Double Pomeron Exchange: from the ISR to the LHC

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Abstract. I discuss Double Pomeron Exchange processes from their first observation at the CERN Intersecting Storage Rings, focusing on glueball searches, through the observations of exclusive $\chi_{c0}, \gamma\gamma$ and di-jets at the Tevatron, to prospects at the LHC for exclusive Higgs boson production.

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When two protons collide at high energies they may emerge with small loss of energy (in the center of mass frame, at most a few percent), having created a low mass system X of particles at central rapidity. There is then a rapidity gap of at least $\Delta y = 3$ (preferably > 4) units between X and each proton p. The t-channel exchanges between p and X can only be color singlets with spin J, or effective spin $\alpha(t), \geq 1$; in the Standard Model (SM) only the photon, γ, or the pomeron, $\mathbb{P}$. The pomeron is at leading order a pair of gluons [gg] in a CP = ++ state. A third possibility is the odderon, at least three gluons with C = -1; there is no good evidence for this yet, and I shall ignore it. Two-photon exchange has been seen at the Tevatron (CDF) [1, 2, 3] as $\gamma\gamma \rightarrow e^+e^-$ and $\mu^+\mu^-$; it is a QED process with small corrections from the proton form factor. Photon-pomeron fusion, or photoproduction, was a minor industry at the HERA $e-p$ collider, recently also observed by CDF [2] in the J/ψ and $\psi(2S)$ states. CMS has now shown candidates for J/ψ and Υ photoproduction. The LHC opens up the possibility of measuring Z-photoproduction; in the SM it is marginally too small ($\lesssim$ 50 fb), but could be enhanced by additional BSM loops that couple to γ, Z and $\mathbb{P}$. CDF published [3] an upper limit a factor ~ 1000 above the SM prediction.

I now restrict myself to $\mathbb{P}\mathbb{P}$ interactions; see [4] for a recent review. They have a special feature in that they do not involve valence quarks (any quarks present must have evolved in as virtual pairs via $g \rightarrow q\bar{q}$), and the properties of X should be independent of the colliding hadrons, no matter whether they are pp, $\Omega^-\bar{\Omega}^+$ or $\pi^+\pi^+$. That is the supposition, not however tested by experiment. I will mention later how we could check it at the LHC for the first time (all fixed target experiments have too low $\sqrt{s}$ to study $\mathbb{P}\mathbb{P} \rightarrow X$ with low background). Furthermore, in $\mathbb{P} + \mathbb{P} \rightarrow X$, the state X has tightly constrained properties; it must have CP = ++, Q = 0, no net flavor, and spin J even (mostly J = 0). Together with its glue dominance this makes D$\mathbb{P}$E an excellent channel for spectroscopy when M(X) $\lesssim$ few GeV, and for studying QCD phenomena (and the pomeron itself) at large M(X). Central masses M(X) extend up to $\sim$ 4% of $\sqrt{s}$ and at the LHC reach the electroweak sector. The Higgs boson has the quantum numbers of the vacuum, obeys all the rules for D$\mathbb{P}$E, and can be produced "exclusively" (meaning no other particles are produced) as $p+p \to p+H+p$. Just as pomeron exchange in $p+p \to p+X$ is called "diffractive excitation of a proton", DIPE can be called "diffractive excitation of the vacuum". Any states with allowed quantum numbers are present virtually in the vacuum and can be "kicked into reality" in the collision of two protons. While in $\gamma\gamma$ processes the impact parameter in the collision is usually several fm, with the scattered protons at correspondingly small $|t|$, the most likely impact parameter, b, in $p+p \to p+H+p$ is intermediate: $b \lesssim 1$ fm but not $b \sim 0$, because in that case of maximum overlap the rapidity gap survival probability is minimal. The Higgs boson couples to the protons only weakly through (mainly) the loop $gg \to t\bar{t} \to H$, which is the dominant inclusive Higgs production mechanism. Normally the protons are left colored after the gluon annihilation and a large number of particles are produced. However it is possible for another gluon of complementary color to be exchanged, for the protons to remain in their ground state, and even to have no hadrons created: $p+p \to p+H+p$, or $\mathbb{P}+\mathbb{P} \to H$. One pays a big price, $\sim 10^{-3} - 10^{-4}$ in cross section, for these conditions, but if even a few events are observed, with the protons well measured and the H-decay detected, the payoff will be big. For the SM Higgs, whether it decays to $b\bar{b}$, $\tau^+\tau^-$, W^+W^- or even $ZZ \to \mu^+\mu^-\nu\bar{\nu}$, the central mass M($X$) = M($H$) can be measured with $\sigma(M) \sim 2$ GeV/c^2 from the missing mass to the two protons [5]. The background should be small [6], and the CP must be ++, the spin J =0 or 2 (and these can be distinguished from the proton azimuthal angles), and the state width can be measured (if $\Gamma \gtrsim 3$ GeV). If there are multiple Higgses, as in SUSY models, they could be separated even if only a few GeV apart. However the expected cross section is low, $\sim$ 1 - 10 fb for the SMH in the Durham model [12], and uncertain (it is higher in the MSSM). Fortunately the calculations can be checked with other DIPE reactions that can be measured at the Tevatron, but before describing these, I return to the origins of DIPE physics at the CERN Intersecting Storage Rings, ISR.

The ISR had first collisions in February 1971, and gave us a large step in $\sqrt{s}$ from 7.6 GeV to 63 GeV. Single diffractive excitation previously only of low mass states (resonances) was found to extend up to about 15 GeV/c^2, well above the resonance region. This was well described by Regge theory (our best approach to strong reactions pre-QCD) in terms of "triple Regge diagrams". A pomeron "emitted" (not really!) from a proton interacts with the other proton: $\mathbb{P}+p \to X$, and the $\mathbb{P}p$ total cross section is related by the optical theorem to “$\mathbb{P}+p$” elastic scattering with another t-channel exchange. For low M(X) the latter is a reggeon (virtual ρ or π exchange), but at high M(X) it should be another pomeron, the diagram including a triple pomeron coupling $g_{\mathbb{P}\mathbb{P}\mathbb{P}}$. A higher order diagram (double-triple pomeron or quintuple pomeron) is then implied, corresponding to the DIPE process $\mathbb{P}+\mathbb{P} \to X$. Several experiments at the ISR sought DIPE, but the evidence was slow to accumulate. The total rapidity range is $2.\ln(2E_{beam}/m_p) = 6.4(8.4)$ at $\sqrt{s}$ = 23 (63), so the possibility of having two gaps $\Delta y \gtrsim 3$ is limited to the higher energies; one also needed detectors in both the central and very forward regions. Eventually DIPE became established, for two (unidentified, but presumed to be $\pi^+\pi^-$) hadrons, with a cross section as expected from Regge phenomenology tuned to single diffraction, elastic and total cross sections. If one fixes the forward rapidity gaps to Δy = 3 (say), the cross section rises with $\sqrt{s}$ as the allowed central region expands. If on the other hand one fixes the central region for the pions to be $|y| < 1.0$ or < 1.5 the cross section decreases slowly as the gaps get longer. The

Split Field Magnet experiments eventually observed resonant f_0/f_2 signals in the $\pi^+\pi^-$ (assumed) spectrum. In the last days of the ISR forward drift chambers were added to the Axial Field Spectrometer [7] and provided measurements of $I\!P I\!P \to \pi^+\pi^-$ with high statistics, as well as $K^+K^-, p\bar{p}$, and 4π with identified particles.

Consider the known particles with the allowed X-quantum numbers. They are the very broad $\sigma(600)$, $f_0(980)$, $f_2(1270)$, $f_0(1400)$...χ_{c0}, and χ_{b0}. Not yet known, but with the allowed quantum numbers, are the Higgs boson(s) and perhaps graviton (in theories with extra dimensions, a spin 2 massive graviton G could exist and be produced (AdS-CFT) in DIPE. The AFS $\pi^+\pi^-$ spectrum showed the $f_0(980)$ as a dip, above a very broad scalar ($J^P = 0^+$) distribution likely to be dominated by the $\sigma(600)$, and a small $f_2(1270)$ under a broad scalar, probably $f_2(1400)$. Interestingly the AFS also saw [7] $\alpha\alpha \to \alpha + \pi^+\pi^- + \alpha$ with the same $\pi^+\pi^-$ spectrum, 100% background-free as the α's must have been coherently scattered (and photon exchange would not be detected by the forward detectors).

The ISR gave way to the Sp$\bar{\text{p}}$S collider, and the focus on W,Z and jet physics did not leave much room for DIPE studies. Proton trackers were added [8] to the UA2 central detector and DIPE was observed, but with poor mass resolution and small statistics. Forward gap triggers allowed a study [9] with the UA1 detector of higher M(X) events, showing some soft jettiness and evidence that the charged multiplicity is higher (and rises faster with M(X)) than in e^+e^- collisions, which is not surprising.

The next step came with CDF (the Collider Detector at Fermilab) at the Tevatron with $\sqrt{s}$ = 1960 GeV, allowing central masses up to about 80 (100) GeV with $x_F > 0.96(0.95)$. So far there have been no results on low mass spectroscopy, because DIPE triggers were not in place until recently. Neither CDF nor DZero now have forward proton spectrometers, but recently we developed a trigger in CDF based on forward rapidity gaps, vetoing on particles with $2.1 < |\eta| < 5.7$ on each side. Either the protons went down the beam pipe or they dissociated into a low mass (M $\lesssim$ 2 GeV) state; in either case the events are $I\!P I\!P \to X$ (with small contributions from $\gamma I\!P$ and $\gamma\gamma$ exchanges). The most efficient luminosity for this data is when the average number of inelastic collisions per bunch crossing is ~ 1 or about $L \sim 4 \times 10^{31}$ cm^{-2}s^{-1} (these days the beams are usually dumped at higher L), and as the cross sections are several μb the event rate is high enough to collect millions of events in a few hours. In the low mass region exclusive hadron pairs ($\pi^+\pi^-, K^+K^-, \phi\phi, ...$) etc. are interesting for spectroscopy, and it may be possible to see hadronic decays of exclusive χ_c states, which would be important for testing calculations of exclusive H production. At high masses, M(X) ~ 50 GeV, many studies of event shapes, jets, multiplicities, Drell-Yan pairs, Bose-Einstein correlations, and so on can teach us about pomeron interactions, provide data to test predictions (e.g. by PHOJET) and learn about backgrounds to exclusive Higgs.

Exclusive dijets, $p + \bar{p} \to p + JJ + \bar{p}$ were studied in CDF [10] by triggering on two jets with a high-x_F antiproton and requiring a rapidity gap on the p-side (there was no $p-$detector). Off-line one found events with most of the central energy contained in two jets, in excess of expectations unless the exclusive process $I\!P + I\!P \to J + J$ is included. The EXHUME program, based on the “Durham process", calculates this as $gg \to J + J$ with another gluon exchange to cancel the color, as in exclusive Higgs production, and the data are in fair agreement (a factor of “a few" in theory and experiment). A model with the pomeron as an object with a multi-$q/\bar{q}/g$ structure such as POMWIG does not give exclusive dijets and fails to reproduce the data. The CDF exclusive dijet study extends up to M(JJ) $\sim$ 120 GeV in only 300 pb^{-1} of luminosity. Recently DZero has seen 26 exclusive dijet events [11] with M(JJ) $>$ 100 GeV (30 pb^{-1} of data), with $5.4^{+4.2}_{-2.9}$ non-exclusive background events.

While the exclusive dijet cross section measurement has model dependence, and there is no *absolute* distinction between exclusive and inclusive dijets, exclusive χ_c production is well-defined; it is $p+\bar{p} \rightarrow p+\chi_c+\bar{p}$ with *no other hadrons* in the final state. The diagram is the same as exclusive H production with the top-loop replaced with a charm-loop, and the χ_{c0} has the same quantum numbers, which makes it a clean comparison. It was observed by CDF [2] with the χ_c central, with $d\sigma/dy|_{y=0} = 76 \pm 10(\mathrm{stat}) \pm 10(\mathrm{syst})$ nb in $\chi_c \rightarrow J/\psi + \gamma$ with $J/\psi \rightarrow \mu^+\mu^-$. Unfortunately the photon has low energy ($\sim$ 200 MeV) so the M($J/\psi+\gamma$) resolution does not distinguish χ_c states; the $\chi_{c0}(3415)$ state should dominate but the $\chi_{c1}(3510)$ and $\chi_{c2}(3556)$ states have 30(17)$\times$ higher branching fractions respectively. It should be possible to distinguish these states using hadronic decays, which have much better mass resolution. About 6% of χ_{c0} decays are to h^+h^- or $2(h^+h^-)$, where $h=\pi$ or K. The width $\Gamma(\chi_{c0})$ = 10 MeV and the mass resolution in CDF is similar; the main issue is continuum background. The CDF observation of $\chi_c \rightarrow J/\psi + \gamma$ does not suffer from either combinatorial or continuum backgrounds; the only significant "background" to $p+\chi_c+\bar{p}$ is undetected dissociation e.g. $p+\chi_c+\bar{p}\pi^+\pi^-$, with the dissociation products not detected in the forward Beam Shower Counters, BSC. We will also search for exclusive open charm: $D^+D^-, D^0\bar{D}^0, D^0_s\bar{D}^0_s$ in hadronic modes.

CDF also published a search for $I\!P I\!P \rightarrow \gamma\gamma$ [13], with $E_T(\gamma) > 5$ GeV, which proceeds through an intermediate quark loop, and is the closest control process to exclusive Higgs as the final state does not have strong interactions. Unfortunately the cross section is small; Ref. [14] predicted 36^{+72}_{-24} fb corresponding to $0.8^{+1.6}_{-0.5}$ events, and three candidates were found. The E_T threshold has since been decreased to $\sim$ 2.5 GeV and there are many more candidates, but the $I\!P + I\!P \rightarrow \pi^0\pi^0$ background has to be understood; it is an interesting channel in itself.

RHIC has now entered the field of DIPE with forward proton measurements in STAR, reported at this meeting by Guryn [15].

At the LHC DIPE studies will be very interesting, both in the low mass exclusive regime and at high masses M(X) $\gtrsim$ 250 GeV (quite apart from the H search). At this meeting Schicker showed some preliminary ALICE data [16]. However at present the experiments are handicapped by having very poor forward coverage. There are $\theta = 0^\circ$ calorimeters (ZDC) for γ and neutrons ($K^0_L/n \lesssim 10^{-2}$), and in CMS the HF calorimeters have $|\eta| < 5.2$, with CASTOR on one side having $5.2 < \eta < 6.4$. About 3 units of η on both sides are uninstrumented, exactly where most rapidity gaps are in diffractive interactions. Events with hadrons between two clean gaps $\Delta y \gtrsim 4$ are confined to $-2.4 < y < +1.2$ (not minding whether the p dissociated). These gaps can be simply covered with sets of scintillation counters (FSC = Forward Shower Counters) [17, 18] along the beam pipes out to $|z| \sim 140$ m. ALICE is installing counters and they are proposed for CMS. Among many other things (including a σ_{inel} measurement and single diffraction) they allow a DIPE trigger based on vetos in FSC, ZDC, CASTOR and HF, together with some minimal central activity. These select $p+X+p$ events, without however detecting the protons, which can be done with the TOTEM detectors in some conditions (not yet done). They also allow DIPE studies with low mass proton dissociation ($p^* + X + p^*$), by triggering on hits in the FSC (both sides) with a veto on HF and a small central energy deposit or track. While this should give a clean sample, more information ($t_1, t_2, \Delta\phi$) would come from detecting the scattered protons, as could be done in CMS+TOTEM. During the expected special high-β^* (90 m) run for TOTEM, the luminosity will be low and perhaps the best use of the time for CMS would be DIPE with a combined trigger (on each side a p and $\overline{ZDC.FSC.HF}$ with some central activity).

I now return to the possibility of comparing DIPE in baryon-baryon and meson-meson collisions at the LHC. Select events with a neutron shower in each ZDC, some hits in the FSC on each side from a π^+ (slightly virtual, $t < 0$), and rapidity gaps in the forward calorimetry ($2 \lesssim |\eta| \lesssim 5$). Low mass central states will have a contribution (dominant(?)) from $\pi^+\pi^+ \to \pi^+ + X + \pi^+$. This could test whether pomerons from $3q$ and $2q$ hadrons are different.

To conclude, DIPE is a special kind of interaction: strong and almost pure glue, with constrained quantum numbers and "clean". The list of allowed central states is small : $f_{0,2}, \chi_{c,b}, \gamma\gamma, JJ, H$. The low mass end addresses glueball and meson spectroscopy, and we have hardly scratched the surface. The high mass end addresses pomeron structure, jets, and much else. We could get much more data at the Tevatron, and we are just starting at the LHC, where we should push for maximal forward coverage (FSC) and forward gaps in level-1 triggers.

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