Double Parton Scattering in $p\bar{p}$ interactions at $\sqrt{s} = 1.96$ TeV

O. Gogota on behalf of the D0 Collaboration

Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Summary. — We present the observation of doubly produced J/ψ mesons as an example of processes containing a substantial fraction of double parton scattering. Measurements of the production cross sections for singly and doubly-produced J/ψ mesons were done with the D0 detector at Fermilab in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 8.1 fb^{-1}. For the first time, the double J/ψ production cross section is separated into two parts: contributions from both single and double parton scattering. This separation allowed us to determine the effective cross section σ_{eff}, a parameter related to the parton spatial density inside the hadron.

PACS `12.38.Qk` – Experimental tests.
PACS `13.20.Gd` – Decays of J/ψ, Υ, and other quarkonia.
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.

1. – Introduction

Multiple parton interactions (MPI) in hadron-hadron collisions are important as a background to processes such as Higgs production or various new phenomena. We talk about single parton scattering(SP) when one parton from the hadron collides with a parton from another hadron. Under double parton scattering(DP) two partons from the hadron collide with two partons from the second hadron. The cross section for double parton scattering, $\sigma_{\rm DP}^{(1,2)}$, is related to $\sigma_{\rm eff}$ [1, 2, 3].

$$\sigma_{\rm DP}^{(1,2)} \equiv \frac{m}{2}\frac{\sigma^{(1)}\sigma^{(2)}}{\sigma_{\rm eff}}. \quad (1)$$

The factor of 1/2 is due to the assumption that the probability of multiple parton interactions in a single proton anti-proton collision follows a Poisson distribution [4]. Here $\sigma^{(1)}$ is a cross section for the process 1, $\sigma^{(2)}$ is a cross section for the process 2, and m is a the combinatorial coefficient, which is equal to 1 for the identical interactions and 2 otherwise. The double parton scattering event contains both types of processes (1,2).

The parameter $\sigma_{\rm eff}$ is related to the distance between partons in the nucleon [1, 2, 3, 5, 6],

$$\sigma_{\rm eff}^{-1} = \int d^2\beta [F(\beta)]^2 \quad (2)$$

with $F(\boldsymbol{\beta}) = \int f(\mathbf{b})f(\mathbf{b}-\boldsymbol{\beta})d^2\mathbf{b}$, where $\boldsymbol{\beta}$ is the vector impact parameter of the two colliding hadrons and $f(\mathbf{b})$ is a function describing the transverse spatial distribution of the partonic matter inside a hadron [5].

An example of a physical process that has both mechanisms (SP, DP) involved is double J/ψ production, shown in Fig. 1. The first observation of double J/ψ meson production was made in 1982 by the NA3 Collaboration [7, 8]. The LHCb Collaboration has measured the double J/ψ production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV [9]. At Tevatron and LHC energies this cross section is dominated by gluon fusion, $gg \to J/\psi J/\psi$ [10, 11].

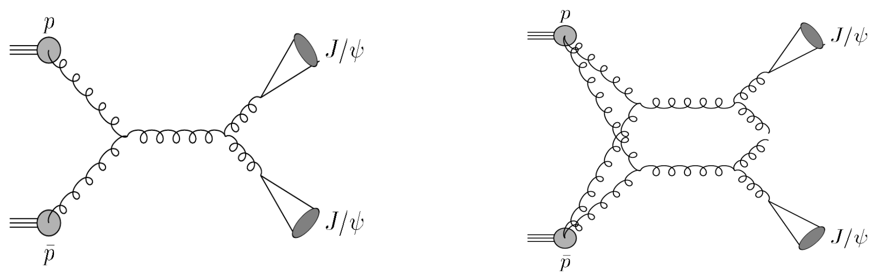

Fig. 1. – Schematic view of J/ψ meson pair production in SP(left) and DP(right) mode.

For this analysis, the factor m in Eq. 1 is equal to 1 because double J/ψ production processes are undistinguishable.

$$\sigma_{\rm eff} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\rm DP}(J/\psi J/\psi)}. \quad (3)$$

2. – Experimental setup

The D0 detector is a general purpose detector described in detail in Ref. [12]. The measurements are based on the data sample collected by the D0 experiment at the Tevatron in proton-antiproton ($p\bar{p}$) collisions at the center-of-mass energy $\sqrt{s} = 1.96$ GeV, and corresponds to an integrated luminosity of 8.1 ± 0.5 fb^{-1} [13]. The most important sub-detectors in this analysis are the muon and the central tracking systems. The central tracking system, used to reconstruct charged particle tracks, consists of the silicon microstrip tracker (SMT) and a central fiber tracker (CFT) detector. The muon detector consists of three layers of drift tubes and three layers of plastic scintillators.

3. – Event selection

We require events to pass at least one of a set of low-p_T dimuon triggers. Muons are identified as having either hits in all three layers of the muon detector or just in one layer in front of the toroids [14]. They are also required to be matched to a track reconstructed by the central tracking system with at least one hit in the SMT and at least two hits in the CFT detectors. The muon candidates must satisfy timing requirements to suppress cosmic rays. Their distance of closest approach to the beam line has to be less than 0.5 cm and their matching tracks have to pass within 2 cm along the beam (z) axis of the event interaction vertex. The $p\bar{p}$ interaction vertex should be within 60 cm of the center of the detector along beam axis. Events that have two such muons with opposite electric charge that satisfy an invariant mass requirement of $2.85 < M_{\mu\mu} < 3.35$ GeV are identified as single J/ψ candidate events. Events having two such pairs of muons are identified as double J/ψ candidate events. Background events are mainly due to random combinations of muons from $\pi^{\pm}$, $K^{\pm}$ decays, continuous non-resonant $\mu^{+}\mu^{-}$ production via Drell-Yan process (both called "accidental background"), and B hadron decays into a $J/\psi + X$. In the case of the double J/ψ production, the background may also be caused by associated production of J/ψ meson and a muon pair not produced by a J/ψ decay ("$J2\mu$" events). The number of single J/ψ events after selections is about 7.4×10^{6}. In

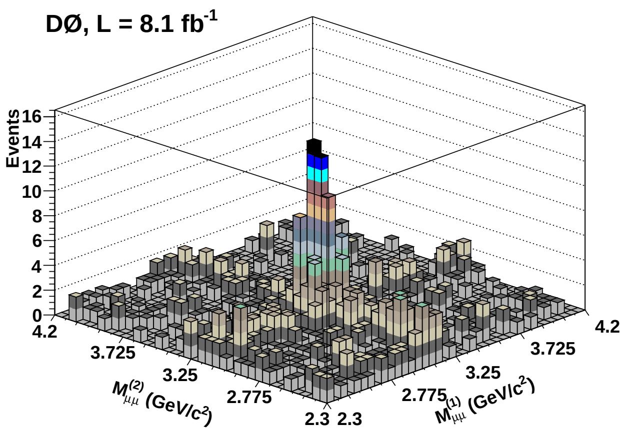

Fig. 2. – Dimuon invariant mass distribution in data for two muon pairs $M^{(1)}_{\mu\mu}$, $M^{(2)}_{\mu\mu}$ after the double J/ψ selection criteria.

total, 242 events remain after double J/ψ selection criteria and 902 such events are found in the wider mass window $2.3 < M_{\mu\mu} < 4.2$ GeV. Fig. 2 shows the distribution of the two dimuon masses ($M^{(1),(2)}_{\mu\mu}$) in these events. After applying cuts to reduce non-prompt background(J/ψ from the B hadron decays), we have 138 events left.

4. – Acceptances, trigger efficiencies

We use PYTHIA generated single J/ψ events to estimate the combined geometric and kinematic acceptance and reconstruction efficiency. The generated and reconstructed events are selected using the same muon selection criteria described above. The product of the acceptance and efficiency for single J/ψ events is found to be $0.221 \pm 0.002(\text{stat}) \pm 0.023(\text{syst})$. For estimation the combined geometric and kinematic acceptance and reconstruction efficiency for double J/ψ events for SP and DP processes DJpsiFDC and

PYTHIA Monte Carlo model were used. We obtain products of the acceptances and the selection efficiencies of $(A\varepsilon_s)^{\mathrm{SP}} = 0.109 \pm 0.002(\mathrm{stat}) \pm 0.005(\mathrm{syst})$ for the SP and $(A\varepsilon_s)^{\mathrm{DP}} = 0.099 \pm 0.006(\mathrm{stat}) \pm 0.005(\mathrm{syst})$ for the DP events, where the systematic uncertainties arise from uncertainties in the modeling of the J/ψ kinematics, muon identification efficiencies and possible non-zero J/ψ polarization effects. The single J/ψ trigger efficiency is estimated using events which pass zero-bias triggers (which require a beam crossing only) or minimum bias triggers (which only require hits in the luminosity detectors), and that also pass the di-muon trigger. Calculated trigger efficiency for the single J/ψ production is $0.124 \pm 0.024\,(\mathrm{stat}) \pm 0.012\,(\mathrm{syst})$. The systematic uncertainty is due to variations in the parametrizations of the functional forms used to fit the signal and background events to data.

To measure the trigger efficiency for double J/ψ selection, we use DP and SP events generated in Monte Carlo. The double J/ψ DP events are generated with the PYTHIA, while the double J/ψ SP events are generated with HERWIG++ Monte Carlo generators. We parametrize di-muon trigger efficiency as a 2D function of the transverse momentum of each of the muons and calculate it for every possible pairing of muons in double parton and single parton Monte Carlo events. Trigger efficiencies are found to be $\varepsilon_{\mathrm{tr}}^{\mathrm{DP}} = 0.48 \pm 0.07$ for DP and $\varepsilon_{\mathrm{tr}}^{\mathrm{SP}} = 0.51 \pm 0.07$ for SP interactions, where the uncertainty is propagated from the uncertainty on the di-muon trigger efficiency.

5. – Prompt fraction

In $p\bar{p}$ collisions J/ψ mesons are produced either promptly (directly at the interaction point or as a radiative product of a heavier charmonium state) or non-promptly, as a decay of a detectably long-lived B hadron state. To distinguish prompt from non-prompt J/ψ mesons, we examine the decay length from the primary $p\bar{p}$ interaction vertex to the J/ψ decay vertex, defined as $c\tau = L_{xy} m_{\mathrm{pdg}}^{J/\psi} / p_T^{J/\psi}$, where L_{xy} is the distance between $p\bar{p}$ vertex and decay vertex of J/ψ meson, $p_T^{J/\psi}$ is the transverse momentum of the J/ψ, $m_{\mathrm{pdg}}^{J/\psi}$ is the world average J/ψ mass [15]. To estimate the fraction of prompt J/ψ mesons in the data sample, we perform a maximum likelihood fit of the $c\tau$ distribution using templates for the prompt J/ψ signal events, taken from the single J/ψ Monte Carlo sample, and for non-prompt J/ψ events, taken from the $b\bar{b}$ Monte Carlo sample. The prompt J/ψ fraction obtained from the fit is 0.814 ± 0.009. The fit result is shown in Fig. 3.

To estimate the fraction of the prompt double J/ψ events, we use a template fit to the 2D $c\tau$ distribution in double J/ψ data. In addition to prompt and non-prompt templates a prompt+non-prompt template was created by randomly choosing $c\tau$ values from the prompt and non-prompt templates. Before fitting, the accidental and $J2\mu$ background is subtracted from the data. We determine prompt fraction of double J/ψ events in our selection of $f_{\mathrm{prompt}} = 0.592 \pm 0.101$. The main source of systematic uncertainty for the prompt fraction is the template fitting and the uncertainty related to the subtraction of the accidental background from the data.

6. – Double parton fraction

In this analysis, we measure double J/ψ production cross section for the DP and SP processes separately. To discriminate between two processes, we use the distribution of the pseudorapidity difference between the two J/ψ candidates, $|\Delta\eta(J/\psi, J/\psi)|$. For

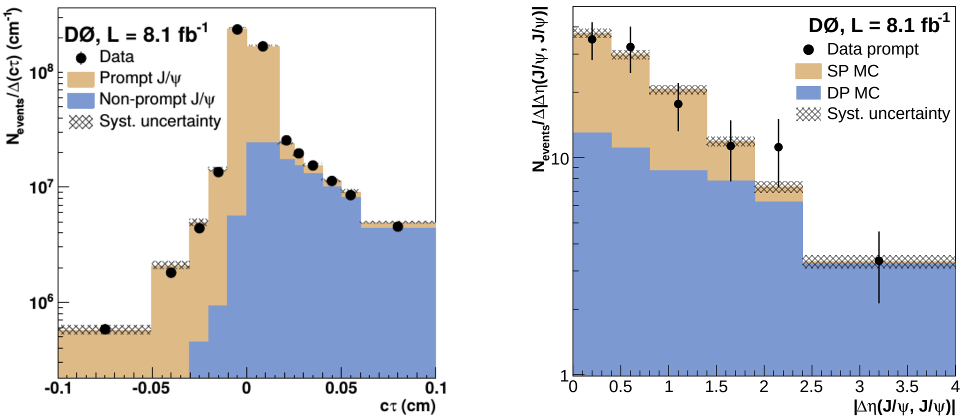

Fig. 3. – Template fit of the J/ψ lifetime distribution(left) and template fit of the J/ψ $|\Delta\eta(J/\psi, J/\psi)|$ distribution(right).

the two J/ψ mesons produced from two uncorrelated parton scatterings with smaller (on average) parton momentum fractions than in the SP scattering, the $|\Delta\eta(J/\psi, J/\psi)|$ distribution is expected to be broader. We use the DP and SP templates obtained from Monte Carlo to obtain the DP and SP fractions from a maximum likelihood fit to the $|\Delta\eta(J/\psi, J/\psi)|$ distribution in $J/\psi J/\psi$ data. Contributions from the accidental background, non-prompt and prompt+non-prompt double J/ψ events are subtracted from the data. The fit result is shown in Fig. 3. To estimate the systematic uncertainties of the DP and SP fractions, we vary all components of the background within their uncertainties. We also create a data-like DP template combining two J/ψ meson candidates from two events randomly selected from the single J/ψ data sample. We find the fractions to be $f^{\mathrm{DP}} = 0.42 \pm 0.12$ and $f^{\mathrm{SP}} = 0.58 \pm 0.12$. The main sources of the uncertainties on DP and SP fractions are the background subtraction, the model dependence, and the template fit.

7. – Results

The fiducial cross section of the prompt single J/ψ production is calculated using the number of J/ψ candidates in data, the fraction of prompt events, the dimuon trigger efficiency, the acceptance and the selection efficiency, as well as the integrated luminosity:

$$\sigma = \frac{N_{data} P}{\varepsilon_{trigg} L A \varepsilon_{sel}} \tag{4}$$

It is found to be

$$\sigma(J/\psi) = 23.9 \pm 4.6(\mathrm{stat}) \pm 3.7(\mathrm{syst})\ \mathrm{nb}. \tag{5}$$

The uncertainties mainly arise from the trigger efficiency and acceptance calculations.

This value is compared to that calculated in the "k_T factorization" approach [11] with the unintegrated gluon density [16]:

$$\sigma_{\mathrm{k_T}}(J/\psi) = 23.0 \pm 8.5 \text{ nb.} \tag{6}$$

In this calculation, the J/ψ meson is produced either directly or through the radiative $\chi_{1(2)} \to J/\psi + \gamma$ process [11]. The uncertainty is determined by variations of the gluon PDF and scale variations by a factor of 2 with respect to the default choice $\mu_R = \mu_F = \hat{s}/4$.

The fiducial cross section of the prompt SP(DP) double J/ψ production is calculated using the number of double J/ψ candidates in data, the fraction of prompt events, the fraction of the SP(DP) events, SP(DP) trigger efficiency, the acceptance and selection efficiency for SP(DP) model and the integrated luminosity. Measured SP cross section is:

$$\sigma_{\mathrm{SP}}(J/\psi J/\psi) = 70 \pm 6(\mathrm{stat}) \pm 22(\mathrm{syst}) \text{ fb.} \tag{7}$$

The prediction for the SP cross section made in the "k_T factorization" approach [11] is

$$\sigma_{\mathrm{k_T}}(J/\psi J/\psi) = 55.1^{+28.5}_{-15.6}(\mathrm{PDF})^{+31.0}_{-17.0}(\mathrm{scale}) \text{ fb.} \tag{8}$$

We also compare our $\sigma_{\mathrm{SP}}(J/\psi J/\psi)$ result to the SP prediction obtained with NRQCD at the leading order approximation in the strong coupling [17].

$$\sigma^{\mathrm{LO}}_{\mathrm{NRQCD}}(J/\psi J/\psi) = 51.9 \text{ fb,} \tag{9}$$

The measured SP cross section is in agreement with the current predictions from NRQCD and "k_T factorization".

The obtained DP cross section is:

$$\sigma_{\mathrm{DP}}(J/\psi J/\psi) = 59 \pm 6(\mathrm{stat}) \pm 22(\mathrm{syst}) \text{ fb,} \tag{10}$$

The DP production cross section predicted by the "k_T factorization" approach according to Eq. 3, and using the fixed effective cross section $\sigma^0_{\mathrm{eff}} = 15$ mb [11], is

$$\sigma^{\mathrm{DP}}_{\mathrm{k_T}}(J/\psi J/\psi) = 17.6 \pm 13.0 \text{ fb.} \tag{11}$$

Using the measured cross sections of prompt single J/ψ and DP production, we calculate the effective cross section, σ_{eff} (see Eq. 3). The main sources of systematic uncertainty in the σ_{eff} measurement are trigger efficiency and the fraction of DP events. By substituting the measured single J/ψ and double J/ψ DP cross sections (Eqs. 5 and 10) into Eq. 3, we obtain

$$\sigma_{\mathrm{eff}} = 4.8 \pm 0.5(\mathrm{stat}) \pm 2.5(\mathrm{syst}) \text{ mb.} \tag{12}$$

The measured σ_{eff} is in agreement with the measurement done by the AFS Collaboration (≈ 5 mb), agrees with the result obtained by CDF Collaboration [2] in the 4-jet final state ($12.1^{+10.7}_{-5.4}$ mb) and D0 Collaboration measurement ($2.2 \pm 0.7(\mathrm{stat}) \pm$

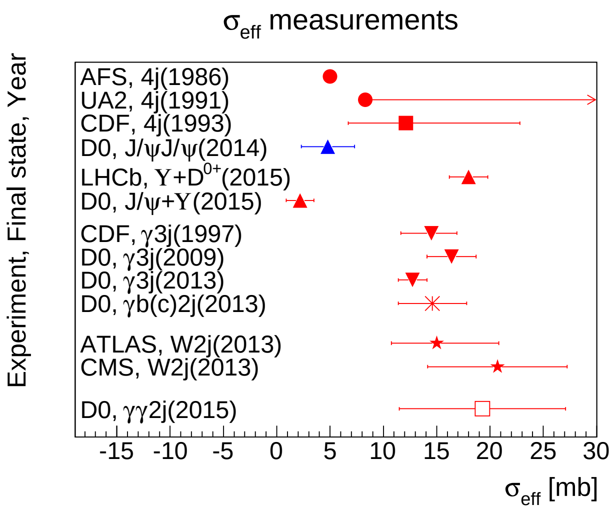

Fig. 4. – Existing measurements of the effective cross section, $\sigma_{\rm eff}$.

0.9(syst)) [18]. However, it is lower than the result obtained by CDF [3] ($14.5 \pm 1.7({\rm stat})^{+1.7}_{-2.3}({\rm syst})$) and D0 [19] ($12.7 \pm 0.2({\rm stat}) \pm 1.3({\rm syst})$) in $\gamma + 3$-jet events, and by ATLAS [20] ($15 \pm 3({\rm stat})^{+5}_{-3}({\rm syst})$) and by CMS [21] ($20.7 \pm 0.8({\rm stat}) \pm 6.6({\rm syst})$) in the W+2-jet final state.

8. – Summary

In conclusion, we have observed double J/ψ production at the D0 experiment and measured its production cross section. We show that this production is due to two components: single and double parton scattering [22]. The measured SP cross section is in an agreement with theoretical predictions, while DP cross section is larger. The measured σ_{eff} may indicate a smaller average distance between gluons than between quarks or between a quark and a gluon, in the transverse space.

REFERENCES

[1] Alitti J. *et al.* [UA2 Collaboration], *Phys. Lett. B*, **268** (1991) 145.
[2] Abe F. *et al.* [CDF Collaboration], *Phys. Rev. D*, **47** (1999) 4857.
[3] Abe F. *et al.* [CDF Collaboration], *Phys. Rev. D*, **56** (1997) 811.
[4] Sjöstrand T. and van Zijl M., *Phys. Rev. D*, **36** (1987) 2019.
[5] Calucci G. and Treleani D., *Phys. Rev. D*, **60** (1999) 054023.
[6] Åkeson T. *et al.* [AFS Collaboration], *Z. Phys. C*, **34** (1987) 163.
[7] Badier J. *et al.* [NA3 Collaboration] , *Phys. Lett. B*, **114** (1982) 457.
[8] Badier J. *et al.* [NA3 Collaboration], *Phys. Lett. B*, **158** (1985) 85.
[9] Aaij R. *et al.* [LCHb Collaboration], *Phys. Lett. B*, **707** (2012) 52.
[10] Berezhnoy A. V.,Likhoded A. K., Luchinsky A. V. and Novoselov A. A., *Phys. Rev. D*, **84** (2011) 094023.
[11] Baranov S. P. *et al.*, *Phys. Rev. D* , **87** (2013) 034035.
[12] Abazov V. M. *et al.* [D0 Collaboration], *Nucl. Instrum. Meth. A*, **565** (2006) 463; Angstadt R. *et al.* [D0 Collaboration], *Nucl. Instrum. Meth. A*, **622** (2010) 298.

[13] Andeen T.*et al.* [D0 Collaboration], FERMILAB-TM-2365, 2007.
[14] Abazov V. M. *et al.* [D0 Collaboration], *Nucl. Instrum. Methods in Phys. Res. Sect. A*, **737** (2014) 281.
[15] Amsler C., *Phys. Lett. B*, **667** (2008) 1.
[16] Hung J., *Mod. Phys. Lett. A*, **19** (2004) 1.
[17] Qiao C.-F. and Sung L.-P., *Chinese Phys. C*, **37** (2013) 033105.
[18] Abazov V. M. *et al.* [D0 Collaboration], *Phys. Rev. Lett.*, **116** (2016) 082002.
[19] Abazov V. M. *et al.* [D0 Collaboration], *Phys. Rev. D*, **89** (2014) 072006.
[20] Aad G. *et al.* [ATLAS Collaboration], *New J. Phys.*, **15** (2013) 033038.
[21] Khachatryan S. V. *et al.* [CMS Collaboration], *J. High Energy Phys.*, **03** (2014) 032.
[22] Abazov V. M. *et al.* [D0 Collaboration], *Phys. Rev. D*, **90** (2014) 111101(R).