GLUEBALL AND HYBRID SEARCHES

Eberhard Klempt

Helmholtz-Institut für Strahlen– und Kernphysik
Universität Bonn
Nußallee 14-16, D-53115 Bonn, GERMANY
e-mail: klempt@hiskp.uni-bonn.de

WORKSHOP "EXOTIC HADRONS", ECT* TRENTO, 21-25 FEB 2005

Introduction

- **In the non–relativistic quark model, most mesons and baryons can be understood as $q\,\bar{q}$ or $q\,q\,q$ objects.**
- **QCD is well established for large momentum transfers with the small parameter α_s**
- **At low momentum tranfer, QCD can be developed as effective field theory with the small parameter $Q\,/\,M$.**
- **Bound states and resonances ?**

The meson spectrum

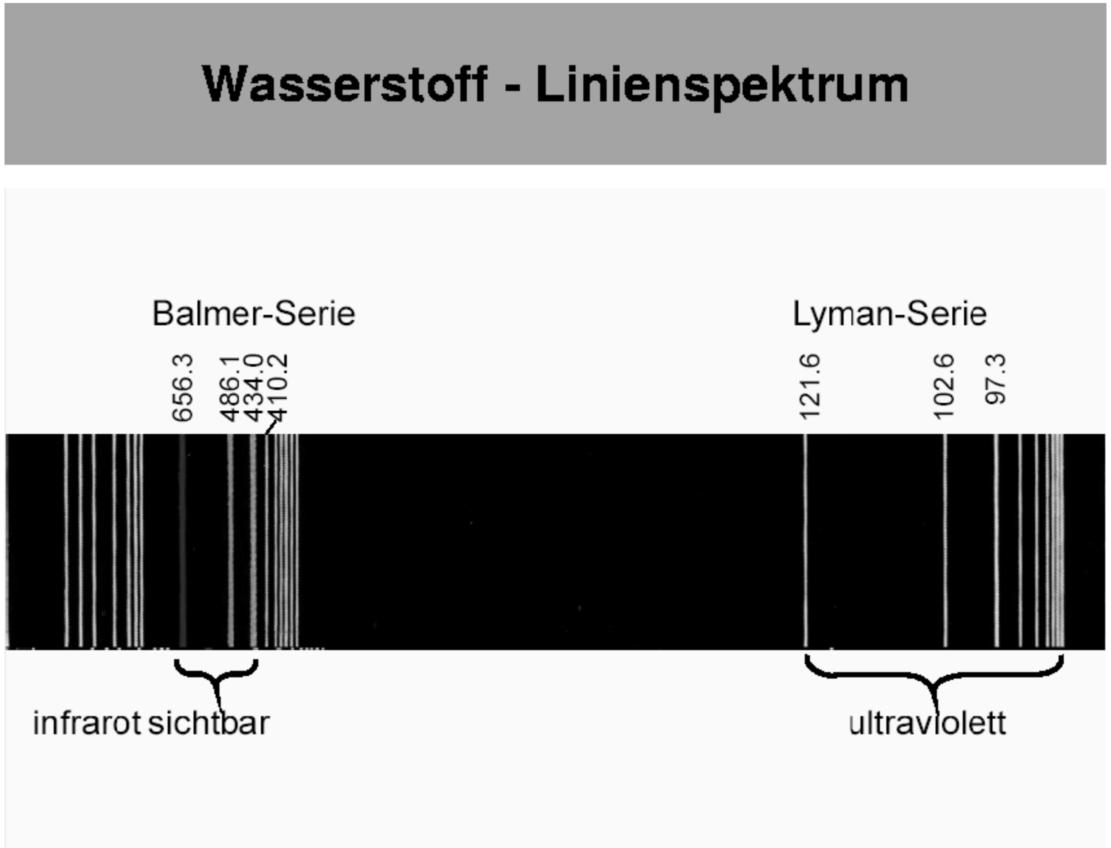
		J^{PC}	$^{2s+1}L_J$	I=1	I=0 $(n\bar{n})$	I=0 $(s\bar{s})$	I=1/2
L=0	S=0	0^{-+}	$^1S_0$	π	η	η'	K
	S=1	1^{--}	$^3S_1$	ρ	ω	Φ	K^*
L=1	S=0	1^{+-}	$^1P_1$	b_1	h_1	h'_1	K_1
	S=1	0^{++}	$^3P_0$	a_0	f_0	f'_0	K^*_0
		1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
		2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2
L=2	S=0	2^{-+}	$^1D_2$	π_2	η_2	η'_2	K_2
	S=1	1^{--}	$^3D_1$	ρ	ω	Φ	K^*_1
		2^{--}	$^3D_2$	ρ_2	ω_2	Φ_2	K_2
		3^{--}	$^3D_3$	ρ_3	ω_3	Φ_3	K^*_3
L=3	S=0	3^{+-}	$^1F_3$	b_3	h	h'_3	K_3
	S=1	2^{++}	$^3F_2$	a_2	f_2	f'_2	K^*_2
		3^{++}	$^3F_3$	a_3	f_3	f'_3	K_3
		4^{++}	$^3F_4$	a_4	f_4	f'_4	K^*_4
L=4	S=0	4^{-+}	$^1G_2$	π_4	η_4	η'_4	K_4
	S=1	3^{--}	$^3G_1$	ρ_3	ω_3	Φ_3	K^*_3
		4^{--}	$^3G_2$	ρ_4	ω_4	Φ_4	K_4
		5^{--}	$^3G_3$	ρ_5	ω_5	Φ_5	K^*_5

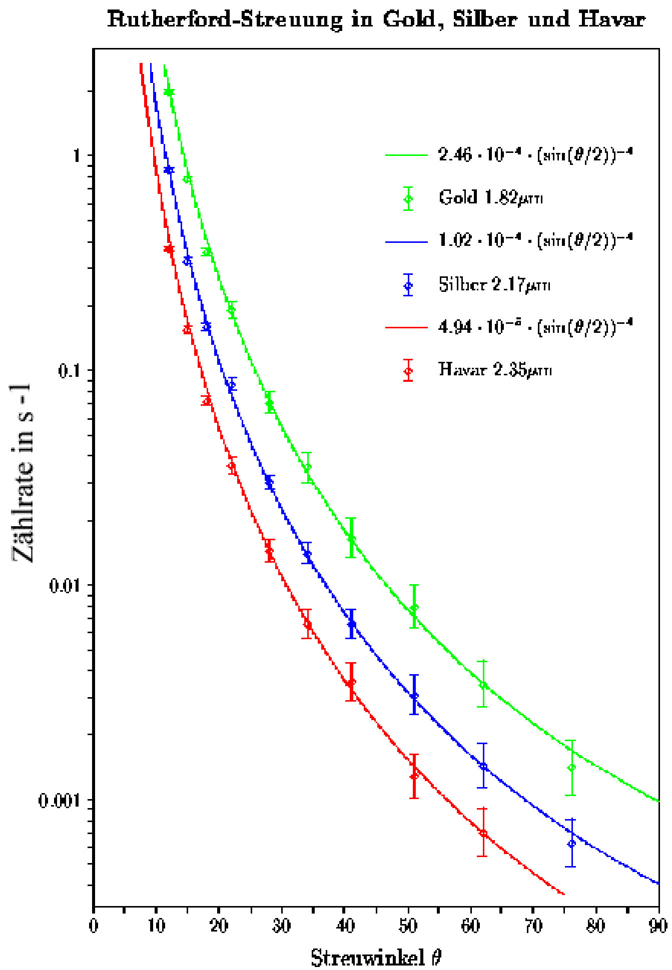
plus baryons: “The particle zoo”

Why should we care about all these states ?

Spectroscopy and **scattering !**

Bohr and **Rutherford**





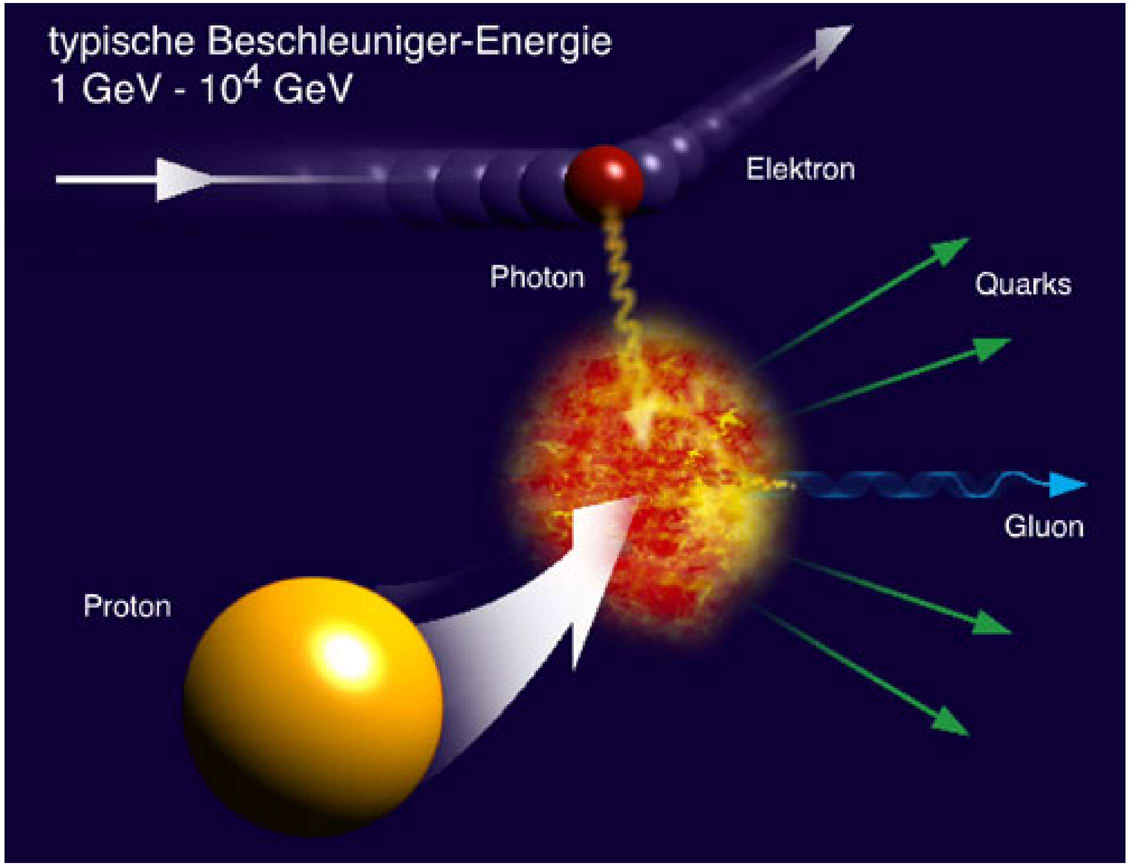
Quantum Electro Dynamic

very well understood

* Praktikumsversuch, Universität Stuttgart

The proton structure

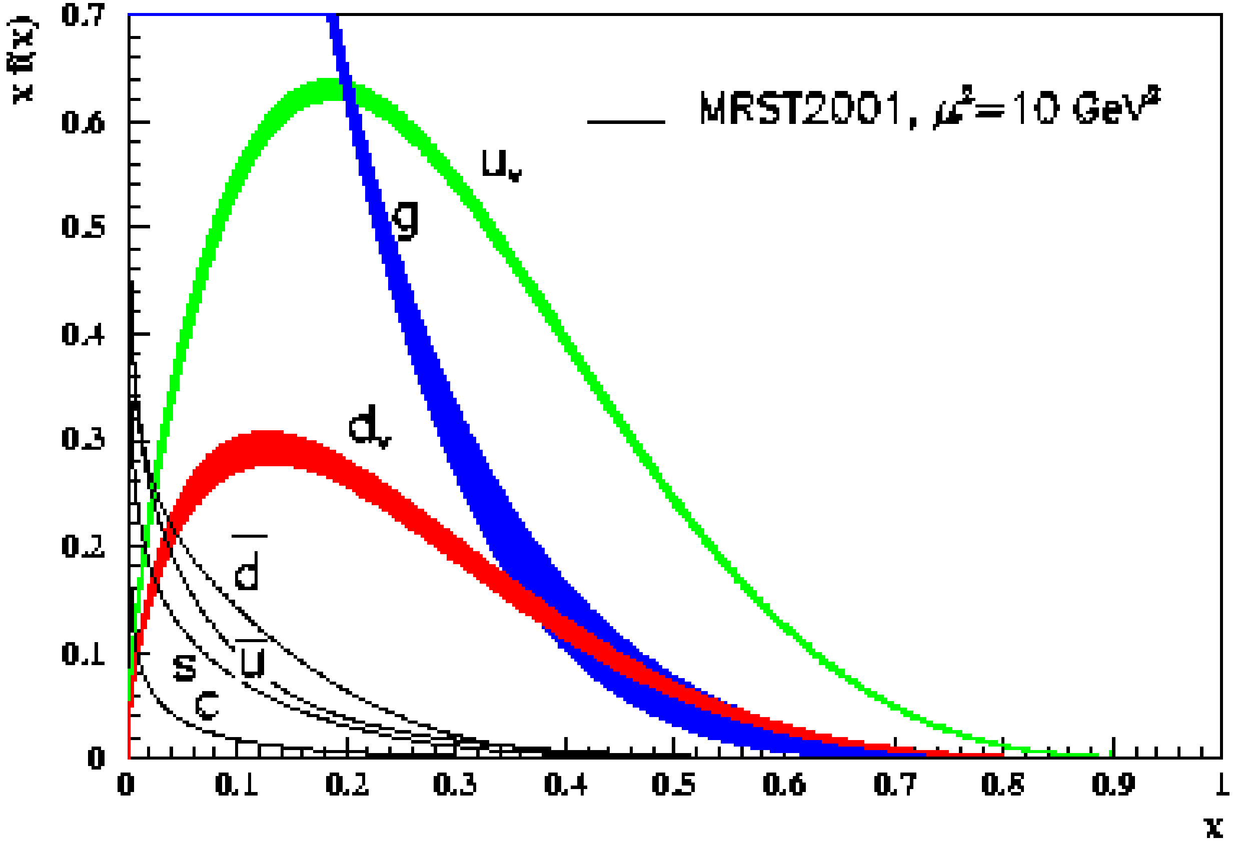
Spectroscopy	and	deep inelastic scattering !
1 GeV	and	10^4 GeV



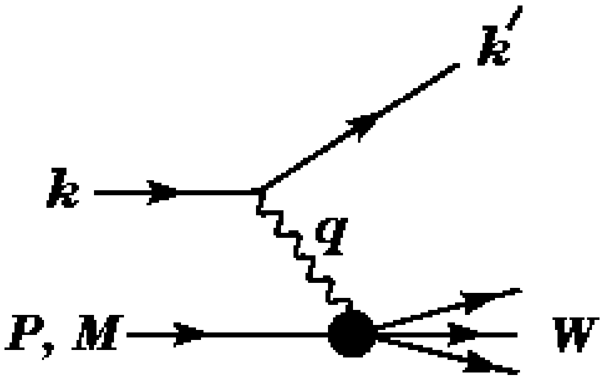
- There are 3 valence quarks in a proton
- Quarks carry 2/3 and -1/3 charges
- Quarks have spin 1/2
- Quarks are confined
- $m_q \sim 5$ MeV from chiral symmetry
- With increasing resolution more and more $q\bar{q}$ pairs show up
- Gluons carry a large fraction of the proton momentum
- Quarks make little contributions to the proton spin

What is the stuff making up a proton ?

$\cdots$ and deep inelastic scattering reveals significant contributions from antiquarks and gluons:

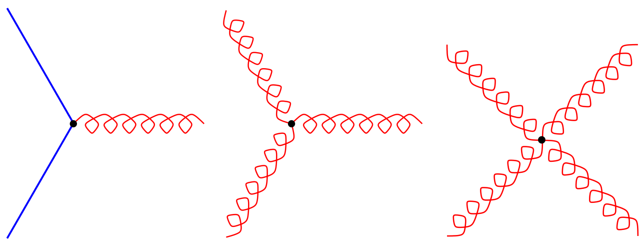


Parton distributions (times x) as functions of x: (for $\mu^2 = 10\,\text{GeV}^2$)



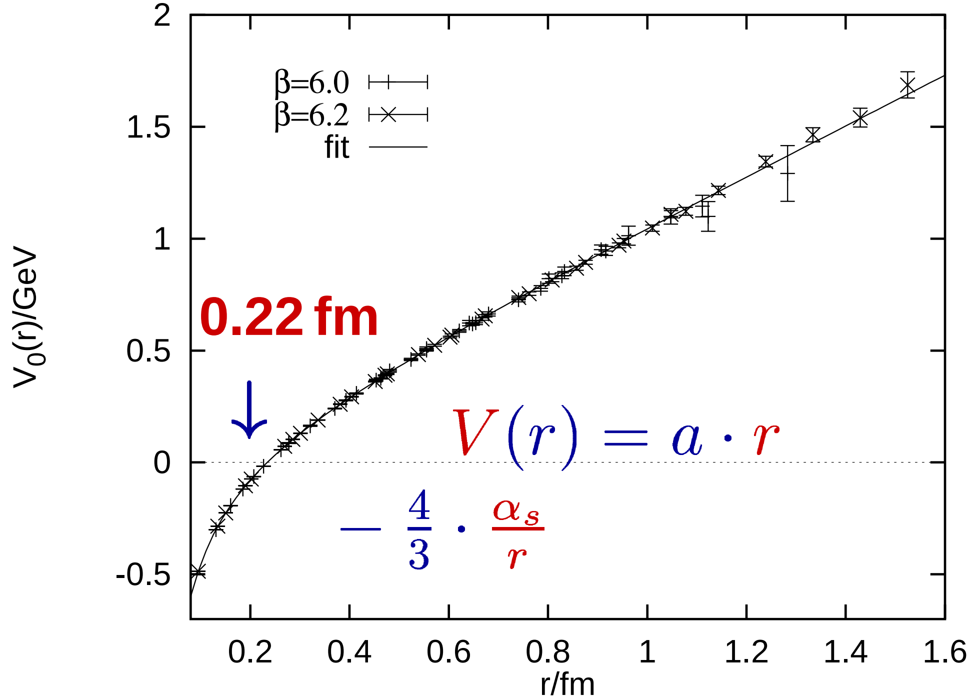
And what are their interactions ?

- **Quarks carry colour red, green, blue**
- **and interact by exchange of gluons**
- **Gluons themselves carry colour and interact**
- **Their interaction leads to perturbative quark-gluon and gluon-gluon interactions, and**



to non-perturbative interactions, including confinement

Confinement potential:



The QCD vacuum

Strongly fluctuating colour fields

Averaging leads to ‘hot spots’
or ‘instantons’ having
‘topological charge’

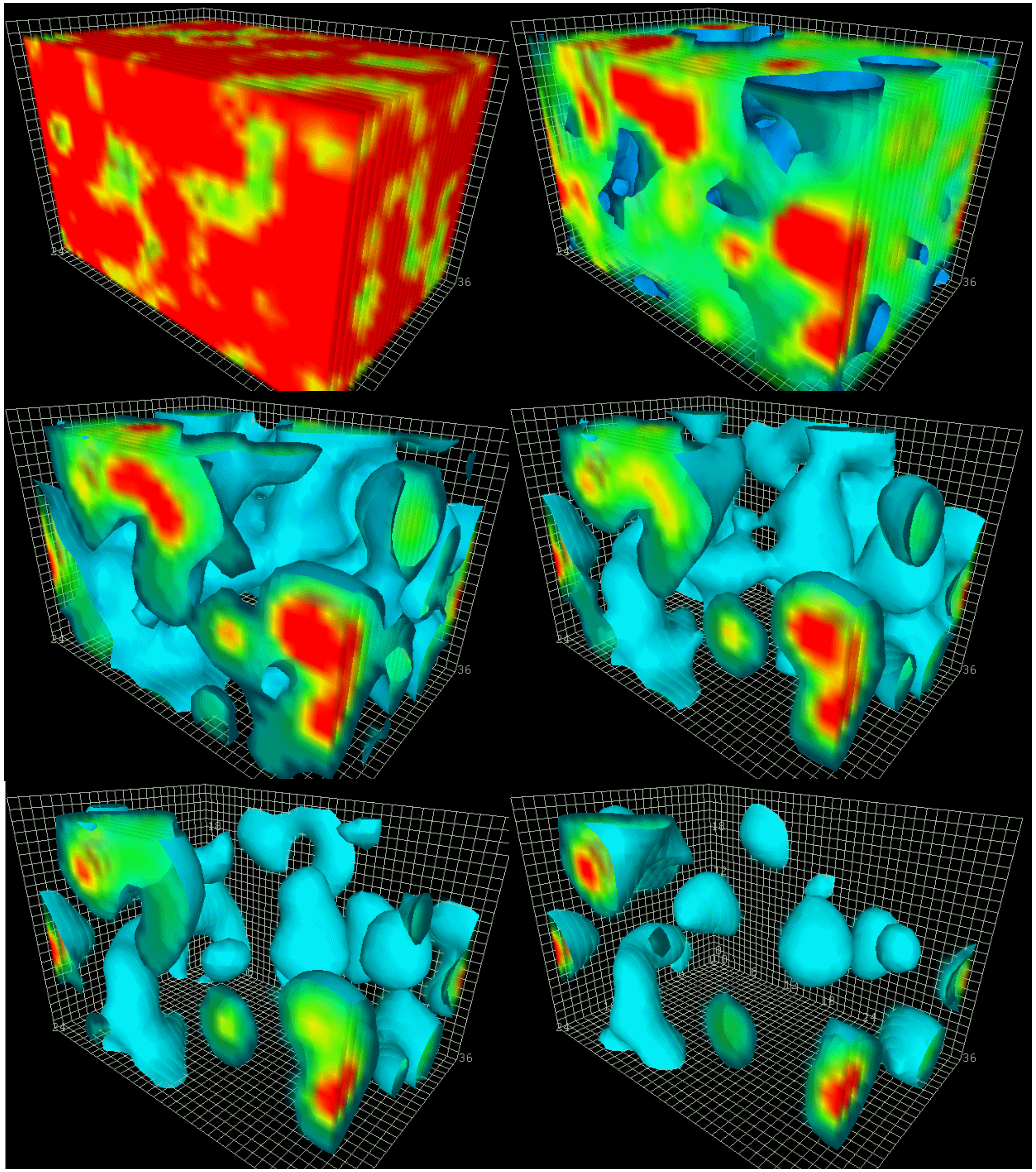
Density $1/(0.3\mathrm{fm}^4/\mathrm{c})$

Quark scattering off ‘instantons’
induces spin flips

Chiral symmetry is spontaneously
broken

Instanton–interactions act only
when spin flips are possible

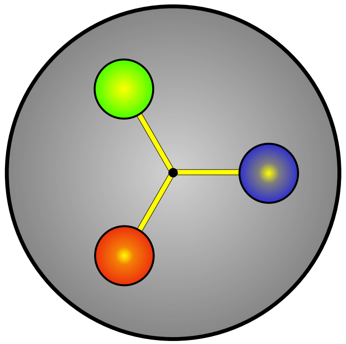
www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/QCDvacuum/

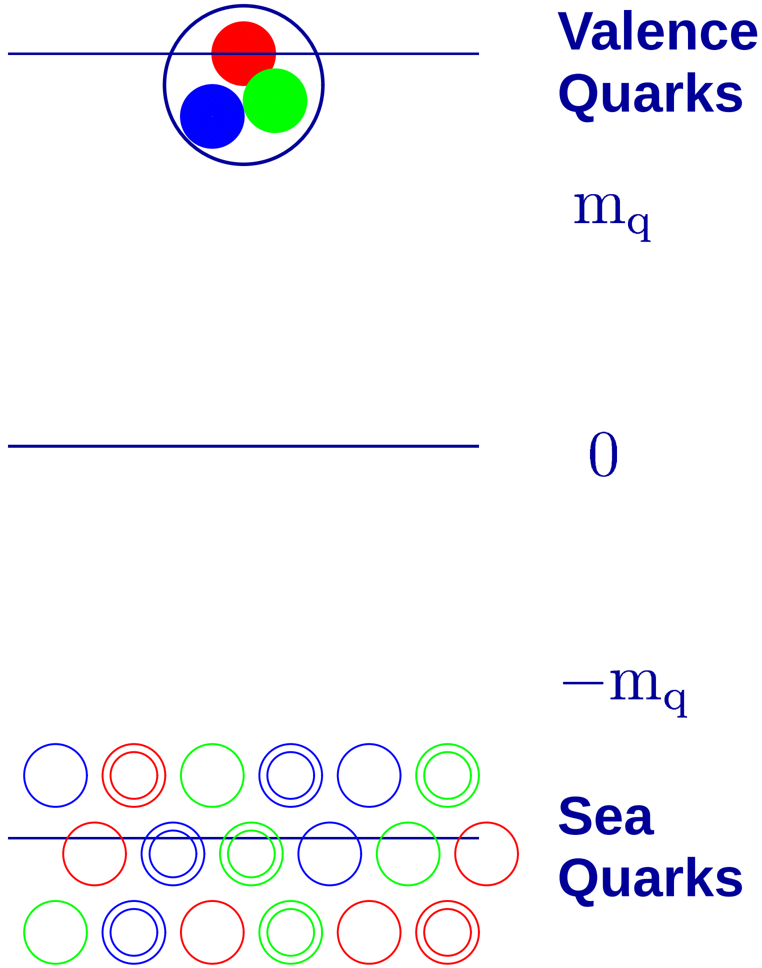


Two views of the proton

Quarks and gluons or the vacuum and condensates

paly a decisive role in understanding the proton





Quarks interact directly via exchange of gluons:

- Effective one-gluon exchange
- Glueballs and hybrids are predicted

Quarks interact indirectly via polarisation of the QCD vacuum

- Instanton–induced interactions
- Multiquark states are predicted

”Chiral Solitons”

Spectroscopy of light mesons and baryons:

The dynamics of quarks in light–quark spectroscopy is driven by instanton–induced interactions and not by one–gluon exchange.

S. Godfrey and N. Isgur, "Mesons in a relativized quark model with chromodynamics," Phys. Rev. D 32 (1985) 189.

S. Capstick and N. Isgur, "Baryons in a relativized quark model with chromodynamics," Phys. Rev. D 34 (1986) 2809.

E. Klempt, B. C. Metsch, C. R. Münz and H. R. Petry, "Scalar mesons in a relativistic quark model with instanton induced forces," Phys. Lett. B 361 (1995) 160.

M. Koll, R. Ricken, D. Merten, B. C. Metsch and H. R. Petry, "A relativistic quark model for mesons with an instanton induced interaction," Eur. Phys. J. A 9 (2000) 73.

R. Ricken, M. Koll, D. Merten, B. C. Metsch and H. R. Petry, "The meson spectrum in a covariant quark model," Eur. Phys. J. A 9 (2000) 221.

U. Löring, K. Kretzschmar, B. C. Metsch and H. R. Petry, "Relativistic quark models of baryons with instantaneous forces," Eur. Phys. J. A 10 (2001) 309.

U. Löring, B. C. Metsch and H. R. Petry, "The light baryon spectrum in a relativistic quark model with instanton-induced quark forces: The non-strange baryon spectrum and ground-states," Eur. Phys. J. A 10 (2001) 395.

U. Löring, B. C. Metsch and H. R. Petry, "The light baryon spectrum in a relativistic quark model with instanton-induced quark forces: The strange baryon spectrum," Eur. Phys. J. A 10 (2001) 447.

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

Extension of the quark model by a Fock space expansion:

$$\text{meson} = \alpha q\bar{q} + \beta_1 q\bar{q}q\bar{q} + ... + \gamma_1 q\bar{q}g + ... + \delta_1 gg + ..$$

$$\text{baryon} = \alpha qqq + \beta_1 qqqq\bar{q} + ... + \gamma_1 qqqg + ...$$

quark model	multi–quark	hybrid component

isoscalar mesons may contain a $\delta_1 gg$ glueball component

$\Updownarrow$

This component vanishes for states with exotic quantum numbers !

The coefficients $\alpha_i, \beta, \gamma_i \cdots$ depend on the momentum transfer.

This is important for resonances like

$f_0(980), a_0(980), D^*_{sJ=0}(2317)^+, D_{sJ=1}(2460)^+, N(1440)P_{11}, \Lambda(1405)S_{01}$

- **Resonances have widths in the order of 10% of their mass**

$$\frac{\Gamma_{\Delta(1232)\to N\pi}}{\mathrm{Mass}_{\Delta(1232)}} = 0.1 \qquad \beta_1 \sim 0.3$$

- **Production of multiquarks /hybrids suppressed by ~ 10:**

$$\beta_1 \sim 0.3 \quad \text{or} \quad \gamma_1 \sim 0.3$$

What do we observe in nature:

Tetraquarks and pentaquarks or glueballs and hybrids ?

> **"Glueballs and hybrids are not predicted by lattice QCD;**
> **if they exist in nature, lattice QCD can explain why."**

Evidence for $J^{PC} = 1^{-+}$ Exotic Mesons

Experiment	Mass (MeV/c^2)	Width (MeV/c^2)	Decay Mode	Reaction
BNL [1]	1370 $\pm 16 {}^{+50}_{-30}$	385 $\pm 40 {}^{+65}_{-105}$	$\eta\pi$	π^-p $\rightarrow \eta\pi^-$p
BNL [2]	1359 ${}^{+16}_{-14} {}^{+10}_{-24}$	314 ${}^{+31}_{-29} {}^{+9}_{-66}$	$\eta\pi$	π^-p $\rightarrow \eta\pi^-$p
CBar [5]	1400 $\pm 20 \pm 20$	310 $\pm 50 {}^{+50}_{-30}$	$\eta\pi$	$\bar{\text{p}}$n $\rightarrow \pi^-\pi^0\eta$
CBar [6]	1360 ± 25	220 ± 90	$\eta\pi$	$\bar{\text{p}}$p $\rightarrow \pi^0\pi^0\eta$
CBar [8]	$\sim$1440	$\sim$400	$\rho\pi$	$\bar{\text{p}}$n $\rightarrow \pi^- 3\pi^0$
Oblx [9]	1384 ± 28	378 ± 58	$\rho\pi$	$\bar{\text{p}}$p $\rightarrow 2\pi^+ 2\pi^-$

[a] States supposed to be distinct are separated by double-lines.

Comments:

1. Definition:

$$J^{PC} = 0^{-+} \qquad \pi$$
$$J^{PC} = 2^{-+} \qquad \pi_2$$
$$J^{PC} = 1^{-+} \qquad \pi_1$$

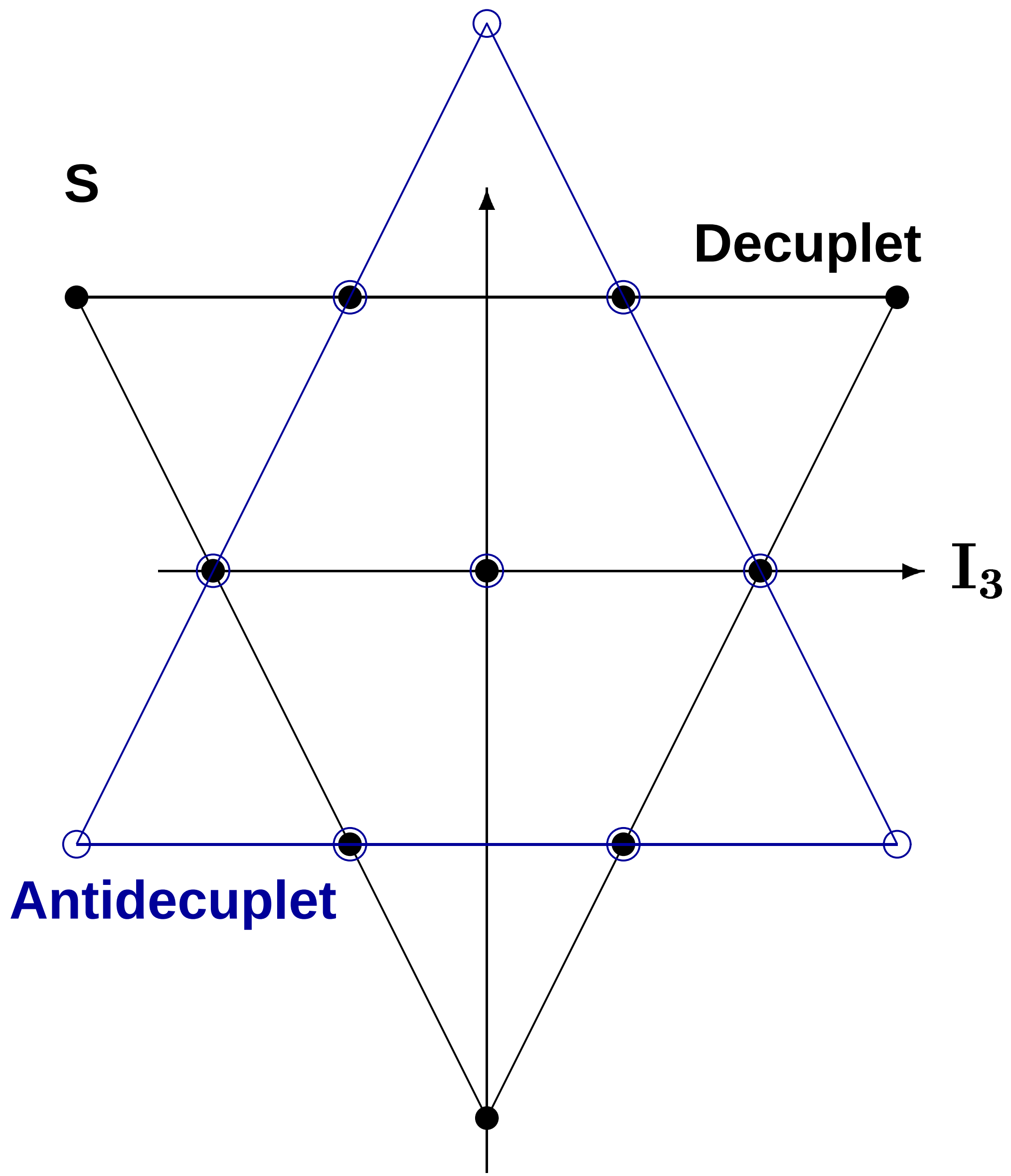
2. The $\pi_1(1370)$ and $\pi_1(1390)$ are likely different particles.

- **a** They are produced in N$\bar{\text{N}}$ annihilation from different atomic states.
- **b** The $\pi_1(1370)$ is not produced in $\pi\rho$ scattering.

3. The $\pi_1(1370)$ cannot belong to an octet (nor to a 27-plet).

- **a** The $\pi_1(1370)$ couples to the octet component of the η (otherwise its $\pi\eta'$ decay would have been observed.
- **b** The $J^{PC} = 1^{-+} \rightarrow J^{PC} = 0^{-+} + J^{PC} = 0^{-+}$ decay must be symmetric with respect to exchange of π and η because of SU(3) and antisymmetric due to parity conservation.

4. The $\pi_1(1370)$ is member of decuplet (or antidecuplet)



(a) Minimum quark model configuration: $qq\bar{q}\bar{q}$ tetraquark

(b) From a decuplet and an antidecuplet we expect:
6 flavor–exotics (like $ud\bar{s}\bar{s}$, $dd\bar{u}\bar{s}$)
No evidence found (with low statistics)

(c) 14 pairwise mass–degenerate flavor–nonexotic states

(d) The $\pi_1(1370)$ and $\pi_1(1390)$ could be 6 of these states

(e) 8 additional vector mesons with strangeness, K^*'s

5. Expected tetraquarks:

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

$$= 1 + 1 + 8 + 8 + 8 + 8 + 10 + \bar{10} + 27$$

6. At least two (possibly three) further π_1 states observed:

Table Ib: Evidence for $J^{PC} = 1^{-+}$ Exotic Mesons [a]

BNL [10]	**1593** $\pm\ 8^{+29}_{-47}$	**168** $\pm 20^{+150}_{-\ 12}$	$\rho\pi$	π^-**p** $\rightarrow \pi^+\pi^-\pi^-$**p**
VES [11]	**1610** ± 20	**290** ± 30	$\rho\pi$	π^-**N** $\rightarrow \pi^+\pi^-\pi^-$**N**
BNL [12]	**1596** $\pm\ 8$	**387** ± 23	$\eta'\pi$	π^-**p** $\rightarrow \pi^-\eta'$ **p**
VES [11]	**1610** ± 20	**290** ± 30	$\eta'\pi$	π^-**N** $\rightarrow \pi^-\eta'$ **N**
BNL [13]	**1664** $\pm\ 8 \pm 10$	**185** $\pm 25 \pm\ 28$	$b_1(1235)\pi$	π^-**p** $\rightarrow \omega\pi^0\pi^-$**p**
CBar [14]	**1590** ± 50	**280** ± 75	$b_1(1235)\pi$	$\bar{\text{p}}$**p** $\rightarrow \pi^+\pi^-\pi^0\omega$
VES [11]	**1610** ± 20	**290** ± 30	$b_1(1235)\pi$	π^-**N** $\rightarrow \omega\pi^0\pi^-$**N**
BNL [15]	**1709** $\pm 24 \pm 41$	**403** $\pm 80 \pm$**115**	$f_1(1285)\pi$	π^-**p** $\rightarrow \eta\pi^+\pi^-\pi^-$**p**

BNL [15]	2001 $\pm 30 \pm 92$	333 $\pm 52 \pm 49$	$f_1(1285)\pi$	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$
BNL [13]	2014 $\pm 20 \pm 16$	230 $\pm$ 32 ± 73	$b_1(1235)\pi$	$\pi^- p \to \omega\pi^0\pi^- p$

7. Is one of these states $\pi_1(1370)$, $\pi_1(1390)$, $\pi_1(1600)$, $\pi_1(1600?)$, $\pi_1(2100)$ a hybrid ?

	Expected	Observed
hybrid octet states	1	} 2 (3)
tetraquarks octet states	4	
tetraquarks decuplet states	2	2

8. There is no need to claim a hybrid and no evidence against a hybrid among the crowd of tetraquarks

[1] D. R. Thompson *et al.*, Phys. Rev. Lett. 79 (1997) 1630.
[2] S. U. Chung *et al.*, Phys. Rev. D60 (1999) 092001.
[3] G. M. Beladidze *et al.*, Phys. Lett. B 313 (1993) 276.
[4] V. Dorofeev *et al.*, “The $J^{(PC)} = 1^{-+}$ hunting season at VES,” AIP Conf. Proc. 619 (2002) 143.
[5] A. Abele *et al.*, Phys. Lett. B423 (1998) 175.
[6] A. Abele *et al.*, Phys. Lett. B446 (1999) 349.
[7] A. Sarantsev, “Antiproton proton annihilation into three pseudoscalar mesons,” Hadron03 conference, Aschaffenburg (2003), www-kp3.gsi.de/∼orth/hadron03.tgz.
[8] W. Dünnweber and F. Meyer–Wildhagen, “Exotic states in Crystal Barrel analyses of annihilation channels,” Hadron03 conference, Aschaffenburg (2003), www-kp3.gsi.de/∼orth/hadron03.tgz; Nucl. Phys. A721 (2003) 605c.
[9] P. Salvini *et al.*, Eur. Phys. J. C 35 (2004) 21.
[10] G. S. Adams *et al.*, Phys. Rev. Lett. 81 (1998) 5760.
[11] Y. Khokhlov *et al.*, Nucl. Phys. A 663 (2000) 596; V. Dorofeev *et al.*, “New results from VES,” Proc. Workshop on Hadron Spectroscopy, Frascati, Italy (1999), p. 3.
[12] E. I. Ivanov *et al.*, Phys. Rev. Lett. 86 (2001) 3977.
[13] M. Lu *et al.*, to be published in Phys. Rev. Lett. (arXiv:hep-ex/0405044 v1).
[14] C. A. Baker *et al.*, Phys. Lett. B 563 (2003) 140.
[15] J. Kuhn *et al.*, Phy. Lett. B595 (2004) 109.
[16] Yu. Guz, “Study of the reaction $\pi^- p \to \eta' \pi^0 n$ at the VES spectrometer”, contribution to ICHEP04, http://ichep04.ihep.ac.cn/db/paper.php, 2004.

Glueballs or $q\bar{q}$ mesons ?

- **The $\eta(1405)$ and the $f_0(1500)/f_0(1710)$ are discussed as glueballs.**
  We start with the $\eta(1440)$.

Pseudoscalar mesons (according to PDG 2004)

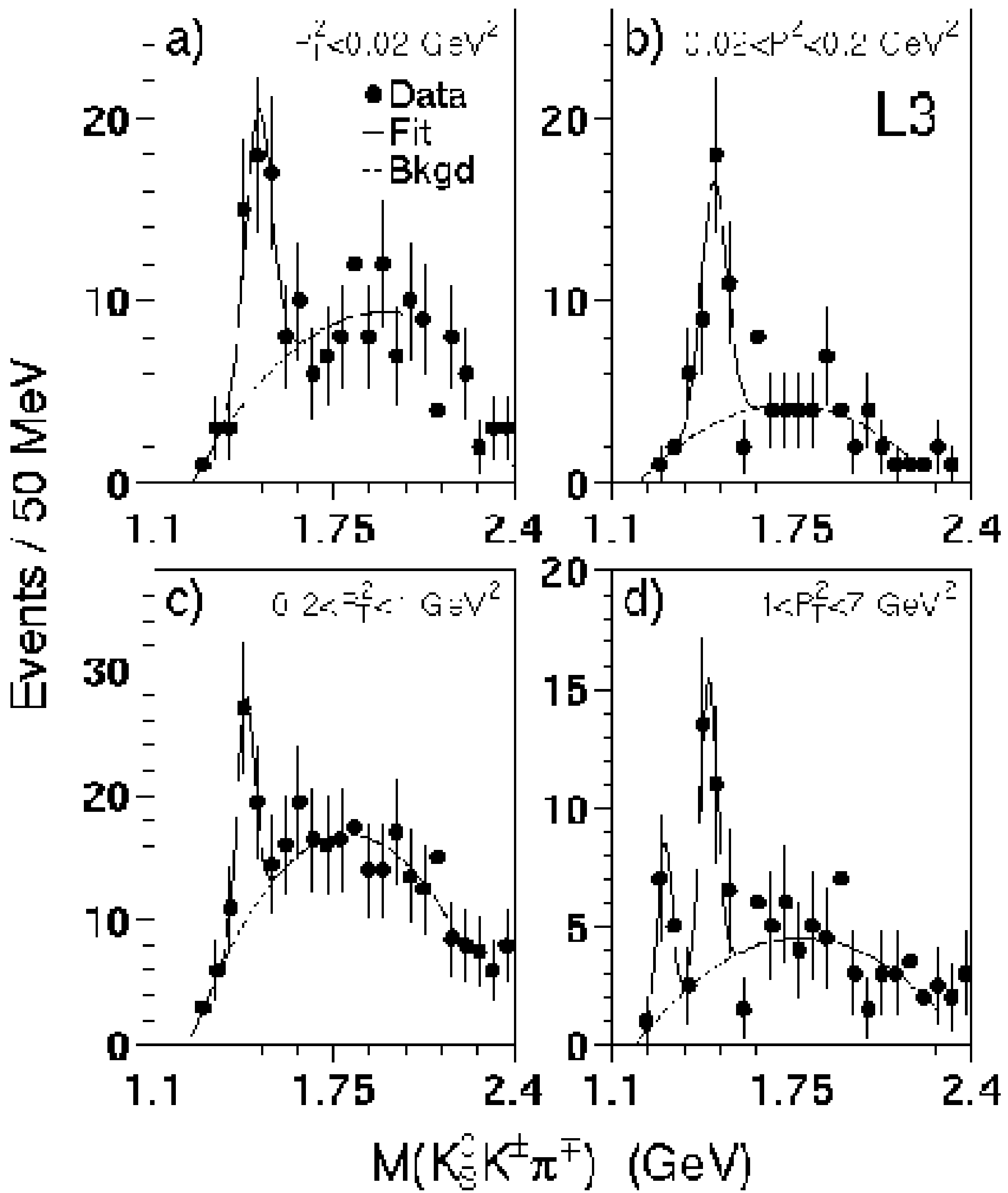
π	η		η'	K
$\pi(1300)$	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$K(1460)$
$n\bar{n}$	$n\bar{n}$	glueball	$s\bar{s}$	$n\bar{s}$

same masses

ideally mixed

$\eta(1405) \to a_0(980)\pi, \sigma\eta$ $\qquad$ $\eta(1475) \to K\bar{K}^* + \bar{K}K^*$

A first warning !



Selection rules:

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

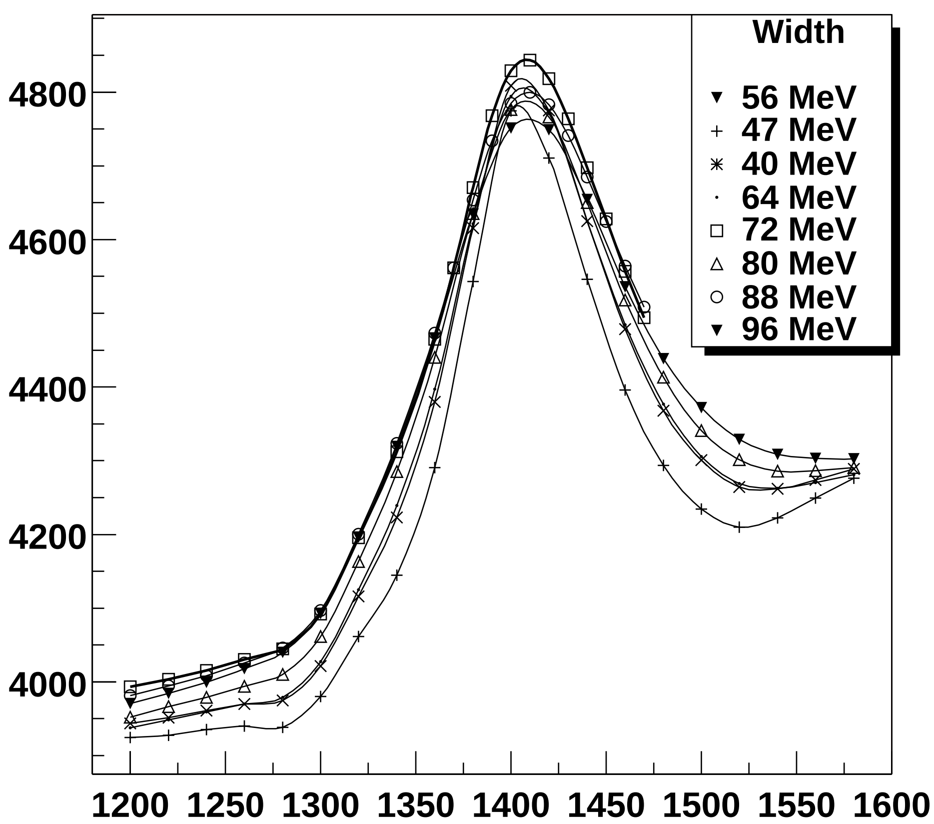
$\gamma\gamma^* \to K_s^0K^\pm\pi^\mp$ from L3.

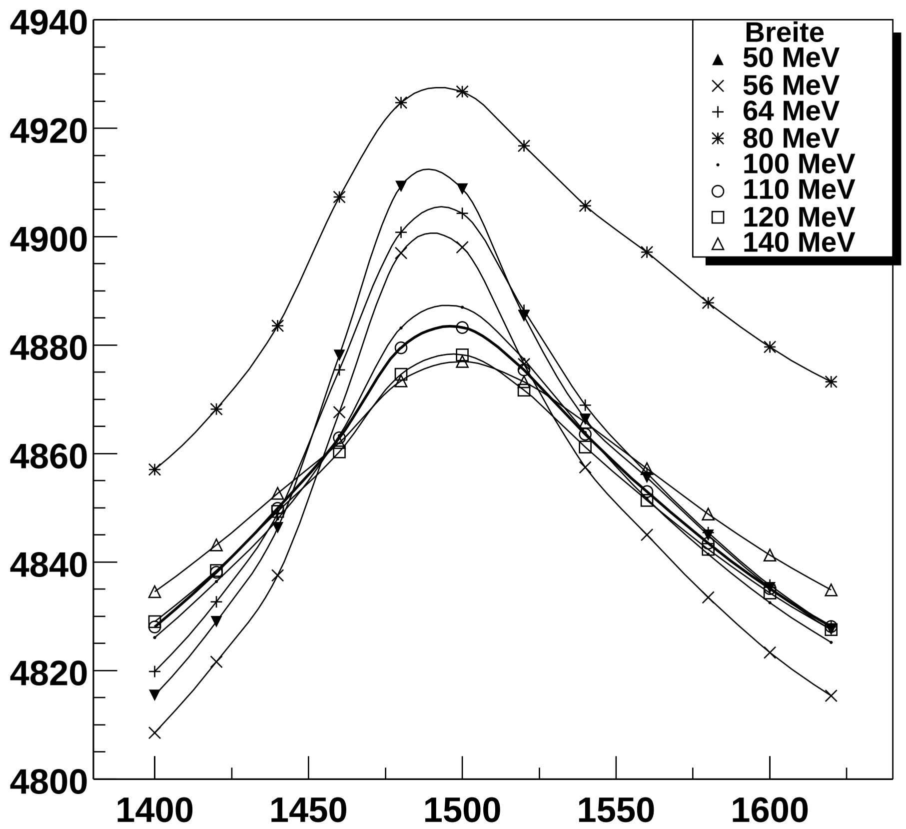
At low and high q^2, peak at 1440 MeV, high q^2 required to produce peak at 1285 MeV.

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

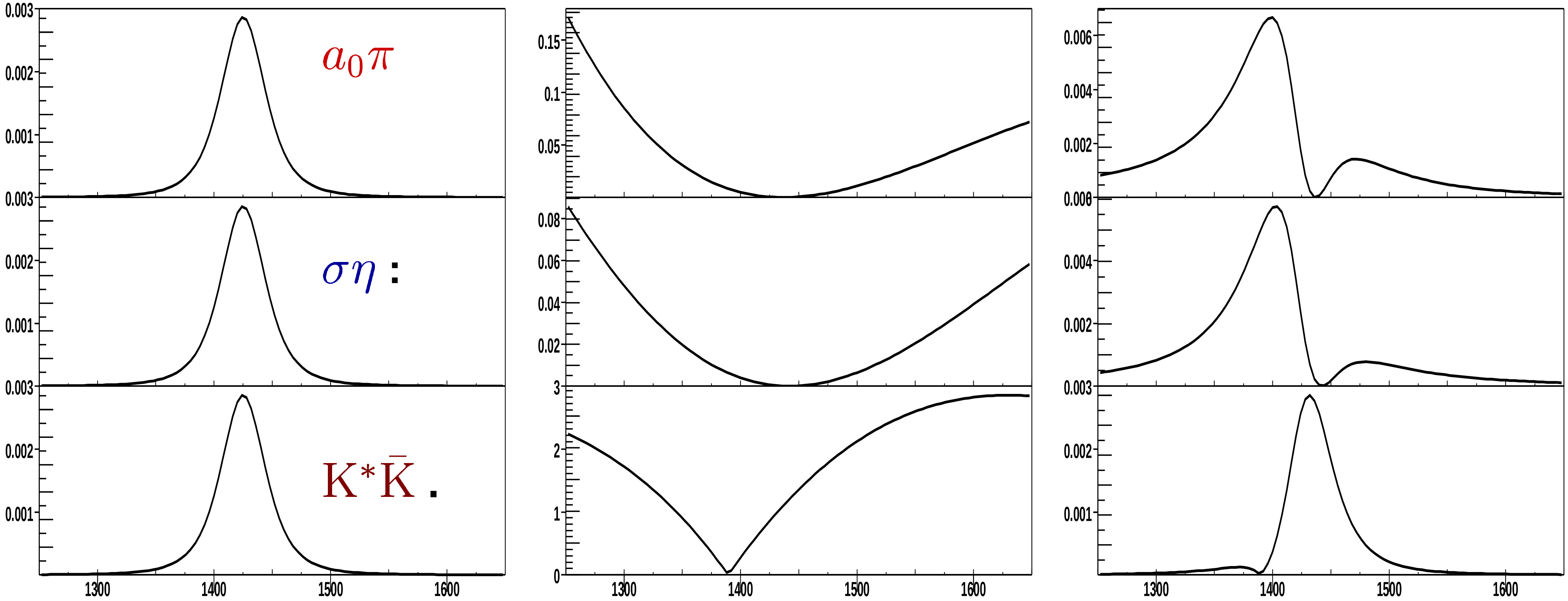




Scan for a $0^{+}0^{-+}$ resonance with different widths. The likelihood optimizes for $M = 1407 \pm 5, \Gamma = 57 \pm 9$ MeV. The resonance is identified with the η_L. A search for a second pseudoscalar resonance (right panel) gives evidence for the η_H with $M = 1490 \pm 15, \Gamma = 74 \pm 10$ MeV.

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

Amplitudes for $\eta(1440)$ decays to

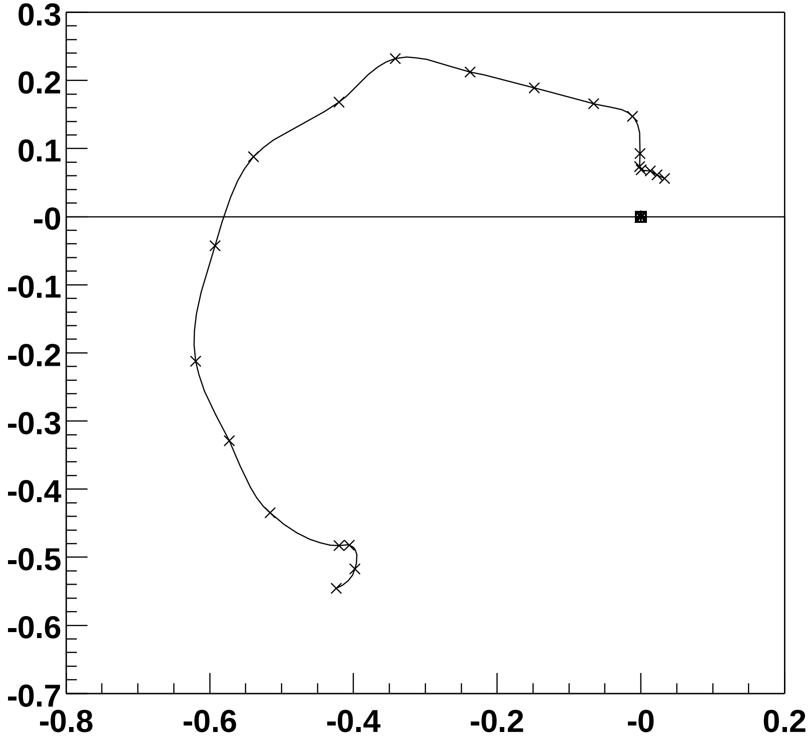


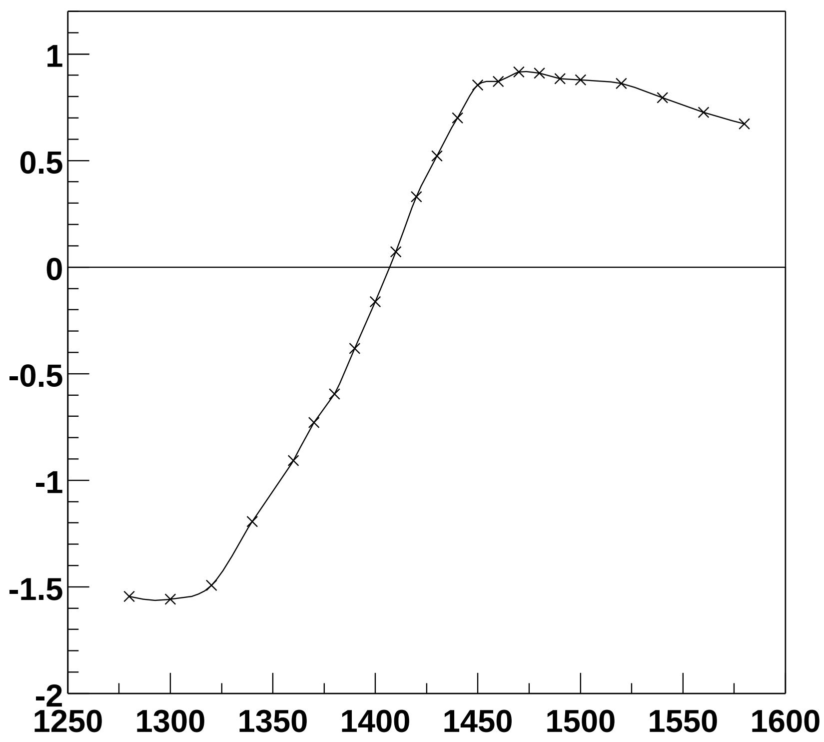
Breit-Wigner functions (left)

squared decay amplitudes (center)

final squared transition matrix element (right).

Phase motion of $\eta(1440)$





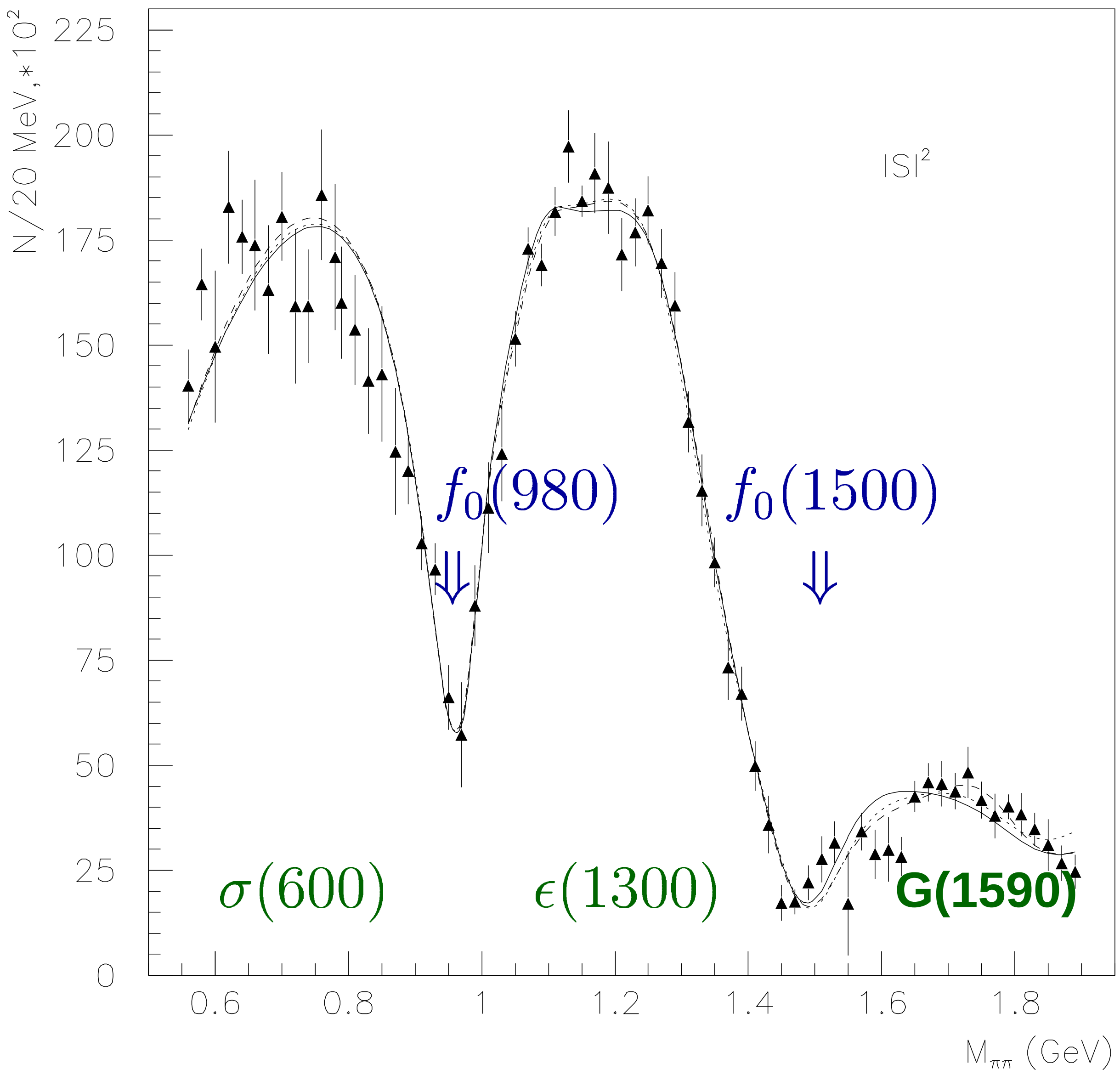
Complex amplitude and phase motion of the $a_0(980)\pi$ isobars in $\mathrm{p\bar{p}}$ annihilation into $4\pi\eta$. In the mass range from 1300 to 1500 MeV the phase varies by π indicating that there is only one resonance in the mass interval. The $\sigma\eta$ (not shown) exhibits the same behaviour.

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 $\eta(1760)$.**

1^1S_0	π	η'	η	K
2^1S_0	$\pi(1300)$	$\eta(1760)$	$\eta(1440)$	K(1460)

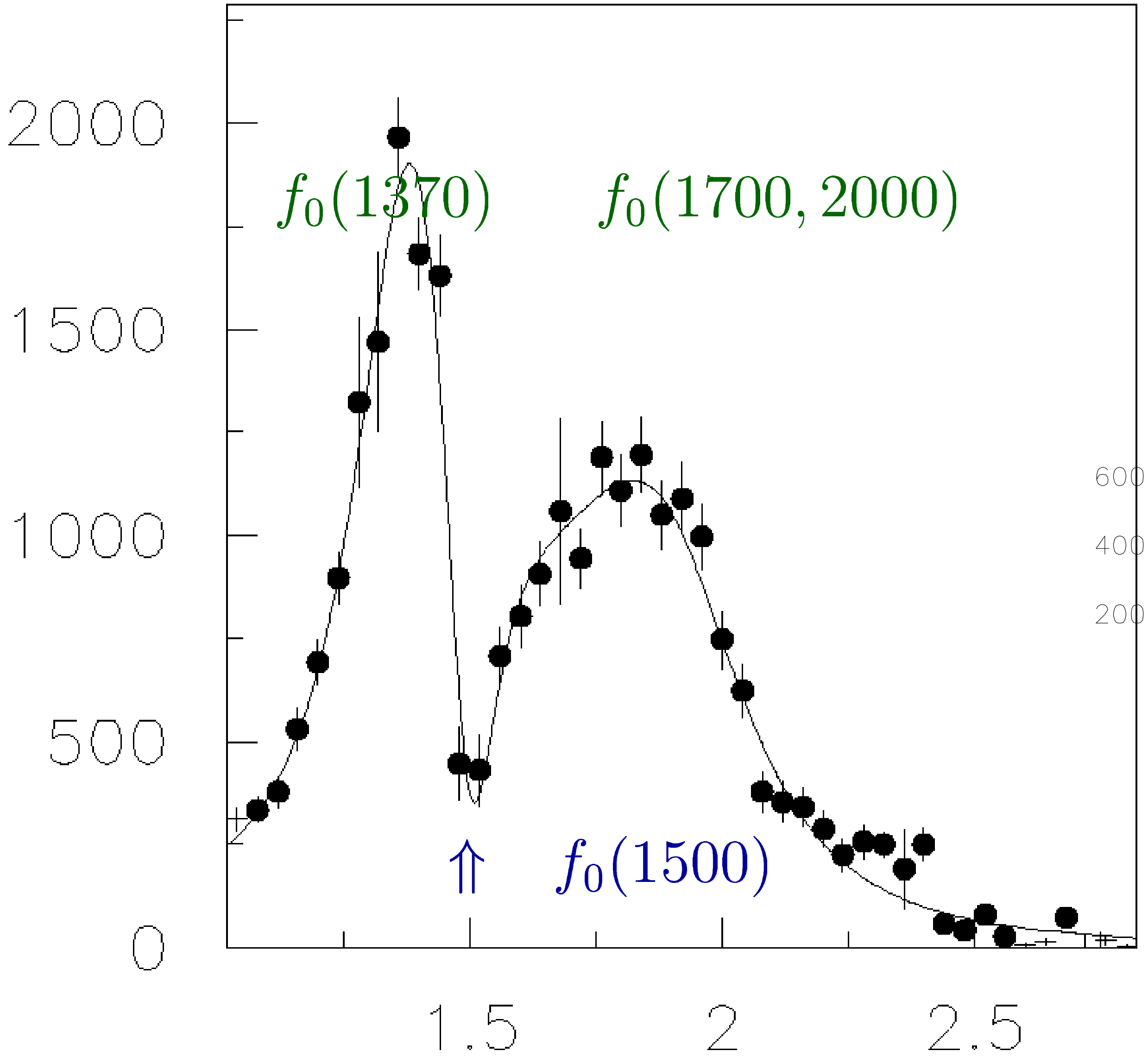
The scalar glueball scrutinized



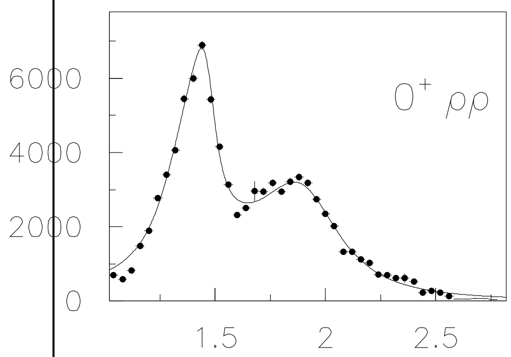
The $\pi\pi$ scattering amplitude measured in the GAMS experiment.

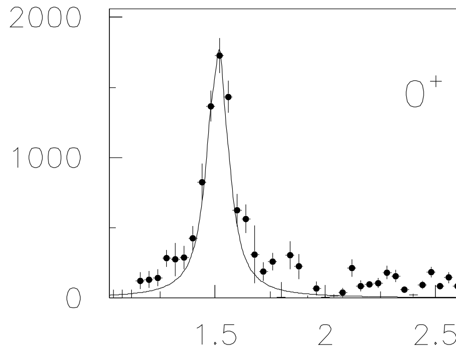
Red dragon = glueball?

P. Minkowski and W. Ochs,
"Identification of the glueballs and the scalar meson nonet of lowest mass,"
Eur. Phys. J. C 9 (1999) 283.



The 4π invariant mass in central production (WA102).





Red dragon $f_0(1500)$

St. Petersburg: K–matrix poles compared to Bonn quark model version B, plus one flavour-blind extra pole at 1400 ± 200 MeV, width ~ 1000 MeV.

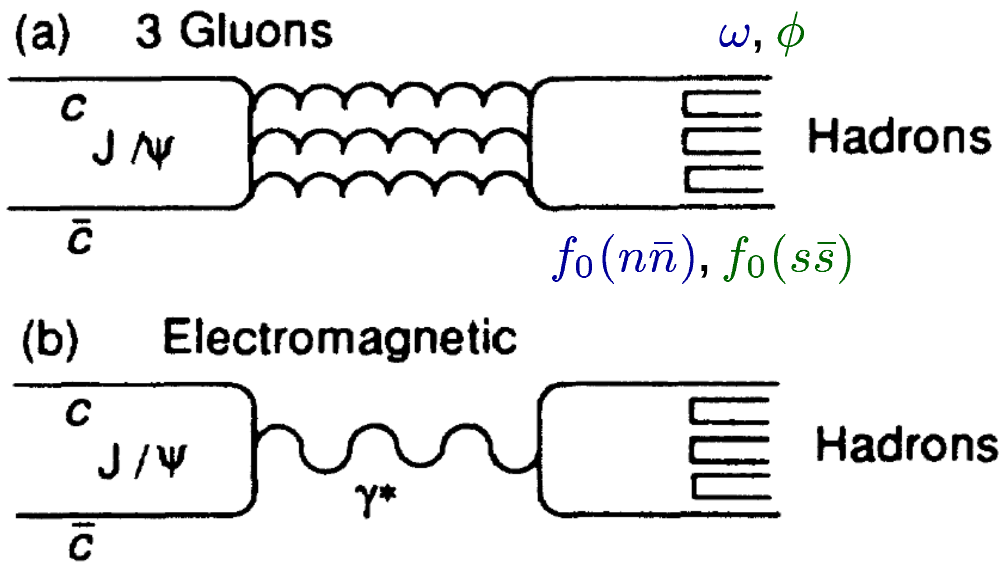
V. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A 16 (2003) 229.

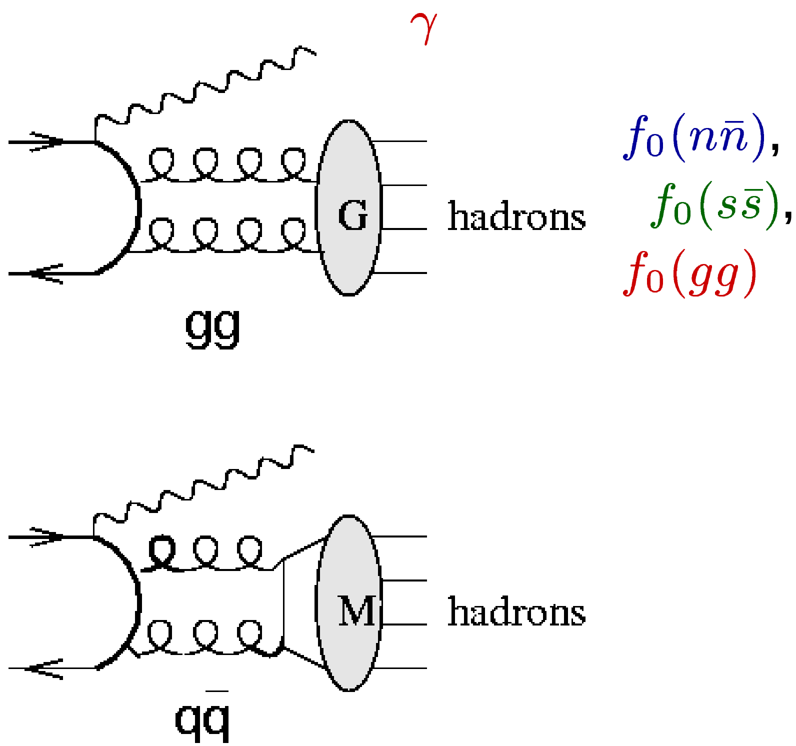
K-matrix poles			Bonn model, B		
	$a_0(980 \pm 30)$	$f_0(680 \pm 50)$		$a_0(1057)$	$f_0(665)$
$K_0^*(1230 \pm 40)$	$a_0(1630 \pm 40)$	$f_0(1260 \pm 30)$	$K_0^*(1187)$	$a_0(1665)$	$f_0(1262)$
		$f_0(1400 \pm 200)$	$\Gamma \sim 1.5$ GeV		
		$f_0(1600)$			$f_0(1554)$
$K_0^*(1885^{+50}_{-100})$			$K_0^*(1788)$		
		$f_0(1810 \pm 50)$			$f_0(1870)$

Can the glueball be made a scientific case ?

YES

Proposed experiment:





J/$\psi \rightarrow$	$\omega\pi\pi$	$\omega K\bar{K}$	$\omega\eta\eta$	$\omega\eta\eta'$	$\omega 4\pi$
J/$\psi \rightarrow$	$\phi\pi\pi$	$\phi K\bar{K}$	$\phi\eta\eta$	$\phi\eta\eta'$	$\phi 4\pi$
J/$\psi \rightarrow$	$\gamma\pi\pi$	$\gamma K\bar{K}$	$\gamma\eta\eta$	$\gamma\eta\eta'$	$\gamma 4\pi$

Conclusions

- **Hadron spectroscopy supports instanton–induced interactions and not effective one–gluon exchange interactions**
- **Hadrons interact via conventional hadron–hadron interactions and may thus form resonances. Likely, the $f_0(600)$ and $f_0(1370)$ are generated this way.**
- **Resonances may have a tetra– or pentaquark component.**
- **In case there is a close–by $q\bar{q}$ meson or qqq baryon, the wave functions mix. The orthogonal components are then not seen experimentally (scattering states ?)**
- **Mesons with exotic quantum numbers are at least partly tetraquarks and not hybrids. The abundancy of exotics in one partial wave supports a tetraquark interpretation.**
- **There is no convincing case for the existence of glueballs.**