Comprehensive evidence about a narrow $p\bar{p}$ state of mass $2.02 \text{ GeV}/c^2$

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Abstract

We report evidence for the existence of a narrow $p\bar{p}$ state with a mass of $2.02 \text{ GeV}/c^2$ and a width below $10 \text{ MeV}/c^2$ produced in $\pi^+p(\pi^-p)$ interactions at $20(12) \text{ GeV}/c$ in six final states, proceeding via baryon exchange mechanism, that could be interpreted as a *baryonium* candidate. The data come from a new analysis of WA56 experiment made with the CERN Ω spectrometer. Our results are based on the study of an unexplored kinematic region of baryon exchange processes, the central production of mesons. An agreement is found between our results and an earlier observation of this state, and an explanation is given why it was not seen in several other experiments.

Key words: exotic resonances, narrow baryonium, baryon exchange, central production.

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1 Introduction

In this paper we would like to draw the attention of the reader to the long-standing problem of narrow $p\bar{p}$ states, customarily called baryonia. There is a common opinion that this problem disappeared after several experiments had failed to confirm baryonium candidates in the beginning and the middle of the 80's. Here we would like to present arguments confronting this common opinion. They come from the study of the data of one of the experiments mentioned above, the CERN WA56 experiment designed to select baryon exchange processes (note that up to now no other comparable data exist, relevant to this class of hadronic reactions).

The specific goal of the WA56 experiment [1] was to confirm two narrow $p\bar{p}$ states of masses 2.02 and 2.20 GeV/c² which have been observed by Benkheiri et al. in π^-p interactions at 9 and 12 GeV/c [2]. The observed states were interpreted as produced via the mechanism of backward production in association with fast forward $\Delta(1232)$ and N(1520) baryons, following a quasi-two-body process (the diagram corresponding to such a process is presented in Figure 1a). The experiment WA56 has shown the absence of these states in the quoted processes at the level of production cross sections smaller by an order of magnitude than those reported in [2]. Analogous, though less restrictive results were obtained in several other backward production experiments [3-6].

Recently, in a new analysis of the WA56 data we have studied the channels which were not investigated before, namely, the baryon exchange reactions involving one particle which went either undetected or was incompletely reconstructed:

$$\pi^+p \rightarrow p_f p\bar{p}(\pi_s^+), \quad (1)$$

$$\pi^+p \rightarrow p_f \pi^+ p\bar{p}(\pi_s^0), \quad (2)$$

$$\pi^+p \rightarrow p_f \pi^+ \pi^+ p\bar{p}(\pi_s^-), \quad (3)$$

at 20 GeV/c and

$$\pi^-p \rightarrow p_f p\bar{p}(\pi_s^-), \quad (4)$$

$$\pi^-p \rightarrow p_f p\bar{p}\pi^-(\pi_s^0), \quad (5)$$

at 12 GeV/c. Here p_f is an identified fast proton whose momentum is greater than half the beam momentum, and the brackets refer to slow pions that go undetected by the Ω apparatus but are however reconstructed imposing 1-C kinematic fits, as explained below. The very good momentum resolution available from the Ω tracks measurements allows a clear separation and identification of one missing pion channels in our data. As an example of this, we refer to the recently published results on the central production of ρ^0 , f_2 and ρ_3^0 mesons in the baryon exchange reaction:

$$\pi^+p \rightarrow p_f \pi^+ \pi^-(\pi_s^+) \quad (6)$$

at 20 GeV/c (the corresponding diagram is shown in Figure 1b), based on the WA56 data [7], where an experimental approach similar to that which will be presented in this work was used. In the analysis of reaction (6) it was shown that, in baryon exchange induced reactions, the central region is particularly suitable for meson spectroscopy studies, providing a good signal/background ratio. The work described in this paper results from the continuation of the investigations in the central region, with events of reactions (1) to (5), which can be

represented by diagrams similar to that in Figure 1b, with ρ, f mesons replaced by exotic objects decaying to $p\bar{p}$ (an example of such a diagram, central production of $p\bar{p}$ state via double Δ exchange is depicted in Figure 1c).

In each of the reactions (1-5) we have found a signal of the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state, in a restricted kinematic region close to the central one, namely in the band of $p\bar{p}$ system c.m. rapidity ranging from 0 to -1 while the π_s rapidity extends from -1 to -3.5 .

Preliminary results of this investigation have been already presented in Conference Proceedings [8, 9]. In this paper we give further details of our analysis. Also, we discuss the compatibility of all relevant experiments and show their mutual consistence. The upper limits on several mesonic decay modes of the observed state ($\pi^+\pi^-$, $2\pi^+2\pi^-$ and K^+K^- among them) are also given and used to show that this state is not coupled prominently to mesons. We conclude from this that the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state is a baryonium candidate. Such states (exotic mesons coupled strongly to baryons and decoupled from mesons) are predicted by a large variety of theoretical models, which can be found, in particular, in Refs. [10-14].

2 Experimental details

2.1 Setup and exposures

The layout of the Ω spectrometer as used in the WA56 experiment (Figure 2) is described in detail in [1, 7]. We recall here that the main trigger requirement was the detection of a fast forward proton with momentum greater than 10 (7) GeV/c in π^+p (π^-p) reactions at an incident momentum of 20 (12) GeV/c . Also, events containing antiprotons of momenta above $2.6 \text{ GeV}/c$ were vetoed.

These trigger conditions were imposed to single out the kinematic region which corresponds to baryon exchange ($0 \geq u_{p_f} \geq -1.5 \text{ GeV}^2$) in the crossed, u -channel (see Figure 1) and to suppress a diffractive background with fast antiprotons from processes like $\pi^\pm p \rightarrow p_f \bar{p} \pi^\pm p_s$.

The fast proton signature was determined with the aid of two downstream multicell atmospheric Cherenkov counters C1 and C2; C1 having momentum thresholds for pions, kaons and protons at 2.6, 9.6 and $18.2 \text{ GeV}/c$, respectively, and C2 having thresholds approximately a factor of 2 higher. We note that due to the high threshold of C1 for kaons we expect, in the case of the π^-p exposure, a large background of K_f^+ triggered events with kaon momenta close to or lower than $9.6 \text{ GeV}/c$.

In addition to the Cherenkov counters two other types of particle identifiers were used: the time of flight measuring system (TOF, consisting of 17 scintillation slabs covering an area 250cm (length) by 106 cm (height) centered at $x=+75 \text{ cm}$, $y=+135\text{cm}$, $z=0$), and the 24-element scintillation hodoscope ("barrel") surrounding the hydrogen target. The TOF, with a measured time resolution $\sigma = 0.7 \text{ ns}$, allowed p/π^+ ($\bar{p}/\pi^-$) separation from 0.4 to $2.0 \text{ GeV}/c$ momenta in π^+p (π^-p) reactions. In the π^-p exposure, the TOF was used also to identify the K^- in K_f^+ triggered events, with resolution of the $K^-/\bar{p}$ and K^-/π^- ambiguities up to $1.5 \text{ GeV}/c$. The barrel, with an average resolution of 30% in dE/dx measurement, allowed separation of p and $\bar{p}$ from π up to $1.0 \text{ GeV}/c$, and K from π up to $0.5 \text{ GeV}/c$ momenta, with a reasonable efficiency. The use of the response of these particle identifiers has proved to be crucial for the confirmation of the validity and quality of the method used for the

association of events to each channel.

Besides the p and/or $\bar{p}$ identification the barrel information was used to detect and identify the slow spectator pions π_s^+ from reactions (1,4) which escaped the track reconstruction in Ω chambers having very low momenta and going (mainly) to the backward direction.

The experimental sensitivities corresponding to the WA56 analysed data are 150 (30) events/nb in π^+p (π^-p) exposure.

The mass resolution for the centrally produced $p\bar{p}$ system in 1-C fit events has been determined to be about 20 MeV/c² using a Monte Carlo simulation, that was confirmed later studying the central production of the ϕ meson (which is a convenient object for such a test having a natural width of 4.4 MeV/c²), with the same method as presented here [15].

2.2 Selection of events

Events were selected according to the following criteria. The data samples were composed of 3-prong events of $++-$ topology (with one charged track undetected by the Ω spectrometer), 4-prong charge-balanced events with a missing neutral(s), and 5-prong events of $++++-$ topology, in the case of reaction (3). Then, following the same method as used in [7] for the study of reaction (6), a 1-C fit procedure was implemented to reconstruct the 4-momenta of missed pions from reactions (1-5). First, the missing mass squared (MM^2), was calculated with appropriate mass hypotheses for the detected particles, where clear signals of lost π_s^+ , π_s^0 and π_s^- were seen (Figure 3). The events were selected if they fell in the m_π^2 band, namely $|MM^2 - m_\pi^2| < 0.16(0.12) (GeV/c^2)^2$ in the π^+p (π^-p) exposure. Then a 1-C momentum-energy balance fit was performed. For the analysis presented here we retained the events (about 50% of those lying in the m_π^2 band) which passed the 1-C kinematic fit with a $P(\chi^2) > 5\%$. However, for events fitting reaction (2) we retained only those having rapidity values $y_{\pi^+} > y_{p\bar{p}}$ and for events fitting reaction (5) we retained only those having $p_{\pi^-} < p_{\bar{p}}$.

Also, from events of reactions (1,4) the sub-samples were separated, in which a kinematically recovered π_s^+ (π_s^-) was detected by an appropriate barrel strip (which means association accuracy $\pm 8^\circ$ in azimuthal angle). This selection suppresses various backgrounds originating from reactions with more than one particle lost (mainly, with one or more additional π^0) to the sample of events of reactions (1,4). Moreover, such a selection leads to an improvement of the mass resolution, eliminating events with badly measured tracks.

2.3 Classification of events according to the number of constraints

The events selected under such conditions (1-C kinematic fit and association of the slow pion with the fired barrel strip) are 2-constraints events. In what follows, we will use this term (2-C events) for clarity. Moreover, we will use the terms 4-C events to distinguish the 2-C events in which p and $\bar{p}$ both were identified, and 5-C events for those of the 4-C events in which the π_s^+ was further identified with the barrel dE/dx measurement.

Analogously, we will use the term 3-C events to mark the 1-C fit events of reactions (2,5) in which p and $\bar{p}$ both were identified.

2.4 Backgrounds

As we know from the previous study of the data [7], the dominating background to events of reactions (1-3) in the π^+p exposure comes from processes similar to (1-3), with additional undetected particles (π^0 's and/or slow π^+, π^-) in the final state. There is no reason to expect that the signal of the $p\bar{p}$ state would differ markedly in all these processes, so the presence of such type of a background seems to be not affecting essentially the experimental signal to background ratio.

The situation is different for the π^-p exposure where the dominating background comes from the K_f^+ triggered events, in which no signal of the $p\bar{p}$ state can be expected. As we will see below, only the use of particle identification allows a satisfactory suppression of the K_f^+ background in events of reactions (4,5).

3 The $p\bar{p}$ mass spectra

3.1 π^+p exposure

The $p\bar{p}$ mass spectra from reactions (1,2) are shown in Figure 4, where peaks at a mass close to 2.02 GeV/c² are clearly seen. Though the signal/background ratios are small, the mass spectra fits reveal that these peaks are well above the background possessing the high statistical significance.

The fits were made with a parameterization of the $p\bar{p}$ mass spectra of the form

$$A(M - M_0)^\alpha \exp\{(M_0 - M)\beta\}(1 + BW) \quad (7)$$

where $M_0 = 2m_p$, and BW means a Breit-Wigner term taken as

$$BW = \frac{\Gamma^2}{(M - M_0)^2 + \Gamma^2/4}$$

(We have also tried fifth-order polinomials for background description which was used in evaluating systematic uncertainties; note, the background yields tend to decrease with the polinomials). The resulting parameters of the BW together with the χ^2 values obtained, the number of degrees of freedom and the statistical significance of the signals (in standard deviation units) are displayed in Table 1. The obtained widths are compatible with our experimental resolution, 20 MeV/c² for 1-C samples, and 10 MeV/c² for the higher-constraint ones, which means that a smaller width of the observed state is not excluded.

Two kinematic cuts were used to suppress the diffractive background and to reinforce the yields of the central regions of reactions (1-5):

i) $\cos \theta_J < 0.6$, where θ_J is the Jackson angle of the $\bar{p}$ in the $p\bar{p}$ rest system, with the z axis taken along the $(\vec{p}_{beam} - \vec{p}_{p_f})$ and $(\vec{p}_{beam} - \vec{p}_{p_f} - \vec{p}_{\pi^+})$ directions for reactions (1) and (2), respectively (the directions of the virtual exchanged baryon in these reactions). In case of $p\bar{p}$ resonance production the $\cos \theta_J$ distribution is expected to be symmetrical while the diffractive background is expected (and was found) to be concentrated in a forward cone.

ii) The cut $\Delta p = |\vec{p}_p| - |\vec{p}_{\pi_s}| > \Delta p_{min}$, with $\Delta p_{min} = 1$ and 0.8 GeV/c for reaction (1,4) and (2,3,5), respectively, turned out to be rather effective to isolate the $p\bar{p}$ system from the slow particles in all reactions under investigation.

Analogous distributions for 2-C fit events of reaction (1) are shown in Figures 5a,b. Figures 5c, 5d show the $p\bar{p}$ mass spectra for 4-C and 5-C events of this reaction, respectively. It can be seen that the use of particle identifiers produces an essential improvement of the signal to background ratio, due to the fact that these selections happen to favour the kinematic region of $p\bar{p}$ production where diffractive background is small. Moreover, improvement of the signal to background ratio with particles being identified disproves the hypothesis that the origin of the observed peaks could be due to a kinematic reflection of known resonances, e.g. the ρ meson.

$p\bar{p}$ mass spectrum for 3-C events of reaction (2) is plotted in Fig.5d. Figure 5e shows the $p\bar{p}$ mass spectrum for 1-C events of reaction (3), where a signal of 2.02 GeV/c² state is also visible.

3.2 π^-p exposure

In π^-p exposure, where the background of K_f^+ triggered events was high, we have found that events of reactions $\pi^-p \rightarrow K_f^+ p \pi^- K_s^-$ contaminate strongly the 3-prong sample, whereas the 4-prong sample is contaminated by the reactions $\pi^-p \rightarrow K_f^+ p \pi^- \pi^- K^0$ and $\pi^-p \rightarrow K_f^+ p \pi^- K^- \pi^0$. To reduce this background we have employed the TOF to identify K_s^- among the negative tracks of events of this exposure resolving the ambiguities K^- versus $\bar{p}$ (reactions 4,5) and K^- versus π^- (reaction 5) with subsequent rejection of the background events.

Figure 6 shows the $p\bar{p}$ mass spectra for events of reactions (4,5) selected under such conditions, in addition to other cuts described above.

3.3 Combining π^+p and π^-p exposures

Combining the $p\bar{p}$ mass distributions of 4-C and 3-C events of reactions (1,2) and (4,5) we plot the 5 MeV/c² bin width spectrum shown in Figure 7. The position of the 2.02 GeV/c² peak was fitted to be $M_0 = (2.015 \pm 0.003)$ GeV/c² which is our most accurate estimate of the mass of this state. Statistical significance of the peak exceeds 5 s.d.

To conclude this section we remark that the mass fit results for the 2.02 GeV/c² $p\bar{p}$ states, given in Table 1, are in good agreement with those of Benkheiri et al. [2]. However, the second $p\bar{p}$ state at a mass of 2.20 GeV/c², reported in [2], is not seen in our data.

4 Production mechanism and integrated cross sections

The rapidity spectra of the fastest (p_f) and of the slowest (π_s) particles of reactions (1,2), (4,5), and of the $p\bar{p}$ system for events selected to have the $p\bar{p}$ mass in the 2.02 GeV/c² region are shown in Figure 8. Though the three corresponding structures are clearly separated only for reaction (1) (see Figure 8a) the other reactions show very similar features indicating a dominance of the central region in what concerns the production of the observed $p\bar{p}$ state.

The momentum transfer distributions u'_{p_f} (reactions 1 and 4) or $u'_{p_f \pi^\pm}$ (reactions 2 and 5), and u'_{π_s} , where $u' = u_{max} - u$, for events in the 2.02 MeV/c² $p\bar{p}$ mass band, show an exponential behaviour, with slopes in the range of 2-3 (GeV/c)⁻², similarly to the central production of the ρ^0 , f_2 and ρ_3^0 mesons studied in [7].

Taking into account these u' dependences and assuming isotropic angular distributions of $p\bar{p}$ state decays, we have calculated the total acceptances of the experiment for the reactions (1,2) and (4,5). Using our mass fits to subtract the background under the observed $p\bar{p}$ peaks we have obtained the numbers of 2.02 GeV/c² mesons produced in the reactions. With these, and for each channel we have obtained the integral cross sections given in Table 2 together with the acceptances and event numbers.

The errors quoted in Table 2 are statistical only. The main sources of systematic errors are the uncertainties in the background contribution and acceptance calculation. We use the variation of background yields when passing from form (7) to fifth-order polynomial as an estimate of the relative background uncertainty due to its shape. It was found to be in the range from 10 to 20%. The systematic errors for acceptance calculation come from the uncertainties in the track reconstruction and trigger efficiency as well as from the variability of the particle spectra and angular distributions generated by kinematic model. The former have been estimated to be less than 20% by comparing the WA56 quasi-two-body reaction cross sections at 12 GeV/c [16] with those of ref. [17], while the latter have been evaluated to be about 20% and 30% for reactions (1,4) and (2,5), respectively, by varying parameters of the central production model used in the acceptance calculations.

These uncertainties (due to production mechanism) are increased abnormally when trying to calculate the experimental acceptance for reaction (3). Therefore we avoid to give the cross section for the production of the 2.02 GeV/c² state in this reaction, restricting only its value to be below 30 nb.

At 12 GeV/c we can compare our cross sections for production of the 2.02 GeV/c² $p\bar{p}$ state in reaction (4) and those reported in [2], which were calculated in terms of the backward production of this state, with a quasi-two-body peripheral production mechanism. Our cross section exceeds those reported in [2] by factors 3 to 9. We have recalculated the cross section for the signals of Ref. [2] assuming our model of central production of the 2.02 GeV/c² $p\bar{p}$ state, and taking into account the geometrical acceptance of the [2] apparatus. We have obtained a cross section of $(120 \pm 25 \pm 20)$ nb, which is in agreement with our result.

5 Baryonium signature of the observed $p\bar{p}$ state

Together with the $p\bar{p}$ final state of the 2.02 GeV/c² resonance we have investigated also the mesonic, $\pi^+\pi^-$, $2\pi^+2\pi^-$, $\pi^+\pi^-\pi^0$ and K^+K^- final states, produced centrally in the baryon exchange reactions:

$$\pi^\pm p \rightarrow p_f \pi^+ \pi^- (\pi_s^\pm) \quad (8)$$

$$\pi^\pm p \rightarrow p_f 2\pi^+ 2\pi^- (\pi_s^\pm) \quad (9)$$

$$\pi^\pm p \rightarrow p_f \pi^+ \pi^- \pi^0 \pi_s^\pm \quad (10)$$

$$\pi^\pm p \rightarrow p_f K^+ K^- (\pi_s^\pm) \quad (11)$$

at 20 (12) GeV/c incident π^+ (π^-) momenta. No peaks at 2.02 GeV/c² were found in any of reactions (8-11). In order to illustrate the behaviour of the data in the vicinity of the 2.02 GeV/c² mass we show in Figure 9 the $\pi^+\pi^-$ and $2\pi^+2\pi^-$ mass spectra from reactions (8,9). Only ρ^0 and f_2 signals are seen, in the $\pi^+\pi^-$ spectra, a feature described in [7, 16]. The upper limits for the 2.02 GeV/c² state production cross sections multiplied by the mesonic branching ratios are given in Table 2.

Recently a quasinuclear approach was proposed for an explanation of $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ data [18]. This approach predicts the existence of narrow quasinuclear states decaying into $p\bar{p}$ as well as into $K^{0*}(892)\bar{K}^{0*}(892)$ final states [19]. We have tried to find the 2.02 GeV/c² signal in the $K^*\bar{K}^*$ final states in the baryon exchange reaction

$$\pi^+p \rightarrow p_f K^+ \pi^+ K^- \pi^- (\pi_s^+) \quad (12)$$

with the same method as described above, to verify this possibility.

No signal was found in the $K^+K^-\pi^+\pi^-$ nor in the $K^{0*}(892)\bar{K}^{0*}(892)$ mass spectra. This gives an upper limit for the cross section for production of the 2.02 GeV/c² state decaying to $K^{0*}(892)\bar{K}^{0*}(892)$ final state, quoted in Table 2, which is at the same level as the $p\bar{p}$ value.

On the other hand, the missing mass spectrum to the $p_f\pi^+$ in two-prong topology of the π^+p exposure shows, when using the selection criteria aimed to separate the neutral system to be in the central region (missing momentum $p_{mis} > 2$ GeV/c, longitudinal momentum of π^+ , $P_{l\pi^+} < 0.4$ GeV/c), a four-standard deviation peak centered at 2.01 GeV/c², shown in Figure 10. This two-prong topology channel is singled out by the absence of the diffractive background. The peak width is in a good agreement with the missing mass resolution in this mass range (± 30 MeV/c²) expected from the Monte Carlo simulation. We interpret this signal as an evidence for the decay of the 2.02 GeV/c² state into neutrals. The branching ratio for this decay mode was found to be about 2 times higher than the expected branching to the $n\bar{n}$ channel alone (see Table 2), however the systematic uncertainties are comparable to the difference¹ and the evidence for unseen mesonic channels is not compelling. Thus we derive an upper limit for the partial width of all neutral mesonic modes roughly equal to the partial width of the two $N\bar{N}$ modes.

From these results and taking into account the small width of the observed $p\bar{p}$ state we believe that it is a firm baryonium candidate, an exotic resonance state, coupled strongly to baryons and decoupled from mesons, as has already been predicted earlier by various theoretical models [10-14].

6 Are all experimental results on the 2.02 GeV/c² $p\bar{p}$ state compatible?

6.1 Production experiments

Apparently, the set of the experimental results on the 2.02 GeV/c² $p\bar{p}$ state in production experiments looks controversial, containing claims *pro* and *contra*. However, they can be put into accordance with a simple consideration that all the results on the production cross sections (or on upper limits for them) are model-dependent, because it is necessary to specify a reaction mechanism in order to calculate the experimental acceptances. This appears to be a point of considerable importance, since different cross sections can be obtained using the same number of fitted events. With this possibility in mind we may proceed to review the experimental results on the production of 2.02 GeV/c² $p\bar{p}$ state.

First of all, the two most obvious problems must be solved: the original WA56 evidence against 2.02 GeV/c² $p\bar{p}$ state [1] confronted with the observation of Benkheiri et al [2], and

¹Systematic error for the cross-section $\pi^+p \rightarrow p_f\pi_s^+ + \text{neutrals}$ reaches 30%, mainly due to the uncertainty in the trigger and slow pion track reconstruction efficiencies.

the inner compatibility of the WA56 results (earlier negative evidence [1] confronted with the present positive one).

We start with the results on the production cross section of Benkheiri et al. [2] for the 12 GeV/c π^- run. The experimental acceptances were calculated in [2] assuming mechanism of backward production of the 2.02 GeV/c² $p\bar{p}$ state. To get a proper comparison of the results, we have recalculated the acceptance of the apparatus [2] using our production mechanism model, as mentioned in Sect.4. The acceptance for 4-constraint events, used in the analysis [2] has turned out to be essentially smaller than the one for backward production mechanism for the following reasons.

A $p\bar{p}$ state produced backward in the c.m. frame (see diagram 1a) is going forward in the lab providing its decay fragments, p and $\bar{p}$, with energy high enough to ensure their effective detection, together with the fast pion (π^- in diagram 1a). Thus, all outgoing particles in a $p\bar{p}$ backward production process are easily detectable. This is not the case for the central production of this system in reactions (1-6) (as an example, see diagram 1c). Here the backward produced particles are low momentum pions, which go mainly backward in the lab frame too. Such pions may escape detection if the experimental setup is not designed properly to catch them.

As a result of the revised acceptance calculation, the 2.02 GeV/c² $p\bar{p}$ state production cross section has been found to be $(120 \pm 25 \pm 20)$ nb in experiment [2], in good agreement with our value. This situation is illustrated by Figure 11.

Similarly, the 4-prong acceptance of the WA56 apparatus calculated in terms of the central production is a factor of 10 smaller than the one for backward production. Using the $p\bar{p}$ spectrum from the 20 GeV/c π^+p run shown in Figure 3b of paper [1] (before selection of the recoil $p_f\pi^+$ system mass in the $\Delta^{++}(1232)$ region) one can obtain an upper limit of 30 nb (at 95% C.L.) for the 2.02 GeV/c² $p\bar{p}$ state which should be compared with the $(23 \pm 4 \pm 5)$ nb cross section reported in this work for reaction (1). As to the 12 GeV/c π^-p exposure, some irregularity around 2.02 GeV/c² can be seen in the $p\bar{p}$ mass distribution in Figure 2b of [1]. The number of events of this irregularity taken as the upper limit for the 2.02 GeV/c² $p\bar{p}$ state corresponds just to the 100 nb cross section, which is again in good agreement with our cross section $(84 \pm 27 \pm 20)$ nb for reaction (4), see Figure 11.

Thus, it is possible to get an agreement for the set of basic results on the production of the 2.02 GeV/c² $p\bar{p}$ state in the baryon exchange experiments reported in [1, 2] and this work. As to the other baryon exchange experiments which have claimed the absence of the 2.02 GeV/c² $p\bar{p}$ state [3-6], it is even easier to get an analogous explanation for them because of their lower experimental sensitivities and weaker restrictions imposed on the 2.02 GeV/c² $p\bar{p}$ state production. Note also the original observation of a signal around 2.02 GeV/c² $p\bar{p}$ mass in the experiment [5] (at a small statistical significance level, about 2 s.d.) presented in [20], which was disregarded later in the paper [5] being attributed to the possible ρ^0 meson reflection contaminating the $p\bar{p}$ spectrum. The same group reported also the negative results of the search for narrow $p\bar{p}$ states in reactions $\bar{p}p \rightarrow (p\bar{p})_f\pi^0$ and $\bar{p}p \rightarrow (p\bar{p})_f\rho^0$ at 5 GeV/c [21]. These reactions are dominated by baryon exchange, and are beam fragmentation region analogons of the backward production processes. We would like to note that in reaction with ρ^0 meson, a 2 s.d. signal is seen at a $p\bar{p}$ mass near 2.02 GeV/c², with corresponding production cross section of (150 ± 80) nb.

Also some irregularities at 2.02 GeV/c², at small signal to background ratios and with statistical significance varying from 2 to 3 s.d., can be seen in the $p\bar{p}$ spectra of experiments

which aimed to study the $p\bar{p}$ system produced diffractively in π^-p interactions at 16 GeV/c [22], in π^+p interactions at 50 GeV/c [23] and in pp interactions at 11.75 GeV/c [24], and of experiment [25] with $p\bar{p}$ interactions at 12 GeV/c. Unfortunately, it is impossible to do a quantitative comparison of these results with those of baryon exchange experiments because of the lack of the data necessary to calculate acceptances for the experiments [22-24], with a proper production mechanism.

Such a comparison can be done for an Ω experiment [26] exploring the central region in π^-p and π^+p induced reactions at 40 GeV/c. The upper limits for the central production of the 2.02 GeV/c² $p\bar{p}$ state are quoted to be about 36 nb in this experiment. For example, a small bump at 2.02 GeV/c² seen in the π^-p data corresponds to a production c. s. of 22 ± 12 nb.

Note also indications on the $p\bar{p}$ structure in the mass region close to 2.02 GeV/c² in experiments on $p\bar{p}$ electroproduction at 11.5 GeV [27], and on $p\bar{p}$ photoproduction at 4.7–6.6 GeV [28].

We summarize all these results, including our own, in Table 3. Those hadron beam experiments which give positive indications for the 2.02 GeV/c² $p\bar{p}$ state for which production cross sections are known or could be calculated, are shown in Figure 12, together with the upper limit for its central production in 20 GeV/c, the 4C channel data of Ref. [1].

We finish the review of the production experiments on the 2.02 GeV/c² state by recalling that a charged narrow state of this mass decaying into $p\bar{n}$ and $\bar{p}n$ has also been reported [29]. The authors claim that the state is not peripherally produced, which effectively implies that central production mechanism is favoured. Unfortunately, with our data we have no possibility to look for this charged state since its central production (and subsequent decay to the $p\bar{n}$ and $\bar{p}n$) would assume two particles going undetected in our experimental configuration (neutron and slow pion). As to the backward production of this charged state, the upper limits for it are given in [30].

6.2 Formation experiments. Restrictions on the width of the 2.02 GeV/c² state

Contrary to the S-meson (a narrow $p\bar{p}$ state at a mass of about 1.94 GeV/c²) the 2.02 GeV/c² mass region has not been investigated comprehensively in formation experiments (this region corresponds to $\bar{p}$ beam momenta around 800 MeV/c). A fine-step scan of this region has been done in four experiments only: two of them, [31, 32], studying the total and charged annihilation $p\bar{p}$ cross sections; and two others studying the backward elastic cross section [33], and the charge exchange ($p\bar{p} \rightarrow n\bar{n}$) cross section, [34]. No signal of the 2.02 GeV/c² state was found; the most accurate restrictions result from the charge exchange experiment [34] (see below). From these results, a very important conclusion about the width of the 2.02 GeV/c² state can be derived using the relation between observable production cross section $\sigma_{exp}^{p\bar{p} \rightarrow n\bar{n}}$ of a resonance having a mass 2.02 GeV/c², and its other quantum numbers such as spin J , elasticity $\beta_{N\bar{N}}$ and width Γ :

$$\sigma_{exp}^{p\bar{p} \rightarrow n\bar{n}}(2.02) \simeq (2J+1)\beta_{N\bar{N}}^2 \times 2.25\text{mb} \times \frac{\Gamma}{2\Delta} \arctan \frac{2\Delta}{\Gamma} \quad (13)$$

where Δ is the experimental mass resolution (for derivation of this relation see Appendix).

The upper limit for the $\sigma_{exp}^{p\bar{p} \rightarrow n\bar{n}}(2.02)$ can be derived from the results obtained in [34] to be about 0.2 mb^2 , the experimental resolution Δ being $\simeq 2 \text{ MeV}/c^2$. Confronting these values with the estimation (A.4) of Appendix and formula (13), one can conclude that the width of the $2.02 \text{ GeV}/c^2$ state is essentially smaller than the quoted resolution (unless the elasticity $\beta_{N\bar{N}}$ is much smaller than 1, which seems to be excluded by its not being seen in mesonic final states, see Sect.5). Thus, from (13) we get an inequality

$$(2J + 1)\beta_{N\bar{N}}^2 \Gamma \leq 0.23 \text{ MeV}/c^2 \quad (14)$$

Assuming $\beta_{N\bar{N}} = 1$ one gets for $J = 0$

$$\Gamma_0 \leq 230 \text{ keV}/c^2 \quad (15)$$

and for $J = 2$

$$\Gamma_2 \leq 50 \text{ keV}/c^2 \quad (16)$$

One can relax these restrictions, supposing that real baryonium can decay into mesonic channels as well ($\beta_{N\bar{N}} < 1$). However, even with $\beta_{N\bar{N}} = 0.5$, the Γ upper limits (15,16) become $1 \text{ MeV}/c^2$ and $200 \text{ keV}/c^2$ respectively, which are still essentially lower than the experimental restriction on the width of the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state obtained in this work ($\Gamma \leq 10 \text{ MeV}/c^2$). This was already noted in [35].

6.3 Remark on the production mechanism of the $2.02 \text{ GeV}/c^2$ state

While double baryon exchange mechanism of (central) production of the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state is capable to put into accordance the set of the experimental results discussed above, the reason why this mechanism dominates over the backward production, i.e. the production through single baryon exchange, has to be explained. Indeed, the central production of ordinary mesons also shows a prevalence over their backward production [7], but the enhancement factor does not exceed 4 in that case, whereas for the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state production this factor is at least 20, as one can see comparing the central production cross sections reported here and the upper limits for the backward production cross sections given in [1].

A simple way to explain such a peculiarity of the measured cross sections, together with the narrowness of the observed $p\bar{p}$ state is to assume that this state is coupled to the $\Delta\bar{\Delta}$ system much stronger than to the $N\bar{N}$ one. If this assumption is true, processes of backward production of the $2.02 \text{ GeV}/c^2$ $p\bar{p}$ state, where double delta exchange is excluded, are naturally suppressed, and the processes dominate illustrated by diagram shown in Figure 1c. Very small width of the observed $p\bar{p}$ state also gets an explanation with this hypothesis: once being produced in the collision of virtual Δ and $\bar{\Delta}$ this state is not allowed to decay

²A close limit can be derived from the experiment [33], in which the differential elastic cross section $d\sigma/d\Omega$ at $\cos(\theta_{c.m.}) = -0.994$ was measured, if one assumes isotropic decay of the $p\bar{p}$ resonant state. The experimental resolution Δ was $3 \text{ MeV}/c^2$ in [33]

into the real $\Delta\bar{\Delta}$ since its mass is below the corresponding threshold, and it is forced to decay via suppressed $p\bar{p}$ channel.

In view of the possible double delta exchange dominance in the 2.02 GeV/c² $p\bar{p}$ state production, future investigations of the problem in the dedicated experiments should account for this possibility. As a good test of it, a careful experimental study of the π^-p and $\bar{p}p$ interactions proceeding via baryon exchange, with events triggered by fast protons and fast π^+ , respectively, and both with the detection of slow π^- produced backward, is strongly advocated.

7 Conclusion

The baryon exchange reactions $\pi^+p \rightarrow p_f p\bar{p}\pi_s^+$, $\pi^+p \rightarrow p_f \pi^+ p\bar{p}\pi_s^0$, $\pi^+p \rightarrow p_f \pi^+ \pi^+ p\bar{p}\pi_s^-$ at 20 GeV/c and $\pi^-p \rightarrow p_f p\bar{p}\pi_s^-$, $\pi^-p \rightarrow p_f p\bar{p}\pi^- \pi_s^0$ at 12 GeV/c incident momenta were identified using the WA56 data obtained at the CERN Ω spectrometer. A narrow $p\bar{p}$ state of mass $M = 2.015 \pm 0.003$ GeV/c² and width $\Gamma \leq 10$ MeV/c² (compatible with experimental resolution) is clearly seen. We have found also evidence for the neutral decay mode of the observed state with a branching ratio close to the $p\bar{p}$ one. However, the explicit mesonic decay modes of this state were not seen, and we conclude from this that the observed state is a baryonium candidate. Its mass and width are in a good agreement with those of the state found by Benkheiri et al. [2]. The large difference in the production cross sections obtained here and reported in [2] can be explained by the different production mechanisms assumed. The apparent dominance of the central production of the 2.02 GeV/c² $p\bar{p}$ state can explain why backward production experiments [1,3-6] have failed to confirm this state, including Z. Ajaltouni et al. [1], who analysed the 4-constraint events of the WA56 experiment. The non-observation of the state in formation experiments done so far is quantitatively understandable in the framework of the same central production mechanism.

We hope that this work may find a use as a basis to a baryonium sector of future hadronic experiments of high resolution and sensitivity. A baryon exchange trigger is a must in production experiments; in formation experiments, the step width (~ 100 keV/c²) is crucial.

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Appendix

The contribution of a resonance with a spin J into the cross section of the process $1 + 2 \rightarrow 1' + 2'$ (formation process) has the form (see [36])

$$\sigma_{BW}(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \times \frac{\pi}{k^2} \frac{B_{in}B_{out}\Gamma_{tot}^2}{(E-E_R)^2 + \Gamma_{tot}^2/4} \quad (\text{A.1})$$

For $N\bar{N} \rightarrow N\bar{N}$ at $E = E_R$ one has

$$\sigma_{BW}^{N\bar{N} \rightarrow N\bar{N}}(E_R) = (2J+1)B_{N\bar{N}}^2 \frac{\pi}{k_R^2} \quad (\text{A.2})$$

At $E_R = 2.02$ one has $k_R \simeq 0.37$ GeV/c and thus

$$\begin{aligned} \sigma_R^{N\bar{N} \rightarrow N\bar{N}}(E_R = 2.02) &\simeq (2J+1)B_{N\bar{N}}^2 \times 23 \text{ GeV}^{-2} \\ &\simeq (2J+1)B_{N\bar{N}}^2 \times 9.0 \text{ mb} \end{aligned} \quad (\text{A.3})$$

Now, for the $p\bar{p} \rightarrow p\bar{p}$ process, taking into account the nucleon isospin Clebsch-Gordan factor, we have an estimate for the cross section at maximum (the same would be true for the $p\bar{p} \rightarrow n\bar{n}$ reaction)

$$\begin{aligned} \sigma_R^{p\bar{p} \rightarrow p\bar{p}}(E_R = 2.02) &\simeq \\ &(2J+1)\beta_{N\bar{N}}^2 \times 2.25 \text{ mb} \end{aligned} \quad (\text{A.4})$$

where $\beta_{N\bar{N}}$ is the elastisity ($\beta_{N\bar{N}} = 1$ for an "ideal" baryonium that decays into $p\bar{p}$ and $n\bar{n}$ only).

Let us take into account an experimental resolution $\pm\Delta$. The cross section averaged over the interval 2Δ around E_R is (for a narrow resonance)

$$\begin{aligned} \sigma_{exp}(E_R) &= \frac{1}{2\Delta} \int_{E_R-\Delta}^{E_R+\Delta} \sigma_{BW}(E) dE \simeq \\ &\sigma_R \times \frac{\Gamma}{2\Delta} \arctan \frac{2\Delta}{\Gamma} \end{aligned} \quad (\text{A.5})$$

Thus,

$$\begin{aligned} \sigma_{exp}^{p\bar{p} \rightarrow p\bar{p}}(2.02) &\simeq \\ &(2J+1)\beta_{N\bar{N}}^2 \times 2.25 \text{ mb} \times \frac{\Gamma}{2\Delta} \arctan \frac{2\Delta}{\Gamma} \end{aligned} \quad (\text{A.6})$$

References

- [1] Z. Ajaltouni et al., Nucl. Phys. B **209** (1982) 301
- [2] P. Benkheiri et al., Phys. Lett. B **69** (1977) 483
- [3] R.M. Bionta et al., Phys. Rev. Lett. **44** (1980) 909
- [4] A.S. Carroll et al., Phys. Rev. Lett. **44** (1980) 1572
- [5] S.U. Chung et al., Phys. Rev. Lett. **45** (1980) 1611
- [6] A.D.J. Banks et al., Phys. Lett. B **100** (1981) 191
- [7] V.F. Perepelitsa et al., Z. Phys. C **52** (1991) 407
- [8] A. Ferrer et al., in **Proceedings of the 2nd Biennial Conference on Low Energy Antiproton Physics LEAP'92, Courmayeur, 1992**; Nucl. Phys. A **558** (1993) 191c
- [9] A. Ferrer et al., in **Proceedings of the 6th International Conference on Hadron Spectroscopy HADRON'95, Manchester, 1995**, edited by M.C.Birse, G.D.Lafferty and J.A.McGovern (World Scientific, Singapore 1996) p.460
- [10] Chan Hong-Mo and H. Högaasen, Phys. Lett. B **72** (1977) 121; Nucl. Phys. B **136** (1978) 401
- [11] M. De Crombrugghe, H. Högaasen and P. Sorba, Nucl. Phys. B **156** (1979) 347
- [12] M. Uehara, Progr. Theor. Phys. **61** (1979) 1137
- [13] G.C. Rossi and G. Veneziano, Phys. Rep. **63** (1980) 149
- [14] Chan Hong-Mo, Nucl. Phys. A **335** (1980) 219
- [15] A. Ferrer et al., Phys. Lett. B **394** (1997), 395
- [16] A. Ferrer et al. (to be published)
- [17] A. Ferrer et al., Nucl. Phys. B **142** (1978) 77
- [18] O.D. Dalkarov, K.V. Protasov, Sov. JETP Lett. **46** (1987) 329; O.D. Dalkarov, K.V. Protasov, I.S. Shapiro, Int. J. Mod.Phys. A **5** (1990) 2155
- [19] O.D. Dalkarov (private communication)
- [20] S.U. Chung et al., in **Proceedings of the 6th International Conference on Experimental Meson Spectroscopy-1980, Brookhaven, 1980**, edited by S.U.Chung and S.J.Lindenbaum (AIP, New York 1981) p.170
- [21] S.U. Chung et al., Phys. Rev. Lett. **46** (1981) 395
- [22] T.A. Armstrong et al., Phys. Lett. B **85** (1979) 304

- [23] W.E. Cleland et al., Phys. Lett. B **86** (1979) 409
- [24] S. Kooijman et al., Phys. Rev. Lett. **45** (1980) 316
- [25] T.A. Armstrong et al., Status Report on WA49, CERN/ SPSC/79-82 SPSC/M.190, 1979 (unpublished)
- [26] W. Beusch et al., **Talk on the XXI International Conference on High Energy Physics, Paris, 1982** (unpublished)
- [27] B.G. Gibbard et al., Phys. Rev. Lett. **42** (1979) 1593
- [28] J. Bodenkamp et al., Phys. Lett. B **133** (1983) 275
- [29] F. Azooz et al., Phys. Lett. B **122** (1983) 471
- [30] P. Benkheiri et al., Phys. Lett. B **81** (1979) 380
- [31] R.P. Hamilton et al., Phys. Rev. Lett. **44** (1980) 628
- [32] T. Sumioshi et al., Phys. Rev. Lett. **49** (1982) 628
- [33] M. Alston-Garnjost et al., Phys. Rev. Lett. **43** (1979) 1901
- [34] R.P. Hamilton et al., Phys. Rev. Lett. **44** (1980) 1179
- [35] V. Perepelitsa, in **Proceedings of the 6th International Conference on Hadron Spectroscopy HADRON'95, Manchester, 1995**, edited by M.C.Birse, G.D.Lafferty and J.A.McGovern (World Scientific, Singapore 1996) p.380
- [36] Review of Particle Properties, Phys. Rev. D **54** (1996) 1

Figure captions.

Figure 1. The diagrams which correspond to: a) the backward production of a $p\bar{p}$ state in π^-p interactions; b) the central production of an (ordinary) meson in π^+p interactions; c) the central production of a $p\bar{p}$ state in π^-p interactions via double Δ exchange.

Figure 2. The layout of the Ω spectrometer as used in the WA56 experiment.

Figure 3. Missing mass spectra a) for events of $++-$ topology in the 20 GeV/c π^+p exposure; b) the same, with missing momentum associated with the barrel strip fired; c) for events of $++++-$ topology in the 20 GeV/c π^+p exposure; d) for events of $++++-$ topology in the 20 GeV/c π^+p exposure; e) for events of $++-$ topology in the 12 GeV/c π^-p exposure; f) for events of $++--$ topology in the 12 GeV/c π^-p exposure. The dashed bands correspond to the events which were fed into 1-C kinematic fit (see text).

Figure 4. Spectra of $p\bar{p}$ mass for 1-C events from a) reaction (1), all events; b) reaction (1), events satisfying the cuts $\Delta p = p_p - p_{\pi_s^+} > \Delta p_{min}$ and $\cos \theta_J < 0.6$; c,d) the same as a,b) for events from reaction (2) with the additional requirement $y(p\bar{p}) < y(\pi^+)$; e,f) the same as in b,d) with p identified by TOF or barrel and/or $\bar{p}$ identified by barrel.

Figure 5. Spectra of $p\bar{p}$ mass for a) 2-C events from reaction (1); b) the same for events which satisfy the cuts as in 4b); c) 4-C events from reaction (1); d) 5-C events from reaction (1); e) 3-C events from reaction (2); f) 1-C events from reaction (3), no cuts.

Figure 6. Spectra of $p\bar{p}$ mass for a) 1-C events from reaction (4) satisfying $\Delta p = p_p - p_{\pi_s^-} > 1$ GeV/c and $\cos \theta_J < 0.6$ cuts; b) 2-C events at the same cuts; c) 1-C events from reaction (5) satisfying $\Delta p = p_p - p_{\pi_s^0} > 0.8$ GeV/c and $\cos \theta_J < 0.6$ cuts; d) the same with $\bar{p}$ identified by TOF or barrel.

Figure 7. Summary spectrum of $p\bar{p}$ mass for 4-C and 3-C events of reactions (1,4) and (2,5).

Figure 8 a-d). Rapidity spectra for fast protons, slow pions and $p\bar{p}$ system for events from reactions (1,2,4,5), respectively.

Figure 9 Spectra of $\pi^+\pi^-$ mass for events from reaction (8) a) π^+p exposure, b) π^-p exposure, and spectra of $2\pi^+2\pi^-$ mass for events from reaction (9) c) π^+p exposure; d) π^-p exposure.

Figure 10. Missing mass spectrum for events of $++$ topology in the 20 GeV/c π^+p exposure, reaction $\pi^+p \rightarrow p_f \pi_s^+ + MM^0$ a) selected under cuts: missing momentum $p_{mis} > 2$ GeV/c, longitudinal momentum of π^+ , $P_{l\pi^+} < 0.4$ GeV/c; b) the same, with the π_s^+ identified by barrel.

Figure 11. The figure shows the cross sections obtained for production of the 2.02 GeV/c² $p\bar{p}$ state measured in [2] and in WA56 experiment, analyzed as originating from i) central (upper part) and ii) backward production (lower part). For backward production, the positive results of [2] were contradicted by the much lower upper limits of [1]. Reanalyzed as central production, the cross section values are higher, reflecting the lower acceptance; and they are in agreement with each other and with the new topological samples used in the present work.

Figure 12. Summary data on the 2.02 GeV/c² $p\bar{p}$ state production cross sections extracted from experiments [1], [2], [21], [25], [26], and this work. Results of experiments Ajaltouni e.a. [1], and Benkheiri e.a. [2] were recalculated with our central production model. The shown errors are statistical only and do not include systematic uncertainties which vary from 15% to 30%.

Table 1.
Parameters of the fits of the $p\bar{p}$ mass spectra from reactions (1-5).

Spectrum	Statistical significance of the $p\bar{p}$ peak (s.d.)	χ^2_{fit}/ndf	Mass of $p\bar{p}$ state (MeV/c ²)	Width of $p\bar{p}$ state (MeV/c ²)
20 GeV/c π^+p data				
Figure 4a	6.0	39/55	2009 $\pm$ 6	30 $\pm$ 12
Figure 4b	7.0	38/55	2012 $\pm$ 6	34 $\pm$ 21
Figure 4c	6.9	51/55	2021 $\pm$ 6	35 $\pm$ 24
Figure 4d	6.0	45/55	2016 $\pm$ 7	39 $\pm$ 20
Figure 4e	4.5	63/55	2012 $\pm$ 7	33 $\pm$ 17
Figure 4f	6.4	61/55	2014 $\pm$ 7	38 $\pm$ 18
Figure 5a	4.4	57/55	2010 $\pm$ 4	17 $\pm$ 9
Figure 5b	4.5	56/55	2009 $\pm$ 4	12 $\pm$ 10
Figure 5c	3.4	53/55	2014 $\pm$ 4	12 $\pm$ 8
Figure 5d	3.8	40/55	2013 $\pm$ 4	12 $\pm$ 10
Figure 5e	3.4	42/55	2018 $\pm$ 6	21 $\pm$ 18
Figure 5f	3.5	60/55	2010 $\pm$ 8	11 $\pm$ 7
12 GeV/c π^-p data				
Figure 6a	3.8	43/55	2024 $\pm$ 5	22 $\pm$ 15
Figure 6b	3.0	49/55	2023 $\pm$ 6	15 $\pm$ 11
Figure 6c	2.9	69/55	2020 $\pm$ 7	10 $\pm$ 5
Figure 6d	4.4	78/55	2015 $\pm$ 4	15 $\pm$ 9
Sum of 4-C and 3-C events				
Figure 7	5.2	92/94	2015 $\pm$ 3	10 $\pm$ 4

Table 2.

Number of events, acceptances and integral cross sections

times branching ratio ($\sigma_{int} \times \text{BR}$) for the centrally produced 2.02 GeV/c² $p\bar{p}$ state.

Channel	Number of events (background subtracted) or upper limit at 95 % CL.	Acceptance (%)	$\sigma_{int} \times \text{BR}$ (nb)
<hr/> 20 GeV/c π^+p data <hr/>			
$\pi^+p \rightarrow p_f p \bar{p}(\pi_s^+)$	256 ± 42	7.4	23 ± 4
$\pi^+p \rightarrow p_f p \bar{p} \pi^+(\pi_s^0)$	458 ± 66	3.2	95 ± 14
$\pi^+p \rightarrow p_f \pi_s^+ + \text{neutrals}$	80 ± 19	1.3	41 ± 10
$\pi^+p \rightarrow p_f p \bar{p} \gamma \pi_s^+$	< 2	1.2	< 1
$\pi^+p \rightarrow p_f \pi^+ \pi^-(\pi_s^+)$	< 20	3.4	< 4
$\pi^+p \rightarrow p_f \pi^+ \pi^- \pi^0 \pi_s^+$	< 20	1.2	< 11
$\pi^+p \rightarrow p_f 2\pi^+ 2\pi^-(\pi_s^+)$	< 40	3.8	< 7
$\pi^+p \rightarrow p_f K^+ K^-(\pi_s^+)$	< 60	4.2	< 10
$\pi^+p \rightarrow p_f K^{0*} \bar{K}^{0*}(\pi_s^+)$	< 80	2.2	< 24
<hr/> 12 GeV/c π^-p data <hr/>			
$\pi^-p \rightarrow p_f p \bar{p}(\pi_s^-)$	47 ± 15	1.9	84 ± 27
$\pi^-p \rightarrow p_f p \bar{p} \pi^-(\pi_s^0)$	51 ± 17	0.8	210 ± 70
$\pi^-p \rightarrow p_f \pi^+ \pi^-(\pi_s^-)$	< 5	1.6	< 10
$\pi^-p \rightarrow p_f \pi^+ \pi^- \pi^0 \pi_s^-$	< 4	0.6	< 20
$\pi^-p \rightarrow p_f 2\pi^+ 2\pi^-(\pi_s^-)$	< 40	2.1	< 30
$\pi^-p \rightarrow p_f K^+ K^-(\pi_s^-)$	< 20	2.2	< 20

Table 3.
 $p\bar{p}(2020)$ signals in production experiments

Reference	Reaction	P_{beam} (GeV/c)	Mass of $p\bar{p}$ state (MeV/c ²)	Width of $p\bar{p}$ state (MeV/c ²)	No. of s.d.
A. Evidence from Omega spectrometer					
Benkheiri et al.[2]	$4C \pi^- p \rightarrow p_f \pi^- p\bar{p}$	9	2020 ± 3	24 ± 12	4.7
		12			3.8
Ajaltouni et al.[1]	$4C \pi^- p \rightarrow p_f p\bar{p} \pi^-$	12	2020	≤ 20	2.9
Ferrer et al.[8]	$1C \pi^+ p \rightarrow p_f p\bar{p} \pi_s^+$	20	2009 ± 6	30 ± 12	6.0
	$1C \pi^+ p \rightarrow p_f p\bar{p} \pi^+ \pi_s^0$	20	2012 ± 6	34 ± 21	7.0
	$1C \pi^- p \rightarrow p_f p\bar{p} \pi_s^-$	12	2024 ± 5	22 ± 15	3.8
	$1C \pi^- p \rightarrow p_f p\bar{p} \pi^- \pi_s^0$	12	2015 ± 4	15 ± 9	4.4
Ferrer et al.[9]	$(1+3)C \pi^+ p \rightarrow p_f p\bar{p} \pi_s^+$	20	2010 ± 4	12 ± 10	4.4
	$(1+2)C \pi^+ p \rightarrow p_f p\bar{p} \pi^+ \pi_s^0$	20	2018 ± 6	21 ± 18	3.4
This work,new result	$1C \pi^+ p \rightarrow p_f p\bar{p} 2\pi^+ \pi_s^-$	20	2010 ± 8	11 ± 7	3.5
This work,new result	$\pi^+ p \rightarrow p_f \pi_s^+ (MM)^0$	20	2005 ± 9		4.4
B. Other results					
Chung et al.[20]	$4C \pi^- p \rightarrow p_f \pi^- p\bar{p}$	16	2020	≤ 20	2.0
Chung et al.[21]	$\bar{p}p \rightarrow (p\bar{p})_f \rho^0$	5	2010	≤ 10	1.8
Armstrong et al.[22]	$4C \pi^- p \rightarrow p_f \bar{p} \pi^- p_s$	16	2025	≤ 10	2.4
Cleland et al.[23]	$4C \pi^- p \rightarrow p_f \bar{p} \pi^- p_s$	50	2025	≤ 10	3.1
Kooijman et al.[24]	$3C pp \rightarrow pp\bar{p}p_s$	11.75	2025	≤ 10	1.8
Armstrong et al.[25]	$1C \bar{p}p \rightarrow p_f \bar{p}_f \pi^+ \pi^-$	12	2030	≤ 15	2.3
Beusch et al.[26]	$\pi^- p \rightarrow (p\bar{p})_{cent} + X^0$	40	2020	≤ 5	1.8
Gibbard et al.[27]	$4C e^- p \rightarrow e^- p\bar{p}p$	11.5	2020	≤ 40	2.3
Bodenkamp et al.[28]	$1C \gamma p \rightarrow p\bar{p}p_s$	4.7-6.6	2023 ± 5	27 ± 12	1.7

Remarks: All the results in Table 3 excepting [9] are statistically independent. The results of Ref. [9] are extracted from the same data as those of [8].

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12