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The combinatorial background of muon pairs in COMPASS

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Abstract. In 2018 the COMPASS experiment measured the pion-induced Drell-Yan process. The experiment detected pairs of muons that fell within the acceptance, but, aside from the Drell-Yan process, other contributions must be taken into account in the analysis of those muon pairs. In this study, a model of the combinatorial background of muon-antimuon pairs produced during the COMPASS measurement is evaluated. In order to obtain this model, the distributions of like-sign muon pairs collected simultaneously with the opposite-sign ones are analyzed. Moreover, this analysis includes a preliminary event selection process required for implementing the model and improving data quality.

Keywords: Drell-Yan, combinatorial background, dimuons, like-sign muon pairs.

1 Introduction

1.1 The COMPASS Experiment

The Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) at CERN is a multipurpose experiment whose main aims involve hadron spectroscopy and the study of the internal structure of nucleons ([1]). In order to achieve these goals, COMPASS went through different phases of data-taking from 2002 to 2022: in this article, the focus will be on the 2015-2018 phase when the muon-pairs from Drell-Yan (DY) process and J/ψ production were measured. To compensate for the low Drell-Yan cross-section, a high-intensity beam of π^- at 190 GeV/c was used.
The experimental setup used for this research is shown in Figure 1.

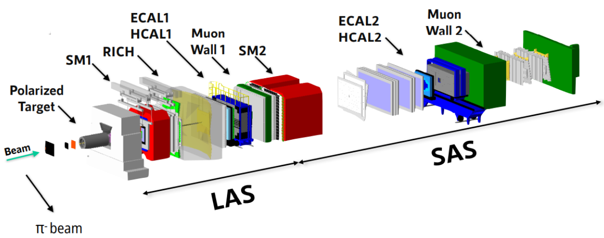

Figure 1. Setup of the COMPASS experiment for studying the Drell-Yan process.

Among the various components of this experiment (described more widely in [2]), an insight into the targets and the spectrometers in use may be useful for the analysis described in this article.

Targets

The targets include two cells of transversely polarized NH_3, with opposite polarization periodically inverted to reduce systematic errors, kept at a temperature of 60 mK, to preserve the spin configuration. Each of the two horizontal cells is 55 cm long.
Moreover, two unpolarized targets, made of ^{27}Al and ^{184}W, give the possibility to study the nuclear dependence of the non-polarized DY process. They are placed at the core of a hadron absorber located immediately downstream of the polarized target. The tungsten target serves both as beam-plug and as a heavy nuclear target (see also [3]).

Spectrometer

The setup includes a two-stage spectrometer used to fulfill the requirements imposed by the physics in this experiment, in particular the necessity of tracking particles scattered over a wide range of angles and momenta. Downstream of the target, the Large Angle Spectrometer (LAS) and the Small Angle Spectrometer (SAS) can be found. This setup provides large angle and momentum acceptance: LAS is designed to detect particles at large angles and smaller momenta whereas SAS detects particles at small angles and with higher momenta.
The spectrometer includes many detectors for tracking the particles, calorimeters, and trigger hodoscopes. These hodoscopes create the trigger signal in a small time window (of the order of a few ns) by finding coincidences: two "simultaneous" hits per muon at the hodoscope pair of a trigger system, corresponding to activated strips that roughly point to the target region. This trigger system helps reduce the amount of data collected during the experiment and will be used to analyze separately the muon pairs that fire different dimuon trigger systems.

1.2 Drell-Yan process

One of the main processes studied in this experiment is the Drell-Yan. This process occurs when two hadrons collide at high energy. A quark-antiquark annihilation occurs,

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with the production of a virtual photon, $\gamma*$, that decays into a lepton-antilepton pair.

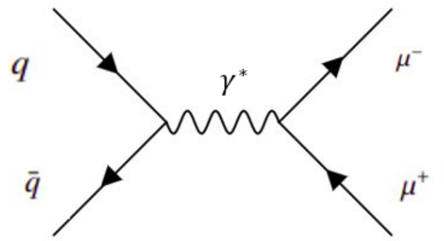

Figure 2. Feynman diagram of the Drell-Yan process: the collision of hadrons from the beam and the target results in a quark-antiquark annihilation which produces a virtual photon that decays into a muon-antimuon pair, the only case considered in this article.

In the experiment, the muon-antimuon pairs (also referred to as dimuons later on) that fall within the acceptance are detected. Besides the Drell-Yan, other physics mechanisms may occur that have the same decay products, such as open-charm, J/ψ, and ψ' production and they overlap for some mass ranges. Nevertheless, those muon pairs with a mass between 4.3 and 8.5 GeV/c^2 provide a relatively pure Drell-Yan sample.

1.3 Combinatorial Background

Besides the various physics processes contributing at low dimuon invariant masses, another source of muon pairs must be considered in the analysis of reconstructed events, the random combinations of uncorrelated muons. Since they are close enough in time and space, they can be reconstructed as coming out of the same vertex. Furthermore, their amount can be estimated using the number of appearances of another type of pairs, the like-sign muons that are in the same conditions as the opposite-sign pairs (close enough in time and space), being seen as coming out of the same vertex. The combinatorial background is described according to the following expression ([4]):

$$N^{+-} = 2\sqrt{N^{++}N^{--}} \qquad (1)$$

One additional requirement to apply this formula for the estimation of the combinatorial background is that the spectrometer must have the same acceptance for both charges. In order to determine if the request is fulfilled, a study on the behavior of like-sign pairs is required.

2 Data Analysis

The selection of muon pairs and further analysis were made using ROOT and PHAST, C++-based frameworks, and they were conducted for both dimuons and like-sign pairs. This research was carried out using data from the second period of 2018.

Variables of interest

The following variables were used in the analysis with the PHAST methods described in [5]:

- PID: particle identification according to GEANT-3 notation (5 or 6 for positive and negative muons, respectively);
- θ : opening angle between the muon particle and the beam direction;
- p and p_T : dimuon total and transverse momentum, respectively;
- x_F: Feynman-x, the ratio between the longitudinal momentum and half of the square root of the center of mass energy of the hadrons collision;
- Z_{First}: first measured point of particle's reconstructed track;
- Z_{Last}: last measured point of particle's reconstructed track;
- $Track's\ \chi^2$: χ^2 distribution, that will be divided by the number of degrees of freedom;
- M : dimuon invariant mass;

These variables were used to study the behavior of each muon and corresponding pair and to apply some conditions to improve the quality of the data.

Cuts applied

In table 1 all of the cuts applied are shown; this process will lead to the selection of the best candidate muon pairs. In particular, for each event, the best primary vertex was taken into consideration, according to the PHAST function iBestCoralPrimaryVertex(). Moreover, the trigger condition was implemented to meet the charge symmetry requirement referred to in Section 1.3, by considering only muons from LAS (trigger bit 8), since this spectrometer is centered with the beamline direction. Anyway, selecting the dimuon trigger bit in the analysis is not enough, further validation on the muon's track is needed to verify that it could have crossed the active area of the hodoscopes.

Variable	Cut
Z_{Last}	> 1500 cm
Z_{First}	< 300 cm
Trigger	LAS-LAS validated
Track time	defined
Muons time difference	< 3 ns
Track χ^2/ndf	< 8
$\sqrt{X^2_{vertex} + Y^2_{vertex}}$	< 2 cm
M	> 1.5 GeV/c^2
x_F	$\in [-1 : 1]$

Table 1. Cuts applied to improve the quality of the data.

Data was divided by target, by restricting the Z coordinate of the best primary vertex to the intervals related to each target, as shown in table 2.

Target	Position [cm]
NH_3 (cell 1)	$-300 < Z_{vertex} < -240$
NH_3 (cell 2)	$-220 < Z_{vertex} < -164$
Al	$-80 < Z_{vertex} < -60$
W	$-40 < Z_{vertex} < -10$

Table 2. Target restrictions over the Z coordinate of the best primary vertex.

3 Results

From the like-sign muon pair distributions of some kinematic variables, it is possible to infer whether the cuts applied to the data improved the quality of the selected sample and led the distributions to be symmetrical (in order to meet the requirement for the acceptance of the spectrometer discussed in Section 1.3). As shown in figure 3, where the distributions presented refer to the first ammonia target, there is a slight excess of negative muon pairs as compared to the positive ones, probably related to the fact that the beam itself consists of negative pions, that decay to negative muon-neutrino pairs. The behavior observed for the other targets is identical.

Nevertheless, the distributions look symmetrical enough to proceed and use the like-sign pairs to estimate the combinatorial background.

The results of the model for the combinatorial background built from the formula mentioned in Section 1.3 can be found in figure 4 for the first ammonia cell (red histograms). Once again, the same behavior is observed for the other targets. These histograms have been superimposed to the distributions of invariant mass, total and transverse momentum and x_F obtained from the dimuons, after applying the quality cuts previously discussed and shown as the blue histograms.

As expected, the contribution of the combinatorial background is more significant for lower invariant masses, up to 3 or 4 GeV/c^2, building up a significant amount of the reconstructions in this range. Then, the distribution of the combinatorial background decreases steeply; this behavior is common for all of the targets but looks more evident for the two ammonia cells.

4 Conclusions

After a selection of the events useful for our analysis, it was possible to compare the distributions of the like-sign pairs of muons to verify their symmetry and fulfill the requirement imposed to estimate the combinatorial background. Then, this background was statistically estimated using the like-sign pairs based model. The distributions of several relevant kinematic variables were compared between combinatorial background and measured dimuons. Even if this background has a purely combinatorial nature, it cannot be neglected when analyzing the measured dimuon mass spectra, as it represents a significant fraction of the sample, especially in the low mass region. These random pairs tend to have lower momenta and be centered at lower x_F values, as compared to the dimuons.

Anyway, building a model for the combinatorial background from the like-sign pairs leads to some evident issues: firstly, the symmetry requirement is not totally satisfied and some conditions used to meet this request are very strict, in particular as regards the condition over the trigger to consider only the muons hitting LAS. Secondly, it is clear that this analysis suffers from low statistics, given that such statistic is limited by the number of like-sign pairs recorded. A possible solution to these problems could be the implementation of the event mixing method to study the combinatorial background. This method does not require a charge symmetric sample and leads to a virtually infinite statistic available. The muon-antimuon pairs are guaranteed to be totally uncorrelated, by selecting each muon from a different event, but requiring that the two muons fulfill proximity criteria compatible with a viable primary vertex, and that the pair could potentially fire one of the dimuon triggers of the experiment. Such a model of combinatorial background, although not able to provide a normalization for the random pairs' distributions, would make it possible to characterize them without statistics limitations.

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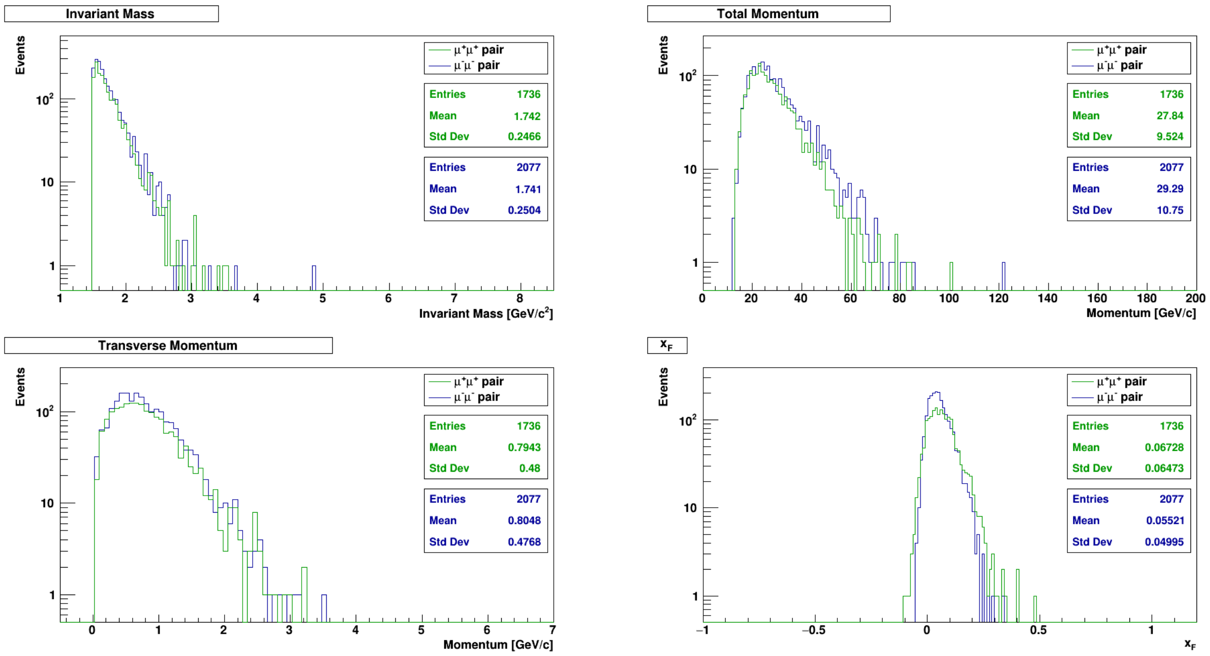

Figure 3. Like-sign muon pairs restricted to the first ammonia target.

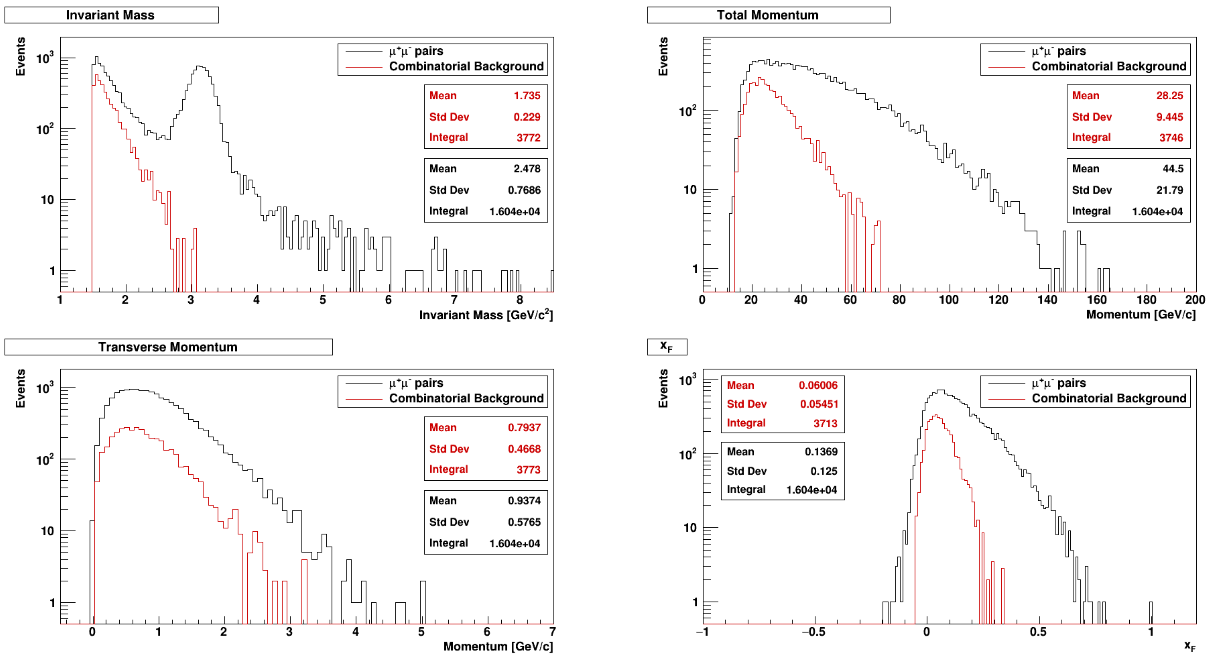

Figure 4. Dimuons and combinatorial background for the first ammonia target.