PANDA perspectives in exotics – Performances in line shape measurements

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on behalf of the PANDA Collaboration

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Summary. — The new Facility for Antiproton and Ion Research (FAIR) is under construction at GSI in Darmstadt (Germany). Antiprotons are planned to be provided by the High Energy Storage Ring, at which the PANDA experiment will directly be located. It represents the central part of the hadron physics programme. The field of hadron spectroscopy has gained new momentum by the discovery of the so-called charmonium-like and bottomonium-like exotic states over the past two decades. The nature of many of the so-called exotic XYZ states in the charmonium region are, however, not yet understood. Precise measurements of hadron masses and widths are mandatory to sort out different theoretical models and clarify the nature of these unexpected states. One example is the $\chi_{c1}(3872)$, formerly known as $X(3872)$ – although being the first of the new charmonium-like states discovered since 2003, the nature of this state is still not clarified. In $p\bar{p}$ annihilation, such XYZ states can be produced in direct formation, allowing for a precise resonance energy scan. Using the example of the $X(3872)$, we quantified the expected sensitivity of energy scans of narrow resonances and how well we can distinguish between models that turn out to be indistinguishable from the LHCb data.

1. – Introduction

Quantum Chromodynamics (QCD) describes bound states of the strong interaction. Especially in the charmonium region, they can be described rather successfully using potential models. Beneath the open-charm threshold, all the predicted states have been observed with the expected properties, and there is excellent agreement between model calculations and experiment. Above the open-charm threshold, however, there are still many predicted states that have not yet been discovered, and a series of unexpected states have surprisingly been observed since 2003. Famous examples of these so-called (exotic)

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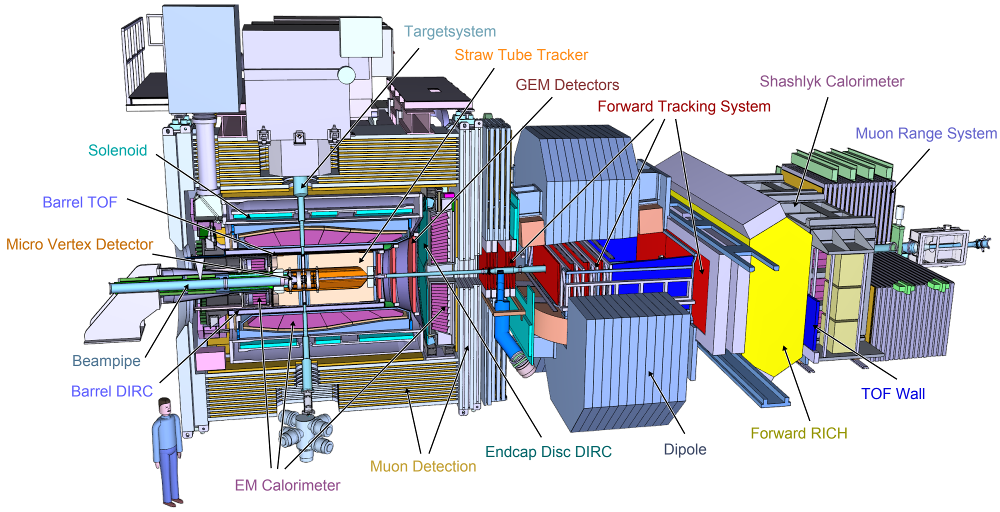

Fig. 1. – Experimental setup of the proposed PANDA fixed-target experiment. It consists of a barrel spectrometer surrounding the target region and an additional forward spectrometer.

charmonium-like "XYZ" states are the $X(3872)$ discovered by Belle [1] in 2003, the $Y(4260)$ and $Y(4360)$, which were both firstly observed by BaBar employing initial state radiation (ISR) [2],[3], and the charged state $Z_c(3900)^{\pm}$ discovered by BESIII [4]. The $Z_c(3900)^{\pm}$ was shortly after confirmed by Belle [5], and due to the mass in combination with the electrical charge, this state is a manifestly exotic state, for a recent overview see e.g. [6]. The nature of the narrow $X(3872)$, though it was the first of these unexpected states reported ten years ago, is not yet understood. A precision measurement of the line shape as it will be feasible with the PANDA experiment, however, will give a handle to sort out different models and to clarify e.g. whether it is a molecular state.

2. – The PANDA experiment at FAIR

One of the main pillars at FAIR that is currently under construction in Darmstadt, Germany, will be the PANDA (antiProton ANnihilation in DArmstadt) experiment dedicated to hadron physics [7]. Apart from hadron spectroscopy in the charm and light quark regions, the physics programme comprises nucleon structure, hyper nuclear and strangeness production physics, and also studies of in-medium modifications of charm in nuclear matter. The multi-purpose fixed-target PANDA experiment consists of a barrel detector surrounding the target region and a forward spectrometer (Fig. 1), ensuring an almost 4π acceptance with excellent tracking, vertexing, particle identification and electromagnetic calorimetry. The PANDA experiment is directly located at the High Energy Storage Ring (HESR) that provides an antiproton beam of momenta from 1.5 to 15 GeV/c for antiproton-proton annihilation antiproton-nucleon reactions, translating to a directly accessible invariant mass range from about 2.2 up to 5.5 GeV/c^2.

There will be two operation modes of the HESR. The High Resolution (HR) mode optimised for beam momentum resolution will provide a beam momentum spread of $\Delta p/p = 2 \times 10^{-5}$ and a luminosity of $\mathcal{L} = 2 \times 10^{31}$ cm^{-2}s^{-1}, whereas the High Luminosity (HL) mode will have a higher luminosity of 2×10^{32} cm^{-2}s^{-1}, while the beam momentum

TABLE I. – *Performances of the beams expected for the PANDA experiment: Momentum spreads* dp/p*, beam-energy resolutions* $dE_{\rm cms}$ *and integrated luminosities* $\mathcal{L}$ *(at* $\sqrt{s} = 3.872$ *GeV) of the three different HESR operation modes, see [8] and references therein.*

HESR mode	$\mathrm{d}p/p$	$\mathrm{d}E_{\rm cms}$ [keV]	$\mathcal{L}$ [1/(day · nb)]
HL	$1 \cdot 10^{-4}$	167.8	13680
HR	$2 \cdot 10^{-5}$	33.6	1368
P1	$5 \cdot 10^{-5}$	83.9	1170

spread will be larger, namely $\Delta p/p = 1 \times 10^{-4}$. In the initial phase, the antiproton beam is expected to be available with $\Delta p/p = 5 \times 10^{-5}$ and $\mathcal{L} = 1 \times 10^{31}$ cm^{-2}s^{-1}. Before the accelerator will be in operation at full performance, we will have an initial phase of the experiment, PANDA Phase One (P1), for which we expect a luminosity a factor of ten lower as compared to the HL mode and a beam energy resolution about a factor of 2.5 worse as compared to HR mode, see Tab. I.

3. – The role of resonance energy scans in view of exotic charmonium states

At PANDA, hadronic states of all fermion-antifermion J^{PC} quantum numbers can be produced via the $\bar{p}p$ annihilation process in direct formation. This is one of the main advantages of using antiprotons as compared to e^+e^- annihilation, in which the hadronic system produced in direct formation is restricted to the quantum numbers of the virtual photon ($J^{PC} = 1^{--}$) that acts as a spin filter.

It is thanks to the cooled antiproton beam with excellent energy resolution available at PANDA, that a very precise mass and width resolution can be achieved by employing the technique of an energy resonance scan (Fig. 2, b), also for resonances with $J^{PC} \neq 1^{--}$, such as the $X(3872)$ with $J^{PC} = 1^{++}$. Given the small and well-controlled beam momentum spread $\Delta p/p$, the beam energy can be scanned in the centre-of-mass energy ($E_{\rm cms}$) range around a narrow resonance, and the energy-dependent event yield can be measured. Given the beam profile is well known, it can be de-convolved, so that an energy dependent resonance cross-section measurement is obtained at high precision.

4. – Quantification of expected performances for resonance energy scans at PANDA using the example of the $X(3872)$

In order to illustrate the unique strength of PANDA in such precision line shape scans, we performed a comprehensive feasibility study [8], for which we used the example of the $X(3872)$ state that is the first of the unexpected XYZ states discovered in 2003 [1], meanwhile renamed by the Particle Data Group to $\chi_{c1}(3872)$ [9]. Theoretical interpretations come along with predictions of the decay width, however, until recently only an experimental upper limit on the absolute width of $\Gamma < 1.2$ MeV was provided by the Belle experiment [10].

To understand the nature of this resonance, a precision measurement of the line shape, *i.e.* the energy-dependent cross section, with sub-MeV resolution has to be performed. We showed in our MC simulation study [8] the feasibility for such a measurement with the $\bar{p}p$ annihilation experiment PANDA. We quantified the performance on the one hand for an absolute Breit-Wigner decay width measurement and on the other hand to distinguish

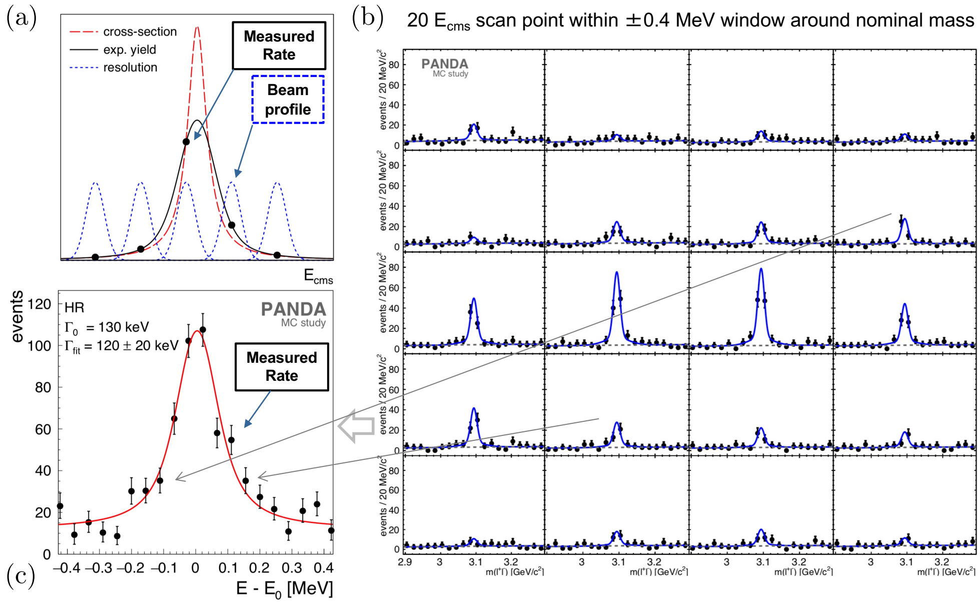

Fig. 2. – Illustration of a MC simulated scan experiment example (σ_s = 100 nb, Breit-Wigner width $\Gamma_0 = 130\,\mathrm{keV}$, two days of data taking per E_{cms} position, HR mode) [8]. *(a)* Schematic to explain the resonance energy scan principle. *(b)* Simulated and reconstructed invariant dilepton spectra at each energy scan positions (going from left to right, top to bottom step-wise through the energy range $(E - E_0)$. *(c)* The resultant energy dependent event yield distribution around the nominal centre-of-mass energy $E_0 = 3.872\,\mathrm{GeV}$ is fitted with a function to extract the parameter of interest; in this example an assumed Breit-Wigner width Γ_0.

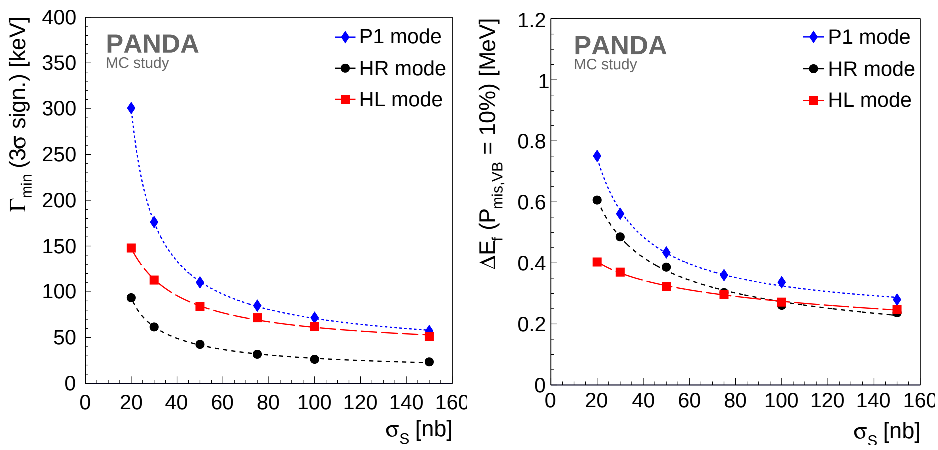

Fig. 3. – Summary of results of the sensitivity study for an absolute (Breit-Wigner) decay width measurement [8]. *Left:* Sensitivity in terms of the minimum decay width $\Gamma_{\min}$ that can be measured with an relative precision of 33 % as a function of the assumed input σ_{S}. *Right:* Sensitivity for line-shape measurements via the E_{f} parameter (Molecule case) to distinguish between a bound and a virtual state scenario in terms of the probability to mis-identify a virtual as a bound state.

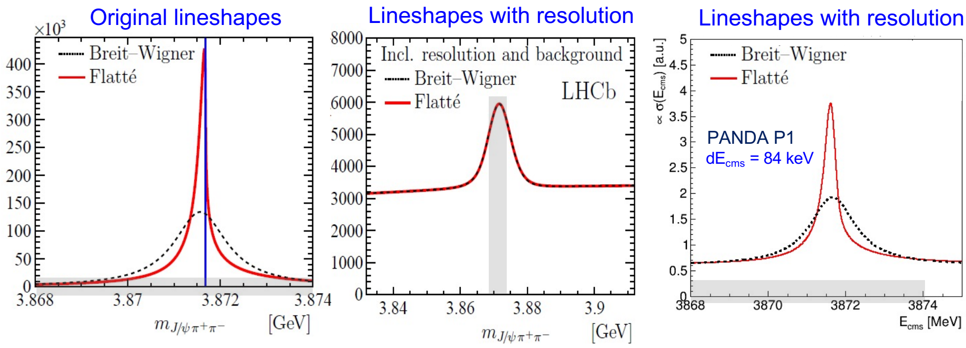

Fig. 4. – Comparison of the Breit-Wigner and Flatté-like line shapes without and with the LHCb and PANDA resolutions convolved. *Left:* The two line shapes (Breit-Wigner vs. Flatté-like) obtained from the fit to the LHCb data [13]. *Centre:* The same two line shapes when including backgrounds and resolution, *i.e.* convolved with the detector resolution. Due to the resolution, the two line shapes cannot be distinguished based on the LHCb data. *Right:* The same two line shapes (Breit-Wigner vs. Flatté-like) convolved with the PANDA beam energy resolution expected for the initial phase (P1) of the experiment. Thanks to the excellent beam energy resolution, they are well distinguishable with PANDA at HESR.

between the bound and the virtual state scenario within a prominent molecular Flatté-like line shape model via the Flatté energy parameter $E_{\rm f}$ that is directly connected with the inverse $D\bar{D}^*$ scattering length [11], [12].

Figure 3 summarises essentially the outcome of that study in terms of the minimum decay width that can be measured with a 3σ accuracy for Breit-Wigner line shape model (Fig. 3, *left*) and in terms of the 10 % mis-identificaton probability $P_{\rm mis}$ to wrongly assign a virtual state as bound state (Fig. 3, *left*), both as a function of the assumed signal production cross section $\sigma_{\rm S}$ of the $X(3872)$. In summary, we will achieve a sub-MeV resolution for both cases, even already in the initial phase of the experiment for the accelerator operation mode P1 within 80 days of data taking.

5. – Addendum to our previous study: Quantification of sensitivity to distinguish between a Breit-Wigner and a Flatteé-like line shape

Lately, a first absolute decay width measurement of $\Gamma_{\rm BW} = 1.39$ MeV has been published by the LHCb Collaboration based on their data. The observed signal in the LHCb data is equally well described by both models, and thus they can not distinguish between a Flatté-like and a Breit-Wigner line shape [13]. The line shapes as obtained by fits to the LHCb data are shown in Fig. 4 *(left)*. When convolved with the resolution, the two line shapes are indistinguishable at LHCb (Fig. 4 *centre*). It is due to the detector resolution that the data is equally well described when using the two corresponding line shape models. The same two line shapes convolved with the PANDA beam energy resolution as expected for the initial phase of the experiment, namely for the accelerator operation mode P1, are displayed in Fig. 4 *(right)*. Thanks to the excellent beam energy resolution, they will be well distinguishable with PANDA at HESR.

As an addendum to our published sensitivity study [8], we investigated and quantified meanwhile the expected PANDA performance in distinguishing these two different line shape models in addition. The assumptions and ingredients we used in the corresponding

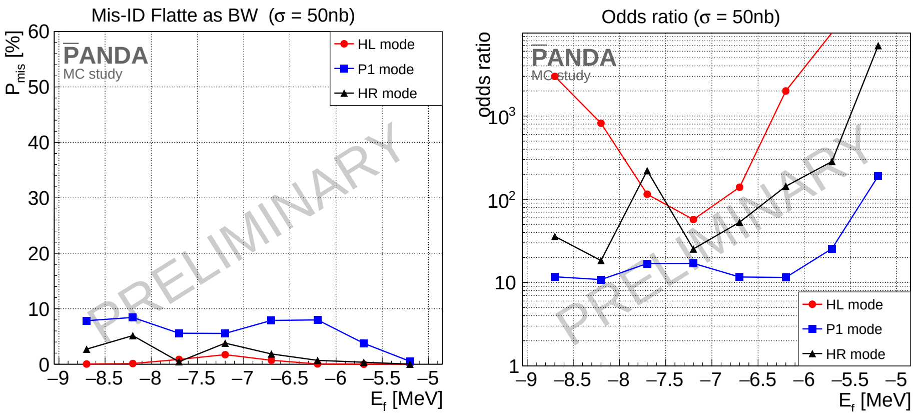

Fig. 5. – *Left:* Sensitivity in terms of the mis-identification probability $P_{\rm mis}$ to wrongly assign the Breit-Wigner line shape instead of the correct Flatté-like line shape as a function of the Flatté energy parameter $E_{\rm f}$, whereas $P_{\rm mis} = 50\,\%$ corresponds to "indistinguishable". *Right:* The correspondingly computed so-called "odds", *i.e.* the number of correct assignments per wrong one, defined as $odds := (1 - P_{\rm mis})/P_{\rm mis}$. Using this measure, the expected performance is at least ten times better than "indistinguishable"

simulations are the same as we employed in [8], whereas this study is now restricted to an assumed signal production cross section of $\sigma_S = 50\,\text{nb}$. We investigated a larger range of line shape parameters for the two different models, namely 10 different Breit-Wigner decay widths Γ and 8 different Flatté energies $E_{\rm f}$. For each setting of input parameters, 10 k data spectra have been generated, to each of which we fitted both models with the parameters left free floating in the fit. And for each input parameter setting, we compared the fit qualities between the best fits of either model to a given spectrum. Whenever the model used for generation of the spectrum has led to a worse fit probability than the competing one, the case has been counted as a mis-identification.

The achievable performance has been evaluated in terms of the mis-identification probability $P_{\rm mis}$ to assign the wrong line shape model, namely the Breit-Wigner line shape for the simulated MC data generated using the Flatté line shape, and vice versa. More details have recently been discussed at QWG2021 and can be found in the presented slides [14], partly also in [15].

The outcome is summarised in Fig. 5. The resultant sensitivities in assigning the correct line shape (shown here for the Flatté-like line shape) are better than 90 % to 98 % (and the results are practically similar for the Breit-Wigner line shape wrongly assigned to be the Flatté-like), depending on the given accelerator operation mode (Fig. 5, *left*). It should be noted that for this figure of merit, a mis-identification probability of $P_{\rm mis} = 50\,\%$ corresponds to "indistinguishable". In order to answer the question, how much better our expected performance is as compared to "indistinguishable", one may consider the so-called "odds" defined as the number of correct assignments per wrong one: $odds := (1 - P_{\rm mis})/P_{\rm mis}$. The corresponding odds computed for the results of our study are shown in Fig. 5, *(left)*. Using this measure, with PANDA, we expect to be at least a factor of 10 better than "indistinguishable".

6. – Summary and conclusions

The future PANDA experiment at FAIR under construction in Darmstadt, Germany, will be the facility to study QCD in Europe. The broad physics programme comprises among others hot topics in hadron spectroscopy, particularly in the charmonium region. The possibility of resonance energy scans with the antiproton beam of excellent energy resolution offers unique opportunities for topics in charmonium and open charm physics.

The achievable performances for precision measurements of absolute decay widths and line shapes have been quantified for the example of the famous charmonium-like exotic $X(3872)$ state by a comprehensive MC sensitivity study for such energy scans of narrow states. The sensitivities have been studied for three anticipated HESR accelerator operation modes (P1, HL, HR). Already in the initial phase P1 of the experiment, PANDA will reach sub-MeV resolutions. Furthermore, a proof principle has been provided for an experimental distinction between different line shapes for the $X(3872)$. The sensitivity to distinguish between a Flatté-like and a Breit-Wigner line shape, which appear indistinguishable based on the LHCb data, has been quantified to be at least ten times better then indistinguishable, again already for the initial phase P1, *cf.* also [16].

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