Double parton scattering as a source of quarkonia pairs in LHCb

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Recent results on production of $J/\psi$ pairs in LHCb initiated discussion on double parton scattering (DPS) contribution to this process, which is not yet elaborated well. In this short report $J/\psi\chi_c$ and $J/\psi Y$ modes are proposed for DPS studies. Estimations for $\Upsilon\Upsilon$ and $J/\psi Y$ production in LHCb are presented.

Recent observation of $J/\psi$-meson pairs at LHCb stimulated discussion on phenomena contributing this process. On the one hand, there is leading order (LO) calculation of the $gg \to J/\psi J/\psi$ process in the color-singlet (CS) model [1-3]. It leads to the total cross section at 7 TeV energy of 24 nb and to 4 nb in LHCb conditions. On the other hand, high flux of incoming partons at LHC energies leads to significant probability of scattering of more than one parton in the same proton-proton collision [4]. Estimations of this double parton scattering (DPS) contribution to the $J/\psi$ pairs production [6] lead to the cross section of approximately 2 nb in the LHCb acceptance [7]. Both SPS and DPS estimations are of the order of first experimental measurement in LHCb [8], $\sigma(pp \to J/\psi J/\psi + X) = 5.6 \pm 1.1$ nb. Meanwhile, both these predictions have some uncertainties. In SPS calculations they are induced mainly by dependencies on $\alpha_s$ and $m_c$ parameters. DPS estimations does not account for correlations in double parton density functions and depend on a phenomenological parameter $\sigma_{\text{eff}}$. Thus further investigation is desirable.

In this work other di-quarkonia final states are considered in addition to the $J/\psi J/\psi$ one. It will be shown that for $J/\psi\chi_c$ and $J/\psi Y$ production DPS should be main source at least at low-invariant-mass region.

Assuming factorization of two hard partonic processes $A$ and $B$ one can write inclusive cross section of a double parton scattering process in a hadron collision in the following form [3]:

$$\sigma_{\text{DPS}}^{AB} = m/2 \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b_1, b_2, Q_1^2, Q_2^2) \times \hat{\sigma}_{ik}^A(x_1, x_1', Q_1^2) \hat{\sigma}_{jl}^B(x_2, x_2', Q_2^2)
\times \Gamma_{kl}(x_1, x_2, b_1 - b, b_2 - b, Q_1^2, Q_2^2) \times dx_1 dx_2 dx_1' dx_2' db_1' db_2',$$

(1)

where $\Gamma_{ij}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2)$ is double parton distribution function (PDF), $\hat{\sigma}_{ik}^A$ — partonic cross sections of processes in question, $b$ — impact parameter and $m = 2$ for different partonic subprocesses and 1 — for identical. It is usually assumed that longitudinal and transverse components of the PDF can be decomposed in the following way:

$$\Gamma_{ij}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) = D_{ij}^l(x_1, x_2; Q_1^2, Q_2^2) f(b_1) f(b_2),$$

(2)

and longitudinal component $D_{ij}^l(x_1, x_2; Q_1^2, Q_2^2)$ is taken as a product of two independent single parton distributions,

$$D_{ij}^l(x_1, x_2; Q_1^2, Q_2^2) = D_{ij}^l(x_1; Q_1^2) D_{ij}^l(x_2; Q_2^2).$$

(3)

This leads to a well-known simple expression for DPS cross-section in which no di-parton correlations are involved:

$$\sigma_{\text{DPS}}^{AB} = m/2 \frac{\sigma_{\text{NSD}}^A \sigma_{\text{NSD}}^B}{\sigma_{\text{eff}}},$$

(4)

CDF and D0 measurements give $\sigma_{\text{eff}} = 14.5$ mb, which is roughly 30% of the non-single diffraction (NSD) cross section at the Tevatron ($\approx 48$ mb). The NSD cross section at LHC is only slightly higher ($\approx 51$ mb). This supports an assumption that $\sigma_{\text{eff}}$ weakly depends on the total energy of interaction [4]. Nonetheless dependence on the resolution scale and consequently on the partonic process can be significant. Model of multiple interactions implemented in Pythia8 [11] MC generator tries to accounts for this dependence and predicts $\sigma_{\text{eff}}$ for double charmonia production of 30 mb ($\sigma_{\text{eff}} = \sigma_{\text{NSD}}/(f_{\text{impact}})$). Further we will use usual value of 14.5 mb.

LO calculations in the CS model [2] lead do the value of double prompt $J/\psi$ production cross section in LHCb acceptance ($2 < y < 4.5$) of approximately

$$\sigma_{\text{SPS}}^{pp \to J/\psi J/\psi + X} = 4 \text{ nb}.$$ 

(5)
This result depends on the $\psi_{J/\psi}(0)$, $m_c$ and $\alpha_s$ parameters. First of them, $\psi_{J/\psi}(0)$, can be determined rather precisely from the leptonic width. $m_c$ was set equal to $m_{J/\psi}/2$. LO running $\alpha_s$ at the transverse mass scale was used. Taking experimentally measured cross section of single $J/\psi$ production in LHCb of $10 \mu b$ \cite{HP} and using expression (4) one gets for the DPS contribution approximately

$$
\sigma_{DPS}^{pp \rightarrow \psi J/\psi + X} = 2 \text{ nb.}
$$

(6)

Sum of these contributions agrees well with the experimentally measured value \cite{HP}

$$
\sigma_{exp.}^{pp \rightarrow \psi J/\psi + X} = 5.6 \pm 1.1 \text{ nb.}
$$

(7)

Several methods to distinguish DPS contribution from the SPS one were proposed \cite{CH, ST}. However it would be easier to deal with process in which one of these contributions in suppressed compared to another.

Crucial feature of the CS model is presence of so-called selection rules. According to the C-parity conservation, C-parity of the final state must be the same as those of 2 initial gluons, which is C-even as they are in CS combination. That is why production of $J/\psi \chi_c$ in SPS is expected to be suppressed. DPS cross section has no suppression in this mode and should be significant as it is known that about 50% of single $J/\psi$ mesons originate from the feeddown from the $\chi_c$ decays. Thus observation of $J/\psi$-pairs accompanied by a photon (from the $\chi_c \rightarrow J/\psi \gamma$ decay) would be a signal of DPS contribution.

Let us consider $\Upsilon(1S)$-meson pair production. Calculations analogous to $J/\psi$-pair production in \cite{HP} lead to the total cross section at 7 TeV of 31 pb and in LHCb acceptance:

$$
\sigma_{SPS}^{pp \rightarrow \Upsilon \Upsilon + X} = 8.7 \text{ pb},
$$

(8)

while estimation of DPS cross section based on the experimental data on single $\Upsilon$ production at LHC \cite{LT} gives

$$
\sigma_{DPS}^{pp \rightarrow \Upsilon \Upsilon + X} = 0.4 \text{ pb}.
$$

(9)

One sees that in the $\Upsilon(1S)\Upsilon(1S)$ mode SPS should dominate. Also feeddown from $\Upsilon(2S)$ and $\Upsilon(3S)$ decays should increase SPS prediction while it is already accounted for in the DPS estimation.

There are basically 3 types of Feynman diagrams for the $gg \rightarrow q\bar{q}q\bar{q}$ process (see fig. 1). Diagrams of first type contain 1 fermion loop while diagrams of second type contain 2 fermion loops connected by an intermediate gluon. In the diagrams of second type final particles are coupled with 2 gluons and consequently these diagrams do not contribute to $S$-wave pairs production due to the $C$-parity conservation. Diagrams of the third type correspond to gluon fragmentation and contribute to CO-states production only. Thereby only diagrams of first type contribute CS $J/\psi$ or $\Upsilon$ pair produced. But there are no LO diagrams contributing CS $J/\psi \Upsilon$ combined production. This final state is however accessible through $\chi_c \chi_b$ production followed by $\chi_c \rightarrow J/\psi + X$ and $\chi_b \rightarrow \Upsilon + X$ decays. Meanwhile $\chi_c \chi_b$ production does not exhibit kinematical peak near the threshold and is not expected to be significant in the low invariant mass region. Prediction of $J/\psi \Upsilon$ production in CO mechanism made in \cite{PM} give in LHCb acceptance

$$
\sigma_{SPS}^{pp \rightarrow J/\psi \Upsilon + X} = 2 \text{ pb},
$$

(10)

while DPS contribution found using expression (4) gives approximately

$$
\sigma_{DPS}^{pp \rightarrow J/\psi \Upsilon + X} = 75 \text{ pb}.
$$

(11)

So in the $J/\psi \Upsilon$ mode prediction for DPS exceeds significantly those for SPS one. It is interesting to notice that for SPS $\sigma_{SPS}^{J/\psi \Upsilon} < \sigma_{SPS}^{\Upsilon \Upsilon} < \sigma_{SPS}^{J/\psi J/\psi}$ while for DPS $\sigma_{DPS}^{J/\psi \Upsilon} < \sigma_{DPS}^{\Upsilon \Upsilon} < \sigma_{DPS}^{J/\psi J/\psi}$. Therefore cross section of $J/\psi J/\psi$ production is saturated by both SPS and DPS contributions, while for $\Upsilon \Upsilon$ and $J/\psi \Upsilon$ final states only one of these regimes prevail.
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