Pair Production of J/ψ as a Probe of Double Parton Scattering at LHCb

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We argue that the recent LHCb observation of J/ψ-pair production indicates a significant contribution from double parton scattering, in addition to the standard single parton scattering component. We propose a method to measure the double parton scattering at LHCb using leptonic final states from the decay of two prompt J/ψ mesons.

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Introduction.—The Large Hadron Collider (LHC) provides a unique environment for precise measurements of hitherto poorly understood phenomena. Since the flux of incoming partons increases with the collision energy, there is a high probability at the LHC of multiparton scattering, i.e., scattering of more than one pair of partons in the same hadron-hadron collision. The parton-parton correlations and distributions of multiple partons within a proton are difficult to address within the framework of perturbative QCD. Therefore, detailed experimental studies of multiparton interactions are of great importance. In particular, it is widely expected that measurements of double parton scattering (DPS) processes with final states carrying relatively large transverse momentum (p_T) will provide relevant information on the nature of multiple scattering. Probing DPS processes by using leptonic final states has been discussed in Ref. [1]. In this Letter, we discuss how observing four-muon final states from pair production of J/ψ could provide additional experimental input.

Taking advantage of high jet production rate at hadron colliders, DPS searches have been performed by the AFS [2], UA2 [3], CDF [4], and D0 [5] Collaborations in the four-jets ($4j$) and $\gamma + 3j$ channels. At the LHC, the pair production of muons from single J/ψ production benefits from a large cross section. This implies a significant DPS production rate of two J/ψ particles, which can subsequently decay into four muons, leading to much cleaner signals compared with those in the jet-based studies. In addition, the measurement of these J/ψ pairs provides complementary information on parton-parton correlations, as the hard processes can be initiated by partons different from those leading to $4j$ and $\gamma + 3j$ events.

A pair of J/ψ mesons can also be produced in a *single* parton scattering (SPS) process, e.g., $gg \to J/\psi J/\psi$. Studies of these SPS processes are expected to provide important insights for improving the theoretical description of single quarkonium production. Understanding the DPS contribution is thus an important task in this context. However, here we are primarily interested in the DPS as a signal process and will regard the SPS production as an irreducible background.

Invariant mass distribution of J/ψ pairs at LHCb.—The low p_T muon trigger at LHCb provides an ideal laboratory for studying four-muon final states from the decay of two J/ψ mesons. The LHCb Collaboration has recently reported a first measurement [6] of this process and compared the two-J/ψ invariant mass ($m_{J/\psi J/\psi}$) distribution with the theoretical prediction of Ref. [7] from direct SPS production of two J/ψ particles using a leading-order (LO) color-singlet result first derived in Ref. [8]. In Fig. 1, we show a comparison between the data and an SPS prediction for the process $gg \to J/\psi J/\psi$, which we implement in the Monte Carlo event generator HERWIG++ v2.4.2 [9]. This process is also implemented in the event generator DJPSIFDC [10]. We neglect the known LO color-octet contributions [11,12] as they are predicted to be negligible at the LHC [11]. In the calculations, the wave function at the origin takes the value $|R(0)|^2 = 0.92\ \mathrm{GeV}^3$. We use the Martin-Stirling-Thorne-Watt (MSTW) 2008 next-to-leading-order (NLO) parton distribution functions [13] and set the renormalization (μ_R) and factorization scales (μ_F) equal to $\sqrt{m_{J/\psi}^2 + p_T^2}$, where $m_{J/\psi} = 3.096$ GeV is the physical J/ψ mass. The J/ψ mesons are produced on-shell and decay isotropically into $\mu^+\mu^-$ pairs with the branching ratio $\mathrm{BR}(J/\psi \to \mu^+\mu^-) = 0.059\,35$. This approximation, ignoring possible J/ψ polarization effects, is justified if one assumes small values of J/ψ transverse momentum [14]. In our studies we require, in correspondence with the experimental analysis, that the J/ψ mesons have rapidities $2 < y_{J/\psi} < 4.5$ and transverse momenta $p_{T,J/\psi} < 10$ GeV.

The framework of HERWIG++ allows us to include effects of the initial state radiation (ISR) and intrinsic p_T of initial state partons. We set the root mean square intrinsic p_T of a Gaussian model in HERWIG++ to 2 GeV. In the figures, they are referred to as ''shower'' and ''intrinsic,'' respectively. As can be seen in Fig. 1, the impact of these effects on the predicted $m_{J/\psi J/\psi}$ distribution is negligible.

Figure 1 shows that the $m_{J/\psi J/\psi}$ shape of the standard SPS contribution does not match the data very well. In particular, it peaks at too low a $m_{J/\psi J/\psi}$ value. The same

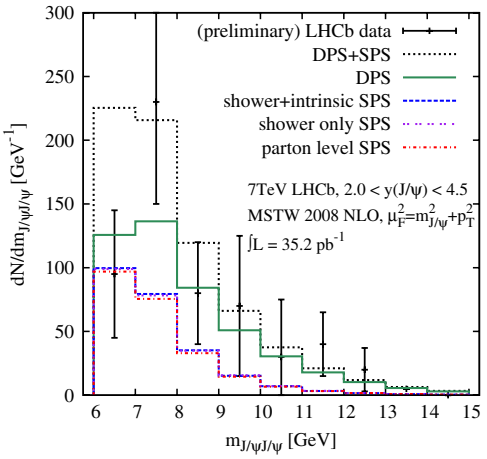

FIG. 1 (color online). Invariant mass distribution of the J/ψ pair ($m_{J/\psi J/\psi}$). The LHCb data are read off the plot in Ref. [6]. From top to bottom, the histograms are the DPS + SPS, DPS only, and three (practically degenerate) SPS predictions including different radiation effects.

conclusion has also been derived in Ref. [6] for the theoretical predictions of Ref. [7]. In addition to the SPS contribution, in Fig. 1 we also show the invariant mass distributions for the DPS process, which will be discussed shortly. The DPS contribution has a broader shape and peaks at higher values of $m_{J/\psi J/\psi}$, leading to much better agreement between the combined SPS + DPS prediction and data than with the SPS contribution alone. The LHCb data could therefore indicate the presence of a significant DPS contribution to the double J/ψ production process.

Our predictions for the DPS double J/ψ production are obtained by using an approximation in which the DPS cross section ($\sigma_{\rm DPS}^{2J/\psi}$) factorizes into a product of two SPS cross sections ($\sigma_{\rm SPS}^{J/\psi}$):

$$d\sigma_{\rm DPS}^{2J/\psi} = \frac{d\sigma_{\rm SPS}^{J/\psi} d\sigma_{\rm SPS}^{J/\psi}}{2\sigma_{\rm eff}}, \tag{1}$$

where

$$d\sigma_{\rm SPS}^{J/\psi} = \sum_{a,b} f_a(x_a, \mu_F) f_b(x_b, \mu_F) d\hat{\sigma}_{\rm SPS}^{J/\psi} dx_a dx_b \tag{2}$$

is the SPS cross section of a single J/ψ and

$$d\hat{\sigma}_{\rm SPS}^{J/\psi} = \sum_{a,b} \frac{1}{2\hat{s}} \overline{|M_{ab\to J/\psi+X}|^2} d{\rm PS}_{J/\psi+X} \tag{3}$$

is the corresponding parton level process, with $\hat{s}$ the partonic center-of-mass energy. The approximation assumes factorization between the longitudinal and the transverse components of the generalized double parton distributions and the assumption of no longitudinal momentum correlations between the partons in the same hadron. In this framework, all the information on the transverse structure of the proton is captured in the factor $\sigma_{\rm eff}$. The assumption of factorization between the longitudinal and transverse components of double parton distributions appears to be not strictly valid within QCD [15–17]. However, given the small values of longitudinal momentum fraction x probed in the J/ψ production at the LHC, this should be a reasonable approximation. For the same reason, the approximation of no longitudinal momentum correlations may also be justified.

The state-of-the-art theoretical description of direct single J/ψ production involves the nonrelativistic QCD factorization approach [18]. Because of the LHCb ability to trigger on low p_T muons, down to 1 GeV, it is essential for our analysis to be able to describe the production of J/ψ with low p_T accurately. Since the fixed-order calculations [19] fail to provide such a description in this regime, we resort to modeling the p_T distribution of the single J/ψ. To do this, we approximate the matrix element for the inclusive production of a prompt J/ψ, assumed to be dominated by the gluon-gluon channel, with a crystal ball function of the form

$$\overline{|M_{gg\to J/\psi+X}|^2} = \begin{cases} K \exp\left(-\kappa \frac{p_T^2}{m_{J/\psi}^2}\right) & p_T \le \langle p_T \rangle, \\ K \exp\left(-\kappa \frac{\langle p_T \rangle^2}{m_{J/\psi}^2}\right)\left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{m_{J/\psi}^2}\right)^{-n} & p_T > \langle p_T \rangle, \end{cases} \tag{4}$$

where $K = \lambda^2 \kappa \hat{s}/m_{J/\psi}^2$. The values of the coefficients κ, λ, n, and $\langle p_T \rangle$ are obtained through a combined fit of $d\sigma/dp_T$ to the LHCb [20], ATLAS [21], CMS [22], and CDF [23] data, using MSTW 2008 NLO parton distribution functions with the factorization scale $\mu_F = \sqrt{m_{J/\psi}^2 + p_T^2}$ and the physical mass $m_{J/\psi} = 3.096$ GeV. The resulting fit gives $\kappa = 0.6$ and $\lambda = 0.327$ for $n = 2$ and $\langle p_T \rangle = 4.5$ GeV. In particular, $\chi^2 \approx 28$ for the fit to 55 LHCb data points.

The parametrization (4) is then used to obtain the cross section for the production of two J/ψ mesons through DPS. The corresponding matrix element is implemented into the framework of HERWIG++, with parton shower and intrinsic p_T broadening switched off as the fitted data already account for these effects.

The value of $\sigma_{\rm eff}$ in the factorized approach to DPS [cf. Eq. (1)], which could be energy- and process-dependent, is one of the properties of the DPS that requires a more precise experimental measurement. In the calculations we use $\sigma_{\rm eff} = 14.5$ mb, a value obtained by the CDF $\gamma + 3j$ study [4]. As clearly seen in Fig. 1, double J/ψ production at LHCb offers a promising opportunity to probe the DPS component. In the following, we propose a method to separate the DPS and SPS contributions.

Measurement of DPS at LHCb.—The majority of kinematic variables used in the literature to distinguish a DPS signal from the SPS background, where all four final states originate from a single parton-parton hard scattering, are based on the idea of pairwise balancing. For DPS, the two final state particles from the same hard scatter will balance against each other on the plane transverse to the collision

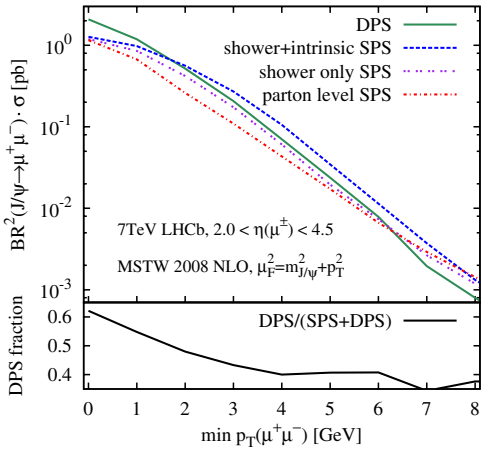

FIG. 2 (color online). DPS and SPS cross sections for $pp \to J/\psi J/\psi + X$, as a function of minimum p_T of J/ψ, constructed from $\mu^+\mu^-$ (upper panel), and the fraction of DPS events using the "shower + intrinsic" SPS calculation (lower panel). Basic selection cuts were applied.

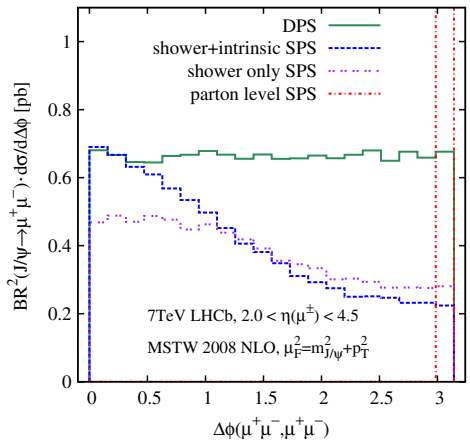

FIG. 3 (color online). Angular separation $\Delta\phi$ on the plane transverse to the beam axis between the two J/ψ's, reconstructed from $\mu^+\mu^-$ pairs, for DPS and SPS contributions to $pp \to J/\psi J/\psi + X$. Basic selection cuts were applied.

axis, resulting in equal but opposite transverse momenta. The balancing is exact at leading order, but, as we will see in the following, radiation effects can have significant impact and reduce the effectiveness of these variables.

In our simulation, we consider events with four muons, each required to have $p_T > 1$ GeV and to lie within the pseudorapidity range $2 < \eta < 4.5$. Out of the two combinatoric ways to form two J/ψ candidates, the combination with invariant mass closest to the physical J/ψ mass is chosen. In the rest of this Letter, we refer to this set of cuts as the "basic cuts." Once the muon candidates fulfill these cuts, 100% reconstruction and detection efficiency is assumed. The same parameter values and parton distribution functions as in the calculation of Fig. 1 are used.

Figure 2 shows the DPS and SPS cross sections as a function of the minimum p_T of a muon pair, after applying the basic cuts. In the upper panel, the effects of the parton shower and the intrinsic p_T broadening on the SPS predictions is shown. These effects are significant, due to the low invariant mass of the two-J/ψ system. In the lower panel, we see that the DPS fraction increases as minimum p_T decreases. Conversely, a cleaner SPS sample might be obtained by imposing a cut on the minimum p_T of the J/ψ.

The impact of the ISR and the intrinsic p_T broadening is also demonstrated in Fig. 3, where we show the distribution of $\Delta\phi \equiv \Delta\phi(\mu^+\mu^-, \mu^+\mu^-)$, the azimuthal angular separation between the two reconstructed J/ψ's. As expected, the signal distribution is flat, a reflection of the independent scattering hypothesis. For the background, while $\Delta\phi = \pi$ at the parton level, the distribution is heavily distorted in the presence of ISR and p_T broadening. In particular, the ISR leads to distributions that are flat or even peaked towards $\Delta\phi = 0$. We conclude that variables based on pairwise balancing might not be the best tools to distinguish between DPS and SPS in this particular analysis.

However, as we now demonstrate, it is possible to use correlations along the *longitudinal* direction between the two J/ψ mesons to extract the DPS signal. The idea relies on the observation that, in order to minimize the invariant mass of the J/ψ pair, the SPS background should on average be characterized by a small rapidity separation (Δy). To see this, note that, in a frame where the p_T of the J/ψ pair is zero,

$$m_{J/\psi J/\psi} = 2\sqrt{m_{J/\psi}^2 + p_T^2}\cosh\left(\frac{\Delta y}{2}\right); \qquad (5)$$

hence, a small $|\Delta y|$ is preferred. However, this constraint does not apply to the DPS signal, which implies a broader distribution. The small invariant mass of the system ensures that overall momentum conservation has negligible impact on the y, and hence the $|\Delta y|$, distributions.

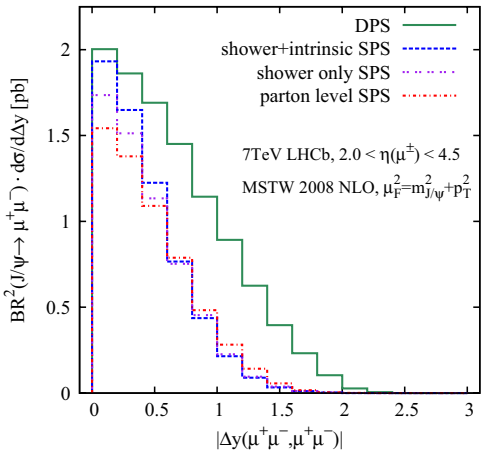

FIG. 4 (color online). Rapidity separation $|\Delta y|$ between the two reconstructed J/ψ's, with basic selection cuts applied.

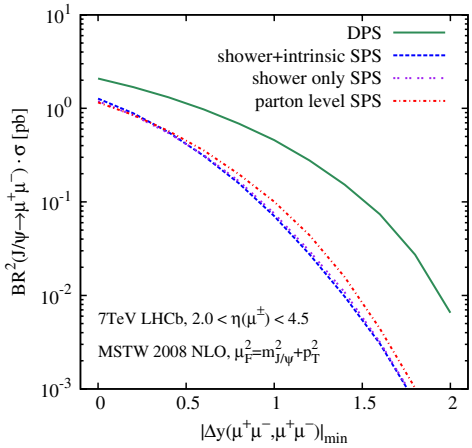

FIG. 5 (color online). DPS and SPS cross sections for J/ψ-pair production with basic selection cuts applied, as a function of a lower cut $|\Delta y|_{\min}$ on rapidity separation.

As shown in Fig. 4, the difference in $|\Delta y|$ distributions persists in the laboratory frame. As expected, the DPS signal is broader and extends to higher values of $|\Delta y|$. The distributions are also more stable against radiation and intrinsic p_T effects when compared with the $\Delta\phi$ distributions, making the predictions more robust.

To extract the DPS signal, we apply a lower cut on the rapidity separation: $|\Delta y| > |\Delta y|_{\min}$. The variation of the cross section with $|\Delta y|_{\min}$ is displayed in Fig. 5. Clearly, the event sample becomes more dominated by DPS contributions for higher values of $|\Delta y|_{\min}$. A summary of the results is displayed in Table I. In the current (7 TeV) LHC run, an integrated luminosity of a few fb^{-1} is expected. By selecting the four-muon signal sample using the basic cuts, a signal to background ratio of a few to one may be achieved. Hence we conclude that DPS can be measured at the LHCb in the four-muon events already at this stage of LHC running.

Summary.—Precise measurement of double parton scattering processes at the LHC is an important step towards understanding multiple interactions in hadron collisions. The characteristics of the LHCb detector make it particularly well suited to study DPS in the production of a J/ψ pair decaying into four muons. We observe that the first LHCb data on the invariant mass distribution of the J/ψ-pair system might already indicate a significant contribution from the DPS production mechanism. The studies presented in this Letter show that it is possible to measure the DPS component in the four-muon events at the LHCb already in the early stages of the LHC running, in particular, with the help of the proposed rapidity separation variable Δy.

TABLE I. DPS and SPS cross sections, including branching ratios into muons. The first row shows the cross section after basic selection cuts, while the rest show the impact of an additional $|\Delta y|_{\min}$ cut. For clarity, only the SPS result with parton shower and intrinsic p_T broadening turned on is shown.

BR^2 × cross sections [pb] at 7 TeV LHCb	DPS	SPS
Basic cuts	2.18	1.27
Basic cuts + $\|\Delta y\| > 1.0$	0.48	0.07
Basic cuts + $\|\Delta y\| > 1.5$	0.11	0.005
Basic cuts + $\|\Delta y\| > 2.0$	0.007	<0.001

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