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CONSTRAINTS ON PARTON-PARTON CROSS-SECTIONS FROM LARGE $p_\perp$ ANGULAR CORRELATIONS

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ABSTRACT

Recent data on rapidity distributions opposite a large $p_\perp$ trigger are analyzed. These data are found to constrain the angular dependence of the hard collision subprocess strongly. Estimates are given for quark - meson and quark - quark scattering. Using these results the behaviour of the position of the maximum of the opposite side rapidity distribution is studied for larger values of the trigger $x_\perp$ and for different trigger and beam particles.

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1. INTRODUCTION

Further progress has been made last year in the study of large transverse momentum hadronic processes [1),2)]. Correlation measurements give increasing evidence in favour of a two-jet picture. A parton mechanism would naturally explain this. But also if such a scheme is accepted, many questions remain to be answered. These concern the quantum numbers and distribution functions of the partons, their cross-section as well as the properties of jets in the final state.

The parton-parton cross-section is usually assumed to be of the form

$$\frac{d\sigma}{d\hat{t}} = \frac{1}{\hat{s}^n} f(\hat{t}/\hat{s})$$

The $p_\perp^{-8}$ behaviour of meson production in pp collisions confirmed now also at FNAL [3)] requires a value $n \approx 4$. This indicates that a scale-invariant gluon-exchange quark-quark diagram $(n = 2)$ does not give the dominant contribution at least at present energies. Instead of this, quark-exchange diagrams, Refs. 4),5), have been studied yielding the observed power behaviour.

On the other hand, there have been attempts to maintain quark-quark scattering as the dominant subprocess, e.g., by the introduction of quark form factors. A particular model of this type has been discussed recently [6)].

Whereas the scale n of the dominant hard scattering process is well known from inclusive single particle distributions, our knowledge of the angular dependence of the parton-parton cross-section, i.e., of $f(\hat{t}/\hat{s})$ is still rather poor. The most direct way to determine this angular dependence would be the measurement of the two-jet cross-section [7)]. Recent momentum analyzed SFM data [8),9)] on the rapidity distribution opposite (in ϕ) a large $p_\perp$ trigger are an important step in that direction.

A basic feature of these data is that at a typical trigger transverse momentum $x_\perp = 2p_\perp/\sqrt{s} \approx 0.1$ there is little correlation between the trigger position (in a range of $20^\circ \ldots 90^\circ$) and the opposite side distribution. It is centered around $y = 0$ widely independent of the trigger rapidity y_1. At somewhat higher values of the trigger transverse momentum $(x_\perp \sim 0.15)$ the ACHM collaboration [10)] finds the maximum slightly shifted into the direction of c.m.s. rapidities opposite the trigger (back-to-back effect). At smaller $p_\perp$ a shift into the trigger direction, i.e., a back-antiback effect is seen [11)].

In the present paper, we study the consequences of these data for the angular dependence of the parton-parton cross-section. Actually the presently available data do not allow a decoupling of $d\sigma/d\hat{t}$ from the hadron fragmentation functions. Thus, the phenomenological result one obtains for $d\sigma/d\hat{t}$ will be different for different hard scattering subprocesses, assumed to be dominant, and depends on the assumptions made for the hadron fragmentation functions. Since we do not prefer any particular scattering mechanism, the best we can do is to determine $d\sigma/d\hat{t}$ for typical choices of the hadron fragmentation functions and to show some trends.

This paper is organized as follows. In chapter 2 we briefly discuss the inclusive two-particle distribution in the framework of a general hard scattering model. In chapter 3, we give estimates for the angular dependence of $d\sigma/d\hat{t}$ under particular assumptions discussed there. Chapter 4 contains a study of the $x_\perp$ dependence of the opposite side rapidity distribution and of some quantum number effects. A brief summary follows.

2. OPPOSITE SIDE RAPIDITY DISTRIBUTION IN HARD COLLISION MODELS

In the following we consider the process

$$A + B \longrightarrow C + D + X \qquad \text{(A)}$$

where the hadrons C and D have large transverse momenta and are observed on opposite sides (in the azimuthal angle ϕ). We discuss this process in the framework of a hard collision model : the incoming hadrons A, B fragment into partons a, b

$$A \to a \,, \quad B \to b$$

which might be quarks, gluons or virtual hadrons. These partons undergo a hard collision

$$ab \to cd$$

The quark - or hadron-like jets - in turn fragment into hadrons.

The double inclusive cross-section for the reaction (A) is given by

$$E_1 E_2 \frac{d\sigma}{d^3p_1\, d^3p_2} = \frac{16}{\pi s\, x_{\perp 1}^2\, x_{\perp 2}^2}\, \delta(\varphi_1 - \varphi_2 + \pi) \sum_{ab,cd} \int \frac{x_1 dx_1\, F_a^A(x_1)\, F_b^B(x_2)}{(\mathrm{ctg}\,\theta_1/2 + \mathrm{ctg}\,\theta_2/2)^2} \times \tag{1}$$

$$\times \left\{ \frac{d\sigma}{d\hat{t}}\, G_c^C(z_1)\, G_d^D(z_2) + \frac{d\sigma}{d\hat{u}}\, G_d^C(z_1)\, G_c^D(z_2) \right\}$$

where

$$x_{\perp i} = \frac{2 p_{\perp i}}{\sqrt{s}} \quad , \quad i = 1,2 \tag{2}$$

$$x_2 = x_1\, \mathrm{tg}\,\theta_1/2\, \mathrm{tg}\,\theta_2/2 \tag{3}$$

$$z_i = \frac{x_{\perp i}}{2 x_1} \left(\mathrm{ctg}\,\theta_1/2 + \mathrm{ctg}\,\theta_2/2 \right) \tag{4}$$

Our notations have been taken from Ref. 12), where these kinematical relations are derived. Possible interference terms are neglected in Eq. (1).

The functions $F(x)$ and $G(z)$ describe the fragmentation of hadrons and jets, respectively. Since we neglect the transverse momentum of partons inside hadrons and of hadrons inside jets, a δ function in the azimuthal angles appears. The higher the transverse momenta of the observed hadrons C, D are, the better this approximation becomes.

The differential cross-section $d\sigma/d\hat{t}$ of the subprocess $ab \to cd$ is assumed to be of the form

$$\frac{d\sigma}{d\hat{t}} = \frac{1}{\hat{s}^n}\, f(\eta) \tag{5}$$

with

$$\hat{s} = x_1 x_2 s \tag{6}$$

and

$$\eta = \frac{-\hat{t}/\hat{s}}{1 + \hat{t}/\hat{s}} = \mathrm{tg}\,\theta_1/2\, \mathrm{ctg}\,\theta_2/2 \tag{7}$$

In terms of η, $d\sigma/d\hat{u}$ is simply expressed as

$$\frac{d\sigma}{d\hat{u}} = \frac{1}{\hat{s}^n} f\left(\frac{1}{\eta}\right) \tag{8}$$

Instead of the polar angle Θ, we will frequently use the rapidity variable

$$dy = \frac{dp_{\parallel}}{E} \tag{9}$$

which equals the pseudo-rapidity

$$y = -\log \mathrm{tg}\, \theta/2 \tag{10}$$

if $E \sim p$.

If the trigger particle C is identified and its transverse momentum is measured, but only the rapidity y_2 of the opposite side large $p_\perp$ particle is known, Eq. (1) becomes

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{\perp 1}} = \frac{16}{\pi x_{\perp 1}^2} \frac{1}{(e^{y_1} + e^{y_2})^2} \sum_{ab,cd} \int x_1 dx_1 F_a^A(x_1) F_b^B(x_2) \times \tag{11}$$

$$\times \left\{ \frac{d\sigma}{d\hat{t}} G_c^C(z_1) \langle n \rangle_d + \frac{d\sigma}{d\hat{u}} G_d^C(z_1) \langle n \rangle_c \right\}$$

The associated multiplicity $\langle n \rangle_d$ is given by

$$\langle n \rangle_d = \sum_D \int_{z_0}^1 \frac{dz}{z} G_d^D(z) \tag{12}$$

The lower limit z_0 is determined by the experimental conditions. Having a fixed cut in $p_\perp$ (or $x_\perp$), z_0 is a function of Θ_1, Θ_2 and x_1 [cf., Eq. (4)]

Equation (11) will be the starting point for the following considerations.

3. ESTIMATES OF THE ANGULAR TERM $f(\eta)$

So far we have specified neither the subprocess $ab \rightarrow cd$ nor the hadron or jet fragmentation functions $F(x)$ and $G(z)$. Precise models will be defined in the following.

We will consider meson production only. In this case, the possible candidates for the hard collision process are

quark + quark → quark + quark (B1)

quark + meson → quark + meson (B2)

quark + antiquark → meson + meson (B3)

Equations (B) characterize the quantum number flow only. We do not associate a specific amplitude [angular term $f(\eta)$] with these processes, but leave it free to be determined from the data.

Recent data on π^0 production in $\pi^{\pm}p$ scattering [13] do not support the idea that antiquarks play a very distinct role in large transverse momentum processes. Therefore we only study the processes (B1) and (B2) in some detail.

We next have to specify the hadron fragmentation functions $F_a^A(x)$. If a is a quark (antiquark) $F(x)$ equals the structure functions determined in deep inelastic lepton scattering. For definiteness, we use the parametrization of Barger and Phillips [Ref. 14), Eq. (64)].

If the parton is a virtual meson, the situation is worse. We use a rather crude ansatz

$$F_M^A(x) \sim \frac{1}{x}(1-x)^{2n_s-1} \qquad (13)$$

suggested by quark counting rules [cf., e.g., Ref. 15)] and Regge behaviour. n_s is the number of spectators, i.e., the necessary number of quarks of the system $A\bar{M}$.

If a jet has meson quantum numbers, it has a (probably small) single particle component. However, because of the trigger bias [16),17)], this single particle component is seen in most cases on the trigger side. Thus we choose as a parametrization of what is seen with present detectors

$$G_M^C(z) = \delta_{M,C}\,\delta(z-1) \qquad (14)$$

This would not work for opposite side jets, but there the jet fragmentation function is integrated off [cf., Eqs. (11) and (12)].

A jet with quark quantum numbers does not have a single particle component. Nevertheless, also in the case of quark-quark scattering, we will assume that the $p_\perp$ of the trigger particle represents almost that of the jet. Thus we actually consider a quantity proportional to the two-jet cross-section.

Only in the case of the SFM data [9] the opposite side particle definitely has a large transverse momentum. Otherwise we have to deal with associated multiplicities. In this case we proceed as follows. We do not fully integrate Eq. (1) over $p_{\perp 2}$ but calculate the jet multiplicity in the quark-quark c.m.s. first. Afterwards the averaging over x_1 is done. For the jet fragmentation we use a model discussed in detail in Refs. 18) and 19) which takes deviations from scaling into account.

As a result, we find that with respect to the position of the maximum of the opposite side, it makes almost no difference whether to calculate really the associated multiplicity or simply to take the two-jet cross-section.

Since the η dependence of $d\sigma/d\hat{t}$ is theoretically not well understood we choose a simple ansatz

$$f(\eta) + f\left(\frac{1}{\eta}\right) = \left(a + \eta + \frac{1}{\eta}\right)^n \quad , \quad a > 0 \qquad (15)$$

where a and n are parameters to be determined. $f(\eta)$ itself is defined by taking all terms

$$\left(\frac{1}{\eta}\right)^m \quad , \quad m > 0$$

and half of the term $m=0$.

We are now prepared to look at the data. Figures 1a-d show opposite side distributions associated with several triggers $x_{\perp 1}$ and y_1. They display the features discussed already in the Introduction. In the case of the CCHK data (Figs.1a,b) for which the charge of both observed particles is known, we have chosen the negative-negative combination. It is this combination which should not be sensitive to leading particle effects. Figures 1c,d show associated multiplicities.

Trying to find an angular distribution $f(\eta)$ in agreement with these data, it turns out that in particular the 20° data ($y_1 \sim 1.65$, Fig. 1b) are very restrictive. In the case of a quark-quark subprocess, reasonable agreement with these data is obtained (cf., Fig.1) by using

$$f(\eta) + f\left(\frac{1}{\eta}\right) = \left(1 + \eta + \frac{1}{\eta}\right)^3 \qquad (16)$$

i.e., $a \sim 1$, $n \approx 3$. We have repeated this analysis for quark-meson scattering (Figs.2a-d) using $a \sim 1$, $n \approx 4$

$$f(\eta) + f\left(\frac{1}{\eta}\right) = \left(1 + \eta + \frac{1}{\eta}\right)^4 \qquad (17)$$

In order to show how significant the opposite side rapidity distribution depends on the angular dependence of $d\sigma/d\hat{t}$ we plot in Fig. 3 the position of the maximum of this distribution for several values of a and n [cf., Eq. (15)]. As an example, quark-meson scattering is considered with a trigger particle $x_{\perp 1} = 0.1$, $y_1 = 1.65$. For $n \leq 3$ the opposite side distribution tends to go with the trigger (back-antiback effect) for all $a \geq 0$, i.e., there is no solution $y_{max} = 0$. Besides the solution $n = 4$, $a \sim 1$ discussed already, one easily finds a second one at $n = 5$, $a \sim 2.3$. More detailed calculations show, however, that this solution has a somewhat unpleasant $x_\perp$ and y dependence and is especially in disagreement with the data of Fig. 1d.

In conclusion, the available data give a rather unique solution for the angular dependence of $d\sigma/d\hat{t}$ if the hadron fragmentation functions are chosen. The details of the angular term $f(\eta)$ depend on this choice. An isotropic behaviour, however, is definitely excluded [cf., also Refs. 20) and 21)].

4. $x_\perp$ DEPENDENCE AND SOME QUANTUM NUMBER EFFECTS

Having chosen a hard scattering mechanism and the corresponding fragmentation functions, the dependence of the opposite side rapidity distribution on the trigger variables $x_\perp$ and y can now be predicted without additional freedom in the kinematical $x_\perp$ range not investigated so far. For the two models studied in Chapter 3, we have calculated the position of the maximum of the opposite side rapidity distribution (y_{max}) as function of $x_\perp$. The results are shown in Fig. 4 for two trigger rapidities $y_1 = 0.75$ and $y_1 = 1.65$, respectively. For medium values of y_1 $(y_1 \sim 0.75)$ no dramatic $x_\perp$ dependence is found up to $x_\perp \sim 0.5$. Going to higher rapidities (smaller angles) a more pronounced back-to-back effect develops with increasing $x_\perp$, but this is partly a kinematical effect.

At rather small $p_\perp$ values and small trigger angles, the data of Ref. 11) show a clear back-antiback effect. Our results qualitatively agree with this trend (cf., Fig.4). We have not tried to make this agreement more quantitative since with decreasing trigger $p_\perp$ the normal underlying event becomes more and more important. A smooth transition to the cluster phenomena known from low $p_\perp$ physics is expected and is shown by the data [11].

Both models we have considered give practically the same $x_\perp$ dependence of y_{max}. Thus a discrimination between different hard scattering models by the study of this $x_\perp$ and y dependence seems unlikely.

This is no longer true if the quantum number content of a large $p_\perp$ event is explored, e.g., if the trigger particle is identified or if different beam particles are used. Unfortunately, predictions cannot be made in this case without more detailed assumptions. Take as example quark-meson scattering. Such a process could be realized by gluon exchange or quark exchange. In the first case no quantum numbers are exchanged. Thus different results for the quantum number distributions are found.

The quark interchange contribution has been recently discussed for several trigger and beam particles [20),22)]. We give a brief discussion of the corresponding gluon exchange process. In this case several quantum number effects arise in a rather transparent way. Because gluons are supposed to be SU(3) singlets, the corresponding quark-meson cross-section $d\sigma/d\hat{t}$ has to be independent of the quark and meson quantum numbers. The result (17) can be used without modifications. All trigger and beam dependence of the opposite side rapidity distribution will result from the different hadron fragmentation functions to be used. Take as example a K^- trigger in proton-proton scattering. The proton fragmentation function into a K^- should considerably differ from that into other mesons (π, K^+). From counting rules, one expects a behaviour

$$\frac{F^{p\to K^-}(x)}{F^{p\to\pi}(x)} \sim (1-x)^4$$

This is roughly consistent with the behaviour of inclusive single particle distributions at low $p_\perp$. Thus, the K^- quark c.m.s. shows a stronger asymmetry in the proton-proton c.m.s., compared with π quark scattering. Since $d\sigma/d\hat{t}$ should be the same one, this effect cannot be compensated. As a consequence, the maximum of the rapidity distribution opposite a K^- should have a tendency to be nearer the trigger rapidity than in the case of a π or K^+ trigger. This effect is shown quantitatively in Fig. 5 for a trigger rapidity

$y_1 = 1.65$. Whereas the differences between a K^- and a π trigger are small at low $p_\perp$ they should be rather pronounced around $x_\perp \sim 0.2$. The simple model we are considering predicts a clear back-antiback effect for a K^- trigger in this $x_\perp$ range.

If this mechanism actually works, a rather remarkable trigger dependence of the opposite side distribution is expected for meson beam reactions. Using again the hadron fragmentation functions (13), we have no freedom in the calculation of the opposite side distribution. Taking π^-p scattering as example, y_{max} as function of the trigger rapidity y_1 is shown for several trigger particles (π^o, π^+, K^-) in Fig. 6. In the case of a π^o trigger y_{max} is practically independent of y_1 but reflects the fact that a fragment of the incoming pion carries a larger average momentum than a proton fragment (in the total c.m.s.). Consequently, y_{max} is slightly positive (all angles are defined with respect to the beam direction). In the case of a K^- or π^+ trigger, the parton-parton c.m.s. is shifted into the pion or proton direction, respectively. The y_1 dependence of y_{max} is correspondingly changed.

We do not claim that this particular gluon mechanism is really the dominant one. It is one possibility among others. This example hopefully shows, however, how useful correlation data from different beams and with identified trigger would be for a better understanding of the quantum number structure of hard collision processes. It deserves a more systematical experimental and theoretical study.

5. SUMMARY AND CONCLUSIONS

Analyzing recent data on opposite side distributions [9),10)] we find significant constraints on the matrix element of a supposed hard collision subprocess. The characteristic feature of these data is that for a trigger $x_\perp$ around 0.1 the position of the opposite side maximum is almost independent of the trigger rapidity (up to $y_1 \sim 1.75$). At somewhat higher transverse momentum, the maximum is found slightly shifted in the direction of c.m.s. rapidities opposite the trigger.

Such a behaviour is not evident for a hard collision model and constrains the form of $d\sigma/d\hat{t}$. An almost isotropic subprocess like quark-antiquark single gluon annihilation would yield a clear back-antiback effect in the considered $p_\perp$ range, since the inverse power in $\hat{s}$ appearing in $d\sigma/d\hat{t}$

$$\frac{d\sigma}{d\hat{t}} = \frac{1}{\hat{s}^n} f(\eta)$$

favours low subenergies. Thus, such a mechanism is definitely ruled out. A more peripheral angular term $f(\eta)$ is necessary to compensate to some extent the energy suppression.

In Chapter 3, estimates for this angular term have been given. It cannot be extracted from present data in a model independent way, but is influenced by the assumptions on the hard scattering mechanism and the corresponding hadron fragmentation functions. Since we considered the parton-parton matrix element as a free quantity to be determined from the data, we cannot rule out any particular scattering mechanism but find slightly different angular terms under different assumptions.

Once a scattering mechanism is chosen and $d\sigma/d\hat{t}$ is determined, one can predict the behaviour of the opposite side rapidity distribution at larger values of the trigger $x_\perp$ and for different trigger particles in pp and πp collisions. This has been discussed in Chapter 4. It has been pointed out that several quantum number effects can discriminate between models. Correlation measurements with a K^- trigger in pp collisions or meson beam reactions with identified trigger would be very useful.

Completing this manuscript, we learnt about a paper by R. Baier et al. [23] who also study the angular dependence of hard collision processes. They use data with a 90° trigger only, but carefully consider the relative normalization of the single and two-particle distribution. They obtain a reasonable description of the chosen set of data using a quark fusion model [cf., process (B3)] with an angular term which corresponds to

$$f(\eta) + f(\tfrac{1}{\eta}) \sim (1+\tfrac{1}{\eta})^3 + (1+\eta)^3 \qquad (18)$$

This is numerically between our results (16) and (17). For a quark fusion model, we would have obtained a slightly more peripheral angular term since the quark-antiquark c.m.s. shows a stronger asymmetry in the pp c.m.s. This is consistent with Ref. 23) where a back-antiback effect is expected for the angular term (18).

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FIGURE CAPTIONS

Figure 1 : Opposite side rapidity distribution calculated for quark-quark scattering and compared with data of Refs. 9) and 10)

a) $x_{\perp 1} \sim 0.1$; $y_1 = 0.75$

b) $x_{\perp 1} \sim 0.1$; $y_1 = 1.65$

c) $x_{\perp 1} \sim 0.15$; $y_1 = 0.$

d) $x_{\perp 1} \sim 0.15$; $y_1 = 0.75$.

Figure 2 : Same as Fig. 1, but for quark-meson scattering.

Figure 3 : Position of the maximum of the opposite side rapidity distribution (y_{max}) for several choices of the angular term $f(\eta)$ [cf., Eq. (15) for the definition of the parameters a, n].

Figure 4 : $x_\perp$ dependence of y_{max} ;

— $y_1 = 0.75$

-- $y_1 = 1.65$.

Figure 5 : $x_\perp$ dependence of y_{max} for a pion and a K^- trigger in pp scattering :

— π

-- K^-

$y_1 = 1.65$

Figure 6 : y_{max} as function of the trigger rapidity y_1 for several trigger particles, $x_{\perp 1} = 0.2$, $\pi^- p$ scattering.

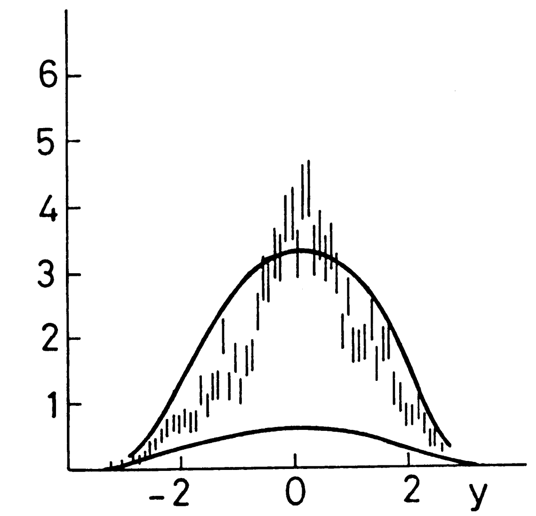

FIG. 1a

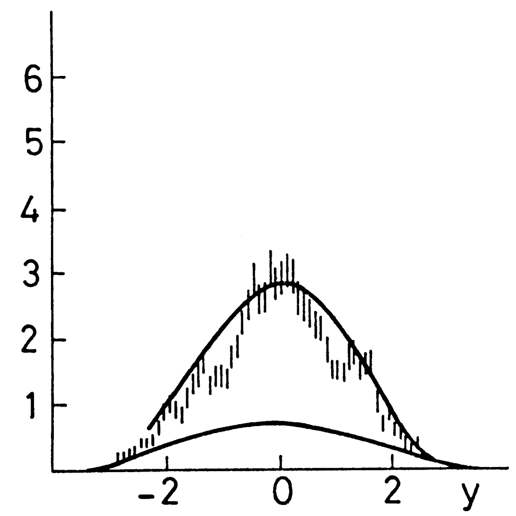

FIG. 1b

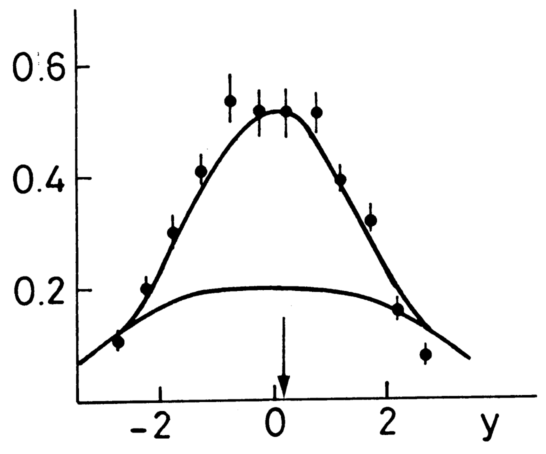

FIG. 1c

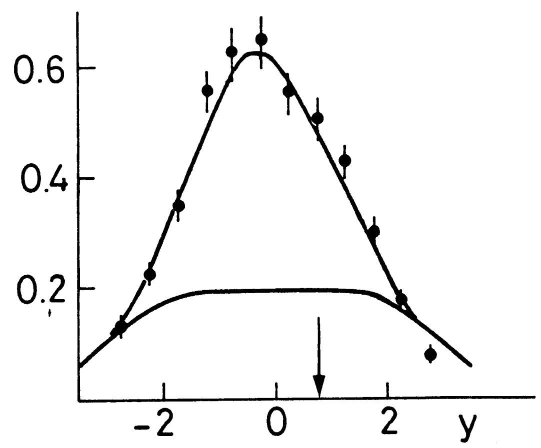

FIG. 1d

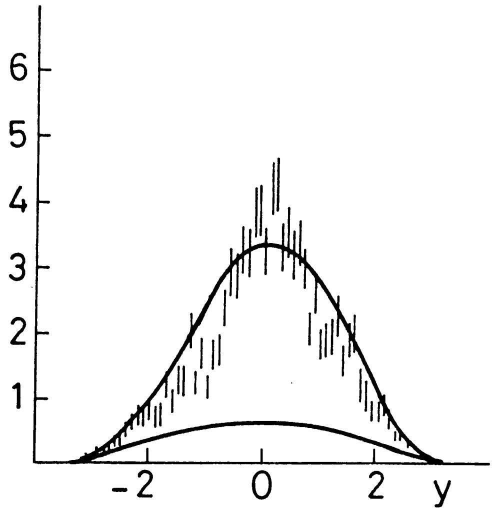

FIG. 2a

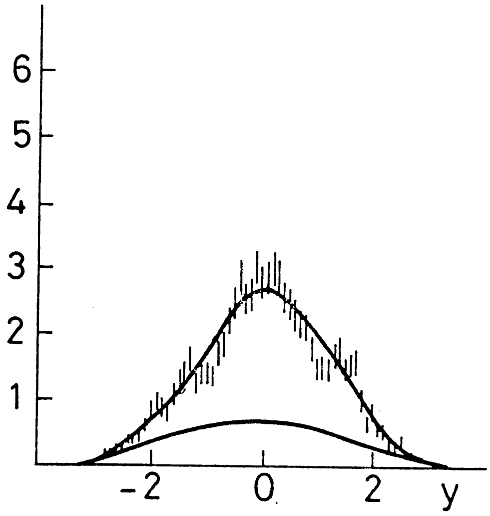

FIG. 2b

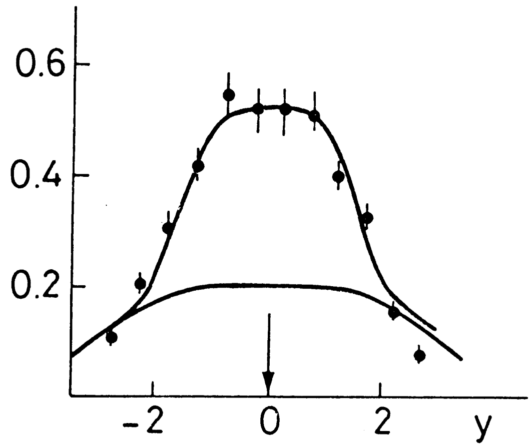

FIG. 2c

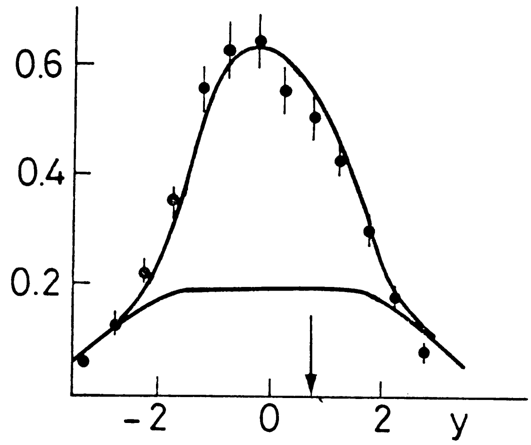

FIG. 2d

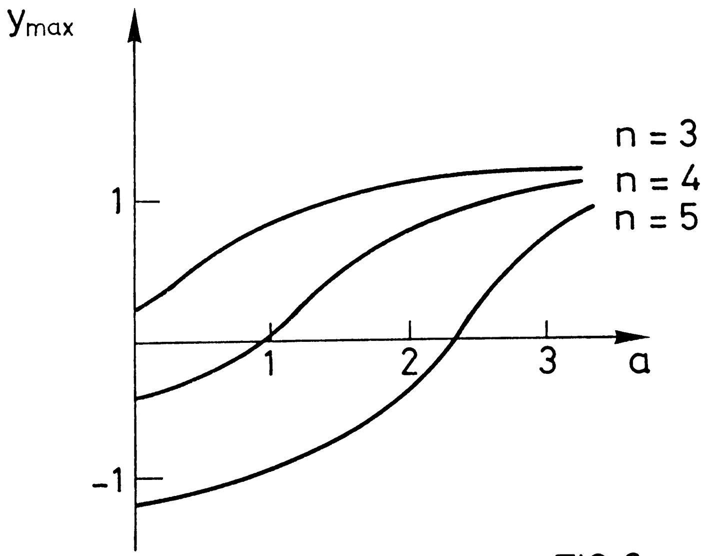

FIG.3

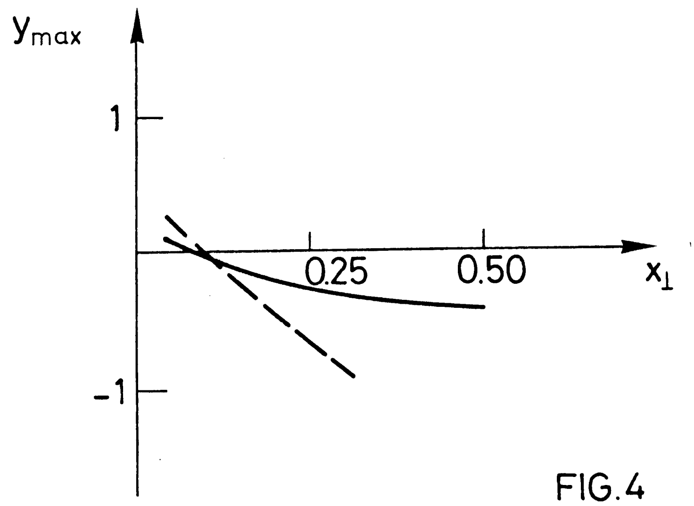

FIG.4

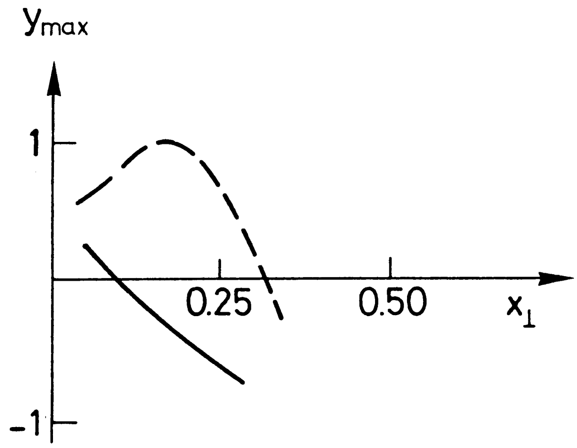

FIG.5

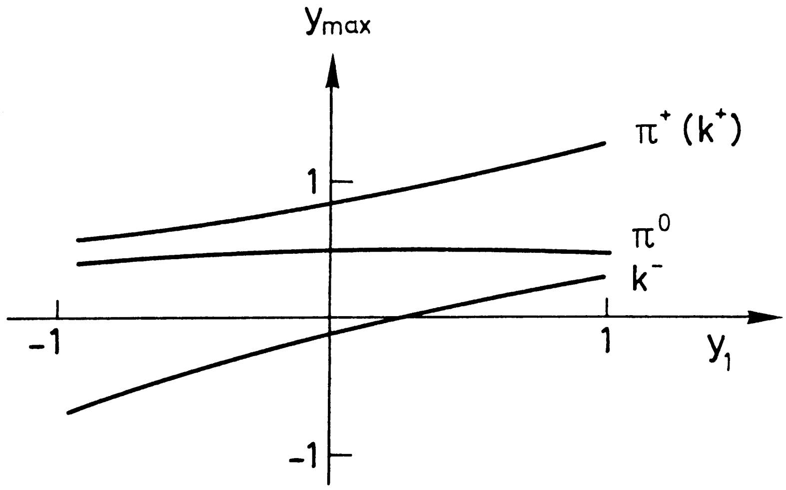

FIG.6