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ARE TWO GLUONS THE QCD POMERON ?

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Abstract

Collider experiments have recently measured the production cross section of hard jets separated by a rapidity gap as a function of transverse momentum and gap size. We show that these measurements reveal the relative frequencies for the production of rapidity gaps in quark-quark, quark-gluon and gluon-gluon interactions. The results are at variance with the idea that the exchange of 2 gluons is a first order approximation for the mechanism producing colorless states, i.e. the hard QCD Pomeron. They do qualitatively support the "soft color" or "color evaporation" scheme developed in the context of bound-state heavy quark production.

I. INTRODUCTION:

lthough we do understand strong interactions in the context of QCD, we can at best ulate on how to calculate elastic scattering. This is just one example of an interaction iated by the exchange of the "Pomeron", a state which carries no net color. The routine ulation has been that it is, to a first approximation, a state of two colored gluons oined into a color singlet. Understanding the Pomeron has been challenging because its amics is revealed in processes which are not subject to perturbative computation, e.g. ic scattering. The hope has been that it may be instructive to study Pomeron dynamics rd processes that are, at least partially, understood in terms of perturbative QCD: the Pomeron. Examples include processes involving colorless pairs of heavy quarks, e.g. or colorless states of light quarks produced in association with a pair of high transverse nentum jets: rapidity gaps. In this paper we will show how a treatment of colorless s in QCD, suggested by the phenomenology of heavy quark bound states, supports a color" model of the Pomeron which is at variance with the idea that it is a structure on a frame composed of two gluons. We will show that recent measurements[1] of elative frequency for the production of rapidity gaps in quark-quark, quark-gluon and n-gluon interactions provides qualitative, yet convincing, confirmation of the soft color ept.

he reason why some data on the production of ψ- and Υ-states radically disagree with predictions, occasionally by well over one order of magnitude, is that the traditional od for performing the perturbative calculation of the cross section is simply wrong[2]. key mistake is to require that the heavy quark pair forms a color singlet at short nces, given that there is an essentially infinite time for soft gluons to readjust the color e $c\bar{c}$ pair before it appears as an asymptotic ψ or, alternatively, $D\bar{D}$ state. We suspect the same mistake is made in the description of rapidity gaps, i.e. the production of a -neutral quark-antiquark pair, in terms of the exchange of a color neutral gluon pair. ψ is, after all, a color neutral $c\bar{c}$ pair and we have shown[2] in quantitative detail that indeed produced by exactly the same dynamics as $D\bar{D}$ pairs; its color happens to be hed by soft final-state interactions. This approach to color is also suggestive of the thodox prescription for the production of rapidity gaps in deep inelastic scattering, osed by Buchmüller and Hebecker[3].

n this paper we emphasize that recent measurements[1] on the formation of rapidity between a pair of high transverse momentum jets shed new light on the problem of how eat color in semi-hard interactions. When applied to the formation of gaps between ir of high transverse momentum jets in hadron collisions, the "soft color" or "color oration" approach suggests a formation rate of gaps in gluon-gluon subprocesses which nilar, or smaller, than in quark-quark induced events. Consequently, formation of gaps ld increase with increased transverse momentum, or reduced collision energy of the jets. prediction happens to be antithetical to the one obtained in 2-gluon exchange Pomeron els. We show that the data resolve the issue in favor of the "soft color" computational me and questions the relevance of approximating the exchange of a color-singlet, hard eron as a pair of gluons. We also exhibit the predictions of the "soft color" model for production of rapidity gaps at the LHC energy.

I. ONIUM CALCULATIONS WITH SOFT COLOR: A BRIEF REMINDER

'he conventional treatment of color in perturbative QCD calculations, i.e., the color et model, has run into serious problems in describing the data on the production of nonium and upsilon states[4]. Specific proposals to solve the onium problem agree on basic solution: onium production is a two-step process where a heavy quark pair is uced first. At this initial stage all perturbative diagrams are included, whether the $c\bar{c}$ forms a color singlet state or not. This is a departure of the textbook approach where diagrams with the charm pair in a color singlet state are selected. In the Bodwin-ten-Lepage (BBL) formalism[5] the subsequent evolution of the pair into a colorless d state is described by an expansion in powers of the relative velocity of the heavy ks in the onium system. A different approach, the color evaporation or soft color method, esents an even more radical departure from the way color singlet states are conventionally ed in perturbation theory. Color is, in fact, "ignored". Rather than explicitly imposing the system is in a color singlet state in the short-distance perturbative diagrams, the arance of color singlet asymptotic states depends solely on the outcome of large-distance uations of quarks and gluons. In other words, color is controlled by nonperturbative actions.

n Fig. 1 we show typical diagrams for the production of ψ-particles representing the peting treatments of the color quantum number. In the diagram of Fig. 1a, the color et approach, the ψ is produced in gluon-gluon interactions in association with a final gluon, which is required by color conservation. This diagram is related by crossing he hadronic decay $\psi \to 3$ gluons. In the color evaporation approach, the color singlet erty of the ψ is ignored at the perturbative stage of the calculation. The ψ can, for ince, be produced to leading order by $q\bar{q}$-annihilation into $c\bar{c}$, which is the color-equivalent he Drell-Yan process, as shown in Fig. 1b. This diagram is calculated perturbatively, dynamics dictated by short-distance interactions of range $\Delta x \simeq m_\psi^{-1}$. It does indeed seem logical to enforce the color singlet property of the ψ at short distances, given that is an essentially infinite time for soft gluons to readjust the color of the $c\bar{c}$ pair before pears as an asymptotic ψ or, alternatively, $D\bar{D}$ state. Alternatively, it is indeed hard nagine that a color singlet state formed at a range m_ψ^{-1}, automatically survives to form This formalism represents the original[6, 7, 8, 9] and, as we have shown[10], correct nod by which perturbative QCD calculations should be performed.

he evidence is compelling that Nature operates according to the color evaporation me. The formalism predicts that, up to color and normalization factors, the energy, x_F- p_T-dependences of the cross section, are identical for the production of onium states and pairs. This is indeed the case[10, 11]. Another striking feature is that the production armonium is dominated by the conversion of a colored gluon into a ψ, as in Fig. 1b. he conventional treatment, where the color singlet property of the ψ is enforced at perturbative level, 3 gluons (or 2 gluons and a photon) are required to produce a ψ. rary to the usual folklore, ψ's are not produced only by gluon–gluon interactions. As a equence color evaporation predicts an enhanced ψ cross section for antiproton beams, the color singlet model predicts roughly equal cross sections for proton and antiproton ns. The prediction of an enhanced $\bar{p}$ yield is obviously correct: antiproton production 's exceeds that by protons by a factor 5 close to threshold. This fact has been known ome time[7, 8, 9]. We should note that for sufficiently high energies, gluon initial states eventually dominate because they represent the bulk of soft partons.

uantitative tests of color evaporation are made possible by the fact that all ψ-production , i.e. photo-, hadroproduction, Z-decay, etc., are described in terms of a single param- the parameter determining the frequency by which a charm pair turns into a ψ via inal state color fluctuations. Once this parameter has been empirically determined for nitial state, the cross section is predicted without free parameters for any other. We demonstrated[11] the quantitative precision of the color evaporation scheme by showıow it accommodates all measurements, including the high energy Tevatron and HERA , which have represented a considerable challenge for other computational schemes. Its meter-free prediction of the rate for Z-boson decay into ψ's is an order of magnitude r than the color singlet model and consistent with data[12].

ı summary, the soft color approach gives a complete picture of charmonium production ıdron-hadron, γ-hadron, and Z decays. The phenomenological success of the soft color ne is impressive and extends to applications to other charmonium and upsilon states[10,

. RAPIDITY GAPS AS COLORLESS STATES OF (LIGHT) QUARKS AND GLUONS

Ve now turn to the implications of the soft color scheme for the dynamics underlying production of rapidity gaps, which refer to regions in phase space where no hadrons ar as a result of the production of a color neutral partonic system. The connection ıarmonium physics is obvious: the ψ is a color-neutral $c\bar{c}$ pair. The important lesson heavy quark phenomenology is that perturbative color octet states fully contribute to ısymptotic production of color singlet states, such as ψ's. We suspect that this is also for the production of a rapidity gap which represents nothing but the creation of a singlet quark-antiquark pair, as shown in Fig. 2a for electroproduction. The diagram esents the production of final state hadrons which are ordered in rapidity: From top ottom we find the fragments of the intermediate partonic quark-antiquark state and of the target. Buchmüller and Hebecker proposed that the origin of a rapidity gap esponds to the absence of a color string between photon and proton remnants, *i.e.* the $\mathbf{3}$ $(=\mathbf{1}+\mathbf{8})$ intermediate quark-antiquark state is in a color singlet state. Because color source of hadrons, only the color octet states yield hadronic asymptotic states. The nable guess that

$$F_2^{(gap)} = \frac{1}{1+8} F_2 \qquad (1)$$

ws from this argument.

lthough this is only a guess, it embodies the essential physics: events with and withgaps are described by the same short-distance dynamics. Essentially non-perturbative -state interactions dictate the appearance of gaps whose frequency may, possibly, be rmined by simple counting. The treatment of color is the same as in the case of heavy k production and leads to similar predictions: the same perturbative mechanisms, i.e. n exchange, dictates the dynamics of color-singlet gap (ψ) and regular deep inelastic n charm) events.

)ur proposal for the (soft) nature of color challenges the orthodox mechanism for prong rapidity gaps sketched in Fig. 2b, where the t-channel exchange of a pair of gluons color singlet state is the origin of the gap. The color string which connects photon proton remnants in diagrams such as the one in Fig. 2a, is absent and no hadrons are uced in the rapidity region separating them. The same mechanism predicts rapidity between a pair of jets produced in hadronic collisions; see Fig. 3a. These have been rved and occur with a frequency of order of one percent[14, 15, 16].

'he arguments developed in this paper question the hard Pomeron approach: it is as ingless to enforce the color singlet nature of the gluon pair as it is to require that the $c\bar{c}$ producing a ψ is colorless at the perturbative level. Following our color scheme the gaps nate from a mere final state color bleaching phenomenon *à la* Buchmüller and Hebecker. can be visualized using the diagram shown in Fig. 3b. At short distances it represents a entional perturbative diagram for the production of a pair of jets. Therefore, the same distance dynamics governs events with and without rapidity gaps, as was the case for roproduction. This is consistent with all experimental information.

roducing a quantitative model for the gap rate may be premature at this point. There t least two consistent interpretations of the present data. The first is based on the g picture for the formation of the final state hadrons shown in Fig. 3b. Color in the state is bleached by strings connecting the **3** jet at the top with the $\bar{\mathbf{3}}$ spectator di-quark e bottom and vice-versa, resulting in color singlet states at the top and bottom. The ability to form a gap can be counted *à la* Buchmüller and Hebecker to be $1/(1+8)^2$ use it requires the formation of singlets in 2 strings. The data[14, 15, 16] is consistent this simple picture which basically predicts that the gap fraction between $p\bar{p}$ jets is the re of that between virtual photon and proton in deep inelastic scattering. One could, natively, argue that, once color has been bleached between one $\mathbf{3}$–$\bar{\mathbf{3}}$ pair, overall color ervation will guarantee the color singlet value of the other pair. This leads to a gap ation rate which is similar in lepto- and hadroproduction, and can be reconciled with lata by introducing a survival probability. The survival probability accounts for the that gaps can be filled by the underlying event, e.g. mini-jet production[17], or by er order processes. The survival probability of the gap is expected to be smaller for oproduction than electroproduction, thus accommodating the data.

)iscussions of rapidity gap physics have routinely ignored that, besides quark-quark, 1-gluon and gluon-quark subprocesses contribute to jet production in hadron collisions. .e gluon-gluon color flow diagram corresponding to Fig. 3b top and bottom protons each into a color octet gluon and a 3-quark remnant in a color octet state. There are now $8)^2$ color final states. Despite the fact that we can at best guess the non-perturbative .mics, it is clear that the soft color formalism predicts a gap rate which is smaller in 1-gluon interactions. This is in contrast with the 2-gluon exchange diagram of Fig. 3a h predicts a gap-rate enhanced by a factor $\left(\frac{9}{4}\right)^2$ in gluon-gluon subprocesses[18]. The ess is clearly enhanced when replacing the interacting quarks by gluons, because of arger gluon-gluon color coupling. The contrasting predictions can be easily tested by ncing the relative importance of quark-quark subprocesses in the experimental sample. can be achieved by increasing the p_T of the jets at fixed energy, or by decreasing the ion energy of the hadrons at fixed p_T. In either case, we anticipate an increased rate for roduction of gaps in the soft color scheme; a prediction opposite to that of the 2-gluon ange model. We next confront the contrasting predictions with recent data[1].

ntroducing the quantities F_{QQ}, F_{QG}, and F_{GG} which represent the frequencies for prong rapidity gaps between a pair of high-p_T jets in hadronic quark-quark, quark-gluon, gluon-gluon collisions, we can write the observed gap fraction as

$$F_{gap}(E_T) = \frac{1}{d\sigma/dE_T}\left(F_{QQ}\frac{d\sigma_{QQ}}{dE_T} + F_{QG}\frac{d\sigma_{QG}}{dE_T} + F_{GG}\frac{d\sigma_{GG}}{dE_T}\right) \quad , \tag{2}$$

e

$$d\sigma = d\sigma_{QQ} + d\sigma_{QG} + d\sigma_{GG} \tag{3}$$

esents the decomposition of the cross section for producing large-E_T jets into quark-k, quark-gluon and gluon-gluon subprocesses. Predictions can be summarized in terms e gap fractions F_{ij}. For the 2-gluon hard Pomeron model[18]

$$F_{QQ} : F_{QG} : F_{GG} = 1 : \frac{9}{4} : \left(\frac{9}{4}\right)^2 \quad . \tag{4}$$

.e soft color calculational scheme the F_{ij} are independent of the center–of–mass energy E_T, satisfying

$$F_{QQ} : F_{QG} : F_{GG} = a : b : c \ , \tag{5}$$

$c < b < a$, in contrast with Eq. (4). Reasonable guesses fall in the range

$$(1/9)^2 < a < 1/9 \ , \tag{6}$$

$$ac < b < \sqrt{ac} \ , \tag{7}$$

$$(1/64)^2 < c < 1/64 \ . \tag{8}$$

n order to determine the gap fractions F_{ij}, we computed the transverse cross sections $/dE_T$ in lowest order perturbative QCD, and subsequently fitted the preliminary DØ [1] shown in Fig. 4. We integrated over the E_T bins given in Table I, imposing that jets have $|\eta| > 1.9$. The 90% CL bounds on the F_{ij} are

$$\begin{aligned} F_{QQ} &= 0.023^{+0.010}_{-0.011} \ , \\ F_{QG} &= 0.00017^{+0.012}_{-0.000} \ , \\ F_{GG} &= 0.0075^{+0.0081}_{-0.0073} \ . \end{aligned} \tag{9}$$

lso show in Fig. 4 the result of our fit.

he data shows that rapidity gaps are mostly formed in quark-quark collisions with the of F_{QQ} exceeding those of F_{GG} and F_{GQ}. The 90% CL upper limits on F_{QG} and F_{GG} are 2 and 0.016, respectively. The dominance of F_{QQ} simple reflects the experimental fact the fraction of events with gaps increases with E_T as the leading order QCD result for $_Q/dE_T)/(d\sigma/dE_T)$; see Table I. Clearly, the data is consistent with the soft color model ne formation of rapidity gaps and does not support the 2-gluon exchange approximation h predicts that processes involving gluons should exhibit larger rapidity gap frequencies. data can be interpreted in terms of the simple color counting previously introduced, h predicts $F_{QQ} \simeq (0.2–0.4)/9 \simeq 2–4\ 10^{-2}$ and $F_{GG} \simeq (0.2–0.4)/64 \simeq 3–6\ 10^{-3}$ for a val probability[19] of 0.2–0.4. This is certainly compatible with our results given the rtain systematics of our procedure.

ur formalism has non-trivial dynamics built in. It assumes that the gap fractions F_{ij} ndependent of any kinematic variables. Therefore, the observed fraction of rapidity gaps nds on kinematical variables only through the relative contributions of the 3 subprocess sections σ_{QQ}, σ_{QG}, and σ_{GG}. The observed gap fractions are, for instance, a function $_T$ only at fixed center–of–mass energy, as shown in Fig. 5. The E_T distribution was outed using uniform binning at Tevatron and LHC energies. Furthermore, we also ict that the gap frequencies are only a function of the scaled variable $x_T = E_T/\sqrt{s}$. efore, the gap frequencies are described by a universal curve at all energies; see Fig. 6.

t LHC energy, the fraction of events exhibiting rapidity gaps associated with moder- E_T jets (< 80 GeV) is quite small ($\sim 0.6\%$) due to the large gluon-gluon luminosity. vithstanding, we anticipate 40 spectacular events for $E_T > 200$ GeV because the gap uency increases to $\sim 0.8\%$ in this E_T range. On a more practical note, overlapping ts may make such observations challenging.

he DØ Collaboration has also measured the dependence of the fraction of events with lity gaps as a function of the rapidity separation of the leading jets for $E_T > 30$ GeV $|\eta| > 1.7$ [20]. Our predictions are successfully confronted with their recent data[1] in 7.

he soft color mechanism can also give rise to rapidity gaps with a different ordering in lity: near the beam are the remnants of an initial hadron, followed by a rapidity gap and hard jets which are separated from the other hadron debris by yet another rapidity gap. e events represent diffractive gaps. In the context of the color evaporation model, quark- k and quark-gluon collisions cannot initiate such events because of the impossibility to ralize the color of the **3** ($\bar{\mathbf{3}}$) remnants with the exchange of soft gluons. Therefore, events only originate in gluon-gluon collisions, and their fraction should decrease with asing E_T, or decreasing center-of-mass energy.

Ve close with some cautionary comments. Do Figs. 2–3 suggest that we have formulated native s- and t-channel pictures to view the same physics? Although they seem at radically different, this may not be the case. Computation of the exchange of a pair olorless gluons in the t-channel is not straightforward and embodies all the unsolved eries of constructing the "Pomeron" in QCD. In a class of models where the Pomeron nstructed out of gluons with a dynamically generated mass[17, 21], the diagram of 3a is, not surprisingly, dominated by the configuration where one gluon is hard and the r soft. The diagram is identical to the standard perturbative diagram except for the ence of a soft, long-wavelength gluon whose only role is to bleach color. Its dynamical is minimal, events with gaps are not really different from events without, suggesting mics similar to color evaporation. Some have argued that in this class of models the Pomeron is no more than an order α_s^2 correction, a view which can be defended on solid theoretical ground[22]. Others have however challenged the theoretical soundness is line of thinking[19, 23]. Also note that our discussion is at best indirectly relevant to pletely non-perturbative phenomena like elastic scattering. There is no short distance defined by a large scale. The Pomeron exists.

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ABLE I. E_T bins used in Fig. 4 and its respective mean value $\bar{E}_T$. For comparison, we also de the cross section integrated over the bins for the quark-quark, quark-gluon, and gluon-gluon ocesses.

GeV)	E_T bin (GeV)	$\int \frac{d\sigma_{QQ}}{dE_T}(pb)$	$\int \frac{d\sigma_{QG}}{dE_T}(pb)$	$\int \frac{d\sigma_{GG}}{dE_T}(pb)$
1.0	15-25	60.8	197	163
.8	25-30	3.25	7.19	4.02
.1	30-35	1.12	2.07	0.97
.3	35-40	0.43	0.68	0.27
.5	40-45	0.18	0.26	0.084
.7	45-50	0.079	0.093	0.028
.4	50-60	0.056	0.057	0.014
.5	> 60	0.027	0.020	0.004

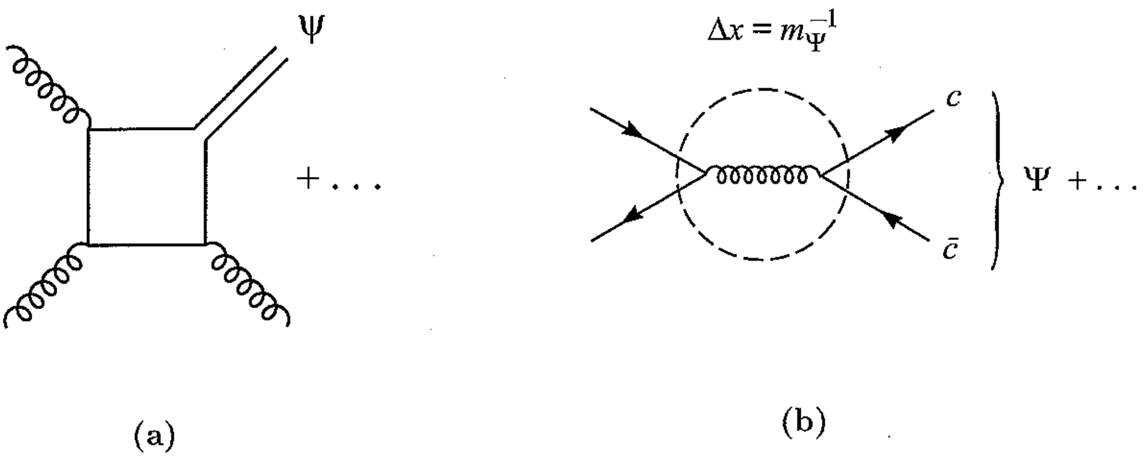
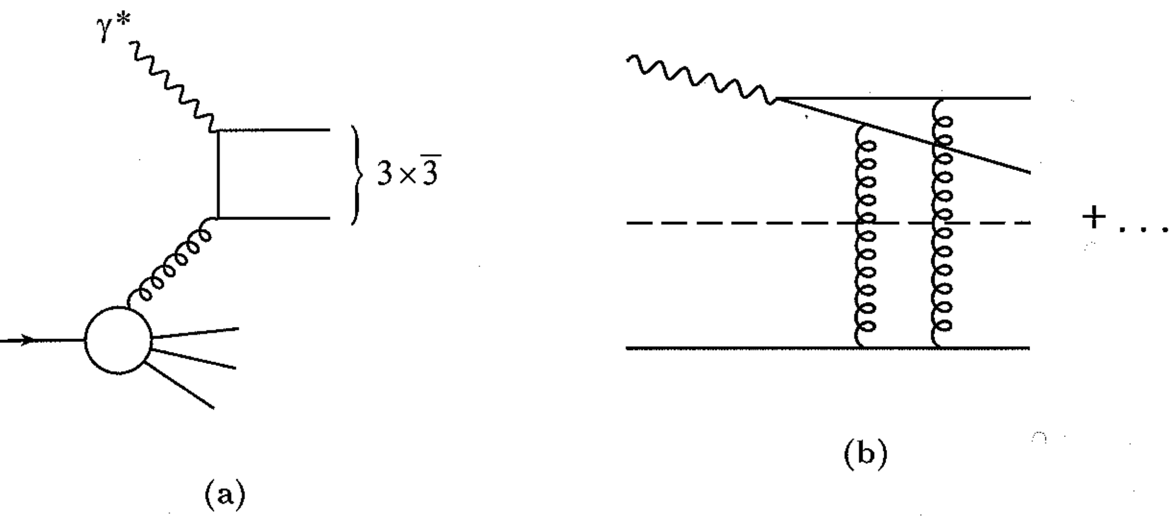
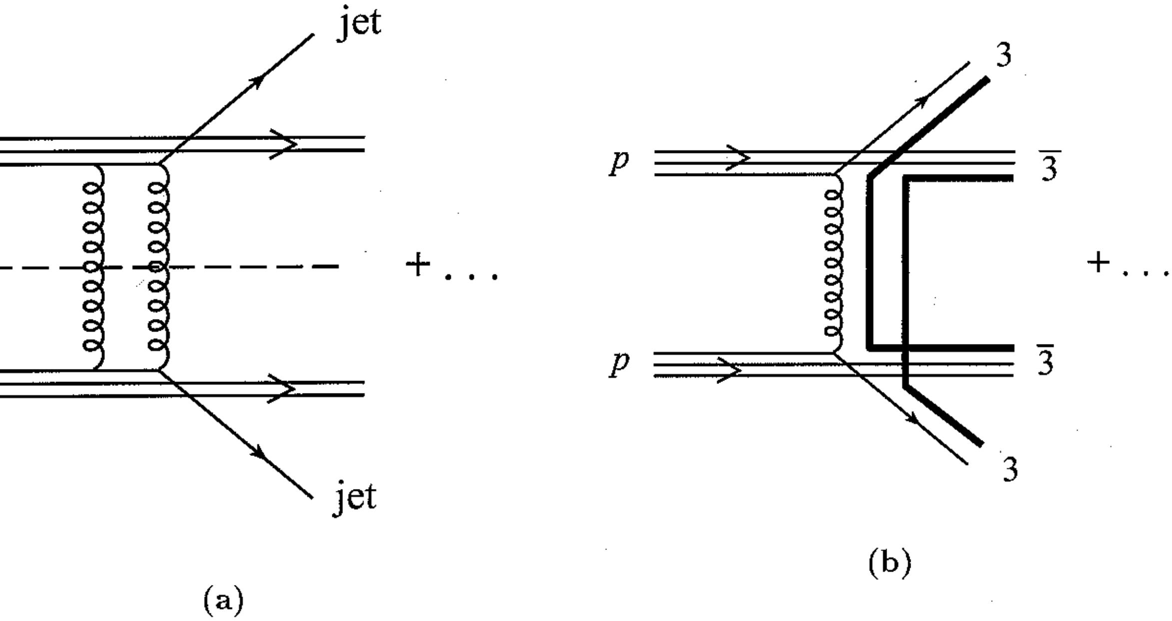


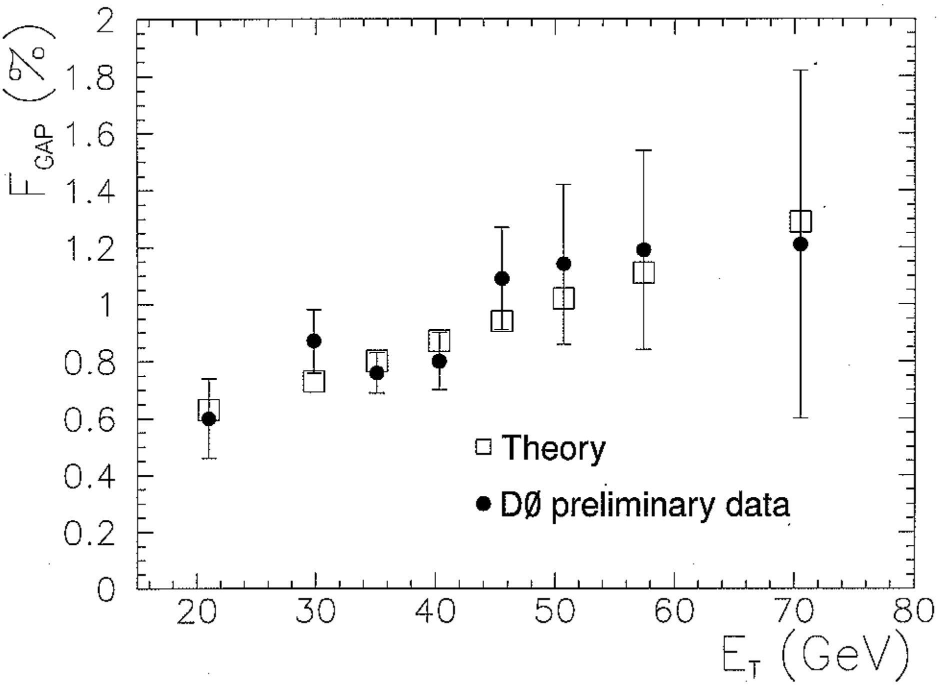
FIG. 1. Quarkonium production: (a) Color Singlet Model; (b) Color Evaporation Model.



IG. 2. Rapidity gaps in deep inelastic scattering: (a) due to soft colors effects; (b) due to eron exchange.



IG. 3. Rapidity gap between jets: (a) due to Pomeron exchange; (b) due to soft color interns.



IG. 4. Theoretical fit to the DØ preliminary data[1]. Notice that each point shown has a ent E_T bin, with the data being plotted at the mean value of E_T for each bin, which is given ble I.

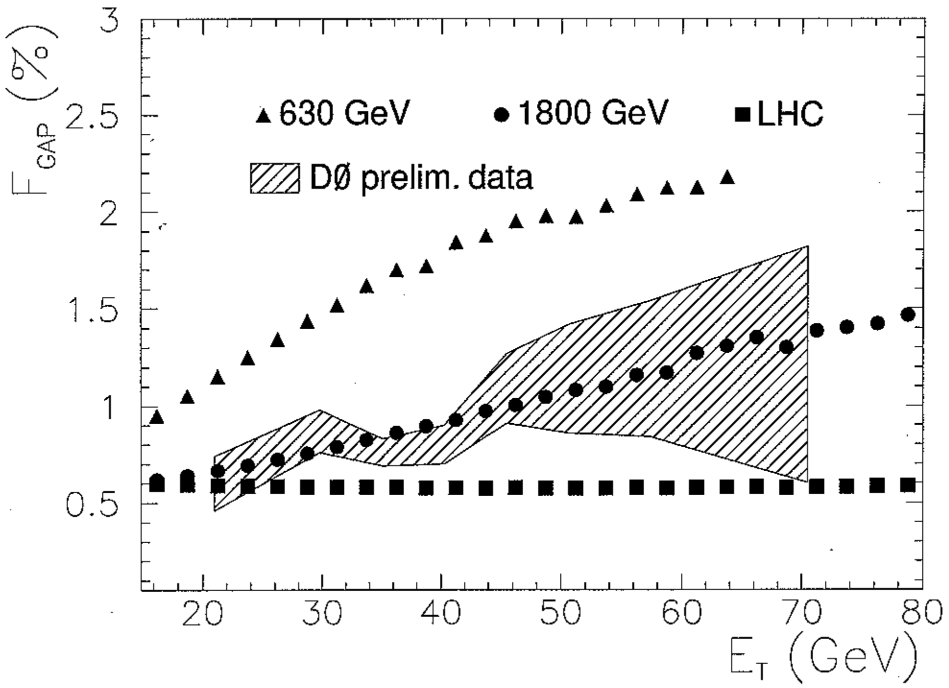
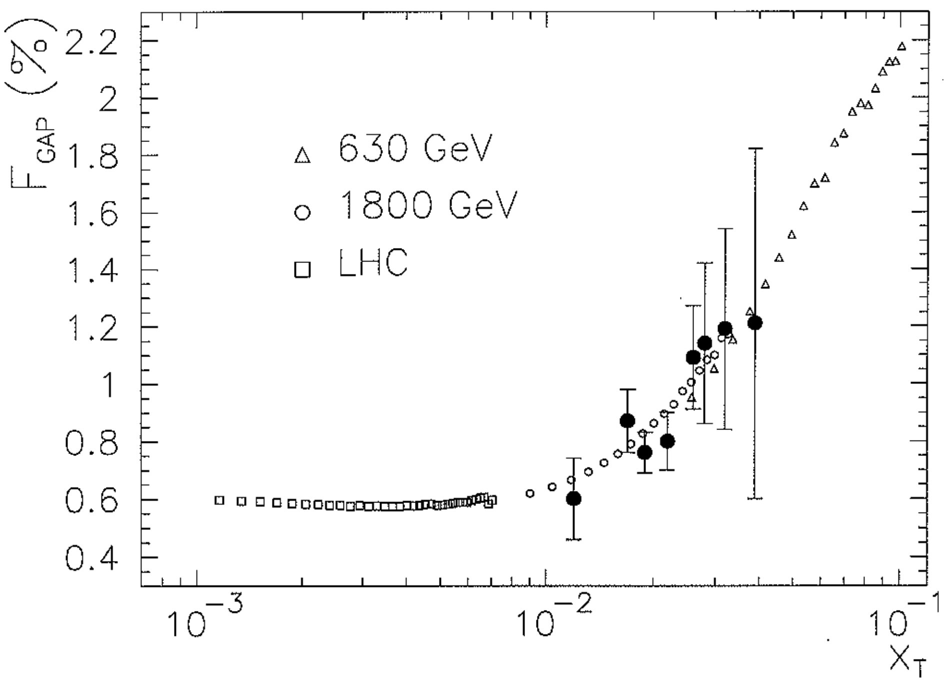
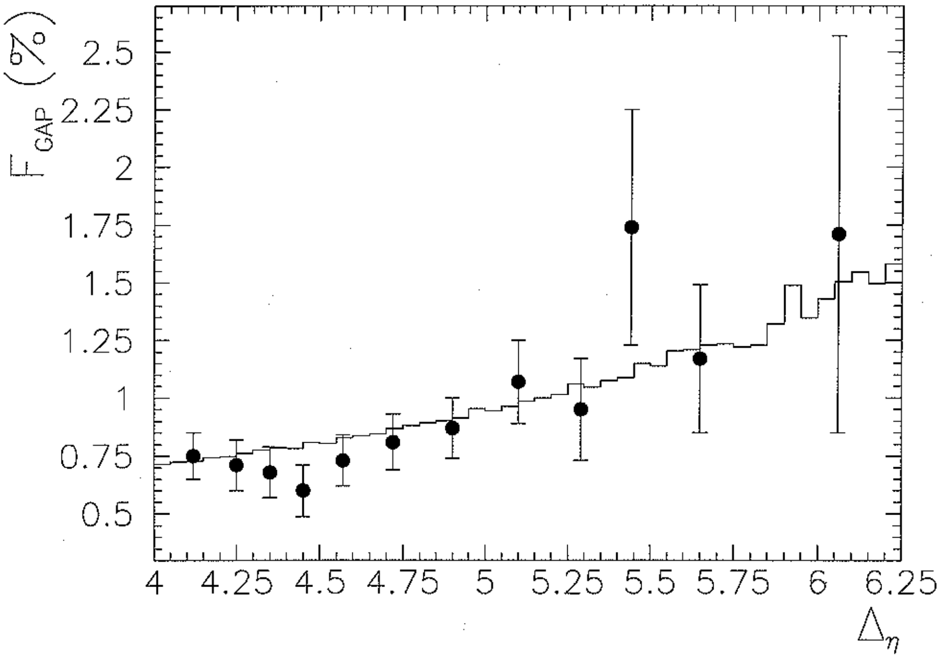


FIG. 5. Our model predictions for rapidity gaps between jets at Tevatron and LHC.



IG. 6. Same results of Fig. 5 as function of the adimensional variable $x_T = E_T/\sqrt{s}$. For
arison we exhibit the recent DØ data[1].



IG. 7. Comparison with the preliminary DØ data[1] of our model prediction for the rapidity fraction as function of the size of the gap.