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SUPERCHIC 2: A NEW MONTE CARLO FOR CENTRAL EXCLUSIVE PRODUCTION*

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We present the first results of the new SuperChic 2 Monte Carlo event generator. This includes significant theoretical improvements and updates, most importantly, a fully differential treatment of the soft survival factor, as well as a greater number of generated processes.

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1. Introduction

The Central Exclusive Production (CEP) is the reaction

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

where '+' signs are used to denote the presence of large rapidity gaps, separating the system X from the intact outgoing protons (anti-protons), see [1–4] for reviews. Theoretically, the study of CEP requires the development of a framework which is quite different from that used to describe

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the inclusive processes more commonly considered at hadron colliders. Moreover, the dynamics of the CEP process leads to unique predictions and effects which are not seen in the inclusive mode. Experimentally, CEP represents a very clean signal, with just the object X and no other hadronic activity seen in the central detector (in the absence of pile-up).

In any detailed phenomenological study of such processes, it is important to have a Monte Carlo (MC) implementation, and for this reason, we have previously produced the publicly available SuperChic MC [5,6], for the CEP of lighter Standard Model (SM) objects. However, there exist a wider range of processes that are not included in earlier versions of SuperChic, but which have much phenomenological relevance, in particular in the light of the measurement possibilities for exclusive processes during Run 2 of the LHC [7]. In addition, there are a number of theoretical updates and improvements which are important to consider.

We present in these proceedings a description of the new SuperChic 2 MC generator, which contains various theoretical improvements and generates a wider range of final states compared to previous versions of the MC. For more details and results, we refer the reader to [8].

2. Theoretical improvements

The CEP process may proceed via photon exchange or via the strong interaction (or through a combination of the two). In the case that it is mediated purely by the strong interaction, then provided the object X mass is large enough, this can be considered in the framework of pQCD, via the so-called Durham model [3,4]. The diagram corresponding to this approach is shown in Fig. 1. The coupling of the two-gluon exchange to the proton can be written in terms of the so-called skewed PDF, which may be related to the standard gluon PDF using the approach of [9]. However, in [10], an improved

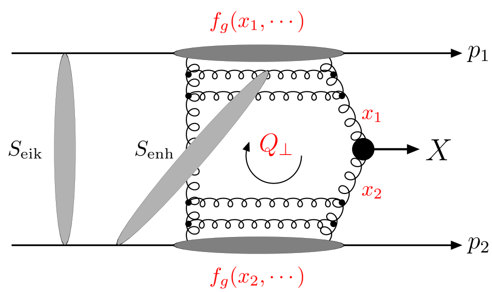

Fig. 1. The perturbative mechanism for the QCD-induced exclusive process $pp \to p + X + p$, with the eikonal and enhanced survival factors shown symbolically.

form for this relation relevant to the CEP case, where the PDF unintegrated over the gluon transverse momentum $k_\perp$ is required, has been derived; this is used in SuperChic 2. Moreover, the correct limit on the z integral in the Sudakov factor (representing the probability of no extra parton emission from each fusing gluon) is used, as described in [11], although in all papers by the authors subsequent to the publication of [11], it is worth emphasizing that the correct limit has been taken.

In addition to these effects, the most significant theoretical improvement involves the treatment of the soft survival factor, denoted by S^2: independent of the hard process, secondary particles may also be produced by additional soft proton–proton interactions. Such underlying event activity will spoil the exclusivity of the event, and the probability that no additional particles are produced by accompanying soft proton–proton interactions is given by S^2, see *e.g.* [12, 13] for some more recent theoretical work.

The survival factor is not a simple multiplicative constant [6], but rather depends quite sensitively on the outgoing proton transverse momenta. Physically, this is to be expected, as the survival factor will depend on the impact parameter of the colliding protons; loosely speaking, as the protons become more separated in impact parameter, we should expect there to be less additional particle production, and thus for the survival factor to be closer to unity. As the transverse momenta $\boldsymbol{p}_{i_\perp}$ of the scattered protons are nothing other than the Fourier conjugates of the proton impact parameters $\boldsymbol{b}_{i_\perp}$, we, therefore, expect the survival factor to depend on these. For this reason, survival effects are included fully differentially in the final-state momenta in SuperChic 2.

Details of how this is achieved for both gluon- and photon-induced exclusive processes are given in [8], while here we only present some brief remarks. To calculate the influence of the soft survival factor, we must consider the amplitude including rescattering effects, $T^{\rm res}$, by integrating over the transverse momentum $\boldsymbol{k}_\perp$, carried round the Pomeron loop (represented by the grey oval labelled '$S^2_{\rm eik}$' in Fig. 1). This is given by

$$T^{\rm res}\left(s, \boldsymbol{p}_{1_\perp}, \boldsymbol{p}_{2_\perp}\right) = \frac{i}{s}\int \frac{d^2\boldsymbol{k}_\perp}{8\pi^2}\, T_{\rm el}\left(s, \boldsymbol{k}_\perp^2\right)\, T\left(s, \boldsymbol{p'}_{1_\perp}, \boldsymbol{p'}_{2_\perp}\right)\,, \tag{2}$$

where T is the usual, so-called 'bare' production amplitude, *i.e.* excluding rescattering effects, and $\boldsymbol{p'}_{1_\perp} = (\boldsymbol{p}_{1_\perp} - \boldsymbol{k}_\perp)$ and $\boldsymbol{p'}_{2_\perp} = (\boldsymbol{p}_{2_\perp} + \boldsymbol{k}_\perp)$, while $T_{\rm el}(s, \boldsymbol{k}_\perp^2)$ is the elastic pp scattering amplitude in the transverse momentum space. We must then add this to T to give the full amplitude, which we can square to give the CEP cross section including survival effects

$$\frac{d\sigma}{d^2\boldsymbol{p}_{1_\perp} d^2\boldsymbol{p}_{2_\perp}} \propto \left|T\left(s, \boldsymbol{p}_{1_\perp}, \boldsymbol{p}_{2_\perp}\right) + T^{\rm res}\left(s, \boldsymbol{p}_{1_\perp}, \boldsymbol{p}_{2_\perp}\right)\right|^2\,. \tag{3}$$

From (3), we can see that screening effects influence the CEP cross section in a $p_\perp$ dependent way, and we may use this expression to implement survival effects in the MC differentially in the outgoing particle momenta. The survival factor is defined in terms of (3) as

$$\langle S^2_{\rm eik} \rangle = \frac{\int d^2\boldsymbol{p}_{1_\perp}\, d^2\boldsymbol{p}_{2_\perp}\, \left|T\left(s,\boldsymbol{p}_{1_\perp},\boldsymbol{p}_{2_\perp}\right) + T^{\rm res}\left(s,\boldsymbol{p}_{1_\perp},\boldsymbol{p}_{2_\perp}\right)\right|^2}{\int d^2\boldsymbol{p}_{1_\perp}\, d^2\boldsymbol{p}_{2_\perp}\, \left|T\left(s,\boldsymbol{p}_{1_\perp},\boldsymbol{p}_{2_\perp}\right)\right|^2} \,. \tag{4}$$

It is important to emphasize that this suppression is, therefore, sensitive to the $p_\perp$ dependence of the specific CEP process. This is seen most clearly in the comparison between two-photon initiated and purely gluonic CEP processes: in the former case, due to the more peripheral photon–proton coupling (which favours smaller outgoing proton $p_\perp$), the expected overall suppression is much less severe than in the latter. However, considering for example two-photon initiated processes then, as shown in detail in [8], the considered final state will also play a role. Thus, in the case of lepton pair production, the specific polarisation structure of the $\gamma\gamma \to l^+l^-$ amplitudes leads to less suppression than for W boson pair production in the same $M_{\gamma\gamma}$ region. Such an effect is not always considered in the literature, see *e.g.* [14].

2.1. Results

In this section, we present some selected results from SuperChic 2. We will consider for brevity the cases of J/ψ photoproduction and two-photon induced lepton pair production, but further results can be found in [8]. For such photon-induced processes, an important constraint is found from considering the modulus of the virtuality of the exchanged photon Q_i^2, which is given by

$$Q_i^2 = \frac{q_{i_\perp}^2 + x_i^2 m_p^2}{1 - x_i} \,, \tag{5}$$

i.e. it is cut off at a kinematic minimum $Q^2_{i,\min} = x_i^2 m_p^2/(1-x_i)$, where x_i and $q_{i_\perp}$ are the longitudinal momentum fraction and transverse momentum of the photon. Thus, when considering variations in the centrally produced object rapidity Y_X and invariant mass M_X, both of which determine x_i (and, therefore, $Q^2_{i,\min}$), the influence of soft survival effects will also vary.

This effect is seen clearly in Fig. 2 (left), which shows the MC prediction for the photoproduced J/ψ rapidity distribution at $\sqrt{s} = 7$ TeV, compared to the LHCb data points from [15]. Normalising to this data, the inclusion of survival effects (represented by the 'screened' curve) is seen to steepen the rapidity distribution, due to the higher average photon x_i, and therefore, photon virtuality, in the higher rapidity region, leading to a better (although far from perfect) agreement with the data. The overall cross section normalisation is also found to strongly prefer the inclusion of survival effects, see [8].

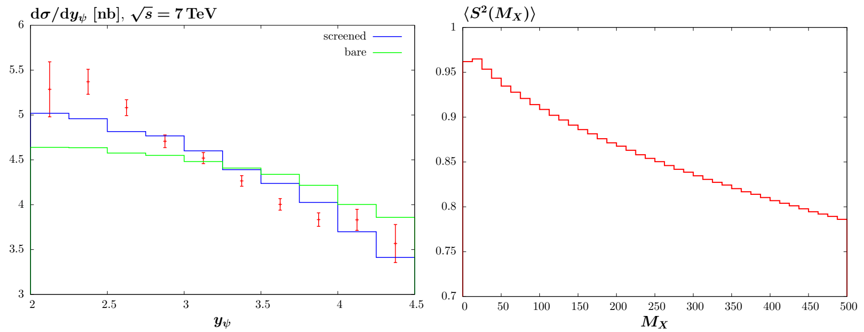

Fig. 2. (Left) Distributions with respect the J/ψ rapidity y_ψ at $\sqrt{s} = 7$ TeV, compared to the LHCb data points from [15]. Theory curves corresponding to the 'bare' and 'screened' cross sections, *i.e.* excluding and including soft survival effects, respectively, are shown, and the integrated cross sections are normalised to the data for display purposes. The correlated systematic errors are not shown. (Right) Average survival factor $\langle S^2_{\rm elk}\rangle = d\sigma_{\rm scr}/d\sigma_{\rm bare}$ as a function of the central system invariant mass M_X for muon pair production, at $\sqrt{s} = 14$ TeV. The muons are required to have $p_\perp > 2.5$ GeV and $|\eta| < 2.5$.

In the case of two-photon induced lepton pair production, the same effect leads to a significant dependence in the survival factor on the lepton pair invariant mass. This is shown in Fig. 2 (right), where the average survival factor is seen to decrease with M_{ll}, due to the higher average photon x_i as the lepton pair invariant mass increases.

Results for a range of QCD-induced exclusive processes are presented in [8]. Of particular interest is the case of exclusive 2- and 3-jet and heavy quarkonium $\chi_{c,b}$ production. In addition to the processes discussed above, other gluon induced final-states which can currently be generated are the SM Higgs boson, light meson pairs ($\pi\pi$, KK, $\eta(')\eta(')$, $\phi\phi$), $\gamma\gamma$, double J/ψ and $\psi(2S)$ quarkonia, while $\rho(770)$, $\phi(1020)$, Υ and $\psi(2S)$ photoproduction are included, and two-photon induced W pair, the SM Higgs boson and $\gamma\gamma$ pairs, in all cases for both proton and electron beams, are also included.

To summarize, in these proceedings, we have presented the new SuperChic 2 MC for CEP. This corresponds to a systematic re-write of earlier code versions, with a wider range of processes being generated and various theoretical improvements implemented. We have briefly described these improvements and presented some selected results. A more in-depth discussion can be found in [8].

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