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A Model for Baryon Production in Quark and Gluon Jets

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Abstract :

Experiments at e^+e^- storage rings show a non-negligible production of baryons, although a detailed structure, in particular the correlation between a baryon and an antibaryon, has not been clarified. We formulate here a simple model for baryon-antibaryon production which is in good agreement with present e^+e^- inclusiva data. We also present a set of predictions of the model that can be tested when more experimental data is available. One interesting property of the model is that the leading particle is more often a baryon or antibaryon in a gluon jet than in a quark jet.

In this note we present a simple model for baryon production in e^+e^- annihilation events. Our basic assumption is that a diquark-antidiquark pair (a colour antitriplet-triplet) can be produced in a colour force field in a way similar to the production of a quark-antiquark pair. The diquark colour antitriplet is treated as one unit and the suppression of baryon-antibaryon production, as compared to the meson production, is determined by the larger diquark mass compared to the quark mass. It is a "minimal" model in the sense that while it takes due account of the symmetry of the baryonic quark states and other kinematical constraints, it has a minimum of new dynamical assumptions.

Our starting point is the Lund model for jet fragmentation [1-3]. In an $e^+e^- \to q\bar{q}$ event a linear colour force field is stretched between the quark and the antiquark. In this field new quark-antiquark pairs can be produced which combine to the final state hadrons. In [1] it is shown that a relativistically invariant and causal treatment of this process gives an iterative structure which is easily implemented in a Monte Carlo generation process [4]. There is a strict ordering of the particles (called rank) such that the mean distance between neighbours in rank (which contain a quark and an antiquark from the same $q\bar{q}$-pair) is of the order of une unit in rapidity.

Massless quarks with no transverse momentum can be produced at one point and pulled apart by the colour field. However, if the quarks have mass and/or transverse momentum they must classically be produced at a certain distance so that the field energy between them can be transformed into the transverse mass $m_t = (m^2 + p_t^2)^{1/2}$. This can be treated as a tunneling phenomenon and the production probability will be proportional to [5-7]

$$\exp(-\tfrac{\pi}{\kappa} m_t^2) = \exp(-\tfrac{\pi}{\kappa} p_t^2) \exp(-\tfrac{\pi}{\kappa} m^2) \qquad (1)$$

where $\kappa \approx 1$ GeV/fm ≈ 0.2 GeV^2 is the energy per unit length in the field. The comparison with QED [5] is motivated if we regard the interior of a colour flux tube between the colour charges as a longitudinal chromoelectric field superimposed on the perturbative vacuum. Equation (1) gives a Gaussian

distribution in p_t and a suppression of the heavier strange quarks

$$u : d : s \approx 1 : 1 : 0.3 \qquad (2)$$

Note that charm quarks are suppressed by a very large factor ($\approx 10^{-11}$) which means that charm and heavier quarks can <u>not</u> be produced in such a soft (long time scale) process. A basic assumption behind the result (1) is that the colour force field has no transverse excitations (cf. [8]) which among other things implies that the quark and the antiquark of a produced pair have equally large and opposite transverse momenta.

We will now assume that a pair of virtual quarks, in a colour antitriplet state, can tunnel out the same way as an antiquark. Thus we assume that the production of a diquark and an antidiquark is determined by the same expression as for a quark-antiquark pair (eq.(1)). We do not expect such a diquark, although equipped with certain quantum numbers like spin, isospin, etc., 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 (constant) chromoelectric field in the colour tube. Further we expect the density of virtual quarks along the field to be high enough so that the probability to find a partner quark in a colour antitriplet diquark state is effectively one.

This assumption is consistent with the observed baryon production rate (see below) and also gives the following observable properties, testable in future experiments:

1. A common Gaussian p_t spectrum is obtained for all primary mesons and baryons. It should be remembered, however, that further p_t contributions come from hard and soft gluons [9] and that decays of resonances modify the spectra differently for baryons and mesons.

2. A baryon and an antibaryon will be neighbours in rank and thus close in rapidity.

3. Equation (1) implies that for $m > \sqrt{\kappa/\pi} \approx 250$ MeV a small increase in m will give a large change in the probability. Thus strange diquarks will be much suppressed compared to nonstrange diquarks. This implies that e.g. a Λ is more often produced together with a K and an $\bar{N}$ than together with a $\bar{\Lambda}$. It also implies that production of Ξ and Ω is strongly suppressed.

All these properties would be modified if the diquarks were produced in a stepwise manner with one quark produced first and the other later (cf. [7]). In such a picture more dynamical assumptions are needed. Our attitude is to compare the available data to the prediction of a simple model in order to find out if there are experimental features which indicate the need for new dynamics.

In order to make use of eq. (1) we are limited by the uncertainty in the diquark masses. It is not quite clear whether current masses or constituent masses should be used. This is more serious for diquarks because the uncertainty in the probability is larger for larger masses. For this reason we used expected diquark masses to fix the relative probability between the different diquarks but fit the overall ratio between diquark-antidiquark and quark-antiquark production to experimental results.

Using data for $R(p+\bar{p})$ from SPEAR Mark II [10] in the 4 GeV energy region we find for the overall diquark to quark ratio (summing over all spin and flavour states):

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

This corresponds to (nonstrange) diquark masses around 450 MeV which is clearly very reasonable, showing that the scheme is consistent. To fix the relative diquark probabilities we make the following assumptions about the masses.

$$\begin{array}{ll} m(ud_0) = 420 \text{ MeV} & m(uu_1) = m(ud_1) = 490 \text{ MeV} \\ m(us_0) = 590 \text{ MeV} & \qquad\qquad m(us_1) = 640 \text{ MeV} \\ & \qquad\qquad m(ss_1) = 790 \text{ MeV} \end{array} \qquad (4)$$

This gives the following relative probabilities

$$\begin{array}{l} P(ud_0) : P(ud_1) : P(uu_1) : P(us_0) : P(us_1) : P(ss_1) \\ = \quad 1 \quad : \ 0.35 \ : \ 0.35 \ : \ 0.06 \ : \ 0.02 \ : \ 0.001 \end{array} \qquad (5)$$

Note however that the spin 1 diquarks will get an extra factor of 3 from counting the different spin states.

As stated before, the numbers in eq. (4) are very uncertain. A ud_0-diquark (which has S=I=0) is expected to have a smaller mass than a uu- or ud_1-diquark (both with S=I=1). This difference, coming from chromomagnetic spin-spin interactions, is related to the Λ-Σ mass difference, but to extract it the quotient of strange to nonstrange quark masses has to be known. The figures above represent the use of current algebra masses, whereas constituent masses would lead to a ud_1-ud_0 mass difference around 200 MeV. This corresponds to a spin 1 to spin 0 diquark suppression factor of 0.05 rather than 0.35. Most of the results presented below, in particular the spectra and total amounts of p , n and Λ are not sensitive to such variations of the mass parameters. The increase in direct Λ production is e.g. compensated by a decrease in production via Σ^0 and Σ^*. Decuplet production is reduced, for Δ:s by a factor 2.5. Again this is less than what naively could be expected, but enough to make a determination from data meaningful in the future. Similarly the strange to nonstrange diquark mass difference is only determined to within some tens of MeV, but with the resulting physics predictions stable to within 10 percent.

A very important point to discuss before making any calculations is the fact that a baryon is a symmetric system of three quarks. A basic property of the Lund jet model is the assumption that the production of a certain qq pair is determined by the density of available final states. When a diquark joins a quark to form a baryon, we therefore weight the different flavour and spin states by the probability that they form a symmetric 3-quark system. This implies that all states in the 56-multiplet become equally probable. The relative probability for a diquark and a quark to join into a baryon is shown in table 1.

One could imagine a suppression of the decuplet relative to the octet states (as the vector mesons seem to be suppressed relative to the pseudoscalars) in addition to the one implied by diquark mass differences. This can easily be introduced in the Monte Carlo program but will not be important for the results presented here.

Everything is now determined for the modifications of the Monte Carlo program in [4]. The results for the p and Λ production in the SPEAR energy region are shown in fig. 1, and we note that both the energy variations and the Λ/p ratio are well reproduced by the model.

The data at 4 GeV were used to fix the ratio P(qq)/P(q) in eq. (3). However, we note that in addition to errors due to limited statistics and the fit itself, systematic uncertainties of ±17% for $p+\bar{p}$ and ±27% for $\Lambda+\bar{\Lambda}$ as well as some uncertainty in the charmed baryon decays and the R values to be used close to the charm threshold means that P(qq)/P(q) may have an error of up to ± 25%. Some caution should also be exercised when applying a jet fragmentation scheme to low energy data close to thresholds.

In fig. 2 we show the proton spectrum at 12 and 30 GeV compared with experimental data from the TASSO collaboration [11]. We conclude that our model well reproduces the proton production in the whole region between 4 and 30 GeV‡. This is achieved by an even production in the whole rapidity plateau. The model also reproduces the increase in the p/π ratio with x. For a u-quark jet the $p+\bar{p}$ fraction of charged particles is 6% for small x and 11-12% for $x>0.4$. This is partly a kinematic effect due to the larger p mass and partly due to resonance decays.

When looking at the data in fig. 1 without a detailed model one may get the impression that the strong increase at the charm threshold indicates a larger probability for the charm quark to produce baryons. One may e.g. imagine that a heavy quark is better localized in coordinate space, giving a stronger colour field close to it and thereby a larger probability to produce diquarks. We have made a calculation assuming a larger probability for diquark production corresponding to an increase

in κ by a factor of 2 close to a charm quark. This gives the dashed lines in fig. 1 which clearly disagrees with the data. Thus experiments indicate an even baryon production in the whole rapidity range. This property could be further tested by studying the proton content in events with a muon trigger, this being a signal for charm or bottom quarks.

We now turn to some predictions from the model which can be tested in future experiments. Although any kind of particle spectrum and correlation can be calculated, this must necessarily be a limited sample and we leave other properties to the interested user of the Lund Monte Carlo program [4].

I. Single particle multiplicities. We exhibit a few examples in table 2.

II. Transverse momentum spectrum. As noted before, baryons do not have a significantly higher mean p_t than mesons. For two-jet events at 30 GeV the $\langle p_t^2 \rangle$ with respect to the sphericity axis is 0.15 $(\mathrm{GeV}/c)^2$ for pions, 0.22 for kaons and 0.23 for protons. Also including three-jet events changes this to 0.21 , 0.32 and 0.35, respectively. The introduction of baryon production does not significantly change the topological properties of the e^+e^- events. As an example, when baryon production is introduced, without any other change of parameters, the sphericity for charged particles decreases from 0.113 to 0.111 at the same time as the charged multiplicity decreases from 13.1 to 12.8.

III. Baryon-antibaryon correlations. Because a baryon and an antibaryon are neighbours in rank they are usually close in momentum space. Due to kinematic effects the rapidity difference will be even somewhat smaller than for two mesons which are neighbours in rank. Thus in a quark jet a $\bar{p}$ is on the average 0.5 units in rapidity behind the associated p. However the distribution in $y_p-y_{\bar{p}}$ is rather wide and also contains negative values. In e^+e^- events the directions of the quark and antiquark jets are not known and the relevant measure is not $y_p-y_{\bar{p}}$ but $|y_p-y_{\bar{p}}|$ which has a larger mean value.

Using the sphericity axis to define rapidity in two-jet events at 30 GeV, this mean rapidity difference between a p and a $\bar{p}$ from the same pair is 1.35. Further, whereas 31% of the events at 30 GeV contain one baryon-antibaryon pair, 5.5% contain more than one pair. This means that out of an average of 0.18 $p\bar{p}$ combinations per event, a full 25% are with p from one pair and $\bar{p}$ from another, increasing the mean distance to 1.40 rapidity units. Finally, three-jet events also have to be taken into account, giving the value 1.26.

A basic assumption in all our considerations up to now has been that the colour force field is in its groundstate with respect to transverse fluctuations. Then the diquark and the antidiquark are given opposite transverse momenta in accordance with eq. (1), and this will then imply a corresponding (anti-) correlation between the produced baryon-antibaryon pair. In the three cases discussed above we obtain for a $p\bar{p}$-pair $\langle\vec{p}_{tp}\cdot\vec{p}_{t\bar{p}}\rangle/\langle\vec{p}_t^{\,2}\rangle = -0.32 \pm 0.79$, -0.30 ± 0.81 and -0.14 ± 0.92, respectively, where the second number is the width of the distribution.

We expect deviations from this "flat-field"-approximation from gluon emission. In [9] we have shown how to incorporate soft gluon emission into the model and computed the corresponding extra p_t contributions for the final state hadrons. This source will give a positive contribution to the transverse momentum correlation. Hence if part of what is normally called fragmentation p_t is actually due to gluon emission, the figures above will be changed, making $p\bar{p}$-pairs an important tool for the study of such gluon effects [9].

We have also studied the distribution of $\cos\theta_{p\bar{p}}$, $\theta_{p\bar{p}}$ being the relative angle between a p and a $\bar{p}$, with some lower momentum cutoff e.g. at 1 GeV/c. Two peaks are then obtained, one close to $\theta_{p\bar{p}} = 0^\circ$, very roughly corresponding to p and $\bar{p}$ from the same pair, and a smaller one around $\theta_{p\bar{p}} = 180^\circ$, essentially for p and $\bar{p}$ from different pairs. More precisely, 25% of the pairs are in the hemisphere $\theta_{p\bar{p}} > 90^\circ$ giving $\langle\cos\theta_{p\bar{p}}\rangle = 0.45$.

IV. Gluon jets. In the Lund model the emission of a hard gluon is treated as an energy and momentum carrying excitation of the force field between a quark and an antiquark. Thus in an $e^+e^- \to q\bar{q}g$ event the colour force field is stretched from the quark to the antiquark via the gluon (the associated nontrivial angular asymmetries have been observed by the JADE-collaboration at PETRA [12]). In such a gluon model the first rank hadron of a gluon jet will be a baryon with the same probability as anywhere else inside the colour field. In a quark jet, however, the first rank hadron always contains the original quark. Therefore first rank hadrons in quark jets will be baryons roughly half as often as in the cases of other hadrons or first rank hadrons in gluon jets. Hence, whereas the probability to have a p or a $\bar{p}$ as fastest charged particle varies between 8% (u) and 6.5% (d) for quark jets, it is 10% for gluon jets.

This means that we do expect a higher baryon fraction on "onia" resonances (J/Ψ, Υ, $t\bar{t}$?) than off them, but that the difference should become less pronounced at higher energies. If a lower momentum cutoff is made in experimental data, one also has to take into account that this corresponds to a cut at a somewhat higher fractional jet energy in case the total energy is shared between three jets (ggg) rather than between two ($q\bar{q}$) so that a further enhancement of the baryon fraction is expected. Due to the difficulties of constructing a proper three gluon jet Monte Carlo at the low energies involved, the translation of these deliberations into numbers is somewhat uncertain. Making a momentum cut at 1 GeV, the fraction of $p+\bar{p}$ among charged particles may be expected to rise from 6% off resonance to 8% on Υ. Lowering the cutoff gives smaller numbers but about the same proportions at least down to 400 MeV. If the indications from the DASP II collaboration [13] of a considerably larger difference (about a factor 5 between on and off resonance) should be substantiated it would then indicate the need for new physical mechanisms of baryon production in gluon jets [##].

V. Leptoproduction. So far, we have dealt exclusively with e^+e^--events, but the soft fragmentation scheme we use is directly applicable also to other hard processes, e.g. leptoproduction and Drell-Yan events. In these cases we have a proton or neutron target, giving an extra baryon in the target jet, which then has to be taken into account by itself in a somewhat different manner from the scheme presented here [14]. For reasonably fast particles in the forward quark jet the target baryon can be neglected, and direct predictions can be made for p and $\bar{p}$ production. As an example, we have chosen to represent leptoproduction events by a single forward u quark jet. The result is shown in fig. 3. For $0.1 < z < 0.9$ it can be parametrized (on the 10% level) as $zD_u^p(z) = 0.065 \cdot (1-z)$ and $zD_u^{\bar{p}}(z) = 0.06 \cdot (1-z)^2$. The introduction of QCD corrections [15] does not significantly modify these shapes, but some decrease in particular of the proton production rate is observed.

VI. $\Lambda(\bar{\Lambda})$ polarization. We have in [8] proposed a simple model for polarization in inclusive Λ production (in baryon fragmentation regions) based on angular momentum conservation in a constant force field without transverse excitations. We note that according to SU(6) a Λ is a $s(ud_0)$ state. Therefore any polarization properties of the Λ are related to the spin of the s-quark. In e.g. a proton fragmentation region, where the ud_0-diquark in general stems from the original proton and therefore is at the end of the colour field [14], the above-mentioned angular momentum conservation effect will cause an s-quark and therefore a Λ polarization in the direction $\vec{p}_\Lambda \times \vec{p}_{beam}$.

In a leptoproduction event (with sufficiently large x_B) we will find a valence-quark at the end of the corresponding force field in the current fragmentation region. Then the ud_0 is produced "behind" the s-quark and we expect that the same mechanism will lead to a Λ polarization along $\vec{Q} \times \vec{p}_\Lambda$. (with $\vec{Q}$ the direction of the virtual probe). Corrections from Λ production due to us_1 and ds_1 diquarks are negligible in this model. We note that the same argument imply $\bar{\Lambda}$ polarisation in leptoproduction events along $\vec{p}_{\bar{\Lambda}} \times \vec{Q}$.

Although a Λ ($\bar{\Lambda}$) mostly is produced together with a $K\bar{N}$ ($\bar{K}N$)

state in this model a $\Lambda\bar{\Lambda}$ pair whenever found will in general be neighbours in rank. An interesting quantity to investigate is $\vec{p}_\Lambda \cdot \vec{p}_{\bar{\Lambda}}$, i.e. the correlation between the polarization directions of the Λ and $\bar{\Lambda}$. In this model there is no correlation (due to the spinlessness of the $ud_0\,\bar{u}\bar{d}_0$ pair). In the "popcorn model" referred to above [7] when the diquarks are produced in a stepwise manner, it is not unreasonable to expect that the $s\bar{s}$ pairs often are produced together for the $\Lambda\bar{\Lambda}$ pair. Then one expects a positive correlation, i.e.

$$\vec{p}_\Lambda \cdot \vec{p}_{\bar{\Lambda}} > 0 \tag{6}$$

according to the mechanism in [8].

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Footnotes

\# Recently further data on p and Λ production around 30 GeV have been presented by the JADE [16], TASSO [17] and MARK II [18] collaborations. While the agreement between our model and the results of the DESY groups is good, there is a consistent deviation from the MARK II proton results, which show a flat or even slightly rising cross section $d\sigma/dp$ between 1 and 2 GeV/c. Such results, if confirmed, are impossible to reproduce in our model. For the Λ spectrum the shape agrees well with the data, although there is some indication that the model gives a somewhat too low overall rate (the discrepancy being $\leq$ 30%) when parameters are fixed from the SPEAR data [10].

\#\# Recently the CLEO collaboration presented data taken on and off the Υ resonances, [19]. In their data sample, which is much larger than the one used by the DASP II group, the fraction of protons on resonance was only approximately 50% higher than in the continuum. This is in good agreement with our expectations.

References:

1. B. Andersson, G. Gustafson, C. Peterson, Z. Physik C1 (1979) 105
2. B. Andersson, G. Gustafson, Z. Physik C3 (1980) 223
3. B. Andersson, G. Gustafson, T. Sjöstrand, Z. Physik C6 (1980) 235
4. T. Sjöstrand, Lund preprint LU TP 80-3
5. J. Schwinger, Phys.Rev. 82 (1951) 664
6. H. Bohr, H. B. Nielsen, NBI-HE-78-3
7. A. Casher, H. Neuberger, S. Nussinov, Phys. Rev. D20 (1979) 179
8. B. Andersson, G. Gustafson, G. Ingelman, Phys. Lett. 85B (1979) 417
9. B. Andersson, G. Gustafson, T. Sjöstrand, Lund preprint LU TP 81-4, to be published in Z. Physik C
10. M. Piccolo et al., Phys. Rev. Lett. 39 (1977) 1503
    G. S. Abrams et al., Phys. Rev. Lett. 44 (1980) 10
11. R. Brandelik et al., Phys. Lett. 94B (1980) 444
    D. Pandoulas, rapporteur talk at the 1980 Wisconsin conference
12. W. Bartel et al., Phys. Lett. 101B (1981) 129
13. H. Albrecht et al., Phys. Lett. 102B (1981) 291
14. B. Andersson, G. Gustafson, I. Holgersson, O. Månsson, Nucl. Phys. B178 (1981) 242
15. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, Z. Physik C9 (1981) 233
    G. Ingelman, T. Sjöstrand, Lund preprint LU TP 80-12
16. W. Bartel et al., Phys. Lett. 104B (1981) 325
17. R. Brandelik et al., Phys. Lett. 105B (1981) 75
18. R. Hollebeek, talk at the Bonn Conference on Lepton and Photon Interactions at High Energies, August 1981
19. M. S. Alam et al., "Baryon production in the Υ region", Contribution to the Bonn Conference.

Figure captions

Fig. 1 Baryon production in e^+e^--events below 12 GeV: $R(p+\bar{p})$ (fig. 1a) and $R(\Lambda+\bar{\Lambda})$ (fig. 1b). Crosses show SPEAR Mark II data [10] with statistical errors. Full lines are our results, showing the separate contributions from u+d+s, c and b events. Dashed lines correspond to a κ twice as large for the breakup closest to a c or b quark, giving $P(qq)/P(q) = 0.3$ there and 0.04 elsewhere.

Fig. 2 The scaling cross section $(s/\beta)d\sigma/dx$ for e^+e^- events. Squares show TASSO data at 12 GeV (open) and 30 GeV (full) with statistical errors [11]. The results for our model are given at 7 GeV (full line), 12 GeV (dashed) and 30 GeV (dash-dotted).

Fig. 3 Baryon fragmentation functions $(1/\sigma)d\sigma/dz$ in a high energy u-quark jet for protons (full line) and antiprotons (dashed).

diquark :	ud_0		ud_1		uu_1	
quark :	u or d	s	u or d	s	u	d or s
octet :	3/4	1/2	1/12	1/6	0	1/6
decuplet :	0	0	2/3	1/3	1	1/3

Table 1 Relative probabilities for a diquark and a quark to join into a symmetric quark state in the octet or the decuplet. (The results for other diquarks are obtained from symmetry arguments.)

	$\pi^++\pi^-$	K^++K^-	$p+\bar{p}$	$n+\bar{n}$	$\Lambda+\bar{\Lambda}$	$\Sigma+\bar{\Sigma}$	$\Xi+\bar{\Xi}$	$\Delta+\bar{\Delta}$	$\Lambda_c+\bar{\Lambda}_c$
12 GeV	7.00	1.09	0.27	0.23	0.08	0.04	0.01	0.22	0.05
30 GeV	10.45	1.49	0.46	0.41	0.13	0.06	0.01	0.42	0.04
	(11)	(1.4)	(0.4)						

Table 2 Particle multiplicities at 30 and 12 GeV. Numbers in paranthesis are experimental data from TASSO [11].

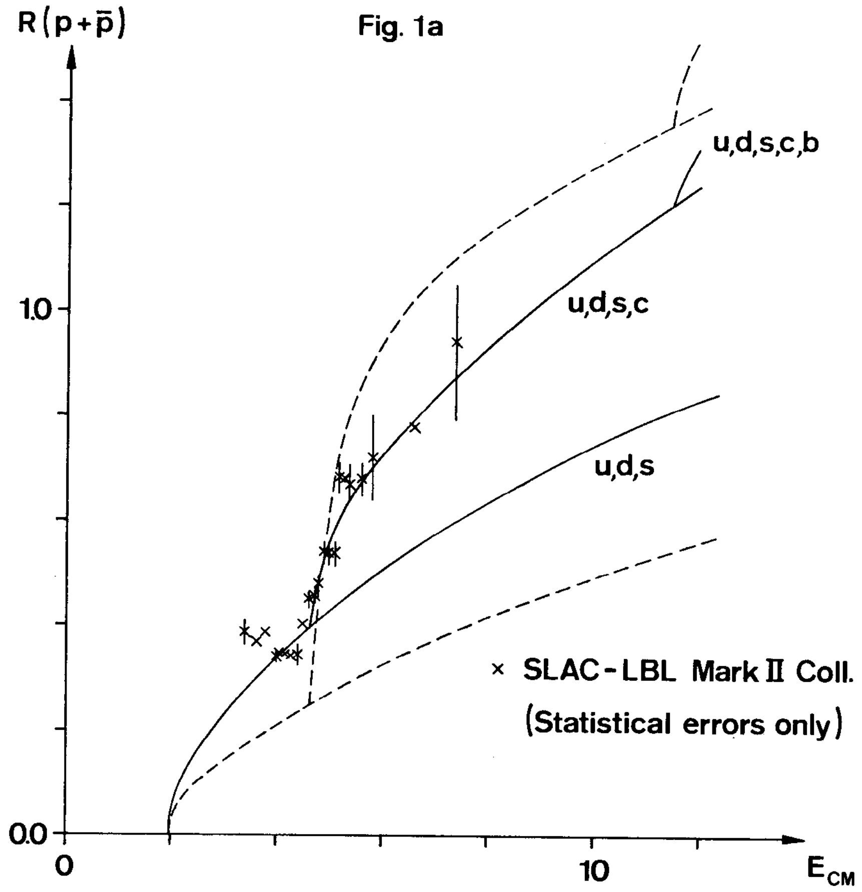


Fig. 1a

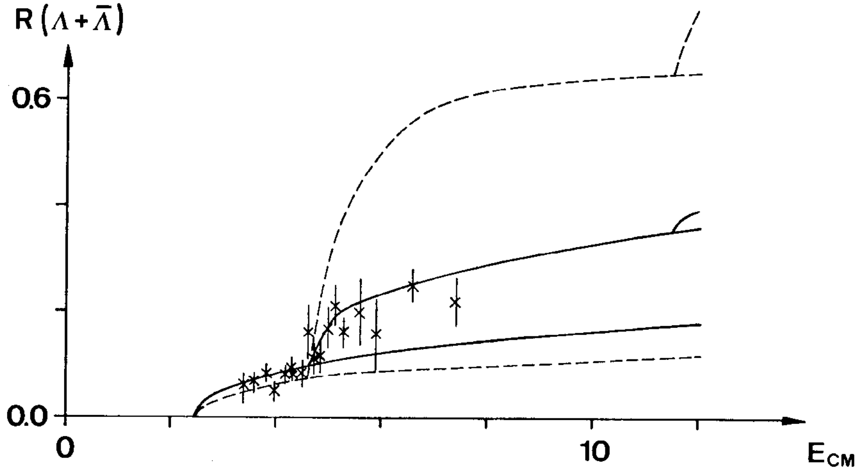
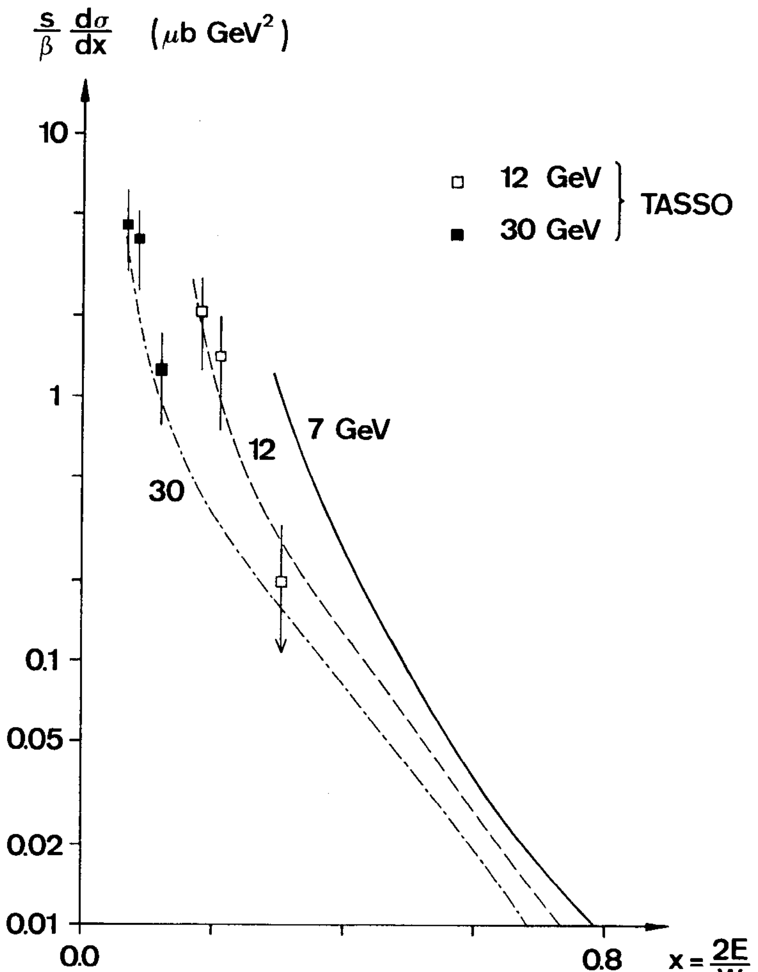


Fig. 1b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1
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$x = \frac{2E}{W}$
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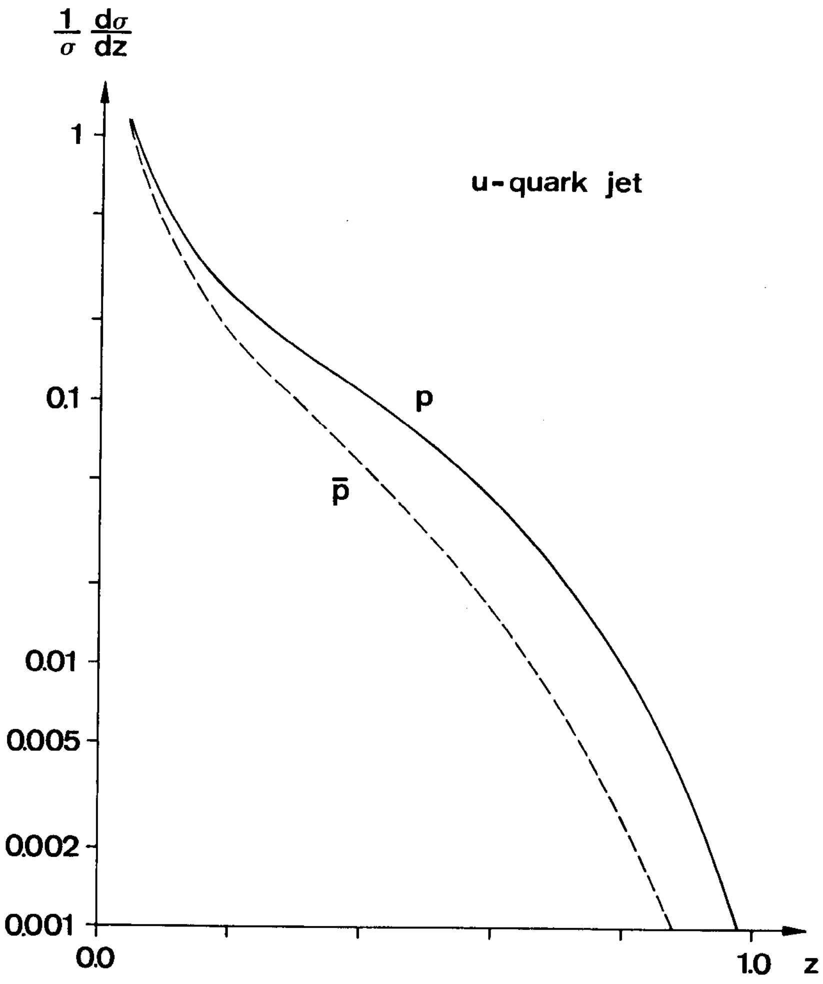
30

Fig. 2


$\frac{1}{\sigma}\frac{d\sigma}{dz}$
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0.01
0.005
0.002
0.001
0.0
1.0
z
u-quark jet
p
$\bar{p}$

Fig. 3