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Abstract

In $\Upsilon(1S)$ decays most observables (sphericity, charged multiplicity, photonic energy fraction, inclusive spectra) can be understood assuming that gluons fragment like quarks. New results from LENA use the (axis-independent) Fox-Wolfram moments for the photonic energy deposition. Continuum reactions show "standard" Field-Feynman fragmentation. $\Upsilon(1S)$ decays show a significant difference in the photonic energy topology. It is more isotropic than with the Field-Feynman fragmentation scheme.
Gluon fragmentation into isoscalar mesons (à la Peterson and Walsh) is excluded. But if one forces the leading particle to be isoscalar, one gets good agreement with the data.

LENA Collaboration: Inst. Nuclear Physics Cracow, University Erlangen, DESY, University Hamburg (I. Institute Experimental Physics), University and NIKHEF Nijmegen, Carnegie-Mellon University, DPhPE-CEN-Saclay, Tel-Aviv University, University Würzburg.

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1. The LENA detector and data sample

Two components of the LENA detector (non-magnetic) have been used for this experiment: the inner track detector and the calorimeter for electromagnetic showers. Together they enabled us to measure the photonic energy distribution in hadronic events.
The hadronic data sample used for this investigation is selected by requiring events with a visible energy $E_{vis} > 900$ MeV. The method of event selection is described in ref.(1). Event numbers are given in table 1.

2. Experimental investigation of gluon fragmentation I

QCD theory predicts that the hadronic decay of the Υ resonance proceeds via a 3-gluon intermediate state

$$\Upsilon \rightarrow 3g \rightarrow h's$$

The $\Upsilon(1S)$ decays can then be used as a gluon factory. The experimental evidence for this decay mechanism (2) is not a single striking experiment like "visible" 3-jet events. But many data contribute to support the QCD prediction.

Table 2 gives a summary of the Υ decay phenomenology (numbers are from LENA). To this list one can add the inclusive particle spectra (3). Fig. 1 shows the π^0 inclusive spectra from $\Upsilon(1S)$ direct decays and for continuum reactions as measured by LENA (new data). The slopes are given in table 3. It is steeper for $\Upsilon(1S)$ decays than for CONT reactions. This is related to the higher multiplicity for Υ decays.

As a result one sees that the $\Upsilon(1S)_{DIR}$ decays and CONTINUUM reactions show a different topology.

It is important to understand the explanation of those differences in $\Upsilon(1S)_{DIR}$ and CONT topology. The data can be understood by the following assumptions:

$$\text{CONT} \rightarrow 2q\text{, q-fragmentation as parametrized by Field \& Feynman} \quad (4)$$
$$\Upsilon(1S)_{DIR} \rightarrow 3g\text{, g-fragmentation as q-fragmentation.}$$

So the different phenomenology comes from the different number of particles in the intermediate state (2 or 3, resp.). No difference in quark and gluon fragmentation is seen in the observables mentioned above.

We continued to search for differences in quark and gluon fragmentation in the Υ energy region. One idea was to compare the data for "single" jets (contrary to Υ or CONT "events"). We have cut the events perpendicular to the thrust axis (Fig.2).

The hope was that one could directly compare the quark fragmentation of the CONTINUUM (at energies below the Υ energy) with the fragmentation of the most energetic gluon (gl) in Υ decays. We failed because we had only 65 % probability to correctly identify gl.

3. Experimental investigation of gluon fragmentation II

3.1. THE FOX-WOLFRAM MOMENTS

The Fox-Wolfram moments (5) are a set of energy weighted angular moments between all particles of an event. They don't need the determination of an event axis which extends the usefulness of detectors with limited solid angle acceptance considerably. They are defined as:

$$H_l = \sum_{ij} \frac{p_i p_j}{E_{vis}^2} \cdot P_l(\cos\Theta_{ij})$$

Θ_{ij} = angle between particles i and j

P_l = Legendre polynomial to order l

p_i = momentum of particle i, for this experiment we use the deposited energy

E_{vis} = visible energy of the event

the sum extends over all particles including i = j.

It is

H_0 = 1 because of energy conservation and

H_1 = 0 because of momentum conservation.

A 2-particle final state ($q\bar{q}$) has

$H_{even} = 1$, $H_{odd} = 0$

To give the reader a feeling for the range of numerical values for these F-W moments I show in fig. 3 two special configurations. Fig. 4 shows the distributions of H_2, H_3, and H_4 of partons in the 3-body final states $e^+e^- \to q\bar{q}g$ and $e^+e^- \to \Upsilon \to 3g$, resp. QCD gives the following average values:

CONT: $\langle H_{even} \rangle = 1 - c_1 \cdot \alpha_s$ c_1 = numerical, calculable constant

$\langle H_{odd} \rangle = c_1 \cdot \alpha_s$ α_s = strong coupling constant

$\Upsilon_{DIR} \to 3\,g$: $\langle H_2 \rangle = 0.62$

Fig. 5 shows the LENA results for the distributions of the ratios H_1/H_0, H_2/H_0, H_3/H_0, and H_4/H_0 both for Υ_{DIR} decays and for CONT reactions. All clusters of energy deposition, charged and photonic particles, are used.

3.2. SOME WORDS ON THEORETICAL IDEAS FOR GLUON FRAGMENTATION

Most experiments now use the "standard" model of gluon fragmentation: gluon fragmentation = quark fragmentation (as parametrized by Field and Feynman).

Brodsky and Gunion (6) have proposed a model in which they find for gluon fragmentation a higher charged particle multiplicity than for quark fragmentation:

$$\langle n_{ch} \rangle_g = 9/4 \langle n_{ch} \rangle_q$$

because the gluons are color octets while the quarks are color triplets (the factor 9/4 is the corresponding Clebsch-Gordon coefficient). This increase in mulitiplicity for gluon fragmentation is excluded by experiment in the Υ region (the theory is derived for asymptotic energies).

Petersen and Walsh (7) have developed a model of gluon fragmentation in analogy to fragmentation of a quark-antiquark string (see fig. 6). While a quark-antiquark string can be broken up by creation of a quark-antiquark pair, this is not possible for a gluon-gluon string. The reason is that between the (color octet) gluons the string is a color octet. A $q\bar{q}$ pair which is produced by such a string is bound to be an isoscalar meson.

How can we find, in the existing data, isoscalar mesons? They have enhanced branching ratios into photonic final states.

3.3. THE PHOTONIC ENERGY FRACTION

Fig. 7 shows the photonic energy fraction of hadronic final states of Υ(1S) direct decays as well as CONTINUUM reactions as a function of c.m. energy. There is no enhancement seen for $\Upsilon(1S)_{DIR}$ decays. This excludes a fragmentation of the 3 gluons in Υ decays into "only isoscalar mesons."

3.4 FOX-WOLFRAM MOMENTS FOR THE PHOTONIC ENERGY

The LENA Collaboration determined the photonic energy topology. Only those energy clusters are kept to which no track of charged particles points. There remain on average 3 to 3.5 photonic energy clusters. It makes no sense to try to determine an axis dependent topological observable with such a low number of photonic energy clusters. But the axis independent Fox-Wolfram moments can give a parametrization of the photonic energy topology.

Fig. 8 shows the distributions of the Fox-Wolfram parameter ratios H_l/H_0, l = 1,2,3 and 4 of the photonic energy clusters, for the CONTINUUM reactions and the $\Upsilon(1S)_{DIR}$ decays. They are compared to the following models:

CONT: $q\bar{q}$ -production and Field-Feynman fragmentation. The particles are tracked in the detector and all analysis cuts are applied. This model reproduces the data.

$\Upsilon(1S)_{DIR}$: $\Upsilon \rightarrow 3g$ QCD matrix-element and, as a first attempt, "standard" gluon fragmentation, i.e. gluon-fragmentation = q-fragmentation. One observes a significant difference between data and model. The data show a wider, more isotropic distribution of photonic energy clusters.

As mentioned above a gluon fragmentation into isoscalar mesons only is excluded. So, as a second trial, we force the leading particle in a Field-Feynman fragmentation (Monte Carlo) program to be isoscalar. This is done in the spirit of the model of gluon string fragmentation. As can be seen from fig.8 this model fits the data.

3.5 WHY ARE THERE ONLY SMALL DIFFERENCES FOR DIFFERENT MODELS?

We make a double comparison (see fig. 9):

primary meson production } for { Field-Feynman fragmentation
stable particle production } for { leading isoscalar fragmentation

The primary particle content of the two fragmentation models is very different. But the stable particle content of both schemes is very similar after decay of the unstable mesons. Only the spatial distribution shows differences which are revealed by the Fox-Wolfram parameters.

We get with the leading isoscalar assumption also a better fit to the sphericity distribution which was sufficient, but not brilliant, with the "standard" assumptions.

3.6 SYSTEMATIC ACCURACY OF THE METHOD

We have changed the energies and angles of the photonic energy clusters within errors. The ratios of the Fox-Wolfram moments are insensitive to those changes.

I want to stress that the best check of our method is that we make a comparison CONT vs. $\Upsilon(1S)_{DIR}$ decays. The CONT data are reproduced by the standard fragmentation models, the data on Υ decays are not.

4. Summary and outlook

The aim of the experiment was to compare $\Upsilon(1S)$ decay topology with CONTINUUM reactions at lower energies to learn about gluon fragmentation by comparing it to quark fragmentation.

The method is

1. use of axis-independent topology measures, i.e. the Fox-Wolfram moments, and
2. the study of the photonic energy topology.

The results are:

CONT: all experimental data can be explained by
- CONT $\rightarrow q\bar{q}$,
- q-fragmentation with Field-Feynman parametrization.

$\Upsilon(1S)_{DIR}$:

a) most observables can be explained by
- $\Upsilon(1S)_{DIR} \rightarrow 3g$,
- g-fragmentation like q-fragmentation

b) photonic energy topology (Fox-Wolfram moments)
- disagrees with g-fragmentation = q-fragmentation (standard model)
- disagrees with g-fragmentation into "only isoscalar mesons"
- favors gluon fragmentation into "leading isoscalar mesons"

To understand this seemingly contradictory situation we observe that in the "leading isoscalar meson" fragmentation the

fraction of primary mesons is very different, the
fraction of stable particles is very similar

to the standard model.

The outlook then is: We have now an indication for a different fragmentation of gluons in Υ decays than from the nearby ~ 9 GeV c.m. energy continuum. The next experiment should measure the fraction of isoscalar mesons in Υ decays and compare it to the continuum.

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Table 1

	energy GeV	luminosity nb^{-1}	# events
Y(1S)	9.46	586	6'339
CONT below	8,63-9,43	1'356	4'360

Table 2

observable	$Y(1S)_{DIR}$	CONT	Y_{DIR} vs. CONT
⟨S⟩	0,40 ± 0,01	0,27 ± 0,01	distribution broader
$\langle n_{ch} \rangle$	8,12 ± 0,11	7,57 ± 0,15	higher
photonic energy fraction	(28 ± 4)%	(28 ± 4)%	same

Table 3

slope	π^0
$Y(1S)_{DIR}$	3,5 ± 0,3
CONT	2,6 ± 0,2

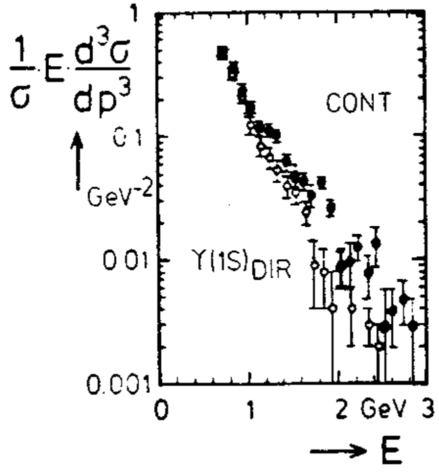

Fig. 1 The inclusive π^0 spectra from $\Upsilon(1S)_{DIR}$ decays and CONTINUUM reactions. Open circles: $\Upsilon(1S)_{DIR}$ decays, full circles: CONT reactions.

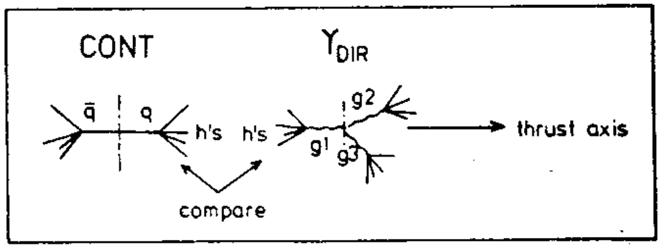

Fig. 2

Comparison of "single" jets from CONT reactions and Υ decays

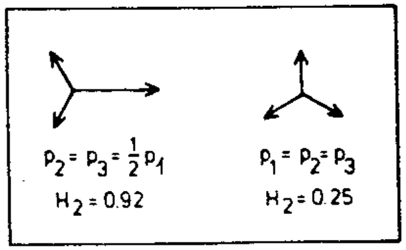

Fig. 3

The Fox-Wolfram moment H_2 for two special cases

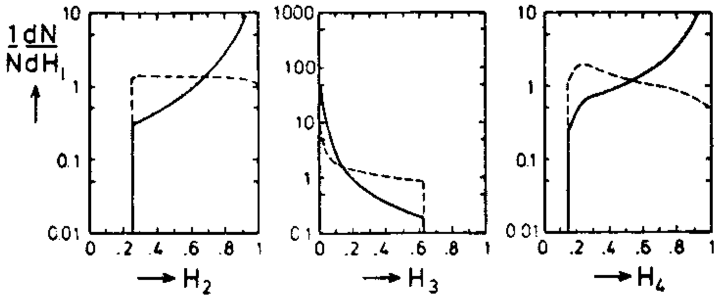

Fig. 4

The Fox-Wolfram moments H_2, H_3, and H_4 of partons for the QCD models $e^+e^- \to \Upsilon \to 3g$ (dashed lines) and $e^+e^- \to q\bar{q}g$ (full lines)

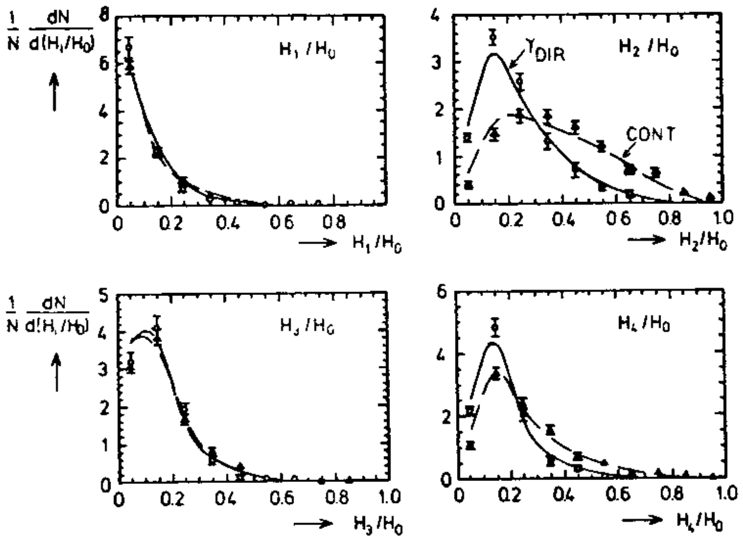

Fig. 5

The distributions of the Fox-Wolfram moment ratios as observed by LENA for Υ_{DIR} decays (open circles) and CONT reactions (full triangles). Charged and neutral energy depositions are used. The data are compared to the QCD models $\Upsilon \to 3g$ (full lines) and CONT $\to q\bar{q}$ (dashed lines), both with detector acceptance folded in

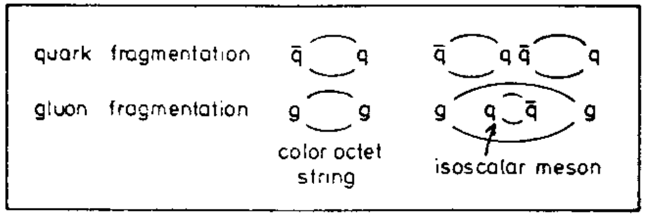

Fig. 6 Quark and gluon fragmentation in the string model (see text)

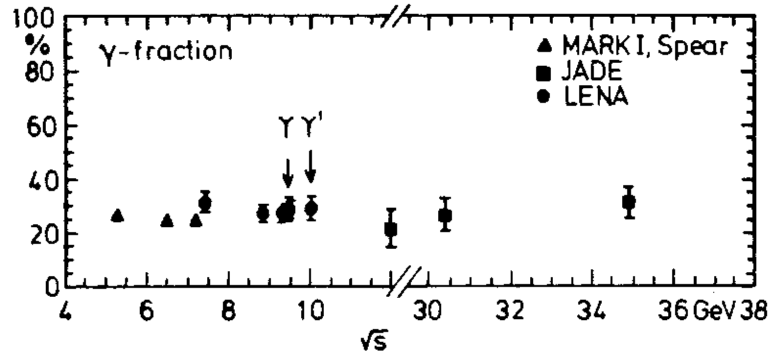

Fig. 7 The photonic energy fraction of hadronic events as a function of the c.m. energy. No enhancement is seen for $\Upsilon(1S)$ and $\Upsilon(2S)$ direct decays.

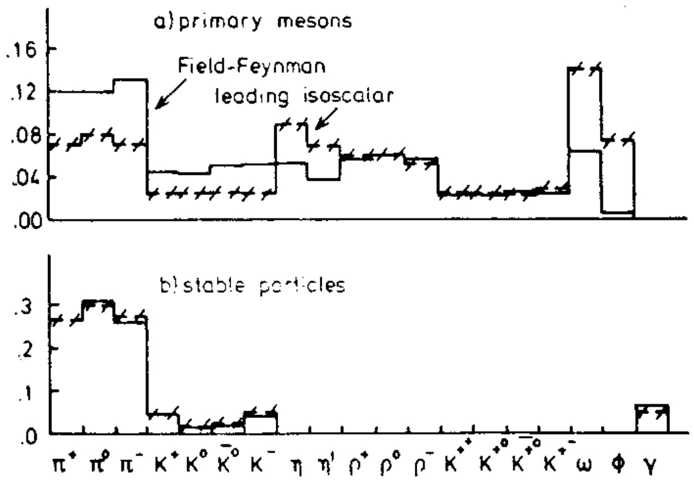

Fig. 9 The particle content of different fragmentation models, a) primary mesons, b) stable particles.

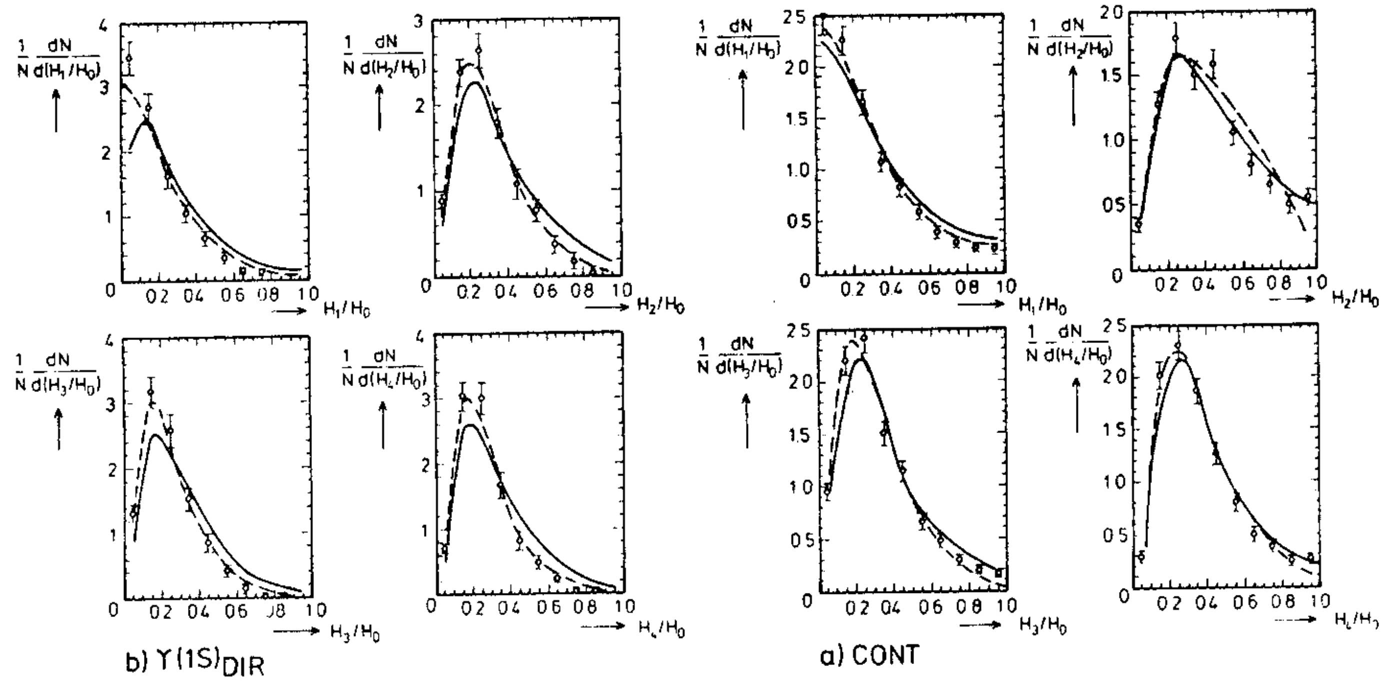

Fig. 8 The distribution of the Fox-Wolfram moment ratios. Only photonic energy deposition is used, a) for CONT reactions, b) for $\Upsilon(1S)_{DIR}$ decays. Comparison to models: full lines are the "standard model", dashed lines force leading particles to be isoscalar (see text).