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Deciphering 40 TeV rapidity gap physics with 2 TeV jet events

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Rapidity gaps may provide an adequate signature for electroweak processes at supercolliders, including the production of the Higgs particle. We show how this important issue can be studied in the dijet final states of operating proton–antiproton colliders and present quantitative predictions.

The study of rare electroweak processes, like the elastic scattering of W's or Higgs boson production, is one of the main objectives of the planned hadron supercolliders. Correspondingly a large amount of work has gone into devising techniques for isolating these events, usually by considering the signal and background processes at the parton level. In addition it was suggested several years ago that the color flow in these events can be used as a distinguishing feature [1] and that the "W-fusion" process $qq \to qqH$, $H \to WW$ with subsequent hadronic decay of one of the W's leads to substantially lower charged particle multiplicities than the dominant QCD backgrounds [2].

Recently Bjorken has substantially extended these ideas by considering the multiplicity distributions of signal and background events in the pseudorapidity–azimuthal angle plane, the lego-plot [3,4]. In a W–W scattering event no color is being transferred between the two beam protons and therefore few hadrons are produced in the central region. For each of the struck protons the event looks like a charged current deep-inelastic-scattering event. Since the momentum transfer (of order m_W) is much smaller than the typical energy of the struck quarks, hadrons will mainly be produced in the regions between these forward spectator quarks and the beam remnants. This leads to the formation of a rapidity gap containing no hadrons between the left- and right-moving jets which originate from the spectator quarks. Overlaying two Monte Carlo generated charged current events at ep-colliders exactly confirms this picture [5].

Such gaps may provide an alternative/complementary trigger for processes which arise from t-channel electroweak boson exchange and this includes the production of Higgs particles. While there is no doubt that such rapidity gaps are formed, they may not provide us with a practical experimental signature if (i) the gap is filled by hadronization products from the beam jets or (ii) purely hadronic processes fake such gaps by fluctuations or dynamics. Unfortunately the theory of average hadronic interactions is insufficiently developed to answer these questions. We here study the possibility of tackling these issues in existing collider experiments. We investigate a search for dijet events whose origin is associated with the exchange of a photon rather than a gluon between the colliding quarks. The importance of such a study cannot be overestimated as positive results could force a rethinking of how electroweak physics is done at supercolliders.

The physics of rapidity gaps can be rehearsed in existing experiments by searching for gaps in two-jet events associated with photon, Z, or W exchange [3,6]. For small scattering angles the cross section for the production of two high-p_T jets via γ-exchange is given by

$$\frac{d\sigma}{d\eta_1\, d\eta_2\, dp_T^2} = \frac{4\pi\alpha^2}{p_T^4} F_2(x_1, Q^2) F_2(x_2, Q^2) . \quad (1)$$

Here quarks with momentum fractions x_1, x_2 produce a pair of jets with transverse momentum p_T and pseudorapidities η_1, η_2. F_2 is the proton structure function. Naively one expects that in the rapidity region between the jets of width

$$\Delta\eta = |\eta_1 - \eta_2| \simeq \ln \frac{x_1 x_2 s}{p_T^2} \quad (2)$$

no hadrons are produced, except in the immediate vicinity of the struck quarks which hadronize into the observed jets. It is this zero-multiplicity region in the lego-plot which constitutes the rapidity gap. If, on the contrary, the exchanged particle is a gluon, as is the case in the majority of the dijet events, color flows between the jets and hadronization associated with this color flow will fill the gap with hadrons.

The cross section for dijet events of electroweak and gluon-exchange origin is shown in fig. 1 as a function of $|\eta_1 - \eta_2|$. We chose here $\sqrt{s} = 1.8$ TeV and required $p_{Tj} > 40$ GeV and $|\eta_j| < 3.5$. These values are illustrative. We have not optimized these values for any specific detector. At large scattering angles the required parton center of mass energy is relatively low, of the order of $2p_{Tj}$, and hence gluon scattering is the most important QCD contribution. As the size of the rapidity gap is increased, the dijet invariant mass rises exponentially and gluon contributions are suppressed relative to quark initiated processes due to their softer structure functions. This effect explains the relative enhancement of the electroweak processes for large rapidity gaps; see fig. 1. In this phase space region which is dominated by quark–quark scattering the cross section ratio is $\sigma_{QCD}/\sigma_{EW} = 1500$, i.e. $\sim (\alpha_s/\alpha)^2$, up to color and charge factors.

The most immediate question is whether the QCD background fakes gaps at this level. It is instructive to study the "background" process with a Monte Carlo event generator. We chose PYTHIA [7] and generated 5.2×10^5 events with $p_T > 40$ GeV and partons separated by a rapidity gap

$$\Delta\eta > 2 + 2(0.7) = 3.4 . \quad (3)$$

In eq. (3) we chose two units of rapidity but increased the gap by 1.4 to make room for the debris of the jets which will inevitably fill the gap near the

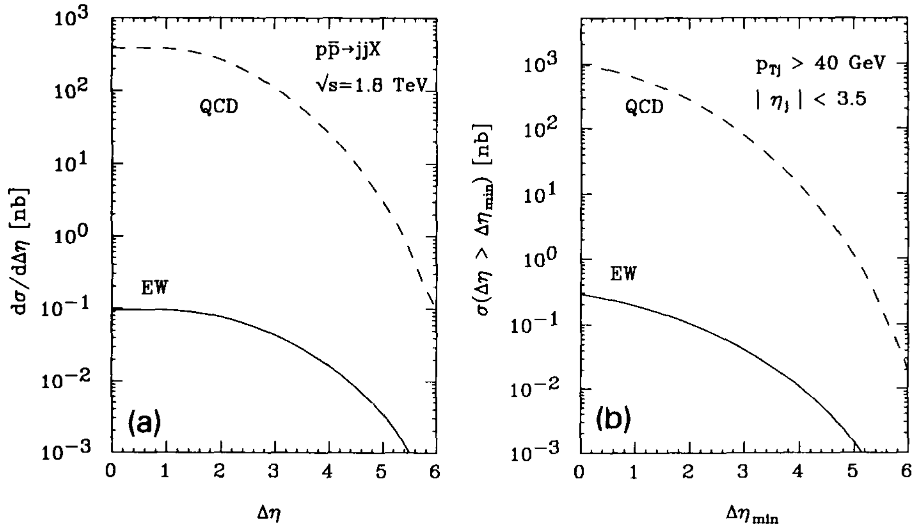

Fig. 1. Cross sections for the production of dijet events at the Tevatron requiring $p_{Tj} > 40$ GeV and $|\eta_j| < 3.5$ for each of the jets. The solid lines give the electroweak contributions from t-channel γ, Z, and W exchange while the dashed line is the tree level expectation from strong interactions only. In part (a) we show the differential $d\sigma/d\Delta\eta$ distribution ($\Delta\eta = |\eta_1 - \eta_2|$) while part (b) gives the same distributions integrated above $\Delta\eta > \Delta\eta_{min}$ as a function of $\Delta\eta_{min}$.

edges. We assumed a 0.7 radius of the jet fragmentation region in the lego-plot.

In fig. 2 we show the rapidity distribution of the number of particles and their transverse energy in a typical event. We are, however, interested in the rare fluctuations in which few particles hadronize inside the gap. We show in fig. 3 the frequency of events as a function of the particle multiplicity inside the "gap" region between the two jets. Here the gap is defined after jet reconstruction. For events with two jets with $p_{Tj} > 40$ GeV at pseudorapidities η_1 and η_2 the gap region is taken as the interval

$$\min(\eta_1, \eta_2) + 0.7 < \eta < \max(\eta_1, \eta_2) - 0.7 . \quad (4)$$

So far the news is good: only four events in 10^5 have less than 5 particles inside the gap. Overlaying two charged current HERA-type events will typically generate two or three particles inside this gap region [5]. Requiring four or less particles inside the gap would hence reduce the QCD background to 6% of the electroweak dijet cross section with $\Delta\eta > 3.4$.

This result is, however, not surprising. In PYTHIA and many other Monte Carlo event generators the underlying event is generated by string fragmentation. Each beam consists of a spectator system and an active parton of opposite color. The left-moving beam-fragment is attached by a string to the right-moving fragment of opposite color and vice versa. Strings thus cover the complete rapidity range between the two jets and thus rapidity gaps can only appear by fluctuations in the string fragmentation. This probability is exponentially small. What we showed is that fluctuations will not prevent one from observing γ-exchange by its rapidity gap signature.

Strings might not represent the full story. In higher order the exchange of two gluons in a color singlet state will lead to events with no color flow between the beam fragments and, therefore, may be the origin of events with a rapidity gap. This mechanism has, in fact, been proposed as a model for the pomeron [8]. Bjorken has recently estimated that the fraction of such QCD dijet events is given by [3]

$$f = \frac{1}{2}\left(\frac{4\pi}{33 - 2n_f}\right)^2 \simeq 0.1 . \quad (5)$$

Here n_f is the number of flavors. f is expected to increase when considering higher-order corrections to two-gluon exchange.

We made an independent calculation of f within the two-gluon exchange model for the pomeron. The matrix element for this reaction can be written in a form particularly suitable for our purposes [9]

$$A(s, t) = \tfrac{2}{9}[\bar{u}(p_3)\gamma^\mu u(p_1)\bar{u}(p_4)\gamma_\mu u(p_2)]I(t) , \quad (6)$$

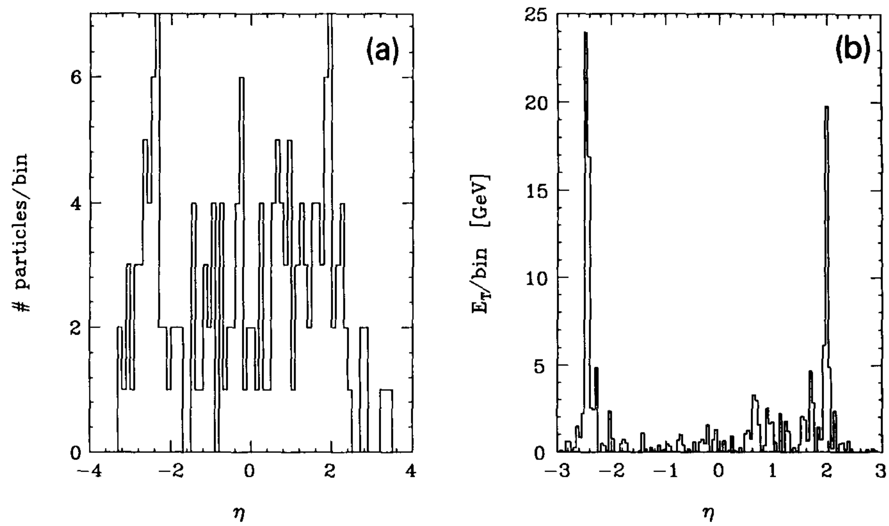

Fig. 2. (a) Multiplicity distribution and (b) transverse energy flow as a function of the rapidity in the lab-frame for a typical dijet event with $p_{Tj} > 40$ GeV at the Tevatron, as generated with the PYTHIA Monte Carlo.

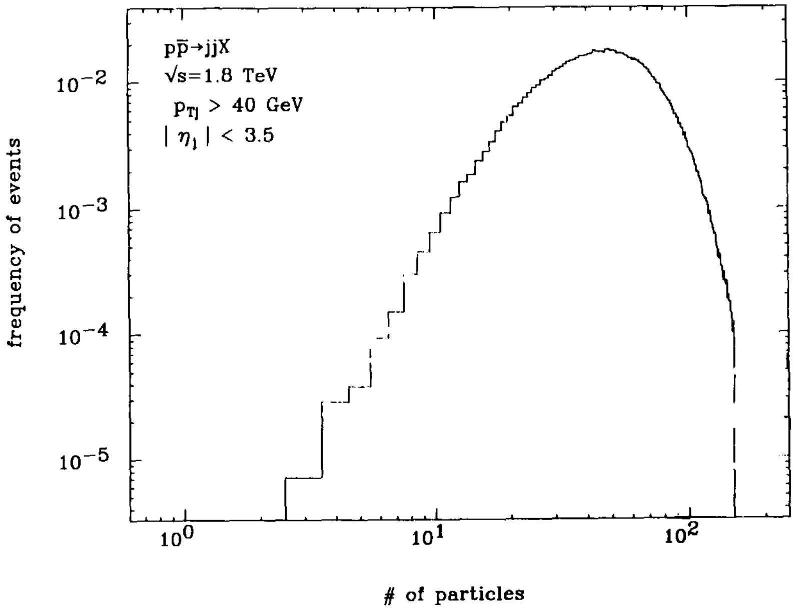

Fig. 3. Multiplicity of charged and neutral particles in the "gap" region in dijet events with $p_{Tj}>40$ GeV and $|\eta_j|<3.5$ at the Tevatron as predicted by PYTHIA. The gap region is defined as the rapidity interval $\min(\eta_1,\eta_2)+0.7<\eta<\max(\eta_1,\eta_2)-0.7$. Shown is the frequency of events of a fixed multiplicity N as a function of N.

where $I(t)$ is given by

$$I(t)=\tfrac{1}{2}\int\frac{d^2k}{(2\pi)^2}g^2D[(k+\tfrac{1}{2}q_T)^2]g^2D[(k-\tfrac{1}{2}q_T)^2]\,. \quad (7)$$

Here $D(k^2)$ is the gluon propagator and $t=-q_T^2$. For $s\gg|t|$ eq. (6) is reduced to $A(s,t)=\frac{4}{9}sI(t)$. In the case of pomeron exchange the transferred momentum is quite small and $I(t)$ is dominated by the $k^2\simeq0$ part of the integral. The singularity that will appear in the calculation is regularized, as proposed by Landshoff and Nachtmann [9], with the use of a nonperturbative propagator, which, due to the confinement properties of the QCD vacuum, does not have a pole at $k^2=0$. This kind of procedure can lead to a consistent pomeron phenomenology as verified by Landshoff and collaborators [10]. For example, let us consider the total cross section for proton–proton scattering, which in the Low and Nussinov scenario [8] is given by [11]

$$\sigma_T=8\alpha_s^2\int_0^s d^2k\,D^2(k^2)[1-2F_1(9k^2)+F_1^2(9k^2)]\,, \quad (8)$$

where $\alpha_s=g^2/4\pi$ is the strong coupling constant and $F_1(k^2)$ is the electromagnetic form factor of the proton, which is given by

$$F_1(t)=\frac{4m_p^2-2.79t}{4m_p^2-t}\frac{1}{(1-t/0.71\ \text{GeV}^2)^2}\,, \quad (9)$$

In eq. (8) $D(k^2)$ must be a well behaved propagator as $k^2\to0$. Here we will use a propagator, obtained by Cornwall [12], which obeys the renormalization group equation. It behaves like the propagator of a massive gluon and fits the numerical solution of the Schwinger–Dyson equation for the gluon propagator. It is given by [12]

$$D^{-1}(k^2)=[k^2+m^2(k^2)]bg^2\ln\left(\frac{k^2+4m^2(k^2)}{\Lambda^2}\right), \quad (10)$$

where $b=(33-2n_f)/48\pi^2$ and the momentum dependent dynamical mass $m(k^2)$ is

$$m^2(k^2)=m^2\left(\frac{\ln[(k^2+4m^2)/\Lambda^2]}{\ln(4m^2/\Lambda^2)}\right)^{-12/11}\,. \quad (11)$$

With the above propagator we obtain the experimental value of the total cross section for $m=370$ MeV with $\Lambda_{QCD}=300$ MeV [13].

The calculation of color singlet two-gluon exchange events proceeds along the same lines. However, here we are interested in events at large momentum transfer ($q_T>40$ GeV). The loop integration is dominated by the configuration where one propagator is soft and the other carries essentially the complete momentum transfer of the event. The soft and hard physics become entangled and some hybrid calculation must be performed. Guided by the computation of the total cross section we compute eq. (7) with one perturbative propagator and the soft one given by eq. (10). The integration of eq. (7) must be performed numerically. We divide the angular integration as follows: from 0 to $\frac{1}{2}\pi$ the factor $(k+\frac{1}{2}q_T)^2$ is large and therefore described by the perturbative propagator. The nonperturbative one will be associated with the momentum $(k-\frac{1}{2}q_T)^2$. For angles between $\frac{1}{2}\pi$ and π the propagators are interchanged.

With $(d\sigma/dt)^{\text{two gluon}}_{\text{singlet}}=|A(s,\ t)|^2/16\pi s^2$ computed as above, and with the one-gluon exchange given by $(d\sigma/dt)^{\text{one gluon}}\simeq 8\pi\alpha_s^2/9t^2$ we obtain the ratio $(d\sigma/dt)^{\text{two gluon}}_{\text{singlet}}/(d\sigma/dt)_{\text{one gluon}}\simeq 0.6$ for $-t>(40\text{ GeV})^2$. Since this ratio is constant for large t we expect the same value for $\sigma^{\text{two gluon}}_{\text{singlet}}/\sigma^{\text{one gluon}}$.

This result is substantially larger than the estimate given by Bjorken [3]. The difference can be traced to the use of a nonperturbative propagator for the soft exchanged gluon in our calculation. Our result of order one for $\sigma^{\text{two gluon}}_{\text{singlet}}/\sigma^{\text{one gluon}}$ can be interpreted as a model for the dressing of the exchanged gluon in QCD quark–quark scattering: confinement requires that only a color-singlet object can be exchanged between the two beam remnants. This view implies, however, that the exchange of two gluons in a color-singlet state will not generally lead to a rapidity gap signature. Since the two-gluon exchange amplitude is completely dominated by the phase space region with one soft gluon, extra radiation is screened only for soft gluons and a substantial emission probability of relatively hard gluons into the gap region may survive. Keeping this view in mind, we shall use Bjorken's estimate of $f\approx 0.1$ as an upper bound for the gap frequency in QCD dijet events.

How often will a rapidity gap survive as an adequate trigger? It is clear that in most events spectator partons will deposit fragmentation products inside the gap. The problem is best visualized in impact parameter space in which the two protons interact as overlapping Lorentz-contracted pancakes. Only in events with impact parameter close to the diameter of the colliding pancakes are the spectators safely outside the small overlap region containing the active partons. Bjorken estimates that at the SSC such an advantageous configuration occurs 5% of the time [3]. This survival probability of the gap $\langle|S|^2\rangle=0.05$ is almost certainly energy dependent. E.g. in the minijet model the gap survival probability depends rather strongly on the jet cross section – it is after all the origin of particles in the gap – with [14]

$$\langle|S|^2\rangle\simeq\int d^2b\,A(b)\exp[-\sigma_{\text{jet}}A(b)]\,. \qquad (12)$$

This leads to an increase in $\langle|S|^2\rangle$ by about a factor of 3 at $\sqrt{s}=1.8$ TeV, where σ_{jet} is reduced by a factor of 5 in magnitude compared to SSC energy [15].

In order to emphasize the importance of doing a test of the rapidity-gap trigger method and summarize the various issues involved, let us compile the possible results of a search for electroweak boson-exchange in two-jet events:

(i) String Monte Carlo event generators represent the underlying event correctly. Gaps are discovered at the $\langle|S|^2\rangle\times(\alpha/\alpha_s)^2\sim 10^{-4}$ level and these events are genuine quark scattering events mediated by the exchange of a photon, Z, or W.

(ii) Gap events are seen at the level $f\langle|S|^2\rangle\simeq 0.1\times 15\%\simeq 1.5\times 10^{-2}$. They represent genuine QCD events. The experiment is consistent with the picture that multiple gluon exchange is the origin of events with a gap at the level of 10% of all dijet events. In addition the rapidity gap associated with these events survives 15% of the time. Monte Carlo generators do not correctly incorporate this physics.

(iii) Dijet events with rapidity gaps are seen at a level somewhere between 10^{-2} and 10^{-4}. The events are a mixture of quark scattering by γ, W, Z exchange and QCD events with two-gluon exchange in a color singlet state. The experiment measures the product $f\langle|S|^2\rangle$ of gap production probability f in QCD dijet events times the gap survival probability $\langle|S|^2\rangle$.

(iv) Rapidity gaps are ubiquitous and occur in more than 1% of the dijet events. No support for rapidity triggers is found. The situation is unlikely to improve with higher energy as the physics is logarithmic in nature. Notice however that even now the effort is not wasted. Fig. 3 represents a powerful test of the underlying event structure in Monte Carlo event generators. Their basic structure would be questioned and their inadequacy pointedly exhibited.

(v) No dijet events with rapidity gaps are found in the data of their level is substantially smaller than 10^{-4}. The survival probability for rapidity gaps is smaller than $\langle |S|^2 \rangle = 0.15$ and whether gap triggers will play a role in distinguishing electroweak events in the SSC data becomes a difficult quantitative issue.

Searching for rapidity gaps in intermediate p_T dijet events at the Tevatron will take a dedicated effort. A $p_{Tj} > 40$ GeV jet trigger is inadequate as the sample will be totally dominated by events with small $\Delta\eta$. A transverse energy trigger will have to be supplemented by requiring large invariant mass of the jet pair of similar means. We leave answering these questions to our experimental colleagues.

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References

[1] Y.L. Dokshitzer, V.A. Khoze and S. Troyan, in: Proc. 6th Intern. Conf. on Physics in collisions (1986), ed. M. Derrick (World Scientific, Singapore, 1987) p. 365.
[2] J.F. Gunion et al., Phys. Rev. D 40 (1989) 2223.
[3] J.D. Bjorken, preprint SLAC-PUB-5545 (1991), Intern. J. Mod. Phys., to be published; preprint SLAC-PUB-5616 (1992).
[4] See also Y.L. Dokshitzer, V.A. Khoze and T. Sjöstrand, Phys. Lett. B 274 (1992) 116.
[5] G. Greenbaum, talk presented at the FAD working group meeting at the SSCL (Dallas, TX, March 1992).
[6] Y. Azimov et al., Phys. Lett. B 165 (1985) 147, Yad. Fiz. 43 (1986) 149.
[7] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 (1987) 43.
[8] F.E. Low, Phys. Rev. D 12 (1975) 163
S. Nussinov, Phys. Rev. Lett. 34 (1975) 1268.
[9] P.V. Landshoff and O. Nachtmann, Z. Phys. C 35 (1987) 405.
[10] A. Donnachie and P.V. Landshoff, Nucl. Phys. B 311 (1989) 509;
J.R. Cudell, A. Donnachie and P.V. Landshoff, Nucl. Phys. B 322 (1989) 55;
J.R. Cudell, Nucl. Phys. B 336 (1990) 1.
[11] J.F. Gunion and H. Soper, Phys. Rev. D 15 (1977) 2617;
E.M. Levin and M.G. Ryskin, Sov. J. Nucl. Phys. 258 (1985) 267.
[12] J.M. Cornwall, Phys. Rev. D 26 (1982) 1453.
[13] F. Halzen, G.I. Krein and A.A. Natale, Madison preprint MAD/PH/702 (1992).
[14] See, e.g., T.K. Gaisser and T. Stanev, Phys. Lett. B 219 (1989) 375.
[15] R.S. Fletcher, private communication.