Cascade Physics

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Workshop:
“CASCADE PHYSICS:
A New Window on Baryon Spectroscopy”
Jefferson Laboratory
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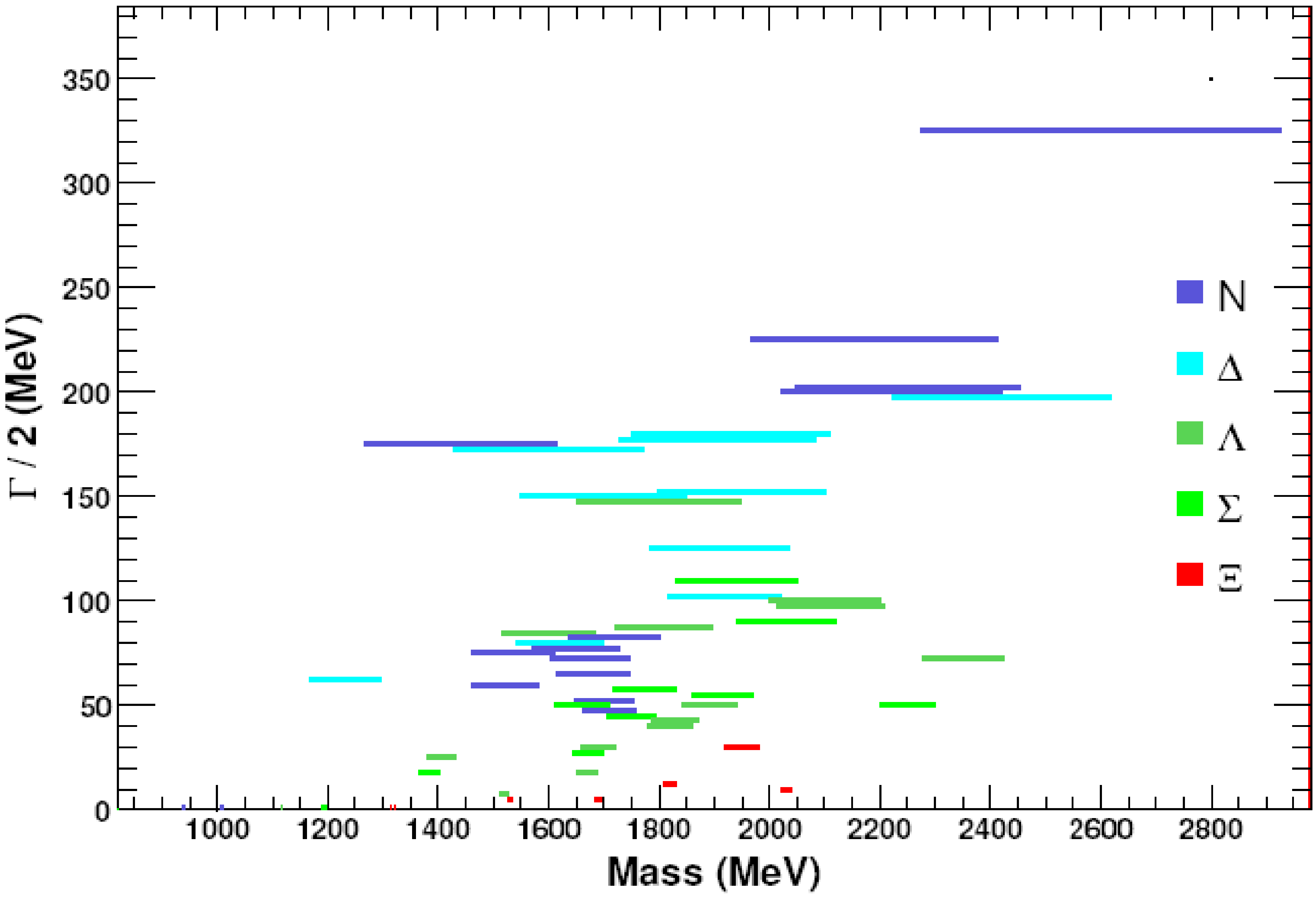
3 and 4-star Baryons: mass vs. width



Cascade Hyperons Ξ

Baryon number: B = +1

Strangeness: S = -2

Isospin: I = ½ electric charge Q = 0, -1

SU(3) classification: octet, decuplet

Experiment:

3 established	M, Γ, J, P	
3 identified	M, Γ,	(3 stars)
2 candidates	M	(2 stars)
3 iffy bumps	M	(1 star)

total 11 Ξ

Expected:

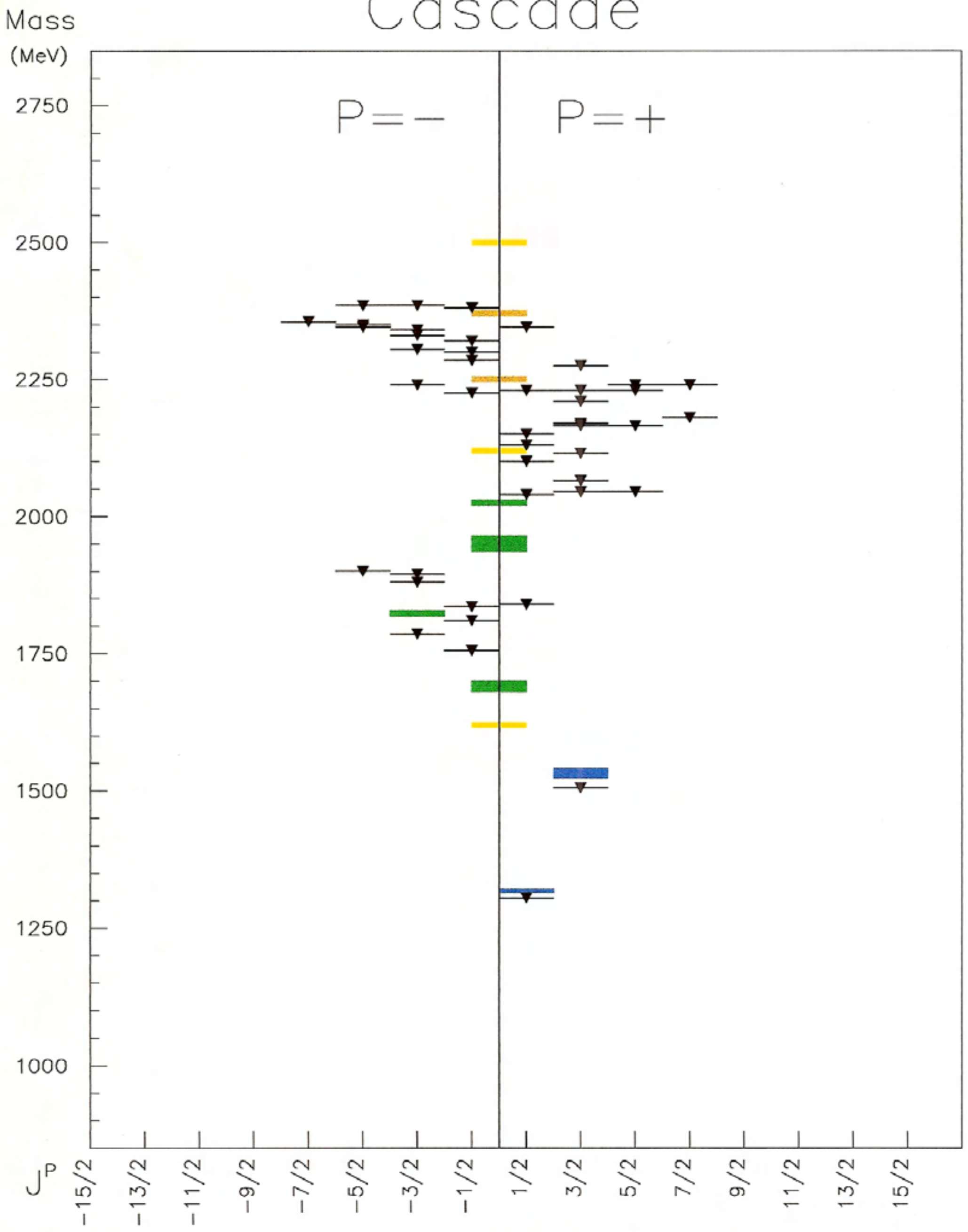
14+10	=24	(3-4 stars)
6+6	=12	(2 stars)
2+6	=8	(1 star)

Total 44Ξ

Capstick-Isgur

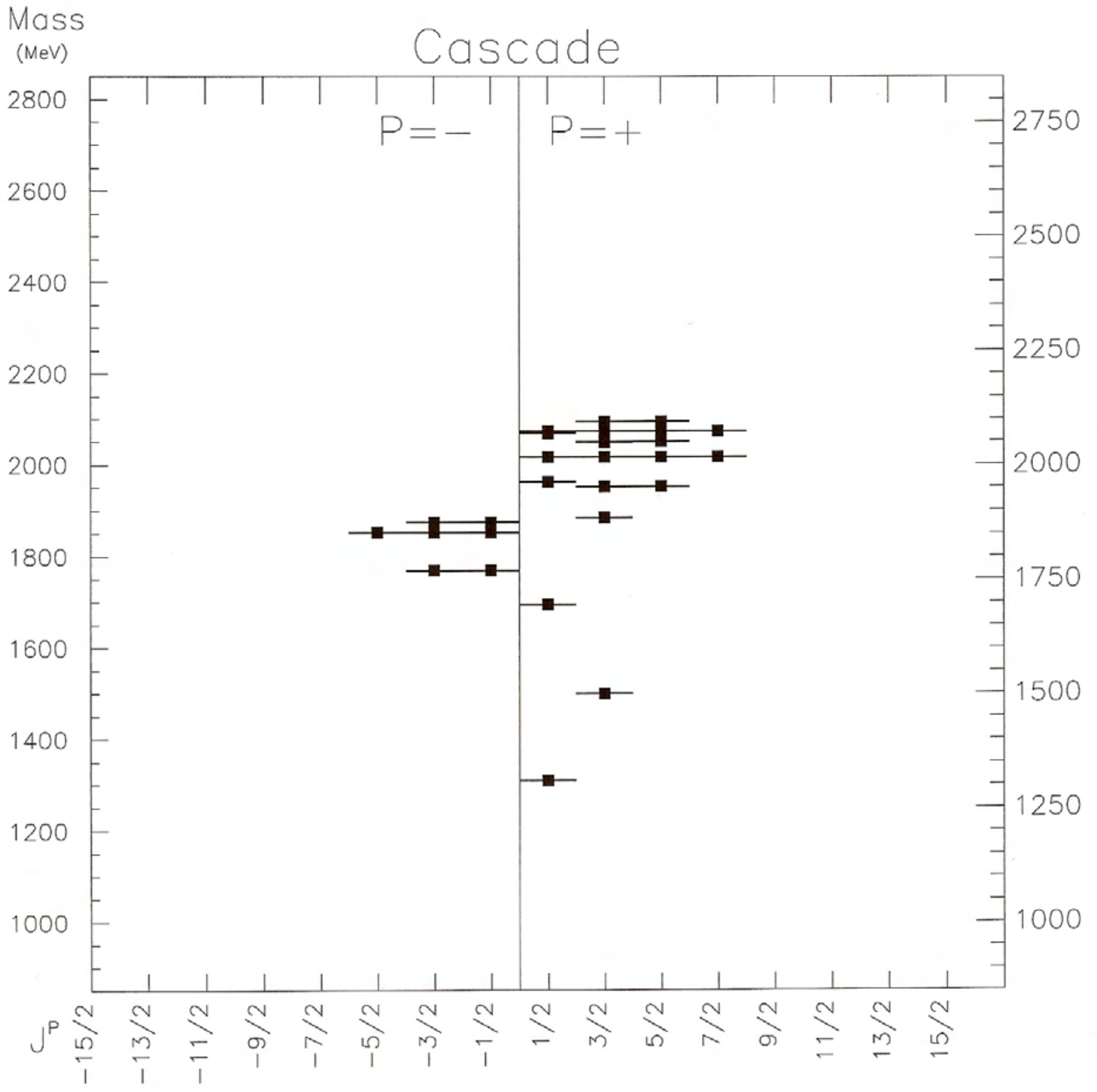
(m < 2.4 GeV) 44Ξ

Cascade



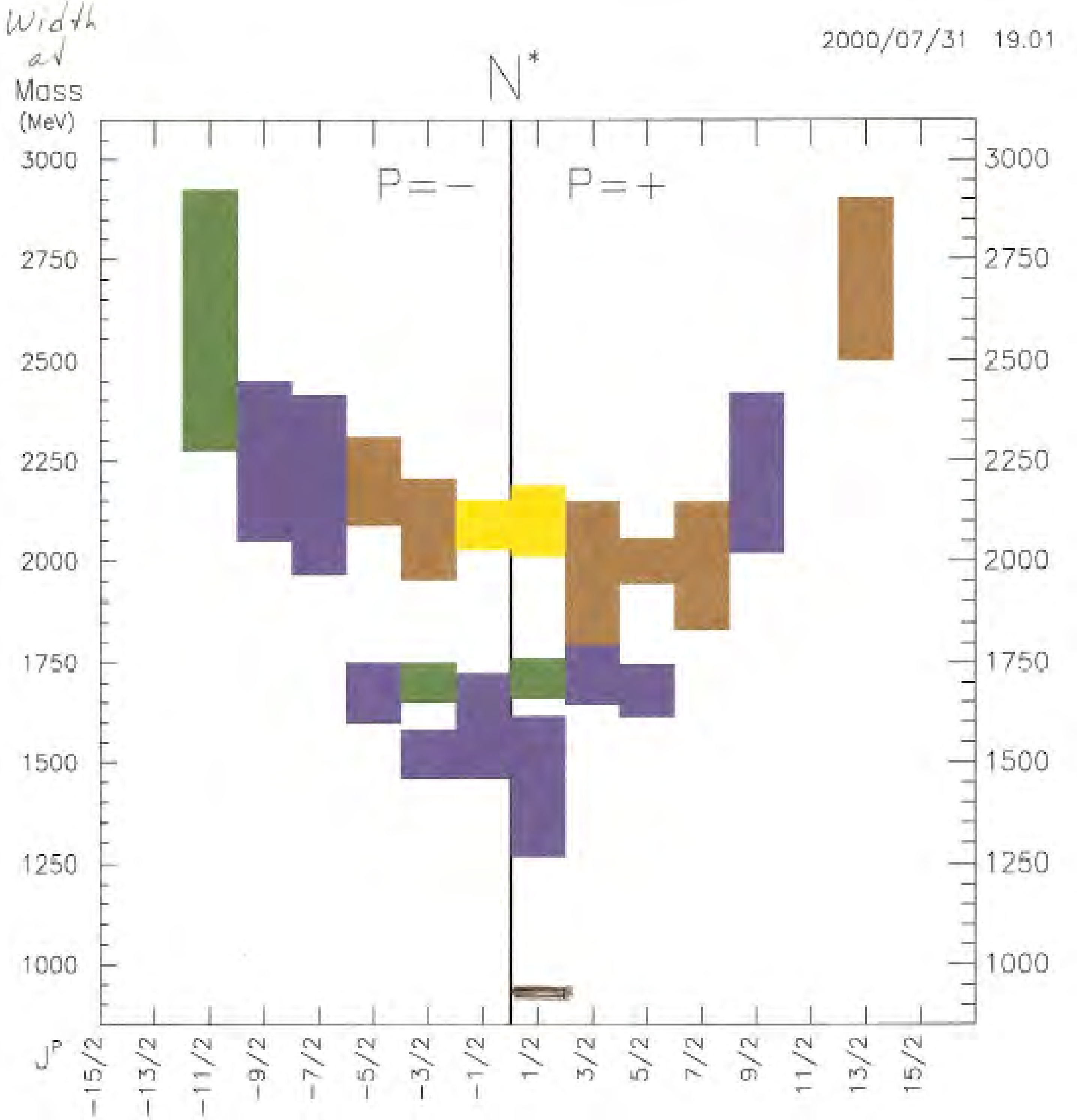
Theory: Capstick - Isgur

missing (m< 2.4 GeV): 41 Ξ states



Theoretical predictions for the Ξ hyperons (black rectangles) by Coester, Dannbom, and Riska, using the Covariant Quark Model.

missing ($m < 2.1$ GeV) : 24 Ξ



The Width, *Γ*, is used to define the mass range

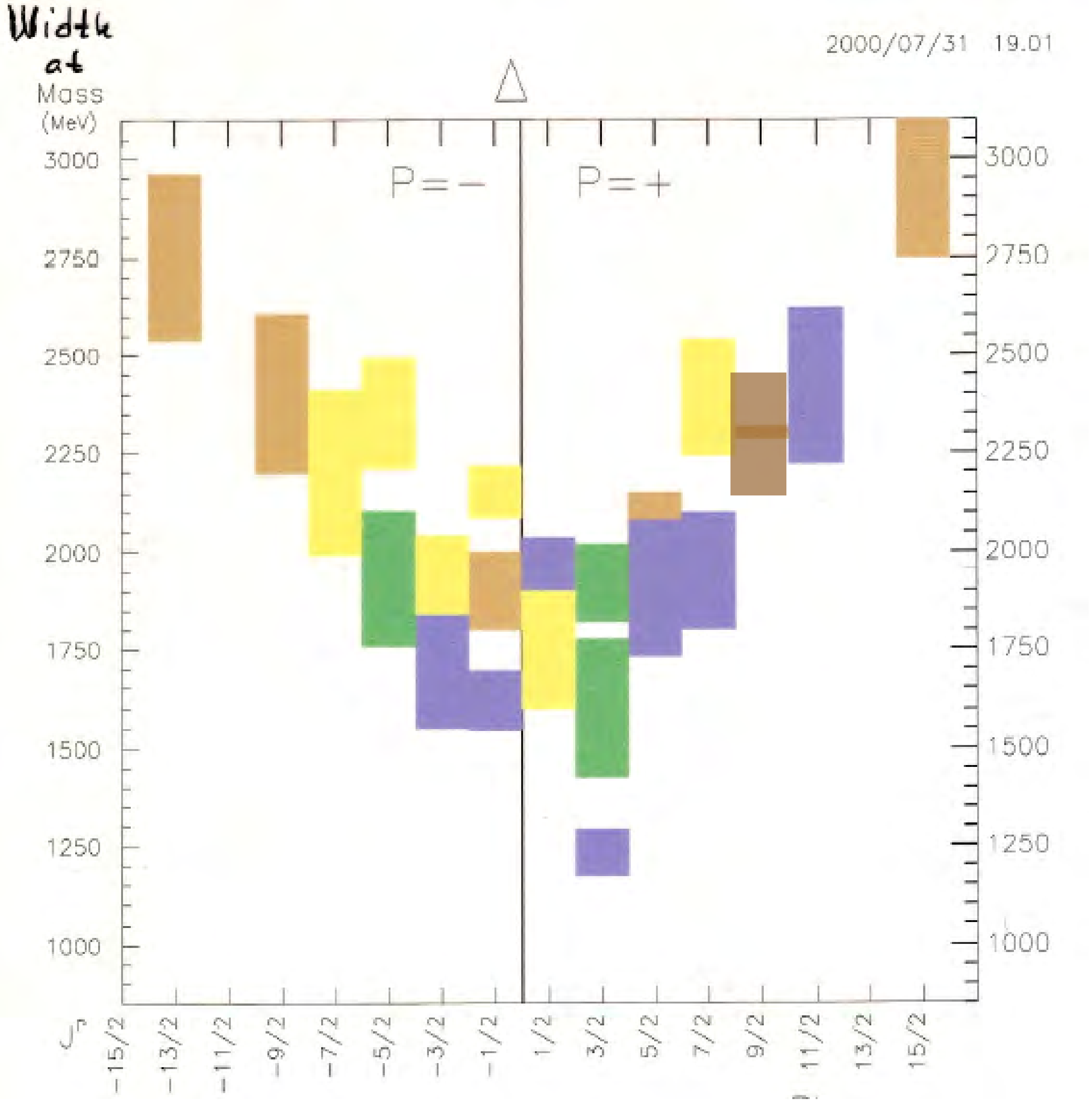
10 Blue=****

4 Green=***

6 Brown=**

2 Yellow=*

24



The Width, *Γ*,
is used to define
the mass range

7 Blue=****
3 Green=***
6 Brown=**
6 Yellow=*

22

The QCD Lagrangian

$$L_{\mathrm{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu}\, F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q\, \gamma^\mu\, (D_\mu)_{ij}\, \psi^j_q - \sum_q m_q\, \overline{\psi}^i_q\, \psi_{qi}\,,$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\, A^a_\nu - \partial_\nu\, A^a_\mu - g_s\, f_{abc}\, A^b_\mu\, A^c_\nu\,,$$

$$(D_\mu)_{ij} = \delta_{ij}\, \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\,,$$

Interpretation

$$L_{\mathrm{QCD}} = L_{\mathrm{glue}} + L_{\mathbf{quark}}$$

$$\begin{aligned} L_{\mathrm{QCD}} &= \overbrace{-\tfrac{1}{4} F_\mu F^\mu}^{L_{\mathrm{glue}}} \overbrace{+ \overline{\Psi}_q \mathrm{D} \Psi_q - \overline{\Psi}_q m_q \Psi_q}^{L_{\mathrm{quark}}} \\ &= \overbrace{-\tfrac{1}{4} F_\mu F^\mu + \overline{\Psi}_q \mathrm{D} \Psi_q}^{L_0} \overbrace{- \overline{\Psi}_q m_q \Psi_q}^{L_m} \\ &= L_0 + L_m \end{aligned}$$

g_s = strong coupling constant.
A_μ = gluon field.
ψ_q = quark field.

$L_{\mathrm{glue}} = f(g_s, A_\mu)$
$L_{\mathrm{quark}} = f(g_s, \Psi_q, A_\mu, m_q)$
$L_0 = f(g_s, A_\mu, \Psi_q)$
$L_m = f(\Psi_q, m_q)$

L_0 embodies the universality of the strong interactions. It conserves isospin, charge symmetry, G-parity, and SU(3).

Consequences of SU(3) FS

A. Occurance

A1. For every N* exists a Λ* of same J^P with

$\delta m \approx 150 \pm 30$ MeV

$m_\Lambda (J^P) = m_{N*}(J^P)[1+(m_s - m_d)/m_{N*} + \delta m(s, fL)$

A2. For every octet Λ* exists a N*

A3. Singlet Λ* has no N* companion

B. Ground state mass relations

B1. Gell-Mann – Okubo: octet relation

B2. Gell-Mann: decuplet equal spacing

B3. Coleman – Glashow: isospin relation

B4. de Rujula – Georgi – Glashow

B5. Okubo – Gursey – Radicati

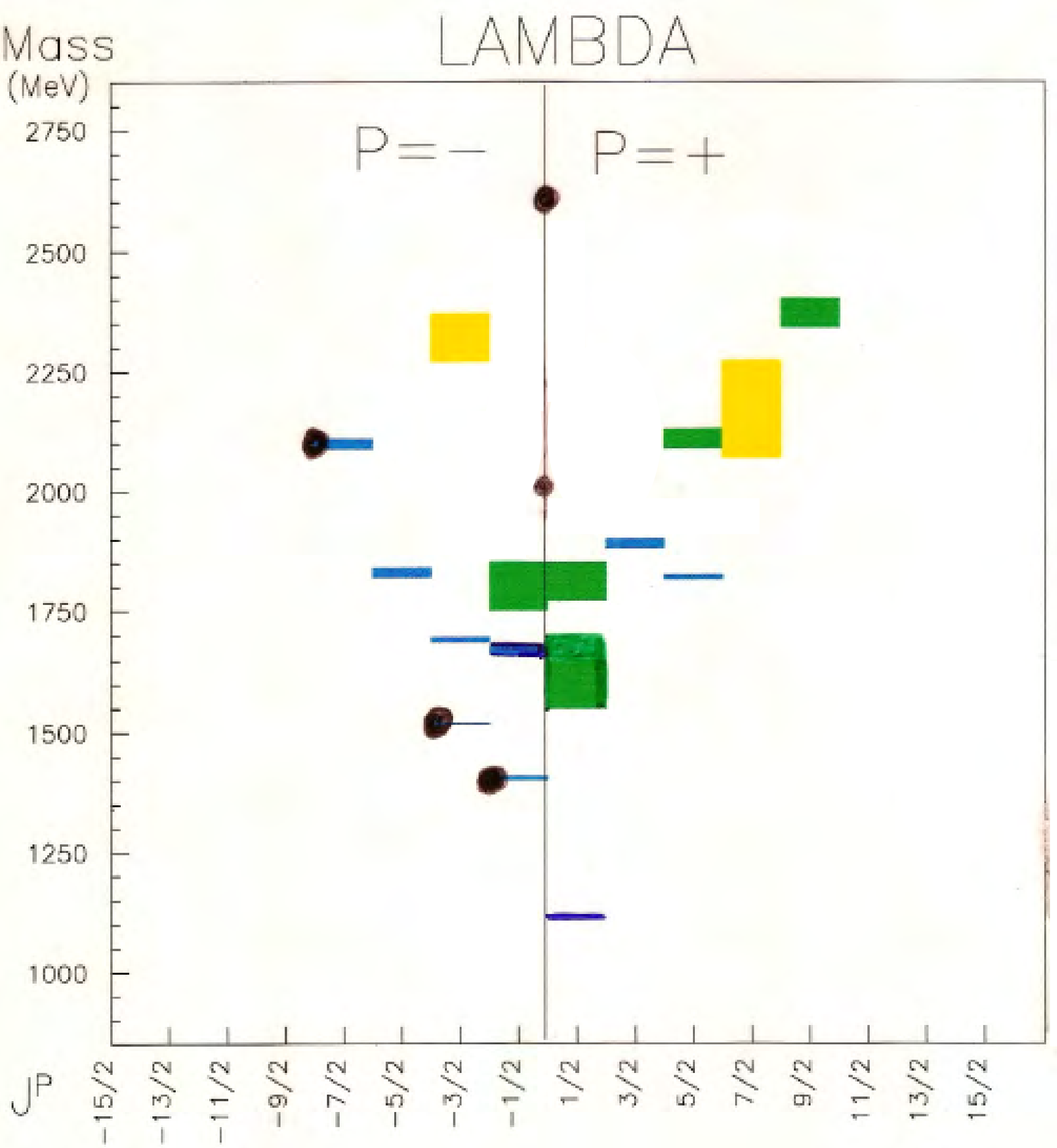
Consequences of SU(3) FS

C. Cross-section, polarization equalities

- C1. $K^- p \to \eta\Lambda \leftrightarrow \pi^- p \to \eta n$
- C2. $K^- p \to \pi^0\pi^0\Lambda \leftrightarrow \pi^- p \to \pi^0\pi^0 n$
  $K^- p \to \pi^0\pi^0\Lambda \leftrightarrow K^- p \to \pi^0\pi^0\Sigma$

D. Distinct features

- D1. Roper charact. $N(1440)\frac{1}{2}^+ \leftrightarrow \Lambda(1600)\frac{1}{2}^+$
- D2. Strong η emitter $N(1535)\frac{1}{2}^- \leftrightarrow \Lambda(1670)\frac{1}{2}^-$

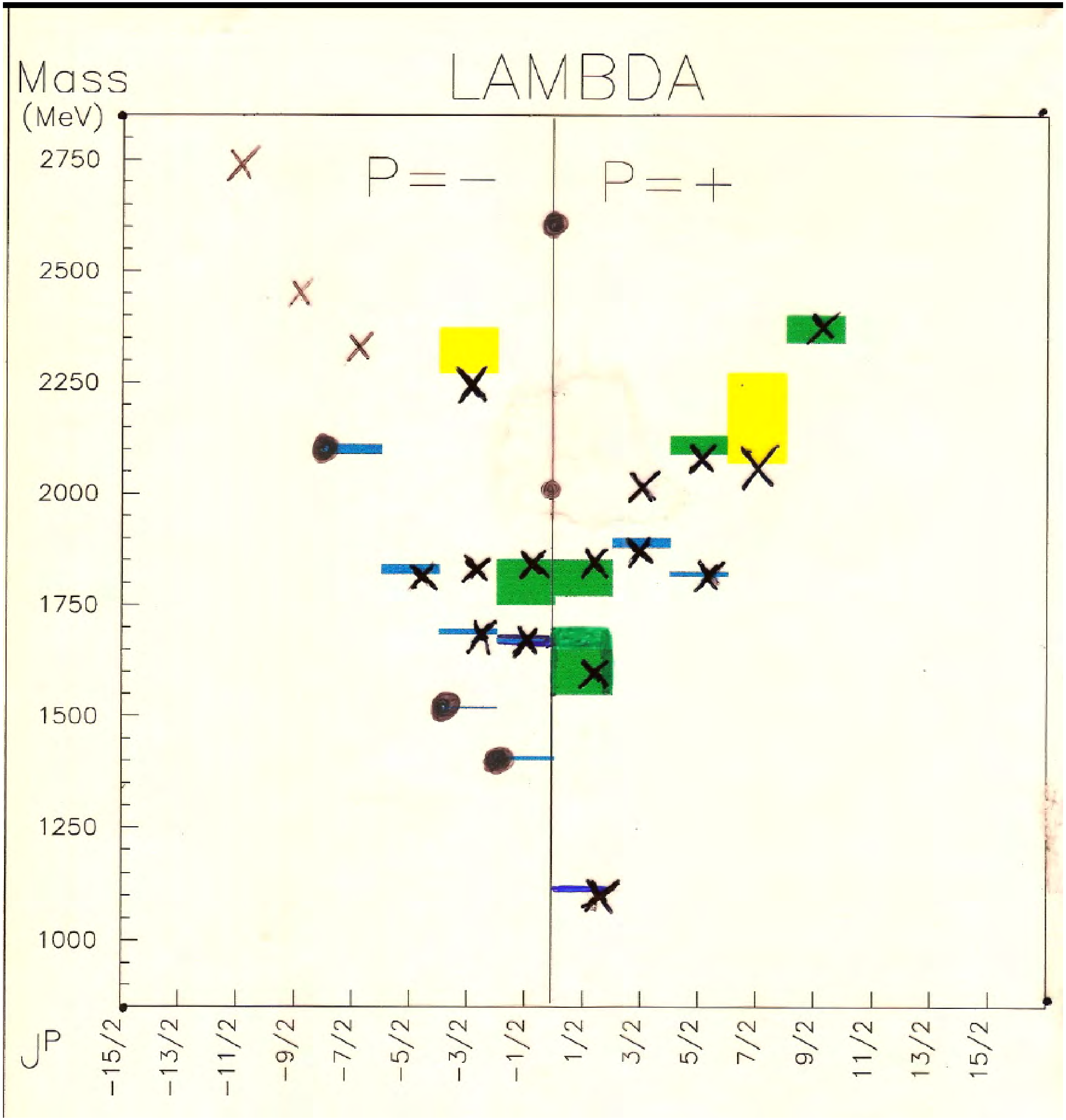


X = N*+160MeV

● = Flavor singlet Λ

9 Blue=****
5 Green=***
0 Brown=**
2 Yellow=*

16



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16

G–M–O Octet Mass Relation

$$3\Lambda + \Sigma \quad = \quad 2(N + \Xi)$$

(L) (R)

J^P	(L–R)/½(L+R)
$\frac{1}{2}^+$	0.5%
$(3/2)^-$	-0.3%
$(5/2)^+$	-0.5%

G–M decuplet equal spacing

Fam. Δ Σ^* Ξ^* Ω^-

Exp. 153 149 139 MeV

average: 147 MeV

$< 0.5\%$

Flavor Symmetry of QCD

$\pi^- p \to \eta n$	$K^- p \to \eta \Lambda$
1. sharp onset	**1.** sharp onset
2. $\sigma = (21 \pm 3) \mu b \times \tilde{p}_\eta$	**2.** $\sigma = (18 \pm 3) \mu b \times \tilde{p}_\eta$
3. $\sigma_{max} = (2.6 \pm 0.3) mb$	**3.** $\sigma_{max} = (1.4 \pm 0.2) mb$
4. bowl-shaped dσ	**4.** bowl-shaped dσ
5.	**5.** Λ-polarization < 0.1
6. $a_{\eta n}$ = large and attractive	**6.** $a_{\eta\Lambda}$ = large and attractive
7. BR($N^* \to \eta n$) = (30 – 55)% anomalously large	**7.** BR($\Lambda^* \to \eta\Lambda$) = (37 ± 7)% anomalously large
8. $N^* = N(1535)\ \frac{1}{2}^-$	**8.** $\Lambda^* = \Lambda(1670)\ \frac{1}{2}^-$

Prediction from isospin invariance:

$$\sigma(\pi^+ p) = \sigma(\pi^- n) \neq \sigma(\pi^+ n)$$

Expand to SU(3) for p~0.7GeV/c

A. $\pi^- p \rightarrow N^* \rightarrow \pi^0 \Delta^0(1232)\ 3/2^+ \rightarrow \pi^0 \pi^0 n$

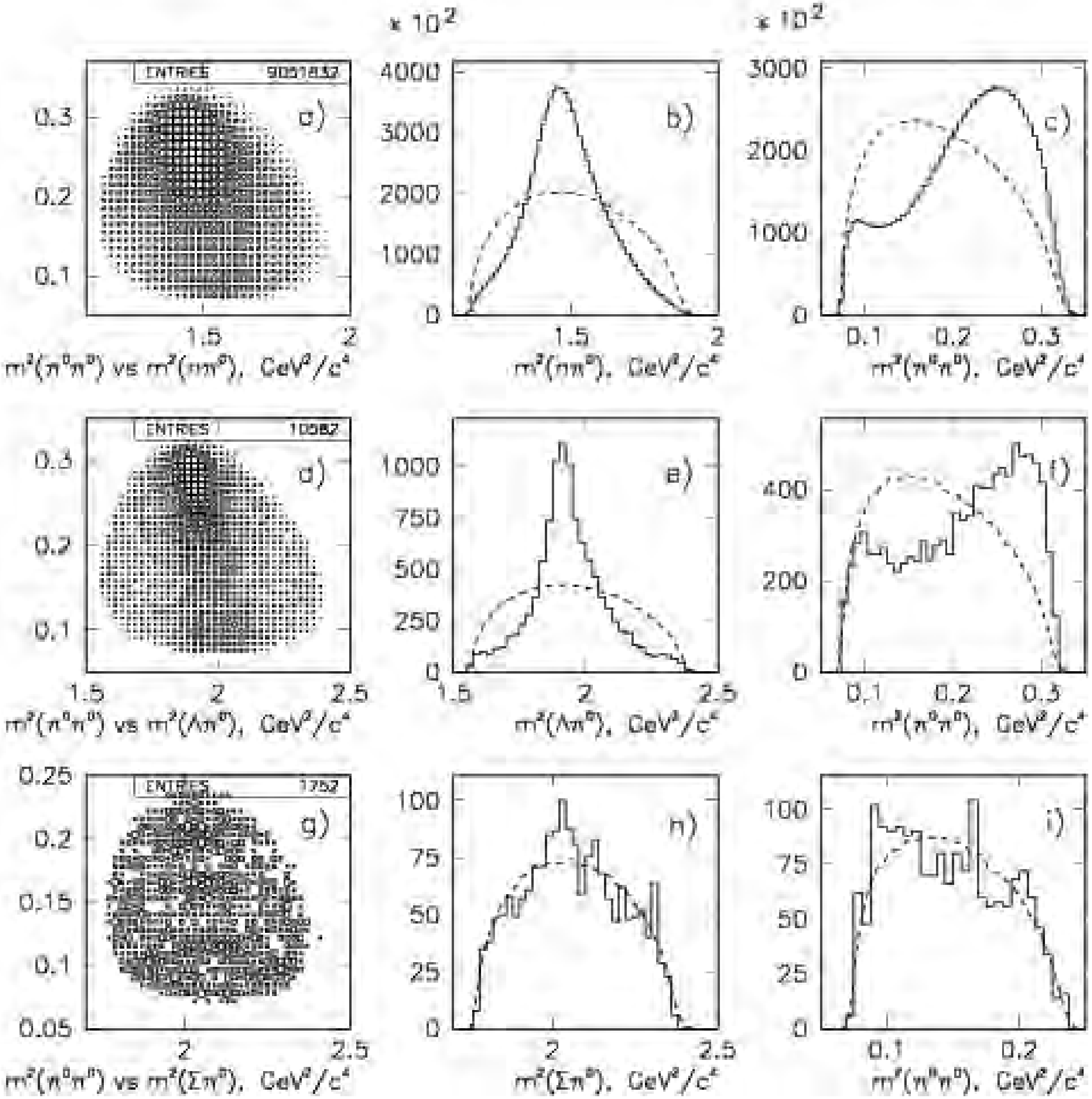
B. $K^- p \rightarrow \Lambda^* \rightarrow \pi^0 \Sigma^0(1385)\ 3/2^+ \rightarrow \pi^0 \pi^0 \Lambda$

C. $K^- p \rightarrow \Sigma^* \rightarrow \pi^0 \Lambda(1405)\ {}^1\!/_2^- \rightarrow \pi^0 \pi^0 \Sigma^0$

D. $\gamma p \rightarrow N^* \rightarrow \pi^0 \Delta^+(1232)\ 3/2^+ \rightarrow \pi^0 \pi^0 p$

SU(3) Flavor Symmetry:

$$A \leftrightarrow B \not\leftrightarrow C \not\leftrightarrow D$$



$\pi^- p \rightarrow \pi^0\pi^0 n$

$K^- p \rightarrow \pi^0\pi^0\Lambda$

$K^- p \rightarrow \pi^0\pi^0\Sigma^0$

Comparison of $2\pi^0$ production by π^-, K^-

$M_{\Xi^*}(J^P) = M_{N^*}(J^P) + 300$ MeV

[= parity doublet

Prediction			**Experimental**	
J^P	m_{Ξ^*}(MeV)	SU(3)	m_{Ξ^*}(MeV)	J^P
½ ⁺	**1238±50**	**8**	**1315**	**½ ⁺**
3/2 ⁺	**1532±40**	**10**	**1532**	**3/2 ⁺**
½ ⁺	**1740±40**	**8**	**1690**	**?**
3/2 ⁻	**1820±40**	**8**	**1820**	**3/2 ⁻**
½ ⁻	1835±40	8		
3/2 ⁺	1900±40	10		
½ ⁻	1920±40	10		
[½ ⁻	1950±40	8		
½ ⁺	2010±40	8		
3/2 ⁻	2020±50	10		
[3/2 ⁺	2040±50	8		
3/2 ⁻	2000±50	8		
3/2 ⁺	2000±50	10		
[**5/2 ⁺**	**1980±40**	**8**	**2025±5**	**≥5/2 ?**
5/2 ⁻	**1980±40**	**8**		
½ ⁺	2210±40	10		
3/2 ⁺	2220±40	10		
[5/2 ⁺	2205±40	10		
5/2 ⁻	2230±40	10		
7/2 ⁻	2490±50	8		
[9/2 ⁺	2520±20	8		
9/2 ⁻	2550±70	8		
11/2 ⁺	2720±50	10		
11/2 ⁻	2950±70	8		

14 octet

10 decup

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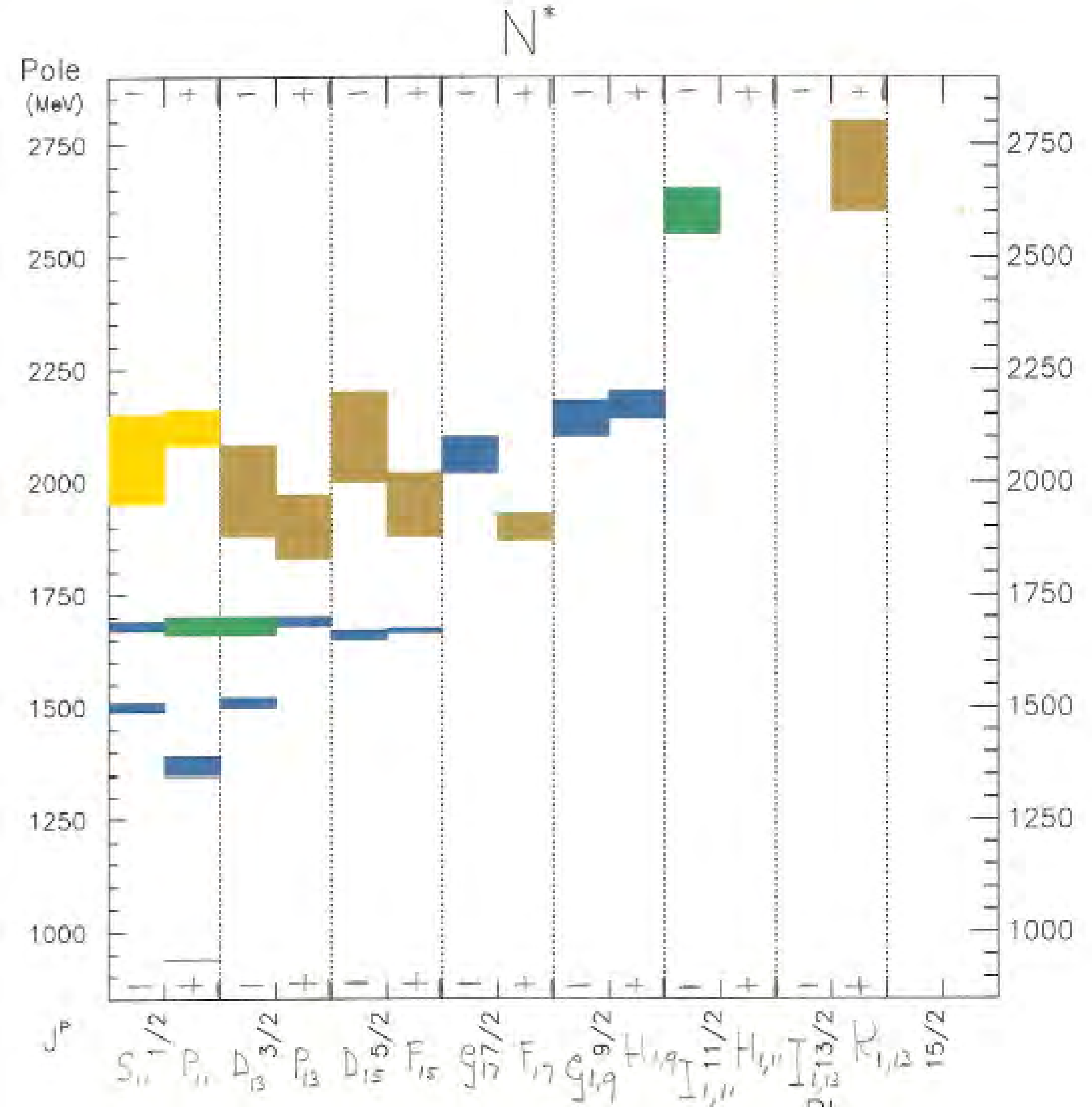
24 total

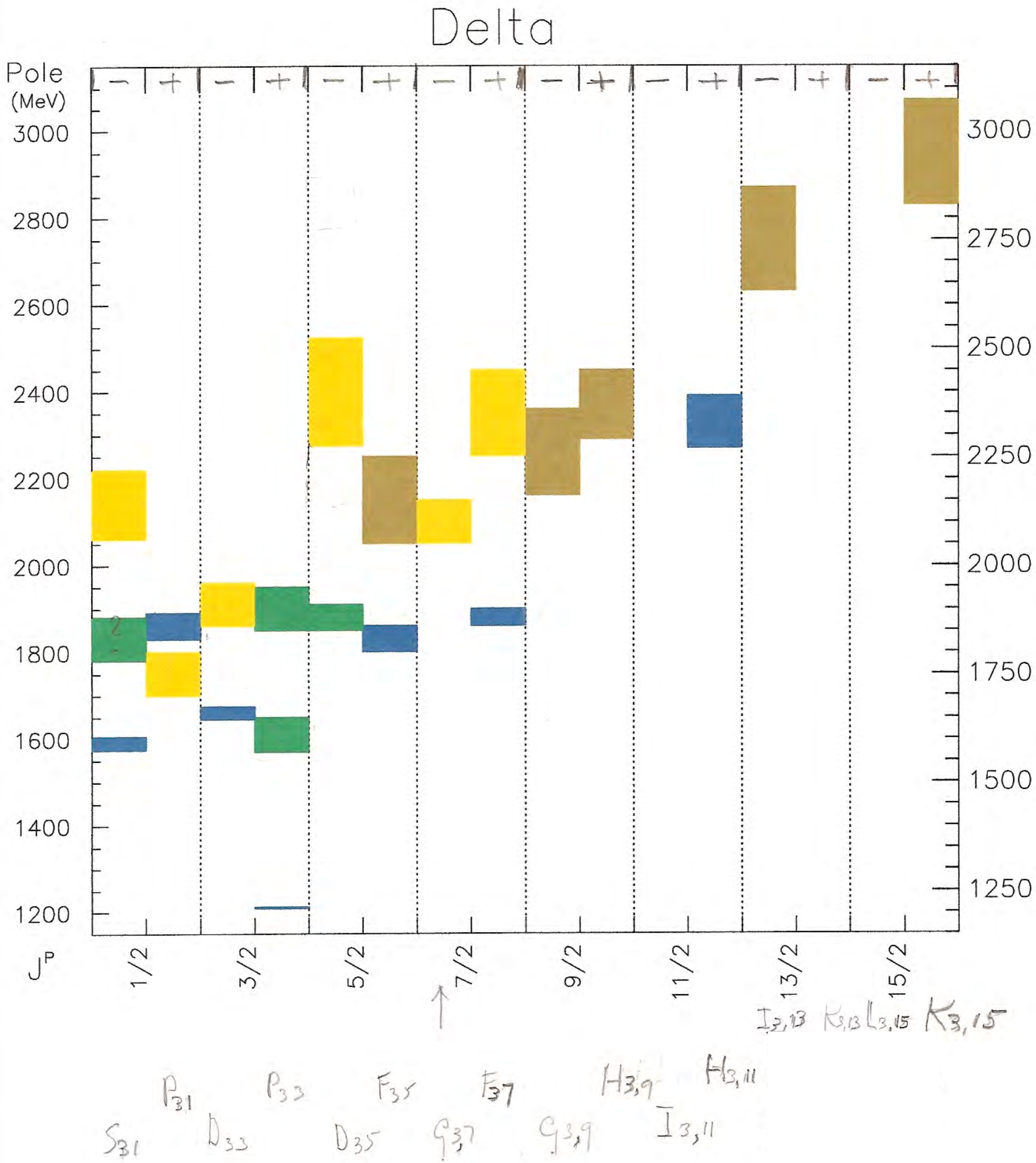


Blue=****

Green=***

Brown=**

Yellow=*

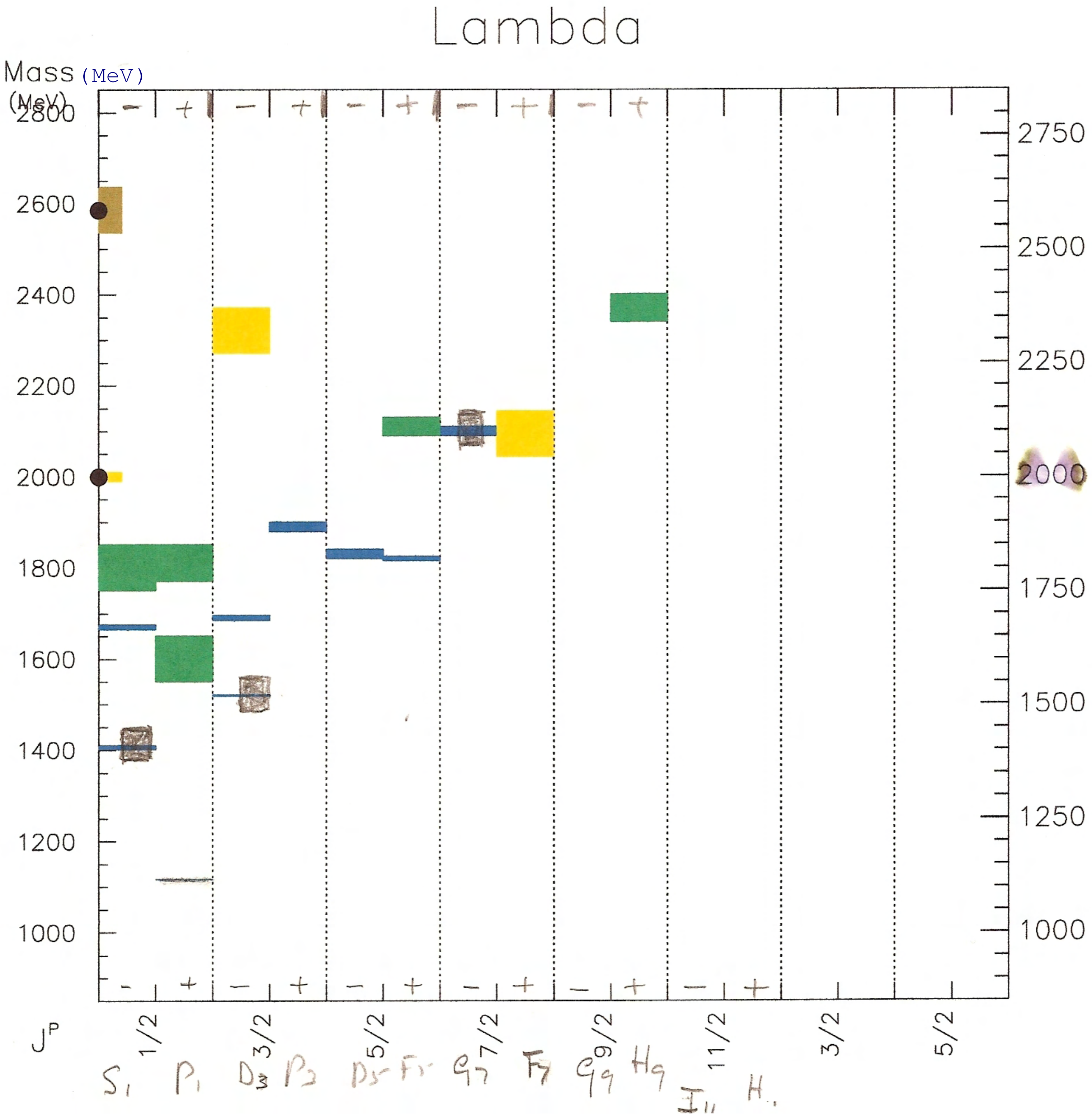


Blue=****

Green=***

Brown=**

Yellow=*



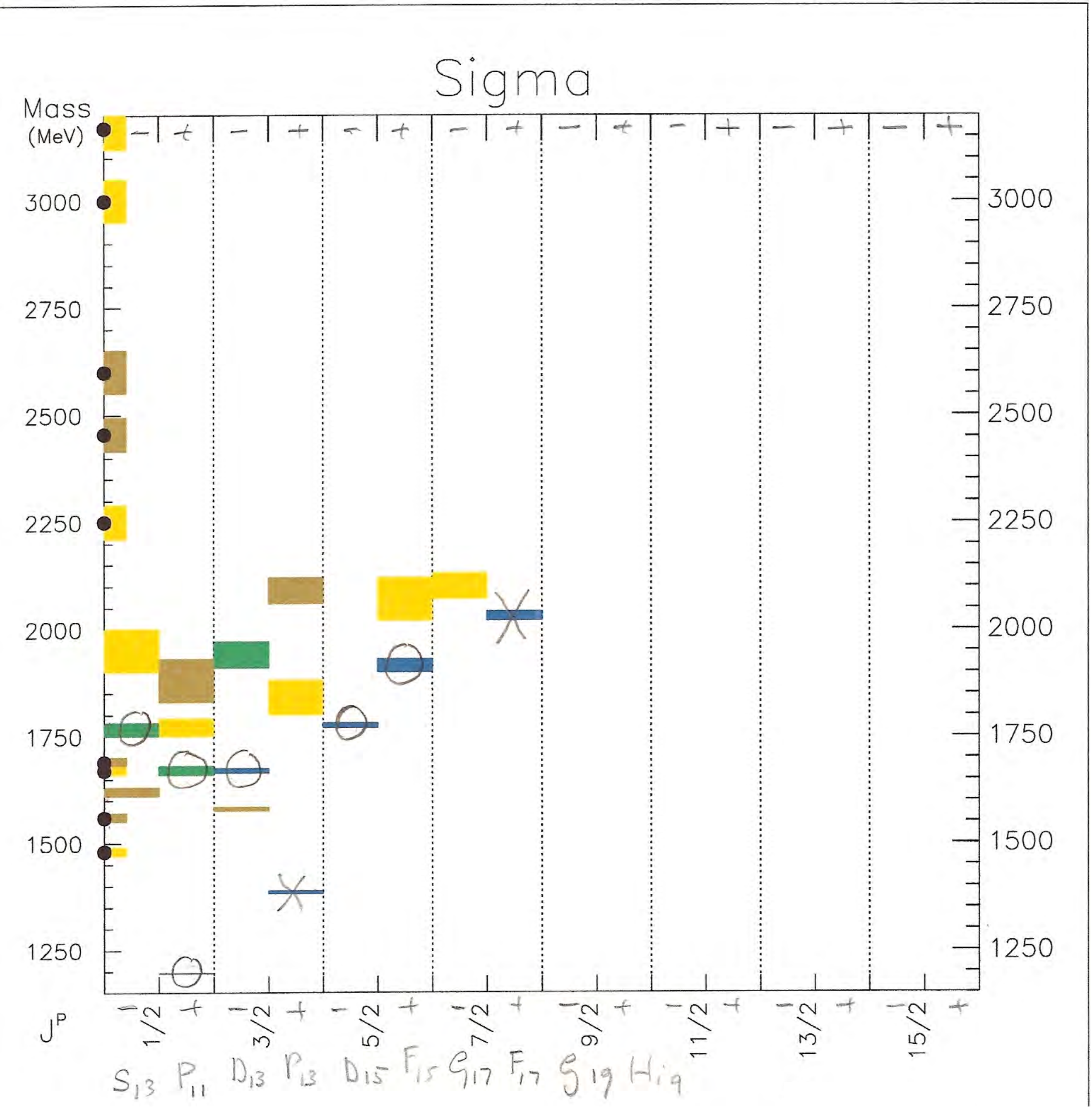
■ = SU(3) singlet

Blue=****

Green=***

Brown=**

Yellow=*



0 = SU(3) octet

x = SU(3) decuplet

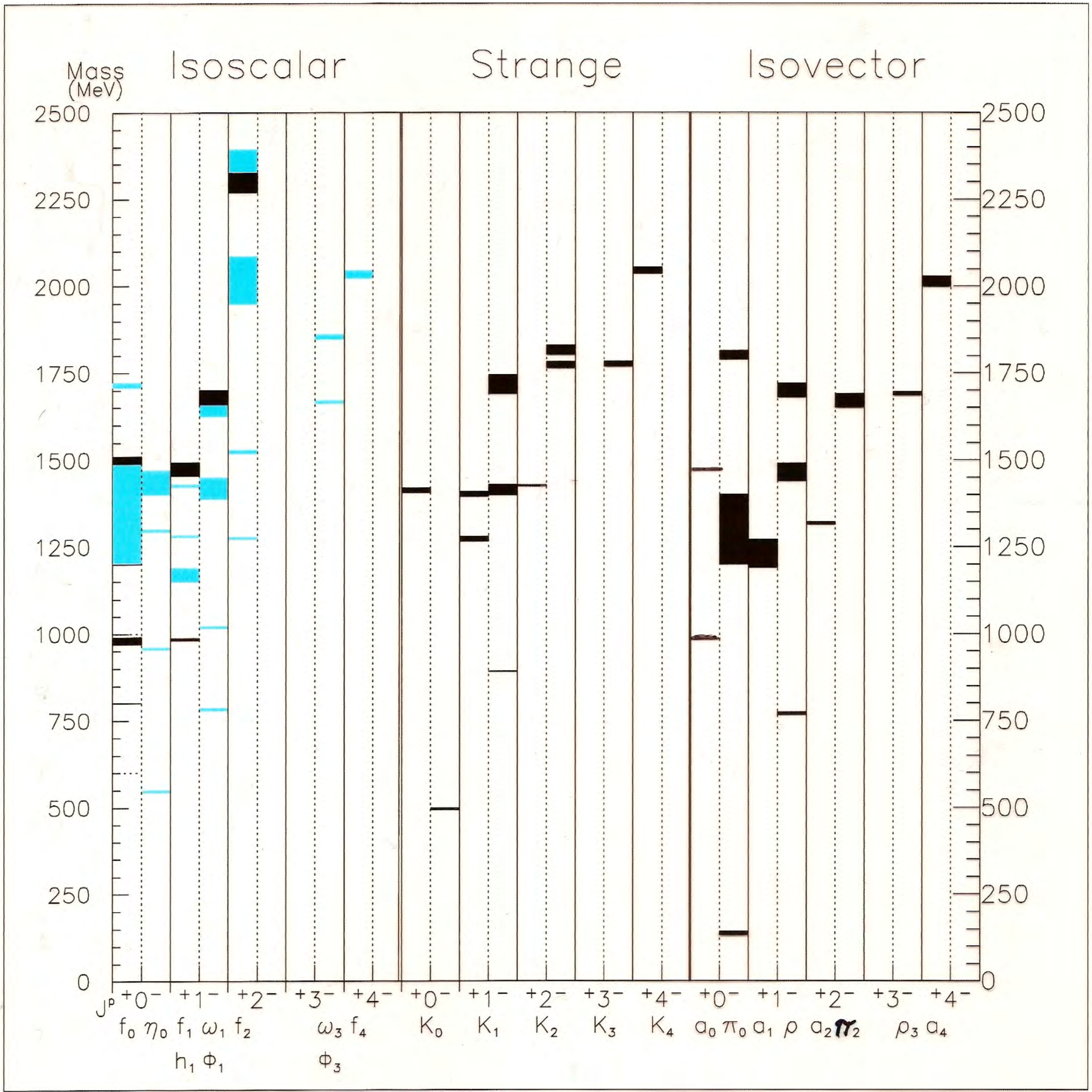
Blue=****

Green=***

Brown=**

Yellow=*

MESONS


Isoscalar
Strange
Isovector
Mass (MeV)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
J^P
+0−
+1−
+2−
+3−
+4−
+0−
+1−
+2−
+3−
+4−
+0−
+1−
+2−
+3−
+4−
f0 η0 f1 ω1 f2
ω3 f4
h1 Φ1
Φ3
K0
K1
K2
K3
K4
a0 π0 a1 ρ a2 π2
ρ3 a4

Positive Parity: $m_\Sigma > m_\Lambda$

J^P	M_Λ (MeV)	$M_\Sigma - M_\Lambda$ (MeV)
½ +	1116	+77 ± 5
½ +	1600	+60 ± 40
½ +	1810	+70 ± 40
5/2 +	1820	+95 ± 40

av. = +75 ± 22 MeV

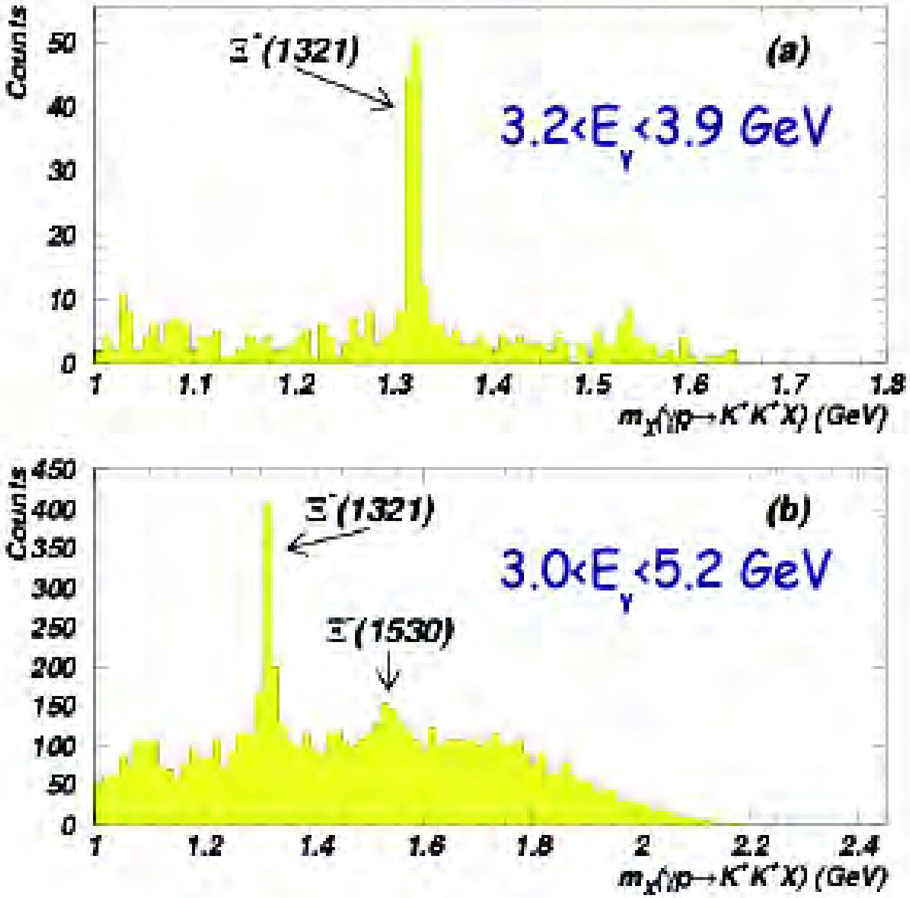
Negative Parity: $m_\Sigma < m_\Lambda$

3/2 -	1690	-20 ± 11
½ -	1670	-50 ± 25
½ -	1800	-50 ± 55
5/2 -	1830	-55 - 11

av. = -44 ± 8 MeV

Quality of Cascade Data

- Recent publication indicates $\sigma_t(\gamma p \rightarrow K^+K^+\Xi^-)$ $=3.5\pm0.5\pm1.5$ nb
- Careful analysis yields very clean signal



$3.2<E_\gamma<3.9$ GeV

$3.0<E_\gamma<5.2$ GeV

Price et al., PRC 71, 058201 (2005)

Analog Reactions

1a. $\Xi_d{}^* \to \eta + \Xi_d(1532) \to \eta + \pi + \Xi_{gs}$

1b. $\Delta^* \to \eta + \Delta(1232) \to \eta + \pi + N$ B-I-L and C-R

2a. $\Xi_d{}^* \to \omega + \Xi_d(1532) \to \omega + \pi + \Xi_{gs}$

2b. $\Delta^* \to \omega + \Delta(1232) \to \omega + \pi + N$ C-R

3a. $\Xi_0{}^* \to \eta + \Xi_{gs}$

3b. $N^*(1535)\ \tfrac{1}{2}^- \to \eta + N$ also $\Lambda^*(1670)\ \tfrac{1}{2}^- \to \eta + \Lambda_{gs}$

4a. $\Xi(1690)\ \tfrac{1}{2}^+ \to \pi + \Xi_d(1532) \to \pi + \pi + \Xi_{gs}$

4b. $N^*(1440)\ \tfrac{1}{2}^+ \to \pi + \Delta_{gs} \to \pi + \pi + N$

Radiative Decays

	B-I-L	L-D-W	W-B-F	Exp (KeV)
$\Xi_d^{0}(1530) \rightarrow \gamma + \Xi_{gs}^{0}$	188	129	172	
$\Xi_d^{-}(1530) \rightarrow \gamma + \Xi_{gs}^{-}$	0	4	6	
$\Delta^{0}(1232) \rightarrow \gamma + n$	341	430	350	
$\Delta^{+}(1232) \rightarrow \gamma + p$	343	430	350	672

B - I - L = Bijker, Iachello, Leviatan

L – D - W = Leinweber. Draper. Woloshyn

W – B – F = Wagner, Buchmann, Faessler

Table 1.1
Quark composition and multiplet mass splittings of the elementary particles. Data from ref. [1.5]

Particle	I, J^P	Quarks	Mass (MeV)	Hadronic mass difference (MeV)
K^0	$\frac{1}{2}, 0^-$	$d\bar{s}$	497.7	
K^+		$u\bar{s}$	493.7	+4.0
K^{*0}	$\frac{1}{2}, 1^-$	$d\bar{s}$	896.5	
K^{*+}		$u\bar{s}$	892.1	$+4.1 \pm 0.4$
D^-	$\frac{1}{2}, 0^-$	$d\bar{c}$	1869.3	
$\overline{D}^0$		$u\bar{c}$	1864.6	$+4.7 \pm 0.3$
D^{*-}	$\frac{1}{2}, 1^-$	$d\bar{c}$	2010.1	
$\overline{D}^{*0}$		$u\bar{c}$	2007.2	$+2.9 \pm 1.3$
B^0	$\frac{1}{2}, 0^-$	$d\bar{b}$	5280	
B^+		$u\bar{b}$	5278	$+1.9 \pm 1.1$
n	$\frac{1}{2}, \frac{1}{2}^+$	dud	939.6	
p		uud	938.3	+1.3
Σ^-	$1, \frac{1}{2}^+$	dds	1197.3	
Σ^0		uds	1192.5	+4.9
Σ^0	$1, \frac{1}{2}^+$	dus	1192.5	
Σ^+		uus	1189.4	+3.1
Σ^{*-}	$1, \frac{3}{2}^+$	dds	1387.2	
Σ^{*0}		uds	1383.7	$+3.5 \pm 1.2$
Σ^{*0}	$1, \frac{3}{2}^+$	dus	1383.7	
Σ^{*+}		uus	1382.8	$+0.9 \pm 1.1$
Ξ^-	$\frac{1}{2}, \frac{1}{2}^+$	dss	1321.3	
Ξ^0		uss	1314.9	$+6.4 \pm 0.6$
Ξ^{*-}	$\frac{1}{2}, \frac{3}{2}^+$	dss	1535.0	
Ξ^{*0}		uss	1531.8	$+3.2 \pm 0.7$

Summary and Conclusions

Advantages of Ξ experiments:

A. Unique S= -2 and B= +1

B. Narrow width, $\Gamma(\Xi) \sim (1/10)\ \Gamma(N^* \text{or } \Delta^*)$

C. Easy identification

  C1. Missing mass e.g. $m(K^+K^+)$ in

$$\gamma + p \rightarrow K^+ + K^+ + \Xi^-$$

  C2. Invariant mass of decay products

e.g. $\Xi^- \rightarrow \pi^- \Lambda$

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

Summary and Conclusions

Advantages of Ξ experiments:

D. Unique background suppression by multivertex condition

$$\gamma + p \rightarrow K^+ + K^+ + \Xi^* \rightarrow K^+ + K^+ + \pi^- + \Xi^0{}_{gs}$$

$$\Xi^0{}_{gs} \rightarrow \pi + \Lambda \qquad\qquad \Lambda \rightarrow \pi^- + p$$

E. Isospin ½ simplicity (nucleonic resonances are mixtures of I=½ & 3/2)

F. SU(3) octet and decuplet families, no singlets.

Summary and Conclusions

Disadvantages:

Need high energy beams

Predict: 24 (3,4 star) states

20 (1,2 star) candidates

? others

> 24 new measurements of

$(m_d - m_u)$ for different J^P

Theory

A

1. Quark-cluster models
2. Independent quark models (3q and 3q G)
3. Isospin breaking new data on $(m_d - m_u)$
4. Parity doublets
5. Höhler clusters
6. Mass sum rules
7. 11 N_c expansion
8. Lattice gauge calcul.

B

Provide means for finding or excluding exotica (hybrids, meson–baryon bound states, $\overline{10}$ and 27 multiplets etc)