A Search for $\mathbf{B^0} \to \omega\pi^\mathbf{0}$

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Abstract

A method for experimentally determining the branching fraction of a particle decay is presented, whereby reconstructed collision events are categorized by a multivariate maximum likelihood fit. The method is then applied to the run 1- 5 data set of the BaBar experiment in an attempt to observe the rare B meson decay $B^0 \to \omega\pi^0$. The final uncorrected signal yield of the ML fit is 5.3$^{+18.2}_{-15.3}$ events, which is used to produce a 90% C.L. upper limit for the branching fraction of 0.6 x 10^{-6}.

Introduction

Many of the influential unanswered questions of modern physics pertain to the realm of the exceedingly small: the elementary particles that are the fundamental building blocks of all matter. However, the experimental study of elementary particles is inherently di􏰅cult, due to the instability of nearly every type of particle. Furthermore, there are no dependable natural sources of heavy, unstable particles (cosmic ray interactions are highly unpredictable), so they must be produced in large quantities in order to be studied. Physicists have addressed the challenge of creating unstable particles by constructing high - energy accelerators, which use precise alternating electric fields to push stable, charged particles to velocities approaching the speed of light, at which point they are then collided together. During a high - energy particle collision, the incident particles interact to form more - massive, unstable particles, which then spontaneously decay into other particles. The average lifetime of an unstable particle is extremely short, in some cases as short as 10^{-23} s, which raises additional experimental di􏰅culties. In fact, due to the timing limitations of modern detection devices, many particles cannot be studied directly during their brief existence. Instead, experimentalists have developed techniques to study them indirectly, by analyzing their decay products and the lingering e􏰀ects that they have on the matter with which they interact. The experimental data is typically gathered by an array of detectors positioned around the collider, which measure the energy, momentum, charge, and trajectory of the various product particles. This information can then be used to reconstruct the collision and study the unstable parent particles.

An unstable particle will decay spontaneously into lighter particles according to the conservation principles that govern elementary interactions. However, these principles leave room for many di􏰀erent product particle combinations, each of which is known as a decay "mode". There is no way to predict with certainty which decay mode a particular unstable particle will undergo; all that can be known is the branching fraction, which is the probability of a particular decay occurring. The quantum theories that describe the interactions of elementary particles (QCD, QED, etc) are, for the most part, computationally cumbersome and do not provide a method for calculating exact values for most decay probabilities. As such, several methods for estimating the branching fractions have been developed. However, these methods quite often yield inconsistent results, and there is no current consensus on which predictions should be given the most weight. Therefore, experimentation still remains the most useful means of determining decay mode branching fractions. Furthermore, experimentally determined branching fractions can be used as a method for theoretical validation. As there can be an enormous number of decay modes for some particles, the task of determining the branching fraction for every possible mode is quite daunting, although of great importance. In the sections that follow, a method will be described for experimentally calculating a branching fraction, and the explicit results will be given for one particular mode, $B^0 \to \omega\pi^0$.

Experimental Design

The currently accepted theory of elementary particles is the Standard Model, which is a quantum field theory that describes three of the four fundamental forces governing the interactions of matter: the weak nuclear, electromagnetic, and strong nuclear (the Standard Model is considered an incomplete theory because it does not provide a quantum explanation for the weakest fundamental force, gravity) [1]. According to the Standard Model, all matter consists of fermionic particles, which do not interact with each other directly, but only through the exchange of bosonic force carrier particles. The fundamental particles are assigned to three categories: mediators, leptons, and quarks. The mediator particles are the bosonic force carrier particles, which are specific to a particular force. The photon mediates the electromagnetic force, the W and the Z mediate the weak force, and there are eight gluons that mediate the strong force. The fermionic fundamental particles, the leptons and quarks, are distinguished by their quantum

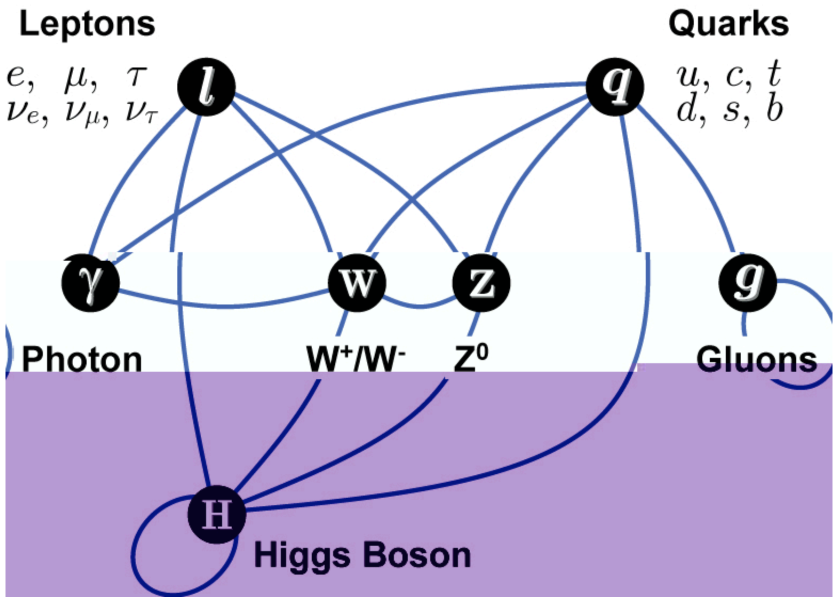

FIG. 1: The fundamental elementary particles and their interactions. A particle couples directly to another particle only if a line is shown between them.

numbers and the forces with which they interact. Leptons carry a lepton number of 1, a baryon number of 0, and do not experience the strong force. There are six leptons, divided into three generations: electron, muon, and tau. Each generation consists of a pair of particles, one a massive charged particle, and the other a neutral non - massive particle known as a neutrino. The quarks carry a lepton number of 0, a baryon number of 1/3, and participate in all of the fundamental interactions. There are six flavors of quark, denoted d, u, s, c, b, and t. Every quark carries a color charge of r, g, or b, and a fractional electric charge: u, c, and t carry +2/3, while d, s, b carry -1/3. In addition to the leptons and quarks, which are the fundamental particles of matter, there are antileptons and antiquarks, which are the fundamental particles of antimatter. Every quark and lepton has an antiparticle, which is identical to its particle counterpart except that its charge and of all of its quantum numbers are reversed (the spin, however, remains the same). The same mediator particles that couple to particles also couple to the antiparticles. All of the elementary particles that are not either mediators, quarks/antiquarks, or leptons/antileptons, are non - fundamental particles and are made up of combinations of quarks and antiquarks.

Although leptons do exist as free particles, quarks do not. This is known as confinement, whereby quarks can only exist in colorless states bound together by the strong nuclear force. A colorless combination occurs either when a quark carrying +1 color charge is bound to an antiquark carrying -1 of the same color charge, or else all three color charges must be present in the same quantity. The former, a bound state of a quark and an antiquark, is a meson, and the latter, the bound state of three quarks, is a baryon. It is in this manner that all of the heavier elementary particles are formed.

The majority of elementary particles, especially the more massive ones, are unstable, and will decay spontaneously into other particles. In fact, it can essentially be viewed as a rule that all particles will decay unless doing so would violate a conservation law. The primary conservation principles that govern all particle interactions are conservation of energy, momentum, angular momentum, electric charge, color charge, baryon number, and lepton number. These principles can be used to determine which particles decays are possible and which are not. In addition, the conservation principles can also be used and to identify stable particles, if there are no possible decays due to these theoretical restrictions.

The total relativistic energy and momentum of a particle are given by the following equations:

$$E = \gamma m c^2 \tag{1}$$

$$p = \gamma m v \tag{2}$$

where the Lorentz factor, γ is:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \geqslant 1 \tag{3}$$

The mass of a particle, m, is invariant under transformation of inertial reference frame. The total energy of a particle, however, is not invariant, which can be seen easily as a consequence of mass invariance. Consider a particle in the frame of reference where it is at rest: v = 0, so γ = 1, and eq. 1 reduces to $E = mc^2$. Now, in another inertial frame where $v \neq 0$, γ is greater than 1, so eq. 1 implies that $E > mc^2$. Therefore, the total energy is not invariant under transformation of reference frame.

Conservation of energy can be used to show several characteristics of particle interactions that are of particular interest to experimental particle physics. For the sake of simplicity, only two - body interactions will be considered, but the results that will be derived are at least qualitatively correct, and applicable to any n - body interaction. The first case of interest is that of a particle decay. Conservation of energy requires that the following equation hold in any reference frame:

$$\gamma_1 m_1 = \gamma_2 m_2 + \gamma_3 m_3 \tag{4}$$

In the rest frame of the incident particle v_1 = 0 so γ_1 = 1, and it follows immediately from eq. 3 and eq 4 that:

$$m_1 \geqslant m_2 + m_3 \tag{5}$$

Thus, the mass of the parent particle is always greater than or equal to the total mass of its product particle. The fact that the relation is an inequality shows that in the relativistic regime, mass is not strictly conserved, because some of the energy associated with the mass of the parent particle, $E = mc^2$, can be "carried away" in the form of KE of the product particles. This principle is typically stated as the tenet that heavier particles can only spontaneously decay into lighter particles. This result can be considered the explanation for particle stability: the stable particles are those for which there are no lighter particles that they can decay into while still obeying conservation principles. For example, electrons are stable because there is no lighter charged particle, and protons are stable because there is no lighter particle with baryon number 1.

The other fundamental situation to consider is the two - body particle collision, which can be approximated as a perfectly - inelastic collision [6]. When viewed in this manner, the two -body collision is essentially the reverse process of the two - body decay. The following equation is a direct result of energy conservation, and the analog to eq. 4:

$$\gamma_1 m_1 + \gamma_2 m_2 = \gamma_3 m_3 \tag{6}$$

It is convenient to consider the collision process in the rest frame of the product particle, where γ_3 = 1 and eq. 6 yields:

$$m_1 + m_2 \leqslant m_3 \tag{7}$$

Thus, it has been shown that the mass of the single product particle in a two - body collision is greater than the combined masses of the incident particles. The degree to which the product particle is larger depends on the velocities of the incident particles: the higher the velocities the more kinetic energy there is to convert to rest energy, yielding a more massive product particle. Although this result has been derived for the simplified case of a single particle resulting from a two - body collision, the principle holds experimentally. In fact, the notion that heavier particles can be formed by colliding two lighter particles is the basis for the entire field of accelerator physics, and is essential to the experimental study of elementary particles.

B - physics is the study of interactions involving the b quark, which is second heaviest quark, having a mass of 4.20 $\pm$ 0.07 GeV [3]. Due to its large mass, particles containing b quarks are highly unstable, and so in order to study them they must be created by colliding lighter particles together in an accelerator. The electromagnetic interaction is mediated by the photon, which can couple to any electrically charged particle and its antiparticle. As such, a b quark and a $\bar{b}$ antiquark pair can couple to the same photon as an electron positron pair. This electromagnetic interaction is used by experimental B - physicists to produce b quarks by colliding highly energetic electrons and positrons. The resulting particles cannot exist individually due to color confinement, and thus bond together forming an Y meson. The lifetime of the Upsilon is .21 x 10^{-20} s, after which it decays into lighter particles, some of which may contain a b quark or a $\bar{b}$ antiquark [3]. In order to create two decay mesons, one containing a b quark and the other containing a $\bar{b}$ antiquark, conservation of energy dictates that the Y must be created in an excited state, known as the Y (4s). In fact, the Y(4s) decays $\sim$ 100% of the time to two B mesons: either a B^0 $\bar{B}^0$ pair or a B^+ B^- pair [3]. This decay occurs when the b and $\bar{b}$ are pulled apart and bond to the appropriate member of either a u$\bar{u}$ pair or a d$\bar{d}$ pair that is formed from the energy built up in the gluon field. The quark compositions of these B mesons are:

$$B^0 : \bar{b}d, \quad \bar{B}^0 : b\bar{d}$$

$$B^+ : \bar{b}u, \quad B^- : b\bar{u}$$

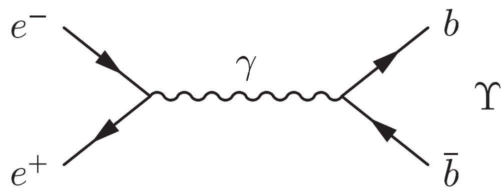

FIG. 2: The creation of the Υ meson from the collision of an electron an a positron.

The B mesons have an unusually long lifetime of 1.67 x 10^{-12} s, after which they undergo one of a huge number of allowed decay modes [3].

The following section will present the details the method that is used to produce B meson pairs at the BaBar experiment. In addition, the procedure for studying a particular decay mode, $B^0 \to \omega\pi^0$, will be discussed, and then a method for calculating its branching fraction will be presented.

Experimental Procedure

A beam of electrons and a beam of positrons are accelerated using the Stanford LInear Accelerator and directed into the PEP II storage rings in opposite directions. The beams are given asymmetric energies, with the electron beam having an energy of 9.0 GeV, and the positron beam having an energy of 3.1 Gev [4]. The asymmetric energy is designed to give the Υ($4s$) a high velocity in the lab frame ($\sim$.5c), so that the track distances of the B meson decay particles can be feasibly measured in the detector. The energies of the beams were chosen to give a center of mass energy of 10.58 GeV, which corresponds to a resonance for the Υ($4s$)[4]. The storage rings are designed such that the two opposing beam trajectories intersect to produce collisions within the array of detectors that measure the particle energies, momenta, charge, and trajectory. The beams are maintained at 10.58 GeV in the storage rings continually and data are taken around the clock. The data are analyzed preliminarily by BaBar software to select out only the events that are likely to represent the production of the Υ($4s$).

The data set used to calculate the branching fraction for the $B^0 \to \omega\pi^0$ decay mode is the run 1-5 data set, which consists of 377 million Υ($4s$) events. After the initial cuts were applied to the full data set at SLAC, an additional round of mode - specific selection cuts were applied in order to eliminate events that were not likely candidates for the $B^0 \to \omega\pi^0$ mode. In order to do this, each event was analyzed and searched for the proper combination of candidates for the particles in the signal decay mode. A π^0 particle decays almost exclusively to two photons, so a π^0 candidate is formed from an observation of two photons in an event. Any two charged tracks and a π^0 form an ω candidate, and the simultaneous occurrence in an event of both an ω candidate and a π^0 candidate form a B^0 candidate. The invariant masses of these reconstructed particles were then calculated and checked for consistency with the known masses of the corresponding particles. The π^0 candidates must have a mass in the range 120 $< m_{\pi^0} <$ 150 MeV/c^2, ω candidates must have a mass in the range 735 $< m_\omega <$ 825 MeV/c^2, and B^0 candidates must have a mass in the range 5.25 $< m_{B^0} <$ 5.29 GeV/c^2. In addition to the mass cuts, there was a cut on the angle between the thrust axis of the B^0 candidate the corresponding $\bar{B^0}$ in the event. This cut is defined such that $cos\theta_T \leqslant .8$. There was also a cut on the difference between the energy of the reconstructed B^0 candidate and the expected value: $|\Delta E| <$ .25 GeV. The final cut was on a composite, event - shape variable known as Fisher: $-4 \leqslant F \leqslant 5$. The cuts were kept relatively wide to allow for high signal detection efficiency. After the cuts were applied and the final data set was obtained, the background modes were then separated from the signal mode to obtain the final signal yield. In order to do this a study of the background modes was undertaken, to identify which modes were likely to have passed the cuts in addition to the signal mode. A set of Monte Carlo simulated data was generated for all known decays of the Υ($4s$), excluding decays involving charm quarks, which are not as likely to be confused with the signal mode. The selection cuts were then applied to the simulated dat set and a list of all of the modes that passed the cuts was generated. These modes constitute the charmless $B\bar{B}$ background modes. All other background that was present is referred to as $q\bar{q}$ background, and was not studied using simulated data, but rather by examining the sidebands of the event - variable ranges for the actual data set. This was done to account for the inability to simulate background events that have not yet been studied or are completely unknown.

After the charmless background modes were identified, three additional sets of Monte Carlo data were generated, one consisting entirely of signal, one entirely of the most dominant charmless background mode (charmless 1), and one a mix of the remaining charmless background modes (charmless 2). Each of these sets was passed through the selection cuts and then histogram plots were made of the following event variables: mES (m_{B^0}), ΔE, Fisher, m_ω, and ω helicity. Plots were also made for $q\bar{q}$ background, using the sidebands of the final data set events. These plots were then fit with appropriate functions (PDFs), to enable differentiation between all of the different types of events that were likely to be present in the final data set. This was implemented using maximum likelihood fitting software, which essentially analyzed each event and compared the measured values of the five event variables to the PDFs to determined which type of event it most likely represented: signal, $q\bar{q}$, charmless $B\bar{B}$ 1, or charmless $B\bar{B}$ 2. A study was then done to determine the bias in the experimental method, as well as the systematic error. Once the number of signal events was determined and corrected for experimental bias, the branching fraction was calculated according to the equation:

$$\mathbf{B} = \frac{N_{corr}}{N_{B\bar{B}}\epsilon\Pi_{br}} \tag{8}$$

where N_{corr} is the signal yield corrected for experimental bias, $N_{B\bar{B}}$ is the total number of $B\bar{B}$ mesons created and observed in the run 1-5 data set at SLAC, ϵ is the overall selection e□ciency, and Π_{br} is the product branching fraction for the omega decay into $\pi^+\pi^-\pi^0$ (89.1%).

Results

The list of identified charmless $B\bar{B}$ background events is presented in figure 3. The dominant background mode was found to be $B^+ \to \omega\rho^+$, which is very similar to the signal mode due to the presence of a real omega. The overall e□ciency of the selection cuts was calculated to be 19.3%. The PDFs for the simulated events passing the preliminary cuts as well as $q\bar{q}$ background are presented in figure 4. The number of events in the real data set that passed the preliminary cuts is 32141. The maximum likelihood fitting gave background yields of: 31904 ± 210 for $q\bar{q}$, and 225 ± 110 for $B\bar{B}$. The signal yield was $5.3^{+18.2}_{-15.3}$ events, which is consistent with zero within 1 σ given the high statistical uncertainty. Therefore, it is unclear whether or not an actual $B^0 \to \omega\pi^0$ event was observed. The study that was used to determine the bias in the experimental method yielded a value of -0.5 ± 0.5 events. The corrected signal yield was then used to calculate the branching fraction according to eq. 8, which produced a result of $\boldsymbol{B}$ = $0.09^{+0.30}_{-0.26}$ x 10^{-6}. The systematic error in this value was found to be 0.01 x 10^{-6}, which is insignificant compared to the statistical error. Although a value for the branching fraction was calculated, the standards of the BaBar collaboration are such that an exact value cannot be published unless the signal yield was at least 4 σ away from zero, thus guaranteeing with a 99.994 % certainty that an actual signal was seen. As such, only an upper limit for the branching fraction of $B^0 \to \omega\pi^0$ can be given from this analysis. The upper limit is calculated at the 90 % confidence level from the uncertainty in the branching fraction (1.81 σ above the mean). Therefore, the resulting upper limit for the branching fraction of $B^0 \to \omega\pi^0$ is $\boldsymbol{B} <$ 0.6 x 10^{-6}.

Conclusions

A search of the run 1-5 Babar data set did not yield any statistically significant evidence for the occurrence of the decay mode $B^0 \to \omega\pi^0$. As a result, the branching fraction for this rare event could not be determined experimentally and compared to the theoretical predictions. However, the lack of a strong signal in 377 million Υ(4s) events allowed for a constraint to be placed on the branching fraction, setting an upper limit to the 90% C.L. of 0.6 x 10^{-6}, which represents a significant improvement over the previously determined experimental value of $\mathbf{B} <$ 1.2 x 10^{-6} [5]. The current upper limit is consistent with the theoretical predictions from both QCD factorization (0.1 x 10^{-6}), and SU (3) (0.01 x 10^{-6}) [2]. In order to accurately measure the branching fraction for the $B^0 \to \omega\pi^0$ mode and attempt to validate one of the two conflicting theoretical predications, a larger data set would be required.

Signal mode Bkg. channel	Mode #	MC ϵ (%)	Est. $\mathcal{B}$ (10^{-6})	$\prod \mathcal{B}_i$	Norm. # $B\bar{B}$ Bkg.	# in PDF Bkg. file
Charmless 1						
$B^+ \to \omega\rho^+(L, f_L = 0.82)$	2768	1.47	$8.7^{+2.1}_{-1.9}$	0.891	43.7	12939
Charmless 2						
$B^+ \to a_1^+(\rho^0\pi^+)\pi^0$	4799	0.68	$26.4^{+6.8}_{-6.8}$	0.500	34.2	1182
$B^+ \to a_1^+(\rho^+\pi^0)\pi^0$	4957	0.28	$26.4^{+6.8}_{-6.8}$	0.500	14	485
$B^+ \to b_1^+(\omega\pi^+)\pi^0$	5271	0.81	4^*	0.891	11	380
$B^0 \to \rho^+\rho^-(L, f_L = 0.96)$	2498	0.12	$24.2^{+3.5}_{-3.6}$	0.96	10.5	364
$B^+ \to \rho^+\pi^0$	1940	0.25	$10.8^{+1.4}_{-1.5}$	1.000	10.2	354
$B^0 \to \pi^0 K^0$	1442	0.46	$10.0^{+0.6}_{-0.6}$	0.343	6	209
$B^+ \to \pi^+\pi^0\pi^0$ $(N.R.)$	1938	0.07	10^*	1.000	2.6	89
$B^0 \to \eta_{3\pi}\pi^0$	1792	1.56	$0.6^{+0.5}_{-0.4}$	0.226	0.8	27
$B^0 \to \pi^0\pi^0 K^{*0}_{K^+\pi^-}$	4148	0.04	1^*	0.667	0.1	3
Total					89.4	3093

FIG. 3: The charmless $B\bar{B}$ background modes that were identified using Monte Carlo simulated data, listed in order of prominence.

[1] D. J. Griffiths, *An Introduction to Elementary Particles*, Wiley, New York, USA (1987).
[2] W. Ford, J. Smith, J. Hirschauer, K. Ulmer, J. Gilman, C. West, and J. Becker, *BaBar Analysis Document 1772* (2007).
[3] *Review of Particle Physics*, W.-M. Yao, *et al.*, Journal of Physics G **33**, 1 (2006).
[4] K. Ulmer, *Study of Rare B Meson Decays Related to the CKM Angle β at BaBar* (2007).
[5] W. Ford, J. Smith, F. Blanc, P. Bloom, and P. Clark, *BaBar Analysis Document 744* (2004).
[6] In practice, it is highly unlikely that a two - body collision would result in a final state consisting of only 1 particle. However, this discussion is intended to be a motivation for the idea that heavier particles can be created during high - energy collisions, when some of the kinetic energy of the incident particles is converted into rest energy of the final state particles.

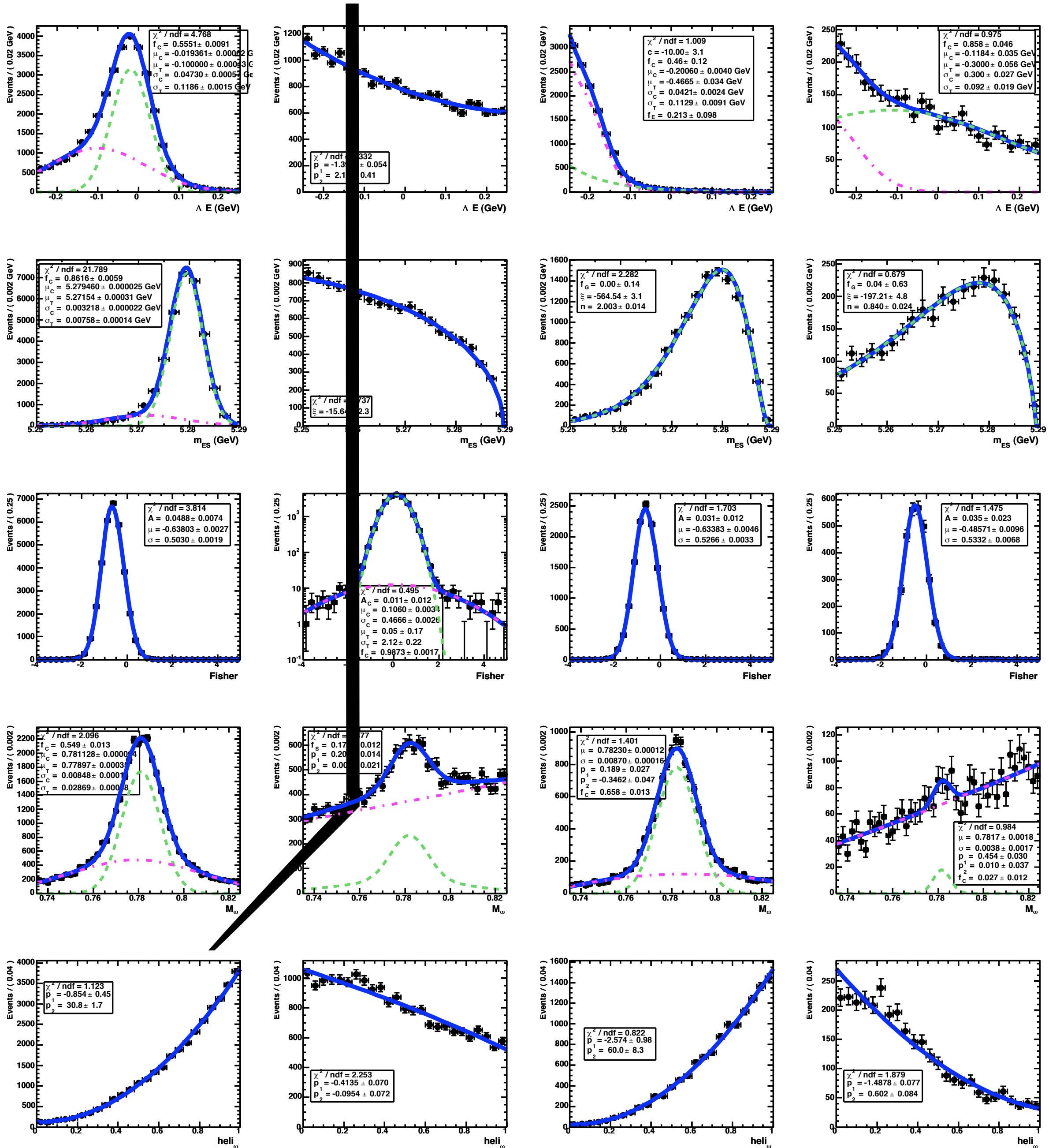

FIG. 4: The PDFs shown on the histogram plots of the event variables (rows from top to bottom): Δ E, mES, Fisher, ω mass, and ω helicity. The columns from left to right are signal, $q\bar{q}$ background, charmless $b\bar{b}$ background 1, and charmless $b\bar{b}$ background 2.