Recent results on hadron spectroscopy from BES

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Abstract The BES-III Detector is a very versatile multipurpose device located at the Institute of High Energy Physics (IHEP) in Beijing, China. Concerning the physics program it ties stringently up to the past BES and BES-II experiments. Since start of the data taking in the middle of 2008 the accumulated dataset of $200 \cdot 10^6$ J/ψ events and $100 \cdot 10^6$ ψ' events already exceeds the world data on these resonances. In addition to studies of the charmonium systems the data offers great opportunity for investigations in the light hadron sector. In detail it will be reported about the confirmation of the enhancement in $p\bar{p}$ invariant mass in radiative J/ψ decays, the search for decays $Y(2175) \rightarrow K^{*0}\bar{K}^{*0}$, observation of a charged $\kappa^{\pm}$ in $K^{\pm}\pi^0$ and observation of a new excited baryon $N^*(2065)$ decaying to $p\pi^0$ and charged conjugate. The first result is based on data taken by BES-II and BES-III, the latter three on data collected by BES-II only.

Key words light hadrons, BES, X(1860), Y(2175), $\kappa^{\pm}$, $N^*(2065)$

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1 Introduction

The general goal of performing hadron spectroscopy is to understand the dynamics and interactions of the constituents. In particular in the sector of light hadron systems perturbative QCD is not applicable, therefore phenomenological methods like effective models or calculations on the lattice are intensively performed to reach that goal.

Besides the conventional forms of matter – quark-antiquark states ($q\bar{q}$) called mesons and states consisting of three quarks (qqq) called baryons – QCD allows the existence of unconventional forms of matter often referred to as exotic states due to its non-Abelian characteristics. These comprise hadrons only made of constituent gluons named glueballs, hadrons which consist of both quarks and constituent or excited glue called hybrids and structures build from more than only a quark-antiquark pair or three quarks named multiquarks. As an example in the near past there has been quite some excitement about the possible observation of so-called pentaquarks consisting of four quarks and one anti-quark which would represent such kind of multiquark state (for a review see [1]).

Although a lot of experimental evidences already have been found which go beyond the simple meson/baryon picture, none of these observations has been unambiguously identified as being exotic or unveiled its true nature.

In the field of excited baryons the situation is not better since many of the predicted excited N^* baryons simply have not been observed so far. For a better understanding of the structure of hadrons it is mandatory to intensify the search for these missing baryon states.

Decays of charmonia like J/ψ, $\psi(2S)$ and also higher mass states provide an ideal laboratory to search for all kinds of exotic states as well as the systematic study of conventional mesons and baryons. On one hand the initial state has well defined properties since it is a bound state, on the other hand it provides a spin filter due to the initial $J^{PC} = 1^{--}$ and therefore naturally suppresses background and allows conclusions about the spin parity of the daughter particles.

2 BES-II and BES-III Detectors

The results presented here are based on datasets accumulated by the BES-II detector and the newer BES-III detector. In the following both devices are

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described more detailed.

2.1 BES-Ⅱ

The BES-Ⅱ detector collected data at the Beijing Electron Positron Collider (BEPC) between 1995 and 2004. The details about the detector can be found elsewhere [2]. It was a conventional cylindrical magnetic detector consisting of a central drift chamber (CDC), main drift chamber (MDC), time-of-flight counters (TOF) (barrel and endcap) and an electromagnetic shower counter (SC) in a solenoid magnet field of 0.4T field strength. The flux return was equipped with additional three layers of muon chambers.

The momentum resolution achieved by the tracking system was $\sigma_{\rm p}/p = 1.7\%\sqrt{1+p^2}$. In addition the tracker provided a measurement of the specific energy loss for particle identification with a precision of $\sigma_{{\rm d}E/{\rm d}x} \approx 8\%$. The energy resolution of the SC was about $\sigma_{\rm E}/E = 22\%/\sqrt{E}$. The TOF system time resolution of $\sigma_{\rm t} = 180$ ps allowed for a reasonable π/K/p separation for particles with momenta < 0.8 GeV/c.

In total BES-Ⅱ collected 58 million events at the J/ψ energy, 14 million events at the ψ(2S) and about 210000 events above the $\rm D\bar{D}$ threshold.

2.2 BES-Ⅲ

In contrast to the upgrade from BES to BES-Ⅱ, the BES-III detector has been build completely new. The technical details about the detector can be found in Ref. [3]. In many respects the performance of this new detector exceeds those of its predecessor by up to an order of magnitude. The BES-III detector consists of a main drift chamber (MDC), time-of-flight system (TOF) and a electromagnetic calorimeter (EMC) made of ca. 6000 CsI(Tl) crystals enclosed in the superconducting magnet coil providing a 1T solenoidal field. The outermost part is the flux return equipped with muon detectors.

The transverse momentum resolution of the tracking system is $\sigma_{p_{\rm t}}/p_{\rm t} = 0.3\%$, the specific energy loss for the purpose of particle identification can be determined with a precision as good as $\sigma_{{\rm d}E/{\rm d}x} = 6\%$. The time resolution achieved by the TOF with $\sigma_{\rm t} \approx 78$ ps is slightly better than the design value of 80 ps, allowing for π/K/p separation up to 1 GeV/c. The energy resolution of $\sigma_{\rm E}/E = 2.3\%/\sqrt{E}$ obtained by EMC is an order of magnitude better than that of the SC of BES-Ⅱ. The 8-9 layers of resistive plate chambers providing information for muon detection achieve an efficiency $> 90\%$ over the full momentum range.

3 Enhancement in $\rm p\bar{p}$

In 2003 the BES Collaboration reported about an enhancement in the invariant $\rm p\bar{p}$ mass close to $M_{\rm p\bar{p}} = 2m_{\rm p}$ threshold in $\rm J/\psi \to p\bar{p}\gamma$ decays [4]. Fitting this enhancement with an acceptance-weighted S-wave Breit-Wigner distribution corresponding to $J^{PC} = 0^{-+}$ after appropriate acceptance correction yields a mass of $M = 1859^{+3}_{-10}$ (stat)$^{+5}_{-25}$ (sys) MeV/c^2 and a total width of $\Gamma = 0\pm21$ MeV/c^2 for the possible resonant state.

There are no well established mesons which could be associated with that enhancement. The proximity to $2m_{\rm p}$ might suggest a nucleon-antinucleon ($\rm N\bar{N}$) bound state, an idea with quite a long history [5].

In order to confirm that enhancement and investigate further about its origin various other channels have been analyzed by different experiments. BES-Ⅱ performed a search in decays $\rm J/\psi \to \omega p\bar{p}$, where essentially the γ is replaced by another 1^{--} particle, but no enhancement was observed in $M_{\rm p\bar{p}}$ [7]. Also the invariant mass $M_{\rm p\bar{p}}$ distribution in $\psi(2S) \to \gamma \rm p\bar{p}$ decays reconstructed by BES-Ⅱ did not reveal any structure with more than 2σ significance in the corresponding region of interest [6].

The result of the analysis of bottonium decays $\Upsilon(1S) \to \gamma \rm p\bar{p}$ performed by CLEO-III was an upper limit on the combined branching ratio involving $\rm X \to p\bar{p}$ decays with no obvious enhancement near threshold [8].

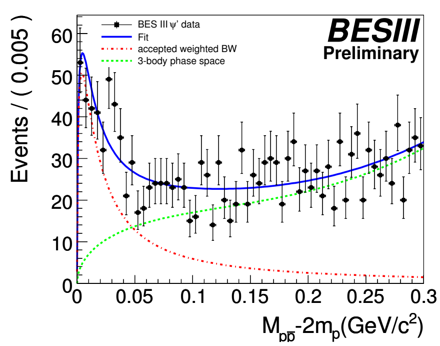

Fig. 1. Enhancement in $M_{\rm p\bar{p}}$ close to threshold in $\rm J/\psi \to p\bar{p}\gamma$ decays reconstructed by BES-III.

Based on the data sample of $100{\cdot}10^6$ ψ(2S) events the search for that enhancement was continued by BES-III during 2008. The reactions considered in this analysis were $\rm J/\psi \to \gamma p\bar{p}$ with the J/ψ originating from $\psi(2S) \to \pi^+\pi^-\rm J/\psi$ decays. Due to the different detector and kinematics of the J/ψ due to the alternative production mechanism, potential systematic effects which might affect the BES-Ⅱ analysis are totally decoupled from those possibly appearing here.

After proper efficiency correction the resulting distribution of the mass $M_{\mathrm{p\bar{p}}} - 2m_{\mathrm{p}}$ is shown in Fig. 1. The fitted signal with the same line shape as above yields values of $M = 1864.6 \pm 5.3$ MeV/c^2 and an upper limit of the with of $\Gamma < 33$ MeV/c^2 (90% C.L.) with given uncertainties being statistically only. The results confirm the previous measurements performed by the BES-II experiment. Further searches in the invariant $\mathrm{p\bar{p}}$ mass of direct decays $\psi(2S) \to \gamma \mathrm{p\bar{p}}$ shown in Fig. 2 did not result in an observation of a corresponding enhancement, which is also consistent with previous investigations in this kind of reactions performed by BES-II. Although the signal has been confirmed still no conclusing can be drawn concerning its nature.

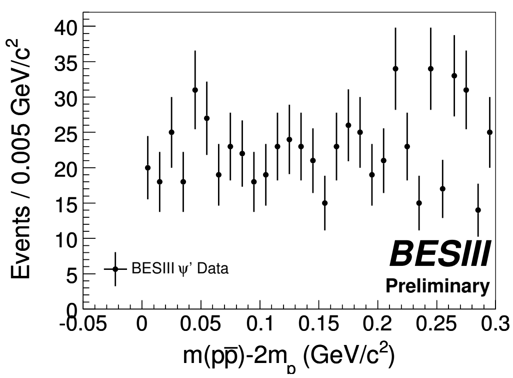

Fig. 2. Mass difference $M_{\mathrm{p\bar{p}}} - 2m_{\mathrm{p}}$ of $\psi(2S) \to \mathrm{p\bar{p}}\gamma$ decays reconstructed by BES-III. No enhancement is visible around threshold.

4 Search for $\mathrm{Y}(2175) \to \mathrm{K}^*\bar{\mathrm{K}}^*$

In 2006 the BaBar Collaboration reported about the observation of a new resonant structure with mass $m = 2175 \pm 10 \pm 15$ MeV/c^2 and width $\Gamma = 58 \pm 16 \pm 20$ MeV decaying to $\phi f_0(980)$ denoted as Y(2175). It was observed in cross section measurement of the exclusive reaction $e^+e^- \to \gamma_{\mathrm{ISR}} K^+K^-\pi^+\pi^-$ when requiring the invariant mass $m(K^+K^-)$ to be consistent with a $\phi \to K^+K^-$ decay and the invariant mass $m(\pi^+\pi^-)$ with the decay $f_0(980) \to \pi^+\pi^-$ [9, 10]. This resonance was confirmed by BES-II with a significance of 5.5σ in decays $J/\psi \to \eta\phi f_0(980)$ with fitted parameters $m = 2186 \pm 10 \pm 6$ MeV/c^2 and $\Gamma = 65 \pm 23 \pm 17$ MeV/c^2 [11].

In order to establish the resonance and learn more about its nature it is mandatory to identify more decay channels. These current observations stimulated theoretical speculation that the Y(2175) could be the strange partner of the previously discovered Y(4260), since both are produced in e^+e^- collisions with $J^{PC} = 1^{--}$ and exhibit similar decay patterns [12, 13]. The inner structure of the Y(4260) is currently discussed as either being a conventional $c\bar{c}$ charmonium state [17], a hybrid $c\bar{c}g$ state with excited glue [14–16] or even a tetraquark $[cs]_S[\bar{c}\bar{s}]_S$ state [18]. Regardless which of the upper scenarios might apply to the Y(2175) [19–21], either case implies that its quark content at least comprises an $s\bar{s}$ pair, expecting the resonance to decay to final states with separated s and $\bar{s}$ like $K\overline{K}$, $K^*\overline{K}^*$ or $\Lambda\overline{\Lambda}$. Among these decay modes, $Y(2175) \to K^*\overline{K}^*$ is of special interest, since it might be forbidden in case of Y(2175) being hybrid state [22] while being allowed for a conventional charmonium.

In the following it is reported about the search for decays $Y(2175) \to K^{*0}\overline{K}^{*0}$ in $J/\psi \to \eta K^{*0}\overline{K}^{*0}$ events based on 58 million J/ψ events collected with the BES-II detector [23].

The considered decay channel has two charged kaons, two charged pions and two photons. A signal event therefore is required to have four good tracks with total charge zero and two isolated signals in the shower counter. The charged tracks have to fulfill certain criteria concerning their origin and reconstruction quality as well as a transverse momentum $p_{\mathrm{t}} > 70$ MeV/c to be identified as good tracks. The neutral candidates have to deposit more than 60 MeV in the electromagnetic shower counter, and their cluster shape and position with respect to the nearest charged track is taken into account for selection. In order to separate kaons from pions the TOF information combined with $\mathrm{d}E/\mathrm{d}x$ measurement is used. The K^{*0} candidates and corresponding charged conjugates are reconstructed from $K^\pm\pi^\mp$ combinations. A 4-constraint fit together with the recoiling $\eta \to \gamma\gamma$ candidate is performed to finally reconstruct the $\eta K^{*0}\overline{K}^{*0}$ candidates.

Based on these events the branching fraction of $J/\psi \to \eta K^{*0}\overline{K}^{*0}$ is determined to be

$$\mathcal{B}(J/\psi \to \eta K^{*0}\overline{K}^{*0}) = (1.15 \pm 0.13) \times 10^{-3},$$

where the error is statistical only.

The invariant mass $m(K^{*0}\overline{K}^{*0})$ is shown in Fig. 3. The shaded histogram represents normalized sideband events from the η, the dashed histogram is the contribution from phase-space to $J/\psi \to \eta K^{*0}\overline{K}^{*0}$. No obvious signal in the mass region around 2175 MeV can be observed.

The distribution is fitted with the sum of a signal function and the two background contributions, where the signal shape has been determined from $J/\psi \to \eta Y(2175)$ MC events with simulation parameters for m and Γ taken from the BaBar measurement. The fit yields $N = 12 \pm 11$ signal events leading to a significance of only 0.88σ.

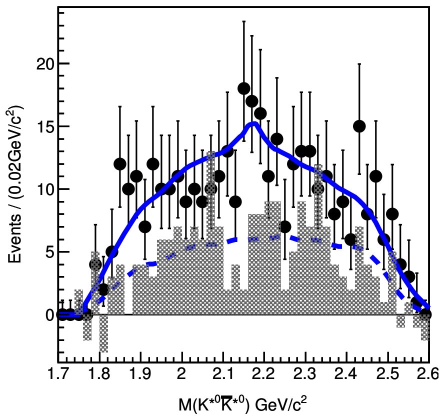

Fig. 3. Invariant mass $m(K^{*0}\overline{K}^{*0})$ from $J/\psi \to \eta K^{*0}\overline{K}^{*0}$ decays reconstructed by BES-II. No obvious Y(2175) signal is observed.

An upper limit for the corresponding combined branching fraction computes to

$$\mathcal{B}(J/\psi \to \eta Y(2175)) \cdot \mathcal{B}(Y(2175) \to K^{*0}\overline{K}^{*0}) < 2.52 \cdot 10^{-4}$$

at 90% confidence level. No conclusion about the structure of the Y(2175) can be drawn due to limited statistics.

5 Observation of charged $\kappa^{\pm}$

In the field of light scalar mesons the existence of the light iso-scalar meson $\sigma(600)$ used to be a controversial problem even after many years of research. Due to several recent observations in various production processes [24–27] the σ mesons now is widely accepted with a mass of around 600 MeV/c^2 and a width of around 500 MeV/c^2 [39].

The existence of the σ suggest now as well the possibility of a nonet ($\sigma(600)$, $\kappa(900)$, $f_0(980)$, $a_0(980)$) as described in various models, e.g. in Ref. [29]. Evidences for the neutral κ have recently been reported by E791 in $D^+ \to K^-\pi^+\pi^+$ decays [30] and by BES-II in $J/\psi \to \overline{K}^*(892)^0K^+\pi^-$ reactions [28]. The FOCUS experiment presented evidence for the existence of a coherent $K\pi$ S-wave contribution to $D^+ \to K^-\pi^+\mu^+\nu$ [31]. The existence of a neutral κ^0 motivates the search for a charged partner.

In the following it is reported about the search for a charged $\kappa^{\pm}$ in $J/\psi \to K^*(892)^+\kappa^- \to K^0_S\pi^+K^-\pi^0$ decays. The final state comprises four charged tracks and two photons. All charged tracks are required to have a good helix fit quality. The two pions from the decay $K^0_S \to \pi^+\pi^-$ are required to be consistent with a common vertex. The two other tracks have to fulfill the good track criteria requiring in addition to be consistent with the interaction point and have a minimum transverse momentum. The two photons have to have an energy deposit larger than a certain threshold, a hit position inconsistent with any of the tracks and a particular shower shape. A 4-constraint is performed for the whole event.

For the finally selected events a partial wave analysis is performed to determine the contributions from the different resonances to the $K^{*+}K^-\pi^0$ (+ c.c.) system.

Besides strong contributions from $K^*(892)^{\pm}$, $K^*(1410)^{\pm}$ and $K^*(1430)^{\pm}$ a significant $J^P = 0^+$ low mass component is needed to describe the $(K^*(892)^{\pm}\pi^0)$ – $(K^*(892)^{\pm}K^{\mp})$ Dalitz plot. Other spin-parities can be excluded with high significance. Fig. 4 shows the projected invariant mass $m(K^{\pm}\pi^0)$.

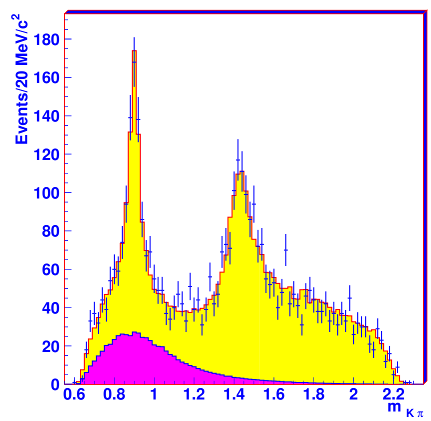

Fig. 4. Invariant mass $m(K^+\pi^0)$ + c.c. from $J/\psi \to \overline{K}^*(892)^+K^-\pi^0$ decays reconstructed by BES-II. The crosses represent data, the histogram is the fit result from a partial wave analysis.

The fitted pole position of that 0^+ component displayed in dark color is

$$m - i\frac{\Gamma}{2} = (849 \pm 51^{+14}_{-28}) - i(288 \pm 101^{+64}_{-30}) \ \ \text{MeV}/c^2.$$

This result is in agreement with a recent CLEO analysis of the resonance structure in $D^0 \to K^+K^-\pi^0$ decays [36], which suggests a $\kappa^{\pm}$ component with parameters $m = (855 \pm 15)$ MeV and $\Gamma = (251 \pm 48)$ MeV.

Moreover the results are in reasonable agreement with the properties of the neutral κ^0.

6 Observation of a new baryon N*(2065)

The nucleon is the simplest system in which the three colors of QCD can combine to form a colorless object. In order to understand strong interaction it is mandatory to unveil the internal quark gluon structure of the nucleon and its excited N* states. Our present knowledge of these comes almost entirely from πN experiments performed more than 20 years ago. Due to the importance to understand non-pQCD a series of new experiments on Nπ physics with electromagnetic probes have recently been started at JLAB, ELSA, GRAAL, and SPRING8. Although some important results have already been produced, our knowledge of the N* resonances remains very poor.

In the following it will be reported about recent studies of reactions $J/\psi \to p\bar{n}\pi^- +$ c.c. [37] as well as $J/\psi \to p\bar{p}\pi^0$ [38]. In the following charged conjugates are also taken into account without being mentioned.

6.1 N*(2065) in $J/\psi \to p\bar{n}\pi^-$

For the $J/\psi \to p\bar{n}\pi^-$ channel the neutron is not detected directly. Therefore the p and π^- are selected from 2-prong events and required to fulfill the good tracks criteria, which basically are given by a minimum transverse momentum, a good trajectory fit and consistency with the interaction point. The missing mass has to be consistent with neutron mass. Particle identification is based on confidence levels $\mathcal{P}^i_{\rm pid}$ computed from TOF and $\mathrm{d}E/\mathrm{d}x$ information for i being π, K or p hypothesis. Positive identification for hypothesis i requires $\mathcal{P}^i_{\rm pid} > \mathcal{P}^j_{\rm pid}$ for $j \neq i$.

In order to investigate the squared amplitude behavior as a function of invariant mass the spectrum is corrected for MC efficiency and phase space. The resulting distributions of $|A|^2$ are shown in Fig. 5, separately for $m(p\pi^-)$ (circles) and $m(\bar{p}\pi^+)$ (squares). Both spectra normalized to the same magnitude are consistent.

There are four clear peaks around 1360, 1500, 1670, and 2065 MeV/c^2 visible. While the peaks around 1500 and 1670 MeV/c^2 correspond to well-known excited states, the lightest and heaviest have not been observed up to now.

The first signal should be from the N*(1440) excited nucleon which has a pole around 1360 MeV/c^2 [39]. It has not been observed directly in decays up to now, since it is usually buried by the Δ(1232) in pN and γN scattering. The other one around 2065 MeV/c^2 might be one or more of the missing N* resonances.

To estimate masses and widths of the resonances a superposition of a set of relativistic Breit-Wigner function together with a smooth background function is fitted to the distribution in Fig. 5.

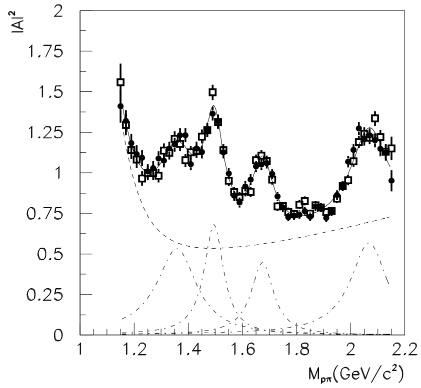

Fig. 5. Data divided by MC phase space for invariant mass $m(p\pi^-)$ + c.c. from $J/\psi \to p\bar{n}\pi^-$ (circles) and $J/\psi \to \bar{p}n\pi^+$ decays (squares) reconstructed by BES-II. The dashed lines represent the contributions of the different resonances.

The fit function is given by

$$|A|^2 = |C_0 + C_0' s_{\pi p}| + \sum_{i=1}^{5} \frac{C_i}{(s_{\pi p} M_i^2)^2 + M_i^2 \Gamma_i^2}$$

with $s_{\pi p} = M^2_{\pi p}$ being the squared invariant mass of the $p-\pi$ system. The first summand represents the smooth background, and a fifth low mass Breit-Wigner is added to describe contribution from nucleon pole and other backgrounds. The fit results for the four resonances are given in Table 1.

Table 1. Fitted masses and width for the 4 resonances in Fig. 5.

mass/(MeV/c^2)	width/(MeV/c^2)
$1358 \pm 6 \pm 16$	$179 \pm 26 \pm 50$
$1495 \pm 2 \pm 3$	$87 \pm 7 \pm 10$
$1674 \pm 3 \pm 4$	$100 \pm 9 \pm 15$
$2068 \pm 3^{+15}_{-40}$	$165 \pm 14 \pm 40$

For the new N*(2065) signal, fitting with orbital momentum $L=0$ leads to significant better fit results than $L=1$, which can be interpreted as a substantial $L=0$ component in this peak. This result limits the spin parity to $1/2^+$ or $3/2^+$, which however cannot be well determined since the differences in fit qualities are rather small and depend on many fitting details.

6.2 N*(2065) in $J/\psi \to p\bar{p}\pi^0$

The decay $J/\psi \to p\bar{p}\pi^0$ with $\pi^0 \to \gamma\gamma$ contains two charged tracks and two photons. As in the section above the tracks have to fulfill certain criteria to be of good quality, and protons are identified based on confidence level computed from TOF and dE/dx information. The neutral candidates have to have an energy deposit of at least 50 MeV, and the position has to be inconsistent with any charged track to be accepted. Due to the possibility of fake photons events with more than two photons are accepted. The π^0s are required to fulfill $|M_{\gamma\gamma}-0.135|<0.03$ GeV/c^2. The final invariant mass $m(\bar{p}\pi^0)$ is shown in Fig. 6.

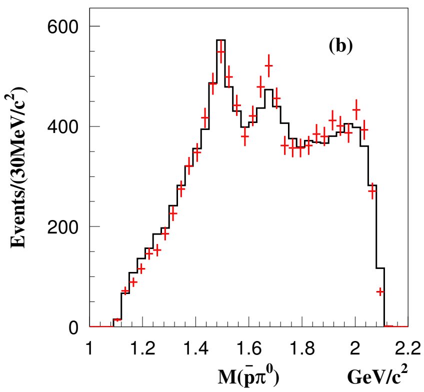

Fig. 6. Invariant mass $m(\bar{p}\pi^0)$ from J/ψ → $p\bar{p}\pi^0$ decays reconstructed by BES-II. The crosses represent data, the histogram is the fit result from a partial wave analysis.

After event selection a partial wave analysis is performed to study the N* states in this decay. The complicated details of these PWA can be found in [38]. Many established states like N(1440), N(1520), N(1535), N(1650), N(1675), N(1680) and some more at higher masses are included in the fit, and various setups have be tried to find the optimum fit. As a result it turns out that the log likelihood value improves significantly when adding the N*(2065) corresponding to $>5\sigma$ significance. The optimized fit setup yields a mass of $M=2040^{+3}_{-4}\pm25$ MeV/c^2 and a width $\Gamma=230\pm8\pm52$ MeV/c^2, which confirm the results obtained for the J/ψ → $p\bar{n}\pi^-$ channel within uncertainties.

7 Summary

In summary it has been reported about the confirmation of the enhancement seen at a mass of $M\approx1860$ MeV/c^2 in $p\bar{p}$ by BES-III, the search for decays Y(2175) → $K^*\overline{K}^*$ by BES-II without observation of a signal, the observation of a charged $\kappa^\pm$ decaying to $K^\pm\pi^0$ by BES-II and the observation of a new baryon resonance N*(2065) in $p\pi^-$ and $p\pi^0$ by BES-II.

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