Central Exclusive Production: Vector Mesons, Dijets, Higgs Boson

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I review the situation of theoretical predictions of central exclusive production, and show that the CDF dijet data can be used to constrain the prediction of central exclusive Higgs boson production. I also show that central exclusive production might be used as a discovery tool for the odderon.

1 Development of Central Exclusive Production and Data

Central exclusive production has been studied for a long time as it is a potential discovery channel for new physics coupled to quarks and gluons. The original idea [1, 2, 3] concerned the production of a light Higgs boson, which would predominantly decay into bottom quarks, and thus be extremely hard to observe in inelastic channels. Over the years, calculations of exclusive production have progressed through the implementation of several crucial features. The first attempt to embed Higgs boson production into a pomeron [1] used non-perturbative gluons, and the calculation was later translated into a perturbative one in [4], at the price of introducing an unknown proton form factor. The possibility of protons breaking could then be modelled, but only in an eikonal framework [3]. This was later generalised [5, 6] for any amplitude, provided that the production is at much smaller distance than the rescatterings. Finally, large perturbative corrections at the production vertex – the so-called Sudakov form factor – were identified in [7].

All these ingredients may be sufficient to estimate the cross section for the production of Higgs bosons and other heavy systems at the LHC. The best known model which incorporates all the above ingredients is that of the Durham group [8]. It successfully predicted the order of magnitude of the cross sections later measured by CDF, for dijets [9], diphotons [10] and χ_c [11]. Indeed, disagreement among theorists was finally settled, as CDF did observe exclusive production of high-mass systems, going up to 130 GeV, and hence one believes that all the ingredients of the Durham model are indeed necessary.

However, several of these elements can be improved, and the general feeling that the uncertainties are of the order of a factor 3 must be reassessed. Hence the first goal of this contribution is to summarise the findings of [12] concerning exclusive production.

The second purpose is to examine central exclusive production not as a means of producing new physics, but rather as genuine new physics in its own right. Indeed, central exclusive production of vector mesons may be used as a discovery channel for the odderon. The general structure of the calculation [13] is similar to that in the pomeron case, and backgrounds due to photon exchange do not seem prohibitive. But, as I shall explain, one is also limited here by the presence of large uncertainties in the theory. Here again, data from CDF are becoming available [11], and may help reduce these uncertainties.

2 Skeleton of an Exclusive Calculation

One must insist first on the fact that the calculations are very inspired by perturbation theory. However, as we shall see later, a large part of the amplitude lies in the soft region, so that one cannot *d*erive the steps of the calculation, but one hopes that the nonperturbative region is not too different from the perturbative one, at least at high s.

The first step [4] is to model pomeron or odderon exchange à la Low-Nussinov, *i.e.* to consider the smallest number of gluons that need to be exchange between quarks to produce the final state via colour-singlet exchange, as shown in Fig. 1. In the pomeron case, one uses cutting rules to calculate the imaginary part of the amplitude, which one assumes to be dominant. In the odderon and photon cases, the calculation is more involved as the odderon-photon and odderon-pomeron amplitudes have different phases. Apart from colour factors, these amplitudes can be calculated either directly or using the BFKL vertices. They are not yet physical, as quark-quark scattering via singlet exchange is infrared divergent.

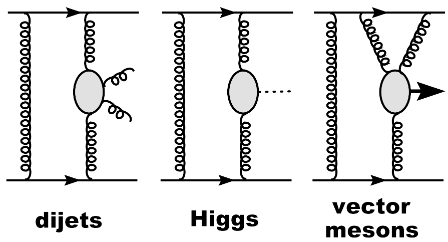

Figure 1: Some of the lowest-order diagrams for the three processes considered here.

To get a finite answer, one needs to consider scattering of colour-singlet objects rather than colour charges, as shown in Fig. 2. In the terminology of BFKL or of Cheng and Wu, this is called the *i*mpact factor, which takes into account the fact that the exchanged gluons can be connected to other quarks or gluons, and leads to convergent integrals in the infrared region. The problem here is that we do not know in general what these objects are. One possibility is to model them via light-cone wave functions [14, 15] but the latter are unknown, too, so that only general properties can be derived. This is the best one can do for odderon (3-gluon) exchange. For 2-gluon exchange, one can do slightly better [16] by forcing the parametrisation to agree with (skewed) off-diagonal structure functions when the gluons are hard. One nevertheless has to take into account the contribution of soft gluons, and ensure that the impact factor goes to zero when one of the gluons goes on shell. The Durham group neglects both of these constraints, and considers a parametrisation which is correct only for hard gluons.

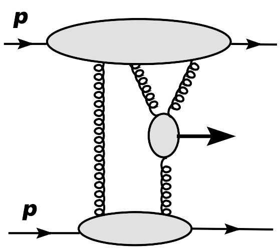

Figure 2: The two impact factors entering the vector-meson calculation.

If one produces a high-mass system, one needs to worry about large virtual corrections at the vertex. Indeed, if the produced system has a scale M, and is linked to gluons of virtuality μ, one knows that there are large Sudakov double logarithms $\log^2(M/\mu)$. The trick to evaluate them is based on the infrared finiteness of inclusive corrections. One knows that, if the gluons go on-shell, then the virtual corrections will cancel the infrared divergences of bremsstrahlung. So the logarithms can be calculated by considering the bremsstrahlung diagrams. The double-logs are under theoretical control, and can be resummed [17]. The situation with single logarithms $\log(M/\mu)$ is more complicated. Some of them can be resummed, and some others cannot, depending on the process. Finally, all this holds if constant terms are small. We found [12] that, for $M \approx 20$ GeV (*i.e.* the first dijet points), this is not the case.

In the Higgs boson case, the upper scale M is given by the Higgs boson mass, and the single logs were evaluated in [18] and lead to angular ordering, together with a determination of the lower scale μ. In the dijet case, other diagrams lead to single logarithms, which cannot be resummed. The extra single logs are fortunately small [19], so that the general structure of the Sudakov form factor is similar to that in the Higgs boson case. However, the gluons-to-jets vertex changes if the jets have sufficient transverse energy, as an extra propagator then enters the loop integrals. This modifies the power of the logarithms in the answer, and hence standard Sudakov techniques apply only if one chooses the transverse energy as an upper scale. In the vector-meson case, the situation is much more complicated, but fortunately the scales involved are small, and the logs cannot be very large.

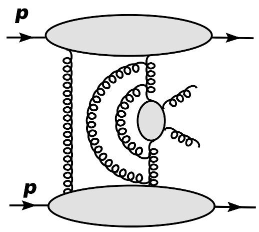

Figure 3: The large Sudakov vertex corrections in the dijet case.

As a final generic ingredient, one has to take into account that factorisation does not hold when one goes from γp to $\bar{p}p$. Hence the impact factors, derived from structure functions, have corrections due to screening. Nobody really knows how to implement these, as knowing them would amount to being able to unitarise pomeron exchange. Many estimates agree within a factor 3 [20], but they are all based on eikonal or multi-channel eikonal schemes. These screening corrections should be folded with the one-pomeron exchange amplitude [5, 6], but we shall simply treat them as an effective factor – the “gap survival probability”.

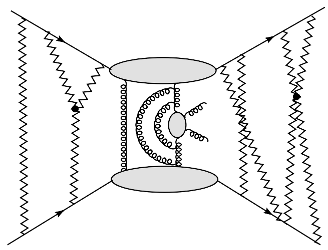
Figure 4: Screening corrections.

Finally, process-specific corrections still have to be performed. In the jet case, some of the particles coming from the partons are missed by the jet-finding algorithm, so that the jet transverse energy is smaller than the parton one. As the cross section falls fast with energy this brings in a rather large correction.

All the above corrections go in the same direction, decreasing the cross section by a factor of the order of 600, as shown in the second column of Table 1. This is the well-known problem of exclusive calculations: although the lowest order is calculable, there are huge corrections coming from nonperturbative or higher-order effects, which overwhelm the lowest order.

3 Properties of the Amplitudes

First of all, as is well-known, it is possible to reproduce almost exactly the dijet data measured by CDF. Figure 5 shows one of the possible curves, for specific choices of the various correction factors outlined above. But this is one of the many possible choices. As we we are about to see, all the corrections have large uncertainties (*factors*), so that a change in one can be compensated by a change in the other.

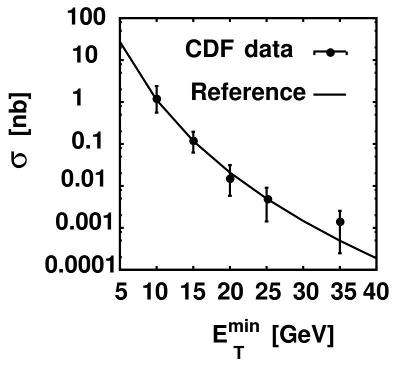

Figure 5: Dijet data and a possible curve.

The second point is indeed that all these corrections have rather large uncertainties. Modest changes of scales in the Sudakov form factor, slightly different parametrisations of impact factors, or modifications in the unitarisation scheme to calculate the splash-out all lead to appreciable differences, as shown in the last three columns of Table 1.

The final property is the most worrisome one. It is well-known that two-gluon or three-gluon exchange between protons has a strong infrared contribution in elastic scattering: although the cross sections are finite, the typical gluon off-shellness is of the order of 600 MeV, and comes directly from the size of the proton, which is included in the impact factors. One might hope that, in the case of exclusive production of heavy objects, the situation would be different, and it has been claimed that the Sudakov form factor would shift the calculation to the perturbative region. This is the case for the Durham model, but it may not be correct. Indeed, one cannot allow highly off-shell partons to come out of the proton without paying a price. In our case, this comes from the impact factor (omitted in [8]), that suppresses highly off-shell partons most of the time. So the shift due to the Sudakov form factor is mostly compensated by the impact factor. If one produces a 100 GeV object, more than half of the cross section comes from a region where one of the gluons has an off-shellness smaller than 1 GeV. Hence, the core of the calculation has a strong non-perturbative component. Note that folding with the gap survival probability (instead of taking it as a constant factor) will increase the long-distance contribution as the gap survival probability is larger at values of the impact parameter.

	Dijets		Higgs boson	Vector mesons
	$\sigma(E_T > 10$ GeV) [nb]	uncertainty factor		
Impact factor	600	3	3	> 3
Sudakov form factor	25	20	7	1
Gap survival	3	3	3	3
Slash-out	1	2	–	–

Table 1: The second column gives the value of the Tevatron dijet cross section after various corrections are included, for $E_T^{min} = 10\,\mathrm{GeV}$. The next three columns show the factor of uncertainty (maximum / minimum) of the correction.

4 Results

4.1 Dijets

As we have seen, it is possible to reproduce the CDF data. Conversely, these give a very useful

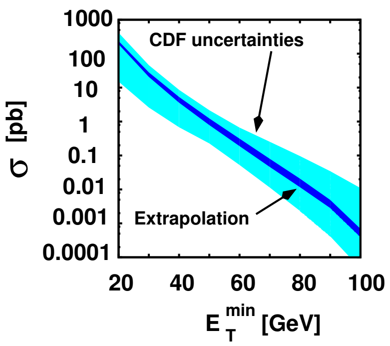

Figure 6: The dijet cross section for FP420 cuts, for $\sqrt{s} = 14$ TeV.

constraint to reduce the theoretical uncertainties, especially as they extend to the mass region of a standard Higgs boson. Hence, we can consider a set of curves going through the error bars of the CDF points, and see how they extrapolate to the LHC. We apply cuts typical of FP420 (proton fractional momentum loss between 0.2% and 2%, jet rapidity less than 1 and mass of the dijet system greater than 50 GeV), to obtain the cross section shown in Fig. 6. The outer band corresponds to the theoretical curves going through the CDF dijet error bars, and the inner band shows the intrinsic extrapolation errors: all the curves making up that band are identical at the Tevatron (and the same as the curve of Fig. 5), but spread when extrapolated to the LHC. We see that the cross section is large enough for a measurement of the dijet cross section in the early LHC. This would further help reduce the ambiguities in the theory.

4.2 Higgs Boson

As above, we can keep the sets of parameters which reproduce the CDF dijet data, and see what they give for the Higgs boson. Although the set of diagrams is not identical [12], it turns out that the dominant ones are, so that the results can be directly translated from the dijets to the Higgs boson. The cross sections predicted for CDF, for a standard Higgs boson heavier than 110 GeV, are always smaller that 0.03 fb, and hence of little interest. At the LHC, the cross section will then be at most 8 fb for a Higgs-boson mass of 100 GeV, and will drop to at most 1 fb for a Higgs-boson mass of 145 GeV [21], again for cuts typical of FP420 (proton fractional momentum loss between 0.2% and 2%, and Higgs-boson rapidity less than 1).

4.3 Vector Mesons

The problem here is the background. In the dijet and Higgs boson cases, the background is negligible. Unfortunately, it is possible to produce a vector meson either via odderon exchange or via photon exchange, as shown in Fig. 7. Both cross sections are of the same order of magnitude, and given that we do not know the impact factor of the odderon, it is hard to be more precise. We show in Table 2 the possible ratios of odderon to photon cross sections, for various vector mesons , and for the Tevatron or the LHC.

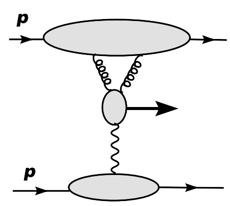

Figure 7: The analog of Fig. 2 for photon exchange.

The various uncertainties in the calculation lead to a range of values for the odderon and for the photon cross section. These uncertainties are somewhat lower in the ratio of these cross sections. We see that the best place to look for the odderon may be the Tevatron, although the best channel (Υ production) is unfortunately the hardest one experimentally. It may be worth pointing out that, due to an interference between pomeron-odderon and odderon-pomeron

ratios of $d\sigma/dy|_{y=0}$	J/ψ odderon / photon	Υ odderon / photon
Tevatron	26–56 %	80 – 170 %
LHC	6 – 15 %	15 -38 %

Table 2: Ratios of the pomeron-odderon and pomeron-photon cross sections for exclusive J/ψ and Υ production in pp and $p\bar{p}$ collisions.

exchanges, the odderon-pomeron cross section for forward production of vector mesons is close to maximum in $\bar{p}p$ collisions, whereas it vanishes in the pp case, and has its maximum around 600 MeV. CDF has published [11] an upper limit $d\sigma/dy|_{y=0} < 2.3$ nb for the odderon cross section, corresponding to a ratio of 90% for the cross sections, thus getting close to the detection level for the odderon.

In order to enhance the signal, the most obvious way would be to concentrate on high-$|t|$ data, as photon exchange fall much faster with $|t|$ than odderon exchange. For instance, cutting the momentum transfer to the proton or the antiproton to be greater than 500 MeV would enhance the odderon signal by a factor 10 [22]. The other way would be to cut on the vector-meson transverse energy. A cut $p_T > 1$ GeV enhances the odderon signal by a factor 4 [22].

5 Conclusion

We have seen that central exclusive production can be reproduced by models which include a number of corrections to the naïve estimates based on lowest-order calculations. These corrections can be approximated (in the case of Sudakov form factors), fitted (in the case of impact factors) or guessed (in the case of gap survival probabilities), and are thus prone to large uncertainties. These uncertainties can be somewhat reduced using the recent CDF data on dijet or vector-meson production.

Further reduction of these uncertainties would be possible if the dijet cross section is measured at the LHC, especially as the extrapolation of the gap survival probability to higher energies is far from certain. At present, one can state that the production cross section for a standard Higgs of 120 GeV should be between 0.3 and 2 fb.

As for the discovery of the odderon, it seems that there is a chance to disentangle it from the photon exchange background, and that CDF is getting close to the level of statistics needed to detect it.

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