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Baryon Production in Lepton-Nucleon Scattering and Diquark Fragmentation

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Abstract :

We study baryon production in deep inelastic scattering using an extended version of the Lund jet model. There are two contributing sources. The first is baryon production in the target fragmentation. In a scheme related to our earlier work on low-p_t baryon fragmentation we present some details of the fragmentation of a diquark into baryons and mesons. A non-negligible baryon-antibaryon production is observed in e^+e^- annihilation. In a previous paper we developed a model for this production, and the same mechanism should also give fast baryons in leptoproduction. In this paper we discuss those features of baryon production which can be more easily studied in a leptoproduction experiment.

1. Introduction

In a previous publication [1] we studied particle production in deep inelastic lepton-nucleon scattering. Those calculations included gluon radiation and photon-gluon fusion in accordance with first order QCD. Baryon production was neglected, however, and the target fragmentation region was not studied. In the present paper we want to discuss these points. In particular we feel that studies of baryon production can give important information about the confinement mechanism.

In a normal leptoproduction event a quark is kicked out and a confining colour force field is stretched between the quark and a diquark, the target remnant. This diquark is expected to give rise to one final state baryon somewhere in the target fragmentation region. In section 2 we discuss a model for diquark fragmentation which is in accordance with our model for proton fragmentation in hadronic collisions in [2].

In e^+e^- annihilation a non-negligible baryon-antibaryon production is observed, and the same production mechanism ought to give extra baryons in the colour field of leptoproduction events. In [3] we propose a model for baryon-antibaryon production and study its implications for e^+e^- annihilation. This model is briefly sketched in section 3.

In case of a photon-gluon fusion reaction $\gamma_V g \rightarrow q\bar{q}$, or when a sea quark is kicked out by the photon, the target remnant is not just a diquark. The more complicated colour structure of these events is discussed in section 4, where we make the assumption that the interacting gluon can be associated to the colour field of one of the valence quarks. This discussion is also relevant e.g. for lepton pair production in hadronic collisions.

The Monte Carlo generation program of [4], which is based on the Lund fragmentation model, is modified to include these properties and some results are presented in section 5.

2. Diquark fragmentation

In [5] we notice a large similarity between proton fragmentation in the ordinary low-p_t hadronic collisions and in deep inelastic lepton scattering. It looks as if in both cases a colour force field is stretched by a diquark. We do not treat this diquark as such a tightly bound system that the two quarks always stick together and go into the same baryon. In [2] we propose a reaction mechanism for hadronic collisions in which a colour triplet field, a colour flux tube, is stretched as indicated in fig. 1. One quark (L) is at the end of the force field followed by a partner (J) in a diquark. If the L-quark is red there is a $\bar{r}r$ field between J and L. If the J-quark is green the diquark is antiblue and to the left of J we have a $b\bar{b}$ colour field.

Quark-antiquark pairs can be produced in the field, and we notice that the field changes direction at the J-quark so that a produced quark is always pulled towards (and an antiquark away from) the J-quark. Thus when the field is divided into pieces, hadrons, by the production of new $q\bar{q}$ pairs, that piece which contains the J-quark becomes a baryon.

The two quarks in the diquark stretch the colour flux tube in a stepwise manner. When it is stretched the fraction x_J of its full length the J-quark has lost its momentum and stops. The L-quark continues, with the fraction $1-x_J$ of the total initial momentum, and stretches the flux tube to its full length. The value of x_J is related to the wave function of the initial proton. In hadronic collisions there is also one more quark, called the I-quark, behind the leading two. We will here, due to lack of information, <u>assume</u> that the x_J distribution is the same in leptoproduction when there is no I-quark. Thus we use the distribution from [2] :

$$\frac{dP}{dx_J} = 6\, x_J\, (1 - x_J) \qquad (1)$$

With the Lund model recipe for dividing the force field into hadrons [6] this implies around 50% probability for a break between the L- and J-quarks. This means that we have about equal probability that the baryon takes one or both of the initial quarks; it always takes at least one.

We assume that when one quark is kicked out of the proton it loses its memory about whether it was more tightly bound to one or the other of the remaining two quarks. Thus for a ud-diquark we expect equal probabilities for the u- and the d-quark to be the L- (J-)quark. This is in contrast to the model for hadronic collisions [2], where the softer reaction mechanism is expected to preserve more information from the initial proton wave function.

An important point is the fact that a baryon is a symmetric state of three quarks. A basic assumption in the Lund hadronization model is that the probability for the colour field to break by the production of a quark-antiquark pair is determined by the density of final states. Therefore we assume that for baryons the probability to produce a certain flavour is weighted by the probability to form a symmetric state in the baryon 56-multiplet. One could imagine a suppression of the decuplet states, but this is not assumed here. For an ud-diquark we also assume the probabilities 3/4 and 1/4 for the states with spin and isospin S=I=0 and S=I=1 respectively, as given by the proton SU(6) wave function.

Together with the old assumptions in the Lund quark jet model [6] this fully determines the diquark fragmentation model. We note that the diquark is not treated as a structureless unit like in [7,8]. In similarity with the model in [9] the diquark has an interior structure, which in our model is described by the parameter x_J. Some characteristic results are shown in fig. 2.

3. Baryon-antibaryon production

Our model for baryon-antibaryon production is described in detail in [3]. Here we only sketch the main properties.

In a colour force field which is stretched between a colour

triplet and an antitriplet, as in $e^+e^- \rightarrow q\bar{q}$ or leptoproduction, the potential energy can be lowered by the production of new $q\bar{q}$ pairs which are pulled apart by the field. Quarks and antiquarks then combine to form the observed mesons in the jets. The longitudinal momentum of a produced hadron is determined by the time difference between two adjacent breakups of the force field. The rapidity difference , Δy, between two primary mesons which are adjacent in rank is of the order of one unit [6]. The distribution in Δy is, however, rather wide with exponential tails at large positive and negative Δy.

A pair of quarks with transverse momenta or heavier strange quarks can not classically be produced in one point and then be pulled apart. Instead the q and $\bar{q}$ have to be produced a certain distance apart so that the field energy between them can be transformed into the (transverse) mass. This can be treated as a tunneling phenomenon in which the virtual quark tunnels out to the classical production point [10,11]. The production probability is then given by

$$P \sim e^{-\frac{\pi}{\kappa}(m^2 + p_t^2)} \qquad (2)$$

where κ is the strength of the colour field (≃ 1 GeV/fm ≃ 0.2 GeV^2) and m and p_t are the mass and transverse momentum of the quark. This gives a Gaussian p_t distribution having a width around 0.3 GeV/c and a suppression of the strange quarks by about a factor 0.3, in good agreement with observations.

In our model for baryon production we have assumed that also a diquark-antidiquark pair (a colour antitriplet-triplet) can be produced in the field in a similar way. We do not expect such a diquark to correspond to a pointlike object, e.g. to be a single elementary excitation of a quantum field. For the small momentum transfers involved in the soft hadronization process, however, we feel that also an extended object will have an effective coupling to the colour field in the flux tube. Thus we assume that the diquark can be treated as one unit in this case and that the production of diquarks and quarks are determined by the same tunneling formula, eq. (2). The experimentaly observed baryon production in e^+e^- annihilation is obtained if a diquark has a mass around 450 MeV and the probability P(qq) in each break of the field to produce a diquark is given by

$$\frac{P(qq)}{P(q)} = 0.065\ (\pm 25\%) \qquad (3)$$

Thus in this model baryons are produced evenly over the whole rapidity range and we note that this is in agreement with the observed energy variation between 4 and 30 GeV.

Just as for the diquark fragmentation in section 2 we assume that the production of a certain diquark is proportional to the probability to form a completely symmetric three quark state. With these assumptions also the observed Λ:p production ratio is reproduced.

The most important question is to determine whether a diquark really does tunnel out as one unit. If it does, this fact ought to tell us something about the confinement mechanism. An essential consequence is the result that the baryon and the antibaryon are usually produced close in rapidity, with the baryon closer to the colour triplet end of the field. This can be more easily tested in leptoproduction than in e^+e^- annihilation because in the latter case the direction of the colour field is not known. This property is also obtained in any model with short range correlations like multiperipheral or Regge models or in models of iterative cascade type like in [7]. However, we feel that the most crucial test is related to the predicted suppression of strange diquarks. A consequence of the m^2 in the exponent in the tunneling formula in eq. (2) is that strange diquarks are more suppressed relative to nonstrange diquarks than strange quarks relative to nonstrange quarks. This effect is not expected if the diquark is produced in a stepwise manner as suggested in [11], in which case also a large rapidity difference between baryon and antibaryon could be obtained.

4. Colour field structure

To first order in QCD we have in addition to the ordinary events with one forward jet also events with two forward jets

(in the lab frame), which correspond to the reactions $\gamma_V q \to gq$ (or $\gamma_V \bar{q} \to g\bar{q}$) and $\gamma_V g \to q\bar{q}$. In our earlier treatment of deep inelastic lepton scattering [1], when we did not study the particles in the target fragmentation region, we could approximate the diquark by an antiquark, and in the case $\gamma_V g \to q\bar{q}$, when the target remnant is a colour octet, it was approximated by a gluon.

In the Lund model a gluon is treated like a kink or a transverse excitation on the force field. Thus for the case $\gamma_V q \to gq$ the colour field is stretched from the quark via the gluon to the diquark (colour antitriplet). This diquark is treated just as discussed in section 2 (see fig. 3a).

For $\gamma_V g \to q\bar{q}$ the colour configuration is more complicated. One quark and one antiquark, which together form a colour octet, go forward whereas the target remnant contains three quarks, also in a colour octet state. The colour field lines can here be stretched in various ways. Because these events are only a rather small fraction of all the events, we think that it would be hard to experimentally distinguish different alternatives. We therefore make the following assumptions, which we feel are reasonable, and which could be modified when more experimental information is available.

We assume that the interacting gluon can be associated to the colour field of one of the valence quarks of the target nucleon. If this quark was originally red, it could radiate off a red-antiblue gluon and turn blue, fig. 3b. The produced antiquark takes the antiblue colour from the gluon and can form a colour singlet together with the original valence quark. The other two valence quarks are green and blue, making an antired diquark, which forms a colour singlet with the produced quark (see fig. 3b). These two colour singlets are treated just like an ordinary $e^+e^- \to q\bar{q}$ event and a leptoproduction event, respectively, but to do this we have to determine how the energy of the proton remnant, when the gluon is removed, is shared between the quark and the diquark. If the quark takes the fraction $\hat{x}$ of the light cone variable $E+p_L$ in the target fragmentation direction (left in fig. 3c) and the diquark the fraction $1-\hat{x}$ we assume

$$\frac{dP}{d\hat{x}} = 2\,(1 - \hat{x}) \qquad (4)$$

which implies that all three valence quarks on the average take one third of the available energy-momentum. The momenta of the produced quark and antiquark (moving to the right in fig. 3c) are determined by the QCD matrix element for the reaction $\gamma_V g \to q\bar{q}$.

In the case when the photon hits a sea quark (antiquark) this must have a partner antiquark (quark) in the proton remnant. The partner to a u or a d sea quark could be assumed to annihilate with one of the valence quarks, but for a struck antiquark or strange quark this is not possible. If we also here associate the sea quark-antiquark pair with a virtual gluon from the colour field of one of the valence quarks, we obtain exactly the same colour structure as in the case above (fig. 3b). The only difference is that the partner sea (anti-) quark is expected to be wee and thus the mass of one of the colour singlets in fig. 3c is small. We assume that this system forms only one single hadron (possibly a resonance) whose momentum is determined by the parameter $\hat{x}$ (if it is a meson) or $1-\hat{x}$ (if it is a baryon).

We note that very similar colour arrangements are obtained in lepton pair production from the crossed reactions $qg \to q\gamma_V$ and $q\bar{q}_s \to \gamma_V$.

5. Results

In this section we present some results which correspond to scattering of 280 GeV/c muons against protons and applying the following convenient cuts: $Q^2 > 5\ (\mathrm{GeV/c})^2$, $W^2 > 40\ \mathrm{GeV}^2$ and $20 < \nu < 260$ GeV.

5.1. p, $\bar{p}$ production

The production of protons and antiprotons is shown in fig. 4.

If a quark is kicked out an antiproton can only be produced as a second rank particle which gives the softer spectrum. We notice that if a diquark can tunnel out as one unit, these spectra are harder than expected from counting rules, counting the number of spectator quarks [7,12].

The energy variation is shown in fig. 5, which also exposes the separate contributions from target fragmentation and baryon-antibaryon pair production. We notice that when W increases the target contribution shrinks to lower values of z and that the pair production increases in such a way that the total spectrum shows somewhat less energy dependence than the separate contributions.

5.2. Λ, $\bar{\Lambda}$ production

As mentioned above an important test of the tunneling hypothesis is to check the prediction that strange diquarks are strongly suppressed. This implies that it is difficult to produce a Λ particle from a u-quark and a ds-diquark. Thus, if the photon kicks out a u-quark, it is difficult to make a Λ as a first rank particle; we have to make the $s\bar{s}$ pair first. Therefore both the Λ and $\bar{\Lambda}$ spectra are similar in shape to the $\bar{p}$ spectrum and approximately $(1-z)^2$. (Of course they differ in the target fragmentation region where the Λ spectrum is much larger.) The spectra obtained are shown in fig. 4.

We also notice that the suppression of strange diquarks implies that a Λ is usually not produced together with a $\bar{\Lambda}$ but more often together with a K and a $\bar{p}$ or $\bar{n}$. The ratio of these two cases is about 1:3 but would be about 2:3 if strange diquarks were no more suppressed than strange quarks. This ratio does not depend much on the amount of resonance production. The production of particles with more than one strange quark, e.g. Ξ is very low, as seen in table 1.

5.3. Rapidity difference in baryon pairs

As discussed in section 3 the baryon and the antibaryon that are produced together in the colour field are usually close in rapidity. Also, the baryon is expected to be closer to the colour triplet (quark) end of the field. At high cms energies the mean value of the rapidity difference, $\Delta y = y_B - y_{\bar{B}}$, in such $B\bar{B}$ pairs is about 0.4. This is smaller than 1 which is the result in the 1-dimensional massless model [6] or the massless Schwinger model [17], mainly due to the effects of finite field lengths and collinear gluon emission [6]. These effects are somewhat larger for baryons than mesons due to the larger masses involved. The distribution in Δy is, as expected, rather wide and has a standard deviation of 1.6. In just over 60% of the pairs the baryon has a larger rapidity. The fact that the baryon is closer in rapidity to the leading quark is, of course, a quite general expectation for fast baryons. In our model, however, this effect can also be observed for centrally produced $B\bar{B}$ pairs. For example, for pairs where both the baryon and the antibaryon has $|x_F| < 0.2$ the baryon is still leading in 60% of the cases.

At low cms energies the mean rapidity difference is somewhat smaller due to mass effects, $\langle \Delta y \rangle = 0.3$ at $W = 7$ GeV. If, in leptoproduction, the baryon from the target remnant is also observed and included when Δy of $B\bar{B}$ pairs is studied the results above are upset. This baryon must hence be excluded by some kind of cuts against baryons in the target fragmentation region. Another complication is that the leading parton can also be an antiquark either from the sea or produced via the photon-gluon fusion mechanism. In these events the rapidity difference will, in general, have the opposite sign giving a not so clear result for a total event sample. However, since the sea contribution dominates at small x_B, events having small and large x_B, respectively, will give different results in this respect. As an example, for a total sample of 280 GeV μp events we find $\langle \Delta y \rangle = 0.27$. For those events having $x_B < 0.1$ this value is 0.25 whereas if $x_B > 0.1$ then $\langle \Delta y \rangle = 0.31$. Here we have avoided the target baryon simply by excluding the baryon with smallest rapidity. In order to make a close comparison with experimental data we suggest the use of the Monte Carlo program to simulate events and apply the same cuts and analysis as on the real events.

5.4. p_t-distributions

Because a diquark is assumed to tunnel out in the same way as a quark according to eq. (2), we expect the same p_t-distribution for all primary hadrons, mesons and baryons, in a jet. However different contributions from resonance decays, and also different fragmentation of gluons and quarks (cf. [3]) imply different p_t spectra for the observable stable particles. In fig. 6 we show p_t distributions for protons and pions. To remove the target contribution only particles with $p_{lab} > 5$ GeV/c are included. A limited experimental momentum range for proton identification may, however, change this spectrum.

Because the diquark and the antidiquark of a pair have compensating p_t we also get a correlation between the p_t of a baryon and an antibaryon. For a proton and an antiproton we find that the distribution in relative azimuthal angle is approximately described by

$$\frac{dN}{d\phi} \sim 3 - \cos\phi \qquad (5)$$

Because a Λ is usually produced together with a kaon, the distribution in the relative azimuthal angle between a Λ and a K^+ is also well described by the expression in eq. (5).

5.5. Polarization

In [13] we propose a model for the polarization of inclusively produced Λ particles in pp collisions. It is based on a correlation between spins and p_t for a $s\bar{s}$ quark pair produced in the colour field. Because a fast Λ is usually produced from a ud-diquark with spin 0 and a s-quark we can use the same arguments here. Thus, if the photon kicks out a quark we expect the Λ to have positive polarization along the direction $\bar{q} \times \bar{p}_\Lambda$ ($\bar{q}$ is the photon momentum) (cf [13]). Notice that fast Λ's are thus polarized in the same direction as Λ's in the proton fragmentation region (negative along the direction $(-\bar{q}) \times \bar{p}_\Lambda$). $\bar{\Lambda}$ particles should be polarized in the opposite direction.

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Table 1

The number of baryons per event is given in total, contribution from the target fragmentation and for fast baryons only ($z > 0.15$). The number of antibaryons per event is also shown.

	p	n	Λ	Σ	Ξ
total	0.71	0.46	0.11	0.034	0.005
target fragm.	0.61	0.39	0.094	0.028	0.005
$z > 0.15$	0.063	0.043	0.013	0.0064	0.0009

	$\bar{p}$	$\bar{n}$	$\bar{\Lambda}$	$\bar{\Sigma}$	$\bar{\Xi}$
total	0.091	0.079	0.019	0.0098	0.0012

Figure Captions

Fig. 1. The colour field (or colour flux tube) stretched by a diquark. One quark (L) is at the end of the field followed by a partner (J). If L is red and J green the field is antired-red between L and J and behind J it is blue-antiblue. In the fields new quark-antiquark pairs can be produced.

Fig. 2a. Pion production in diquark jets. The experimental data on $ud \to \pi^+, \pi^-$ come from the reaction $\bar{\nu} p \to \pi X$ in [14]. Note that $z \to 1$ corresponds to the target fragmentation region in this case.

Fig. 2b. Nucleon production in diquark jets. Baryon-antibaryon production in the field is not included.

Fig. 2c. Λ production in diquark jets. The data come from the

DECO experiment on ep scattering [15], which roughly corresponds to a ud-diquark jet. However the experimental data correspond to a rather low energy (and the Feynman-x variable is used) whereas the theoretical curves are for infinite energy, and no production in the field.

Fig. 3a. The colour field resulting from the process $\gamma_v q \to gq$ is stretched from the quark via the gluon to the diquark in the target remnant.

Fig. 3b. The photon-gluon fusion process with the assumed colour structure.

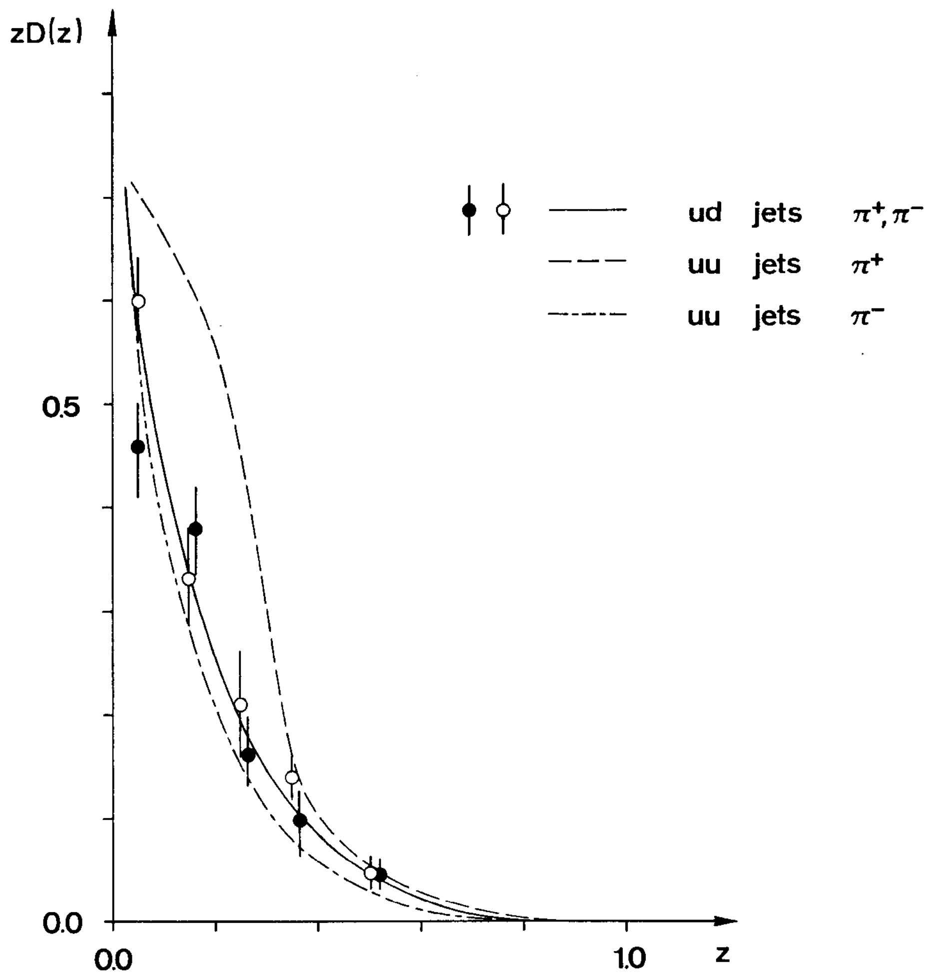
Fig. 3c. From the process $\gamma_v g \to q\bar{q}$ two colour singlets are obtained.

Fig. 4. Production of p, $\bar{p}$, Λ and $\bar{\Lambda}$ vs. $z=E_h/\nu$. The data points are results for p and $\bar{p}$ at 120 and 280 GeV from the EMC collaboration [16]. The agreement with data is somewhat improved (in particular at small z) if the experimental momentum range for proton identification is taken into account.

Fig. 5. Proton production at low W (a) and large W (b). The dotted line corresponds to the target fragmentation and the dashed line to baryon-antibaryon pair production.

Fig. 6. p_t^2 distributions for p and π^+. To remove the contribution from the target fragmentation only particles with $p_{lab} > 5$ GeV/c are included.

Fig. 1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uu jets π^-

Fig. 2a

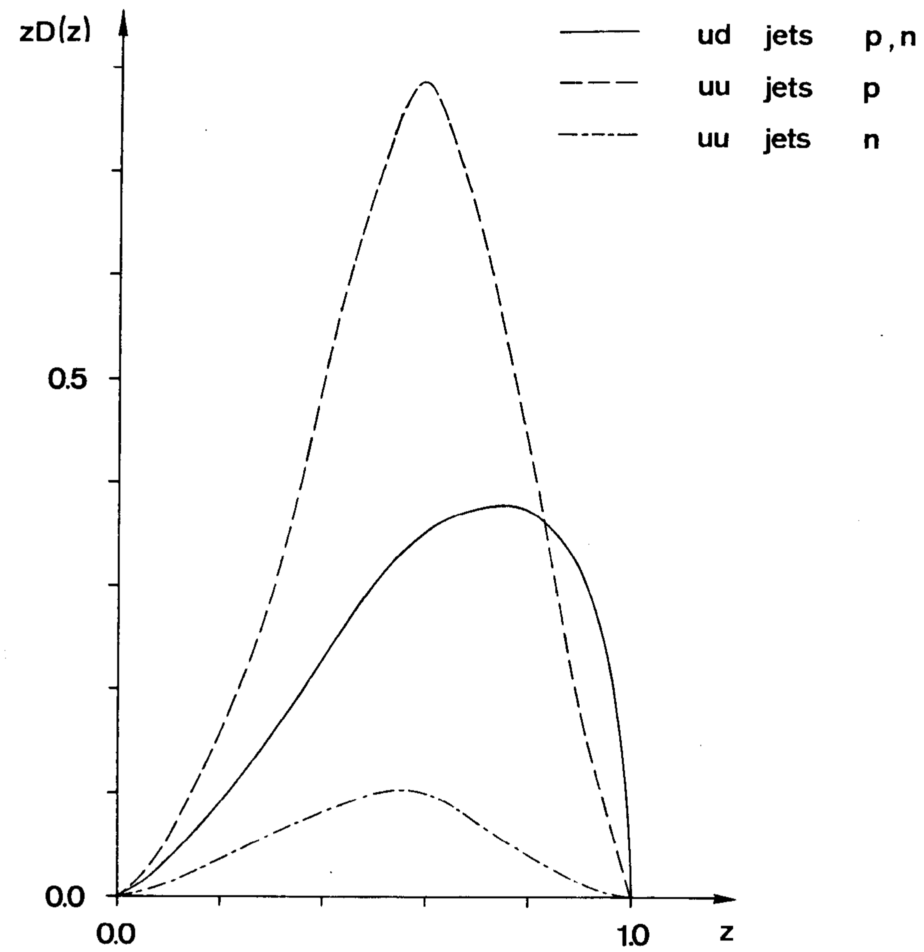
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Fig. 2b

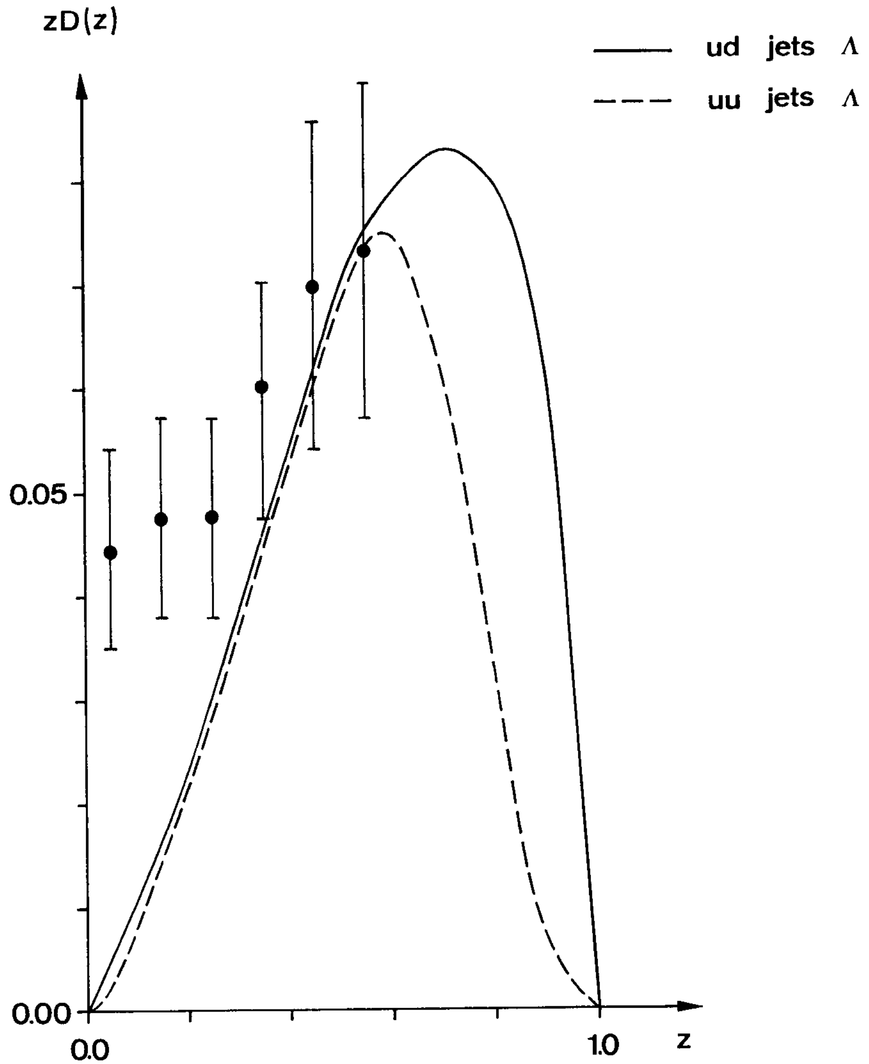


Fig. 2c

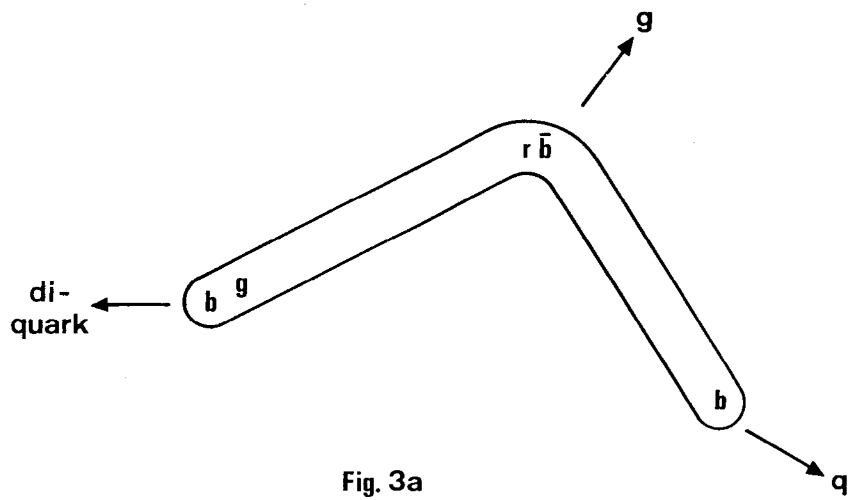


Fig. 3a

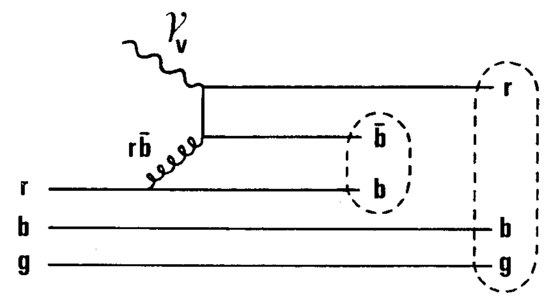


Fig. 3b

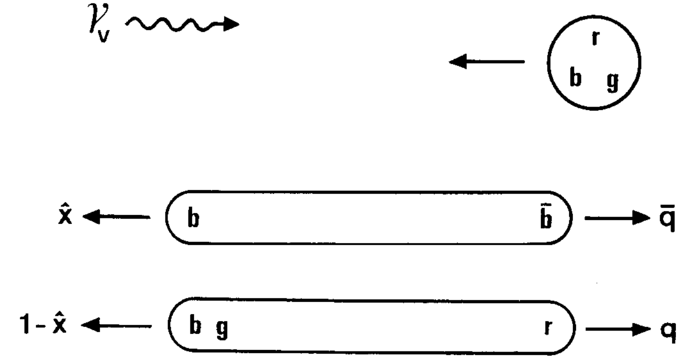
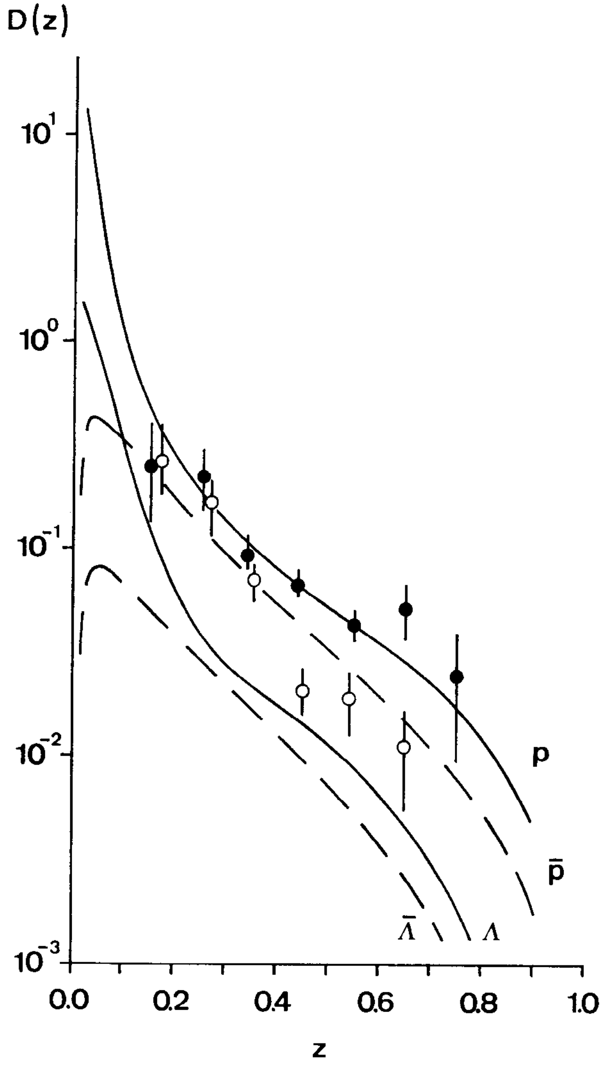


Fig. 3c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10^0
10^-1
10^-2
10^-3
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0.4
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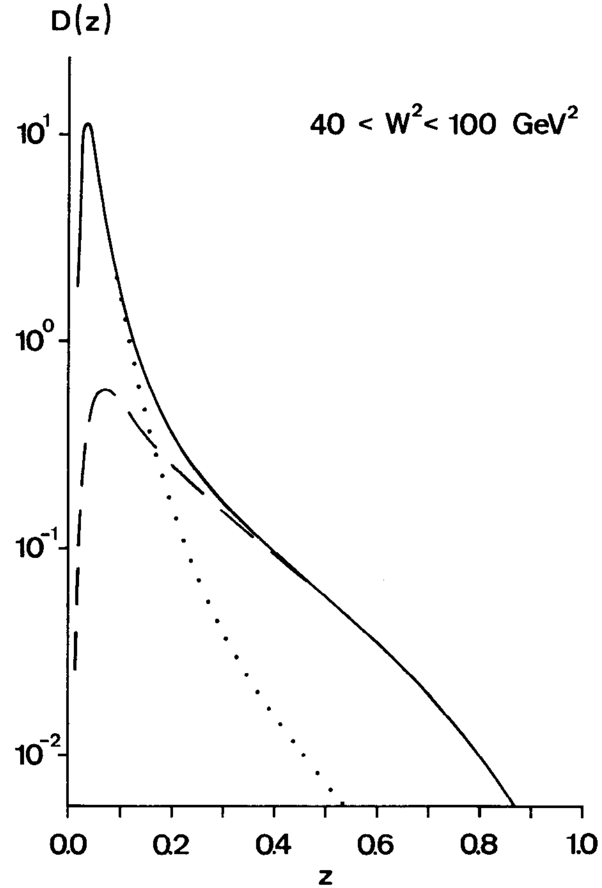
z
p
p̄
Λ̄
Λ

Fig. 4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10^0
10^-1
10^-2
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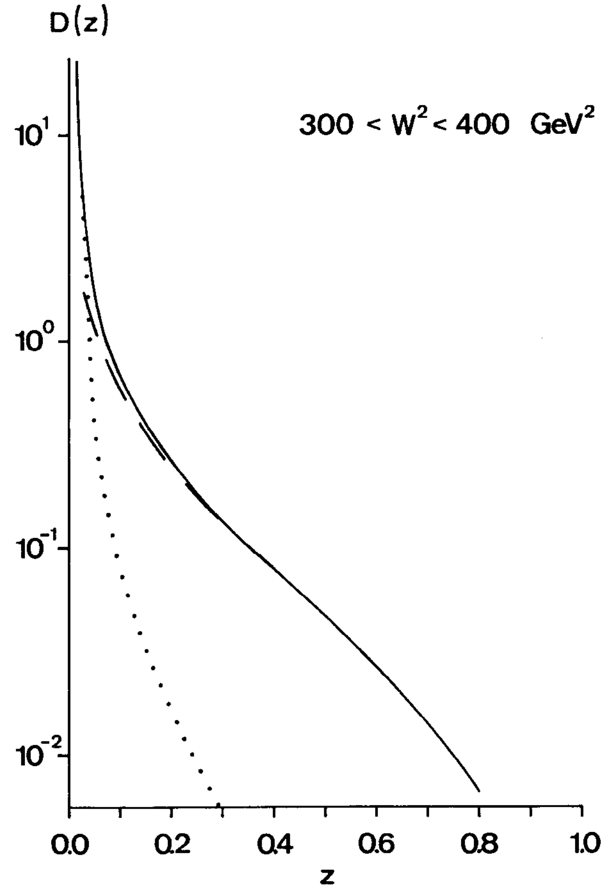
0.2
0.4
0.6
0.8
1.0
z

Fig. 5a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10⁻²
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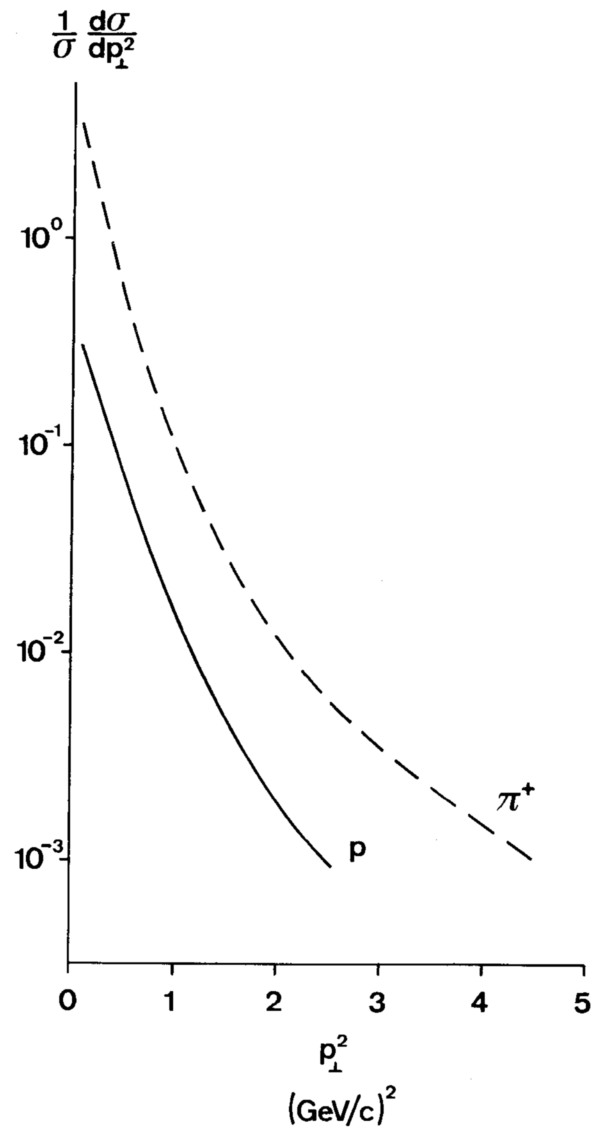
0.6
0.8
1.0
z

Fig. 5b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10⁻¹
10⁻²
10⁻³
π^+
p
0
1
2
3
4
5
$p_\perp^2$
$(GeV/c)^2$

Fig. 6