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2014 J. Phys.: Conf. Ser. 503 012007

(http://iopscience.iop.org/1742-6596/503/1/012007)

FAIRNESS 2013: FAIR NExt generation of ScientistS 2013 IOP Publishing
Journal of Physics: Conference Series **503** (2014) 012007 doi:10.1088/1742-6596/503/1/012007

The $\psi(4040)$ at the future $\overline{\mathsf{P}}$ANDA experiment

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Abstract. The $\overline{\mathsf{P}}$ANDA experiment will be carried out at the future FAIR facility, it will be a fixed target experiment, where antiproton beams, of unprecedented quality and intensity, will be used to study interactions on protons and on nuclei. $\overline{\mathsf{P}}$ANDA will be an excellent tool to investigate those final states which include short-lived particles. Since different charmonium states can be accessed in direct formation with all the available quantum numbers in $\bar{p}p$ annihilations, the charmonium spectroscopy is one of the main goal of the experiment.
The $\overline{\mathsf{P}}$ANDA experiment represents a unique possibility to improve both statistics and precision of existing data and to further explore the physics in the charm quark sector. Indeed, an energy scan with high precision over the full charm spectrum is still missing and it will not be delivered by future experiments currently planned as upgrade of the existing facilities. A detailed description of the possibility to reconstruct the $\psi(4040) \to D^{*+}D^{*-}$ at $\overline{\mathsf{P}}$ANDA, together with the study of the huge hadronic background suppression will be presented. The importance of the Micro-Vertex Detector for the reconstruction of D mesons decay will be showed.

1. Introduction

The $\overline{\mathsf{P}}$ANDA (AntiProton Annihilation at DArmstadt) experiment is one of the projects at the future Facility for Antiproton and Ion Research (FAIR) which is currently under construction as an extension of the existing GSI Laboratory (Helmholtzzentrum für Schwerionenforschung). The FAIR facility [1] will feature a complex structure of new accelerators; primary proton and ion beams as well as secondary beams of antiprotons and radioactive ions will be provided by the FAIR accelerators with high energy, high intensity and high quality.
The $\overline{\mathsf{P}}$ANDA spectrometer will be built as a general purpose fixed target detector that will study $\bar{p}$-p and $\bar{p}$-A annihilations [2]. It will benefit from the antiproton beams, with unprecedented intensity and quality, provided by the High Energy Storage Ring (HESR). The antiproton beam momentum will range from 1.5 GeV/c to 15 GeV/c.
The $\overline{\mathsf{P}}$ANDA scientific program foresees charmonium spectroscopy studies as well as search for exotic hadrons, nucleon structure studies and investigation about the hadron mass in-medium modification and hypernuclear physic [2].

2. Charmonium Spectroscopy

The recent discoveries at the B-factories of unpredicted states above the $D\overline{D}$ threshold, known as X, Y and Z, have renewed the interest in the charmonium spectroscopy field. $\overline{\mathsf{P}}$ANDA with its available energy in the center of mass system, up to $\sqrt{s} = 5.5$ GeV/c^2, will have the chance to explore deeply this mass region.

Charmonium and open charm studies cover a large and important fraction of the $\overline{\text{P}}$ANDA physics program. Compared to past experiments, such as Fermilab E760/E835, $\overline{\text{P}}$ANDA will feature a higher momentum resolution and larger machine luminosity. The main challenge is due to the presence of the large hadronic background in $\bar{p}p$ annihilations. The ability to study charmonium states above the $D\overline{D}$ threshold is of fundamental importance in investigations of open-charm spectroscopy, search for hybrids and CP violation. In particular the reaction $\bar{p}p \to D\overline{D}$ is a benchmark channel to test the capability of background suppression. Moreover, since channels with short-lived particles in the final state will be studied, an optimal secondary vertices reconstruction is required.

3. The $\psi(4040)$ at $\overline{\text{P}}$ANDA

The $\psi(4040)$ is the 3^3S_1 excitation of charmonium. For the $\psi(4040)$, 25 decay modes have been observed but for only a few of them it was possible to fix limits on the branching fraction. The $\psi(4040)$ features a large total width (80 MeV [3]), 2 order of magnitude larger than the lower-lying 1^{--} $c\bar{c}$ states, and a weak coupling to leptons. Moreover, the decay to hidden-charm is not favored due to the availability of open-charm channels (i.e. with charmed mesons in the final states).
The reaction channel investigated in this work is:

$$\begin{aligned} p\overline{p} &\to \psi(4040) \to D^{*+}D^{*-} & \\ D^{*+(-)} &\to D^0(\overline{D^0})\pi^{+(-)} & BR: 67.7\% \\ D^0(\overline{D^0}) &\to K^-\pi^+(K^+\pi^-) & BR: 3.88\% \end{aligned}$$

where the antiprotons have a momentum of 7.71 GeV/c. The main focus of this benchmark study aims to test the capability to reconstruct secondary vertices of D-mesons, and in this way to investigate the possibility to separate the charmed signal from the huge hadronic background.

3.1. $\bar{p}p \to \psi(4040)$ Formation Cross Section

For $\bar{p}p$ annihilations the charm production cross section is so far unknown. A Breit-Wigner approach can be used to calculate the cross section for the $\psi(4040)$ resonance formation [3].

$$\sigma_R(s) = \frac{4\pi\hbar^2c^2}{(E/2)^2}\frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{B_{in}B_{out}\Gamma^2/4}{(E-E_r)^2+\Gamma^2/4} \quad (1)$$

where: B_{in} is the branching ratio of $\psi(4040) \to p\bar{p}$, B_{out} is the BR of $\psi(4040) \to D^{*+}D^{*-}$, E is the center of mass energy, E_r=4039 ± 1 MeV, Γ=80 ± 10MeV [3], and S_1, S_2, and J are the spins of p, $\bar{p}$, and $\psi(4040)$, respectively.

No measurement of B_{in} is available, but it can be estimated to be $\sim 2.5 \cdot 10^{-6}$, using the branching ratio of the J/ψ resonance, and scaling the individual width of both charmonium states [2]. Using a decay branching ratio B_{out} ∼33% [4] and considering the missing contribution from the continuum production, the estimated cross section is:

$$\sigma(\bar{p}p \to \psi(4040) \to D^{*+}D^{*-}) = 2.2\ nb \quad (2)$$

Taking into account the relative branching ratio of the following D-meson decays and the total inelastic cross section of $\sigma(p\bar{p} \to X)$=35 mb[3], it is possible to estimate that the $D\overline{D}$ production cross section will be suppressed at least by 11 orders of magnitude.

3.1.1. Hadronic Background The pattern of this benchmark channel features six charged tracks in the detector. Of all the 6-prong reactions, three have been investigated in detail since they could suggest the main background contamination features, and they can be considered the most effective compared to the signal. The first two contain only pions, and require a good particle identification, to be suppressed: $p\overline{p} \rightarrow 3\pi^+3\pi^-\pi^0$ has a cross section of $\sigma = 1.3$ mb, $p\overline{p} \rightarrow 3\pi^+3\pi^-$ $\sigma = 0.21$ mb. The channel that could represent the largest background source is 2K4π, since it features exactly the same signature of the considered decay channel; its cross section is $\sigma = 0.029$ mb. The contribution from this channel could be suppressed only exploiting a precise tracking which clearly identifies the secondary vertices of the delayed D-meson decays.
A two-fold approach has been followed to evaluate the background contributions and the rejection power of the applied selections. Based on the Dual Parton Model (DPM) event generator, which describes generic $p\overline{p}$ interactions at intermediate energies [5], $2.25 \cdot 10^7$ events have been generated. In a second approach the three channels mentioned above have been simulated separately.

3.2. MC Detector Setup
The detector setup used to simulate the $\psi(4040)$ benchmark channel consists of the full $\overline{\text{P}}$ANDA spectrometer, see [2]. In particular the analysis has taken advantages of only tracking devices:

- **MVD**: the Micro Vertex Detector is the innermost detector of $\overline{\text{P}}$ANDA. It is designed to measure charged particle hits as close as possible to the interaction point (IP). Its main goal is to reconstruct the decays of short-lived particles [6].
- **STT**: the Straw Tube Tracker is the central tracker of $\overline{\text{P}}$ANDA. The achievable spatial resolution is better than 150µm on x-y coordinate and it is of the order of 3mm along the z-coordinate. It will allow together with the MVD to achieve a momentum resolution of the order of 1%, for further details see [7].
- **GEM**: Gas electron multiplier disks will be placed downstream to the IP, at 1.1, 1.4 and 1.9m in order to cover the geometrical acceptance of the STT below 22° of the polar angle [2].
- **FTS**: the forward tracking system will allow to track charged particle emitted at small polar angle, in particular in the polar range below ±10° and ±5° in the horizontally and vertically direction with respect to the beam axis. Six sets of planes, will be placed before, in the middle and after the dipole magnet [2].

4. Phase Space, Acceptance Consideration
Exploiting the MC-matching routine available in the PandaRoot framework, acceptance effects, momentum and secondary vertex resolution were investigated. The $\psi(4040)$ has been studied in the decay to $D^{*+}D^{*-}$, whose momentum spans from 3.4 to 4.3 GeV/c. The subsequent decay of the $D^{*+}(D^{*-})$ mesons proceeds as a 2-body decay into a $D^0(\overline{D^0})$ meson and a $\pi^+(\pi^-)$. Because of the mass difference between the pions and the D^0-mesons, the latter carry most of the momentum boost, and their momentum ranges from ∼3.1 GeV/c up to ∼4.1 GeV/c. The $\pi^+(\pi^-)$ features a lower momentum distribution, as shown in Fig.1.a, and for this reason in the following it will be referred as *soft-pions*. Their low momentum and their preferred direction in the forward region are the main responsible of the low reconstruction efficiency of the studied benchmark channel. Indeed, because of the track bending due to the magnetic field, only less than 50% of the soft-pions could be properly reconstructed. The remaining four charged tracks which have to be reconstructed are coming from the weak decay of the $D^0(\overline{D^0})$ meson. Because of the mass difference between kaons and pions, the kaons will be confined in the forward direction, while pions can be found also in the backward region, as shown in Fig.1.b and 1.c.

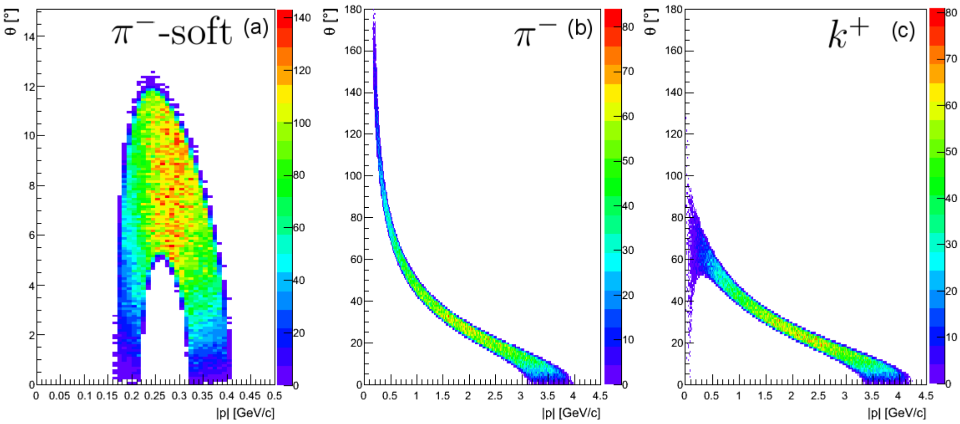

Figure 1. Phase space of the 3 particles coming from the decay of D^{*+}: respectively soft-pions (a), hard-pions (b) and kaons (c).

5. Analysis Strategy and Results

The analysis method presented in this work has been developed and tuned within the PandaRoot (rev.21574) and the FairRoot packages, April-2013.
It must be pointed out that only kinematic constraints are used. In order to suppress the expected huge hadronic background, different cuts on the momentum and mass distribution as well as kinematic and vertex fits have been applied, both on the simulated signal and on the simulated background channels. In order to take into account the detector resolution, limits on the particle momenta were set considering a range of 2σ on the momentum variable, and a tolerance interval of 10% on the angular distributions.
The method consists of four main steps:

- Build the candidates sample of six charged type of particles: K^+, K^-, π^+, π^- and two additional soft-π^+, soft-π^-. Kaons and pions feature different momentum distributions, hence a huge amount of candidates can be filtered out just imposing some general selections.
- Build the candidates sample of D^0-$\overline{D^0}$. The candidate samples are filtered out applying an initial kinematical fit which constraints the mass to the known value m_{D^0}=1.865 GeV/c^2 [3]. Afterward a mass window of $\pm 3\sigma = \pm 30$ MeV/c^2 has been choosen for a cut. Moreover, to refine the selections, further cuts on the momentum distribution have been performed, before applying a vertex fit to identify a common vertex of the Kπ pairs to get rid of the soft pions component. A cut on the $D^0(\overline{D^0})$ distance from the IP of 0.2 cm has been applied. The obtained secondary vertex resolution of neutral D-mesons is $\sim$30 μm in x-y and $\sim$110 μm along the z direction.
- Build the candidates sample of D^{*+}-D^{*-}. The candidate data samples have been filtered within a mass range of $\pm 3\sigma = \pm 36$ MeV/c^2.
- Build the cleanest data sample for $\psi(4040)$ combining the survived $D^{*+}D^{*-}$ pairs. After the candidate sample has been filtered by means of a 4C-fit, which constrains the total initial 4-momentum; in case of multiple candidates, the choice is based on the best χ^2.

The invariant mass of $D^{*+}D^{*-}$ pairs is shown in Fig.2. The peak is centered at 4040.0 MeV/c^2 and the achieved mass resolution is $\sim$1.4 MeV/c^2 , the obtained reconstruction efficiency is 3.3%.
The expected data rate can be calculated using the integrated maximum achievable luminosity of $L_{int} = 3.1 \cdot 10^{39}$cm^{-2} (considering 6 months of data taking) and the estimated cross section of Eq.2. About 6.84$\cdot$10^6 $\psi(4040)$ should be produced, and around $\sim$4700, should decay into

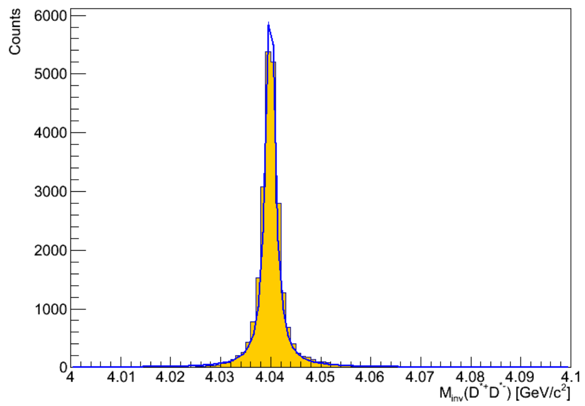

Figure 2. Invariant mass of $D^{*+}D^{*-}$ pairs.

$D^{*+}D^{*-}$. Considering the reconstruction efficiency of the $\psi(4040) \rightarrow D^{*+}D^{*-}$ channel, the number of observable $\psi(4040)$ in one year of data taking should be $\sim$160. Using a statistical sample of $1.5{\cdot}10^7$ events for the 2K4π reactions, $2{\cdot}10^7$ for the 6π and 7π channels, and on a data sample of $2.25{\cdot}10^7$ inelastic $p\bar{p}$ reactions, the S/B ratios, reported in Tab.1, were evaluated.

Channel	S/B
2K4π	$> 2.7{\cdot}10^{-2}$
6π	$>4.9{\cdot}10^{-3}$
7π	$\geq 8{\cdot}10^{-4}$
$p\bar{p}$	$> 3.3{\cdot}10^{-5}$

Table 1. Signal to background ratio for the main background sources, a lower limit is listed when no $\psi(4040)$ was reconstructed in the data sample.

6. Conclusion

The $\psi(4040) \rightarrow D^{*+}D^{*-}$ decay chain has been investigated in detail. The reconstruction efficiency is found to be 3.3%, all the simulated backgrounds events were successfully suppressed. In particular in this work only the dominant charged decay of the D mesons has been considered; including further decay channels, such as semi-leptonic decay modes, the expected charmed signal yield should significantly improve. Furthermore, the real production cross sections of $D\overline{D}$ may be larger, which would drastically increase the charmed signal yield. The PANDA detector in its given setup will be able to contribute to investigate various physics topics in the charmonium mass region.

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