GLUEBALLS, HYBRIDS, PENTAQUARKS:

A Survey of Exotic Hadrons

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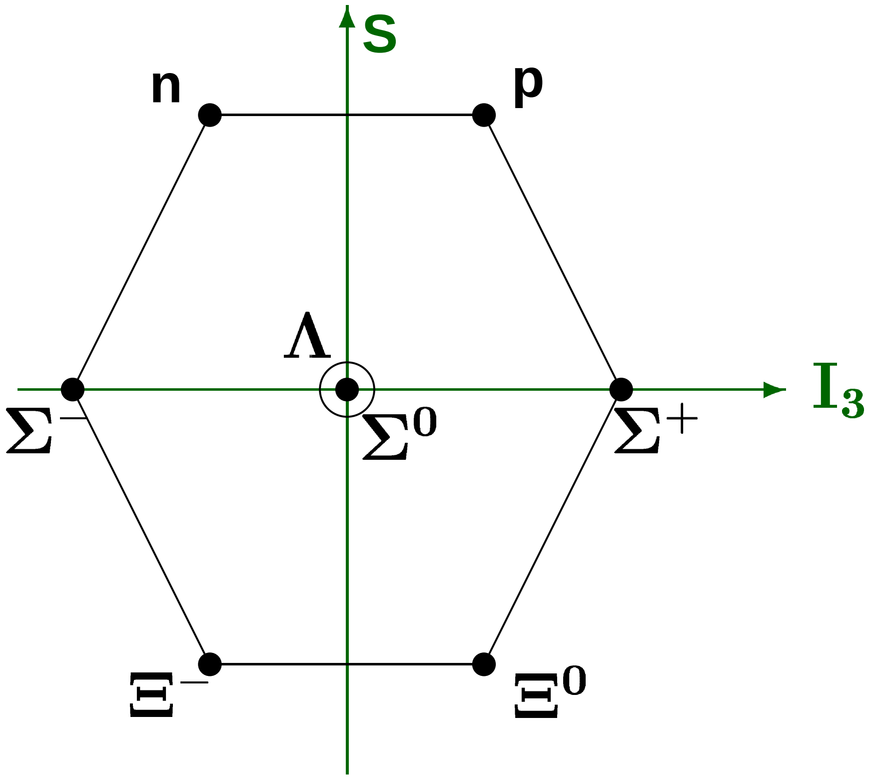
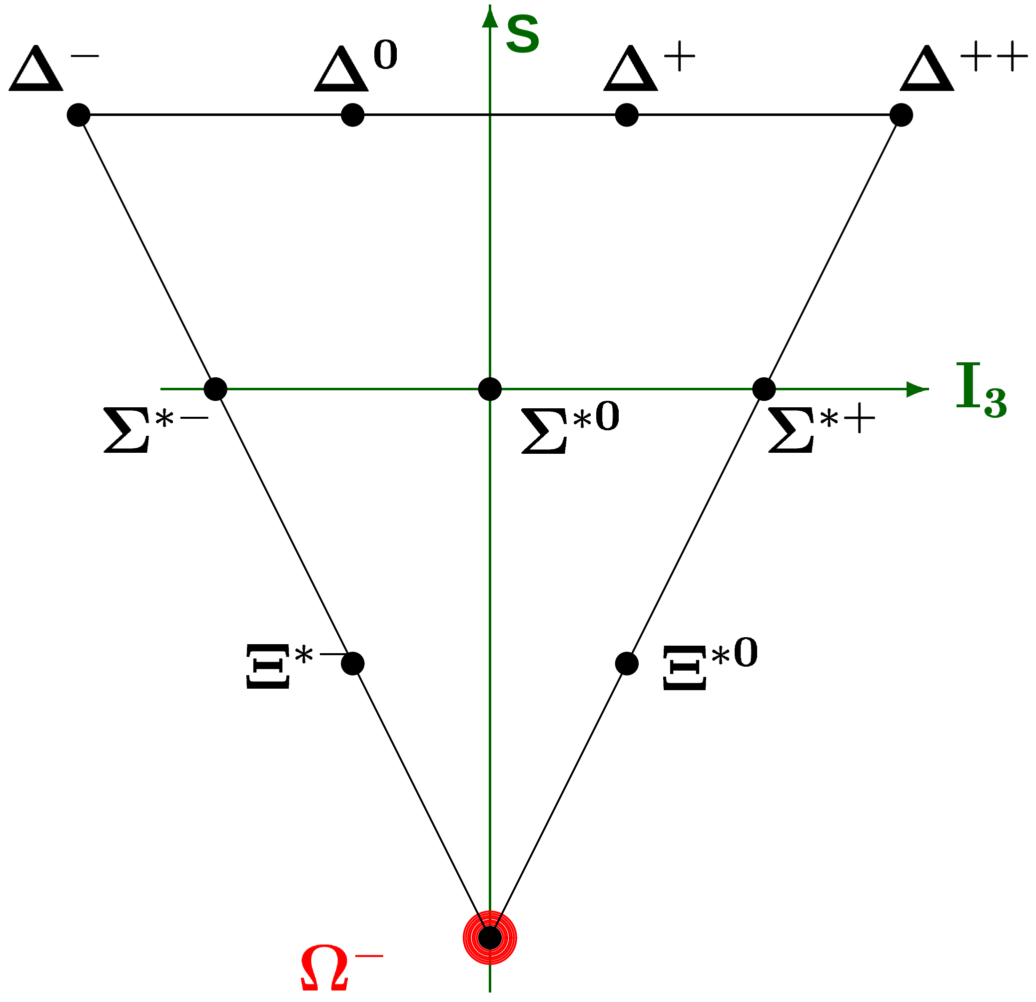
Glueballs, Hybrids, Pentaquarks

- Pentaquarks or hybrid baryons
- Tetraquarks or hybrid mesons
- Glueballs and the $\eta(1440)$
- Is there a scalar glueball ?
- Gluon exchange versus instanton–induced forces
- Conclusions

Octet **Well established** **Decuplet**





Ω^- : Predicted by Gell-Mann in 1964

: Found by V. E. Barnes et al. in 1964

Triumph of SU(3)
and the quark model

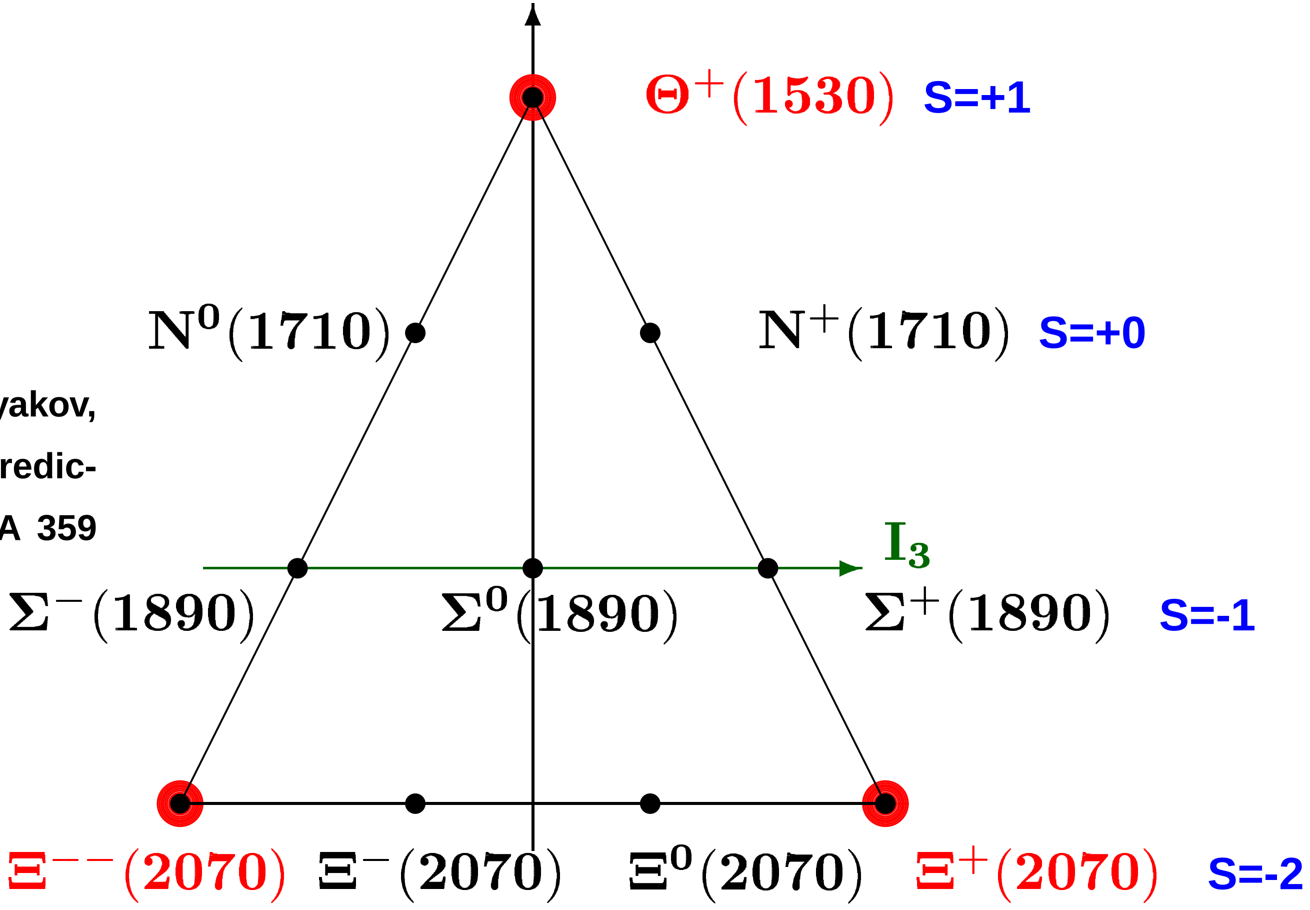
Antidecuplet

Predicted by

chiral soliton model

antidecuplet

D. Diakonov, V. Petrov and M. V. Polyakov, "Exotic anti-decuplet of baryons: Prediction from chiral solitons," Z. Phys. A 359 (1997) 305



Summary of measurements of pentaquarks. The systematic errors given in parentheses are not quoted in the papers but were estimated to be small.

Mass (MeV)	Width (MeV)	$\mathrm{N}_{\mathrm{event}}$	Statist. signif.	Reaction	Experiment
$\Theta^+(1540)$					
$1540 \pm 10 \pm 5$	< 25	19 ± 2.8	$\sim 2.7\sigma$	$\gamma\mathrm{C} \rightarrow \mathrm{C'K^+K^-}$	**LEPS**
$1539 \pm 2 \pm 2$	< 9	29	$\sim 3.0\sigma$	$\gamma\mathrm{p} \rightarrow \mathrm{nK^+K^0_s}$	**DIANA**
$1542 \pm 2 \pm 5$	< 21	43	$\sim 3.5\sigma$	$\gamma\mathrm{d} \rightarrow \mathrm{pnK^+K^-}$	**CLAS**
$1540 \pm 4(\pm 3)$	< 25	63 ± 13	4.8σ	$\gamma\mathrm{p} \rightarrow \mathrm{nK^+K^0_s}$	**SAPHIR**
$1533 \pm 5(\pm 3)$	< 20	27	$\sim 4.0\sigma$	ν–induced	**CERN, FNAL**
$1555 \pm 1 \pm 10$	< 26	41	$\sim 4.0\sigma$	$\gamma\mathrm{p} \rightarrow \mathrm{nK^+K^-\pi^+}$	**CLAS**

Mass (MeV)	Width (MeV)	$\mathrm{N}_{\mathrm{event}}$	Statist. signif.	Reaction	Experiment
1528 ± 4	< 19	~ 60	$\sim 4\sigma$	γ^*–induced	HERMES
$1526 \pm 3 \pm 3$	< 24	50	3.5σ	p-p reaction	SVD-2
1530 ± 5	< 18		3.7σ	p-p reaction	COSY
1545 ± 12	< 35	~ 100	$\sim 4\sigma$	p-A reaction	YEREVAN
$1521.5 \pm 1.5^{+2.8}_{-1.7}$	< 6	221	4.6σ	Fragmentation	ZEUS
$\Xi(1862)$					
1862	< 21		4.6σ	ν–induced	NA49
$\Theta_c(3099)$					
$3099 \pm 3 \pm 5$			5.4σ	γ^*–induced	HERA

T. Nakano *et al.* [LEPS Collaboration], “Evidence for a narrow $S = +1$ baryon resonance in photoproduction from the neutron,” Phys. Rev. Lett. 91 (2003) 012002.

J. Barth *et al.* [SAPHIR Collaboration], “Evidence for the positive-strangeness pentaquark Θ^+ in photoproduction with the Saphir detector at Elsa,” Phys. Lett. B 572 (2003) 127.

V. V. Barmin *et al.* [DIANA Collaboration], “Observation of a baryon resonance with positive strangeness in K$^+$ collisions with Xe nuclei,” Phys. Atom. Nucl. 66 (2003) 1715.

R. N. Cahn and G. H. Trilling, “Experimental limits on the width of the reported $\Theta(1540)^+$,” Phys. Rev. D 69 (2004) 011501.

S. Stepanyan *et al.* [CLAS Collaboration], “Observation of an exotic S = +1 baryon in exclusive photoproduction from the deuteron,” Phys. Rev. Lett. 91 (2003) 252001.

V. Kubarovsky *et al.* [CLAS Collaboration], “Observation of an exotic baryon with S = +1 in photoproduction from the proton,” arXiv:hep-ex/0311046.

A. E. Asratyan, A. G. Dolgolenko and M. A. Kubantsev, “Evidence for formation of a narrow $\mathrm{K}^0_\mathrm{s}\mathrm{p}$ resonance with mass near 1533 MeV in neutrino interactions,” arXiv:hep-ex/0309042.

E. Lesquoy, A. Muller, F. A. Triantis, A. Berthon, L. Montanet, E. Paul and P. Saetre, “Partial waves in the $\mathrm{K}^+\mathrm{p}$ interaction between 1.2 GeV/c and 1.7 GeV/c,” Nucl. Phys. B 99 (1975) 346.

A. Airapetian *et al.* [HERMES Collaboration], “Evidence for a narrow $|$S$|$ = 1 baryon state at a mass of 1528-MeV in quasi-real photoproduction,” arXiv:hep-ex/0312044.

A. Aleev *et al.* [SVD Collaboration], “Observation of narrow baryon resonance decaying into $\mathrm{pK_s^0}$ in p A interactions at 70-GeV/c with SVD-2 setup,” arXiv:hep-ex/0401024.

M. Abdel-Bary *et al.* [COSY-TOF Collaboration], “Evidence for a narrow resonance at 1530-MeV/c^2 in the $\mathrm{K^0p}$ system of the reaction $\mathrm{pp} \to \Sigma^+\mathrm{K^0p}$ from the COSY-TOF experiment,” arXiv:hep-ex/0403011.

P. Z. Aslanyan, V. N. Emelyanenko and G. G. Rikhkvitzkaya, “Observation of S=+1 narrow resonances in the system K_s^0p from p+C_3H_8 collision at 10 GeV/c,” arXiv:hep-ex/0403044.

[ZEUS Collaboration], “Evidence for a narrow baryonic state decaying to $\mathrm{K_s^0p}$ and $K_s^0\bar{p}$ in deep inelastic scattering at HERA,” arXiv:hep-ex/0403051.

J. J. Engelen *et al.*, “Multichannel analysis of the reaction $\mathrm{K^-p} \to \mathrm{\bar{K}^0}\pi^-\mathrm{p}$ at 4.2 GeV/c,” Nucl. Phys. B 167 (1980) 61.

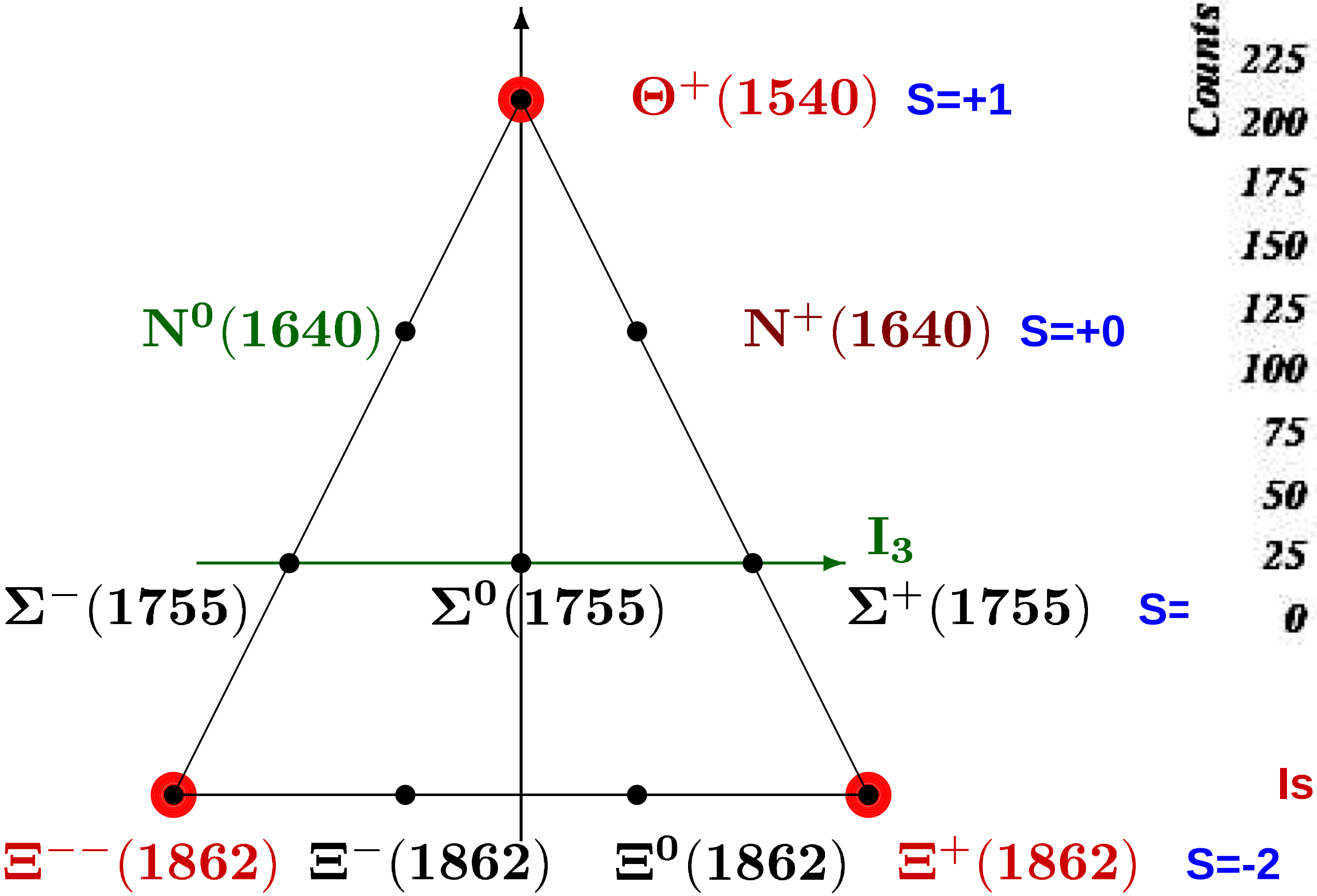
K. T. Knöpfle, M. Zavertyaev and T. Zivko [HERA-B Collaboration], “Search for Θ^+ and $\Xi_{(3/2)}$–pentaquarks in HERA-B,” arXiv:hep-ex/0403020.

J. Z. Bai *et al.* [BES Collaboration], “Search for the pentaquark state in $\psi(2S)$ and J/ψ decays to $\mathrm{K_s^0pK^-\bar{n}}$ and $\mathrm{K_s^0\bar{p}K^+n}$,” arXiv:hep-ex/0402012.

C. Alt *et al.* [NA49 Collaboration], “Observation of an exotic S = -2, Q = -2 baryon resonance in proton proton collisions at the CERN SPS,” arXiv:hep-ex/0310014.

[H1 Collaboration], “Evidence for a narrow anti-charmed baryon state,” arXiv:hep-ex/0403017.

Antidecuplet



$\Theta^+(1540)$ S=+1

$N^0(1640)$ $N^+(1640)$ S=+0

I_3

$\Sigma^-(1755)$ $\Sigma^0(1755)$ $\Sigma^+(1755)$ S=

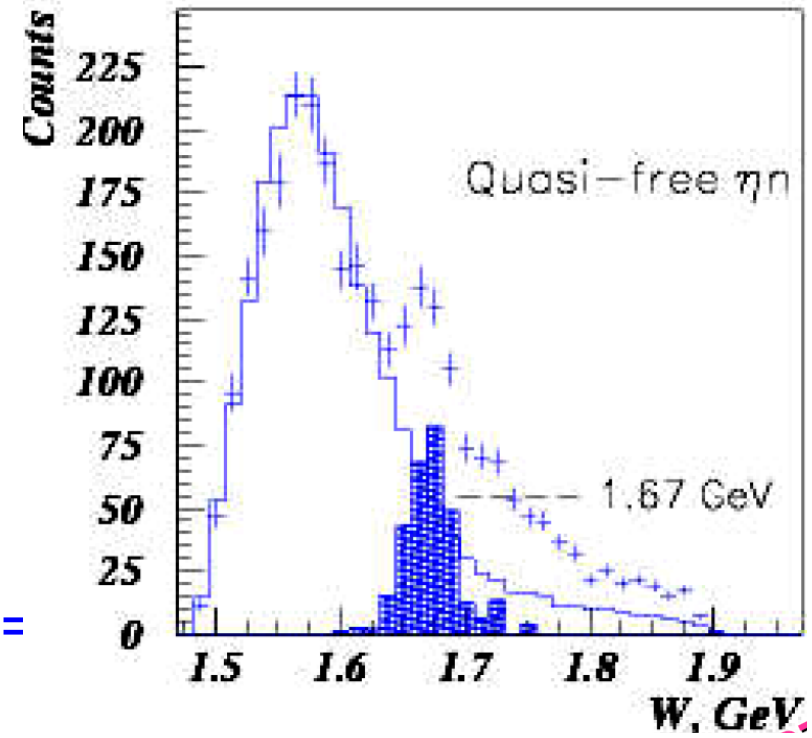
$\Xi^{--}(1862)$ $\Xi^-(1862)$ $\Xi^0(1862)$ $\Xi^+(1862)$ S=-2

$N^+(1640) \to p\eta$ weak

$N^0(1640) \to n\eta$ strong

GRAAL Experiment

$\gamma n \to n\eta$



Is the $N^0(1640) \to n\eta$ discovered ?

Graal, collaboration, N*2004, Grenoble, preliminary

Extension of the quark model:

Fock space expansion of minimum quark–model configuration:

$$\begin{array}{lclcl}
\text{meson} & = & \alpha q\bar{q} & + & \beta_1 b\bar{q}q\bar{q} + \ldots + \gamma_1 q\bar{q}g + \ldots \\
\text{baryon} & = & \alpha qqq & + & \beta_1 qqqq\bar{q} + \ldots + \gamma_1 qqqg + \ldots
\end{array}$$

quark model multiquark hybrid

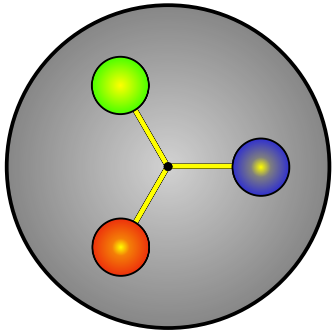
Observation of multiquark states or hybrids reduced by ~ 10:

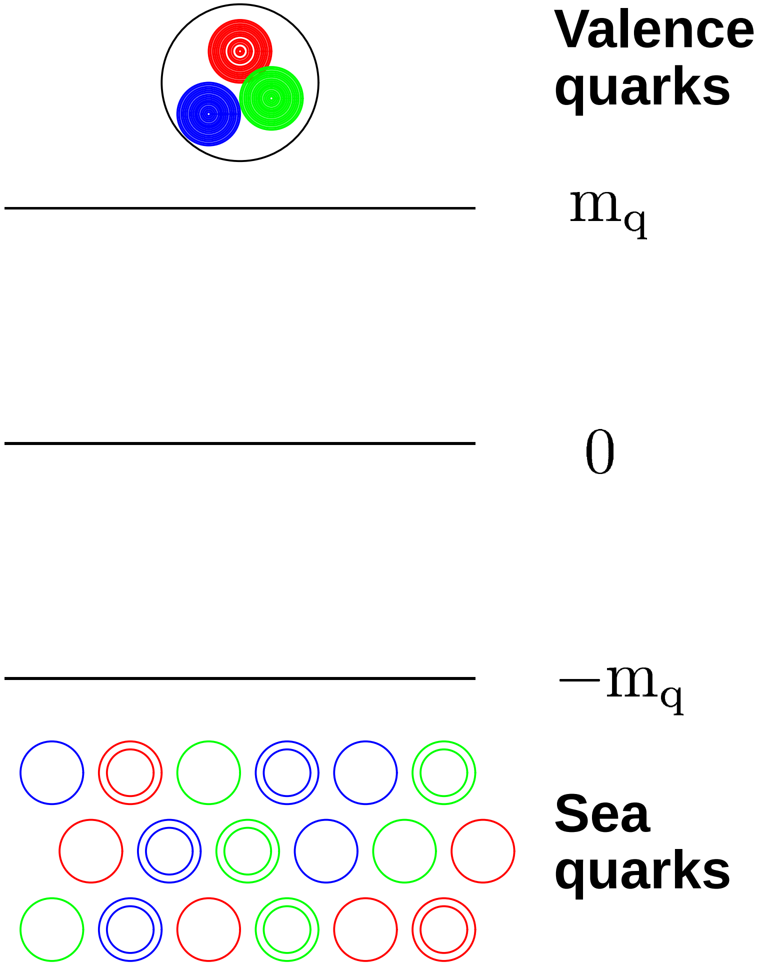
$\beta_1 \sim 0.3$ or $\gamma_1 \sim 0.3$

Two pictures of hadrons

Quarks and gluons or **the vaccuum and condensates**

play the decisice role in low–energy QCD





Quarks interact via exchange of gluons:

- **Hybrids and glueballs**
- **Effective one–gluon exchange**

Quark interact via changes of the QCD vaccuum

- **Multiquarks**
- **Instanton–induced interactions**

Quarks interact via exchange of gluons:

The self–energy leads to constituent quarks.

At low energies the gluon field is concentrated in a flux tube.

Consequences:

- The flux tube connecting a $q\bar{q}$ pair can rotate around the axis, with angular momentum Λ in the direction of axis.
- Such excitations are called hybrids
- Hybrids, baryonic hybrids, and glueballs are predicted
- The $\rho - \pi$ and $\mathbf{\Delta} - \mathrm{N}$ mass splittings are color–magnetic in origin.
- The interaction between constituent quarks can be described by a confinement plus effective one–gluon exchange

Quark interact via changes of the QCD vaccuum

Quarks and sea quarks are dynamically coupled.

Constituent quarks require their mass by spontaeous symmetry breaking.

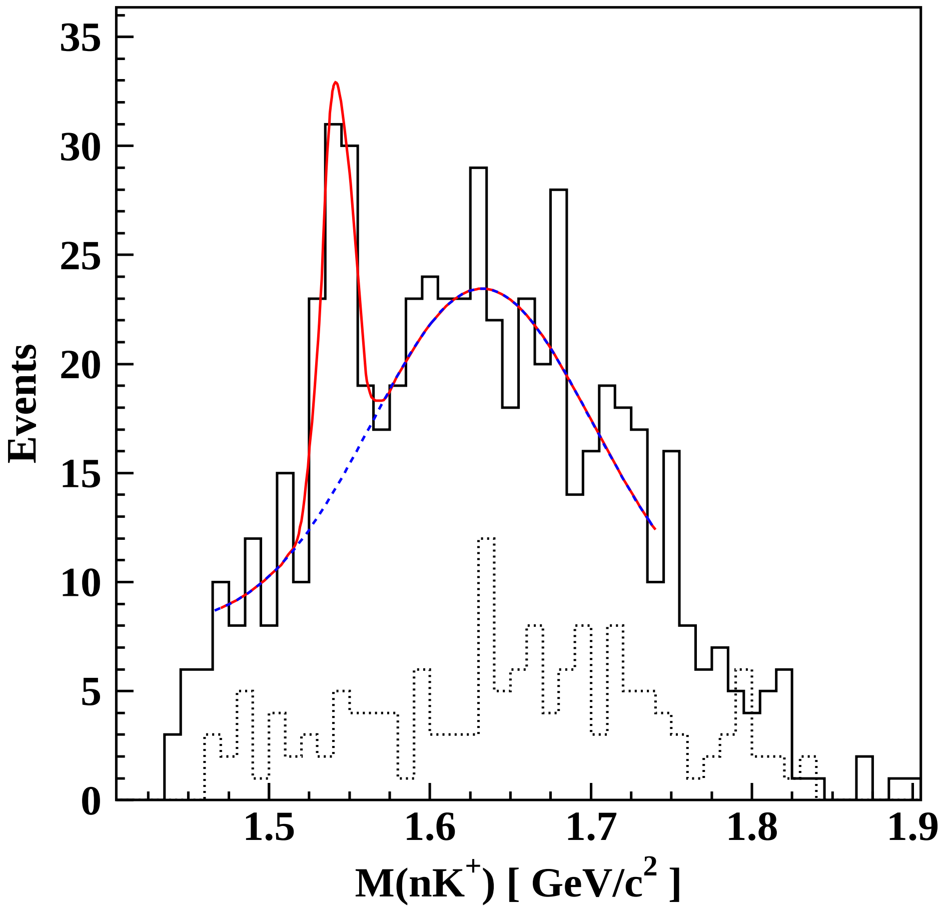
Consequences:

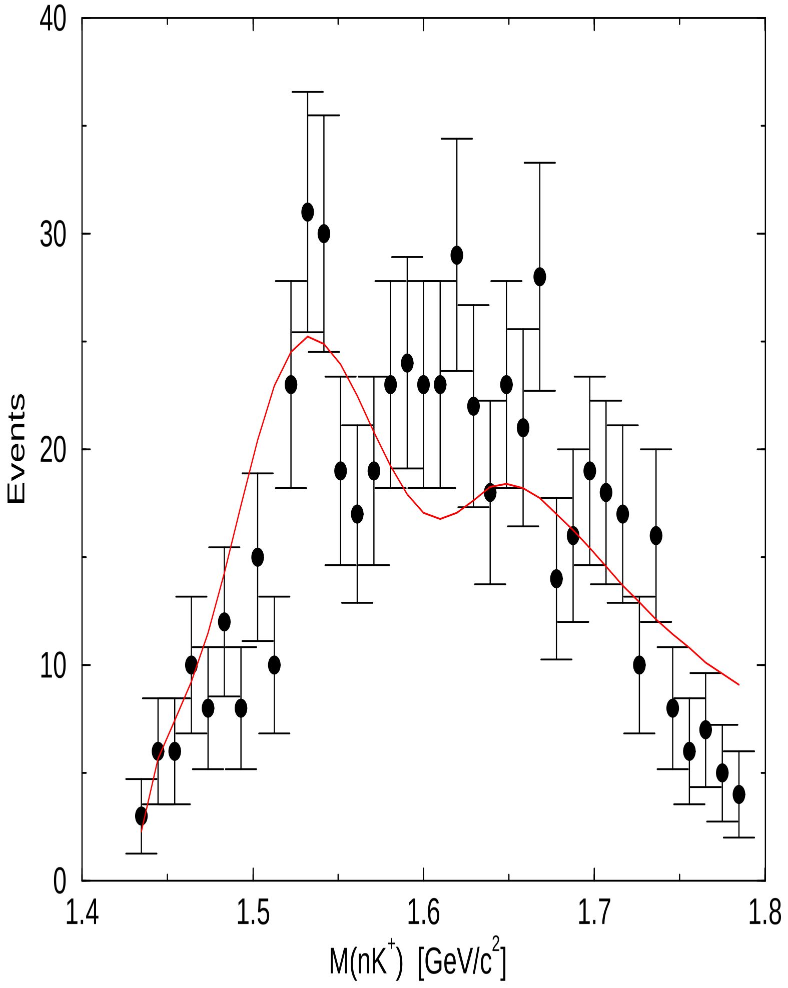
- Hybrids or glueballs do not need to exist.
- The see quarks might carry flavor quantum numbers: $\Rightarrow$
  Exotic quark configurations should exist
- The equations of motion support soliton solutions which can be organized into multiplets.
- The lowest lying multiplets are 8 and 10 and $\overline{10}$.
- The interaction between constituent quarks can be described by a confinement plus instanton–induced interactions

Pentaquarks or hybrid baryons

Does the $\Theta^+(1540)$ exclude the gluonic picture ?

Two fits:





with $\Theta^+(1540)$ and **without $\Theta^+(1540)$**

No solid evidence for baryonic hybrids

A. R. Dzierba, D. Krop, M. Swat, S. Teige and A. P. Szczepaniak,
"The evidence for a pentaquark signal and kinematic reflections," Phys. Rev. D 69 (2004) 051901

Tetraquarks or hybrid mesons

What about mesons ? Hybrids or multiquarks ? Evidence for J^{PC} = 1^{-+} exotics

Experiment	mass (MeV/c^2)	width (MeV/c^2)	decay mode	reaction
BNL	$1370 \pm 16 \, {}^{+}_{-} \, {}^{50}_{30}$	$385 \pm 40 \, {}^{+65}_{-105}$	$\eta\pi$	π^-p $\to \eta\pi^-$p
BNL	$1359 \, {}^{+}_{-} \, {}^{16}_{14} \, {}^{+}_{-} \, {}^{10}_{24}$	$314 \, {}^{+31}_{-29} \, {}^{+9}_{-66}$	$\eta\pi$	π^-p $\to \eta\pi^-$p
CBar	$1400 \pm 20 \pm 20$	$310 \pm 50 \, {}^{+50}_{-30}$	$\eta\pi$	$\bar{p}n \to \pi^-\pi^0\eta$
CBar	1360 ± 25	220 ± 90	$\eta\pi$	$\bar{p}p \to \pi^0\pi^0\eta$
CBAR	$\sim$1440	$\sim$400	$\rho\pi$	$\bar{p}n \to \pi^-3\pi^0$
BNL	$1593 \pm 8 \, {}^{+29}_{-47}$	$168 \pm 20 \, {}^{+150}_{-12}$	$\rho\pi$	π^-p $\to \pi^+\pi^-\pi^-$p
BNL	1596 ± 8	387 ± 23	$\eta'\pi$	π^-p $\to \pi^-\eta'$p
VES	1610 ± 20	290 ± 30	$\rho\pi, \eta'\pi$	π^-N$\to \pi^-\eta'$N
BNL	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	$f_1(1285)\pi$	π^-p $\to \eta\pi^+\pi^-\pi^-$p
BNL	$1664 \pm 8 \pm 4$	$185 \pm 25 \pm 12$	$b_1(1235)\pi$	π^-p $\to \omega\pi^0\pi^-$p
CBAR	1590 ± 50	280 ± 75	$b_1(1235)\pi$	$\bar{p}p \to \pi^+\pi^-\pi^0\omega$
BNL	$\sim 2003 \pm 88 \pm 148$	$306 \pm 132 \pm 121$	$f_1(1285)\pi$	π^-p $\to \eta\pi^+\pi^-\pi^-$p
BNL	$2000 \pm 20 \pm 10$	$230 \pm 32 \pm 15$	$\omega\pi^0\pi^-$	π^-p $\to \omega\pi^0\pi^-$p

Hybrids or Tetraquarks ?

- The $\pi_1(1360)$ must be a tetraquark.

  SU(3) argument: assume $8_1 \to 8 \otimes 8$ decay.

  $\pi_1(1360) \to \eta\pi$ requires symmetric SU(3) d_{ijk} structure functions.

  $\pi_1(1360) \to \eta\pi$ requires (antisymmetric) $\mathrm{l} = 1$.

  $\pi_1(1360)$ cannot be a member of 8, it must be 10 or $\overline{10}$.

- The multitude of states suggests tetraquarks.

$$(\bar{\mathbf{3}} + \mathbf{6}) \otimes (\mathbf{3} + \bar{\mathbf{6}}) = \bar{\mathbf{3}} \otimes \mathbf{3} + \bar{\mathbf{3}} \otimes \bar{\mathbf{6}} + \mathbf{6} \otimes \mathbf{3} + \mathbf{6} \otimes \bar{\mathbf{6}}$$

$$= \mathbf{1} + \mathbf{8} + \mathbf{8} + \mathbf{10} + \mathbf{8} + \overline{\mathbf{10}} + \mathbf{1} + \mathbf{8} + \mathbf{27}$$

Four octets plus one $10 + \overline{10}$ expected !

Only one or two hybrids predicted.

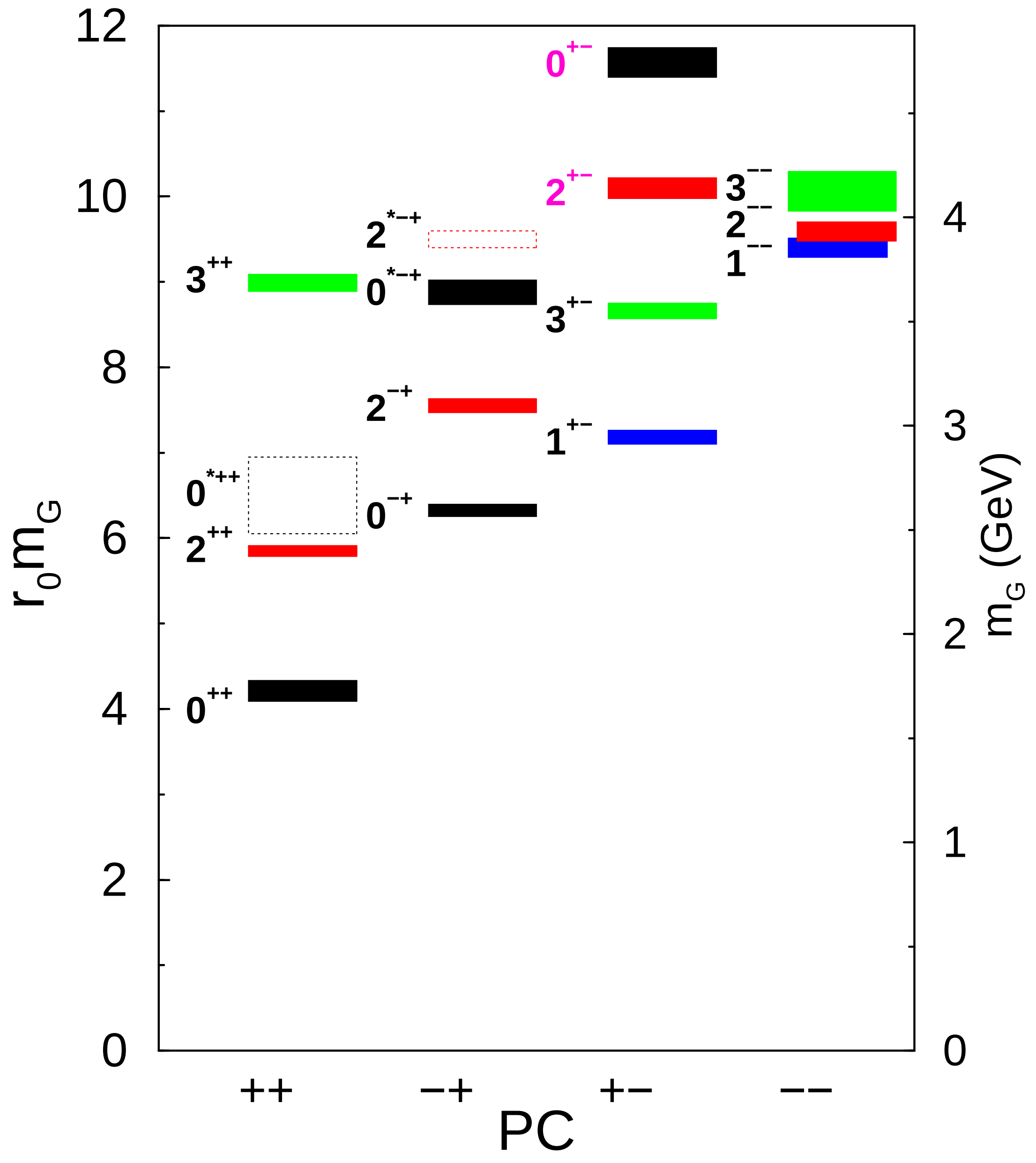
There is no arguments against the possibility that a hybrid hides in the crowd of tetraquarks (and no argument in favour neither)

Glueballs and the $\eta(1440)$

Glueballs

The glueball spectrum from an anisotropic lattice study (Morningstar). The scalar glueball is expected at 1.7 GeV, the tensor glueball at 2.3 GeV. Pseudoscalar glueball should have a mass of about 2.6 GeV.

We discuss first the $\eta(1440)$



The $\boldsymbol{\eta}(1440)$ is split

Pseudoscalar mesons:

$\boldsymbol{\pi}$	$\boldsymbol{\eta}$		$\boldsymbol{\eta'}$	$\boldsymbol{K}$
$\boldsymbol{\pi}(1300)$	$\boldsymbol{\eta}(1295)$	$\boldsymbol{\eta}(1405)$	$\boldsymbol{\eta}(1475)$	$\boldsymbol{K}(1460)$
$\boldsymbol{n\bar{n}}$	$\boldsymbol{n\bar{n}}$	**glueball**	$\boldsymbol{s\bar{s}}$	$\boldsymbol{n\bar{s}}$

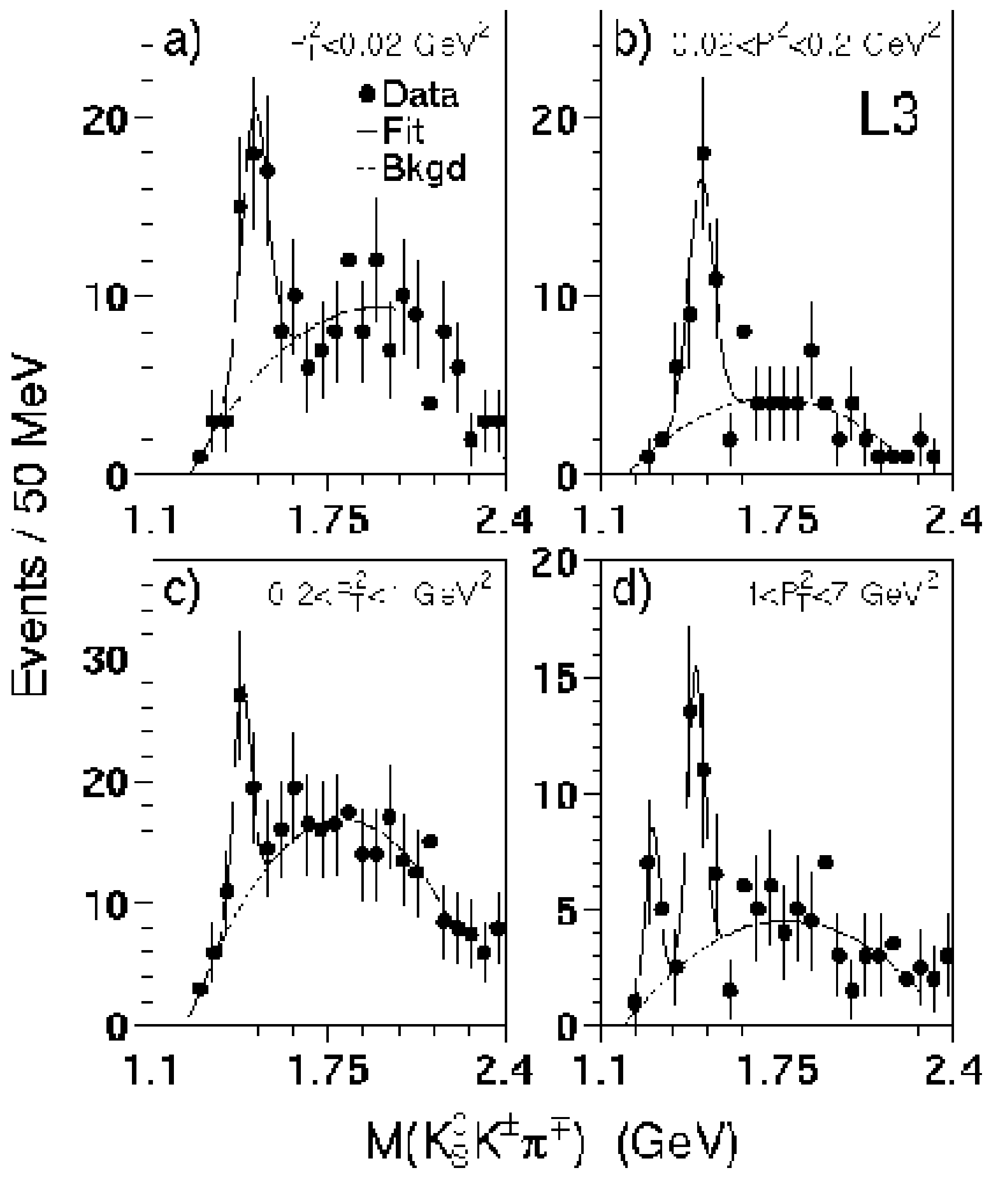
same masses

ideally mixed

$\boldsymbol{\eta}(1405) \to a_0(980)\pi, \sigma\eta$

$\boldsymbol{\eta}(1475) \to K\bar{K}^* + \bar{K}K^*$

A first warning !



Selection rules:

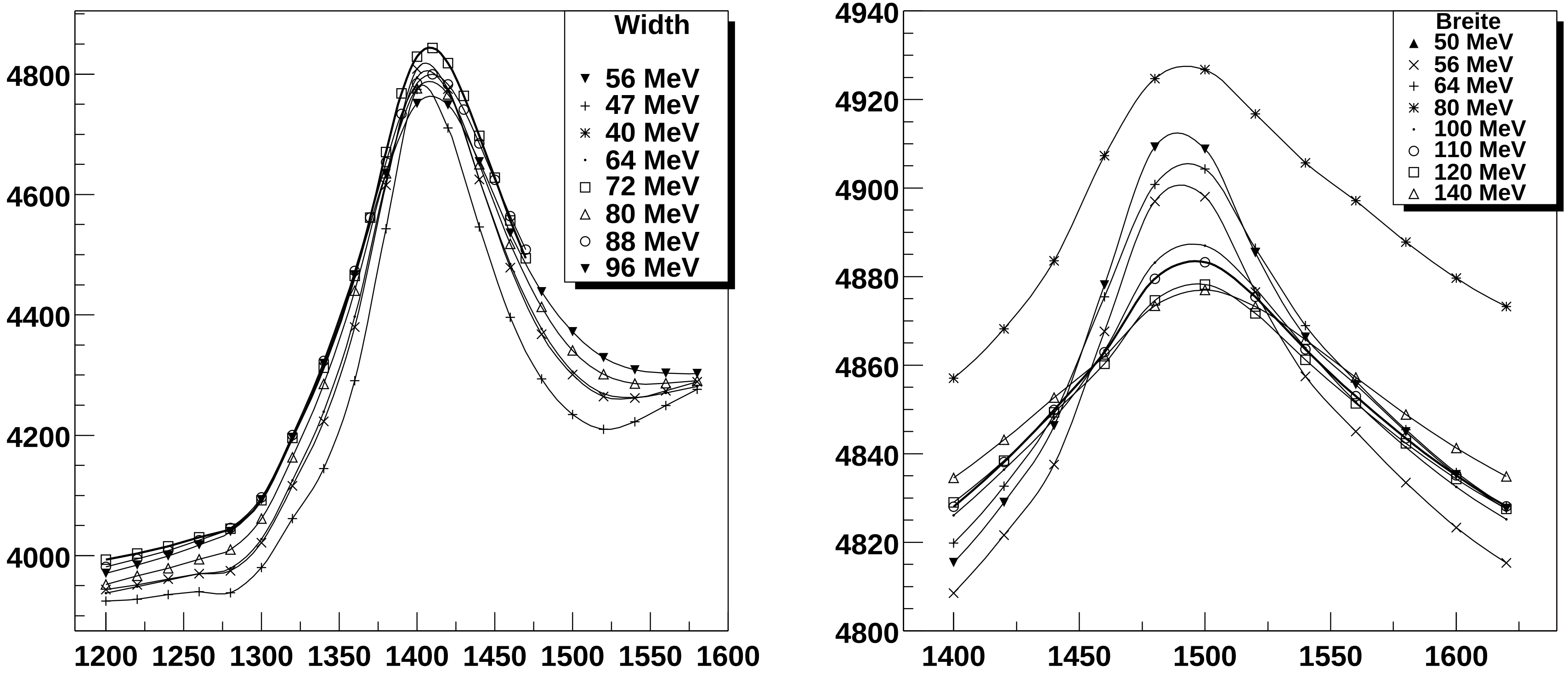
A pseudoscalar states can be produced also at small and high q^2. $J^{PC} = 1^{++}$ is forbidden for $q^2 \to 0$.

$\gamma\gamma^* \to \mathrm{K^0_s K^\pm}\pi^\mp$ from L3. At low and high q^2, peak at 1440 MeV, high q^2 required to produce peak at 1285 MeV.

Peak at 1285 MeV is due to the $f_1(1285)$ and not due to $\eta(1295)$.

No $\eta(1295)$ in $\gamma\gamma$

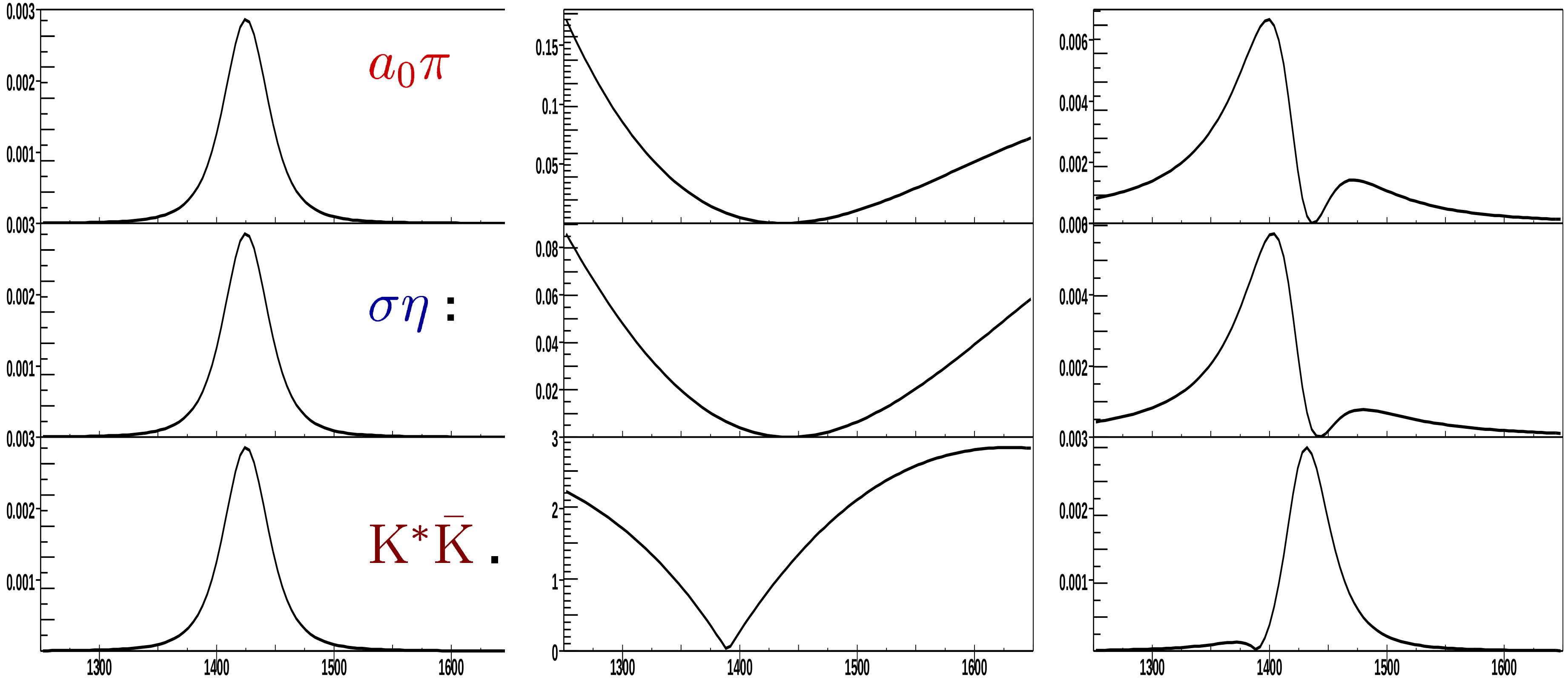
The $\eta(1440)$ in $\bar{p}p$ annihilation



Scan for a $0^{+}0^{-+}$ resonance with different widths. The likelihood optimizes for $M = 1407 \pm 5, \Gamma = 57 \pm 9$ MeV. The resonance is identified with the η_L. A search for a second pseudoscalar resonance (right panel) gives evidence for the η_H with $M = 1490 \pm 15, \Gamma = 74 \pm 10$ MeV.

Splitting of $\eta(1440)$ due to wave function node

Amplitudes for $\eta(1440)$ decays to

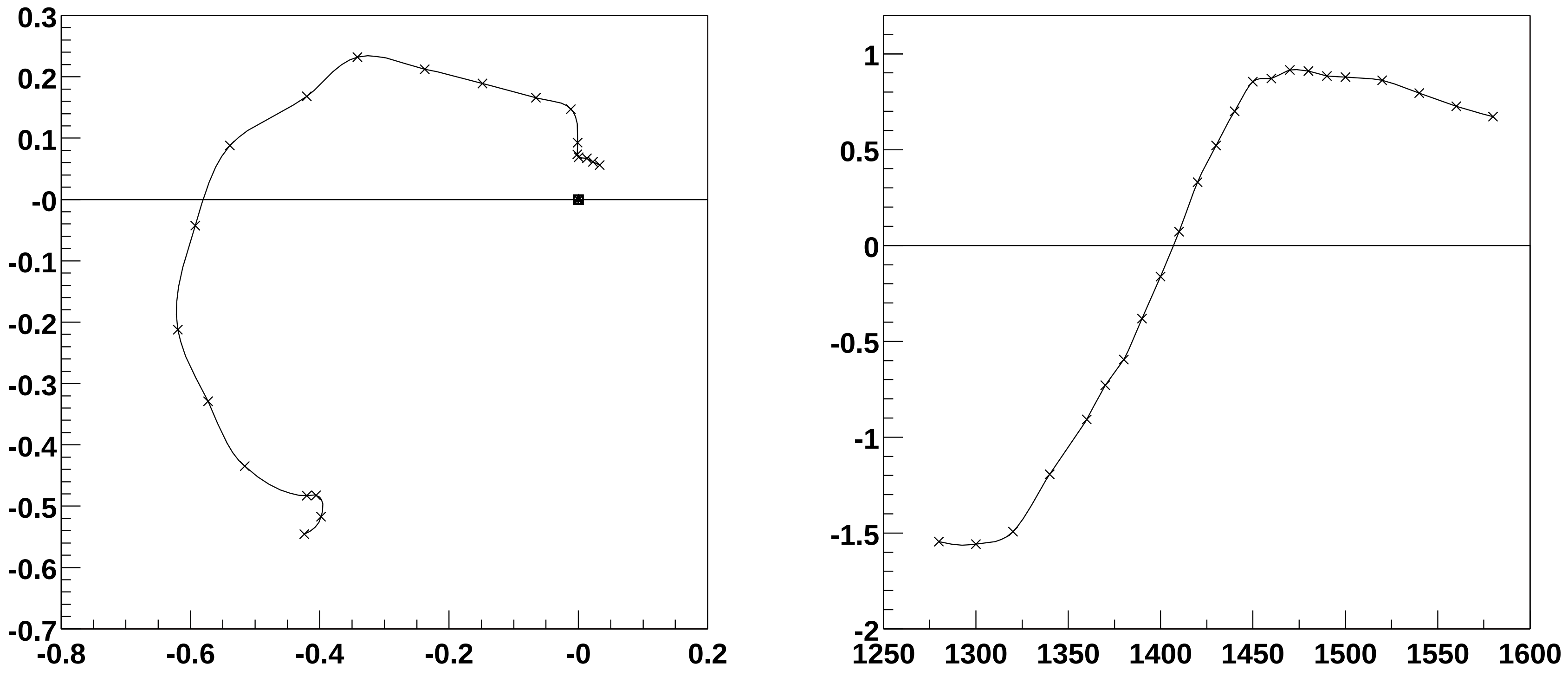


Breit-Wigner functions (left)

squared decay amplitudes (center)

final squared transition matrix element (right).

Phase motion of $\eta(1440)$



Complex amplitude and phase motion of the $a_0(980)\pi$ isobars in $\mathrm{p\bar{p}}$ annihilation into $4\pi\eta$. In the mass range from 1300 to 1500 MeV the phase varies by π indicating that there is only one resonance in the mass interval. The $\sigma\eta$ (not shown) exhibits the same behaviour.

Summary on $\eta(1440)$.

- The $\eta(1295)$ is not a $q\bar{q}$ meson.
- The $\eta(1440)$ wave function has a node leading to two appearantly different states $\eta(1405)$ and $\eta(1475)$.
- The node suppresses OZI allowed decays into $a_0(980)\pi$ and allows K^*K decays.
- There is only one η state, the $\eta(1440)$ in the mass range from 1200 to 1500 MeV and not 3 !
- The $\eta(1440)$ is the radial excitation of the η.
- The radial excitation of the η' is expected at about 1800 MeV; it might be the $\eta(1760)$.

Summary on radial excitations of pseudoscalar mesons.

$1^1\mathrm{S}_0$	π	η'	η	K
$2^1\mathrm{S}_0$	$\pi(1300)$	$\eta(1760)$	$\eta(1440)$	K(1460)

Warning lesson from the $\iota(1440)$:

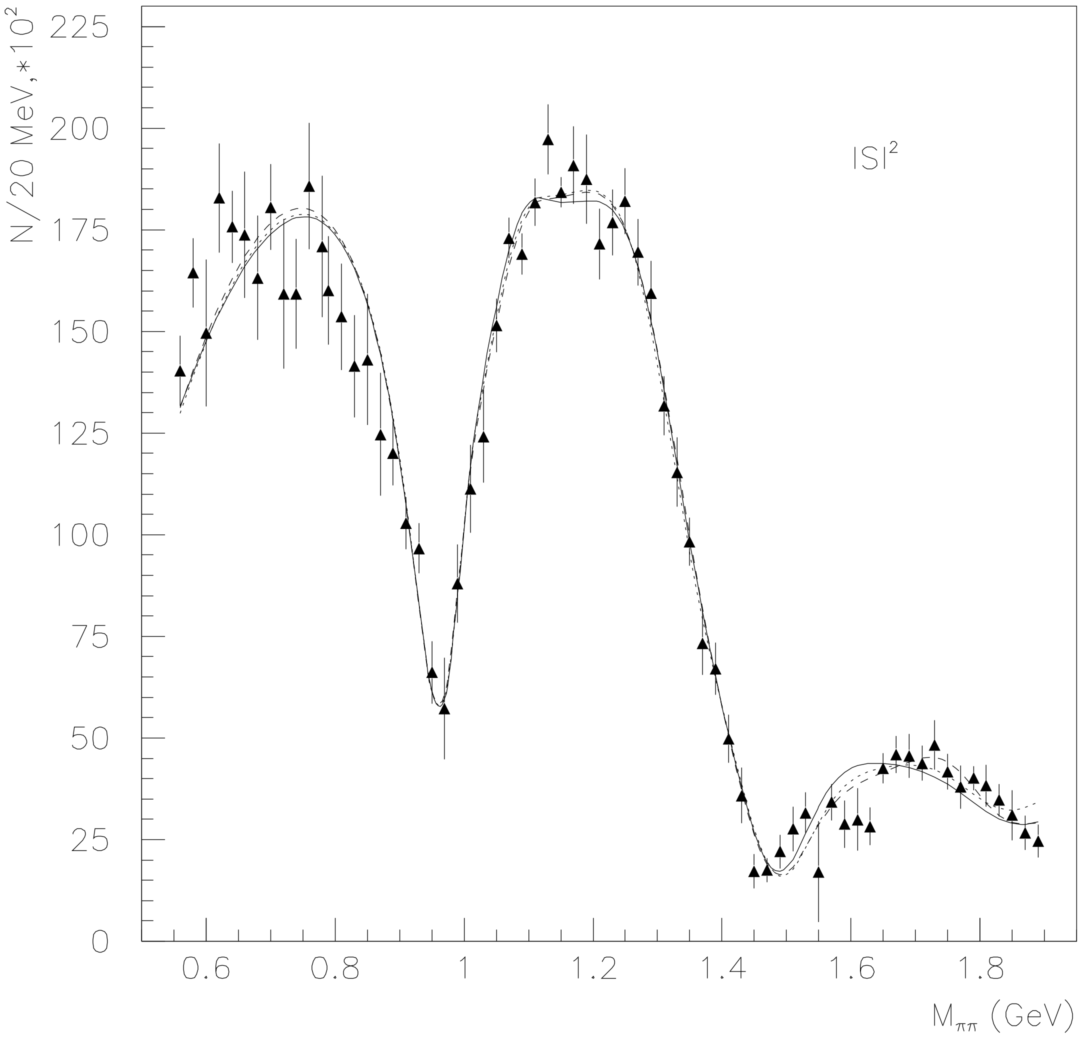
You can build up a case, convince the community and still be wrong !

Is there a scalar glueball ?

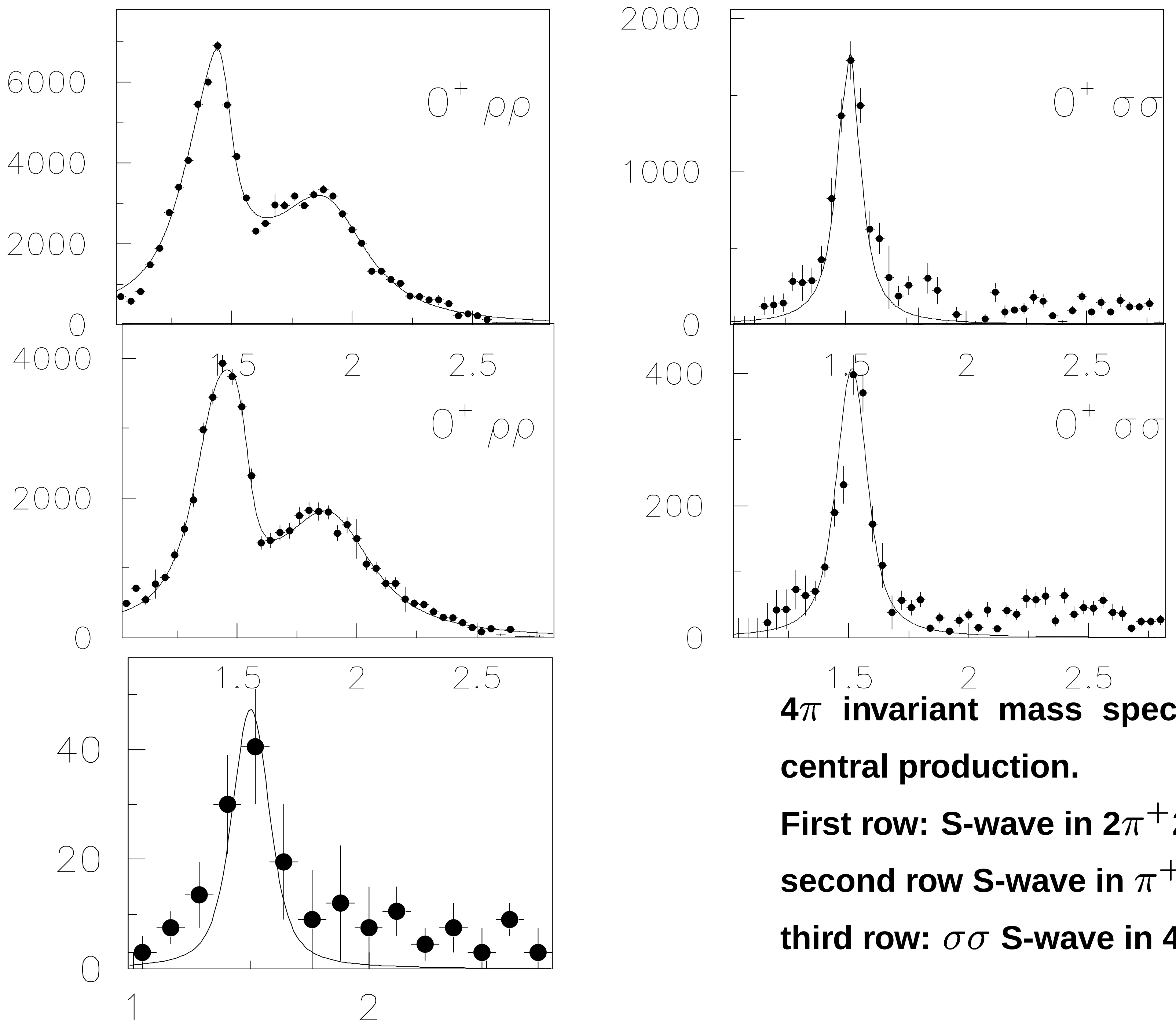
Possible interpretation of the scalar mesons. The 3 states $\mathrm{f_0(1370)}$, $\mathrm{f_0(1500)}$ and $\mathrm{f_0(1710)}$ originate from 2 $q\bar{q}$ states and a glueball.

I = 1/2	I = 1	I = 0	
		$\mathrm{f_0(600)}$	$\sigma(600)$ meson
K(900)			chiral partner of the π
	$\mathrm{a_0(980)}$	$\mathrm{f_0(980)}$	$\mathrm{K\bar{K}}$ molecules
		$\mathrm{f_0(1370)}$	$\mathrm{q\bar{q}}$ state
$\mathrm{K_0^*(1430)}$	$\mathrm{a_0(1490)}$	$\mathrm{f_0(1500)}$	2 $\mathrm{q\bar{q}}$ states, glueball
		$\mathrm{f_0(1710)}$	$\mathrm{q\bar{q}}$ state
$\mathrm{K_0^*(1950)}$			$\mathrm{q\bar{q}}$ state
		$\mathrm{f_0(2100)}$	$\mathrm{q\bar{q}}$ state
		$\mathrm{f_0(2200, 2330)}$	$\mathrm{q\bar{q}}$ state

The scalar glueball scrutinized



The $\pi\pi$ scattering amplitude measured in the GAMS experiment.



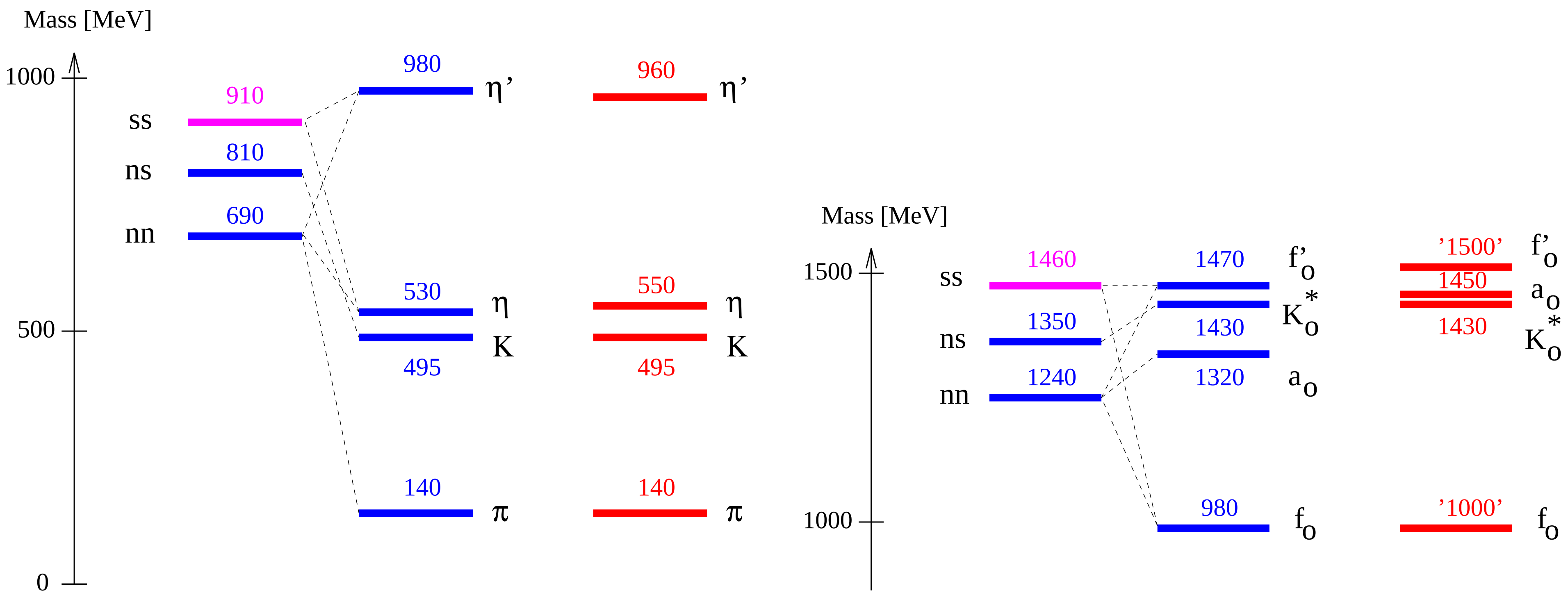
4π invariant mass spectra from central production.
First row: S-wave in $2\pi^+2\pi^-$;
second row S-wave in $\pi^+\pi^-2\pi^0$;
third row: $\sigma\sigma$ S-wave in $4\pi^0$.

Alternative interpretation of the scalar mesons without glueball.

I = 1/2	I = 1	I = 0	
		$f_0(600)$	$\sigma(600)$ meson
K(900)			chiral partner of the π
	$a_0(980)$	$f_0(980)$	
		$f_0(1370)$	dynamically generated
$K_0^*(1430)$		$f_0(1500)$	1^3P_0 states
	$a_0(1490)$		
		$f_0(1710)$	
$K_0^*(1950)$			2^3P_0 states
		$f_0(2100)$	
		$f_0(2200, 2330)$	

Gluon exchange versus instanton–induced forces

The $\mathrm{UA}(1)$ anomaly and instantons

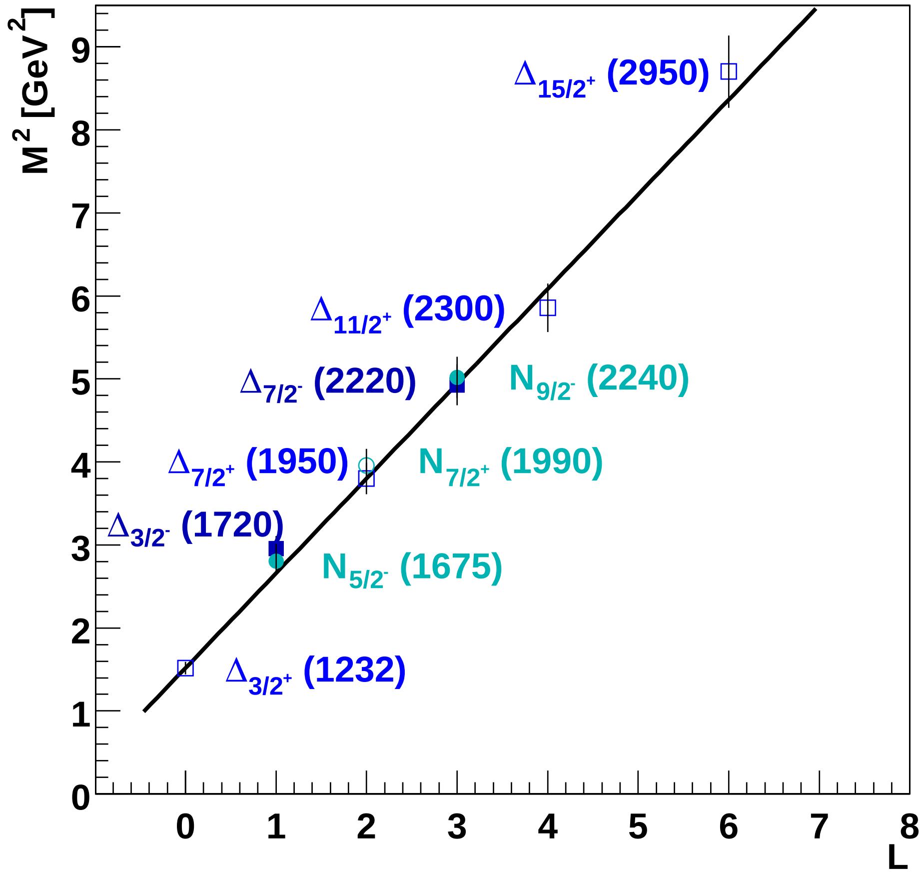


The action of instantons in the mass spectrum of pseudoscalar and scalar mesons. The spectra are calculated using a confinement potential and the mass shifts resulting from instantons.

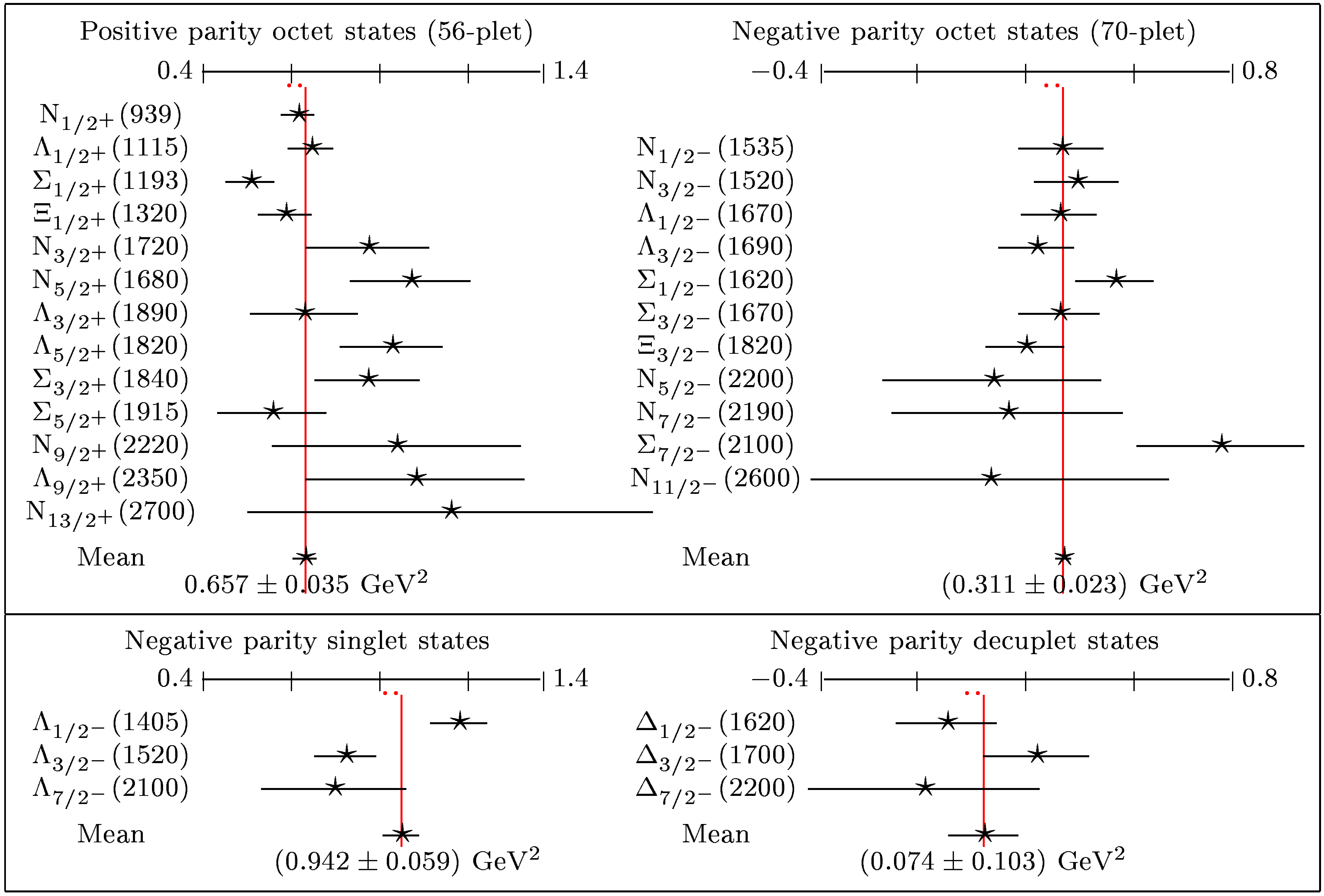
Instanton–induced interactions in baryons ?

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

Status of baryon resonances according to the The Particle Data Group.



Regge trajectory for Δ^* resonances with intrinsic spin $S = 1/2$ and and for N*'s with spin $S = 3/2$.


Positive parity octet states (56-plet)
0.4
1.4
$N_{1/2+}$ (939)
$\Lambda_{1/2+}$ (1115)
$\Sigma_{1/2+}$ (1193)
$\Xi_{1/2+}$ (1320)
$N_{3/2+}$ (1720)
$N_{5/2+}$ (1680)
$\Lambda_{3/2+}$ (1890)
$\Lambda_{5/2+}$ (1820)
$\Sigma_{3/2+}$ (1840)
$\Sigma_{5/2+}$ (1915)
$N_{9/2+}$ (2220)
$\Lambda_{9/2+}$ (2350)
$N_{13/2+}$ (2700)
Mean
0.657 ± 0.035 GeV^2
Negative parity octet states (70-plet)
-0.4
0.8
$N_{1/2-}$ (1535)
$N_{3/2-}$ (1520)
$\Lambda_{1/2-}$ (1670)
$\Lambda_{3/2-}$ (1690)
$\Sigma_{1/2-}$ (1620)
$\Sigma_{3/2-}$ (1670)
$\Xi_{3/2-}$ (1820)
$N_{5/2-}$ (2200)
$N_{7/2-}$ (2190)
$\Sigma_{7/2-}$ (2100)
$N_{11/2-}$ (2600)
Mean
(0.311 ± 0.023) GeV^2
Negative parity singlet states
0.4
1.4
$\Lambda_{1/2-}$ (1405)
$\Lambda_{3/2-}$ (1520)
$\Lambda_{7/2-}$ (2100)
Mean
(0.942 ± 0.059) GeV^2
Negative parity decuplet states
-0.4
0.8
$\Delta_{1/2-}$ (1620)
$\Delta_{3/2-}$ (1700)
$\Delta_{7/2-}$ (2200)
Mean
(0.074 ± 0.103) GeV^2

A baryon mass formula

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

where

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

$\mathrm{M_N}, \mathrm{M_\Delta}, \mathrm{M_\Omega}$ **are input parameters taking from PDG,** $a = 1.142$**/GeV**^{2} **is the Regge slope as determined from the meson spectrum.** I_{sym} **fraction of wave function with** qq **pair antisymmetric in spin and flavor (which can undergo instanton–induced interactions.)**

All 100 (but 2) known baryon resonances reproduced

Very good evidence for instanton–interactions in hadron spectroscopy !

Conclusions

- **There is more evidence for tetraquark and pentaquark states than for hybrids and glueballs**
- **There is more evidence for the role of instanton–induced interactions in light hadron spectroscopy than for gluon exchange**