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Results for a Simulated Resonance Scan of the X(3872) at $\overline{\text{P}}$ANDA

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The $\overline{\text{P}}$ANDA experiment – which will be built as part of the planned FAIR expansion of the existing GSI facility – is planned to start operation in 2017. It will utilize cooled antiproton beams with momentum resolutions of $\Delta p_{\text{beam}}/p_{\text{beam}} \leq 2 \cdot 10^{-5}$ provided by the storage ring HESR. In this work we present results for a simulated resonance scan of X(3872) under realistic assumptions. For the reconstruction the channel $\text{X(3872)} \rightarrow J/\psi\ \pi^+\pi^-$ with a subsequent $J/\psi \rightarrow e^+e^-$ decay was chosen. All simulations were performed in the PandaRoot software framework taking a detailed model of the detector into account. As input parameters for the resonance scan, the X(3872) was assigned a mass of 3.872 GeV and a width of 100 keV. The production cross section for $p\bar{p} \rightarrow \text{X(3872)}$ was assumed to be equal to 50 nb and the branching ratio for $\text{X(3872)} \rightarrow J/\psi\ \pi^+\pi^-$ was set to 0.1. The simulation was performed for 20 equidistant scan points with 2 days of data taking per scan point at 50% accelerator duty factor. Background from $p\bar{p} \rightarrow J/\psi\ \pi^+\pi^-$ with a constant cross section of 1.2 nb was taken into account. Background from inelastic processes was studied using a dual parton model based generator.

The MC data points were fitted with a constant plus a convolution of a Breit-Wigner and a Gaussian distribution of a fixed width. The width of the X(3872) was reconstructed as $\Gamma_{X(3872)}$=86.9±16.8 keV which is consistent with the input width of 100 keV. We conclude that the $\overline{\text{P}}$ANDA detector is particularly qualified to perform resonance scans of exclusively produced charmonium(-like) states with non-exotic quantum numbers.

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1. The $\overline{\text{P}}$ANDA Experiment

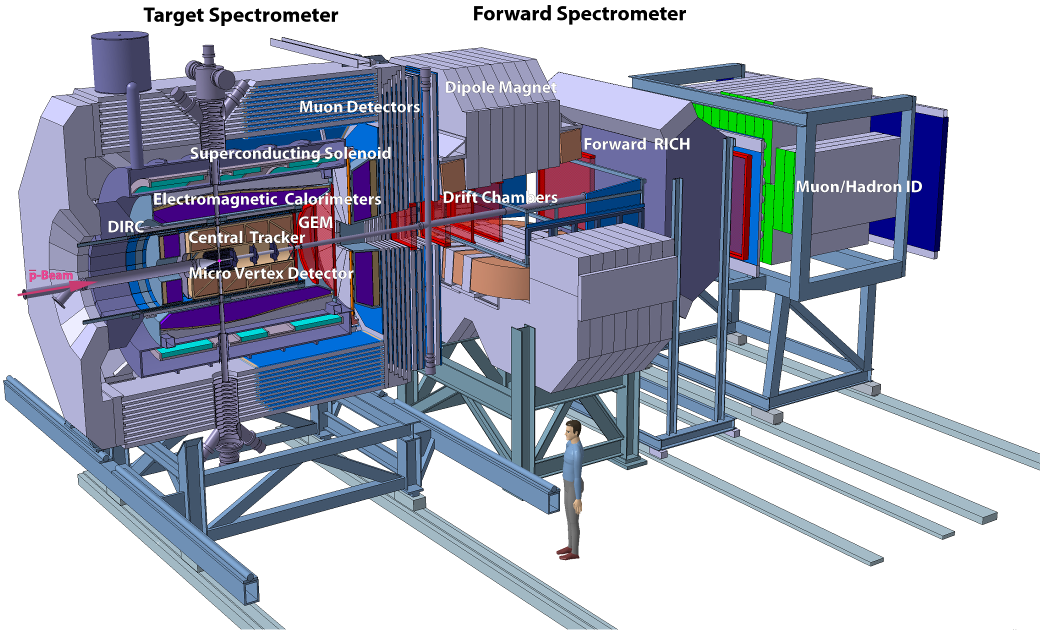

Figure 1: Artistic view of the $\overline{\text{P}}$ANDA Detector as shown in [1].

The $\overline{\text{P}}$ANDA (anti-Proton ANnihilations at DArmstadt) experiment is designed to investigate $\overline{\text{p}}+\text{p}$ and $\overline{\text{p}}+A$ collisions with an internal proton (p) or nuclear (A) target and an anti-proton ($\overline{\text{p}}$) beam in the momentum range from about 1 to 15 GeV which corresponds to a center of mass energy between about 2.0 and 5.5 GeV. It is a part of the future FAIR (Facility for Anti-Proton and Ion Research, see fig. 2) extension of the existing GSI (Heavy Ion Research Lab) facility in Darmstadt, Germany.

The $\overline{\text{P}}$ANDA Physics case extends from questions regarding confinement, hadron mass, the structure of the nucleon and spin degrees of freedom to search for color neutral objects. Its measurement capabilities range from meson spectroscopy (D mesons, charmonium, glueballs, hybrids, tetraquarks, molecules), charmed and multi-strange baryon spectroscopy and electromagnetic processes ($\text{p}\overline{\text{p}}\rightarrow \text{e}^+\text{e}^-$, $\text{p}\overline{\text{p}}\rightarrow\gamma\gamma$, Drell-Yan) to measurements of properties of single and double hypernuclei and of hadrons in nuclear matter.[1, 2]

The requirements for the $\overline{\text{P}}$ANDA detector are quite high: It was designed to achieve nearly 4π solid angle coverage with good particle identification capabilities and high resolutions for particle tracking and calorimetry. Its readout needs to be capable of handling high rates up to $2\cdot 10^7$ interactions per second with versatile event selection.

The $\overline{\text{P}}$ANDA experiment combines a phase-space cooled antiproton beam with dense internal targets to offer unique possibilities for studies of numerous aspects of the strong interaction. Utilizing a hydrogen target $\overline{\text{P}}$ANDA can access charmonium resonances R of all non-exotic quantum numbers in direct formation $\text{p}\overline{\text{p}}\rightarrow R$.

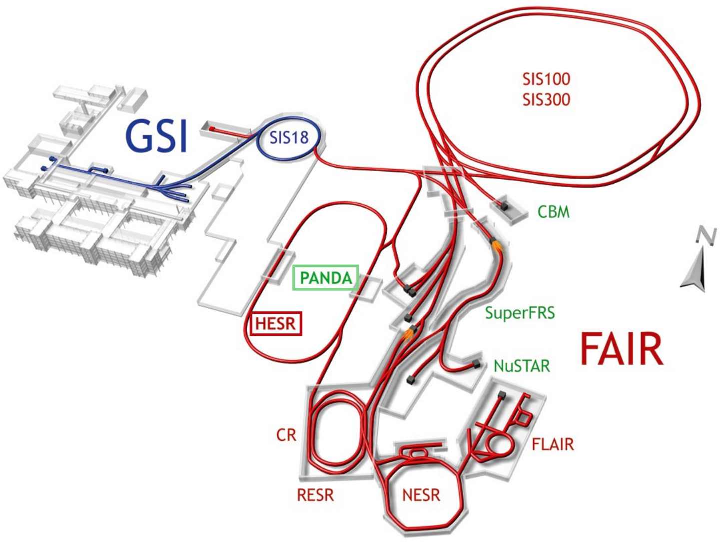

Figure 2: Layout of the existing GSI facility (in blue) and the planned FAIR expansion (in red and green) as published in [3]. Indicated are the locations of various planned experiments, synchrotrons as well as storage, accumulator and collector rings. More details can be found in [4].

The detector is comprised of a target and a forward spectrometer as shown in figure 1. Both feature charged particle identification, tracking and electromagnetic calorimetry "to allow to detect the complete spectrum of final states relevant for the $\overline{\text{P}}$ANDA physics objectives." [1]

2. The X(3872) Resonance

The X(3872) is a narrow state which has been observed by numerous experiments in several decay channels. However, it does not fit into predictions of potential model calculations and is therefore discussed as a candidate for a molecular $D^0\bar{D}^{*0}$ state. Several other interpretations exist [5]: It could be the first excited state of conventional charmonium $\chi_{c1}(2P)$ [6], an S-wave threshold effect of $D^0\bar{D}^{*0}$ [7], a cusp effect [8], a diquark anti-diquark bound state [9], hybrid charmonium [10] or a tetraquark state [11].

To date, little information is available about the X(3872) resonance. For its width $\Gamma_{\text{X(3872)}}$ only an upper limit of 1.2 MeV at 90% confidence level is published [12]. The actual value could be significantly smaller. For its quantum numbers there are two possible assignments: The observed decay into $J/\psi\ \gamma$ allows the assignment of positive charge conjugation $C = +1$. A high statistics analysis by CDF [13] allows $J^{PC} = 1^{++}$ and $J^{PC} = 2^{-+}$. A paper by Belle favors 1^{++} [14] whereas BaBar favors 2^{-+} [15]. The resonance scan simulation presented in this work assumes that the 1^{++} assignment holds.

The cross section for X(3872) formation in $\text{p}\bar{\text{p}}$ annihilations with a subsequent decay into the $J/\psi\ \pi^+\pi^-$ channel is estimated in [5] using model based calculations for the $D^0\bar{D}^{*0}$ molecule interpretation and for the $\chi_{c1}(2P)$ possibility. The authors published that $\sigma[\text{p}\bar{\text{p}} \to \text{X(3872)} \to J/\psi\ \pi^+\pi^-]$ should be within the interval from 3.57 to 443 nb for the assumption that the X(3872) is a loosely bound molecule of $D^0\bar{D}^{*0}$. Assuming the X(3872) is $\chi_{c1}(2P)$ the calculated range is 2.19 to 238 nb. The results strongly depend on $\Gamma_{\text{X(3872)}}$ as a parameter which the authors consider to be between 136 keV and 2.3 MeV. The dependence of the estimated total cross sections at threshold is illustrated in figure 3. Smaller widths yield larger estimated cross sections.

In order to determine the width of the X(3872), a resonance scan is a suitable experimental method. In a resonance scan the center of mass energy $\sqrt{s}$ is scanned across a resonance's excitation curve by adjusting the beam momentum p_{beam}. As the center of mass energy $\sqrt{s}$ can be accurately determined by the known nominal antiproton beam momentum the resolution is not limited by the detector resolution. $\text{p}\bar{\text{p}}$ annihilations are particularly suitable for this experimental method, because resonances of all non-exotic quantum numbers can be formed directly whereas the formation of resonances with quantum numbers other than $J^{PC} = 1^{--}$ is suppressed in e^+e^- collisions. In addition, e^+e^- machines are usually optimized for a certain fixed $\sqrt{s}$ and their luminosities drastically decrease when they are operated outside their optimal $\sqrt{s}$.

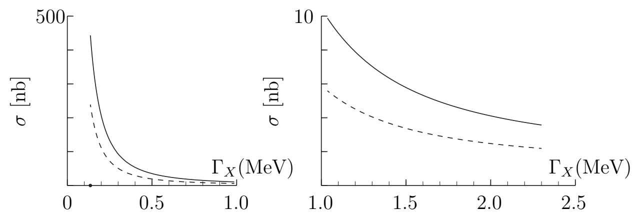

Figure 3: The estimated total cross section $\sigma[\text{p}\bar{\text{p}} \to \text{X(3872)} \to J/\psi\ \pi^+\pi^-]$ at the threshold as a function of the X(3872) width $\Gamma_{\text{X(3872)}}$ as published in [5]. The solid and dashed lines represent the interpretation of X(3872) as a molecule of D-mesons and as $\chi_{c1}(2P)$, respectively.

3. Results from the Resonance Scan Simulation

For the resonance scan simulation the channel $\text{X(3872)} \to J/\psi\ \pi^+\pi^-$ with a subsequent decay of $J/\psi \to \text{e}^+\text{e}^-$ was chosen. All Monte Carlo simulations presented in this work were carried out using the PandaRoot framework [16] – the official simulation and reconstruction software framework for the $\overline{\text{P}}$ANDA experiment. For the simulations a detailed model of the $\overline{\text{P}}$ANDA detector was used. The interference of magnetic fields was taken into account. Conformal map based track finder and track fitter algorithms were used for pattern recognition to achieve a realistic signal reconstruction.

EvtGen [17] was used as an event generator for the simulation of the formation and decay chain of the X(3872) resonance and for the background from the $\text{p}\bar{\text{p}} \to J/\psi\ \pi^+\pi^-$ process with subsequent $J/\psi \to \text{e}^+\text{e}^-$ decay. Final state radiation was simulated using the PHOTOS [18] software package. After the events generation, background and signal events were treated in exactly the same way: The particles were transported through the geometry of the $\overline{\text{P}}$ANDA detector using Geant3 [19, 20] and digitization, reconstruction and particle identification was carried out. The analysis treated the output of the simulation like real data.

As a first step, an electron/pion discrimination was applied to classify all charged particles present in the events into $e^{\pm}$ and $\pi^{\pm}$ candidates. All combinations of one electron and one positron candidate in the same event were used to calculate the two particle invariant mass. If the result fell within the J/ψ mass region from 2.6 GeV to 3.4 GeV, this combination was regarded as a J/ψ candidate.

For all $\pi^+\pi^-$ candidates in the same event, the missing mass was calculated. If the result fell in the range from 2.95 GeV to 3.35 GeV the event was further analysed.

If the event contained one or more suitable J/ψ candidates and at least one possible $\pi^+\pi^-$ pair with a missing mass in the correct region, the corresponding four particle invariant mass was calculated. If the result fell within the interval from 3.3 GeV to 4.2 GeV, the X(3872) candidate counter for the scanpoint was raised by one.

This analysis scheme was used in the same way for the X(3872) signal ($\mathrm{p\bar{p}} \to$ X(3872) $\to J/\psi\ \pi^+\pi^- \to \mathrm{e^+e^-}\pi^+\pi^-$) as well as for the background from $\mathrm{p\bar{p}} \to J/\psi\ \pi^+\pi^- \to \mathrm{e^+e^-}\pi^+\pi^-$.

The X(3872) candidate counts from the background and the signal were added for each point of the resonance scan. The results are shown in figure 4. The fit which was then applied has no information about how many counts originated from background processes or signal events.

In order to simulate a resonance scan of X(3872) with the $\overline{\text{P}}$ANDA experiment, several currently unknown properties of X(3872) had to be assumed[1].

The X(3872) production cross section in $\mathrm{p\bar{p}}$ annihilations was simulated according to the Breit-Wigner distribution given by

$$\sigma_{\mathrm{BW}}(\sqrt{s}) = \frac{(2J+1)\cdot 4\pi}{\sqrt{s}^2 - 4m_{\mathrm{p}}^2} \cdot \frac{\mathrm{BR}(\mathrm{X(3872)} \to \mathrm{p\bar{p}}) \cdot \Gamma_{\mathrm{X(3872)}}{}^2}{4(\sqrt{s} - m_{\mathrm{X(3872)}})^2 + \Gamma_{\mathrm{X(3872)}}{}^2}.$$

in which the width $\Gamma_{\mathrm{X(3872)}}$ was chosen as 100 keV and therefore, small enough to be treated as a constant. The simulation assumed the branching ratio $\mathrm{BR}(\mathrm{X(3872)} \to J/\psi\ \pi^+\pi^-)$ to be equal to 0.1 and that the quantum number assignment $J^{PC} = 1^{++}$ holds for X(3872). $m_{\mathrm{X(3872)}}$ was set to 3.872 GeV, m_{p} denotes the mass of the proton. The production cross section[2] in $\mathrm{p\bar{p}}$ was assumed to be equal to 50 nb for $\sqrt{s} = m_{\mathrm{X(3872)}}$. This estimate is of the same order of magnitude as the corresponding ψ' cross section [21] and it is consistent with the predictions in [5] for relatively large widths $\Gamma_{\mathrm{X(3872)}}$. However, our simulation combined a very narrow width and a relatively small cross section. If the model calculations in [5] are correct, either $\Gamma_{\mathrm{X(3872)}}$ should be significantly larger for the assumed cross section or the cross section should be significantly larger if the true width is in the range of 100 keV.

The excitation curve of X(3872) was investigated with a resonance scan of 20 energy scanpoints and a total of 40 days of simulated data taking. A small energy shift of 10 keV between the closest scan point's $\sqrt{s}$ and the true X(3872) mass was assumed. Half of the scan points were simulated at energies greater than the true $m_{\mathrm{X(3872)}}$ and the other half below this value with equidistantly spaced scan point energies ranging from 3871.540 MeV to 3872.490 MeV.

HESR was assumed to be operated in high resolution mode with an accelerator duty factor of 50%. That yields a luminosity of 864 nb^{-1} per day. The antiproton beam momenta were assumed

[1] A full summary of the simulation parameters is provided in table 1.

[2] The assumed cross section allows to calculate the corresponding branching ratio $\mathrm{BR}(\mathrm{p\bar{p}} \to \mathrm{X(3872)}) \simeq 3.9 \cdot 10^{-5}$ for $J = 1$ and $\mathrm{BR}(\mathrm{p\bar{p}} \to \mathrm{X(3872)}) \simeq 2.3 \cdot 10^{-5}$ for $J = 2$ which other experiments could assess.

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Resonance Scan	
Experiment	$\overline{\mathsf{P}}$ANDA
Resonance	X(3872)
Decay channel	$J/\psi\ \pi^+\pi^-$
Subsequent decay	$J/\psi \to e^+e^-$
Number of scan points	20
Time requirement	2 days per scan point
Spacing	Equidistant
$\sqrt{s}$ interval	$[3871.54\ \text{MeV}, 3872.49\ \text{MeV}]$
HESR	High resolution mode
p_{beam} distribution	Gaussian, rms $\Delta p_{\text{beam}}/p_{\text{beam}} = 2\cdot 10^{-5}$
$\sqrt{s}$ distribution	Gaussian, rms $\Delta\sqrt{s} \simeq 33.568$ keV
Accelerator duty factor	50%
Integrated luminosity	0.864 pb^{-1}/day
X(3872)	
Mass $m_{\text{X(3872)}}$	3.872 GeV
Width $\Gamma_{\text{X(3872)}}$	100 keV
Cross section model	Breit-Wigner
Production cross section in $p\bar{p}$	$\sigma_{\text{BW}} = 50$ nb for $\sqrt{s} = m_{\text{X(3872)}}$
Branching ratio into $J/\psi\ \pi^+\pi^-$	0.1
Decay model	VVPiPi
Subsequent J/ψ Decay	
Branching ratio into e^+e^-	0.06
Decay model	VLL
Background Processes	
Direct: $p\bar{p} \to J/\psi\ \pi^+\pi^-$	$\sigma = 1.2$ nb for $\sqrt{s} \simeq m_{\text{X(3872)}}$
All other	Assumed to be suppressible with PID

Table 1: Summary of the parameters used for the simulation of a resonance scan of X(3872) at $\overline{\mathsf{P}}$ANDA. The entire simulation chain from event generation, over transport, digitization, reconstruction, particle identification and analysis was carried out in the PandaRoot framework.

to be Gaussian distributed with standard deviations corresponding to HESR's high resolution mode ($\Delta p_{\text{beam}}/p_{\text{beam}} = 2 \cdot 10^{-5}$). As a result, the corresponding center of mass energy distribution was also approximately Gaussian distributed with standard deviations $\Delta\sqrt{s} \simeq 33.568$ keV.

In analogy to equation (2.5) in [1] the number of signal events $n(\sqrt{s_0})$ that need to be simulated for a given scan point with nominal center of mass energy $\sqrt{s_0}$ can be calculated by:

1. multiplying the Breit-Wigner production cross section $\sigma_{\text{BW}}(\sqrt{s})$ with the center of mass energy distribution $B(\sqrt{s}, \sqrt{s_0})$ of the utilized machine and integrating over the energy acceptance of the detector

2. multiplying the result of the integration with the luminosity $\mathscr{L}$, the accelerator duty factor α, the time per scan point T and the branching ratios for the decay chain of interest

$$n(\sqrt{s_0}) = \text{BR}(\text{X}(3872) \to J/\psi\,\pi^+\pi^-) \cdot \text{BR}(J/\psi \to \text{e}^+\text{e}^-) \cdot \mathscr{L} \cdot \alpha \cdot T \cdot \int \sigma_{\text{BW}}(\sqrt{s}) \cdot B(\sqrt{s}, \sqrt{s_0})\, d\sqrt{s}$$

In [5] the cross section for the background process $\text{p}\bar{\text{p}} \to J/\psi\,\pi^+\pi^-$ was estimated to be approximately 1.2 nb and to remain nearly constant over the center of mass energy range of interest. Multiplying this cross section with the luminosity, the accelerator duty factor, the number of days per scanpoint and with $\text{BR}(J/\psi \to \text{e}^+\text{e}^-) \simeq 0.06$ [22] yields $\simeq 124$ background events that need to be simulated for each scan point. Background events were simulated separately from signal events, but analyzed with the same macros as the signal. For each scan point, counts of reconstructed X(3872) candidates from signal and background events were added and the resulting counts were plotted against the respective nominal center of mass energy of the scan point. The lineshape obtained from the simulation of the X(3872) resonance scan with $\overline{\text{P}}$ANDA is presented in figure 4. The MC data points were fitted with a convolution of a Breit-Wigner distribution and a Gaussian – describing the center of mass energy distribution which results from the beam momentum spread – plus a constant for the direct $\text{X}(3872) \to J/\psi\,\pi^+\pi^-$ background. The applied fit had no information about how many counts originate from background processes or from signal events. For the fit the mass and width of the X(3872) and the background level were free parameters whereas the width of the Gaussian was fixed. All parameters were allowed to be varied over several orders of magnitude and the starting values were chosen to be close to, but reasonably distant from the true values. All reconstructed values are in good agreement with the input parameters. In particular, the reconstructed width of 86.9 ± 16.8 keV is consistent with the input width of 100 keV.

4. Study of Inelastic Hadronic Background

A detailed simulation of inelastic hadronic background reactions in the center of mass energy region corresponding to the mass of the X(3872) is crucial for determining the feasibility of a X(3872) resonance scan with $\overline{\text{P}}$ANDA. Background events were simulated using a dual parton model based generator (DPM) [23]. In order to obtain meaningful results under given computing and time limitations two different types of events were simulated: $2 \cdot 10^6$ inelastic hadronic background events and a second sample of $2 \cdot 10^6$ $\text{p}\bar{\text{p}} \to \pi^+\pi^-\pi^+\pi^-$ events. We assume that this

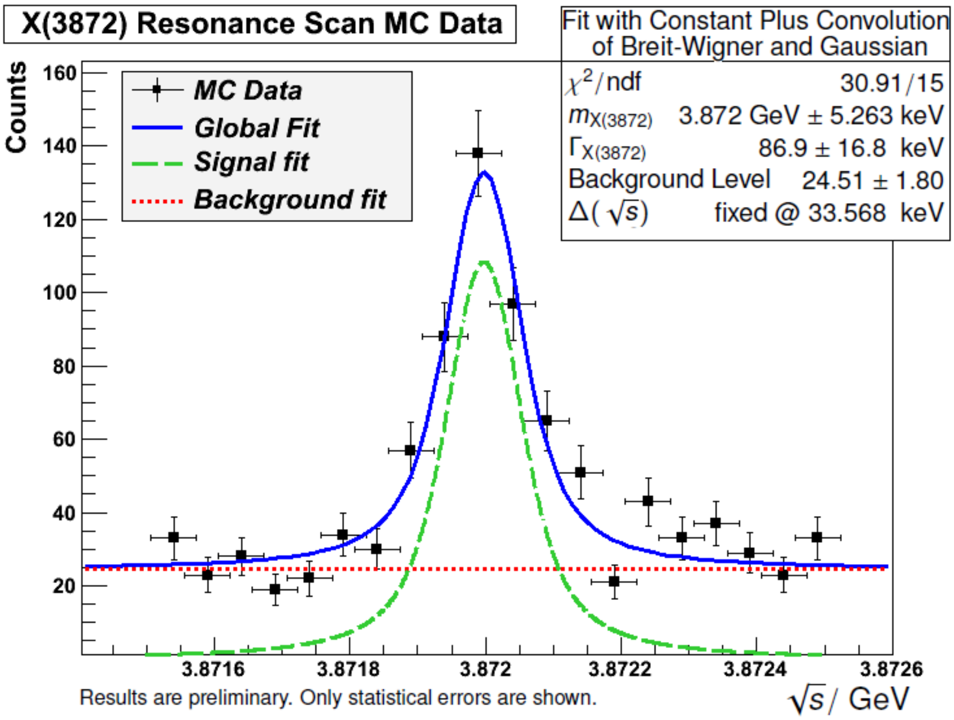

Figure 4: Result for the simulated resonance scan of X(3872) with 20 equidistant center of mass energy scan points. The process $\text{p}\bar{\text{p}} \to \text{X}(3872) \to J/\psi\, \pi^+\pi^-$ with subsequent $J/\psi \to \text{e}^+\text{e}^-$ decay was simulated within the PandaRoot framework. Direct background from $\text{p}\bar{\text{p}} \to J/\psi\, \pi^+\pi^-$ was taken into account. The simulation parameters are summarized in table 1.
Electron/pion discrimination was used for particle identification. The center of mass energy distribution was approximated by a Gaussian. The corresponding standard deviation was calculated for each energy scan point according to the beam momentum spread for HESR in high resolution mode.
The fit to the simulated signal including background was performed with a convolution of a Gaussian – representing the center of mass energy spread and detector inaccuracies – and a Breit- Wigner distribution – describing the X(3872) cross section – plus a constant – taking the background from the direct J/ψ $\pi^+\pi^-$ production into account. The fit constrained the standard deviation of the Gaussian distribution. The reconstructed $\Gamma_{X(3872)}$ of 86.9 ± 16.8 keV is in good agreement with the input width of 100 keV.

process should account for most of the background events for the simulated resonance scan which arise from particle misidentification.

The resulting four particle invariant mass spectra are presented in figure 5 for all inelastic hadronic events on the left and for $\text{p}\bar{\text{p}} \to \pi^+\pi^-\pi^+\pi^-$ events on the right. The aforementioned cuts on the missing mass of the $\pi^+\pi^-$ candidates and on the invariant mass of all e^+e^- candidates were enforced, but the electron/pion discrimination was not applied. As expected, without PID the process $\text{p}\bar{\text{p}} \to \pi^+\pi^-\pi^+\pi^-$ yielded significantly more possible X(3872) candidates in the appropriate mass region. The simulation shows that by additionally applying electron/pion discrimination in the analysis of the simulated background events, all fake X(3872) candidates can be rejected.

Computing time constraints did not allow for a full simulation of larger background samples. Future Monte Carlo simulations will have to follow in order to give a definite answer to the question what ratio of signal to inelastic hadronic background could be expected for a real resonance scan.

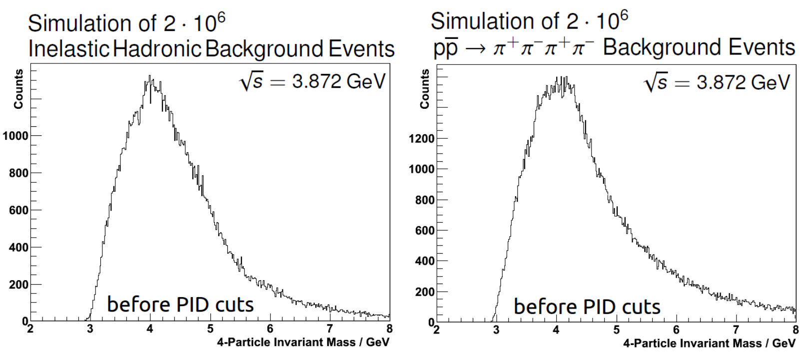

Figure 5: The plots show the invariant mass spectra of four oppositely charged particles for all inelastic hadronic events from the DPM generator (left hand side) and for $p\bar{p} \to \pi^+\pi^-\pi^+\pi^-$ filtered DPM events (right hand side). No particle identification information was used, the cuts on the missing mass of the $\pi^+\pi^-$ candidates and on the invariant mass of all e^+e^- candidates were enforced. A large amount of possible X(3872) candidates was found in both types of background at masses around 3.872 GeV. After application of particle identification cuts in both cases no fake signals were observed.

5. Conclusions and Outlook

We performed a detailed simulation of a X(3872) resonance scan with the $\overline{\text{P}}$ANDA experiment under realistic assumptions (see table 1 for more details) within the PandaRoot framework. The reconstructed width $\Gamma_{X(3872)} \simeq 86.9 \pm 16.8$ keV from the simulation is consistent with the input width that was chosen as 100 keV. We conclude[24] that $\overline{\text{P}}$ANDA will be able to either measure $\Gamma_{X(3872)}$ or at least significantly improve the current upper limit of $\Gamma_{X(3872)} \leq 1.2$ MeV at 90% C.L.. Generally speaking, $\overline{\text{P}}$ANDA will be well suited for resonance scan investigations of narrow resonances which can be directly formed in $p\bar{p}$. A study of larger background samples will have to follow in order to determine the final resolution which can be expected from the $\overline{\text{P}}$ANDA detector for a X(3872) resonance scan.

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