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Physics with charmonia at the SPD experiment

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Physics with charmonia at the SPD experiment

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Abstract. The J/ψ production is a powerful probe of hadron structure, which is complementary to other parts of the SPD physics program. In this work, the current experimental status and modern theoretical approaches to J/ψ and charmonia production are reviewed. In this context, the SPD performance and feasibility of key measurements are discussed.

1. Introduction

The spin-dependent parton structure is a fundamental property of a proton, which might be a key to resolve famous “spin crisis”. It has been a subject of dedicated studies for several decades but our understanding remains fragmentary and the worst known piece of the puzzle are spin-dependent parton distributions of gluons. The current situation is expected to be significantly improved by a new experiment with polarized beams at the NICA accelerator complex. The proton-proton and proton-nucleon collisions will be collected by the Spin Physics Detector (SPD) [1]. The CMS energy for proton-proton collisions at NICA varies from 10 GeV to 27 GeV.

There are several physical tools to probe the internal structure of the nucleon: the Drell-Yan process, prompt photons, charmonia production, and inclusive hadron production. Here the physics with charmonia is considered. On the parton level, the J/ψ production is expected to be dominated by gluon-gluon fusion but the contribution of quark-antiquark annihilation may be significant in some kinematic regions. This makes inclusive charmonia production complementary to prompt photons and Drell-Yan studies. From the experimental point of view, the simplest charmonia state to study is J/ψ due to a large production cross-section and a clean experimental signature in the dimuon decay mode. It has the same observables as the Drell-Yan process. For the unpolarized case, they are the total cross-section, the J/ψ p_T and x_F spectra and polarization. For polarized hadron collisions, the transverse structure of hadrons can be probed by measuring spin asymmetries of the J/ψ production or studying the cross-section angular modulations. In particular, the transverse single spin asymmetries (TSSA) are associated with the Sivers effect for gluons (e.g. see [2]). Probing quark transverse momentum dependent parton distribution functions through J/ψ spin asymmetries might be also possible (similarly to what is suggested in Ref. [3] for the $p\bar{p}$ collisions) but depends on the relative contribution of the quark-antiquark annihilation process. The challenging part is the interpretation of experimental results due to the lack of theoretical understanding of the charmonia production process. The interpretation is further complicated due to the fact that about 40% J/ψ mesons are produced not directly in parton-parton interaction but through so-called “feed-down” decays of $\chi_{c1,c2} \to \gamma J/\psi$ and $\psi(2S) \to \pi\pi J/\psi$.

Compared to the previous mostly fixed-target experiments, SPD is expected to have several advantages. It is designed as an open spectrometer with a high momentum resolution and allows studying J/ψ alongside with χ_{c1}, χ_{c2} and $\psi(2S)$. Moreover, the high expected statistics should allow for a precise measurement of $\psi(2S)$ production properties, that does not suffer from the feed-down contributions, as well as provide an improved measurement of J/ψ TSSA. In general, the experiment is expected to validate current theoretical approaches and use them to interpret observables for polarized beams. As a by-product, the validated theoretical models can be used to extract pion and kaon gluon parton distribution functions in future experiments like AMBER [4].

2. Available experimental results

A good review of experimental results on the inclusive J/ψ production cross-section in proton-proton and proton-nucleon collisions at low energies can be found in Ref. [5] The cross-section measurements corrected for the nuclear dependence and the SPD energy range are shown in Fig. 1. The results are mostly obtained in fixed-target experiments with a pion absorber, thus making it impossible to study χ_{cJ} and conduct a detailed investigation of $\psi(2S)$ production properties. It must also be noted that shown results are not well-consistent. For the highest available energies at SPD, the cross-section is about 200-250 nb.

The p_T spectrum obtained by the NA3 collaboration at $\sqrt{s} = 19.4$ in pp collisions is shown in Fig. 5. It shows that typical transverse momenta are of order of 1 GeV/c and is comparable to $M_{J/\psi}c$. The x_F distribution at low energies is measured by NA3 [6], E705 [7], and E866 [8] to validate relative contributions from gluon-gluon fusion and quark-antiquark annihilation in the model (or to phenomenologically separate them). The worst known observable, and the most interesting for the model validation, is J/ψ polarization. At these energies, its kinematic dependence on p_T and x_F is measured by two experiments E866 [9] and HERA-B [10]. The results are notably different but cover different kinematic regions.

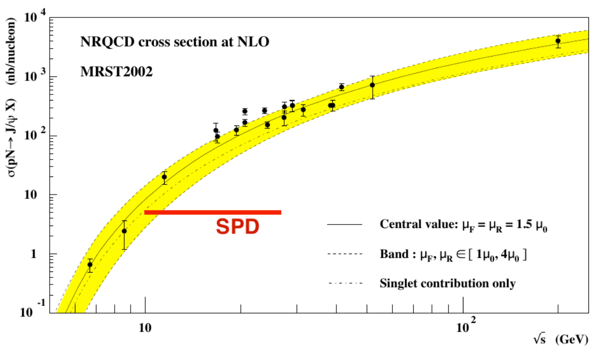

Figure 1. Inclusive J/ψ production cross-section as a function of $\sqrt{s}$ in proton-proton and proton-nucleon collisions from Ref. [5]. The SPD energy range is shown by the red line.

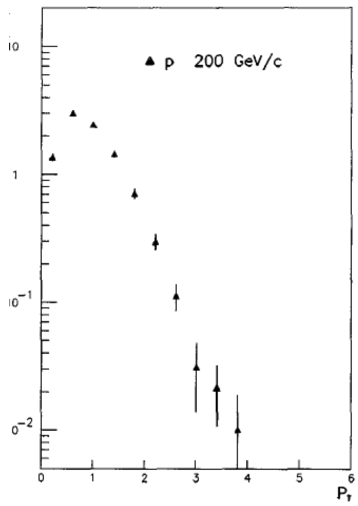

Figure 2. The p_T spectra of J/ψ measured by NA3 at $\sqrt{s} = 19.4$ GeV [6].

For the polarized beams, the PHENIX collaboration reported nonzero TSSA in the forward x_F region with statistical significance of 3.3σ based on data set of approximately 22,000 collected

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J/ψ events [11]. The indication of nonzero TSSA are also reported in a recent publication of this collaboration [12].

Decays of χ_{c1} and χ_{c2} are known to contribute about 30% of inclusive J/ψ events. These states are poorly known: their production cross-sections are measured with huge uncertainties and their polarization has not been measured yet. Their relative contribution to J/ψ decays is especially essential for validation of theoretical models but also remains quite uncertain. The known experimental results on the states at low energies are summarized in Ref. [13].

Production properties of $\psi(2S)$ at the SPD energies are unknown except for the total cross-section due to limitations of previous fixed-target experiments. Proton-nucleon experimental results are reviewed in Ref. [5] the production cross-section is about 15% of the one for J/ψ.

3. Charmonia production models

There are two contemporary models for inclusive J/ψ production: Color Evaporation Model (CEM) and Non-Relativistic QCD (NRQCD). In both models, charmonia state hadronizes from a perturbatively produced $c\bar{c}$ pair, but there is a notable difference in the hadronization process, number of free non-perturbative parameters and predicted observables. Both models are mostly used with the collinear factorization, which is assumed in the following review of models. As it will be discussed later, this factorization is not appropriate for SPD energies, so possible alternatives will be discussed later.

Before proceeding to description of the models, the difference in their predictions for the relative contribution the gluon-gluon fusion and quark-antiquark annihilation in the x_F spectrum is shown in Fig. 3.

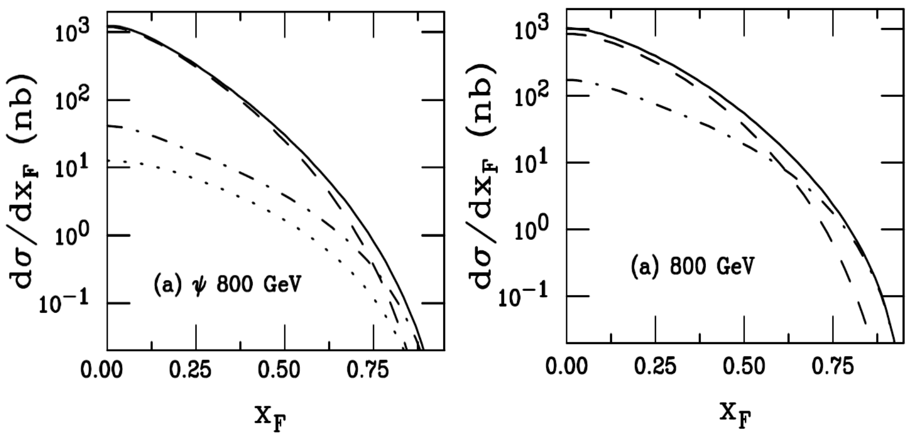

Figure 3. NRQCD (left) and CEM (right) predictions of x_F spectra in pp collisions at $\sqrt{s} = 39$ GeV from Ref. [8]. The dashed and dashed-and-doted lines show gluon-gluon fusion and quark-antiquark annihilation, respectively.

3.1. Color evaporation model

In CEM, production cross-section of a charmonia state is assumed to be proportional to the one of a $c\bar{c}$ pair with the invariant mass between $2m_c$ and the open charm threshold, where m_c is the mass of c-quark. In this model, the sum over colors (they are assumed to be neutralized by emission of soft gluons) and spins of the quark and antiquark is implied. Explicit formulas can be found e.g. in Ref. [8]. The proportionality coefficients for a given charmonium state are assumed to be process-independent. Despite its simplicity, this phenomenological model provides reasonably good descriptions of $\sqrt{s}$-dependence, $d\sigma/dx_F$ [14]. At NLO, it can also reasonably describe p_T distribution if k_T smearing is considered [15]. At the same time, the process independence of proportionality coefficients holds only approximately [15]. Even more importantly, the model predicts that all charmonia states have the same shape of kinematic distributions, which is not supported by experimental data [16].

3.2. NRQCD

The NRQCD [17] is more rigorous approach to charmonia production. It is based on two points, the first one is the factorization conjecture proven only for sufficiently high p_T. It assumes that for a charmonia state H the inclusive production cross-section on the parton level can be written as

$$\hat{\sigma}(ij \to H + X) = \sum_n C_n^{ij} \langle O_n^H \rangle.$$

Here indexes i and j denote interacting partons, X states for the rest of produced particles. The perturbative sort-distance coefficients (SDC) C_n^{ij} describe production of a $c\bar{c}$ pair in the state n (n denotes their relative momentum, spin alignment and color state) on the scale of $1/m_c$. Finally, the non-pertubative long-distance matrix elements (LDME) $\langle O_n^H \rangle$ describe hadronization of the produced $c\bar{c}$ pair to charmonia state H. An important consequence of this factorization is the process independence for LDME (e.g. in hadron collisions, photoproduction, e^+e^- annihilation). The second point is that there is a hierarchy of LDME $\langle O_n^H \rangle$ with respect to v ($v^2 \sim 0.2 - 0.3$) – typical velocity of heavy quark in the charmonium system. The color-octet LDME are obtained from fits to the data. The model predicts the full spectra of observables including J/ψ polarization. Verification of the LDME universality in different J/ψ production processes is one of the direct tests of NRQCD. The Ref. [18] reviews NLO NRQCD fits to different data sets, that include the p_T distribution in proton-proton collisions (ATLAS, CDF), the same distribution in photoproduction at H1, the polarization data (CDF) and the J/ψ production in e^+e^- annihilation at Belle showing that all available data sets can not be described simultaneously by one set of LDME. Inability to simultaneously describe p_T spectra and polarization may be related to the so-called "polarization puzzle" – NRQCD difficulties to describe the observed weak J/ψ polarization. One of the possible solutions to the puzzle is significant contribution of the feed-down decays. It is based on the observed difference in polarization between $\Upsilon(1S)$ and its radial excitations $\Upsilon(2S)$ and $\Upsilon(3S)$ measured by E866 [19]. For charmonia Ref. [20] suggests cancellation of χ_{c1} and χ_{c2} contributions as a possible explanation, while χ_{c1} production cross-section is usually strongly underpredicted in NRQCD. New experimental data on χ_{cJ} contributions and their polarization, as well as polarization measurements for $\psi(2S)$ are necessary to verify these ideas. Another problem of the reviewed fits can be fitting of low-p_T data, where collinear factorization may not be applicable (typically p_T spectra are fitted above 3 GeV or larger cut-off values).

3.3. Theoretical approaches for SPD

The p_T spectrum measured by NA3 at $\sqrt{s} = 19.4$ GeV (see Fig. 2) shows that typical transverse momentum of J/ψ at SPD is about 1 GeV/c and its maximum expected value is about 4 - 5 GeV/c. The description of this kinematics is challenging from the theoretical point of view and requires taking into account transverse momentum of partons. There are several approaches within the framework of NRQCD, that may be suitable for SPD. Firstly, it is Parton Reggeization Approach [21], which is capable of describing the whole J/ψ p_T spectra in high energy experiments and has preliminary predictions for SPD. Secondly, there is a set of works applying k_T-factorization to charmonia production (see Ref. [22] and following works of the authors). It is important to outline that both these approaches have nontrivial implications for other observables like J/ψ polarization. It has also been a recent attempt to significantly improve color evaporation model [23, 24]. Despite good p_T description, it fails to describe J/ψ polarization measured at HERA-B [10].

4. Study of charmonia at SPD

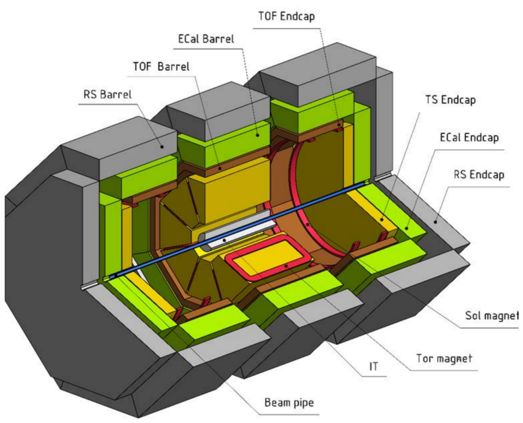

Figure 4. Possible set-up of SPD [25].

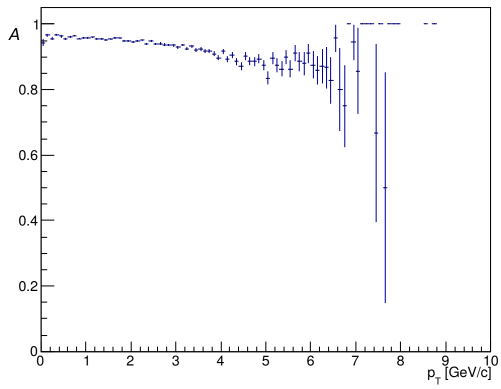

Figure 5. Detector acceptance for the J/ψ as a function of p_T.

The final detector set-up has not been completed yet (see Ref. [25] for the details and the designed performance). One of its possible configurations is shown in Fig. 4. The detector has close to 4π geometrical acceptance and consists of a vertex detector, a straw tracker, an electromagnetic calorimeter (ECAL) and a range system (RS) for muon identification. The magnet field is provided by the hybrid magnetic system, which is toroidal in the barrel part and solenoidal in the endcaps. The detector is expected to have an average momentum resolution of about 1–2% and the designed energy resolution of ECAL is $5\%/\sqrt{E}$. The experiment is expected to accumulate about 20 million J/ψ events during one year of smooth data taking.

The basic event simulation takes into account the magnetic field and the material map in the detector and is performed with the SPDRoot software. It shows that at the collision energy of 26 GeV more than 90% of muons produced in J/ψ decays reach RS. The detector acceptance for inclusive J/ψ events is defined as a relative fraction of events when both muons reaching RS. It is shown in Fig. 5 and Fig. 6 as a function of p_T and x_F, respectively. Keeping in mind the model fits from Fig. 3, one can expect SPD to cover the x_F region where the contribution of the quark-antiquark annihilation becomes strong or dominant.

The χ_{c1} and χ_{c2} are reconstructed from the $\gamma J/\psi$ decay mode. The detector has good acceptance for the decay photons and in about 80% of such events muons reach RS and the photon reaches ECAL and has energy above 100 MeV. Preliminary generator-level studies show that ECAL energy resolution may be sufficient to determine relative contributions of χ_{c1} and χ_{c2}. Fig. 7 shows simulated $\Delta M = M_{\mu^+\mu^-\gamma} - M_{\mu^+\mu^-}$ distribution for χ_{c1} and χ_{c2}. Here charged track momentum and photon energy smearing is introduced to simulate the detector response. The feasibility of the unique measurement of χ_{cJ} decays contribution to J/ψ polarization is unclear and will depend on the background.

5. Summary

Study of charmonia is a promising part of the SPD physics program. The designed experiment will be capable to significantly improve existing experimental knowledge of charmonia production

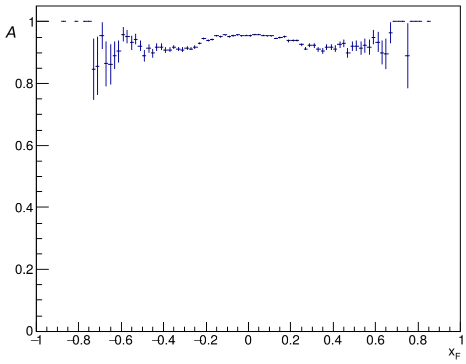

Figure 6. Detector acceptance for the J/ψ as a function of x_F.

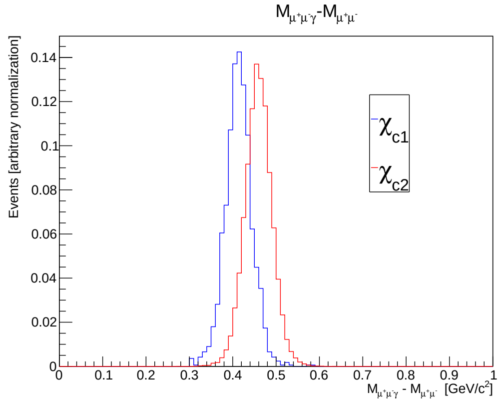

Figure 7. $\Delta M = M_{\mu^+\mu^-\gamma} - M_{\mu^+\mu^-}$ for χ_{c1} and χ_{c2}.

by providing precise and consistent measurement of its properties. For unpolarized beams, it is of a special interest for the χ_{c1}, χ_{c2}, and $\psi(2S)$ states. This experimental input would be crucial for the validation of theoretical models (like CEM and NRQCD) and proper factorization approaches at SPD energies. In case of polarized beams, the high statistics and good detector performance will allow for a precise measurement of spin asymmetries. In particular, SPD will be able to validate the evidence for nonzero TSSA reported by the PHENIX Collaboration. If a proper approach to charmonia production is found and validated, it will provide new and significant information on transverse structure of proton.

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