

# HEAVY QUARKONIUM PRODUCTION WITH POLARIZED HADRONS AND PHOTONS \*

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We investigate the inclusive production of prompt  $J/\psi$  mesons in polarized hadron-hadron and photon-hadron collisions in the factorization formalism of NRQCD. Numerical results are presented for BNL RHIC-Spin and the approved SLAC fixed-target experiment E161 to assess the feasibility to access the spin-dependent parton distributions in the polarized proton and photon. We point out that data on  $J/\psi$  production taken by the PHENIX Collaboration in unpolarized proton-proton collisions at RHIC tend to favor the NRQCD factorization hypothesis, while they significantly overshoot the theoretical prediction of the CSM.

## 1 Introduction

Before the advent of the non-relativistic QCD (NRQCD) factorization formalism, heavy quarkonium production with polarized proton or photon beams was believed to provide reliable information on the spin-dependent gluon distributions of the polarized proton or photon. At present, however, we are faced with the potential problem that NRQCD predictions at lowest order have a considerable normalization uncertainty due to the introduction of non-perturbative color-octet matrix elements, which were not present in the color-singlet model (CSM) and which also have to be extracted from experiment [1].

In order to clarify the question if heavy quarkonium production with polarized proton or photon beams remains to be a useful probe of the polarized gluon densities, we investigate inclusive  $J/\psi$  production in polarized  $pp$  and

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$\gamma p$  collisions at RHIC-Spin and E161. Other processes with the potential to constrain the polarized gluon distributions include the production of low-mass lepton pairs [2]. Numerical results relevant for  $J/\psi$  production in polarized  $\gamma\gamma$  collisions at DESY TESLA as well as a complete list of analytical results for all polarized partonic cross sections can be found in Ref. [3].

## 2 $J/\psi$ production at BNL RHIC-Spin and SLAC E161

At RHIC, proton beams with longitudinal polarization of approximately 70% collide with center-of-mass energy up to  $\sqrt{S} = 500$  GeV and luminosity  $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ . In E161, circularly polarized photons with energies between 35 and 48 GeV will collide on a fixed target made of longitudinally polarized deuterium [4]. In Figs. 1 and 2, NRQCD and CSM predictions for the

unpolarized cross sections  $d\sigma/dp_T$  and  $d\sigma/dy$  or  $d\sigma/dz$  are displayed in the first panel, while those for the double longitudinal-spin asymmetry  $\mathcal{A}_{LL}$  are shown in the second and third panels. The  $p_T$  distributions are integrated over the intervals  $|y| < 2.4$  and  $0.3 < z < 0.8$ , respectively, while the  $y$  or  $z$  distributions are integrated over all kinematically allowed values of  $p_T$  in excess of 15 and 1.5 GeV. The shaded bands indicate the theoretical uncertainties in the NRQCD and CSM default predictions. As our default polarized parton densities, we employ the GRStV-STD set in the proton and the GRSi-MAX set in the photon [5] (for a detailed discussion of our input parameters see [3]). We assume the ideal case of 100% beam polarization. Realistic polarization is accounted for by scaling  $\mathcal{A}_{LL}$  with  $[P(p)]^2$  and  $P(\gamma)P(D)$ , respectively.

At RHIC-Spin, the differences in  $\mathcal{A}_{LL}$  for various parton densities are large against the combined theoretical uncertainties from other sources, so that sufficiently precise measurements will increase our knowledge on the spin-dependent parton structure of the polarized proton. The NRQCD and CSM  $p_T$ -dependences incidentally almost coincide, so that the polarized proton densities can be explored in a model-independent fashion. On the other hand, the NRQCD and CSM predictions for the  $y$  distribution exhibit strikingly different shapes in the forward and backward directions.

At E161, the situation is less favorable since the theoretical uncertainties are larger, due to the low photon-nucleon center-of-mass energy  $\sqrt{S} = m_N(2E_\gamma + m_N) \approx 9.2$  GeV. This is especially the case for the NRQCD prediction shown

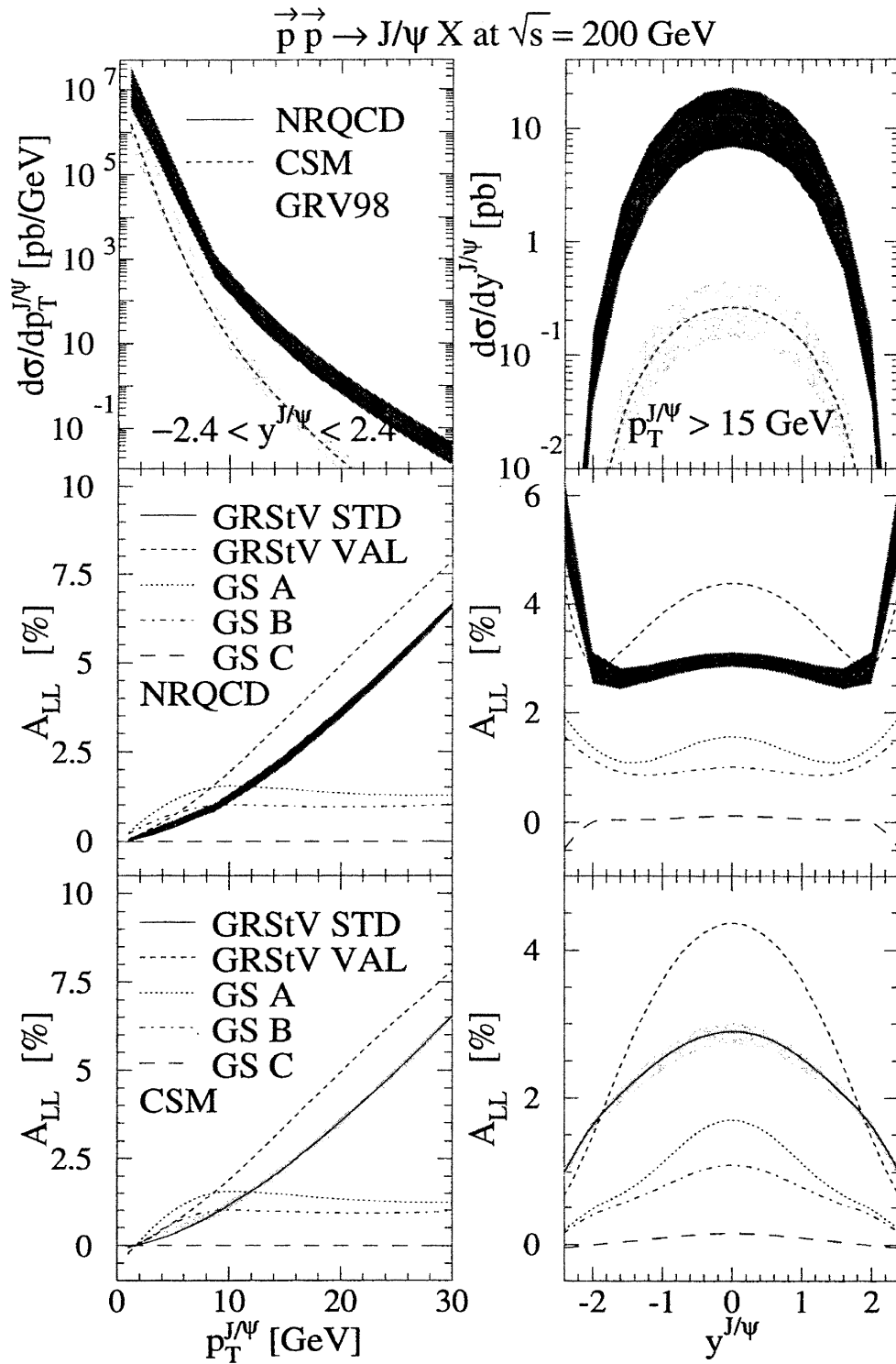


Figure 1: Cross sections  $d\sigma/dp_T$  and  $d\sigma/dy$  (first panel) and asymmetries  $A_{LL}$  (second and third panels) of  $pp \rightarrow J/\psi + X$  at RHIC-Spin with  $\sqrt{s} = 200$  GeV as functions of  $p_T$  (left) and  $y$  (right) in NRQCD and the CSM.

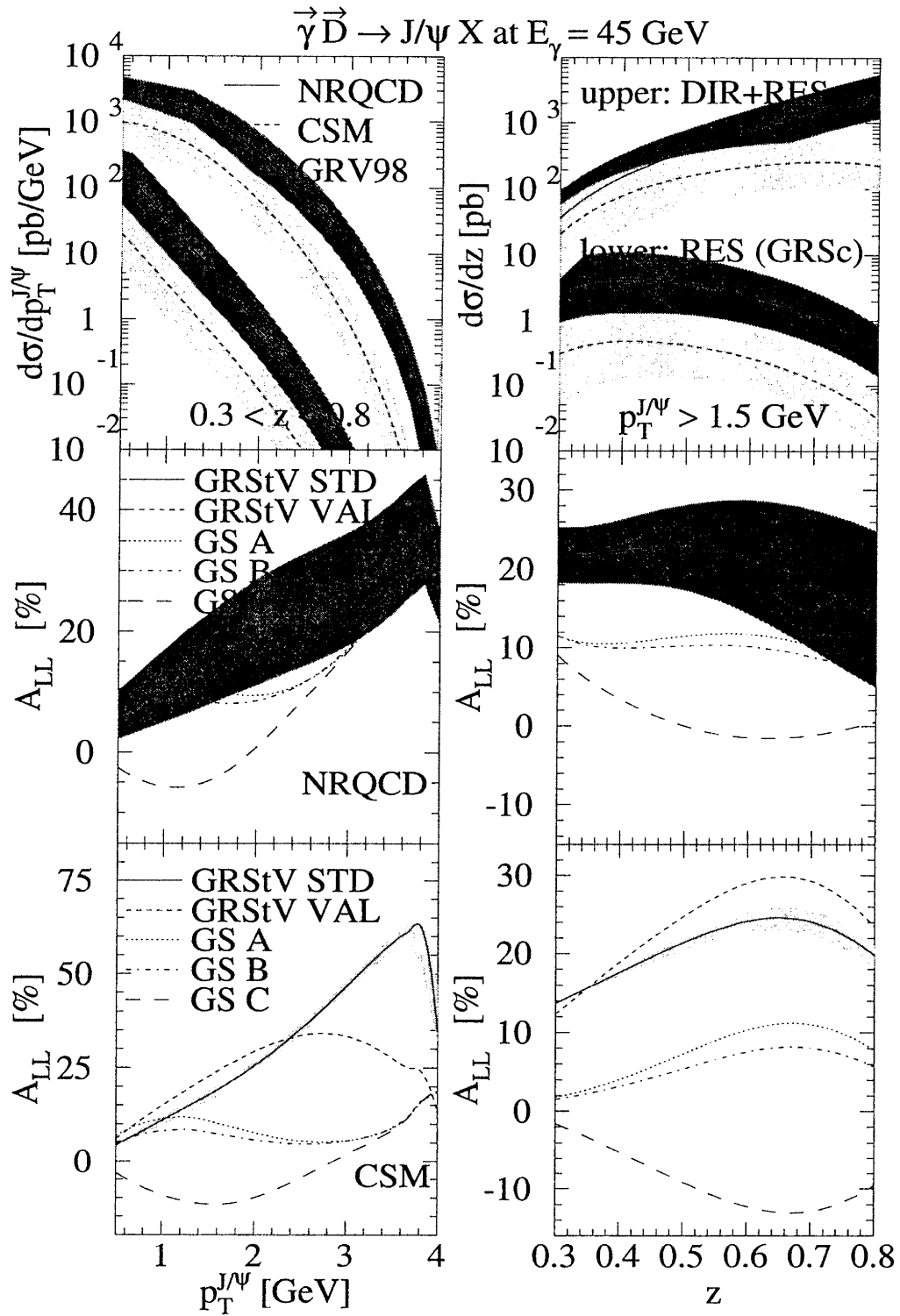


Figure 2: Same as in Fig. 1, but for  $\gamma D \rightarrow J/\psi + X$  at E161 with  $E_\gamma = 45$  GeV. Inelasticity  $z$  is used instead of rapidity  $y$ . In the first panel, the resolved-photon contributions are also shown separately.

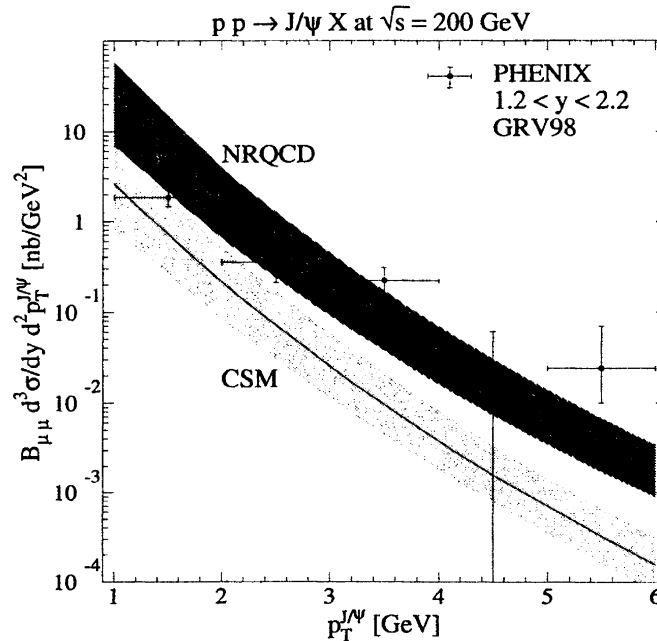


Figure 3: PHENIX data for  $B(J/\psi \rightarrow \mu^+\mu^-)d^3\sigma/dy d^2p_T$  at RHIC with  $\sqrt{S} = 200$  GeV and in the interval  $1.2 < y < 2.2$  as a function of  $p_T$  are compared with NRQCD and CSM predictions.

in the second panel of Fig. 2. Nevertheless, it should be possible to discriminate between the GRStV and GS sets. In the CSM, the resolving power of  $\mathcal{A}_{LL}$  used to be much better, as is evident from the third panel of Fig. 2. In this sense, the introduction of NRQCD, which was necessary to overcome phenomenological and conceptual problems of the CSM, led to some aggravation.

As can be seen from the first panels in Figs. 1 and 2, the normalization of the unpolarized cross section is a distinctive discriminator between NRQCD and the CSM. In fact, data from the PHENIX Collaboration [6] at RHIC, with  $\sqrt{S} = 200$  GeV, tend to favor the NRQCD prediction compared to the CSM one (see Fig. 3). Since the  $J/\psi$  mesons are tagged through their decays to  $\mu^+\mu^-$  pairs, the factor  $B(J/\psi \rightarrow \mu^+\mu^-) = (5.88 \pm 0.10)\%$  is included in the theoretical predictions. We observe that, for  $p_T > 2$  GeV, the data are nicely described by the NRQCD prediction, while they significantly overshoot the CSM one. In the bin  $1 \text{ GeV} < p_T < 2 \text{ GeV}$ , the comparison has to be taken with a grain of salt since the NRQCD prediction and the  $P$ -wave contribution to the CSM one suffer from infrared and collinear singularities at  $p_T = 0$ , which still feed into that bin as an artificial enhancement.

### 3 Summary

For inclusive production of prompt  $J/\psi$  mesons in polarized hadron-hadron and photon-hadron collisions at RHIC and E161, we found that the spread in the asymmetries for different parton densities in general considerably exceeds the combined theoretical uncertainties from other sources, which we estimated rather conservatively. Therefore, even within the NRQCD formalism these experiments have discriminative power w.r.t. the spin structure of the proton and photon. As a by-product, we found that PHENIX data of unpolarized hadroproduction of  $J/\psi$  mesons at RHIC favor NRQCD as compared to the CSM. This is in line with previous findings in  $pp$ ,  $\gamma p$ , and  $\gamma\gamma$  collisions [1, 7].

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