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Central exclusive production in CDF

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Summary. — In the Collider Detector at Fermilab, CDF, we have made the first observations of several "exclusive" processes in $p\bar{p}$ collisions, defined as $p + \bar{p} \to p(*) \oplus X \oplus \bar{p}(*)$, where the beam (anti)protons are diffractively scattered, with or without dissociation, the "$\oplus$" denotes a large rapidity gap $\Delta\eta > 4.5$ with no hadrons, and "X" is a simple state fully measured. The main part of the talk focuses on recent $X = \pi^+\pi^-$ data, through the double-pomeron exchange mechanism.

PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 13.75.Lb – Meson-meson interactions.
PACS 14.40.Be – Light mesons ($S = C = B = 0$).

At collider energies about 25% of the total $pp(p\bar{p})$ cross section is elastic scattering, in which the (4-momentum-transfer)^2 between the protons is carried by a pomeron. Despite its name the pomeron $\mathbb{P}$ (named after Pomeranchuk) is not a particle, as it only appears in the t-channel, and although it should be part of QCD it involves low-Q^2, very non-perturbative, interactions that we do not yet know how to calculate. In QCD language it is at leading order a pair of gluons in a color singlet state with vacuum quantum numbers; at higher orders loops of quarks, gluons, pions, etc. form a ladder. As we are in the regime where $\alpha_S(Q^2) \sim 1$ such loops are not suppressed, hence the theoretical difficulties. Phenomenologically (and pre-dating QCD) the pomeron is described as a Regge trajectory $\alpha_{\mathbb{P}}(t) = \alpha_0 + \alpha' t \sim 1.08 + 0.2t$, while mesons have Regge trajectories (reggeons) like $\alpha_\rho \sim 0.55 + 0.9t$ [1]. The latter describe well the (s,t) behavior of reactions such as: $\pi^- + p \to \pi^0 + n$, which QCD is not (yet) able to do. The value of $\alpha(0)$ determines the s-dependence of elastic scattering, when the reggeon (pomeron) is exchanged, and of total cross sections, which are related through the optical theorem. Meson exchanges with $\alpha(0) < 1.0$ decrease with increasing s, or equivalently increasing rapidity gap Δy, while pomeron exchange, with $\alpha(0) > 1.0$, grows. For a rapidity gap $\Delta y \sim \Delta\eta \gtrsim 4$

(called here a "large" gap) the t-channel exchange is only the pomeron, or the photon with spin $J = 1$ (Coulomb scattering, with a larger range and therefore usually smaller $|t|$ than pomeron exchange). With a single gap we have elastic scattering and single and double diffractive dissociation. At the Tevatron and the LHC the rapidity range $\Delta y_{total} = 2 \times y(p) = 2 \times \ln(\sqrt{s}/m_p) = 15.3$ and 18.1, respectively, allowing space for more than one large rapidity gap. With two large gaps we have $p + \bar{p} \to p(*) \oplus X \oplus \bar{p}(*)$, where the two t-channel exchanges across the gaps are either photons or pomerons, so there are three classes: $\gamma + \gamma$, $\gamma + \mathbb{P}$, and $\mathbb{P} + \mathbb{P}$. In the Collider Detector at Fermilab, CDF, we observed the first two for the first time in hadron-hadron collisions. The third reaction, double pomeron exchange or D$\mathbb{P}$E, was studied at the SPS (fixed target) and ISR [2] (pp with $\sqrt{s} = 23$–$63\,\mathrm{GeV}$), but without such large rapidity gaps, allowing some non-$\mathbb{P}$ background. At the ISR the masses of the central state, $M(X)$, were limited to about $3\,\mathrm{GeV}/c^2$, which is a good region for meson spectroscopy studies. The quantum numbers of the central state X are restricted to be $I^G\,J^{PC} = 0^+(\mathrm{even})^{++}$, which allows glueball formation as they are isoscalars and the pomerons are "glue-rich". Quoting from the PDG [3] "The scalar (isoscalar) mesons are especially important to understand because they have the same quantum numbers as the vacuum. Therefore they can condense into the vacuum and break a symmetry such as a global chiral $U(N_f) \times U(N_f)$. The details of how this symmetry breaking is implemented in Nature is one of the most profound problem in particle physics". So even without talking about glueballs, D$\mathbb{P}$E must be extremely interesting (see [4] for a review).

Photon-photon collisions are "bread and butter" at e^+e^- colliders (no pomerons), but were observed for the first time in hadron-hadron collisions in CDF, both with $X = e^+e^-$ [5] and $X = \mu^+\mu^-$ [6,7]. The results agree with QED expectations, which provides an excellent control of the experiment. The $\mu^+\mu^-$ spectrum shows very prominent J/ψ and $\psi(2S)$ signals; these $J^{PC} = 1^{--}$ states are photoproduced, $\gamma + \mathbb{P}$, and have been studied extensively in ep collisions at HERA but were seen here for the first time in hadron-hadron collisions. Unique to hadron-hadron collisions are $\mathbb{P} + \mathbb{P}$ interactions, producing single mesons with the allowed quantum numbers, such as $f_0(600)/\sigma$, $f_0(980)$, $f_2(1270)$, etc., already seen at lower energies [2], and the χ_c states [6]. Of course *any* hadron states can be produced in pairs, including glueballs or states with exotic (non-$q\bar{q}$) quantum numbers. Exclusive χ_b is expected at the LHC, and the same diagram but with a top-quark loop instead of a c, b loop can produce exclusive Higgs bosons at the LHC: $p + p \to p \oplus H \oplus p$ with no other produced particles. Seeing these events would be a very interesting, and very different, way of investigating the $H(125)$, as the production is only $gg \to H$ through loops (mainly top) and only $CP = ++$ is allowed. Thus seeing the $H(125)$ this way proves that it has P = + without assumptions about CP conservation in the Higgs sector. When this was first proposed for the Tevatron [8] the cross section predictions were spread over orders-of-magnitude. In CDF we then set out to observe $X = \gamma\gamma$ events which have the same mechanism, but with (mainly) a u-quark or c-quark loop instead of a t-quark loop. This first (and so far, only) observation of $p \oplus \gamma\gamma \oplus p(\bar{p})$ events [9] constrains the theory, such that we now expect $\sigma(p \oplus H(125) \oplus p) \sim 2^{\times 2}_{\div 2}\,\mathrm{fb}$. This is small, but similar to $\sigma(H) \to ZZ^* \to l_1^+ l_1^- l_2^+ l_2^- \sim 1\,\mathrm{fb}$; in both cases the continuum background is comparable to the signal, given the good mass resolution from the proton measurements.

I now focus on $\mathbb{P} + \mathbb{P}$ interactions in CDF. In the central region the detector has silicon-strip and drift-chamber trackers in a solenoidal field, and a barrel of time-of-flight scintillators, surrounded by electromagnetic and hadronic calorimeters and muon chambers. In both forward directions there is an array of 48 gas Cherenkov counters,

$3.7 < |\eta| < 4.7$, and Beam Shower Counters (BSC) $5.4 < |\eta| < 5.9$. These had lead in front to detect photons. For the observation of exclusive $\gamma\gamma$ [9] there were more BSC out to $|\eta| = 7.4$ giving good efficiency for rejecting proton diffractive dissociation. These were not available for the $\pi^+\pi^-$ data presented below, so diffractive dissociation is included in the data. At $\sqrt{s} = 1960\,\mathrm{GeV}$ CDF found 43 events with two γ-candidates with $E_T > 2.5\,\mathrm{GeV}$, $|\eta| < 1.0$ and no tracks or unassociated calorimeter clusters in $-7.4 < \eta < +7.4$. The possible background of exclusive $\pi^0\pi^0$ events was consistent with zero. The cross section is $2.48^{+0.40}_{-0.35}(\mathrm{stat})^{+0.40}_{-0.51}(\mathrm{syst})$ pb, in agreement with a Durham Group prediction [10]. The ingredients in that prediction are the cross section for $g + g \to \gamma + \gamma$ through quark loops, the unintegrated gluon distribution $g(x, x')$ which comes in as the fourth power, the Sudakov requirement of no gluon or hadron radiation, and no other parton-parton collisions (the rapidity gap survival factor). Together these contribute to a theoretical uncertainty [11] of about $^{\times 2}_{\div 2}$ which feeds in to a similar uncertainty on $\sigma(p \oplus H \oplus p) \sim 2\,\mathrm{fb}$ at the LHC. At least this cross section is no longer uncertain by *orders of magnitude*, as was the case earlier. To improve the prediction for $\sigma(p \oplus H \oplus p)$ at the LHC the best procedure would probably be to measure $\sigma(p + p \to p \oplus \gamma\gamma \oplus p)$ at $\sqrt{s} = 13\,\mathrm{TeV}$. This requires some low-pileup running, with at most a few interactions per bunch crossing, and preferably selecting single interactions. A CMS search at $\sqrt{s} = 7\,\mathrm{TeV}$ [12] found no candidates, but in only $5\,\mathrm{pb}^{-1}$ of effective (no-pileup) luminosity L_{eff}. Suppose we could get 250 hours (< 2 weeks) with mean pileup $\mu = 1$. With 2800 bunches one gets $L_{\mathrm{eff}} \sim 200\,\mathrm{pb}^{-1}$. Using the Durham Group's central prediction one can expect (with the right trigger, and assuming 60% efficiency) about 180 events with $|\eta(\gamma)| < 3.0$ and $M(\gamma\gamma) > 10\,\mathrm{GeV}/c^2$, *i.e.* $< 10\%$ uncertainty. The backgrounds are small because $p_{T\gamma 1} \sim p_{T\gamma 2}$ and $\Delta\phi(\gamma\gamma) \sim 180°$. These latter conditions probably allow one to also use events with $\mu = 2 - 4$. If one cannot measure both protons (*e.g.* with upgraded TOTEM detectors) one has to use Forward Shower Counters, FSC, and other very forward "gap-detectors" and estimate the dissociation contribution. Independent of predicting the exclusive Higgs cross section, this measurement is an excellent test of the above ingredients of the QCD calculation. $\mathbb{P} + \mathbb{P} \to \gamma + \gamma$ is so simple, what could be nicer for studying the pomeron?

Another CDF result is the observation of exclusive dijets [13]. A Roman pot spectrometer was used, a set of three pots with scintillating fiber hodoscopes to measure antiproton tracks. These were behind quadrupole and dipole magnets and measured the momenta of diffractively scattered antiprotons. Events with $\bar{p}$ track, at least two central jets with $E_T > 10\,\mathrm{GeV}$ and a rapidity gap on the outgoing p-side (which did not have Roman pots) were selected. The total mass $M(X)$ of all calorimeter signals ($|\eta| < 5.2$) and the mass of the two leading jets $M(JJ)$ were compared, as the ratio $R(JJ) = M(JJ)/M(X)$ should be close to 1.0 for an *exclusive* dijet. An event generator that does not include exclusive dijets, POMWIG [14], fails to describe the data (with jet E_T up to 35 GeV) for $R(JJ) \gtrsim 0.8$, but the addition of EXHUME [15] gives agreement, taken as evidence for exclusive dijets. This is another important test of the "Durham mechanism", and is in reasonable agreement. Nearly all of these exclusive dijets should be gg, with a small admixture of $b\bar{b}$; not only is this study important for QCD *per se*, it tells us about the background to exclusive $H \to b\bar{b}$. At the Tevatron D0 also measured exclusive dijets [16].

I now present preliminary results on $p+\bar{p} \to p(*) \oplus \pi^+\pi^- \oplus \bar{p}(*)$ in CDF. It was possible to trigger on two central ($|\eta| < 1.3$) calorimeter towers with a threshold as low as 0.5 GeV by vetoing on signals in the BSC counters and the forward plug calorimeter. There was then very little pileup, easily removed by requiring exactly two tracks (and their

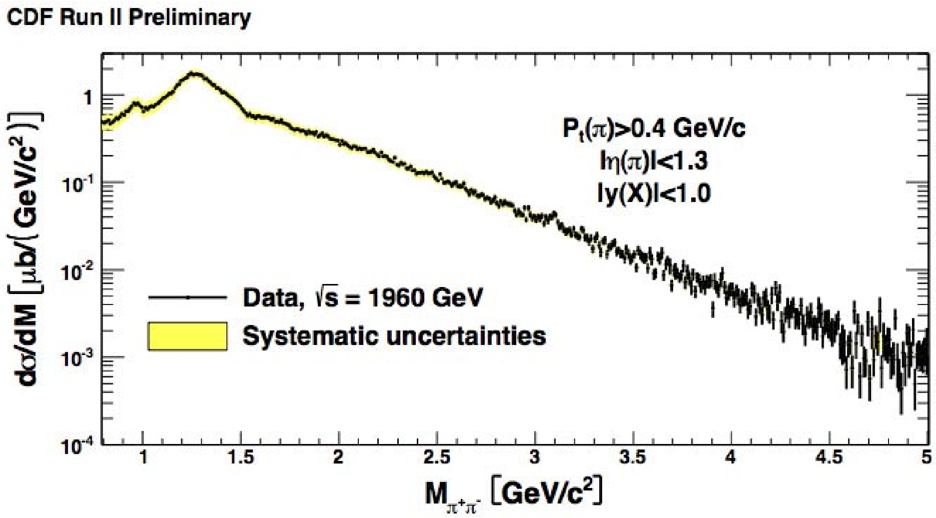

Fig. 1. – Differential cross section $\mathrm{d}\sigma/\mathrm{d}M$ for two particles, assumed to be $\pi^+\pi^-$, in the stated kinematic region, between two forward rapidity gaps $\Delta y > 4.6$, at $\sqrt{s} = 1960\,\mathrm{GeV}$.

associated calorimeter signals) and no other activity in $|\eta| < 5.9$. This led to events with two rapidity gaps of $\Delta\eta > 4.6$. We recorded 90 (22) million events at $\sqrt{s}$ = 1960 (900) GeV, the lower energy data in a special 38-hour run we proposed mainly for this purpose. To make the *exclusivity cuts* it was important to know the noise levels in all elements of the detector, for which we used 0-bias events, recording bunch crossings with no other requirements. The probability of the whole detector ($|\eta| < 5.9$) being empty as a function of the individual bunch luminosity is an exponential with intercept 1.0, and the slope gives the inelastic cross section within that coverage, which at 1960 GeV agrees well with the expectation: $\sigma(\mathrm{vis}) = (0.85 \pm 0.05) \times \sigma(\mathrm{inel})(61.0 \pm 1.8\,\mathrm{mb})$. At $\sqrt{s} = 900\,\mathrm{GeV}$ the luminosity monitors were not calibrated and we used the relation $\sigma(\mathrm{vis}) = (0.90 \pm 0.05) \times \sigma(\mathrm{inel})(52.7 \pm 1.6\,\mathrm{mb})$ to normalise the cross sections The $\sigma(\mathrm{inel})$ values come from a global fit including TOTEM values [17]. After all exclusivity and quality cuts we have 350,223 (9,349) h^+h^- events. A study of the time-of-flight shows that $> 92\%$ of the events are $\pi^+\pi^-$. Even though the collision time is not well known, the h^+ and h^- have different momenta and different path lengths, so identification is possible for most tracks. The acceptance is a function of both $p_T(\pi\pi)$ and $M(\pi\pi)$ and is calculated for $|y(\pi\pi)| < 1.0$, assuming isotropic decay of "X" $\rightarrow \pi\pi$. As the acceptance is zero for low $p_T(\pi\pi)$ below $M(\pi\pi) = 800\,\mathrm{MeV}/c^2$, we only present the cross section, integrated over $p_T(\pi\pi)$, for higher masses. Figure 1 shows the cross section (assuming pion masses) up to $5\,\mathrm{GeV}/c^2$ at $\sqrt{s} = 1960\,\mathrm{GeV}$. Features are the $f_0(980)$, a large bump probably both $f_2(1270)$ and $f_0(1370)$, a break at about $1550\,\mathrm{MeV}/c^2$ followed by a smooth, almost-exponential fall off. A small peak at $3100\,\mathrm{MeV}/c^2$ is consistent with photoproduced J/ψ decaying to e^+e^- (events with muons were excluded). The data at $\sqrt{s} = 900\,\mathrm{GeV}$ look similar, but with much lower statistics; however in detail there are differences as shown by the ratio plot, fig. 2. As the acceptance is almost identical at the two energies the systematic uncertainties are small. Some clear structures in this ratio still require explanation. One difference is that the rapidity gaps extend to $|\eta| = 5.9$ at

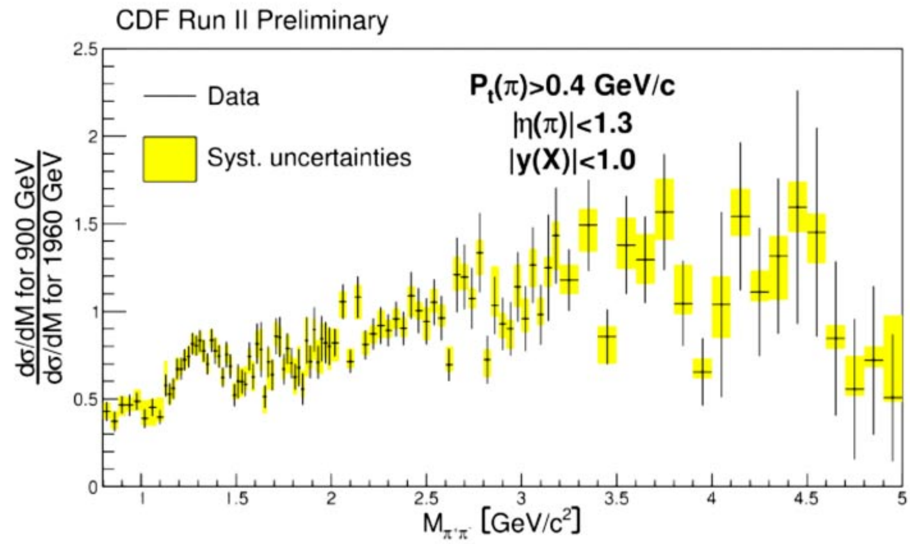

Fig. 2. – Ratio of $\mathrm{d}\sigma/\mathrm{d}M(\pi^+\pi^-)$ at $\sqrt{s} = 900{:}1960\,\mathrm{GeV}$ in the stated kinematic region.

both energies, while the beam (true) rapidity is $y_{beam} = \ln(\sqrt{s}/m_p) = 6.87$ and 7.64, so that higher diffractive masses are included at $\sqrt{s} = 1960\,\mathrm{GeV}$.

In our previous observation of exclusive $\chi_{c0}(3415) \to J/\psi + \gamma$ [6] we could not resolve the three χ_c states, and gave a cross section *assuming* only χ_{c0}. We can look for $\chi_{c0} \to \pi^+\pi^-(K^+K^-)$ which have the highest branching fractions for the χ_{c0}, and the mass resolution easily resolves these states. Fitting the spectrum between $2.5\,\mathrm{GeV}/c^2$ and $4.5\,\mathrm{GeV}/c^2$ with an empirical function excluding the χ_{c0} region, we place upper limits on its exclusive production: $\mathrm{d}\sigma/\mathrm{d}y(\chi_{c0})|_{y=0} \lesssim 20\,\mathrm{nb}$ (at 90% C.L.). This is only compatible with our previous observation if $< 25\%$ of the $J/\psi + \gamma$ events were from χ_{c0}; note that the branching fractions of $\chi_{c1}(\chi_{c2}) \to J/\psi + \gamma$ are $30 \times (17.4\times)$ higher, so they are still suppressed in production, as expected [18].

We also studied the angular distributions ($\mathrm{d}N/\mathrm{d}\cos\theta^*$) of the $X \to \pi^+\pi^-$, and found them to agree with S-wave up to $1.5\,\mathrm{GeV}/c^2$, above which they deviate, becoming increasingly forward-backward peaked. If the dominant resonance peak around $1.27\,\mathrm{GeV}/c^2$ is the $f_2(1270)$ it does not show up as a deviation from isotropy. The Legendre coefficients show a "wave" structure between 1.5 and $2.5\,\mathrm{GeV}/c^2$, which is not understood.

We have more data available for other channels. We are currently studying $X = \pi^0\pi^0$, $\eta^0\eta^0$, $\eta^0\eta'$, and $\eta'\eta'$ production with four photon showers and 0, 1, or 2 pairs of charged pions. The Durham Group predicts a hierachy, with $\eta(')\eta(') > \pi^0\pi^0$ at large $M(X)$ because (a) the η and η' are isoscalars, and (b) they probably have a high glue component. This would be very interesting; we have data but the analysis is ongoing.

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