A study on the feasibility of a precise measurement of the \( \tau \)-dependence of the cross sections for Drell-Yan experiments at moderate energies

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Recently, a reconsideration of Drell-Yan cross sections at moderate energies and masses has suggested the possibility of relevant enhancements of the cross sections in some kinematical regions. If confirmed, these predictions could largely affect the planning of Drell-Yan experiments aimed at transverse spin measurements after 2010. More in general, the problem is present of a precision measurement of the \( \tau \) dependence of Drell-Yan cross sections. Here we discuss the feasibility of such a measurement within short time at the COMPASS apparatus, and its relevance for the PANDA experiment.

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I. INTRODUCTION

In a recent series of papers\(^1\) detailed Montecarlo studies have been produced for Drell-Yan \( \mu^+\mu^- \) experiments at moderate center of mass energies and dilepton masses (\( S \sim 30-400 \text{ GeV}^2, \ M < 12 \text{ GeV}/c^2 \)). These experiments would measure unpolarized, single and double spin asymmetries and include proposals and plans at GSI\(^2\), RHIC\(^3\), and at COMPASS\(^4\).

For the following discussion the relevant variables are the squared center of mass energy \( S \), the parton longitudinal fractions \( x_1 \) and \( x_2 \), the dilepton mass \( M \), and \( \tau \equiv M^2/S = x_1 x_2 \). At magnitude level

\[
\frac{d\sigma}{dx_1 dx_2} \sim N \frac{f(x_1)f(x_2)}{S\tau}.
\]

For the cases considered here \( N \) can be 1 nbarn or smaller. The product \( f(x_1)f(x_2) \) is a symbolic way to represent a bilinear combination of partonic distribution functions, that decreases fastly towards zero for \( x_1, x_2 \) or \( \tau \gg 0.1 \).

According to the above equation we have small overall event rates, fastly decreasing at increasing \( \tau \); However, all transverse spin related measurements require one or both of the longitudinal momentum fractions in the valence region, corresponding to average \( \tau \) values that cannot be too small.

In a recent publication\(^5\) the cross sections for Drell-Yan \( \mu^+\mu^- \) production in the kinematical ranges relevant for the quoted experiments has been reconsidered, with resummation of soft gluon emissions near the partonic threshold \( \tau = 1 \), rising the cross sections in a \( \tau \)-dependent way. The effect is predicted to be huge for \( \tau \sim 1 \), but present anyway, and sometimes strong, also for \( \tau \ll 1 \). If compared to the numbers by\(^\text{ref.}\), the enhancement factors can range from 2 to over 10 in regions that are relevant for the quoted experimental proposals at \( S < 300 \text{ GeV}^2 \) (for \( S = 300-500 \text{ GeV}^2 \) the cross sections are fixed by experimental data, see e.g.\(^\text{ref.}\)).

If the predictions of ref.\(^\text{ref.}\) are respected, several plans for quantities to be measured at GSI could be reconsidered. This makes an experimental confirmation of the prediction, if possible, an urgent matter. Apart for competing predictions, it would be useful to establish the \( \tau \)-dependence of the cross sections as precisely as possible.

In our opinion this confirmation is possible within a few years with the COMPASS hadronic beam facility\(^6\), using a pion beam at 50 GeV/c. The measurement is rather tricky. The predicted cross section enhancements can arrive to a factor 2, but at relatively large \( \tau \), where events are few. When the cross sections are integrated over a large mass range (equivalently, \( \tau \) range) these enhancements are much less evident.

Here a Montecarlo simulation is organized to study the proposed measurement at COMPASS, and also the case of the PANDA experiment\(^7\) at GSI, where the effect is expected to be especially strong. The Montecarlo apparatus is the same as described in ref.\(^\text{ref.}\), so all the related details can be found in that group of references. K-factors (i.e. overall \( \tau \)-dependent factors renormalizing the cross sections) have been rewritten so that cross section values follow alternatively the behavior predicted in refs.\(^\text{ref.}\) and\(^\text{ref.}\).

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II. THE SIMULATION

For COMPASS we consider (negative) pion-nucleon Drell-Yan with $S = 100$ GeV$^2$. We assume that the measurement is performed on a fixed target with $Z/A = 0.5$. We produce 50,000 simulated events for $4 < M < 9$ GeV/$c^2$, $x_F > 0$ and $1 < P_T < 3$ GeV/$c$. This means about 35,000 events in the lower mass bin 4-5 GeV/$c^2$. The cut $x_F > 0$ is related with the strong possibility that fixed target experiments have reduced acceptance for negative $x_F$ (see e.g. the event scatter plot in ref.[8]). The $P_T$ cutoffs are related with the selection of Drell-Yan events in strict sense (see the discussions in ref.[1]). We perform the simulation both for the case of “normal” cross sections, and with the enhancement factors shown in ref.[7]. So we will speak of “enhanced” and “non enhanced” data sets.

Defining $\Delta M$ as the overall mass range, we divide it into 5 equal subranges, and compare the simulated event population of the larger mass bins with the population of the lowest mass one. Since the populations of the lower mass bins are practically equal in the enhanced and non enhanced cases (about 35,000 events), we may limit ourselves to studying the populations of the upper mass bins. The underlying necessary assumption is that these populations are extracted from well normalized samples of 50,000 events.

For each case (enhanced and non-enhanced cross sections) the simulation is repeated ten times, so that for each mass bin we may calculate the average number of events and its fluctuation. The results are shown in fig.1. In figs. 2 and 3 we show the laboratory angle and energy distributions, useful for the discussion on the feasibility of the measurement.

![Graph showing event mass distribution](image)

**FIG. 1: COMPASS: Event mass distribution for enhanced (triangles) and non-enhanced (circles) cross sections;**

Fig.1 shows a delicate but interesting situation. In the last three mass ranges (6-7, 7-8, 8-9 GeV/$c^2$) the average event numbers are, in the enhanced vs non-enhanced cases:

- $3300 \pm 60$ vs $2443 \pm 57$
- $734 \pm 20$ vs $432 \pm 19$
- $97 \pm 9$ vs $43 \pm 8$

The statistical fluctuation is small enough to separate clearly the two possible outcomes in each mass bin. The very last mass bin contains a too small event number, so we forget about it and focus the rest of our analysis on the mass bin 7-8 GeV/$c^2$. The conclusions are valid for the mass bin 6-7 GeV/$c^2$ as well.

The errors in the evaluation of the relative populations of the higher mass bin (7-8 GeV/$c^2$) to the lower mass bins (4-5 GeV/$c^2$) may arise from two sources especially:

1) The background of random coincidence events with large mass, that in the case of a pion beam is due to coincidence between a beam halo muon with large energy and a collision-originated muon with small energy. The estimation of the fraction of “wrong” pairs in real experiments is normally based on the examination of like-charge pairs. According to the analysis in ref.[8]($S \approx 470$ GeV$^2$), and ref.[8]($S \approx 250$ GeV$^2$), this noise is not a problem
FIG. 2: COMPASS: Upper panel: Laboratory polar angle distribution for (mixed) positive and negative muons for pair invariant mass in the range 4-5 GeV/c². Lower panel: the same for mass in the range 7-8 GeV/c².

FIG. 3: COMPASS: Upper panel: Laboratory energy distribution for (mixed) positive and negative muons for pair invariant mass in the range 4-5 GeV/c². Lower panel: the same for mass in the range 7-8 GeV/c².

since (i) the background falls as steeply as the true data frequency at increasing masses, (i) it remains at least one order of magnitude below data.

2) The precision by which the relative acceptances for large and small mass events is estimated. This is potentially a problem if muons associated with large and small mass events distribute very differently in the laboratory frame phase space.

Section 4 of ref.[9] is devoted to a detailed study of the acceptance, for a π⁻-nucleus Drell-Yan experiment that presents some analogies with the COMPASS case. They show a flat efficiency in dilepton-track reconstruction for
FIG. 4: PANDA case: event mass distribution for enhanced (triangles) and non-enhanced (circles) cross sections; The large error bars in the second and third point are related with uncertainties in the prediction of the $J/\psi$ production rate.

mass up to 6.8 GeV/$c^2$. The case of larger masses is not shown.

In fig.2 we show the distribution of single muon polar angles in the (fixed target) laboratory reference frame. These muons belong to simulated Drell-Yan events in the above Compass conditions (without distinguishing between positive and negative muons). The upper panel reports the distribution of 10,000 events belonging to the dilepton mass region 4-5 GeV/$c^2$, the lower panel an equal number of events belonging to the mass region 7-8 GeV/$c^2$. Despite there are differences, the two distributions are similar enough to exclude problems related with differential angular acceptance.

In fig.3 we show the corresponding distributions for the muon laboratory energy. In this case there are important differences, but the major point is that both distributions assume non-negligible values in a large fraction of all the available energy phase space. An examination of the $\mu^+\mu^-$ correlations shows that for each event $E_+ + E_- \approx \text{constant}$ (34 ± 7 GeV in the lower mass range, 45 ± 4 GeV in the higher mass range) with a strong level of energy asymmetry $A_E = 2|E_+ - E_-|/(E_+ + E_-)$. In both cases $A_E$ follows an approximate distribution $1 + 1.4(A_E)^2$ meaning that most events concentrate towards larger energy asymmetry.

The above analysis means that identifying a dilepton pair requires, at small as at large masses, a good and well understood acceptance level throughout all the energy range, since the typical pair includes both a low-energy and a high-energy muon. A lack in this sense can decrease seriously the acceptance, but does not necessarily discriminate pairs with different masses.

To better estimates the potential errors introduced by ignorance about energy acceptance, we simulate a really extreme situation: we suppose that the acceptance for single muons with energy $< 20$ GeV is reduced by 50 % and one is not aware of this. In other words, one is convinced that the apparatus acceptance is $\approx 1$ at all energies, but this is true for $E > 20$ GeV only. In this case the fraction of silently lost pairs is

49 % in the low mass range, 46 % in the high mass range.

Things are worse in the opposite case (the acceptance is reduced to 50 % for energy $> 20$ GeV, and one is not aware of this). Now the fraction of lost pairs is

40 % in the low mass case, 51 % in the high mass case.

So, the lack of knowledge about true acceptance would lead to an error 20 % in the estimation of the relative population of the two mass bins. The proposed examples are really pessimistic ones, since normally acceptance is reconstructed with far larger precision than this. Despite this, also in these situations the event ratio reconstruction is precise enough to estimate the searched enhancement factor.

For PANDA (GSI) we consider $\bar{p}p$ Drell-Yan with $S = 30$ GeV$^2$, in the mass range 2-4.5 GeV$^2$. The other cuts are the same as for the COMPASS case. To avoid influence by the $J/\psi$ region on the event normalization, we normalize the collected data set with the requirement: 40,000 events in the mass range 2-2.5 GeV/$c^2$. For masses between 2.5 and 3.5 GeV/$c^2$ we base the simulation on Drell-Yan data by ref.\[10\] at large $x_F$, where gluon-gluon $J/\psi$ production
is partially suppressed as it would happen at PANDA. This still leaves room for a large uncertainty factor in the $J/\psi$ production rates (see fig.4). We assume the threshold enhancement to be the same for the $J/\psi$ peak and for the background. As evident from fig.4, for masses over 3.5 GeV/c$^2$ event numbers increase by one order and there is no doubt on the benefit PANDA would receive from the enhancement.

To summarize, the threshold enhancement can be verified with satisfactory precision in the COMPASS apparatus for pion beams. The enhancement would be much more striking at PANDA (GSI), with large increases in the counting rates at masses $> 3.5$ GeV/c$^2$.

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