SEARCH FOR PRODUCTION OF CHARGED HIGGS PARTICLES

CELLO Collaboration

H -J BEHREND, J BURGER, L CRIEGEE, J B DAINTON [1], H FENNER, J H FIELD, G FRANKE, J MEYER, V SCHRODER, U TIMM, G G WINTER, W ZIMMERMANN
Deutsches Elektronen-Synchrotron DESY D-2000 Hamburg, Fed Rep Germany

P J BUSSEY, C BUTTAR, A J CAMPBELL, D HENDRY, G McCURRACH, J M SCARR, I O SKILLICORN, K M SMITH
University of Glasgow, Glasgow G12 8QQ UK

J AHME, V BLOBEL, M FEINDT, J HARJES, J H PETERS, M POPPE [2], H SPITZER
II Institut für Experimentalphysik, Universitat Hamburg, D-2000 Hamburg, Fed Rep Germany

W -D APEL, A BOHRER, J ENGLER, G FLUGGE [3], D C FRIES, J FUSTER[4], K GAMERDINGER, P GROSSE-WIESMANN [5], J HANSMEYER, G HOPP, H JUNG, J KNAPP, M KRUGER, H KUSTER, P MAYER, H MULLER, K H RANITZSCH, H SCHNEIDER, J WOLF
Kernforschungszentrum Karlsruhe and Universitat Karlsruhe, D-7500 Karlsruhe, Fed Rep Germany

W DE BOER, G BUSCHHORN, G GRINDHAMMER, B GUNDERSON, Ch KIESLING [6], R KOTTHAUS, H KROHA, D LUERS, H OBERLACK, P SCHACHT, G SHOOSHTARI, W WIEDENMANN
Max-Planck-Institut für Physik und Astrophysik D-8000 Munich, Fed Rep Germany

M DAVIER, J -F GRIVAZ, J HAISSINSKI, P JANOT, V JOURNÉ, F LE DIBERDER, A SPADAFORA[7], J -J VEILLET
Laboratoire de l Accelerateur Lineaire, F 91405 Orsay Cedex, France

R GEORGE, M GOLDBERG, O HAMON, F KAPUSTA, F KOVACS, L POGGIOLI, M RIVOAL
Laboratoire de Physique Nucleaire et Hautes Energies, Universite de Paris F-75230 Paris Cedex, France

G D'AGOSTINI, F FERRAROTTO, M GASPERO, B STELLA
University of Rome and INFN I-00185 Rome, Italy

G COZZIKA, Y DUCROS, Y LAVAGNE, F OULD SAADA [8], J ŽÁČEK [9]
Centre d Etudes Nucleaires Saclay F-91191 Gif-sur-Yvette Cedex, France

G ALEXANDER, G BELLA, J GRUNHAUS, A KLATCHKO, A LEVY and C MILSTÉNE
Tel Aviv University 69978 Ramat Aviv, Israel

Received 3 May 1987

0370-2693/87/$ 03 50 © Elsevier Science Publishers B V
(North-Holland Physics Publishing Division)

A search has been performed for the production of charged Higgs bosons in e^+e^- annihilation at center of mass energies up to 46 8 GeV From the absence of both hadronic and leptonic decay signatures, we exclude them up to a mass of 19 GeV/c^2 independent of the hadronic and leptonic branching ratios

1 Introduction A fundamental feature of the Standard Model (SM) of electroweak interactions is that it requires the presence of at least one scalar Higgs doublet, which leads to the prediction of a neutral boson [1] However, the SM does not constrain the total number of such doublets, and several models designed to solve some of its difficulties and ambiguities enlarge this Higgs sector (e g models for *CP*-violation [2] or addressing the strong *CP*-problem [3], and all supersymmetric models [4] [#1]) All of them are characterized by the appearance of new charged Higgs bosons ($H\pm$) which can be produced in e^+e^- annihilations according to the differential cross section

$$\frac{d\sigma}{d\Omega}(e^+e^- \to H^+H^-) = \frac{3}{32\pi}\sigma_{\mu\mu}\beta^3 \sin^2\theta , \qquad (1)$$

where $\sigma_{\mu\mu} = (4/3s)\pi\alpha^2$ is the total μ-pair cross section, β is the Higgs velocity and θ is the relative angle between the incoming and outgoing particles The total cross section is $\frac{1}{4}\sigma_{\mu\mu}\beta^3$

The weak decay into fermions depends on several parameters The present knowledge about the quark mixing angles, the fermion masses and the bounds on the fermion–Higgs couplings [6] imply the decay modes $H^\pm \to \tau\nu$, cs, cb to be dominant for Higgs masses in the PETRA energy range, thus giving rise to the following ractions

$$e^+e^- \to H^+H^- \to \tau\nu\tau\nu$$

tau final state,

$$e^+e^- \to H^+H^- \to cqcq' \quad (q, q' = s, b)$$

hadronic final state,

$$e^+e^- \to H^+H^- \to \tau\nu cq \quad (q = s, b)$$

mixed tau and hadronic final state

Higgs production could also change the total cross section of taus and multihadrons

In this paper we report an experimental search for unstable [#2] charged Higgs bosons using the signatures mentioned above It should be noted that these signatures hold also for technipions as predicted by technicolor models [7]

2 Data collection and detector properties The data used for the present study were collected with the CELLO detector operating at the PETRA e^+e^- collider The total integrated luminosity used for this analysis was 34 pb^{-1}, most of it (27 pb^{-1}) was taken at a fixed center of mass energy of 44 GeV, the rest in an energy scan from 42 5 GeV to 46 8 GeV The CELLO detector has been described in detail elsewhere [8] Here we summarise the main features of the apparatus used in this analysis

– The central tracking device measures momenta of charged particles with a set of cylindrical drift- and proportional chambers inside a 1 3 T solenoidal magnetic field The resolutions obtained in polar angle (θ), azimuthal angle (ϕ), and transverse momentum (p_t) are $\sigma_\theta = 3$ mrad $\sin^2\theta$, $\sigma_\phi = 2$ mrad, and $\sigma(p_t)/p_t = 0\ 02 p_t$ for $|\cos\theta| < 0\ 9$

– The liquid argon electromagnetic calorimeter is divided into two parts The barrel part covers the

[1] Permanent address University of Liverpool, Liverpool L69 3BX, UK
[2] Present address CERN, CH-1211 Geneva 23, Switzerland
[3] Present address III Physikalisches Institut, RWTH, D-5100 Aachen, Fed Rep Germany
[4] Present address Instituto de Fisica Corpuscular, Universidad de Valencia, Valencia, Spain
[5] Present address Stanford Linear Accelerator Center, Stanford, CA 94305, USA
[6] Heisenberg-Stipendiat der Deutschen Forschungsgemeinschaft
[7] Present address Lawrence Berkeley Laboratory Berkeley, CA 94720, USA
[8] Present address II Institut für Experimentalphysik, Universitat Hamburg, D-2000 Hamburg, Fed Rep Germany
[9] Permanent address Nuclear Center, Charles University, CS-18000 Prague 8, Czechoslovakia

[#1] For introductions to the phenomenology of supersymmetry, see for instance ref [5]

[#2] We assume that the $H^\pm$ decay with a decay length less than 10^{-2} m

$|\cos\theta|$ range up to 0 86 and the end caps cover the region $0\ 92 < |\cos\theta| < 0\ 99$ It has a total thickness of 20 radiation lengths and the showers are sampled 7 times in depth The fine lateral segmentation provides an angular resolution $\sigma_\phi = 6$ mrad and $\sigma_\theta = 8$ mrad The energy resolution is $\sigma_E/E = 0\ 05 + 0\ 10/\sqrt{E}$, where E is the shower energy in GeV

– The so called "hole tagger" is a lead scintillator sandwich which closes the gap between the barrel and the end cap colorimeters ($0\ 86 < |\cos\theta| < 0\ 92$) Though its energy resolution is poor, it is efficient in tagging events with photons escaping in the hole between the barrel and end cap calorimeter

The triggers of interest for the present analysis require either

(1) at least 2 GeV deposited energy in the barrel liquid argon calorimeter and one or more charged particles in the central detector with a momentum greater than 650 MeV/c transverse to the beam (as determined by a fast hardware processor), or

(2) two charged particles with a minimum opening angle of 135° in the $r\phi$ plane perpendicular to the beam and a transverse momentum greater than 650 MeV/c

The data processing was carried out be the standard CELLO reconstruction programs After this procedure we selected all topologies of interest by applying different sets of cuts which are described in detail below

3 Tau final states The decay of both Higgs bosons into $\tau\nu$ leads to a characteristic signature of events with two charged tracks coming from the τ decay ($Br(\tau \to 1$ prong$) \sim 86\%$ [9]) and missing energy –momentum due to the undetected neutrinos

To select such events and suppres standard QED background we required

(1) two tracks in the inner detector within $|\cos\theta| < 0\ 85$ and originating from the vertex,

(2) a momentum above 2 5 GeV for both charged particles or above 6 GeV for one charged particle and 1 GeV for the other,

(3) the acoplanarity angle of the two tracks (defined as the acollinearity in the plane $r\phi$) between 35° and 170°,

(4) a missing transverse momentum, as calculated from the two charged particles only, above 3 GeV/c,

(5) the acoplanarity of the τ-jet axes, obtained by using both charged and neutral particles, greater than 20°,

(6) photons either in the barrel or in the hole tagger or in the end cap had to give an invariant mass with one of the charged particles < 2 GeV/c^2, else the event was considered to be a $\tau\tau\gamma$ candidate and rejected

Cut 3 removes collinear lepton pair production and cuts 2, 3, and 4 effectively suppress lepton paris from two photon scattering which tend to be balanced in transverse momentum Cut 6 removes events from tau pair production with two very acoplanar tracks of which one has low momentum

No candidate event is left after the cuts, while the residual background expectation from QED is 0 3 events The detection efficiency with these criteria is 12% for $H^\pm$ masses around 22 GeV/c^2 and falls linearly to zero at 5 GeV/c^2

From the absence of such a signal we exclude $H^\pm$ masses at 95% CL in the range between 5 6 GeV/c^2 and 19 5 GeV/c^2 (assuming 100% branching ratio for $H \to \tau\nu$) The contour labelled as $H^\pm \to$tau's in fig 1 shows the dependence of the limits on the branching ratio

4 Hadronic final states If both charged Higgs particles decay into quarks ($H^\pm \to$cs, cb) and have a relatively high mass (> 8 GeV/c^2) the most obvious

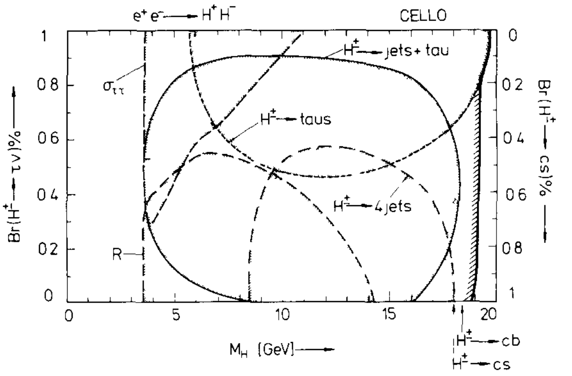

Fig 1 Limits at 95% CL on the mass of the charged Higgs particles as a function of the branching ratio into leptons or hadrons The area on the shaded side of the contour is excluded in each case and they are obtained from the different analysis explained in the text The combined limit for all of them (thick line) shows that charged Higgs bosons below 19 GeV/c^2 are excluded

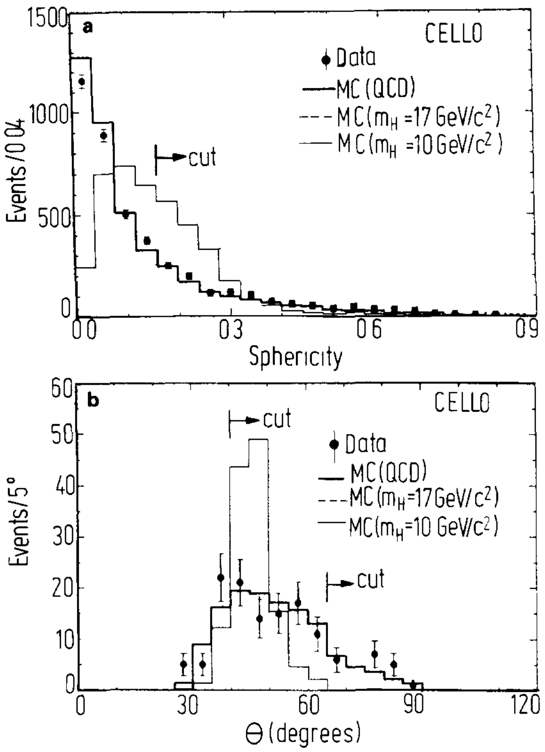

Fig. 2. (a) Sphericity distribution for the events accepted by the multihadron selection. (b) Minimum angular separation between jets in the four-jet event sample. The expectations from second order QCD and charged Higgs production with masses of 17 GeV/c^2 and 10 GeV/c^2 are also shown. All distributions are normalized to the total number of events found in data.

signal after quark hadronization is an excess in the number of four jet events. In contrast to those originating from QCD processes these events will show two jet combinations with an invariant mass clustering at the corresponding Higgs mass.

The multihadron preselection is the same as described in ref. [10]. The main requirements are:

(1) The multiplicity of charged particles $n_{ch}>4$.

(2) Energy of charged particles $E_{ch}>0.10\sqrt{s}$.

(3) Energy of neutral particles $E_{neu}>0.08\sqrt{s}$.

(4) Total energy of all particles $E_{tot}>0.40\sqrt{s}$.

To enhance the Higgs signal we required in addition:

(5) Energy of charged particles $E_{ch}>0.30\sqrt{s}$.

(6) Large sphericity values ($S>0.15$) (see fig. 2a).

(7) The polar angle (θ_{sph}) of the sphericity axis constrained to $|\cos\theta_{sph}|<0.75$.

(8) The charged energy greater than the neutral energy.

(9) Four and only four jets found by a cluster algorithm [#3] where these jets in addition were required to have:

(a) a jet energy (neutral plus charged) larger than 3 GeV with its axis constrained to $|\cos\theta|<0.8$,

(b) a particle multiplicity (neutral plus charged) for each jet larger than 2,

(c) no particle having more than 90% of the corresponding jet energy,

(d) a minimum angle between any two jets of 65° (see fig. 2b). For small Higgs masses this cut is too restrictive and it was loosened to 40° as will be discussed hereafter.

(10) For the remaining four jet events, the jet four-momenta were recalculated from the measured jet directions and known quark masses. In this way large mass fluctuations due to poorly measured or unobserved particles are avoided and the mass resolution for the $H^{\pm}$ candidates is improved. Only well reconstructed events with little missing energy and momentum were accepted by requiring the rescaling of the jet energies and momenta to be between 0.5 and 2.5.

(11) Once the event was reconstructed kinematically, only clean four jet events were selected by requiring that all jet–jet combinations showed a large invariant mass ($Y=(m_{ij}/\sqrt{s})^2>0.05$) and that the difference between the invariant masses of the two jet pairs was less than 10 GeV/c^2 for at least one of the two wrong jet–jet combinations. The wrong jet pairings were distinguished from the correct pairing by calculating the probability for all possible jet pairings via a least square fit requiring pair production of particles with equal masses. From a Monte Carlo simulation the Higgs mass resolution was found to be 1–2 GeV/c^2 in the mass range of interest.

No event survived these cuts and the detection efficiency was found to be 5–6% for Higgs masses above 13 GeV/c^2. The expected background from second order QCD processes is 0.8 events.

For smaller Higgs masses the jets become more collimated and so we made slightly different cuts.

[#3] This cluster algorithm is a utility routine in the Lund Monte Carlo program [11], version JETSET5.2. The parameter defining the cluster resolution (d_{join}) was chosen to be 2 GeV/c.

(1) The angular separation between jets was required to be only $>40°$ (see fig 2b)

(2) The correct jet–jet combinations had to have a small invariant mass ($Y<0$ 06) and all other combinations had to have $m_{ij}>18$ GeV/c^2, since this configuration gives large invariant masses for the wrong jet combinations

One event remained, which was kept as a candidate ($M_H=10$ GeV/c^2), the expectation from second order QCD background is 0 6 events The detection efficiency for these selection criteria is 4% around 13 GeV/c^2 and falls to zero at 8 GeV/c^2 From these efficiencies and the observed number of events we exclude $H^{\pm}$ masses between 8 7 GeV/c^2 and 18 GeV/c^2 at 95% CL (for 100% branching ratio $H^{\pm}\to cs$) These limits are shown in fig 1 as function of the branching ratio by the curve labelled $H^{\pm}\to 4$ jets Since the number of events surviving the cuts were only 0 or 1, we did not make any QCD background subtraction for the limit calculations, thus obtaining conservative limits which do not depend on uncertainties from multijet production from higher order QCD

For the Monte Carlo simulations the LUND string fragmentation [11,12] including initial state radiative corrections was used A variation of the fragmentation parameters σ_q and the vector meson probability for the c and b quarks within reasonable limits do not affect the $H^{\pm}$ detection efficiency significantly

The different hadronic decay modes $H^{\pm}\to cs$ or $H^{\pm}\to cb$ show similar detection efficiencies The limit contour in fig 1 labelled as $H^{\pm}\to 4$ jets corresponds to the case $H^{\pm}\to cs$ The somewhat better limit for the decay $H^{\pm}\to cb$ has been indicated at the bottom of the figure

5 Mixed hadronic and tau final state When one Higgs decays into a $\tau\nu$ and the other into quarks (cs, cb), the cleanest signature for the detection of charged Higgs is evidence of an excess of multihadron events with an isolated track and missing energy -momentum

After a multihadron preselection softer than the one used in the preceeding section ($n_{ch}>2$, $E_{ch}>0$ $1\sqrt{s}$, $E_{neu}>2$ 0 GeV), the following requirements were made

(1) A missing total energy greater than 0 $25\sqrt{s}$

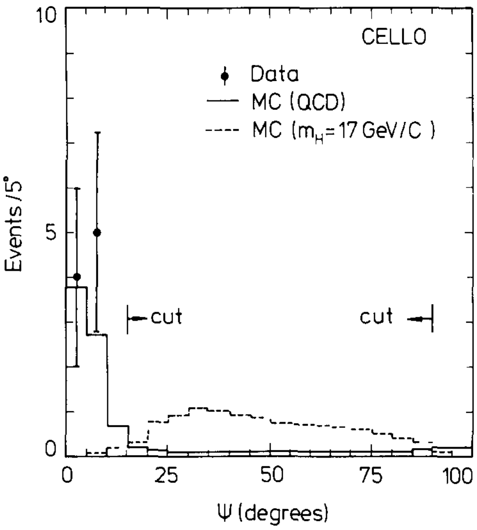

Fig 3 Acollinearity distribution for the accepted multihadron events with an isolated charged track (as expected in a mixed hadronic and leptonic $H^{\pm}$ decay) This is compared with the second order QCD prediction and the charged Higgs production with a mass of 17 GeV/c^2 All distributions are normalized to the total number of events in data

(2) An absolute missing momentum greater than 0 $1\sqrt{s}$ and pointing in the barrel calorimeter

(3) The polar angle θ_{sph} of the sphericity axis – calculated including the missing four momentum in the event – had to satisfy $|\cos\theta_{sph}|<0$ 6

(4) One charged track isolated by more than 60° from any other charged track and having a minimum energy of 1 5 GeV

(5) Inside this cone not more than 3 neutral particles were allowed, in addition the neutral energy was not allowed to exceed the energy of the isolated track by more than a factor 1 5 and the averge energy of the particles inside the cone had to be larger than 1 GeV

(6) Since heavy Higgs particles are slow, $\beta^2=(p_{tot}/E_{tot})^2$ was required to be less than 0 95, where p_{tot} and E_{tot} [#4] are the summed momentum and energy of all particles outside the cone defined above

(7) The acollinearity of the two momentum sums of the particles inside and outside the cone was required to be between 15° and 90° (see fig 3)

Cuts 6 and 7 efficiently reject $\tau\tau$ background Cut

[#4] E_{tot} was calculated under the assumption that all charged particles were pions

2 rejects events from $\gamma\gamma$ collisions with one of the radiating electrons scattered into the acceptance of the detector No event survived these cuts, the expected background from QCD is 1 event The detection efficiency for this decay mode is 5–6% when the Higgs branching ratio is assumed to be 50% for both leptonic and hadronic channels With this assumption we exclude at 95% CL $H^{\pm}$ masses between 4 2 and 18 2 GeV/c^2 The contour labelled $H^{\pm}\rightarrow$jets+"tau" shows the limit as a function of the branching ratio

These cuts still yield a sizeable efficiency for a 100% branching ratio into hadrons, since heavy quark decays can produce isolated charged particles when the Higgs mass is big enough The overlap in efficiency for these selection criteria and those used in the four jet analysis is estimated to be less than 1%, so the data samples are practically independent, thus allowing one to make a combined limit

6 Total cross sections for tau and multihadron production The main purpose of this analysis is to search for the production of Higgses in the low mass corners of fig 1 not accesible by the analysis described in the previous sections The pair production of Higgs bosons decaying into multihadrons gives an increase of 0 25β^3 in the ratio R of the measured total hadronic cross section and the muon pair production cross section Such a large increase is easily excluded from the combined results on R of the various PEP and PETRA experiments [13] To obtain the limit as function of the $H^{\pm}$ mass and the branching ratio we fitted simultaneously the strong coupling constant α_s and the branching ratio of the charged Higgs for a given mass The value of the electroweak mixing angle $\sin^2\theta_W$ was kept fixed at the world average of 0 23 [14] The fitted value of α_s was always close to the one without the Higgs contribution The excluded mass range at 95% CL as function of the branching ratios are shown in fig 1 as the contour labelled R We have also tried a fit in which α_s was kept small ($\Lambda_{QCD}=10$ MeV), so that most of the excess over the quark parton model prediction can be attributed to Higgs production In this case the area excluded by the contour R in fig 1 is roughly reduced to half its size The limits determined from R depend on the relative detection efficiency for the Higgs bosons and the normal multihadron production For CELLO this ratio is close to one and we have assumed it to be one also for all other detectors

A similar fit has been performed to our measurements of the total cross section for tau production [15] The results are shown by the curve labelled $\sigma_{\tau\tau}$ in fig 1

No attempts have been made to exclude $H^{\pm}$ with masses below the threshold for decay into taus, since this region has been excluded already [16]

7 Conclusion In a search for unstable charged Higgs particles we did not observe any signal in either hadronic or leptonic decay modes using data up to the highest PETRA energy of 46 8 GeV The combined results on the searches for all possible decay modes exclude charged Higgs bosons with masses below 19 GeV/c^2 at 95% CL independent of the branching ratio This limit also holds for technipions which have the same signatures [7]

The present result improves significantly previous ones from PEP and PETRA [17], none of which exluded by itself charged Higgs bosons idependently of their decay mode

We gratefully acknowledge the outstanding efforts of the PETRA machine group which made possible these measurements We are indebted to the DESY computer center for their excellent support during the experiment We acknowledge the invaluable effort of many engineers and technicians from the collaborating institutions in the construction and maintenance of the apparatus, in particular the operation of the magnet system by M Clausen, P Ropnack and the cryogenic group The visiting groups wish to thank the DESY Directorate for the support and kind hospitality extended to them

This work was partially supported by the Bundesministerium für Forschung und Technologie (Germany), the Commissariat á l'Energie Atomique and the Institut National de Physique Nucléaire et de Physique des Particules (France), the Istituto Nazionale di Fisica Nucleare (Italy), the Science and Engineering Research Council (UK), and the Israeli Ministry of Science and Development

References

[1] S L Glashow, Nucl Phys 22 (1961) 579,
S Weinberg, Phys Rev Lett 19 (1967) 1264,

A Salam Proc 8th Nobel Symp (Stockholm), ed N Svartholm (Almqvist and Wiksell, Stockholm, 1968) p 367
[2] S Weinberg Phys Rev Lett 40 (1978) 223
F A Wilczek, Phys Rev Lett 40 (1978) 279
[3] T D Lee, Phys Rev D 8 (1973) 1226,
S Weinberg, Phys Rev Lett 37 (1976) 657,
F A Anselm and D I D'Yaknov, Nucl Phys B 145 (1978) 271
R D Peccei and H R Quinn, Phys Rev D 16 (1977) 1791
[4] S Dimopoulos and H Georgi, Nucl Phys B 193 (1981) 150
J Wess and B Zumino, Nucl Phys B 70 (1974) 39,
A Salam and B Strathdee, Phys Rev D 11 (1975) 1521
[5] H E Haber and G Kane, Phys Rep 117 (1985) 75,
R M Barnett Proc 1985 SLAC Summer Institute on Particle Physics
[6] C F Abbott P Sikivie and M B Wise, Phys Rev D 21 (1980) 1393,
G G Athanasiu and F J Gilman Phys Lett B 153 (1985) 274,
G G Athanasiu, P J Franzini and F J Gilman, Phys Rev D 32 (1985) 3010
M Drees, M Gluck and K Grassie, Phys Lett B 159 (1985) 118
E Reya, Phys Rev D 33 (1986) 773,
L A T Bauerdick, Z Phys C 32 (1986) 459
[7] E Eichten, I Hinchliffe, K D Lane and C Quigg, Phys Rev D 34 (1986) 1547, and references therein
[8] CELLO Collab, H-J Behrend et al, Phys Scr 23 (1981) 610
[9] Particle Data Group, M Aguilar-Benitez et al, Phys Lett B 170 (1986) 78
[10] CELLO Collab, H-J Behrend et al, Phys Lett B 181 (1986) 178
[11] T Sjostrand Comput Phys Commun 27 (1982) 243 28 (1983) 229
[12] B Andersson, G Gustafson, G Ingelman and T Sjostrand Phys Rep 97 (1983) 31
[13] CELLO Collab, H-J Behrend et al, Phys Lett B 183 (1987) 400
[14] W de Boer MPI-PAE/Exp El 167, Proc XVIIth Intern Symp on Multiparticle dynamics (Seewinkel, Austria) eds M Markytan, W Majerotto and J MacNaughton (1986) p 73, and references therein
[15] V Journe Ph D thesis, LAL 84/20,
H Kuster, Diplomarbeit, KfK 3160
Cello Collab Contrib Intern Conf on High energy phys (Berkeley 1986)
[16] CLEO Collab, A Chen et al Phys Lett B 122 (1983) 317
[17] CELLO Collab, H-J Behrend et al Phys Lett B 114 (1982) 287,
JADE Collab, W Bartel et al, Phys Lett B 114 (1982) 211, Z Phys C 31 (1986) 359,
MARK-J Collab, B Adeva et al, Phys Lett B 115 (1982) 345, B 152 (1985) 439,
TASSO Collab, M Althoff et al, Phys Lett B 122 (1983) 95,
MARK-II Collab, C A Blocker et al, Phys Rev Lett 49 (1982) 517