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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

S.E. Baru, M.V. Beilin, A.E. Blinov,
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A.I. Vorobiov, V.N. Zhilich, A.A. Zholents

TOTAL CROSS SECTION OF TWO PHOTON PRODUCTION OF HADRONS

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НОВОСИБИРСК

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A.E.Undrus, A.I.Vorobiov, V.N.Zhilich, A.A.Zholents.

Institute of Nuclear Physics,
Novosibirsk, USSR

ABSTRACT

The total cross section for $\gamma\gamma \to$hadrons was measured as a function of the invariant mass W of the system (1.25 to 4.25 GeV) at the e^+e^--collider VEPP-4 with the detector MD-1. For the first time the data were obtained by detecting both scattered leptons with almost zero emission angles. The mean squared four-momentum transfer $< q^2 >$ is $-$ 0.005 GeV^2, the W rms resolution is 100 – 250 MeV. The data on the mean charged multiplicity $<n_c>$ are well described by the function $<n_c>=(1.62\pm0.37)+(1.83\pm0.45)\cdot \ln(W(\mathrm{GeV}))$. The W-dependence of the total cross section is consistent with the theoretical prediction $\sigma(\mathrm{nb}) = 240+270/W(\mathrm{GeV})$.

INTRODUCTION

The information on the two photon reaction $\gamma\gamma \to$hadrons is extracted from the data on the reaction

$$e^+e^- \to e^+e^- + \text{hadrons}\,. \tag{1}$$

The kinematics of this reaction is completely determined by the four-momenta of the incoming and scattered electrons and positrons (everywhere below for brevity – scattered electrons). In Fig.1 $p_{1,2}$ and $p'_{1,2}$ are four-momenta of the incoming and scattered electrons, $q_{1,2}$ – four-momenta of the virtual photons. Using the energy – momentum conservation laws at small scattering angles and omitting the terms of the order $(m_e/E)^2$, one can find

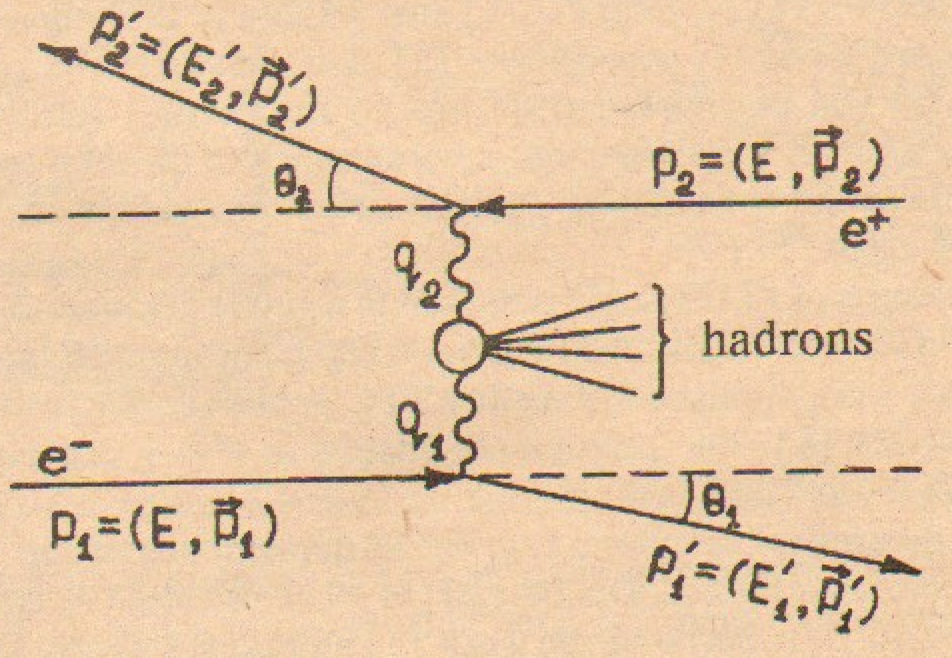

Fig. 1. Kinematics of the reaction e^+e^--hadrons.

the invariant mass (W) of the produced system and the photon masses squared (q_i^2):

$$W = 4\,(E - E_1')\,(E - E_2')\,,$$

$$q_i^2 = -EE_i'\,\theta_i^2\,, \qquad (2)$$

where E, $E_{1,2}'$ are the energy of the incoming and scattered electrons respectively, θ_i is the scattering angle.

Usually the tagging systems can detect scattered electrons with emission angles greater than 20 – 30 mrad.

Three different kinds of e^+e^- experiments can be defined depending on detection conditions of scattered electrons: 1) double tag – the detection of both scattered electrons is required; 2) single tag – one of the scattered electrons is detected, another escapes at a zero angle; 3) antitag – both scattered electrons escape at zero angles.

The double tag mode is attractive due to the possibility of the direct measurement of the invariant mass of the produced system, but in this case the extrapolation of cross section to zero q^2 is nesessary leading to some model dependence of the result. In the antitag mode there is no problem with the extrapolation because both photons are almost on the mass shell, but it is nesessary to determine W under conditions of the incomplete efficiency for the produced hadrons that also is impossible in a model independent way. The single tag method is in some intermediate position.

The first experiments on the total cross section measurement were performed in 1979–1981 by PLUTO [1] and TASSO [2] collaborations both in the single tag mode. It was shown [3] that these results can be well described by GVDM extrapolation to zero q^2. But further TASSO analysis with the larger data set has shown that determination of the total cross section was impossible without assuming some a priori knowledge of the model parameters [4, page 117].

The new results of PLUTO [5] obtained in a single tag mode appeared in 1984, in 1984–1986 the results of TPC double tag experiment [6] and PLUTO [7] antitag data were published. Recently TPC published the results of their single tag analysis [8]. The preliminary results of MD-1 experiment were reported in 1985, 1986 and 1990 [9].

The first theoretical calculation of the W dependence of the total cross section was performed by J.L. Rosner [10] in 1972 and slightly corrected by I.F. Ginzburg and V.G. Serbo in the work [3] mentioned above. During last few years some new calculations of the total cross section have been published [11 – 13].

THE MD-1 DETECTOR

The main advantage of the MD-1 detector for the study of two photon reactions is the magnetic field transverse to the orbit plane of the colliding beams. The system for the detection of the scattered electrons (tagging system) provides the possibility to detect scattered electrons in a wide energy region with extremely small emission angles. It makes possible a measurement of the invariant mass in the double tag mode for practically real intermediate photons.

The experiment was performed at the VEPP-4 collider during 1984–1985. The center of mass energy of the colliding beams was varied in the region 7.7–9.7 GeV, and the integrated luminosity was 19.7 pb^{-1}. The lay-out of the MD-1 detector is shown in Fig. 2. The detailed description of the detector can

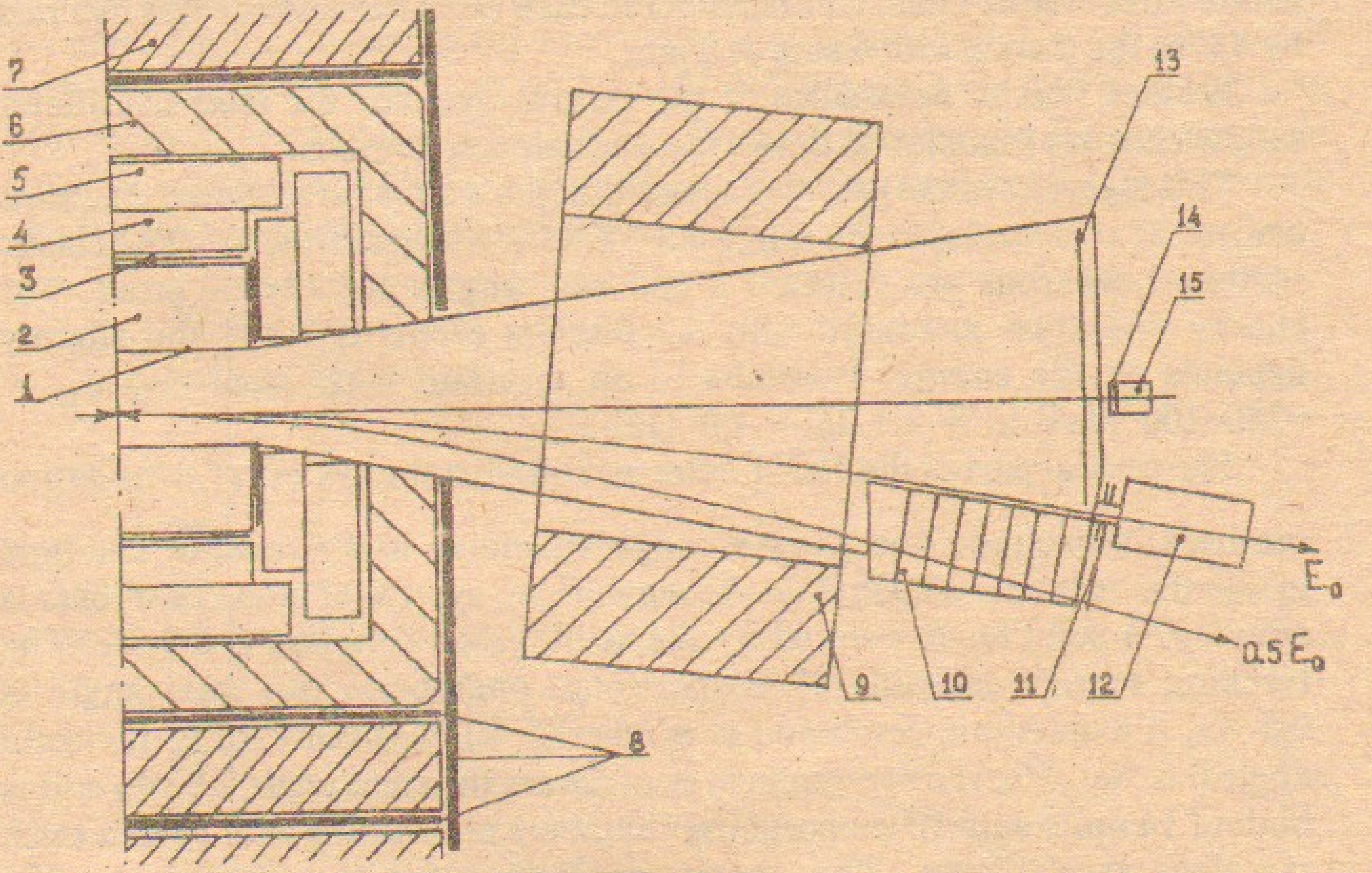

Fig. 2. MD-1 detector. Section by the orbit plane: *1* – vacuum chamber; *2* – coordinate chambers; *3* – scintillation counters; *4* – Čerenkov counters; *5* – shower-range chambers; *6* – magnet winding; *7* – magnet yoke; *8* – muon chambers; *9* – bending magnet; *10* – tagging system; *11* – luminosity monitor; *12* – lens; *13* – synchrotron radiation receiver; *14* – ionization chambers for the orbit stabilization; *15* – sandwich for bremsstrahlung photons detection.

be found elsewhere [14,15]. Here we will give only the main features essential for this experiment.

The magnetic field in the central part of the detector is transverse to the orbit plane and equals 12 kG at the beam energy of 5 GeV. On both sides of the main magnet two additional magnets are installed and behind them two blocks of the tagging system at the distance of 3.5 m to the interaction point are located.

Each block contains seven proportional chambers and three scintillation counters. The counters are used for trigger, the chambers – for measurement of the momenta and emission angles of the scattered electrons. Three chambers in each block operate in the cathode read out mode using the delay lines. They measure the Y-coordinate (transverse to the orbit in the orbit plane) with an accuracy of 0.2 mm. The vertical coordinate (Z) is measured by another three chambers operating in usual anode read out mode with the anode wires step of 4 mm. One chamber in each block has anode wires inclined by 45° to the Z-axis with a step of 3 mm.

Besides that at both sides of the central detector the lead-scintillator sandwiches are installed to detect bremsstrahlung photons.

This tagging system provides a possibility to detect the scattered electrons emitted at zero angles in the range 0.5 – 0.85 of the beam energy. The elastic scattered electrons are detected if emission angles are 12–100 mrad. The energy resolution measured with the Bhabha events is 1.3% and slightly depends on the energy. It results in an invariant mass resolution $\sigma_W =$ =250–100 MeV at $W = 1.25 - 4.0$ GeV.

The central part of the MD-1 detector contains the system of scintillation counters, coordinate and shower-range chambers and Čerenkov counters inside the magnet coil. Outside the magnet the system of muon chambers is situated. A solid angle covered by the scintillation counters is $0.9 \cdot 4\pi$. The tracking system contains 38 proportional chambers, the solid angle is $0.8 \cdot 4\pi$, a momentum resolution is $\sigma_p/p = (5-10)\% \cdot p(\mathrm{GeV}/c)$ in the solid angle $0.6 \cdot 4\pi$. The shower-range system covers the solid angle $0.8 \cdot 4\pi$ and is built of 14 units with 10 proportional chambers alternating with 13 mm thick stainless steel plates. The energy resolution for the photons $\sigma_E/E = ((20.5)^2/E + (12.6)^2)^{1/2}\%$ [16]. The angular resolution is $\sigma_\theta = \sigma_\varphi = (1-2)^\circ$. The luminosity is measured using the processes of single bremsstrahlung and small angle Bhabha scattering with an accuracy of 2.5% [17].

TRIGGER

In trigger the signals of at least one scintillation counter and of one shower-range unit were required. To reject the background from bremsstrahlung and other processes with small transverse momenta a strip in the shower-range system of ±11 cm width lying in the orbit plane was excluded from the trigger. Fast on-line computer analysis rejected cosmic ray events as well as beam-gas background events with the tracks close to the orbit plane. The selected events were recorded with a rate of 3 Hz at the luminosity of $3 \cdot 10^{30}$ cm^{-2} s^{-1}.

EVENT SELECTION

The double tagged events were selected for the study of the reacton (1). To suppress the single bremsstrahlung background in the tagging system each detected scattered electron was required to have an angle to the orbit plane greater than 0.5 mrad. It leads to the averaged q^2-value $-5 \cdot 10^{-3}$ GeV^2. Besides that it was required to have not more than one detected bremsstrahlung photon in the event. These cuts have reduced the amount of recorded events from $3.3 \cdot 10^7$ to $1.1 \cdot 10^5$ with the statistics loss in the tagging system by a factor of 2.5. The tagging efficiency is shown in Fig. 3 versus the invariant mass of the produced system. In order to select multi-hadron events the following criteria were applied.

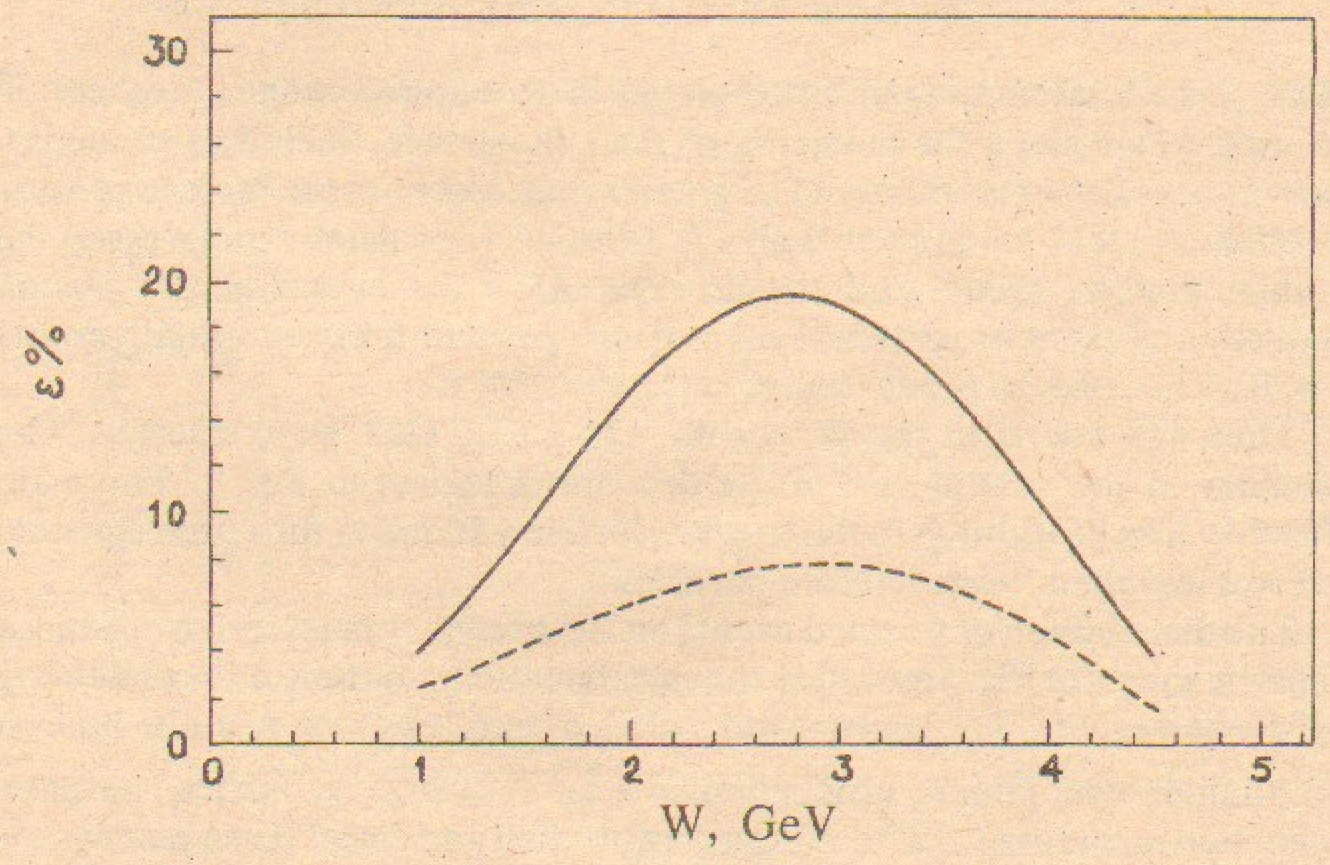

Fig. 3. Detection efficiency of both scattered electrons versus invariant mass:Solid line – without emission angle cut; dashed – for the emission angle >0.5 mrad.

1) Not less than 3 particles detected in the cetral part of the detector with at least 1 charged originating from the interaction region were required.

2) The parameter "weight" was defined as a linear combination of the number of detected particles, the number of the hits in the shower-range system on each track and an angle between each track and the orbit plane with the coefficients determined by the optimization of the efficiency and the background suppression. This parameter should be greater than some proper value providing the efficiency loss not greater than 1%.

3) For events containing only 1 charged detected particle its angle to the orbit plane should be greater than 3.5°. For events with 2 charged tracks the azimuthal angle between them was required to be greater than 2.5°.

4) Further background suppression was performed with a help of the following three parameters:

a) $$AC = \ln \{\min_{\vec{n}} \sum_i (\vec{n}_i \times \vec{n})\} (1+N) ,$$

b) $$AP = \ln \{\min_{\vec{n}} \sum_i (\vec{n}_i \cdot \vec{n})\} (1+N) ,$$

c) $$AH = \ln \sum_i \{n_{iz}\} (1+N) ,$$

where N is a total number of hitted planes in the shower-range chambers, $\vec{n}_i$ is a unit vector along the momenta of the i-th particle (including photons). Each of these parameters should be greater than some proper value to provide the efficiency loss not greater than 1%. The AC – parameter suppressed the residual Bhabha events and cosmic rays; AP – the events of two photon production of pairs of particles; AH – beam-gas and bremsstrahlung events as well as two photon production of soft pairs.

Thus 448 events in the W region 1.25 – 4.25 GeV were selected. The efficiency in the central part of the detector is shown in Fig. 4. The main efficiency loss in addition to the trigger efficiency is due to the requirement to have not less than three detected particles.

The distribution of selected events on the invariant mass of the produced system is shown in Fig. 5 as well as the calculated contribution of the remaining background events. The background includes beam-gas events, multi-hadron annihilation, two photon production of e^+e^-- and $\mu^+\mu^-$-pairs, $\pi\pi$-pairs production including $f(1270)$ meson contribution and also C-even resonances $a_2(1320)$ and $f'_2(1525)$. The beam-gas background was estimated using special background runs with vertically separated beams with a proper

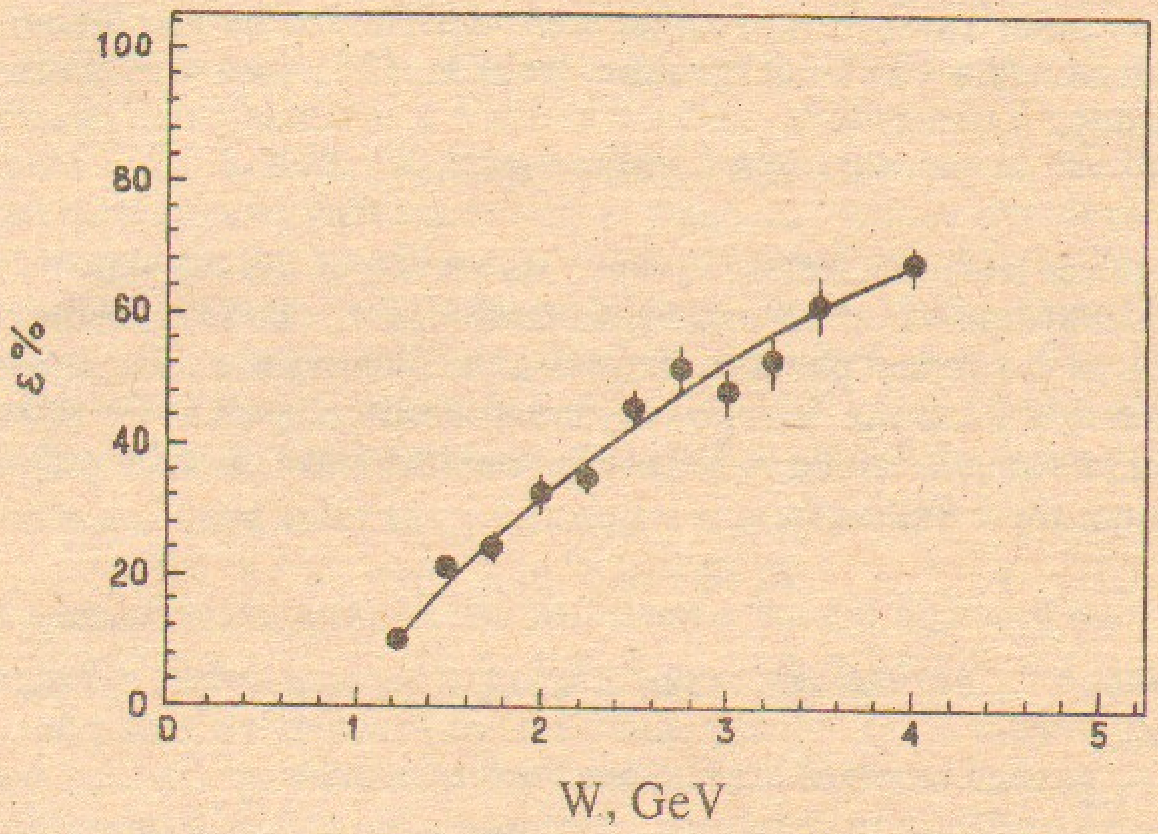

Fig. 4. Detection efficiency in the central part of the detector versus invariant mass: Points – MC simulation; line – quadratic fit.

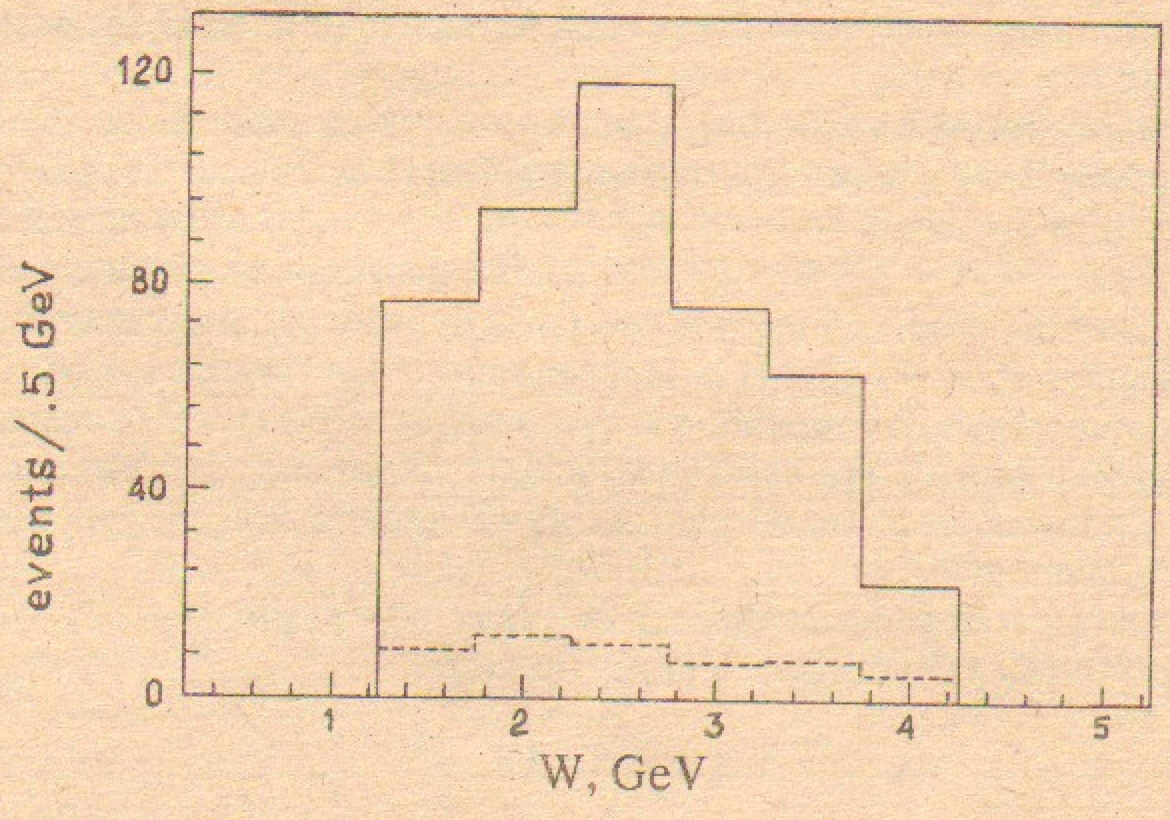

Fig. 5. Distribution of the selected events over invariant mass: Solid histogram – all selected events; dashed – background.

normalization as well as by visual scanning of selected events and was about 3%. The other background sources were determined by the Monte Carlo simulation. The total background level is 12% and was subtracted statistically.

MONTE CARLO SIMULATION

As it was shown in Ref. [18] the cross section of the reaction (1) in the most general case contains 6 invariant quantities corresponding to the various helicities of the virtual photons. But when the photons are close to the mass shell (small q^2) and the detector is symmetric with respect to the orbit plane the general formula can be considerably simplified and the differential cross section has the following form:

$$E_1' E_2' d\sigma / d^3 p_1' d^3 p_2' =$$

$$= 4\alpha^2((q_1 q_2)^2 - q_1^2 q_2^2)^{1/2} (32\pi^4 E^2 q_1^2 q_2^2)^{-1} \rho_1 \rho_2 \sigma_{TT} (W, q_1^2, q_2^2) ,$$

where $\rho_{1,2}$ are elements of the photons density matrix:

$$2\rho_1 = (2p_1 q_2 - q_1 q_2)^2 / X + 1 + 4m_e^2/q_1^2 ; \quad \rho_2 = \rho_1 (1 \leftrightarrow 2) ;$$

$$X = (W^2 - q_1^2 - q_2^2)^2 / 4 - q_1^2 q_2^2 .$$

This differential cross section was used for the simulation of the scattered electrons.

The produced hadronic system was sampled under the following assumptions: 1) all produced particles are pions; 2) mean neutral and charged multiplicities are equal: $<n_0> = <n_c> = <n_+> = <n_->$; 3) charged multiplicity was $<n_c> = 2 + 1.8 \cdot \ln(W)$; 4) the distribution of the transverse momenta of the produced pions is described by isotropic phase space; 5) the cross section of $\gamma\gamma \rightarrow$ hadrons is independent of the invariant mass. In the further analysis we have modified the parameters of the model to achieve the best agreement with the experimental data in various distributions. The Monte Carlo sample of the selected events was greater than the experimental one by a factor of 2.3.

Penetration of particles through the detector was simulated by the program UNIMOD [19] developed in our Institute.

RESULTS

The requirement of detection of not less than 3 particles in the central part of the detector leads to the loss of the experimental information about two pion production. Thus the cross section reported here excludes final states of two hadrons and we prefer to make no assumptions concerning them.

In order to determine the W-dependence of the cross section all statistics was divided into 6 bins with a width of 0.5 GeV, as shown in the first line of the Table 1. In each bin the distributions on the number of the detected charged particles and photons as well as mean squared transverse momenta of the charged particles were compared to the simulated distributions. The mean charged multiplicity $<n_c>$ for each bin was optimized to achieve the best agreement with experimental distributions described above. The charged multiplicity distribution was chosen of the KNO [20] shape that seems to be proper for hadronic reactions [4, page 112]. The ratio of the mean value and dispersion was fixed at the value 2.8 similar to that for the e^+e^- annihilation [21].

The results of the optimization are shown in the second line of the Table 1 in terms of χ^2 values for n_D degrees of freedom, the optimal $<n_c>$ values and estimated errors are shown in the third line. The W dependence of the mean charged multiplicity was fitted by the function $<n_c> = a + b \cdot \ln(W)$. The optimal values of a and b are respectively 1.62 ±0.37 and 1.83 ±0.45 with the correlation coefficient $r = -0.93$ and $\chi^2/n_D = 6.9/4$. The results of this fit are shown in the fourth line of the Table 1. The charged multiplicity data are shown also in Fig.6. The fitted $<n_c>$ values were used to determine the detection efficiency of the central part of the detector.

The radiative corrections due to the photon emission by electrons and positrons were estimated in accordance with the radiation probabilities calculated in [22]. These corrections are 2–10% and were included into the cross section value.

The obtained cross section and statistical errors are shown in fifth and sixth lines of the Table 1.

Table 1

W, GeV	1.5	2.0	2.5	3.0	3.5	4.0
χ^2/n_D	7.0/11	10.5/13	16.2/13	23.8/12	6.2/11	4.2/5
$<n_c>$	2.67 ±.26	2.59 ±.21	2.95 ±.42	4.30 ±.40	3.90 ±.40	4.25 ±.85
fit	2.36 ±.21	2.89 ±.14	3.30 ±.15	3.63 ±.20	3.91 ±.26	4.16 ±.31
σ, nb	606	352	356	260	352	214
stat. error	100	49	42	37	59	64
syst. error	61	35	33	22	42	28
tot. error	117	59	53	43	72	70

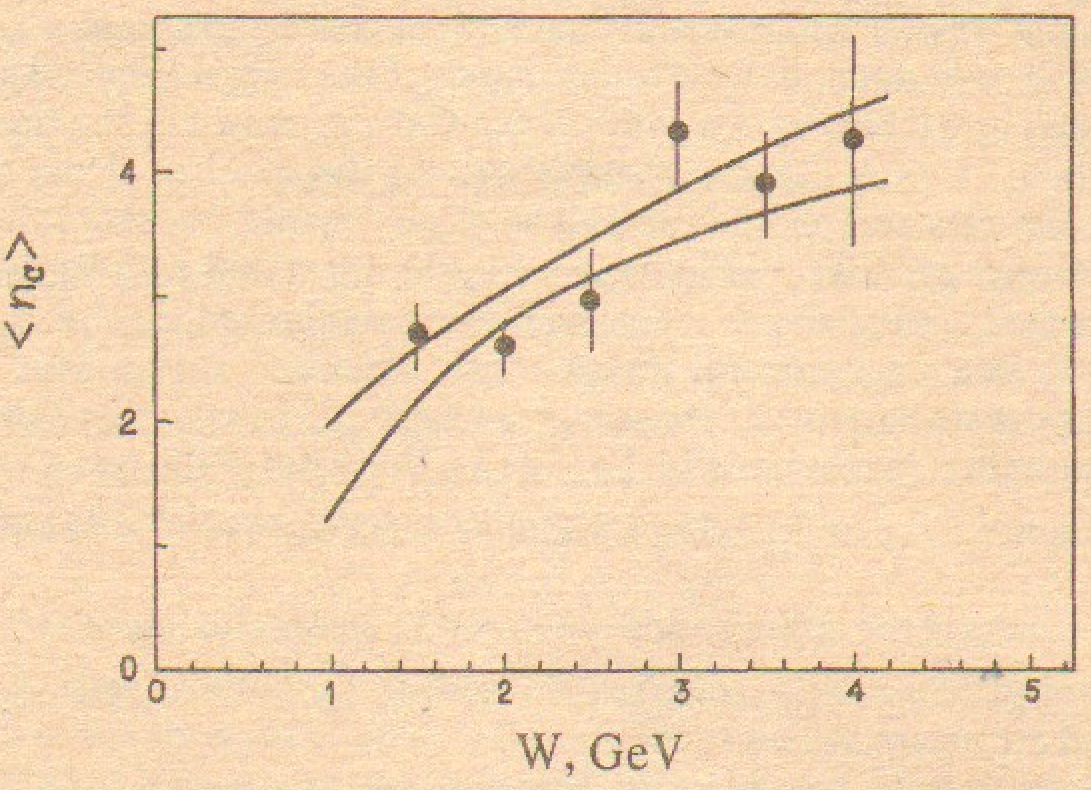

Fig. 6. Mean charged multiplicity versus invariant mass: Points – the results of optimization; lines – $\pm 1\sigma$ fit.

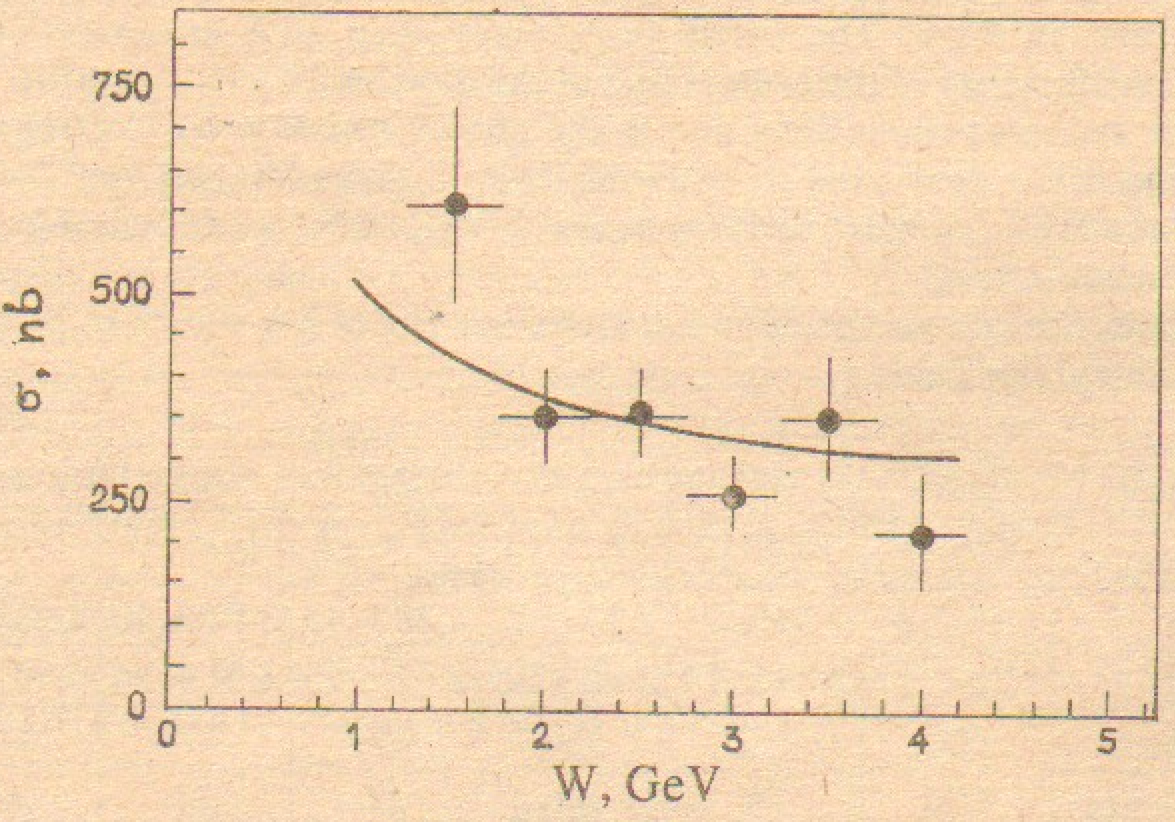

Fig. 7. Total cross section of the reaction $\gamma\gamma \rightarrow$hadrons versus invariant mass. Points – experimental data; vertical bars – statistical and systematic errors added in quadrature; horizontal – intervals of cross section averaging. Line – $240+270/W$.

The systematic errors caused by the $<n_c>$ dependence of the efficiency, the uncertainties of the radiative corrections, simulation of nuclear interactions, acceptance of the tagging system, beam orbit instability and the luminosity monitoring are about 10% in each W bin. The systematic errors as well as the statistical and systematic errors added in quadrature are shown in the last two lines of the Table 1. (The cross sections values and all errors shown are in nanobarns).

As it was mentioned above, we have excluded from our data the processes of two pion production including $f(1270)$ meson and also $a_2(1320)$ and $f_2'(1525)$ mesons. Their calculated total contribution to the bin 1.25–1.75 GeV is 190 nb and does not exceed 2–3 nb for the others.

Results on the total cross section measurement presented in the Table 1 and Fig. 7 are in good agreement with the early prediction [10] – σ (nb)= $=A + B/W$(GeV) with A = 240nb, B = 270nb · GeV ($p(\chi^2)$ = 29%), and apparently do not contradict to the calculation [3]: A = 255 – 300nb, B = 315±55nb · Gev ($p(\chi^2)$ = 1.4% for average values of A and B). The other theoretical expectations [11–13] predict larger cross section for small W and do not agree with our results.

As far as A and B extraction from the experimental data is concerned, their values have almost complete negative correlation and are very sensitive to the variations of the experimental points especially in the case when W-dependence of the cross section is comparable with the experimental errors. The similar conclusion is made also in the work [8]. So we prefer not to present A and B value as a final result

COMPARISON TO OTHER EXPERIMENTS

Our data on the charged multiplicity are in good agreement with PLUTO [1, 5] approximation and are slightly higher than TPC [6]. The total cross section data of the experiments [5 – 8] and our results are shown in Fig. 8. Our results are in reasonable agreement with the other four experiments when systematic errors are taken into account.

For more detailed comparison of the data we have averaged our data over W intervals as shown in Table 2. One can see that our data are in a good agreement with the PLUTO antitag [7] and TPC double tag data [6], the differences are inside one standard deviation. The single tag data of PLUTO [5] and TPC [8] give the cross section value by 100 – 200 nb larger, the maximal difference is 2.5 standard deviations.

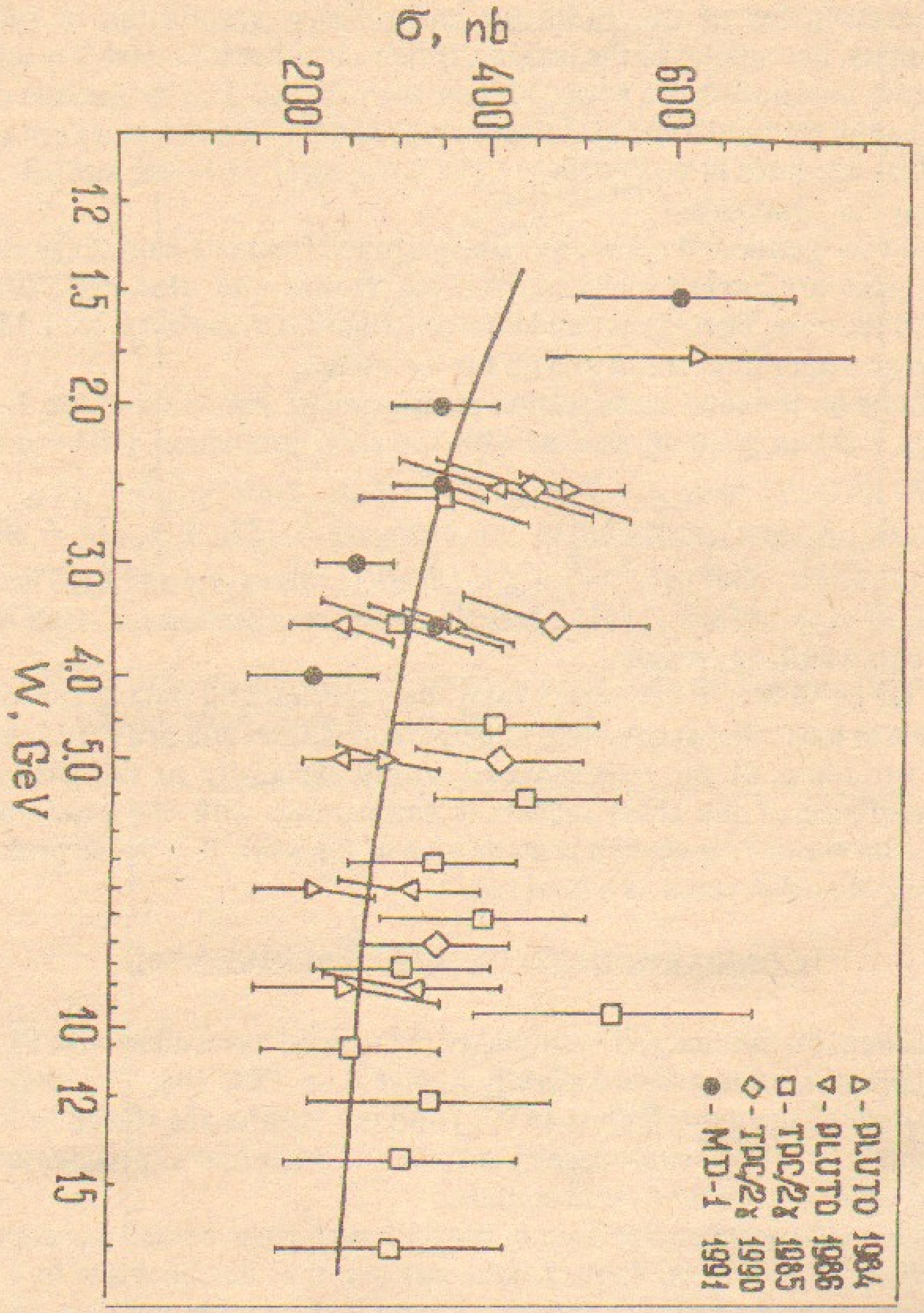

Fig. 8. Data of various experiments on the total cross section. Systematic errors are added in quadrature. PLUTO 1984 – single tag data [5], PLUTO 1986 – antitag data [7], TPC/2γ 1985 – single tag data [6], TPC/2γ 1990 – single tag data [8], MD-1 1991 – this experiment. Line – $240 + 270/W$.

CONCLUSIONS

The total cross section of γγ→hadrons in the invariant mass range 1.25 – 4.25 GeV was measured in the e^+e^--collisions. For the first time the data were obtained in the double tag mode for almost real photons $(<q^2> = -5 \cdot 10^{-3})$ GeV with good W resolution $(\sigma_W$=100 – 250 MeV), providing small systematic errors due to the hadron system features and no q^2 extrapolation. The cross section data are compatible with the calculation of J.L.Rosner and do not contradict to the calculation of I.F. Ginzburg and V.G. Serbo. In the same W region the data on charge multiplicity in the assumption of KNO Poisson-like distribution are obtained.

Table 2

	W intervals, GeV		
	1.5 – 2	2 – 3	3 – 4
Experiment	cross section, nb		
PLUTO 1984, single tag [5]	627 ±163	489 ±54	369 ±55
PLUTO 1986, antitag [7]		408 ±104	247 ±53
PEP-4 TPC/PEP-9 2γ 1985, double tag [6]		353 ±91	305 ±82
TPC /2γ Collab. 1990, single tag [8]		452 ±104	476 ±102
MD-1 1991, double tag, zero angles	448 ±56	334 ±29	257 ±34

In conclusion the authors express their gratitude to V.G. Serbo and V.L. Chernyak for usefull discussions, E.A. Kuraev and V.S. Fadin for the help in the analysis of radiative corrections. We would especially like to thank the staff of MD-1 and VEPP-4 who made possible the work described here.

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В.И.Тельнов, А.Б.Темных, Ю.А.Тихонов,
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С.И.Эйдельман, Ю.И.Эйдельман

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