Central exclusive production and the Durham diffractive program

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Recent results in central exclusive production within the Durham model are presented. A wide range of processes are considered, and their theoretical and phenomenological interest is discussed.

1. Introduction

Central exclusive production (CEP) processes of the type

$$pp(\bar{p}) \to p + X + p(\bar{p}) \,, \tag{1}$$

can significantly extend the physics program at hadron colliders. Here X represents a system of invariant mass M_X, and the '+' signs denote the presence of large rapidity gaps. Such reactions represent an experimentally very clean signal and provide a very promising way to investigate both QCD dynamics and new physics in hadron collisions. The study of such processes is becoming particularly topical at the current time due to the range of exclusive measurements proposed and underway at the LHC; as such this forms an important part of the LHC working group on forward physics and diffraction, see for example [1].

We will present here the latest phenomenological results with the so–called 'Durham' model of CEP, see for example [2] for an early paper, and [3] for a more recent discussion. We will discuss some of the most topical and interesting of such exclusive processes, considering both their theoretical interest and the existing measurements and future experimental possibilities at the LHC and elsewhere.

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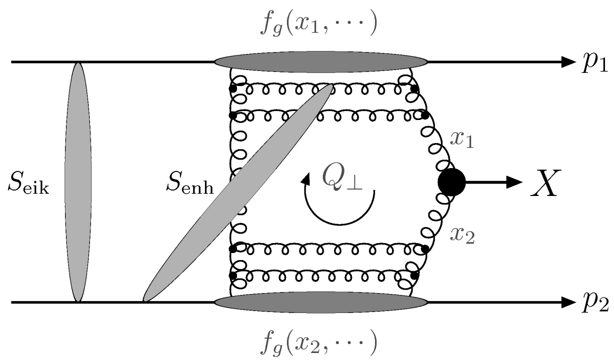

Fig. 1. The perturbative mechanism for the exclusive process $pp \to p + X + p$, with the eikonal and enhanced survival factors shown symbolically.

2. The Durham Model

The perturbative mechanism for CEP, is shown schematically in Fig. 1. The subprocess $gg \to X$ initiated by gluon–gluon fusion and the second t–channel gluon needed to screen the color flow across the rapidity gap intervals. It is given by

$$\begin{aligned} T \;=\; \pi^2 \int \frac{d^2\mathbf{Q}_\perp\,\mathcal{M}}{\mathbf{Q}_\perp^2(\mathbf{Q}_\perp-\mathbf{p}_{1_\perp})^2(\mathbf{Q}_\perp+\mathbf{p}_{2_\perp})^2} \\ \times f_g(x_1,x_1',Q_1^2,\mu^2;t_1)f_g(x_2,x_2',Q_2^2,\mu^2;t_2)\;, \end{aligned} \tag{2}$$

where the 'skewed' PDFs f_g couple the t–channel gg state to the proton

$$f_g(x,x',Q^2,\mu^2) = \frac{\partial}{\partial\ln(\mathbf{Q}_\perp^{\mathbf{2}})}\left[R_g\left(xg(x,Q^2)\right)\sqrt{T(\mathbf{Q}_\perp,\mu^{\mathbf{2}})}\right]\;, \tag{3}$$

where $\mu \sim M_X$. A crucial ingredient in the calculation of this amplitude is the correct inclusion of the Sudakov factor $T(\mathbf{Q}_\perp,\mu^{\mathbf{2}})$, representing the probability of no gluon emission from the fusing t–channel gluons. The form that this factor takes in the amplitude is largely dictated by requiring all leading and next–to–leading logarithms in $M_X/Q_\perp$ to be correctly resummed, see for example [4] for a detailed discussion of this. In this way a reliable result, which is largely insensitive to the region of low gluon transverse momentum, $Q_\perp$, is achieved. In the kinematic regime relevant to CEP, the skewed PDFs are related via Eq. (3) to the conventional PDFs, with the R_g factor encoding the degree to which these differ; typically we have $R_g \sim 1.2 - 1.4$. In [5] the importance of including the Q^2 dependence of this factor (which was commonly ignored in previous calculations) was highlighted, and a simple technique for doing so was demonstrated.

While the discussion above concerns the hard process, that is the probability for producing such an exclusive configuration in a short–distance interaction, we must in general also include the possibility that the protons may interact quite independently of this hard scatter, that is via non-perturbative rescattering, which may also lead to the production of additional particles. The probability that this does not occur is known as the (eikonal) survival factor $\langle S^2_{\rm eik}\rangle$, and it must be modeled phenomenologically and fitted to the available soft hadronic data. An up–to–date model, including the $\sqrt{s} = 7$ TeV TOTEM measurements is found in [6]: typically this suppression is sizable, with $\langle S^2_{\rm eik}\rangle \sim 1$ %. An additional factor due to the rescattering of the protons and the partons which initiate the hard process, the so–called 'enhanced' survival factor $\langle S^2_{\rm enh}\rangle$, should also be included, although the suppression due to this is not nearly as large, see [7].

A final important feature of interest in this production mechanism is the dynamical selection rule which operates for CEP. In particular, in the limit that the outgoing protons scatter with zero $p_\perp$, the only transverse momentum of the fusing gluons is provided by the loop momentum $Q_\perp$, and thus the gluons must have equal and opposite transverse momenta. It can readily be shown that, in terms of the $gg \to X$ production subprocess, where for $Q^2_\perp \ll M^2_X$ the gluons are quasi–on–shell, this translates into a correlation between the helicities of the gluons, with only an even parity combination of $J_z = 0$ (i.e. $++$ or $--$ along the gg axis) helicities contributing. This is in complete contrast to the usual inclusive case, where all gluon helicities contribute, and as we will see leads to some very non–trivial predictions. In general, the outgoing protons may have some small non–zero $p_\perp$, and so this selection rule is only approximate, but an explicit calculation shows that the production non–$J^P_z = 0^+$ states are strongly suppressed by about two orders of magnitude.

Finally, we note that from the experimental point of view the best way to select exclusive events is to actually measure the outgoing intact protons via proton tagging detectors installed near to the beam pipe (such detectors are proposed at the LHC, see e.g. [8] and references therein). However, if this is not possible, dominantly exclusive data can also be selected by simply vetoing on additional hadronic activity (i.e. other than the object X of interest) over a large enough rapidity region. Although here there will be some background from the case that one or both proton dissociates, if the rapidity region is large enough this will be small.

3. Heavy quarkonium production

The first cross section predictions for the CEP of χ_{q0} quarkonium ($q = c, b$) were presented in [9], while in [10] this was extended to include all three

$J = 0, 1, 2$ spin states. Exclusively, we have the non–trivial prediction that the χ_{c0} should be strongly dominant. For the χ_{q1} the coupling of this vector state to two quasi–on–shell (boson) gluons is strongly suppressed due to the Landau–Yang theorem, while χ_{q2} production is suppressed due the $J_z = 0$ selection rule, as in the non–relativistic quarkonium approximation the coupling of the χ_{q2} to two gluons in a $J_z = 0$ state vanishes, and so this state can only be produced for the (strongly suppressed) case that the gluons are in a $|J_z| = 2$ configuration.

However, when for example χ_c production was observed via the $\chi_c \to J/\psi\gamma$ decay channel by CDF [11], with insufficient photon energy resolution to distinguish the three spin states, it cannot be naively assumed that only the χ_{c0} will contribute, as in this case the much larger branching ratios for the $\chi_{c(1,2)}$ states decays may compensate the suppression in their exclusive production cross sections. This was demonstrated explicitly in [10], where it was predicted that the contribution of these higher spin states to the $\chi_c \to J/\psi\gamma$ cross section will be of a similar size to the χ_{c0}. This was supported by a subsequent preliminary measurement by LHCb of exclusive χ_c production [12]. The production of all three spin states was observed, with the measured cross sections in good agreement with the Durham predictions for the $\chi_{c(0,1)}$ states, and somewhat higher for the χ_{c2}. The source of this discrepancy may be due to the non–exclusive component of this data, or to additional theoretical corrections needed for the production of these lower mass states, see [13] for more discussion. Other observables, such as χ_b and $\eta_{c,b}$ production are discussed in detail in [3].

A further, and so far relatively unexplored, possibility is to observe the CEP of the 'exotic' XYZ charmonium–like states which have been discovered over the past 10 years, see for example [14] for a review. To give one topical example, we may consider the well–known $X(3872)$, the quantum numbers of which have recently been established to be $J^{PC} = 1^{++}$ by LHCb [15], an assignment which leaves both the more exotic (e.g. as a $D^0\overline{D}^{*0}$ molecule) and a conventional $\chi_{c1}(2^3P_1)$ interpretation in principle available. The observation of *exclusive* $X(3872)$ production would immediately provide clear evidence, so–far lacking, of a direct (i.e. not due to feed–down from the decay of higher mass states) production channel $gg \to X$. Moreover, if as discussed in [16], in the case of a molecular $D^0\overline{D}^{*0}$ interpretation the hadroproduction of such a state with the size of cross section observed inclusively, must in general take place in an environment where additional particles are emitted, than the observation of exclusive production would strongly disfavor such a purely molecular interpretation. On the other hand, if the $X(3872)$ is simply a conventional $\chi_{c1}(2^3P_1)$ state, then the ratio of the CEP cross sections $\sigma(\chi_{c1}(2P))/\sigma(\chi_{c1}(1P))$ is predicted to first approximation (ignoring reasonably small corrections due to the different masses, relativistic effects etc) to be simply given by the ratio of the respective squared wavefunctions at the origin $|\phi'_P(0)|^2$. That is, we will expect them to be of comparable sizes. More generally, the $X(3872)$ may be a mixture of a $\chi_{c1}(2P)$ and a molecular $D^0\overline{D}^{*0}$ state, and so the CEP process may shed light on the size of each component, see [13] for a more detailed discussion.

4. Production of light meson pairs

Cross sections for the exclusive production of light meson pairs, M_3, M_4, were first calculated within the Durham model in [17], with the $gg \to M_3M_4$ subprocess modeled using the 'hard exclusive' formalism described in [18]: the full amplitude is calculated in terms of the parton–level process, $gg \to q\overline{q}q\overline{q}$, where the outgoing partons are collinear with the parent meson and have the correct color and spin quantum numbers, and a 'distribution amplitude' $\phi(x)$, representing the (non–perturbative) probability for the partons to form the meson state.

This approach led to quite unexpected predictions for flavor–singlet and non–singlet mesons, with the former expected to be strongly enhanced. This was due to the different contributing parton–level amplitudes in the two cases, with an additional 'ladder–type' set of diagrams shown in Fig. 2 (right), being possible for flavor–singlet mesons, but vanishing due to isospin conservation for flavor–non–singlets, where only the diagram type shown in Fig. 2 (left) contributes. Crucially, it was found that for $J_z = 0$ incoming gluons, it was only the contribution from these ladder–type diagrams which was non–vanishing, and thus we expect a strong suppression in the production of flavor–non–singlet meson pairs ($\pi\pi$, KK) at sufficiently high transverse momentum $p_\perp$ that this perturbative approach (both the Durham model and hard exclusive formalism) can be reliably applied. This prediction was supported by the CDF [19] observation of exclusive $\gamma\gamma$ production, for which the contamination caused by $\pi^0\pi^0$ production was determined experimentally to be very small, and consistent with zero (finding $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$, at 95% C.L.). Without this additional $J_z = 0$ suppression discussed above, we would naively expect $N(\pi^0\pi^0)/N(\gamma\gamma) \sim 1$.

In [20] this approach was extended to include a gg valence component for the case of the flavor–singlet η' (and also, through mixing, η) mesons. This will contribute at the same (leading) order to the $q\overline{q}$ component, via the parton–level $gg \to gggg$ and $gg \to ggq\overline{q}$ processes, and an explicit calculation showed that any sizable gg component of the η' (and η) can have a strong effect on the CEP cross section, increasing (or decreasing) it by up to $\sim$ an order of magnitude, depending on the specific size and sign of the gg component. Thus by observing the CEP of $\eta(')\eta(')$ meson pairs, we may shed light on the size of such a gg component, a question which so

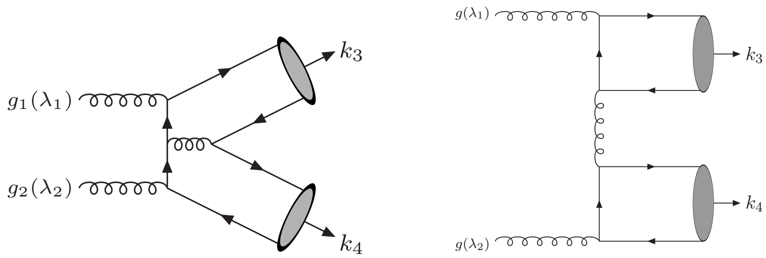

Fig. 2. (Left) A typical diagram for the $gg \to M\overline{M}$ process. (Right) Representative 'ladder' diagram, which contributes to the production of flavor–singlet mesons.

far remains unresolved, see [20] for more discussion.

5. Exclusive jet production and the Higgs Boson

The observation of exclusive dijet production (with $X = jj$ in (1)) was reported by CDF in 2008 [21] and D0 in [22]. The CDF data was found to be in quite good agreement with the `ExHuME` Monte Carlo implementation [23] of the Durham model, with the inclusion of the Sudakov factor as in (3) essential to describe the invariant mass M_{jj} and transverse energy $E_\perp^j$ distributions. Using the existing CMS+TOTEM detectors, some limited preliminary data for central jet production has been taken at the LHC during low luminosity runs [24], with plans to take further such measurements currently under discussion. The possibilities for performing such measurements at higher luminosity using the proposed forward tagging AFP and PPS detectors at ATLAS and CMS, are also being considered [8].

For the case of exclusive jet production, the CEP $J_z = 0$ selection rule leads to some non–trivial predictions which are not observed in the standard inclusive production process. In particular, as the leading–order $gg \to q\overline{q}$ amplitude for massless quarks and $J_z = 0$ incoming gluons vanishes, we expect exclusive gg jets to be strongly dominant. This therefore presents the potentially unique possibility of a clean observation of isolated gluon jets at a hadron collider, and thus of a probe of the QCD predictions for gluon jet properties (particle multiplicity, correlations etc). In the three jet case, this leads to a suppression in $gq\overline{q}$ production as the gluon become soft or collinear to the quark/anti–quark, and thus we expect a relative enhancement in such a final–state with the jets in a well–separated 'Mercedes' configuration. A detailed quantitative study and comparison of the the exclusive three–jet topologies for ggg and $gq\overline{q}$ production would provide an interesting test of the underlying theory.

Another interesting possibility, which has thus far not been observed, is the exclusive production of the Higgs Boson. Although the expected cross sections are quite low, this would in principle be possible with the proposed forward tagging AFP and PPS detectors at ATLAS and CMS, see e.g. [8] and references therein. A particularly interesting result in the case of exclusive $H \to b\overline{b}$, is that, as discussed above, the leading order QCD background $gg \to b\overline{b}$ is strongly dynamically suppressed, making an observation via this channel with $S/B \sim 1$ in principle possible: in the inclusive case, the signal is typically swamped by the direct QCD process. A further interesting point is that any CP–odd term in the $gg \to H$ vertex (possible if the Higgs state is in fact not purely CP–even, an issue which will take some time to clarify experimentally) will show up as an asymmetry in the distribution with respect to ϕ, the azimuthal angle between the outgoing protons. Further details and discussion can be found in [13].

6. Conclusion

CEP provides a very promising and potentially unique framework, complementary to more standard inclusive channels, in which to study SM and BSM signals. These processes therefore offer a rich phenomenology at high–energy colliders, with a detailed program of theoretical work ongoing and a wide range of experimental measurements being explored at the LHC.

LHL thanks the organizers for support and for a very interesting and productive conference.

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