

Central Exclusive Production at the Tevatron

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DOI: <http://dx.doi.org/10.3204/DESY-PROC-2009-01/22>

Abstract

In CDF we have observed several exclusive processes: $\gamma\gamma \rightarrow e^+e^-$ and $\mu^+\mu^-$, $\gamma + \mathbb{P} \rightarrow J/\psi, \psi(2S)$, and $\mathbb{P} + \mathbb{P} \rightarrow \chi_c$. The cross sections agree with QED, HERA photoproduction data, and theoretical estimates of $gg \rightarrow \chi_c$ 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 $p + p \rightarrow p + H + p$ 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 $p + \bar{p} \rightarrow p + X + \bar{p}$, 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 \mathbb{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 $\mathbb{P} = gg$ 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 \mathbb{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 $D^0\bar{D}^0$ 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.

At the LHC M_X can reach ≈ 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/c². 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 $\mathbb{P}\mathbb{P}$ production. Two-photon collisions $\gamma\gamma \rightarrow l^+l^-, W^+W^-, \tilde{l}\tilde{l}$ 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 $H \rightarrow W^+W^-$. $H \rightarrow ZZ$ 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 $\sigma(M_X) \approx 2 \text{ GeV}/c^2$ 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 $\sigma(gg \rightarrow X)$, 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^{+3}_{-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 $E_T > 4 \text{ GeV}$ 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 $M(\gamma\gamma) > 10 \text{ GeV}/c^2$. From wire proportional chambers at the shower maximum we concluded that two were perfect $p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ candidates and one was also consistent with being a $p + \bar{p} \rightarrow p + \pi^0\pi^0 + \bar{p}$ event. The Durham prediction [10] was 0.8^{+3}_{-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 $p + \bar{p} \rightarrow p + e^+e^- + \bar{p}$ events, with $M(e^+e^-) > 10 \text{ GeV}/c^2$ (up to $38 \text{ GeV}/c^2$), the QED $\gamma\gamma \rightarrow e^+e^-$ 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 $\pi - \Delta\phi < \frac{0.8 \text{ GeV}}{M(l^+l^-)}$ 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 $p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$ with $3 \text{ GeV}/c^2 < M(\mu\mu) < 4 \text{ GeV}/c^2$. This is a very rich region, with the J/ψ and $\psi(2S)$ vector mesons that can only be produced exclusively by photoproduction $\gamma + \mathbb{P} \rightarrow \psi$, or

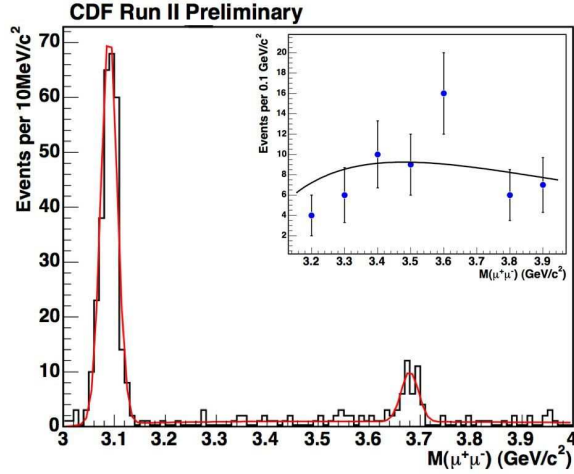


Fig. 1: Exclusive dimuon mass spectrum in the charmonium region, together with the sum of two Gaussians and the QED continuum, shown in the inset, excluding the 3.65 - 3.75 GeV/c^2 bin ($\psi(2S)$). All line shapes are predetermined, with the normalization free.

possibly by odderon exchange: $O + IP \rightarrow \psi$. 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 $(3.92 \pm 0.62)\text{nb}$ and $(0.54 \pm 0.15)\text{nb}$, 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 $IP \rightarrow \chi_c$, with about 20% of the γ being not detected (giving a background of 4% under the exclusive J/ψ). We measure $\frac{d\sigma}{dy}(\chi_c)|_{y=0} = (75 \pm 14)\text{nb}$. 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^{+4}_{-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 $O + IP$), and $IP + IP \rightarrow \chi_b$. 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 $\chi_b \rightarrow \Upsilon + \gamma$

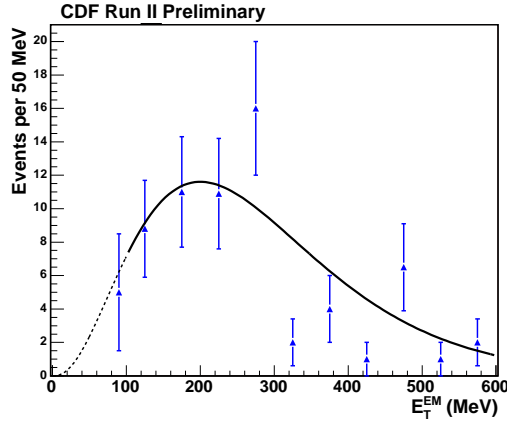


Fig. 2: The E_T spectrum of electromagnetic showers associated with J/ψ , together with an empirical function to estimate the fraction under the 80 MeV cut. These are χ_{c0} (3415) candidates.

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: $\gamma + \mathbb{P} \rightarrow Z$. In the Standard Model the (integrated) cross section at the Tevatron is too small to see, $\sigma_{excl}(Z) = 0.3\text{fb}$ [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 $M(l^+l^-) > 40 \text{ GeV}/c^2$. There are 8 exclusive candidates with $\sigma(p + \bar{p} \rightarrow p + (\gamma\gamma \rightarrow l^+l^-) + \bar{p}) = 0.24_{-0.10}^{+0.13} \text{ pb}$ (for $|\eta(\mu)| < 4.0$), agreeing with $\sigma(\text{QED}) = 0.256 \text{ pb}$. All the events have $\pi - \Delta\phi < 0.013(\text{rad})$ and $p_T(\mu^+\mu^-) < 1.2 \text{ GeV}/c$. 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 $p \rightarrow p^*$ dissociation. 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 $\sigma_{excl}(Z) < 0.96 \text{ pb}$ 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 $E_T > 4 \text{ GeV}$ should be possible, hopefully observing $\Upsilon \rightarrow e^+e^-$, $\gamma\gamma \rightarrow e^+e^-$, $\mathbb{P}\mathbb{P} \rightarrow \gamma\gamma$, and $\chi_b \rightarrow \Upsilon + \gamma \rightarrow e^+e^- \gamma$. Clean single interactions are surely needed for the χ_b and $\mathbb{P}\mathbb{P} \rightarrow \gamma\gamma$; 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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