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New data for the reaction $e^+e^- \to \Upsilon(9.46)$ have been obtained using the DASP detector at the DORIS storage ring. The electronic width Γ_{ee} is (1.5 ± 0.4) keV. The branching ratio for the decay into muon pairs is $(2.5 \pm 2.1)\%$. Energy spectra for inclusive production of hadrons are given. Topology variables of the multi-hadron decay are compared with the predictions of three-gluon decay.

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Following the discovery of Υ-mesons by Herb et al.[1], the same mesons were clearly seen[2,3] in e^+e^- - annihilations with the upgraded storage ring DORIS at DESY. The measured electronic width supports models which assume the Υ(9.4) to be the ground state of a new family of quark-antiquark states with a fifth quark of about 4.7 GeV mass. Here we report further data on the decay properties of the Υ(9.4), measured with the Double Arm Spectrometer DASP. The apparatus, which has been described before[4], is shown in Figs.1 and 2.

An integrated luminosity of about 500 nb^{-1} has now been accumulated at centre-of-mass energies on and around the Υ-resonance.

THE HADRONIC CROSS SECTION

The cross section of the reaction $e^+e^- \to$ hadrons has been remeasured and the new data added to that previously reported[2]. All events have been reanalyzed using the same event selection criteria with the sole exception that a computer program has been substituted for the visual scan. The resulting visible cross section vs. energy is shown in Fig.3. The curve is the best fit of a gaussian with radiative corrections and a 1/s background. The mass of the Υ, (9.457 ± .010) GeV remains unchanged from that reported earlier.

The partial width Γ_{ee} for the decay $\Upsilon \to e^+e^-$ can be obtained from the integrated cross section, $\int \sigma_h dE$, for hadron production. With the assumption

$$R \equiv \frac{\sigma_h}{\sigma_{\mu\mu}} = 4.5 \pm 0.5 \quad \text{at} \quad 9.4 \text{ GeV},$$

we determine the acceptance of our detector (including selection criteria) for multi hadron events off resonance to be $\eta_c = 42\%$. Since the average multiplicity that we measure for events increases slightly on resonance over its off resonance value, we estimate that the acceptance of our detector increases to 47% on resonance. Including radiative corrections[5], we get an integrated hadronic cross section of:

$$\int \sigma_h \, dE = (370 \pm 100) \text{ MeV nb}.$$

The error contains the estimated systematic uncertainties.

DECAY INTO HADRON PAIRS

While the magnetic spectrometer of the DASP detector covers only 5% of the sphere, it permits excellent separation of charged hadrons, muons and electrons. Thus we used it to look for collinear pairs of charged particles. On the Υ resonance we observed 6 muon pairs and 37 Bhabha e^+e^- pairs, but no hadron pairs.

DECAY INTO MUON PAIRS

We used the inner detector to look for the reaction $e^+e^- \to \Upsilon \to \mu^+\mu^-$. The selection criteria for such events were: exactly two tracks, no showers and the tracks should be collinear. To eliminate cosmic ray muons, the time of flight to the fifth layer of the scintillator hodoscope had to be equal to within 1 ns. For cosmic ray muons the difference is typically 6 ns.

The detector-blocks above and below the beam tube could not be used since there the flight path was too short for sufficient discrimination against cosmic rays. Finally, the events had to occur in coincidence with the bunch-crossing. The two muon tracks were interconnected by a straight line and its intercept with the beam trajectory was plotted. From the vertex distribution obtained this way, the remaining background was subtracted.

The visible cross section for muon pair production in the continuum outside the resonance, obtained using identical criteria, is

$$\sigma^{C}_{\mu\mu\ \mathrm{vis}} = (0.30 \pm 0.08)\ \mathrm{nb}\ ,$$

which determines the acceptance of the detector, $\eta_{\mu\mu} = 0.31 \pm 0.08$.

The visible cross section in the peak of the resonance is

$$\sigma^{\Upsilon}_{\mu\mu\ \mathrm{vis}} = (0.41 \pm 0.07)\ \mathrm{nb}.$$

Combining the results, we find the integrated cross section of $e^+e^- \to \Upsilon(9.4) \to \mu^+\mu^-$:

$$\int \sigma_{\mu\mu}\, dE = (10 \pm 8)\ \mathrm{MeV\ nb}.$$

RESONANCE WIDTHS

We assume the three leptonic widths Γ_{ee}, $\Gamma_{\mu\mu}$ and $\Gamma_{\tau\tau}$ of the $\Upsilon(9.46)$ are equal and estimate, that about half of the $\tau\tau$ decays are included in our measured hadronic cross section. This allows us to combine results (1) and (3) to obtain values for the partial width Γ_{ee} and the branching ratio $B_{ee} = \Gamma_{ee}/\Gamma$:

$$\Gamma_{ee} = (1.5 \pm 0.4)\ \mathrm{keV}\ .$$

$$B_{ee} = B_{\mu\mu} = (2.5 \pm 2.1)\%.$$

The quoted errors are one standard deviation, including estimated systematic errors. The two values favor the assignment of charge 1/3 e_0 to the new fifth quark and indicate that the $\Upsilon(9.46)$ is a $b\bar{b}$ state.

Thus the total width Γ of the $\Upsilon(9.46)$ has a best estimate of 60 keV and a two-standard deviations lower limit of 20 keV; the statistics obtained do not yet permit us to give a reasonable upper limit.

ENERGY SPECTRUM OF INCLUSIVE HADRONS

Figures 4a and b show the invariant production cross section for the inclusive reactions

$$e^+e^- \to \pi^\pm X,\ K^\pm X,\ p^\pm X$$

as a function of the particle energy on the resonance and off the resonance. Above the momentum cutoff of 200 MeV/c, the pions show a purely exponential spectrum $E\, d^3\sigma/dp^3 \propto \exp(-E/E_0)$ with

$$E_0 \text{ (on resonance)} = (260 \pm 25) \text{ MeV},$$

$$E_0 \text{ (off resonance)} = (240 \pm 25) \text{ MeV}.$$

Within the statistical accuracy, there is no difference between the values on and off resonance. The kaons on and off resonance and the protons on resonance follow roughly the well-known law that they are produced as frequently as pions with the same particle energy. The relative abundance of kaons is about the same on resonance as it is off resonance.

EVENT TOPOLOGIES

The following investigations are motivated by a QCD prediction[6] for the decay of the $\Upsilon(9.46)$ into hadrons. According to QCD, the predominant decay mode of a heavy quark-antiquark $^3S_1$ state is[7]:

$$Q\bar{Q} \rightarrow 3 \text{ gluons} \rightarrow 3 \text{ gluons jets} .$$

Assuming that this decay is the only direct decay mode of the $\Upsilon(9.46)$ and taking the quark charge as $-1/3\, e_0$, reference 6 predicted $\Gamma_{ee} : \Gamma = 1 : 27$, which is compatible with the result of this experiment, $(2.5 \pm 2.1)\%$. Is there any more direct evidence for the existence of gluon jets?

All events with the visible cross section of Fig.3, i.e. events of the reaction

$$e^+e^- \rightarrow (\geq 3) \text{ hadrons}$$

with three or more visible tracks*), including converted photons, were fully reconstructed in the inner detector. From this reconstruction we obtain the number of tracks and their directions θ and ϕ. The acceptance of the inner detector in $\cos\theta$ and ϕ is shown in Fig.5.

*) See reference 2 for all selection criteria.

Fig.6 shows the average visible multiplicity of charged tracks and converted photons in the selected events as a function of the centre-of-mass energy. The multiplicities have not been corrected for the acceptance of the detector. As can be seen in the figure, there is a small but clear rise of the average multiplicity by approximately 10% in the resonance region. This result is not in agreement with Ref.6 where a rise by a factor 1.4 to 2 was expected. The result agrees, however, with our observation that the inclusive energy spectra above $p = 200$ MeV/c are nearly the same on and off resonance.

The existence of quark jets in e^+e^- annihilation has been successfully demonstrated by the use of the topology variable sphericity[8]. Four topology variables have been proposed[9] to search for 3-gluon-jet events: Sphericity, sherocity, thrust and acoplanarity. The first three essentially measure the particles' transverse momenta with respect to a preferred axis, and the fourth one measures the momentum components perpendicular to a preferred plane. Two-jet events have small spheri(o)city and small acoplanarity, whereas 3-jet events are supposed to show bigger values of the spheri(o)city but comparably small values of the acoplanarity.

Since we cannot determine particle momenta with the DASP inner detector, we study the behaviour of four "pseudo" topological variables and determine them for each event:

$$\text{Pseudosphericity} = \frac{3}{2} \text{Min} < \sin^2\delta > ,$$

$$\text{Pseudospherocity} = \left(\frac{4}{\pi} \text{Min} < |\sin\delta| >\right)^2,$$

$$\text{Pseudothrust} = \text{Max} < |\cos\delta| > ,$$

$$\text{Pseudoacoplanarity} = 4 \cdot (\text{Min} < |\cos\delta| >)^2,$$

where δ is the angle of each track with respect to the preferred axis, or, for pseudoacoplanarity, with respect to the normal to the preferred plane. Our four definitions would coincide with those of reference 9, if all particles had equal momenta.

Figs.7a-7d show the mean values of the distributions of the four quantities as a function of the centre-of-mass energy; and Fig.8 shows two distributions of the pseudospherocity averaged over all centre-of-mass energies on and off resonance. We note a definite change in all four mean values at the centre-of-mass energy of the resonance and a definite change of the distributions with Fig.8 as one example. When going from off-resonance to on-resonance, the two-jet character of the events decreases, the events become more isotropic. This increase of isotropy takes place in three (and not only in two) dimensions, since the acomplanarity is also increasing. The changes in event topology are so pronounced that they are even seen in geometrical quantities without knowledge of the particle momenta. Are these observations in agreement with a possible decay of the $\Upsilon(9.46)$ into three-gluon jets?

Since there are no theoretical predictions for our geometrical quantities and since the detector acceptance has an appreciable influence on their values, we have tried a simple Monte-Carlo simulation of 2-jet- and 3-jet events. Two-jet events are generated according to an angular distribution

$$d\sigma(\text{jet})/d\Omega \propto 1 + \cos^2\theta(\text{jet})$$

and to a "standard" fragmentation[10] into pions with $\langle p_t(\pi)\rangle$ = 320 MeV/c. Three-jet events are generated according to the jet-momentum distribution described in reference 6 and assuming that gluons fragment into pions exactly the way quarks do. All events are passed through a rough model of the detector acceptance and are treated afterwards exactly like real events. The results are summarized in Table 1.

The experimental column shows the relative change of the values from off-resonance to on-resonance energies, and the Monte Carlo column includes non-resonant background and resonance decays through the one-photon channel. The agreement between the two columns is surprisingly good. It even reproduces the small change in the average visiable multiplicity.

We draw the following conclusions from this agreement: If the $\Upsilon(9.46)$ decays into hadrons by way of three gluons, then these gluons must fragment into hadrons in a way very similar to quark fragmentation, with nearly the same $p_{\parallel}$-distribution and nearly the same p_t-distribution. Direct evidence for the decay of the $\Upsilon(9.46)$ into three gluons remains to be found.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig.1 Schematic view of the DASP detector. See Ref.4 for details.

Fig.2 Schematic view of the DASP inner detector along the beam direction.

Fig.3 Visible cross section of the reaction $e^+e^- \to$ hadrons. The solid curve is a single resonance with Gaussian energy resolution and radiative corrections. One standard deviation of the energy resolution is 7.6 MeV.

Fig.4 Invariant production cross section for the inclusive reactions $e^+e^- \to \pi^\pm X$, $K^\pm X$, $p^\pm X$ on and off the $\Upsilon(9.46)$ resonance.

Fig.5 Solid angle covered by the DASP inner detector.

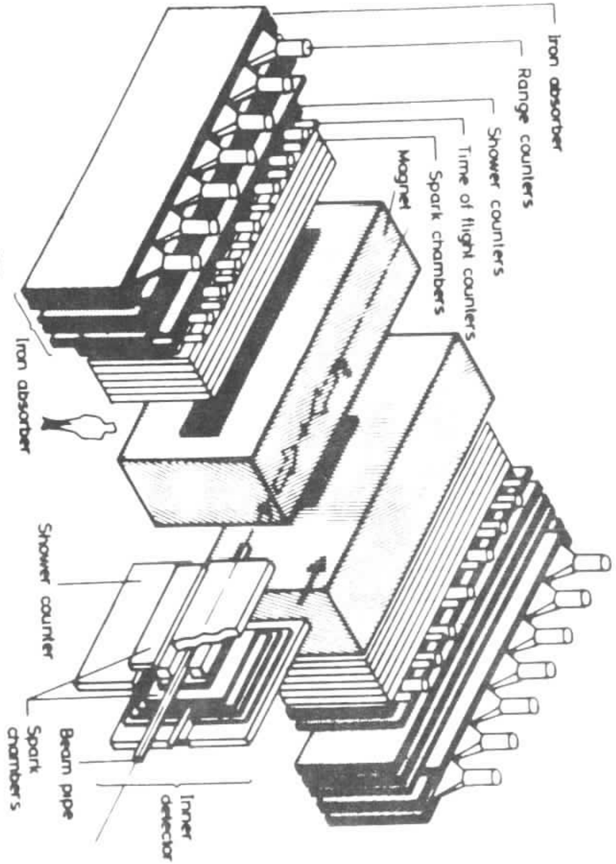
Fig.6 Average visible multiplicity of charged particles and converted photons in the inner detector. The values are not corrected for acceptance.

Fig.7 Mean values of the topology variables as a function of centre-of-mass energy.

Fig.8 Distribution of the pseudospherocity near the resonance (open points) and for the direct resonance decay (full points). The direct decay distribution is obtained by subtracting the resonance background and decays through the one photon channel.

TABLE 1

CHANGE ON/OFF	EXP [%]	MC [%]
< Pseudoacoplanarity >	18.8 ± 4.0	23.0
< Pseudosphericity >	9.1 ± 1.8	9.8
< Pseudospherocity >	9.5 ± 2.0	14.0
< Pseudothrust >	- 2.8 ± 0.6	- 3.1
< Multiplicity >	8.4 ± 2.0	7.0



Spectrometer DASP

Fig.1

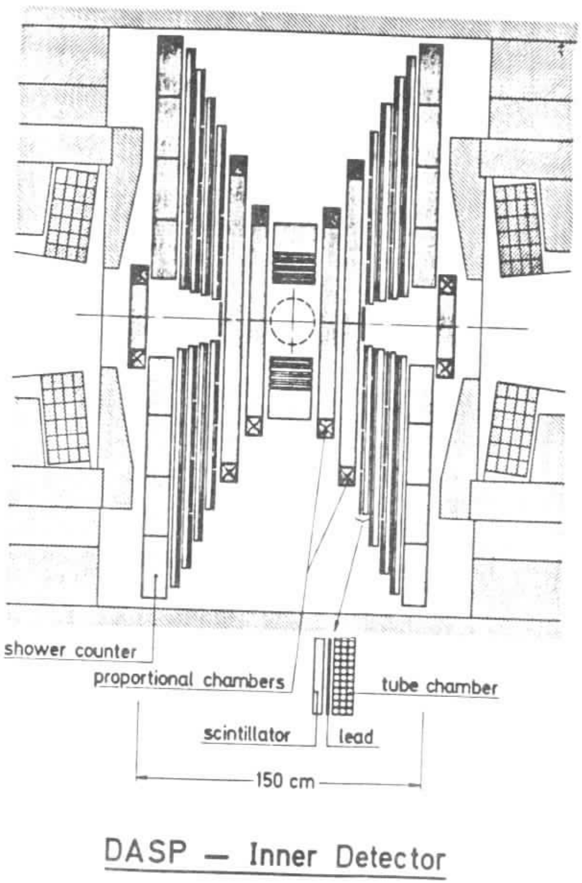

shower counter
proportional chambers
tube chamber
scintillator
lead
150 cm
DASP — Inner Detector

Fig.2

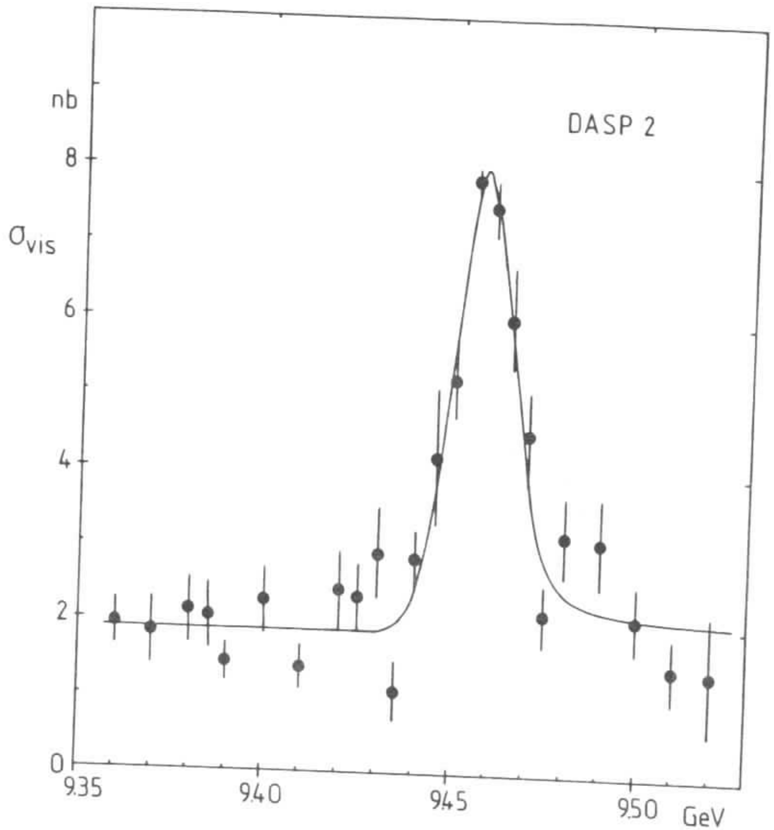
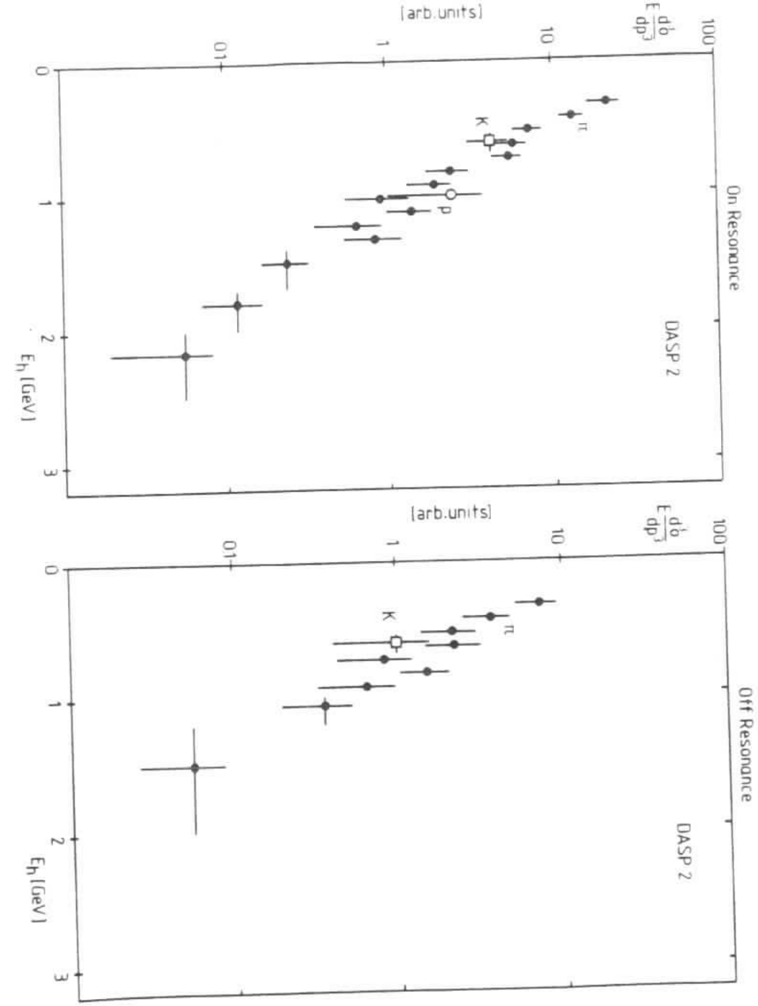
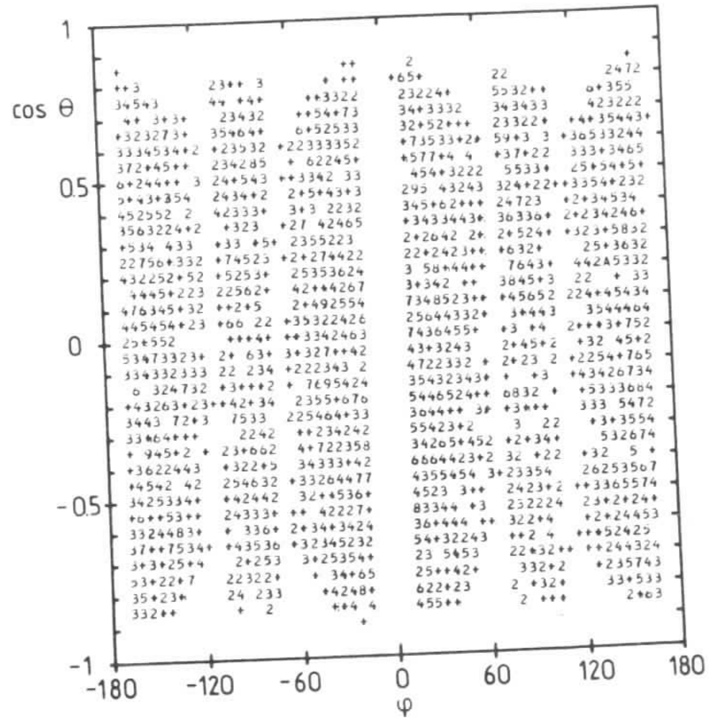

nb
DASP 2
σvis
0
2
4
6
8
9.35
9.40
9.45
9.50
GeV

Fig.3



On Resonance
DASP 2
Off Resonance
DASP 2
[arb.units]
E_h [GeV]

Fig.4



cos Θ
φ

Fig.5

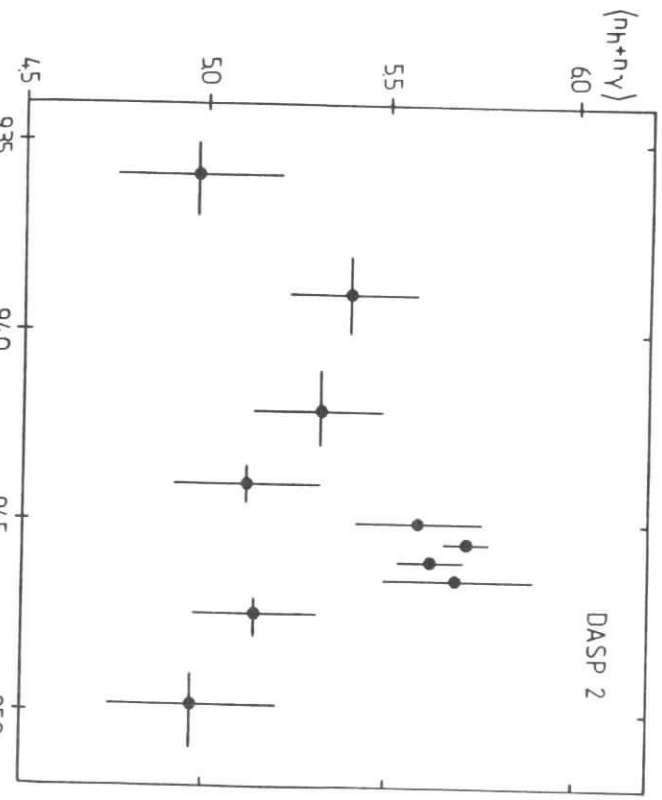

⟨nh+nγ⟩
6.0
5.5
5.0
4.5
9.35
9.40
9.45
9.50
GeV
DASP 2

Fig.6

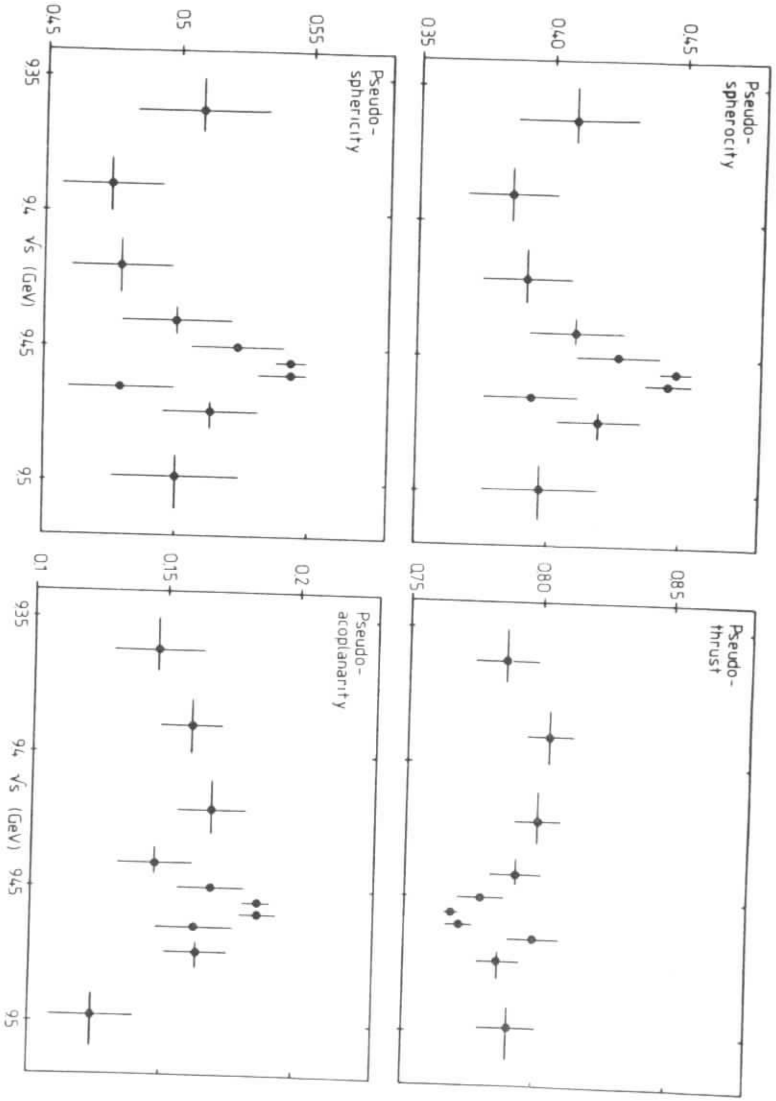

Pseudo-
spherocity
0.45
0.40
0.35
Pseudo-
sphericity
0.55
0.5
0.45
9.35
9.4
√s (GeV)
9.45
9.5
Pseudo-
thrust
0.85
0.80
0.75
Pseudo-
acoplanarity
0.2
0.15
0.1

Fig.7

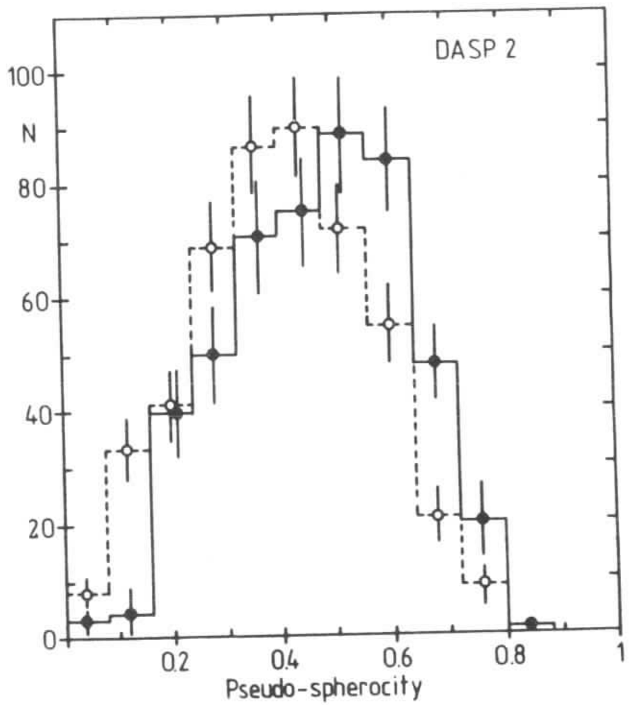


Fig.8