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A STUDY OF FINAL STATES WITH FOUR CHARGED LEPTONS IN e^+e^- INTERACTIONS

by

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A study of final states with four charged
leptons in e^+e^- interactions.

Abstract:

Electron-positron interactions producing the final states $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $e^+e^-\tau^+\tau^-$ and $\mu^+\mu^-\mu^+\mu^-$ have been studied in the CELLO detector at PETRA. Results are presented on 10 events where the four particles emerge at large angle ($> 23^0$) with respect to the beam axis. Comparison is made with QED predictions, and an indication is found for an excess of events where all l^+l^- masses ($l=e,\mu,\tau$) are large.

INTRODUCTION

Four lepton final states from e^+e^- interactions are examples of order α^4 QED processes. Most results so far originate from 2-photon interactions where 1(single-tag) or 2(no-tag) electrons are undetected and are at small angle θ with respect to the beam axis [1]. In these kinematic regions, cross sections are dominated by the two multiperipheral processes (Fig.1 a,b).

Requiring that all leptons be emitted at large angle has a twofold interest. First, in this domain, virtual bremstrahlung processes (Fig.1 c for an example) are expected to be dominant and the production of two virtual photons(Fig.1 d) becomes measurable. Second, should high mass new particles decaying into leptons be produced, or new currents be present, an excess of events would appear above the QED prediction. In this spirit, we were specially motivated by the peculiar event we have observed at a c.m. energy of 43.45 GeV, in which 2 isolated energetic muons have been produced together with 2 jets [2] .

In this letter, we present the results of a search for 4 lepton events in the CELLO detector at the PETRA collider.

The following reactions have been considered:

$$e^+e^- \longrightarrow e^+e^-e^+e^- \quad (1)$$

$$e^+e^- \longrightarrow e^+e^-\mu^+\mu^- \quad (2)$$

$$e^+e^- \longrightarrow \mu^+\mu^-\mu^+\mu^- \quad (3)$$

$$e^+e^- \longrightarrow e^+e^-\tau^+\tau^- \quad (4)$$

We compare the results obtained with the QED prediction, with special attention to the events with high invariant masses of lepton pairs with zero leptonic charge.

THE EXPERIMENT

The CELLO detector [3] provides good multiparticle event detection and lepton identification.

Cylindrical wire chambers measure charged particle momenta over 92% of the solid angle. The momentum resolution is $\sigma(P_t)/P_t \simeq 0.013\sqrt{1+P_t^2}$ (P_t in GeV/c) using a constrained vertex.

Electromagnetic showers are measured in a lead-liquid Argon calorimeter over 87% of 4π steradians with an energy resolution $\sigma(E)/E \simeq 0.025 + 0.10/\sqrt{E}$.

The muon detector consists of large planar wire chambers mounted on a hadron absorber made of 80 cm thick iron. Muon identification is possible over 92% of 4π steradians with wire chambers with a spatial resolution of 0.6 cm.

The data presented here have been collected at 3 fixed c.m. energies of 14, 22 and 34 GeV,and during the scan between 40 and 46.7 GeV. The integrated luminosities respectively accumulated during those 4 periods are 1.0, 2.5, 7.7, and 13.5 Pb^{-1}. Four track events where at least one high energy electron showers in the central calorimeter are efficiently (more than 96%) triggered by using neutral energy (typically 1.2 GeV) in coincidence with a single-track trigger. At the 3 fixed energies,a 2-charged-particle trigger provided an efficient(> 99%) way of collecting events with four tracks.

The events were obtained during a search for isolated leptons [2,4]. The selection criteria for the 4-lepton subsample are the following:

- the 4 charged particles must be in the region defined by $|\cos(\theta)| < .92$ with a momentum above 0.3 GeV/c.
- at least one isolated lepton with momentum above 1.5 GeV/c in the angular region defined by $|\cos(\theta)| < .87$. The isolation means that there is no other charged particle emitted within a cone of 18 degrees (half- angle) around the track considered.
- At least 3 identified leptons in the event.
- any pair of charged particles of zero leptonic charge must have an effective mass above 1 GeV/c^2. This cut removes potential background from radiative events.

Identification criteria for leptons are the following:

- an identified electron must hit the barrel calorimeter($|\cos(\theta)| < .87$) , have a momentum p above 1 GeV/c, its shower energy E must be consistent with p, the fraction of E measured in layers 2 and 3(between about 1 and 5 radiation lengths at $\theta = 90^0$) must be larger than 10%, and the energy measured in the last layer (between 17 and 21 radiation lengths at $\theta = 90^0$) must be smaller than 500 Mev, as expected for electromagnetic showers.

- an identified muon must have a reconstructed track in the central detector ($|\cos(\theta)| < .92$) , have a momentum p larger than 1.3 GeV/c in order to get through the hadron filter, and have at least one associated hit in the muon chambers. In addition, when it traverses the shower counter, its energy deposition must be consistent with that expected from a minimum ionising particle.

These identification cuts are rather loose compared to criteria used in other CELLO analyses, but we use them in order to maximize detection efficiency, since, as we shall see, we do not suffer from background contamination.

Since we are dealing with reactions where electrons are involved, we accept events with one neutral electromagnetic shower. The total number of candidates is 10.

In the following stage of analysis,we separate candidates of reactions (1) to (3) from those of reaction (4).

a)reactions (1) to (3): For the first 3 reactions,we require the fourth charged particle,if not identified,to be consistent with conservation of leptonic number from charged particles only, i.e. assuming there is no leptonic charge carried out by neutrinos. Nine events are kept. We then perform kinematic fitting, using 4(4C), 3(3C) and 1(1C) constraints fits. The 3C fit considers a photon along the beam direction, as expected from initial state radiation. The 1C fit handles any radiative events with an undetected γ. We accept the 1C fit if the missing photon direction is consistent within errors with the blind regions of the calorimetry. The 9 events give an acceptable kinematic fit. Five belong to reaction (1), four to reaction (2) and none to reaction (3).

The main background to be expected comes from the $e^+e^-\tau^+\tau^-$ final state where both τ's decay into one charged particle, one of them being an e or a μ. To study this contribution we used the Monte-Carlo calculation described in the next section. However, since there are neutrinos emitted in this reaction, the expected contamination is much less than 1 event.

Another potential background is the $e^+e^-h^+h^-$ final state, h being a hadron. All 4 prong events containing an identified e^+e^- pair also contain a third positively identified lepton. Therefore, the absence of candidates for the $e^+e^-h^+h^-$ final state allows us to compute a 95% confidence upper limit of 0.3 event for this contamination, taking into account the probabilities for a hadron to be misidentified as a lepton (typically 2% and 5% for e's and μ's respectively for the momenta considered).

b)reactions (4): The tenth event, collected at 46.45 GeV c.m. energy, has 3 identified electrons. Its missing energy is 9 GeV. The fourth charged particle starts showering after 5 radiation lengthes, which is unlikely for an electron(probability<3%). We therefore attribute this event to reaction (4), where one τ decays leptonically to an electron(+undetected ν's), the other decaying into a charged hadron plus undetected neutral(s).

COMPARISON WITH QED AND DISCUSSION

a)reactions (1) to (3): QED calculations of 4 lepton final states have been initially done for 2-photon physics [5]. Recently, complete calculations of all possible diagrams of order 4 have been made for reactions (1) to (3), assuming vanishing lepton masses [6]. Our sample contains also four events with a hard photon(above 1 GeV) in the vicinity of one of the emerging leptons(two events with a γ from kinematics, and two with detected electromagnetic showers). We therefore have to handle the radiative corrections without any available specific calculation [7]. Since no event with a hard γ along the beam axis is found, we consider only final state radiative corrections. Let us call k_γ the ratio of the photon energy to the sum of the energies of the photon and the accompanying lepton. Using the semiclassical method of an equivalent radiator thickness [8] , we would have expected 1.5 events with $k_\gamma > 0.2$, where 4 are observed. The effect of the final state radiative corrections on the total cross sections are small(of order α) due to Kinoshita-Lee-Nauenberg cancellations [9]. Thus we have used the calculations to order 4 in which we have introduced our acceptance cuts and our efficiencies in order to compute the expected number of events and distributions. Table 1 shows the results of the comparison between the observed number of events and the prediction.

Within the limited statistics, there is good agreement at this stage.

Events with large l^+l^- ($l=e,\mu$) masses are of special interest since this is the region where potential deviations from QED would be the largest. We have therefore looked at the l^+l^- mass distribution in the following way. For the 4 electron final state, we consider the smallest of the 4 possible combinations. For $e^+e^-\mu^+\mu^-$, we consider the smallest of e^+e^- and $\mu^+\mu^-$ combinations. In order to merge the sets of data taken at various energies, we scale the mass by E_b, the beam energy and use the variable $X = M(l^+l^-) / E_b$ [10]. Whenever there is a γ close to one of the leptons, it is taken into account in the corresponding mass computation, and we use $X = M(l^+l^-\gamma) / E_b$. Fig.2 a) shows the X distribution of our 9 events, compared to the Monte-Carlo prediction. Although the low statistics does not allow a precise comparison with QED, there is some suggestion of an excess at high mass values. To estimate the significance of this excess, we compare the number of events observed above any X value with the Monte-Carlo prediction. From Poisson statistics, we compute the probability P(X) for the observed number to exceed the prediction. This

probability is shown in Fig.2 b) and has its minimum around X=0.4. Above this value, 1.03 event are expected, whereas 6 are observed. Taking into account the X interval(0.4-0.7) over which the excess is observed, the probability that it is due to a statistical fluctuation of the QED prediction is 0.2% .

Because of this low probability, it is worthwhile to look in more detail at the large X events. The 4-vectors of the 9 events are shown in table 2, together with their X values. The only peculiarity is the planarity of the seventh event(Fig.3), collected at a c.m. energy of 41.08 GeV. The angle between the e^+e^- and $\mu^+\mu^-$ planes is 1.0^0 ,whereas from QED,a rather uniform distribution is expected.

This planarity is reminiscent of the exotic event [2] we have observed at 43.45 GeV, where the angle between the $\mu^+\mu^-$ plane and the jet-jet plane is 3^0

<u>b)reactions (4):</u> We now consider reaction (4).In order to compute the number of expected events, we use the calculation of reaction (2), where we reduce the cross section by the factor $\beta(3-\beta^2)/2$, β being the velocity in the $\tau^+\tau^-$ system taken as the $\mu^+\mu^-$ system.(This procedure is partly justified because the dominant graphs produce τ pairs through a virtual photon). We take into account leptonic(B_l=35%) and topological ($B_{1\text{-prong}}$=85%) branching ratios in order to get at least 3 leptons in a 4-prong event. The additional acceptance reduction due to the softening of the charged particle momentum spectrum as well as the angular smearing in the decay of the τ are neglected. The predicted numbers are therefore considered as upper limits, and are reported in table 1. In total, we expect less than 0.7 event and observe 1. It is interesting to note that the smallest l^+l^- mass for this event is 11.2 GeV/c^2 corresponding to an X of 0.48(see table 2)[11].

There is no apparent explanation for the observed excess of high mass events.

CONCLUSION

Electron-positron interactions going to the final states $e^+e^-e^+e^-$ and $e^+e^-\mu^+\mu^-$ have been detected in the CELLO apparatus at PETRA. We have observed 9 events where the four particles emerge at large angle ($> 23^0$) with respect to the beam axis. This number is consistent with the QED prediction of 6.8, although there is an indication for an experimental excess for events, where large mass systems of zero leptonic charge are produced.

In addition, an $e^+e^-\tau^+\tau^-$ candidate is observed at $\sqrt{s}$= 46.45 GeV where the l^+l^- masses are also large.

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6) R.Kleiss, N.P.B241(1984) 61

7) Such calculations have been made so far only for the 2 multiperipheral processes. See F.A.Berends et al., Leiden preprint(1984).

8) For each lepton l, we compute the probability of hard photon emission from the integral of the photon spectrum

$$1/\sigma_0 . d\sigma/dk = \alpha/\pi . (1/k-1+k/2) . [Ln(q^2/m_l^{\ 2})-1]$$

where σ_0 and σ are the lowest order and radiatively corrected cross sections respectively. m_l is the lepton mass and q^2 the mass squared of the corresponding lepton pair. q^2 is ambiguous for reaction (1), but this ambiguity leads to minor differences, due to the weak logarithmic dependence.

9) -T.Kinoshita, J.Math. Phys. 3(1962),650.
-T.D.Lee and Nauenberg, Phys. Rev. B1549(1964),133

10) This is actually a scaling variable in QED, when all lepton masses are neglected.

11) If we add reaction (4) to the analysis of the X distribution, the lowest P(X) goes down by at least a factor 2. There is some ambiguity in the X definition for reaction (4), because there is no possibility to know whether e's and μ's are directly produced or originate from τ decays. Exact calculation would require a full simulation.

FIGURE CAPTIONS

Fig.1 a) and b) Multiperipheral diagrams.
c) an example of virtual bremstrahlung diagram
d) diagram for e^+e^- annihilation into two virtual photons.

Fig.2 a) distribution of $X = M(l^+l^-) / E_b$ for real events and QED prediction
b) variation of P(X)
$P(X)=\exp(-i)*\Sigma_{l=n}^{\infty} i^{l} / l!$, where n is the observed number of events above X, and i is the expected number in the same region.

Fig.3) Event nb. 7 view in the plane perpendicular to the beam axis. Particles 1 and 3 are identified as muons in chambers of the central part and of the doors of the detector respectively. Particle 2 is identified as

an electron in the barrel liquid argon detector and particle 4 points towards a non-instrumented region of the calorimeter.

C.M. energy (Gev)	Integrated Luminosity (Pb^{-1})	PROCESS 1 eeee, 2 $ee\mu\mu$, 3 $\mu\mu\mu\mu$, 4 $ee\tau\tau$	
		Expect. number of events	Observed number of events
40.0 - 46.6	13.5	1 1.19 2 1.42 3 — 4 $\leqslant$.30	1 2 — 1
34.0	7.7	1 1.11 2 1.16 3 .07 4 $\leqslant$.20	2 1 0 0
22.0	2.5	1 .49 2 .64 3 .04 4 $\leqslant$.10	1 0 0 0
14.0	1.0	1 .29 2 .36 3 .02 4 $\leqslant$.05	1 1 0 0
TOTAL		1 3.08 2 3.56 3 .13 4 $\leqslant$.66 1 to 3 6.76 1 to 4 7.32	5 4 0 1 9 10

T A B L E 1

TABLE 2

List of events with their 4-vectors(Px,Py,Pz,E) and X values.

(the z axis is along the incident e^- direction)
Units are GeV and GeV/c.

Event number 1 ECM= 14.000 GeV X=0.41

0.270	0.398	-0.402	0.627	(e^+)
4.854	2.061	-3.303	6.222	e^+
-2.827	-0.560	2.088	3.558	e^-
-2.298	-1.900	1.771	3.468	e^-
0.000	0.0	-0.154	0.154	(γ)

Event number 2 ECM= 14.000 GeV X=0.63

1.773	1.144	0.330	2.136	e^-
-0.009	-2.110	2.594	3.344	μ^+
-3.211	1.985	1.276	3.985	μ^-
1.013	-0.582	-2.618	2.867	(e^+)
0.437	-0.443	-1.579	1.697	(γ)

Event number 3 ECM= 22.000 GeV X=0.48

-2.840	-1.081	-1.570	3.420	e^+
4.049	1.244	0.076	4.236	e^-
3.724	0.628	6.163	7.228	e^-
-1.052	0.247	-1.988	2.263	(e^+)
-3.886	-1.069	-2.687	4.844	γ

Event number 4 ECM= 34.000 GeV X=0.07

1.212	-9.563	2.951	10.081	e^-
-1.606	16.547	-2.075	16.754	e^+
-0.114	-5.897	-0.664	5.935	μ^+
0.525	-1.071	-0.201	1.210	μ^-

Event number 5 ECM= 34.000 GeV X=0.57

-1.510	-5.306	-7.490	9.302	e^+
-3.479	3.622	4.308	6.617	e^-
0.715	7.212	-3.800	8.183	e^+
4.276	-5.524	6.994	9.885	e^-

Event number 6 ECM= 34.000 GeV X=0.18

1.044	-0.437	0.093	1.136	e^+
-3.608	-5.481	-1.399	6.709	e^-
-1.816	15.032	-2.242	15.306	e^+
0.757	-2.122	0.138	2.257	e^-
3.618	-6.990	3.411	8.578	γ

Event number 7 ECM= 41.080 GeV X=0.66

8.659	7.161	-0.720	11.260	μ^+
-8.682	-5.499	3.543	10.870	e^-
-2.248	2.949	6.840	7.780	μ^-
2.312	-2.472	-6.426	7.263	(e^+)
-0.035	-2.149	-3.246	3.893	(γ)

Event number 8 ECM= 43.020 GeV X=0.08

-7.064	1.793	-8.534	11.223	e^-
-0.828	4.936	-5.884	7.725	e^-
9.205	-6.461	16.695	20.129	e^+
-1.665	-0.188	-2.894	3.344	(e^+)
0.334	-0.145	0.501	0.620	γ

Event number 9 ECM= 44.200 GeV X=0.52

0.131	5.764	1.022	5.855	μ^-
0.994	-3.898	-5.402	6.735	μ^+
-7.891	-3.697	-11.396	14.346	e^+
6.766	1.832	15.776	17.263	(e^-)

Event number 10 ECM= 46.450 GeV

14.212	0.434	4.417	14.889	e^-
-3.339	-10.862	-1.043	11.411	e^+
1.403	4.413	-1.411	4.841	e^-
-5.679	3.416	-1.926	6.901	h^+

Notes: 1)For events 1 to 9, the fitted values are quoted, whereas for event 10, the measured values are given.
2) For charged particles,the brackets mean that their nature is inferred from lepton number conservation. For photons, the brackets mean that they are not detected but deduced from a 1C or a 3C fit.

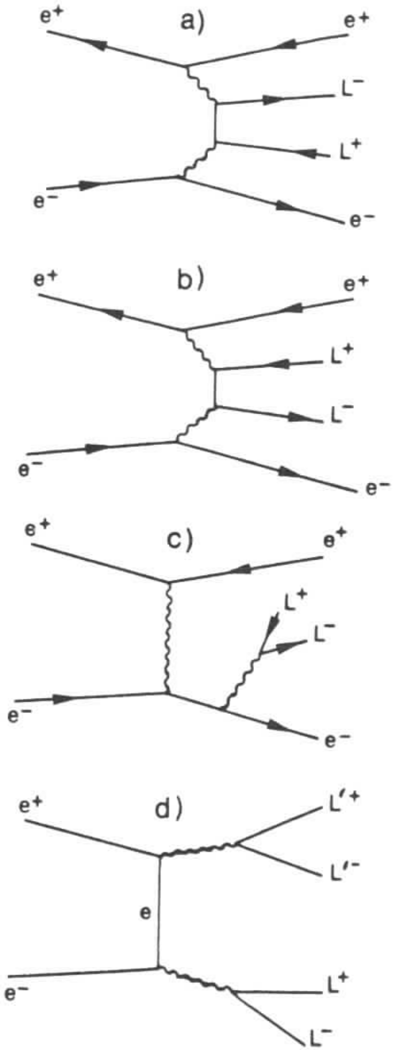

FIG.1

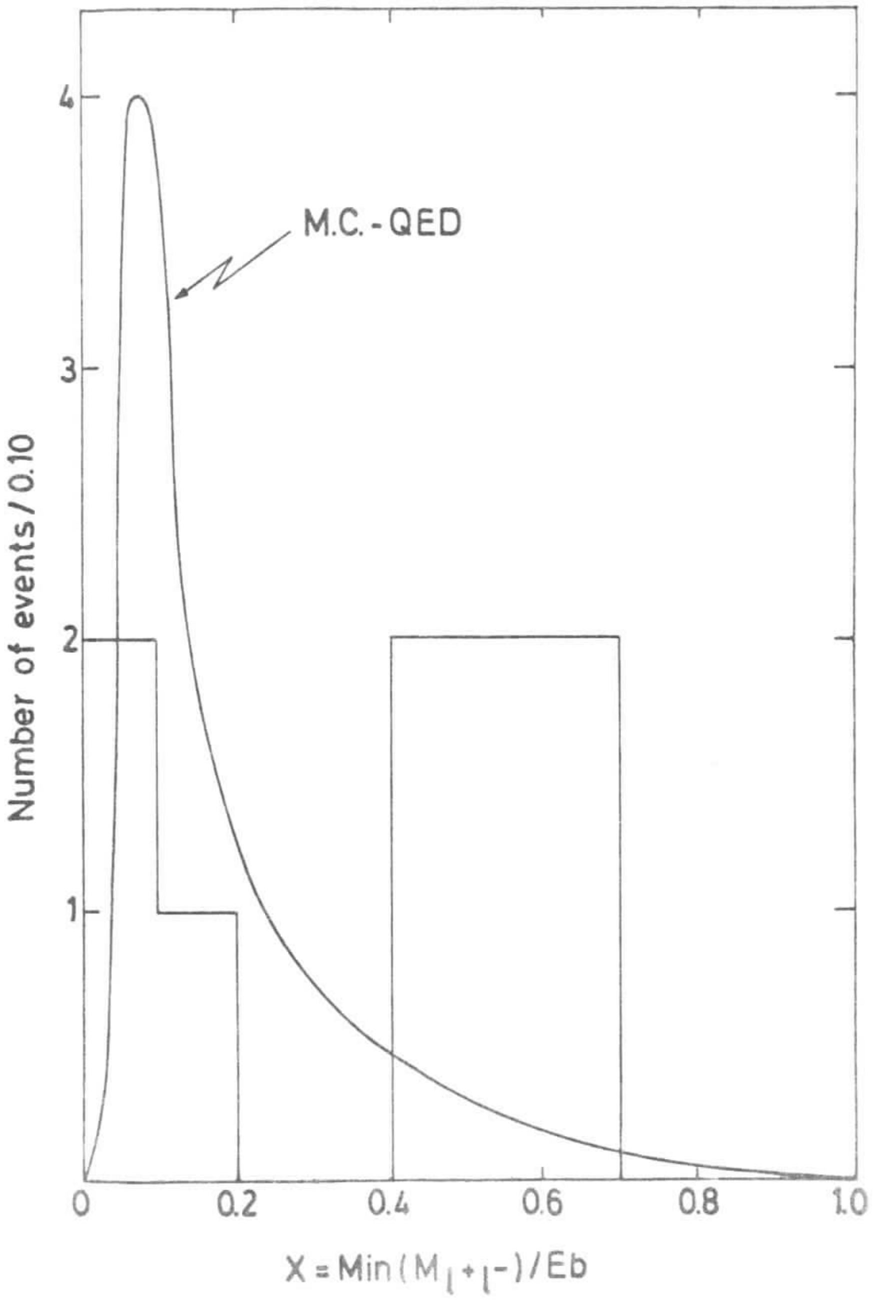
M.C. - QED
Number of events / 0.10
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
X = Min (M l+l-) / Eb

Fig. 2a

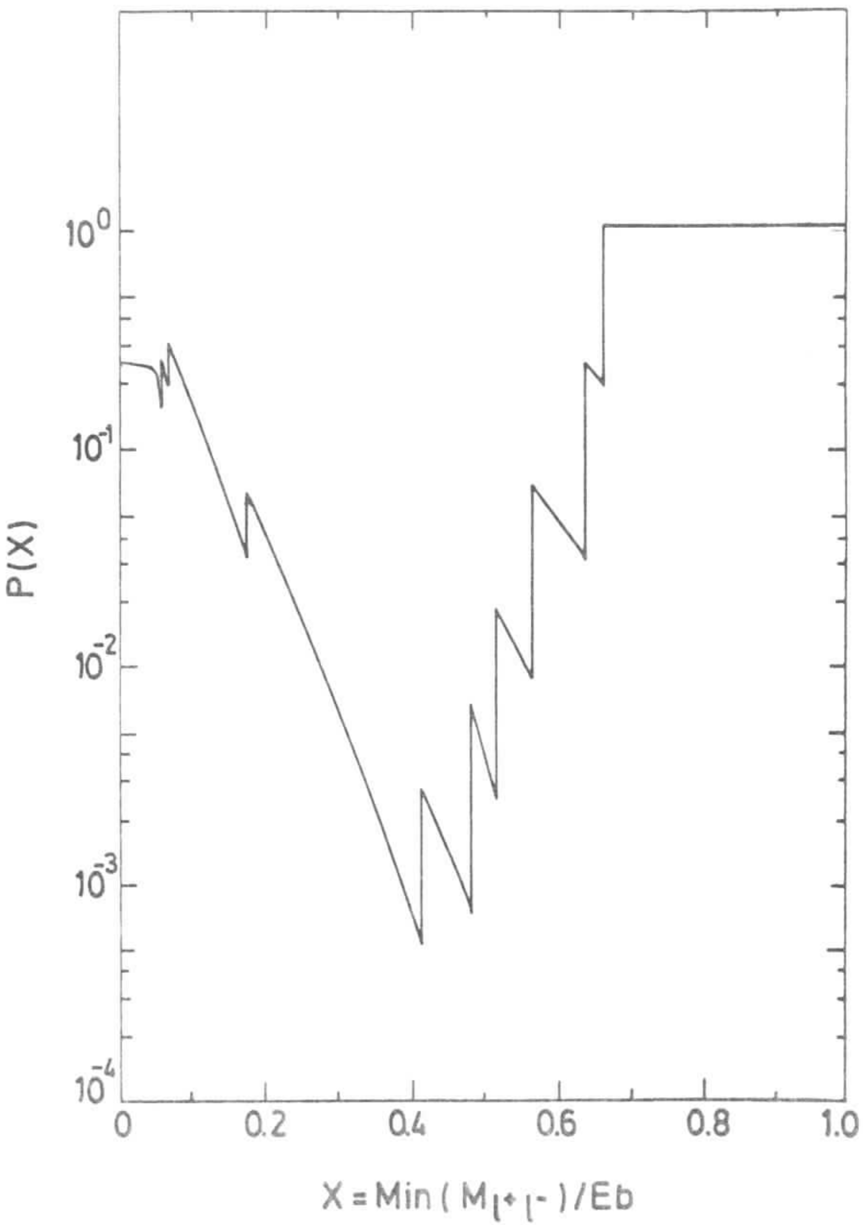
P(X)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1.0
X = Min (M l+l-) / Eb

Fig. 2b

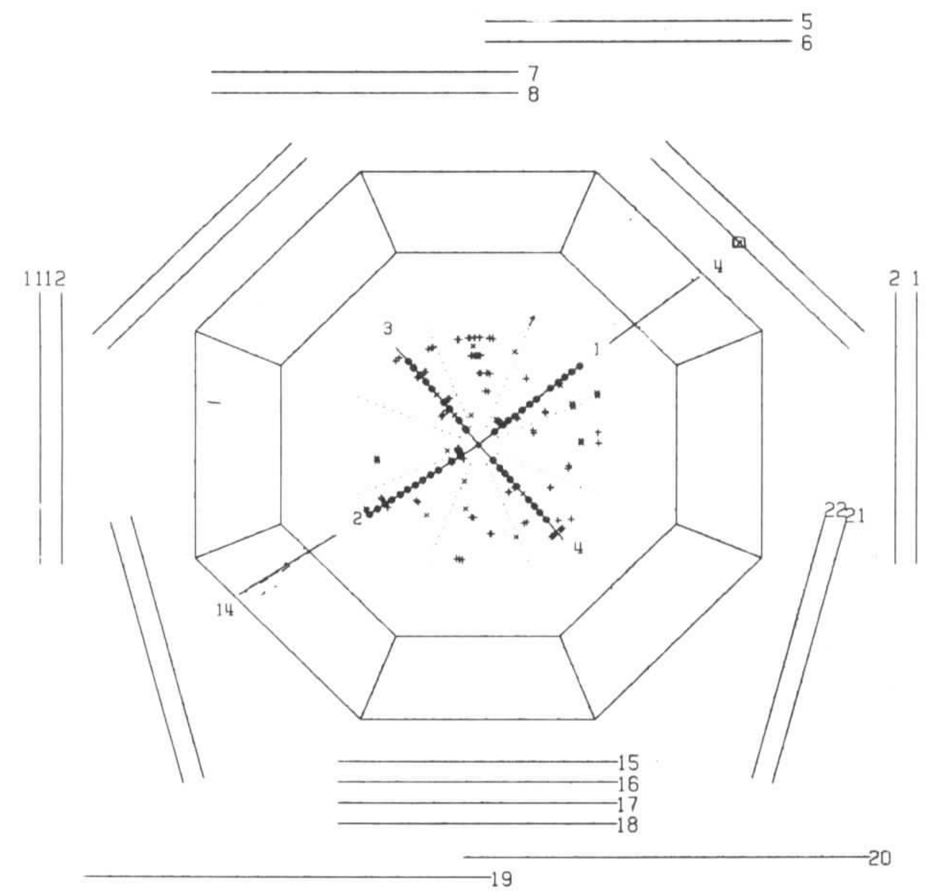

Fig. 3