JET ANALYSIS OF THE Υ(9.46) DECAY INTO CHARGED HADRONS

PLUTO Collaboration

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The direct decay into four and more charged particles of the Υ(9.46) formed in e^+e^- collisions is analysed for hadron-jet configurations. The results are compared with the expectations of phase space, a $q\bar{q}$ two-jet model and a QCD three-gluon decay mechanism. Out of these three models, the three-gluon decay describes best the data.

The recent observation of the Υ(9.46) as a narrow resonance formed in e^+e^- collisions with $\Gamma_{ee} \sim 1.2$ keV [1–3] strongly supports its interpretation as a $b\bar{b}$ quark-pair bound state. Further, it has been reported [4] that the e^+e^- multi-hadron events at the Υ mass energy deviate significantly from the two-jet structure observed for $e^+e^- \to$ hadrons at lower nearby energies [4,5]. In the context of the QCD model, one of the interesting suggestions is that the Υ decay into hadrons should mainly be mediated via three gluons [6]. A direct consequence of this suggestion is the formation of three hadron jets coming from the gluons' fragmentation. These gluons, however, are produced with a relatively low energy and a predicted angular distribution which favours two of the gluons to have a relatively small angle between them [7]. This being the case, the resulting three hadron jets may well be experimentally unresolvable in space even when gluons fragment like quarks. Hence, several authors

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[7–10] have investigated the expected features of the Υ decay into three gluons in terms of multi-particle variables used in jet analyses such as sphericity and thrust. In particular, since the three gluons are produced in a plane, one may expect that the Υ decay particles will be confined to a flat momentum space volume. In addition, QCD also specifies the angular distributions for that decay plane and for the most energetic gluon flight direction relative to the beam axis. In this letter we present our results for the Υ direct decay into hadrons analysed with some of the methods proposed for the detection of the three-gluon decay mechanism.

The experiment was carried out at the e^+e^- storage ring DORIS with the magnetic detector PLUTO having a geometrical acceptance of $0.92 \times 4\pi$ sr for charged hadrons and $0.94 \times 4\pi$ sr for photons and electrons. The e^+e^--annihilation data used here were taken in the center-of-mass energy range of 9.30 to 9.48 GeV with a total integrated luminosity of 396 nb^{-1}. Following our previous two-jet structure analysis [4], we have selected events having at least four fully reconstructed charged tracks coming from the interaction region and any number of neutrals. Appropriate cuts have been introduced to remove beam–gas interactions and QED background and to reduce the contribution from multi-prong τ-decay events. With these cuts the remaining background in our multi-hadron sample is estimated to be less than 3%. Description of the cuts and other details concerning the experiment have been given elsewhere [1,4]. For the analysis we have taken the Υ mass region to be between 9.45 and 9.47 GeV containing after cuts 1669 events. The 470 events accumulated in the 9.30 to 9.44 GeV region (off-resonance sample with 9.4 GeV average energy) were used to determine the $e^+e^- \to$ hadrons features of the continuum under the Υ resonance.

The contributions to the multi-hadron events in the Υ mass region come from three sources: the non-resonating continuum, the Υ decay via the vacuum polarisation (one-photon decay) and the Υ direct decay. Since here we are interested in the Υ direct decay, the contributions of the other two sources have to be subtracted. The subtraction used throughout this analysis was made with the help of the expression

$$\sigma^{\mathrm{dir}} = \sigma^{\mathrm{on}} - \sigma^{\mathrm{off}} - \sigma^{\mathrm{VP}} = \sigma^{\mathrm{on}} - \sigma^{\mathrm{off}} - \sigma^{\mathrm{off}}(\sigma^{\mathrm{on}}_{\mu\mu} - \sigma^{\mathrm{off}}_{\mu\mu})/\sigma^{\mathrm{off}}_{\mu\mu} ,$$

where σ^{dir} is the Υ direct decay cross section, σ^{on} and σ^{off} are our measured cross sections at the Υ energy and at 9.4 GeV [1] and σ^{VP} is the Υ partial decay into hadrons via the vacuum polarisation. Using our measured value $(\sigma^{\mathrm{on}}_{\mu\mu} - \sigma^{\mathrm{off}}_{\mu\mu})/\sigma^{\mathrm{off}}_{\mu\mu} = 0.24 \pm 0.22$ [12] and the number of events in the two energy regions, an unnormalised distribution for the Υ direct decay is given by the distribution at the Υ mass subtracted by 1.32 times the off-resonance distribution where the subtraction is made bin by bin. In this method the contribution of the τ events to the Υ hadron sample is subtracted as well. Since the main subtraction is due to the continuum, the results for the Υ direct decay are rather insensitive to the vacuum polarization contribution, given the small value of $(\sigma^{\mathrm{on}}_{\mu\mu} - \sigma^{\mathrm{off}}_{\mu\mu})/\sigma^{\mathrm{off}}_{\mu\mu}$.

In the present analysis we have compared our data with three alternative models. The first, a $q\bar{q}$ two-jet model formulated by Field and Feynman [13] and the second a multi-pion phase space. The third model considered is the proposed three-gluon decay for the Υ direct transition into hadrons. To this end we have used the Υ three-gluon decay matrix element described in ref. [8]. In addition we have assumed [7,8] that the gluon jet has the same features as the observed hadron jets of the continuum data at a similar energy. The predictions of these three models were calculated by a Monte-Carlo method simulating the detector and all experimental cuts. The topological quantities which we present in this paper are thus observed data, with the exception of $\langle n_{\mathrm{ch}} \rangle$.

To measure the deviation of the Υ multi-hadron decay from a two-jet structure, we have first used the sphericity variable defined as

$$S = (3/2)\min\left(\sum_i p_{ti}^2\right)\Big/\left(\sum_i p_i^2\right) ,$$

where the summation runs over all charged particles and p_t is the transverse momentum relative to a given axis. To calculate the sphericity we formed for each event the tensor [14]

$$T^{\alpha\beta} = \sum_i (p_i^2 \delta^{\alpha\beta} - p_i^\alpha p_i^\beta) ,$$

where α and β are the coordinate indices. Ordering the eigenvalues λ_k of $T^{\alpha\beta}$ so that $\lambda_1 \geqslant \lambda_2 \geqslant \lambda_3$ the sphericity is given by

$$S = 3\lambda_3/(\lambda_1 + \lambda_2 + \lambda_3) .$$

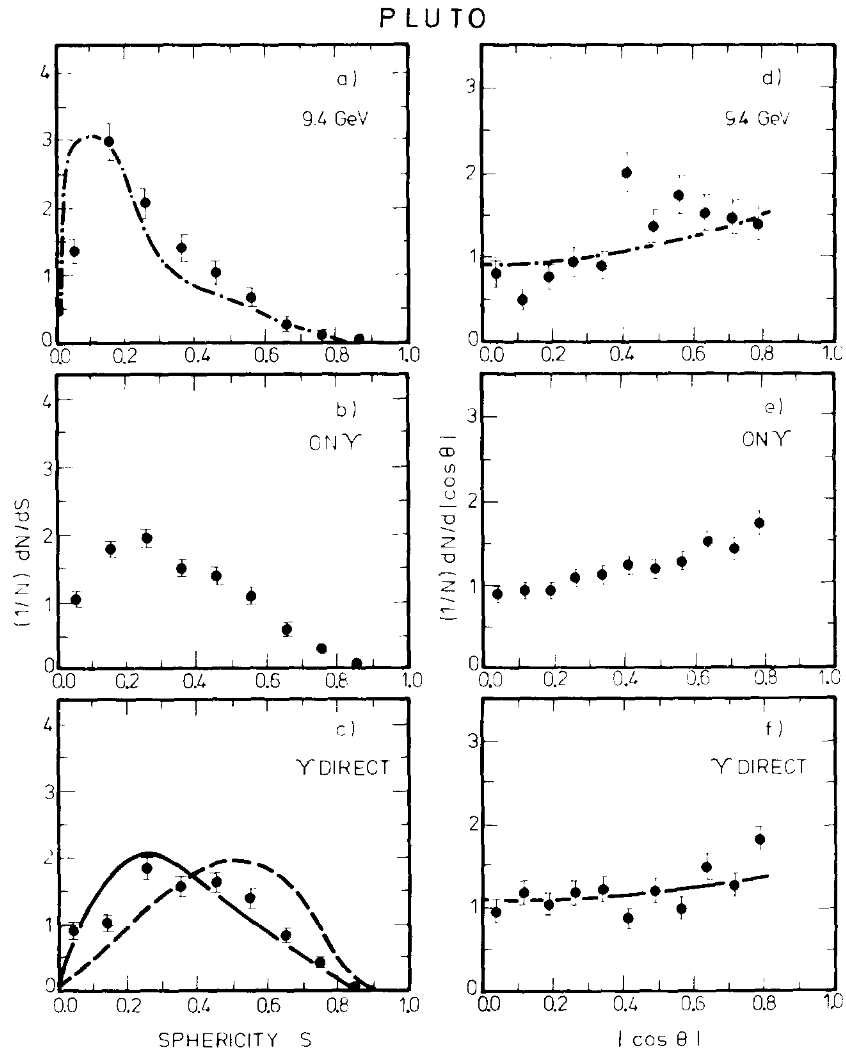

Fig. 1. Differential sphericity distributions and the sphericity axis angular distributions. The dash–dotted line in (a) represents the two-jet model. The dashed and solid lines in (c) represent respectively phase space and the three-gluon decay models. The dash–dotted line in (d) is proportional to $1 + \cos^2\theta$ and the solid line in (f) to $1 + 0.39 \cos^2\theta$.

In figs. 1a–c we show the differential sphericity distributions for the off-resonance data, the data at the Υ mass and the subtracted distribution for the Υ direct decay. For comparison we show in fig. 1a the two-jet model prediction (dash–dotted line) and in fig. 1c the expectations of phase space (dashed line) and the three-gluon decay model (solid line).

The off-resonance data are adequately described by the two-jet model. The distribution for the Υ direct decay is seen to be shifted to higher sphericity values, approaching phase space, but it is best described by the three-gluon decay. These features are further illustrated in fig. 2a where the mean sphericity $\langle S \rangle$ is plotted for the Υ data and for data from our experiment at lower energies [4]. The phase space expectation is shown in the same figure by the shaded area. The width of this area is the estimated variation in $\langle S \rangle$ due to uncertainties in the multiplicity and the fraction of neutrals to be taken for the phase space calculations. The dash–dotted line in the figure, which represents

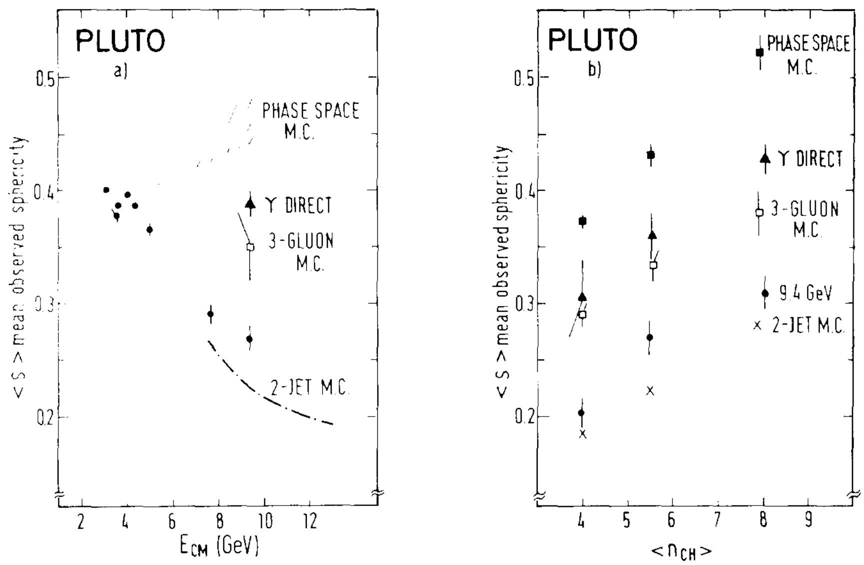

Fig. 2. The mean observed sphericity ⟨S⟩ compared to phase space, two-jet model and three-gluon decay mechanism. (a) ⟨S⟩ as a function of E_{cm} for events with ⩾4 prongs. (b) ⟨S⟩ as a function of multiplicity for the data at 9.4 GeV and for the Υ direct decay.

the two-jet model prediction, is lower than the continuum data [‡1]. In making this comparison one should note that in the two-jet model, formulated in ref. [13], charm production is not accounted for. A large increase over the 9.4 GeV continuum is seen for ⟨S⟩ of the Υ direct decay which reaches the value 0.38 ± 0.01.

[‡1] The comparison is made only at the higher energy end of our data where the two-jet model should be at its best. Note that the value of the Monte-Carlo point at 9.4 GeV is somewhat lower than that given by us previously [4] due to an improved acceptance calculation.

This value is about four standard deviations away from phase space and is consistent within errors with the value of the Υ three-gluon decay generated sample (see also table 1). We have repeated the jet analysis using the alternative thrust variable T proposed as a convenient quantity for QCD calculations [10,15]. The conclusions obtained from the thrust analysis are very similar to those derived from the sphericity study. As can be seen from table 1, our experimental mean thrust value of ⟨T⟩ = 0.76 ± 0.01 is in agreement with that obtained for the generated three-gluon decay sample.

In the framework of the three-gluon decay it is ex-

Table 1
The observed mean values for sphericity S, Q_1, P_{out}, thrust T and acoplanarity A. The data are compared with three models computed via the Monte-Carlo method to simulate the experimental conditions. The errors given for the observed data values are statistical only, whereas those of the phase space and three-gluon decay models include systematic uncertainties.

	M.C. 2-jet	Data		M.C.	
		9.4 GeV	Υ direct	3-gluon	phase space
⟨S⟩	0.22	0.27 ± 0.01	0.39 ± 0.01	0.35 ± 0.03	0.46 ± 0.02
⟨Q_1⟩	0.030	0.036 ± 0.002	0.056 ± 0.003	0.050 ± 0.005	0.067 ± 0.005
⟨p_{out}⟩	0.115	0.118 ± 0.003	0.129 ± 0.003	0.140 ± 0.006	0.177 ± 0.006
⟨T⟩	0.84	0.82 ± 0.01	0.76 ± 0.01	0.76 ± 0.01	0.73 ± 0.01
⟨A⟩	0.084	0.099 ± 0.005	0.15 ± 0.01	0.14 ± 0.01	0.16 ± 0.01

pected [8,9,17] that the hadron multiplicity of the Υ direct decay will be higher than that of the continuum at nearby energies. In our experiment we observe a rise in the mean charged multiplicity from $\langle n_{ch} \rangle = 6.3 \pm 0.4$ at 9.4 GeV to $\langle n_{ch} \rangle = 8.0 \pm 0.3$ for the Υ direct decay [‡2]. This observed rise is not inconsistent with the theoretical expectation [11]. We have checked whether the relative change in $\langle S \rangle$ at the Υ energy is only due to the increase in the mean observed multiplicity. To answer this question we divided our data into three multiplicity groups of 4 prongs, 5 and 6 prongs, and 7 and more prongs. The $\langle S \rangle$ values for these charge-multiplicity groups are shown in fig. 2b for the 9.4 GeV continuum data and for the Υ direct decay. As can be seen, the mean sphericity increases with multiplicity. However, in all three multiplicity groups the $\langle S \rangle$ value for the Υ direct decay is significantly higher than the corresponding continuum value and consistent within errors with the three-gluon decay prediction.

Next we examine the angular distribution of the two-jet axis with respect to the beam direction. In the case of a three-gluon decay, this axis should coincide with the direction of the most energetic gluon. The angular distribution of that axis has recently been evaluated theoretically [7] to be of the form $1 + \alpha \times \cos^2\theta$. The value of α is expected to vary from +1 for perfectly aligned gluons to 0.2 for equal energy gluons. The value of $\langle \alpha \rangle$, averaged over the whole S (or T) range, is estimated to be 0.39 and should be rather independent of the detailed gluon fragmentation properties. Due to our limited statistics we are unable to study this distribution as a function of S or T. Hence we show in figs. 1d–f the experimental angular distributions of the two-jet axis, as determined by the sphericity, for the off- and on-resonance data and for the Υ direct decay for all the events. These distributions are corrected for the detector acceptance losses. As has already been shown previously [4], the distribution for the off-resonance data is consistent with $1 + \cos^2\theta$, in accordance with a $q\bar{q}$ two-jet production. A fit to the angular distribution of the Υ direct decay data yields the value $\langle \alpha \rangle = 0.83 \pm 0.23$ to be compared with the theoretical QCD estimate of 0.39.

The three gluons, proposed as a mechanism for the Υ decay into hadrons, are produced in one plane. Consequently, in the process of fragmentation some degree of planar configuration should be retained. A measure of the flatness of an event can be extracted from the eigenvalues λ_k discussed above. For this purpose we introduce the quantities Q_k defined as

$$Q_k = 1 - \frac{2\lambda_k}{\lambda_1 + \lambda_2 + \lambda_3} = \frac{\Sigma_i (p_{\parallel}^k)^2}{\Sigma_i (p)^2} ,$$

where $p_{\parallel}^k$ is the particle momentum component along the axis associated with the eigenvalue λ_k. For the order $\lambda_1 \geqslant \lambda_2 \geqslant \lambda_3$ one obtains $Q_1 < Q_2 < Q_3$. The quantity Q_1 is then a measure for the flatness of the event and it can vary from 0 for an ideal planar event to 1/3 for a perfect spherical configuration. Since $Q_1 + Q_2 + Q_3 = 1$, the overall spatial configuration of an event can conveniently be represented by a point in an equilateral Dalitz-like triangle with the x-axis equal to $(Q_3 - Q_2)/\sqrt{3}$ and the y-axis equal to Q_1. With the condition $Q_1 \leqslant Q_2 \leqslant Q_3$ the allowed region is restricted to a rectangular sub-triangle of the type shown in fig. 3a where for illustration we show the distribution of the two-jet-model generated events. In that sub-triangle, the vertex A ($Q_1 = Q_2 = Q_3 = 1/3$) corresponds to a perfect spherical configuration, the vertex B ($Q_1 = 0; Q_2 = Q_3 = 1/2$) to a planar circular disc and the vertex C ($Q_1 = Q_2 = 0; Q_3 = 1$) to a perfectly aligned two-jet structure.

In fig. 3 we show the three-dimensional triangle plots for our off-resonance data and for the Υ direct decay. In these plots the height over the different triangle regions is proportional to the relative event density. For comparison we show in the same figure the triangle plots for the three Monte-Carlo generated samples of the models. As expected, the two-jet model sample is concentrated near the vertex C where evidently the Q_1 values are very small implying a flat event configuration. The distribution of the phase space events is spread over a large region of the triangle. We observe that the off-resonance data are similar to the generated two-jet sample. The triangle plot for the Υ direct decay data on the other hand, is best described by the three-gluon decay sample and is significantly different from both the phase space and two-jet model distributions.

The mean values of Q_1 are shown in fig. 4a for the

[‡2] The quoted $\langle n_{ch} \rangle$ values are the mean charge multiplicities using all events with two or more charged prongs, corrected for the experimental acceptance, the errors are statistical only.

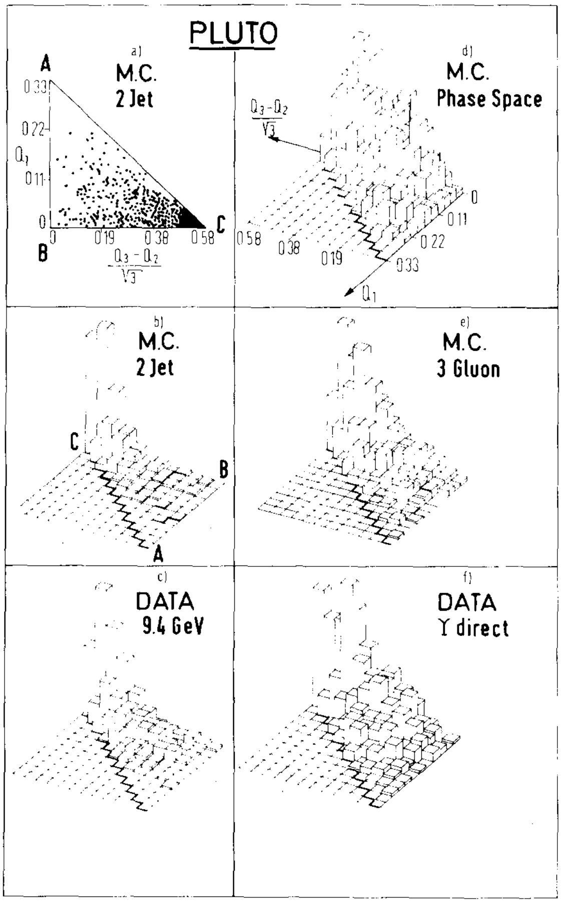

Fig. 3. Triangle plots of the momentum space configuration, Q_1 against $(Q_3 - Q_2)/\sqrt{3}$, for the data and for the three Monte-Carlo samples. The vertices A, B and C correspond, respectively, to a perfect sphere, a planar circular disc and a perfect two-jet structure.

Υ data and for our data at lower energies. In the same figure we also show the phase space expectation and the prediction of the $q\bar{q}$ two-jet model. Below ~5 GeV, including the J/ψ resonance, the data are consistent with phase space. Above 5 GeV, a gradual decrease of $\langle Q_1 \rangle$ is seen as the event configuration is becoming more and more dominated by a two-jet structure. At 9.4 GeV the $\langle Q_1 \rangle$ of the continuum is just slightly above the value of the two-jet model. A sharp rise is seen for the $\langle Q_1 \rangle$ of the Υ direct decay reaching the value of 0.054 ± 0.003, significantly below the phase space region but in good agreement with the corresponding value for the three-gluon-decay generated sample. We have observed this rise of the $\langle Q_1 \rangle$ value to occur in all event multiplicity groups.

In figs. 4b and 4c we show the normalised inclusive p_{out} distributions for all charged particles where p_{out} is the particle momentum component perpendicular to the plane associated with Q_1. The distribution for the off-resonance data, shown in fig. 4b, is in good agreement with the two-jet model. The corresponding distribution for the Υ direct decay, shown in fig. 4c, is again well described by the three-gluon decay model and is clearly inconsistent with phase space (see also table 1).

An alternative measure for the planar configuration of a multi-particle event is given by the acoplanarity variable [11] defined as

$$A = 4\min\left[\left(\sum_i |p_{out}|\right)\Big/\left(\sum_i |p|\right)\right]^2 .$$

To calculate the value A for our events we have utilised the combinatorial method proposed in ref. [16]. The results for the mean acoplanarity $\langle A \rangle$ are given in table 1 where they are compared with the expectations of the different models. Here, as before, the two-jet model is in agreement with the off-resonance data and the Υ direct decay result matches the three-gluon decay expectation.

In summary, we have shown that the properties of the Υ direct decay into hadrons do deviate strongly from the two-jet structure observed for the non-resonating data at 9.4 GeV. This observation rules out a dominant Zweig-rule violating decay of the Υ into two light quarks. The data are, on the other hand, clearly inconsistent with a multi-pion phase space model. All the quantities related to the momentum space configuration of our data are found to be in good agreement with the proposed three-gluon decay mechanism. This is the case for the differential distributions as well as the mean values of the quantities summarized in table 1. More elaborate tests proposed for the three-gluon decay hypothesis, such as the angular behaviour of the sphericity axis, are less conclusive due to the statistical limitation of the present data.

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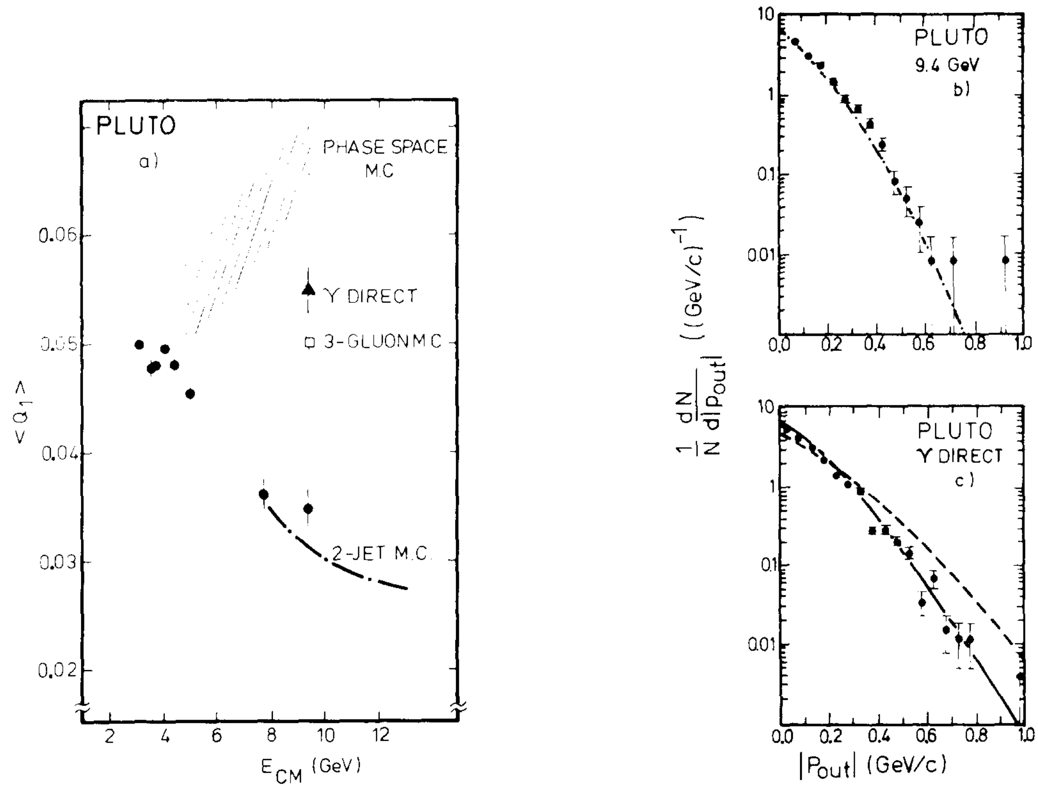

Fig. 4. (a) The mean observed Q_1 as a function of E_{cm} for events with ≥4 prongs. (b) and (c) The inclusive p_{out} distributions for the 9.4 GeV data and for the Υ direct decay. The dash–dotted line in (b) represents the two-jet model. The dashed and solid lines in (c) represent, respectively, phase space and three-gluon decay.

their continuous service. Our thanks are also due to H.G. Sander for providing us with an event generator based on a $q\bar{q}$ two-jet model. Finally, we would like to thank K. Koller, H. Krasemann and T.F. Walsh for many instructive discussions. The non-DESY members of the PLUTO group would like to thank the DESY directorate for their kind hospitality. The work at Aachen, Hamburg and Siegen has been supported by the Bundesministerium für Forschung und Technologie.

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