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How Omega helped to establish the existence of non-$q\overline{q}$ mesons

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Abstract

The non-Abelian nature of QCD suggests that particles that have a gluon constituent, such as glueballs or hybrids, should exist. This paper describes several non-$q\overline{q}$ candidates observed by experiments WA76, WA91 and WA102 at the CERN Omega Spectrometer and discusses the status and future prospects for this field.

1 An introduction to non-$q\overline{q}$ mesons

1.1 What are non-$q\overline{q}$ mesons?

Early experiments at the Omega Spectrometer investigated the quark model which predicted that only two types of quark configurations were required to account for all strongly interacting particles: baryons composed of three quarks (qqq) and mesons composed of a quark-antiquark pair ($q\overline{q}$). This description was found to be very successful in grouping the known particles into multiplets of a given spin parity. With the advent of Quantum ChromoDynamics (QCD) as the field theory describing strong interactions it was realised that QCD not only describes how quarks and antiquarks interact by the exchange of gluons but also predicts that the gluons, which are the quanta of the field, will themselves interact to form mesons. If the object formed is composed entirely of valence gluons the meson is called a glueball, however if it is composed of a mixture of valence quarks, antiquarks and gluons (i.e. $q\overline{q}g$) it is called a hybrid. In addition, $q\overline{q}q\overline{q}$ states are also predicted.

The prediction of these states is a crucial feature of QCD and the proof of their existence is one of the missing links of the Standard Model.

1.2 Mass calculations

Several calculations have been made based on the bag model [1] in an attempt to calculate the glueball mass spectrum but the agreement between the different predictions is only fair. However most of the models converge in assigning quite low masses to these new states some of which should have masses in the 0.5 to 2.0 GeV region [2]. More recently predictions have been made using lattice gauge theory [3] which show that

$$m(2^{++})/m(0^{++}) = 1.5$$

and

$$m(0^{++}) = (1500 - 1750)\mathrm{MeV}.$$

The flux tube model has been used to calculate the masses of the lowest lying hybrid states and recent predictions [4] are that

$$m(1^{--}, 0^{-+}, 1^{-+}, 2^{-+}) \approx 1900 \text{ MeV}.$$

Hence, these non-$q\overline{q}$ states are predicted to be in the same mass range as the normal $q\overline{q}$ nonet members.

1.3 How to look for gluonic states

From the preceeding section it can be seen that the non-$q\overline{q}$ mesons are predicted to occur right in the middle of the standard $q\overline{q}$ nonets and hence we need a method of identifying them.

The following have been suggested as possible ways to identify gluonic states.

1. To look for "oddballs": States with J^{PC} quantum numbers not allowed for normal $q\overline{q}$ states. For example $J^{PC} = 1^{-+}$.
2. However the lightest non-$q\overline{q}$ states are predicted to have the same quantum numbers as $q\overline{q}$ states. Therefore we need to look for extra states, that is states that have quantum numbers of already completed nonets and that have masses which are sufficiently low that they are unlikely to be members of the radially excited nonets and hence they can not be described as being pure $q\overline{q}$ states.
3. If extra states are found then in order to isolate which state is the likely non-$q\overline{q}$ state we can
   a) Look for states with unusual branching ratios.
   b) Look for states preferentially produced in gluon rich processes. These processes are described in the following section.

1.4 Where to look for gluonic states

Fig. 1 summarises several dynamical configurations which have been suggested as possible sources of gluonium and where experiments have been performed.

1. Pomeron-Pomeron scattering is shown in fig. 1a). The Pomeron is an object which can be described as a multi-gluon state, and is thought to be responsible for the large cross sections of diffractive reactions. Consequently Double Pomeron Exchange (DPE) is considered to be a possible source of glueballs.
2. The J/ψ decay is believed to be a highly glue rich channel either via the hadronic decay shown in fig. 1b), or via the radiative decay shown in fig. 1c).
3. Figure 1d) shows proton-antiproton annihilation; the annihilation region of quarks and antiquarks is a source of gluons where glueballs and hybrids could be produced.
4. Special hadronic reactions, an example of which is shown in fig. 1e) where the $\phi\phi$ system is thought to be produced via an intermediate state containing gluons. Reactions of this kind which have disconnected quark lines are said to be OZI violating [5].

The first reaction is the one studied by experiments WA76, WA91 and WA102 at the Omega spectrometer. In this paper the non-$q\overline{q}$ candidates observed in these experiments will be discussed and the current status of non-$q\overline{q}$ mesons will be presented.

2 The Omega Central production experiments

2.1 Introduction

Experiments WA76, WA91 and WA102 are designed to study exclusive final states formed in the reaction

$$pp \to p_f(X^0)p_s \tag{1}$$

where the subscripts f and s indicate the fastest and slowest particles in the laboratory respectively and X^0 represents the central system that is presumed to be produced by a double exchange processes.

At high centre-of-mass energies these double exchange process are believed to be dominated by Double Pomeron Exchange (DPE), where the Pomeron is thought to have a large gluonic content, leading to the conclusion that Pomeron-Pomeron scattering could be a source of gluonic states [6].

The experiments have been performed at incident beam momenta of 85, 300 and 450 GeV/c, corresponding to centre-of-mass energies of $\sqrt{s} = 12.7$, 23.8 and 28 GeV.

2.2 Layout of the Omega Spectrometer

The layout of the 1994 run of WA91 is shown in fig. 2. The positively charged H1 beam in the West Area was incident on a 60 cm long hydrogen target. A set of ten 20 μm pitch μ-strip detectors were used to perform an accurate measurement of the incident beam's trajectory. The outgoing fast track, which had a momentum in the range 300 to 450 GeV/c, was measured by two sets of 4 μ-strip detectors placed 8 and 12 m downstream from the target. The standard Ω MWPC's and Drift Chambers were used to measure the medium momentum tracks (≈ 1 to 40 GeV/c) leaving the interaction region, with particle identification coming from two threshold Cerenkov counters C1 and C2. Photon detection was provided by the GAMS-4000 and OLGA lead glass calorimeters.

The trigger was designed to enhance double exchange processes with respect to single exchange and elastic processes. Details of the trigger conditions, the data processing and event selection have been given in previous publications [7].

3 Non-$q\overline{q}$ candidates

3.1 The $E/f_1(1420)$ observed in the $K^0_SK^\pm\pi^\mp$ channel

The $E/f_1(1420)$ has been observed in the reaction $pp \rightarrow p_f(K^0_SK^\pm\pi^\mp)p_s$ [8]. Fig. 3 shows the $\mathrm{K^0_SK^\pm}\pi^\mp$ effective mass spectrum where clear signals of the $f_1(1285)$ and E/$f_1(1420)$ can be seen. The $f_1(1285)$ is the undisputed light quark member of the 1^{++} nonet.

A spin parity analysis of the $K^0_SK^\pm\pi^\mp$ system using Zemach tensors shows that the $E/f_1(1420)$ decays predominantly to $K^*(892)\overline{K}$ and has $J^{PG} = 1^{++}$. The observation of the $E/f_1(1420)$ in the $K^0_SK^0_S\pi^0$ channel shows that its C parity is positive and hence its quantum numbers are determined to be $I = 0$, $J^{PC} = 1^{++}$.

Originally, the E/$f_1(1420)$ was thought to be the $s\overline{s}$ isoscalar member of the ground state 1^{++} nonet, the other members being the $a_1(1260)$ triplet, the $K_1(1270)$ and the $f_1(1285)$. However, it is not seen in K^- incident experiments where $s\overline{s}$ objects should be preferentially produced. Instead in the reaction [9]

$$K^-p \rightarrow \mathrm{K^0_SK^\pm}\pi^\mp\ \Lambda$$

a state is observed with a mass of 1527 ± 5 MeV and a width of 106 ± 14 MeV, called the D$'/f_1(1530)$. A partial wave analysis shows that it has $\mathrm{J}^{PC} = 1^{++}$ and that it decays to $K^*\overline{K}$. It has been suggested that this state is a better candidate for the $s\overline{s}$ member of the 1^{++} nonet, if so, then the E/$f_1(1420)$ is left as an extra state.

Further information comes from experiments studying $\gamma\gamma$ collisions [10] where a state is observed in the $K^0_S K^{\pm}\pi^{\mp}$ mass spectrum having a mass and width consistent with the E/$f_1(1420)$. This state is only seen when one of the two γs is off mass shell and not when both γs are real which via Yangs theorem [11] indicates a spin 1 state. A spin-parity test [12] shows that it is consistent with having $J^{PC} = 1^{++}$.

The $\gamma\gamma^*$ width for the E/$f_1(1420)$ meson is found to be

$$\Gamma = 4 \pm 1 \pm 1 \text{ keV}$$

but the $\gamma\gamma^*$ width has been calculated to be $\Gamma(E) = 0.1$ keV assuming the E to be a $s\overline{s}$ state [13]. This therefore suggests that the E/$f_1(1420)$ has a large light quark content. However the $f_1(1285)$ is the undisputed light quark member of the ground state 1^{++} nonet, so that if the E/$f_1(1420)$ is a $q\overline{q}$ state it would have to be a member of an excited nonet. According to the GI model [14] the lowest mass excited 1^{++} state should have a mass of 1820 MeV/c^2.

Therefore it would appear that the E/$f_1(1420)$ can not be explained as a conventional $q\overline{q}$ state. As a 1^{++} state its mass is too low to be a glueball or hybrid state, and a possible explanation is that it is a four quark [15] or $K^*\overline{K}$ molecule [16].

3.2 The $\theta/f_J(1720)$ observed in the K^+K^- and $K^0_SK^0_S$ channels

The $\theta/f_2(1720)$ was observed, for the first time in hadron collisions, by the WA76 experiment in the K^+K^- and $K^0_SK^0_S$ decay modes [17]. Fig. 4 shows the centrally produced K^+K^- mass spectrum which contains several resonance structures; in particular, the $\phi(1020)$ and the $f_2'(1525)$ are clearly seen. A structure can also be seen in the 1.7 GeV region called the $\theta/f_J(1720)$.

The $\theta/f_J(1720)$ is also observed in the $K^0_SK^0_S$ channel which shows that it must have $J^{PC} = (even)^{++}$. However, both the J^{PC} $=0^{++}$ and 2^{++} nonets are full. In order to try to distinguish between 0^{++} and 2^{++} the K^+K^- angular distributions have been studied in the Gottfried-Jackson frame [17]. A fit to the $f_2''(1525)$ and the $\theta/f_J(1720)$ regions using density matrix elements shows that the two regions are dominated by D wave ($67 \pm 6\%$ for the $f_2'(1525)$ region and $80 \pm 4\%$ for the $\theta/f_J(1720)$ region). Therefore it is likely that the $\theta/f_J(1720)$ has $J^{PC} = 2^{++}$.

The only other place the $\theta/f_J(1720)$ has been observed is in radiative J/ψ decays [18] which is believed to be a gluon rich process. Also, despite its dominant $K\overline{K}$ decay mode it is not observed in K^-p reactions [19] nor is it observed in $\gamma\gamma$ collisions where on the other hand the $f_2(1270)$ and $f_2'(1525)$ are produced [20].

Therefore the fact that there is an extra state which has only been observed in reactions which are believed to be gluon rich has led to the $\theta/f_J(1720)$ being considered to be a very good glueball candidate.

3.3 The $f_0(1500)$ and $f_2(1930)$ observed in the $\pi^+\pi^-\pi^+\pi^-$ channel

The WA76 collaboration reported the observation of two previously unobserved mesons in the $\pi^+\pi^-\pi^+\pi^-$ final state at 300 GeV/c [21]. Fig. 5a shows the $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum; a clear peak is seen at 1.28 GeV which is due to the $f_1(1285)$. There is also evidence for structures around 1.45 and 1.9 GeV. The cross section for the centrally produced $f_1(1285)$ decreases with energy [21].

In contrast, no clear evidence was seen for the states at 1.45 and 1.9 GeV in the 85 GeV/c data of the same experiment. This increase in signal to background ratio with increased incident energy [21] is consistent with the formation of these states via a double Pomeron exchange mechanism, which as mentioned above is predicted to be a source of gluonic states [6]. The analysis of the structure at 1.45 GeV shows that it has $I^G(J^{PC}) = 0^+(0^{++})$ and it has been identified with the $f_0(1500)$ [22] a good candidate for being the lightest glueball [23]. The structure at 1.9 GeV has $I^G(J^{PC}) = 0^+(2^{++})$ and lies on the Pomeron trajectory.

3.4 Summary of the non-$q\overline{q}$ mesons observed at Omega

Experiments WA76, WA91 and WA102 have performed a dedicated search for non-$q\overline{q}$ mesons in central production and several candidates have been observed.

$$\mathrm{E}/f_1(1420),\ \theta/f_J(1720),\ f_0(1500) \text{ and } f_2(1930)$$

None of these states can easily be classified in $q\overline{q}$ nonets.

4 Gluonium 95

Following the studies performed at Omega, at LEAR, in J/ψ decay and elsewhere the Gluonium 95 workshop was held in Corsica from 30th June to 4th July 1995. It was organised by Jean-Pierre Stroot and Geof West and sponsored by the "Mouvement de la Corse du XXIe Siecle". The aim of this workshop was to bring together experimentalists and theorists currently active in the field to discuss the question "Where do we stand in the search for non-$q\overline{q}$ mesons ?".

The outcome of the workshop was unanimous agreement that there are definitely too many "gold plated" states for the $q\overline{q}$ nonet scheme. Hence we can definitely say that there is **evidence for non-$q\overline{q}$ mesons** .

The remaining task was to identify the gluonic constituents of these mesons and hence identify the glueballs.

5 A Glueball-$q\overline{q}$ filter in central production ?

As was disscussed above the remaining puzzle to be solved is to isolate the glueballs. In order to do this it would be nice to be able to use a glueball-$q\overline{q}$ filter. In this section the possibility of such a filter in central production will be discussed.

The central production experiments try to isolate a sample of events enriched in DPE. However, even in the case of pure DPE the exchanged particles still have to couple to a final state meson. The coupling of the two exchanged particles can either be by gluon exchange or quark exchange. Assuming the Pomeron is a colour singlet gluonic system if a gluon is exchanged then a gluonic state is produced, whereas if a quark is exchanged then a $q\overline{q}$ state is produced (see figures 6a) and b) respectively). It has been suggested recently by Close and Kirk [24] that for small differences in transverse momentum between the two exchanged particles an enhancement in the production of glueballs relative to $q\overline{q}$ states may occur. The difference in the transverse momentum vectors (dP_T) is defined to be

$$dP_T = \sqrt{(P_{y1} - P_{y2})^2 + (P_{z1} - P_{z2})^2}$$

where Py_i, Pz_i are the y and z components of the momentum of the ith exchanged particle in the pp centre of mass system.

Figures 7a) and b) show the effect of the dP_T cut on the K^+K^- mass spectrum. As can be seen, the $f_2'(1525)$ is produced dominantly at high dP_T, whereas the $f_J(1710)$ is produced dominantly at low dP_T.

In the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum a dramatic effect is observed, see figures 7c) and d). The $f_1(1285)$ signal has virtually disappeared at low dP_T whereas the $f_0(1500)$ and $f_2(1930)$ signals remain.

In summary, the undisputed $q\overline{q}$ states are observed to be suppressed at small dP_T, but the glueball candidates $f_0(1500)$, $f_J(1710)$, and $f_2(1930)$ survive.

6 Conclusions

Quantum ChromoDynamics (QCD) not only describes how quarks and antiquarks interact to form the standard $q\overline{q}$ mesons but also predicts the existence of glueballs, hybrids and four-quark states. These states are being searched for using several different production mechanisms, one of which is Double Pomeron Exchange (DPE).

Omega has played an essential role in the establishment of non-$q\overline{q}$ mesons and has isolated several states in its own right.

Preliminary results show that there is the possibility of a glueball-$q\overline{q}$ filter mechanism in central production and we can only hope that the data collected before the shutdown of Omega will allow us to answer the question **where are the Glueballs ?**

References

[1] J.F. Donoghue et al., Phys. Lett. **B99** (1981) 416;
M. Chanowitz and S. Sharpe, Nucl. Phys. **B222** (1983) 211

[2] C.E. Carlson, **D30** (1984) 1594.

[3] G. Bali et al. (UKQCD), Phys. Lett. **B309** (1993) 378;

D. Weingarten, hep-lat/9608070;

J. Sexton et al., Phys. Rev. Lett. **75** (1995) 4563;

F.E. Close and M.J. Teper, "On the lightest Scalar Glueball" Rutherford Appleton Laboratory report no. RAL-96-040; Oxford University report no. OUTP-96-35P

[4] N. Isgur, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 3

[5] S. Okuba, Phys. Lett. **5** (1963) 165;
G. Zweig, CERN/TH 401,402,412 (1964);
J. Iizuka, Prog. Theor. Phys. Suppl. **37-38** (1966) 21.

[6] D.Robson, Nucl Phys **B130** (1977) 328;
F.E. Close, Rep. Prog. Phys. **51** (1988) 833.

[7] T.A. Armstrong *et al.,* Nucl. Instr. and Methods **A274** (1989) 165;
F. Antinori *et al.,* Il Nuovo Cimento **A107** (1994) 1857.

[8] T. A. Armstrong *et al.,* Phys. Lett. **B146** (1984) 273;
Zeit. Phys. **C34** (1987) 23;
Phys. Lett. **B221** (1989) 216.

[9] Ph. Gavillet et al., Zeit. Phys. **C16** (1982) 119;
D. Aston et al., Nucl. Phys. **B301** (1988) 525.

[10] H. Aihara et al., Phys. Rev. Lett. **57** (1986) 2500;
G. Gidal et al., Phys. Rev. Lett. **59** (1987) 2016.

[11] C.N. Yang, Phys. Rev. **77** (1950) 242.

[12] D.O. Caldwell, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 465.

[13] F.M. Renard, Nuovo Cimento **80** (1984) 1.

[14] S. Godfrey and N. Isgur, Phys. Rev. **D32** (1985) 189.

[15] F.E. Close, Rep. Prog. Phys. **51** (1988) 833;
D. Caldwell, Mod. Phys. Lett. **A2** (1987) 771.

[16] J. Weinstein, AIP. Conf. Proc. 185, Particles and Fields 36, Glueballs, hybrids and exotic hadrons, (1988) 400.

[17] T.A.Armstrong et al., Phys. Lett. **B227** (1989) 186.

[18] J.E. Augustin et al., L'Accelérateur Linéair d'Orsay preprint, LAL 85-27 (1985);
R.M. Baltrusaitis et al., Phys. Rev. **D35** (1987) 2077.

[19] D. Aston et al., Nucl. Phys. **B301** (1988) 525.

[20] M. Aihara et al., Phys. Rev. Lett. **57** (1986) 404.

[21] T.A. Armstrong et al., Phys. Lett. **B228** (1989) 536.

[22] D. Barberis et al., Phys. Lett. **B388** (1996) 853.

[23] C. Amsler and F.E. Close, Phys. Lett. **B353** (1995) 385.

[24] F.E. Close and A. Kirk, RAL-96-101.

Figures

Figure 1: Gluon rich channels. Dynamical configurations that have been used to study light hadron spectroscopy in a search for glueball states.

Figure 2: Layout of the Ω spectrometer for WA91.

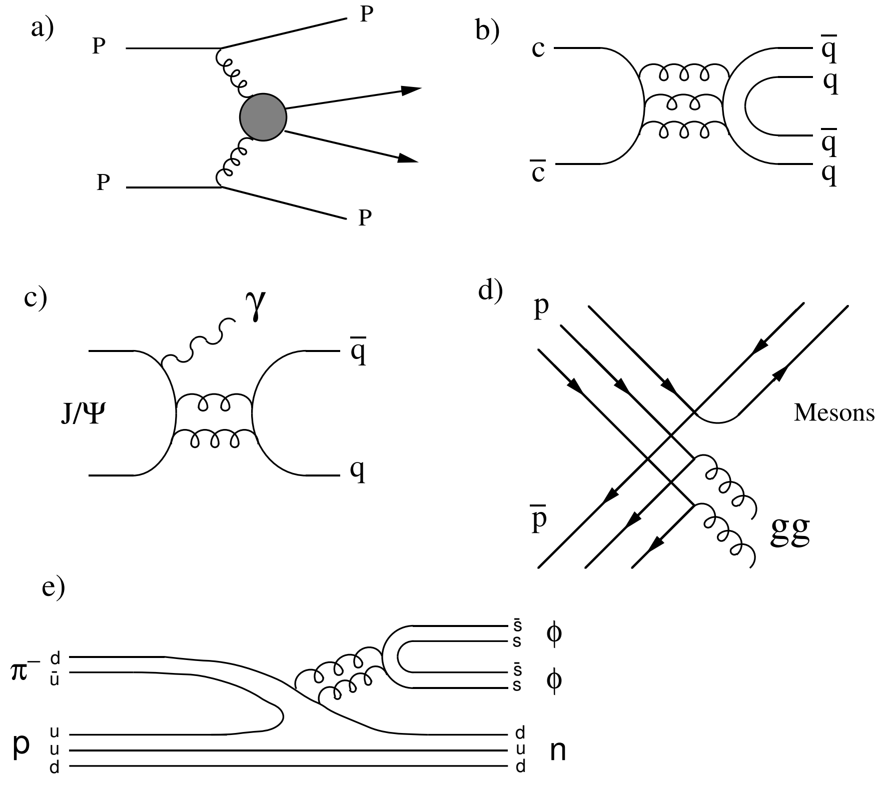
Figure 3: The $K^0_S K^{\pm} \pi^{\mp}$ mass spectrum.

Figure 4: The K^+K^- effective mass spectrum.

Figure 5: The $\pi^+\pi^-\pi^+\pi^-$ effective mass spectrum with fit. a) Total spectrum and b) low t.

Figure 6: Schematic diagrams of the coupling of the exchange particles into the final state meson for a) gluon exchange and b) quark exchange.

Figure 7: K^+K^- mass spectrum for a) $dP_T < 0.2$ GeV and b) $dP_T > 0.5$ GeV and the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum for c) $dP_T < 0.2$ GeV and d) $dP_T > 0.5$ GeV.



a)
P
P
P
P
b)
c
$\bar{c}$
$\bar{q}$
q
$\bar{q}$
q
c)
γ
J/Ψ
$\bar{q}$
q
d)
p
$\bar{p}$
Mesons
gg
e)
π⁻
d
ū
p
u
u
d
s̄
s
s̄
s
φ
φ
d
u
d
n

Figure 1:

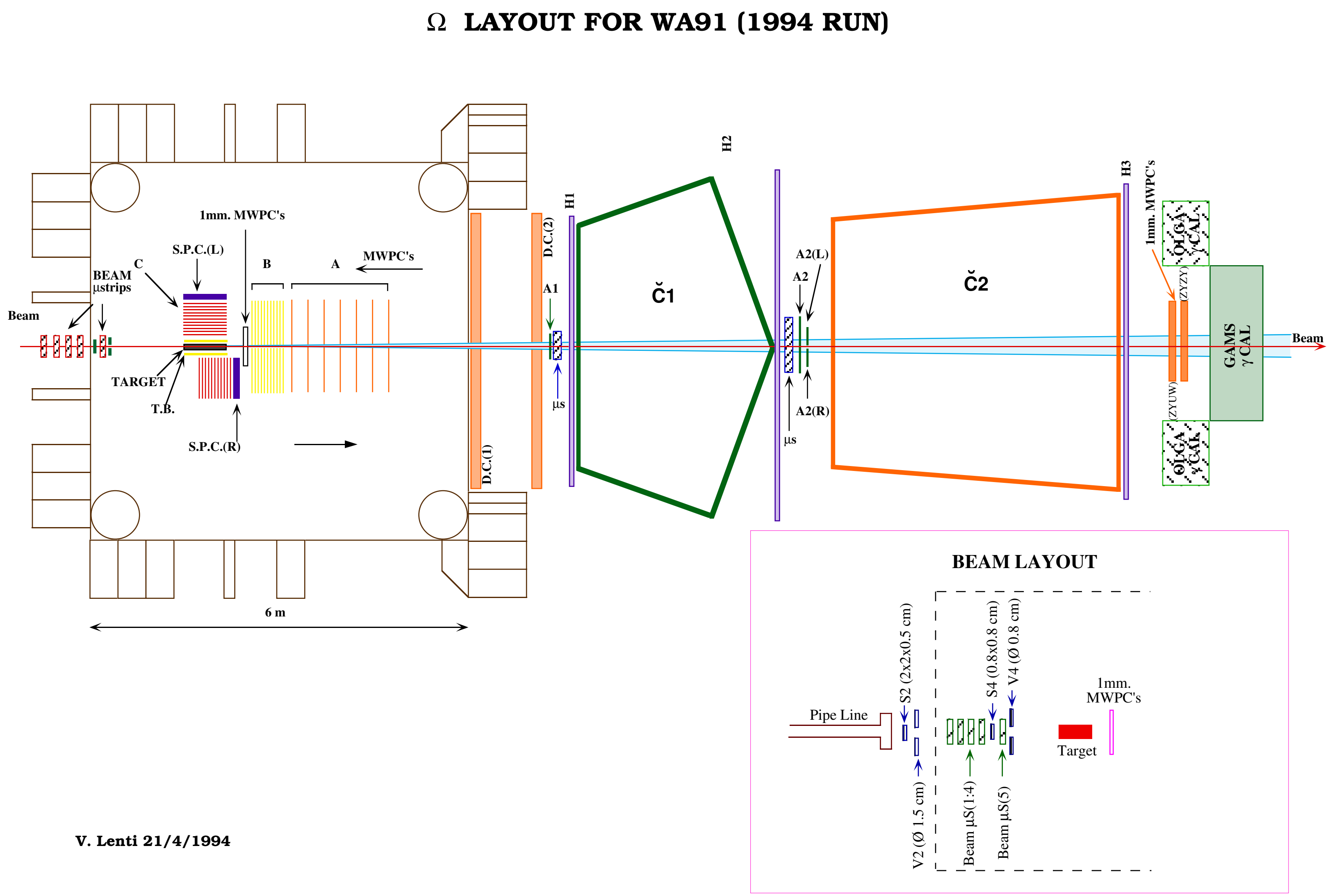

Ω LAYOUT FOR WA91 (1994 RUN)
Beam
BEAM
μstrips
C
S.P.C.(L)
1mm. MWPC's
B
A
MWPC's
TARGET
T.B.
S.P.C.(R)
D.C.(1)
D.C.(2)
A1
μs
H1
H2
Č1
A2(L)
A2
A2(R)
μs
Č2
H3
1mm. MWPC's
OLGA
γ CAL
(ZYZY)
(ZYUW)
GAMS
γ CAL
Beam
6 m
V. Lenti 21/4/1994
BEAM LAYOUT
Pipe Line
S2 (2x2x0.5 cm)
V2 (Ø 1.5 cm)
Beam μS(1:4)
S4 (0.8x0.8 cm)
V4 (Ø 0.8 cm)
Beam μS(5)
Target
1mm.
MWPC's

Figure 2:

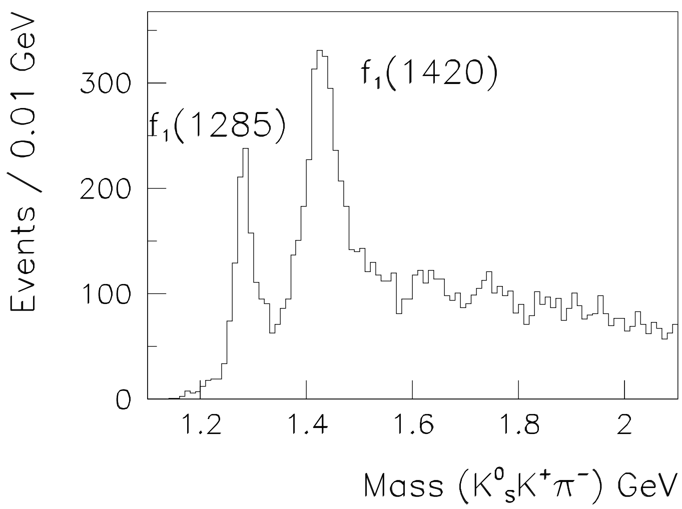

Events / 0.01 GeV
300
200
100
0
$f_1(1285)$
$f_1(1420)$
1.2
1.4
1.6
1.8
2
Mass ($K^0_s K^+ \pi^-$) GeV

Figure 3:

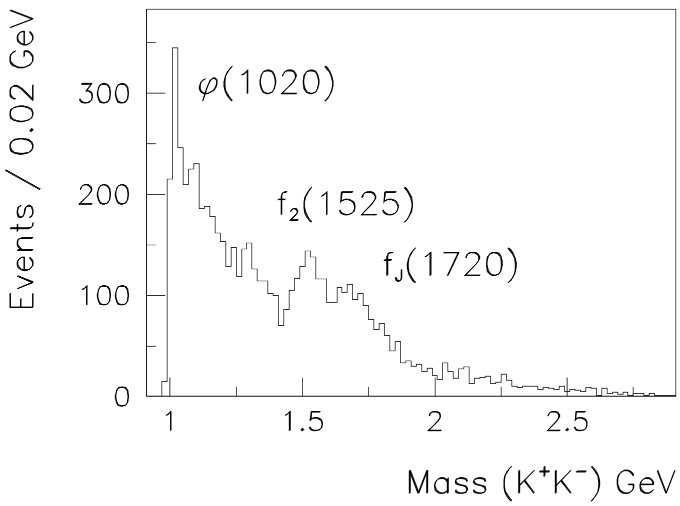

Events / 0.02 GeV
300
200
100
0
1
1.5
2
2.5
Mass (K^+K^-) GeV
$\varphi(1020)$
$f_2(1525)$
$f_J(1720)$

Figure 4:

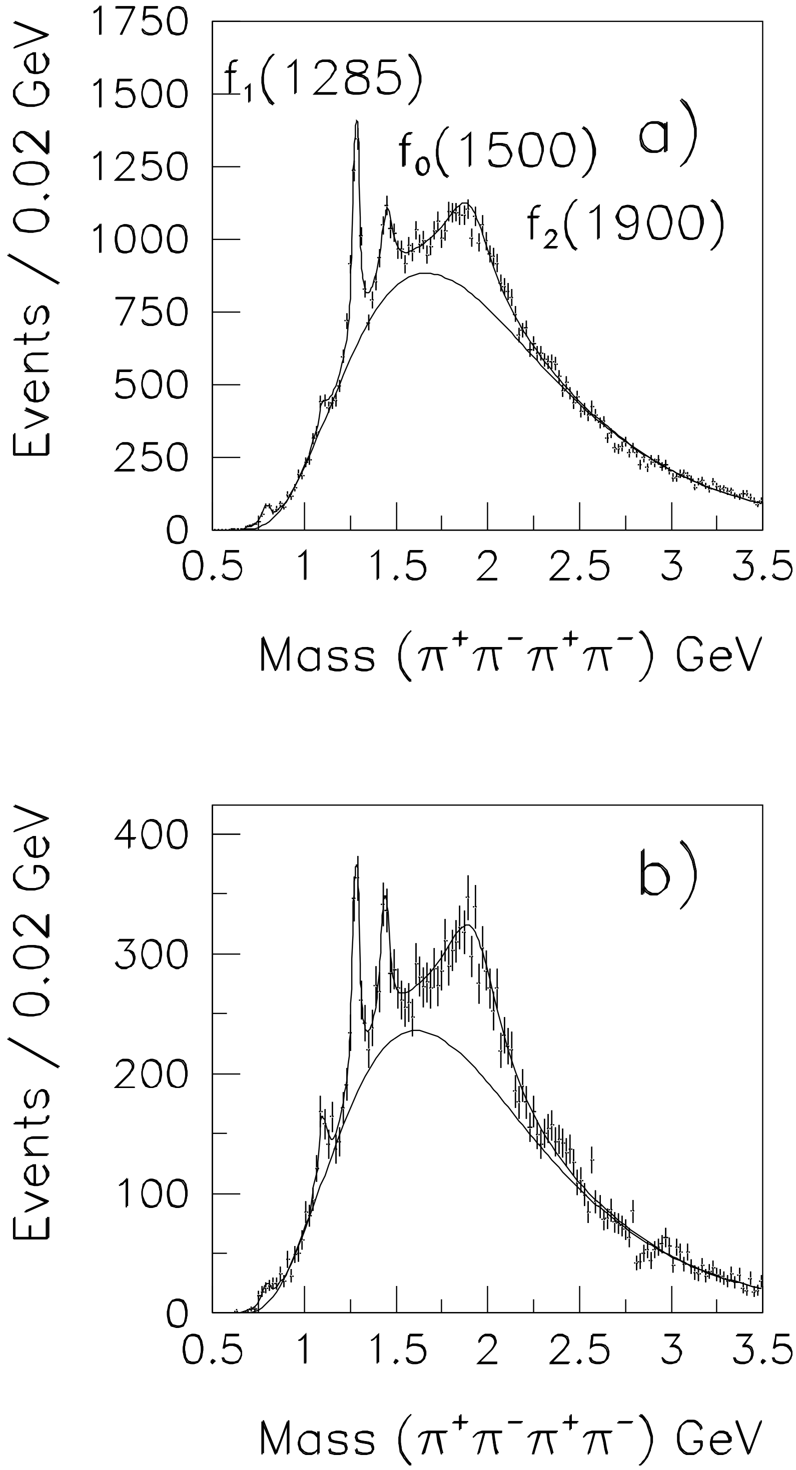

f$_1$(1285)
f$_0$(1500)
a)
f$_2$(1900)
Events / 0.02 GeV
1750
1500
1250
1000
750
500
250
0
0.5
1
1.5
2
2.5
3
3.5
Mass ($\pi^+\pi^-\pi^+\pi^-$) GeV
b)
Events / 0.02 GeV
400
300
200
100
0
0.5
1
1.5
2
2.5
3
3.5
Mass ($\pi^+\pi^-\pi^+\pi^-$) GeV

Figure 5:

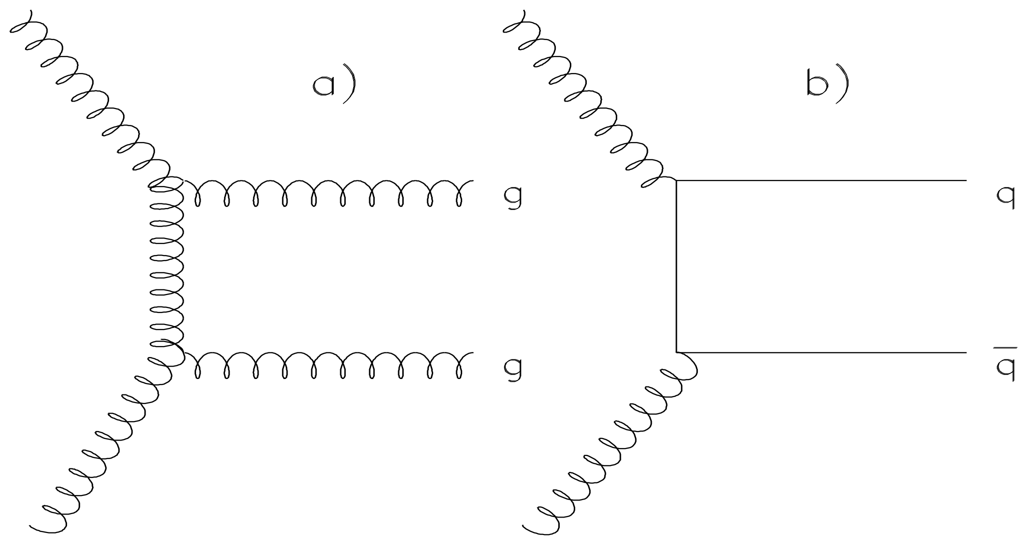


Figure 6:

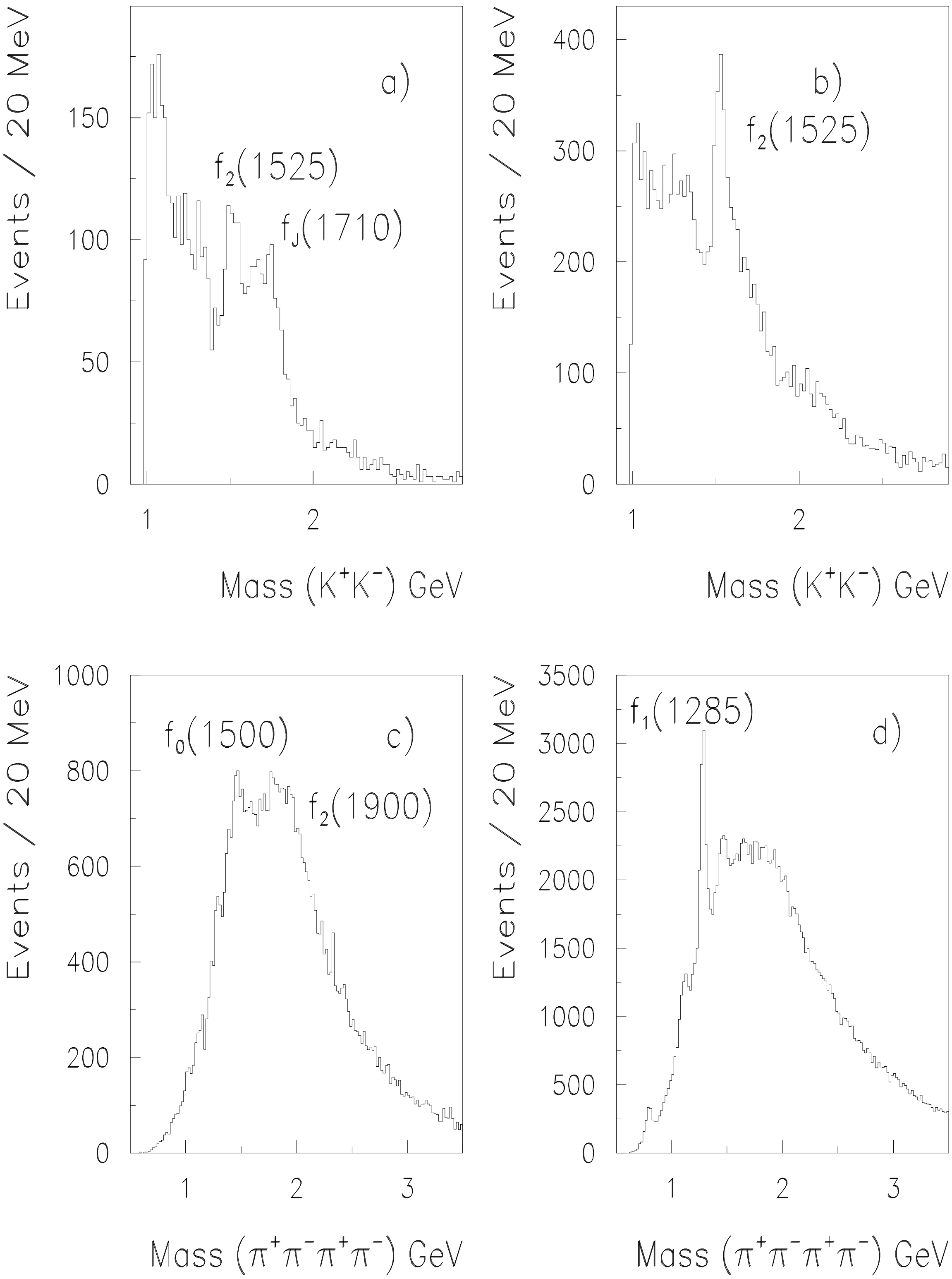

a)
f2(1525)
fJ(1710)
Events / 20 MeV
Mass (K+K-) GeV
b)
f2(1525)
Events / 20 MeV
Mass (K+K-) GeV
c)
f0(1500)
f2(1900)
Events / 20 MeV
Mass (π+π-π+π-) GeV
d)
f1(1285)
Events / 20 MeV
Mass (π+π-π+π-) GeV

Figure 7: