****	
Λ(1810)	$1/2^+$	≈ 150	***	2.8	Σ(1915)	$5/2^+$	≈ 120	****	
Λ(1820)	$5/2^+$	≈ 80	****		Σ(1940)	$3/2^-$	≈ 220	***	< 2.8
Λ(1830)	$5/2^-$	≈ 95	****		Σ(2030)	$7/2^+$	≈ 180	****	
Λ(1890)	$3/2^+$	≈ 100	****	0.8	Σ(2250)	$?^?$	≈ 100	***	
Λ(2100)	$7/2^-$	≈ 200	****						
Λ(2110)	$5/2^+$	≈ 200	***						
Λ(2350)	$9/2^+$	≈ 150	***						

$$\left|M_{1/2^\pm}\right|^2,\ \left|M_{5/2^\pm}\right|^2 \propto \left(E_N \mp M_N\right)\left(E_\Xi \mp M_\Xi\right)$$

$$\left|M_{3/2^\pm}\right|^2,\ \left|M_{7/2^\pm}\right|^2 \propto \left(E_N \pm M_N\right)\left(E_\Xi \pm M_\Xi\right)$$

Photoproduction



with $\Sigma(2030, 7/2^+)$

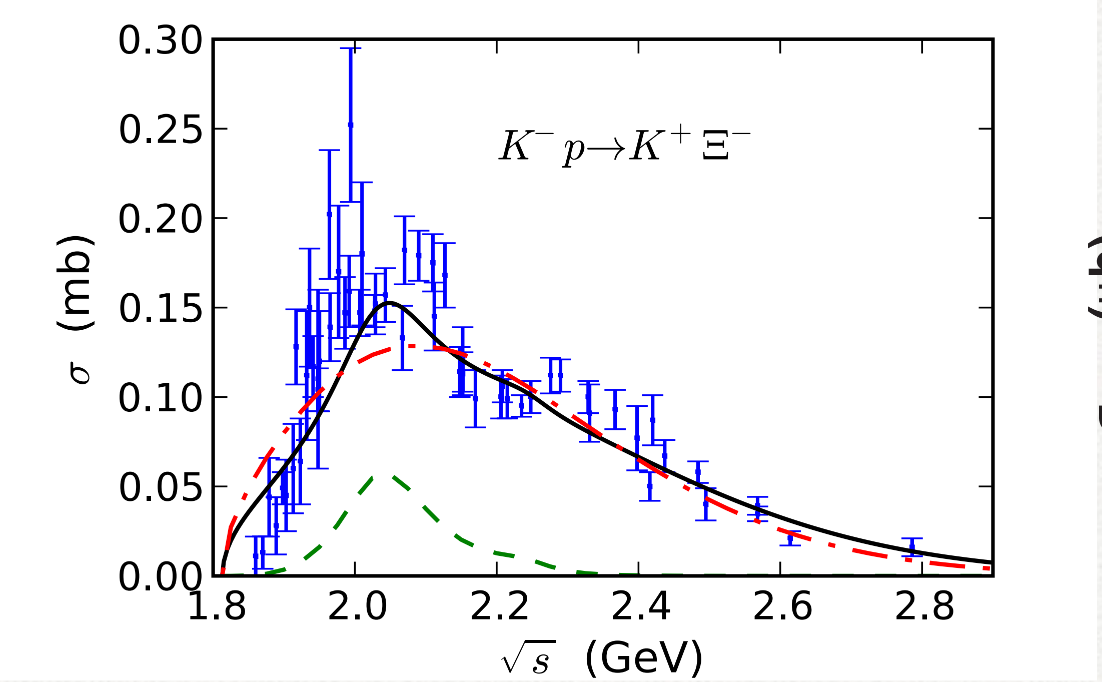
without $\Sigma(2030, 7/2^+)$

Nakayama, YO, Haberzettl, PRC **74** (2006) 035205
Man, YO, Nakayama, PRC **83** (2011) 055201

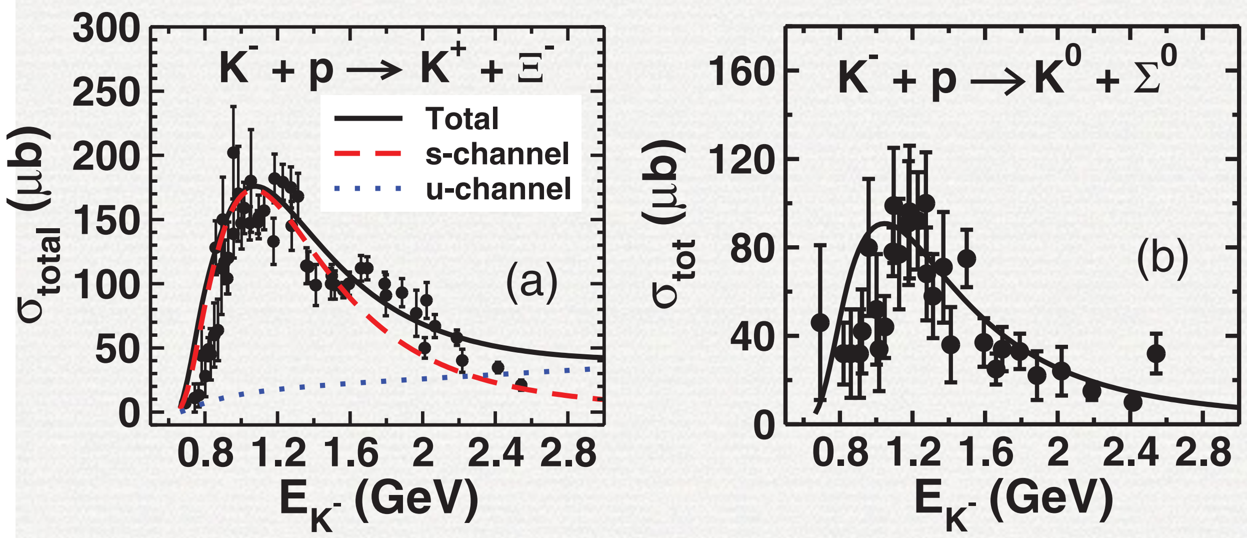
Kaon-Nucleon Scattering

- Ξ production in $\bar{K}N \to K\Xi$

Sharov, Korotkikh, Lanskoy, EPJA **47** (2011)



Shyam, Scholten, Thomas, PRC **84** (2011)



best fit without high resonances

best fit with high resonances

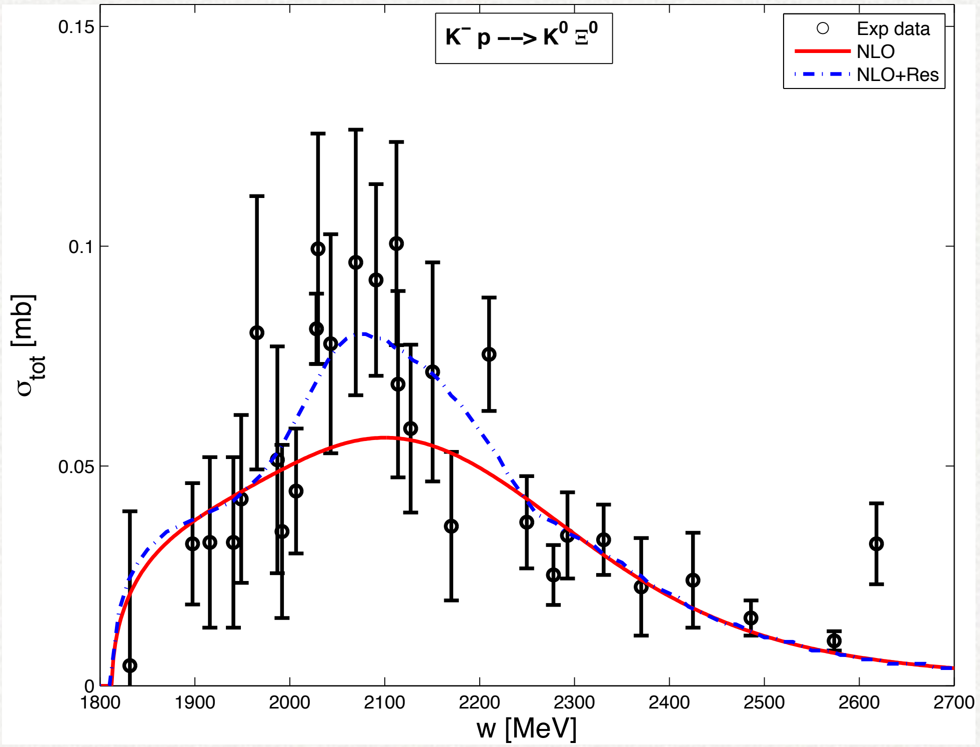
contribution from $\Sigma(2030)$ and $\Sigma(2250)$

the role of $\Lambda(1520)$ is stressed

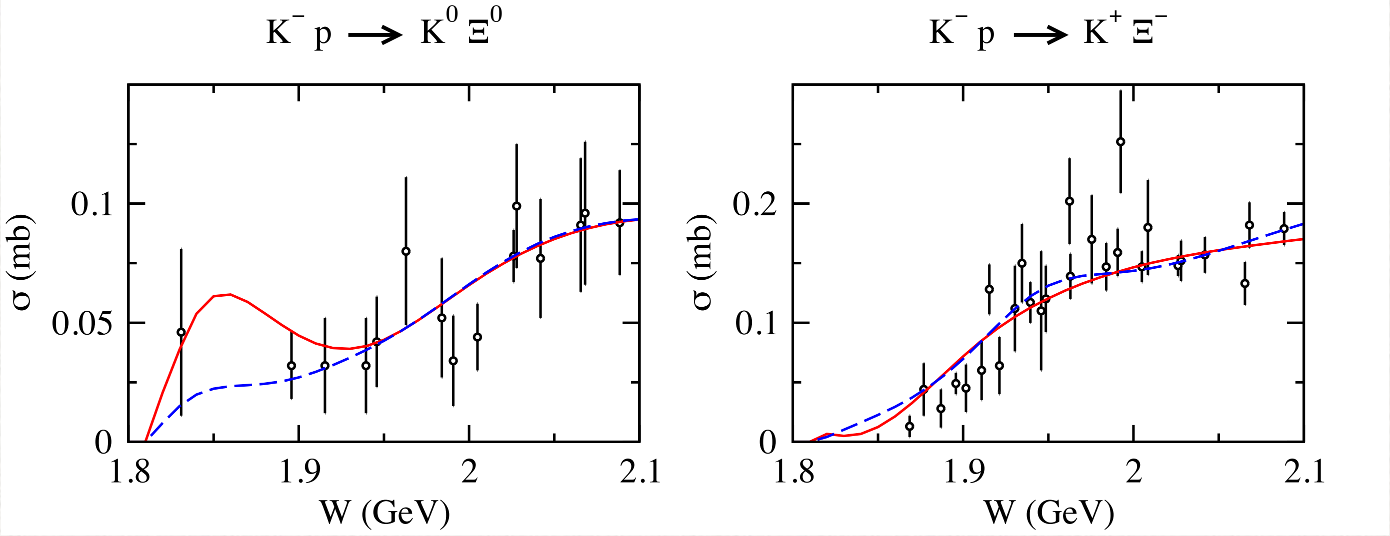
Kaon-Nucleon Scattering

- Coupled channel models

Magas, Feijoo, Ramos, AIPCP **1606** (2014)



Kamano, Nakamura, Lee, Sato, arXiv:1407.6839



Highly model-dependent
Needs more precise data

PARITY DETERMINATION

Issue

- Spin-parity quantum numbers
  - not easy: cf. spin of the Ω^- *BABAR*, PRL **97** (2006)
  - parity of $\Xi(1318)$?

Ξ^0 $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $****$

The parity has not actually been measured, but $+$ is of course expected.

$\Xi(1530)$ P_{13} $I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: $****$

This is the only Ξ resonance whose properties are all reasonably well known. Assuming that the Λ_c^+ has $J^P = 1/2^+$, AUBERT 08AK, in a study of $\Lambda_c^+ \to \Xi^- \pi^+ K^+$, finds conclusively that the spin of the $\Xi(1530)^0$ is 3/2. In conjunction with SCHLEIN 63B and BUTTON-SHAFER 66, this proves also that the parity is $+$.

Parity Determination

- Difficulty
  - Mostly, the decay distribution is used
  - Ground state: no strong decay
  - Remove model-dependence
- A model-independent method (based on symmetries only)
  - Use the anti-kaon beam: larger cross section

    $$\bar{K}(q)N(p) \to K(q')\Xi(p')$$

  - Define

    $$\hat{\mathbf{n}}_1 \equiv (\mathbf{q} \times \mathbf{q}') \times \mathbf{q} / |(\mathbf{q} \times \mathbf{q}') \times \mathbf{q}|$$
    $$\hat{\mathbf{n}}_2 \equiv (\mathbf{q} \times \mathbf{q}') / |\mathbf{q} \times \mathbf{q}'|$$

  - Choose $\hat{\mathbf{q}} = \hat{\mathbf{z}}, \quad \hat{\mathbf{n}}_1 = \hat{\mathbf{x}}, \quad \hat{\mathbf{n}}_2 = \hat{\mathbf{y}}$

    $\hat{\mathbf{q}}$ and $\hat{\mathbf{n}}_1$ form the reaction plane

Spin Structure

- The general spin-structure of the reaction amplitude

$$\hat{M}^{+} = M_0 + M_2 \boldsymbol{\sigma} \cdot \hat{\mathbf{n}}_2, \qquad \text{for positive parity } \Xi$$

$$\hat{M}^{-} = M_1 \boldsymbol{\sigma} \cdot \hat{\mathbf{n}}_1 + M_3 \boldsymbol{\sigma} \cdot \hat{\mathbf{n}}_3, \qquad \text{for negative parity } \Xi$$

$$\Rightarrow \hat{M} = \sum_{m=0}^{3} M_m \sigma_m$$

where $M_1 = M_3 = 0$ for positive parity Ξ

and $M_0 = M_2 = 0$ for negative parity Ξ

- The cross section

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \operatorname{Tr}\left(\hat{M}\hat{M}^{\dagger}\right) = \sum_{m=0}^{3} |M_m|^2$$

Spin-Transfer Coefficient

- (Diagonal) spin-transfer coefficient

$$\frac{d\sigma}{d\Omega} K_{ii} = \frac{1}{2} \mathrm{Tr} \left(\hat{M} \sigma_i \hat{M}^\dagger \sigma_i \right) = |M_0|^2 + |M_i|^2 - \sum_{k \neq i} |M_k|^2$$

$$K_{ii} = \frac{d\sigma_i(++) - d\sigma_i(+-)}{d\sigma_i(++) + d\sigma_i(+-)} \qquad d\sigma_i(s_N, s_\Xi)$$

- Therefore, when *i*=*y*, $K_{ii} = \pi_\Xi (= \pm 1)$
- Double polarization observable
  - The Ξ is self-analyzing, so we need polarized nucleon target only
  - should be possible to measure at J-PARC
- Generalization to Ξ* resonances and to Ξ photoproduction is also possible

$$\pi_\Xi = \frac{K_{yy}}{\Sigma}$$

Nakayama, YO, Haberzettl, PRC **85** (2012) 042201(R)

Single Spin Asymmetries

- Target Nucleon asymmetry

$$\frac{d\sigma}{d\Omega}T_i \equiv \frac{1}{2}\mathrm{Tr}\left(M\sigma_i M^\dagger\right) = 2\mathrm{Re}[M_0 M_i^*] + 2\mathrm{Im}[M_j M_k^*]$$

- Recoil Cascade asymmetry

$$\frac{d\sigma}{d\Omega}P_i \equiv \frac{1}{2}\mathrm{Tr}\left(MM^\dagger\sigma_i\right) = 2\mathrm{Re}[M_0 M_i^*] - 2\mathrm{Im}[M_j M_k^*]$$

Positive parity Cascade

$$\frac{d\sigma}{d\Omega}(T_y + P_y) = 4\mathrm{Re}[M_0 M_2^*]$$

$$\frac{d\sigma}{d\Omega}(T_y - P_y) = 0$$

Negative parity Cascade

$$\frac{d\sigma}{d\Omega}(T_y + P_y) = 0$$

$$\frac{d\sigma}{d\Omega}(T_y - P_y) = 4\mathrm{Im}[M_3 M_1^*]$$

- More details for spin-1/2 and 3/2 Ξ baryon production can be found in Jackson, YO, Haberzettl, Nakayama, PRC 89 (2014) 025206

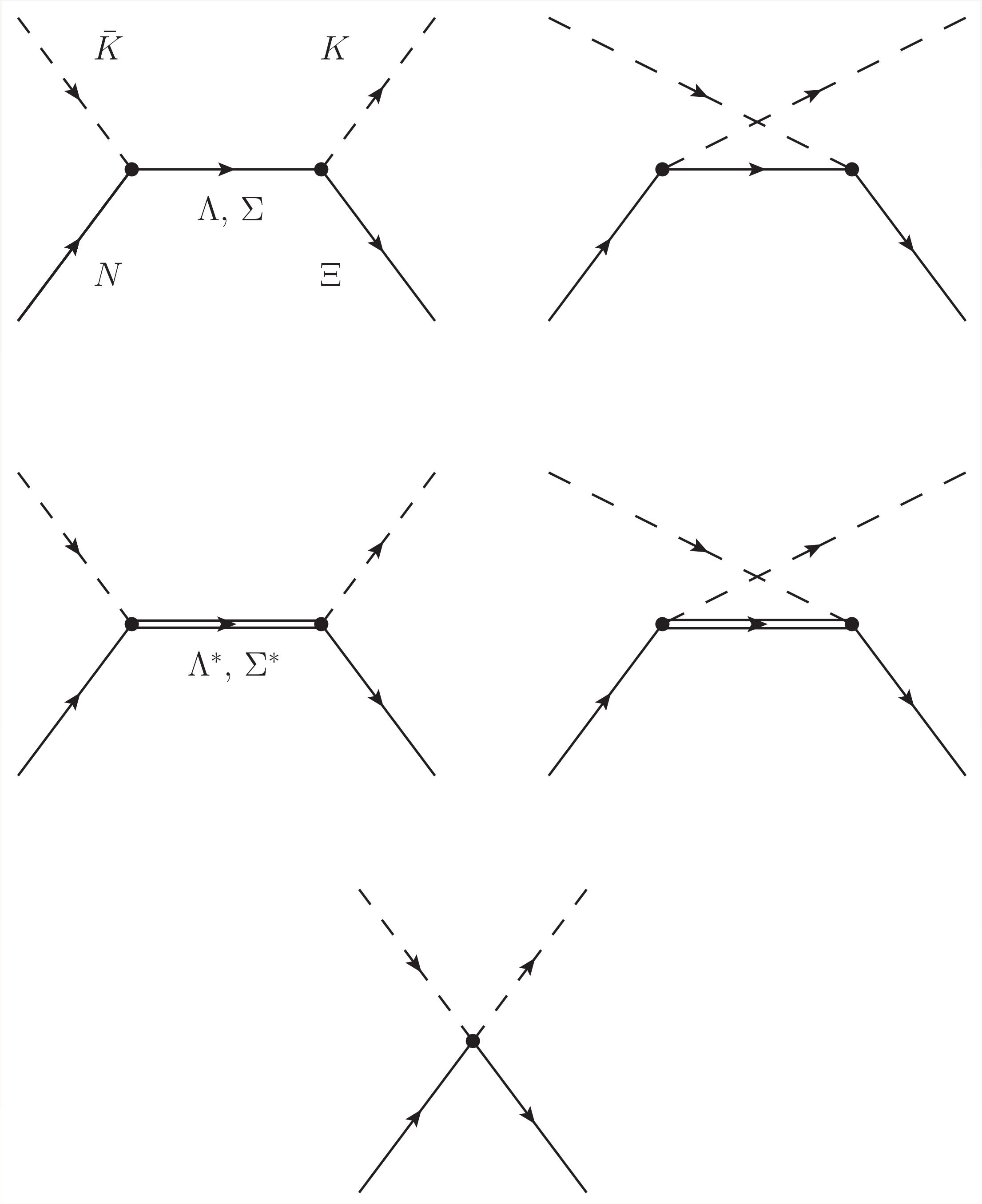
MODEL STUDIES ON Ξ PRODUCTION

PLANS

- JLab
  - 12 GeV upgrade: The Very Strange Collaboration
  - Ξ spectroscopy program and Ω photoproduction
- J-PARC
  - $\bar{K}N \to K\Xi$ and $\pi N \to KK\Xi$
- PANDA @ FAIR
  - $\bar{p}p \to \bar{\Xi}\Xi$
- The reaction of $\bar{K}N \to K\Xi$
  - the simplest way to produce Ξ
  - data of 1970s and 1980s
  - Theoretical studies are rare.

MODEL DESCRIPTION

- Effective Lagrangian
- Tree level calculation
- No *t*-channel exchange (no exotics)
- Hyperon resonances (Λ^*, Σ^*)



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HYPERON RESONANCES

- PDG List

TABLE I. The Λ and Σ hyperons listed by the Particle Data Group [17] as three-star or four-star states. The decay widths and branching ratios of high-mass resonances $m_Y > 1.6$ GeV are in a broad range, and the coupling constants are determined from their central values.

Λ states					Σ states				
State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Lambda K}\rvert$	State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Sigma K}\rvert$
Λ(1116)	$1/2^+$		****		Σ(1193)	$1/2^+$		****	
Λ(1405)	$1/2^-$	≈ 50	****		Σ(1385)	$3/2^+$	≈ 37	****	
Λ(1520)	$3/2^-$	≈ 16	****						
Λ(1600)	$1/2^+$	≈ 150	***	4.2	Σ(1660)	$1/2^+$	≈ 100	***	2.5
Λ(1670)	$1/2^-$	≈ 35	****	0.3	Σ(1670)	$3/2^-$	≈ 60	****	2.8
Λ(1690)	$3/2^-$	≈ 60	****	4.0	Σ(1750)	$1/2^-$	≈ 90	***	0.5
Λ(1800)	$1/2^-$	≈ 300	***	1.0	Σ(1775)	$5/2^-$	≈ 120	****	
Λ(1810)	$1/2^+$	≈ 150	***	2.8	Σ(1915)	$5/2^+$	≈ 120	****	
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Λ(1830)	$5/2^-$	≈ 95	****		Σ(2030)	$7/2^+$	≈ 180	****	
Λ(1890)	$3/2^+$	≈ 100	****	0.8	Σ(2250)	$?^?$	≈ 100	***	
Λ(2100)	$7/2^-$	≈ 200	****						
Λ(2110)	$5/2^+$	≈ 200	***						
Λ(2350)	$9/2^+$	≈ 150	***						

EFFECTIVE LAGRANGIAN

Interaction Lagrangian

For spin-5/2 hyperons [25, 65],

$$\mathcal{L}^{5/2(\pm)}_{\Lambda NK} = \frac{g_{\Lambda NK}}{m_K^2}\bar{\Lambda}^{\mu\nu}\left\{D^{5/2(\pm)}_{\mu\nu}\bar{K}\right\}N + H.c. \ , \quad \text{(A.5a)}$$

$$\mathcal{L}^{5/2(\pm)}_{\Sigma NK} = \frac{g_{\Sigma NK}}{m_K^2}\bar{\mathbf{\Sigma}}^{\mu\nu}\cdot\left\{D^{5/2(\pm)}_{\mu\nu}\bar{K}\right\}\boldsymbol{\tau}N + H.c. \ , \quad \text{(A.5b)}$$

$$\mathcal{L}^{5/2(\pm)}_{\Xi\Lambda K_c} = \frac{g_{\Xi\Lambda K_c}}{m_K^2}\bar{\Xi}\left\{D^{5/2(\pm)}_{\mu\nu}K_c\right\}\Lambda^{\mu\nu} + H.c. \ , \quad \text{(A.5c)}$$

$$\mathcal{L}^{5/2(\pm)}_{\Xi\Sigma K_c} = \frac{g_{\Xi\Sigma K_c}}{m_K^2}\bar{\Xi}\boldsymbol{\tau}\left\{D^{5/2(\pm)}_{\mu\nu}K_c\right\}\cdot\mathbf{\Sigma}^{\mu\nu} + H.c. \ . \quad \text{(A.5d)}$$

For spin-7/2 hyperons [25, 65],

$$\mathcal{L}^{7/2(\pm)}_{\Lambda NK} = \frac{g_{\Lambda NK}}{m_K^3}\bar{\Lambda}^{\mu\nu\rho}\left\{D^{7/2(\pm)}_{\mu\nu\rho}\bar{K}\right\}N + H.c. \ , \quad \text{(A.6a)}$$

$$\mathcal{L}^{7/2(\pm)}_{\Sigma NK} = \frac{g_{\Sigma NK}}{m_K^3}\bar{\mathbf{\Sigma}}^{\mu\nu\rho}\cdot\left\{D^{7/2(\pm)}_{\mu\nu\rho}\bar{K}\right\}\boldsymbol{\tau}N + H.c. \ , \quad \text{(A.6b)}$$

$$\mathcal{L}^{7/2(\pm)}_{\Xi\Lambda K_c} = \frac{g_{\Xi\Lambda K_c}}{m_K^3}\bar{\Xi}\left\{D^{7/2(\pm)}_{\mu\nu\rho}K_c\right\}\Lambda^{\mu\nu\rho} + H.c. \ , \quad \text{(A.6c)}$$

$$\mathcal{L}^{7/2(\pm)}_{\Xi\Sigma K_c} = \frac{g_{\Xi\Sigma K_c}}{m_K^3}\bar{\Xi}\boldsymbol{\tau}\left\{D^{7/2(\pm)}_{\mu\nu\rho}K_c\right\}\cdot\mathbf{\Sigma}^{\mu\nu\rho} + H.c. \ . \quad \text{(A.6d)}$$

$$D^{1/2(\pm)}_{B'BM} \equiv -\Gamma^{(\pm)}\left[\pm i\lambda + \frac{1-\lambda}{m_{B'} \pm m_B}\not{\partial}\right] \ ,$$

$$D^{3/2(\pm)}_{\nu} \equiv \Gamma^{(\mp)}\partial_\nu \ ,$$

$$D^{5/2(\pm)}_{\mu\nu} \equiv -i\Gamma^{(\pm)}\partial_\mu\partial_\nu \ ,$$

$$D^{7/2(\pm)}_{\mu\nu\rho} \equiv -\Gamma^{(\mp)}\partial_\mu\partial_\nu\partial_\rho \ ,$$

$$\hat{S}^{5/2}_r(p_r) = \left[(\not{p}_r - m_r)g - i\frac{\Delta}{2}\Gamma_r\right]^{-1}\Delta,$$

where

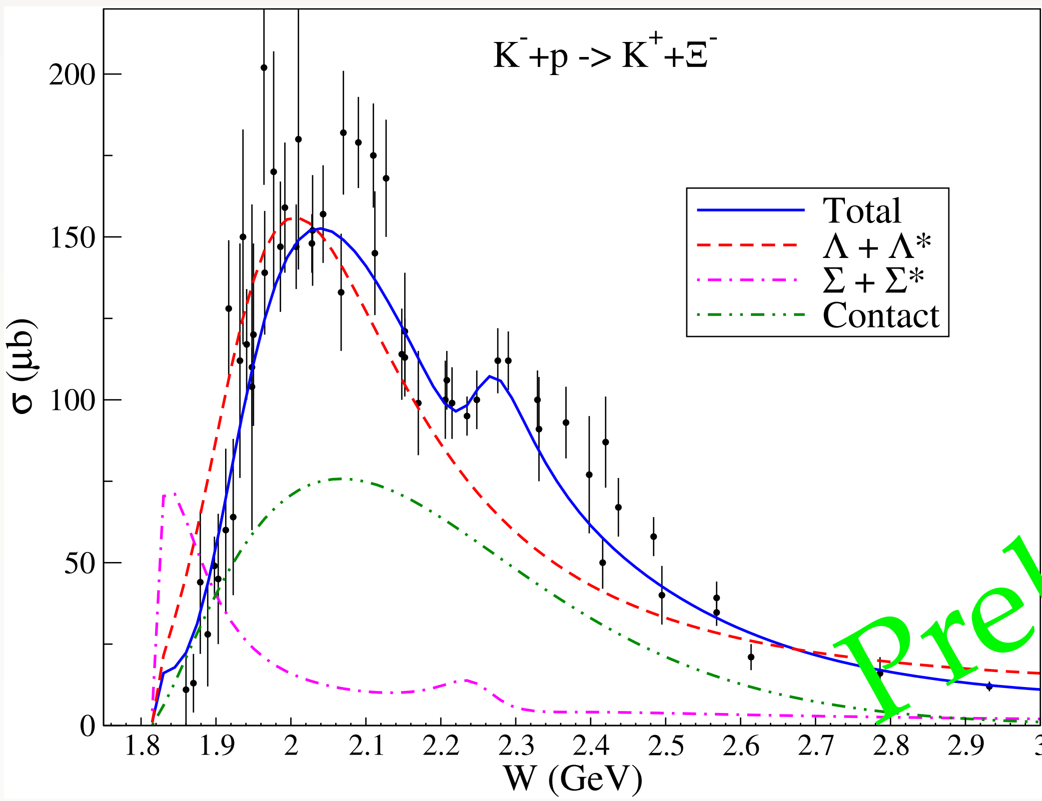
$$\begin{aligned}\Delta &\equiv \Delta^{\beta_1\beta_2}_{\alpha_1\alpha_2} \\ &= \frac{1}{2}\left(\bar{g}^{\beta_1}_{\alpha_1}\bar{g}^{\beta_2}_{\alpha_2} + \bar{g}^{\beta_2}_{\alpha_1}\bar{g}^{\beta_1}_{\alpha_2}\right) - \frac{1}{5}\bar{g}_{\alpha_1\alpha_2}\bar{g}^{\beta_1\beta_2} \\ &- \frac{1}{10}\left(\bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_1}\bar{g}^{\beta_2}_{\alpha_2} + \bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_2}\bar{g}^{\beta_1}_{\alpha_2} + \bar{\gamma}_{\alpha_2}\bar{\gamma}^{\beta_1}\bar{g}^{\beta_2}_{\alpha_1} \right. \\ &\left. + \bar{\gamma}_{\alpha_2}\bar{\gamma}^{\beta_2}\bar{g}^{\beta_1}_{\alpha_1}\right)\end{aligned}$$

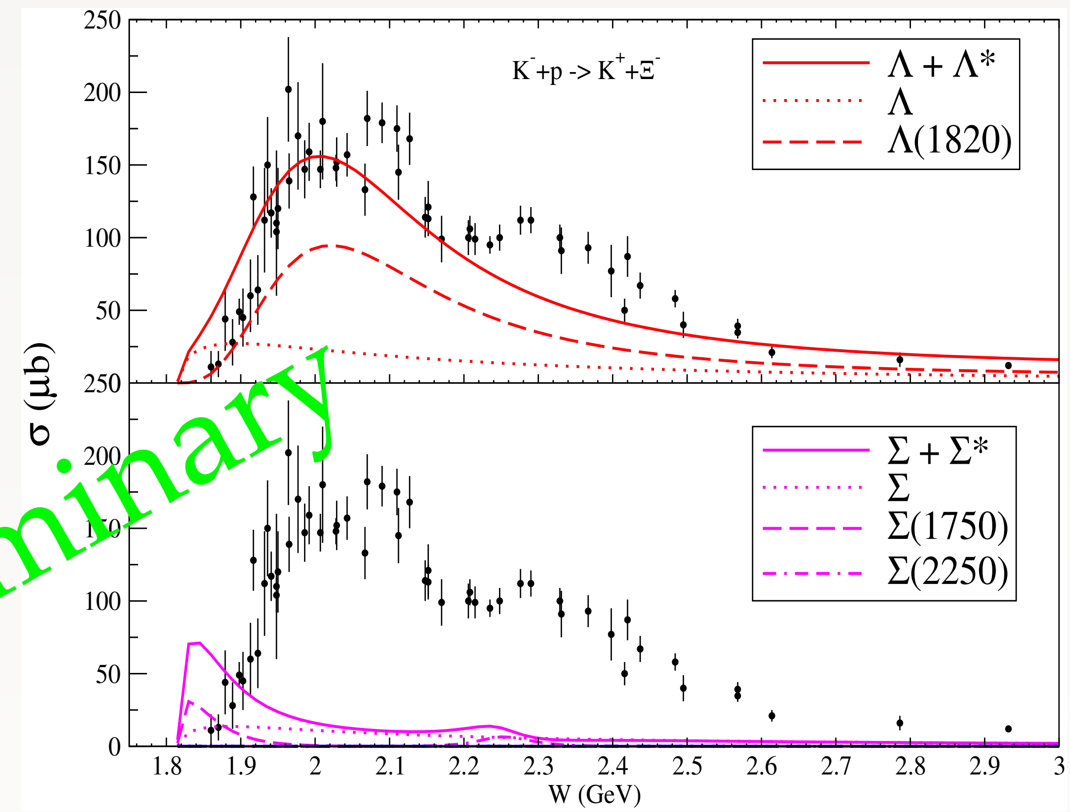
with

$$\bar{g}^{\mu\nu} \equiv g^{\mu\nu} - \frac{p^\mu p^\nu}{m_r^2}, \qquad \bar{\gamma}^\mu \equiv \gamma^\mu - \frac{p^\mu\not{p}}{m_r^2}.$$

RESULTS

- $K^- p \to K^+ \Xi^-$

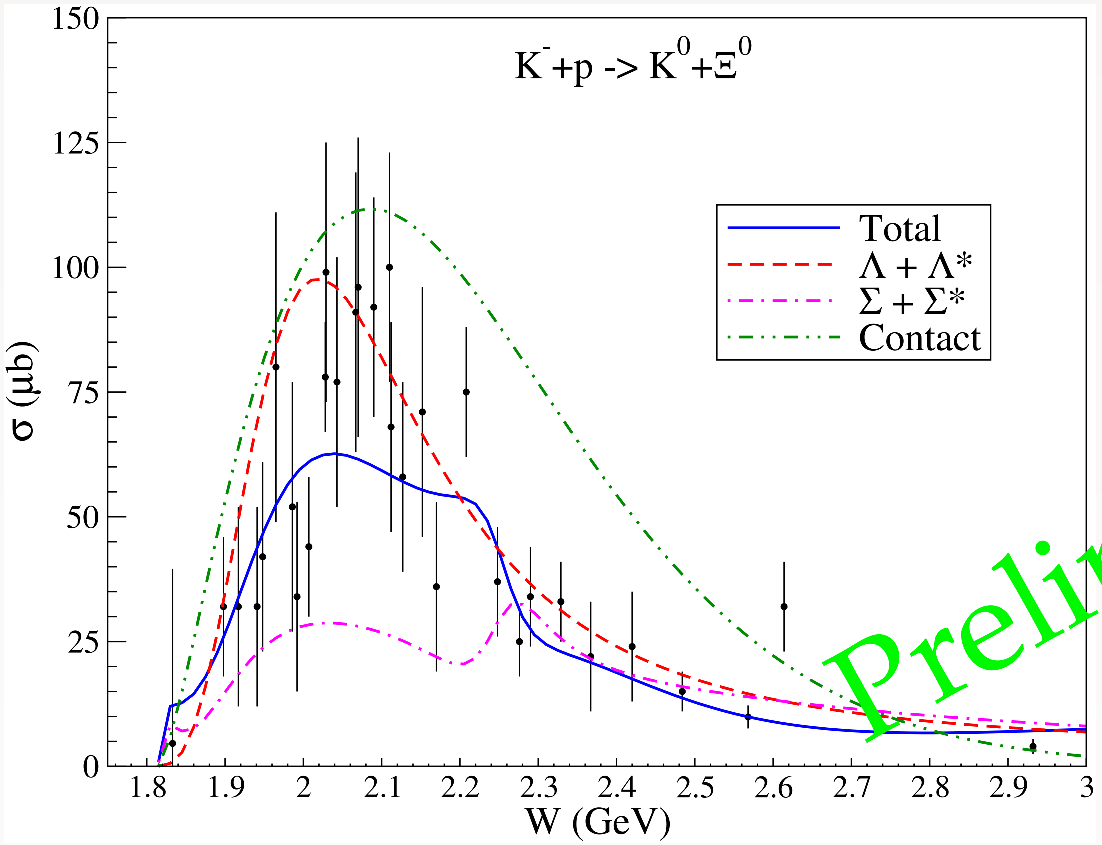


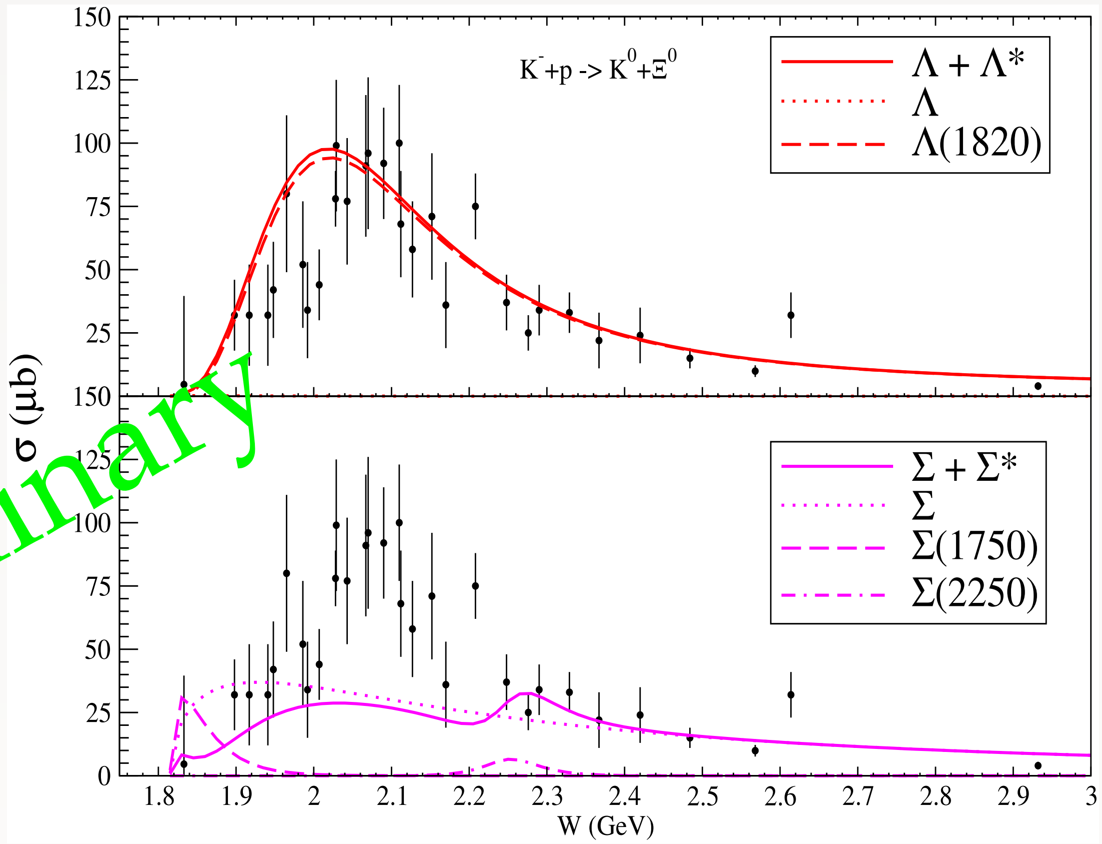


Y	J^P	$g_{N\Lambda K}$	$\lambda_{N\Lambda K}$	$g_{\Xi\Lambda K}$	$\lambda_{\Xi\Lambda K}$	Λ (MeV)	L'	$a^0_{L'}$	$a^1_{L'}$	$b^0_{L'}$	$b^1_{L'}$
$\Lambda(1116)$	$\frac{1}{2}^+$	**−13.24**	**1.0**	**3.52**	**1.0**	900	0	0.1392	−0.0610		
$\Lambda(1820)$	$\frac{5}{2}^+$	−5.85		5.85		900	1	−4.9423	−0.3853	−0.4508	−0.0903
$\Sigma(1193)$	$\frac{1}{2}^+$	**3.58**	**1.0**	− 13.26	**1.0**	900	2	5.0922	1.8164	−0.3853	0.7257
$\Sigma(1750)$	$\frac{1}{2}^-$	−0.66	1.0	0.66	1.0	900					
$\Sigma(2250)$	$\frac{3}{2}^+$	−0.24		0.24		900		$\Lambda_S = 1$ GeV		$\alpha = 2.75$	

Jackson, YO, Haberzettl, Nakayama, in preparation

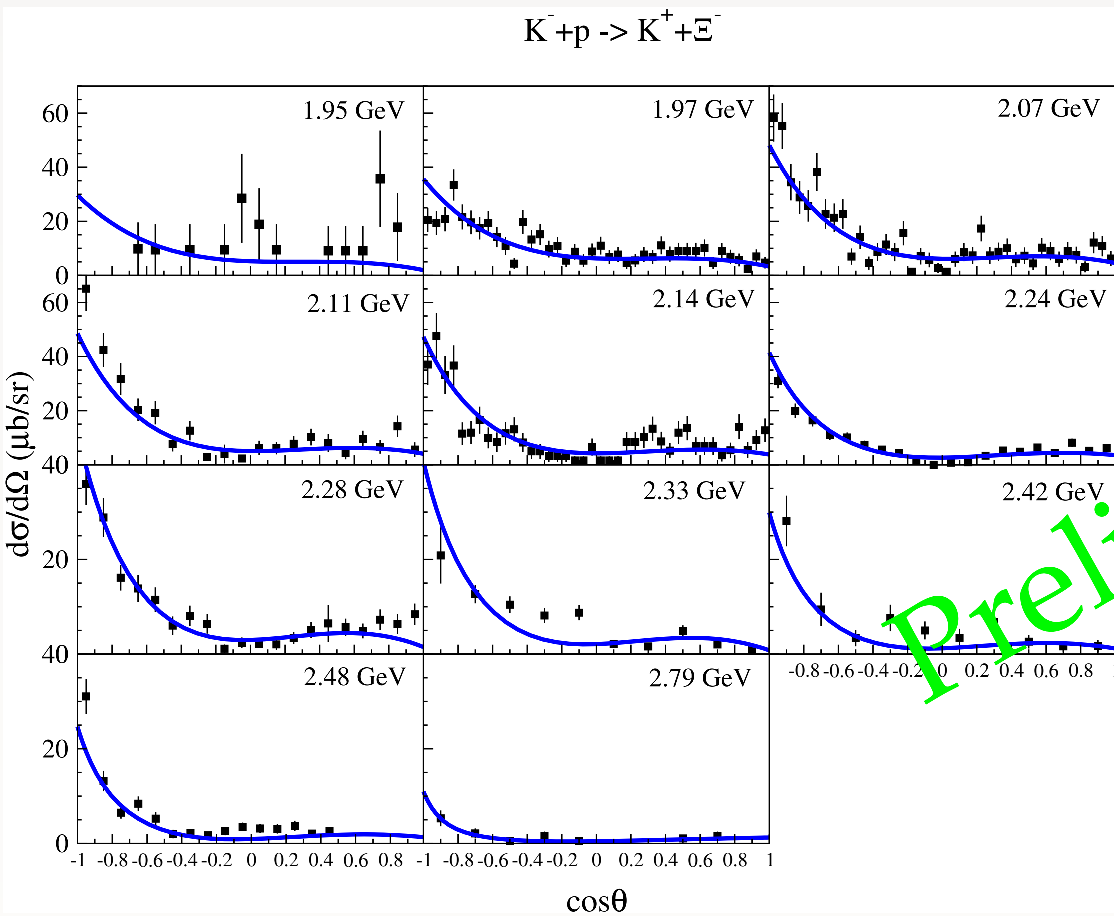
$K^- p \to K^0 \Xi^0$

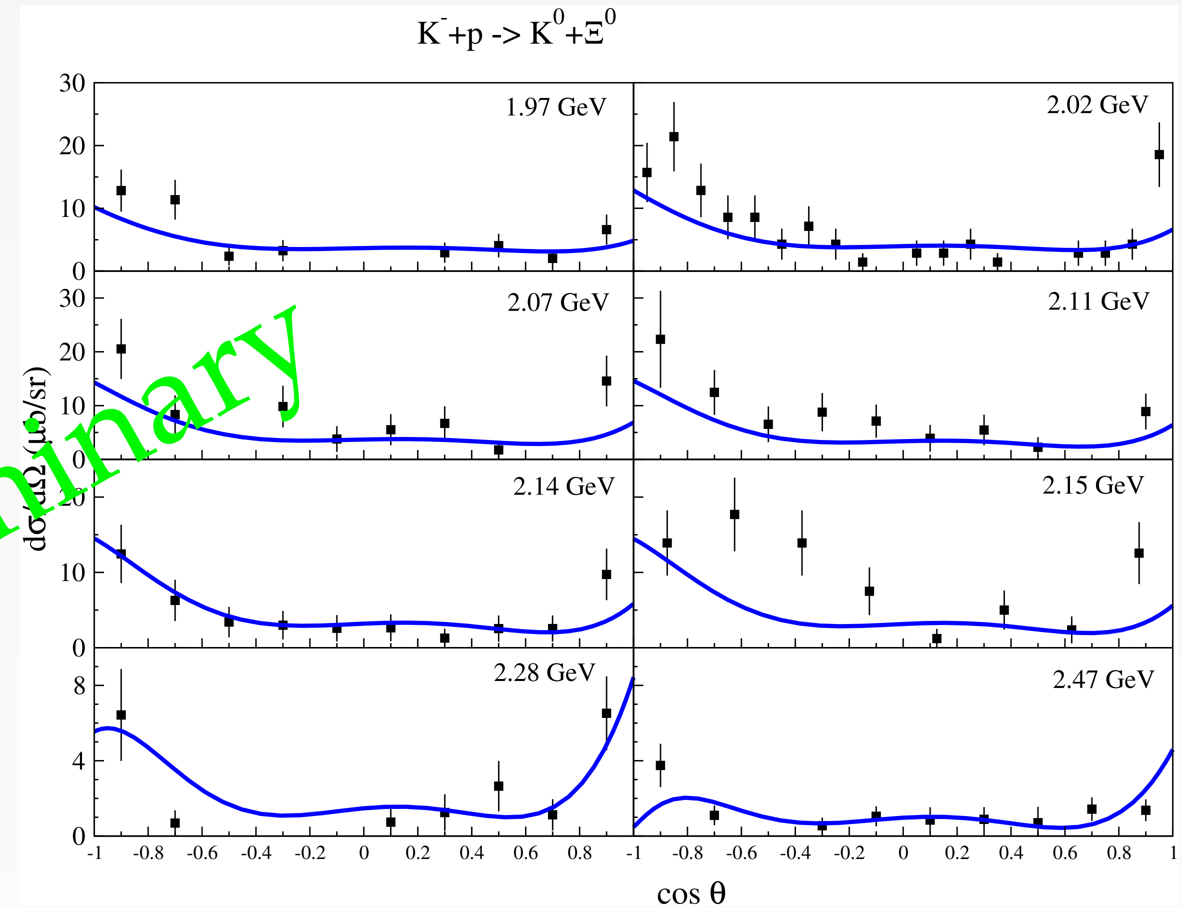

K-+p -> K0+Ξ0
Total
Λ + Λ*
Σ + Σ*
Contact
σ (μb)
W (GeV)


K-+p -> K0+Ξ0
Λ + Λ*
Λ
Λ(1820)
Σ + Σ*
Σ
Σ(1750)
Σ(2250)
σ (μb)
W (GeV)
Preliminary

RESULTS

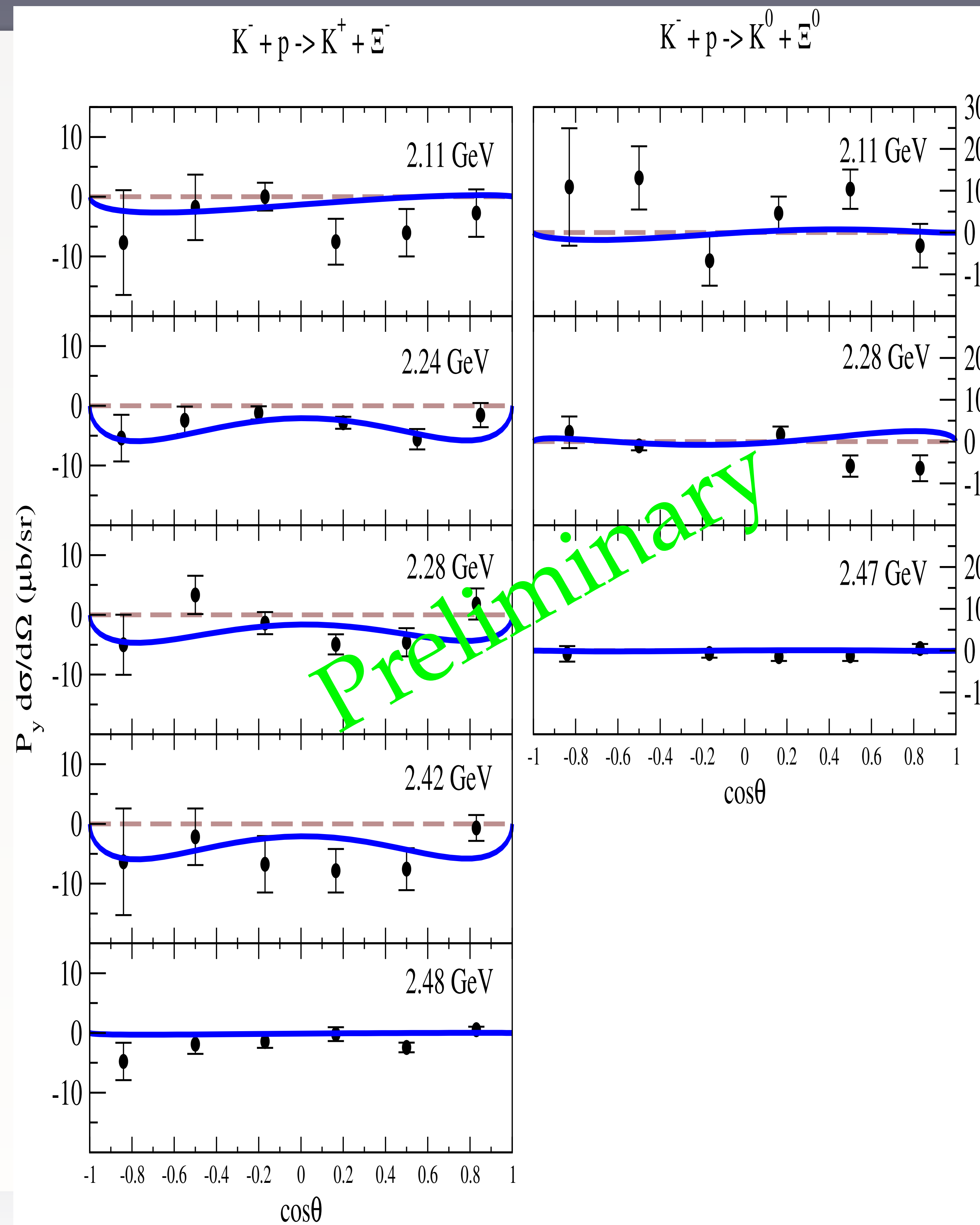
- differential cross sections (with *W*)





RESULTS

- recoil asymmetry *P*



SUMMARY & OUTLOOK

Summary & Outlook

- Study on the spectrum of Ξ baryons
  - opens a new window for understanding baryon structure
- Theoretical models for Ξ spectrum
  - different and even contradictory predictions
  - mass and quantum numbers of the third lowest state
  - Skyrme model: Ξ(1620) and Ξ(1690) as analogue states of *Λ*(1405)
- Experimental side: More precise data are needed
  - existence of Ξ(1620)
  - should confirm other poorly established Ξ resonances and their quantum numbers
  - almost no information about *Ω* baryons

Summary & Outlook

- Role of Λ and Σ resonances in Ξ production processes
  - offers a chance to study these resonances
  - higher mass and high spin resonances
- J-PARC gives a new chance for Ξ physics.
  - larger yields than photoproduction
  - needs various polarization measurements
- CLAS12 will open a new window.
- Production of Omega baryons