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Gluonic Excitations:

Theory vs Experiment

1. General aspects of hadron spectroscopy

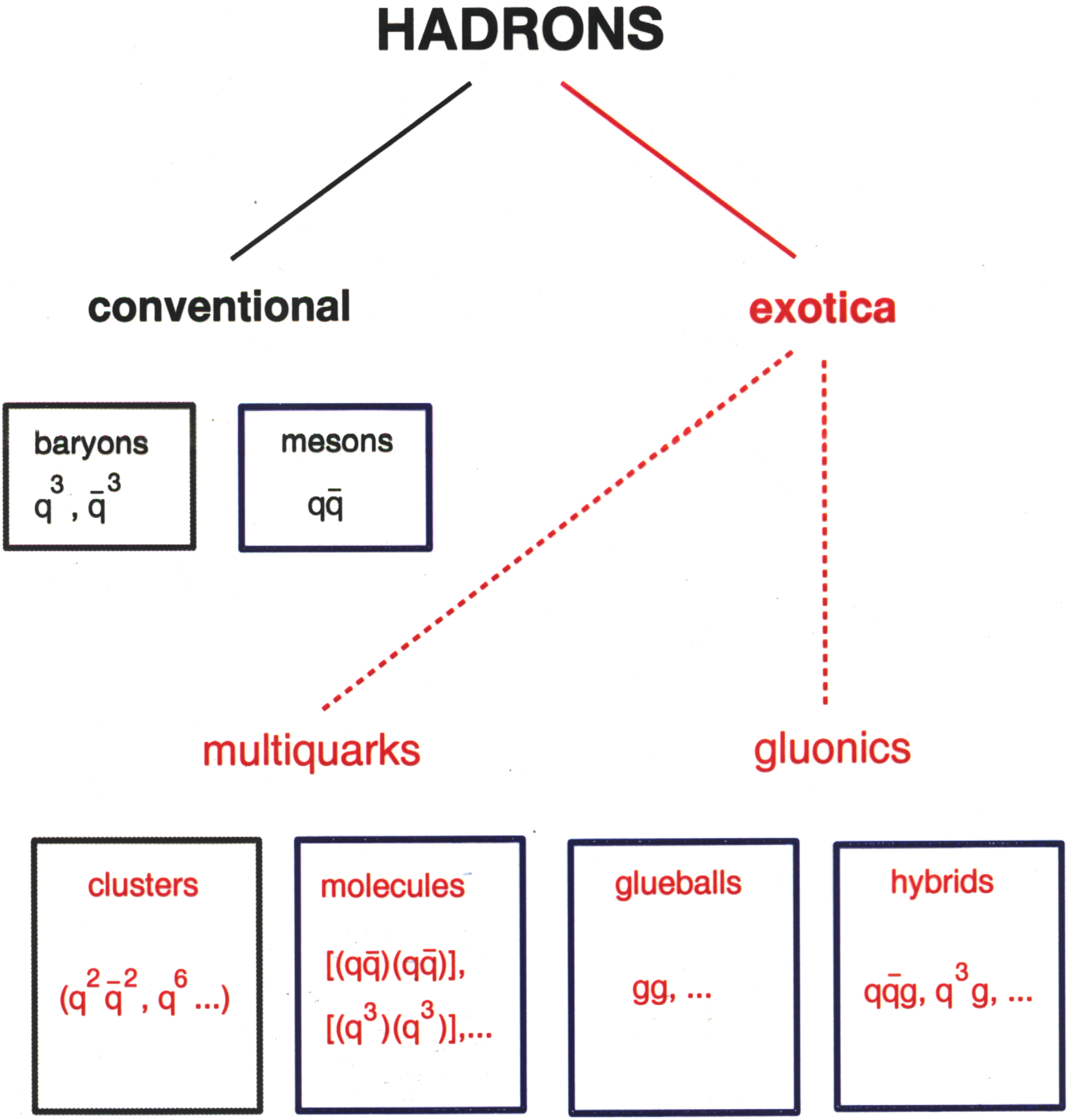
2. Glueballs

3. Hybrids

...and everything else, including the $D_s^*(2317)^+$.

Color singlets – approx. Hilbert space classification.

Mixing may be significant!



HADRONS

conventional

exotica

baryons

q^3, $\bar{q}^3$

mesons

$q\bar{q}$

multiquarks

gluonics

clusters

($q^2\bar{q}^2$, q^6 ...)

molecules

$[(q\bar{q})(q\bar{q})]$,

$[(q^3)(q^3)]$,...

glueballs

gg, ...

hybrids

$q\bar{q}g$, q^3g, ...

$q\bar{q}$ meson J^{PC} quantum numbers

$S = 1/2 \times 1/2 = 0,1$ $L = 0,1,2,\ldots$ $J = S \times L$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

table of allowed $q\bar{q}$ states $^{2S+1}L_J$

...etc

J^{PC}	$--$	$-+$	$+-$	$++$
3	$^3D_3$, $^3G_3$	🟦 3^{-+}	$^1F_3$	$^3F_3$
2	$^3D_2$	$^1D_2$	🟦 2^{+-}	$^3P_2$, $^3F_2$
1	$^3S_1$, $^3D_1$	🟦 1^{-+}	$^1P_1$	$^3P_1$
0	🟦 0^{--}	$^1S_0$	🟦 0^{+-}	$^3P_0$

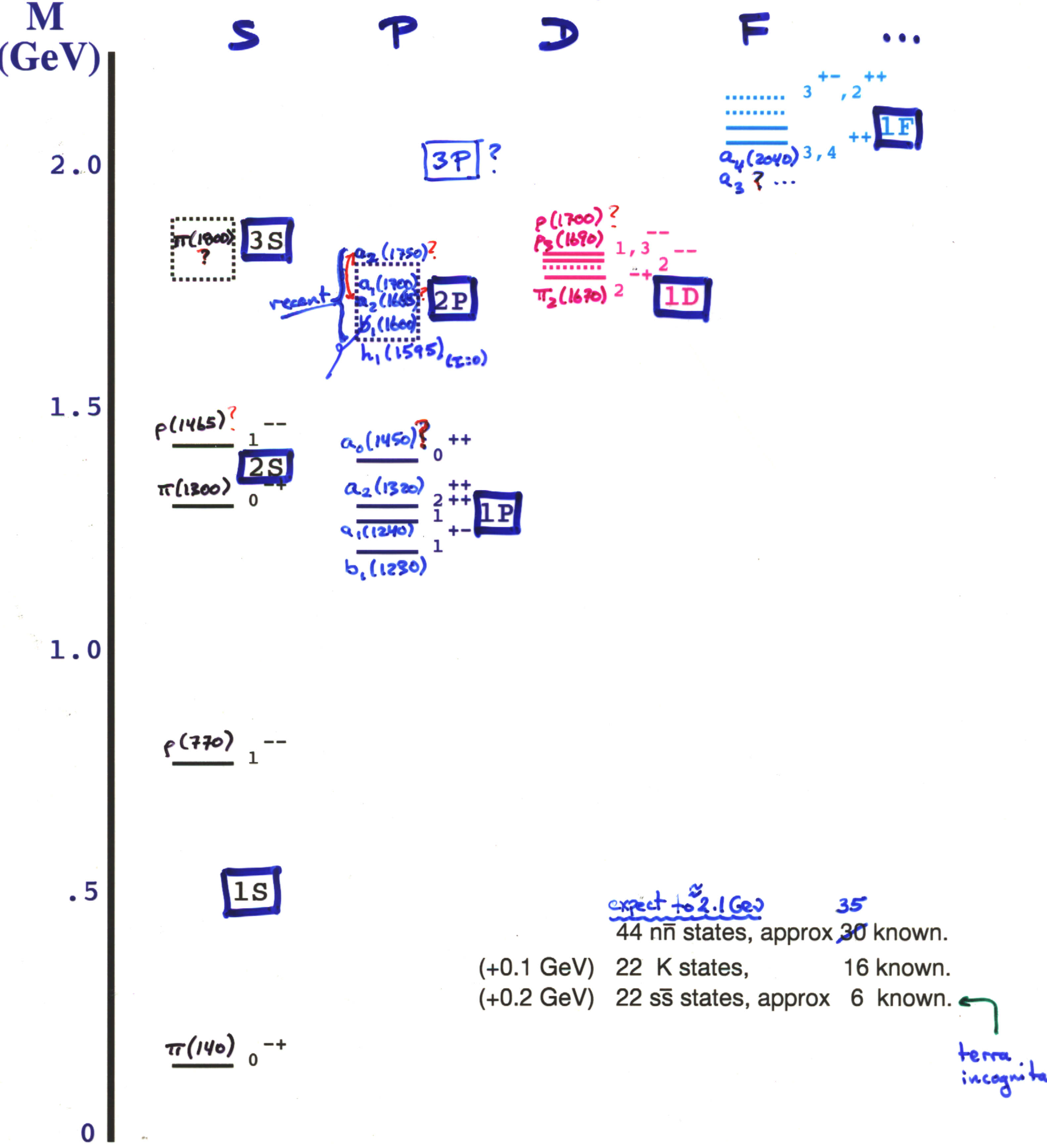
🟦 J^{PC} – exotic

forbidden to $q\bar{q}$

"background" of $q\bar{q}$ states (e.g. of I=1 $q\bar{q}$) ca. ~~1997~~ 2003 (w/additi

Schematic light $q\bar{q}$ spectrum to approx 2.1 GeV.

dots = expected



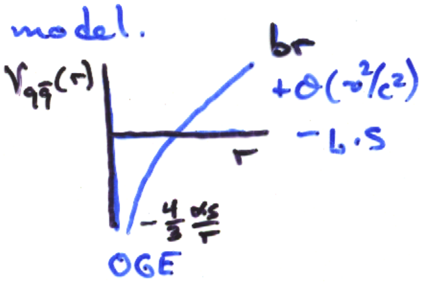
expect to ≲2.1 GeV

44 $n\bar{n}$ states, approx ~~30~~ 35 known.

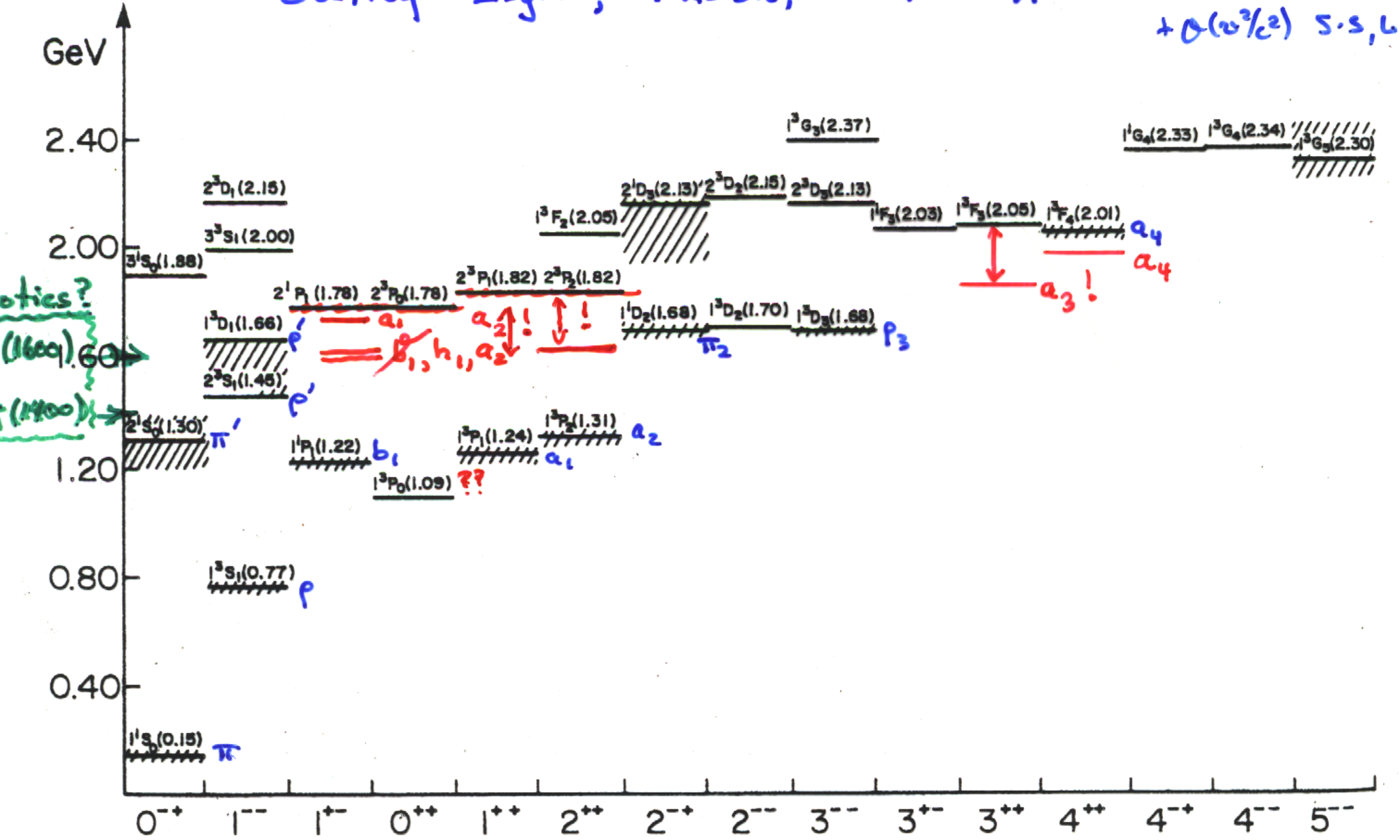
(+0.1 GeV) 22 K states, 16 known.

(+0.2 GeV) 22 $s\bar{s}$ states, approx 6 known.

Relativized Cou + Lin potential model.



Godfrey + Isgur, PRD32, 189 (1985).



Hope to distinguish $q\bar{q}$ from non-$q\bar{q}$ by strong decay BFs.

FIG. 3. The isovector mesons $[-u\bar{d}, \sqrt{1/2}(u\bar{u}-d\bar{d}), d\bar{u}]$. The dominant spectral composition and predicted masses of states in GeV are shown near solid bars representing their masses. Shaded areas correspond to the experimental masses and their uncertainties, normally taken from the Particle Data Group (1984). The comparison of the 1^{--} and 0^{++} sectors with experiment requires special consideration: see Secs. VA and VD, respectively. Significant spectroscopic mixing in this sector: $1^{--}(1.45) \simeq 1.00(2\,^3S_1)+0.04(1\,^3D_1)$.

PHYSICAL REVIEW D VOLUME 55, NUMBER 7 1 APRIL 1997

Higher quarkonia

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(Received 2 October 1996)

+ w/ $\underline{s}$ quarks
Barnes, Black, Page
nucl-th/
0208072
PRD to appea
43 states
all 525 modes
891 amps.
(2-body)

In this paper we survey all radial and orbital excitations of the $I=0$ and $I=1$ $n\bar{n}$ system anticipated up to 2.1 GeV. We give detailed predictions of their quasi-two-body branching fractions and identify characteristic decay modes that can isolate quarkonia; this should be useful in distinguishing quarkonia from glueballs and hybrids. Several of the "missing mesons" with $L_{q\bar{q}}=2$ and $L_{q\bar{q}}=3$ are predicted to decay dominantly into certain $S+P$ and $S+D$ modes, and should appear in experimental searches for hybrids in the same mass region. We also consider the topical issues of whether some of the recently discovered or controversial meson resonances, including glueball and hybrid candidates, can be accommodated as quarkonia. [S0556-2821(97)02205-4]

PACS number(s): 12.39.Mk, 12.39.Jh, 13.25.−k

I. INTRODUCTION

Theoretical studies of light hadron spectroscopy have led to the widespread belief that gluonic excitations are present in the spectrum of hadrons, and so more resonances should be observed than are predicted by the conventional $q\bar{q}$ and qqq quark model. The two general categories of gluonic mesons expected are glueballs (dominated by pure glue basis states) and hybrids (dominated by basis states in which a $q\bar{q}$ is combined with a gluonic excitation).

Some of these novel states, notably the light hybrids, are predicted to have exotic quantum numbers (forbidden to $q\bar{q}$), such as $J^{PC}=1^{-+}$. The confirmation of such a resonance would be proof of the existence of exotic non-$q\bar{q}$ states and would be a crucial step towards establishing the spectrum of gluonic states. There are detailed theoretical predictions for the decays of these exotic hybrids [1,2], which have motivated several experimental studies of purportedly favored hybrid channels such as $b_1\pi$ and $f_1\pi$.

Although one would prefer to find these unambiguously non-$q\bar{q}$ J^{PC} exotics, glueballs and hybrids with nonexotic quantum numbers are also expected. For example, in the flux tube model the lowest hybrid multiplet, expected at $\approx$1.8–1.9 GeV [3,4], contains the nonexotics $J^{PC}=0^{-+}$, $1^{\pm\pm}$, 1^{+-}, and 2^{-+} in addition to the exotics 0^{+-}, 1^{-+}, and 2^{+-}. To identify these nonexotic states one needs to distinguish them from the "background" of radial and orbital $q\bar{q}$ excitations in the mass region $\approx$1.5–2.5 GeV, where the first few gluonic levels are anticipated [5,6].

Our point of departure is to calculate the two-body decay modes of all radial and orbital excitations of $n\bar{n}$ states ($n=u,d$) anticipated up to 2.1 GeV. This includes $2S$, $3S$, $2P$, $1D$, and $1F$ multiplets, a total of 32 resonances in the $n\bar{n}$ sector. We also summarize the experimental status and important decays of candidate members of these multiplets and compare the predictions for decay rates with experiment.

We start by briefly reviewing the established $1S$ and $1P$ states that confirm that ${}^3P_0$ pair creation dominates most hadronic decays. Simple harmonic oscillator (SHO) wave functions are employed for convenience; these lead to analytic results for decay amplitudes and are known to give reasonable empirical approximations. This is sufficient for our main purpose, which is to emphasize selection rules and to isolate major modes to aid in the identification of states. In addition to the $1S$ and $1P$ states we also find reasonable agreement between the model and decays of $1D$, $2P$, and $1F$ states where data exist; this confirms the extended utility of the model and adds confidence to its applications to unknown states.

Examples of new results include the following.

The radial $2\,{}^3P_1$ $a_{1R}\to\rho\pi$ is strongly suppressed in S wave and dominant in D wave. This contrasts with the expectation for a hybrid a_1. The model's prediction of a dominant D wave has been dramatically confirmed for the $a_1(1700)$ [7,8] and thereby establishes 1.7 GeV as the approximate mass of the $n\bar{n}$ members of the $2P$ nonets. This includes the 0^{++} nonet whose $I=0$ members share the quantum numbers of the scalar glueball.

In the scalar glueball sector, we find that the decays of the $f_0(1500)$ and the $f_J(1710)$ are inconsistent with radially excited quarkonia.

We identify the $2S$ 0^{-+} nonet. The η members are predicted to have narrow widths relative to the π counterpart. This is consistent with the broad $\pi(1300)$ and the narrower candidates $\eta(1295)$ and $\eta(1440)$.

The vector states $\rho(1465)$ and $\omega(1419)$ are interesting in that the decay branching fractions appear to show anomalous features requiring a hybrid component. We identify the experimental signatures needed to settle this question.

The $\pi(1800)$ has been cited as a likely hybrid candidate [2,9,10] on the strength of its decay fractions. The $3S$ 0^{-+} $q\bar{q}$ π is also anticipated in this region. We find that the

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0556-2821/97/55(7)/4157(32)/$10.00

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WARNING: $q\bar q$ may prefer S+P decays too!

e.g. do $q\bar q \to$ S+P mainly in some cases?

"Higher Quarkonia." All 374 modes of 32 $n\bar n$ states.

TABLE XIV. Partial widths of $2\,^1P_1 b_1$ and h_1 states (MeV).

Mode	$b_1(1700)$	Mode	$h_1(1700)$
$(1S)^2$			
$\omega\rho$	56	$\rho\pi$	173
$\rho\eta$	18	$\omega\eta$	17
$\rho\rho$	60		
$(2S)(1S)$			
$\omega(1419)\pi$	13	$\rho(1465)\pi$	31
$(1P)(1S)$			
$h_1(1170)\pi$	0	$b_1(1231)\pi$	0
$a_0(1450)\pi$	2		
$a_1(1230)\pi$	10		
$a_2(1318)\pi$	67		
$(1S)^2$ strange			
K^*K	30		30
Total			
$\Sigma_i\Gamma_i$	257		252

TABLE XV. Partial widths of $^3D_J\,\rho_J$ states (MeV).

Mode	$\rho_3(1691)$	$\rho_2(1670)$	$\rho_1(1700)$
$(1S)^2$			
$\pi\pi$	59		48
$\omega\pi$	19	73	35
$\rho\eta$	2	28	16
$\rho\rho$	71	15	14
$(2S)(1S)$			
$\pi(1300)\pi$	0		0
$\omega(1419)\pi$	0	0	0
$(1P)(1S)$			
$h_1(1170)\pi$	6	5	124
$a_0(1450)\pi$		0	
$a_1(1230)\pi$	1	3	134
$a_2(1318)\pi$	4	201	2
$(1S)^2$ strange			
KK	9		36
K^*K	2	44	26
Total			
$\Sigma_i\Gamma_i$	174	369	435
Γ_{expt}	215(20)		235(50)

$^3D_1$ $n\bar n$ 1^{--}

TABLE XVI. Partial widths of $^3D_J\,\omega_J$ states (MeV).

Mode	$\omega_3(1667)$	$\omega_2(1670)$	$\omega_1(1649)$
$(1S)^2$			
$\rho\pi$	50	221	101
$\omega\eta$	2	27	13
$(2S)(1S)$			
$\rho(1465)\pi$	0	0	0
$(1P)(1S)$			
$b_1(1231)\pi$	7	8	371
$(1S)^2$ strange			
KK	8		35
K^*K	2	44	21
Total			
$\Sigma_i\Gamma_i$	69	300	542
Γ_{expt}	168(10)		220(35)

$\omega_H \not\to b_1\pi$ f.t.m.

TABLE XVII. Partial widths of $^1D_2\,\pi_2$ and η_2 states (MeV).

Mode	$\pi_2(1670)$	Mode	$\eta_2(1645)$
$(1S)^2$			
$\rho\pi$	118	$\rho\rho$	33
$\omega\rho$	41	$\omega\omega$	8
$(2S)(1S)$			
$\rho(1465)\pi$	0		
$(1P)(1S)$			
$b_1(1231)\pi$	0		
$f_0(1300)\pi$	0	$a_0(1450)\pi$	0
$f_1(1282)\pi$	1	$a_1(1230)\pi$	5
$f_2(1275)\pi$	75	$a_2(1318)\pi$	189
$(1S)^2$ strange			
K^*K	30		26
Total			
$\Sigma_i\Gamma_i$	250		261
Γ_{expt}	258(18)		$180^{+40}_{-21}(25)$

TABLE XVIII. Partial widths of $^3F_J\,a_J$ states (MeV).

Mode	$a_4(2037)$	$a_3(2080)$	$a_2(2050)$
$(1S)^2$			
$\eta\pi$	12		13
$\eta'\pi$	3		13
$\rho\pi$	33	86	37
$\omega\rho$	54	28	19
$(2S)(1S)$			
$\eta(1295)\pi$	1		0
$\pi(1300)\eta$	0		0
$\rho(1465)\pi$	0	1	0
$(1P)(1S)$			
$b_1(1231)\pi$	20	12	140
$f_0(1300)\pi$		4	
$f_1(1282)\pi$	2	6	36
$f_2(1275)\pi$	10	67	14
$a_0(1450)\eta$		0	
$a_1(1230)\eta$	0	1	16
$a_2(1318)\eta$	0	24	4
$h_1(1170)\rho$	0	40	21
$b_1(1231)\omega$	0	17	5
$(2P)(1S)$			
$b_1(1700)\pi$	0	0	2
$f_0(1700)\pi$		0	
$f_1(1700)\pi$	0	0	0
$f_2(1700)\pi$	0	1	0
$(1D)(1S)$			
$\eta_2(1645)\pi$	0	3	67
$\rho_1(1700)\pi$	0	1	1
$\rho_2(1670)\pi$	0	1	89
$\rho_3(1691)\pi$	2	127	1
$(1S)^2$ strange			
KK	8		14
K^*K	4	28	15
K^*K^*	9	5	2
$(1P)(1S)$ strange			
$K_0^*(1429)K$		0	
$K_1^*(1273)K$	0	3	91
$K_1^*(1402)K$	0	0	0
$K_2^*(1429)K$	0	31	4
Total			
$\Sigma_i\Gamma_i$	161	483	606
Γ_{expt}	427(120)	340(80)	

$a_1(1700)$

$2\,{}^3P_1$ $n\bar{n}$?

H ?

$\pi\rho$ mode
confirms $n\bar{n}$

1^{++} $f_1\pi$

large 1^{++} signal in πf_1 at 1.7GeV.
$q\bar{q}$? hybrid? !?
What would an $a_1(1700)$ 2^3P_1 decay to?

BNL E818
Lee et al
Possible 1^{-+}
exotic
in πf_1.

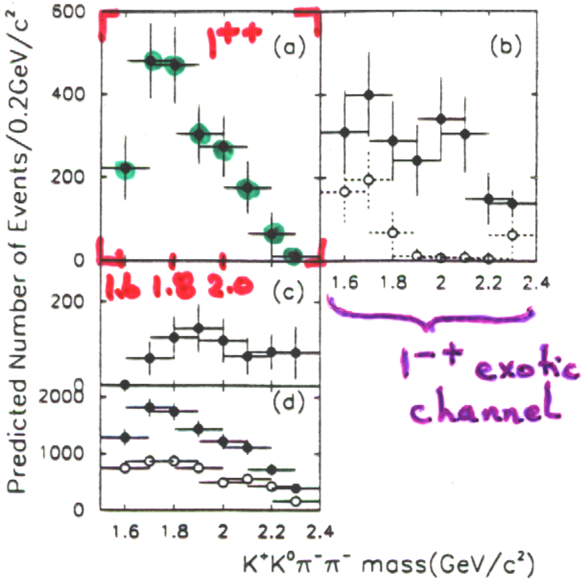


Fig. 3. The partial-wave intensity distributions as a function of $f_1\pi^-$ mass. (a) $J^{PC}M^\epsilon = 1^{++}0^+$ wave. (b) $J^{PC}M^\epsilon = 1^{-+}1^+$ wave with combined $f_1(1285)\pi$ and $\eta(1295)\pi$ decay modes. The dotted spectrum shows $\eta(1295)$ wave only. (c) $J^{PC}M^\epsilon = 2^{++}1^+$. (d) All partial waves included in the fit. The open circles in the plot show the background.

distributions with the predicted ones, and found good agreement.

The results of the fit, in the form of the predicted number of events attributed to the spin–parity states, are given in fig. 3. It was found that the states $J^{PC}[\text{isobar}]M^\epsilon = 1^{++}[f_1(1285)]0^+$, $1^{-+}[f_1(1285)$ and $\eta(1295)]1^+$, $2^{++}[f_1(1285)]1^+$, all produced via natural-parity exchange, and an incoherent phase-space background wave, were sufficient to describe the data. The high background level (See fig. 3d) is due to the tail of the $f_1(1420)$ (~ 35%) and a non-resonant contribution (~ 15%) in the data sample. All the other waves turned out to be very small including the spin-zero waves, which can only be produced via unnatural-parity exchange. The $f_1(1285)\pi^-$ decay mode was required for all the waves, and a $\eta(1295)\pi$ decay mode was needed only in the $J^{PC} = 1^{-+}$ wave, contributing ~ 11% of the total events above the background.

It was pointed out recently that the helicity-coupling amplitudes acquire extra energy-dependent factors beyond those arising from the usual angular-momentum barrier effect because of the requirement of Lorentz invariance [27]. According to this prescription, the $1^{++}[f_1(1285)]$ amplitudes should be multiplied by a factor $m(f_1\pi)$, while the $1^{-+}[f_1(1285)]$ and $2^{++}[f_1(1285)]$ amplitudes acquire a factor $E(f_1)/m(f_1)$ – in the rest frame of the $f_1(1285)\pi$ system – if the f_1 helicity is zero. These factors have been tried in our fit; however, the results do not change by more than 15% throughout all the mass bins when compared to those without the extra factors.

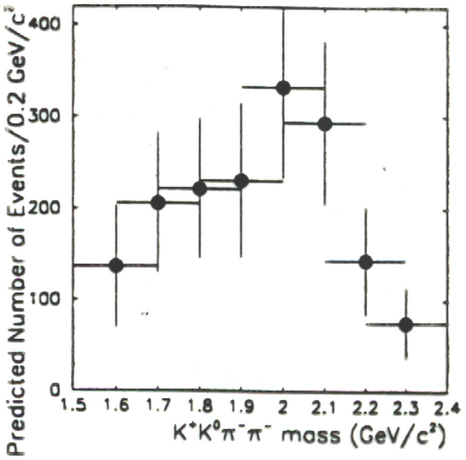


Fig. 4. Predicted number of $1^{-+}[f_1(1285)]1^+$ events as a function of $K^+\overline{K}^0\pi^-\pi^-$ mass.

The salient features of the results from PWA on the data are follows:

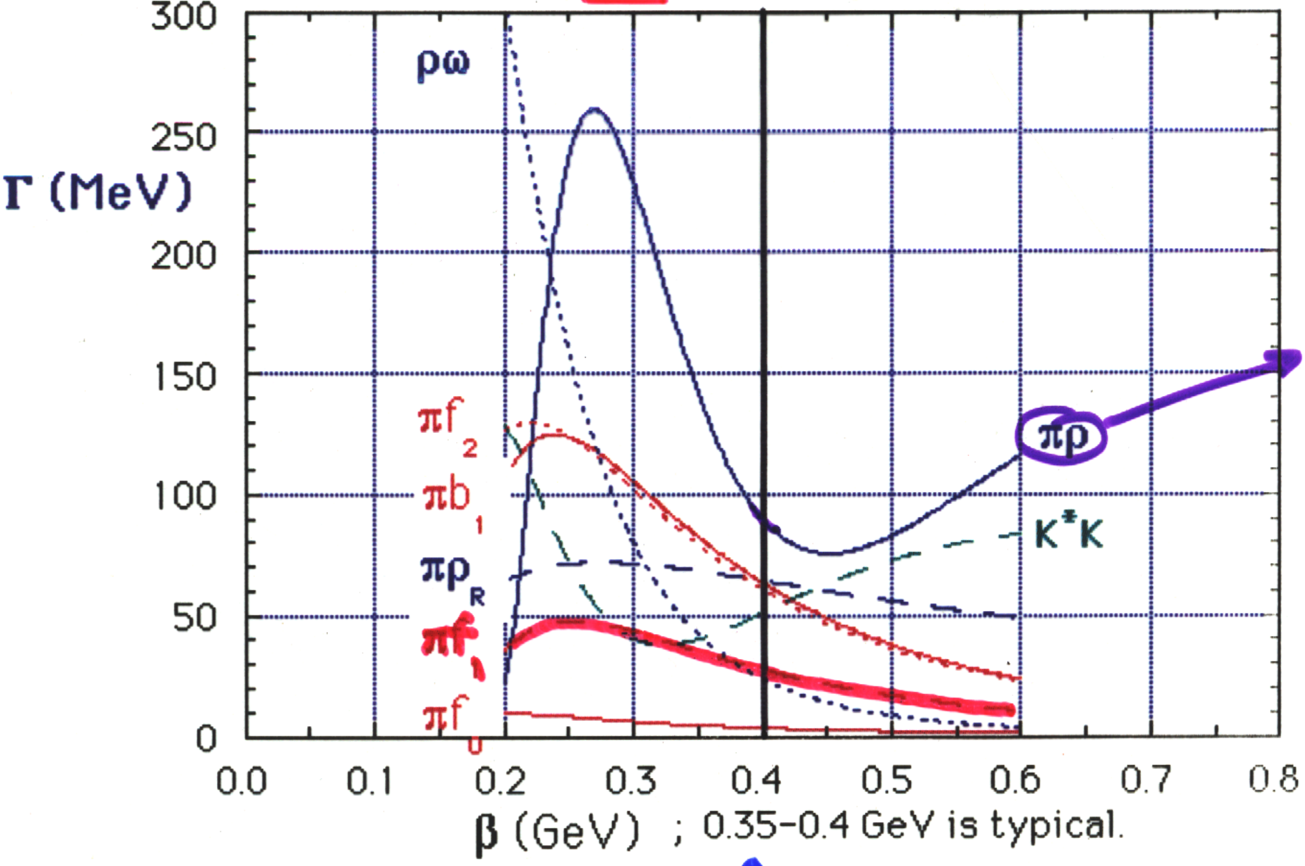
(i) The data are well described by reflectivity = + waves only, i.e., the reaction (1) is dominated by natural-parity exchange processes, presumably $f_2(1270)$ or ρ exchange. This is in sharp contrast to our initial expectation for a substantial $b_1(1235)$ exchange.

(ii) The ratio of the 1^{-+} wave to total is substantial, at 45 ± 6%, and it shows a broad structure in the mass region from 1.6 to 2.2 GeV/c^2. This structure is suggestive of being a composite of two objects, at 1.7 and 2.0 GeV/c^2 (see fig. 3b). The 1^{-+} "object" near 2.0 GeV/c^2 is dominated by the $f_1(1285)$ channel (see fig. 4), whereas that at 1.7 GeV/c^2 appears to have a substantial coupling to the $\eta(1295)$ channel. The relative phase of $1^{-+}[f_1(1285)]1^+$ vs. $1^{++}[f_1(1285)]0^+$ is shown in fig. 5. The phase variation could be interpreted as being due to a resonant

2^3P_1 $a_1(1700)$

Partial widths of a 2^3P_1 $a_1(1700)$ radial excitation.

($^3P_0$ decay model, with $\gamma=0.5$ and wavefunction parameter β variable.)



Is $a_1(1700)$ Seen in $\rho\pi$?

standard wfn length scale

$J^{PC} = 1^{++}$

$I = 1$

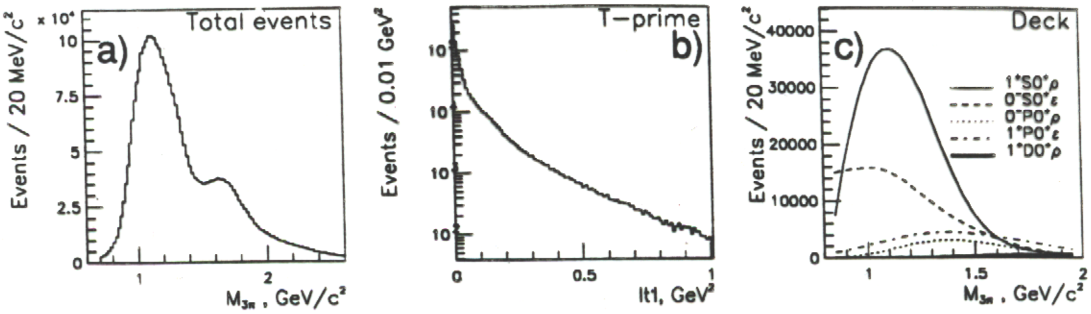
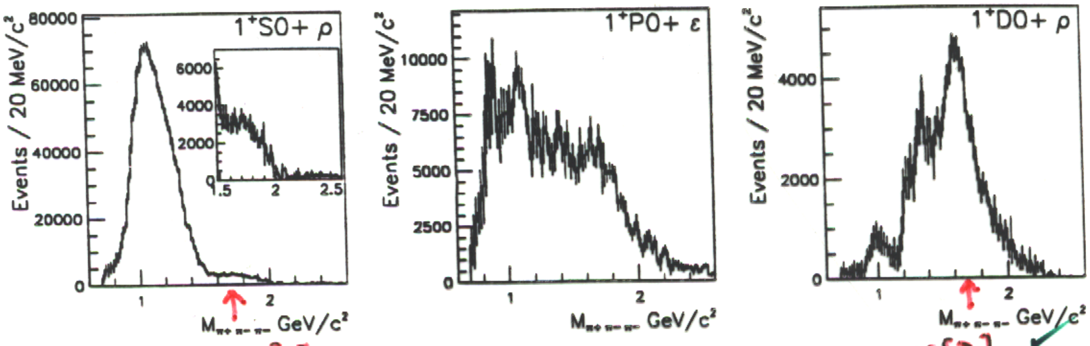


Fig. 1. Effective mass distribution, acceptance corrected (a); t' distribution (b); Deck model predictions for some waves (c).



$\pi\rho[S]$

$\pi\rho[D]$ ✓

Fig. 2. Main $J^{PC} = 1^{++}$ waves.

1^{++} 1.7GeV dominated by D-wave $\rho\pi$.

value significantly exceeds the expected contribution from the Deck effect. In the region 0.8–1.3 GeV this wave is badly measurable due to the huge signal in the $1^+S0+\rho$ wave and its shape depends on the $\rho(770)$ parameterization. So we don't consider the structures in this region as significant.

A significant excess of the $1^+S0+\rho$ wave over the Deck effect together with the structure in $1^+D0+\rho$ and possibly $1^+P0+\epsilon$ waves can be considered as an indication of an existence of an object with $J^{PC} = 1^{++}$, $M \approx 1.7$ GeV, which decays into all those channels with comparable probability. A similar signal in the 1^{++} wave was observed in $f_1(1285)\pi$ channel [14].

$J^{PC} = 2^{-+}$. The waves with $J^{PC} = 2^{-+}$ are shown in Fig. 3. In the wave 2^-S0+f_2 a clear signal is seen from the $\pi_2(1670)$ resonance. In the wave $2^-P0+\rho$ an enhancement in the π_2 region and a broad maximum at $M \approx 1.2$ GeV are observed. This wave around the maximum has a small coherence factor with respect to the diffractive waves and large systematic errors. In the $2^-D0+\epsilon$ wave one can observe the structure with two maxima at $M \approx 1.7$ GeV and $M \approx 2.1$ GeV. The first one can be identified as $\pi_2(1670)$ while the second is probably a new object. The first indication of its existence was presented earlier in [9]. In the wave 2^-D0+f_2 one can see a signal with the maximum at $M \approx 1.8$ GeV. This signal has a non-Breit-Wigner shape and phase motion, and the reason of its appearance can be an interference of two objects seen in $2^-D0+\epsilon$. The wave $2^-D0+f_0(980)$ is an order of magnitude smaller than the wave $2^-D0+\epsilon$, which is in accordance with the expectations for the decays of isovector $q\bar{q}$ mesons. Parameters of this objects were determined by the K-matrix formalism [15,9]. The two poles, a Deck background and a polynomial background were included in the model. The parameters of the K-matrix poles are

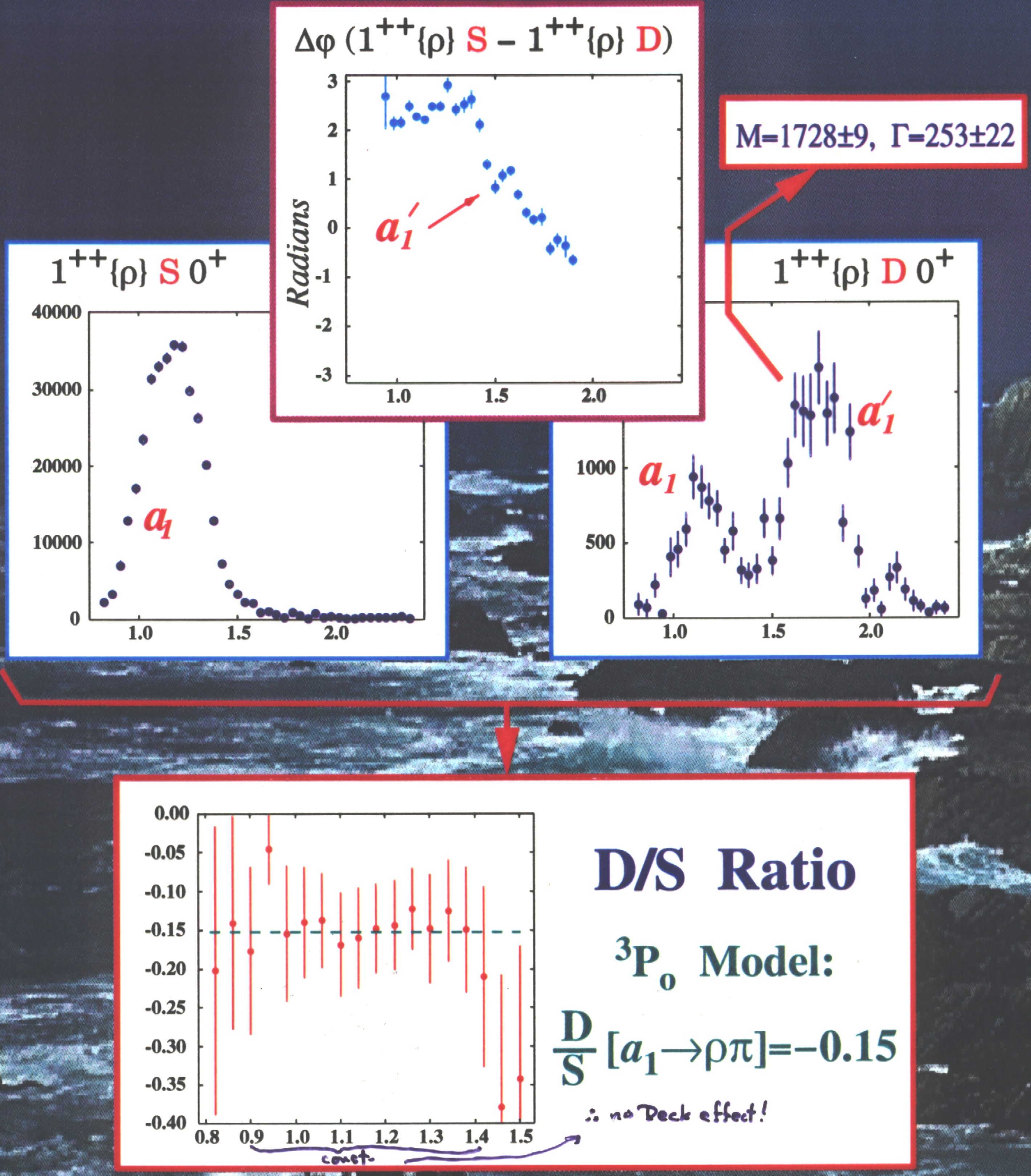
$$\pi_2: \quad M = 1.73 \pm 0.02\ \text{GeV}, \ \Gamma = 310 \pm 20\ \text{MeV},$$

$$\pi_2': \quad M = 2.09 \pm 0.03\ \text{GeV}, \ \Gamma = 520 \pm 100\ \text{MeV}.$$

Errors include both systematic and statistical ones. These values are consistent with the results of the previous work [9].

$\pi^+\pi^-\pi^-$ $a_1(1700)$, radial ex. of a_1. $(\rho\pi)_D$ predicted ($^3P_0$). BNL E852 ∴ $q\bar{q}$ not hybrid.

$a_1(1260)$ and $a_1(1700)$



M=1728±9, Γ=253±22

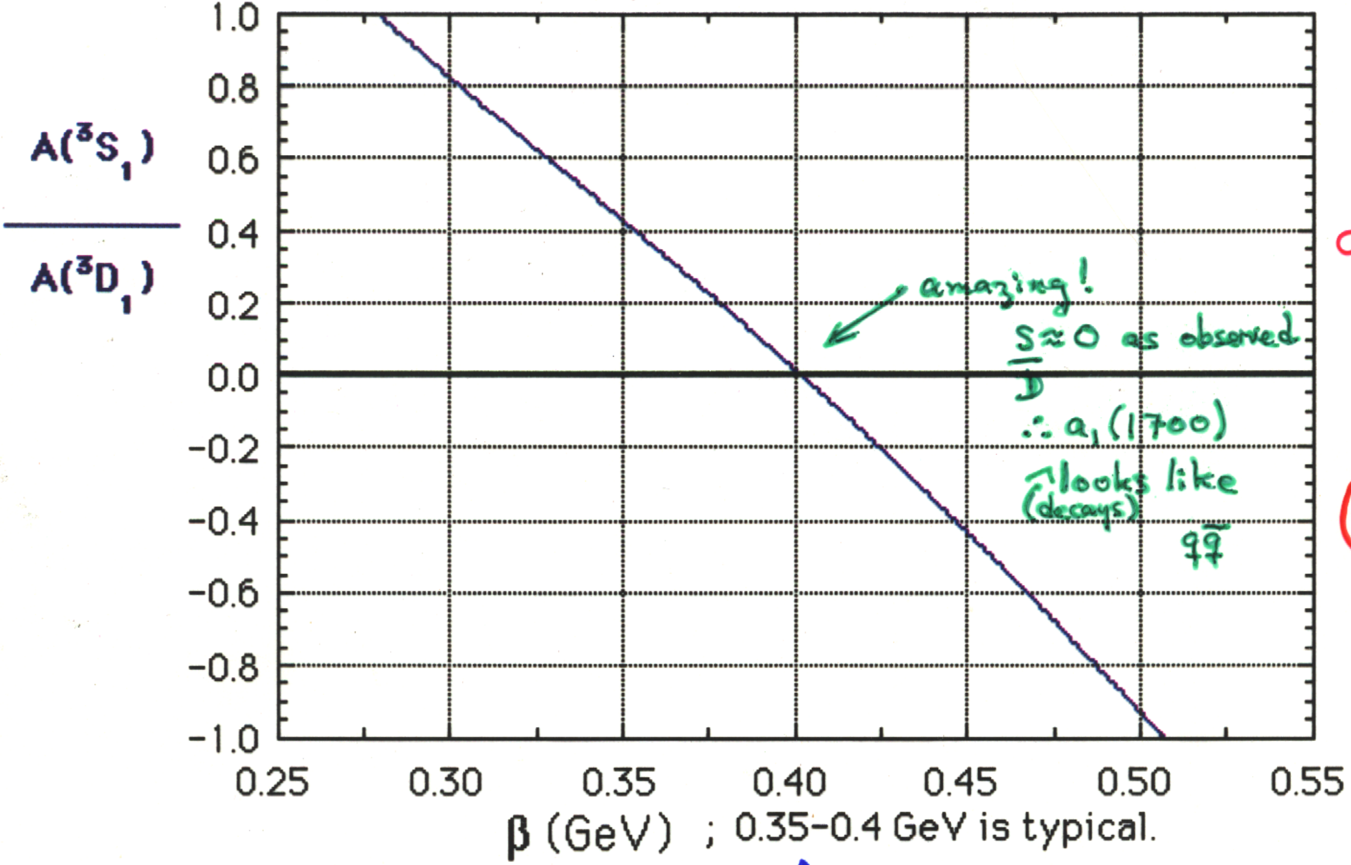
D/S Ratio

$^3P_0$ Model:

$$\frac{D}{S}[a_1\rightarrow\rho\pi]=-0.15$$

∴ no Deck effect!

2^3P_1 $a_1(1700)$ $\to \rho\pi$



S/D amplitude ratio for $A(2^3P_1\ a_1(1700) \to \rho\pi)$.

($^3P_0$ decay model, with γ_0=0.5 and wavefunction parameter β variable.)

amazing!

$\frac{S}{D} \approx 0$ as observed

$\therefore a_1(1700)$ looks like (decays) $q\bar{q}$

$a_{1R} \to \rho\pi$

$\frac{S}{D}$

(not D/S)

↑

std. quark model length scale

now prefer $\gamma = 0.4$ (Tables < Figs which show $\gamma = 0.5$)

$\beta = 0.4$ GeV

TABLE IV. Partial widths of 2P and hybrid $a_1(1700)$ states.

	$\rho\pi$	$\rho\omega$	$\rho(1465)\pi$	$\boxed{b_1\pi}$	$f_0(1300)\pi$	$f_1\pi$	$f_2\pi$	K*K	total
$a_{1(2P)}(1700)$	57.	15.	41.	41.	2.	18.	39.	33.	246.
$a_{1(H)}(1700)$	30	0	110	0	6	60	70	20	≈ 300

$\rho\pi$ mostly $(\rho\pi)_S$

$b_1\pi$

$f_1\pi$

Γ_{tot}

mostly $(\rho\pi)_D$

Hybrid & 2^3P_1 $a_1(1700)$ assignments give similar predictions. (abs. rates)

In future $b_1\pi$ might distinguish them.

Treasure hunt ?

Many possibilities.

~ ½ the 32 $n\bar{n}$ "higher quarkonia" are not establishe

an e.g. Missing $^3D_2$ 2^{--} states

$\rho_2(1670)$

↓

$a_2\pi$	54%
$\omega\pi$	20%

$\Gamma_{tot} \cong 370$ MeV

$\omega_2(1670)$

↓

$\rho\pi$	74%
K^*K	15%
$\omega\eta$	9%

$\Gamma_{tot} \cong 300$ MeV

2) "Exotica"

Other color-singlet combinations are mathematically possible, and these exotica should exist in nature as well. They are:

MULTIQUARKS

/molecules
↑ ok

| q q qbar qbar > , | qqqqqq >, ...

(baryonia, dibaryons. H dibaryon.) **WARNING**: controversial, may not exist as resonances. The "multiquark fiasco". "fall-apart" decays allow direct coupling (q q qbar qbar) (q qbar) (q qbar) without an interaction.

GLUEBALLS

"excited glue"

| gg > , | ggg >, ... (maybe 1 known)

Popular with the LGT community.

HYBRIDS

"quarks + excited glue"

| q qbar g > , | qqqg >, ...

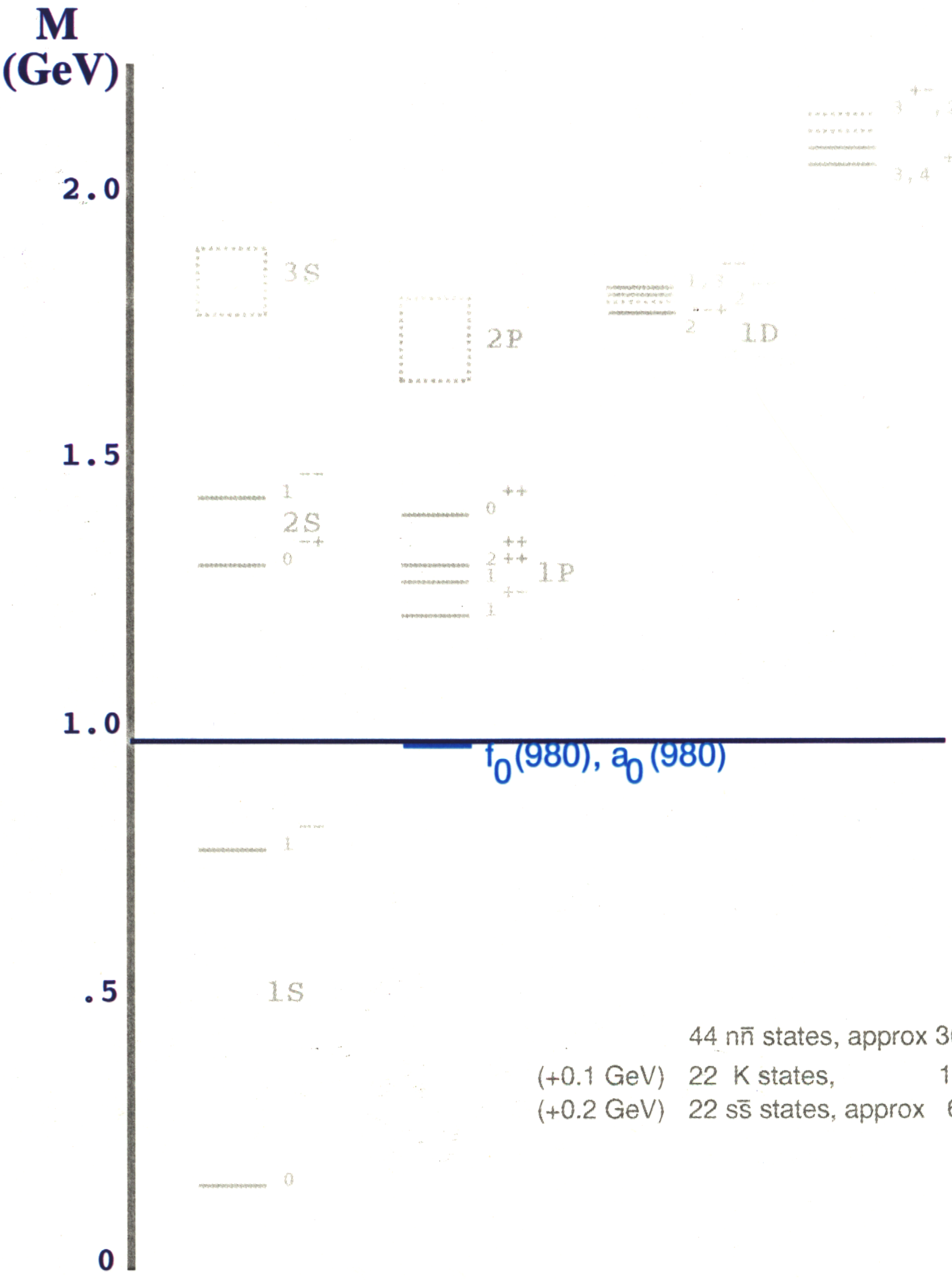
(maybe 2-3 known) The most attractive experimentally.

Exotic quantum numbers.

$q\bar{q}g$ → [illegible] nonets

molecules / multiquarks

Schematic light $q\bar{q}$ spectrum to approx 2.1 GeV.



***$K\bar{K}$* threshold 990 MeV**

Many $q^2\bar{q}^2$ states were predicted e.g. MIT bag mod

"baryonia"

44 $n\bar{n}$ states, approx 30 known.

(+0.1 GeV) 22 K states, 16 known.

(+0.2 GeV) 22 $s\bar{s}$ states, approx 6 known.

9-16 May 1982
Erice

Physics at LEAR with Low-Energy Cooled Antiprotons

Edited by

Ugo Gastaldi
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University of Mainz
Mainz, Federal Republic of Germany

and

Robert Klapisch
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Geneva, Switzerland

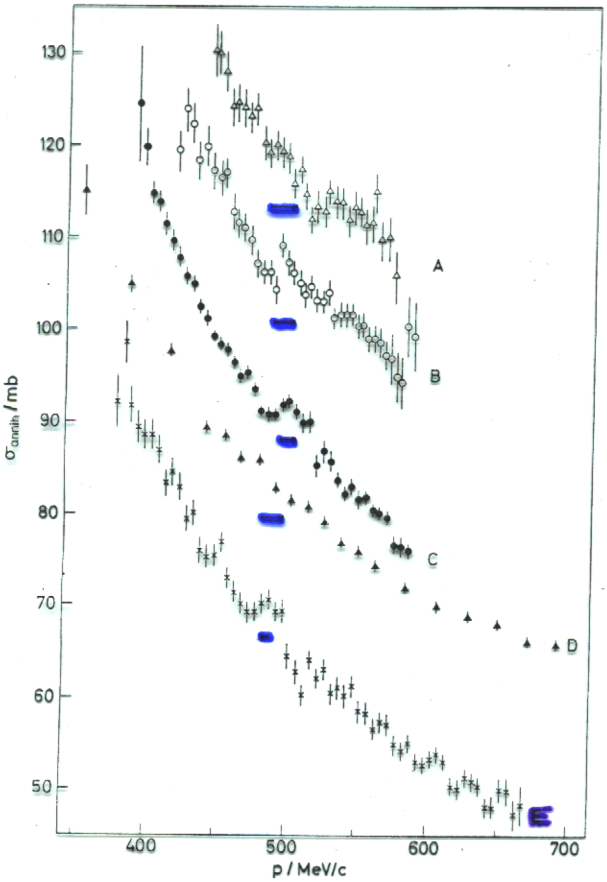
Plenum Press • New York and London

baryonia ? $(q^2\bar{q}^2)$

Th. Walcher
Erice '82

and again demonstrates that the structure depends on the resolution, i.e. the target thickness. A further check was that the structure occurred in two independent measurements, about one month apart. The structure is also seen in the spectra due to the up and down detectors separately. All these tests have not revealed any experimental problem.

Although there may still be doubts about the statistical significance of the structure, it is remarkable that it occurs at a momentum of 495 MeV/c² or 1936 MeV/c², which is just the value of the S meson. In Fig. 8 a comparison of the new result (spectrum E)

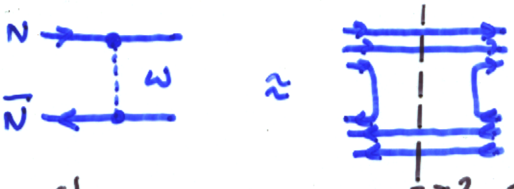


"S(1936)"

("Γ~4 MeV")

Fig. 8. Comparison of several recent annihilation spectra: A (Ref. 7), B (Ref. 8), C (Ref. 6), D (Ref. 5), E (this work). The spectra have been shifted by: A, +20 mb; B, +10 mb; C, 0 mb; D, -10 mb; E, -20 mb. The spectrum E is the same as in Fig. 5 multiplied by a factor of 4.3 (see text).

narrow baryonia ∃ ?



strong
attraction
if ω-ex.
is real effect.

$q^2\bar{q}^2$ "baryonia"

many states predicted

may be narrow. (may be ☺)

31 Mar – 9 Apr 1984
Erice

2 years later

Fundamental Interactions in Low-Energy Systems

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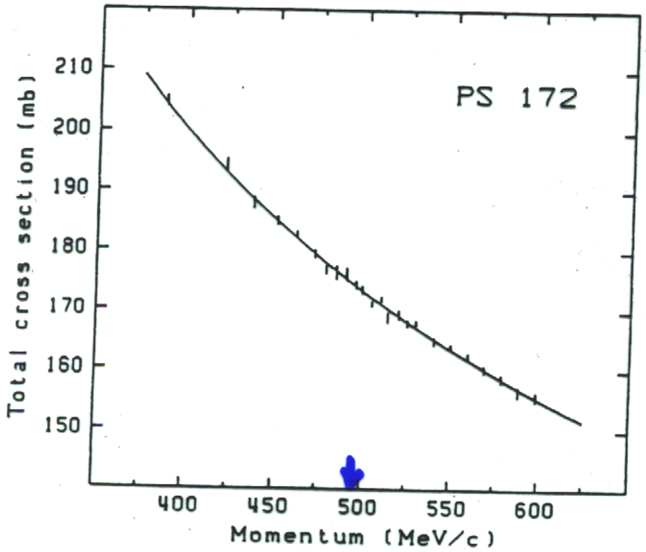
Plenum Press • New York and London

F. Bradamante
Erice '84



no
S(1936)

Fig. 3. Total cross-section as a function of laboratory momentum fitted by a function (a + b/p) where a = 65.78 (± 1.71), b = 53759 (± 845). $\chi^2 = 40.9$

"narrow baryonia"
did not survive LEAR

Madison 85

LOW ENERGY ANTIMATTER

Proceedings of the Workshop on the Design of a
Low Energy Antimatter Facility held at the University
of Wisconsin-Madison, October, 1985

Edited by

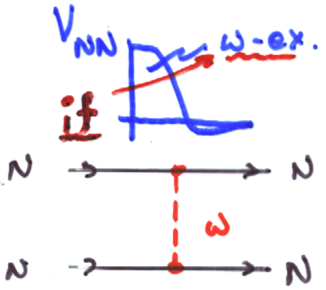
David B. Cline

World Scientific

C. Dover
Madison '85

high intensity low energy $\bar{p}$ facility, with a capability for polarized beams and targets, would shed light on a variety of fundamental questions.

RELATION BETWEEN NN AND N$\bar{\text{N}}$ INTERACTIONS



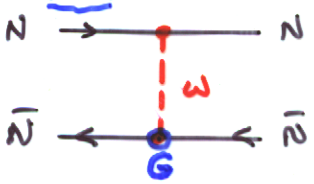
The connection between the meson exchange contribution to the NN and N$\bar{\text{N}}$ potentials (real, non-annihilation part) is provided by the G-parity rule. Given an interaction potential

$$V_{NN} = \sum_i V_i \tag{1}$$

for the nucleon-nucleon (NN) system, where i labels the contribution of any meson exchange ($i = \{\pi, \eta, \rho, \omega, \delta, \varepsilon \ldots\}$), the corresponding potential $V_{N\bar{N}}$ is given by

$$V_{N\bar{N}} = \sum_i G_i V_i \, , \tag{2}$$

then



↳ deeply bound states

where G_i is the G-parity of meson i. In coordinate space, the potentials V_i have the form

$$V_i = \left(\begin{matrix}1\\ \underset{\sim}{\tau}_1 \cdot \underset{\sim}{\tau}_2\end{matrix}\right) \cdot \left(V_0^i + V_\sigma^i \, \underset{\sim}{\sigma}_1 \cdot \underset{\sim}{\sigma}_2 + V_{LS}^i \, \underset{\sim}{L} \cdot \underset{\sim}{S} + V_T^i S_{12} + V_{LS2} Q_{12}\right) \tag{3}$$

corresponding to isoscalar (1) or isovector ($\tau_1 \cdot \tau_2$) exchanges. The tensor and quadratic spin orbit operators S_{12} and Q_{12} have the well known form

$$\begin{aligned} S_{12} &= 3\underset{\sim}{\sigma}_1 \cdot \hat{r} \;\; \underset{\sim}{\sigma}_2 \cdot \hat{r} \; - \underset{\sim}{\sigma}_1 \cdot \underset{\sim}{\sigma}_2 \\ Q_{12} &= 1/2 \; (\underset{\sim}{\sigma}_1 \cdot \underset{\sim}{L} \;\; \sigma_2 \cdot \underset{\sim}{L} + \underset{\sim}{\sigma}_2 \cdot \underset{\sim}{L} \;\; \underset{\sim}{\sigma}_1 \cdot \underset{\sim}{L}) \end{aligned} \tag{4}$$

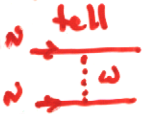
where $\underset{\sim}{L}$ is the relative orbital angular momentum and $\underset{\sim}{S} = (\underset{\sim}{\sigma}_1 + \underset{\sim}{\sigma}_2)/2$ is the total intrinsic spin.

The apparently innocent phase factor $G_i = \pm 1$ produces an N$\bar{\text{N}}$ potential which is qualitatively different from that for the NN case. The key concept[1] is coherence, namely the tendency for all mesons i to yield a contribution of the same sign to certain components of the interaction. For the NN system, scalar (ε) and vector (ω) meson exchange add coherently in the spin orbit term V_{LS}, while they tend to cancel in the central part V_0. Pseudoscalar (π) and vector (ρ) contributions appear with like signs in V_σ and opposite signs in V_T. The coherent spin-orbit potential is evident in NN scattering, for instance, the zero in the $^3P_0$ phase shift is due to the short range coherent and repulsive V_{LS} (which gives δ<0) competing against the long range attraction arising from π exchange (which alone leads to δ>0).

... iff meson ex. is realistic at $r_{NN} \sim \frac{1}{m_\omega} \sim 0.2$ fm.
A good question!

For N$\bar{\text{N}}$, in contrast, coherences occur in the central (ω+ε), tensor (π+ρ) and quadratic spin-orbit potentials. The very strong N$\bar{\text{N}}$ attraction due to V_0 leads one to predict a number of bound states[1], ~~most of which are~~ expected to be very broad and difficult to observe. The coherent tensor force for N$\bar{\text{N}}$ has several striking consequences for spin observables, which we discuss later. To summarize, although

Isgur '99
Hard to tell



from

expected after the LEAR experiments!

(some did say this before "fall-apart decays")

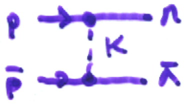
('84)
Isgur : ω exchange is unphysical.

ψ_{3q} wfns. overlap.

$r_{NN} \approx 0.2$ fm $= 1/m_V$

∴ Heavy vector meson ex. is an inaccurate picture.
Should involve qdq.

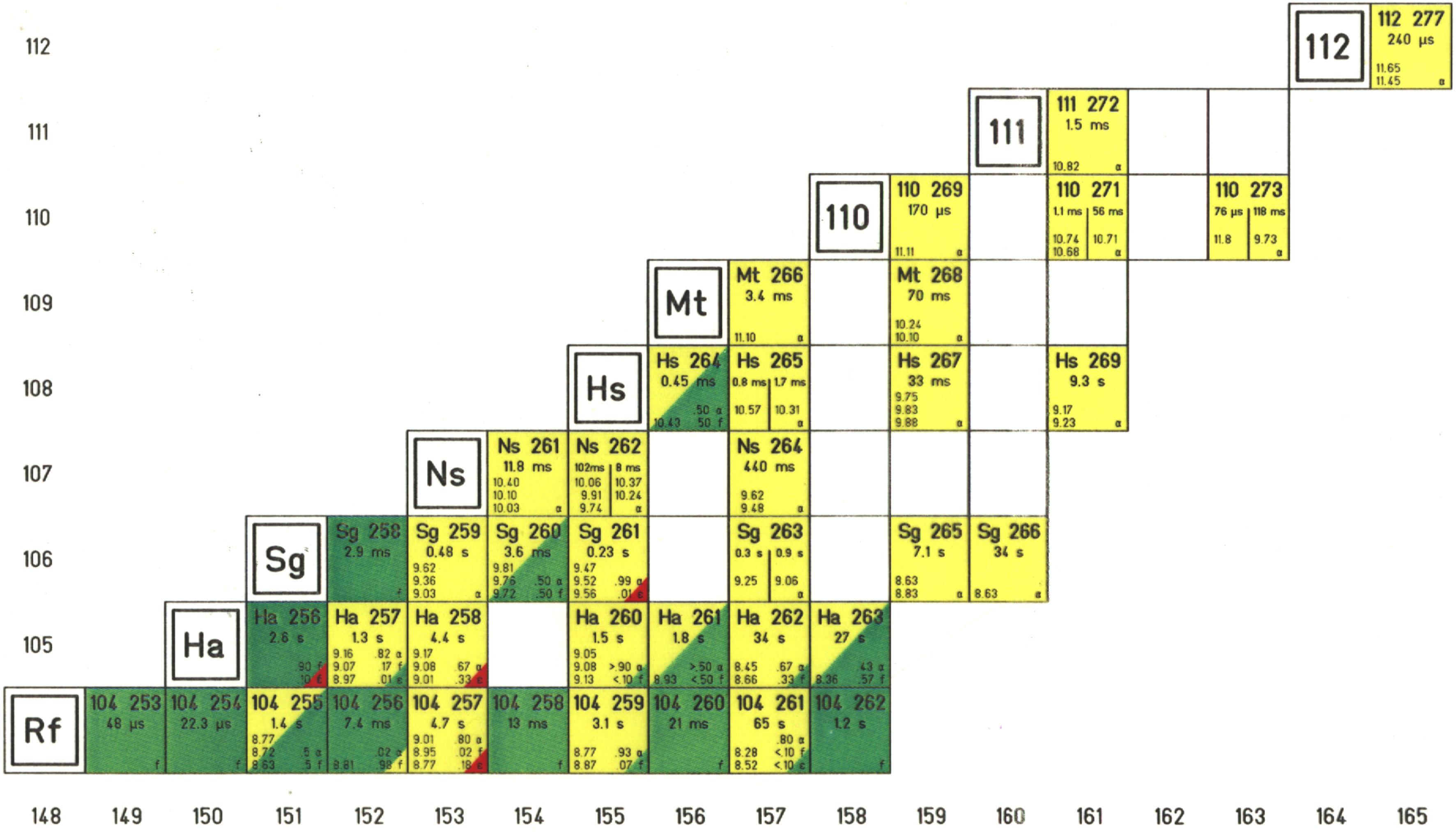
However, deSwart (94) argues
$p\bar{p} \to \Lambda\bar{\Lambda}$ data looks just like K ex!



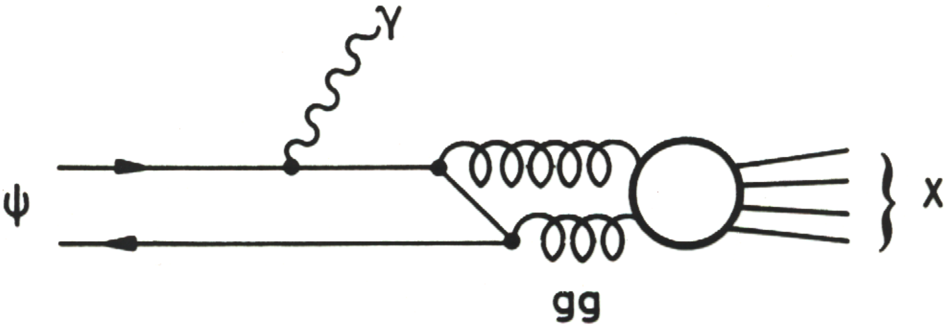
→ read off m_K from t-dep.

molecules <u>are</u> well established.

here are a few...



Ancyent glueballs (late 1970s : ψ radiative decays)
- early 1980s



scan M_X
in specific
hadronic
final state

Figure 9. Two-gluon intermediate states in $\phi\to X\gamma$.

A theoretical analysis of the $\phi\to\gamma gg$ Feynman diagram [17] leads one to expect the production of $J^P=2^{++}$ tensor mesons as well as 0^{++} an 0^{-+} scalars and pseudoscalars. One generally scans specific final states X in $\phi\to X\gamma$ for prominent resonances in M(X) which do not correspond to known $q\bar{q}$ states. States thus far identified have all been $J^{PC}=2^{++}$ or 0^{-+}; their measured branching fractions in $\phi\to X\gamma$ are shown in figure 10.

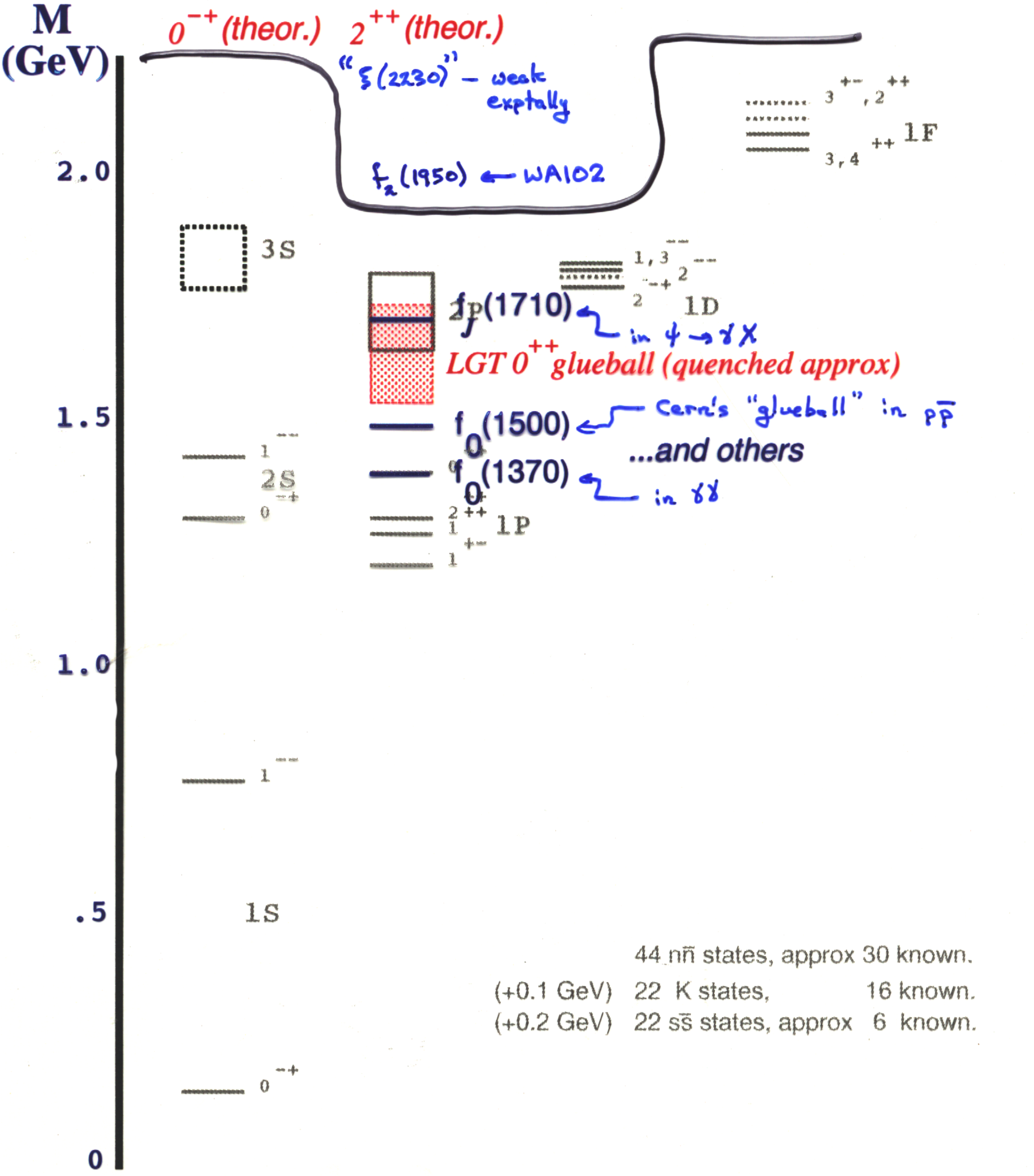
[17] = R. Lacaze & H. Navelet, Nucl. Phys. B186, 247 (1981).
2^{++} dominant, some $0^{\pm +}$

Prominent states seen in $\psi\to\gamma X$:

η η' f_2 ... and

glueballs   no exotics ≲ 4 GeV (LGT)

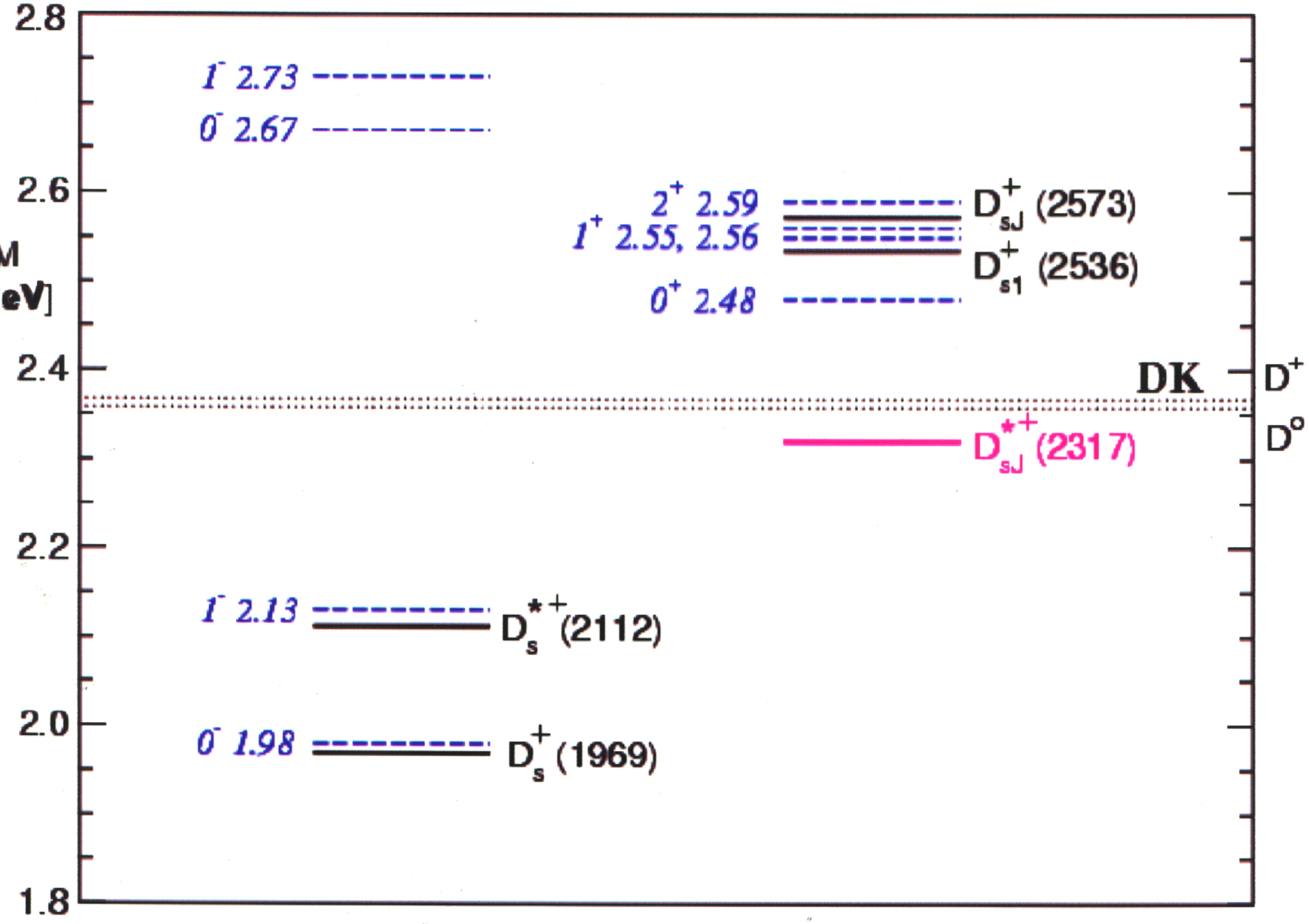
Schematic light $q\bar{q}$ spectrum to approx 2.1 GeV.



44 $n\bar{n}$ states, approx 30 known.

(+0.1 GeV) 22 K states, 16 known.

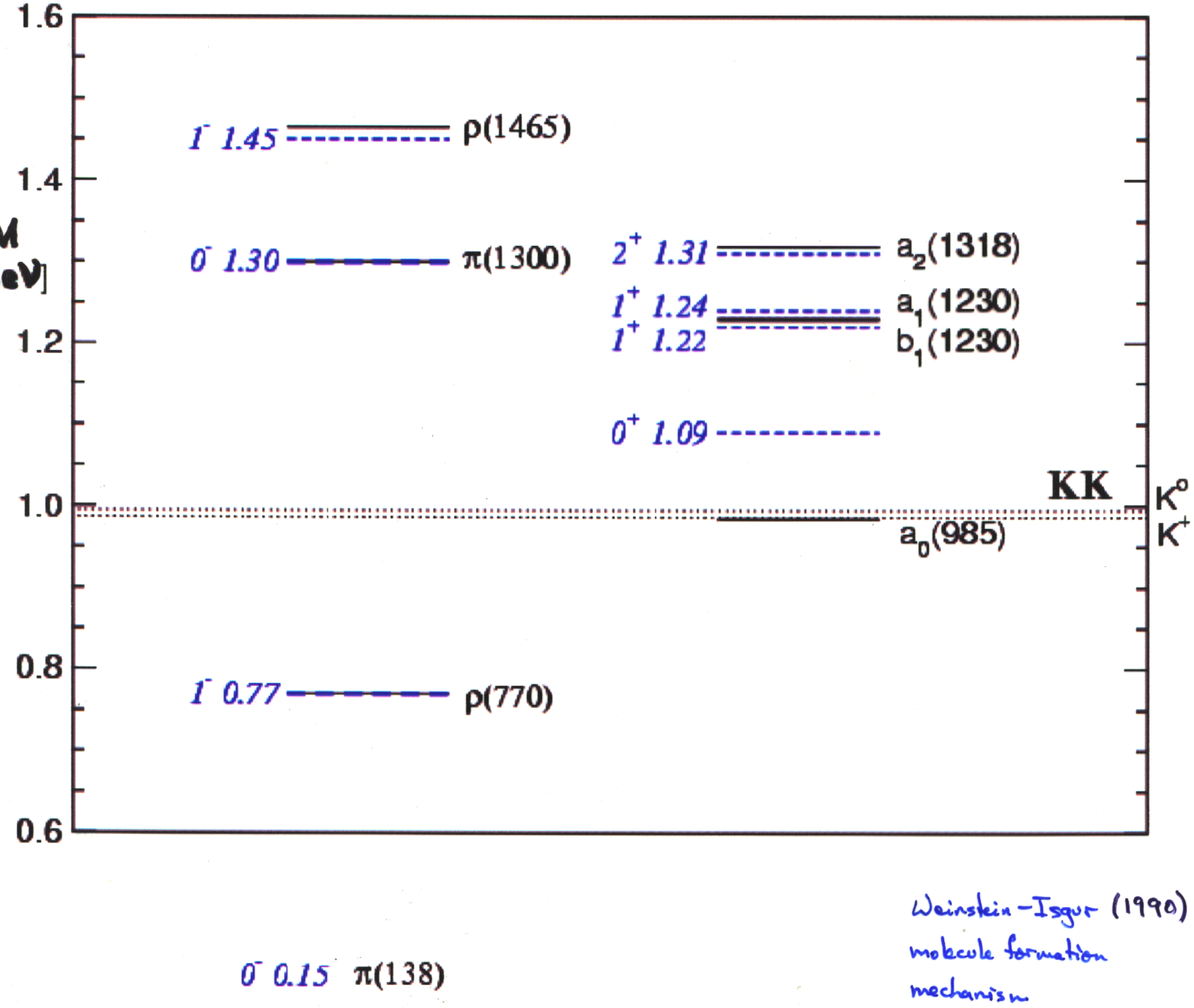
(+0.2 GeV) 22 $s\bar{s}$ states, approx 6 known.



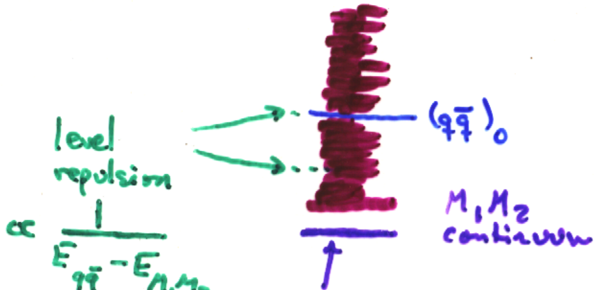
A DK molecule ?

Barnes, Close & Lipkin

hep-ph/0305025



Weinstein–Isgur (1990)
molecule formation
mechanism



"molecule" bound state
separates

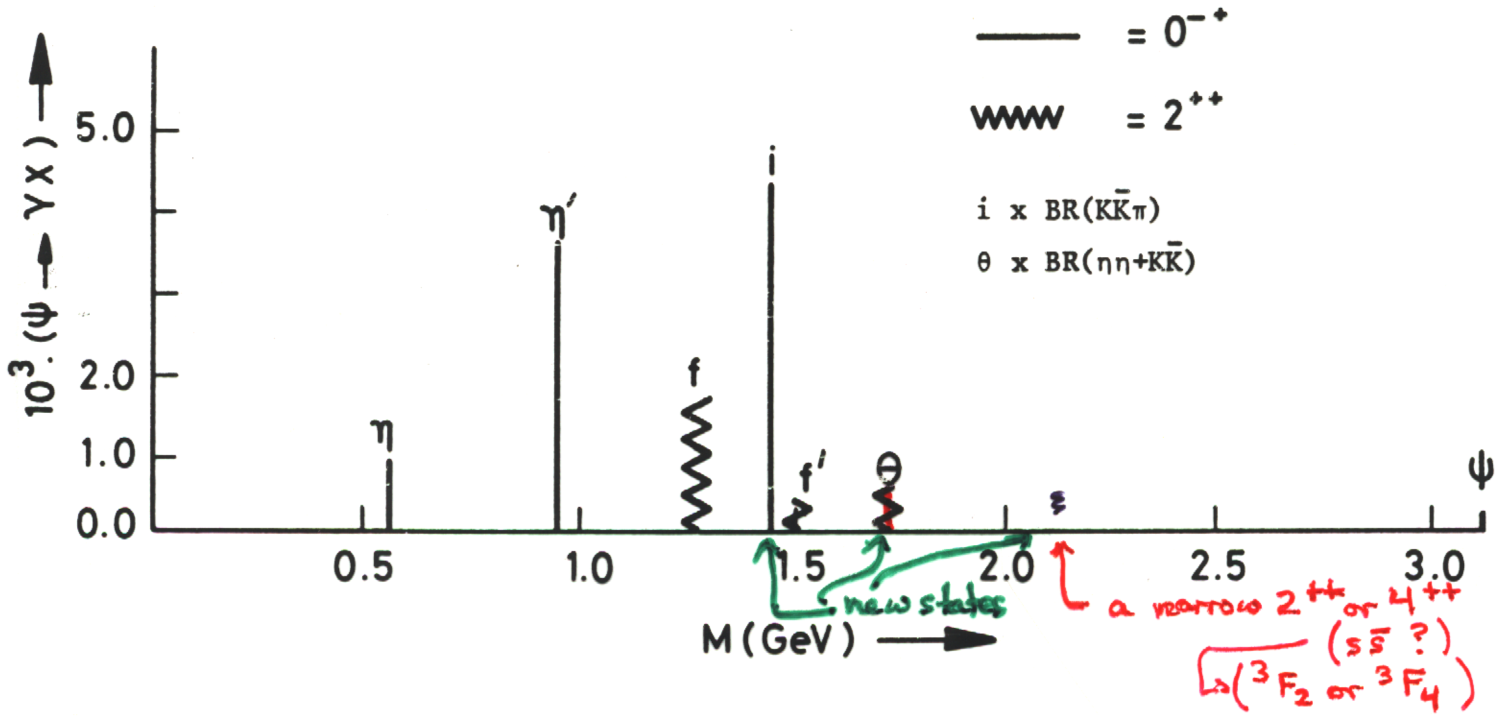


Figure 10. Identified resonances in psi radiative decays.

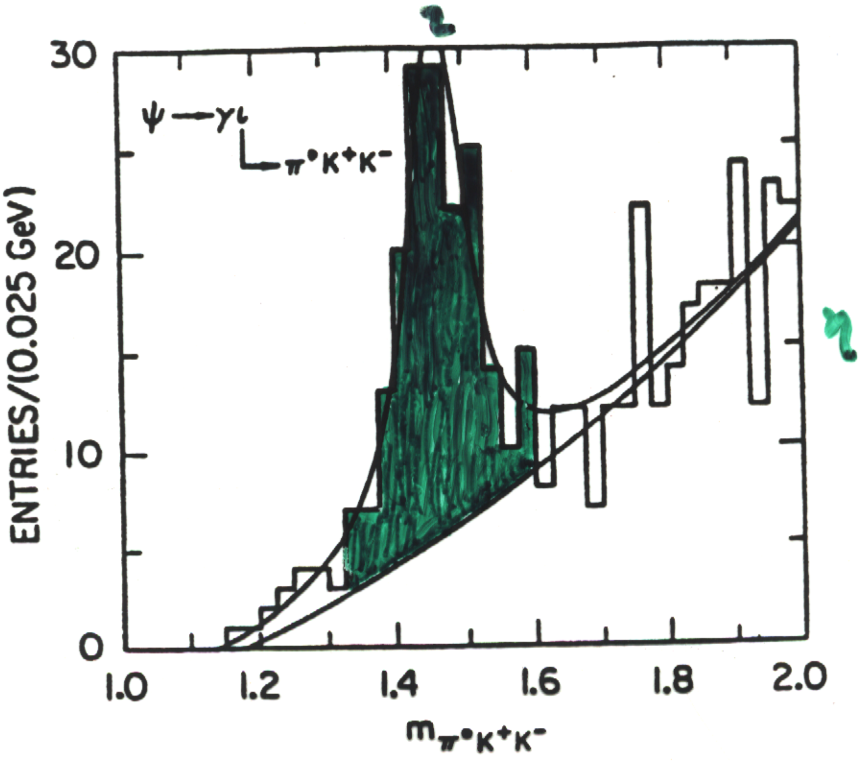
$\eta(1440)$ $f_0(1710)$

The two surprises are the large signals from the iota and theta, which had not been clearly identified before. In summary, their properties are

J^{PC}	Mass (Mev)	Width (Mev)		Final States and Comments	
$i(0^{-+})$ $\eta(1440)$	1440±10 1440 (20)	76 ±10 60 (30)	PDG 1990	$K\bar{K}\pi$ $\eta\pi\pi$(?) $\gamma\rho$(?)	May be $(q\bar{q})_R$, $q\bar{q}g$ or ~~gg~~.
θ(~~2++~~) 0^{++} (1990!) MIII $f_{\cancel{2}\,0}(1720)$	1690±30 1713^{+2}_{-5}	180 ±50 138^{+12}_{-9}	PDG 1990 J=0 not 2 1990, 1991 Mark III reanalysis	$\eta\eta$ $K\bar{K}$ $\pi\pi << \eta\eta$, $K\bar{K}$, so is [illegible] $f_R(q\bar{q})$.	

First thought this was the 1^{++} E(1420), now $f_1(1420)$.
Funny quantum numbers for a glueball!
M. Chanowitz PRL 46, 981 (1981) suggested $J^{PC} = 0^{-+}$ + glueball possibility.
More careful J^{PC} study → 0^{-+}! (In 1963 E(1420) had appeared to possess both 1^{++} and 0^{-+} components.)

In the early 1980s these masses looked plausible for $0^{-+}(1440)$, $2^{++}(\sim1700)$ glueballs.



$\eta(1440)\ 0^{-+}$

$\pi^0 K^+ K^-$

Fig. 22. The ι(1440) in $\pi^0 K^+ K^-$ at Mark III [53].

[53] W. Toki, SLAC-PUB-3262 (1983).

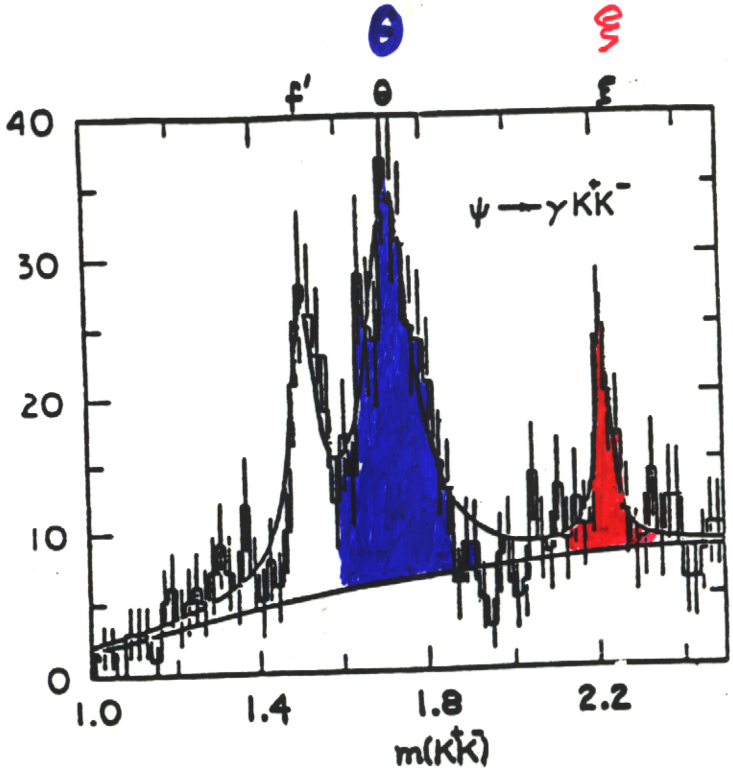


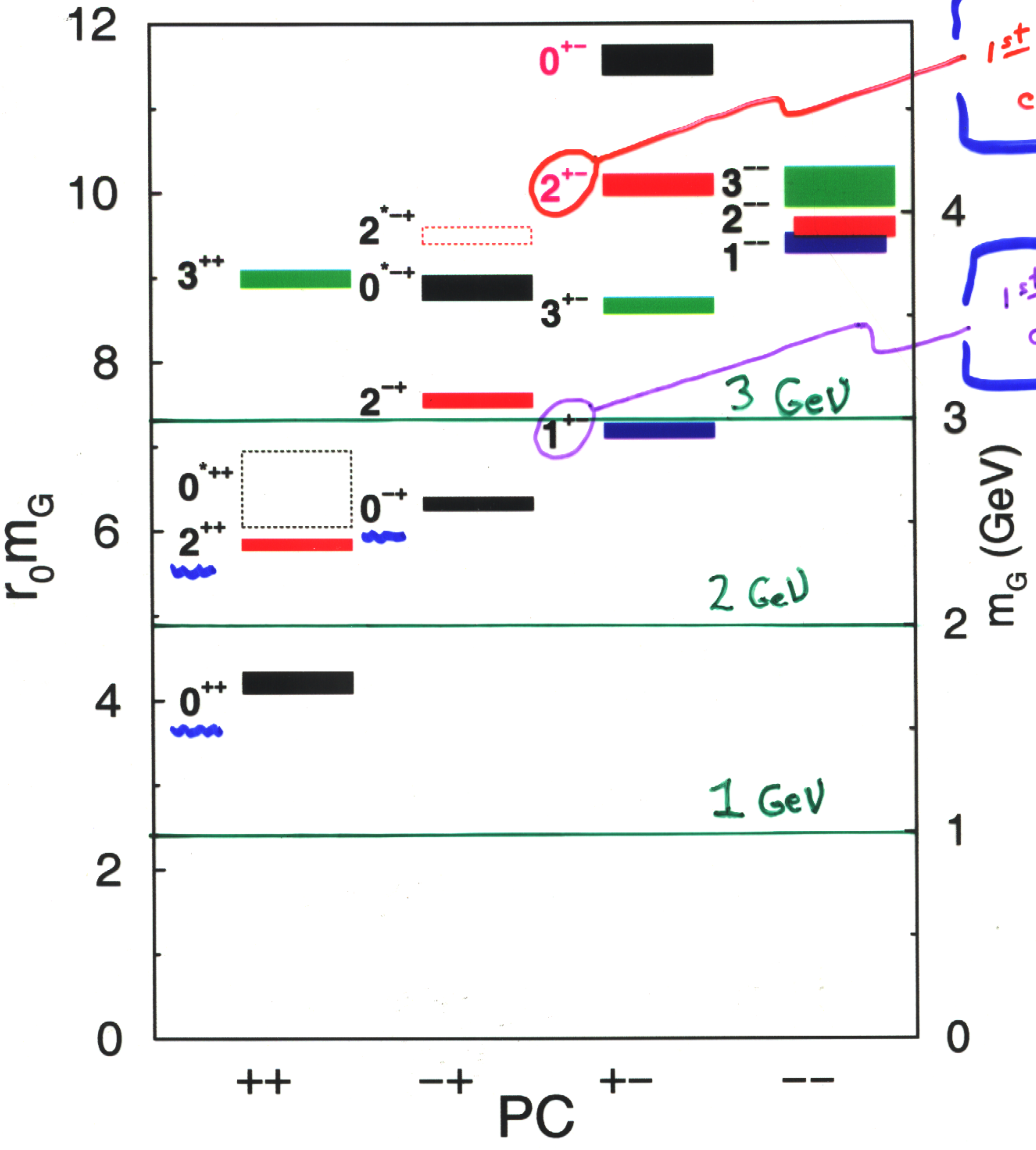
Fig. 28. The ξ(2220) meson in $\psi \to \gamma\xi, \xi \to K^+K^-$ at Mark III [53].

$f_{0(2)}(1710)$

ξ(2230)
2^+? 4^+? ~~$s\bar{s}$~~?
∃ ? ∄!

C. Morningstar & M. Peardon
hep-lat/9901004 v2

LGT glueball spectrum



1st J^{PC} exotic
ca. 4 GeV !

1st C=(−) glueball
ca. 3 GeV

0^{-+}
2^{++}

0^{++}

HEP 83

Rutherford
Appleton
Laboratory

PROCEEDINGS OF HEP83

International Europhysics Conference
on High Energy Physics

Brighton (UK), 20–27 July, 1983

Editors
J. Guy
C. Costain

Organised by the Rutherford Appleton Laboratory

Sponsored by the Science and Engineering Research Council and the
European Physical Society

LGT, 1983

I. Halliday
Brighton '83

Here as above the $m_G \cdot a$ is found from

$$(m_G \cdot a)(\beta) = \ln \frac{F(t)}{F(t+1)}$$

The operators $\hat{O}$ are loops of various shapes and sizes up to size 8 bonds. Then the $m_G \cdot a$ is measured at two values of $t = 1, 2$. These are not large compared to the loops. The systematic shift down from $t = 1$ to 2 is worrying. The calculation of Ishekawa et al [10] is shown below. Here the "constant" $m_G(\beta)$ is presented for both 0^{++}, 2^{++} states on a $4^3 \times 8$ lattice.

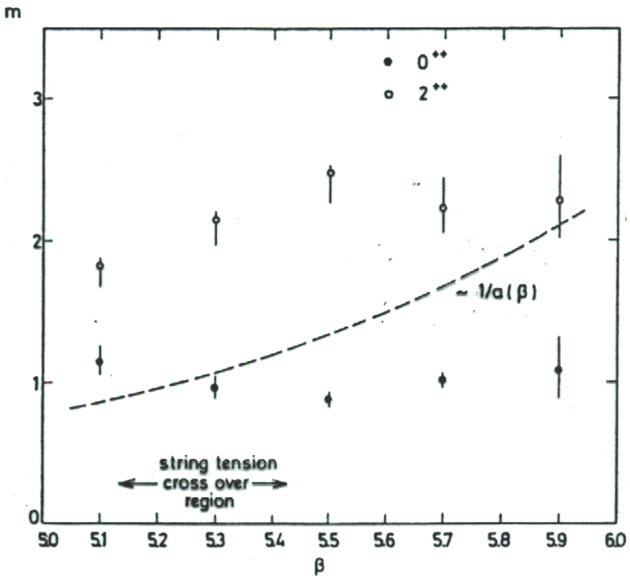


fig. 5

LGT
glueball spectrum

The only check on being near the continum limit is the constancy of these graphs over some restricted β range.

Taking $\sqrt{K} = (1/2\pi\alpha)^{1/2} \sim 400$ MeV gives a glueball spectrum of

$M(0^{++}) = 740 \pm 40$ MeV

$m(0^{++}) = 740 \pm 40$ MeV   Scaling check

$m(0^{-+}) = 1420 \pm {}^{240}_{170}$ MeV

$m(2^{++}) = 1620 \pm 100$ MeV   Scaling check

$M(1^{-+}) = 1730 \pm 220$ MeV

$m(0^{--}) = 2880 \pm 300$ MeV

error?

br input

0^{-+} 1420^{+240}_{-170}

2^{++} 1620 ± 100

By playing with loop sizes they expect the glueball diameter to be ~ .5 fermi. while from their Wilson loop measurements and $\sqrt{K} \sim 400$ MeV their lattice (4a) is ~ 1 fermi across. The value of a(5.7) = .27 Fermi while a(6) = .19 fermi using their own string tension measurement.

These are substantially different from the lattice spacings measured in

expt "$\iota(1440)$" 0^{-+}
"$\theta(1640)$" 2^{++}

now $\eta(1440)$
$f_0(1710)$

$\psi \to \gamma X$

Physics Letters B 323 (1994) 233–241
North-Holland

PHYSICS LETTERS B

Observation of two $J^{PC} = 0^{++}$ isoscalar resonances at 1365 and 1520 MeV

Crystal Barrel Collaboration

V.V. Anisovich [h,1], D.S. Armstrong [a], I. Augustin [g,2], C.A. Baker [d], B.M. Barnett [i], C.J. Batty [d], K. Beuchert [b], P. Birien [a], P. Blüm [g], R. Bossingham [a], K. Braune [k], J. Brose [j], D.V. Bugg [h], M. Burchell [e,3], T. Case [a], A. Cooper [h], K.M. Crowe [a], T. Degener [b], H.P. Dietz [k], M. Doser [e], W. Dünnweber [k], D. Engelhardt [g], M. Englert [k], M.A. Faessler [k], C. Felix [k], G. Folger [k,4], R. Hackmann [j], R.P. Haddock [i], F.H. Heinsius [f], N.P. Hessey [e], P. Hidas [c], P. Illinger [k], D. Jamnik [k,5], Z. Jávorfi [c], H. Kalinowsky [j], B. Kämmle [f], T. Kiel [f], J. Kisiel [k,6], E. Klempt [j], M. Kobel [e,7], H. Koch [b], C. Kolo [k], K. Königsmann [k,8], M. Kunze [b], R. Landua [e], J. Lüdemann [b], H. Matthäy [b], M. Merkel [j,3], J.P. Merlo [j], C.A. Meyer [ℓ], L. Montanet [e], A. Noble [e], K. Peters [b], C.N. Pinder [d], G. Pinter [c], S. Ravndal [b], J. Salk [b], A.H. Sanjari [h,9], A.V. Sarantsev [h,1], E. Schäfer [j], B. Schmid [e,10], P. Schmidt [f], S. Spanier [j], C. Straßburger [j], U. Strohbusch [f], M. Suffert [m], C. Völcker [k], F. Walter [j], D. Walther [j], U. Wiedner [f], N. Winter [g], J. Zoll [e] and B. Zou [h]

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Crystal Barrel expt.
LEAR at CERN

$p\bar{p} \to \pi^0\pi^0\pi^0$

$p\bar{p} \to \eta\eta\pi^0$

Received 20 December 1993
Editor: K. Winter

$f_0(1500)$ CHLS '95

From a simultaneous analysis of data on $\bar{p}p \to \pi^0\pi^0\pi^0$ and $\bar{p}p \to \eta\eta\pi^0$ at rest, two $I = 0$, $J^{PC} = 0^{++}$ resonances are identified above 1 GeV. The first has mass $M = 1365^{+20}_{-55}$ MeV and width $\Gamma = 268 \pm 70$ MeV, close to the $f_0(1400)$ of the Particle Data Group. The second has $M = 1520 \pm 25$ MeV, $\Gamma = 148^{+20}_{-25}$ MeV.

---

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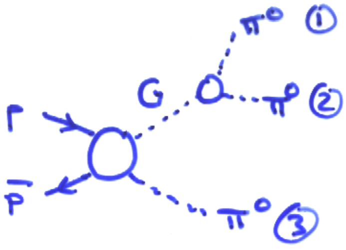
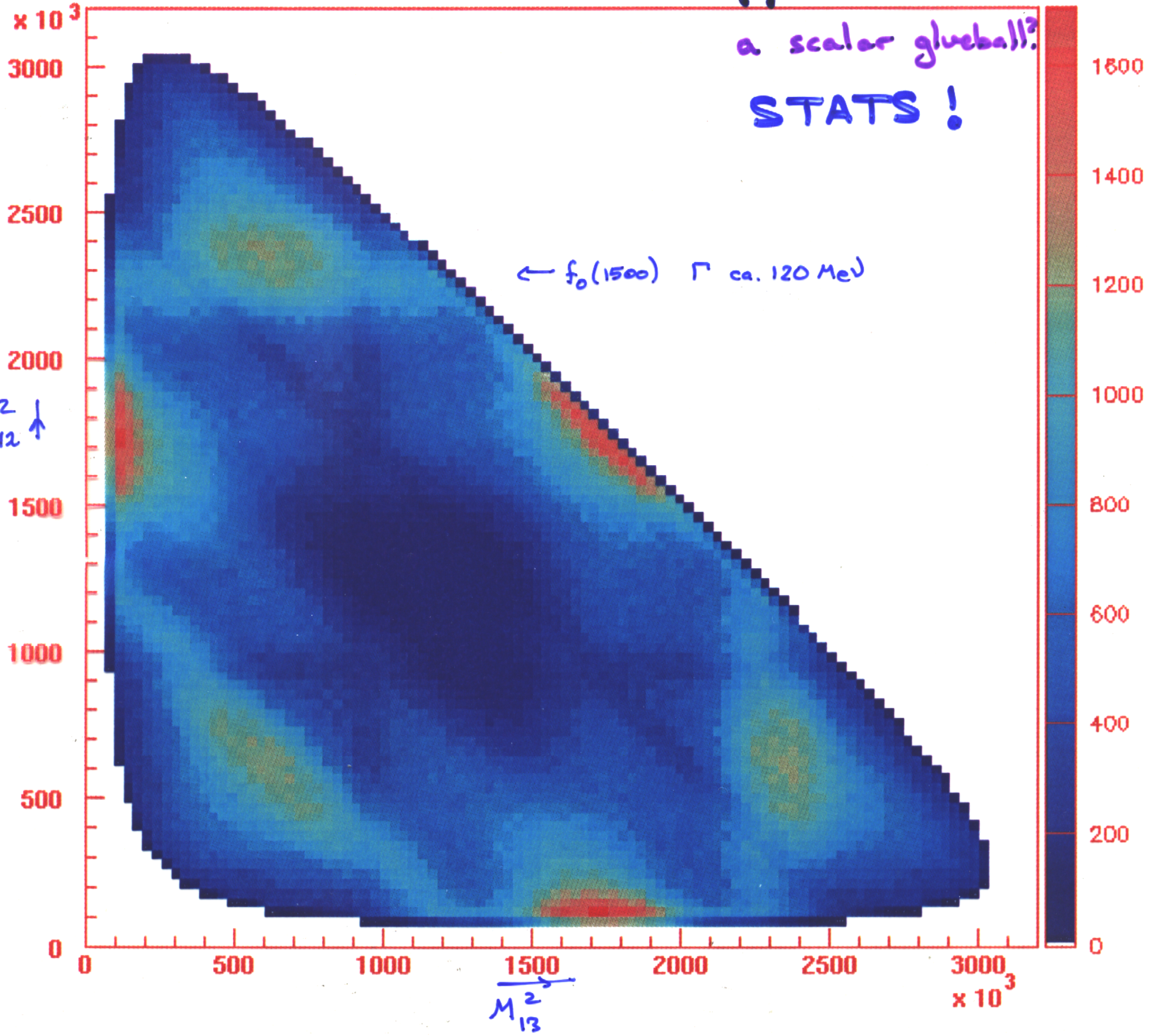
SSDI 0370-2693(94)00123-O



ca. 0.5M events
(high stats was the trick)

Crystal Barrel @ LEAR @ CERN

$p\bar{p} \to \pi^0\pi^0\pi^0$



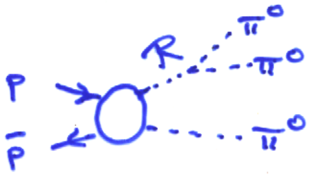
a scalar glueball?

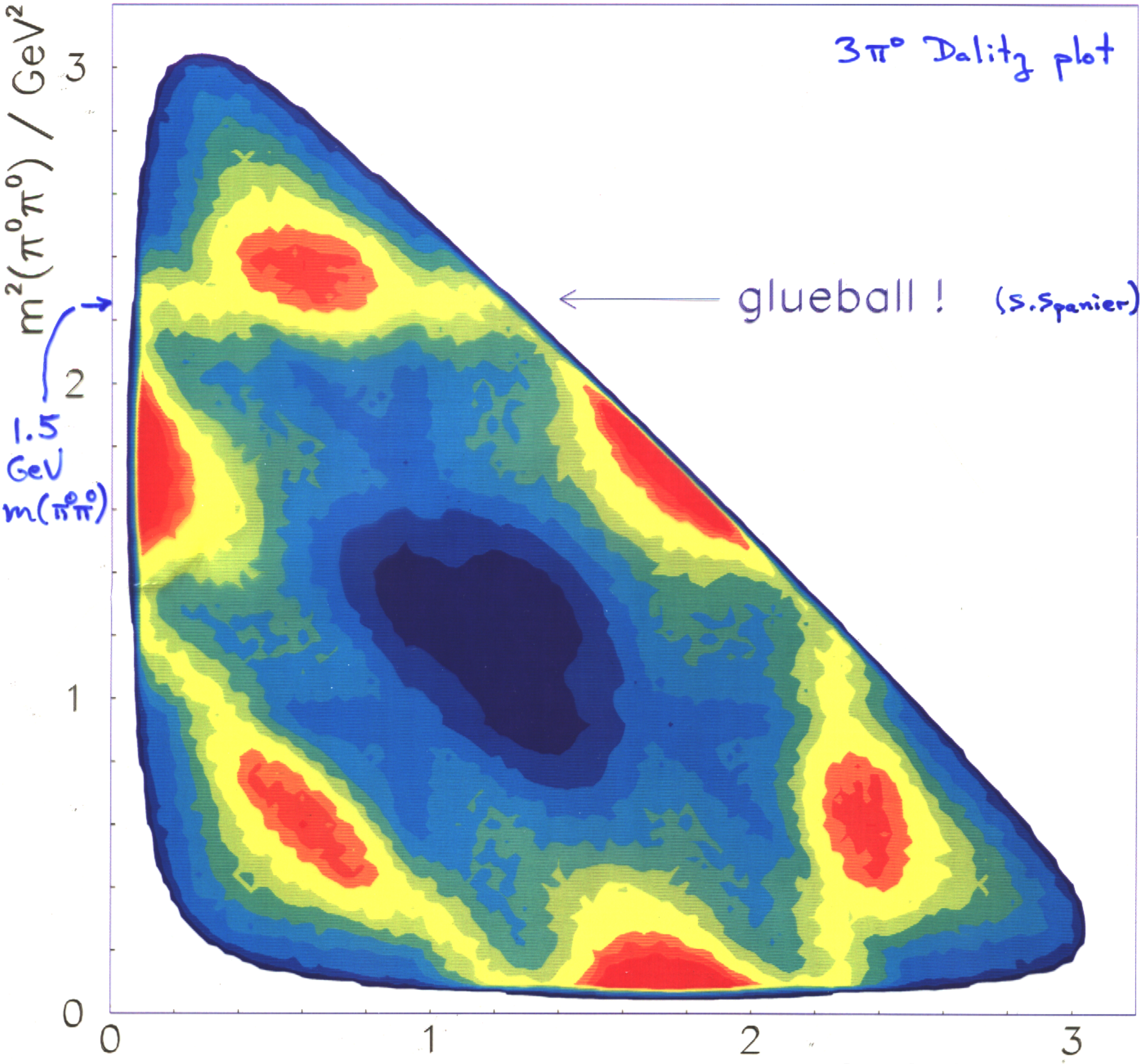
STATS !

← $f_0(1500)$ Γ ca. 120 MeV

Crystal Barrel web site

CMU

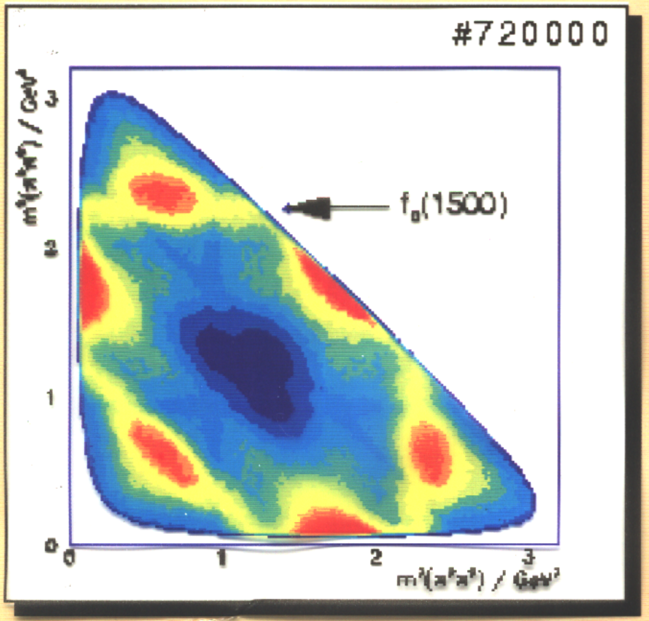




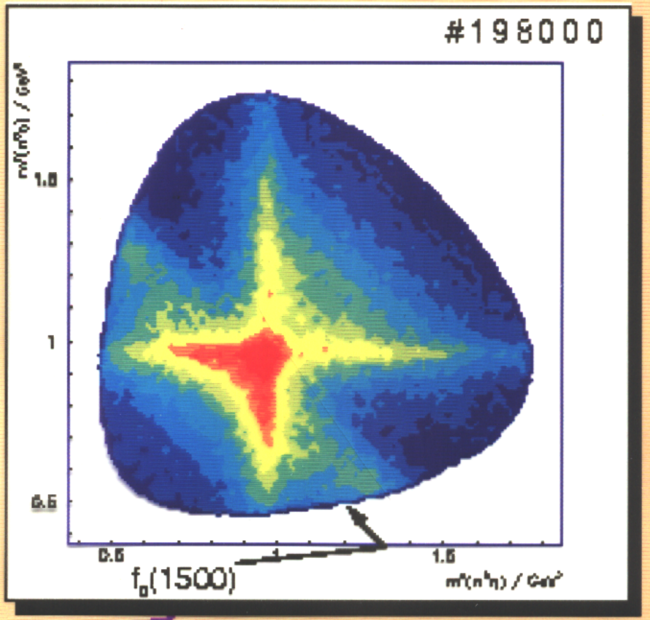
Crystal Barrel

Search for the scalar groundstate glueball with the Crystal Barrel detector at LEAR of CERN.

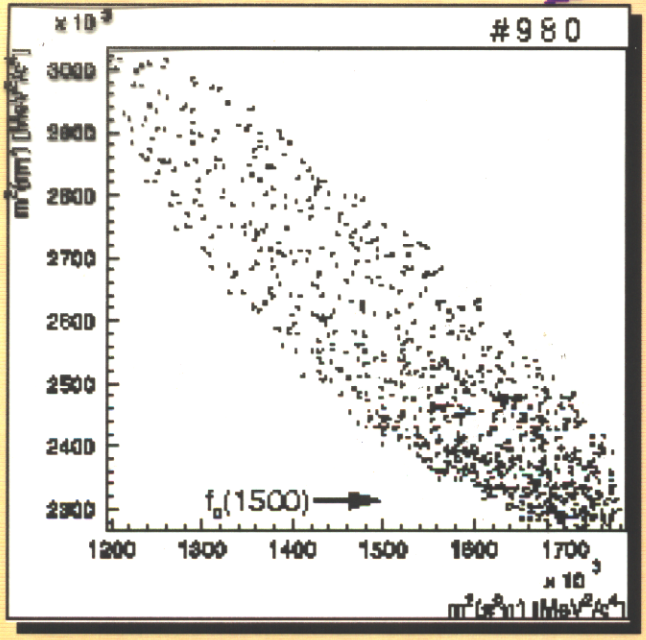
$p\bar{p} \rightarrow 3\pi^0 \rightarrow 6\gamma$



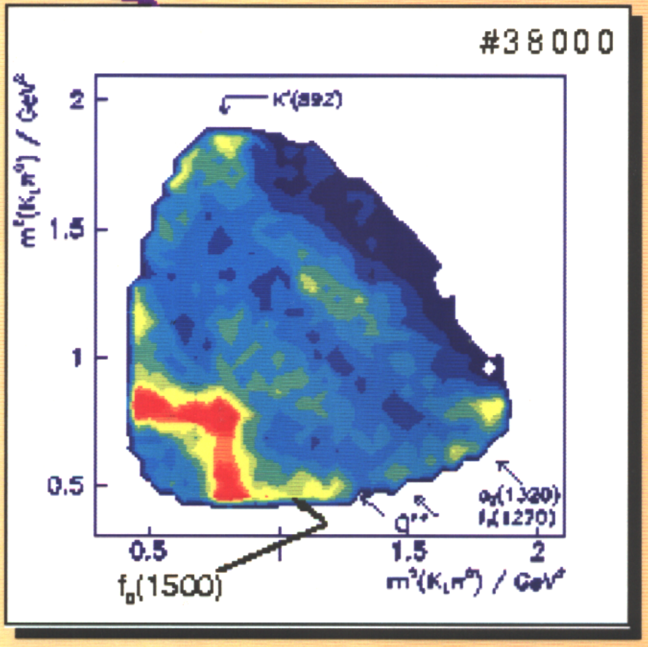
$p\bar{p} \rightarrow \pi^0\eta\eta \rightarrow 6\gamma$



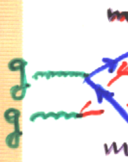
$p\bar{p} \rightarrow f_0(1500)\,\pi^0$



$p\bar{p} \rightarrow \pi^0\eta\eta' \rightarrow 6\gamma$



$p\bar{p} \rightarrow K_L K_L \pi^0 \rightarrow 3\gamma$

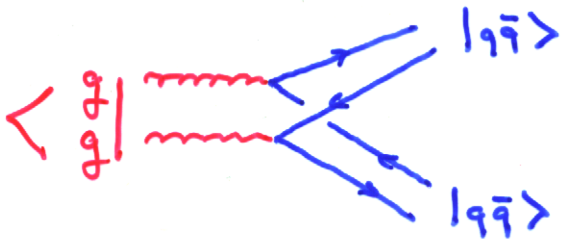


relati
decay
probabil
to
$\pi\pi : \eta$
$: K\bar{K}$

oops!

The problem with both f_0 glueball candidates:

they don't decay like flavor $\underset{\sim}{1}$.



$\Gamma_i = |A|^2 \cdot \text{p.s.}$

	$\|A\|^2$	$\pi\pi$	$K\bar{K}$	$\eta\eta$	$\eta\eta'$	$\eta'\eta'$
flavor $\underset{\sim}{1}$	$\pi^0\pi^0 \equiv 1$	3	4	1	0	1

Expt. observed partial widths or b.f.s :

	$\pi\pi$	$K\bar{K}$	$\eta\eta$			4π "$\sigma\sigma$",ρ
$f_0(1500)^{\dagger}$	29.0(7.5)%	3.5(.3)%	4.6(1.3)%	1.2(.3)%	–	61.7(9.6)%
$f_0(1700)^{\dagger}$	$3.9^{+.2}_{-2.4}$%	38^{+9}_{-19}%	18^{+3}_{-13}%			

Possibly an "η-η'" system with large $n\bar{n} \leftrightarrow G \leftrightarrow s\bar{s}$
Zweig-viol. mixing

$f_0(1700)$
$f_0(1500)$
$f_0(1300)$

large for 0^{-+} and 0^{++}

Both Weingarten and Close-Amsler have described 3-state mixing models like this.

LGT future → 4π?
$q\bar{q} \leftrightarrow G$ mixing

† C.Amsler RMP 70, 1293 ('98).

† PDG98

Weingarten LGT

0^{++}

reduced coupling vs m_{ps}.

∴ intrinsic $G - \overset{Ps}{q\bar{q}}\,\overset{Ps}{q\bar{q}}$ couplings may be strongly m_q-dependent.

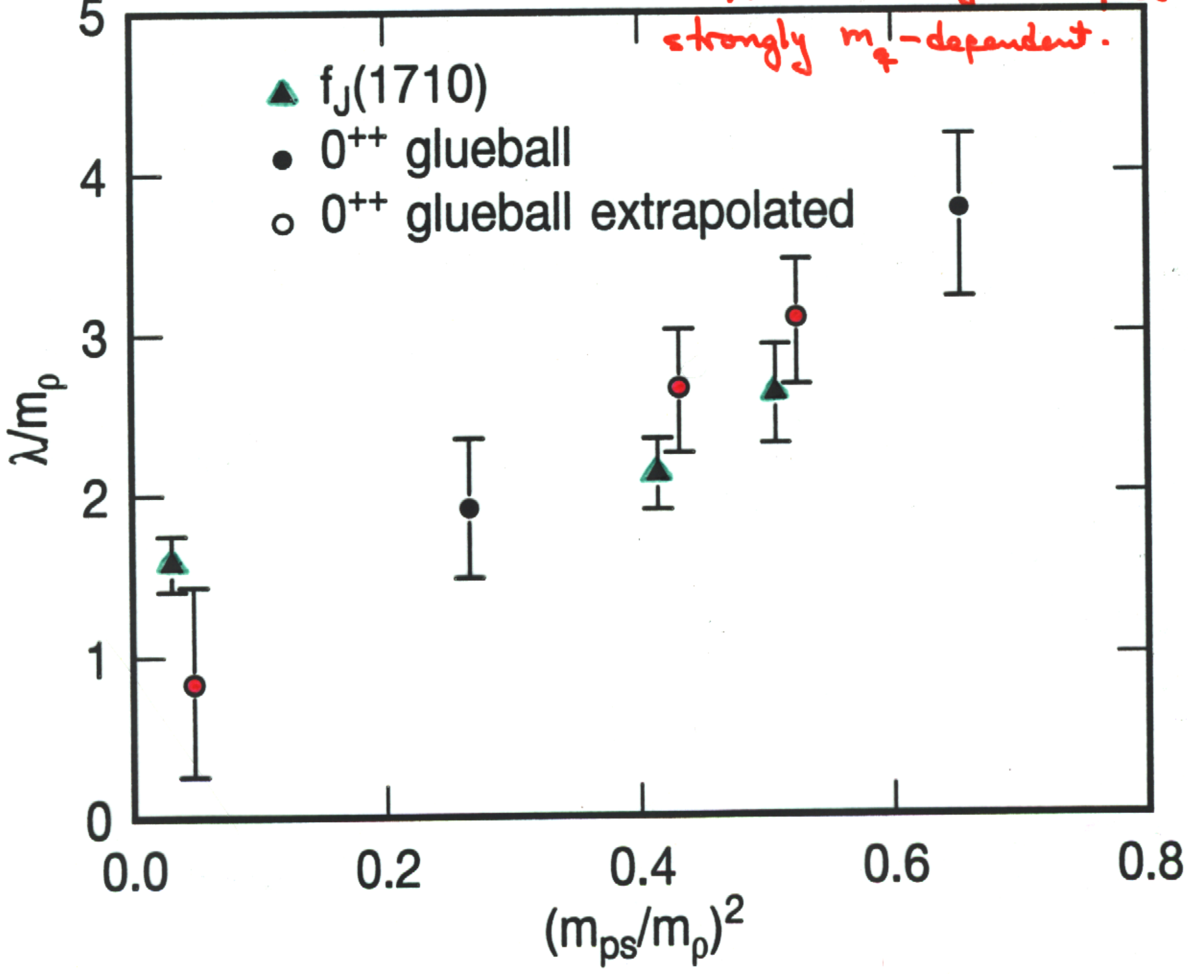
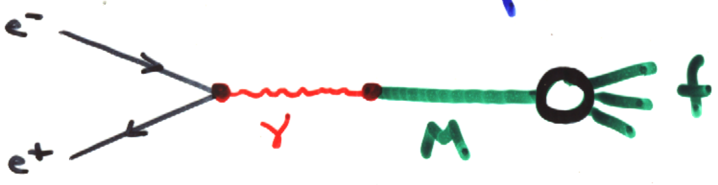


Figure 1: Decay couplings.

Hadrons at e^+e^- Machines

SLAC, DESY, CESR, future DAPHNE, B-factory
BEPC, ~~LEP~~, KEK

The obvious way



Restrictions: $J^{PC}(M) = 1^{--}$ only study vectors

2 EM vertices: $\sigma \propto \alpha^2/s$

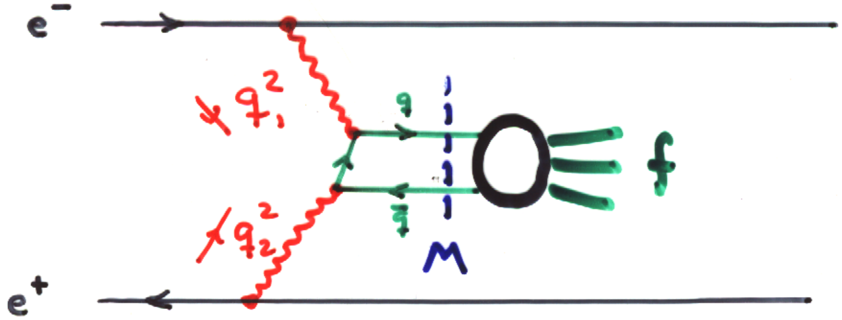
$\uparrow$
γ prop.

$\psi \rightarrow \gamma X$
$\rightarrow$ hadrons

$\phi \rightarrow \gamma a_0, \gamma f_0, \ldots$
$\rightarrow K\bar{K}$

ρ, ω + excitations

The less obvious way



"two-photon physics"

idea due to F. E. Low
PR120, 582('60)
(e^-e^-)

Restrictions: $C = (+)$

$q_1^2 = q_2^2 = 0$ $\quad J^{PC} = 0^{\pm +}\ 2^{\pm +}\ 3^{\pm +}\ 4^{\pm +} \ldots$

Many interesting states!
(No exotics.)
(1^{-+} if $q_i^2 \neq 0$)

$\lambda_{\gamma\gamma} = 0, 2$ for even^{++}

4 EM vertices! Ouch! $\sigma \propto \alpha^4$. Stats problem.

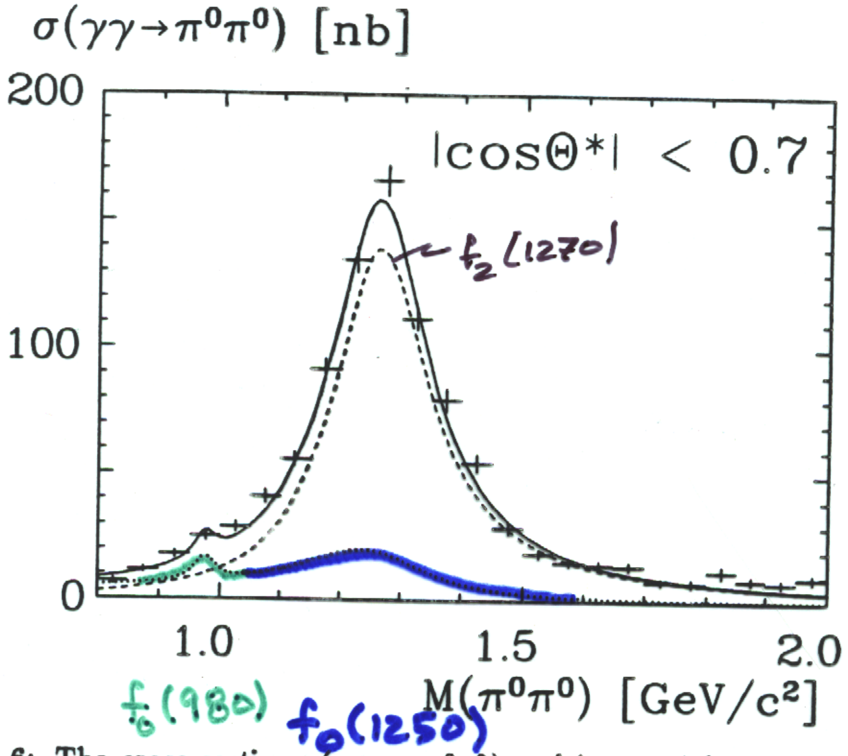
$$\boxed{\sigma(e^+e^- \rightarrow e^+e^- f) = \text{[illegible]} \cdot \overset{(2J_M+1)}{\downarrow} \cdot \underbrace{\Gamma(M \rightarrow \gamma\gamma)}_{\text{Physics from quark model.}} \cdot B_{M \rightarrow f}}$$

$q_i^2 \approx 0$

You don't want to know.

H. Bienlein
Phot-Phot Worksh
San Diego (1992)

X Ball



$\Gamma^{thy}_{\gamma\gamma}(u\bar{u}\,0^{++})$
large

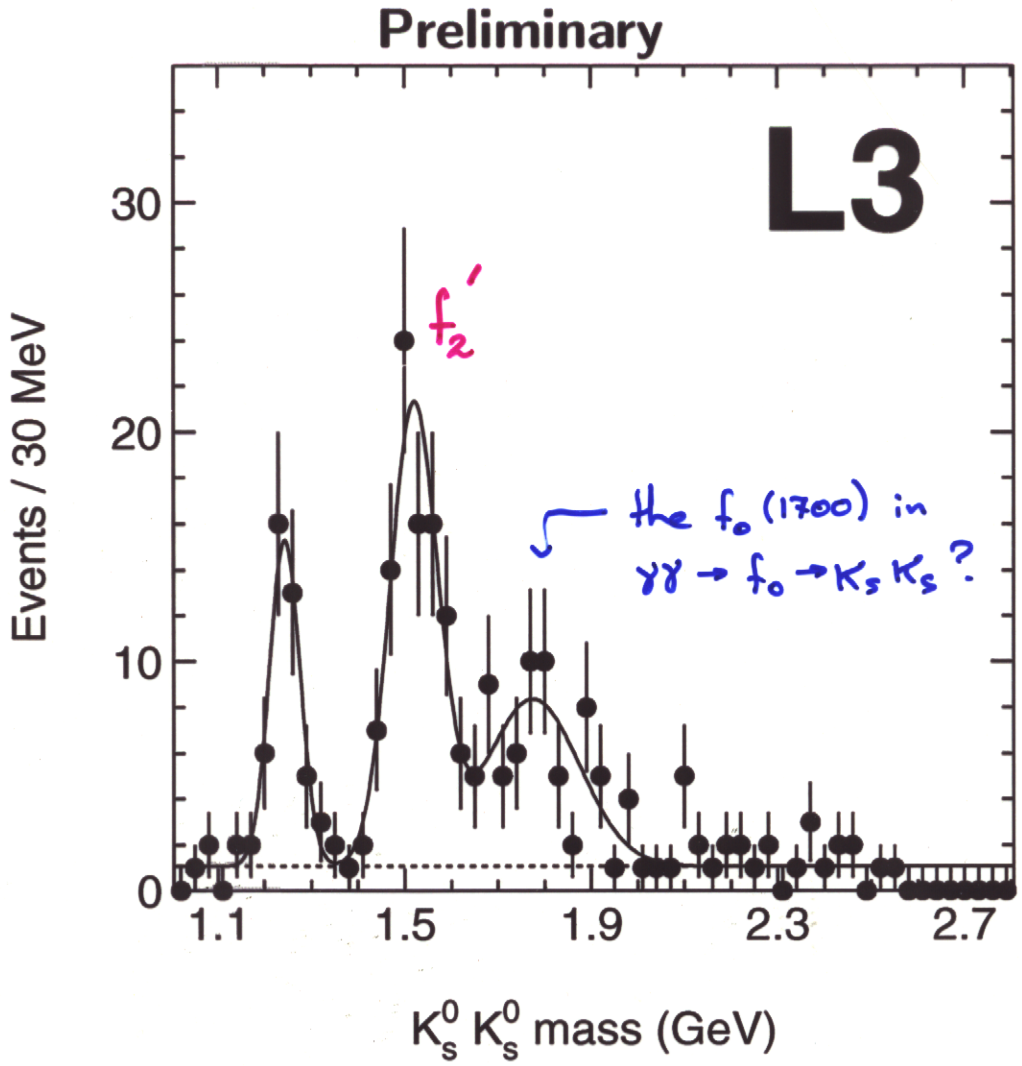
Figure 6: The cross section $\sigma(\gamma\gamma \to \pi^0\pi^0)$ and its partial wave decomposition as a function of the invariant mass. Points with error bars: data, full line: Breit-Wigner fit, dashed line: $D-$wave, dotted line: $S-$wave.

An e.g. of identifying $q\bar{q}$ and non-$q\bar{q}$ in $\gamma\gamma$.

$K_s^0 K_s^0$ – Mass Spectrum

Finally, 253 $K_s^0 K_s^0$ events were selected. The spectrum of the $K_s^0 K_s^0$ invariant mass is dominated by the $f_2'(1525)$ resonance. The region $f_2(1270)$ – $a_2(1320)$ shows a destructive interference predicted by SU(3). A clear enhancement is visible in the 1750 MeV region.

In an attempt to determine a resonance spin-parity, the angular distribution of decay products can be analysed in the resonance rest frame.



f_2'

the $f_0(1700)$ in $\gamma\gamma \to f_0 \to K_s K_s$?

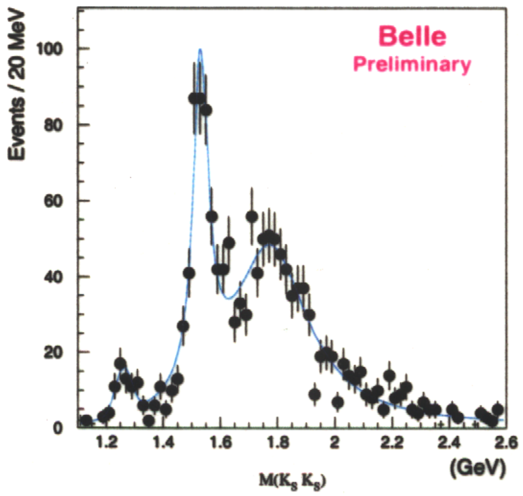


Figure 5: The $K_S^0 K_S^0$ invariant mass spectrum for the $\gamma\gamma \to K_S^0 K_S^0$ process. The solid line is a fit with two Breit-Wigner functions for the $f_2'(1525)$ and 1750 MeV region, and a Gaussian for the $f_2(1270) - a_2^0(1320)$ region plus a constant background. See the text for details.

Table 1: Results of the fit to the $K_S^0 K_S^0$ mass spectrum.

	$f_2'(1525)$	1750 MeV
Mass (MeV)	1532 ± 4	1768 ± 9.6
Width (MeV)	64 ± 6.8	323 ± 29
No. of Events	414 ± 36	967 ± 72

MeV. To obtain a background shape, we fit the $M_{K_S K_S}$ distribution with a linear function from 2.11 to 2.35 GeV, excluding the signal region. We observed 36 events in the signal region and the expected background is 27.0. Using a Poisson distribution with background, we obtain an upper limit of 20.7 signal events at the 95% C.L. Assuming $(J, \lambda) = (2, 2)$ for $f_J(2220)$, this corresponds to

$$\Gamma_{\gamma\gamma}(f_J(2220)) \times \mathcal{B}(f_J(2220) \to K_S^0 K_S^0) < 1.17\text{eV}$$

at 95% C.L. without considering the systematic errors.

4.4 Angular Analysis

We have applied the same method of partial wave analysis, described in Sec. 3.3, to the $K_S^0 K_S^0$ data sample. The angular distribution of each W bin is fit by Eq. 2. Figure 6 shows the W dependences of the fitted results, $\mathcal{Z}'/5$ and $\mathcal{X}$, which correspond to the contribution of $J = 2$ and $J = 0$ components in the total cross section, respectively. It is clear that the peak of $f_2'(1525)$ is dominated by spin-2 component as expected. However, there is a large spin-0 component in the 1750 MeV region while some spin-2 structure appears around 1.8 – 2.0 GeV.

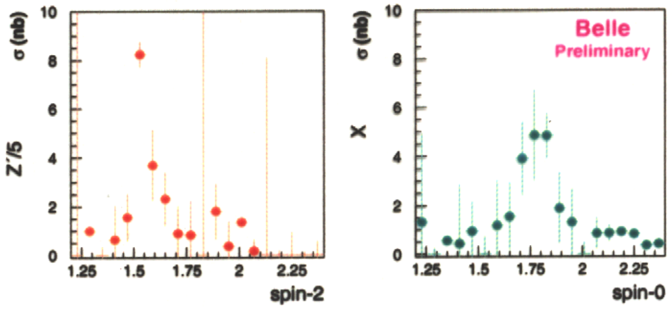


Figure 6: The contribution to the total cross section from the components (a) $\mathcal{Z}'/5$, dominated by spin-2 component, and (b) $\mathcal{X}$, dominated by spin-0 component.

5 Summary

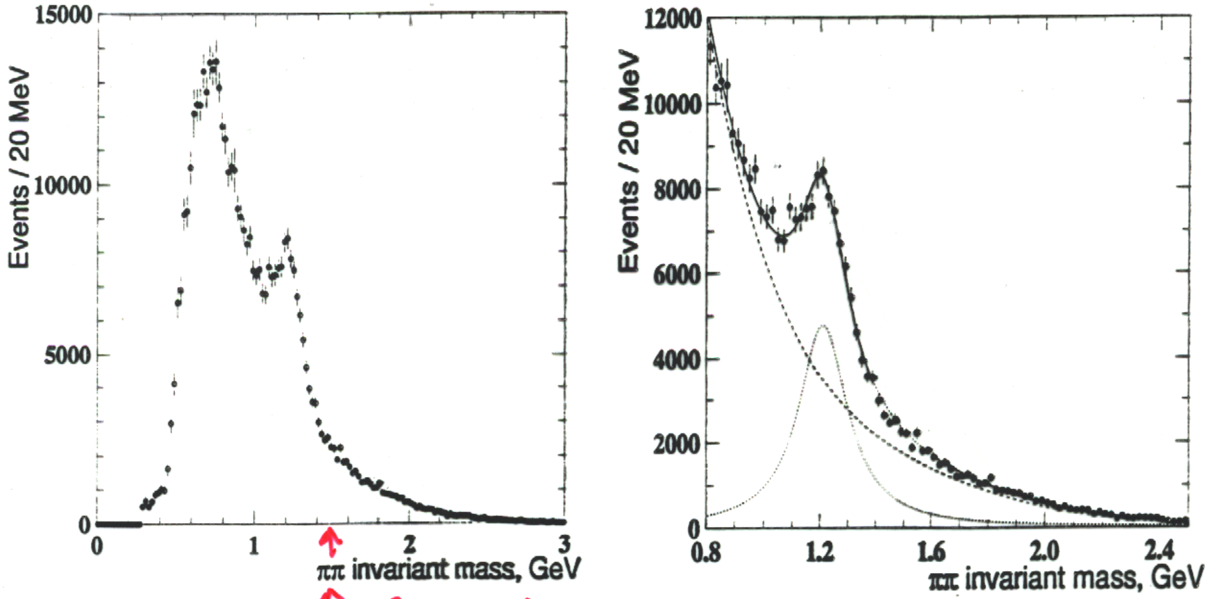
We have studied the reactions $\gamma\gamma \to K^+K^-$ and $\gamma\gamma \to K_S^0 K_S^0$ using the large data samples collected by the Belle experiment at KEKB. A prominent $f_2'(1525)$ resonance is observed in both channels. A broad structure in the 1.7–2.1 GeV region is found in K^+K^- and an enhancement around 1750 MeV is observed in $K_S^0 K_S^0$. A partial wave analysis has been performed to explore these resonance structures. Upper limits for $f_J(2220)$ are also obtained in both channels, respectively.

References

1. TASSO Collaboration, M. Althoff *et al.* Phys. Lett. **121B** (1982) 216; PLUTO Collaboration, Ch. Berger *et al.* Z. Phys. **C37** (1988) 329; and CELLO Collaboration, H.J. Behrend *et al.* Z. Phys. **C43** (1989) 91.
2. L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B363** (1995) 119; *ibid.* **B501** (2001) 173.
3. BES Collaboration, J.Z. Bai *et al.*, Phys. Rev. Lett. **76** (1996) 3502; **77** (1996) 3959.
4. CLEO Collaboration, R. Godang *et al.*, Phys. Rev. Lett. **79** (1997) 3829; M.S. Alam *et al.*, *ibid.*, **81** (1998) 3328.
5. The Belle Collaboration, A. Abashian *et al.*, KEK Progress Report 2000-4, to be published in Nucl. Instr. Meth. A.
6. *KEKB B-Factory Design Report*, KEK Report 95-7, June 1995.
7. VENUS Collaboration, F. Yabuki *et al*, J. Phys. Soc. Japan **64** (1995) 435.
8. Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. **C15** (2000) 1.
9. H.J. Lipkin, Nucl. Phys. **B 7** (1968) 321.

3 Fitting the mass spectrum

The $\pi^+\pi^-$ invariant mass spectrum obtained is shown in figure 1. The clear peak in the spectrum above 1 GeV can be identified with the known tensor resonance $f_2(1270)$. The experimental



↑ $f_0(1500)$ region

Figure 1: The invariant mass distribution for two-pion final states: data (left) and the fit to data (right) with the Breit-Wigner for the $f_2(1270)$ (dotted line), the polynomial for the background (dashed line) and the combination of these functions (solid line) are shown. The dotted line from 1.38 to 1.62 GeV indicates the exclusion of this region from the fit.

$\Gamma_{\gamma\gamma}^{\text{expt}}$ exciting new results

(... incl. prev. glueball candidates!).

$\pi_2(1670)$ $^1D_2$ quark model state

$3\pi^0 : \pi^+\pi^-\pi^0$

In 1990, CBall & CELLO reported

$$\Gamma_{\gamma\gamma}(\pi_2)\cdot b_{\to 3\pi} \approx 1.\ \text{KeV}$$

Yay $\gamma\gamma \to$ excited-L is on!

but thy. (AB) 0.1 → 0.3 KeV

$m_q = 330 \to 220$ MeV

In 1997 it's gone ...

< 0.19 KeV	Argus	$\pi^+\pi^-\pi^0$	90% cl
< 0.072 KeV	L3	$\pi^+\pi^-\pi^0$	

"ι"
G candidate
pre-LGT

$\eta(1440)$ 2^1S_0 quark model? $n\bar{n}/s\bar{s}$?

$\eta(1295)$?

an η/η' system? very interesting to disentangle $|n\bar{n}\rangle \leftrightarrow |s\bar{s}\rangle$ content.

$\Gamma_{\gamma\gamma}$ can do this. ($\gamma\rho^0, \gamma\omega, \gamma\varphi$ is better).

Can
Sep. η
from
f_1
by
$\gamma\gamma \leftrightarrow \gamma\gamma^*$

$$\Gamma_{\gamma\gamma}(\eta(1440))\cdot B_{K\bar{K}\pi} = 212 \pm 50 \pm 23\ \text{eV}$$

$$\eta\pi\pi \quad < 95\ \text{eV}$$

$$\eta(1295)\cdot \quad \eta\pi\pi \quad < 66\ \text{eV}$$

A pure $n\bar{n}$ 2^1S_0 $\eta_n(1300)$ has $\Gamma_{\gamma\gamma}^{\text{thy}} \approx 1.3$ KeV.

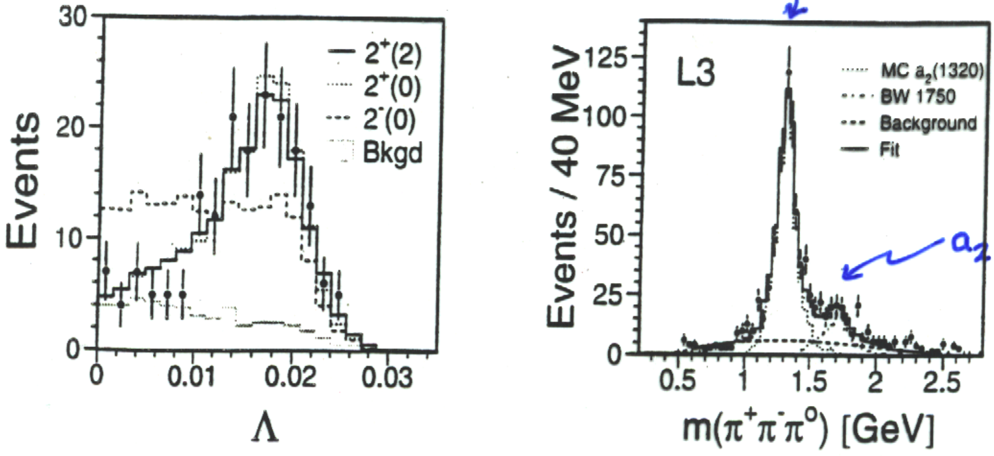
pure $s\bar{s}$ is naively $\frac{2}{25}$ · this ≈ 0.1 KeV.

A problem for 1295/1440? Unclear. All BFs are listed as "seen".

At least we have a $\Gamma_{\gamma\gamma}\cdot B$ for one channel to set the scale.

S.R. Hou (L3)   Proc. HAD97, pp. 745-748

$a_2(1752)$



$a_2(1320)$

$a_2(1752)$?

FIGURE 2. Distributions of the Λ parameter and the $\pi^+\pi^-\pi^0$ invariant mass.

$m = 1323 \pm 4 \pm 3$ MeV and $\Gamma = 105 \pm 10 \pm 11$ MeV for a_2; $m = 1752 \pm 21 \pm 4$ MeV and $\Gamma = 150 \pm 110 \pm 34$ MeV for the high-mass Breit-Wigner term.

1st report of a radial excitation in $\gamma\gamma$

$$\gamma\gamma \to a_2(1752) \to \pi^+\pi^-\pi^0$$

fit gives $\Gamma_{\gamma\gamma}(cc) \cdot B_{\pi^+\pi^-\pi^0} = 0.29(4)(2)$ KeV. $\lambda = 2$ as expected for $q\bar{q}$.

we expect $B_{\pi^+\pi^-\pi^0} \approx 0.3$ in $^3P_0$ model (next page)

so

$$\Gamma_{\gamma\gamma}(a_2(1752)) \approx 1.0 \text{ KeV} \approx \Gamma_{\gamma\gamma}(a_2(1320))$$

agrees with theor. expectation: little $\Gamma_{\gamma\gamma}$ suppression with radial excitation!

Important to check this. Usefulness of $\gamma\gamma \to q\bar{q}$ depends on this as a test case to check theory.

$\gamma\gamma$ (L3)

$\gamma\gamma$ (we know $\Gamma_{\gamma\gamma}(a_0)/\Gamma_{\gamma\gamma}(a_2)$) theor.

Table B5. Partial widths of $2\,^3\mathrm{P}_J$ a_J states (MeV).

1752(21)(4)

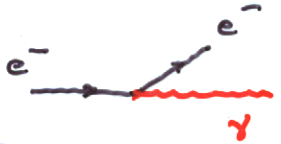
Mode	$a_2(1700)$	$a_1(1700)$	$a_0(1700)$
$(1S)^2$			
$\eta\,\pi$	23.		5.
$\eta'\,\pi$	10.		5.
$\rho\,\pi$	104.	58.	
$\omega\,\rho$	109.	15.	46.
(2S)(1S)			
$\eta(1295)\,\pi$	3.		43.
$\rho(1465)\,\pi$	0.	41.	
(1P)(1S)			
$b_1(1231)\,\pi$	28.	41.	165.
$f_0(1300)\,\pi$		2.	
$f_1(1282)\,\pi$	4.	18.	30.
$f_2(1275)\,\pi$	20.	39.	
$(1S)^2$ strange			
K K	20.		0.
K* K	17.	33.	
total			
$\sum_i \Gamma_i$	336.	246.	293.

150(110)(34)

eported in $^{+}\pi^{-}\pi^{0}$

Glueballs @ TJ ?

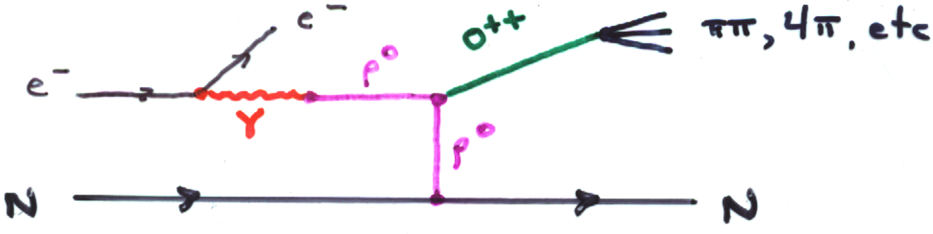
It can be imagined...



C = (−)

not very promising

however



certainly happens.

& recall large $f_0(1500) \to \rho\rho$, "σσ" coupling.

∴ Just study γprod of $\pi^0\pi^0$, 4π ...

“You get this for free.[†]”

[†] free = at no additional cost

c. hybrids

|hybrid meson> =

| q + qbar + excited glue> + ...

Construction of |q qbar g> basis states shows that all **J^{PC}** are allowed, unlike |q qbar>.

Exotic J^{PC} are

0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}...

Experimental J^{PC}-exotic mesons are usually considered hybrid candidates, since theorists at present have no other class of J^{PC}-exotic that cannot "fall apart" into light |qqbar> meson pairs.

If a J^{PC}-exotic meson is found, you are certainly beyond the |qqbar> quark model.

Hybrid masses and quantum numbers:

1) bag model, lowest hybrid multiplet

$q \times \bar{q} \times g$ (here q=u,d,s)

Dirac and Helmholz eqs. + OGE forces

$$\text{lowest } J^P = \underbrace{0^-, 1^-}_{\substack{q\bar q \ \ L=0 \\ S=0,1}} \times \underset{\substack{\text{bag} \\ \text{TE gluon}}}{1^+} = \left\{ \begin{array}{cc} S_{q\bar q}=0 & S_{q\bar q}=1 \\ & 2^{-+} \\ 1^{--} & 1^{-+} \\ & 0^{-+} \end{array} \right.$$

J^{PC} exotic !

= forbidden to $q\bar q$

$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, ..$

Spectrum of states:

T.Barnes, Caltech PhD (1977) — Feynman notes
NPB158, 171 (1979)
TB,F.E.Close, PL116B, 365 (1982)
M.Chanowitz, S.R.Sharpe, NPB222, 211 (1983)
TB,FEC, F.deViron, NPB224, 241 (1983)
Flensberg, Pet~~e~~ersen, Skold, ZPC22, 293 (1984)
...
(all MIT bag model)

We had $M \approx 1.4$ GeV $\rightarrow \eta\pi$.

mix $|q\bar q\rangle \leftarrow\cdots\rightarrow |q\bar q g\rangle \leftrightarrow |q\bar q gg\rangle$

nonexotic J^{PC}

result:

etc

Specific models of hybrids

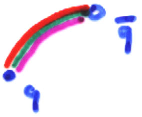
Models of the spectrum of hybrids use a physical picture of the nature of excited glue. These are

$\psi\left(q\,\cdot \;\; \begin{matrix}\cdot\, g\\ \circ\, \bar q\end{matrix}\right)$

1) bag model

1′) constituent gluon model

2) flux tube model



Exotic masses are also predicted by

3) QCD ~~r~~sum rules $\langle \mathcal{O}^{\dagger}(\vec{x},\tau)\,\mathcal{O}(\vec{0},0)\rangle \to e^{-M_{\mathcal{O}}\tau}$

4) LGT

which require no assumption about the nature of excited glue; they just extract masses from operator matrix elements. As input they require

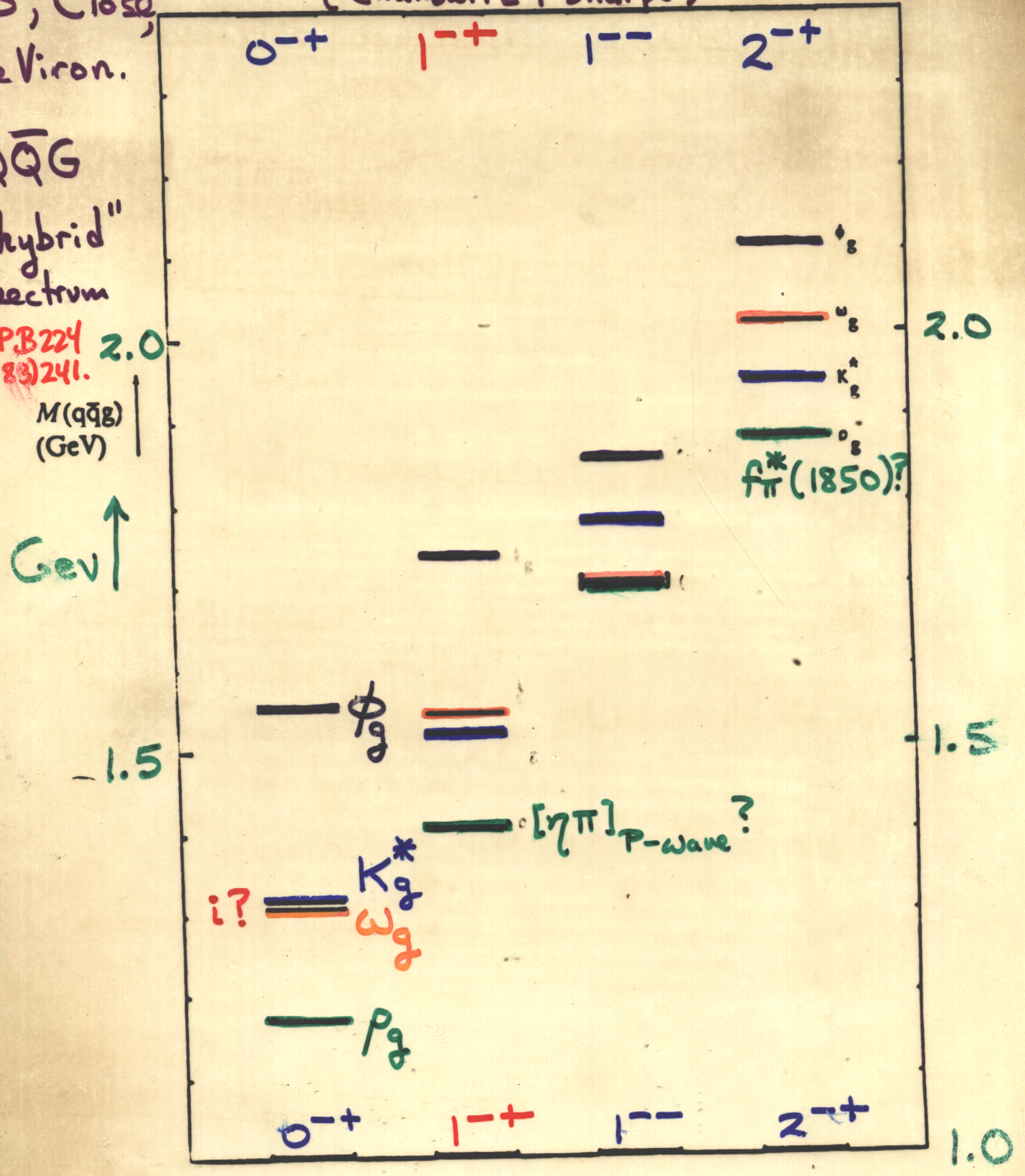
3) VEVs “vacuum condensates”,

4) one physical mass.

B, Close,
le Viron.

QQ̄G
"hybrid"
spectrum
PB224
('83)241.

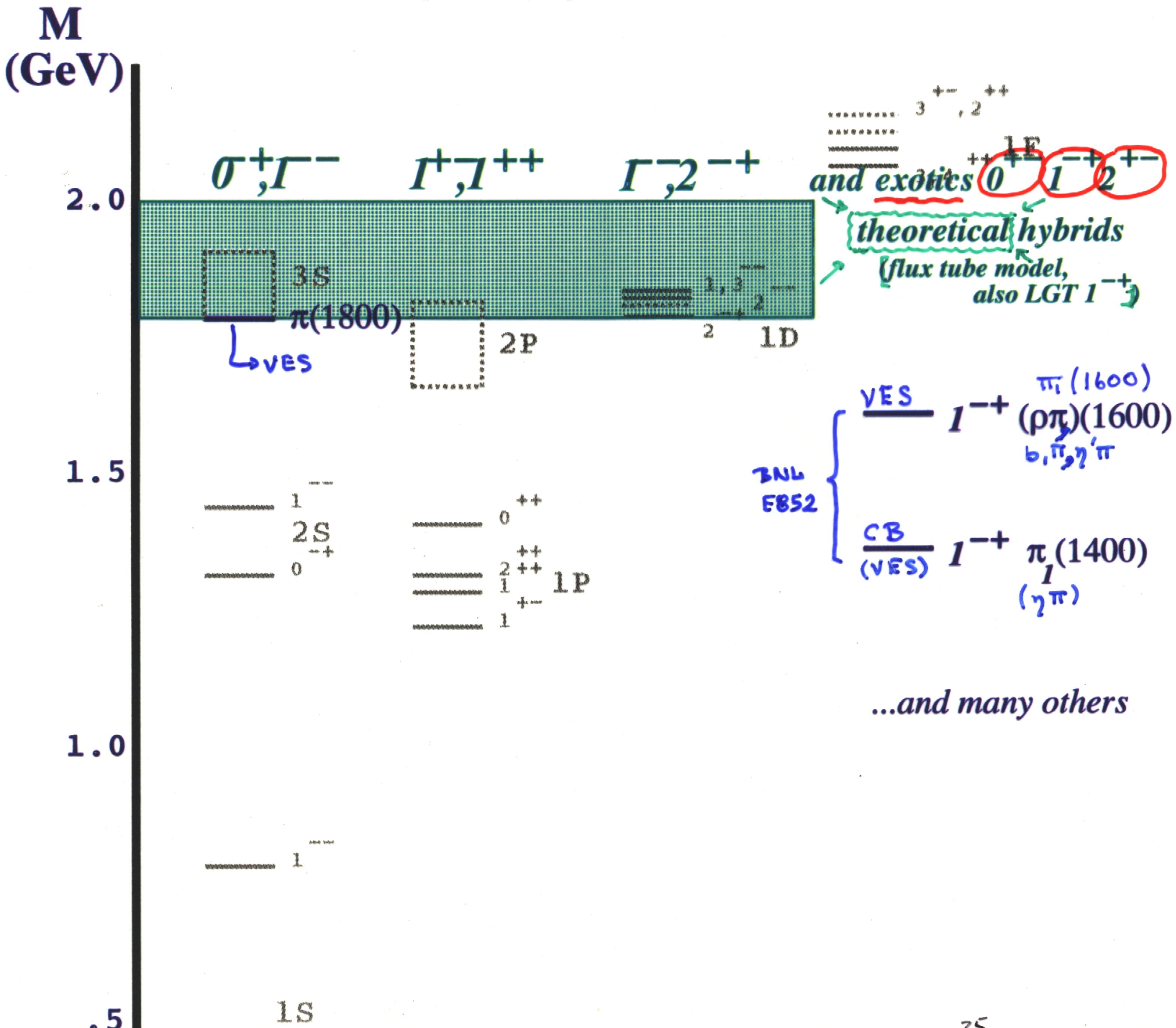
(Chanowitz & Sharpe)



1. Hybrid meson masses. Parameters are $a = 6\ \mathrm{GeV}^{-1}$, $\alpha_s = 2.2$; this gives $E_0 = 1.52$ GeV.

hybrids

Schematic light $q\bar{q}$ spectrum to approx 2.1 GeV.



44 $n\bar{n}$ states, approx ~~30~~ 35 known.

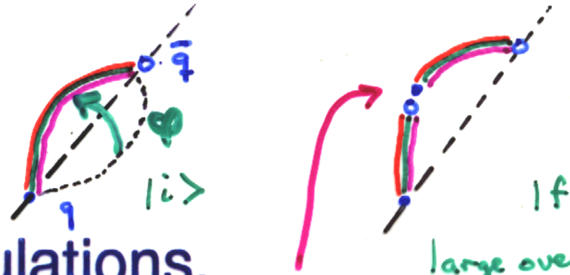
(+0.1 GeV) 22 K states, 16 known.

(+0.2 GeV) 22 $s\bar{s}$ states, (approx) 6 known.

“exotic J^{PC}” = $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

$\neq q\bar{q}$

$\psi \propto e^{i\Lambda\varphi}$



Hybrid meson decay calculations.

decay due to f-t breaking ($\approx {}^3P_0$)

large overlap requires S+P orbital $q\bar{q}$ ($\Lambda=1$)

Previous (most familiar work)

N.Isgur, R.Kokoski and J.Paton, PRL54, 869 (1985).

Properties of lightest hybrid mesons in the flux tube model.

$M(n\bar{n}-H)$ = 1.9(1) GeV

Preferred decay modes are S+P.

e.g. $1^{-+} \to b_1\pi,\ f_1\pi$

IKP however only considered the J^{PC}–exotics, 0^{+-}, 1^{-+}, 2^{+-} .

There are also 5 nonexotic hybrid J^{PC} combinations in this lightest 1.9 GeV flux tube hybrid multiplet, each is a flavor nonet.. What do these nonexotic hybrids decay to? How wide are they? Would any stand out clearly as non–qq states?

Nonexotic hybrid decay calculations (and check of exotics) by

F.E.Close and P.R.Page, NPB443, 233 (1995).

$J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, 1^{--}$.

Concl: Yes there are some interesting predictions of relatively narrow nonexotic flux–tube hybrids, with characteristic decay modes:

N. Isgur, R. Kokoski, J. Paton PRL54, 869('85).

Gluonic Excitations of Mesons: Why They Are Missing and Where to Find Them

TABLE I. The dominant decays of the low-lying exotic meson hybrids.

S+P modes dominant

Hybrid state[a]	J^{PG}	$(\text{Decay mode})_{L\text{ of decay}}$	Partial width (MeV)
x_2^{+-} (1900) I=1	2^{++}	$(\pi A_2)_P$ $(\pi A_1)_P$ $(\pi H)_P$	450 100 150
y_2^{+-} (1900) I=0	2^{+-}	$(\pi B)_P$	500
z_2^{+-} (2100) $s\bar{s}$	2^{+-}	$[K\bar{K}^*(1420)+\text{c.c.}]_P$ $(\bar{K}Q_2+\text{c.c.})_P$	250 200
x_1^{-+} (1900)	1^{--}	$(\pi B)_{S,D}$ $(\pi D)_{S,D}$	100,30 30,20
y_1^{-+} (1900)	1^{-+}	$(\pi A_1)_{S,D}$ $[\pi\pi(1300)]_P$ $(\bar{K}Q_2+\text{c.c.})_S$	100,70 100 ~ 100
z_1^{-+} (2100)		$(\bar{K}Q_1+\text{c.c.})_D$ $(\bar{K}Q_2+\text{c.c.})_S$ $[\bar{K}K(1400)+\text{c.c.}]_P$	80 250 30
x_0^{+-} (1900)	0^{++}	$(\pi A_1)_P$ $(\pi H)_P$ $[\pi\pi(1300)]_S$	800 100 900
y_0^{+-} (1900)	0^{+-}	$(\pi B)_P$	250
z_0^{+-} (2100)	0^{+-}	$(\bar{K}Q_1+\text{c.c.})_P$ $(\bar{K}Q_2+\text{c.c.})_P$ $[\bar{K}K(1400)+\text{c.c.}]_S$	800 50 800

$J^{PC_n} = 2^{+-}$

$I=1$ 1^{-+} ⇒

1^{-+}

0^{+-}

hopelessly broad

$I=1$ 1^{-+} relatively narro $\pi b_1, \pi f_1$

[a] x, y, and z denote the flavor states $(1/\sqrt{2})(u\bar{u}-d\bar{d})$, $(1/\sqrt{2})(u\bar{u}+d\bar{d})$, and $s\bar{s}$. The subscript on a state is J; the superscripts are P and C_n.

→ Exotic members only of lightest flux tube hybrid multiplet. $(0,1,2)^{+-,-+}$; $1^{++,--}$

8 J^{PC} states

decays mainly to $[A_1(1275)\pi]_S$ and $[\pi(1300)\pi]_P$; considering the notorious difficulty of seeing the A_1 and the large width of the $\pi(1300)$, we see that these channels would probably not be conducive to our finding the y_1^{-+}. Similar difficulties would seem likely to obscure the z_1^{-+} (2100). The remaining four states, while still presenting formidable challenges, should be easier to see: y_2^{+-} (1900) and y_0^{+-} (1900) both decay dominantly to $[B(1235)\pi]_P$, z_2^{+-} (2100) will decay much of the time to $[K^*(1420)\bar{K}+\text{c.c.}]_P$, and the x_1^{-+} (1900) will be found most of the time in $[B(1235)\pi]_S$.

Neither the flux-tube model masses nor the widths of Table I are at this time very precise: The predicted masses are uncertain by about 100 MeV and, even without the changes in phase space thereby induced, the predicted widths are uncertain by an overall strength factor of 1.5 from the flux-tube overlap factor K and a further model error of about 1.2 (based on the mean errors found in the ordinary meson analysis of Ref. 3). Nevertheless, the main message of Table I is clear and compelling: Exotic meson hybrids *must* be in these channels with the general characteristics that we have detailed.

It remains to discuss how to produce these exotic states. In this case we can provide some suggestions, but no quantitative results. One of the implications of the flux-tube model is that the hadronic spectrum becomes very dense with new non-quark-model states for masses greater than about 2 GeV. These states are all strongly interacting and so, in particular, meson hybrids will be produced as copiously as ordinary mesons in hadronic collisions which probe such mass scales. We would suggest that high-mass meson diffractive scattering will be particularly rich in hybrids. In the case where the beam flux tube is simply "plucked" by the target one will produce hybrids with the flavor and spin of the beam: A π beam would, for example, produce by this mechanism the nonexotic $I=1$, $J^{PC}=1^{++}$ and 1^{--} hybrids. More complicated spin-flip and quantum-number exchange mechanisms in which the hybrid is produced by quark scattering rather than pure glue scattering could produce the other hybrids, including the desirable exotic ones. Diffractive photoproduction, on the other hand, can produce "plucked" ρ, ω, and ϕ states and so could be a good source for all four of the desirable exotics y_2^{+-}, z_2^{+-}, x_1^{-+}, and y_0^{+-}. Traditional "gluon-rich" channels

$n\bar{n}$-hybrids

Close & Page

Table 3: Dominant widths in MeV for $\sqrt{\frac{1}{2}}(u\bar{u} - d\bar{d})$ *hybrid* $A \to BC$ for various J^{PC} in partial wave L. The quark model assignments for the mesons are those of the PDG tables [28]. All β's are rescaled from the ISGW / Merlin values by 5/4 to form "effective" β's consistent with that of $\beta = 0.4$. Hybrid masses before spin splitting are 2.0 GeV, except for 0^{+-} (2.3 GeV), 1^{+-} (2.15 GeV) and 2^{+-} (1.85 GeV), following ref. [29]. Final states containing π have $\tilde{\beta} = 0.36$ GeV, otherwise $\tilde{\beta} = 0.40$ GeV. For the hybrid we use $\beta_A = 0.27$ GeV. η indicates $\sqrt{\frac{1}{2}}(u\bar{u} + d\bar{d})$ at 550 MeV. The ${}^3P_1/{}^1P_1$-mixing is 34° in the $L_B = 1$ kaon sector.

xtra" π_2

A	B,C	L	Γ	A	B,C	L	Γ	A	B,C	L	Γ
2^{-+}	$f_2(1270)\pi$	S	40	1^{+-}	$a_2(1320)\pi$	P	175	1^{-+}	$f_1(1285)\pi$	S	40
		D	20		$a_1(1260)\pi$	P	90			D	20
	$b_1(1235)\pi$	D	40		$h_1(1170)\pi$	P	175		$b_1(1235)\pi$	S	150
	$a_2(1320)\eta$	S	~ 40		$b_1(1235)\eta$	P	150			D	20
	$K_2^*(1430)K$	S	~ 30		$K_2^*(1430)K$	P	60		$a_1(1260)\eta$	S	50
2^{+-}	$a_2(1320)\pi$	P	200		$K_1(1270)K$	P	250		$K_1(1270)K$	S	20
	$a_1(1260)\pi$	P	70		$K_0^*(1430)K$	P	70		$K_1(1400)K$	S	~ 125
	$h_1(1170)\pi$	P	90	1^{++}	$f_2(1270)\pi$	P	175	0^{-+}	$f_2(1270)\pi$	D	20
	$b_1(1235)\eta$	P	~ 15		$f_1(1285)\pi$	P	150		$f_0(1300)\pi$	S	~ 150
0^{+-}	$a_1(1260)\pi$	P	700		$f_0(1300)\pi$	P	~ 20		$K_0^*(1430)K$	S	~ 200
	$h_1(1170)\pi$	P	125		$a_2(1320)\eta$	P	50	1^{--}	$a_2(1320)\pi$	D	50
	$b_1(1235)\eta$	P	80		$a_1(1260)\eta$	P	90		$a_1(1260)\pi$	S	150
	$K_1(1270)K$	P	600		$K_2^*(1430)K$	P	~ 20			D	20
	$K_1(1400)K$	P	150		$K_1(1270)K$	P	40		$K_1(1270)K$	S	40
					$K_1(1400)K$	P	~ 20		$K_1(1400)K$	S	~ 60

"extra" ρ

Table 4: As in table 3 but for initial hybrid $\sqrt{\frac{1}{2}}(u\bar{u} + d\bar{d})$.

extra" η_2

extra" ω

A	B,C	L	Γ	A	B,C	L	Γ	A	B,C	L	Γ
2^{-+}	$a_2(1320)\pi$	S	125	2^{+-}	$b_1(1235)\pi$	P	250	1^{++}	$a_2(1320)\pi$	P	500
		D	60	h_2	$h_1(1170)\eta$	P	30		$a_1(1260)\pi$	P	450
	$f_2(1270)\eta$	S	~ 50	0^{+-}	$b_1(1235)\pi$	P	300		$f_2(1270)\eta$	P	70
	$K_2^*(1430)K$	S	~ 30		$h_1(1170)\eta$	P	90		$f_1(1285)\eta$	P	60
1^{+-}	$b_1(1235)\pi$	P	500		$K_1(1270)K$	P	600		$K_2^*(1430)K$	P	~ 20
	$h_1(1170)\eta$	P	175		$K_1(1400)K$	P	150		$K_1(1270)K$	P	40
	$K_2^*(1430)K$	P	60	1^{-+}	$a_1(1260)\pi$	S	100		$K_1(1400)K$	P	~ 20
	$K_1(1270)K$	P	250	η_1		D	70	0^{-+}	$a_2(1320)\pi$	D	60
	$K_0^*(1430)K$	P	70		$f_1(1285)\eta$	S	50		$f_0(1300)\eta$	S	~ 200
1^{--}	$K_1(1270)K$	S	40		$K_1(1270)K$	S	20		$K_0^*(1430)K$	S	~ 200
	$K_1(1400)K$	S	60		$K_1(1400)K$	S	~ 125				

Z. Phys. C 71, 227–238 (1996)

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Evidence for two isospin zero $J^{PC} = 2^{-+}$ mesons at 1645 and 1875 MeV

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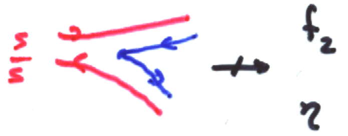
Abstract. Data on $\bar{p}p \to \eta\pi^0\pi^0\pi^0$ taken at beam momenta of 1.2 and 1.94 GeV/c reveal evidence for two $I = 0$ $J^{PC} = 2^{-+}$ resonances in $\eta\pi\pi$. The first, at 1645 ± 14(*stat.*) ± 15(*syst.*) MeV with width 180 $^{+40}_{-21}$ ± 25 MeV, decays to $a_2(1320)\pi$ with $L = 0$. It may be interpreted as the $q\bar{q}$ $^1D_2$ partner of $\pi_2(1670)$. A strong signal is also observed just above threshold in $f_2(1270)\eta$ with $L = 0$. It is 11-22 times stronger than is expected for the high mass tail of the 1645 MeV resonance. It can be fitted as a second 2^{-+} resonance at 1875 ± 20 ± 35 MeV with width 200 ± 25 ± 45 MeV. A third resonance having $J^{PC} = 2^{++}$ is observed at 2135 ± 20±45 MeV with $\Gamma = 250 \pm 25 \pm 45$ MeV, decaying to both $a_2(1320)\pi$ and $f_2(1270)\eta$ with $L = 1$. There is no evidence for resonances with decays to $a_0(980)\pi$, $\sigma\eta$ or $f_0(980)\eta$.

$\eta_2 \to f_2\eta$: not $s\bar{s}$



$n\bar{n} \leftrightarrow s\bar{s}$ mixing in η_2 sector?

1 Experiment and data processing

An isospin $I = 0$ $^1D_2$ $q\bar{q}$ resonance is expected in the vicinity of 1650-1700 MeV, as partner for $\pi_2(1670)$. Also, in the cavity model of glueballs proposed by Jaffe and Johnston [1], a 2^{-+} state is predicted. These missing states have prompted us to study $\eta\pi\pi$ states in $\bar{p}p \to (\eta\pi^0\pi^0)\pi^0$. There is evidence already for a 2^{-+} state at ~ 1870 MeV from the Crystal Ball [2] and Cello [3] experiments, and we shall make comparisons with their results.

The data were taken with the Crystal Barrel detector using $\bar{p}$ beams of 1.2 and 1.94 GeV/c from LEAR. The detector has been described in detail earlier [4]. For present purposes, the γ detection is crucial. A barrel of 1380 CsI crystals, each of 16 radiation lengths, covers 98% of the solid angle around a liquid hydrogen target 4 cm long. Immediately surrounding the target are two multiwire chambers which are used here to veto events producing charged particles. The resulting trigger selects final states containing only neutral particles. The trigger includes a coincidence with silicon counters which detect the incident $\bar{p}$ just upstream of the target: it also in-

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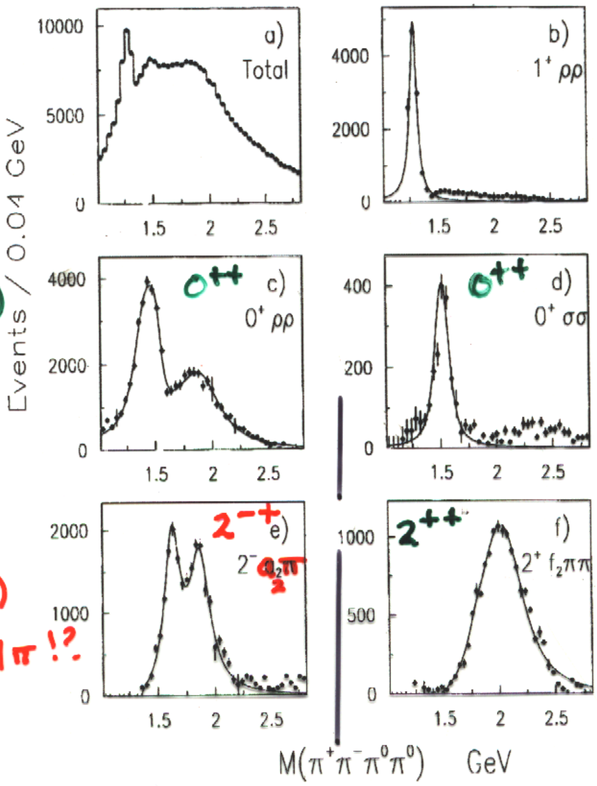
2^{-+} ! not just $0^{++}, 1^{++}, 2^{++}$ states



$f_0(1500)$ ρρ

$f_0(1500)$ "σσ"

$\eta_2(1645)$
$\eta_2(1870)$
both → 4π !?
η/η' ?
hybrid ?

$f_2(1950)$
→ $f_2(\pi\pi)_S$
glueball ?
$^3F_2$ $n\bar{n}$?

Fig. 2. The $\pi^+\pi^-\pi^0\pi^0$ channel. a) The total mass spectrum, b) 1^{++} $\rho\rho$, c) 0^{++} $\rho\rho$, d) 0^{++} $\sigma\sigma$, e) 2^{-+} $a_2(1320)\pi$ and f) 2^{++} $f_2(1270)\pi\pi$. The superimposed curves are the resonance contributions coming from the fits described in the text.

parameterization of the σ found from the $\pi^0\pi^0\pi^0\pi^0$ analysis is used. If the parameterizations of the σ used to fit the $\pi^+\pi^-\pi^+\pi^-$ channel in our previous publication [4] are used here, the same conclusion would be drawn, i.e. no $J^{PC}=0^{++}$ $\sigma\sigma$ wave is required. Hence as was stated in the introduction the parameterization used to describe the σ is crucial. There is no need for any $J^{PC}=0^{++}$ $\pi^*(1300)\pi$ wave irrespective of the parameterization used.

Superimposed on the $J^P=1^+$ $\rho\rho$ wave shown in Fig. 2b is a Breit–Wigner convoluted with a Gaussian used to describe the $f_1(1285)$ in the fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum [4]. As can be seen the $f_1(1285)$ is well described.

The $J^P=0^+$ $\rho\rho$ distribution in Fig. 2c shows a peak at 1.45 GeV together with a broad enhancement around 2 GeV. A fit has been performed to the $J^P=0^+$ $\rho\rho$ amplitude in Fig. 2c using a single channel K matrix formalism [13] including poles to describe the interference between the $f_0(1370)$, the $f_0(1500)$ and a possible state at 2 GeV. No account has been made for the $\rho\rho$ threshold in this fit. The result of the fit is superimposed on the $J^P=0^+\rho\rho$ distribution shown in Fig. 2c and describes the data well. The resulting T-matrix sheet II pole positions [14] for the resonances are

$$f_0(1370) \quad M=(1309\pm24)-i(163\pm26)\,\text{MeV},$$
$$f_0(1500) \quad M=(1513\pm12)-i(58\pm12)\,\text{MeV},$$
$$f_0(2000) \quad M=(1989\pm22)-i(224\pm42)\,\text{MeV}.$$

These parameters are consistent with the PDG [12] values for the $f_0(1370)$ and $f_0(1500)$.

$q\bar{q}$ option for $f_2(1950)$?

$\approx f_2(1950)$?

TABLE XIX. Partial widths of ^3F_J f_J states (MeV).

$^3F_2$ 2^{++}

Mode	$f_4(2044)$	$f_3(2050)$	$f_2(2050)$
	$(1S)^2$		
$\pi\pi$	62		34
$\eta\eta$	2		4
$\eta\eta'$	0		5
$\eta'\eta'$	0		0
$\rho\rho$	86	37	31
$\omega\omega$	27	11	9
	$(2S)(1S)$		
$\pi(1300)\pi$	2		1
	$(3S)(1S)$		
$\pi(1800)\pi$	0		0
	$(1P)(1S)$		
$a_0(1450)\pi$		2	
$a_1(1230)\pi$	9	20	113
$a_2(1318)\pi$	22	192	40
$f_0(1300)\eta$		0	
$f_1(1282)\eta$	0	0	13
$f_2(1275)\eta$	1	25	5
	$(2P)(1S)$		
$a_0(1700)\pi$		0	
$a_1(1700)\pi$	0	0	1
$a_2(1700)\pi$	0	3	0
	$(1D)(1S)$ strange		
$\pi_2(1670)\pi$ → $f_2\pi\pi$	1	4	197
	$(1S)^2$ strange		
KK	9		14
K^*K	5	26	15
K^*K^*	10	4	2
	$(1P)(1S)$ strange		
$K_0^*(1429)K$		0	
$K_1^*(1273)K$	0	2	91
$K_1^*(1402)K$	0	0	0
$K_2^*(1429)K$	0	23	4
	Total		
$\Sigma_i\Gamma_i$	237	350	579
Γ_{expt}	208(13)		

TABLE XX. Partial widths of $^1F_3$ b_3, and h_3 states (MeV).

Mode	$b_3(2050)$	Mode	$h_3(2050)$
	$(1S)^2$		
$\omega\pi$	37	$\rho\pi$	115
$\rho\eta$	13	$\omega\eta$	13
$\rho\eta'$	4	$\omega\eta'$	4
$\rho\rho$	33		
	$(2S)(1S)$		
$\omega(1419)\pi$	1	$\rho(1465)\pi$	1
$\rho(1465)\eta$	0	$\omega(1419)\eta$	0
	$(1P)(1S)$		
$h_1(1170)\pi$	0	$b_1(1231)\pi$	0
$b_1(1231)\eta$	0	$h_1(1170)\eta$	0
$a_0(1450)\pi$	1		
$a_1(1230)\pi$	14		
$a_2(1318)\pi$	107		
$a_1(1230)\omega$	3	$a_1(1230)\rho$	12
	$(2P)(1S)$		
$h_1(1700)\pi$	0	$b_1(1700)\pi$	0
$a_0(1700)\pi$	0		
$a_1(1700)\pi$	0		
$a_2(1700)\pi$	1		
	$(1D)(1S)$		
$\pi_2(1670)\pi$	0		
$\omega_1(1700)\pi$	0	$\rho_1(1700)\pi$	0
$\omega_2(1670)\pi$	1	$\rho_2(1670)\pi$	2
$\omega_3(1667)\pi$	48	$\rho_3(1691)\pi$	138
	$(1S)^2$ strange		
K^*K	22		22
K^*K^*	5		5
	$(1P)(1S)$ strange		
$K_0^*(1429)K$	0		0
$K_1^*(1273)K$	0		0
$K_1^*(1402)K$	0		0
$K_2^*(1429)K$	17		17
	Total		
$\Sigma_i\Gamma_i$	308		330

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[1] N. Isgur, R. Kokoski, and J. Paton, Phys. Rev. Lett. **54**, 869 (1985).

[2] F. E. Close and P. R. Page, Nucl. Phys. **B443**, 233 (1995); Phys. Rev. D **52**, 1706 (1995).

[3] N. Isgur and J. Paton, Phys. Rev. D **31**, 2910 (1985).

[4] T. Barnes, F. E. Close, and E. S. Swanson, Phys. Rev. D **52**, 5242 (1995); see also Michael [5].

[5] UKQCD Collaboration, G. Bali *et al.*, Phys. Lett. B **309**, 378 (1993); D. Weingarten, in *Lattice '93*, Proceedings of the International Symposium, Dallas, Texas, edited by T. Draper *et al.* [Nucl. Phys. B (Proc. Suppl.) **34**, 29 (1994)]; C. Michael, Liverpool Report No. LTH 370, hep-ph/9605243, 1996 (unpublished); F. E. Close and M. J. Teper, "On the lightest Scalar Glueball," Report No. RAL-96-040/OUTP-96-35P, 1996 (unpublished).

[6] J. Sexton, A. Vaccarino, and D. Weingarten, Phys. Rev. Lett. **75**, 4563 (1995).

[7] VES Collaboration, D. V. Amelin *et al.*, Phys. Lett. B **356**, 595 (1995).

[8] S. U. Chung (private communication).

[9] F. E. Close, in *Proceedings of the XXVII International Conference High Energy Physics*, Glasgow, Scotland, 1994, edited by P. Bussey and I. Knowles (IOP, London, 1995), p. 1395.

[10] VES Collaboration, A. M. Zaitsev, in *Proceedings of the XX-*

TABLE VI. Partial widths of 1D and hybrid $\eta_2(1875)$ states.

	$\rho\rho$	$\omega\omega$	$f_2\eta$	$a_0(1450)\pi$	$a_1\pi$	$a_2\pi$	K*K	total
$\eta_{2(D)}(1875)$	147.	46.	45.	1.	43.	264.	61.	607.
$\eta_{2(H)}(1875)$	0	0	20	2	0	160	10	≈ 190

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Photoproduction of an isovector $\rho\pi$ state at 1775 MeV

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(Received 19 June 1990)

Evidence is presented for the charge-exchange photoproduction, in two distinct reactions, of an isovector $\rho\pi$ state of mass ~ 1775 MeV. Results of an analysis of the decay-angular distributions are also presented, from which it is concluded that $J^P = 1^-, 2^-$, or 3^+.

About fifteen years ago Deutschmann *et al.*[1] presented evidence for an isovector 3π state at a mass of ~ 1.8 GeV/c^2. Their analysis, utilizing data from a 16-Gev/$c\,\pi^+ p$ experiment, employed the thesis that the decay pions from higher-mass states would exhibit larger values of the transverse momentum than pions from competing processes. Somewhat later the Amsterdam-Briston-CERN-Cracow-Munich-Rutherford (ACCMOR) Collaboration,[2] in a massive study of the reaction $\pi^- p \to \pi^-\pi^-\pi^+ p$, confirmed the existence of the $\pi_2(1670)$ (formerly denoted as A_3) as a ($J^P=2^-$) state with dominant $f_2(1270)\pi$ decay, but also with a substantial $\rho\pi$ decay mode. They also observed a second isovector $J^P=2^-$ state at a mass of ~ 1.85 GeV/c^2 which, when combined with a multichannel analysis, indicated a resonant mass of ~ 2.1 GeV/c^2. Subsequently, Chanowitz and Sharpe[3] observed that, since this heavier state was unlikely to be a radial excitation of the $\pi_2(1670)$, because of the proximity of their masses, this second 3π state was a strong candidate for a hybrid ($q\bar{q}g$) state[3] (even if its mass was as great as 2.1 GeV/c^2). Another strong indication of the existence of an isovector 3π state in this mass region has been presented by Aston *et al.*,[4] who observed such a state, with substantial $\rho\pi$ decay, at a mass of ~ 1760 MeV/c^2, as a 6.6σ enhancement in the photoproduction reaction $\gamma p \to (p\pi^\pm)(\pi^+\pi^-\pi^\mp)$. A similarly positioned peak can also be seen in the $\rho^0\pi^+$ spectrum, presented by Eisenberg *et al.*,[5] from the reaction $\gamma p \to n\pi^+\pi^+\pi^-$, where the charge-exchange photoproduction of the $a_2(1320)$ was first reported. In a related matter, we have recently presented evidence[6] that peripheral Δ^{++} production, in the reaction $\gamma p \to \Delta^{++}\pi^+\pi^-\pi^-$, was consistent with production via the absorptive one-pion-exchange model.

©1991 The American Physical Society

G. T. Condo et al SLAC PRD43, 2787 ('91) $J^{PC}n = 1^{-+}, 2^{-+}, 3^{++}$

$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

$\rho^0\pi^+$ events. The fit to the full spectrum (smooth curve) shown on this figure yields a resonance mass of 1787±18 MeV/c^2 with a width of 118±60 MeV. In Fig. 2(b) we present the dipion mass spectrum for 3π events in the range 1.7–1.9 Gev/c^2. After correcting for direct ρ^0 production, which we estimate by the excess of forward-going ρ^0 to be ~20% of the ρ^0 signal we find the $\rho^0\pi^+/f_2\pi^+$ branching ratio to be 1.8±0.5.

Thus we have observed, in two distinct channels, evidence for an isovector, predominantly $\rho\pi$, state at a mass of ~1775 MeV/c^2 with a width of ~100–200 MeV. This is apparently the state first observed by Aston *et al.*[4] Because of the relatively large mass and branching-ratio differences between the photoproduced state and the $\pi_2(1670)$ it would not seem to be identifiable as the latter. It should be pointed out that all previous observations of the $\pi_2(1670)$ have been made in experiments employing pion beams where diffractive Deck processes can be important ($\pi^\pm \rightarrow \pi^\pm\rho^0$, $\pi^\pm f^0, \ldots$). The current experiment uses a photon beam which because of charge-conjugation

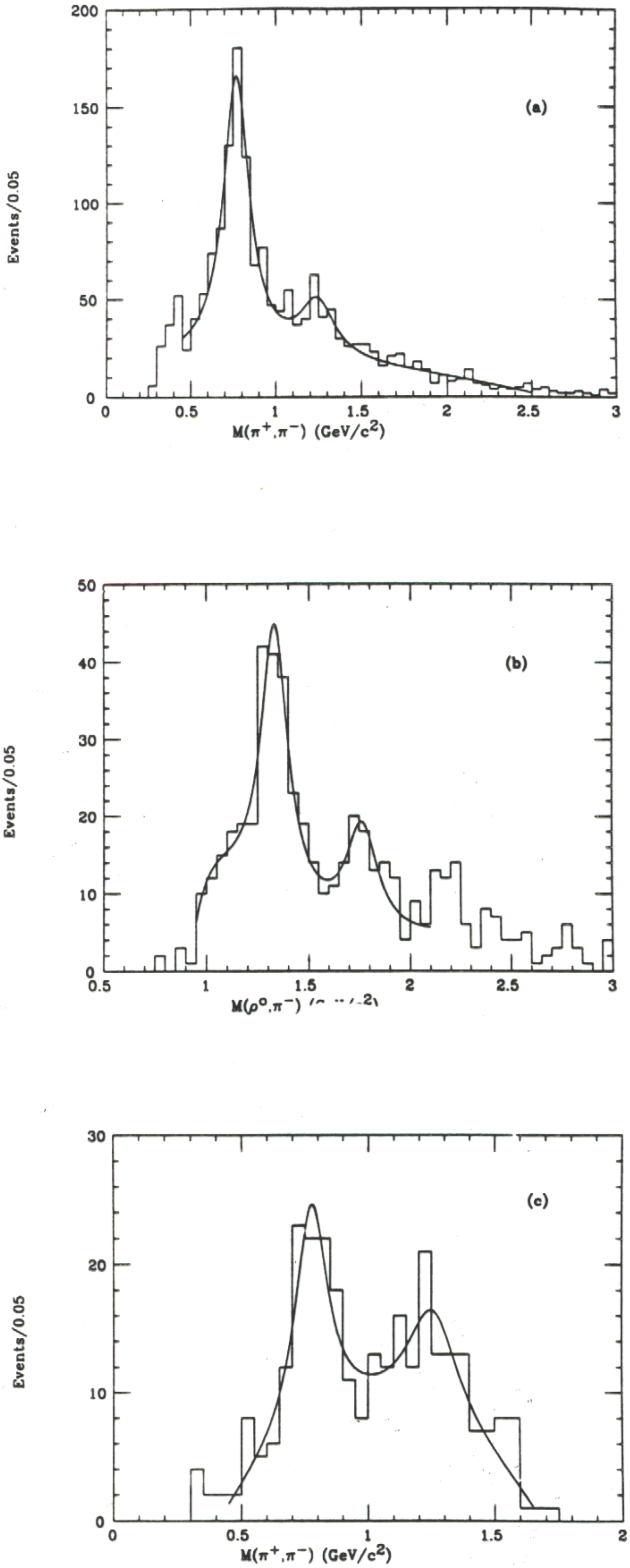


FIG. 1. For the reaction $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$ at $|t'_{\gamma,3\pi}| < 0.2$ GeV^2 (no peripheral $\rho^0 N^{*+}$): (a) The neutral-dipion spectrum; (b) the $\rho^0\pi^-$ spectrum; (c) the $\pi^+\pi^-$ spectrum for events with $1.65 \leq M(3\pi) \leq 1.95$ GeV/c^2.

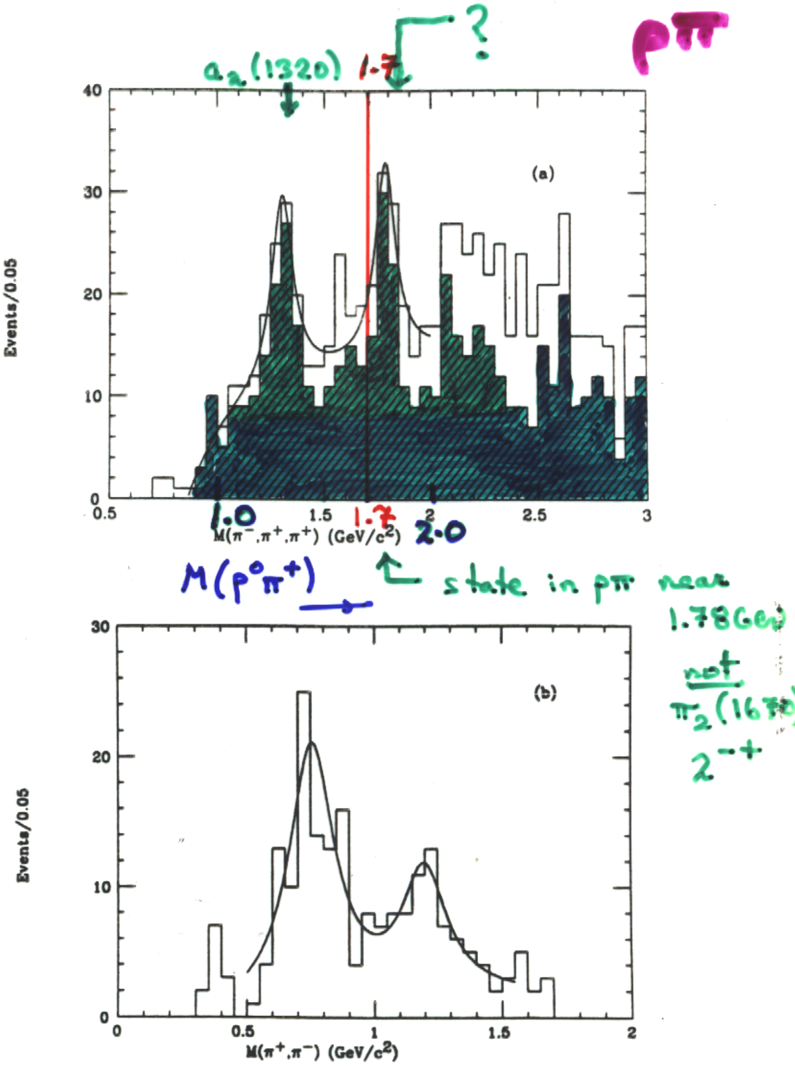
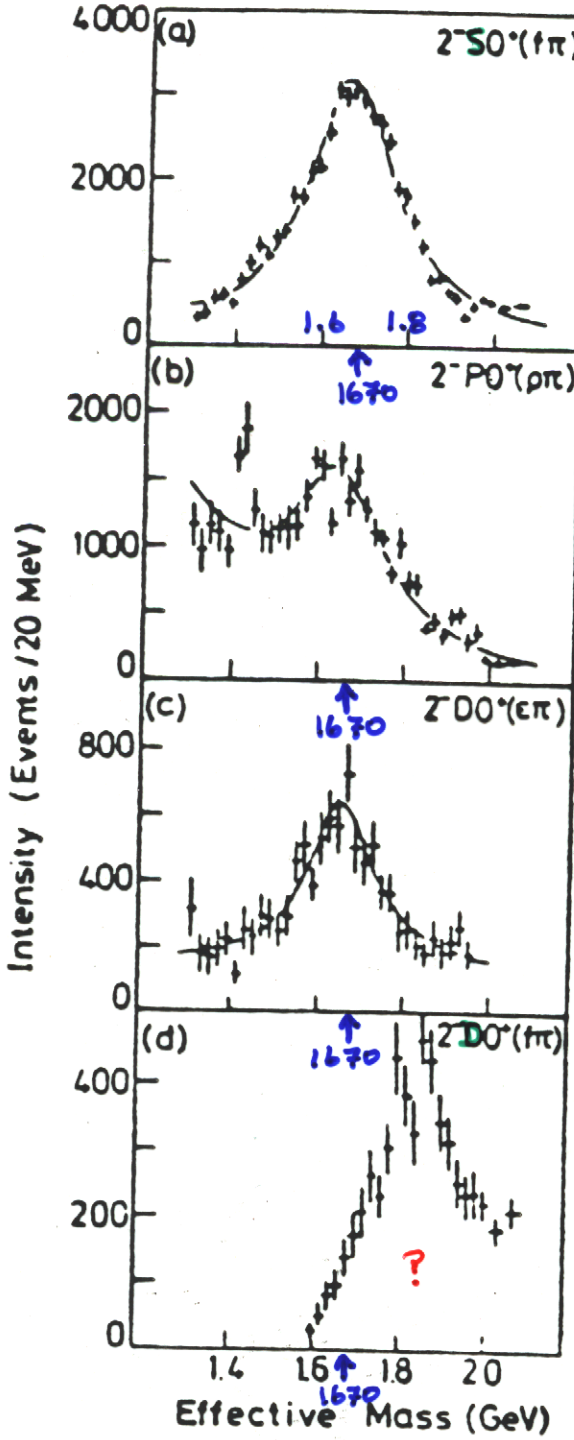


FIG. 2. For the reaction $\gamma p \rightarrow n\pi^+\pi^+\pi^-$: (a) The full 3π mass spectrum at $|t'_{\gamma,3\pi}| < 0.1$ GeV^2. The shaded area indicates the results of requiring at least one $\pi^+\pi^-$ combination to be a ρ^0; (b) the $\pi^+\pi^-$ spectrum for events with $1.7 \leq M(3\pi) \leq 1.9$ GeV/c^2.



$(f_2\pi)$ 2^{-+}
S

$\pi_2(1670)$ $^1D_2$ $q\bar{q}$

$(\rho\pi)$ 2^{-+}
P

$\pi_2(1670)$

$(f_0\pi)$ 2^{-+}
D

D. Aston et al
ACCMOR collab.
NPB189, 15 (1981).

$\pi_2(1670)$

$(f_2\pi)$
D

Peaks at about 1850Mev in 2^-

Not the $\pi_2(1670)$ 2^{-+}.

!!!

Next $q\bar{q}$ $I=1$ 2^{-+} expected at ≈ 2.2 Gev!

Figure 9. Intensities of 3π partial waves, showing the $f\pi(1850)$ enhancement.

TABLE V. Partial widths of 1D and hybrid $\pi_2(1800)$ states.

	$\rho\pi$	$\omega\rho$	$\rho_R\pi$	$b_1\pi$	$f_0\pi$	$f_1\pi$	$f_2\pi$	K*K	total
$\pi_{2(D)}(1800)$	162.	69.	0.	0.	1.	5.	86.	49.	372.
$\pi_{2(H)}(1800)$	8	0	5	15	1	0	50	1	80

	$\rho\pi$	$\rho\omega$	$\rho(1465)\pi$	$f_0(1300)\pi$	$f_2\pi$	K^*K	total
$\pi_{3S}(1800)$	30	74	56	6	29	36	231
$\pi_H(1800)$	30	0	30	170	6	5	≈240
		↑		↑			

	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	KK	K^*K	$h_1\pi$	$a_1\pi$	total
$\rho_{2S}(1465)$	74	122	25	–	35	19	1	3	279
$\rho_D(1700)$	48	35	16	14	36	26	124	134	435
$\rho_H(1500)$	0	5	1	0	0	0	0	140	≈150
	↑	↑					↑	↑	

$s\bar{s}$-hybrids CP

Table 5: As in table 3 but for an initial $s\bar{s}$-hybrid. Hybrid masses before spin splitting are 2.15 GeV, except for 0^{+-} (2.25 GeV). Final states containing K have $\tilde{\beta} = 0.40$ GeV, otherwise $\tilde{\beta} = 0.44$ GeV. For the hybrid we use $\beta_A = 0.30$ GeV.

"extra" $\eta_2^{s\bar{s}}$

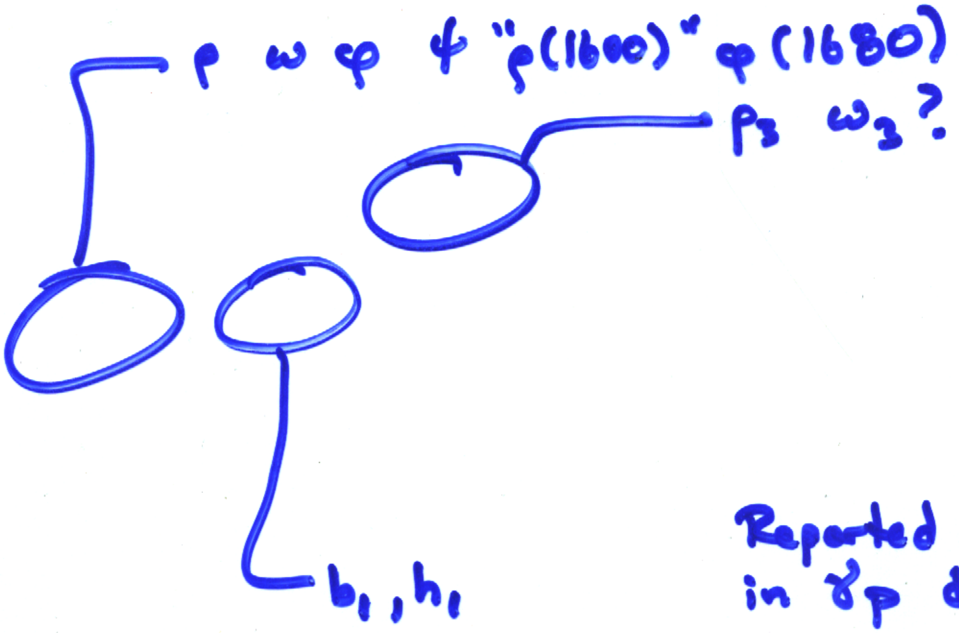
$s\bar{s}g$	B, C	L	Γ	$s\bar{s}g$	B, C	L	Γ	$s\bar{s}g$	B, C	L	Γ
2^{-+}	$K_2^*(1430)K$	S	100	1^{-+}	$K_1(1270)K$	S	40	0^{+-}	$K_1(1270)K$	P	400
	$K_1(1270)K$	D	20			D	60		$K_1(1400)K$	P	175
1^{+-}	$K_2^*(1430)K$	P	70		$K_1(1400)K$	S	250	0^{-+}	$K_2^*(1430)K$	D	20
	$K_1(1270)K$	P	250	2^{+-}	$K_2^*(1430)K$	P	90		$K_0^*(1430)K$	S	400
	$K_0^*(1430)K$	P	125		$K_1(1270)K$	P	30	1^{--}	$K_2^*(1430)K$	D	20
1^{++}	$K_2^*(1430)K$	P	125		$K_1(1400)K$	P	70		$K_1(1270)K$	S	60
	$K_1(1270)K$	P	70						$K_1(1400)K$	S	125
	$K_1(1400)K$	P	100								

"extra" φ

$h_2^{s\bar{s}}$

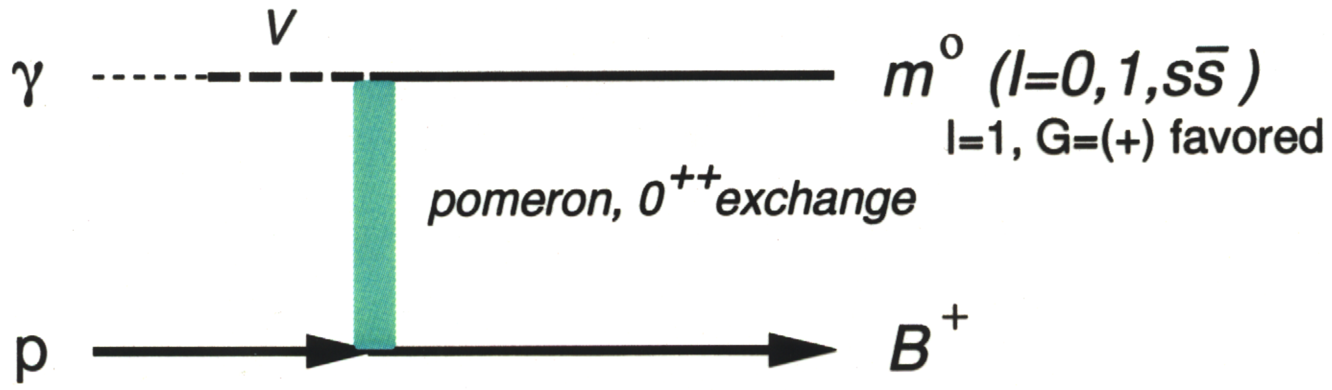
Table 6: Partial wave amplitudes $\check{M}_L(A \to BC)$ indicated in terms of the functions defined in eqn. 22 and named in accordance with partial waves S, P, D, F or G. We display various J^{PC} of the initial hybrid A decaying into pseudoscalar 0^{-+} (P) or vector 1^{--} (V) final mesons. Starred amplitudes vanish even with non-S.H.O. radial wave functions.

A	BC	$\check{M}_L$	A	BC	$\check{M}_L$	A	BC	$\check{M}_L$
2^{-+}	VP	$-\sqrt{15}P/\sqrt{2}$	1^{--}	PP	$0 \times P^*$	1^{+-}	VP	$2\sqrt{3}S$
		F		VP	$3P$			$\sqrt{3}D/\sqrt{2}$
	VV	$3\sqrt{5}P$		VV	$3\sqrt{2}P$		VV	$0 \times S^*$
		F			$0 \times F^*$			$3D$
1^{-+}	PP	$3P$	2^{+-}	PP	$\sqrt{3}D$	0^{+-}	PP	$-\sqrt{6}S$
	VP	$3P/\sqrt{2}$		VP	$3D/\sqrt{2}$		VV	$-\sqrt{2}S$
	VV	$3\sqrt{2}P$		VV	$2\sqrt{10}S$			$-2D$
		F			$2\sqrt{2}D$	1^{++}	VP	$\sqrt{6}S$
0^{-+}	VP	$\sqrt{6}P$			G			$-\sqrt{3}D$
	VV	$0 \times P^*$					VV	$2\sqrt{3}S$
								$-\sqrt{6}D$



Reported prev.
in γp diffr.

$V = (\rho^0, \omega, \varphi)$



$$J^{PC}\Big|_{m^0} = 1^{--} \quad \begin{array}{cccc} \boxed{2^{+-}} & 3^{--} & \boxed{4^{+-}} & 5^{--} \\ 1^{+-} & 2^{--} & 3^{+-} & 4^{--} \\ \boxed{0^{+-}} & 1^{--} & \boxed{2^{+-}} & 3^{--} \end{array} \quad \ldots$$

J^{PC}–exotic mesons accessible to diffractive protoproduction at CEBAF.

and elsewhere...

TABLE I. Partial widths of 2S, 1D and hybrid ρ states.

	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	KK	K*K	$h_1\pi$	$a_1\pi$	total
$\rho_{2S}(1465)$	74.	122.	25.	-	35.	19.	1.	3.	279.
$\rho_D(1700)$	48.	35.	16.	14.	36.	26.	124.	134.	435.
$\rho_H(1500)$	0	5	1	0	0	0	0	140	≈ 150

$\pi\pi$ $\pi\omega$ πh_1 πa_1

H marker

Donnachie-Kalashnikov
Close-Page

- $2S \rightarrow \pi\pi,\ \omega\pi$

  $\not\rightarrow \pi h_1,\ \pi a_1$

Clegg-Donnachie
$e^+e^- \rightarrow V$
review

Γ $\rho_R(1465)$ ~ 190 MeV
$\rightarrow \pi a_1$

$\pi h_1 \ll \pi a_1$
$\pi\pi \sim 20$ MeV
$\omega\pi \sim 60$ MeV

Γ $\rho_R(1700)$
$\pi\pi \sim 100$ MeV
$\omega\pi \sim 0$ MeV
$4\pi + 6\pi \sim 300$ MeV

- $D \rightarrow \pi\pi,\ \omega\pi$

  $\rightarrow \pi h_1,\ \pi a_1$

- $H \not\rightarrow \pi\pi,\ \omega\pi$

  $\not\rightarrow \pi h_1$

  $\rightarrow \pi a_1$

---

rst
case :

States may be

$$c_{2S}\,|2S\rangle + c_D\,|D\rangle + c_H\,|H\rangle$$

Barnes, Close, Page, Swanson. 99.

Kokoski-Isgur 99.

TABLE II. Partial widths of 2S, 1D and hybrid ω states.

	$\rho\pi$	$\omega\eta$	KK	K*K	$b_1\pi$!	total
$\omega_{2S}(1419)$ KI	328. 257.	12.	31. 12.-45.	5. 19.	1. 2.	378.
$\omega_{1D}(1649)$ KI	101. 72.	13.	35. 45.	21.	371. 440.	542.
$\omega_H(1500)$	20	1	0	0	0	≈ 20

Page: flux tube ω hybrid w/ M = 1.5 GeV !!!

xpt
uggests:

(Clegg - Donnachie)

$\Gamma^{\omega(1440)}$

$\rho\pi$ 240 MeV

$\omega\pi\pi$ 0

Γ_{tot} = 240(70) MeV

$\Gamma^{\omega(1606)}$

$\rho\pi$ 84 MeV

$\omega\pi\pi$ 29 MeV !

Γ_{tot} = 113(20) MeV

usually reported wider

1-peak fit

M = 1628(18) MeV

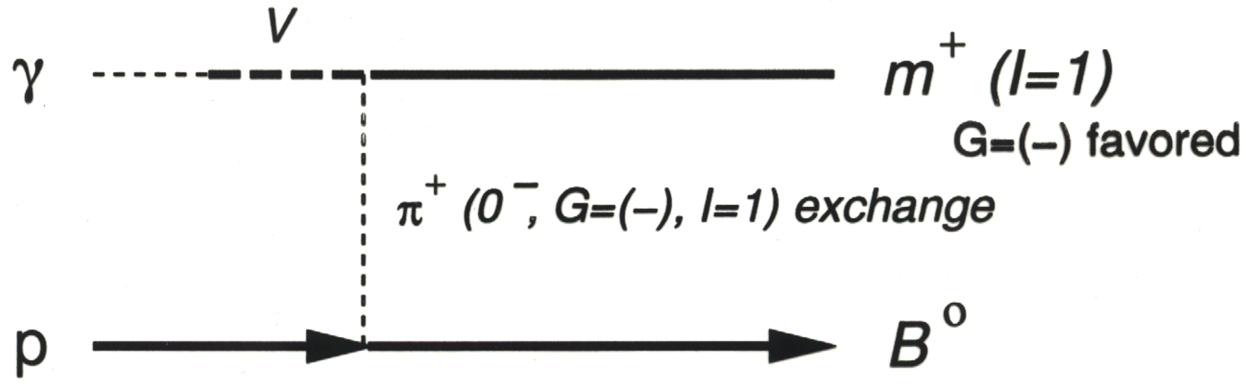
Γ = 381(49) MeV

Γ

$\rho\pi$ = 160 MeV

$\omega\pi\pi$ = 220 MeV

$V = (\rho^0, \omega, \varphi)$



$$J^{PC_n}\Big|_{m^+} = 1^{++} \quad \begin{array}{cccc} 2^{-+} & 3^{++} & 4^{-+} & 5^{++} \\ \boxed{1^{-+}} & 2^{++} & \boxed{3^{-+}} & 4^{++} \\ 0^{-+} & 1^{++} & 2^{-+} & 3^{++} \end{array} \quad \cdots$$

G=(–), C_n =(+) shown; G=(+), C_n =(–) also allowed but weaker.

J^{PC}–exotics produced by charged pion exchange photoproduction at CEBAF.

II. Experiment: (J^{PC} exotics)

a) $\pi_1(1600)$ Do we have a problem?

LGT predicts a $\pi_1(2000)$ exotic, with estimated error of ca.100 MeV.

The flux tube model predicted a $\pi_1(1900 +/- 100)$, with dominant decay modes $b_1\pi$ and $f_1\pi$.

Experimentally, we have 2 exotic candidates, $\pi_1(1600)$ and $\pi_1(1400)$, 400-600 MeV below the LGT mass prediction. Decays are not dominantly $b_1\pi$ and $f_1\pi$.

The $\pi_1(1600)$ is the clearest signal, our “best exotic”, since it is reported in 3 modes and has a relatively narrow reported width...

1^{-+} Exotic Discovery(?) $\pi_1(1400)$

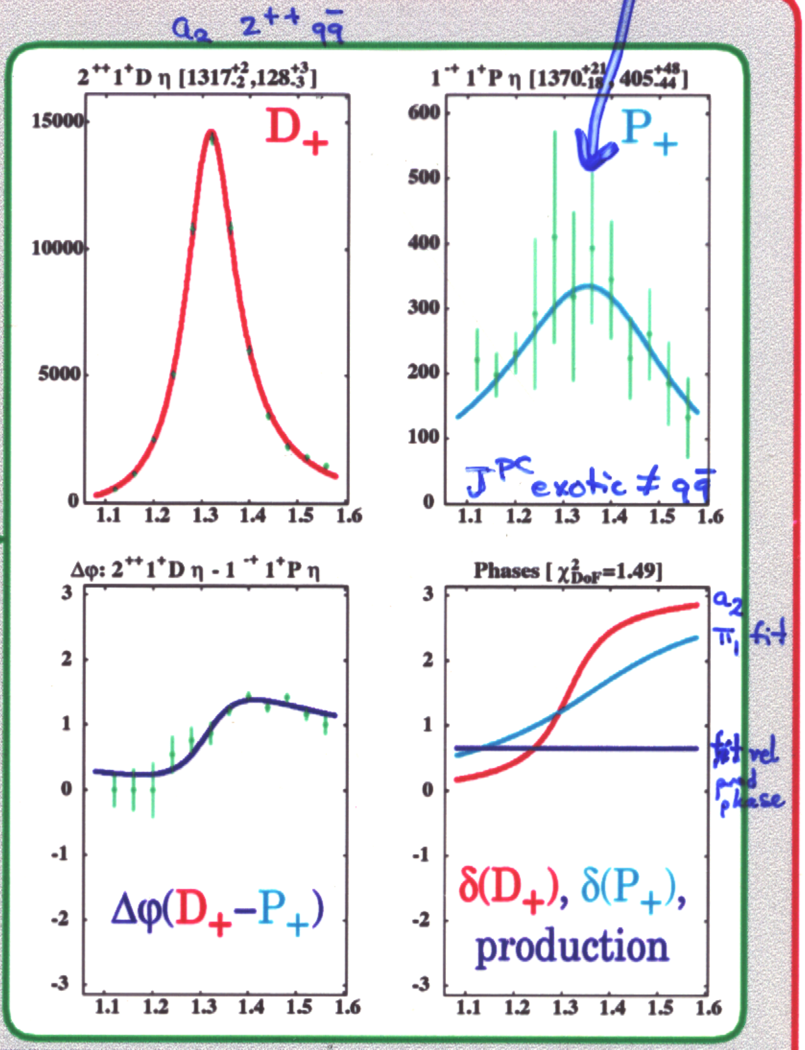
E852 HADRON97

$\pi^- p \to \underbrace{(\eta\pi^-)}\overline{p} \ldots$

$\eta\pi^-$

Breit–Wigner Parameterization

- ✧ Mass–dependent PWA with Breit–Wigner parameterized production amplitudes
- ✧ Mass–independent PWA: χ^2 fit of the results



- ✤ Resonant D_+
  Resonant P_+
  Constant Prod.Phase
  χ^2=1.49
- ✤ Resonant D_+
  Nonresonant P_+
  Linear Prod.Phase
  (slope –4.9 rad/GeV)
  χ^2=1.55
- ✤ Resonant D_+
  Nonresonant P_+
  Constant Prod.Phase
  χ^2=7.09

Multiple χ^2 fits of the randomly choosen ambiguous solutions

$J^{PC}=1^{-+}$ $\pi_1(1370)$:

$$M=1370\pm16^{+50}_{-30}\ \mathrm{MeV}/c^2$$

$$\Gamma=385\pm40^{+65}_{-105}\ \mathrm{MeV}/c^2$$

ELSEVIER

19 March 1998

PHYSICS LETTERS B

Physics Letters B 423 (1998) 175–184

$\bar{p}n \rightarrow \eta\pi^0\pi^-$

Exotic $\eta\pi$ state in $\bar{p}d$ annihilation at rest into $\pi^-\pi^0\eta\, p_{\mathrm{spectator}}$

Crystal Barrel Collaboration

1^{-+} $\pi_1(1400)$
confirmed?

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M. Benayoun [l], A. Berdoz [m], K. Beuchert [b], S. Bischoff [h], P. Blüm [h], K. Braune [k],
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N. Djaoshvili [h], S. v. Dombrowski [o,1], M. Doser [f], W. Dünnweber [k], A. Ehmanns [c],
D. Engelhardt [h], M.A. Faessler [k], P. Giarritta [o], R.P. Haddock [j], F.H. Heinsius [a,2],
M. Heinzelmann [o], A. Herbstrith [h], M. Herz [c], N.P. Hessey [k], P. Hidas [d], C. Hodd [i],
C. Holtzhaußen [h], K. Hüttmann [k,4], D. Jamnik [k,5], H. Kalinowsky [c], B. Kämmle [g],
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U. Kurilla [b], M. Lakata [a], R. Landua [f], H. Matthäy [b], R. McCrady [m], J. Meier [g],
C.A. Meyer [m], L. Montanet [f], R. Ouared [f], F. Ould-Saada [o], K. Peters [b], B. Pick [c],
C. Pietra [o], C.N. Pinder [e], M. Ratajczak [b], C. Regenfus [k], S. Resag [c], W. Roethel [k],
P. Schmidt [g], I. Scott [i], R. Seibert [g], S. Spanier [o], H. Stöck [b], C. Straßburger [c],
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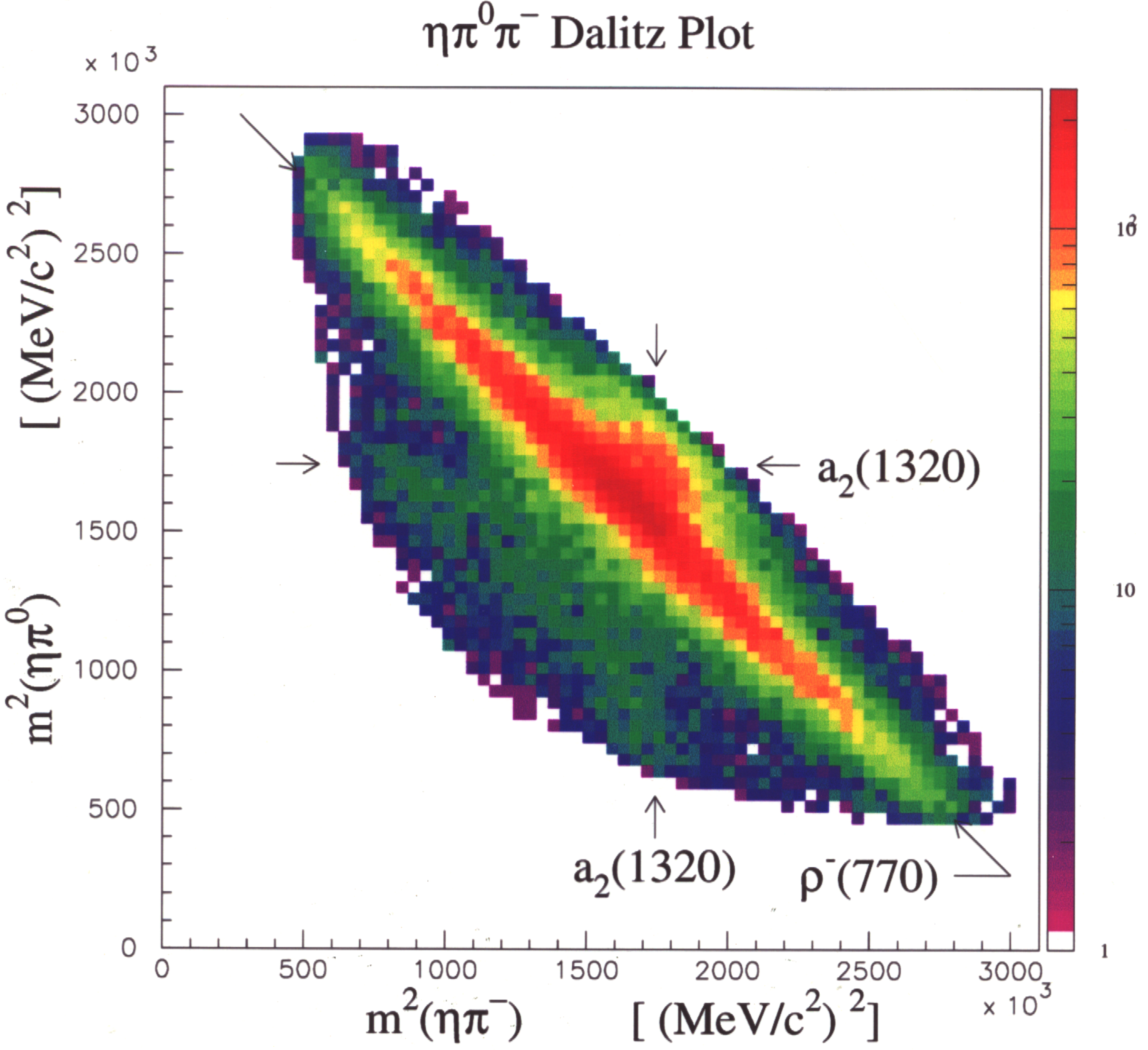
Abstract

With antiprotons stopped in liquid deuterium, the $\bar{p}n$ annihilation channel $\pi^-\pi^0\eta$ was studied using a final sample of 52 576 events obtained for a spectator proton momentum < 100 MeV/c. In the intensity distribution the $\eta\pi$ P-wave is clearly apparent by its interferences with the dominant $\rho^-(770)$ and $a_2^-(1320)$ two-meson resonances. A partial wave analysis of the data yields evidence for resonant behaviour of the $\eta\pi$ P-wave, which has the non-$q\bar{q}$ quantum numbers $I^G = 1^-$, $J^{PC} = 1^{-+}$. The extracted Breit-Wigner resonance parameters are $m = (1400 \pm 20 \pm 20)$ MeV/c^2 and $\Gamma = (310 \pm 50^{+50}_{-30})$ MeV/c^2. © 1998 Published by Elsevier Science B.V.

0370-2693/98/$19.00 © 1998 Published by Elsevier Science B.V. All rights reserved.

PII S0370-2693(98)00123-3

Crystal Barrel Confirmation of the $\pi_1(1400)$ exotic signal in $\bar{p}n \rightarrow \eta\pi^0\pi^-$



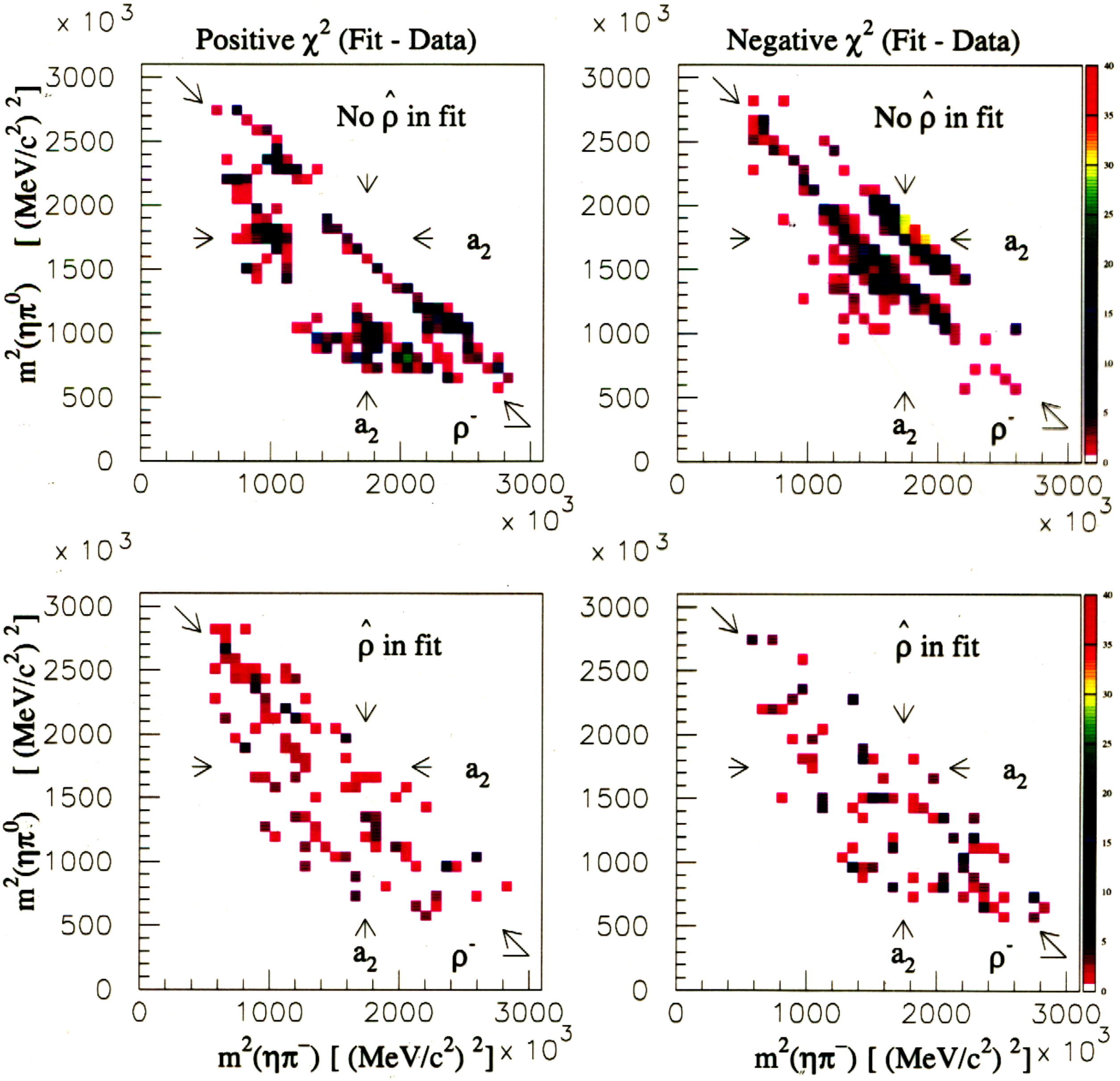

Positive χ^2 (Fit - Data)
Negative χ^2 (Fit - Data)
No $\hat{\rho}$ in fit
No $\hat{\rho}$ in fit
$\hat{\rho}$ in fit
$\hat{\rho}$ in fit
a_2
a_2
ρ^-
$m^2(\eta\pi^0)$ [(MeV/c^2) ^{2}]
$m^2(\eta\pi^-)$ [(MeV/c^2) ^{2}]
x 10^3
0
500
1000
1500
2000
2500
3000
0
5
10
15
20
25
30
35
40

TABLE II. Comparison of the results of E852 and the Crystal Barrel for the parameters of the $J^{PC} = 1^{-+}$ resonance.

	Mass (MeV/c^2)	Width (MeV/c^2)
E852	$1370 \pm 16\ ^{+50}_{-30}$	$385 \pm 40\ ^{+65}_{-105}$
Crystal Barrel	$1400 \pm 20 \pm 20$	$310 \pm 50\ ^{+50}_{-30}$

Only problem if this state ∃ is $M \ll M_{\text{theor.}} \cong 1.9$ GeV !

Also surprisingly broad since $\eta\pi$ is not a favored mode.

Other explanations needed,

e.g. inelastic effect like $b_1\pi$ channel opening fakes a resonant phase ?

nb

Dzierba — E852 bkg shows rapid variation near 1.4 GeV & is comparable in size to signal

Hybrid decay modes ?   flux tube model ($\sim {}^3P_0$ model)

≈ confirm Isg. Pat. Kok.

Table 2
Widths in MeV for *hybrid* $A \to BC$ for exotic hybrid J^{PC} in partial wave L. Here π, ω and ϕ indicate flavour states $\sqrt{\frac{1}{2}}(u\bar{u} - d\bar{d})$, $\sqrt{\frac{1}{2}}(u\bar{u} + d\bar{d})$ and $s\bar{s}$ respectively. We adopted hybrid masses of 1.9 GeV (π, ω) and 2.1 GeV (ϕ); a ${}^3P_1/{}^1P_1$ mixing of 45° in the P-wave kaon sector; and assumed $f = 1$, $\kappa = 1$, $\delta = 1$ in order to *compare* with the widths Γ_2 of Ref. [16]. Our optimal fit to Ref. [16] gives widths Γ_1 (see Section 4).

I=1 1^{-+}

A	B, C	L	Γ_1	Γ_2
$\pi 1^{-+}$	$b_1(1235)\pi$	S	100	100
		D	20	30
	$f_1(1285)\pi$	S	30	30
		D	20	20
$\omega 1^{-+}$	$a_1(1260)\pi$	S	90	100
		D	60	70
	$K_1(1400)K$	S	100	100
$\pi 2^{+-}$	$a_2(1320)\pi$	P	350	450
	$a_1(1260)\pi$	P	100	100
	$h_1(1170)\pi$	P	125	150

A	B, C	L	Γ_1	Γ_2
$\phi 1^{-+}$	$K_1(1270)K$	D	90	80
	$K_1(1400)K$	S	200	250
$\pi 0^{+-}$	$a_1(1260)\pi$	P	600	800
	$h_1(1170)\pi$	P	100	100
$\omega 0^{+-}$	$b_1(1235)\pi$	P	250	250
$\phi 0^{+-}$	$K_1(1270)K$	P	500	800
	$K_1(1400)K$	P	70	50
$\omega 2^{+-}$	$b_1(1235)\pi$	P	350	500
$\phi 2^{+-}$	$K_2^*(1430)K$	P	300	250
	$K_1(1400)K$	P	250	200

π_1 not broad if at 1.9GeV! $\eta\pi$... expected weak.

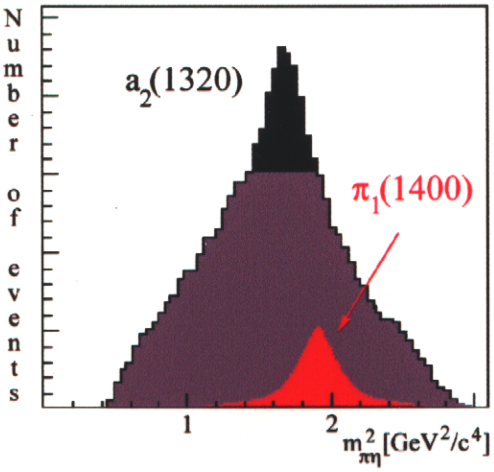
If we use the same hadron masses as Ref. [16], follow their prescription (as outlined in Ref. [15]) of ignoring all quark flavour symmetry breaking and normalizing the decays as above, we find that the optimal comparison with Ref. [16] follows with $\beta_A = 0.27$ GeV and $\tilde{\beta} = 0.28$ GeV throughout: this gives the widths in Table 2. We confirm their result that the decays indicated are dominant, except for the case $J^{PC} = 0^{+-}$ where we find also prominent decays $(\pi, \omega)0^{+-} \to K_1(1270)K$ (with width 400 MeV) and $\pi 1^{-+} \to K_1(1400)K$ (with width 100 MeV) which were not listed in Ref. [16].

Our analysis provides an independent check on the results of Ref. [16] and enables us to examine their sensitivity to the parameters. This merits attention since the best fit to the widths of conventional mesons by Ref. [15] used a rather different value for β, namely $\beta_A = \tilde{\beta} = 0.4$. Indeed, this is in line with the modern preferred values from harmonic oscillator basis approximations to meson spectroscopy e.g. in the ISGW work [18]. Our preferred choice today is to adopt the harmonic oscillator basis fit to spin-averaged meson spectroscopy of Ref. [18]. Wherever values for β are not available, we abstract them from the mean meson radii of Merlin [27]. We take the string tension $b = 0.18$ GeV^2, and the constituent-quark masses $m_u = m_d = 0.33$ GeV, $m_s = 0.55$ GeV and $m_c = 1.82$ GeV. Meson masses are taken from Ref. [28], and where not available (as in the case of ${}^3P_1/{}^1P_1$ mixing angles) we abstract them from spectroscopy predictions [26] suitably adjusted relative to known masses. Hybrid β's,

2.1.3.2 Light Hybrids

Two spin-exotic 1^{-+} states, $\pi_1(1400)$ and $\pi_1(1600)$, have been found in $\pi^- p$ reactions and more recently in $\bar{p}p$ annihilations [23,24,18,19]. The most striking feature is that their production rate in $\bar{p}p$ annihilation is comparable to that of normal $q\bar{q}$ states (see Figure 2.9). This feature makes annihilation reactions a prime tool in the search for further exotic states.

Several predictions put 1^{-+} hybrids at masses around 2 GeV/c² [22,32]. The discrepancy between these predictions and the experimentally measured $\pi_1(1400)$ and $\pi_1(1600)$ needs further clarification. This can be done by measuring an entire spectrum of light hybrids by means of formation and production experiments. As in the search for charmonium hybrids, experiments would take advantage of the dynamical selection rule forbidding $c\bar{c}g \rightarrow (\bar{c}q)_{L=0} + (c\bar{q})_{L=0}$ reactions and thus enhancing light-hybrid decays into specific final states, e.g., $f_1(1285)\pi$, $b_1(1235)\pi$ and $K_1\bar{K}$. Given the relatively large cross sections (on the order of μb), conclusive results should be achievable within a few months of measuring time.



large $\pi_1(1400)$
exotic signal
in $\bar{p}d \rightarrow [\pi^-\eta]\pi^0 p$

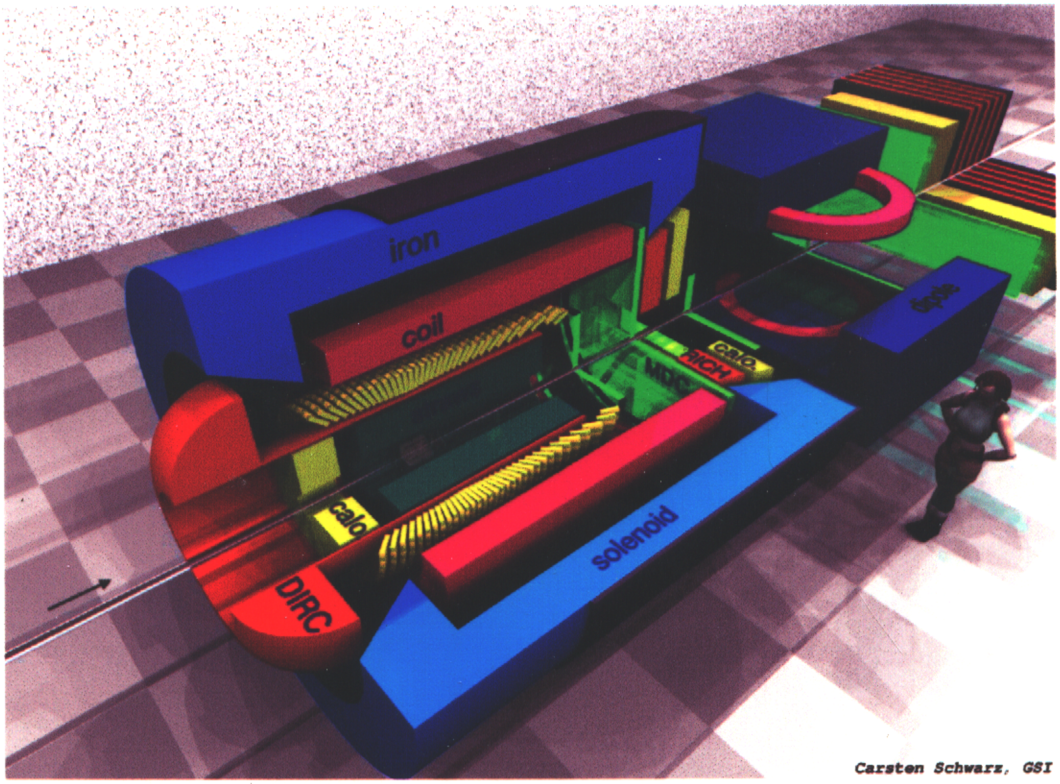
Figure 2.9. Square of the invariant $\pi^-\eta$ mass as measured in the $\bar{p}d \rightarrow \pi^-\eta\pi^0 p$ reaction by the Crystal Barrel Collaboration at LEAR [18]. The peak at 1.7 GeV²/c⁴ corresponds to the well known $2^{++}\bar{q}q$ meson $a_2(1320)$, the structure at 2.0 GeV²/c⁴ to the exotic $\pi_1(1400)$. The shoulder at 2.4 GeV²/c⁴ is a kinematical reflection of the $\rho(770)$. The π_1 state has the quantum numbers $J^{PC} = 1^{-+}$ and thus cannot be a $\bar{q}q$ state. The a_2 and the π_1 signals are of similar size, thus demonstrating that $\bar{q}q$ and exotic states are produced in $\bar{p}N$ annihilations at similar rates.

2.1.3.3 Glueballs

There have been many searches for the glueball ground state over the last twenty-five years, but the best candidate has emerged recently from $\bar{p}p$ annihilation experiments. This rather narrow state, called $f_0(1500)$, has the non-exotic quantum numbers $J^{PC} = 0^{++}$. Since it mixes with nearby conventional $0^{++}q\bar{q}$-states, the $f_0(1500)$

GSI project

scientists, mainly from Europe with particularly strong participation from Italy and Germany.



Carsten Schwarz, GSI

Figure 2.1. Artist's view of the universal detector system for experiments at the internal target of the antiproton storage ring. It allows the detection and identification of neutral and charged particles generated over the relevant angular and energy range. This task will be shared by the combination of a central and a forward spectrometer of modular design which are optimized for the specific kinematics of the antiproton annihilation process.

In comparison with other facilities, the physics opportunities outlined in the present proposal go far beyond the earlier SUPER-LEAR concept and are complementary to the physics program at the planned Japanese High Intensity Hadron Facility which is focused on kaon- and neutrino beams. The search for gluonic excitations at HESR is complementary to the corresponding program at the proposed 12 GeV upgrade at Jefferson lab which – due to the accelerator energy – is limited to light quark hybrids. There is partial overlap with research at BES and the D meson physics program proposed at Cornell where - being e^+e^- colliders - studies of in-medium meson properties can, however, not be performed. With the realization of the HESR-project, GSI will thus play a pioneering and unique role in the experimental exploration of *long distance (non-perturbative) QCD* and the *structure of hadronic matter*. GSI has a distinguished history of many important contributions to the physics of the strong interaction. This program will enable GSI to play an equally significant role in the future.

The exotic everyone likes. (as a hybrid candidate)

Observation of a New $J^{PC} = 1^{-+}$ Exotic State in the Reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c

$\pi_1(1600) \to \rho\pi$

BNL E852

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also VES.
Evidence in $\rho\pi$
$b_1\pi$
$\eta'\pi$.

(Received 4 June 1998)

A partial-wave analysis of the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c has been performed on a data sample of 250 000 events obtained by Brookhaven experiment E852. The expected $J^{PC} = 1^{++} a_1(1260)$, $2^{++} a_2(1320)$, and $2^{-+} \pi_2(1670)$ resonant states are clearly observed. The exotic $J^{PC} = 1^{-+}$ wave produced in the natural parity exchange processes shows distinct resonancelike phase motion at about 1.6 GeV/c^2 in the $\rho\pi$ channel. A mass-dependent fit results in a resonance mass of $1593 \pm 8^{+29}_{-47}$ MeV/c^2 and a width of $168 \pm 20^{+150}_{-12}$ MeV/c^2. [S0031-9007(98)07994-0]

PACS numbers: 12.39.Mk, 13.25.Jx, 13.85.Hd, 14.40.Cs

Much progress has been made in recent years in the theoretical description of hadrons which lie outside the scope of the constituent quark model. Quantum chromodynamics (QCD) predicts the existence of multiquark $q\bar{q}q\bar{q}$ and hybrid $q\bar{q}g$ mesons as well as purely gluonic states. The most suggestive experimental evidence for an exotic meson would be the determination of quantum numbers $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$, etc. A $q\bar{q}$ pair cannot form a state with such quantum numbers.

Several isovector 1^{-+} exotic candidates have been reported recently. A 1^{-+} signal in the $\eta\pi$ channel has been seen by several groups. Although early measurements [1,2] were inconclusive, the most recent measurements [3,4] have presented strong evidence for a 1^{-+} state near 1.4 GeV/c^2. Another 1^{-+} state with a mass of 1.6 GeV/c^2 was observed in the $\eta'\pi$ [2] and $\rho\pi$ [5] channels. Additionally, a state with resonant phase behavior has been seen above 1.9 GeV/c^2 in the $f_1\pi$ [6] channel.

Theoretical predictions for the mass of the lightest 1^{-+} hybrid meson are based on various models. The flux tube model [7,8] predicts 1^{-+} states at 1.8–2.0 GeV/c^2. Similar results are obtained in the calculations based upon lattice QCD in the quenched approximation [9]. Earlier bag model estimates suggest somewhat lower masses in the 1.3–1.8 GeV/c^2 range [10]. Quantum chromodynamics sum-rule predictions vary widely between 1.5 and 2.5 GeV/c^2 [11]. The diquark cluster model [12] predicts the 1^{-+} state to be at 1.4 GeV/c^2. Finally, the constituent gluon model [13] concludes that light exotics should lie in the region 1.8–2.2 GeV/c^2. Most of these models predict the dominance of such decay modes of the hybrid meson as $b_1(1235)\pi$ or $f_1(1285)\pi$, with small (but non-negligible) $\rho\pi$ decay probability [14].

In this Letter we present experimental evidence for an isovector 1^{-+} exotic meson produced in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$. Experiment E852 was performed at the Multi-Particle Spectrometer facility at Brookhaven National Laboratory (BNL). The experimental apparatus is described elsewhere [3,15,16]. A π^- beam of momentum 18.3 GeV/c and a liquid hydrogen target were used. The trigger was based on the requirement of three forward-going charged tracks and one charged recoil track. Seventeen million triggers of this type were recorded by the experiment during the 1994 run. After reconstruction, 700 000 events with the correct topology remain. Of these, 250 000 events remain after kinematic cuts are applied to ensure an exclusive sample of events with a proton recoil.

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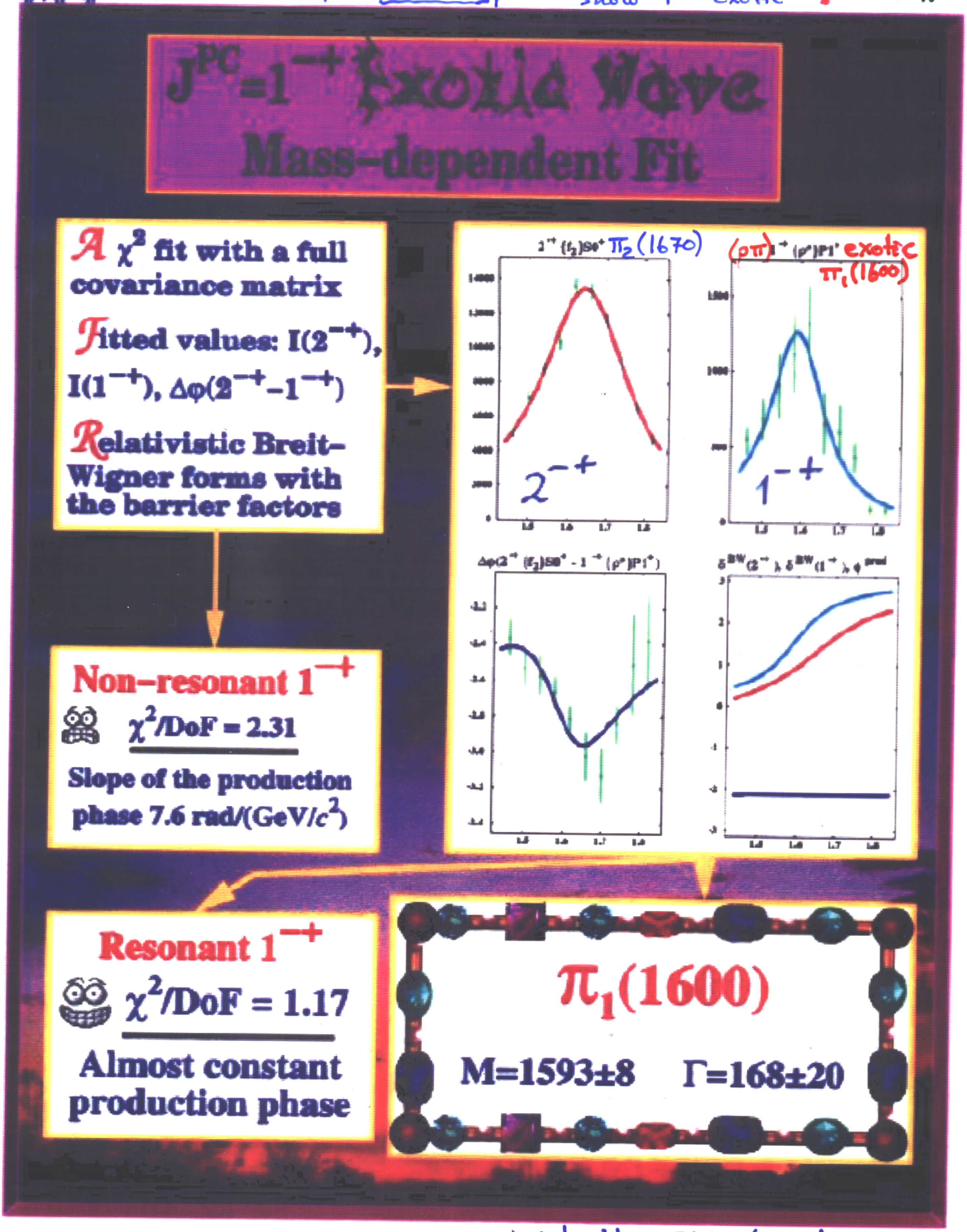
$\pi^+\pi^-\pi^-$ E852 $\pi^- p \rightarrow \boxed{\pi^+\pi^-\pi^-}\, p \longrightarrow$ $\rho\pi$ amplitudes show 1^{-+} exotic ! "quacks like a duck"



$J^{PC}=1^{-+}$ Exotic Wave
Mass-dependent Fit

A χ^2 fit with a full covariance matrix

Fitted values: $I(2^{-+})$, $I(1^{-+})$, $\Delta\varphi(2^{-+}-1^{-+})$

Relativistic Breit–Wigner forms with the barrier factors

Non-resonant 1^{-+}

χ^2/DoF = 2.31

Slope of the production phase 7.6 rad/(GeV/c^2)

Resonant 1^{-+}

χ^2/DoF = 1.17

Almost constant production phase

$\pi_1(1600)$

M=1593±8 Γ=168±20

A. Ostrovidov, E852 (BNL)

E852 $\pi_1(1600)$ in $\eta'\pi^-$

Observation of Exotic Meson Production in the Reaction $\pi^- p \rightarrow \eta'\pi^- p$ at 18 GeV/c

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(Received 2 February 2001)

An amplitude analysis of an exclusive sample of 5765 events from the reaction $\pi^- p \rightarrow \eta'\pi^- p$ at 18 GeV/c is described. The $\eta'\pi^-$ production is dominated by natural parity exchange and by three partial waves: those with $J^{PC} = 1^{-+}$, 2^{++}, and 4^{++}. A mass-dependent analysis of the partial-wave amplitudes indicates the production of the $a_2(1320)$ meson as well as the $a_4(2040)$ meson, observed for the first time decaying to $\eta'\pi^-$. The dominant, exotic (non-$q\bar{q}$) 1^{-+} partial wave is shown to be resonant with a mass of $1.597 \pm 0.010^{+0.045}_{-0.010}$ GeV/c^2 and a width of $0.340 \pm 0.040 \pm 0.050$ GeV/c^2. This exotic state, the $\pi_1(1600)$, is produced with a t dependence which is different from that of the $a_2(1320)$ meson, indicating differences between the production mechanisms for the two states.

DOI: 10.1103/PhysRevLett.86.3977 PACS numbers: 13.85.Ni, 14.40.Cs, 25.40.Qa

Exotic mesons—those whose valence structure is not composed of a quark-antiquark ($q\bar{q}$) pair—have been discussed [1–10] for many years but have only recently been observed experimentally. The underlying structure of the observed exotic states at 1.4 GeV/c^2 decaying into $\eta\pi^-$ [11–13] and at 1.6 GeV/c^2 decaying into $\rho^0\pi^-$ [14] is not yet understood. Possible explanations for these $I = 1$ states could be that they are hybrid mesons, consisting of a $q\bar{q}$ pair and a constituent gluon, or four-quark ($q\bar{q}q\bar{q}$) states. However, within the framework of the flux-tube model the masses of these states are somewhat low to be hybrid mesons [6]; and four-quark states are expected to be very broad [1].

Since the models for exotic mesons typically predict masses, widths, and branching ratios, and since it is important to classify the exotic states to provide necessary input to the QCD models, there is a strong motivation to search for additional states as well as to search for additional decay modes for the observed states. In this paper, we describe the search for exotic states decaying into the $\eta'\pi^-$ final state using the reaction $\pi^- p \rightarrow \eta'\pi^- p$, where $\eta' \rightarrow \eta\pi^+\pi^-$ and $\eta \rightarrow \gamma\gamma$.

The data sample was collected during the 1995 run of experiment E852 at the Multi-Particle Spectrometer facility at Brookhaven National Laboratory (BNL). A π^- beam with laboratory momentum 18 GeV/c and a liquid hydrogen target were used. A detailed description of the experimental apparatus can be found elsewhere [12].

The trigger required three forward-going charged tracks, a charged recoil track, and a signal in a lead-glass electromagnetic calorimeter (LGD). A total of 165×10^6 triggers of this type were recorded. After reconstruction, 1.37×10^6 events satisfied the trigger topology and had two clusters in the LGD. The η signal is seen in the $\gamma\gamma$ effective mass distribution in Fig. 1(a). Applying kinematic

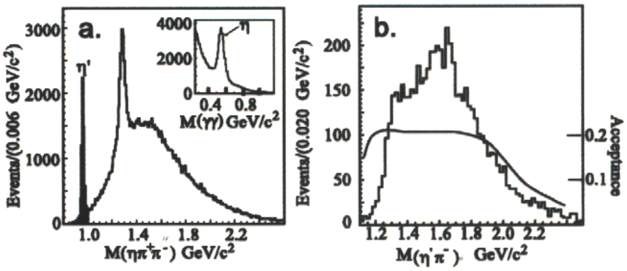

FIG. 1. (a) The $\eta\pi^+\pi^-$ effective mass distribution for events consistent with the reaction $\pi^- p \rightarrow p\eta\pi^+\pi^+\pi^-$ (two entries per event). The inset shows the $\gamma\gamma$ effective mass distribution in 0.01 GeV/c^2 bins. (b) The $\eta'\pi^-$ effective mass distribution. The distributions are uncorrected for acceptance. The smooth curve in (b) shows the true mass acceptance based upon the angular distributions determined in the partial-wave analysis.

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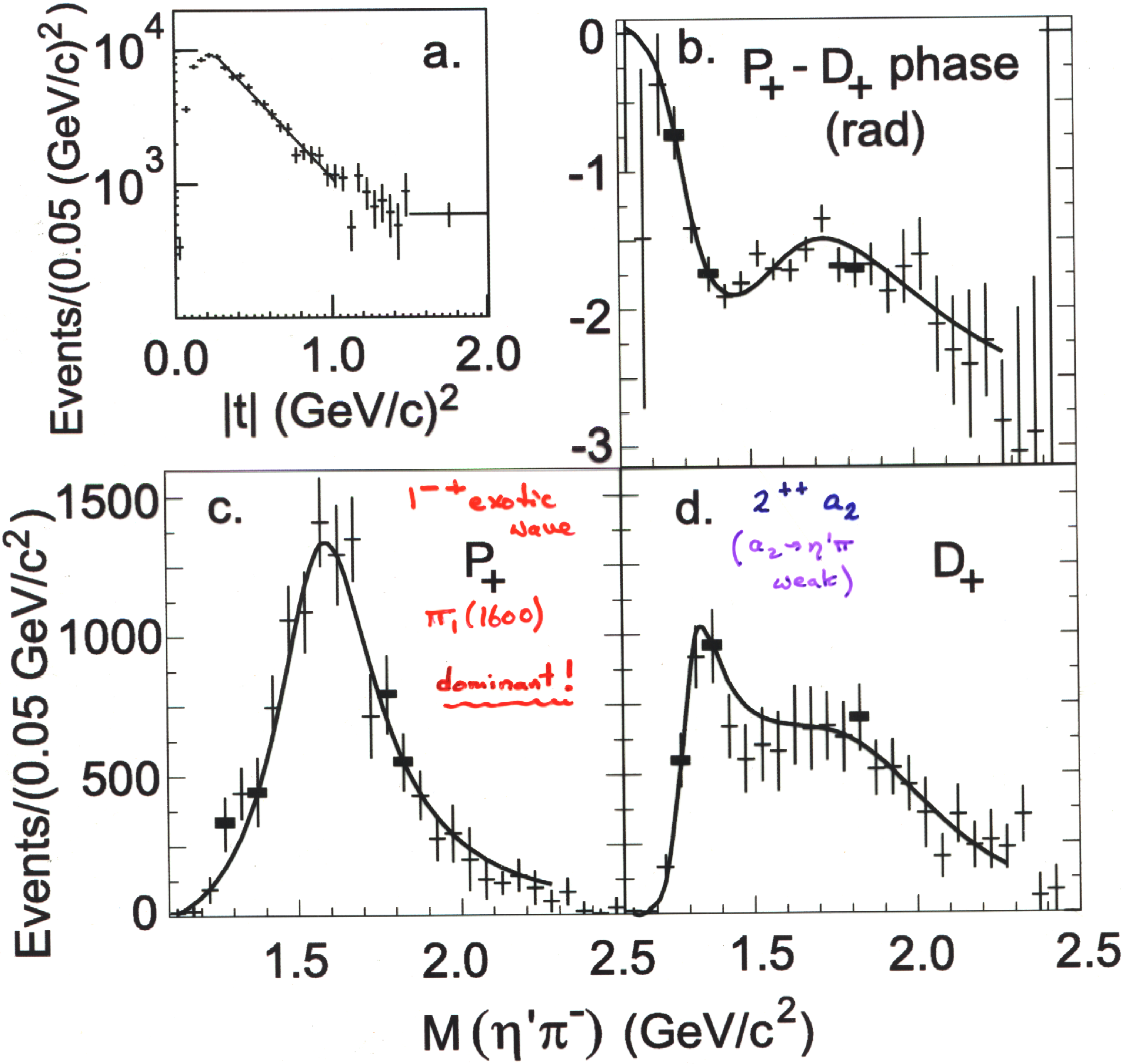
E852 $\eta'\pi^-$



1^{-+} exotic wave

$\pi_1(1600)$

dominant!

2^{++} a_2

($a_2 \to \eta'\pi$ weak)

$I=1$ hybrids, "forbidden" S+S modes

Table 7: Dominant widths in MeV for $\sqrt{\frac{1}{2}}(u\bar{u}-d\bar{d})$ *hybrid* $A \rightarrow BC$, where B and C are both L=0 quarkonia. $\Gamma = \Gamma_R \times (eqn.\ 24)$. $\eta(\eta')$ indicates $\sqrt{\frac{1}{2}}(u\bar{u}+d\bar{d})$ at 550 MeV (960 MeV) respectively. Starred Γ's tend to be < 1 MeV, and are highly sensitive to model dependent assumptions about final state β's.

A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ
π_2 2^{-+}	$\rho\pi$	P	40	8	1^{+-}	$\omega\pi$	S	70	15	1^{--}	$\omega\pi$	P	40	8
	$\rho\eta$	P	15	4		K^*K	S	200	30		K^*K	P	30	4
	$\rho\eta'$	P	8	2	1^{-+}	$\eta\pi$	P	40	*	1^{++}	$\rho\pi$	S	80	20
	K^*K	P	15	2		$\eta'\pi$	P	40	*		$\rho\eta$	S	60	15
	$\rho\omega$	P	70	*		$\rho\pi$	P	40	8		$\rho\eta'$	S	70	15
0^{-+}	$\rho\pi$	P	150	30		$\rho\eta$	P	20	4		K^*K	S	125	15
	$\rho\eta$	P	70	15		$\rho\eta'$	P	9	2		$\rho\omega$	S	125	*
	$\rho\eta'$	P	40	8		K^*K	P	15	2					
	K^*K	P	60	8		$\rho\omega$	P	50	*					

$\pi_1 \rightarrow$ S+S modes, f.t.m.

n.b. Close & Lipkin suggest another $\pi_1 \rightarrow \eta'\pi$ decay mech.

$I=0$ hybrids, "forbidden" S+S modes

Table 8: As in table 7 but for initial hybrid $\sqrt{\frac{1}{2}}(u\bar{u}+d\bar{d})$.

A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ
1^{--}	$\rho\pi$	P	100	20	2^{-+}	K^*K	P	15	2	1^{+-}	$\rho\pi$	S	200	40
	$\omega\eta$	P	30	7	1^{-+}	$\eta'\eta$	P	30	*		$\omega\eta$	S	100	20
	$\omega\eta'$	P	15	3		K^*K	P	15	2		$\omega\eta'$	S	150	30
	K^*K	P	30	4	1^{++}	K^*K	S	125	15		K^*K	S	200	30
2^{+-}	$\rho\pi$	D	5	1	0^{-+}	K^*K	P	60	8					

Table 9: As in table 7 but for initial hybrid $s\bar{s}$, and $\eta(\eta')$ indicating $s\bar{s}$ at 550 MeV (960 MeV) respectively.

A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ	A	B,C	L	Γ_R	Γ
1^{--}	K^*K	P	90	15	1^{+-}	K^*K	S	150	20	1^{-+}	$\eta'\eta$	P	70	*
	$\phi\eta$	P	60	8		$\phi\eta$	S	350	40		K^*K	P	50	6
	$\phi\eta'$	P	15	2		$\phi\eta'$	S	350	40	1^{++}	K^*K	S	80	10
2^{+-}	K^*K	D	6	1	0^{-+}	K^*K	P	175	30	2^{-+}	K^*K	P	40	6

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Hybrid Baryons (a brief review)

I. Status of hybrid *mesons*

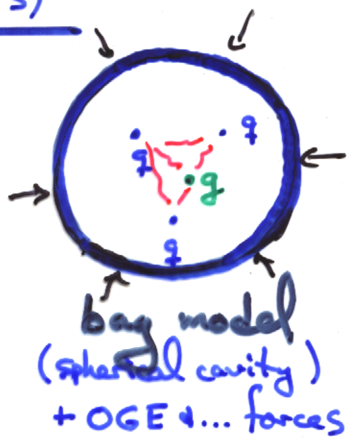
II. Theoretical expectations:

Bag model
QCD sum rules
Flux tube model

III. Experiment

(short section: basically isn´t any).

T. Barnes + F E Close PL128B, 277 (1983)



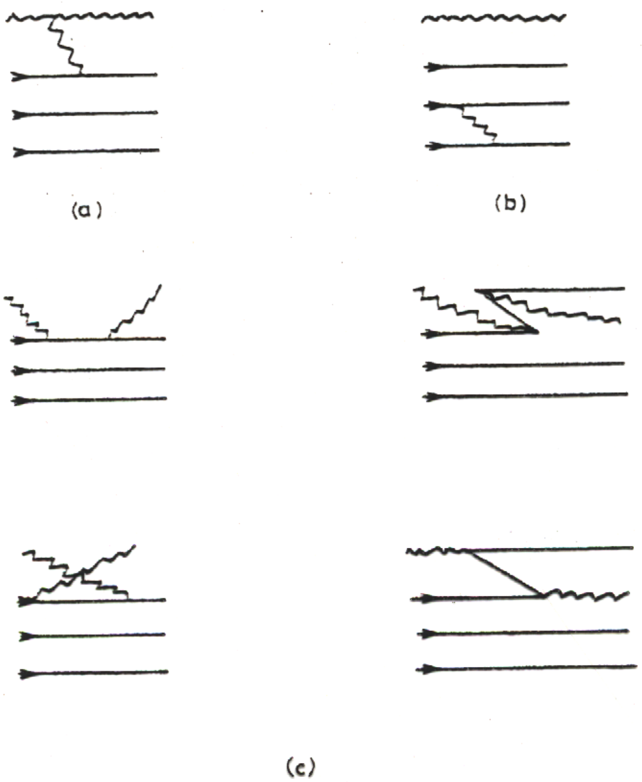


Fig. 1. O(α_s) energy shifts. (a) Gluon hyperfine. (b) Quark hyperfine. (c) Compton and Z graphs.

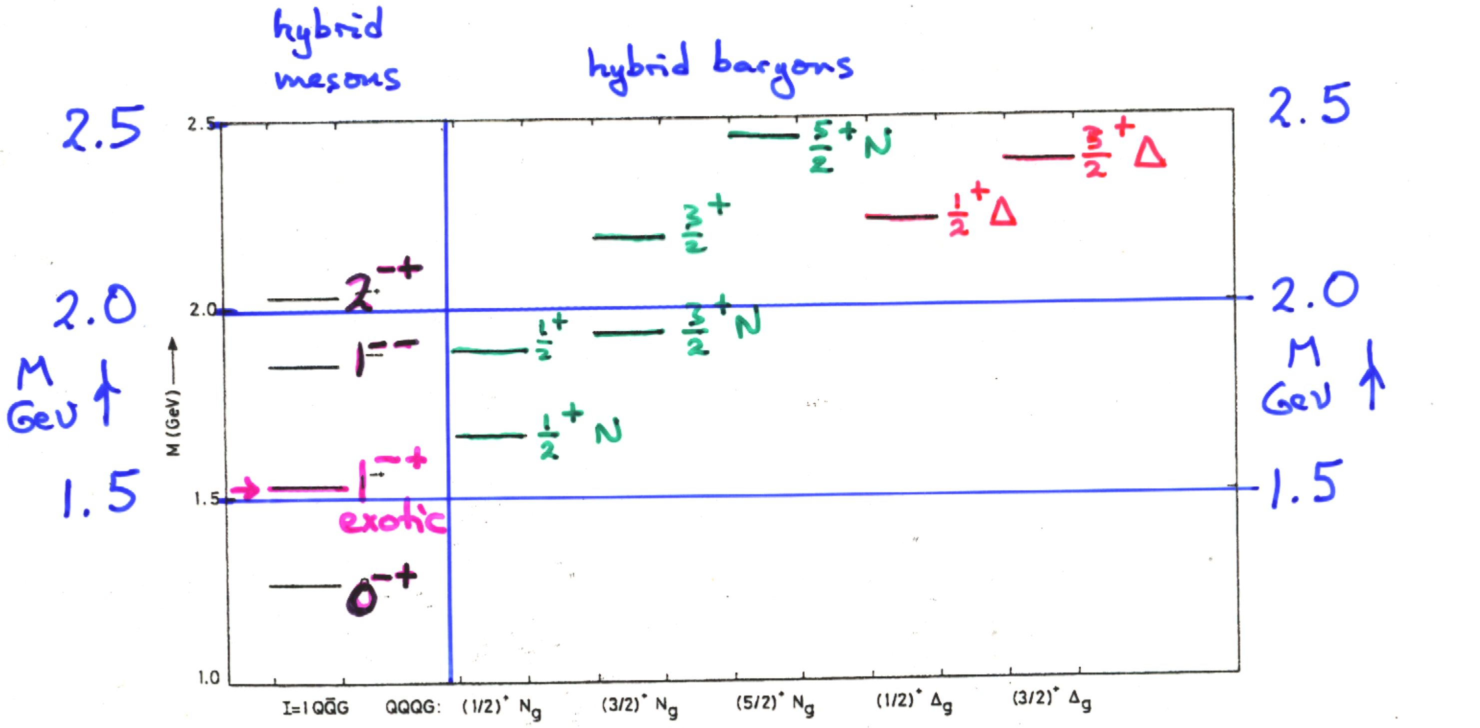
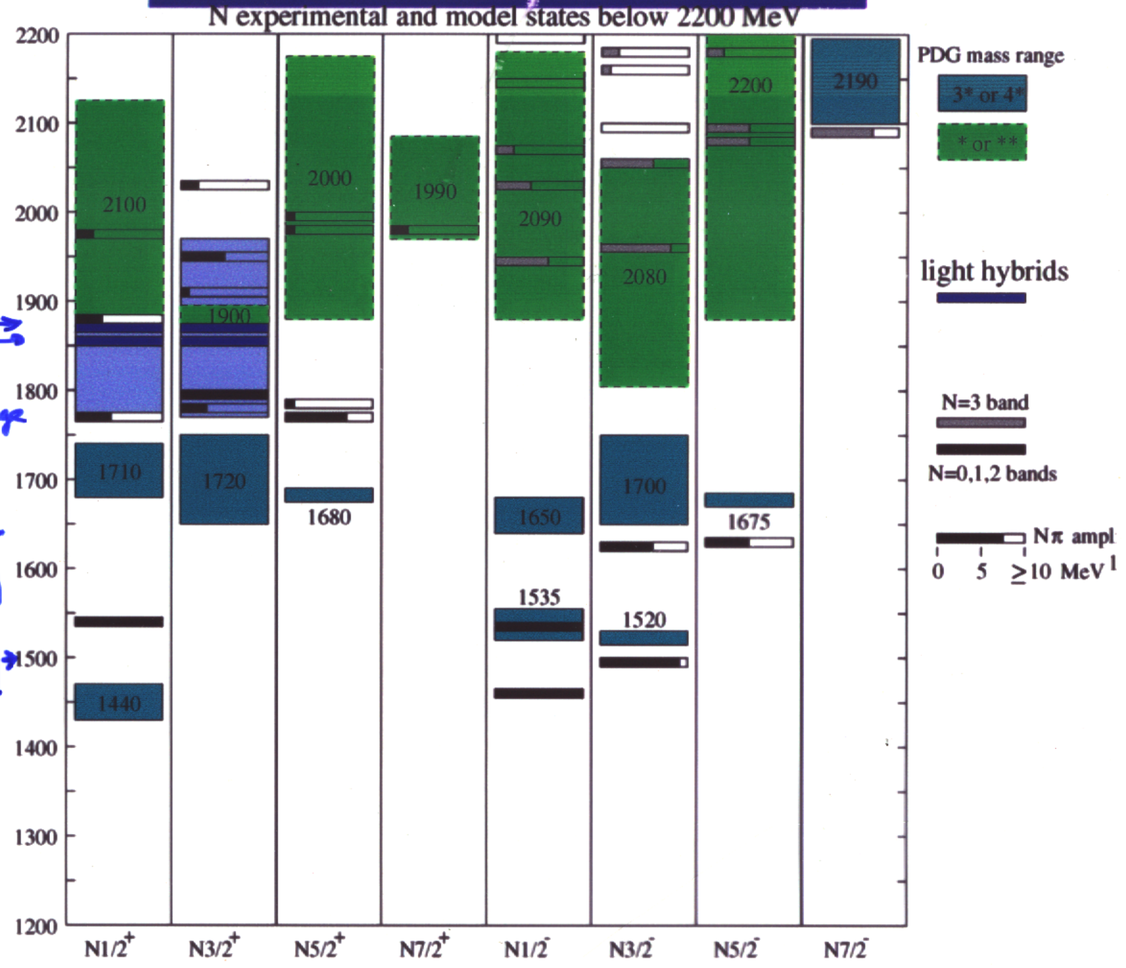


Fig. 2. Spectrum of states. The $Q\bar{Q}G$ spectrum is that of fig. 1, ref. [3], with a slightly smaller radius to fit the lowest experimental candidate, $\pi'(1270)$. Constant bag pressure is assumed in determining the relative unperturbed meson and baryon radii. The overall baryon mass scale is subject to an uncertainty of order ±100 MeV relative to the mesons, due to possible small differences in radii and corresponding Coulomb shifts or centre of mass modifications (section 2.3 of ref. [3]).

Light Hybrid N Baryons



≈ ----- cosy range

f-t model ⇒
Capstick/Page

bag model

QCD Σ rules

- hybrids mix with *qqq*

  → surfeit of states; decay signatures; electromagnetic couplings light quark component.

These results are quite different. The largest difference comes from differences in the unmixed masses, with Teper having $m_{\bar uu} = 1.36$, $m_{\bar ss} = 1.61$ and $m_g = 1.48$ GeV and the GF11 group having $m_{\bar uu} = 1.47$, $m_{\bar ss} = 1.51$ and $m_g = 1.63$ GeV. Note that in the first analysis the unmixed $\bar ss$ is heavier than the glueball, while in the second it is lighter. Not surprisingly, the heaviest physical particle is mostly $\bar ss$ or mostly glueball, respectively. Clearly it is important to know whether the quenched $\bar ss$ is heavier than the quenched glueball, and the GF11 group has attacked this question by calculating quarkonium and glueball masses on the same samples.

It is also interesting to test the effects of dynamical quarks on the glueball spectrum. In principle this is tricky, since a full QCD spectrum calculation with a glueball source operator will produce the masses of the physical states, which are mixtures of glueballs and quarkonia. In practice, the calculations that have been done so far have used quark masses large enough that the quarkonium mass exceeds the glueball mass, and it is reasonable to simply say thay they have measured the glueball mass. The largest calculation is from the TχL/SESAM collaborations[25], and another preliminary result from UKQCD was presented at this conference[26]. The TχL/SESAM results for the 0^{++} glueball are within errors of the quenched results, although they do see hints of a larger dependence on the lattice size. However, the preliminary UKQCD results have a much smaller mass, despite being done at approximately the same sea quark mass, as measured by m_π/m_ρ. The UKQCD results are done on much coarser lattices, albeit with the clover action rather than the Wilson quark action. (UKQCD used $\beta = 5.2$ while TχL/SESAM used 5.6.) The 0^{++} glueball mass has long been known to be small on coarse lattices[27], but the preliminary UKQCD results are even smaller than we would expect from our experience with the quenched theory.

Since the exotic 1^{-+} signal found in experiments at 1400 MeV is much lower than expected from lattice calculations (and most other theoretical approaches), it is tempting to ask whether it could be something else, most likely a 4-quark

LGT 1^{-+}
hybrid mass

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hep-lat/9909088
see also
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hep-lat/0009314

(reviews)

Table 1
Some results for 1^{-+} hybrid masses

Date	Ref.	Method	ΔM (GeV)	
$\bar bbg - \bar bb$:				
1990	[9]	St.	1.11(3)(?)	
1993	[10]	NR.	0.8(?)(?)	
1997	[13]	NR.	1.68(10)	
			1.40(14)	(1)
1997	[15]	NR.	1.14(21)	
1997	[14]	St.	1.3	
1998	[18]	NR.(An.)	**1.542(8)**	
1999	[19]	St+NR(An.)	**1.49(2)(5)**	
$\bar ccg - \bar cc$:				
1990	[9]	St.	0.94(3)	
1996	[12]	Rel.(Wil.)	**1.34(8)(20)**	
1998	[17]	Rel.(Clo.)	**1.22(15)(?)**	
1999	[18]	NR.(An.)	**1.323(13)**	
$\bar ssg$			M (GeV.)	
1996	[11]	Rel.(Clo.)	**2.00(20)**	(2)
1996	[12]	Rel.(Wil.)	**2.17(8)(20)**	(3)
$\bar udg$				
1996	[11]	Rel.(Clo.)	**1.88(20)**	(4)
1996	[12]	Rel.(Wil.)	**1.97(9)(30)**	(5)
1998	[16]	Rel.(Wil.)	**1.90(20)**	(6)
1998	[17]	Rel.(Clo.)	**2.11(10)(?)**	(7)

+9.45 GeV
↳ 10.99(1)
GeV

+3.07 GeV
↳ 4.39(1)
GeV

GeV
↳ rather
larger
than
1.6Ge
of
π_1(1600

Abbreviations: St. = Static, NR. = NRQCD, Rel. = Relativistic, An. = anisotropic, Wil. = Wilson, Clo. = clover.

Notes: (1): value with a determined differently, (2): $a = 0.095$ fm, (3): $a = 0.075$ fm, (4): Model to extrapolate to $m_q = 0$, 120 MeV below $\bar ss$ mass, $a = 0.095$ fm, (5): Extrapolation from several am_q values, $a = 0.075$ fm, (6): $N_f = 2$ dynamical quarks, extrapolate from several am_q values, $a = 0.086$ fm, (7): Same as (5).

$(\bar q\bar qqq)$ state. In principle, this question is answerable with lattice methods, but it is a difficult subject. Nonetheless, there is a small but growing body of work on lattice 4-quark states[28,29], beginning with the simplest case where all four quarks are static, and moving into the case of two static and two moving quarks. An amusing limit has recently been studied by Michael and Pennanen[29], where the two quarks are very heavy, and the two antiquarks light. The two quarks have an attractive interaction in the $\bar 3$ color combination, and since they are very heavy they can bind into

PHYSICAL REVIEW D, VOLUME 65, 094505 (2002).

Hybrid meson decay from the lattice

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(Received 4 January 2002; published 18 April 2002)

We discuss the allowed decays of a hybrid meson in the heavy quark limit. We deduce that an important decay will be into a heavy quark nonhybrid state and a light quark meson, in other words, the deexcitation of an excited gluonic string by emission of a light quark-antiquark pair. We discuss the study of hadronic decays from the lattice in the heavy quark limit and apply this approach to explore the transitions from a spin-exotic hybrid to $\chi_b \eta$ and $\chi_b S$ where S is a scalar meson. We obtain a signal for the transition emitting a scalar meson and we discuss the phenomenological implications.

e.g. χ_J
$H_{c\bar{c}} \to$ + π
$\eta J/\psi$ (cc + η
(etc
$\ell^+\ell^-$
very nice mod
if indeed
not suppressed

DOI: 10.1103/PhysRevD.65.094505 PACS number(s): 12.38.Gc, 11.15.Ha, 13.20.Gd, 14.40.Cs

I. INTRODUCTION

Hybrid mesons are those with nontrivial excited gluonic components. The simplest such case is when the spin-parity is exotic, namely, not allowed in the quark model. Here we specialize to heavy quarks and so our comparisons with experiment will be for $b\bar{b}$ systems. In this context, there will be a spin-exotic ($J^{PC}=1^{-+}$) meson whose properties can be determined from lattice QCD. We review here first the information on the nature and spectrum of such excited gluonic states. We then discuss in general the allowed decay modes of such a state. In most of this discussion we focus on predictions in the heavy quark limit, so with heavy quark, spin-flip neglected.

We then review lattice methods to extract hadronic transition matrix elements. In the case of hybrid decay, we explore the creation of a light quark-antiquark state from the gluonic field of the hybrid meson. It is possible to fulfill the rather restricted conditions on a lattice and we are able to explore these transitions. We study hybrid meson transitions to $\chi_b \eta$ and $\chi_b S$ where S is a scalar meson. We obtain a signal for the transition emitting a scalar meson and we discuss the phenomenological implications.

II. HYBRID STATES ON THE LATTICE

The static quark approach gives a very straightforward way to explore hybrid quarkonia. These will be $Q\bar{Q}$ states in which the gluonic contribution is excited. The ground state of the gluonic degrees of freedom has been explored on the lattice, and, as expected, corresponds to a symmetric cigar-like distribution of color flux between the two heavy quarks at separation R. One can then construct less symmetric color distributions which would correspond to gluonic excitations. For a review see Ref. [1]. The properties of the physical states can then be obtained from these static potentials by solving the Schrödinger equation in the adiabatic approximation.

The way to organize this is to classify the gluonic fields according to the symmetries of the system. This discussion is very similar to the description of electron wave functions in diatomic molecules. The symmetries are (i) rotation around the separation axis z with representations labeled by J_z, (ii) CP with representations labeled by g and u and (iii) $C\mathcal{R}$. Here C interchanges Q and $\bar{Q}$, P is parity and $\mathcal{R}$ is a rotation of 180° about the mid-point around the y axis. The $C\mathcal{R}$ operation is only relevant to classify states with $J_z=0$. The convention is to label states of $J_z=0,1,2$ by Σ,Π,Δ respectively.

In lattice studies the rotation around the separation axis is replaced by a four-fold discrete symmetry and states are labeled by representations of the discrete group D_{4h}. The ground state configuration of the color flux is then Σ_g^+ (A_{1g} on the lattice). The exploration of the energy levels of other representations has a long history in lattice studies [2,3]. The first excited state is found to be the Π_u (E_u on a lattice)—see Fig. 1 for an illustration. This can be visualized as the symmetry of a string bowed out in the x direction minus the same deflection in the $-x$ direction (plus another component of the two-dimensional representation with the transverse direction x replaced by y), corresponding to flux states from a lattice operator which is the difference of U-shaped paths from quark to antiquark of the form $\sqcap - \sqcup$.

A summary of lattice determinations of the energy of this lowest hybrid state [1] puts it at $m(H)=10.76(7)$ GeV for b quarks, so approximately 1.3 GeV heavier than the Υ. This hybrid state in the adiabatic approximation will have lowest angular momentum $L=1$ and combining this with the heavy quark spins gives 8 degenerate J^{PC} values. Of special interest is the spin exotic state with $J^{PC}=1^{-+}$ which is expected to be the lightest spin-exotic meson. Since it is spin-exotic, it cannot mix with the non-hybrid $Q\bar{Q}$ states and is thus of considerable theoretical and experimental interest.

III. HYBRID MESON DECAYS

We shall be discussing hybrid meson decays in the heavy quark limit, so our conclusions will be more applicable to b

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0556-2821/2002/65(9)/094505(9)/$20.00

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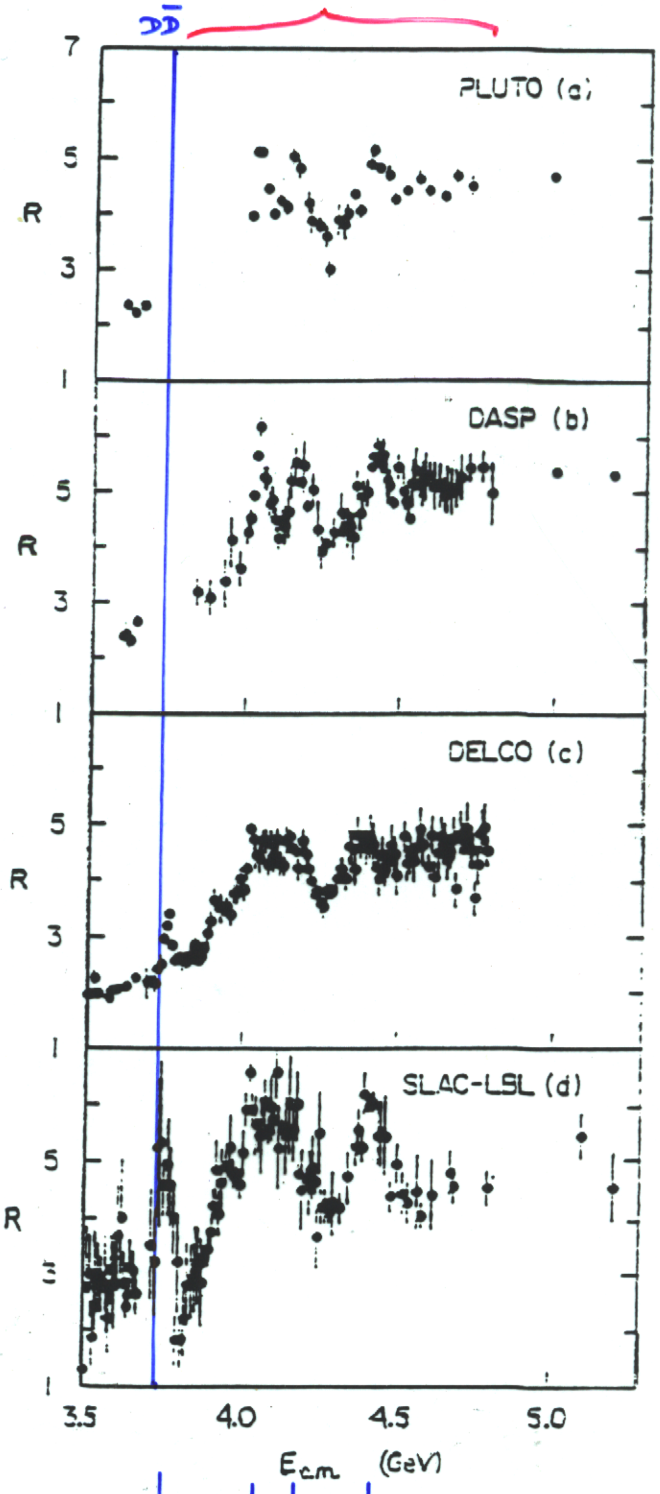
What is known about $c\bar{c} > 3.73$ GeV ?

A quick glance in ca. 1978 from e^+e^- machines.

"R" only

terra animalium mirabilium



3770 $^3D_1$

4040 4160 4415

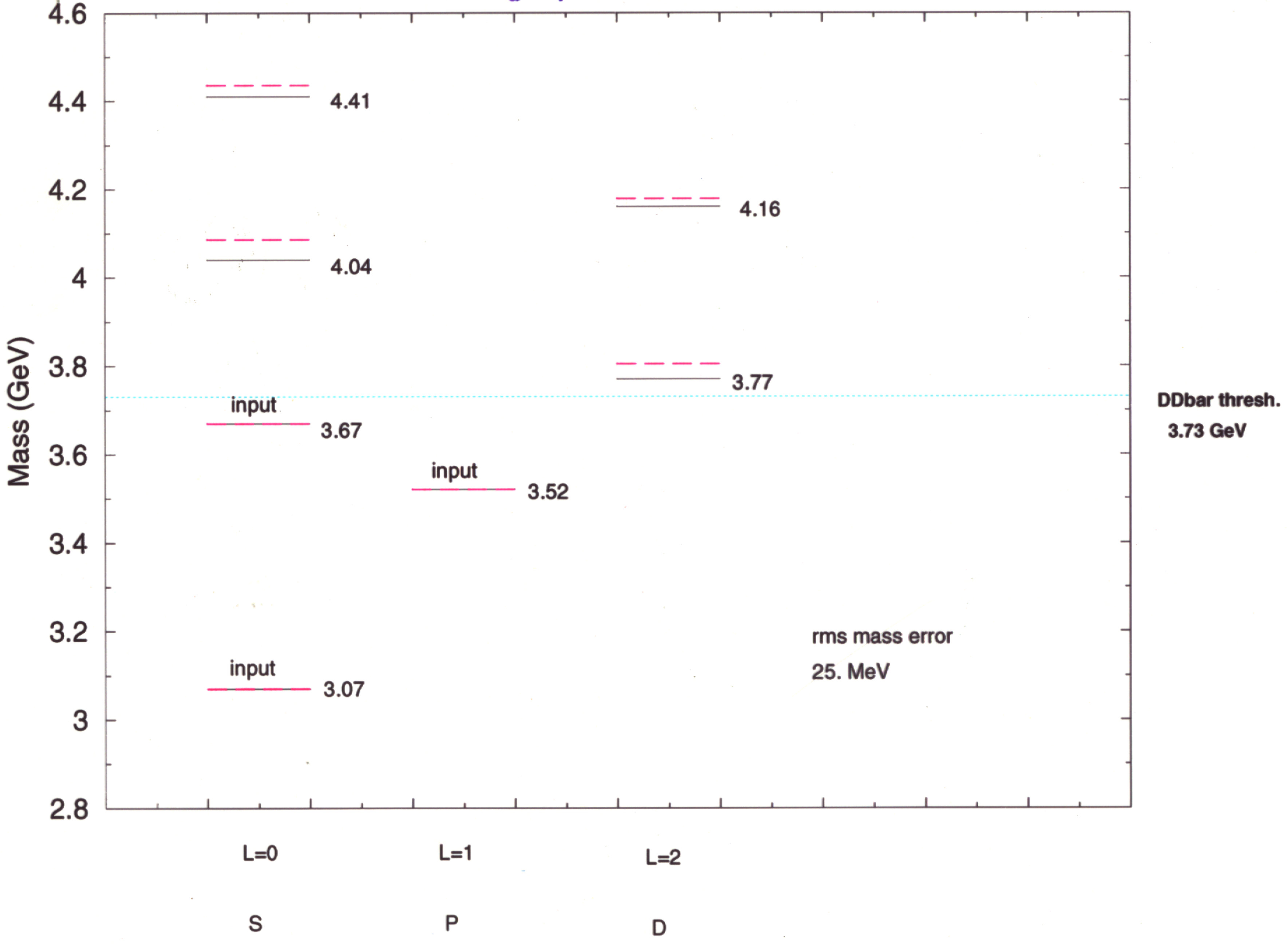
probably a rich spectrum of $c\bar{c}$, hybrids, "charm molecules".

Unexplored.

24.10.99 kph106

Mean ccbar multiplet positions (GeV).

*NR Cou+lin Schro 1S1P2S cogfit: alphas=0.5099, b=0.1521 GeV**2, mc=1.4502 GeV.*



Summary + prospects

We have a strong $\mathcal{H}$ candidate, $\pi_1(1600)$

Systematic study of all possible strong modes.

$\exists$ flavor nonet partners?

Don't forget the $K^*(1400)$

Do couplings to decay channels shift masses by 100s of MeV??

(Q for quark model)

$f_0(1500)$ $\mathcal{G}$ candidate. Are PsPs couplings strongly m_q-dep?

What are VV... couplings?

Future expt. γ (tj, focus), $\gamma\gamma$ (BaBar, CLEO-c, ...)

[J/ψ reloaded] $e^+e^- \to 1^{--}$ $p\bar{p}$

$\underbrace{c\bar{c} \text{ and } c\bar{c}\text{-}\mathcal{H}}_{\text{theorists too!}}$ CLEO-c attractive simplicity.

To Ithaca!