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Production of Pairs of Heavy Quarks by Double Gluon Fusion

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1 Double Parton Interactions

The rapid growth of the parton flux at small x gives rise to a dramatic increase of cross sections with large momentum transfer in pp collisions at high energies. In the case of production of mini-jets at the LHC, the inclusive cross section may in fact exceed the value of the total inelastic cross section, for not unrealistically small values of the transverse momenta. One faces therefore a unitarity problem with the large momentum transfer cross sections at high energies, which is solved by introducing Multiple Parton Interactions (MPI) in the process. MPI take into account the possibility of having two or more elementary partonic interactions in a given inelastic hadronic collision and unitarity is restored by MPI because the inclusive cross section is proportional to the multiplicity of interactions. In this way, the inclusive cross section is no more bounded by the value of the total inelastic cross section, when the average multiplicity of interactions is large.

The simplest case of MPI is Double Parton Scattering (DPS). When looking for MPI, one should keep into account that, hard interactions are localised in a space region much smaller as compared to the hadron size and, once the final state is given, the main contribution from MPI is due to the processes which maximise the incoming parton flux.

In DPS the hard component of the interaction is thus disconnected and the non-perturbative components are factorised into functions which depend on two fractional momenta and on the relative transverse distance b between the two interaction points. The non-perturbative input to the DPS cross section, namely the double parton distribution functions, depend therefore explicitly on the relative transverse distance b. By neglecting spin and color, the inclusive double parton-scattering cross-section, for two parton processes A and B in a pp collision, is given by [1]:

$$\sigma^D_{(A,B)} = \frac{1}{1+\delta_{A,B}} \sum_{i,j,k,l} \int \Gamma_{i,j}(x_1, x_2; b)\hat{\sigma}^A_{i,k}(x_1, x_1')\hat{\sigma}^B_{j,l}(x_2, x_2')\Gamma_{k,l}(x_1', x_2'; b) \times dx_1\, dx_1'\, dx_2\, dx_2'\, d^2b \tag{1}$$

where the Γs represent the double parton distributions and $\hat{\sigma}^{A,B}_{i,k}$ the elementary partonic cross sections. Notice that the dependence of $\sigma^D_{(A,B)}$ on the total transverse energy, of the final state partons with a large p_t, is very well characterised and very strong: it is in fact equal to the square of the dependence on the total transverse energy of a single hard scattering cross section. The characteristic dependence of the DPS cross section on the total transverse energy of final state partons with large p_t represents therefore a rather non trivial experimental test of the interaction dynamics.

One may include all unknowns in the process in a quantity with dimensions of a cross section, the *effective cross section*, and the inclusive DPS cross section can thus be expressed by the simplest *pocket formula*, widely used in the experimental analysis of DPS processes:

$$\sigma^D_{(A,B)} = \frac{1}{1+\delta_{A,B}} \frac{\sigma_A \sigma_B}{\sigma_{eff}} \tag{2}$$

where σ_A and σ_B are the single scattering inclusive pp cross sections for producing the processes A and B respectively. Of course the pocket formula makes sense only if, when comparing with experiment, the effective cross section turns out to be weakly dependent on the kinematics of the process.

The double parton distribution $\Gamma_{i,j}(x_1, x_2; b)$ must therefore depend on the relative transverse distance b between the two partons with fractional momenta x_1 and x_2. The limiting case of very small b is non-trivial, since in that limit the process cannot be considered a double interaction any more. If b is small enough the two initial state partons can be originated by perturbative splitting, which implies that $\Gamma_{i,j}(x_1, x_2; b)$ is singular in the limit $b \to 0$ [2].

One should thus take into account the contributions to DPS due to parton splitting [3] and that, when splitting is included, some of the contributions to DPS appear also in the single parton scattering cross section [2]. A recent discussion on the matter can be found in [4]: At small b, the double parton distributions are conveniently expressed by the sum of a regular and a singular term and the DPS cross section is defined introducing an appropriate regulating function, which cuts the small b region and thus avoids double counting.

On the other hand, for phenomenological studies it is convenient to use the simplest pocket formula, where all unknowns of the process are factorised into a single quantity (the effective cross section). The pocket formula is in fact rather successful in describing the observed DPS cross sections, with values of the effective cross section which show little dependence on the reaction channel and on the kinematical regime (e.g. [5]).

One should stress that the dependence of $\sigma^D_{(A,B)}$ on the total transverse energy of final final state partons is very strong and approximately constant values of σ_{eff} represent a non-trivial experimental indication on the interaction process.

2 Double J/ψ Production

Double J/ψ production has been studied by several groups, both theoretically and experimentally. A widely used theoretical approach is non-relativistic QCD (NRQCD), an effective theory for heavy quarkonium production (e.g. [7], [8]).

A distinctive feature is that in NRQCD, the heavy quark-antiquark pairs may appear both as color singlet (CS) and color octet (CO) states.

Full LO NRQCD SPS predictions of prompt J/ψ, J/ψ hadroproduction (including CS and CO contributions) have been compared [9] with CMS measurements [10]. Although theoretical uncertainties are rather large, SPS at LO underestimates the cross section by more than one order of magnitude, both at small and at large invariant masses and relative rapidities of the J/ψ, J/ψ system.

On the other hand, in production of heavy quarks at large p_t, the NLO contribution to the cross section can be more than a factor of 10 larger, as compared with the Color Singlet Model contribution at the LO [11]. At large p_t, the contribution to the cross section, due to the lowest order diagram, goes in fact as $(1/p_t)^8$, while the contribution to the cross section due to real NLO radiative corrections, has an additional light parton in the final state, which allows the production of a color octet heavy quark pair at a distance of $\mathcal{O}(1/p_t)$. As a consequence, the corresponding contribution to the cross section of heavy quarkonium production goes as $(1/p_t)^6$ at large p_t. NLO contributions may thus explain the large difference of the Color Singlet Model LO result with experimental evidence at small invariant masses of the J/ψ, J/ψ system.

By working out J/ψ pair production by SPS at 7 TeV c.m. in NRQCD, including NLO contributions, one in fact finds agreement with CMS data at small invariant masses of the J/ψ, J/ψ system [12]. The NLO contributions cannot however explain the very strong disagreement (up to three orders of magnitude) of the SPS cross section with CMS data at large invariant masses. To find agreement with the CMS data at large invariant masses one needs to include the contribution of DPS to the process [13].

Double J/ψ production has been studied by LHCb at 13 TeV and the data are compared with theoretical calculations [14]. Also in the LHCb acceptance, SPS at LO gives a negligible contribution to the cross section, except in the case of k_t dependent parton distributions. By evaluating the SPS contribution at the lowest order, with k_t dependent parton distributions, one takes in fact effectively into account most of the NLO contributions.

At small ΔY and at small invariant masses, the SPS cross section at NLO is of the right order of magnitude. DPS is on the contrary dominant at large ΔY and at large invariant masses. The sum the SPS contribution at NLO, or of SPS at the lowest order with k_t dependent parton distributions, and of the DPS contribution reproduce the data reasonably well.

An extensive study of multiple production of heavy quarks at the LO, using k_t dependent parton distributions and off shell interaction matrix elements, is due to Antoni Szczurek and collaborators [15] [16], which show that in the case of D^0D^0 production, DPS dominates also at small invariant masses. The sum of the SPS contribution, at the LO with k_t dependent parton distributions, and of the DPS contribution are able to reproduce the trend of the data LHCb data [17] reasonably well. One should anyhow keep in mind that the k_t dependent parton distributions are still determined with considerable uncertainty and different choices of the k_t dependent parton distributions can easily change the final DPS cross section by a factor two [15].

3 Summary

DPS is increasingly important at large c.m. energies and at relatively low transverse momenta and thus play a particularly important role in the case of multiple production of heavy quark pairs at high energies. In the case of production of heavy quarks, the process can in fact be reliably evaluated without introducing cuts in the transferred momenta.

Double J/ψ production has been studied with particular attention both from the experimental and from the theoretical point of view.

The DPS cross sections are characterised by the corresponding values of the "effective cross section" σ_{eff}, which although with large experimental uncertainties, turns out to be close to the universal value of 15 mb in almost all measurements. Double J/ψ production by DPS is an exception. In most cases of double J/ψ production by DPS, the observed value of σ_{eff} is in fact smaller (which implies that the production cross section is larger) with respect to the typical values of σ_{eff} observed in all other channels.

At small invariant masses, double J/ψ production is dominated by SPS, which needs to be evaluated at NLO, the LO collinear-factorisation SPS contribution to the cross section being one order of magnitude smaller as compared with presently available data.

At large invariant masses, double J/ψ production is on the contrary dominated (by orders of magnitude) by DPS.

Both for the SPS and for the DPS contributions, a reasonably good agreement with available data on heavy quarks production is obtained by evaluating the cross section at LO with k_t dependent parton distributions and off-shell interaction matrix elements.

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