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Rapidity-Gap Events in e^+e^- Annihilation*

James D. Bjorken
Stanley J. Brodsky
Hung Jung Lu

Stanford Linear Accelerator Center, Stanford, CA 94309

Abstract

We discuss the significance of events containing rapidity-gaps in high-energy scattering processes, in particular in e^+e^- annihilation and/or W, Z decays. We compute explicitly the fraction of events containing rapidity-gaps in $e^+e^- \to q\bar{q}q\bar{q}$ and $e^+e^- \to q\bar{q}gg$ processes at low jet-pair invariant mass limit. These events follow a distinctive $\sin^2\theta$ distribution in the jet-pair scattering angle. Similar processes are candidate backgrounds for important Higgs and W^+W^- scattering physics at the SSC and LHC.

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In soft and hard diffraction processes we encounter events containing "rapidity-gaps", i.e., regions of longitudinal phase space containing no produced particles. These events are commonplace in hadron-hadron collisions but rare in e^+e^- annihilation into hadronic final states. This is a consequence of the fact that many initial-state angular momenta are allowed in the former case, but not in the latter. In addition, in the case of e^+e^- annihilation, the color separation of the produced color-triplet quark and antiquark requires a mechanism which fills in the gap [1]–at least most of the time. Nevertheless, there must be exceptions. For example, the decay rate for $Z \to \pi\pi$ is small but non-vanishing at all energies, and it produces a splendid rapidity gap.

In this paper we study what seems to be the most probable parton-level mechanisms for producing rapidity-gaps in e^+e^- annihilation and/or Z decay processes. While small rapidity-gaps may be produced via random fluctuations, we are interested here in mechanisms intrinsic to QCD that use the concept of color screening [2]. We have recently learned that such mechanisms were first studied twelve years ago by J. Randa [3], and his paper contains the central ideas of this one. In the intervening years since Randa's work the context has changed, and there are new reasons to reconsider Randa's mechanisms, the most important of which is the existence of LEP and SLC.

In Fig. 1 we depict two Feynman diagrams of these processes. Consider, for instance, the process indicated in Fig. 1(a). In the center-of-mass frame, the quark and antiquark in the upper pair are produced in almost the same direction in space to the left, and similarly the lower pair is produced collinearly to the right. The color algebra analysis reveals that 88.9% of the time these $q\bar{q}$ pairs are produced in color-singlet states. Under these circumstances, the two ultrarelativistic small color-dipoles of this early-time configuration recede from each other at nearly the speed of light. Because of time-dilatation, their spatial growth is slow, and by the time they have matured to a size of order one fermi, they are too far apart to interact [1,4]. A similar situation happens with the $q\bar{q}$ and gg pairs in Fig. 1(b), although the color algebra is less favorable in this case – only 12.5% of the time do these jet pairs form separate color-singlet states.

We find that in e^+e^- annihilation and Z-decays, these events are expected to be rare but to occur at an observable rate. An experimental search for them is of interest for several reasons:

1. If gap events are found at a rate larger than expected, say, in Z-decay, it can be new physics:

$$\begin{aligned} &Z \to X + \overline{X} \quad , \\ &X, \overline{X} \to \text{hadrons} \quad , \end{aligned} \tag{1}$$

   with X a colorless object of low enough mass to be relativistic and produce the rapidity-gap: in practice $m_X \leq 5 - 10$ GeV is sufficient to produce a good gap.

2. Rapidity gaps plus jets in hadron-hadron collisions may provide important new-physics and QCD signatures. A prime example [5,6] is the case of

$$p\, p \to Higgs + X \quad , \tag{2}$$

   where the underlying subprocess is (Fig. 2)

$$W^+W^- \to Higgs \to W^+W^- \to q\bar{q}q\bar{q} \quad . \tag{3}$$

These events are very distinctive and can be defined by even a simple detector. Some possible backgrounds to this process are indicated in Fig. 3a and Fig. 3b. A good understanding of the background processes is needed in order to extract the underlying Higgs physics. Therefore, experience from e^+e^- phenomenology will be valuable in calibrating the situation there.

3. Rapidity gap events should be statistically distinguishable from random fluctuation of other jet events. Unlike two-jet events, where there is a uniform production of final state hadrons per unit rapidity between the two jets, for large-gap events we expect few or no hadron fragments to be produced between the two color-singlet clusters [7]. The measurement of gap events provides an important and non-trivial test of the conventional ansatz that hadron production follows the color flow of the colored objects.

4. A detailed measurement of rapidity gap events provides a new test of perturbative QCD, where the argument of α_s is controlled by the kinematics (see Eq. (10) below.)

5. In the limit where the invariant masses of the jet-pairs become small and finite, one connects with the conventional analyses of exclusive (both invariant masses small) and semi-exclusive (one small, one large) processes [8]. For finite invariant masses, the power-law behavior of the cross sections agree with perturbative QCD dimensional counting.

An appropriate tool for the analysis of multi-hadron final states is the so-called lego plot [9], where the various produced hadrons are described by their rapidity y (or pseudorapidity η), their azimuthal angle ϕ and their transverse momentum

p_t, all relative to a specified axis. The reference axis is often chosen to lie in the beam direction.

In Fig. 4 we depict a typical lego plot for the process $e^+e^- \rightarrow q\bar{q}q\bar{q}$ shown in Fig. 1(a). The hadronic fragments are produced around each color-singlet jet-pair, leaving a rapidity gap between the two clusters. The $e^+e^- \rightarrow q\bar{q}gg$ process features a similar lego plot, with a gg-pair replacing one of the $q\bar{q}$-pairs.

From dimensional counting, the ratio of total rapidity gap events to the total hadronic events is expected to fall like

$$R_{\text{gap}} = \sigma_{\text{gap}}/\sigma_{\text{tot}} \sim \alpha_s^2 \left(\frac{M_1^2}{s}\right)\left(\frac{M_2^2}{s}\right) \quad , \tag{4}$$

where M_1 and M_2 are the invariant masses of the jet-pairs and s the square of the total center-of-mass energy. The event rate of color-singlet jet-systems involving more quarks or final-state gluons are down by additional factors of α_s/s due to the presence of more gluon propagators.

An important feature of rapidity-gap events is that physical quantities referring only to the global properties of the clusters are insensitive to the QCD hadronization process. The event rate for this process is thus computable from perturbative QCD.

In the following we will neglect quark masses and only consider the small invariant jet-pair mass limit: $M_1^2, M_2^2 \ll s$. In this limit, the particles within each pair are essentially collinear. The kinematic variables can be specified as indicated in Fig. 1, where P_1 and P_2 are the four-momenta of the jet-pairs, and x_1 and x_2 are the momentum fractions carried by a particular jet within each jet-pair.

We will perform our calculation for the Z-boson mediated case. The virtual photon mediated case can be readily obtained by reinterpreting the various parameters in the formulae for the Z-boson mediated case (see Eq. (16) below.)

It is convenient to introduce the following notation for the various weak charges involved in the matrix element computation. We define the two-component weak charge of a fermion f to be:

$$\mathbf{Q}_f \equiv \begin{pmatrix} Q_f^L \\ Q_f^R \end{pmatrix} = \begin{pmatrix} \sec\theta_W I_f - \sin\theta_W \tan\theta_W Q_f \\ -\sin\theta_W \tan\theta_W Q_f \end{pmatrix} \quad , \tag{5}$$

where θ_W is the weak angle, I_f the isospin and Q_f the electric charge of the fermion f. Using this notation, the total e^+e^- annihilation cross section around the Z resonance can be conveniently expressed as

$$\sigma_Z = \frac{\pi}{3} \frac{\mathbf{Q}_e^2 \mathbf{Q}_Z^2 \alpha_W^2 s}{(s - M_z)^2 + \Gamma_Z^2 M_Z^2} \quad , \tag{6}$$

with

$$\begin{aligned} &\mathbf{Q}_Z^2 = \sum_f \mathbf{Q}_f^2 = \sum_l \mathbf{Q}_l^2 + 3 \sum_q \mathbf{Q}_q^2 \simeq 3.771 \quad , \\ &(l = e, \mu, \tau; q = u, d, c, s, b), \\ &\mathbf{Q}_f^2 = {Q_f^L}^2 + {Q_f^R}^2 \quad , \\ &\alpha_W = \frac{g_W^2}{4\pi} = \frac{e^2}{4\pi \sin^2\theta_W} \simeq \frac{1}{29.3} \quad , \\ &M_Z, \Gamma_Z = \text{mass and width of the Z boson.} \end{aligned} \tag{7}$$

We shall later use this cross section to normalize the production rate of rapidity-gap events. Initial-state radiation induces a substantial correction to the above result for σ_Z [10]. However, the same effect is present in rapidity-gap events; thus we expect these effects to largely cancel when we consider the ratio of the cross sections.

The helicity-averaged squared matrix element for color-singlet jet-pair final states with two different quark flavors a and b is given by

$$
\begin{aligned}
|\mathcal{M}_{q\bar{q}q\bar{q}}|^2 = \left(\frac{8}{3}\right)^2 \frac{(4\pi)^4 \alpha_W^2 \mathbf{Q}_e^2 \sin^2\theta}{(s-M_z)^2 + \Gamma_Z^2 M_Z^2} \Big\{ & \mathbf{Q}_a^2 \alpha_s^2(\mu_1^2) F(x_1, x_2) \\
& + \mathbf{Q}_b^2 \alpha_s^2(\mu_2^2) F(x_2, x_1) - 2\mathbf{Q}_a \cdot \mathbf{Q}_b \alpha_s(\mu_1^2) \alpha_s(\mu_2^2) \Big\} \quad ,
\end{aligned}
\tag{8}
$$

where θ is the scattering angle that the first jet-pair forms with the beam direction, and

$$
F(x_1, x_2) = \frac{x_1}{1-x_1} \frac{1-x_2}{x_2} \quad . \tag{9}
$$

If the momentum squared of the exchanged gluon is considered as the natural scale for the strong coupling constant, then the coupling scales in Eq. (8) in the $\overline{\mathrm{MS}}$ scheme are given by (see Ref. [11])

$$
\begin{aligned}
\mu_1^2 &= e^{-5/3}\,(1-x_1)x_2\, s \quad , \\
\mu_2^2 &= e^{-5/3}\,(1-x_2)x_1\, s \quad .
\end{aligned}
\tag{10}
$$

By studying rapidity-gap events over a range of kinematic regions, in principle we can test this hypothesis and study the running of the strong coupling constant. However, in the following we shall perform our calculation by treating α_s as constant.

Notice that, remarkably, the angular distribution of the two hadronic systems has a $\sin^2\theta$ law rather than the usual $1+\cos^2\theta$ distribution expected for spin 1/2 quarks. This follows because of helicity conservation and the fact that the hadronic systems are effectively super-mesons produced with total spin-projection $J_z = 0$ or 2.

Similarly, after summing and averaging the helicities of the various initial and final particles, symmetrizing the roles of $q\bar{q}$ and gg jet-pairs, and taking into account the identical-particle nature of the two gluons inside the colorless gg jet-pair, the squared-amplitude for the process $q\bar{q}gg$ is given by

$$|\mathcal{M}_{q\bar{q}gg}|^2 = \frac{4}{3}\frac{(4\pi)^4\alpha_W^2\alpha_s^2\mathbf{Q}_e^2\mathbf{Q}_a^2\sin^2\theta}{(s-M_z)^2+\Gamma_Z^2M_Z^2}\Big\{G(x_1)+G(x_2)\Big\} \ , \tag{11}$$

where

$$G(x_1) = \frac{1}{x_1(1-x_1)} \ . \tag{12}$$

Notice that this amplitude also shares the $\sin^2\theta$ law pointed out previously.

The phase space integral can be expressed in term of the kinematic variables M_1^2, M_2^2, x_1, x_2 and θ, where M_1 and M_2 are the invariant masses of the first and second jet-pair, respectively. The differential cross-section has the following expression in the small-invariant-mass limit

$$d\sigma = \frac{|\mathcal{M}|^2}{8(4\pi)^5 s} dM_1^2 dM_2^2 dx_1 dx_2 d\cos\theta \ . \tag{13}$$

Summing over all possible flavor combinations we obtain

$$\begin{aligned} R_{q\bar{q}q\bar{q}} = \frac{\sigma_{q\bar{q}q\bar{q}}}{\sigma_Z} &= \frac{N_q}{3}\left(\frac{\alpha_s}{\pi}\right)^2\frac{\mathbf{Q}_{\mathrm{had}}^2}{\mathbf{Q}_Z^2}\int\frac{dM_1^2}{s}\frac{dM_2^2}{s}dx_1dx_2d\cos\theta \\ &\qquad \sin^2\theta\left\{F(x_1,x_2)+F(x_2,x_1)-2\rho_{\mathrm{had}}\right\} \ , \\ R_{q\bar{q}gg} = \frac{\sigma_{q\bar{q}gg}}{\sigma_Z} &= \frac{1}{8}\left(\frac{\alpha_s}{\pi}\right)^2\frac{\mathbf{Q}_{\mathrm{had}}^2}{\mathbf{Q}_Z^2}\int\frac{dM_1^2}{s}\frac{dM_2^2}{s}dx_1dx_2d\cos\theta \\ &\qquad \sin^2\theta\left\{G(x_1)+G(x_2)\right\} \ , \end{aligned} \tag{14}$$

where, at the Z-peak we have

$$
\begin{aligned}
N_q &\equiv \text{number of light quark flavors} = 5 \quad , \\
\mathbf{Q}^2_{\text{had}} &\equiv \sum_q \mathbf{Q}^2_q \simeq 1.094 \quad , \\
\rho_{\text{had}} &\equiv \frac{\left(\sum_q \mathbf{Q}_q\right)^2}{N_q \sum_q \mathbf{Q}^2_q} \simeq 0.080 \quad ,
\end{aligned}
\tag{15}
$$

and the summation is performed over the various quark flavors (u, d, c, s, and b.) Notice that ρ_{had} is effectively the correlation index of the weak-charge system of the quarks.

For the virtual-photon-mediated case, we obtain similar expressions

$$
\begin{aligned}
R^{\gamma}_{q\bar{q}q\bar{q}} &= \frac{\sigma_{q\bar{q}q\bar{q}}}{\sigma(e^+e^- \to \text{hadrons})} = \frac{N_q}{9}\left(\frac{\alpha_s}{\pi}\right)^2 \int \frac{dM_1^2}{s}\frac{dM_2^2}{s} dx_1 dx_2 d\cos\theta \\
&\qquad \sin^2\theta \left\{F(x_1,x_2) + F(x_2,x_1) - 2\rho^{\gamma}_{\text{had}}\right\} \quad , \\
R^{\gamma}_{q\bar{q}gg} &= \frac{\sigma_{q\bar{q}gg}}{\sigma(e^+e^- \to \text{hadrons})} = \frac{1}{24}\left(\frac{\alpha_s}{\pi}\right)^2 \int \frac{dM_1^2}{s}\frac{dM_2^2}{s} dx_1 dx_2 d\cos\theta \\
&\qquad \sin^2\theta \left\{G(x_1) + G(x_2)\right\} \quad ,
\end{aligned}
\tag{16}
$$

where N_q is the number of light-quark flavors, and the electric-charge correlation index is

$$
\rho^{\gamma}_{\text{had}} \equiv \frac{\left(\sum_q Q_q\right)^2}{N_q \sum_q Q^2_q} = \begin{cases} 0 & \text{for } N_q = 3 \ , \\ 1/10 & \text{for } N_q = 4 \ , \\ 1/55 & \text{for } N_q = 5 \ . \end{cases}
\tag{17}
$$

(Here Q_q is the electric charge of the quark q, not to be confused with the two-component weak charge $\mathbf{Q}_q$.)

Now let us impose the gap conditions. We shall use the jet-pair direction as the reference axis for measuring rapidities. Experimentally, this direction may be identified as the thrust axis [12] in the collinear limit. The rapidities of the various quarks along the jet-pair axis have the following expressions

$$
\begin{aligned}
y_a &= \frac{1}{2}\ln(s/M_1^2) + \frac{1}{2}\ln\left(\frac{x_1}{1-x_1}\right) \quad , \\
y_{\bar b} &= \frac{1}{2}\ln(s/M_1^2) - \frac{1}{2}\ln\left(\frac{x_1}{1-x_1}\right) \quad , \\
y_b &= -\frac{1}{2}\ln(s/M_2^2) - \frac{1}{2}\ln\left(\frac{x_2}{1-x_2}\right) \quad , \\
y_{\bar a} &= -\frac{1}{2}\ln(s/M_2^2) + \frac{1}{2}\ln\left(\frac{x_2}{1-x_2}\right) \quad .
\end{aligned}
\tag{18}
$$

Let us consider the case of a symmetric gap cut (see Fig. 4); that is, we will integrate out all gap events where the quarks and antiquarks belonging to different jet-pairs have rapidities with absolute value larger than $g/2$. Due to the hadronization process, the hadron fragments of each quark jet are concentrated within a circle of radius ~ 0.7 in the lego plot (see Ref. [5-7,9]). Thus the physically observed gap is expected to have a width $g_{\rm eff} \simeq g - 1.4$. An analytical expression can be obtained for the production rate of rapidity-gap events with a symmetric gap cut

$$
\begin{aligned}
R^{\rm sym}_{q\bar q q\bar q}(g) &= \frac{40}{9}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{\mathbf{Q}^2_{\rm had}}{\mathbf{Q}^2_Z}\left[(2-2\ln 2)^2 - (2\ln 2 - 1)^2 \rho_{\rm had}\right]\exp(-2g) \quad , \\
R^{\rm sym}_{q\bar q gg}(g) &= \frac{2}{3}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{\mathbf{Q}^2_{\rm had}}{\mathbf{Q}^2_Z}\left[2\ln 2 - 1\right]\exp(-2g) \quad .
\end{aligned}
\tag{19}
$$

From these expressions, we can see that the process $q\bar q gg$ is subleading to the process $q\bar q q\bar q$ by a factor $R^{\rm sym}_{q\bar q gg}/R^{\rm sym}_{q\bar q q\bar q} \sim 0.159$.

In Fig. 5 we plot the production rate $R^{\rm sym}_{\rm gap} = R^{\rm sym}_{q\bar q q\bar q} + R^{\rm sym}_{q\bar q gg}$ per million Z events, for values of the strong coupling constant in the range $0.10 \le \alpha_s \le 0.15$. (The effective value of α_s is somewhat larger than $\alpha_{\overline{\rm MS}}(M_z^2)$ due to the softer momenta carried by the virtual gluons. See Eq. (10).) Notice that the gap condition automatically imposes a cut in the invariant masses of the jet-pairs

$$M_1^2, M_2^2 \leq \exp(-g)\ s \quad . \tag{20}$$

Thus the small invariant mass approximation is valid for large values of g. Incidentally, the gap condition also eliminates the typical collinear divergences associated with jet events, because the quark and antiquark originating from the gluon propagator are required to go in opposite directions across the gap. Therefore the momentum squared of the virtual gluon is generally hard.

Now let us relax the condition of requiring a symmetric gap cut. We compute next the rate of events where the particles of the one jet-pair are separated from the particles of the other jet-pair by a gap larger than g, independent of the location of the gap. The numerical result of $R_{\text{gap}} = R_{q\bar{q}q\bar{q}} + R_{q\bar{q}gg}$ is plotted in Fig. 6 for various values of invariant mass cut: $M_1, M_2 \leq M_c$. We expect the approximation of small invariant mass to break down around $M_c \gtrsim 0.3\ s^{1/2}$.

From our calculation we can see that events with a three- or more-unit rapidity gap should be observable (recall that there are currently $\sim 2 \times 10^6$ Z-events at LEP). Physically these events would only have gaps of width ~ 1.6 or more due to the smearing effect in the hadronization stage. However, further study is clearly needed in order to separate rapidity-gap events from random fluctuations of non-gap events [13].

While we have concentrated on e^+e^- processes in this paper, there are other processes where a search is appropriate. For example in ep collisions at HERA, the process which we have computed has its analogue in the search for a transverse rapidity-gap in the photon fragmentation region (Fig. 7a). Note that more conventional gaps arise from diffractive mechanisms in *ep* collisions (Fig. 7b) and are not to be confused with this process. Also note that because the gap is produced while the photon is "small", it is not affected by absorption corrections (the survival probability $< |S|^2 >$ discussed in Ref. [6]), provided the momentum partition of the leading "supermeson" is reasonably symmetric. This is not the case for the Drell-Yan process shown in Fig. 7(c), which may also be of interest. In such a process the considerations of this paper must be combined with those of Ref. [5,6], and further discussion of it is beyond the scope of this work.

In summary, we have computed the rapidity-gap event rate in e^+e^- annihilation process and obtained the event fraction containing gaps for small jet-pair invariant masses. We have shown that rapidity-gap events are a class of perturbatively-calculable processes of considerable interest for a variety of reasons. The measurement of rapidity-gap events allows us to search for new physics and to test perturbative QCD where the argument of α_s is controlled by the kinematics, with large logarithmic corrections absent. It is also an interesting test of the ideas of color flow and color screening in the phenomenology of QCD fragmentation.

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REFERENCES

[1] S. J. Brodsky and J. F. Gunion, Phys. Rev. Lett. 37 (1976) 402.

[2] For a description and references to color screening and color transparency, see
G. A. Miller, preprint DOE-ER-40427-27-N91;
L. Frankfurt, G. A. Miller and M. Strikman, preprint DOE-ER-40427-26-N91.

[3] J. Randa, Phys. Rev. D 21 (1980) 1795.

[4] The analogous situation in QED is known as the Chudakov effect, see
A. E. Chudakov, Izv. Akad. Nauk SSSR, Ser. Fiz. 19:650 (1955).

[5] Yu. L. Dokshitzer, V. A. Khoze and S. I. Troyan, in Proceedings of the 6th International Conference on Physics in Collision (1986), ed. M. Derrick, (World Scientific, Singapore, 1987),417;
Yu. L. Dokshitzer, V. A. Khoze and T. Sjöstrand, Phys. Lett. B 274 (1992) 116;
J. D. Bjorken, preprints SLAC-PUB-5545.

[6] J. D. Bjorken, preprint SLAC-PUB-5616.

[7] This has been checked explicitly via Monte-Carlo simulations by G. Greenbaum (private communication).

[8] See S. J. Brodsky and G. P. Lepage in Perturbative Quantum Chromodynamics, ed. A. H. Mueller, (World Scientific, Singapore, 1989), 93.

[9] See J. D. Bjorken, preprint SLAC-PUB-5593, for an extensive discussion of the uses of the lego plot.

[10] R. N. Cahn, Phys. Rev. D 36 (1987) 2666, J. P. Alexander, G. Bonvicini, P. S. Drell and R. Frey, Phys. Rev. D 37 (1988) 56.

[11] S. J. Brodsky, G. P. Lepage and P. M. Mackenzie, Phys. Rev. D28 (1983) 228.

[12] A. de Rújula, J. Ellis, E. G. Floratos and M. K. Gaillard, Nucl. Phys. B 138 (1978) 387; E. Farhi, Phys. Rev. Lett. 39 (1977) 1587.

[13] P. N. Burrows (private communication) has recently examined the gap distributions predicted by the Lund Monte-Carlo code; there appears to be a large background expected for gaps as large as 4 units due to statistical fluctuations in e^+e^- annihilation events.

FIGURE CAPTIONS

1) Two leading mechanisms for producing gap-events in e^+e^- annihilation: (a) $e^+e^- \rightarrow q\bar{q}q\bar{q}$, (b) $e^+e^- \rightarrow q\bar{q}gg$. The dashed lines indicate that the particle pairs are produced in color-singlet states; x_1 and x_2 are the momentum fractions carried by one of the particles within each pair. The exchanged boson can be either a Z-boson or a virtual photon.

2) A possible channel of detecting Higgs signature in p p collision. The quark-antiquark pairs are produced in color-singlet states; thus, a gap structure is expected to be present.

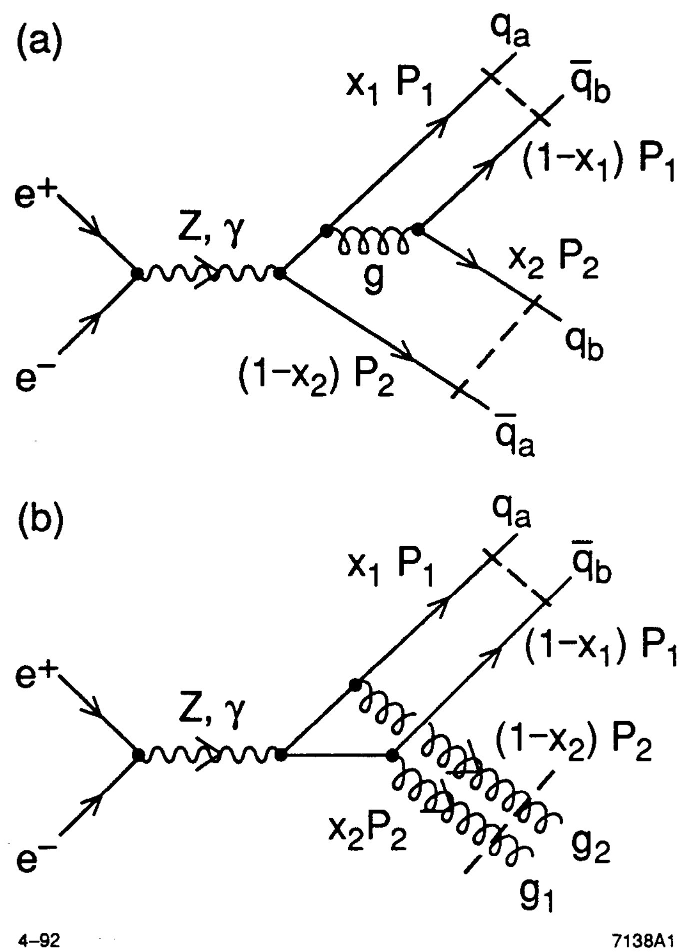
3) Some possible backgrounds to the process indicated in Fig. 2: (a) Generation of color-singlet jet-pairs through $W^+W^- \rightarrow Z \rightarrow q\bar{q}q\bar{q}$, (b) Pomeron-Pomeron scattering, where the final-state Pomerons decay into color-singlet jet-pairs.

4) A typical lego plot for a gap event associated with Fig. 1. In principle the gap needs not to be symmetric. The physically observed gap is expected to be $g_{eff} \simeq g - 1.4$ due to hadronization effects.

5) Number of rapidity-gap events per million Z-events, where the gap-cut is symmetric. The range of strong coupling constant considered is $0.10 \leq \alpha_s \leq 0.15$.

6) Number of events containing gaps larger than g, independent of the location of the gap. M_c is the jet-pair invariant-mass cut. The range of strong coupling constant considered is $0.10 \leq \alpha_s \leq 0.15$.

7) Some other processes exhibiting rapidity gaps: (a) Deep Inelastic Scattering experiment, (b) A background to the previous process through diffractive mechanism, (c) Drell-Yan processes. The event patterns in the lego plot are also presented. In (a), the event has been exhibited in extended phase space (see Ref. [9]).



(a)
q_a
$x_1\ P_1$
$\bar{q}_b$
$(1-x_1)\ P_1$
e^+
Z, γ
g
$x_2\ P_2$
q_b
e^-
$(1-x_2)\ P_2$
$\bar{q}_a$
(b)
q_a
$x_1\ P_1$
$\bar{q}_b$
$(1-x_1)\ P_1$
e^+
Z, γ
$(1-x_2)\ P_2$
x_2P_2
g_2
e^-
g_1
4–92
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Fig. 1

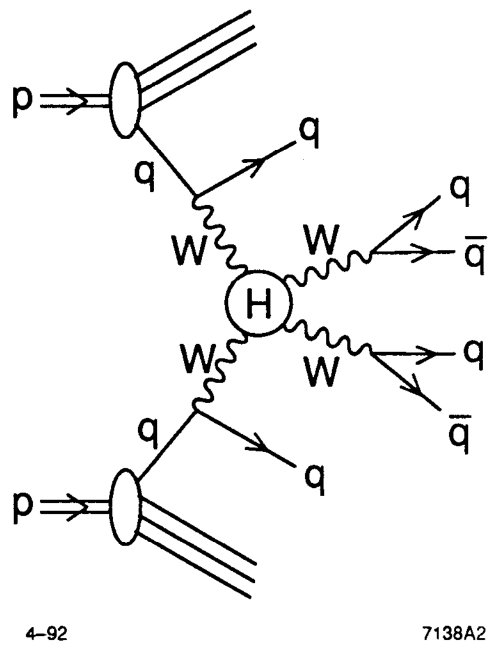


Fig. 2

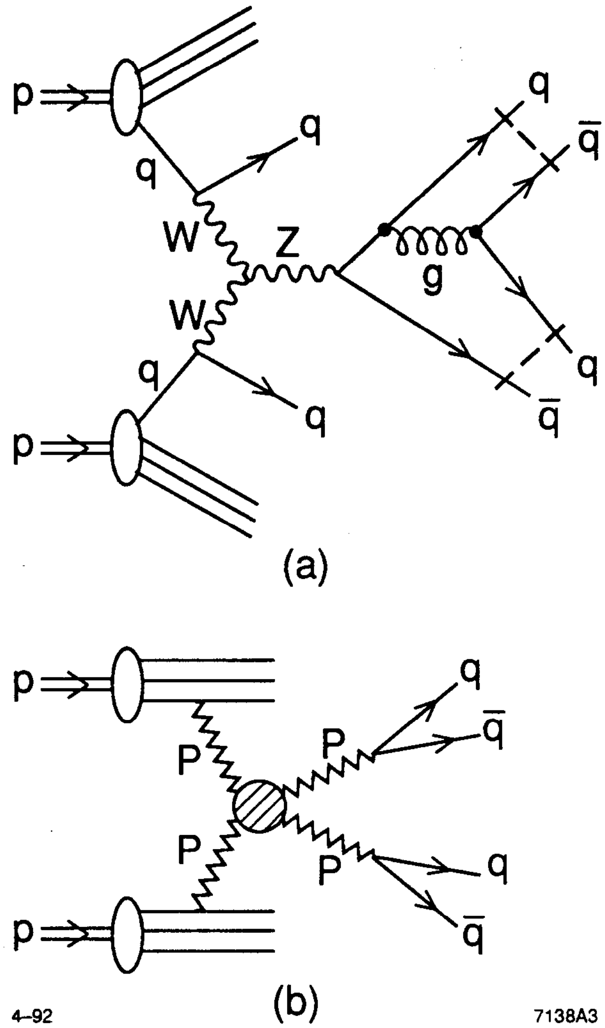


Fig. 3

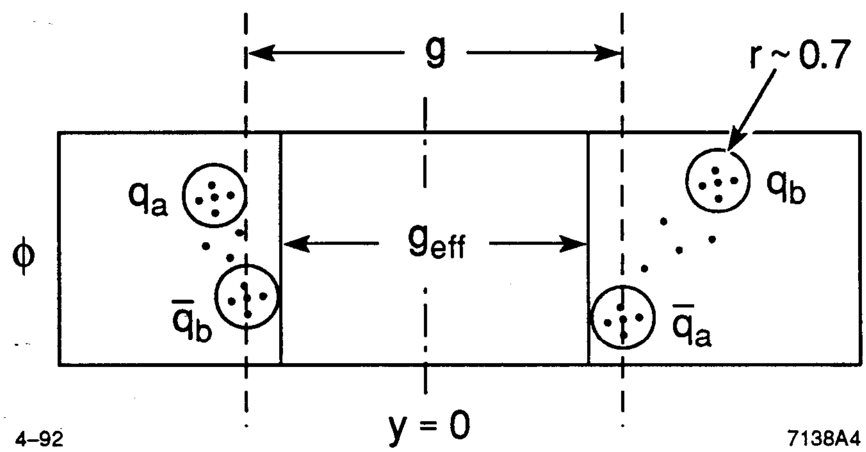
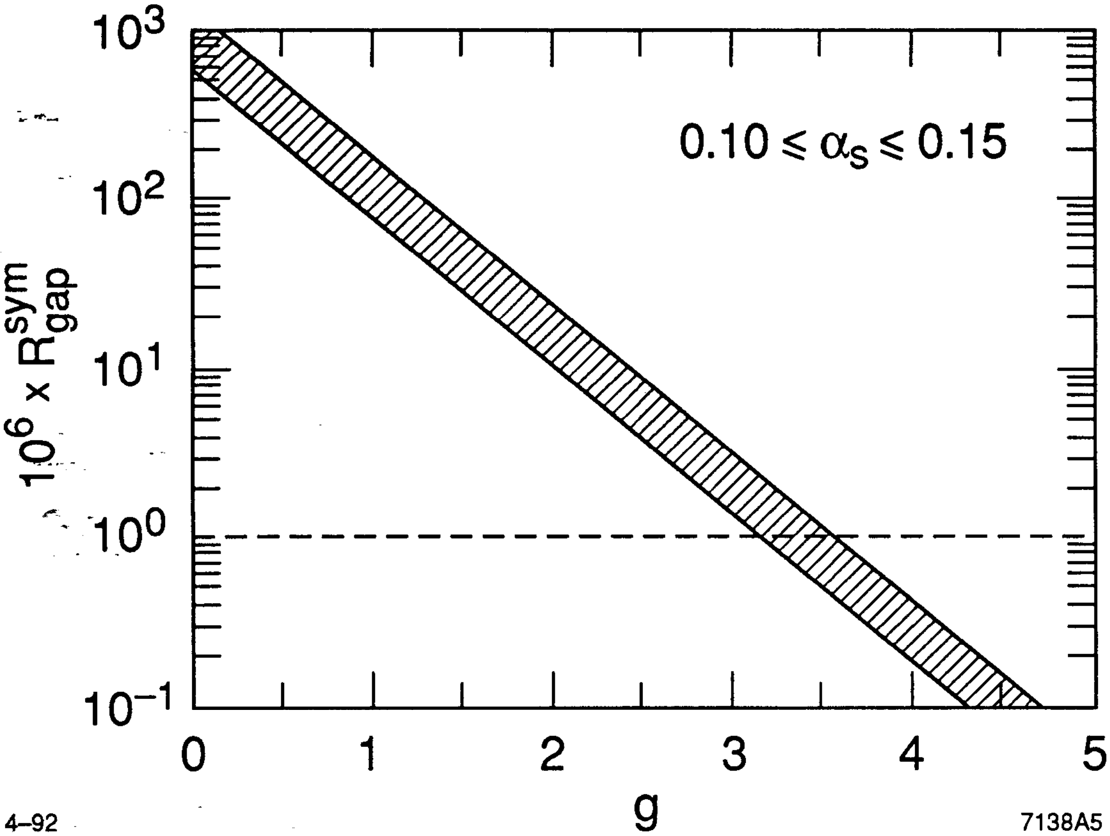


Fig. 4



10^3
10^2
10^1
10^0
10^{-1}
$10^6 \times R_{gap}^{sym}$
$0.10 \leqslant \alpha_s \leqslant 0.15$
0
1
2
3
4
5
g
4–92
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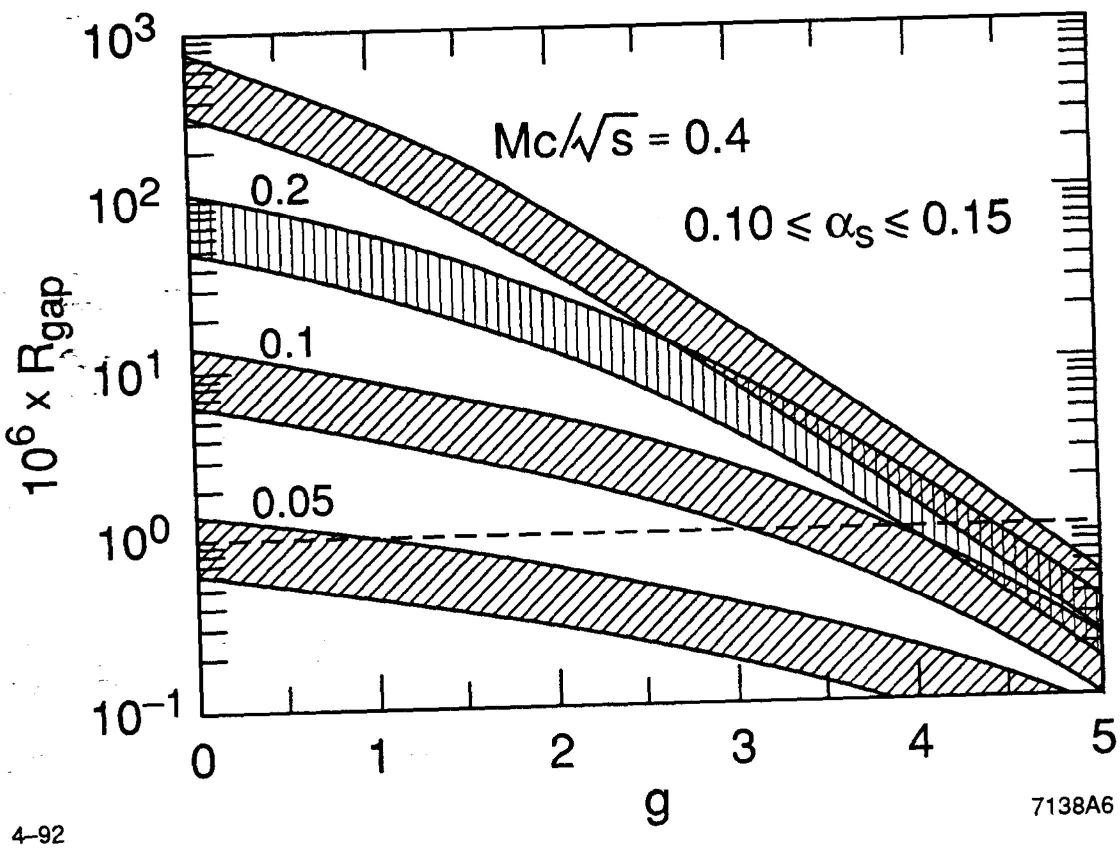
Fig. 5



10^3
10^2
10^1
10^0
10^{-1}
$10^6 \times R_{gap}$
$Mc/\sqrt{s} = 0.4$
0.2
0.1
0.05
$0.10 \leqslant \alpha_s \leqslant 0.15$
0
1
2
3
4
5
g
7138A6
4–92

Fig. 6

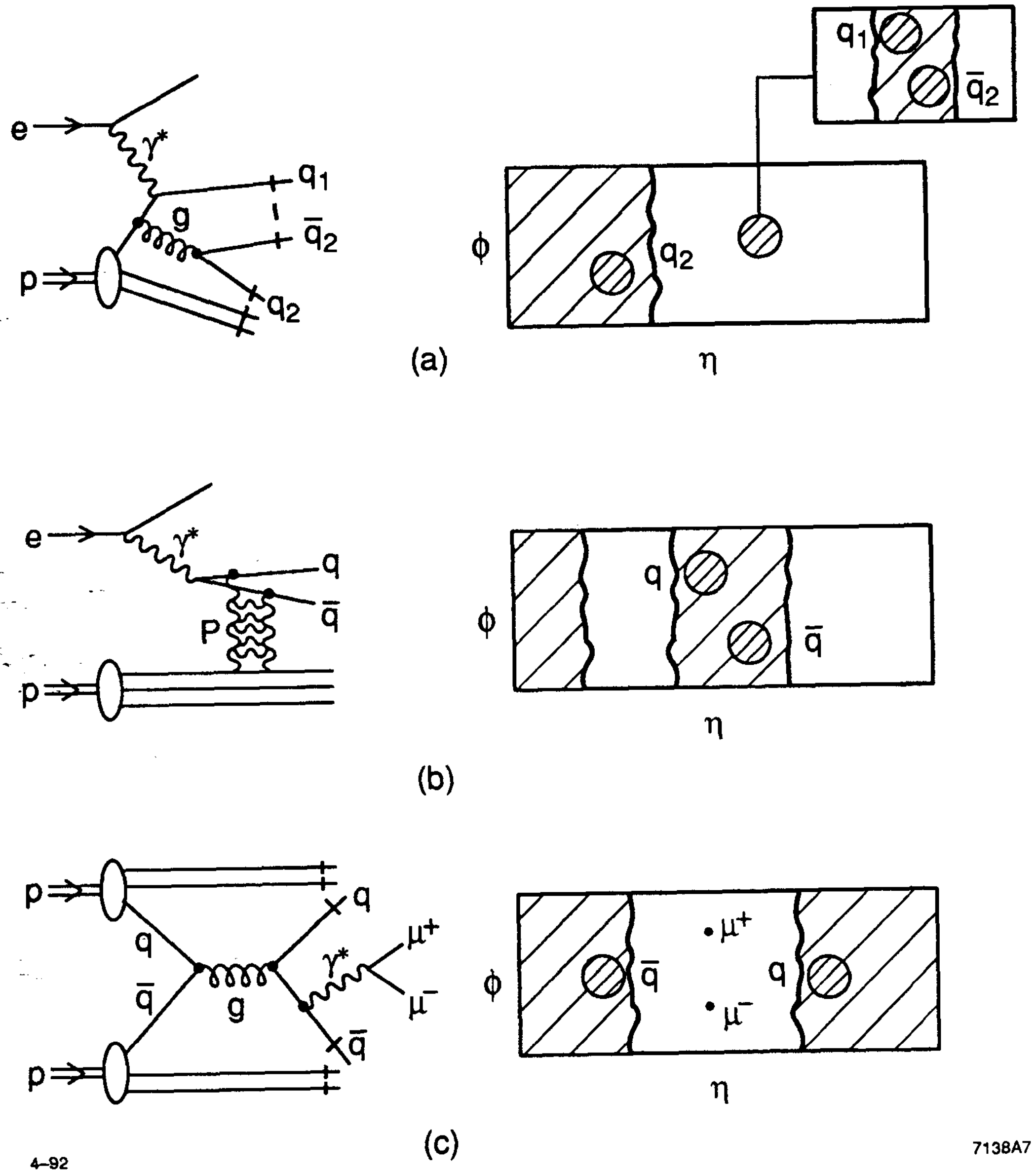


Fig. 7