Feasibility study for the search of intrinsic charm 
at the COMPASS experiment 
and at the STAR fixed-target program

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Abstract

In this paper we conduct a feasibility study for the search of the intrinsic charm mechanism at the COMPASS experiment using the CERN $\pi^-$ beam at 190 GeV/c and at the STAR fixed-target program using the proton beam of the Relativistic Heavy Ion Collider (RHIC) at 200 GeV/c. We also re-review the double $J/\psi$ production data provided by the NA3 experiment using the CERN pion beam at 150 and 280 GeV/c with incident on hydrogen and platinum targets. The different production mechanisms are discussed.

1 Introduction

Almost four decades have passed since the intrinsic heavy quark mechanism was proposed \cite{1}, stating that heavy quarks are present in the proton’s wavefunction from the outset.

The existence of heavy quarks in the proton’s light-front (LF) wavefunction at a large LF momentum fraction $x$ is in fact predicted by QCD if one analyzes the higher Fock states $|uudc\bar{c}\rangle$ and $|uudc\bar{c}\bar{c}\rangle$ in the hadronic eigenstate, i.e., Fock states where the heavy quark pairs are multi-connected to the valence quarks. LF wavefunctions, the eigensolutions of
the QCD LF Hamiltonian, are defined at fixed LF time $\tau = t + z/c$ and are thus off-shell in the invariant mass. For example, in QED, positronium has an analogous Fock state $|e^+e^-\mu^+\mu^-\rangle$ due to the insertion of light-by-light scattering in the positronium self-energy amplitude. In such an “intrinsic charm” Fock state $|uudc\bar{c}\rangle$, the maximum kinematic configuration occurs at minimum invariant mass where all quarks are at rest in the hadron’s rest frame, i.e., at equal rapidity in the moving hadron. Equal rapidity implies $x_i \propto (m^2 + \vec{k}_i^2)^{1/2}$ for each quark, so that the heavy quarks in the Fock state carry most of the hadron’s LF momentum. The operator product expansion predicts that the probability of intrinsic heavy-quark Fock states $|uudQ\bar{Q}\rangle$ scales as $1/m_Q^2$ due to the non-Abelian couplings of QCD [2,3].

Even though there is no clear observation of the mechanism, the baryonic states $\Lambda_c(udc)$ and $\Lambda_b(udb)$ were both discovered at the Intersecting Storage Rings at high values of the Feynman momentum fraction $x_F$ [4–6]. The SELEX experiment provided the observation of a double charm baryon $|ccd\rangle$ at a large mean value for $x_F$ and a relatively small mean transverse momentum [7,8]. In addition, the NA3 experiment measured both the single-quarkonium hadroproduction $\pi A \rightarrow J/\psi X$ [9] and the double-quarkonium hadroproduction $\pi A \rightarrow J/\psi J/\psi X$ [10] at high $x_F$. In fact, all of the $\pi A \rightarrow J/\psi J/\psi X$ events were observed with a total value of $x_F > 0.4$. These results are even more surprising if taking into account the values of the ratio $\sigma(J/\psi J/\psi)/\sigma(J/\psi)$ measured at NA3 and the respective values measured at the DØ detector at Fermilab at $\sqrt{s} = 1.97 \text{TeV}$ and the LHCb detector at CERN at $\sqrt{s} = 7 \text{TeV}$ (cf. Table 1).

| Experiment | $\sigma(J/\psi J/\psi)/\sigma(J/\psi)$ | Beam/Energy |
|------------|------------------------------------|-------------|
| NA3        | $(3 \pm 1) \times 10^{-4}$         | $\pi^- A$, $p_{\pi^-} = 150, 280 \text{GeV}/c$ |
| DØ         | $\sim 5 \times 10^{-6}$            | $p\bar{p}$, $\sqrt{s} = 1.97 \text{TeV}$ |
| LHCb       | $(5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$ | $pp$, $\sqrt{s} = 7 \text{TeV}$ |

Table 1: Ratios $\sigma(J/\psi J/\psi)/\sigma(J/\psi)$ for the NA3 [10], DØ [11], and LHCb [12] experiments.
Figure 1: Partonic cross section for $Q\bar{Q}$ and $Q\bar{Q}Q\bar{Q}$ production [13]. The histograms show the exact leading-order results, i.e. the exact matrix elements integrated over the exact phase space. The coupling $\alpha_S$ is set to one. For the $c$-quarks ($m_c = 1.5$ GeV) we choose upper bounds for the rapidities of $Y < 3.4$ for NA3, $Y < 13$ for DØ, and $Y < 15.5$ for LHCb.

Actually, in perturbative QCD it is very unlikely that NA3 has measured the same production rate for double $J/\psi$ as the LHCb at $\sqrt{s} = 7$ TeV and a production rate of two orders of magnitude higher as measured by the DØ detector at Tevatron (cf. Fig. 1).

Indeed, as we show below, the NA3 kinematic features and the production rate can be a result of a misunderstanding of the detector acceptance.

Fortunately, the NA3 measurement can be complemented or disproved at the COMPASS experiment using the CERN $\pi^-$ beam at 190 GeV/$c$ and the STAR fixed-target program using the proton beam of the Relativistic Heavy Ion Collider (RHIC) at 200 GeV/$c$.

In this paper we discuss different production mechanism of $J/\psi$ pairs. Kinematic features and analysis strategies are also discussed.
In order to understand the NA3 data, we give a short overview over the layout of the NA3 detector (see Ref. [14] for a more complete description). The NA3 detector consisted of a spectrometer with fixed targets of liquid hydrogen (proton target, 30 cm long) and platinum (nuclear target, 6 cm long). The targets were separated by a distance of 45 cm.

For the measurements the NA3 experiment used the beams of $p$, $\bar{p}$, $K^\pm$, $\pi^\pm$ with intensities of $(3−5) \cdot 10^7$ particles per second. To reduce the particle flux through the spectrometer, a beam dump absorbing about 80% of the charged particle flux was installed behind the platinum target. The dump was made of a 1.5 m block of stainless steel and had a conical core made of tungsten and uranium. The aperture angle of the cone could be chosen as either 20 or 30 mrad. The stainless steel blocks surrounded the conical core of the dump. Along the beam behind the dump, other parts of the spectrometer were located such as a spectrometer magnet, tracking detectors, counter hodoscopes and trigger hodoscopes. At the end of the spectrometer an additional 1.8 m long iron absorber was placed which played the role of a muon filter and reduced the low energy particle background. Together with the other trigger hodoscopes, the trigger hodoscope placed behind the muon filter had the purpose to select muons originated from the targets. The trigger system imposed a condition on the vertical component of the transverse momentum of the muons. To be registered, a single muon had to satisfy the condition $p_T > 1$ GeV/$c$, while for two muons in the event one had to have $p_T > 0.6$ GeV/$c$ for each of the muons. Such requirements eliminated a large fraction of pion and kaon decays and rejected low mass resonances like $\rho$, $\phi$ and $\omega$ mesons.

In order to be registered, muons had to pass more than 3 m of iron. As charged particles, on this way they interacted with nucleons of the matter and spent some of their energy for ionization and radiative effects. For example, by passing through 3 m of iron a muon with energy of 150 GeV/$c$ looses more than 7.5 GeV of its energy. This leads to
an acceptance notion which mostly depends on the geometry of the setup, but also on the
kinematics of the particles.

The Monte Carlo approach to estimate the NA3 setup acceptance for the double \(J/\psi\)
production studies was based on the utilization of pairs of uncorrelated \(J/\psi\)'s. Such a
sample can give a good acceptance estimation for Double Parton Scattering but neither
for Single Parton Scattering nor for the Intrinsic Charm mechanism.

In the data analysis for single \(J/\psi\) selection a criterium \(x_1 - x_2 > 0\) was used for both
the 150 GeV and 280 GeV data samples. Here \(x_1\) and \(x_2\) are the Bjorken variables for pion
and nucleon, respectively. For \(x_1 - x_2 < 0\) the NA3 acceptance was dropping fast. It
means that \(J/\psi\) should had a minimal longitudinal momentum to pass the setup and to be
detected. For the 150 GeV beam this threshold was about 27 GeV/c, and 39 GeV/c for the
280 GeV beam. For the double \(J/\psi\) state these thresholds should be multiplied roughly
by two. Because the acceptance was dropping down near the threshold, there was a low
probability to detect an event with a momentum close to the threshold (Fig. 2).

This means that it is not possible to detect a double \(J/\psi\) state with \(x_F < 0.4\) for
150 GeV and with \(x_F < 0.3\) for 280 GeV since low energy muons will either be absorbed
by the matter of the setup or rejected by the trigger. In addition, because of the dropping
of the acceptance, events detected \textit{de facto} by NA3 have values of \(x_F\) larger than the
thresholds for both data samples.

3 Revisiting double \(J/\psi\) production at NA3

Using the CERN pion beam at 150 and 280 GeV/c to produce charm particles with incident
on hydrogen and platinum targets, the NA3 experiment provided data on the production
of the double \(J/\psi\) with the respective production cross sections of \(18 \pm 8\) pb and \(30 \pm 10\) pb
per nucleon and the ratio \(\sigma(J/\psi J/\psi)/\sigma(J/\psi) = (3 \pm 1) \times 10^{-4}\) at both energies.
3.1 $\sigma(J/\psi J/\psi)$ production via Single Parton Scattering

With a special choice of parameters, in Ref. [15] it was found that most of the measured cross section is due to $q\bar{q} \rightarrow J/\psi J/\psi$. However, as mentioned above, such a high production rate is unexpected at NA3 energies. Therefore, it is interesting to analyze the production rate instead of the double $J/\psi$ production cross section.

The production cross section of the quarkonium can be obtained as an application of the quark–hadron duality principle known as color evaporation model (CEM) [16]. In this model the cross section of quarkonium was obtained by calculating the production of a $Q\bar{Q}$ in the small invariant mass interval between $2m_Q$ and the threshold to produce open heavy-quark hadrons, $2m_H$. The $Q\bar{Q}$ pair has $3 \times 3 = (1 + 8)$ color components, consisting of a color-singlet and a color-octet. Therefore, the probability that a color-singlet is formed and produces a quarkonium state is given by $1/(1 + 8)$, and the model predicts

$$\sigma(Q\bar{Q}) = \int_{2m_Q}^{2m_H} dM_{Q\bar{Q}} \frac{d\sigma_{Q\bar{Q}}}{dM_{Q\bar{Q}}} ,$$

where $\sigma_{Q\bar{Q}}$ is the production cross section of the heavy quark pairs and $\sigma(Q\bar{Q})$ is a sum.
of production cross sections of all quarkonium states in the duality interval. For example, in case of charmonium states one has \( \sigma(Q\bar{Q}) = \sigma(J/\psi) + \sigma(\psi(2S)) + \ldots \). According to a simple statistical counting, the fraction of the total color-singlet cross section into a quarkonium state is given by

\[
\sigma(X) = \frac{1}{9} \cdot \rho_X \cdot \sigma(Q\bar{Q})
\]

(\( X = J/\psi, \psi(2S), \ldots \)) with

\[
\rho_X = \frac{2J_X + 1}{\sum_i (2J_i + 1)},
\]

where \( J_X \) is the spin of the quarkonium state \( X \) and the sum runs over all quarkonium states. In case of the \( J/\psi \) meson the calculation gives

\[
\rho_{J/\psi} \approx 0.2.
\]

These formulas can be easily generalized to the calculation of the production of double quarkonium,

\[
\sigma(J/\psi J/\psi) = \frac{1}{99} \rho_{J/\psi} \rho_{J/\psi} \cdot \sigma(c\bar{c} + c\bar{c}).
\]

Using the NA3 rate it is easy to estimate that

\[
\frac{\sigma(c\bar{c} + c\bar{c})}{\sigma(c\bar{c})} > 10^{-2}.
\]

Even making the unrealistic assumption that all \( c\bar{c} \) pairs in \( \sigma(c\bar{c} + c\bar{c}) \) are lying in the duality interval, the production rate seems to be absolutely untrusted.

The fact that the double \( J/\psi \) cross section at NA3 is the same order of magnitude as the respective single parton scattering value \( \sigma_{SPS}(J/\psi J/\psi) \sim 20 \text{ pb} \) \footnote{1} measured by the DØ collaboration, causes even more skepticism.

### 3.2 \( \sigma(J/\psi J/\psi) \) production via Double Parton Scattering

The significance of the double parton scattering (DPS) in associate charmonium production has been investigated by the Tevatron and the LHC by measuring the productions of
$J/\psi + W^{[17]}$, $J/\psi + Z^{[18]}$, $J/\psi + \text{charm}^{[19]}$, and $J/\psi + J/\psi^{[11,12,20,22]}$. Therefore, it is interesting to investigate a possible contribution of such a mechanism to the NA3 data on double $J/\psi$ production.

As we expect, one obtains a small difference in the momentum distribution between the $J/\psi$ for the SPS mechanism and a higher momentum gap for DPS. It is interesting to investigate the DPS signal in such kinematic distributions (cf. Fig. 3).

We can see that the data are present only in the area where the main statistics for the Single Parton Scattering mechanism is expected. As we discussed above, on the other hand side the acceptance excludes the small Feynman-$x$ region as the result is strict in the $\Delta x_F$ region. We also can see that the data density is distributed equally around the $\Delta x_F$ region which is more preferable for the Double Parton Scattering.

3.3 $\sigma(J/\psi J/\psi)$ production via the Intrinsic Charm mechanism

The production of double $J/\psi$ is discussed in detail in Refs. [26, 27]. Let us only remind the reader that perturbative QCD and intrinsic charm contributions have principally both different slopes and different regions where the main statistic is expected (cf. Fig. 4) [28]. Based on these distributions, in Ref. [27] it was proposed that all the NA3 data came from the intrinsic charm mechanism.

3.4 Concluding remarks on the $\sigma(J/\psi J/\psi)$ production

As we have learned from the analysis above, the NA3 measurements on the production of pairs of $J/\psi$ mesons are puzzling and do not allow a simple interpretation. It is definitely interesting to reproduce such measurements at modern experiments with higher statistics.

As it has been demonstrated, the slope of the Feynman-$x$ distribution can separate the effect of the intrinsic heavy quark mechanism from those of the Single and Double Parton Scattering mechanisms. In case of SPS+DPS dominance, the distribution for $\Delta x_F =$
Figure 3: The upper panels show $\Delta x_F$ distributions for the DPS and SPS production mechanisms at the 150 GeV/c (left panel) and at the 280 GeV/c $\pi$ beam (right panel). The DPS is obtained in Pythia 8 [23], and the SPS is obtained in HELAC-Onia [24, 25]. The bottom panels shows $\Delta x_F$ distributions from the NA3 data at the 150 GeV/c (left panel) and at the 280 GeV/c $\pi$ beam (right panel).
Figure 4: NA3 events (shaded area), pQCD prediction [15] (blue left curve) and prediction of the heavy quark mechanism (red right curve) at the 150 GeV/c (left panel) and at the 280 GeV/c π beam (right panel).

\[ x_1(J/\psi) - x_2(J/\psi) \]

where \( x_1(J/\psi) \) and \( x_2(J/\psi) \) are the Feynman-x for the two \( J/\psi \) mesons, can separate SPS and DPS from each other.

4 Double \( J/\psi \) production at the COMPASS experiment and the STAR fixed-target program

4.1 The COMPASS experiment

COMPASS, a fixed target experiment at CERN, uses the high intensity \( \pi^- \) beam of 190 GeV at the Super Proton Synchrotron (SPS) at CERN for Drell–Yan (DY) measurements, producing charmonium, possible exotic states and dimuons in the set of polarized targets [29]. The experiment had several DY runs in 2014, 2015 and 2018. The COMPASS DY configuration setup is quite similar to the NA3 setup. It uses two cylindrical cells (of 55 cm length and 4 cm in diameter each) of ammonia as a target and a hadron absorber to reduce the particle flux through the setup. The absorber made of alumina and stainless
steel with the central tungsten plug is placed downstream of the target. The outgoing charged particles are detected by two spectrometers (Large Angle Spectrometer and Small Angle Spectrometer). At each spectrometer, the muon identification was accomplished by a system of muon filters. To be detected, at least two muon candidates from the target region should hit the trigger hodoscopes of the first spectrometer \(25 < \theta_{\mu} < 160 \text{ mrad}\), or one should hit the trigger hodoscopes of the first and the other the trigger hodoscopes of the second spectrometer \(8 < \theta_{\mu} < 45 \text{ mrad}\). A muon passed through the peripheral part of the absorber and the material of one of two muon filters (stainless steel or concrete) loses an energy of about 10 GeV, defining the lower limit for its reconstruction.

As the COMPASS has similar detector setup as the one at NA3, we can estimate that double \(J/\psi\) events detected by COMPASS should have \(x_F > 0.3\) as threshold. Therefore, COMPASS can give a significant contribution to the understanding of the double \(J/\psi\) production mechanisms. In 2015 the COMPASS collaboration collected about one million of dimuon events \[30\], and a factor of at least 1.5 more statistics is expected in the 2018 run \[31\]. The \(x_F\) and \(\Delta x_F\) distributions for the COMPASS kinematics and for the different
Figure 6: Prediction for the $x_F$ distributions for SPS, DPS and the intrinsic charm production mechanisms (left panel), and for the $\Delta x_F$ distribution for SPS and DPS (right panel) in case of the STAR experiment.

production mechanisms are shown in Fig. [5].

4.2 The STAR fixed-target program

The STAR fixed-target program is a fixed-target experiment using the proton beam of the Relativistic Heavy Ion Collider (RHIC) with up to 250 GeV/$c$ and the Au beam with up to 100 GeV/$c$ colliding with a wired target [32]. The $x_F$ and $\Delta x_F$ distributions for the different production mechanisms are shown in Fig. [6]. As we can see, at the energies of the STAR fixed-target program there is no such clear difference in the $\Delta x_F$ distributions between the SPS and DPS mechanisms. Still it is possible to estimate the DPS contribution using the experimentally known $J/\psi$ production cross section and $\sigma_{\text{eff}}$.

In contrast to the NA3 and the COMPASS detectors, the STAR detector does not include any absorbers in its setup. Therefore, it provides access also to small values of Feynman-$x$. Therefore, STAR is able to search for the production of charmed particles nearly at rest as predicted by the intrinsic charm mechanism (cf. discussion in Refs. [28,33]).
4.3 The SMOG fixed-target program at the LHCb

The SMOG fixed-target program is a fixed-target experiment using the LHCb detector and utilizing the LHC proton or nucleus beams to produce particles in proton–nucleus and nucleus–nucleus collisions on various targets with $\sqrt{s}$ up to 110.4 GeV [34].

Recently the LHCb published the first measurement of charm production in the fixed-target mode [35]. The LHCb provided data on the production of $J/\psi$ and $D^0$ mesons with beams of protons of different energies colliding with gaseous targets of helium and argon with nucleon-nucleon centre-of-mass energies of $\sqrt{s} = 86.6$ GeV and 110.4 GeV, respectively. The $J/\psi$ and $D^0$ production cross-sections in pHe collisions in the rapidity range [2, 4.6] are found to be $652 \pm 33 \text{(stat)} \pm 42 \text{(syst)}$ nb per nucleon and $80.8 \pm 2.4 \text{(stat)} \pm 6.3 \text{(syst)}$ µb per nucleon.

The production of the double quarkonium via the Single Parton Scattering and the Double Parton Scattering mechanisms is investigated in Ref. [36], while the production via the Intrinsic Charm mechanism is investigated in Ref. [26].

Even though the LHCb does not have access to the high Feynman-$x$ region or to rapidities less than 2 where the main contribution of the Intrinsic Charm mechanism is expected, it would be still interesting if the LHCb provides the double $J/\psi$ production cross section at small Feynman-$x$ values.

5 Summary

In this paper we discussed the opportunity to observe a signal of the intrinsic charm mechanism at the COMPASS experiment by using the CERN $\pi^-$ beam at 190 GeV/$c$, and at the STAR fixed-target program by using the proton beam of the Relativistic Heavy Ion Collider (RHIC) at 200 GeV/$c$. We also discussed a possible contribution of the Double Parton Scattering mechanism, and we demonstrated that the NA3 results on the production of the pairs of $J/\psi$ mesons are not fully trustable and do not allow for a clear interpretation.
In the end, let us to remind the reader that utilizing the CERN proton beam at 400 GeV/c with incident on a platinum target, the NA3 experiment provided a measurement of the double $J/\psi$ production cross section of $27 \pm 10$ pb per nucleon $^{[37]}$. Using the measurements of the NA50 collaboration for $Br(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(pA \rightarrow J/\psi)$, given by $3.791 \pm 0.019$ nb per nucleon at tungsten and $3.715 \pm 0.016$ nb per nucleon at lead targets with a 400 GeV/c proton beam $^{[38]}$ and taking into account $Br(J/\psi \rightarrow \mu^+\mu^-) = (5.961 \pm 0.033)\%$ $^{[39]}$ we can estimate $\sigma(J/\psi J/\psi)/\sigma(J/\psi) \sim 4 \times 10^{-4}$. This value is comparable to the ratio $\sigma(J/\psi J/\psi)/\sigma(J/\psi)$ measured by the NA3 collaboration with pion beams at 150 GeV/c and 280 GeV/c, but it cannot be explained with the quark-antiquark annihilation as leading process.

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