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Central Exclusive Production at the Tevatron

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Abstract
In CDF we have observed several exclusive processes: $\gamma\gamma \to e^+e^-$ and $\mu^+\mu^-$, $\gamma + I\!P \to J/\psi, \psi(2S)$, and $I\!P + I\!P \to \chi_c$. The cross sections agree with QED, HERA photoproduction data, and theoretical estimates of $gg \to \chi_c$ with another gluon exchanged to screen the color. This observation of exclusive χ_c, together with earlier observations of exclusive dijets and exclusive $\gamma\gamma$ candidates, support some theoretical predictions for $p + p \to p + H + p$ at the LHC. Exclusive dileptons offer the best means of precisely calibrating forward proton spectrometers.

1 Central Exclusive Production

Central exclusive production at the Tevatron is the process $p + \bar{p} \to p + X + \bar{p}$, where "+" means a rapidity gap Δy exceeding 3 units, and X is a simple system fully measured. Exchanges (t-channel) over such large gaps must be color singlets with spin J [or Regge intercept $\alpha(0)$] $\geq$ 1.0. Only photons γ and pomerons $I\!P$ qualify, apart from W and Z bosons which always cause the proton to break up. The gluon g would qualify apart from its color, but if another gluon is exchanged that can be cancelled, and $I\!P = gg$ is often a good approximation. It cannot be exact; QCD forbids a pure gg state, and a $q\bar{q}$ component certainly grows as Q^2 increases. The $I\!P$ has C = +1; in QCD one should also have a ggg state with C = -1, the odderon [1] O, not yet observed. The central masses M_X are roughly limited to $M_X \lesssim \frac{\sqrt{s}}{20}$ with the outgoing protons having Feynman $x_F > 0.95$. Hence $M_X \lesssim 3$ GeV at the CERN ISR [2], appropriate for glueball spectroscopy, where $M(\pi^+\pi^-)$ shows a broad $f_0(600)$, a narrow $f_0(980)$ and still unexplained structure possibly associated with $f_0(1710)$, a glueball candidate. The study of X = hadrons, e.g. $\phi\phi$ and $D^\circ\bar{D}^\circ$ to name two channels among many, has not been studied above ISR energies, but CDF is a perfect place to do it and hopefully it will be done [3].

At the LHC M_X can reach $\approx$ 700 GeV, into the electroweak sector, and we can have $X = Z, H, W^+W^-, ZZ$, slepton pairs $\tilde{l}\tilde{l}$, etc. Measuring the forward protons after 120m of 8T dipoles, in association with the central event, as the FP420 [4] proponents hope to do at ATLAS and CMS, one can measure M_X with $\sigma(M_X) \approx 2$ GeV per event [5], and for a state such as H, also its width if $\Gamma(H) \gtrsim 3$ GeV/c^2. There are scenarios (e.g. SUSY) in which FP420 could provide unique measurements, e.g. if there are two nearby states both decaying to $b\bar{b}$ or to W^+W^-. The quantum numbers of X are $J^{PC} = 0^{++}$ or 2^{++} (and these are distinguishable) for $I\!PI\!P$ production. Two-photon collisions $\gamma\gamma \to l^+l^-, W^+W^-, \tilde{l}\tilde{l}$ become important at the LHC thanks to the intense high momentum photons, orders of magnitude more than at the Tevatron, giving > 50 fb for W^+W^- as a continuum background to $H \to W^+W^-$. $H \to ZZ$ does not have this background.

While there is a gold mine of physics in $p+X+p$ at the LHC, we need to show that (a) the cross sections are within reach, and (b) one can build the spectrometers with resolution $\sigma(M_X) \approx$ 2 GeV/c^2 and calibrate their momentum scale *and resolution*, to measure $\Gamma(H)$, and perhaps to distinguish nearby states. Both these issues are addressed by CDF in a "TeV4LHC" spirit, and they are also very interesting in their own right. The calculation of cross sections (e.g. [6]) involves, in addition to $\sigma(gg \to X)$, the unintegrated gluon distribution $g(x_1, x_2)$, rapidity gap survival probability (no other parton interactions), and the Sudakov factor (probability of no gluon radiation producing hadrons). The Durham group predicts $\sigma(SMH)$ for $p+H+p$ at the LHC = $3^{\times 3}_{\div 3}$ fb. At the Tevatron $p+H+\bar{p}$ is out of reach, but the process $p+\chi_c(\chi_b)+\bar{p}$ is identical as far as QCD is concerned, as is $p+\gamma\gamma+\bar{p}$. Measuring these constrains the SMH cross section. In CDF we have looked for both exclusive $\gamma\gamma$ [7] and χ_c [8], without however having detectors able to see the p and $\bar{p}$. Instead we added forward calorimeters ($3.5 < |\eta| < 5.1$) and beam shower counters BSC ($5.5 < |\eta| < 7.4$). If these are all empty there is a high probability that both p and $\bar{p}$ escaped intact with small $|t|$. We also measured [9] exclusive dijets.

For the exclusive $\gamma\gamma$ search we triggered on events with two electromagnetic (EM) clusters with $E_T > 4$ GeV in the central calorimeter, with a veto on signals in the BSC. This killed pile-up events and enabled us to take data without prescaling the trigger. We required all other detectors to be consistent with only noise; then our *effective* luminosity is only about 10% of the delivered luminosity. We found [7] 3 events with exactly two back-to-back EM-showers (assumed to be photons) with $M(\gamma\gamma) > 10$ GeV/c^2. From wire proportional chambers at the shower maximum we concluded that two were perfect $p+\bar{p} \to p+\gamma\gamma+\bar{p}$ candidates and one was also consistent with being a $p+\bar{p} \to p+\pi^\circ\pi^\circ+\bar{p}$ event. The Durham prediction [10] was $0.8^{\times 3}_{\div 3}$ events, clearly consistent. We have since accumulated more data, with a lower threshold, now being analysed.

With the above trigger we also found [11] 16 $p+\bar{p} \to p+e^+e^-+\bar{p}$ events, with $M(e^+e^-) > 10$ GeV/c^2 (up to 38 GeV/c^2), the QED $\gamma\gamma \to e^+e^-$ process [12]. Exclusive 2-photon processes had not previously been observed in hadron-hadron collisions; the cross section agrees with the precise theory prediction. This process has been suggested as a means of calibrating the LHC luminosity; then it must be done in the presence of pile-up, and one will need to know the acceptance etc. at the few % level. More interesting for FP420 is that measurement of an exclusive lepton pair gives both forward proton momenta, with a precision dominated by the incoming beam momentum spread ($\frac{\delta p}{p} \approx 10^{-4}$, or 700 MeV). One can do this with pile-up, selecting dileptons with no associated tracks on the l^+l^- vertex and $\Delta\phi \approx \pi$. One can also cut on $p_T(l^+l^-)$ (correlated with $\Delta\phi$), but $\Delta\phi$ has better resolution. In CDF we found that a cut $\pi - \Delta\phi < \frac{0.8GeV}{M(l^+l^-)}$ rads is suitable for QED-produced pairs. For each pair one can predict ξ_1 and ξ_2, and, if a proton is in the FP420 acceptance, compare ξ_i and ξ_{420}. This can also possibly map the acceptance A($\xi, t \approx$0), as the cross section shape is known from QED, and the (Coulomb) protons have very small t.

CDF also used a "muon+track" trigger, again with BSC veto, to study $p+\bar{p} \to p+\mu^+\mu^-+\bar{p}$ with 3 GeV/c^2 $< M(\mu\mu) <$4 GeV/c^2. This is a very rich region, with the J/ψ and $\psi(2S)$ vector mesons that can only be produced exclusively by photoproduction $\gamma + I\!P \to \psi$, or

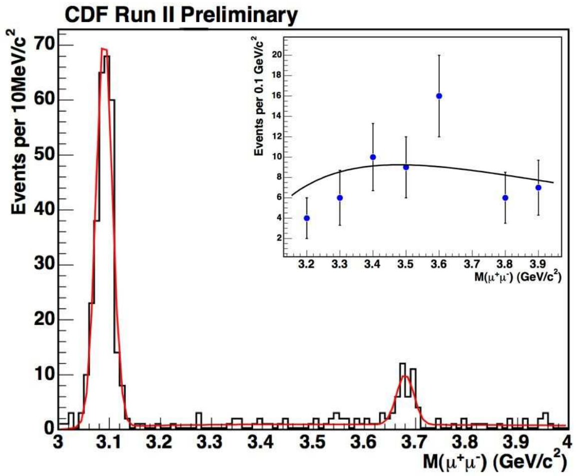

Fig. 1: Exclusive dimuon mass spectrum in the charmonium region, together with the sum of two Gaussians and the QED continuum, shown in the inset, excluding the 3.65 - 3.75 GeV/c^2 bin ($\psi(2S)$). All line shapes are predetermined, with the normalization free.

possibly by odderon exchange: $O + I\!\!P \rightarrow \psi$. We know what to expect for photoproduction from HERA, so an excess would be evidence for the elusive O. The spectrum [8] is shown in Fig. 1, together with the sum of three components: the vector mesons and a continuum, $\gamma\gamma \rightarrow \mu^+\mu^-$, which is again consistent with QED. These central exclusive spectra are exceptionally clean; in fact the biggest background ($\approx$ 10%) is the identical process but with an undetected $p \rightarrow p^*$ dissociation. The J/ψ and $\psi(2S)$ cross sections $\frac{d\sigma}{dy}|_{y=0}$, are (3.92$\pm$0.62)nb and (0.54$\pm$0.15)nb, agreeing with expectations [13, 14]. Thus we do not have evidence for O exchange, and put a limit $\frac{O}{\gamma} < 0.34$ (95% c.l.), compared with a theory prediction [15] 0.3 - 0.6.

While the QED and photoproduction processes in Fig. 1 should hold no surprises, their agreement with expectations validates the analysis. We required no EM tower with $E_T^{EM} >$ 80 MeV. If we allow such signals (essentially γ's) the number of J/ψ events jumps from 286 to 352, while the number of $\psi(2S)$ only increases from 39 to 40. The spectrum of EM showers is shown in Fig. 2. These extra J/ψ events are very consistent with being $\chi_{c0}(3415) \rightarrow J/\psi + \gamma$, from $I\!\!P I\!\!P \rightarrow \chi_c$, with about 20% of the γ being not detected (giving a background of 4% under the exclusive J/ψ). We measure $\frac{d\sigma}{dy}(\chi_c)|_{y=0}$ = (75$\pm$14)nb. The existence of this process implies that $p + H + p$ must happen at the LHC (assuming H exists), as the QCD physics is qualitatively identical. The χ_c cross section agrees with predictions: 150nb [16] and 130$^{\times 4}_{\div 4}$nb [6]. It is therefore likely that $\sigma(p + p \rightarrow p + SMH + p)$ is of order 0.5-5 fb, within reach of FP420. In SUSY models the cross section can be much higher [4].

We are looking for $p+\bar{p} \rightarrow p+\Upsilon+\bar{p}$ (by photoproduction, or by $O+I\!\!P$), and $I\!\!P+I\!\!P \rightarrow \chi_b$. The Υ should be measurable in the presence of pile-up using $n_{ass} = 0$, $\Delta\phi$ and p_T cuts (n_{ass} is the number of additional tracks on the dilepton vertex). We have candidate events, with the $\Upsilon(1S)$, $(2S)$ and $(3S)$ states resolved; cross sections are now being determined. The $\chi_b \rightarrow \Upsilon+\gamma$

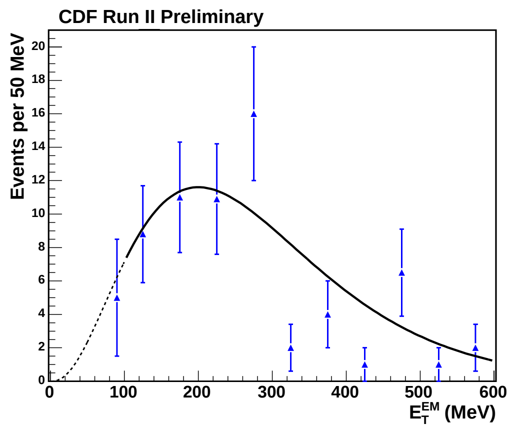

Fig. 2: The E_T spectrum of electromagnetic showers associated with J/ψ, together with an empirical function to estimate the fraction under the 80 MeV cut. These are $\chi_{c0}(3415)$ candidates.

probably can not be studied in the presence of pile-up, and it is challenging. We have also made a search [17] for exclusive Z, allowed only through photoproduction: $\gamma + I\!P \rightarrow Z$. In the Standard Model the (integrated) cross section at the Tevatron is too small to see, $\sigma_{excl}(Z)$ = 0.3fb [14] or 1.3fb [18], before branching fractions. In White's pomeron theory [19] the cross section is expected to be much larger, but a quantitative prediction is lacking. Our search uses both e^+e^- and $\mu^+\mu^-$ pairs with $M(l^+l^-) > 40$ GeV/c^2. There are 8 exclusive candidates with $\sigma(p + \bar{p} \rightarrow p + (\gamma\gamma \rightarrow l^+l^-) + \bar{p}) = 0.24^{+0.13}_{-0.10}$ pb (for $|\eta(\mu)| < 4.0$), agreeing with σ(QED) = 0.256 pb. All the events have $\pi - \Delta\phi < 0.013$(rad) and $p_T(\mu^+\mu^-) < 1.2$ GeV/c. Only one event had a $\bar{p}$ in the acceptance of the Roman pots when they were operational, and a track was observed, showing that the event was exclusive, and that at the LHC such $l^+l^- + p$ events will be available for calibration. If we remove the requirement that the BSC should be empty there are 4 additional events, interpreted as $p \rightarrow p^*$ dissocation. One of them has $M(\mu^+\mu^-) \approx M(Z)$ and a larger $\Delta\phi$ and p_T than the others, but we cannot claim it to be truly exclusive. We put a limit on exclusive $\sigma_{excl}(Z) < 0.96$ pb at 95% c.l. Clearly it will be interesting to look for exclusive $p + Z + p$ at the LHC. In early running of the LHC, when bunch crossings without pile-up are not yet rare, it is important to measure these exclusive processes, to the extent possible without complete forward coverage. In CMS we have plans to add forward shower counters [20] around the beam pipe to help tag rapidity gaps, together with the ZDC and forward hadron calorimeters. With large forward gaps in both directions, a trigger on two EM showers with $E_T > 4$ GeV should be possible, hopefully observing $\Upsilon \rightarrow e^+e^-, \gamma\gamma \rightarrow e^+e^-$, $I\!PI\!P \rightarrow \gamma\gamma$, and $\chi_b \rightarrow \Upsilon + \gamma \rightarrow e^+e^-\gamma$. Clean single interactions are surely needed needed for the χ_b and $I\!PI\!P \rightarrow \gamma\gamma$; both channels are excellent tests of $p + H + p$. One may even hope that when exclusive Higgs production is measured, the coupling ggH can be derived by comparing the three cross sections!

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