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TWO GAUGE–BOSON PHYSICS AT VERY HIGH ENERGIES*

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ABSTRACT

Use of a rapidity-gap signature can lead to observation of interesting processes involving collisions of gauge-bosons at the SSC. This includes production of the heavy Higgs boson (500 GeV–1 TeV), which appears straightforward.

1. Introduction

Long ago there used to be a series of electron-photon conferences. Later it was changed to the present series of lepton-photon conferences. Nowadays it is dominated by discussion of the hadronic decays of the Z-boson.

This series of conferences may suffer in the future a similar fate, turning into a series on the collisions of electroweak bosons with each other, with the subject matter being dominated by the consideration of the decays of technirhos into techniquarks.

It is in partial anticipation of this phenomenon to which this talk is dedicated. We will discuss the collision of intermediate-bosons with each other, especially W's, with a special eye toward the resonant production of the Higgs boson—assuming it has a mass not far from the TeV mass scale. The bottom line is the following[1]:

1. The SSC is the cleanest machine for electroweak physics.
2. It is simple to find a 1 TeV Higgs boson at the SSC.
3. Just about any old detector can do it—even the full-acceptance detector (FAD) I spend my time promoting—and it doesn't have to cost much either.

The key to this assertion is a proposed signature for Higgs detection consisting of an event pattern containing simultaneously rapidity gaps and jets. The most immediate relevance to this meeting is that data involving $\gamma - \gamma$ collisions can be helpful in evaluating the feasibility of utilizing the aforementioned signature.

2. Rapidity gaps and jets

Rapidity gaps are endemic in hadron-hadron collisions: they are the unpopulated regions of the lego plot (pseudorapidity η versus azimuthal angle ϕ) which

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occur in diffractive events, whether elastic scattering, single diffraction, or multiple diffraction. They are on the other hand rare in, e.g. Z-decays, because there is color separation of the outgoing quarks, with string formation and breakage, etc. which fills in the intermediate region.[2]

Rapidity-gaps can however be created in hard collisions mediated by an exchange of a color-singlet system such a photon, W, Z, or color-singlet gluon pair. In case of photon or W exchange, the final state at the naive level is a composite of two "HERA" final states, where by a HERA state we mean the fragments of a beam proton after being struck by an electron. At a less naive level there will be an absorption correction. Not only will the partons which exchanged the electroweak boson interact, but also a number of the spectators. They can create debris which fills up the candidate rapidity gap. I estimate[1] that the fraction of events for which the rapidity gap survives is 5%, with an uncertainty of a factor 3 or so.

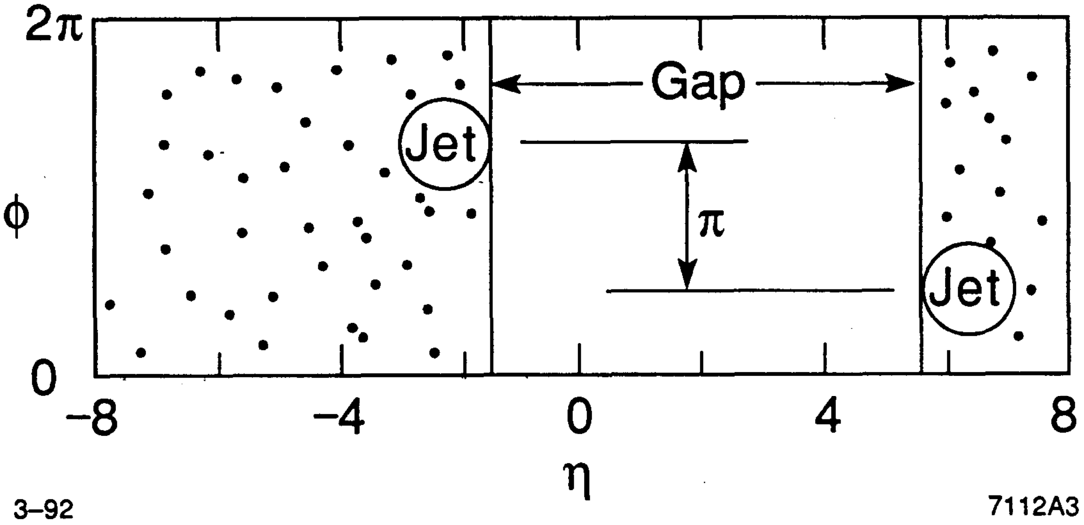

Figure 1. Event morphology for virtual photon exchange between two protons at large q^2, with survival of the rapidity gap assumed.

In the absence of the final state absorption, the pattern in the lego plot is shown in Fig. 1. The quarks recoiling after emitting or absorbing the exchanged electroweak boson are found in the lego plot as "tagging jets", with p_t equal to the p_t of the exchanged gauge boson. If these jets are given the conventional definition of the contents of a circle of radius 0.7 in the lego plot, then the boundary of the rapidity gap is conveniently defined as the tangent to the circle as shown in the figure. The amount of leakage across the gap by fluctuations is easily estimated analytically, and can be checked by running HERA Monte Carlo code.[3] The answer is that the average leakage is one hadron per gap per event (Fig. 2).

These single exchanges are probably masked by a large background of strong, high-p_t double-diffraction events mediated by (more or less) two gluon exchange,

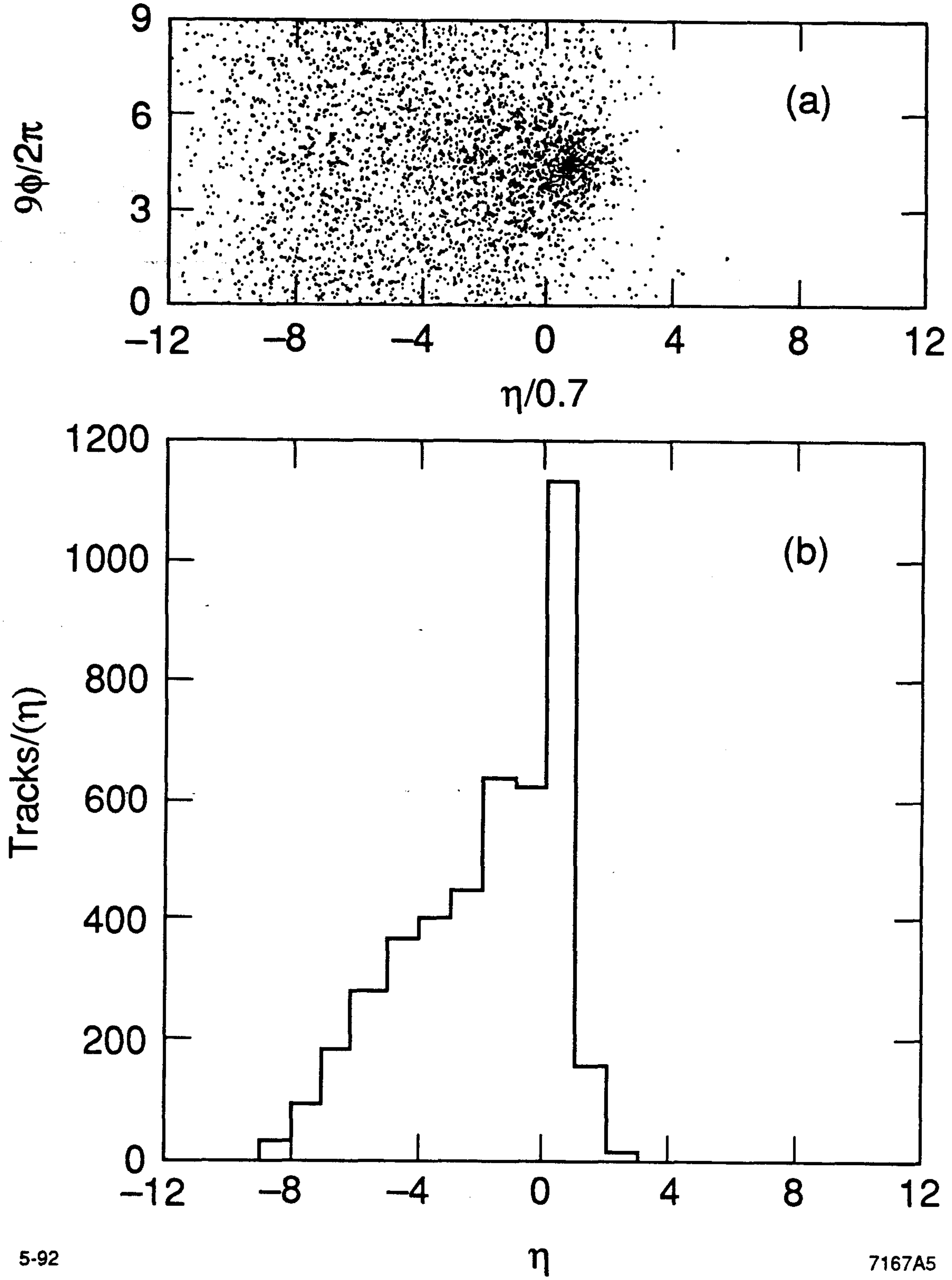

Figure 2. (a) Distribution[3] in the lego plot of proton beam-fragments for 100 HERA *ep* events, all with essentially the same location of the tagging-jet in the lego plot. (b) Projection of the above distribution onto the η-axis.

with the gluons in a color singlet configuration. While these are interesting for their own sake as well as for engineering purposes (what is meant by this hopefully becomes clearer later on), we shall move on to the boson-boson fusion processes which are the subject matter of this conference. The singular example is the aforementioned Higgs production via WW fusion, to which we now turn.

3. A Higgs signature

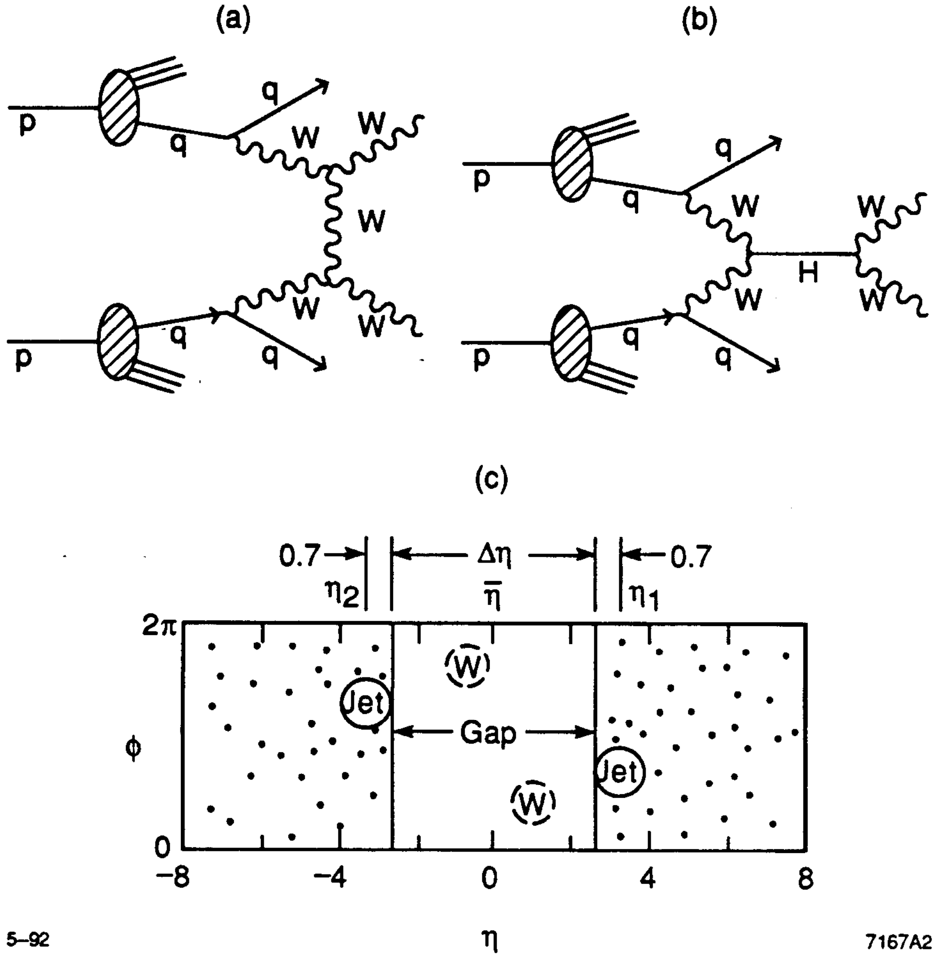

Figure 3. (a) Basic mechanism for producing W-W interaction processes in high-energy pp collisions, with the presence of a rapidity-gap in the final state; (b) Event morphology in lego variables for the processes depicted in (a). The tagging jets are the hadronization products of the quarks, while for large Higgs masses, almost all of the W-decay products lie within the dashed circles. The remaining region, marked gap, contains on average no more than 2 or 3 hadrons.

Again at the most naive level, the dominant, well studied production mechanism shown in Fig. 3 leaves a rapidity gap[4] between the tagging jets, except for the decay products of the Higgs itself. Again we estimate the survival probability of the gap to be of order 5%. In order for a good rapidity gap to exist kinematically, it is sufficient that the cms energy of the qq system, which emits the W's which fuse to resonantly make the Higgs, be several TeV. If this is the case, then automatically the decay products of the Higgs land in the gap. This has been checked by Roberto Vega[5]; the rapidity distribution of the tagging jets and the Higgs decay products are well separated (Fig. 4).

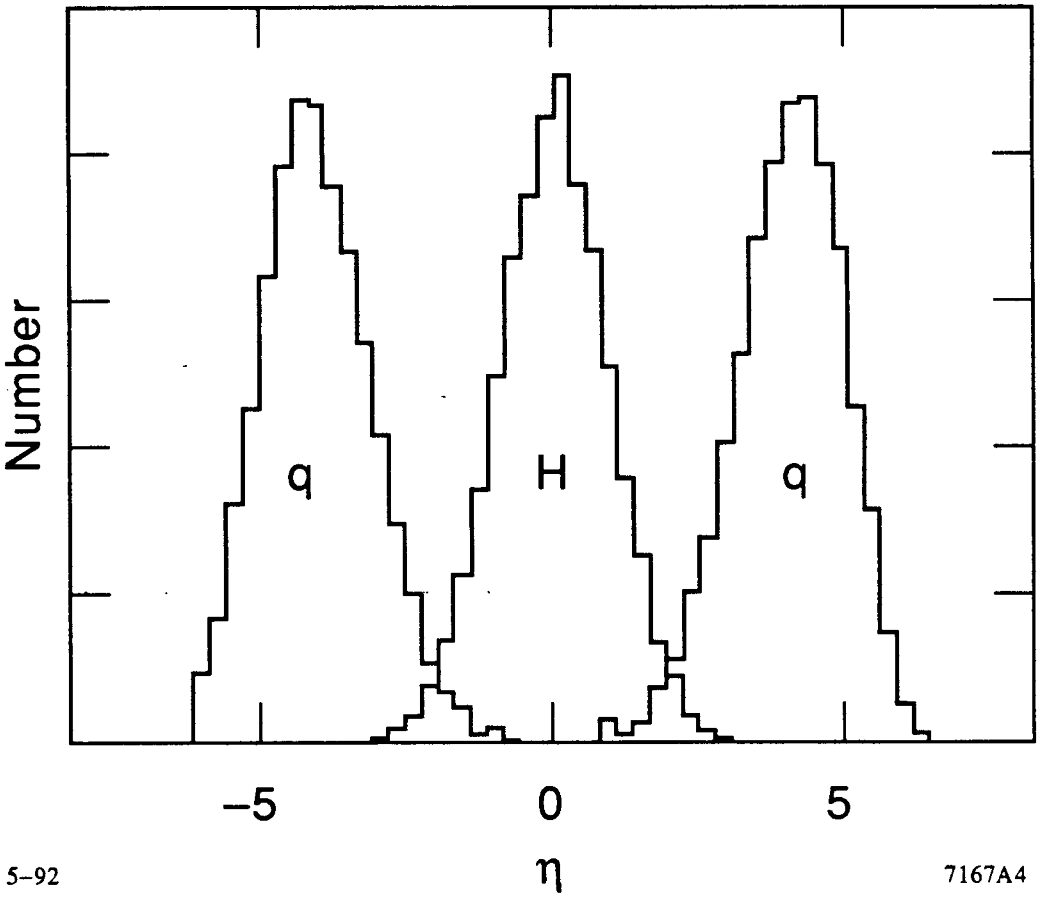

Figure 4. Rapidity distribution of tagging-jets (left and right hand peaks) and 1 TeV Higgs boson (central peak) for $\sqrt{s} = 40$ TeV.

It also turns out that the cross section for producing the Higgs is for a given large qq cms energy almost independent of the Higgs mass.[6] Therefore the cross section for producing the Higgs of any assumed mass into a gap of large, defined width will be almost independent of mass.

Experimentally, the cleanest case occurs for the heaviest Higgs mass, because then the decay products, two W's or two Z's, are quite relativistic.[7] The fragments of each W or Z will all land within a circle of radius 0.7, with two subcores (for hadronic decays) inside the circle. The algorithm for the signature is an experimentalist's dream come true. It is what one wants to observe, with no underlying-event debris anywhere nearby. In fact for the acceptance of the a SSC detector the remainder of the detector, with the possible exception of the far-forward plug calorimeters, should be completely devoid of secondary particles. For the most difficult case of double hadronic decay, the algorithm in detail might go more or less as follows:

1. Demand a nominal four jet final state with the p_t of each jet at least, say, 30 GeV, and the total p_t above 300 GeV.
2. Construct the fiducial region for the rapidity gap as the region between the two "beam jets", using the tangent-to-the-circle-of radius-0.7 construction described above.
3. After excluding the region of the lego plot populated by the other two jets (again using circles of radius 0.7) demand that the total multiplicity in the remaining gap region be no more than 2. (The average number expected in typical events is about 80 or so.)
4. Look in detail inside each central jet and demand a pair of jets, with a total mass consistent with the intermediate-boson mass.

After these cuts I expect the only background remaining will be nonresonant production of W pairs. The biggest QCD background I have been able to locate[1] is sixth order in α_s and has three requirements of color-transparency structure as well. It looks several orders of magnitude too small. And in half the final states there will be at least one leptonic gauge-boson decay. For these I cannot even find a candidate background; the usual sources such as top production and decay do not leave the requisite rapidity gaps.

I may have not looked hard enough for backgrounds, and there will have to be a lot more study to be sure that this strategy is sound. But I am not as worried about the competition from other background sources as I am about the estimate of the survival probability of the gap. How sound is that calculation? Can there be some experimental inputs this side of the SSC commissioning? It is here that photon-photon collisions might play a role.

4. Survival of the gap: how $\gamma - \gamma$ collisions can help

The collisions for which the rapidity gap survives will most likely be peripheral. I will not here go into much detail regarding the estimates of that survival probability which I have made. Suffice it to say that the most simple estimate is just to weight the hard cross section, differential in the impact parameter of the incident protons, with the probability that protons at that impact parameter pass through each other unscathed (the transmission probability $|S(b)|^2$). This transmission probability is measured in elastic scattering,[8] and the convolution done this

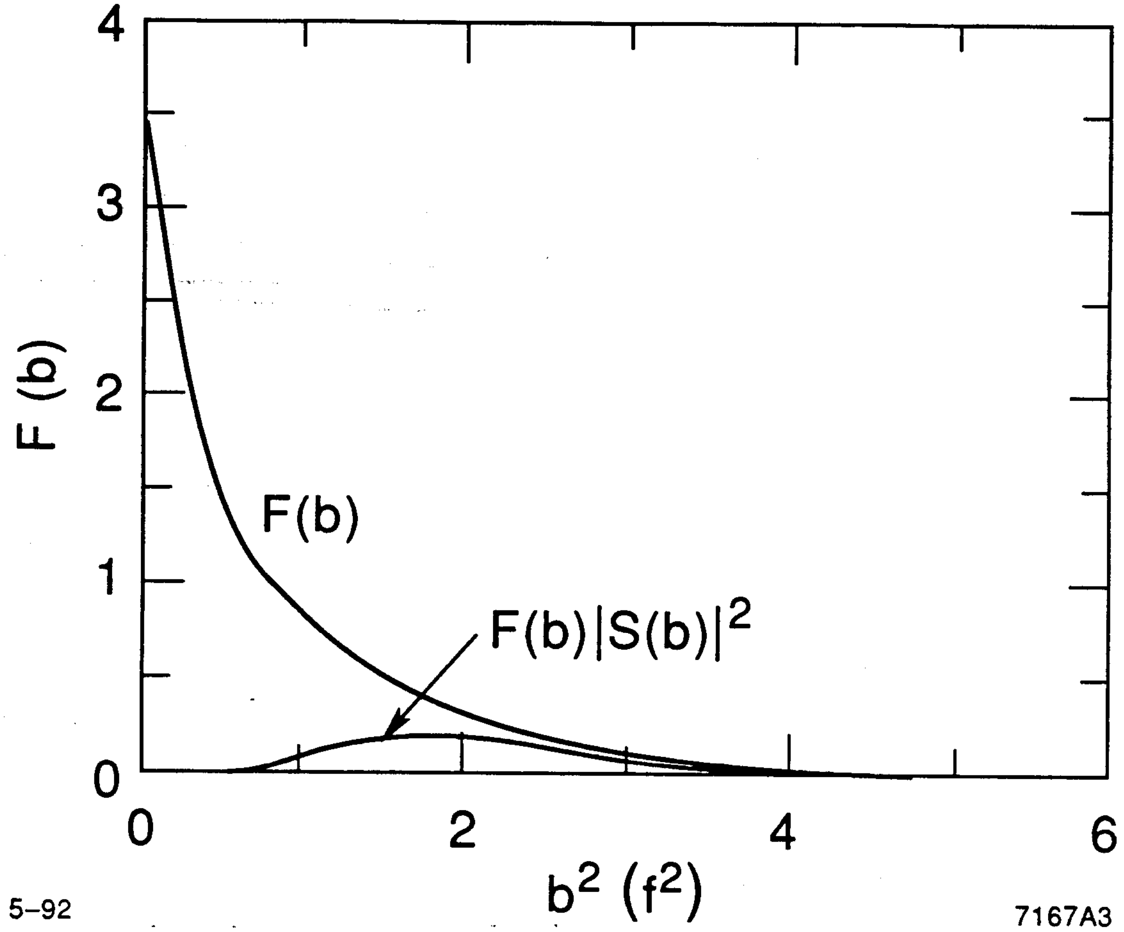

Figure 5. The function $F(b)$ defining the impact-parameter dependence of hard-collision luminosity, along with $F(b)|S(b)|^2$. The estimate of $|S(b)|^2$ is taken from Block *et al.*, Ref. 8.

way gives a survival of about 10%, with the typical impact parameters for which survival is not improbable being 1–2 fermi (Fig. 5).

Short of the Higgs process itself, the cleanest accessible process for independently determining this quantity appears to be dilepton production via $\gamma - \gamma$ collisions, with the dilepton landing in the rapidity gap. The problems are that the cross section will be rather small, and that it is necessary that breakup of the protons be observed in order to limit the impact parameter between the projectiles and accurately simulate the previous situation. And of course it must be done at a hadron machine.

Alternatives using only strong-interaction processes may also be possible. But they are clouded by the "small-x" problem of perturbative QCD.[9] At very large s, the naive two-gluon-exchange contribution is enhanced by extra gluons exchanged in a ladder structure described by the BFKL equation.[10] The net effect of these extra contributions is a rapid growth of the cross-section, which if left unchecked violates the Froissart bound. In pictorial terms, even the partonic quarks interact strongly at large fixed t when s becomes sufficiently large. These BFKL effects, not in especially good theoretical control, can also affect the survival probability. One way this may manifest itself is that not only must one require that the protonic matter go through the collision unscathed, but also the clouds of partons closely surrounding the quarks that interacted to make the dilepton or Higgs.

It is of course appropriate here to mention that the cleanest theoretical environment to consider the BFKL small-x question is in collisions of spacelike virtual photons. For now this is a theoretical laboratory, because the requisite photon-photon cms energy should be in the TeV region. But in the long run it would be nice to have the data as well. I prefer to call the small-x problem the large-s problem. It is a big, not little problem, and deserves more attention from theorists and experimentalists.

5. Conclusions

I think there is a promising future for the use of the rapidity-gap signature in the study of collisions of electroweak gauge bosons in hadron colliders. If this strategy works, there is no cleaner environment for such studies. Not only does one not have to worry about the background from underlying events, something which is becoming serious even for TeV e^+e^- linear colliders,[11] but also there is less concern regarding beam-halo backgrounds. The proton or antiproton beams are essentially coasting beams, with no energy being put into them. So the amount of halo can be simply estimated from the beam lifetimes. If the lifetimes are long, the halo cannot be an overwhelming problem from energy conservation alone. Indeed those who work in such machines, even in the far forward direction near the beam, confirm this inference. This argument is not applicable to fixed-target experiments or circular e^+e^- machines. Another advantage is that the tagging jets,in the case of W exchange, provide polarization information on the W: if the p_t is below the W mass longitudinal polarization is favored, and if p_t is above the W mass, transverse polarization is favored.[12]

And the rates are good. If one compares to the "gold-plated" yield ($H \to ZZ \to 4\ell$ with $\ell = e$ or μ), the benefits and costs at the SSC ($\mathcal{L} = 10^{33}\text{cm}^{-2}\,\text{sec}^{-1}$) are as follows:

Benefits:

Essentially all decay modes are seen	factor $(6\%)^{-2} \approx 250$
$H \to WW$ as well as $H \to ZZ$ is seen	factor 3
No underlying-event background	(≥ 1)

Costs:

Survival of the gap	5%
$\mathcal{L} \leq 3 \times 10^{32} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$ (no more than one interaction/bunch crossing)	30%

Net yield:

Gap events/gold-plated events ≥ 10

The rapidity-gap-plus-jet strategy is a special case of an approach to experimental observations which emphasize full acceptance and the acquisition of complex patterns in individual events as a signature for interesting physics.[13] At present the Working Group for a Full Acceptance Detector at the SSC, with a membership of 120 or so, is exploring a variety of physics topics and a detector design which hopefully will lead to formation of a collaboration and an SSC proposal within the next one to two years. I invite any interested person to contact me (BJORKEN at SLACVM) for more details.

6. Acknowledgements

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