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Double Pomeron opportunities at $\sqrt{s} = 1.8$ TeV

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I describe possible ways to discover hard double Pomeron exchange (HDPE) with the existing detectors at the Fermilab Tevatron, by using the small-angle "luminosity" counters as a veto. Estimates of the cross sections and backgrounds are made. In addition to the intrinsic importance of HDPE, its observation would be useful for calibrating the detectors, and for estimating the "survival probability" of rapidity gaps.

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I. INTRODUCTION

Typical $\bar{p}p$ interactions at $\sqrt{s} = 1.8\,\text{TeV}$ produce a large number of particles, which are distributed rather uniformly in pseudorapidity $\eta = -\ln\tan\frac{\theta}{2}$, with $dN/d\eta \sim 6$ for $|\eta| < 4$. There can nevertheless exist final states with one or more "rapidity gaps," defined as intervals of length $\Delta\eta > 2$ to 3 containing zero particles. Long rapidity gaps are by definition governed by the Pomeron, which is believed related to the s-channel unitarity phenomenon of shadow scattering. A QCD-based understanding of the Pomeron remains elusive, although a qualitative description as a two-gluon system with vacuum quantum numbers is promising [1–4].

The "granddaddy" of rapidity gap processes is elastic scattering, which makes up $\sim 20\%$ of σ_{tot}. Inelastic single diffraction, defined by a gap with a leading p or $\bar{p}$ at one end, is also responsible for a sizable fraction of σ_{tot}, and has been seen to exhibit hard-scattering effects [5]. Double Pomeron exchange (DPE), defined by *two* rapidity gaps, has been observed using special detectors for small-angle quasielastic protons at $\sqrt{s} = 0.063\,\text{TeV}$ [6] and $\sqrt{s} = 0.63\,\text{TeV}$ [7]. DPE has been proposed as a source of Higgs-boson production with an attractively clean signature [8].

A complete study of rapidity gap physics demands detectors that cover a long range in η to establish the absence of particles in one or more gap regions while detecting particles outside the gaps. Such detectors have been proposed for the Superconducting Super Collider (SSC) ($\sqrt{s} = 40\,\text{TeV}$) [9] and the Fermilab Tevatron ($\sqrt{s} = 1.8\,\text{TeV}$) [10]. The point of the present paper, however, is to consider some *hard double-pomeron exchange* (HDPE) processes that can be studied at the Tevatron in the working Collider Detector at Fermilab (CDF) [11] and D0 detector [12], which cover roughly $-4 < \eta < 4$. The processes are defined by rapidity gaps of $-4 < \eta < -2$ and $2 < \eta < 4$, with an experimentally clean high-Q^2 object in the central region. That object should be producible from two Pomerons, which are assumed to have vacuum quantum numbers.

Promising candidates for the central object are (1) pairs of $b\bar{b}$ bound states $\Upsilon(1S)\Upsilon(1S)$ or $\Upsilon(2S)\Upsilon(2S)$, (2) single $b\bar{b}$ bound states $\chi_{b0}(1P)$, $\chi_{b0}(2P)$, $\chi_{b2}(1P)$, or $\chi_{b2}(2P)$, or (3) two jets separated by $\Delta\eta < 1$. The odd-C $b\bar{b}$ states can be detected by $\Upsilon \to e^+e^-$ or $\mu^+\mu^-$. The even-C states can be detected by $\chi \to \gamma\Upsilon$ followed by $\Upsilon \to e^+e^-$ or $\mu^+\mu^-$ [13].

If any of these $\Upsilon\Upsilon$ or χ_b final states are observed, the DPE nature of their production can be demonstrated by showing that the cross section does not decrease drastically when the required rapidity gaps are extended into the central rapidity region. There is plenty of room for this in the case of the $b\bar{b}$ states. For the 2-jet final states, the requirement $\Delta\eta < 1$ also leaves some room for extending the rapidity gaps into the central region to make this test. One can also check that single Υ states are strongly suppressed relative to χ_b, since they cannot be made from two Pomerons according to charge conjugation [14].

I will show that the above processes offer a reasonable opportunity to observe the hard scattering of two pomerons (HDPE). The Υ and χ_b states are especially attractive because their $b\bar{b}$ wave functions are relatively well understood, which will facilitate attempts to compute the production. Because of their low multiplicity and accurately known masses, these states will also be valuable experimentally for calibrating the energy resolution and noise level of the detector.

II. TRIGGER AND BACKGROUNDS

At current Tevatron luminosities, interactions occur at a rate of a few $\times 10^5$ per second, while events can be recorded at a rate of a few per second. Background events must therefore be rejected by $\sim 10^{-5}$. The trigger decision is made in a series of stages, with the initial rejection of 10^{-2} to 10^{-3} based on rather incomplete information. I propose to cope with this trigger challenge as follows.

A minor part of the D0 detector consists of scintillation counters that cover approximately $-4 < \eta < -2$ and $2 < \eta < 4$. Similar counters cover $3.24 < |\eta| < 5.90$ in the CDF. Normal triggers require a coincidence between hits in these "luminosity" (D0) or "beam-beam" (CDF) coun-

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*Electronic address (bitnet): PUMPLIN@MSUPA ters to make a first estimate of the interaction vertex by timing, and to discriminate against beam+gas interactions. *The crucial experimental proposal I make is to use the luminosity counters instead as a veto.* A trigger defined by an absence of hits in these counters, in coincidence with some indication of hard scattering in the central region $|\eta| < 2$, will eliminate a large fraction of "ordinary" events to look for HDPE.

To study the trigger, I use the QCD Monte Carlo program HERWIG5.5 [15] to simulate events. Events that contain no charged particles in the veto regions $-4 < \eta < -2$ and $2 < \eta < 4$ are analyzed in a simple model of a calorimeter detector, consisting of cells 0.20×0.20 in $\eta \times$ azimuthal angle ϕ. Requiring a transverse energy $E_T > 2.5\,\mathrm{GeV}$ or an electromagnetic transverse energy $E_T^{\mathrm{EM}} > 1.5\,\mathrm{GeV}$ in at least one of the cells in the central region, and no electromagnetic or hadronic energy above 0.1 GeV in the veto regions, I find a cross section of $\sim 1\,\mu\mathrm{b}$ according to the "minimum bias" mode of HERWIG.

A second opinion on the minimum bias physics can be obtained from the $2 \to 2$ QCD hard scattering mode of HERWIG, with the the minimum transverse momentum in hard scattering set to a small value (2.2 GeV) chosen to produce the entire inelastic cross section. This "minijet" model predicts a somewhat smaller rate $\sim 0.03\,\mu\mathrm{b}$ for the single hot cell trigger described in the preceding paragraph.

It will be better to trigger on coincidences between two cells above an E_T threshold in the central region. This will reduce the trigger rate from minimum bias physics, and at the same time suppress nonphysics backgrounds from detector noise, beam halo, and beam-gas collisions. According to HERWIG, the trigger rate for two cells above $E_T^{\mathrm{had}} > 2.5\,\mathrm{GeV}$ or $E_T^{\mathrm{EM}} > 1.5\,\mathrm{GeV}$ with a veto for $2 < |\eta| < 4$ is given by $\sim 0.04\,\mu\mathrm{b}$ ("minimum-bias" prediction) or $\sim 0.01\,\mu\mathrm{b}$ ("minijet" prediction). These are small enough that it will be possible to look for HDPE processes, which are of course not simulated by HERWIG, down to the smallest cross sections visible at the Tevatron luminosity.

III. ESTIMATES OF SIGNALS

I estimate diffractive $\Upsilon\Upsilon$ production by a pole-dominance model, used long ago to calculate DPE $\pi^+\pi^-$ production [16]. The amplitude from Fig. 1 is

$$\begin{aligned} \mathcal{M} = {} & T(p_1\, q \to p_3\, p_4)\,(q^2 - M_\Upsilon^2)^{-1} \\ & \times [1 - A(q^2 - M_\Upsilon^2)]^{-1}\, T(p_2\, {-q} \to p_6\, p_5) \end{aligned} \quad (1)$$

An exchanged graph is obtained by $p_4 \leftrightarrow p_5$. The two-body Υp elastic amplitudes are

$$T(p_1\, q \to p_3\, p_4) = i\, s_{34}\, \sigma_{\Upsilon p}\, e^{\beta\, t_{13}/2} \quad (2)$$

where $s_{34} = (p_3 + p_4)^2$ and $t_{13} = (p_1 - p_3)^2$. Reasonable guesses for the Υp total cross section and forward elastic slope are $\sigma_{\Upsilon p} = 2\,\mathrm{mb}$ and $\beta = 6\,\mathrm{GeV}^{-2}$. Equation (1) includes an off-shell suppression factor controlled by the parameter A, which is hard to guess but expected to be $\sim 1\,\mathrm{GeV}^{-2}$. For $A = 1\,\mathrm{GeV}^{-2}$, this model gives 4 nb for $\Upsilon\Upsilon$ production. Allowing for the branching fractions $\Upsilon \to e^+e^-$ or $\mu^+\mu^-$ for both of two $\Upsilon(9460)$'s, and making the rapidity and E_T cuts above reduces the estimate to 4 pb. *At the anticipated Tevatron integrated luminosity of* $50\,pb^{-1}$*, this will lead to 200 events* and be clearly visible. This estimate could of course be wildly optimistic, since it is based on a rather large off-shell extrapolation.

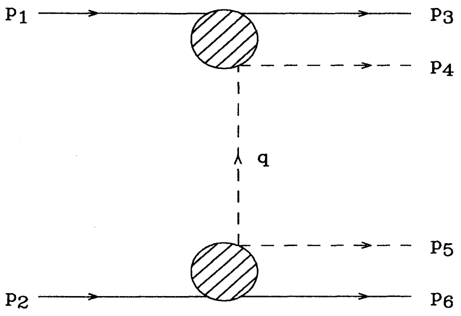

FIG. 1. Pole model for DPE production of $\Upsilon\Upsilon$ or $J/\psi J/\psi$. The blobs represent elastic scattering, which is dominated by pomeron exchange.

The pole-dominance model predicts that DPE production of $J/\psi\, J/\psi$ will also be observable. Assuming $\sigma_{J/\psi\,\mathrm{p}} = 3\,\mathrm{mb}$ and again using $A = 1\,\mathrm{GeV}^{-2}$ leads to 20 nb for $J/\psi\, J/\psi$ production. When both J/ψ decay to e^+e^- or $\mu^+\mu^-$, at least one of the four leptons has $E_T > 3\,\mathrm{GeV}$ more than half of the time. This relatively large E_T arises because the individual J/ψ transverse momenta are comparable to $M_{J/\psi}$, even though their sum is small. The DPE $J/\psi J/\psi$ leptonic final states will therefore also generally pass our proposed trigger.

I next attempt to estimate the diffractive production of single χ_b states. First note that these states can be formed by gluon+gluon fusion with a coupling strength that is measured by their hadronic width:

$$\hat{\sigma}_{gg\to\chi} = (\pi^2\, \Gamma_{\chi\to gg}/16M_\chi)\, \delta(\hat{s} - M_\chi^2) \quad , \quad (3)$$

which includes a factor 1/256 from spin and color averaging. The state $\chi_{b0}(2P)$ has $M_\chi = 10.23\,\mathrm{GeV}$ and $\Gamma_{\mathrm{hadronic}} \approx 400\,\mathrm{keV}$ [13]. According to a simple parton-model calculation, it is formed by $g+g$ fusion, with a production cross section integrated over $|\eta| < 1.5$ of $\sim$20 nb. Including the poorly known branching ratios to $\gamma\Upsilon$ followed by $\Upsilon \to e^+e^-$ or $\mu^+\mu^-$ reduces the observable cross section for this *non-Pomeron* process to $\sim 30\,\mathrm{pb}$.

One can imagine a second gluon exchange that modifies the $g + g$ fusion process and makes the overall exchange between beam and target a color singlet. This color singlet exchange does not necessarily produce a large average number of particles per unit of rapidity. It can occasionally produce zero particles in the veto regions $-4 < \eta < -2$ and $2 < \eta < 4$. If the price for the two gaps is less than a factor $\sim 1/300$, the DPE production rate of the χ_b state will be observable. For a discussion of this idea, see Ref. [17].

A similar estimate can be made for $g + g \to \mathrm{jet} + \mathrm{jet}$. From HERWIG, the cross section for two jets with $E_T > 10\,\mathrm{GeV}$, $|\eta| < 1.3$, and $|\eta_1 - \eta_2| < 1.0$ is $\sim 3 \times 10^7\,\mathrm{pb}$.

If a second gluon exchange can produce rapidity gaps as suggested above, the corresponding HDPE process will be observable even if the gap requirement suppresses this huge cross section by 10^{-8}.

A recent prediction of open $b\bar{b}$ production in double pomeron exchange gives $\sim 3\,\text{nb}$ [18]. If this estimate is correct, the resulting b-mesons should be easy to detect using the rapidity gap trigger.

IV. CONCLUSION

I have shown that a trigger based on two rapidity gaps can be used to look for hard double pomeron interactions in the existing detectors at the Tevatron. Trigger rates and nondiffractive backgrounds are small enough to look for these processes down to $\sim 0.1\,\text{pb}$.

Crude estimates suggest that several HDPE processes will be observable. I have emphasized processes with one or two $b\bar{b}$ states, because they have experimentally very clean e^+e^- and γe^+e^- decay modes with sufficient transverse energy to satisfy the trigger. The $b\bar{b}$ states are also attractive theoretically because one can use their known wave functions in attempting to calculate the production. Final states involving two J/ψ instead of two Υ, with nothing else visible in the detector, are also worth looking for.

Final states with two jets nearby in rapidity, with gaps on either side, will allow the most sensitive search for HDPE, since two-jet production must have a relatively large cross section compared to the other processes I consider. Requiring $|\eta_1 - \eta_2| < 1.0$ for the jet axes, with jets defined by cones $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.7$, leaves an average of 2.8 units in η on either side of the jj system to define the rapidity gaps. Assuming one observes HDPE candidates, in which no particles (or no calorimeter cells above the noise level) appear in the gap regions, it will be important to study the distribution in the number of particles in the gap regions. One must see if there is a peak at 0 particles which signals HDPE; or if the 0-particle events appear to be simply fluctuations of normal hard scattering. According to a HERWIG simulation, the background due to fluctuation has a cross section less than $\sim 10\,\text{pb}$ for jets defined by $E_T > 10\,\text{GeV}$. The multiplicity distribution of the background, for small multiplicity, corresponds roughly to a Poisson distribution of "clusters," where each cluster decays to an average of ~ 2 particles according to an independent Poisson distribution.

Observing HDPE processes would also establish the survival of rapidity gaps, which offer important possibilities for Higgs boson and WW scattering physics at the SSC [19].

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