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The hadronic properties of the photon in γp interactions

Gerhard A. Schuler and Torbjörn Sjöstrand
Theory Division, CERN
CH-1211 Geneva 23
Switzerland

Abstract

We propose a consistent formulation of high-energy γp interactions, in which these are built up as a sum of three contributions. A significant rôle is played by the hadronic structure of the photon. From the total cross section at low energy we determine the relative sizes of the hadronic contribution and of the components that make a photon distinctly different from a vector-meson, i.e. direct and anomalous photon components. We then obtain predictions for γp collisions at higher energies. Special attention is paid to semi-hard cross sections (mini-jets) and the origin of constituents in the photon.

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The hadronic structure of the photon arises from its direct coupling to quarks, i.e. the possibility it has to split into a quark–antiquark pair or to transform to a vector meson V. High-energy hadronic interactions involving the photon reveal its internal structure. Often, however, it is convention whether a certain reaction is said to probe the hadronic nature of the photon. In deep inelastic lepton–nucleon scattering, for example, the modification due to the transformation

$$\gamma \leftrightarrow V \tag{1}$$

is associated entirely with the target. By contrast, in the photoproduction of a vector meson V from a nucleon, the real high-energy photon is assumed to transform into the V before interacting with the target. In general, however, there is no sharp distinction between effects due to the internal structure of the photon, to the internal structure of the target, and to the mutual properties of the interaction [1].

The hadronic properties of the photon can be probed in fixed-target photoproduction (and leptoproduction), in prompt photon production at $\mathrm{e^+e^-}$ and $\mathrm{p\overline{p}}$ colliders, and in two-photon physics, both in inclusive scattering and in jet production. In this paper we shall study the hadronic properties of the photon in photon–proton interactions. There the c.m. energy so far was restricted to about 18 GeV. The ep collider HERA at DESY offers the possibilities to study γp interactions at considerably higher energies, up to 300 GeV photon–proton c.m. energies ([2] and references therein). We shall show that the photon's hadronic nature can be investigated in two complementary ways in γp interactions: through studies of exclusive events and of global event properties.

We consider the answers to the following questions as important steps in the understanding of the hadronic properties of the photon:

- How can one define the contribution originating from (1), i.e. the "VDM photon" [see Eq. (3)]? How big is it in high-energy γp interactions, and what are the signatures of the VDM photon?

- The VDM photon is expected to give rise to (semi-)hard QCD scatterings (so-called mini-jets) in γp interactions just as these occur in $\mathrm{p\overline{p}}$ collisions (Fig. 1a). How is the transition between the "high-p_T" and "low-p_T" events achieved? And what does the photon remnant look like?

- The photon also couples directly to the partons of the proton (Fig. 1b). Can the p_T cut-off p_0, necessary to regulate the basic QCD processes, be related to physical observables? Does the direct photon component contribute to minimum-bias events or only to the high-p_T jet sample?

- How can we test the so-called anomalous photon contributions? These originate from the perturbative splitting $\gamma \to \mathrm{q\overline{q}}$, where one of the partons coming from the subsequent QCD evolution then interacts with a parton in the proton (Fig. 1c). We expect such events to be somewhere in between the direct photon events, where the photon couples directly to the partons inside the proton, and the high-p_T VDM photon events, where partons inside the V collide with the partons of the proton.

- What influence do the mini-jets have on the (anticipated) rise of the total γp cross section? Do multiple interactions occur as they do in p$\bar{\text{p}}$ collisions at high energy? Could an effective size of the photon play a rôle?
- Is it at all possible to describe γp interactions in terms of an incoherent sum of three basic event categories?

In the following we shall try to develop a consistent description of high-energy γp interactions. We shall give explicit predictions which will try to answer the above questions. Yet, in order that our ideas about the hadronic properties of the photon can be tested in high-energy γp interactions, we propose four different variations of our basic scenario, i.e. a total of five "models", each emphasizing or reflecting a different hadronic nature of the photon. All scenarios are consistent with existing low-energy data, where a separation was not possible. Our choice of the various models becomes apparent when we discuss the three mechanisms that contribute to photon–proton interactions.

We decompose the total γp cross section into three pieces, VDM, direct, and anomalous:

$$\sigma_{tot}^{\gamma p}(s) = \sigma_{VDM}^{\gamma p}(s) + \sigma_{dir}^{\gamma p}(s) + \sigma_{an}^{\gamma p}(s) \ . \tag{2}$$

All three pieces do contribute to the cross section, but the incoherent sum (2) is an ansatz, which has to be confronted with experiments. Different models are arrived at by giving different weights to the individual pieces of (2), as described in the following.

The VDM photon is defined using the following ingredients:

- The diagonal vector-meson-dominance model (VDM)

$$\sigma_{VDM}^{\gamma p}(s) = \sum_{V=\rho^0,\omega,\phi} \frac{4\pi\alpha}{f_V^2}\, \sigma^{Vp}(s) \ . \tag{3}$$

- The energy-independent photon to vector-meson couplings of [1].
- The additive quark model.
- The parametrizations of the total pion– and kaon–proton cross sections of [3].

This results in the VDM contribution to the total γp cross section shown in Fig. 2 as a function of the c.m. energy $\sqrt{s}$. By comparing with the parametrization [3] of $\sigma_{tot}^{\gamma p}(s)$, also shown in Fig. 2, we find that VDM constitutes about 80% of the total cross section, approximately independent of the c.m. energy $\sqrt{s}$.

As any hadronic cross section, $\sigma_{VDM}^{\gamma p}$ receives contributions from diffractive and non-diffractive reactions. Parametrizations similar to that of [3] do not exist for these reactions. Based on Regge theory [4] we parametrize cross sections for hadron–proton elastic and diffractive scattering. Details of these fits will be given elsewhere. Invoking again VDM we obtain predictions for γp reactions. We show the results for the "elastic" reactions

$$\gamma + \text{p} \rightarrow V + \text{p} \qquad\qquad (V = \rho^0, \omega, \phi) \ , \tag{4}$$

as well as for diffractive reactions

$$\begin{aligned} \gamma + \text{p} &\rightarrow V + X & (5)\\ \gamma + \text{p} &\rightarrow X + \text{p} & (6)\\ \gamma + \text{p} &\rightarrow X_1 + X_2 \ , & (7) \end{aligned}$$

in Fig. 2, again as function of the γp c.m. energy. It is understood that the respective cross sections are represented by the distance between two neighbouring lines. We find that reactions (4–7) contribute a fair fraction to the total VDM cross section, varying between 25% and almost 40%. In passing we note that their measurements will answer the important question whether the couplings $4\pi\alpha/f_V^2$ describing (1) are constant or energy-dependent. Furthermore, such measurements will allow detailed studies of the soft pomeron, the perturbative pomeron, and the interesting transition region.

We now turn to the non-diffractive part of $\sigma_{VDM}^{\gamma p}$. We define it as the difference between the total VDM cross section and the cross sections for reactions (4–7), see Fig. 2. This non-diffractive cross section consists of two parts, a soft part, contributing only to low-p_T minimum-bias events, and a (semi-)hard part that describes QCD parton–parton scatterings (mini-jets). It appears plausible to us to treat $\sigma_{VDM}^{\gamma p}$[non-diffr.] in exactly the same way as a purely hadronic cross section.

Let us first discuss the case where the mini-jet cross section is small compared with the non-perturbative one, i.e. the case of sufficiently small $\sqrt{s}$. Then soft and semi-hard cross sections can simply be added:

$$\sigma_{VDM}^{\gamma p}[\text{non-diffr.}](s) = \sigma_{VDM}^{\gamma p}[\text{soft}](s) + \sigma_{VDM}^{\gamma p}[\text{semi-hard}](s) \ . \tag{8}$$

The mini-jet cross section can be calculated perturbatively, as the convolution of the partonic $2 \rightarrow 2$ cross sections with the parton distribution functions of the proton and the VDM photon. The latter we define as those of the appropriately scaled distributions of the neutral pion:

$$f_a^{VDM}(x, \mu^2) = \frac{4\pi\alpha}{f_V^2}\, f_a^{\pi^0}(x, \mu^2) \ . \tag{9}$$

Furthermore we regularize the partonic cross sections by a p_T cut-off $p_{T min}$. The photon remnants are connected to the hard scattering, as if the photon was a V [5, 6]. In soft events the proton and photon "remnants" are connected directly to each other, without any intervening hard scattering.

Now we come to the modifications necessary at higher energies. First note that hadronic cross sections show a universal rise $\propto s^\epsilon$ with $\epsilon \approx 0.08$ up to at least $\sqrt{s} = 1.8\,\text{TeV}$ [3]. This power behaviour, valid from about 15 GeV onwards, seems to be unchanged by the onset of mini-jets at about 100 GeV. Since mini-jet cross sections rise faster than s^ϵ with energy, they will eventually exceed the total cross section. Therefore, the mini-jet cross sections have to be unitarized. This we do by allowing multiple parton–parton scatterings [7], assuming the VDM photon has the same size as a pion.

The most important quantities in this approach are the cut-off parameter $p_{T min}$ and the parton distributions functions (and α_s). The cut-off can be determined by fits to p$\bar{\text{p}}$ data such as multiplicity distributions, energy flows, forward-backward correlations, etc. One finds values of the order of 1 to 2 GeV. In previous studies on mini-jets, the parton distributions have been frozen at some minimal scale μ_0^2. Important contributions to the cross section arise from very low values of μ^2, and also at very small x values at high energies. At very small x and/or μ^2, however, the parton distributions enter a non-perturbative regime, and a sensible behaviour has to be enforced.

We link the small-x behaviours of the valence and sea/gluon distributions to the high-energy behaviour of the reggeon and pomeron parts of the total γp cross section, $\sigma_{tot}^{\gamma p} = Xs^{\epsilon} + Ys^{-\eta}$, similarly to what was done for the electromagnetic structure function $F_2^{em}(x,\mu^2)$ [8]. At small x we require the gluon and sea distributions to behave like $x^{-\epsilon}$ and valence distributions to vanish like x^{η}. The low-μ^2 behaviour we model by power-like scaling violations proportional to $(\mu^2/(\mu^2+m_{R,P}^2))^{\delta_{P,R}}$ where the powers $\delta_{P,R}$ are fixed by demanding an analytical behaviour in the limit $x,\mu^2 \to 0$ at fixed x/μ^2. Furthermore we make the valence distributions harder at low μ^2. Requiring that $F_2^{em}(x,\mu^2)$ approaches (a certain fraction of) the total γp cross section in the $\mu^2 \to 0$ limit, and comparing with recent small-x data [9], allows us to constrain the normalization constants and the mass parameters $m_{P,R}$. Details of the above extension of given parametrizations will be given elsewhere. Here we note that the use of these modified parton distribution functions significantly reduces the spread between different parametrizations. Refitting the p$\overline{\text{p}}$ data, we now obtain $p_{T min} \approx 1.3\,\text{GeV}$.

Now we come to the direct and anomalous photon contributions to (2). These are the contributions that make γp processes different from the corresponding hadronic ones, see Fig. 1. The component where the photon interacts directly with the partons inside the nucleon (Fig. 1b) is established so far for high-p_T reactions: in the comparison of photon- and hadron-induced production of ρ^0 mesons at $\sqrt{s} \approx 15\,\text{GeV}$, an excess of the γp data was found at $p_T \geq 2\,\text{GeV}$ [10], in good agreement with the basic direct photon processes, i.e. QCD Compton and photon–gluon fusion. Anticipating that the anomalous photon contribution to the total photoabsorption cross section is small at fixed target energies, we identify the difference between the total and the VDM cross sections as coming from direct photon events (at $\sqrt{s_0} \approx 10\,\text{GeV}$):

$$\sigma_{dir}^{\gamma p}(s_0) = \sigma_{tot}^{\gamma p}(s_0) - \sigma_{VDM}^{\gamma p}(s_0)\ . \tag{10}$$

This results in a (perhaps surprisingly) large direct photon cross section of about 20%. Equation (10) determines the p_T cut-off p_0, necessary to regularize the QCD cross sections. We find $p_0 = 0.5\,\text{GeV}$ with some uncertainties from proton-distribution functions and α_s.

Photon–proton interactions therefore require (at least) two distinctly different scales. First the cut-off $p_{T min}$ for the hard scatterings of the VDM photon. And secondly the scale p_0, which acts as a cut-off for the direct photon scatterings. We shall identify p_0 also with the reference scale for the anomalous component of the photon–parton distributions. Two further arguments let us believe that our choice is indeed sensible. First, we include vector mesons up to about a mass of 1 GeV in (3). Therefore direct (and anomalous) photon contributions should start at $p_0 \sim p_T \sim m_V/2 \sim 0.5\,\text{GeV}$. Secondly, we obtain parton distributions of the photon by adding to (9) the (completely calculable) anomalous component:

$$f_a^{\gamma}(x,\mu^2) = f_a^{VDM}(x,\mu^2) + f_a^{an}(x,\mu^2;p_0^2)\ . \tag{11}$$

One can then compare the photon structure function (11) with parametrizations on the market [11]. Keeping in mind that these differ greatly, we find reasonable agreement for $\mu \sim 0.5\,\text{GeV}$. (Note that $f_a^{an}(x,\mu^2;p_0^2)$ vanish as $\mu^2 \to p_0^2$.)

The energy dependence of the direct photon cross section is shown in Fig. 2. The variation depends on our assumption of parton-density behaviours at small x and μ^2, as discussed above. The sum of direct and VDM cross sections always stays below the total γp cross section. Note that the large direct component of about 10% to 20% (Fig. 2), together with the steep behaviour of p_T distributions, implies a substantial direct photon contribution to low momentum-transfer reactions, i.e. to minimum-bias events.

The third and last contribution to the total γp cross section (2) is the anomalous photon part. It consists of parton–parton scatterings with one parton each from the proton and the photon (Fig. 1c). These (semi-)hard parton cross sections are the same as for hadronic collisions. VDM and anomalous mini-jets differ by the photon–parton distributions: for the former they are given by (9), while for the latter they are that (perturbatively calculable) parts that originate from the photon to quark–antiquark pair splitting, $f_a^{an}(x,\mu^2)$. As argued above, we identify the reference scale in f_a^{an} with p_0, and take (for the moment) the same p_T cut-off $p_{T min}$ for hard scatterings due to the VDM photon and the anomalous one.

For the inclusive jet cross section, the VDM and anomalous jet cross sections may be added to form the resolved photon contribution. The sum is then given in terms of the photon–parton distribution functions. While the anomalous contribution is predicted theoretically, it is not yet seen in the data: although evidence for photon constituents is reported in two-photon collisions [12], the analysis is not conclusive, i.e. does not distinguish between VDM and anomalous photon contributions.

The anomalous photon cross section grows very fast. From Fig. 2 we observe that the sum of VDM plus direct plus anomalous photon cross sections exceeds the expected total cross section. Several possibilities are open to ensure that eq. (2) is fulfilled, corresponding to different pictures of the photon ("models"). Let us first note that the anomalous photon contribution is an inclusive jet cross section. In p$\overline{\text{p}}$ collisions the jet cross section can be interpreted as being the product of a total cross section times an average jet multiplicity. The fast rise of the jet cross section does then not imply a similar fast rise of the total cross section, but rather gives rise to multiple scatterings. For the anomalous photon cross section we do, however, not expect multiple scatterings because there is just the single splitting $\gamma \to \text{q}\overline{\text{q}}$. Two extreme possibilities then appear:

- **Model I:** The anomalous photon cross section is forced to stay small. More precisely, its magnitude is defined by (2), given the other cross sections. This can be achieved by making the p_T cut-off energy-dependent: $p_{T min}^{an} = p_{T min}^{an}(s)$. At $\sqrt{s} = 200\,\text{GeV}$ a value $p_{T min}^{an} = 2.2\,\text{GeV}$ is required. Model I is our preferred scenario, because we would like to believe that the f_V couplings are energy-independent.

- **Model II:** The anomalous photon cross section is not reduced. In order that (2) is fulfilled, the photon-to-V couplings are made energy-dependent: $f_V = f_V(s)$.

Even if there are no multiple partons in the anomalous photon, there can be multiple scatterings due to partons emitted during the evolution. So far, nobody knows how to model these. As a first estimate one might try:

- **Model III:** Combine the anomalous photon contribution with the VDM-photon contribution to a resolved photon term, i.e. treat also the anomalous photon like a hadron. Then the machinery of multiple scatterings (and periphal collisions) is applied to this

VDM plus anomalous pseudo-meson. The direct-event class is kept separate at the expected rate (i.e. with $p_0 = 0.5\,\text{GeV}$).

In order to test the genuinely non-hadronic nature of the photon, we propose to compare these models with scenarios where the components that distinguish a photon from a vector-meson are switched off:

- **Model IV:** The photon does have a direct contribution, but there is no anomalous part. We leave $\sigma_{dir}^{\gamma p}$ unchanged but increase $\sigma_{VDM}^{\gamma p}$ by suitably scaling up the VDM couplings, which thus become energy-dependent.
- **Model V:** This is the extreme case where the photon is treated as a pure hadron. Photon–proton interactions are then nothing but scaled pion–proton ones. Apart from somewhat harder valence parton distributions, γp interactions can then be compared with p$\overline{\text{p}}$ interactions at the same energy.

We implemented these various models in PYTHIA [5, 6]. In Figs. 3 and 4 we show two representative distributions for γp collisions at $\sqrt{s} = 200\,\text{GeV}$. Figure 3 gives the multiplicity distribution of charged particles for inclusive events. The two most prominent features are the large tail obtained in model III and the small rate of low-multiplicity events in model II. The (partonic) jet rate is largest in model III, because jets from both VDM and anomalous photon are taken in full strength through the unitarization procedure. A large jet rate in turn implies large particle multiplicities. In model II the anomalous photon contribution is kept at maximal strength (i.e. $p_{Tmin}^{an} = \text{const.} = 1.3\,\text{GeV}$), at the expense of VDM low-p_T (and therefore low multiplicity) events.

Figure 4 is an example of how jet samples can help to differentiate between various models. Direct photon events are peaked in the photon direction because there is no photon remnant. The VDM contribution is rather central, pretty much like a p$\overline{\text{p}}$ (πp) distribution at the same energy. The anomalous photon contribution has characteristics in between those of the other two mechanisms. Important to note is the relative cross sections of the mechanisms: $0.11\,\mu\text{b} : 0.07\,\mu\text{b} : 0.38\,\mu\text{b}$ for VDM to direct to anomalous photon contribution for jets with $E_T > 10\,\text{GeV}$. Even though the total cross section is the same in all models, jet cross sections are very sensitive to the "genuine" photon contributions, direct and anomalous. This can clearly be seen in the lower part of Fig. 4: model IV results in much smaller jet rates than models I–III, and model V gives even smaller rates. In conclusion, we expect measurements of hadronic final states in γp interactions at HERA energies to significantly enhance the understanding of the hadronic structure of the photon.

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References

[1] T.H. Bauer et al., Rev. Mod. Phys. **50** (1978) 261.

[2] G.A. Schuler, Theoretical aspects of low-Q^2 physics at HERA. In W. Buchmüller and G. Ingelman, eds., Physics at HERA (DESY, Hamburg, 1991).

[3] A. Donnachie and P.V. Landshoff, Total cross sections, Preprint CERN-TH 6635/92, September 1992.

[4] P.D.B. Collins, An introduction to Regge theory and high energy physics (Cambridge University Press, 1977).

[5] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. **46** (1987) 43.

[6] T. Sjöstrand, PYTHIA 5.6 and JETSET 7.3: physics and manual, Preprint CERN-TH 6488/92, May 1992.

[7] T. Sjöstrand and M. van Zijl, Phys. Rev. D **36** (1987) 2019.

[8] A. Donnachie and P.V. Landshoff, Nucl. Phys. B **244** (1984) 322.

[9] NMC: P. Amaudruz et al., Proton and deuteron F_2 structure functions in deep inelastic muon scattering, Preprint CERN-PPE/92-124, July 1992.

[10] WA69: R.J. Apsimon et al., Z. Phys. C **53** (1992) 581.

[11] H. Plothow-Besch, PDFLIB: a library of all available parton density functions of the nucleon, the pion and the photon and the corresponding α_s calculations, Preprint CERN-PPE/92-123, July 1992.

[12] AMY Collaboration: R. Tanaka et al., Phys. Lett. B **277** (1992) 215.

Figure captions

Fig. 1: Contributions to hard γp interactions: a) VDM, b) direct, and c) anomalous.

Fig. 2: Photon–proton cross sections versus c.m. energy.

Fig. 3: Multiplicity distribution of γp interactions at 200 GeV c.m. energy. Upper figure: individual contributions: elastic plus diffractive (short-dashed), non-diffractive VDM (full), direct (dash-dotted), anomalous (long-dashed). Lower figure: total-multiplicity contribution in various models: I (full), II (long-dashed), III (short-dashed), IV (dotted), V (dash-dotted).

Fig. 4: Jet rapidity distribution in γp interactions at $\sqrt{s} = 200\,\text{GeV}$. A jet is required to have $E_T > 10\,\text{GeV}$ inside an (η, ϕ) cone of radius $R = 1$. Notation as in Fig. 3 (note that elastic and diffractive events do not contribute and are therefore absent in the top plot).

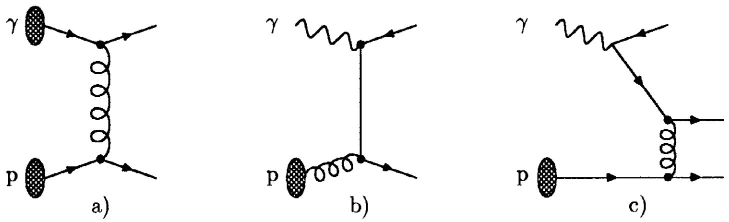

Figure 1

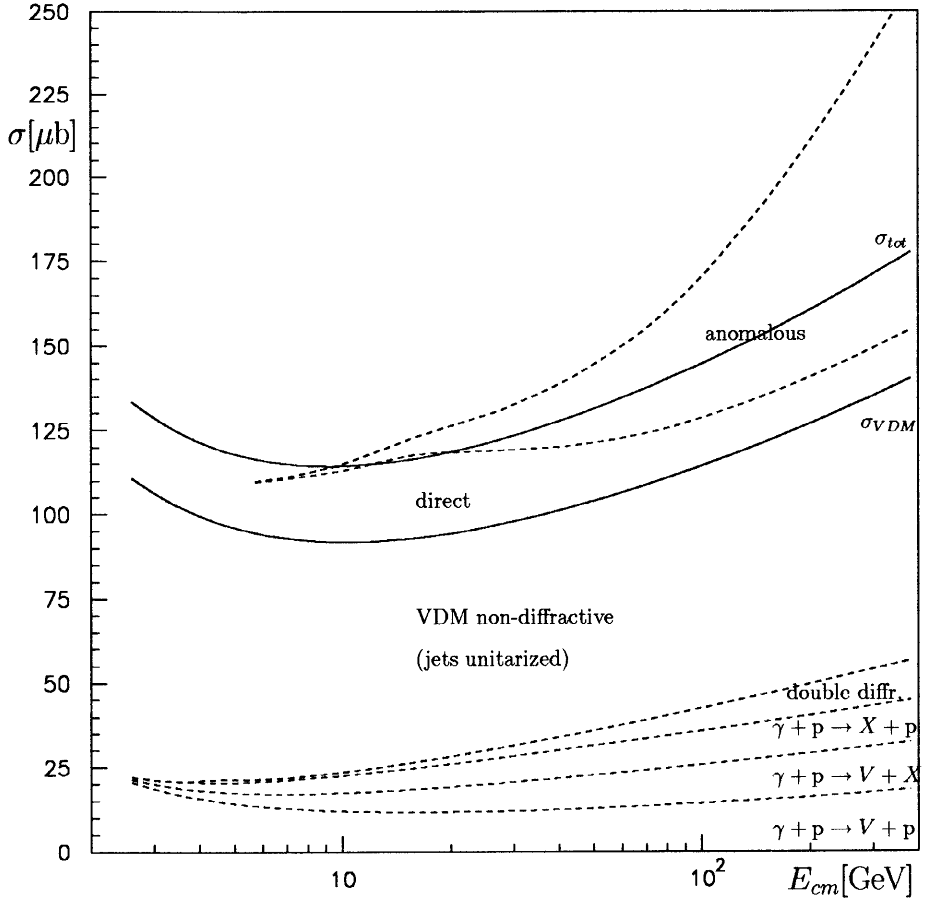

Figure 2

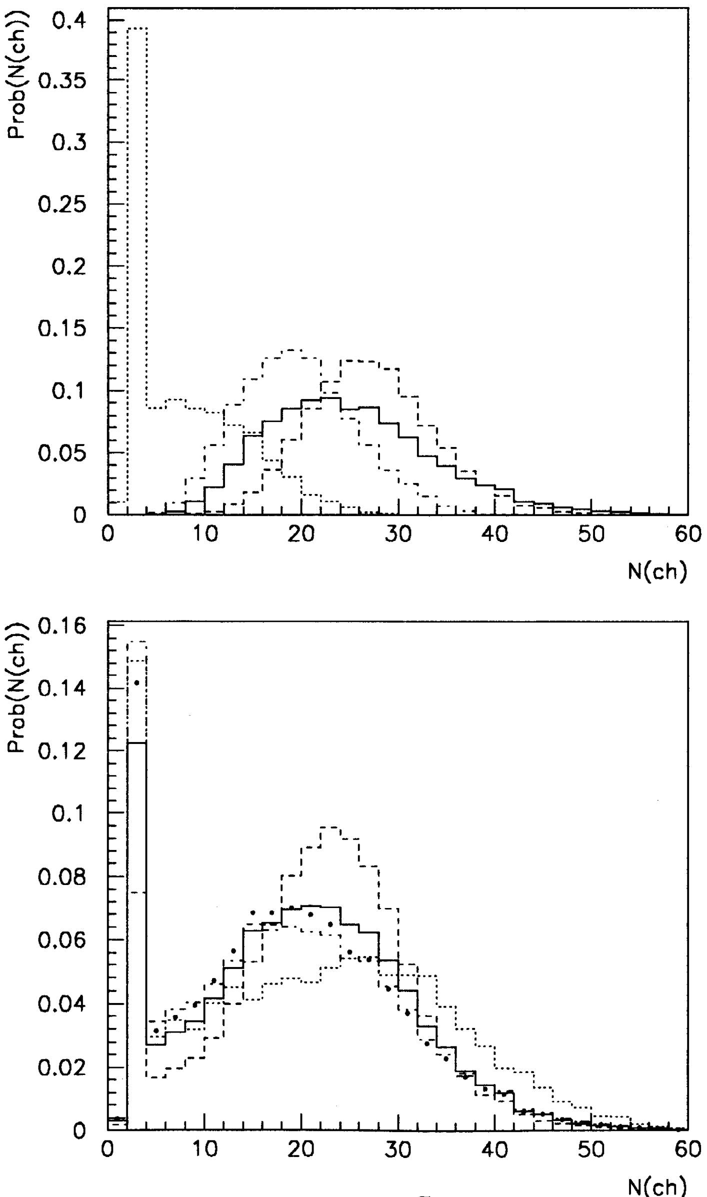

Figure 3

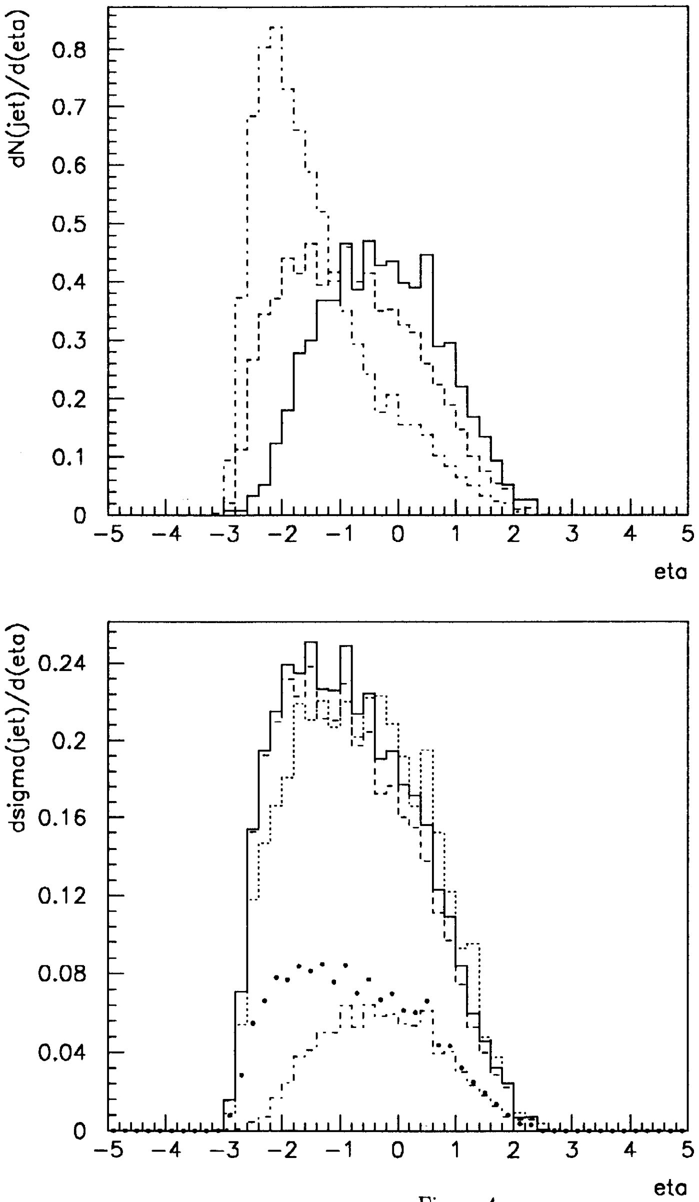

Figure 4