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Baryon Resonances

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- **Introduction**
- **Regge trajectories**
- **A mass formula for baryon resonances**
- **Chiral symmetry restoration ?**
- **Missing resonances**
- **Outlook: new data from Crystal Barrel**

WHY BARYON SPECTROSCOPY ?

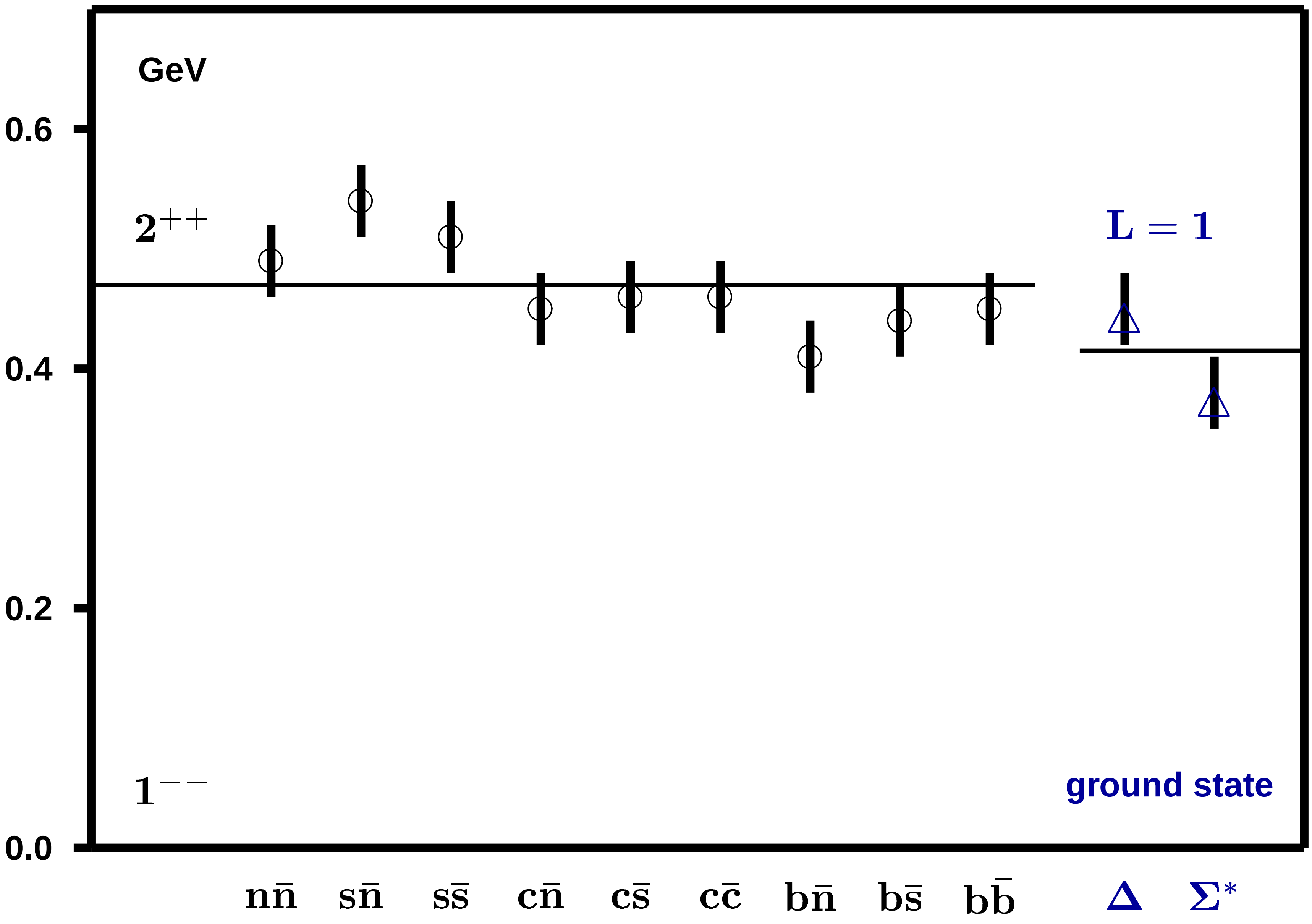
- **Spectroscopy is a powerful tool to study internal dynamics**

  1. **Balmer formula** $\longrightarrow$ **Hydrogen atom**
  2. **Magic numbers** $\longrightarrow$ **Tensor forces in nuclear physics**
  3. **Existance of Ω** $\longrightarrow$ **Triumph of SU(3)**
  4. **No 'ionized' protons** $\longrightarrow$ **Confinement**
  5. $c\bar{c}$ **and** $b\bar{b}$ **families** $\longrightarrow$ **One-gluon exchange linear confinement**

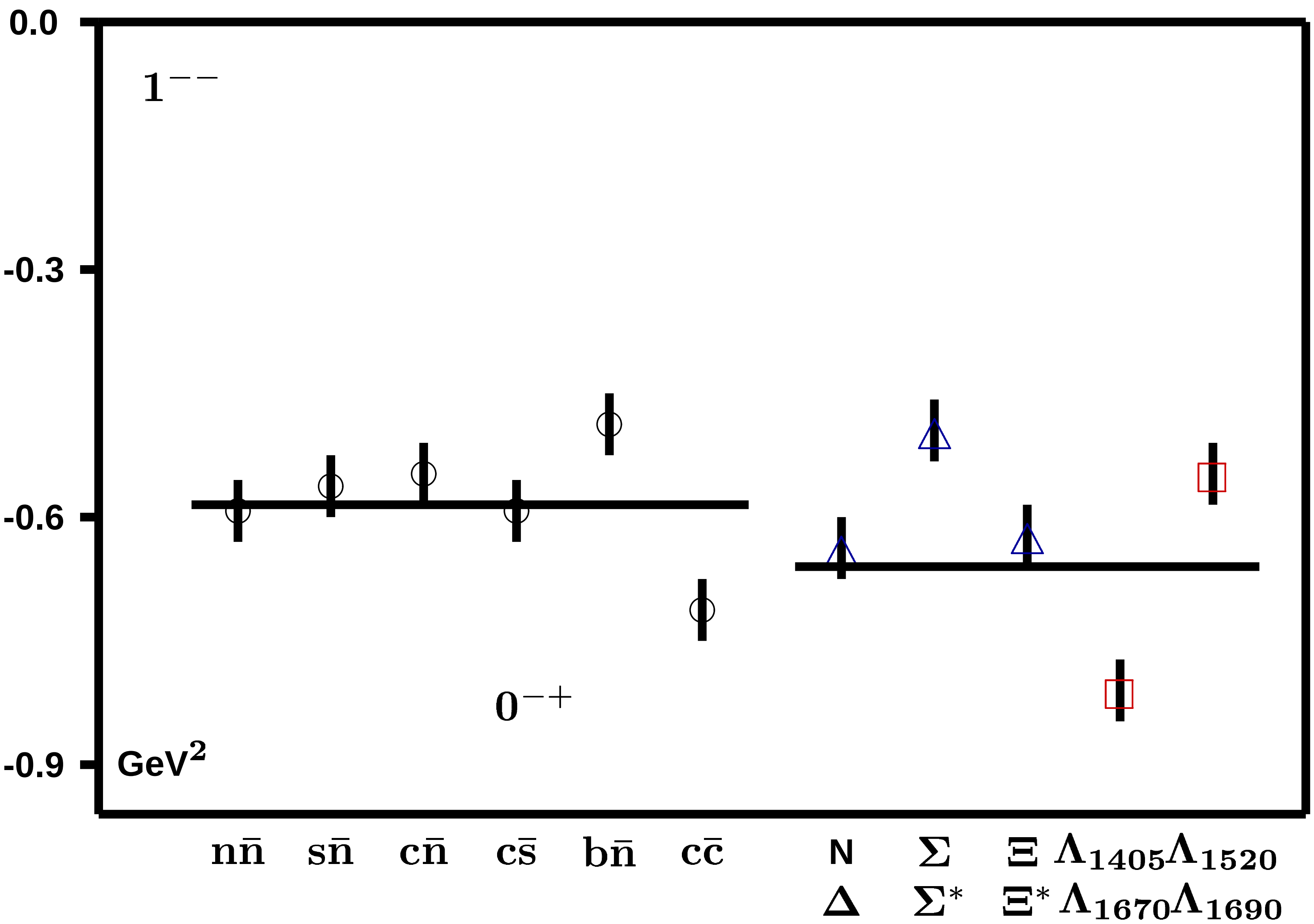
- **Baryons have $\mathrm{N_F} = \mathrm{N_C}$**

  1. **True non-abelian system** $\longrightarrow$ **test of QCD related ideas**
  2. **Rich dynamics of three-body system** $\longrightarrow$ **Insights beyond meson physics**
  3. **Truely complicated** $\longrightarrow$ **Intelectually and experimentally demanding**

- **BUT: Baryons are not fundamental, meson physics is "better".**



Mass differences between ground states and L=1 states



Mass square differences between pseudoscalar and vector mesons (circles) and for octet-decuplet, and for singlet-octet ground states with L=1.

Experimental Status

The Particle Data Group lists:

Octet	N		Σ	Λ	Ξ	
Decuplet		Δ	Σ		Ξ	Ω
Singlet				Λ		
****	11	7	6	9	2	1
***	3	3	4	5	4	1
**	6	6	8	1	2	2
*	2	6	8	3	3	0
No J	-	-	5	-	8	4
Total	22	22	26	18	11	4

- ~ 100 **resonances**
- ~ 85 **known spin and parity**
- ~ 50 **established baryons of known spin parity**
- **K. Hagiwara** *et al.*, **Phys. Rev. D 66, 010001 (2002).**

Theoretical models and results

- **Assume quarks move in an effective confinement potential generated by a very fast colour exchange between quarks (antisymmetrising the total wave function)**
- **Assume the light quarks acquire effective mass by spontanous symmetry breaking**
- **Assume residual interactions**
  - **One gluon exchange**

    relativized **quark model,**

    S. Capstick and N. Isgur, Phys. Rev. D 34 (1986) 2809.

    OGE fixed to HFS (N-Δ)

    $\vec{L} \cdot \vec{S}$ large, in contrast to data

    Set to zero

    (comp. by $\vec{L} \cdot \vec{S}$ from Thomas prec. ?)

- **Goldstone (pion) exchange**

  Take spin-spin, neglect tensor interactions,

  L. Y. Glozman, W. Plessas, K. Varga and R. F. Wagenbrunn,

  Phys. Rev. D 58, 094030 (1998).

- **Instanton interactions**

  Relativistic quark model with instanton-induced forces

  U. Löring, B. C. Metsch and H. R. Petry,

  Eur. Phys. J. A 10 (2001) 395-446, 447-486

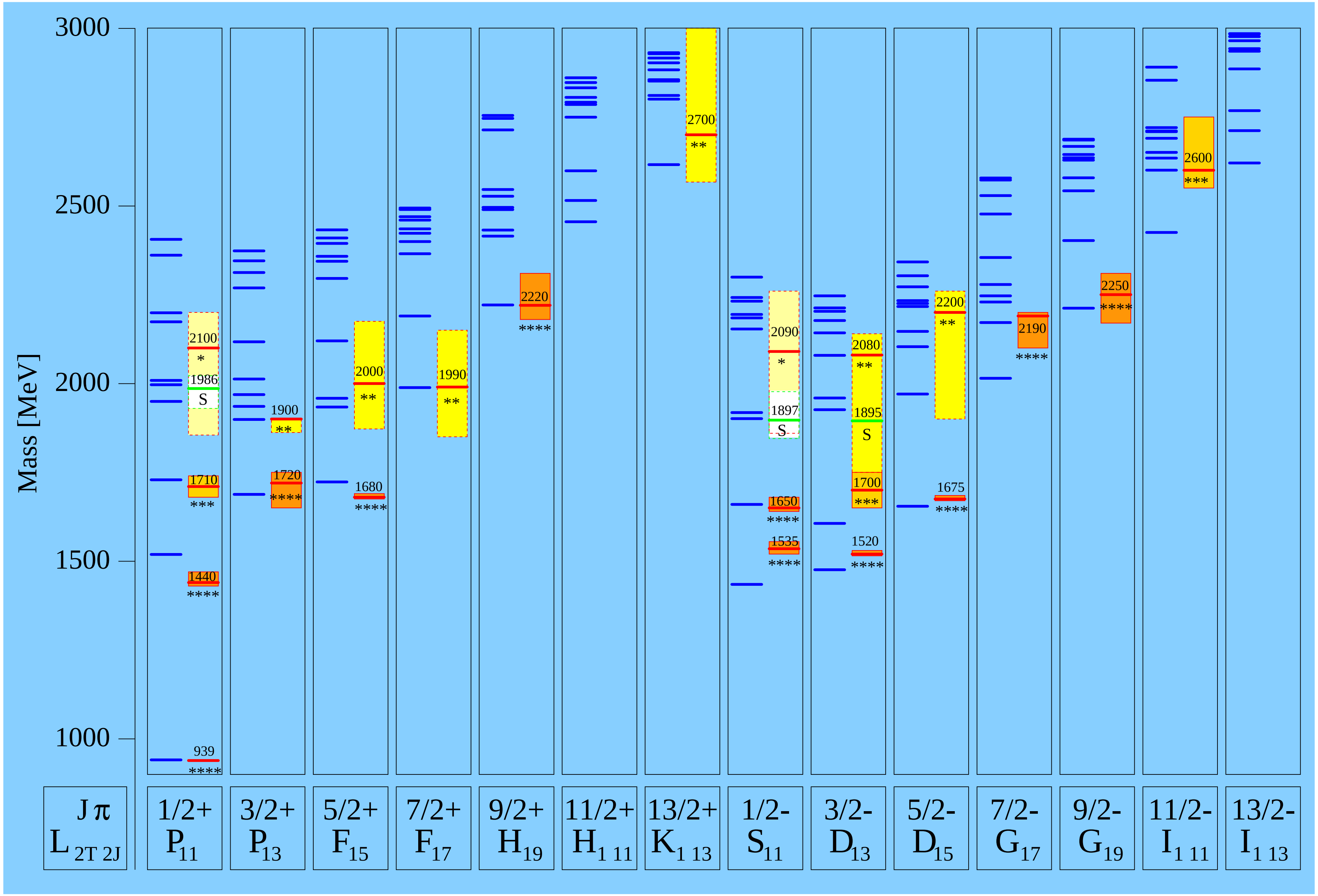
- **Solve equation of motion**

  (using wave functions of the harmonic oscillator)

N^* resonances with instanton induced forces

Bonn model

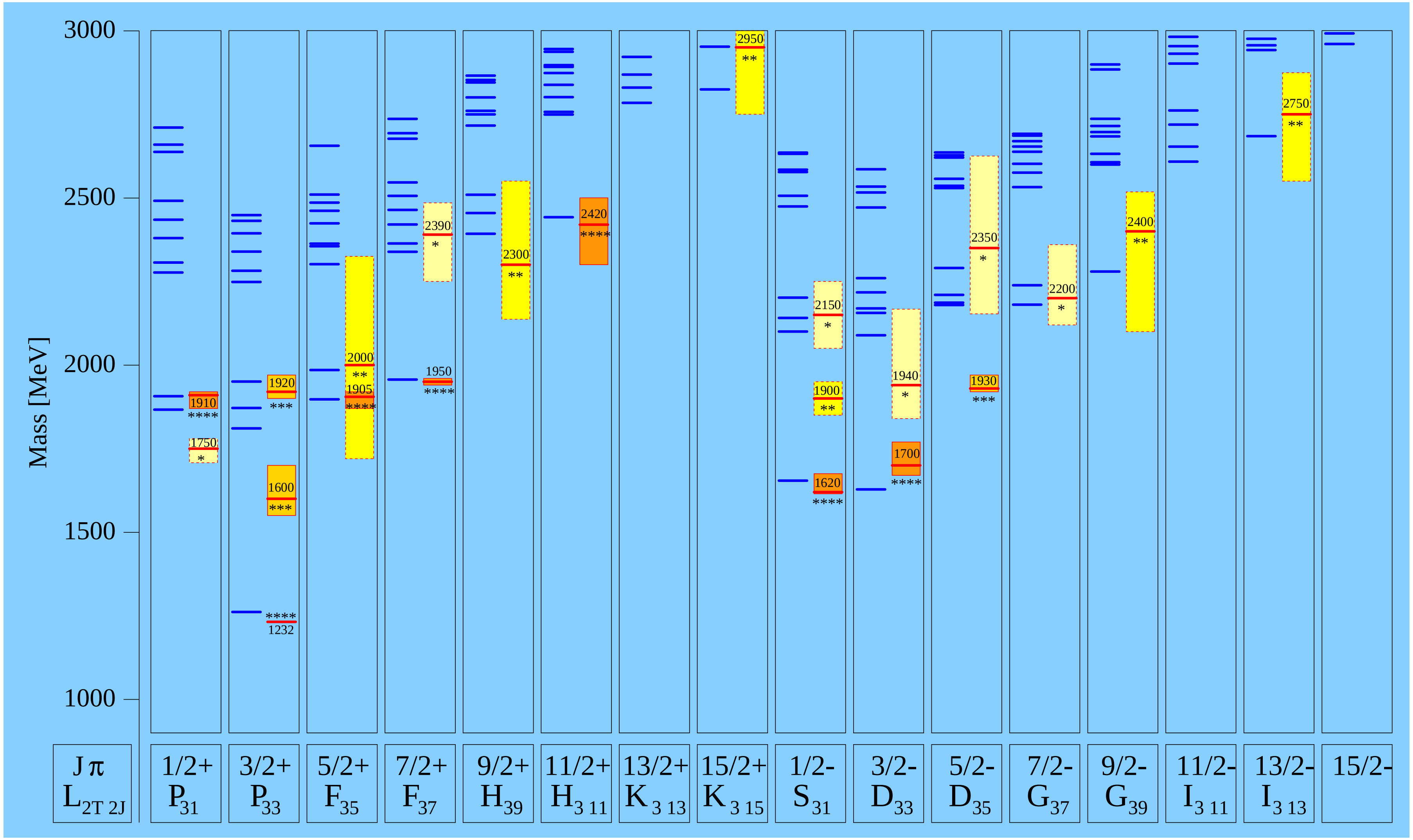
U. Löring, B. Metsch, H. Petry and others



Δ^* resonances with instanton induced forces

Bonn model

U. Löring, B. Metsch, H. Petry and others



Many problems still unsolved:

$\rightarrow$ **What is the relation between quark models and structure functions ?**

$\rightarrow$ **Which model is right ?**

$\rightarrow$ **Is it true that one interaction dominates ?**

$\rightarrow$ **Decay properties of resonances**

$\rightarrow$ **Missing resonances**

$\rightarrow$ **Low mass of Roper, $\Delta_{3/2^+}(1600)$ ...**

$\rightarrow$ **Low mass of negative-parity Δ^*'s at 1950 MeV**

Here:

Try to get at physics from phenomenolgy

The Baryon Wave Function

$$|\mathbf{qqq}> = |\mathbf{colour}>_{\mathbf{A}} \cdot \quad |\mathbf{space, spin, flavour}>_{\mathbf{S}}$$

$$\mathbf{O(6)} \qquad \mathbf{SU(6)}$$

The total wave function must be antisymmetric w.r.t. the exchange of any two quarks. The colour wave function is antisymmetric, hence the space-spin-flavour wave function must be symmetric. We now construct wave functions.

SU(6)

Baryons (with 3 quarks): **3 flavours x 2 spins.**

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56} \oplus \mathbf{70_M} \oplus \mathbf{70_M} \oplus \mathbf{20}$$

$$\begin{aligned} \mathbf{56} &= {}^{4}\mathbf{10} \oplus {}^{2}\mathbf{8} \\ \mathbf{70} &= {}^{2}\mathbf{10} \oplus {}^{4}\mathbf{8} \oplus {}^{2}\mathbf{8} \oplus {}^{2}\mathbf{1} \\ \mathbf{20} &= {}^{2}\mathbf{8} \oplus {}^{4}\mathbf{1} \end{aligned}$$

The 56-plet contains

N^*'s with spin 1/2

Δ^*'s with spin 3/2

The 70-plet contains

N^*'s with spin 1/2 and with spin 3/2

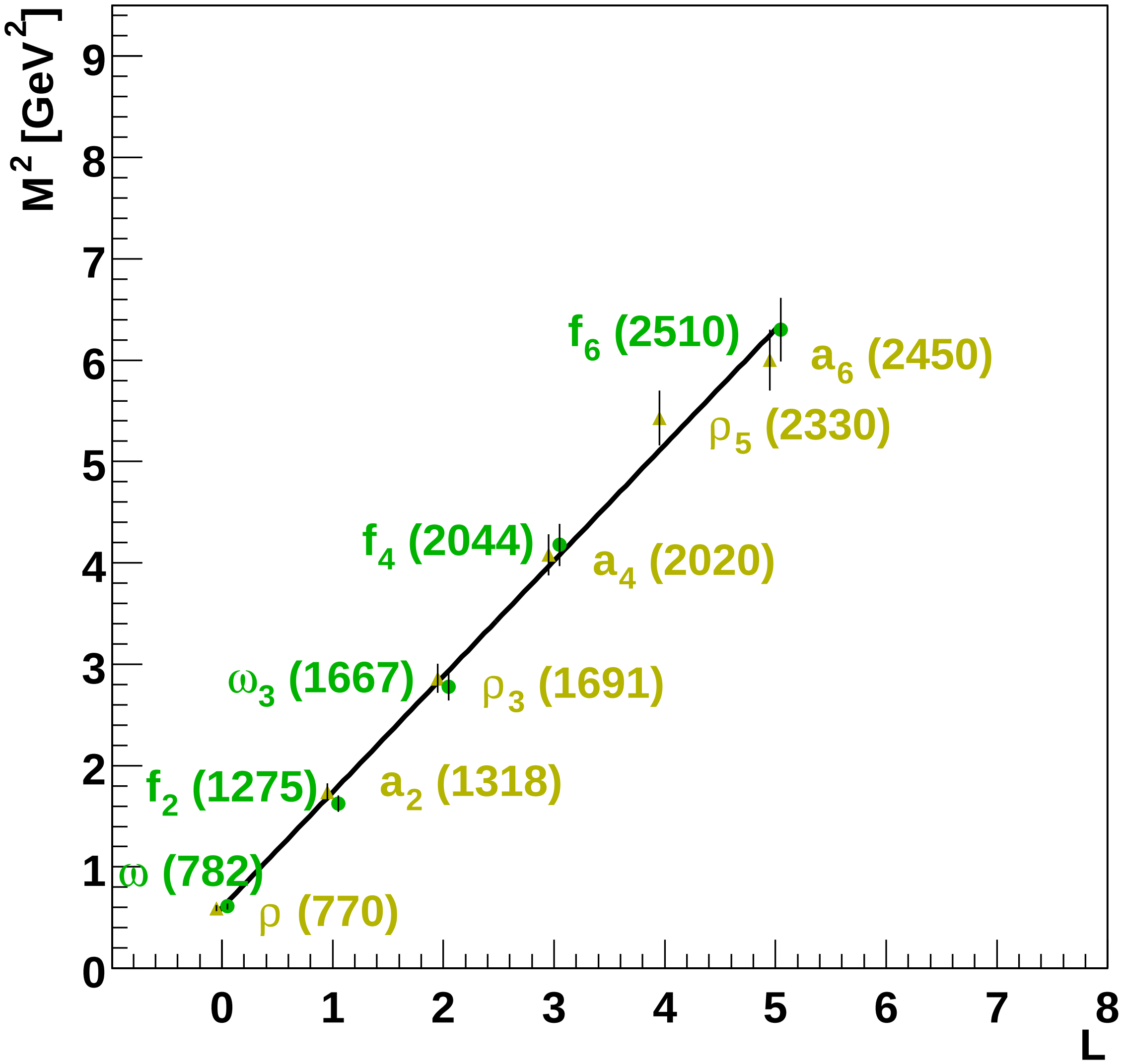
Δ^*'s with spin 1/2

The singlet contains

N^*'s with spin 1/2

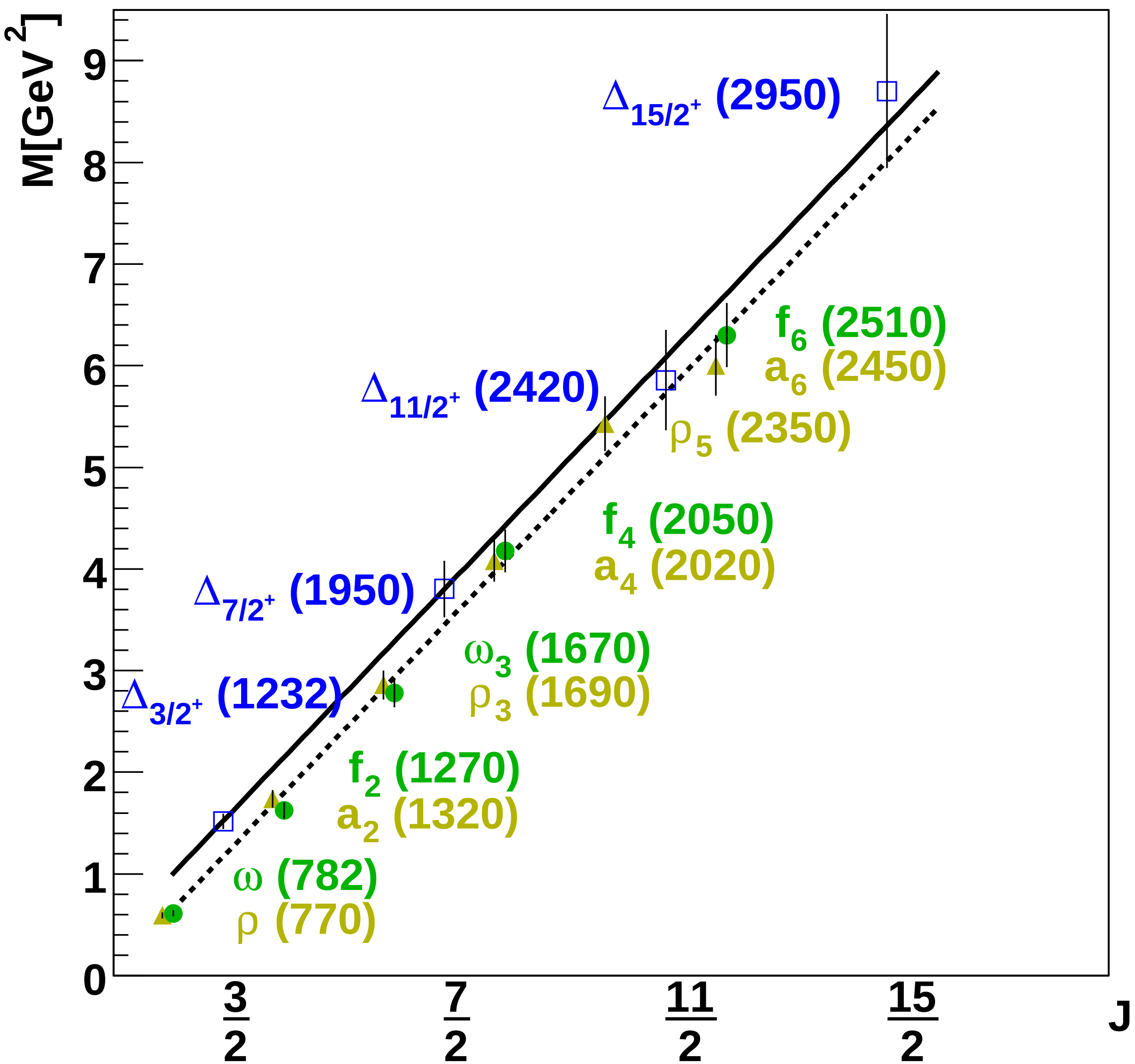
(8_M) have a mixed flavour symmetry,
the 10 multiplet is symmetric,
the 1 antisymmetric in flavour space.

Phenomenological approach to the baryon mass spectrum using Regge trajectories



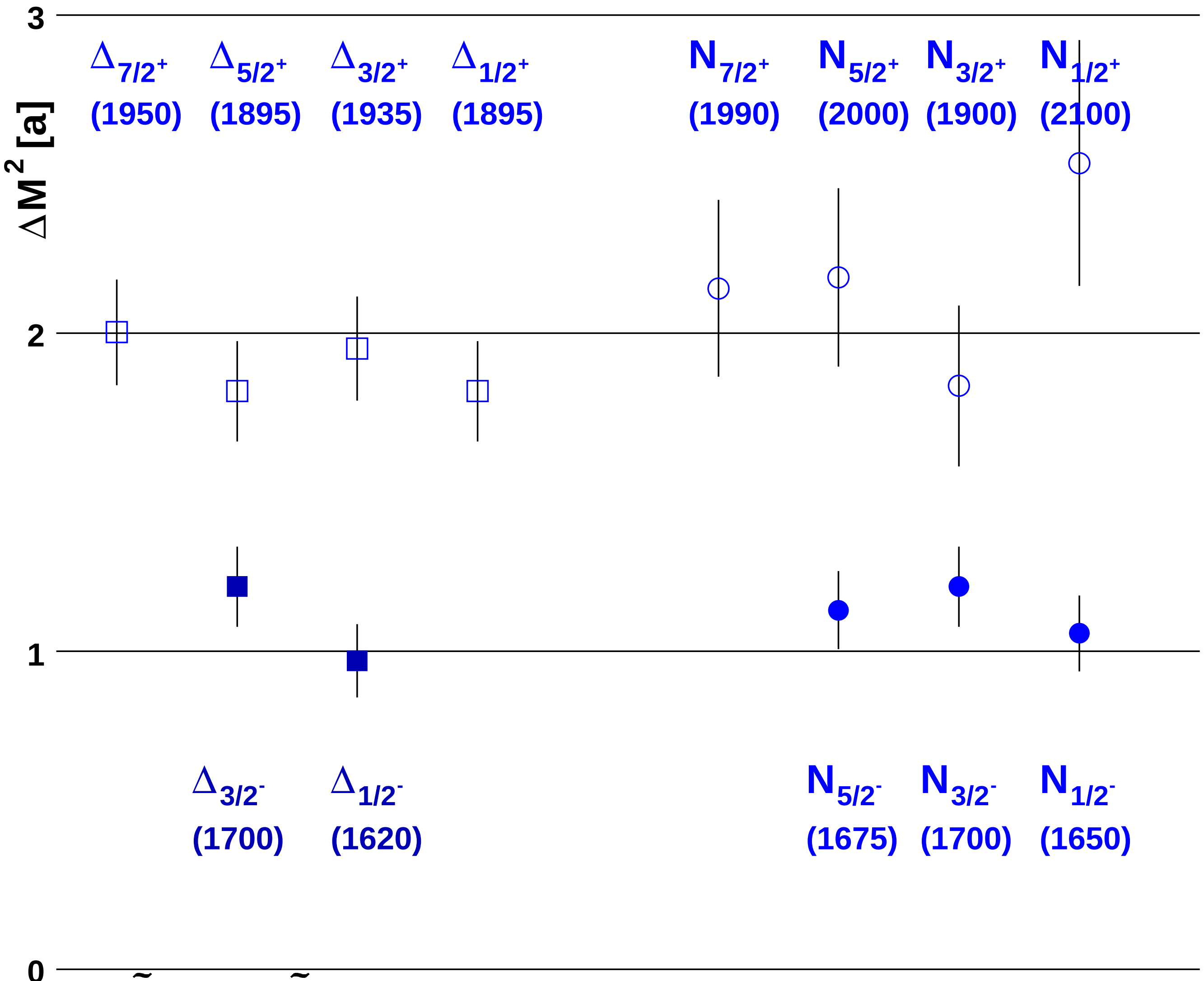
Mesons with $\mathbf{J} = \mathbf{L} + \mathbf{S}$ lie on a Regge trajectory with a slope of 1.142 GeV^2.

Meson and baryon trajectories



$\mathbf{\Delta}^*$'s with $\mathbf{L}$ even and $\mathbf{J = L + 3/2}$ have the same slope as mesons.

Spin-orbit couplings



$\tilde{L}(1) + \tilde{S}(1/2)$
$= \tilde{J}(3/2^+, 1/2^+)$

Δ and N resonances assigned to supermultiplets with defined orbital angular momentum.

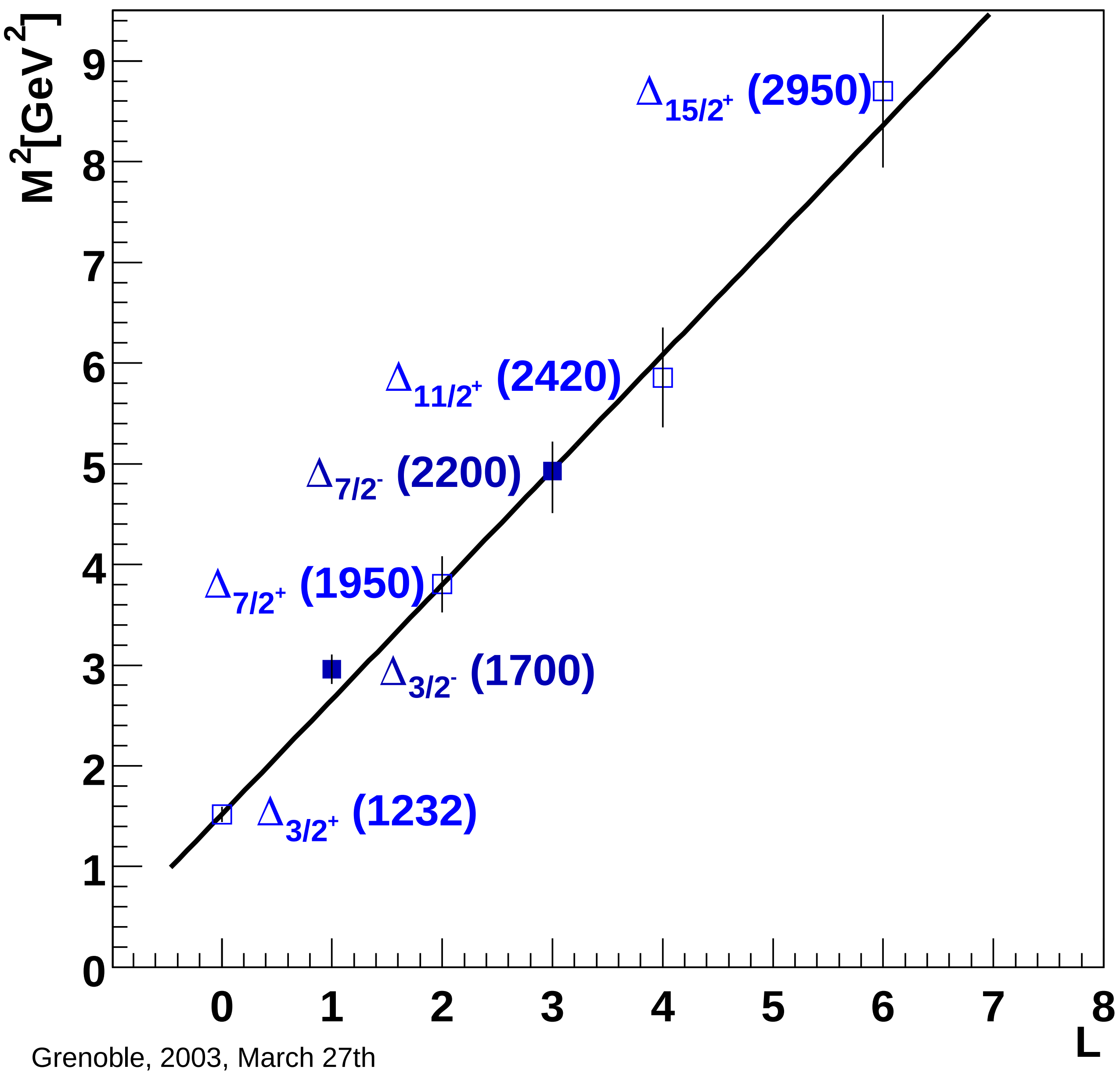
$\tilde{L}(2) + \tilde{S}(3/2) = \tilde{J}(7/2^+, 5/2^+, 3/2^+, 1/2^+)$.

$\tilde{L}(1) + \tilde{S}(3/2) = \tilde{J}(5/2^+, 3/2^+, 1/2^+)$

Multiplet structure of N* and Δ^*

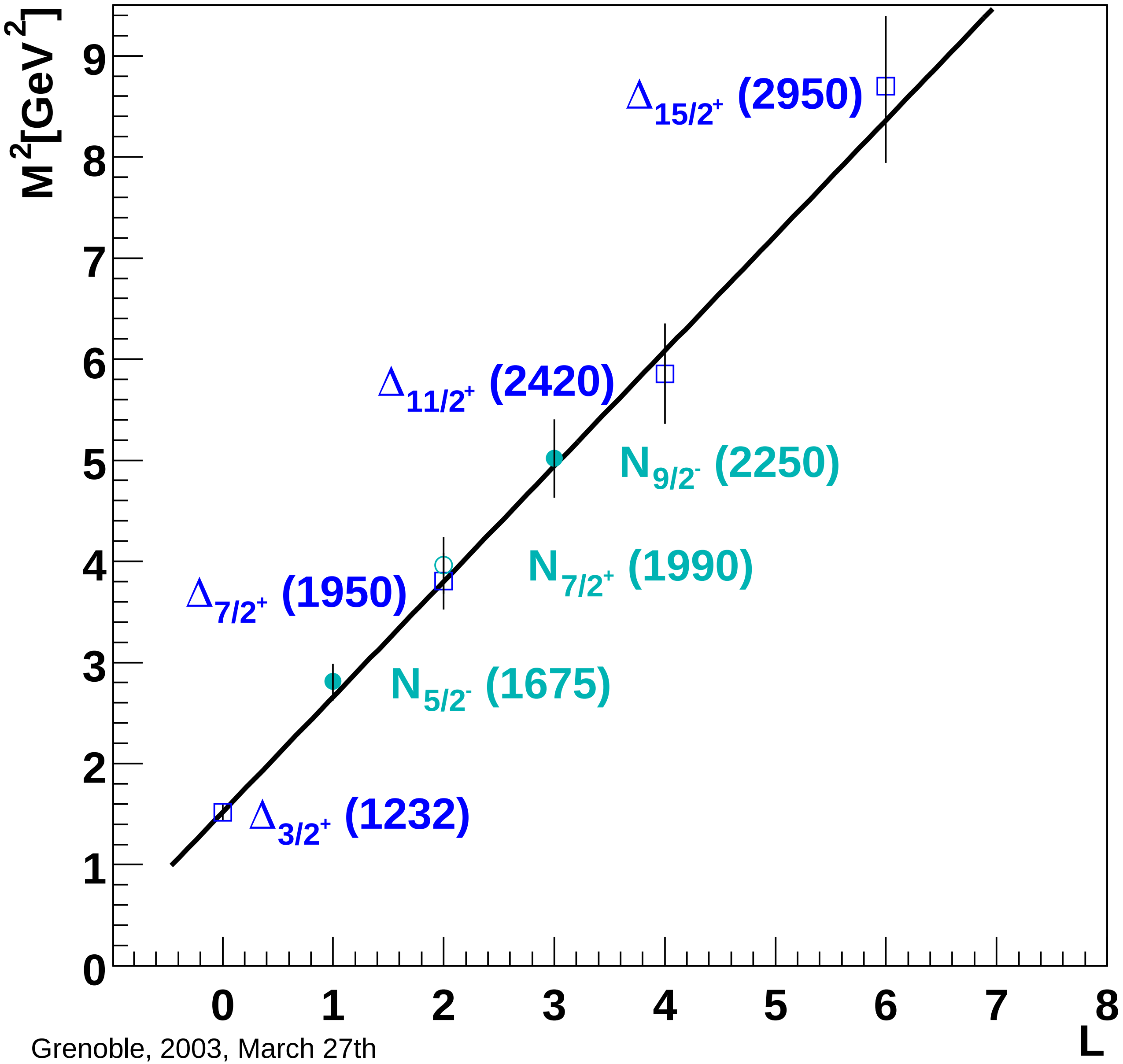
D	S	L	N					Mass (2)
56	1/2	0	0,1,2,3	$N_{1/2+}$(939)	$N_{1/2+}$(1440)	$N_{1/2+}$(1710)	$^{1}N_{1/2+}$(2100)	939 MeV
	3/2	0	0,1,2,3	$\Delta_{3/2+}$(1232)	$\Delta_{3/2+}$(1600)	$\Delta_{3/2+}$(1920)		1232 MeV
70	1/2	1	0		$N_{1/2-}$(1535)	$N_{3/2-}$(1520)		1530 MeV
	3/2	1	0		$N_{1/2-}$(1650)	$N_{3/2-}$(1700)	$N_{5/2-}$(1675)	1631 MeV
	1/2	1	0		$\Delta_{1/2-}$(1620)	$\Delta_{3/2-}$(1700)		1631 MeV
56	1/2	1	1		$N_{1/2-}$	$N_{3/2-}$		1779 MeV
	3/2	1	1		$^{a}\Delta_{1/2-}$(1900)	$^{b}\Delta_{3/2-}$(1940)	$^{c}\Delta_{5/2-}$(1930)	1950 MeV
70	1/2	1	2		$^{1}N_{1/2-}$(2090)	$^{2}N_{3/2-}$(2080)		2151 MeV
	3/2	1	2		$N_{1/2-}$	$N_{3/2-}$	$N_{5/2-}$	2223 MeV
	1/2	1	2		$\Delta_{1/2-}$(2150)	$\Delta_{3/2-}$		2223 MeV
56	1/2	2	0		$N_{3/2+}$(1720)	$N_{5/2+}$(1680)		1779 MeV
	3/2	2	0	$^{a}\Delta_{1/2+}$(1910)	$^{b}\Delta_{3/2+}$(1920)	$^{c}\Delta_{5/2+}(1905)$	$^{d}\Delta_{7/2+}$(1950)	1950 MeV
70	1/2	2	0		$N_{3/2+}$	$N_{5/2+}$		1866 MeV
	3/2	2	0	$N_{1/2+}$	$^{2}N_{3/2+}$(1900)	$^{3}N_{5/2+}$(2000)	$^{4}N_{7/2+}$(1990)	1950 MeV
	1/2	2	0		$\Delta_{3/2+}$	$\Delta_{5/2+}$		1950 MeV

Negative-parity Δ's



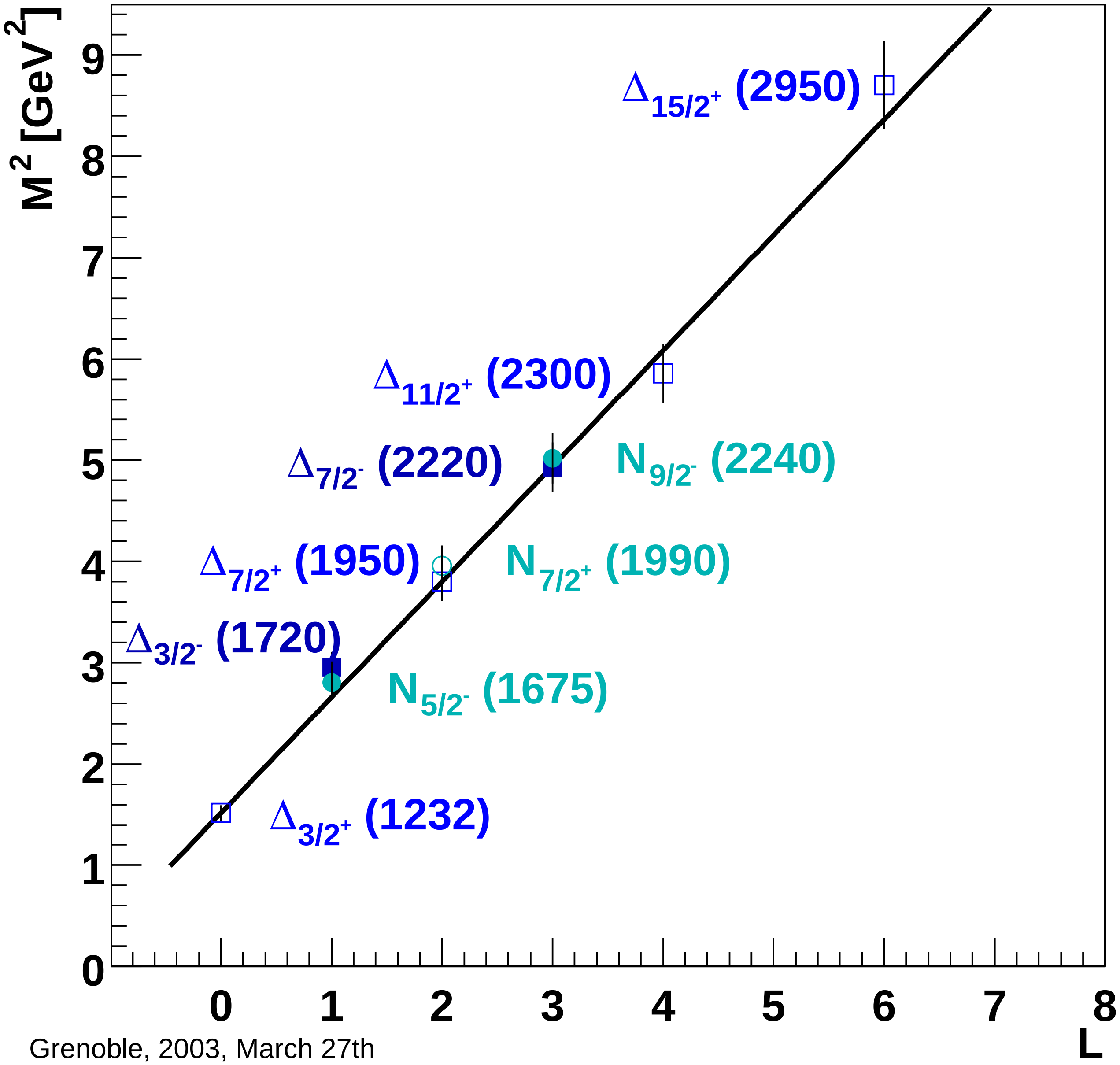
Δ^*'s with odd $\mathbf{L}$ and $\mathbf{J} = \mathbf{L} + 1/2$ fall on the same trajectory.

N*'s and Δ's with $S = 3/2$



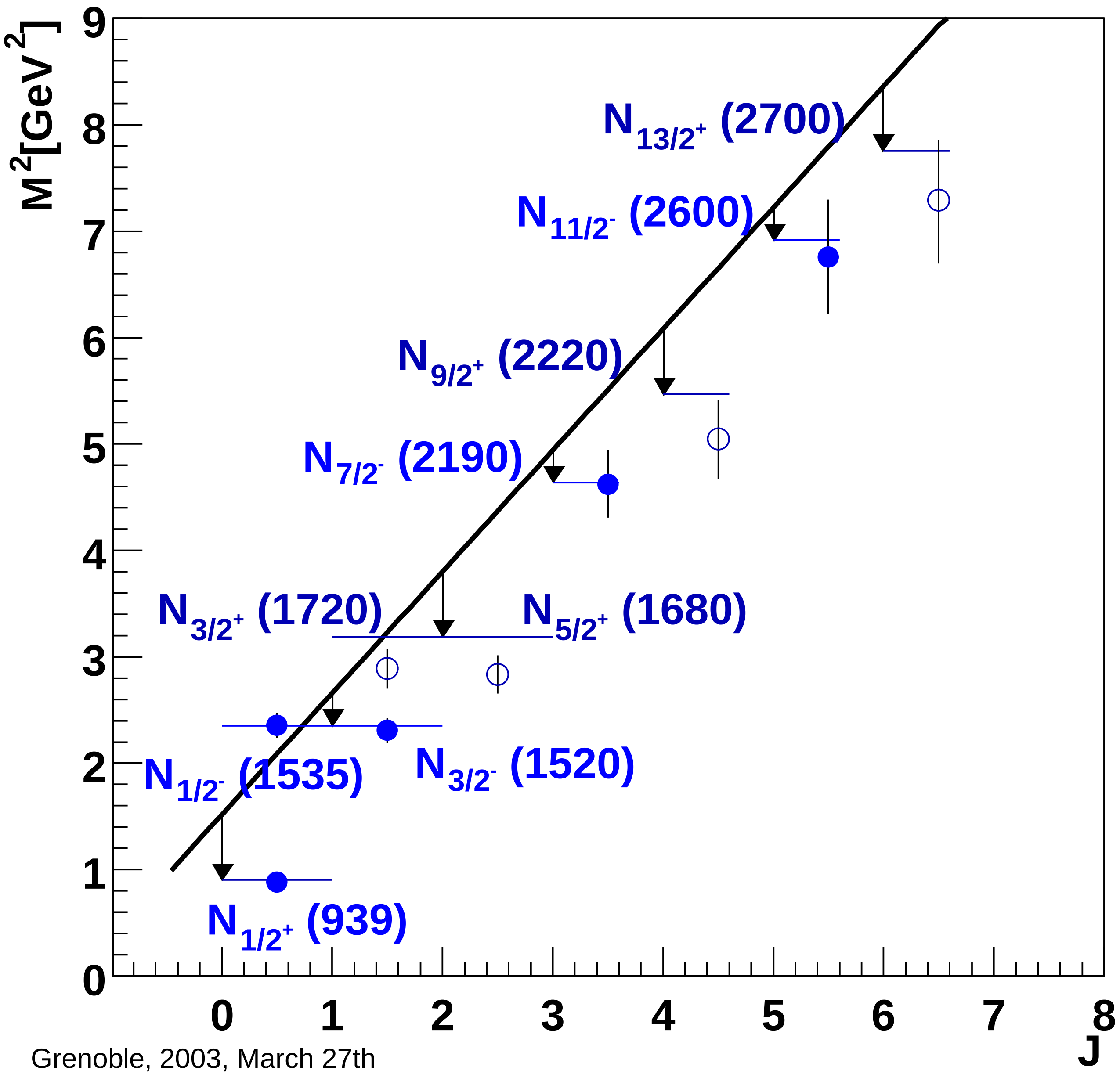
N*'s with intrinsic spin 3/2 fall on the same trajectory.

N*'s ($S = 3/2$) and Δ's ($S = 1/2, 3/2$)

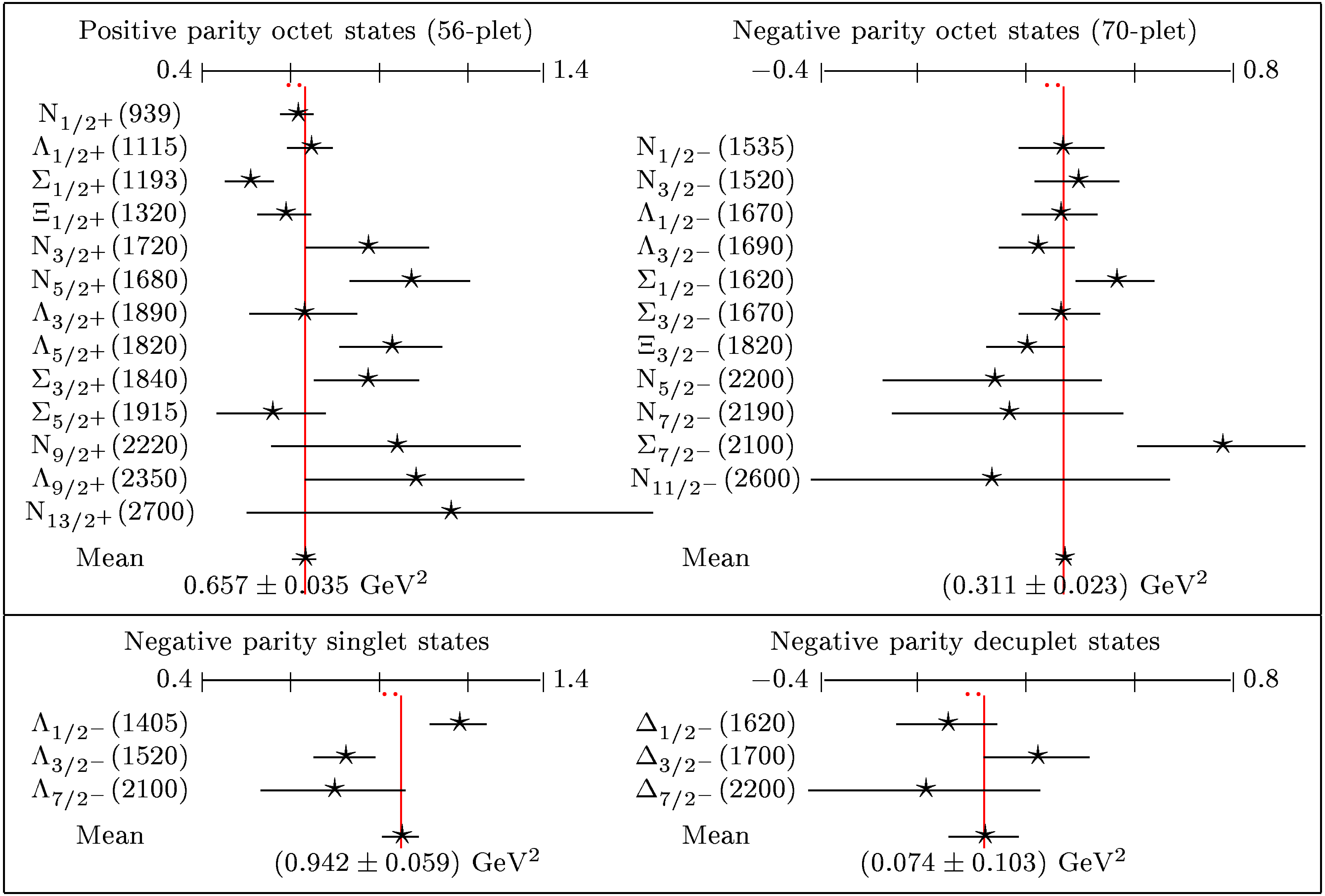


The lowest $\mathbf{\Delta}^*$ (with spin 1/2 and 3/2) and the N^*'s with intrinsic spin 3/2 and $\mathbf{J} = \mathbf{L} + \mathbf{3/2}$ fall on the same Regge trajectory.

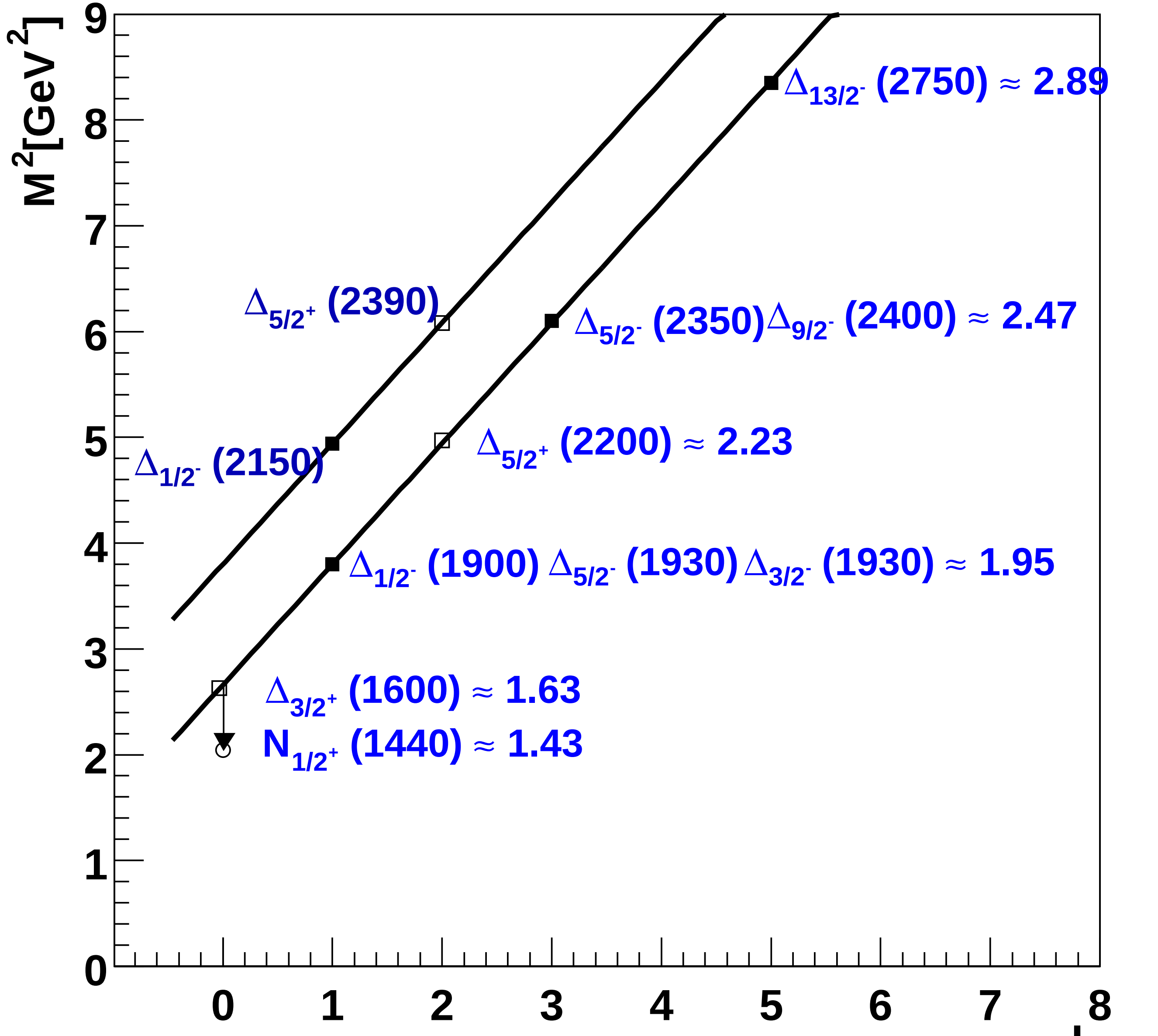
What is about N^* with intrinsic spin $\mathrm{S} = 1/2$?

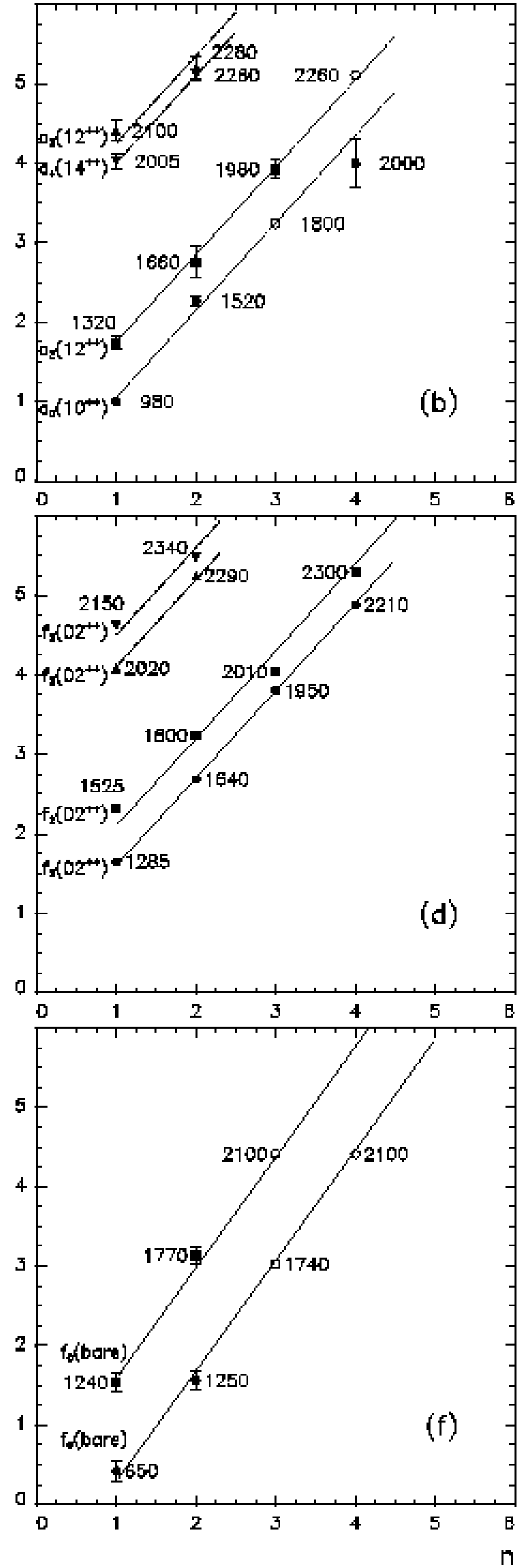


The N^* masses (with intrinsic spin $\mathrm{S} = 1/2$) lie below the standard Regge trajectory. They are smaller by about 0.6 GeV^2 for N^* in the 56-plet, and by 0.3 GeV^2 for N^* in the 70-plet.


Positive parity octet states (56-plet)
0.4
1.4
N1/2+ (939)
Λ1/2+ (1115)
Σ1/2+ (1193)
Ξ1/2+ (1320)
N3/2+ (1720)
N5/2+ (1680)
Λ3/2+ (1890)
Λ5/2+ (1820)
Σ3/2+ (1840)
Σ5/2+ (1915)
N9/2+ (2220)
Λ9/2+ (2350)
N13/2+ (2700)
Mean
0.657 ± 0.035 GeV²
Negative parity octet states (70-plet)
−0.4
0.8
N1/2− (1535)
N3/2− (1520)
Λ1/2− (1670)
Λ3/2− (1690)
Σ1/2− (1620)
Σ3/2− (1670)
Ξ3/2− (1820)
N5/2− (2200)
N7/2− (2190)
Σ7/2− (2100)
N11/2− (2600)
Mean
(0.311 ± 0.023) GeV²
Negative parity singlet states
0.4
1.4
Λ1/2− (1405)
Λ3/2− (1520)
Λ7/2− (2100)
Mean
(0.942 ± 0.059) GeV²
Negative parity decuplet states
−0.4
0.8
Δ1/2− (1620)
Δ3/2− (1700)
Δ7/2− (2200)
Mean
(0.074 ± 0.103) GeV²

Radial excitations





Radial excitations have masses larger by one $\hbar\omega$, like mesons

Grenoble, 2003, March 27th

Baryon	δM^2 (GeV^2)	Baryon	δM^2 (GeV^2)
$N_{1/2+}(939)$		$\Delta_{3/2+}(1232)$	
$N_{1/2+}(1440)$	$1 \cdot 1.18$	$\Delta_{3/2+}(1600)$	$1 \cdot 1.04$
$N_{1/2+}(1710)$	$2 \cdot 1.02$	$\Delta_{3/2+}(1920)$	$2 \cdot 1.08$
$N_{1/2+}(2100)$	$3 \cdot 1.18$		
$\Delta_{1/2-}(1620)$		$\Delta_{3/2-}(1700)$	
$\Delta_{1/2-}(1900)$	$1 \cdot 0.99$	$\Delta_{3/2-}(1940)$	$1 \cdot 0.87$
$\Delta_{1/2-}(2150)$	$2 \cdot 1.00$		
$N_{1/2-}(1530)$		$N_{3/2-}(1520)$	
$N_{1/2-}$**(1897)**	$1 \cdot 1.26$	$N_{3/2-}$**(1895)**	$1 \cdot 1.28$
$N_{1/2-}(2090)$	$2 \cdot 1.01$	$N_{3/2-}(2080)$	$2 \cdot 1.01$
$\Lambda_{1/2+}(1115)$		$\Sigma_{1/2+}(1193)$	
$\Lambda_{1/2+}(1600)$	$1 \cdot 1.24$	$\Sigma_{1/2+}(1560)$	$1 \cdot 1.04$
$\Lambda_{1/2+}(1810)$	$2 \cdot 0.98$	$\Sigma_{1/2+}(1880)$	$2 \cdot 1.06$

Table 1: Radial excitations of baryon resonances; in red: two Saphir resonances.

Observations and conclusions

1. The slope of the Regge trajectory for mesons is the same as for Δ^*, $a = 1.142\,\mathrm{GeV}^2$ $\Rightarrow$ **Effective quark - diquark interaction !**
2. N and Δ resonances with spin $S = 3/2$ lie on a common Regge trajectory. $\Rightarrow$ **No significant genuine octet-decuplet splitting.**
3. Δ^* resonances with S=1/2 and S=3/2 are on the same Regge trajectory. $\Rightarrow$ **No significant genuine spin-spin interaction.**
4. N^*'s and Δ^*'s can be grouped into supermultiplets with defined L and S but different J. $\Rightarrow$ **No significant $\tilde{L} \cdot \tilde{S}$ splitting.**
5. There is a mass shift $\propto$ to $(q_1 q_2 - q_2 q_1)(\uparrow\downarrow - \downarrow\uparrow)$ in baryonic wave functions. $\Rightarrow$ **Instanton interactions are important.**

6. **Daughter trajectories have the same slope and an intercept which is higher by $\mathbf{a = 1.142\,GeV^2}$ per $\mathbf{n}$, both for mesons and baryons.**

$\Rightarrow$ Effective quark - diquark interaction !

7. **For L larger than 3,**

N^*'s have J = L + 1/2 ;

Δ^*'s have J = L + 3/2 **$\Rightarrow$ Spin and flavor are locked !**

These observations can be condensed into a baryon mass formula

A mass formula for baryon resonances E. Klempt, Phys. Rev. C 66 (2002) 058201

$$M^2 = M_\Delta^2 + \frac{n_s}{3} \cdot M_s^2 + a \cdot (L + N) - s_i \cdot I_{sym}$$

where

$$M_s^2 = \left(M_\Omega^2 - M_\Delta^2\right), \qquad s_i = \left(M_\Delta^2 - M_N^2\right),$$

M_N, M_Δ, M_Ω are input parameters (PDG), n_s number of strange quarks in a baryon. $a = 1.142$/GeV^2 Regge slope (from meson spectrum). $L = l_\rho + l_\lambda$, $N = n_\rho + n_\lambda$, L+2N harmonic-oscillator band *N*.

I_{sym} is the fraction of the wave function (normalized to the nucleon wave function) which is antisymmetric in spin and flavor:

$\mathbf{I_{sym}} =$	**1**	**for S=1/2 and**	**octet in 56-plet;**
$\mathbf{I_{sym}} =$	**1/2**	**for S=1/2 and**	**octet in 70-plet;**
$\mathbf{I_{sym}} =$	**3/2**	**for S=1/2 and**	**singlet;**
$\mathbf{I_{sym}} =$	**0**	**otherwise.**	

N^*'s

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$N_{1/2^+}(939)$	****	$(56,^2 8)_0$	0	939	-	-	-	-	-
$N_{1/2^+}(1440)$	****	$(56,^2 8)_0$	1	1450	1423	250-450	87	37	0.53
$N_{1/2^+}(1710)$	***	$(56,^2 8)_0$	2	1710	1779	50-250	176	53	1.69
$^1N_{1/2^+}(2100)$	*	$(56,^2 8)_0$	2	2100	2076	-	251	70	0.12
$N_{1/2^-}(1535)$	****	$(70,^2 8)_1$	0	1538	1530	100-250	114	41	0.04
$N_{3/2^-}(1520)$	****	$(70,^2 8)_1$	0	1523	1530	110-135	114	41	0.03
$N_{1/2^-}(1650)$	****	$(70,^4 8)_1$	0	1660	1631	145-190	139	46	0.4
$N_{3/2^-}(1700)$	***	$(70,^4 8)_1$	0	1700	1631	50-150	139	46	2.25
$N_{5/2^-}(1675)$	****	$(70,^4 8)_1$	0	1678	1631	140-180	139	46	1.04
$N_{3/2^+}(1720)$	****	$(56,^2 8)_2$	0	1700	1779	100-200	176	53	2.22
$N_{5/2^+}(1680)$	****	$(56,^2 8)_2$	0	1683	1779	120-140	176	53	3.28
$N_{3/2^+}(1900)$	**	$(70,^4 8)_2$	0	1900	1950	-	219	62	0.65

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$N_{5/2+}(2000)$	**	$(70,^4 8)_2$	0	2000	1950	-	219	62	0.65
$N_{7/2+}(1990)$	**	$(70,^4 8)_2$	0	1990	1950	-	219	62	0.42
$N_{1/2-}(2090)$	*	$(70,^2 8)_1$	2	2090	2151	-	269	74	0.68
$N_{3/2-}(2080)$	**	$(70,^2 8)_1$	2	2080	2151	-	269	74	0.92
$N_{5/2-}(2200)$	**	$(70,^2 8)_3$	0	2220	2151	-	269	74	0.87
$N_{7/2-}(2190)$	****	$(70,^2 8)_3$	0	2150	2151	350-550	269	74	0
$N_{9/2-}(2250)$	****	$(70,^4 8)_3$	0	2240	2223	290-470	287	78	0.05
$N_{9/2+}(2220)$	****	$(56,^2 8)_4$	0	2245	2334	320-550	315	84	1.12
$N_{11/2-}(2600)$	***	$(70,^2 8)_5$	0	2650	2629	500-800	389	102	0.04
$N_{13/2+}(2700)$	**	$(56,^2 8)_6$	0	2700	2781	-	427	111	0.53
						dof:	21	$\sum \chi^2$:	17.53

Δ

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Delta_{3/2^+}(1232)$	****	$(56,^4 10)_0$	0	1232	1232	-	-	-	-
$\Delta_{3/2^+}(1600)$	***	$(56,^4 10)_0$	1	1625	1631	250-450	139	46	0.02
$\Delta_{1/2^+}(1750)$	*	$(70,^2 10)_0$	1	1750	1631	-	139	46	6.69
$\Delta_{1/2^-}(1620)$	****	$(70,^2 10)_1$	0	1645	1631	120-180	139	46	0.09
$\Delta_{3/2^-}(1700)$	****	$(70,^2 10)_1$	0	1720	1631	200-400	139	46	3.74
$\Delta_{1/2^-}(1900)$	**	$(56,^4 10)_1$	1	1900	1950	140-240	219	62	0.65
$\Delta_{3/2^-}(1940)$	*	$(56,^4 10)_1$	1	1940	1950	-	219	62	0.03
$\Delta_{5/2^-}(1930)$	***	$(56,^4 10)_1$	1	1945	1950	250-450	219	62	0.01
$\Delta_{1/2^+}(1910)$	****	$(56,^4 10)_2$	0	1895	1950	190-270	219	62	0.79
$\Delta_{3/2^+}(1920)$	***	$(56,^4 10)_2$	0	1935	1950	150-300	219	62	0.06
$\Delta_{5/2^+}(1905)$	****	$(56,^4 10)_2$	0	1895	1950	280-440	219	62	0.79
$\Delta_{7/2^+}(1950)$	****	$(56,^4 10)_2$	0	1950	1950	290-350	219	62	0

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Delta_{1/2-}(2150)$	*	$(70,^2 10)_1$	2	2150	2223	-	287	78	0.88
$\Delta_{7/2-}(2200)$	*	$(70,^2 10)_3$	0	2200	2223	-	287	78	0.09
$^1\Delta_{5/2+}(2000)$	**	$(70,^2 10)_2$	1	2200	2223	-	287	78	0.09
$\Delta_{5/2-}(2350)$	*	$(56,^4 10)_1$	0	2350	2467	-	348	92	1.62
$\Delta_{9/2-}(2400)$	**	$(56,^4 10)_3$	1	2400	2467	-	348	92	0.53
$\Delta_{7/2+}(2390)$	*	$(56,^4 10)_4$	0	2390	2467	-	348	92	0.7
$\Delta_{9/2+}(2300)$	**	$(56,^4 10)_4$	0	2300	2467	-	348	92	3.3
$\Delta_{11/2+}(2420)$	****	$(56,^4 10)_4$	0	2400	2467	300-500	348	92	0.53
$\Delta_{13/2-}(2750)$	**	$(56,^4 10)_5$	1	2750	2893	-	455	118	1.47
$\Delta_{15/2+}(2950)$	**	$(56,^4 10)_6$	0	2950	2893	-	455	118	0.23
						dof:	21	$\sum \chi^2$:	22.31

Σ

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Sigma_{1/2+}(1193)$	****	$(56,^2 8)_0$	0	1193	1144	-	-	30	2.67
$\Sigma_{3/2+}(1385)$	****	$(56,^4 10)_0$	0	1384	1394	-	-	30	0.11
$\Sigma(1480)$	*								
$\Sigma(1560)$	**	$(56,^2 8)_0$	1	1560	1565	-	32	31	0.03
$\Sigma_{1/2+}(1660)$	***	$(70,^2 8)_0$	1	1660	1664	40-200	57	33	0.01
$\Sigma_{1/2+}(1770)$	*	$(70,^2 10)_0$	1	1770	1757	-	80	36	0.13
$\Sigma_{1/2+}(1880)$	**	$(56,^2 8)_0$	2	1880	1895	-	115	42	0.13
$\Sigma_{1/2-}(1620)$	**	$(70,^2 8)_1$	0	1620	1664	-	57	33	1.78
$\Sigma_{3/2-}(1580)$	**								
$\Sigma_{3/2-}(1670)$	****	$(70,^4 8)_1$	0	1675	1664	40-80	57	33	0.11
$\Sigma(1690)$	**	$(70,^2 10)_1$	0	1690	1757	-	80	36	3.46
$\Sigma_{1/2-}(1750)$	***	$(70,^4 8)_1$	0	1765	1757	60-160	80	36	0.05
$\Sigma_{5/2-}(1775)$	****	$(70,^4 8)_1$	0	1775	1757	105-135	80	36	0.25

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Sigma_{1/2^-}(2000)$	*	$(70,^2 8)_1$	1	2000	1977	-	135	45	0.26
$\Sigma_{3/2^-}(1940)$	***	$(70,^2 8)_1$	1	1925	1977	150-300	135	45	1.34
$\Sigma_{3/2^+}(1840)$	*	$(56,^2 8)_0$	2	1840	1895	-	115	42	1.71
$\Sigma_{5/2^+}(1915)$	****	$(56,^2 8)_0$	2	1918	1895	80-160	115	42	0.3
${}^1\Sigma_{3/2^+}(2080)$	**	$(56,^4 10)_0$	2	2080	2056	-	155	49	0.24
${}^1\Sigma_{5/2^+}(2070)$	*	$(56,^4 10)_0$	2	2070	2058	-	155	49	0.06
${}^1\Sigma_{7/2^+}(2030)$	****	$(56,^4 10)_0$	2	2033	2056	150-200	155	49	0.22
$\Sigma(2250)$	***	$(70,^2 8)_3$	0	2245	2248	60-150	203	59	0
$\Sigma_{7/2^-}(2100)$	*	$(70,^2 8)_3$	0	2100	2248	-	203	59	6.29
$\Sigma(2455)$	**	$(56,^2 8)_4$	0	2455	2424	-	247	69	0.2
$\Sigma(2620)$	**	$(70,^2 8)_5$	0	2620	2708	-	318	85	1.07
$\Sigma(3000)$	*	$(56,^2 8)_6$	0	3000	2857	-	355	94	2.31
$\Sigma(3170)$	*	$(70,^2 8)_7$	0	3170	3102	-	416	108	0.4
						dof:	24	$\sum \chi^2$:	23.13

Λ

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Lambda_{1/2+}(1115)$	****	$(56,^2 8)_0$	0	1116	1144	-	-	30	0.87
$\Lambda_{1/2+}(1600)$	***	$(56,^2 8)_0$	1	1630	1565	50-250	32	31	4.4
$\Lambda_{1/2+}(1810)$	***	$(56,^2 8)_0$	2	1800	1895	50-250	115	42	5.12
$\Lambda_{1/2-}(1405)$	****	$(70,^2 1)_1$	0	1407	1460	50	6	30	3.12
$\Lambda_{3/2-}(1520)$	****	$(70,^2 1)_1$	0	1520	1460	16	6	30	4
$\Lambda_{1/2-}(1670)$	****	$(70,^2 8)_1$	0	1670	1664	25-50	57	33	0.03
$\Lambda_{3/2-}(1690)$	****	$(70,^2 8)_1$	0	1690	1664	50-70	57	33	0.62
$\Lambda_{1/2-}(1800)$	***	$(70,^4 8)_1$	0	1785	1757	200-400	80	36	0.6
$\Lambda_{5/2-}(1830)$	****	$(70,^4 8)_1$	0	1820	1757	60-110	80	36	3.06
$\Lambda_{3/2+}(1890)$	****	$(56,^2 8)_2$	0	1880	1895	60-200	115	42	0.13
$\Lambda_{5/2+}(1820)$	****	$(56,^2 8)_2$	0	1820	1895	70-90	115	42	3.19

Λ

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Lambda(2000)$	*	$(70,^4 8)_2$	0	2000	2056	-	155	49	1.31
$\Lambda_{5/2^+}(2110)$	***	$(70,^4 8)_2$	0	2115	2056	150-250	155	49	1.45
$\Lambda_{7/2^+}(2020)$	*	$(70,^4 8)_2$	0	2020	2056	-	155	49	0.54
$\Lambda_{7/2^-}(2100)$	****	$(70,^2 1)_3$	0	2100	2101	100-250	166	51	0
$\Lambda_{3/2^-}(2325)$	*	$(70,^2 8)_1$	2	2325	2248	-	203	59	1.7
$\Lambda_{9/2^+}(2350)$	***	$(56,^2 8)_4$	0	2355	2424	100-250	247	69	1
$\Lambda(2585)$	**	$(70,^4 8)_2$	0	2585	2551	-	279	76	0.2
						dof:	18	$\sum\chi^2$:	31.34

Ξ

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Xi_{1/2^+}(1320)$	****	$(56,^2 8)_0$	0	1315	1317	-	-	30	0
$\Xi_{3/2^+}(1530)$	****	$(56,^4 10)_0$	0	1532	1540	9	-	30	0.07
$\Xi(1620)$	*			1620					
$\Xi(1690)$	***	$(56,^2 8)_0$	1	1690	1696	$<$30	21	30	0.04
$\Xi_{3/2^-}(1820)$	***	$(70,^2 8)_1$	0	1823	1787	14-39	43	32	1.27
$\Xi(1950)$	***	$(56,^2 8)_2$	0	1950	2004	40-80	98	39	1.92
$\Xi(2030)$	***	$(56,^2 8)_2$	0	2025	2004	15-35	98	39	0.29
$\Xi(2120)$	*	$(56,^4 10)_2$	0	2120	2157	-	136	45	0.68
$\Xi(2250)$	**	$(56,^4 10)_2$	0	2250	2157	-	136	45	4.27
$\Xi(2370)$	**	$(70,^2 8)_3$	0	2370	2340	-	182	55	0.3
$\Xi(2500)$	*	$(56,^2 8)_4$	0	2500	2510	-	224	64	0.02
						dof:	10	$\sum\chi^2$:	8.86

Ω

Baryon	Status	D_L	N	M_e	M_m	Γ_e	Γ_m	σ	χ^2
$\Omega_{3/2^+}(1672)$	****	$(56,^4 10)_0$	0	1672	-	-	-	-	-
$\Omega(2250)$	****	$(56,^4 10)_2$	0	2252	2254	37-73	77	36	0
$\Omega(2380)$	**	-	-	2380	-	-	-	-	-
$\Omega(2470)$	**	$(70,^2 10)_0$	1	2474	2495	39-105	137	46	0.21
						dof:	2	$\sum \chi^2$:	0.21

- $\chi^2 = 105$ for 97 data points.
- All but 4 observed states are predicted:

  $\Rightarrow$ No evidence for (baryonic) hybrids !

  $\Rightarrow$ No evidence for pentaquarks !

- Where are the missing resonances ?

Symmetry of wave functions

Spatial	spin_s	flavour_f
S Symmetric,	$S = 3/2$	
MS Mixed symmetric	$S = 1/2,$	$s_1 + s_2 = 1$
MA Mixed antisymmetric	$S = 1/2,$	$s_1 + s_2 = 0$

Ground states :

$\mathbf{S} \otimes \mathbf{S_s} \otimes \mathbf{S_f}$ $\qquad {}^4\Delta_{3/2^+}(1232)$ **56**

$\mathbf{S} \otimes (\mathbf{MS_s} \otimes \mathbf{MS_f} \oplus \mathbf{MA_s} \otimes \mathbf{MA_f})$ $\qquad {}^2N_{1/2^+}(938)$ **56**

$\mathbf{L = 1}$ states :

$(\mathbf{MS} \otimes \mathbf{MS_s} + \mathbf{MA} \otimes \mathbf{MA_s}) \otimes \mathbf{S_f}$ $\qquad {}^2\Delta_{1/2^-}(1620)\ {}^2\Delta_{3/2^-}(1700)$ **70**

$(\mathbf{MA} \otimes \mathbf{MA_s} - \mathbf{MS} \otimes \mathbf{MS_s}) \otimes \mathbf{MS_f}$ +

$(\mathbf{MS} \otimes \mathbf{MA_s} + \mathbf{MA} \otimes \mathbf{MS_s}) \otimes \mathbf{MA_f}$ $\qquad {}^2N_{1/2^-}(1535)\ {}^2N_{3/2^-}(1520)$ **70**

$\mathbf{MS} \otimes \mathbf{S_s} \otimes \mathbf{MS_f} + \mathbf{MA} \otimes \mathbf{S_s} \otimes \mathbf{MA_f}$

${}^4N_{1/2^-}(1650)\ {}^4N_{3/2^-}(1700)\ {}^4N_{5/2^-}(1675)$ **70**

Symmetries determine pattern of states !

Spatial Wavefunctions

We need to construct spatial wave functions with defined symmetry properties under permutations !

Jacobean coordinates:

$$\mathbf{r_1} - \mathbf{r_2}$$
$$\mathbf{r_1} + \mathbf{r_2} - \mathbf{2r_3}$$
$$\mathbf{r_1} + \mathbf{r_2} + \mathbf{r_3}$$

- **Two relevant separable motions**
- **System is bound** $\Rightarrow$
- **Two harmonic oscillators** ρ, λ

N	n	l_1	l_2	n_1	n_2	L	$\sum n$	N	n	l_1	l_2	n_1	n_2	L	$\sum n$
0	1	0	0	0	0	0	1 / 1	4	9	4	0	0	0	4	
1	3	1	0	0	0	1		4	9	0	4	0	0	4	
1	3	0	1	0	0	1	6 / 6	4	21	3	1	0	0	2,3,4	
2	5	2	0	0	0	2		4	21	1	3	0	0	2,3,4	
2	5	0	2	0	0	2		4	25	2	2	0	0	1,2-4	
2	5	1	1	0	0	2		4	5	2	0	1	0	2	
2	3	1	1	0	0	1		4	5	0	2	1	0	2	
2	1	1	1	0	0	0		4	9	1	1	1	0	0,1,2	
2	1	0	0	1	0	0		4	5	2	0	0	1	2	
2	1	0	0	0	1	0	21 / 12	4	5	0	2	0	1	2	
3	7	3	0	0	0	3		4	9	1	1	0	1	0,1,2	
3	7	0	3	0	0	3		4	1	0	0	2	0	0	
3	15	2	1	0	0	1,2,3		4	1	0	0	0	2	0	
3	15	1	2	0	0	1,2,3		4	1	0	0	1	1	0	126 / 30
3	3	1	0	1	0	1									
3	3	0	1	1	0	1									
3	3	1	0	0	1	1									
3	3	0	1	0	1	1	56 / 20								

Harm osc wf as λ, ρ excitations.

$\sum n =$ total number of realizations.

Only excited oscillator: N in blue.

λ, ρ excitations $\mathrm{N} = 4, \mathrm{L} = 2$

Example: L=2 and N=1

Two oscillators, $\mathbf{l}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\rho, \mathbf{n}_\lambda$. Contributing configurations:

$$(\mathbf{l}_\rho, \mathbf{n}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\lambda) = (\mathbf{2}, \mathbf{1}, \mathbf{0}, \mathbf{0}) = |\mathbf{0}> \quad ; \quad (\mathbf{0}, \mathbf{0}, \mathbf{2}, \mathbf{1}) = |\mathbf{8}>$$

$$(\mathbf{l}_\rho, \mathbf{n}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\lambda) = (\mathbf{2}, \mathbf{0}, \mathbf{0}, \mathbf{1}) = |\mathbf{2}> \quad ; \quad (\mathbf{0}, \mathbf{1}, \mathbf{2}, \mathbf{0}) = |\mathbf{6}>$$

$$(\mathbf{l}_\rho, \mathbf{n}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\lambda) = (\mathbf{2}, \mathbf{0}, \mathbf{2}, \mathbf{0}) = |\mathbf{4}> \quad ;$$

$$(\mathbf{l}_\rho, \mathbf{n}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\lambda) = (\mathbf{3}, \mathbf{0}, \mathbf{1}, \mathbf{0}) = |\mathbf{1}> \quad ; \quad (\mathbf{1}, \mathbf{0}, \mathbf{3}, \mathbf{0}) = |\mathbf{7}>$$

$$(\mathbf{l}_\rho, \mathbf{n}_\rho, \mathbf{l}_\lambda, \mathbf{n}_\lambda) = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{0}) = |\mathbf{3}> \quad ; \quad (\mathbf{1}, \mathbf{0}, \mathbf{1}, \mathbf{1}) = |\mathbf{5}>$$

These wave functions are needed to construct wave funtions of defined symmetry under exchange of two quarks.

States of defined permutational symmetry:

$$|\mathbf{S0}> = +\sqrt{\frac{1}{6}}\cdot\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> + |\mathbf{8}>) + \sqrt{\frac{7}{18}}\cdot\frac{1}{\sqrt{2}}(|2> + |6>) - \sqrt{\frac{4}{9}}|4>$$

$$|\mathbf{S1}> = +\sqrt{\frac{7}{12}}\cdot\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> + |\mathbf{8}>) + \sqrt{\frac{1}{36}}\cdot\frac{1}{\sqrt{2}}(|2> + |6>) + \sqrt{\frac{7}{18}}|4>$$

$$|\mathbf{MS0}> = +\sqrt{\frac{1}{4}}\cdot\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> + |\mathbf{8}>) - \sqrt{\frac{7}{12}}\cdot\frac{1}{\sqrt{2}}(|2> + |6>) - \sqrt{\frac{1}{6}}|4>$$

$$|\mathbf{MS1}> = +\sqrt{\frac{3}{10}}\cdot\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> - |\mathbf{8}>) - \sqrt{\frac{7}{10}}\cdot\frac{1}{\sqrt{2}}(|2> - |6>)$$

$$|\mathbf{MS2}> = +\sqrt{\frac{7}{10}}\cdot\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> - |\mathbf{8}>) + \sqrt{\frac{3}{10}}\cdot\frac{1}{\sqrt{2}}(|2> - |6>)$$

$$|\mathbf{MA0}> = +\sqrt{\frac{4}{25}}\cdot\frac{1}{\sqrt{2}}(|1> + |7>) - \sqrt{\frac{21}{25}}\cdot\frac{1}{\sqrt{2}}(|3> + |5>)$$

$$|\mathbf{MA1}> = -\sqrt{\frac{21}{25}}\cdot\frac{1}{\sqrt{2}}(|1> + |7>) - \sqrt{\frac{4}{25}}\cdot\frac{1}{\sqrt{2}}(|3> + |5>)$$

$$|\mathbf{MA2}> = +\sqrt{\frac{3}{10}}\cdot\frac{1}{\sqrt{2}}(|1> - |7>) + \sqrt{\frac{7}{10}}\cdot\frac{1}{\sqrt{2}}(|3> - |5>)$$

$$|\mathbf{A0}> = -\sqrt{\frac{7}{10}}\cdot\frac{1}{\sqrt{2}}(|1> - |7>) + \sqrt{\frac{3}{10}}\cdot\frac{1}{\sqrt{2}}(|3> - |5>)$$

Single quark excitation hypothesis:

The initial state after excitation of a baryon is given by $\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}|\mathbf{0}> \pm \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}|\mathbf{8}>$

Consequences:

- **Resonances with symmetric wave functions ($\mathrm{S0}$, $\mathrm{S1}$ and $\mathrm{MS0}$) and with mixed symmetric wave functions ($\mathrm{MS1}$ and $\mathrm{MS2}$) are coherently excited**

$$\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> + |\mathbf{8}>) = \sqrt{\frac{1}{6}}|S0> + \sqrt{\frac{7}{12}}|S1> + \frac{1}{2}|MS0>,$$
$$\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{0}> - |\mathbf{8}>) = \sqrt{\frac{3}{10}}|MS1> + \sqrt{\frac{7}{10}}|MS2> .$$

- **Baryon resonances are wave packets with defined phase but uncertain in quantum number ($\delta\phi \cdot \delta\mathbf{n} \sim \hbar$).**
- **Large reduction in the number of states**
- **Resonances with antisymmetric and mixed antisymmetric wave functions are not excited.**
- **Only relevant quantum numbers are $\mathbf{L} = \mathbf{l}_\rho + \mathbf{l}_\lambda$ and $\mathbf{N} = \mathbf{n}_\rho + \mathbf{n}_\lambda$.**
- **These are used in the baryon mass formula.**

Is there evidence for chiral symmetry restoration in the high-mass nucleon spectrum ? L. Y. Glozman, Phys. Lett. B 541, 115 (2002)

Quarks are (nearly) massless; there is chiral symmetry.

At low energies, chiral symmetry is broken, e.g. by instanton-induced interactions:

- **Quarks acquire mass**
- **The masses of pion and of the lowest scalar meson $f_0(650)$ are different**
- **The mass of the $N_{1/2^+}$(938) and of the $N_{1/2^-}$(1535) are different.**

Chiral symmetry might be restored

- **at large temperatures**
- **and high densities**
- **at high excitation energies**

$J = \frac{1}{2}$	1	$N_{1/2+}(2100)$	$N_{1/2-}(2090)$	a	$\Delta_{1/2+}(1910)$	$\Delta_{1/2-}(1900)$
$J = \frac{3}{2}$	2	$N_{3/2+}(1900)$	$N_{3/2-}(2080)$	b	$\Delta_{3/2+}(1920)$	$\Delta_{3/2-}(1940)$
$J = \frac{5}{2}$	3	$N_{5/2+}(2000)$	$N_{5/2-}(2200)$	c	$\Delta_{5/2+}(1905)$	$\Delta_{5/2-}(1930)$
$J = \frac{7}{2}$	4	$N_{7/2+}(1990)$	$N_{7/2-}(2190)$	d	$\Delta_{7/2+}(1950)$	$\Delta_{7/2-}(2200)$
$J = \frac{9}{2}$	5	$N_{9/2+}(2220)$	$N_{9/2-}(2250)$	e	$\Delta_{9/2+}(2300)$	$\Delta_{9/2-}(2400)$
$J = \frac{11}{2}$	6	$N_{11/2+}$	$N_{11/2-}(2600)$	f	$\Delta_{11/2+}(2420)$	$\Delta_{11/2-}$
$J = \frac{13}{2}$	7	$N_{13/2+}(2700)$	$N_{13/2-}$	g	$\Delta_{13/2+}$	$\Delta_{13/2-}(2750)$
$J = \frac{15}{2}$	8	$N_{15/2+}$	$N_{15/2-}$	h	$\Delta_{15/2+}(2950)$	$\Delta_{15/2-}$

Parity doublets of N^* and Δ^* resonances of high mass, after Glozman. The states in boldface are predicted to have the same mass as their chiral partner when chiral symmetry is restored in the high-mass excitation spectrum of baryon resonances. We suggest that the states marked with in red should have considerably higher masses than their chiral partners while the other states in blue should be degenerate in mass with corresponding states of opposite parity.

High Δ states with negative parity

There are three high-mass Δ states with negative parity:

- $\Delta_{5/2^-}$(1930)
- $\Delta_{9/2^-}$(2400)
- $\Delta_{13/2^-}$(2750)

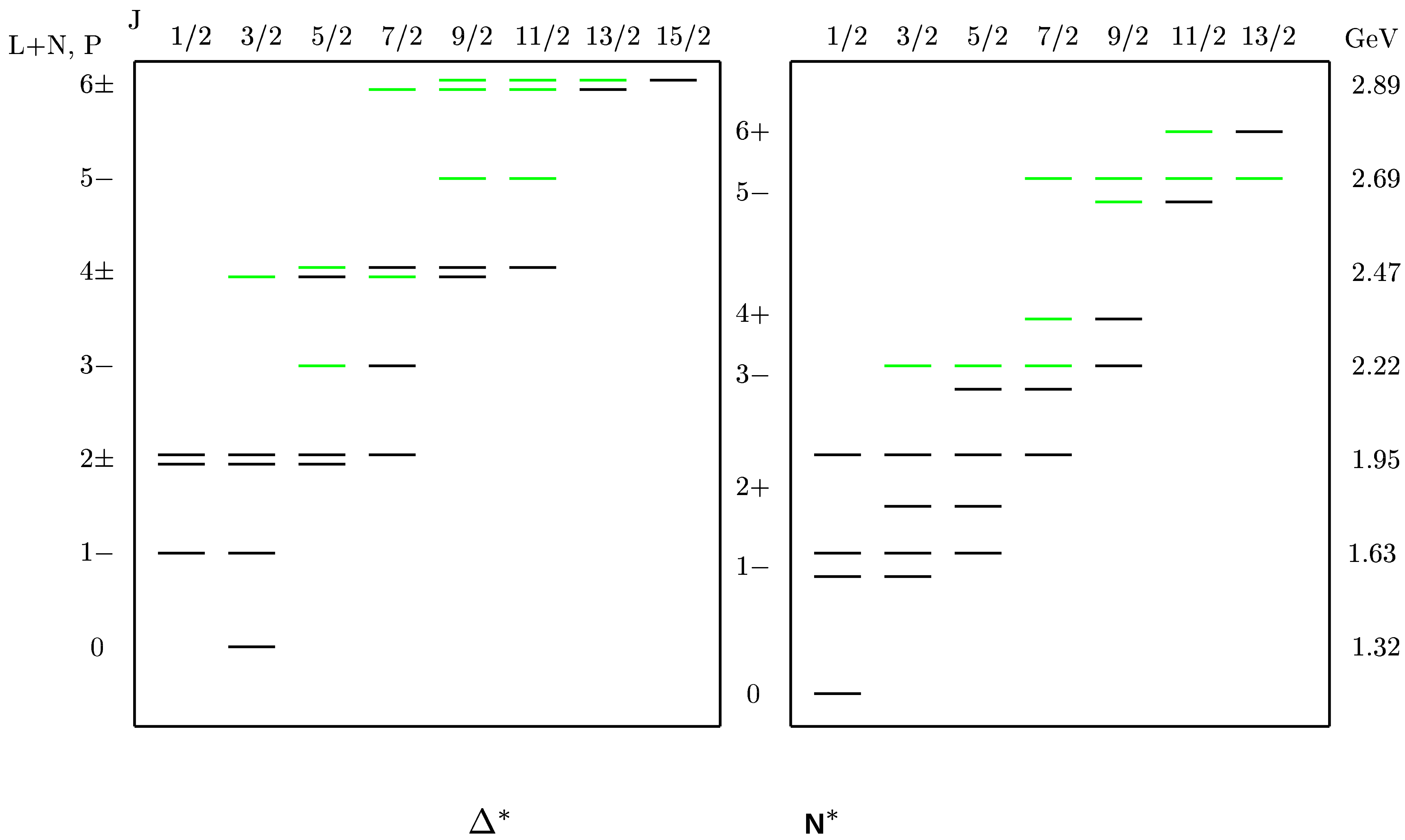
Possible L,S configurations:

Unlikely			Likely		
$\Delta_{5/2^-}$(1930)	$\Delta_{9/2^-}$(2400)	$\Delta_{13/2^-}$(2750)	$\Delta_{5/2^-}$(1930)	$\Delta_{9/2^-}$(2400)	$\Delta_{13/2^-}$(2750)
L=3, S=1/2	L=5, S=1/2	L=7, S=1/2	L=1, S=3/2	L=3, S=3/2	L=5, S=3/2

Flavor wave function: symmetric; spin wave function: symmetric.

$\rightarrow$ spacial wave function must be symmetric !

One unit of radial excitation required !

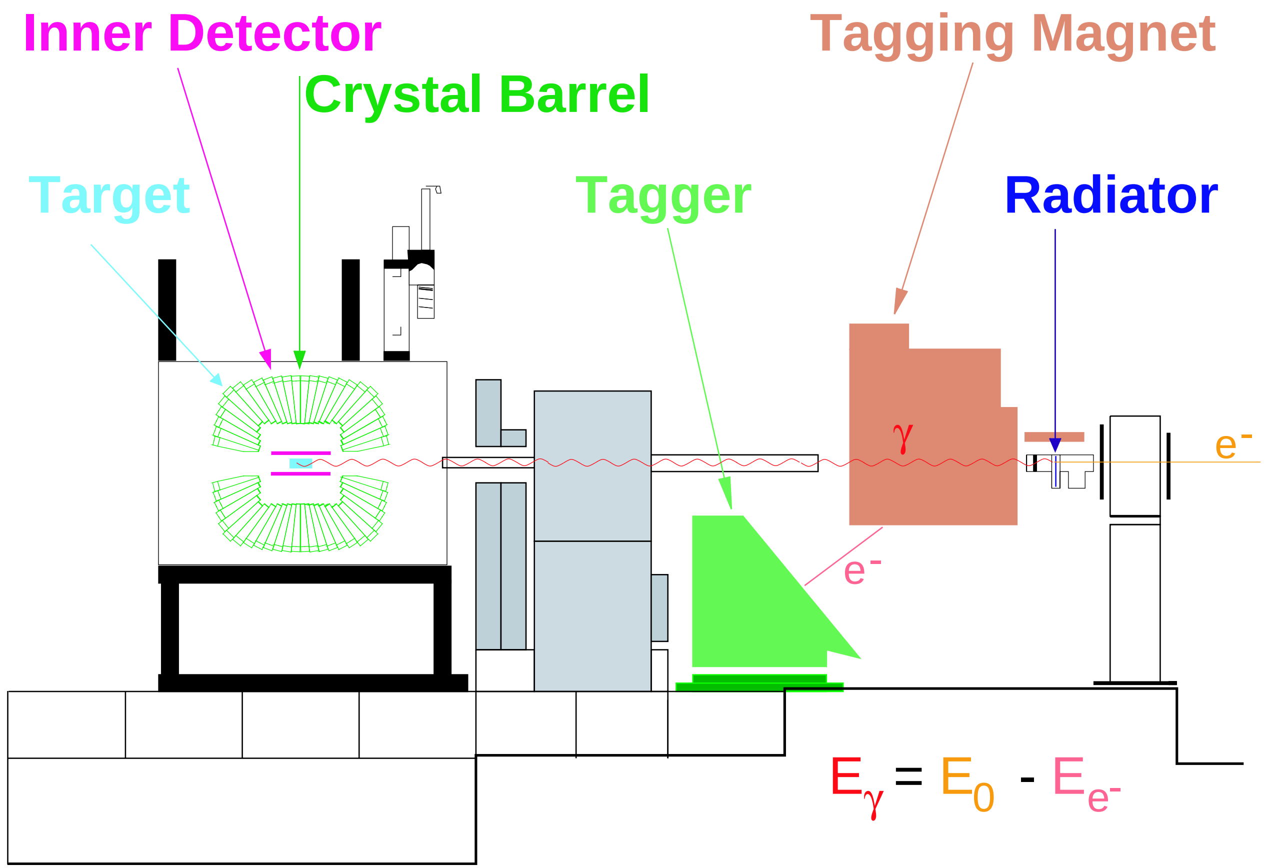

J
L+N, P
1/2 3/2 5/2 7/2 9/2 11/2 13/2 15/2
6± 5− 4± 3− 2± 1− 0
6+ 5− 4+ 3− 2+ 1− 0
1/2 3/2 5/2 7/2 9/2 11/2 13/2
GeV
2.89 2.69 2.47 2.22 1.95 1.63 1.32
Δ*
N*

Schematic diagram of the energy levels of Δ^* (left) and N* (right) resonances. The vertical axis is linear in squared baryon masses, mass values are given on the right axis. For mass degenerate states, negative-parity states are drawn below those with positive parity. Observed states: dark lines, expected ones: green lines.

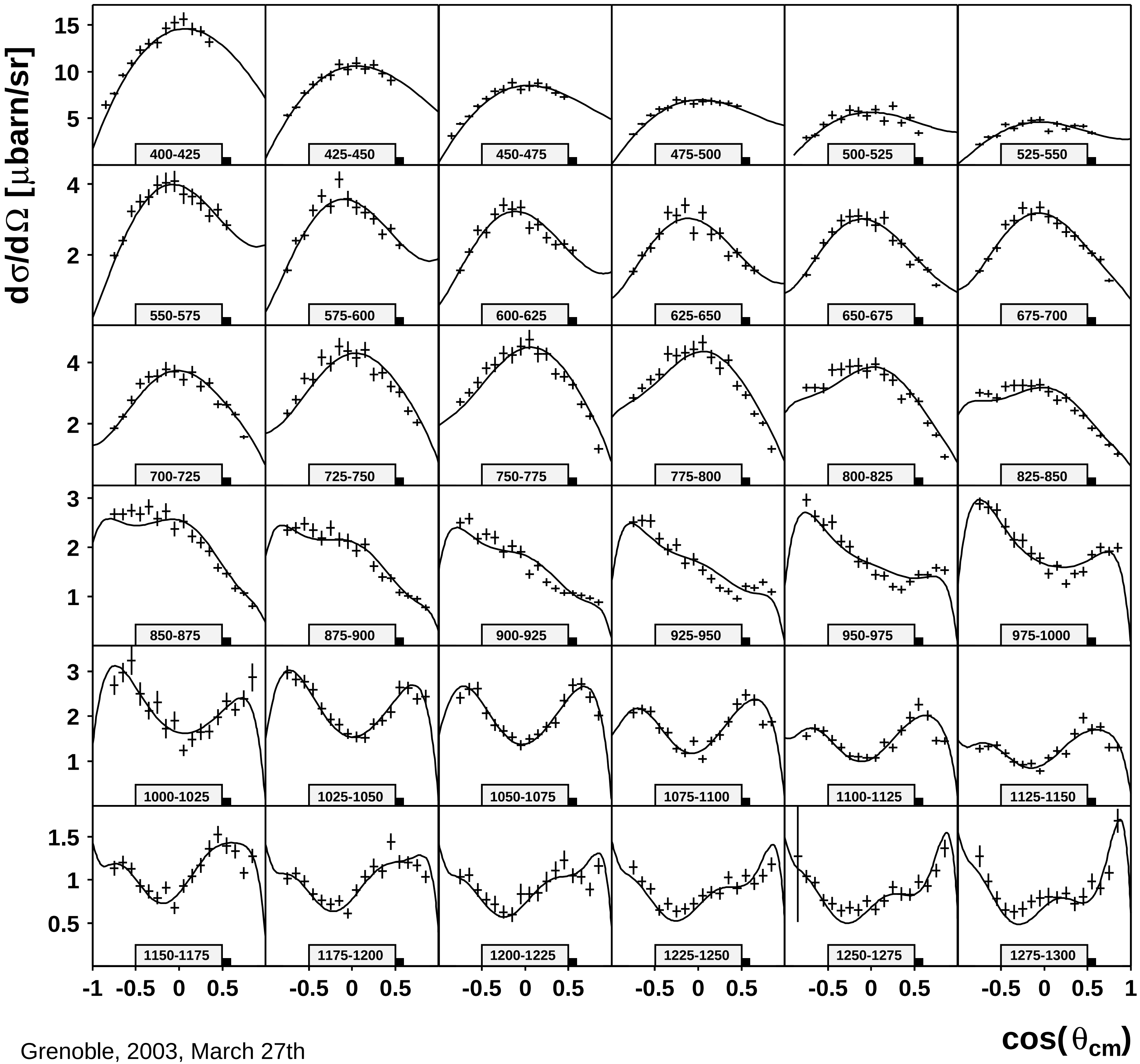
E. Klempt, Phys Lett. B, in print, arXiv:hep-ph/0212241.

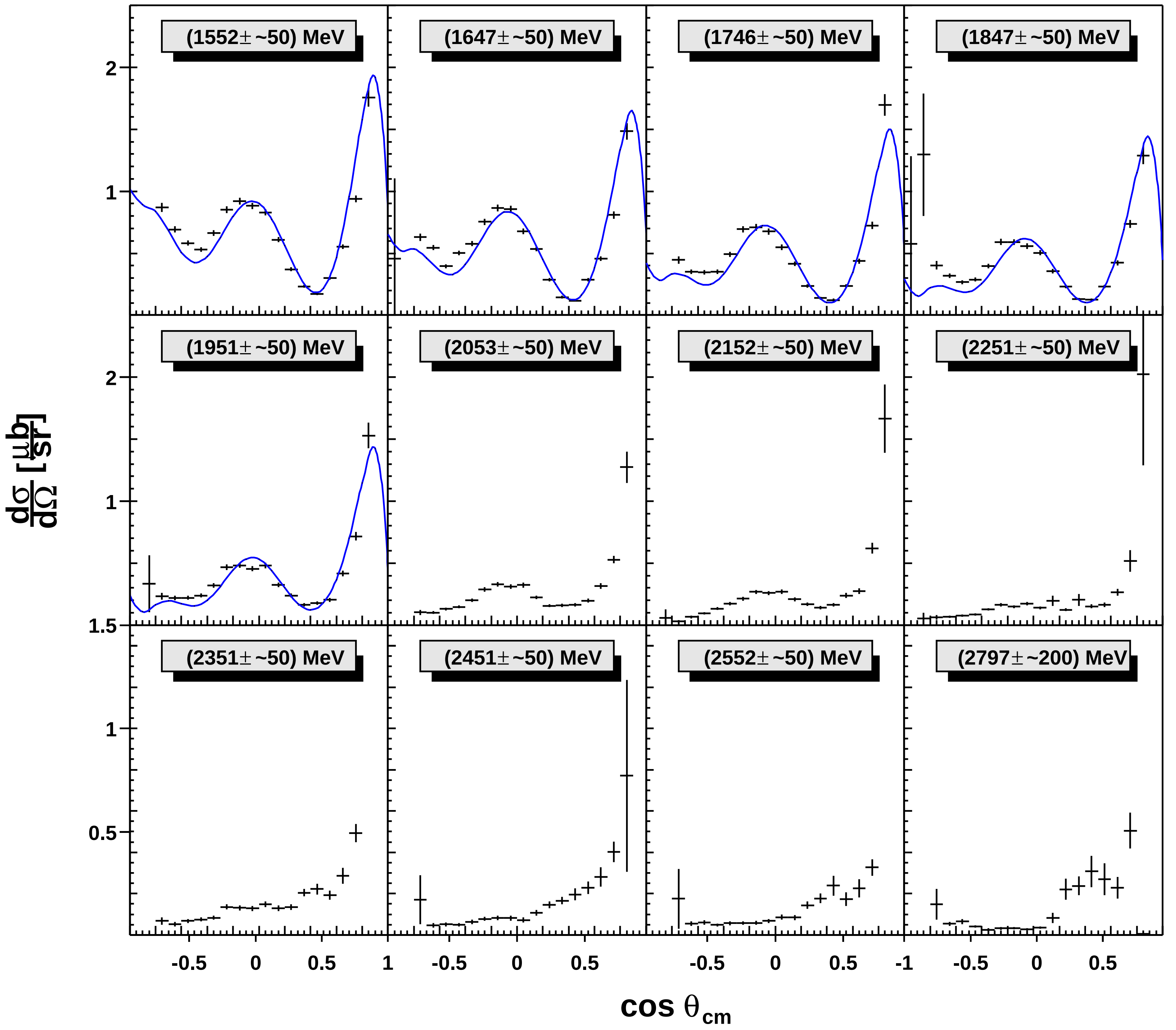
Data from the Crystal Barrel experiment at ELSA

- **WARNINGS:**
- **All results are preliminary !**
- **Systematic errors are not yet evaluated.**



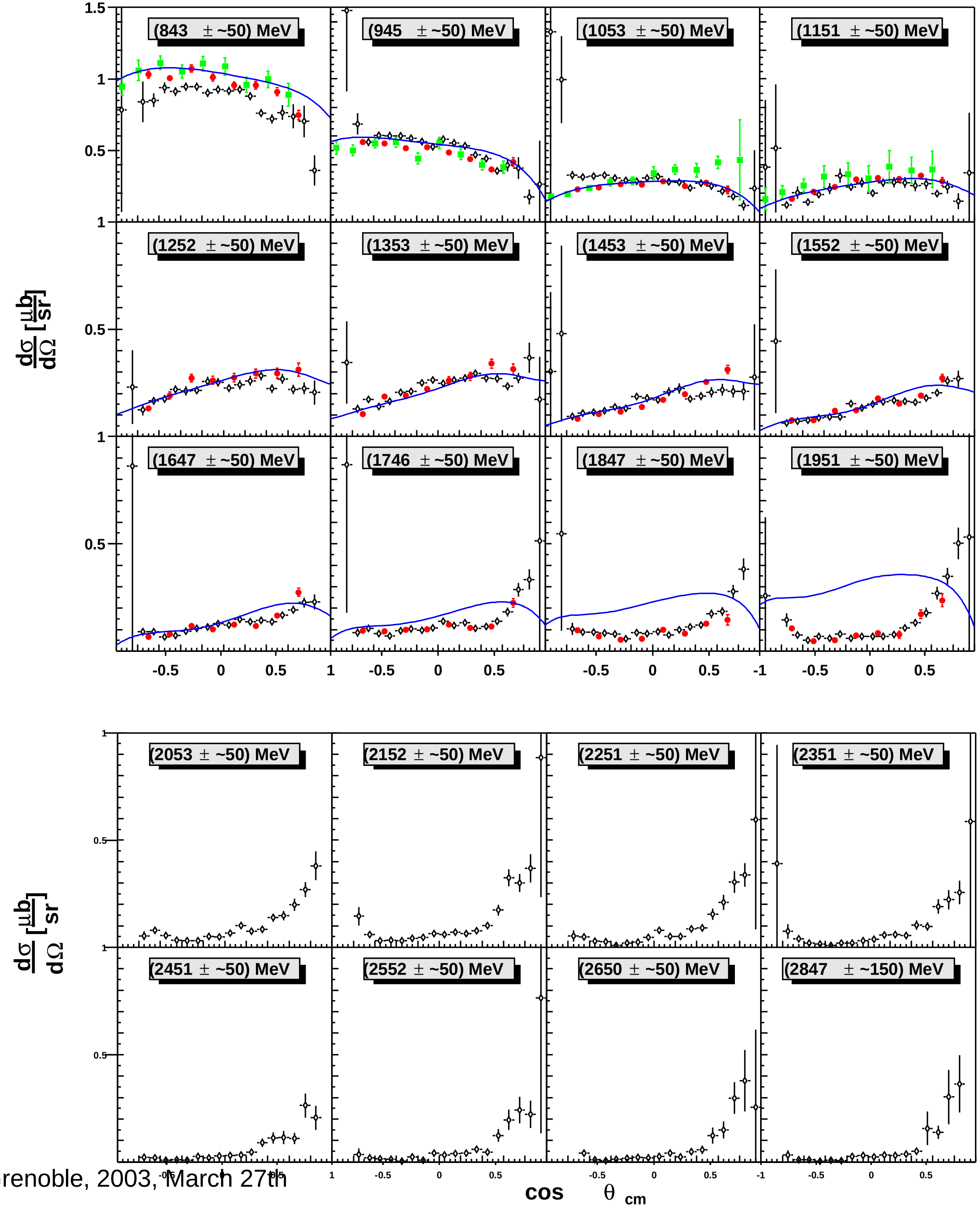
$\gamma p \to p\pi^0$

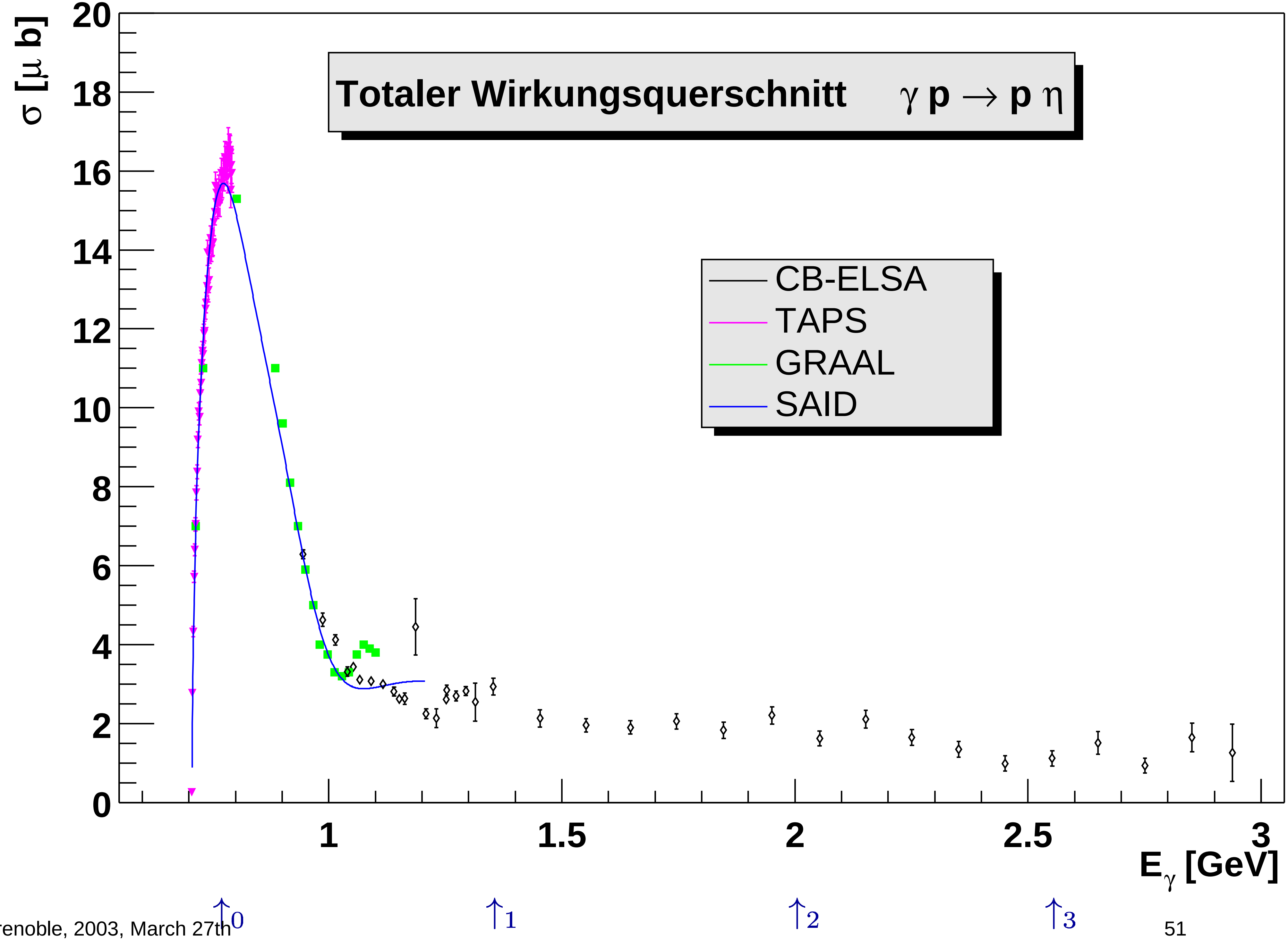




$\gamma p \to p\pi^0$

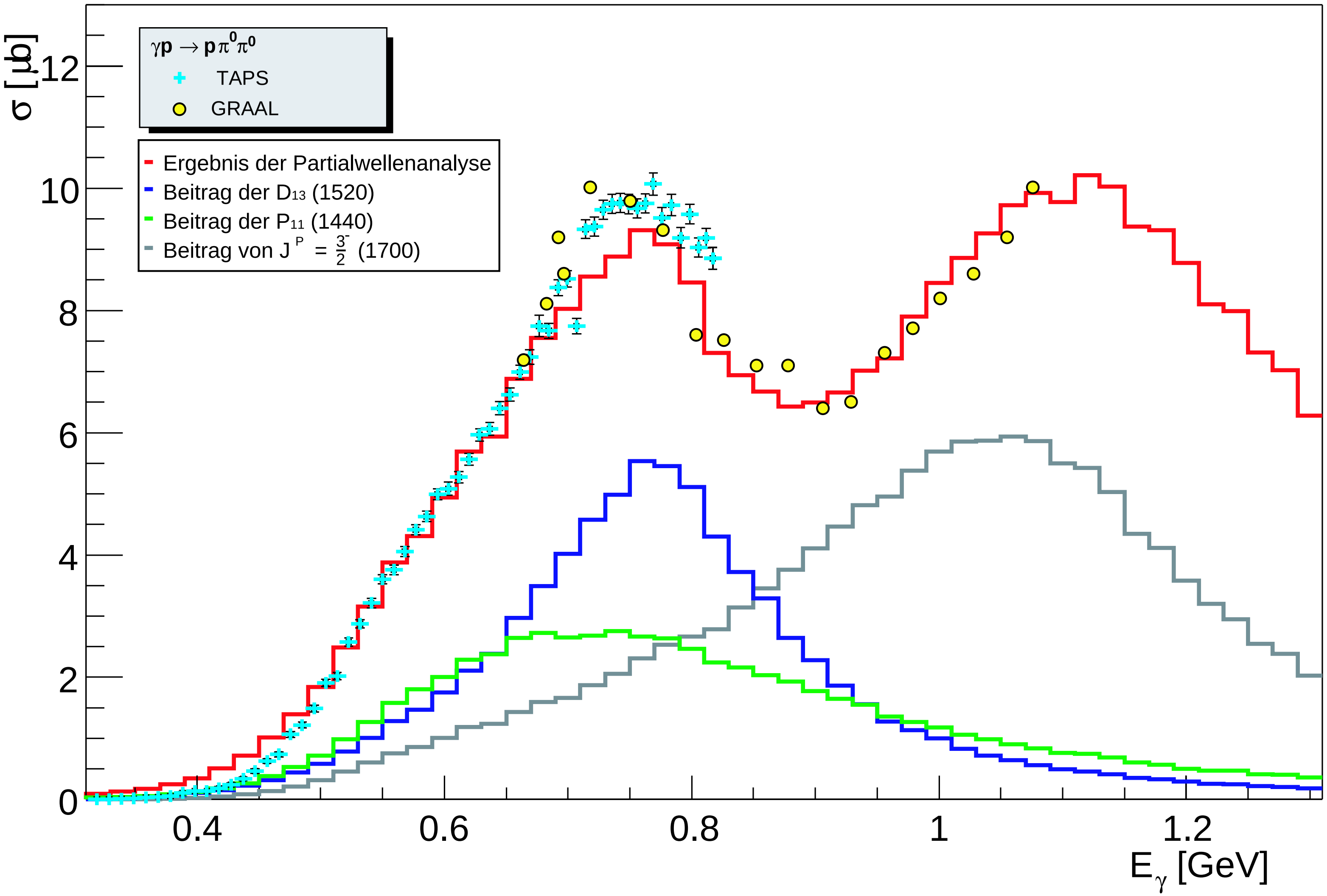
$\gamma p \to p\eta$





Totaler Wirkungsquerschnitt γ p → p η
σ [μ b]
CB-ELSA
TAPS
GRAAL
SAID
E_γ [GeV]
↑0
↑1
↑2
↑3

$\gamma p \to p\pi^0\pi^0$



$\Downarrow$

350 MeV $<$ E$_\gamma$ $<$ 1330 MeV

(1240 MeV/c^2 $-$ 1900 MeV/c^2)

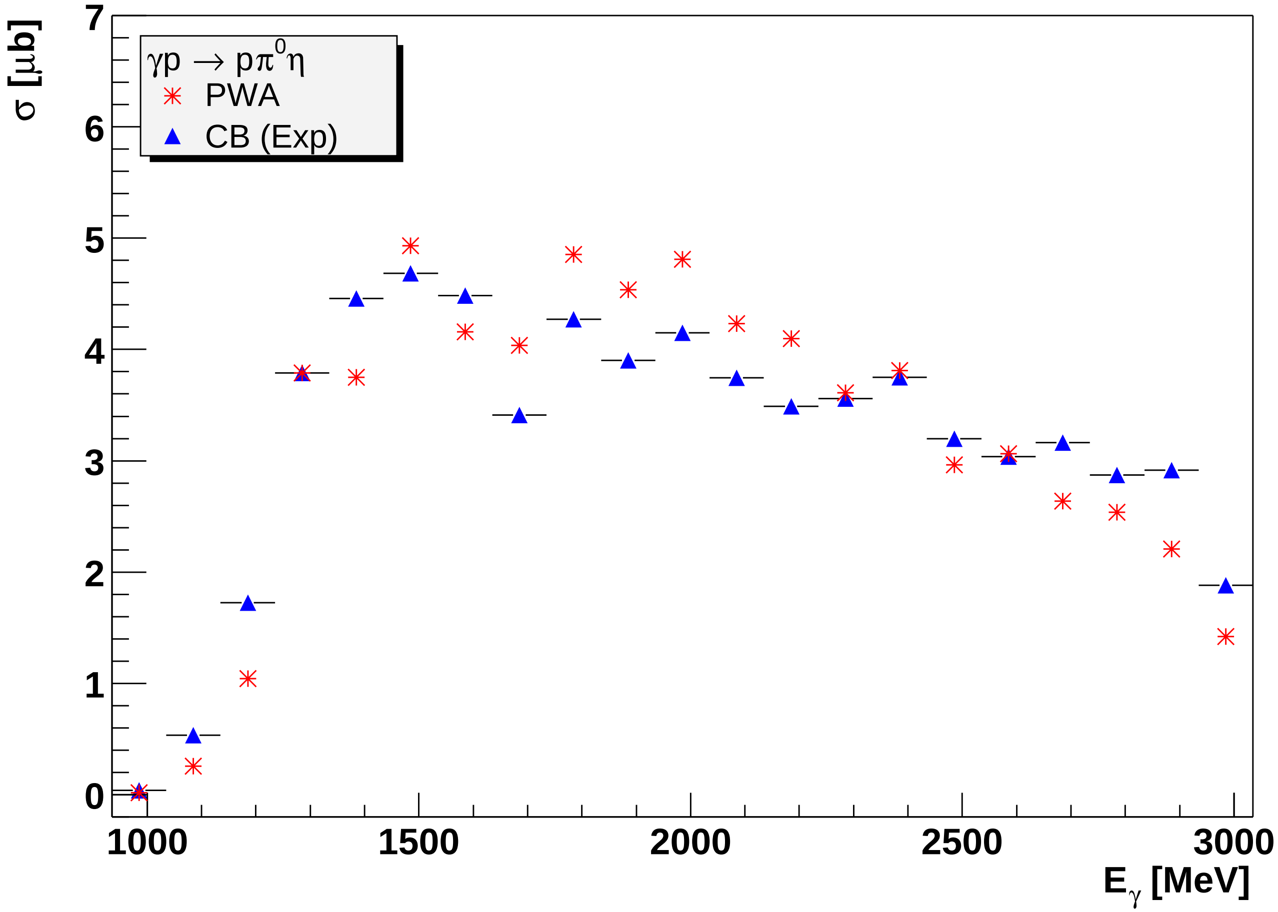
N$_{3/2^-}(1520)$ (****)

N$_{1/2^+}(1440)$ (****)

N$_{3/2^-}(1700)$ (***) $\quad$ **$\Delta_{3/2^-}(1700)$ (****)**

Total cross section

$\gamma p \rightarrow p\pi^0\eta$



Preliminary solution

I	J^P	Mass	Width	Fraction	PDG
$\frac{3}{2}$	$\frac{3}{2}^-$	$\approx$ 2175	300 - 400	$\approx$ 50 %	
$\frac{3}{2}$	$\frac{3}{2}^-$	$\approx$ 1915	$\approx$ 330	$\approx$ 13 %	$\Delta(1940)D_{33}$ (*)
$\frac{3}{2}$	$\frac{5}{2}^-$	$\approx$ 1965	300 - 400	$\approx$ 7 %	$\Delta(1930)D_{35}$ (***)
$\frac{3}{2}$	$\frac{1}{2}^+$	$\approx$ 1940	$\approx$ 300	$\approx$ 16 %	$\Delta(1910)P_{31}$ (****)
$\frac{3}{2}$	$\frac{3}{2}^+$	$\approx$ 2390	300 - 400	$\approx$ 14 %	
$\frac{3}{2}$	$\frac{5}{2}^+$	$\approx$ 1945	300 - 400	$\approx$ 11 %	$\Delta(1905)F_{35}$ (****)

Summary

- **Meson and baryon resonances lie on Regge trajectories**
- **Mesonic and baryonic Regge trajectories have a common slope**
- **Baryons with pairs of quarks which are antisymmetric in spin and flavor undergo a mass shift due to instanton-induced interactions**
- **All observed baryon resonances can be understood as single quark excitations. They form form coherent superpositions of harmonic oscillator eigenstates of defined symmetries.**

- **Crystal Barrel at ELSA has yielded first promissing data !**

What are instantons ?

Strong interactions of massless quarks:

Chiral symmetry

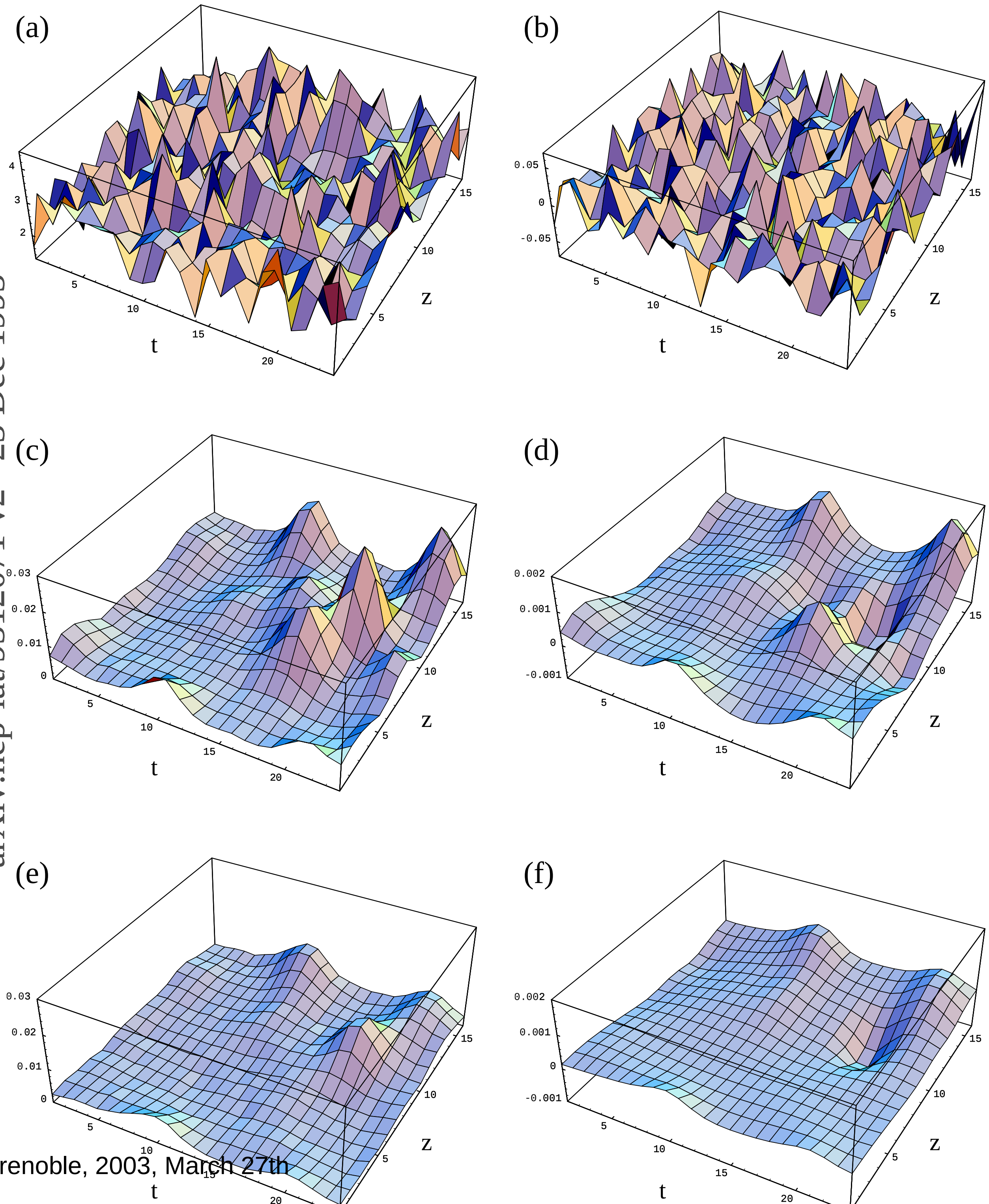
However:

- **Strong fluctuations of gluon fields**
- **QCD allows solutions with vortices (topological charge, winding number)**
- **Quarks can be bound to these vortices (zero modes)**
- **Quarks can flip spin under change of topological charge**
- **Chirality of quarks is not conserved**
- **Chiral symmetry is spontaneously broken**
- **Glodstone boson acquire mass**

Symmetry breaking :

	Magnetism	QCD
spontaneous	Weiss-	Constituent
	districts	quarks
induced	magnetic field	Higgs field
		$m_u \sim 4$ MeV
		$m_d \sim 7$ MeV
		$m_u \sim 120$ MeV

Instantons on the lattice



Action density (left) and topological charge (right) as functions of space and time before cooling (a,b) and after cooling (c-f).