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Exclusive reconstruction of excited B states

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Abstract

A search for excited B states has been performed through the study of $B\pi$ correlations in a sample of exclusively reconstructed B events (1991-1993 data sample). A possible narrow structure is observed at a $B\pi$ mass of $5.91\,GeV/c^2$, but more data is needed to confirm its statistical significance. A possible excess of events is observed in a broad mass region around $5.65\,GeV/c^2$, but, again, more data is needed to evaluate its statistical significance, and to compare with theoretical predictions for the $l = 1$ orbitally excited B^{**} resonances. This note serves to document the analysis and the results based on the existing data sample, before any additional data (particularly the 1994 data) is analyzed.

1 Introduction

The existence of excited B states may be of interest for several reasons. Such states can tag the flavour of the heavy quark at its creation and therefore could prove a very powerful tool in studying mixing and CP violation in the neutral B system [1]. Furthermore, they can provide valuable information for the understanding of Heavy Quark Effective Theory (HQET) and for testing its predictions [2].

In this note we present the results of a search for such excited states via $B\pi$ correlations in exclusive B decays. First we describe briefly the B sample and the reconstruction algorithm. Section 3 is devoted to the resonance reconstruction, including the track selection criteria and their effects on the signal efficiency. The results are presented and discussed in section 4. In section 5 the theoretical predictions for the $l = 1$ orbitally excited B states are discussed briefly. We summarize and conclude in section 6.

2 B Reconstruction

This analysis has been based on data taken in 1991, 1992 and 1993 (1.6M hadronic Z^0 decays). The starting data sample consists of 150 events, each containing a fully-reconstructed B decay.

These events were collected from two different reconstruction analyses ([3], [4]), utilising decays in a variety of hadronic channels. Most of these decays are of the form $B \to D^{(*)}\pi^{\pm}$, $D^{(*)}\rho^{\pm}$ or $D^{(*)}a_1^{\pm}$; five of the decays are $B^{\pm} \to J/\psi K^{\pm}$. The estimated purity of the B sample is $(76 \pm 6)\%$. The contribution of each B hadron type is presented in table 1.

Events	b	$\bar{b}$	all
charged	37	33	70
neutral	36	44	80
all	73	77	**150**

Table 1: The B sample composition

In order to avoid any possible biases from the different reconstruction techniques employed by the two analyses, a uniform reconstruction algorithm was developed. This takes as inputs the daughter tracks from the above reconstructions and then performs successive mass constraint fits to all levels (π^0's, K_s^0's, D's, J/ψ's and in the end for the final B). Special attention was paid in order to have a consistent treatment of the error matrices of the particles (even for neutral tracks like photons and π^0's). Thus, the algorithm provides a valid error matrix for the B track which can subsequently be used to get an error estimate for the mass of the $B\pi$ combination.

3 Resonance reconstruction

The reconstructed B tracks, with their mass constrained to the nominal B mass [5] (as described in the previous section), are then combined with additional charged pions π_{**} in an attempt to reconstruct resonances which decay to $B\pi$. The selection of the π_{**} track is explained in the next section.

3.1 Track selection of the π_{**}

3.1.1 General criteria

The tracks are first subjected to a number of soft cuts, in order to ensure tracking quality and compatibility with a resonance decay:

- Tracks which have been used in the B reconstruction are excluded.
- Required track quality:
  - TPC hits ≥ 4
  - (VDET hits ≥ 1) OR (ITC hits ≥ 4)
  - $\mid Z0 \mid < 5cm$
  - momentum > 0.2 GeV

- Tracks must originate from the primary vertex (probability $\geq 0.5\%$)
- If dE/dx is available, tracks should be consistent with being pions within $\pm 3\sigma$
- Tracks should give a low mass combination with the B ($m_{B\pi} \leq 7.3\,GeV/c^2$, ie. $2\,GeV/c^2$ above the mass of the B; this is mainly to avoid combinations with hard tracks from nearby gluon jets in events with more than two jets.)

3.1.2 Right sign and wrong sign combinations

All tracks passing the above cuts can be used to form $B\pi$ combinations. However, not all of them can have originated from a resonance. For a particular B hadron type (eg. B^+), only tracks of one sign (i.e. π^-) can be from the decay of a B resonance into $B\pi$. We call these combinations *'right-sign'* combinations (*rs*) (see table 2). The others, the *'wrong-sign'* combinations (*ws*), can be used as a check on our estimate of the background. The two $B\pi$ mass distributions are plotted in fig. 1.a for all combinations from simulated events in the absence of any B resonances. A clear excess of the *rs* combinations is observed in the low mass region. The explanation of this lies in the fragmentation process. The first pion produced after the B in the fragmentation is expected to be a right-sign pion and often forms a low mass combination with the B. The situation is reversed in the presence of a resonance. Then the first pion in the string is a wrong-sign pion with respect to the B hadron. Therefore, in the case of significant resonance production, the fragmentation effect as seen in fig. 1 is reduced. Furthermore, if an algorithm which selects only one combination of each kind per event is chosen (see below), then the concentration of *rs* combinations in a certain region (around the resonance mass) will suppress the continuum of the *rs* distribution so that it is possible that the *ws* distribution is an overestimation of the background.

In conclusion, it is not straightforward to extract information for the background from the *ws* combinations. However, the distinction between *rs* and *ws* combinations is useful because it reduces the background by almost a factor of 2. It does have some efficiency cost, though, due to $B^0 - \bar{B}^0$ mixing. We estimate the efficiency loss to be about 6.5% in our sample. In table 3 we summarise the efficiency losses due to all the above reasons. The final efficiency for the signal up to this point is $(82 \pm 3)\%$

right sign	*wrong sign*
$B^-\pi^+$ $B^+\pi^-$	$B^-\pi^-$ $B^+\pi^+$
$\bar{B}^0\pi^-$ $B^0\pi^+$	$\bar{B}^0\pi^+$ $B^0\pi^-$

Table 2: Right sign and wrong sign combinations for all B hadron types

3.1.3 Discrimination of the π_{**} from fragmentation tracks

From the discussion above about *rs* and *ws* combinations, it becomes clear that the main source of background is the fragmentation pions. The selection criteria applied so far have very little

Cut	Efficiency loss (%)
Track quality	4.6 ± 1.7
Primary vertex compatibility	6.9 ± 2.1
dE/dx for pion hypothesis	0.3 ± 0.3
$B^0 - \bar{B}^0$ mixing	6.5 ± 2.1
Total efficiency loss	**18.3 ± 3.4**

Table 3: Efficiency loss due to the various cuts

discriminating power between these and the pions coming from the decay of a B resonance (π_{**}). Fortunately, the signal pions differ from those from fragmentation in some kinematic quantities. Due to the hard b-fragmentation, the B hadron takes most of the string momentum, leaving the fragmentation tracks behind. Therefore, the pion originating from a resonance decay is expected to be boosted more forward than the fragmentation pions or, in other words, its component of momentum along the B direction (p_l) is expected to be larger. The same concept is described more demonstratively by the cosine of the decay angle of the pion in the rest frame of the B ($cos(\theta^*)$), which peaks strongly at -1 (fig. 2) for fragmentation pions, whereas for pions coming from a resonance decay it is expected to be symmetric (for example, if the resonance decay is isotropic and the acceptance of the B reconstruction does not introduce any biases[1] then the $cos(\theta^*)$ distribution for signal pions will be flat.)

By cutting on one of the above quantities it is possible to suppress the background from fragmentation. Another approach is to select one combination per event with an algorithm based on one of the above variables (highest p or p_l track, highest $cos(\theta^*)$ track, lowest mass combination). Choosing only one combination per event is an attractive feature of these algorithms, especially when dealing with low statistics. Among them, the 'highest p_l' algorithm has been shown in Monte Carlo studies to have good performance ($Signal/\sqrt{(bkg)}$), and to be less susceptible to picking up hard tracks from nearby jets. The efficiency of this algorithm is $(94 \pm 2)\%$ for the signal events which have passed the previous selection criteria.[2] Therefore, the overall efficiency for the signal (after B reconstruction) is $(77 \pm 4)\%$. The results presented in the next sections will be based on this 'highest p_l' algorithm.

3.2 $B\pi$ mass resolution

An important experimental parameter in this study is the mass resolution of the $B\pi$ combination. Simulated events were used to study this mass resolution in the mass region of interest. It was found (fig. 3) that it is of the order of a few MeV/c^2 and increases almost linearly with mass. The Monte Carlo results were used to calibrate the mass errors calculated using the uniform reconstruction algorithm. From Monte Carlo mass pull distributions we estimate that a correction factor of 1.3 ± 0.1 has to be applied to the calculated mass errors. As a check, the pull distribution

[1]this is not entirely true; we return to this point in the next section

[2]The mass dependence of this efficiency has not yet been studied. The quoted value is calculated for a $B\pi$ mass around $5.9\,GeV/c^2$.

for the B reconstruction was also studied and there was good agreement between data and Monte Carlo.

4 Results

4.1 $B\pi$ invariant mass: Monte Carlo

The 'highest p_l' *rs* and *ws* $B\pi$ invariant mass distributions are plotted in fig. 1.b for simulated events (no resonances). These Monte Carlo distributions were fitted to a background function (fig. 4) which consists of a phase space factor ($\sqrt{m^2 - m_0^2}$) times a fourth order polynomial. These shapes of background were subsequently used to fit the background in the data.

4.2 $B\pi$ invariant mass: Data

The data distributions are plotted in fig. 5 with the 'highest p_l' algorithm. Superimposed on this figure are the Monte Carlo background functions (shown in fig. 4), normalized to the same number of reconstructed B's.[3] A possible narrow structure appears in the right-sign plot at about $5.91\,GeV/c^2$.

The statistical significance of this signal is difficult to estimate, and the possibility that this is just a fluctuation can certainly not be ruled out at this time. The Poisson probability that the background of 2.0 ± 0.2 events (estimated from the Monte Carlo background curve seen in fig. 5.a) will fluctuate to at least 9 is 2.9×10^{-4}, which must be multiplied by the number of bins (100) in the histogram. Thus the probability that this structure is a one-bin fluctuation of the background is at the three percent level. The only way to clarify the statistical significance of the structure is by adding more data, and therefore we look forward to an analysis of the 1994 data with the same cuts as described herein.

Assuming this structure to be real, we will now extract its characteristics. We have checked that these characteristics would be similar with different choices of algorithm.

An unbinned likelihood fit was performed to the right-sign mass distribution, where the background shape was taken from the Monte Carlo fits (fig. 4.a) and a Gaussian was used for the narrow structure.[4] The results of the fit for the Gaussian are:

$$m = 5911.0^{+3.1}_{-3.4}\,MeV/c^2$$

$$\sigma = 6.7^{+3.0}_{-1.8}\,MeV/c^2$$

$$Area = 7.6^{+3.5}_{-2.9}\text{ events}$$

[3]The Monte Carlo background distributions shown in fig. 5 include only $B\pi$ combinations made with true B's. They may differ somewhat from the corresponding data distributions which of course include combinations formed with fake B's.

[4]This is an approximation. The correct function would be a Breit-Wigner convoluted with a Gaussian with σ the individual error on the mass for each event.

The mass resolution in this region is $\sigma_{res} = 5.6 \pm 0.5\, MeV/c^2$. If the above structure corresponds to the production and decay of a resonance via the $B\pi$ channel, then, from the above numbers, its mass, width, and relative production rate (*P.R.*) $\times$ branching ratio to $B\pi^{\pm}$ are:

$$m = 5911.0^{+3.1}_{-3.4}\, MeV/c^2$$

$$\sigma_{natural} = 3.7^{+5.5}_{-3.3}\, MeV/c^2$$

$$P.R. \times B.R.(B\pi^{\pm}) = (8.6^{+3.9}_{-3.2})\% \times P.R.(B_{u,d})$$

where the errors quoted are statistical only. Possible systematic biases due to the background shape or due to fitting have not yet been estimated.

It is difficult to associate the above structure with any of the theoretical predictions for excited B states, especially the $l = 1$ orbitally excited B states. Both its mass and width are inconsistent with all known predictions.

In fig. 6, a mass ideogram for the events in the peak has been plotted. This is a consistency check showing that the events have a reasonable distribution. Several other basic checks have been made. We have checked that the events are from different B decay modes, runs/years, B-reconstruction analyses, B hadron types. One distribution to note is the $cos(\theta^*)$ distribution of the events in the peak, which is not flat but peaks at negative values just like the background (fig. 7). We would normally expect a symmetric $cos(\theta^*)$ distribution for a resonance decay. Monte Carlo studies have shown that some bias could be introduced due to the B-reconstruction (in particular, the use of a $\approx 30\, GeV$ cut on the B momentum would tend to push the $cos(\theta^*)$ distribution to negative values), but it is doubtful that this could have such a strong effect.

5 Theoretical predictions for the B^{**}

The HQET predictions about the $l = 1$ orbitally excited B states are summarized in [2]. Four states are expected, grouped in two doublets according to the angular momentum of the *'light degrees of freedom'* j_l. They have spin-parity $J^P_{j_l} = 0^+_{\frac{1}{2}}, 1^+_{\frac{1}{2}}, 1^+_{\frac{3}{2}}, 2^+_{\frac{3}{2}}$. The first two can decay to $B^{(*)}\pi$ via an S-wave ($l = 0$) and therefore are expected to to be broad. The second two should lie about $100 MeV$ above, at a mass $\approx 5.77\, GeV/c^2$, and can only decay to $B^{(*)}\pi$ via a D-wave. Thus they should be narrow ($\Gamma \approx 20 MeV$). In particular, $1^+_{\frac{3}{2}}$ can only go to $B^*\pi$ whereas $2^+_{\frac{3}{2}}$ can decay both to $B^*\pi$ and $B\pi$. The splitting between $1^+_{\frac{3}{2}}$ and $2^+_{\frac{3}{2}}$ is estimated to be very small ($12 MeV$ in [2]). The corresponding narrow states in the D system have been observed [7] and their properties are in good agreement with HQET.

Looking at the fit of the *rs* distribution (fig. 5), there is perhaps some excess of events above the fitting curve in the low mass region. Based on the above theoretical predictions (HQET) and in the light of the inclusive search results in ALEPH [6], one might very tentatively attempt to attribute this excess to the B^{**} states. By simply counting the event excess in the region a rough estimate of the production rate for all the B^{**} states can be made which is compatible with the inclusive search results (25%). We are currently working on extracting information concerning the existence and properties of the various B^{**} states from the data distributions in this mass region. We expect that the additional data provided by the 1994 data sample will make the picture clearer.

6 Conclusions

The study of $B\pi$ correlations in a sample of exclusive B decays has revealed a possible narrow structure in the right-sign $B\pi$ invariant mass spectrum at a mass of $5.91\,GeV/c^2$. Also observed is a possible excess of right-sign events above the expected background in a broad region about $5.65\,GeV/c^2$. To evaluate the statistical significance of these structures, the analysis described in this document will be repeated, with all cuts frozen, on the 1994 data sample.

Acknowledgements

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References

[1] M. Gronau, A. Nippe and J. Rosner, *Phys. Rev. D* **47** (1993) 1988

[2] E.J. Eichten, C.T. Hill and C. Quigg, *Phys. Rev. Lett* **71** (1994) 4116
and a recent update *FERMILAB-CONF-94/118-T*

[3] B. Jacobsen, 'The mass of B^0 and B^+ in ALEPH ', contribution to *Rencontres de Moriond* (1992)

[4] D. Calvet and J. Carr *ALEPH 94-100 PHYSIC 94-086* (1994)

[5] Particle Data Group, *Phys. Rev. D* **50** (1994)

[6] Talk given by S. Schael in the Thursday meeting of 7/12/1994

[7] CLEO collaboration, P. Avery *et al., Phys. Lett. B* **331** (1994) 264

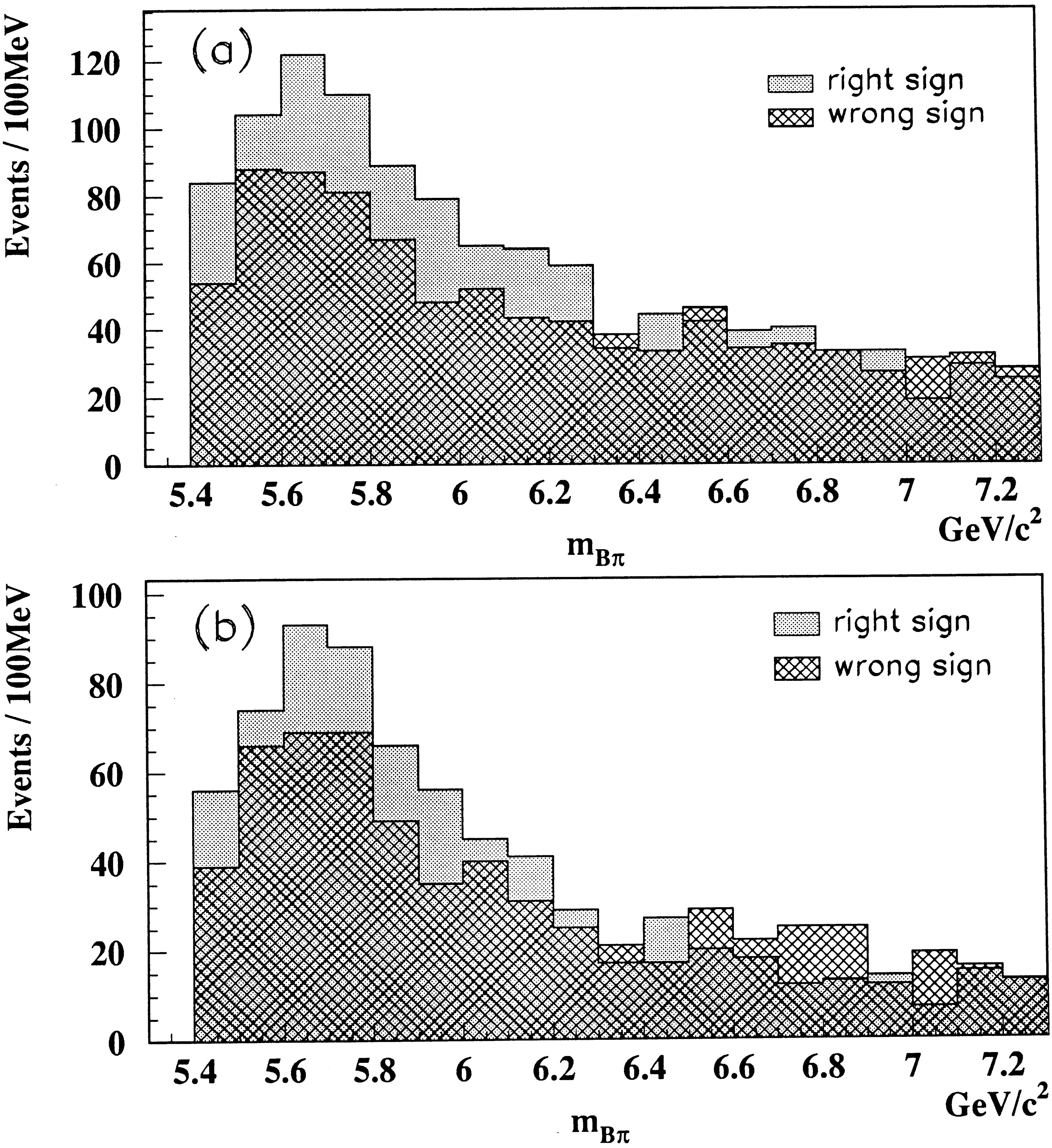


Figure 1: Invariant mass distributions for $B\pi$ combinations from simulated events with no resonances. (a) All combinations, (b) only the 'highest p_l' combination per event

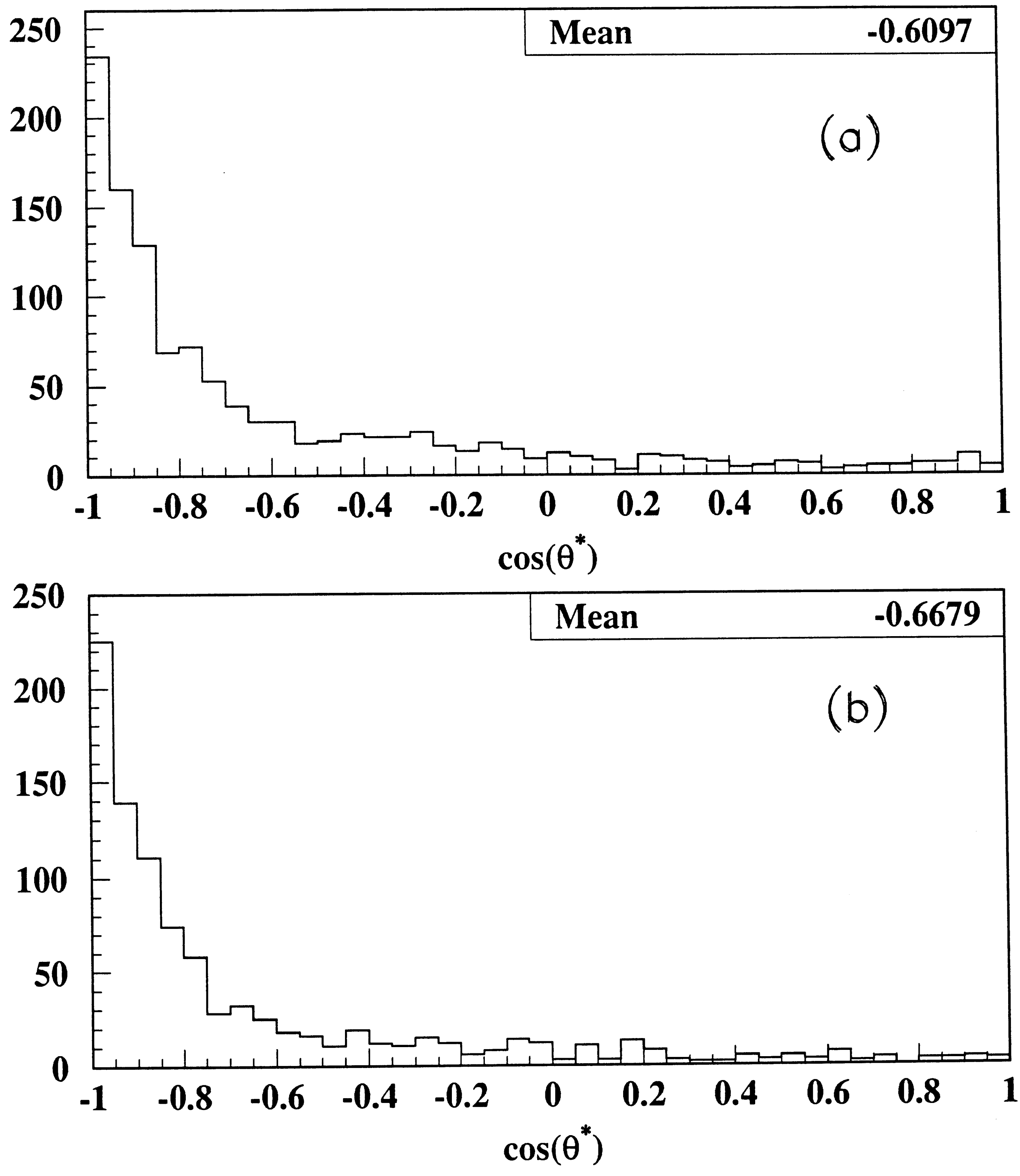


Figure 2: $cos(\theta^*)$ distributions from simulated event (no resonances). (a) right-sign (b) wrong-sign combinations

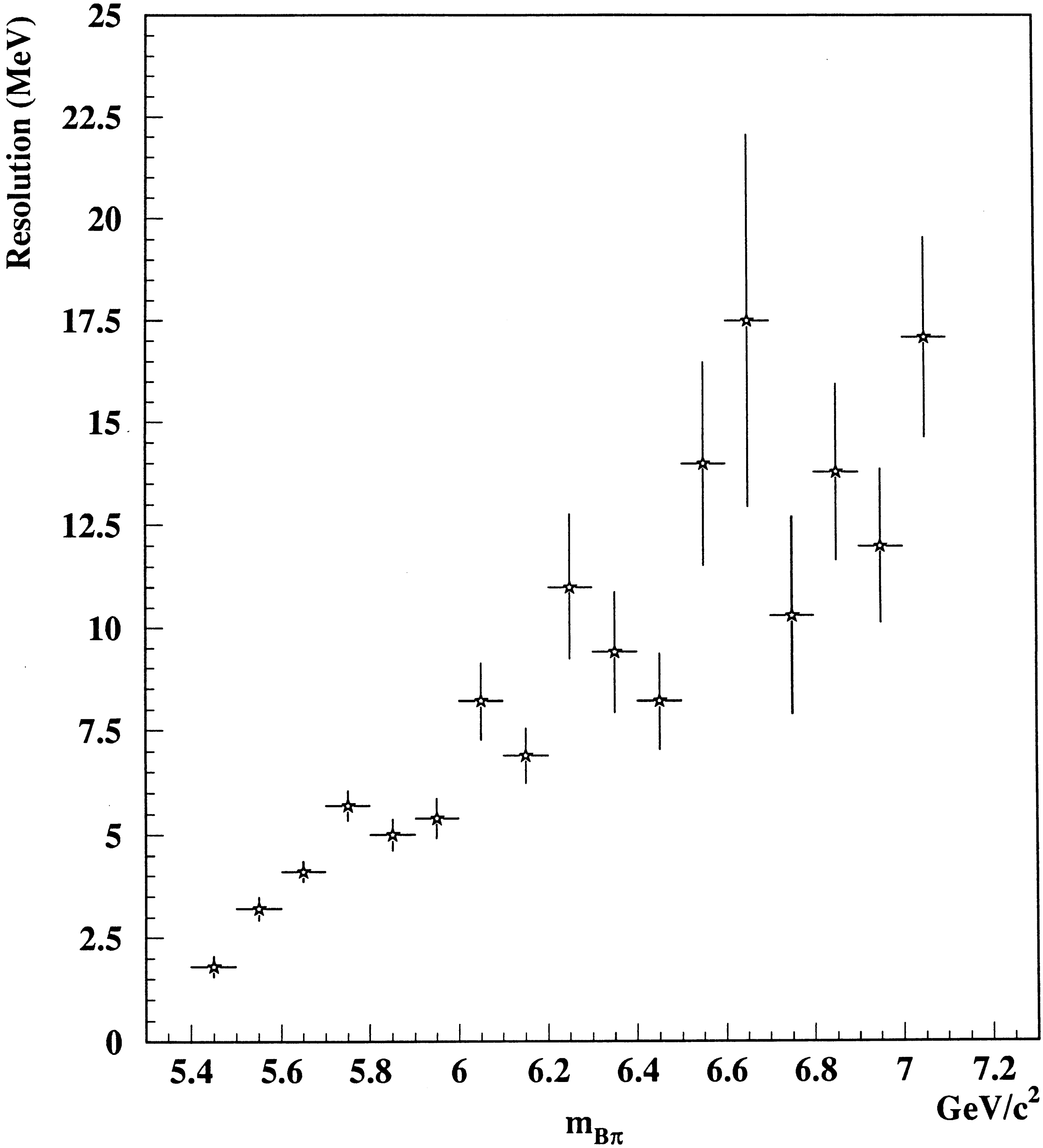
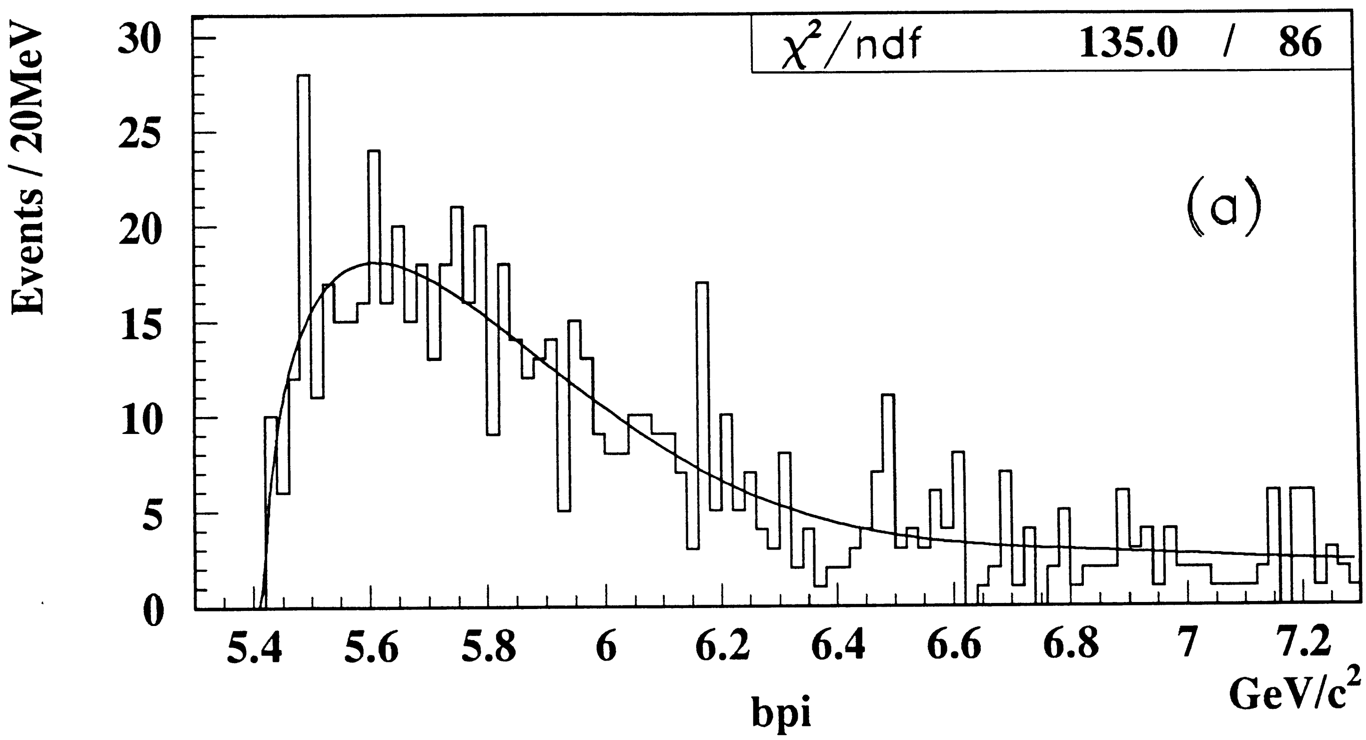


Figure 3: Mass resolution from simulated events



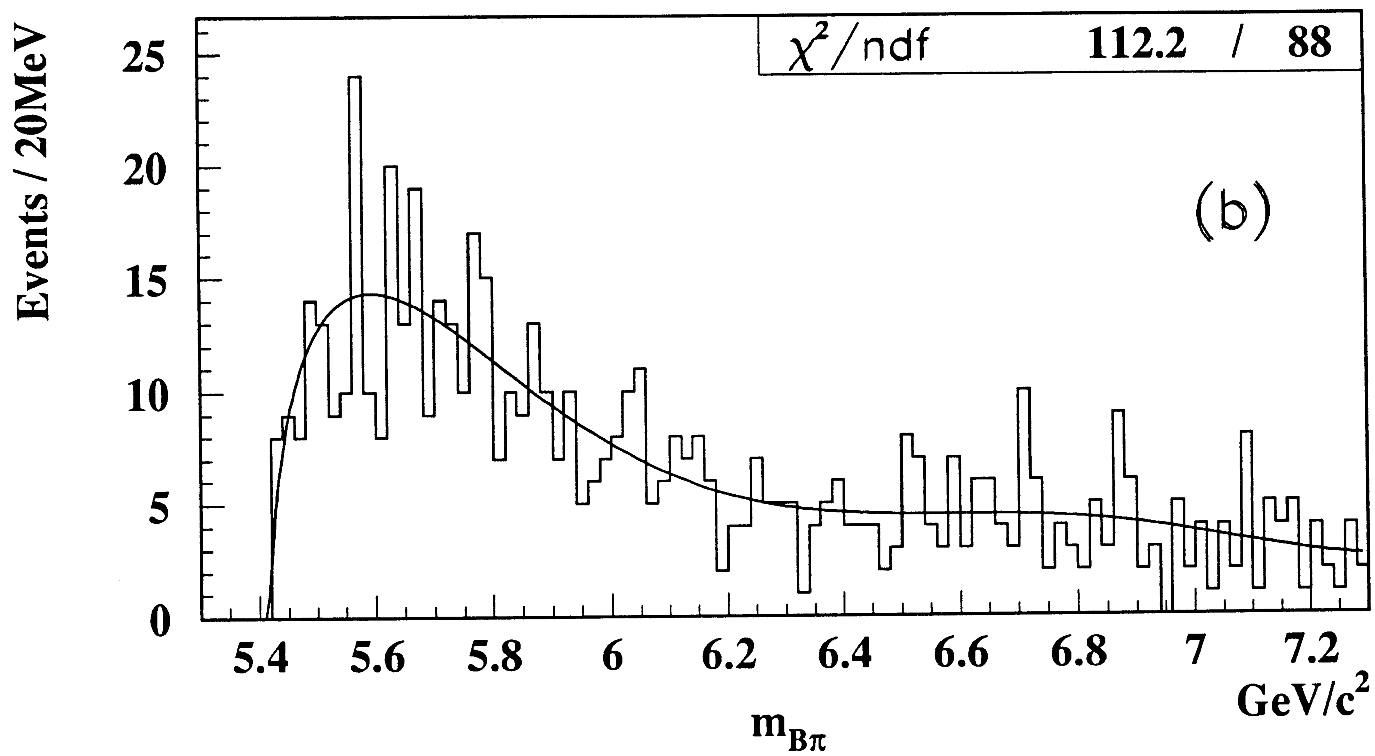


Figure 4: Fits of the of the background distributions in simulated events: (a) right-sign (b) wrong-sign combinations ('highest p_l' algorithm)

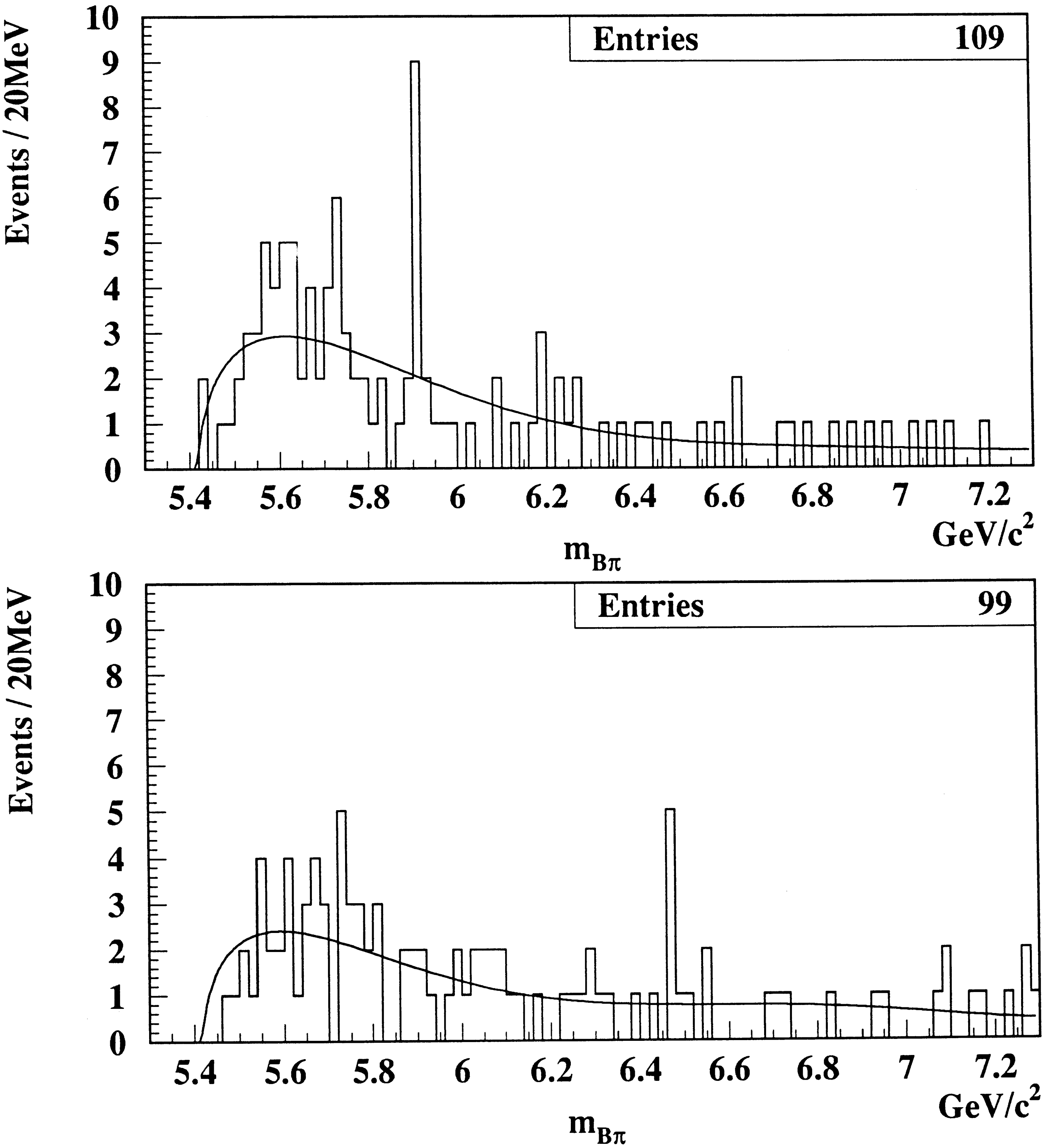


Figure 5: Invariant mass distributions in the data: (a) right-sign (b) wrong-sign combinations ('highest p_l' algorithm). Superimposed are the Monte Carlo background functions (shown in fig. 4), normalized to the same number of B's.

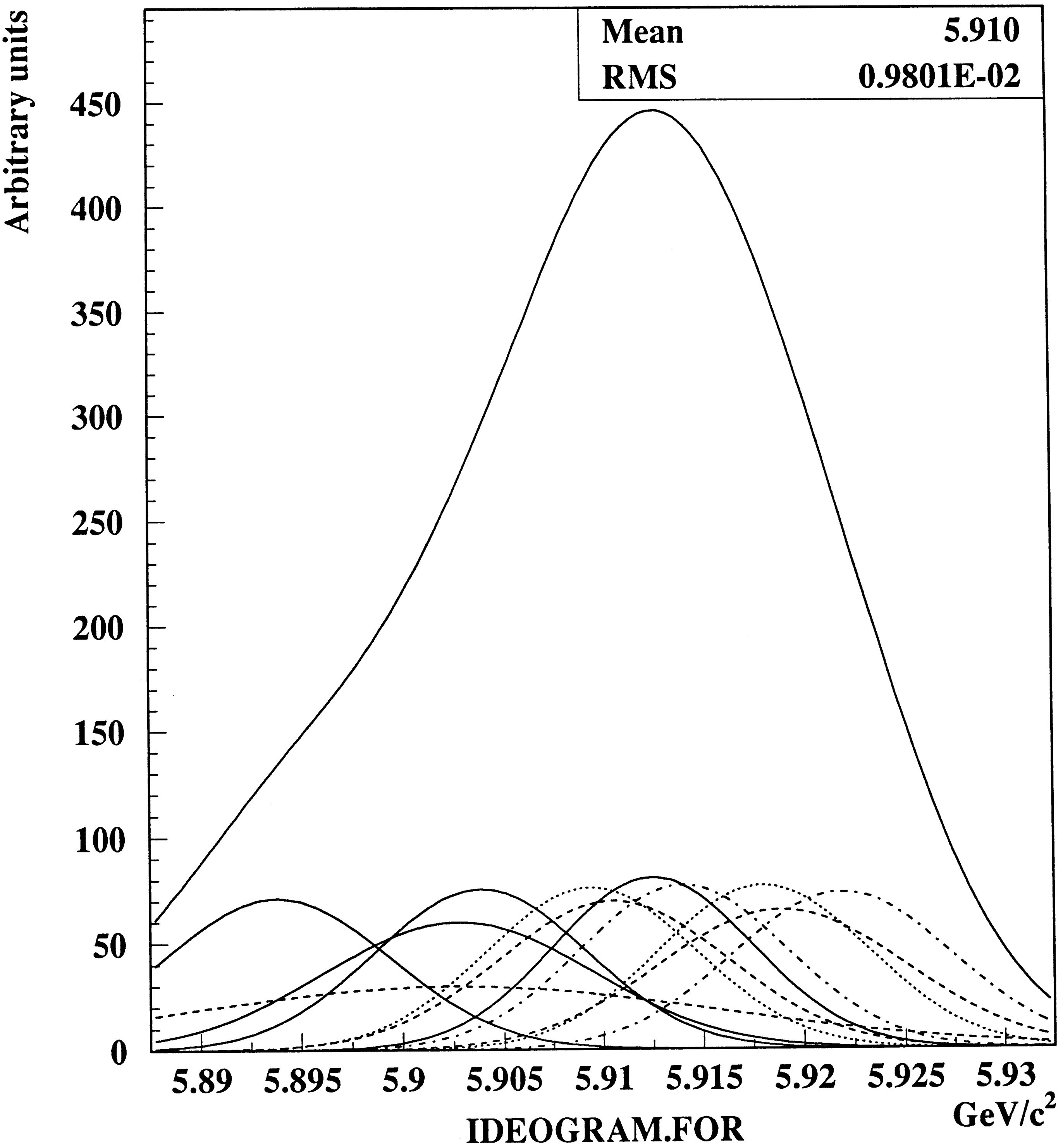


Figure 6: Mass ideogram for the structure at $5.91\, GeV/c^2$. About 4 background events are expected in this region

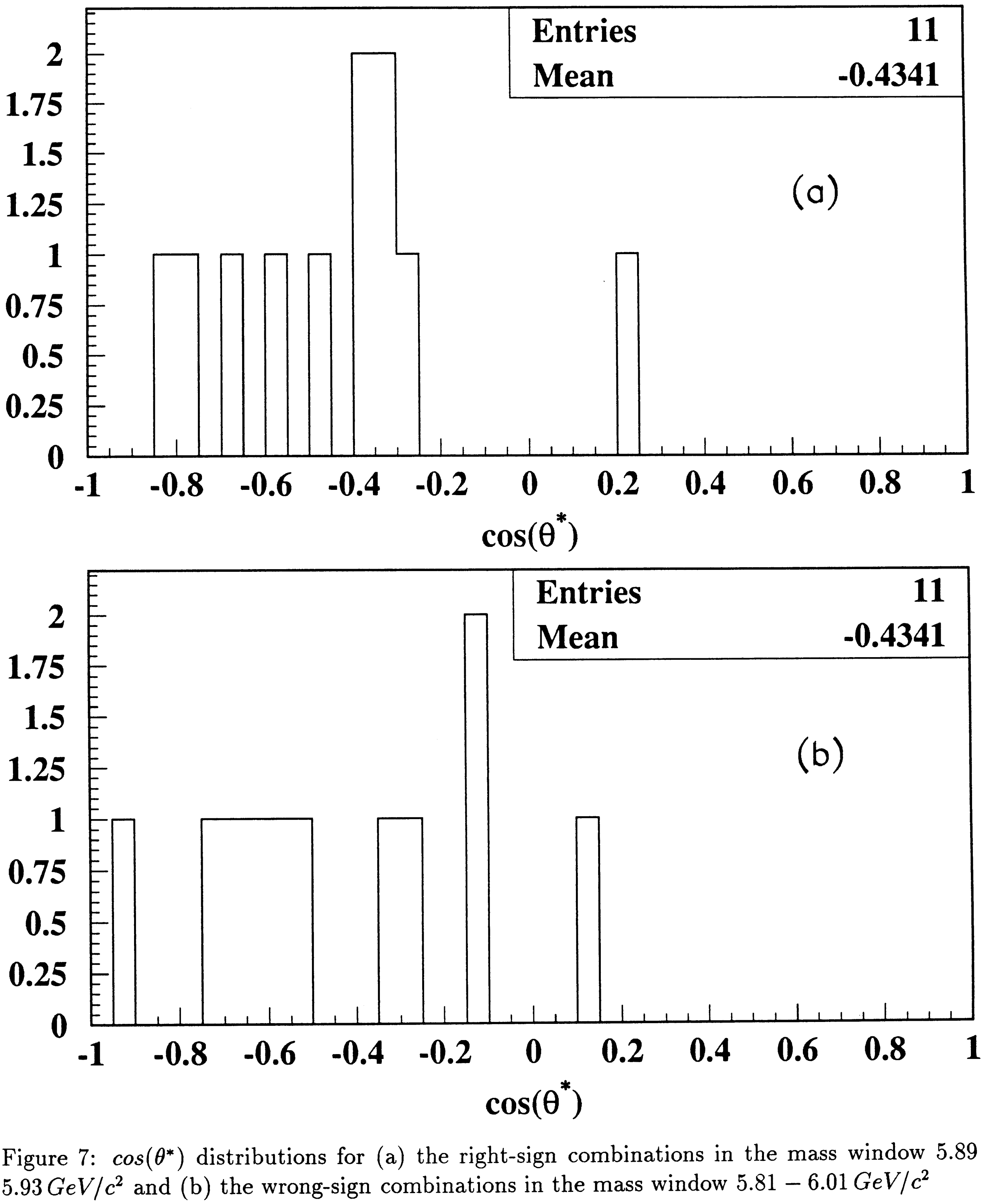


Figure 7: $cos(\theta^{*})$ distributions for (a) the right-sign combinations in the mass window $5.89 - 5.93\,GeV/c^2$ and (b) the wrong-sign combinations in the mass window $5.81 - 6.01\,GeV/c^2$