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Measurement of central exclusive $\pi^+\pi^-$ producction in $p-\bar{p}$ collisions at $\sqrt{s}$ = 0.9 and 1.96 TeV at CDF.

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We have measured exclusive $\pi^+\pi^-$ production in proton-antiproton collisions at center-of-mass energies $\sqrt{s}$ = 0.9 and 1.96 TeV in the Collider Detector at Fermilab. We selected events with two oppositely charged particles, assumed to be pions, with pseudorapidity $|\eta| < 1.3$ and with no other particles detected in $|\eta| < 5.9$. We required the $\pi^+\pi^-$ system to have rapidity $|y| < 1.0$. The production mechanism of these hadrons is dominated by double pomeron exchange, which constrains the quantum numbers of the central state. The data are potentially valuable for isoscalar meson spectroscopy, and for understanding the pomeron in a region of transition between non-perturbative and perturbative quantum chromodynamics. The data extend up to dipion mass 5000 MeV/c^2, and show resonance structures attributed to f$_0$ and f$_2$(1270) mesons. We place upper limits on exclusive χ_{c0}(3415) production using the $\pi^+\pi^-$ and K^+K^- decay channels.

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1. Introduction

The Collider Detector at Fermilab, CDF, experiment undertook a program of measuring central exclusive production, CEP, in $p\bar{p}$ collisions at the Tevatron. These are reactions of the type $p + \bar{p} \rightarrow p(^*) + X + \bar{p}(^*)$, where X is fully measured in the central detector, and is separated by large rapidity gaps Δy from the leading particles. In most cases those were not detected, and low-mass diffraction dissociation ($p \rightarrow p^*$) is allowed, as long as all forward particles have $|\eta| > 5.9$ The four-momentum transfer from the initial to the final protons is through a photon γ or pomeron $I\!P$, which at leading order is a pair of gluons in a color-singlet. We made the first observations, in hadron-hadron collisions, of $\gamma\gamma \rightarrow e^+e^-$ [1, 2] and $\mu^+\mu^-$ [3], γ + $I\!P \rightarrow J/\psi, \psi(2S)$ [3], and $I\!P$ + $I\!P \rightarrow$ exclusive di-jets [4], $\gamma\gamma$ [5, 6] and χ_c [3]. In most cases these events have very little background, after requiring all the CDF detectors out to $|\eta|$ = 5.9 to be empty, i.e. compatible with noise, apart from the photons or lepton tracks. In the case of $\gamma\gamma$ a possible background was $I\!P$ + $I\!P \rightarrow \pi^0\pi^0$, but there was no evidence for that, and it is expected to be small at large $M(X)$. However at low $M(X) \lesssim$ 3000 MeV/c^2, exclusive dipion production has a large cross section ($\sim \mu$b), and that is the subject of this talk.

There are two main motivations for studying the double pomeron exchange, D$I\!P$E , reaction $I\!P$ + $I\!P \rightarrow \pi^+\pi^-$. The channel is a *quantum number filter*, only allowing direct production of states with $I^GJ^{PC} = 0^+(\text{even})^{++}$. This makes it an excellent channel for isoscalar meson spectroscopy, especially for scalar and tensor (J = 2) glueballs G, since the pomeron is glue-dominated. The Regge trajectory of the pomeron, continued into the s-channel, crosses $J = 2$ at about 2000 MeV/c^2, where a tensor glueball may be expected. The scalar (J = 0) glueball should be lighter, and it cannot be on the pomeron trajectory. The D$I\!P$E process is unique in being able to produce a glueball in isolation, as the outgoing protons are far away in rapidity. Glueballs are isoscalar hadrons with no valence quarks, and although their spectroscopy is still unclear, we now know that the lightest glueball should have $J^{PC} = 0^{++}$, with $M(G) > 1000$ MeV/c^2 and a width of at least 100 MeV/c^2. This means that when it is produced in a typical inelastic pp collision it decays within the hadronization region, never in isolation; that only happens in D$I\!P$E . The scalar glueball has vacuum quantum numbers, and so the vacuum can fluctuate briefly to a virtual G, and then it can be excited to a real state by the colliding protons. For recent reviews, see Ref. [7]. So the D$I\!P$E process can be called “vacuum excitation". One can of course also produce glueballs with any other quantum numbers in pairs.

The established states in the Particle Data Group [8] that can be produced singly in D$I\!P$E are the $f_0(500, 980, 1370, 1500, 1710)$, $f_2(1250, 1525, 1950, 2010, 2300, 2340)$, $\chi_{c0}, \chi_{c2}, \chi_{b0}, \chi_{b2}$, and H! (At the LHC the Higgs boson can be produced singly: $pp \rightarrow p + H + p$, with a cross section $\sim$2 fb. Seeing this would require special proton detectors at $z = \pm$ 420 m.) Scalar and tensor glueballs should be among the f_0 and f_2 states, not as pure gg-states, but mixed with $q\bar{q}$ states. While the pomeron is a very important part of strong interaction physics, with $\sim$ 40% of the total pp cross section being due to pomeron exchange (elastic scattering and other diffractive interactions), it is still not well understood, basically because the strong coupling $\alpha_S(Q^2)$ becomes of order 1 and perturbative QCD breaks down. It is a challenge to theory to “unify" Regge theory and QCD, i.e. derive the properties of the pomeron and other Regge exchanges from QCD. Data on inelastic collisions involving pomeron exchange, such as D$I\!P$E , may be important in making progress. The data presented here on $\mathbb{P} + \mathbb{P} \rightarrow \pi^+\pi^-$ extend to $M(\pi\pi)$ = 5000 MeV/c^2, higher than in previous experiments at lower $\sqrt{s}$, and with less background, thanks to the larger gaps Δy and low noise in the detector.

2. CDF : The detector

CDF is a general-purpose detector at the Tevatron, which provided proton-antiproton collisions at $\sqrt{s(p\bar{p})}$ = 1960 GeV. Before the Tevatron was turned off in 2012, when it became no longer competitive with the LHC for high-mass and high-Q^2 physics, we proposed to take data at $\sqrt{s}$ = 300 GeV (injection energy) and $\sqrt{s}$ = 900 GeV (the LHC injection energy). This special running, for diffractive and high cross section physics, took place in only five days, with low luminosity (no low-β^* and only a few bunches). Here I report on recently published [9] exclusive $\pi^+\pi^-$ production and its energy dependence from 900 - 1960 GeV.

CDF had a central detector with silicon and drift-chamber tracking and a barrel of time-of-flight scintillation counters in a 1.4T solenoidal magnetic field, surrounded by electromagnetic and hadronic calorimetry. In the forward directions there were arrays of gas Cherenkov counters (CLC) for luminosity measurement, and beam shower counters (BSC) extended the η-coverage to $\pm$ 5.9. The events of interest for this study have exactly two tracks of opposite charge with $|\eta| <$ 1.3, and no other particles detected in -5.9 $< \eta <$ +5.9. Outgoing protons were not detected, and as the beam rapidities were 6.87 and 7.64 at $\sqrt{s}$ = 900 and 1960 GeV respectively, low mass diffractive dissociation could occur without being detected. The trigger for this data required at least two calorimeter towers with $|\eta| <$ 1.3 to have transverse energy $E_T >$ 0.5 GeV and all the detectors with $|\eta| >$ 2.11 (Plug calorimeter, CLC, and BSC) to be in veto. Only single, no pile-up interactions are used, and the data is mostly taken at the end of stores when pile-up is low.

3. Data selection

Off-line we selected events with exactly two tracks on a common vertex, and the whole detector to be “empty", i.e. consistent with noise, outside cones of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$ around the tracks extrapolated to the calorimeters. Noise levels in all the detectors were determined using zero-bias (random bunch-crossing) triggers, and dividing those events into a “no-interaction" class (no tracks, no muon stubs, and no CLC hits) and an “interaction" class (all other events). Distributions of energy, or ADC counts, or the largest signal in a PMT determine the noise levels or “exclusivity cuts". The probability in zero-bias events that the whole detector is empty as a function of bunch luminosity is an exponential distribution, with nominal slope $\sigma_{inel:|\eta|<5.9}$. Convoluting this with the bunch luminosity distribution of the data-taking period gives L_{eff}, the effective luminosity when only single interactions are allowed. This was L_{eff} = 1.15 pb^{-1} (0.059 pb^{-1}) at 1960 (900) GeV.

Tracks were required to be of good quality, to have $p_T >$ 0.4 GeV/c and $|\eta| <$ 1.3 and to have opposite charge. The $Q = \pm$ 2 events were 6.5% of the total, an indication of some background e.g. from $\pi^+\pi^-\pi^+\pi^-$ events with two missed tracks, due to an inefficiency or tracks having very low p_T. The final sample contains 127,340 (6,240) events at 1960 (900) GeV. Time-of-flight was used to identify the hadrons as π, K or p, and showed that $\sim$ 90% of the pairs are $\pi^+\pi^-$. As the

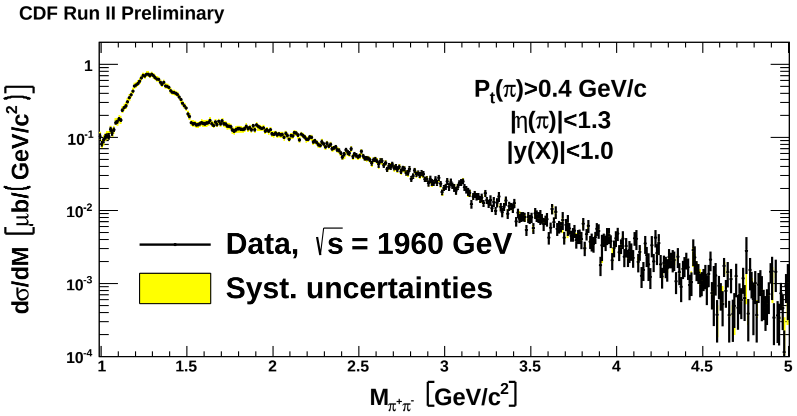

Figure 1: Differential cross section $d\sigma/dM(\pi\pi)$ at $\sqrt{s}$ = 1.96 TeV for two charged particles, assumed to be $\pi^+\pi^-$, with $p_T > 0.4$ GeV/c, $|\eta| < 1.3$ and $|y(\pi\pi)| < 1.0$ between two rapidity gaps $1.3 < |\eta| < 5.9$.

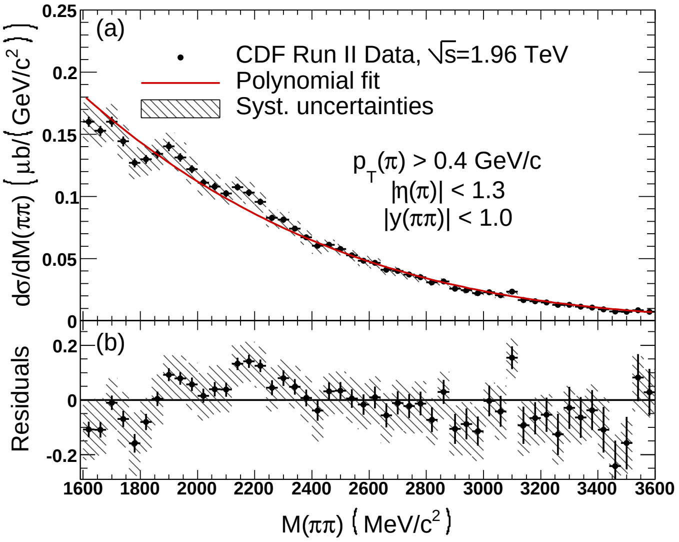

Figure 2: High mass data at 1.96 TeV with a fit to a fourth-order polynomial, showing some structures.

identification efficiencies are very mass-dependent, we did not select the identified $\pi^+\pi^-$ events, but included all pairs, giving tracks the pion mass when calculating pair mass $M(\pi\pi)$ and $y(\pi\pi)$.

The acceptance is low for $M(\pi\pi) < 1000$ MeV/c^2 and small $p_T(\pi\pi)$ but there is no significant $\rho(770)$, which is forbidden in DPE. A correction for acceptance was then made, starting with the single pion acceptance and trigger efficiency, as a function of (Q, p_T, η, ϕ). The next step is the pair acceptance as a function of $p_T(\pi\pi), M(\pi\pi)$ and $y(\pi\pi)$, for which we assumed an isotropic decay. The data is compatible with an isotropic decay up to $M(\pi\pi)$ = 1500 MeV/c^2, after which it becomes more forward-backward peaked. The acceptance is > 80% in the two regions we present: $M(\pi\pi) > 1$ GeV/c^2 for all $p_T(\pi\pi)$, and $p_T(\pi\pi) > 1$ GeV/c for all $M(\pi\pi)$.

After correcting for acceptance the differential cross section at $\sqrt{s}$ = 1.96 TeV is shown in Fig.

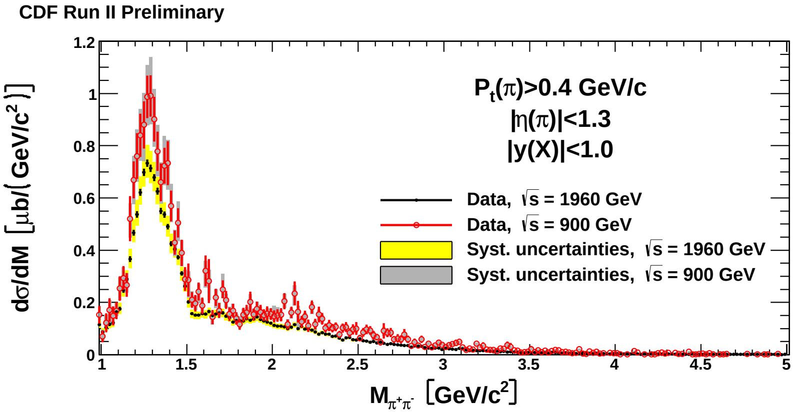

Figure 3: Differential cross section $d\sigma/dM(\pi\pi)$ for two charged particles, assumed to be $\pi^+\pi^-$, with $p_T > 0.4$ GeV/c, $|\eta| < 1.3$ and $|y(\pi\pi)| < 1.0$ between two rapidity gaps $1.3 < |\eta| < 5.9$. Red open circles for $\sqrt{s}$ = 0.9 TeV and black points for $\sqrt{s}$ = 1.96 TeV.

1 for $M(\pi\pi) > 1000$ MeV/c^2, integrated over $p_T(\pi\pi)$. The $f_2(1270)$ and a shoulder attributed to the $f_0(1370)$ are seen, with small structures between 1500 MeV/c^2 and 2000 MeV/c^2, above which the cross sections falls approximately exponentially to 5000 MeV/c^2. There are no predictions for this full spectrum, but Harland-Lang *et al.* [10] have calculated the semi-perturbative region above 2500 MeV/c^2. They have to assume a $\pi\pi\mathbb{P}$ form factor; an exponential form is in reasonable agreement with the data between 3000 MeV/c^2 and 4000 MeV/c^2 but falls too steeply with $M(\pi\pi)$; an Orear-like form factor is higher than the data [9]. To show the significance of the structures above 1600 MeV/c^2, we fit the spectrum from 1600 - 3600 MeV/c^2 to a fourth-order polynomial, and show it with residuals in Fig. 2. Since the acceptance here is nearly 100% the dip-bump structure appears to be significant. There is an $f_0(2200)$ in the PDG[8] but it is not in the summary tables, and we cannot make any firm conclusions. (The narrow peak at 3100 MeV/c^2 is consistent with being photoproduced $J/\psi \rightarrow e^+e^-$.) There is CDF data on exclusive K^+K^- and $K^0_S K^0_S$, currently being analysed, and which may help the interpretation, but the statistics are lower by a factor $\sim$ 40. We may hope that LHC experiments with low pile-up running can contribute with more statistics and other channels, including $\phi\phi$ in which the $f_2(2010, 2300$, and 2340) were seen.

Fig. 3 shows the cross section at the two $\sqrt{s}$ values, 0.9 and 1.96 TeV. From Regge phenomenology we expect a ratio $R(0.9:1.96) \sim$ 1/ln(s) = 1.3 if the protons stay intact, and this data agrees with this for $1000 < M(\pi\pi) < 2000$ MeV/c^2, although our data include diffractive dissociation with higher masses allowed at $\sqrt{s}$ = 1.96 TeV. For $M(\pi\pi) > 2000$ MeV/c^2 the ratio is higher, which was unexpected.

Fig. 4 shows the cross section for $p_T(\pi\pi) > 1$ GeV/c, where the acceptance extends to low masses. One now sees that at $M(\pi\pi)$ = 1000 MeV/c^2 there is a rapid drop in the cross section, coinciding with the $K^+K^-/K^0\overline{K^0}$ threshold and the $f_0(980)$ resonance. A contribution of the $f_0(500)$ to the low mass region is expected, but it is a very wide state, with full width Γ = 400 - 700 MeV [8]. We have verified that the low-mass data are consistent with isotropy, i.e S-wave.

The data can also be used to look for exclusive $\chi_c(3415) \rightarrow \pi^+\pi^-$ or K^+K^- (which would appear at $\sim$ 3280 MeV/c^2 when the kaons are given the pion mass). No significant signals are ob-

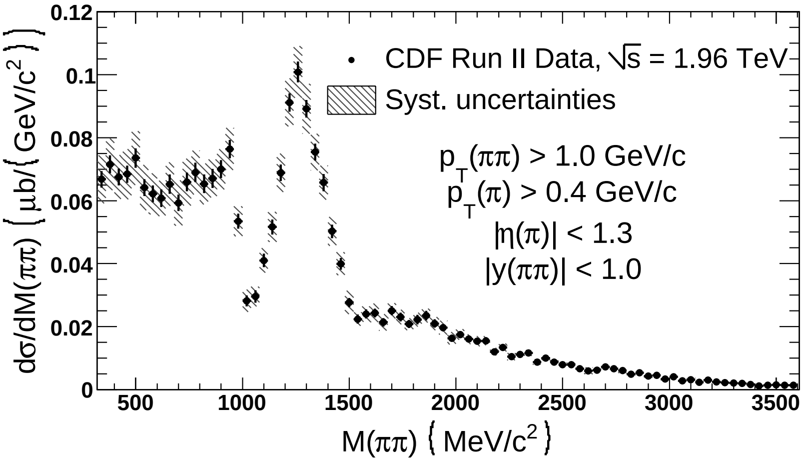

Figure 4: As Fig. 3 at $\sqrt{s}$ = 1.96 TeV, but with $p_T(\pi\pi) > 1.0$ GeV/c for which the acceptance extends to low $M(\pi^+\pi^-)$.

served, implying that $<$ 50% of our previous observation [3] of $\chi_c \to J/\psi + \gamma$ was due to $\chi_{c0}(3415)$.

In summary the exclusive $\pi^+\pi^-$ spectrum from double pomeron exchange, which selects $I^G J^{PC} = 0^+(\text{even})^{++}$, and favors glue-rich mesons, shows strong production of known resonances with $M(\pi\pi) < 1500$ MeV/c^2, and some higher mass structures which we cannot clearly assign to known states. Isoscalar mesons are important in better understanding the strongly-interacting vacuum. It is to be hoped that more DIPE data in other channels and with high statistics can allow us to make firm conclusions on this spectroscopy.

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