

Decays of the $\psi(2S)$ Meson to Baryonic Final States

Thesis by
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Although dissertations such as this are supposed to be individual efforts, no research can exist in a vacuum. The results of this thesis were made possible by a collaborative effort of a few hundred physicists and engineers for more than a decade. I'd like to thank the entire BES collaboration and the BEPC staff for their hard work and dedication.

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Abstract

From 1993 to 1995, the Beijing Electron-Positron Collider produced 3.7 million $\psi(2S)$ mesons in the Beijing Spectrometer (BES) experiment. This sample is used to study decays of the $\psi(2S)$ meson which result in exclusive pairs of octet and decuplet baryons. I report branching ratios for $\psi' \rightarrow p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Xi^-\bar{\Xi}^+$, $\Delta^{++}\bar{\Delta}^{--}$, $\Sigma^{*+}\bar{\Sigma}^{*-}$, $\Xi^{*0}\bar{\Xi}^{*0}$, and $\Omega^-\bar{\Omega}^+$. Results are compared to expectations based on perturbative QCD, the SU(3)-flavor symmetry and factorization.

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Chapter 1 Introduction

With the introduction of the Gell-Mann quark model [1] in 1964, particle physics entered the modern era. The independent discoveries by Richter and Ting of the J/ψ meson [2][3] in the mid 1970's were proofs of principle for the fledgling Standard Model of particle physics.

1.1 Standard Model

The Standard Model ties matter and energy interactions together into one coherent picture. This picture, in statement form, is relatively simple:

- All matter is made up of quarks and leptons.
- All matter is bound together with gauge bosons.

In reality, however, the Standard Model is slightly more complicated.

Table 1.1 shows the components of the standard model, along with their masses. The leptons and quarks are each grouped into three generations, and the gauge bosons are split into four types. The quark generations are split into “up-type,” with charge $2/3$ and “down-type,” with charge $-1/3$. The leptons are split into charged and neutral members, with the neutral members called neutrinos. Gauge bosons are split according to what kind of force they carry. Photons carry the electromagnetic force, Z and W carry the weak force, and gluons carry the strong force.

The interaction between the matter-constituents and the force-carriers can be summarized by the Electroweak and QCD Lagrangians. The Electroweak Lagrangian

Leptons spin=1/2			Quarks spin=1/2		
Flavor	Mass GeV/ c^2	Charge	Flavor	Approx Mass GeV/ c^2	Charge
ν_e	$< 5 \times 10^{-9}$	0	u	0.005	2/3
e	0.000511	-1	d	0.01	-1/3
ν_μ	< 0.0003	0	c	1.5	2/3
μ	0.106	-1	s	0.2	-1/3
ν_τ	< 0.03	0	t	170	2/3
τ	1.7771	-1	b	4.7	-1/3

Bosons spin=1		
Flavor	Mass GeV/ c^2	Charge
γ (photon)	0	0
$W^\pm$	80.22	± 1
Z^0	91.187	0
g (gluon)	0	0

Table 1.1: Components of the Standard Model

is given by[4]:

$$\begin{aligned}
\mathcal{L}_{\mathcal{F}} = & \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{gm_i H}{2M_W} \right) \psi_i - e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \\
& - \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma^5) (T^+ W_\mu^+ + T^- W_\mu^-) \psi_i \\
& - \frac{g}{2 \cos \theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu ,
\end{aligned} \tag{1.1}$$

where θ_W is the weak mixing angle, $e = g \sin \theta_W$ is the positron charge, q_i is the charge on the fermion in units of e , H is the Higgs scalar field (left after symmetry breaking), W and Z are the charged and neutral weak boson fields, g_V and g_A are the vector and axial vector couplings to the Z field, $T^\pm$ are the weak isospin raising and lowering operators, ψ_i are the four component fermion spinors, and A is the massless photon field.

The QCD Lagrangian is given by[5]:

$$\begin{aligned}
\mathcal{L}_{\text{QCD}} = & \sum_q \bar{\psi}_q (i \not{\partial} - g_s \gamma^\mu B_\mu - m_q) \psi_q - \frac{1}{2} \text{tr}(G_{\mu\nu} G^{\mu\nu}) , \\
G_{\mu\nu} = & \partial_\mu B_\nu - \partial_\nu B_\mu + i g_s f_{abc} B_\mu^b B_\nu^c , \\
B_\mu = & \frac{1}{2} \lambda^l b_\mu^l ,
\end{aligned} \tag{1.2}$$

where g_s is the QCD coupling constant, ψ_q are four component quark spinors, $b_\mu^l(x)$ ($l = 1, \dots, 8$) are the eight gluon fields, the λ matrices are the generators of $SU(3)$ transformations, and f_{abc} are the structure constants of the $SU(3)$ algebra ($[\lambda_a, \lambda_b] = \lambda_a \lambda_b - \lambda_b \lambda_a = 2i f_{abc} \lambda_c$).

While Equations 1.1 and 1.2 are daunting, they can be quickly broken down into their component parts. The first term of $\mathcal{L}_{\mathcal{F}}$ is simply the Dirac mass term for the fermions, with an additional Yukawa coupling to the Higgs. Next is the term which describes electromagnetic (QED) interactions. The last two terms in Equation 1.1 are the coupling of fermions to charged and neutral weak fields, respectively.

$\mathcal{L}_{\text{QCD}}$ starts off with a covariant form of the Dirac propagator, replacing ∂_μ with $\partial_\mu + g_s B_\mu$, to insure that $\mathcal{L}_{\text{QCD}}$ is invariant under local gauge transformations $\psi \rightarrow S\psi$,

$S \equiv e^{-iq\lambda\cdot\phi(x)/\hbar c}$. This term describes quark propagation, and the qqg coupling. The second term is the description of the free gluon field and describes the gluon propagator, ggg and $gggg$ coupling.

1.2 Charmonium

Two charm quarks in a bound state ($c\bar{c}$) exhibit an energy spectrum remarkably similar to that of positronium, as seen in Figure 1.2. The major difference is in the energy scale of the splitting, which comes from the facts that the c quark is 3000 times as massive as an electron, and that the strength of the strong force is much greater than the strength of the electromagnetic.

The 1^{--} states are the easiest charmonium states to examine experimentally as they are the only states able to be created via the reaction $f\bar{f} \rightarrow c\bar{c}$ (see Figure 1.1). This is because the virtual photon (Z) in the reaction is in the 1^{--} state, and all quantum numbers are conserved in the reaction.

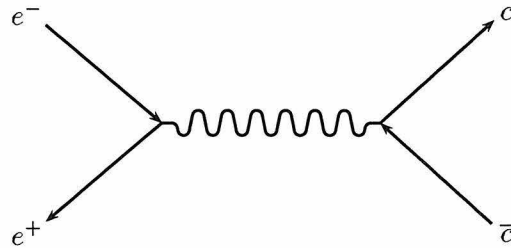


Figure 1.1: Feynman diagram for charmonium production at tree level.

The $c\bar{c}$ state that this thesis is concerned with is the first radial excitation of the lowest 1^{--} state. The lowest 1^{--} state was discovered simultaneously at Brookhaven and SLAC[3][2], and named J and ψ by the respective collaborations (now commonly called J/ψ). Within a month, the first radial excitation was seen at SLAC, and

following their naming structure, was called the ψ' [6]. Following the tradition of spectroscopic notation, the J/ψ and the ψ' are also called the $\psi(1S)$ and the $\psi(2S)$.

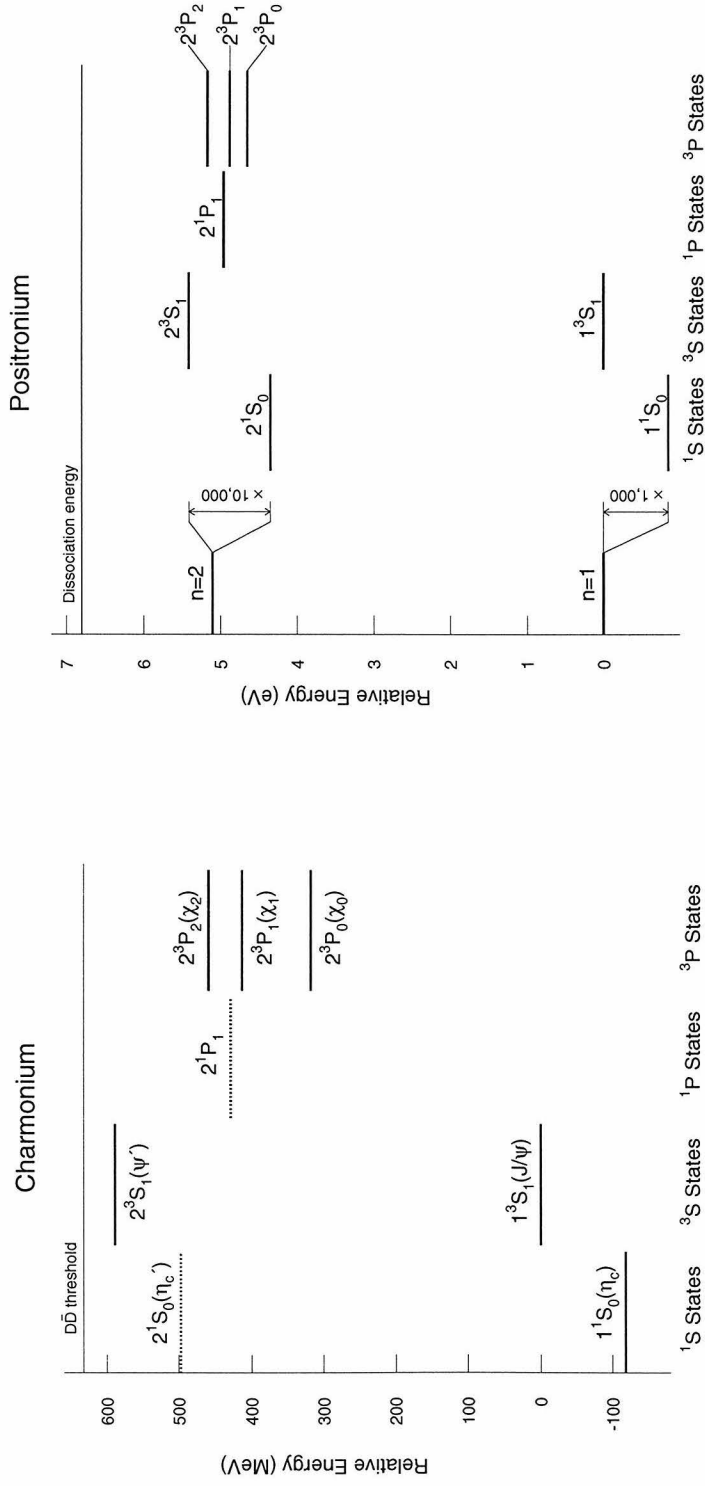


Figure 1.2: Energy level diagram for charmonium and positronium. Dotted lines in the charmonium diagram indicate states that need confirmation. Note that the scale for the charmonium plot is a factor of 10^7 larger than the positronium plot. This is caused by the mass difference of c and e , the difference between $\alpha_s(M_{\psi(n)})$ and α_{EM} , and the fact that QCD is not strictly a coulombic interaction.

Chapter 2 Apparatus

2.1 The Beijing Electron-Positron Collider

The Beijing Electron-Positron Collider (BEPC), located 12 km west of center-city Beijing, has a structure similar to a giant badminton racquet,[7] as illustrated in Figure 2.1. The 200 meter long “handle” is a linear accelerator delivering electrons and positrons at up to $1.55 \text{ GeV}/c$. The “paddle” portion is a roughly circular storage ring ($70 \text{ m} \times 76 \text{ m}$) with a circumference of 240 m. This storage ring delivers e^+e^- collisions at center of mass energies from 3–5 GeV/c at each of two interaction regions.

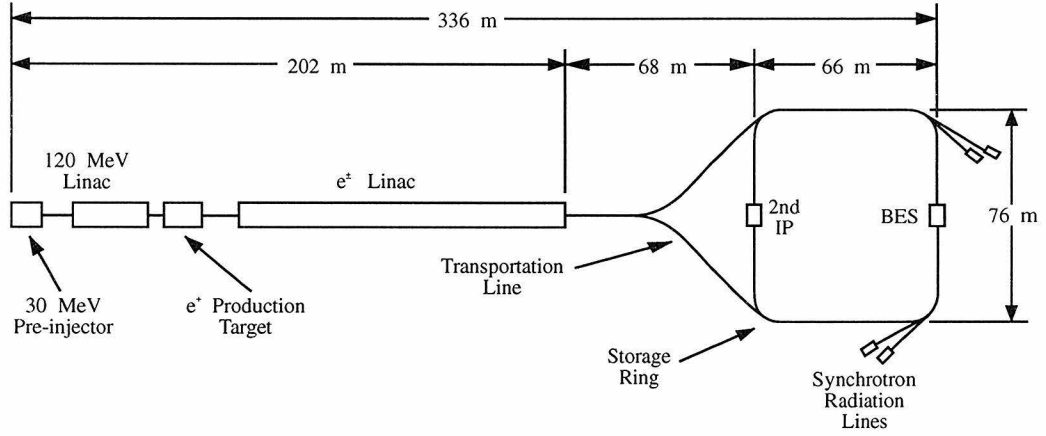


Figure 2.1: The Beijing Electron-Positron Collider.

Table 2.1 shows the nominal operating parameters of BEPC. From these, the nominal machine luminosity can be calculated[8]:

$$\mathcal{L} = \frac{N N_b^2 f_0}{4\pi \sigma_x^* \sigma_y^*} \approx 2.4 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}.$$

The actual luminosity measured by the BES luminosity monitor (see Section 2.2.6) was typically a few $\times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, consistent with expectations.

Table 2.1: BEPC operating parameters adapted from [9] and [10]

Center of mass energy	E	3–5 GeV
Storage ring circumference	L	240.400 m
Bunch spacing	t_b	801.888 ns
Number of bunches/beam	N	1
Natural bunch length	σ_l	5.20 cm
Number of particles per bunch at injection	N_b	6.8×10^{10}
Revolution frequency	f_0	1247.057 kHz
Horizontal beta function at IP	β_x^*	103.00 cm
Vertical beta function at IP	β_y^*	8.5 cm
Horizontal spot size at IP	σ_x^*	592 μm
Vertical spot size at IP	σ_y^*	38.7 μm
Beam-beam linear	$\Delta\nu_x$	0.035
tune shifts	$\Delta\nu_y$	0.035
Beam-pipe inner radius at IP	r^*	7.5 cm

2.2 The Beijing Electron Spectrometer

The Beijing Electron Spectrometer (BES) is a conventional cylindrical detector optimized for examining physics in the few GeV regime. Figure 2.2 shows axial and longitudinal sections of the detector. The major components of the detector are described in the following sections. This configuration is for the detector as it stood between 1989 and 1995. After 1995, the detector and beamline were upgraded, thus the configuration has changed.

2.2.1 Central Drift Chamber and Beampipe

The innermost radius of the BES detector consists of a 0.3 mm thick aluminum beampipe with a 2 mm carbon fiber support structure. The outer diameter is 154 mm, and the beampipe contributes 2.33×10^{-2} radiation lengths to multiple scattering at 90 degrees to the beam.

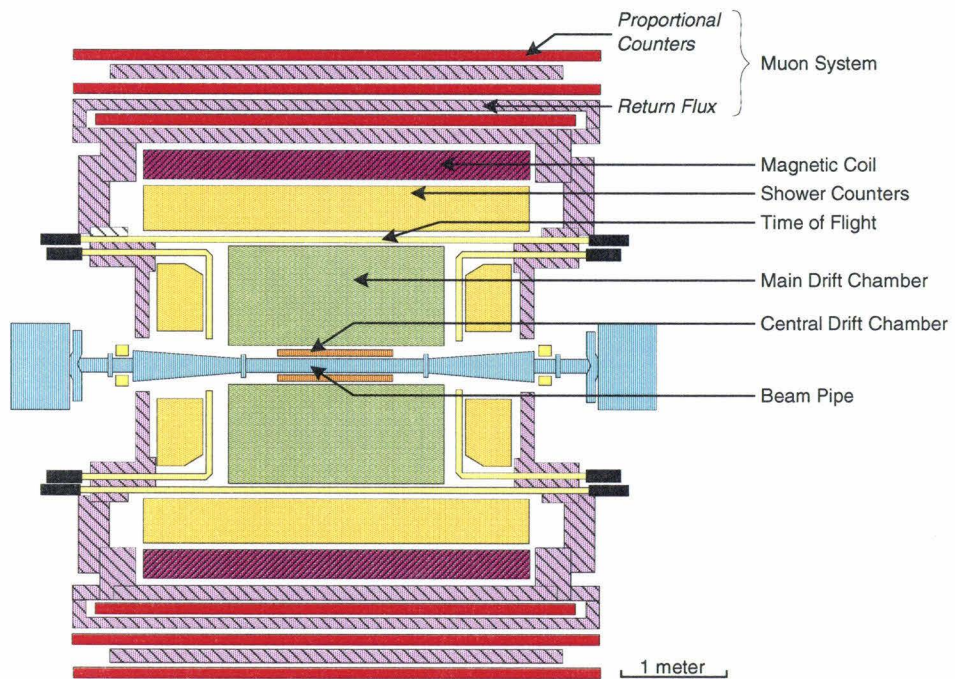
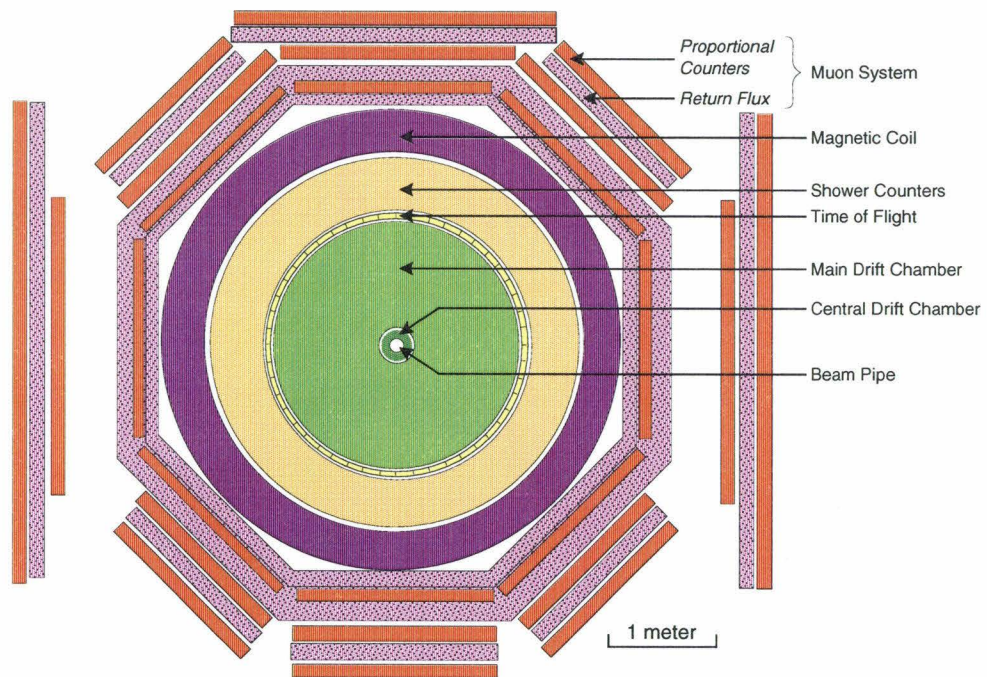


Figure 2.2: Cross sections of the BES detector.

Just outside, and integral with, the beam pipe is the Central Drift Chamber (CDC). This 4-layer tracking system (IR=92 mm, OD=149 mm, L=1100 mm, 48×1 sense-wire cells per layer) is designed to improve momentum and position resolution when used in conjunction with the Main Drift Chamber (Section 2.2.2). The CDC operates in proportional mode using a mixture of Ar/CO₂/CH₄=89/10/1, with a resolution of $\sigma_x=150$ mm, $\sigma_z = 1$ cm (charge division), and a solid angle coverage of 98% of 4π .

2.2.2 Main Drift Chamber

Next outward from and concentric with the CDC is the Main Drift Chamber (MDC). An inner 2 mm Carbon fiber wall at a radius of 155 mm contributes 9×10^{-3} radiation lengths to multiple scattering. The MDC is laid out with 10 layers of 4 sense wire drift cells, one octant of which is shown in Figure 2.3. Even numbered layers (numbered radially outward) are axial, while odd numbered layers are stereo with a 2 to 5 degree wire pitch to provide z position resolution. The number of cells per layer ranges from 48 at the inner radius to 108 at the outer. As in the CDC (Section 2.2.1), the gas used is Ar/CO₂/CH₄=89/10/1.

Position measurements are provided via pulse time readouts of the various sense wires. Single wire resolution is typically 200–250 μm in the r - ϕ plane. Total momentum resolution is $\Delta p/p = 0.021\sqrt{1+p^2}$ (p in GeV/ c). Along with timing, the pulse height is also recorded. This provides dE/dx information for particle identification, shown in Figure 2.4. Pions and kaons are effectively separated at up to 500 MeV/ c , and protons are well identified at 1 GeV/ c . Solid angle coverage for layer 10 of the MDC is 70% of 4π .

2.2.3 Time of Flight System

Along with the dE/dx information from the Main Drift Chamber, particle identification is provided by the Time of Flight (TOF) counters. Located just outside the Main Drift Chamber (Section 2.2.2), the TOF consists of two sections. The Barrel TOF

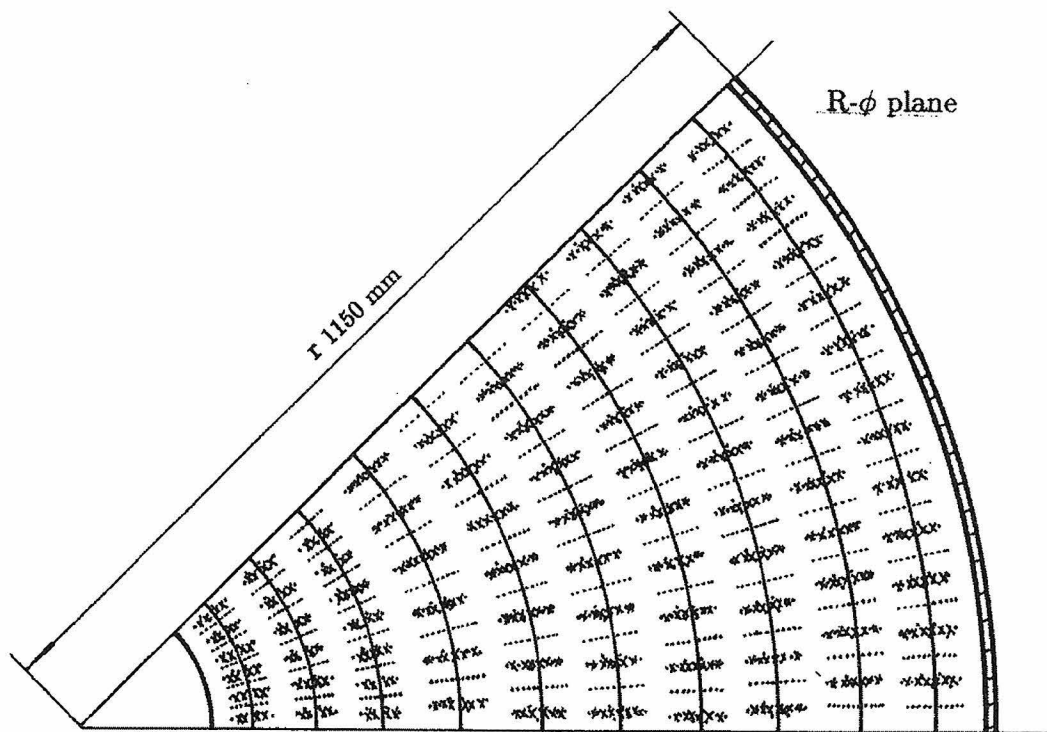


Figure 2.3: One octant of the BES Main Drift Chamber, showing cell and wire layout.

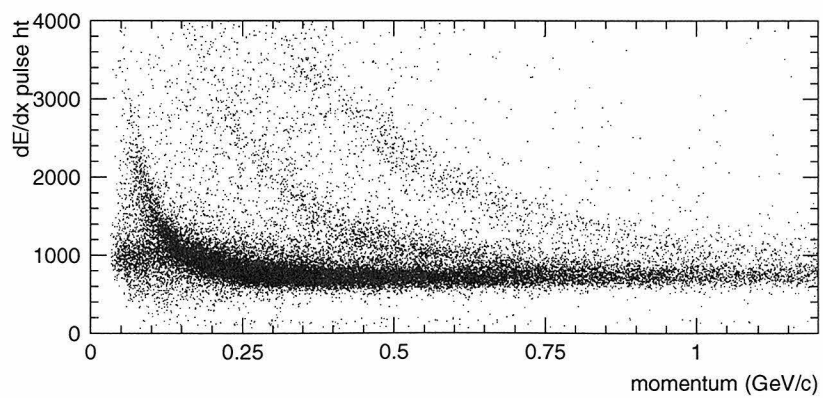


Figure 2.4: dE/dx pulse height *vs.* particle momentum. π , K , and p bands can be seen.

is a cylindrical array of 48 $15\text{ cm} \times 5\text{ cm} \times 284\text{ cm}$ scintillators, arranged concentric with the MDC and CDC. The Endcap TOF system is made up of two disk-shaped arrays of trapezoidal scintillators, 24 per disk, each piece 2.5 cm thick (ID 75 cm, OD 211 cm). All scintillators are read out through lucite light guides into XP2020 photomultipliers. Timing resolution for electrons was $\approx 300\text{ ps}$ in 1990, and $\approx 400\text{ ps}$ in 1994, when the bulk of the data for this thesis was taken. Total solid angle coverage for the TOF system is 96% of 4π , with 75% for the barrel counters only.

2.2.4 Shower Counter

Outside the TOF system lies the BES shower counter, or calorimeter system. This system is divided into three sections, the barrel (BSC: ID 247.0 cm, OD 338.2 cm, Length 385.0 cm), and two endcap sections (ESC: ID 74.6 cm, OD 192.0 cm, Thickness 41 cm). Each portion consists of 24 layers of self-quenching streamer mode tubes alternating with lead absorber material, for a total thickness of 12 radiation lengths, as shown in Figures 2.5 and 2.6. Resolution in the BSC is $\Delta E/E = 22\%/\sqrt{E}$ (E in GeV), $\sigma_\phi = 7.9\text{ mrad}$, and $\sigma_z = 36\text{ mm}$. In the ESC, energy resolution is the same, with $\sigma_x = 15\text{ mm}$ and $\sigma_y = 17\text{ mm}$. Coverage for the BSC is 70% of 4π , with combined coverage of 94% of 4π .

One important feature of the barrel portion of the shower counter system is the support rib structure, five of which are spaced equally along the length of the BSC. As these ribs are “dead” regions, they severely degrade energy measurements, as shown in Figure 2.7. Modes in this thesis which use the BSC as an integral part of the analysis will exclude these regions of the BSC from consideration.

2.2.5 Magnet and Muon System

The entire tracking and calorimetry region of the BES detector is contained within a 4 kG axial magnetic field. This field, used for momentum measurements, is generated by a conventional, water-cooled, aluminum solenoid (ID=3.48 m, OD=4.14 m). This solenoid, along with the rest of the detector, is supported by an iron yoke/flux return,

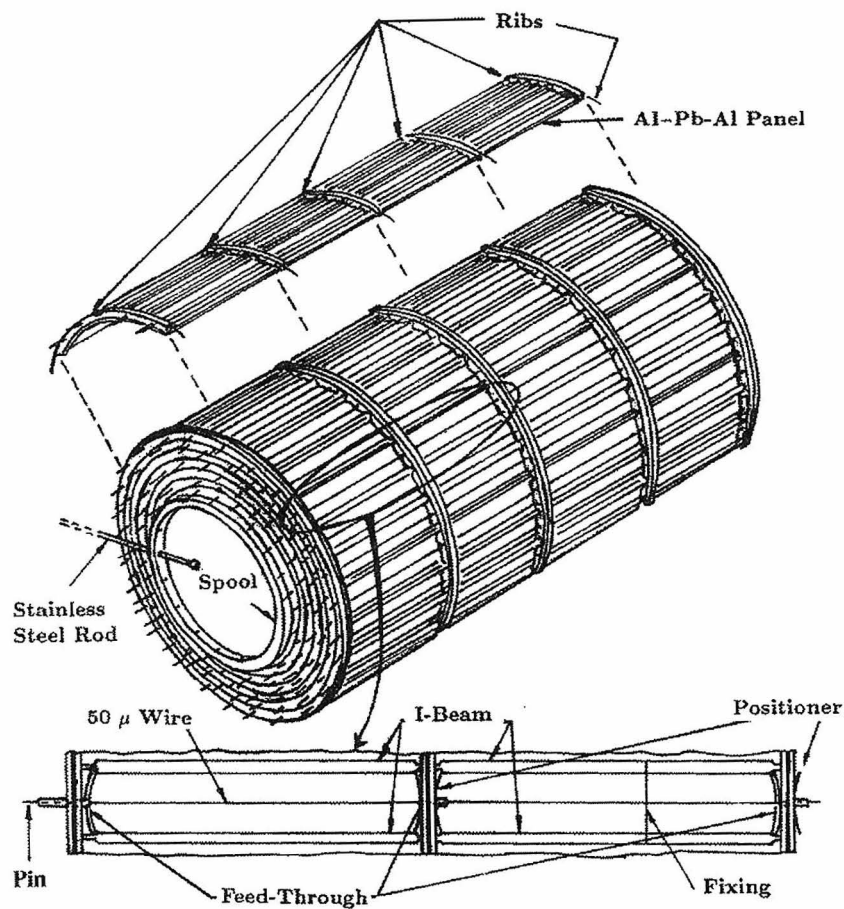


Figure 2.5: Exploded view of the Barrel Shower counter.

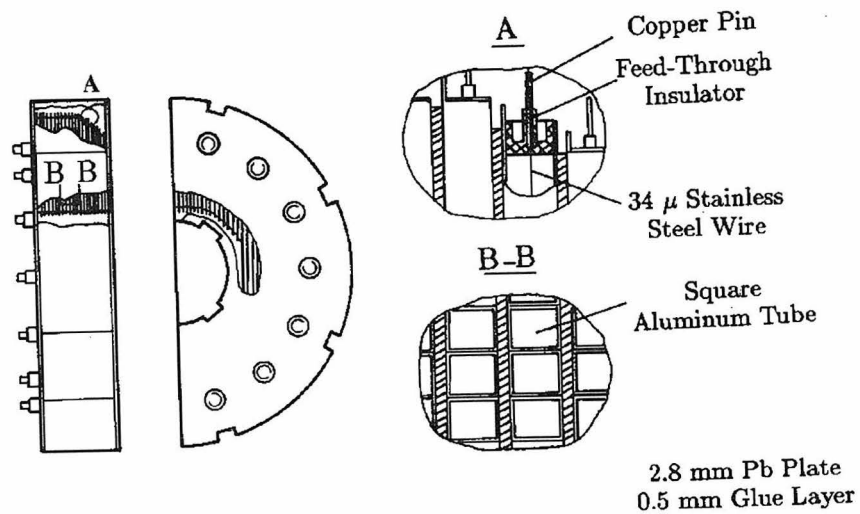


Figure 2.6: Exploded view of the Endcap Shower counter.

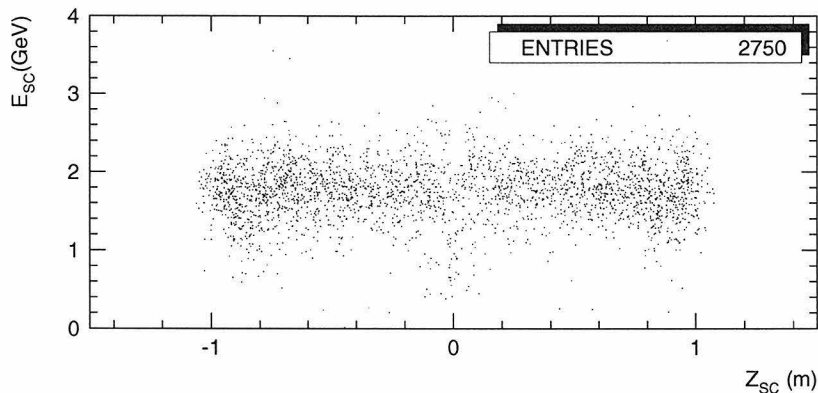


Figure 2.7: Energy deposited in the Barrel Shower Counter with respect to the z intercept of tracks for p candidates. Ribs show up as a dip in the energy spectrum.

weighing in at 330 tons.

The muon tracker is the outermost subsystem of the BES detector. Three double layers of proportional counters are sandwiched between layers of iron flux return, acting as absorber material. Position resolution is $\sigma_z = 5$ cm, $\sigma_{r\phi} = 3$ cm, with the solid angle coverage of the outermost layer 63% of 4π .

2.2.6 Luminosity Monitor

The last subsystem of BES to be described in this thesis is the luminosity monitor. This apparatus consists of two pairs of plastic and scintillator/shower-counter telescopes, which point at the interaction region, as shown in Figure 2.8. The shower counters, defined as S_n in the figure, consist of alternating layers of 5.6 mm lead plates and 6 mm plastic scintillator, with a total thickness of 11 radiation lengths. The actual luminosity is determined by measuring the rate at which small angle Bhabhas enter the detectors. The accuracy of the luminosity measurement given by this method is good to within 5 or 10 percent. The luminosity measurement is not used in this thesis, as it is easier to determine the number of ψ' produced via alternate

methods.

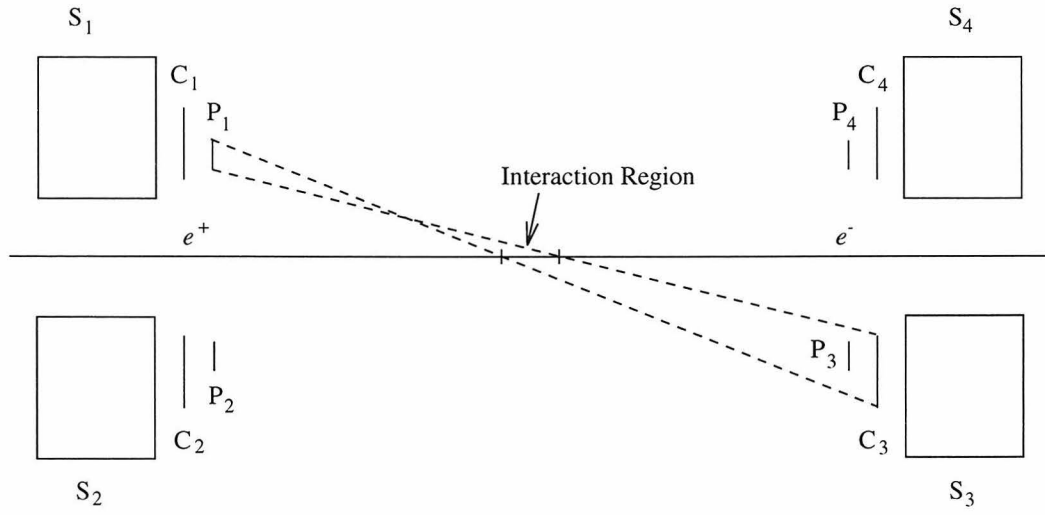


Figure 2.8: The BES luminosity monitor, showing the coincidence (C) and beam-positioning (P) scintillators, along with the shower-counters (S). The angular acceptance is shown for one set of counters.

Chapter 3 Theory

3.1 Factorization

In the decay $\psi^{(\prime)} \rightarrow B\bar{B}$, the $\psi^{(\prime)}$ emits three gluons which subsequently hadronize into a baryon-antibaryon pair, as shown in Figure 3.1. If one assumes that this diagram is factorizable, then the branching ratios of ψ' and J/ψ can be related by Equations 3.1 and 3.2.

$$\begin{aligned}\Gamma(J/\psi(\psi') \rightarrow ggg) &\propto \alpha_s^3 \frac{|\Psi(0)|^2}{M_{\psi(\psi')}^2} \\ \Gamma(J/\psi(\psi') \rightarrow e^+e^-) &\propto \alpha^2 \frac{|\Psi(0)|^2}{M_{\psi(\psi')}^2}\end{aligned}\tag{3.1}$$

$$\begin{aligned}\frac{\mathcal{B}(\psi' \rightarrow ggg)}{\mathcal{B}(J/\psi \rightarrow ggg)} &= \left[\frac{\alpha_s(\psi')}{\alpha_s(J/\psi)} \right]^3 \frac{\mathcal{B}(\psi' \rightarrow e^+e^-)}{\mathcal{B}(J/\psi \rightarrow e^+e^-)} \\ &= 0.116 \pm 0.022.\end{aligned}\tag{3.2}$$

α_s is calculated using the method given by the Particle Data Group [4], with $\Lambda^{(4)} = 280$ MeV. The ratio $\alpha_s(\psi')/\alpha_s(J/\psi)$ is calculated to be about 0.8 by this method. In most cases this relation is true [11], [12], [13], but in a few cases, notably $\rho\pi$ and K^*K , the factorization hypothesis is violated at greater than 10σ [4].

There are several theories why the factorization hypothesis is violated in certain systems. Some of these theories are discussed in the following subsections.

3.1.1 Gluonia

One explanation of the dichotomy between the J/ψ and ψ' vector-pseudoscalar decay rates was advocated in the early 1980's by Hou and Soni [14] and subsequently refined

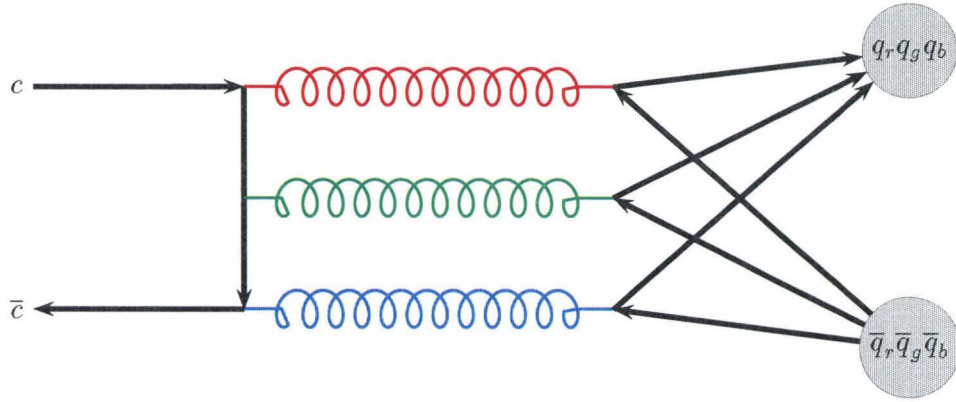


Figure 3.1: Baryon pair production from $c\bar{c}$ initial state, lowest order in α_s .

by Brodsky, Lepage, and Tuan [15]. These groups hypothesized the existence of an intermediate vector gluonium state ($\mathcal{O}$) that would account for the enhancement of the J/ψ branching ratios via the process $J/\psi \rightarrow \mathcal{O} \rightarrow \{\rho\pi, K^*K\}$, as shown in Figure 3.2.

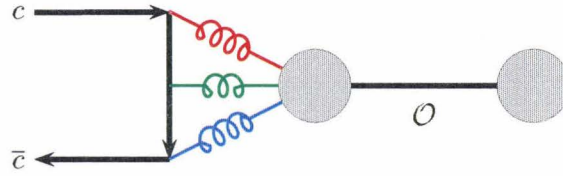


Figure 3.2: The formation of gluonium from the three gluon intermediate state during the hadronization of the J/ψ .

Final states which can proceed with the aid of the $\mathcal{O}$ state will satisfy the rela-

tionship

$$Q_h \equiv \frac{\Gamma(\psi' \rightarrow h)}{\Gamma(J/\psi \rightarrow h)} = \frac{\Gamma(\psi' \rightarrow e^+e^-)}{\Gamma(J/\psi \rightarrow e^+e^-)} \frac{(M_{J/\psi} - M_{\mathcal{O}})^2 + \Gamma_{\mathcal{O}}^2/4}{(M_{\psi'} - M_{\mathcal{O}})^2 + \Gamma_{\mathcal{O}}^2/4},$$

given the assumption that the couplings of charmonium to gluonium scale with the e^+e^- coupling. h in the above equation is the hadronic final state of interest. Q_h is small if $M_{\mathcal{O}} \approx M_{J/\psi}$, thus

$$(M_{J/\psi} - M_{\mathcal{O}})^2 + \frac{1}{4}\Gamma_{\mathcal{O}}^2 \lesssim 2.6 Q_h \text{ GeV}^2.$$

Using the experimental limit for $\rho\pi$ of $Q_{\rho\pi} < 0.0022$ [16], I obtain

$$[(M_{J/\psi} - M_{\mathcal{O}})^2 + \frac{1}{4}\Gamma_{\mathcal{O}}^2]^{\frac{1}{2}} \lesssim 60 \text{ MeV}.$$

From this, the resulting gluonium state would have to both have a mass within 60 MeV/ c^2 of the J/ψ , and have a width of less than 120 MeV/ c^2 . This resonance would be very difficult to detect, and at this time, no evidence has been seen suggesting such a state in such a location.

The most important signatures of a gluonium state would be found in the exclusive modes $J/\psi \rightarrow K^*Kh, \rho\pi h, h = \pi\pi, \eta, \eta'$. However, with the constraint above on the $\mathcal{O}$ mass and width, these modes aren't available due to a lack of phase space. A search could still be carried out by examining the equivalent ψ' decays. Another way to search for gluonium, pointed out by Hou and Soni [14], is to examine the inclusive reaction $\psi' \rightarrow (\pi\pi) + X$ where $(\pi\pi)$ is an isosinglet. Three gluon states should show up as peaks in the M_X distribution.

3.1.2 Intrinsic Charm

One mechanism, put forward by Brodsky and Karliner[17], for the vector-pseudoscalar suppression is a possible intrinsic charm content in light mesons. Suppose the ρ had the wavefunction: $\rho^+ = \Psi_{u\bar{d}}^\rho |u\bar{d}\rangle + \Psi_{u\bar{d}c\bar{c}}^\rho |u\bar{d}c\bar{c}\rangle + \dots$. According to reference [17],

the $\Psi_{u\bar{d}c\bar{c}}$ wavefunction would be maximal at minimal invariant mass, and in the spin configuration where the $u\bar{d}$ are in the pseudoscalar state, minimizing QCD spin-spin interactions. The $c\bar{c}$ pair thus carries the spin projection of the ρ , and is in an S-wave configuration with no nodes in the radial wave function, thus minimizing the kinetic energy and invariant mass of the charm quarks, as stated above.

The $|u\bar{d}c\bar{c}\rangle$ state would allow $J/\psi \rightarrow \rho\pi$ to occur via rearrangement of incoming and outgoing quark lines, as in Figure 3.3. But, the decay $\psi' \rightarrow \rho\pi$ will be suppressed, as the radial wave function of the ψ' is orthogonal to the configuration of the $c\bar{c}$ in the $|u\bar{d}c\bar{c}\rangle$.

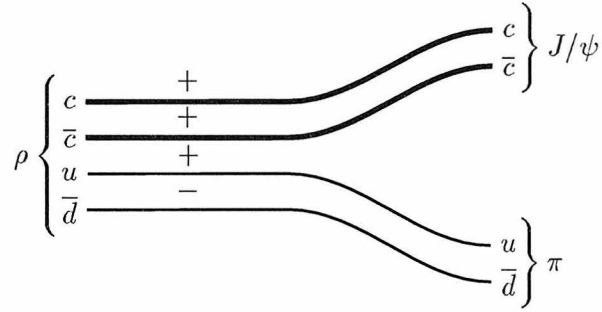


Figure 3.3: Quark line rearrangement diagram for the decay $J/\psi \rightarrow \rho\pi$. The $+/-$ signs on the quark lines denote helicity states.

Brodsky and Karliner also make a rough estimate of the decay rate $J/\psi \rightarrow \rho\pi$ by comparison to $\phi \rightarrow \rho\pi$; the assumption is made that the ϕ decay is equivalent to the J/ψ decay with the replacement of $c\bar{c}$ by $s\bar{s}$ in the wavefunction of the ρ . As there is implicitly a hard gluon connecting the $u - c$ and $\bar{d} - \bar{c}$ pairs in the ρ wavefunction (and analogously, $\bar{s} - \bar{d}$), the ratio of probabilities for intrinsic charm to strangeness for light hadrons is of order:

$$R_{(c\bar{c}/s\bar{s})} = \frac{m_s^2 \alpha_s^4(m_c^2)}{m_c^2 \alpha_s^4(m_s^2)} \sim 10^{-3}.$$

This is consistent with the magnitude of the ratio of intrinsic charm to strangeness obtained from deep inelastic scattering in nucleons.

The ratio $\Gamma(J/\psi \rightarrow \rho\pi)/\Gamma(\phi \rightarrow \rho\pi)$ from quark line rearrangement should scale with $R_{(c\bar{c}/s\bar{s})}$ times phase space. Given that $\Gamma(\phi \rightarrow \rho\pi) \approx 6 \times 10^{-4} \text{ GeV}[4]$, then $\Gamma(J/\psi \rightarrow \rho\pi) \sim 10^{-6} \text{ GeV}$, which is consistent with the measured rate.

The K^*K system has a similar analysis, with a $|u\bar{s}c\bar{c}\rangle$ component in the K^* wave function in place of the $|u\bar{d}c\bar{c}\rangle$ in the ρ . Intrinsic charm in the π wavefunction will also allow the $J/\psi \rightarrow \rho\pi$ decay to proceed via quark line rearrangement in a similar manner.

3.1.3 Hadronic Form Factors

We can denote the intermediate state in 3-gluon J/ψ decays with the 3-gluon quantum number, $|3g\rangle$ which represents the continuum. At first approximation, this state is an isospin and $\text{SU}(3)_F$ singlet. However, because of symmetry breaking, it contains a small octet portion:

$$|3g\rangle = \alpha |1\rangle + \beta |8\rangle, \quad (3.3)$$

with the constraint $|\alpha|^2 + |\beta|^2 = 1$. In addition, there is an isospin violating state, $J/\psi \rightarrow \gamma^* \rightarrow h$, so the intermediate state is written as

$$|3g\rangle + \gamma |\gamma\rangle = \alpha |1\rangle + \beta |8\rangle + \gamma |\gamma\rangle, \quad (3.4)$$

with the above normalization intact.

Using the experimental values for $\mathcal{B}(J/\psi \rightarrow \{\rho\pi, K^*K, \pi^+\pi^-, a_2\rho\})$, Chaichian and Törnqvist [18] obtain

$$|3g\rangle + \gamma |\gamma\rangle = 0.967 |1\rangle - 0.255 |8\rangle + 0.388e^{i \times 64^\circ} |\gamma\rangle. \quad (3.5)$$

Using Equation 3.5, and counting helicity states, one can get a fair agreement between

the J/ψ data and this model, as shown in columns two and three of Table 3.1.

Decay Channel	J/ψ Decays		ψ' Decays		
	$\mathcal{B} \times 10^4$	$ggg + \gamma$	$\mathcal{B} \times 10^4$	$ggg + \gamma$	$k_0^2 = 0.49$
$\rho\pi$ sum	128.0 ± 1.0	<u>127.00</u>	< 0.83	72.89	0.70
K^+K^{*-}	55.0 ± 7.0	45.56	< 0.179	27.59	0.45
K^*K sum	74.6 ± 9.3	<u>76.79</u>		46.54	1.21
$\eta\omega$	19.0 ± 4.0	14.39		8.13	0.05
$\pi^+\pi^-$	1.47 ± 0.23	<u>1.47</u>	0.8 ± 0.5	<u>0.80</u>	<u>0.30</u>
K^+K^-	2.35 ± 0.30	2.54	1.0 ± 0.7	1.44	0.27

Table 3.1: Predictions for various two meson decays of J/ψ and ψ' . Underlined values are inputs to the theory. Data is taken from reference [18].

To scale from the J/ψ data to the ψ' data, the simplest thing that could be done would be to scale the expression in Equation 3.5 by a constant factor. Using the $\pi^+\pi^-$ mode as input, as it is purely electromagnetic, this factor is fixed at 0.321. The results are shown in column five of Table 3.1. The correspondence between the ψ' data in column four and the rescaling in column five is rather poor, at best.

Column six in Table 3.1 is obtained by describing the three-meson vertex, $C \rightarrow AB$, as the overlap integral

$$g_{CAB} \propto \int d^3k \psi_A^*(\mathbf{k}) \psi_B^*(-\mathbf{k}) \psi_C(\mathbf{k}_A - \mathbf{k}) I(\mathbf{k}_A + \mathbf{k}). \quad (3.6)$$

If the nonrelativistic bound state is described by a harmonic oscillator potential, the three wave functions fall off as gaussians, $\psi(k) \propto \exp[-3k^2/(2k_0^2)]$. The rms. radius of the hadron is $r_0 = 3/(\sqrt{2}k_0)$. Then, with equal radii for A , B and C , the overlap integral (Equation 3.6) becomes

$$g_{CAB} \propto \exp(-\mathbf{k}_A^2/k_0^2). \quad (3.7)$$

When the masses of the product mesons (A and B) are much smaller than the mass of the primary (C), $k_A^2 \cong m_C^2/4$. This is true for all modes listed in Table 3.1.

The suppression due to the hadronic form factor is thus:

$$|g_{CAB}(m_{\psi'}^2)/g_{CAB}(m_{J/\psi}^2)| = \exp[-(m_{\psi'}^2 - m_{J/\psi}^2)/4k_0^2]. \quad (3.8)$$

A value of 0.49 GeV^2 is used for k_0^2 , corresponding to a hadronic radius of about 0.6 fm . The square of Equation 3.8 times a three-gluon coupling factor of

$$\frac{\Gamma(\psi' \rightarrow e^+e^-)/m_{\psi'}}{\Gamma(J/\psi \rightarrow e^+e^-)/m_{J/\psi}} \left(\frac{\alpha_s(m_{\psi'}^2)}{\alpha_s(m_{J/\psi}^2)} \right)^3 \approx 0.3$$

is used to scale the gluonic part of Equation 3.5. The electromagnetic portion is scaled using $\psi' \rightarrow \pi^+\pi^-$ as input. The results of this scaling is shown in Column 6 of Table 3.1.

3.2 Direct Predictions

In the literature, there are very few direct calculations of the decay of charmonium to baryonic final states. One of the most comprehensive is the perturbative analysis by Bolz and Kroll [19]. The analysis starts by laying out the valence Fock states of the octet baryons:

$$\begin{aligned} |B_8, +\rangle &= \frac{\epsilon_{a_1 a_2 a_3}}{\sqrt{3!}} \int [dx][d^2\mathbf{k}_\perp] \left\{ \Psi_{123}^{B_8} |f_{1+}^{a1} f_{1-}^{a2} f_{2+}^{a3}\rangle + \Psi_{213}^{B_8} |f_{1-}^{a1} f_{1+}^{a2} f_{2+}^{a3}\rangle \right. \\ &\quad \left. - (\Psi_{132}^{B_8} + \Psi_{231}^{B_8}) |f_{1+}^{a1} f_{1+}^{a2} f_{2-}^{a3}\rangle \right\} \\ |\Lambda, +\rangle &= \frac{\epsilon_{a_1 a_2 a_3}}{\sqrt{2}} \int [dx][d^2\mathbf{k}_\perp] \left\{ \Psi_{123}^{\Lambda} |u_+^{a1} d_-^{a2} s_+^{a3}\rangle - \Psi_{213}^{\Lambda} |u_-^{a1} d_+^{a2} s_+^{a3}\rangle \right. \\ &\quad \left. + (\Psi_{132}^{\Lambda} - \Psi_{231}^{\Lambda}) |u_+^{a1} d_+^{a2} s_-^{a3}\rangle \right\} \end{aligned} \quad (3.9)$$

where $|B_8, +\rangle$ holds for all octet baryons other than the uds states Λ and Σ^0 . There are similar Fock wave functions for the decuplet:

$$\begin{aligned}
|\Delta^{++}, +\rangle &= \frac{\epsilon_{a_1 a_2 a_3}}{\sqrt{2}} \int [dx][d^2 \mathbf{k}_\perp] \Psi_{123}^\Delta |u_+^{a_1} u_-^{a_2} u_+^{a_3}\rangle \\
|B_{10}, +\rangle &= \frac{\epsilon_{a_1 a_2 a_3}}{\sqrt{3!}} \int [dx][d^2 \mathbf{k}_\perp] \left\{ \Psi_{123}^{B_{10}} |f_{1+}^{a_1} f_{1-}^{a_2} f_{2+}^{a_3}\rangle + \Psi_{213}^{B_{10}} |f_{1-}^{a_1} f_{1+}^{a_2} f_{2+}^{a_3}\rangle \right. \\
&\quad \left. + \Psi_{132}^{B_{10}} |f_{1+}^{a_1} f_{1+}^{a_2} f_{2-}^{a_3}\rangle \right\}
\end{aligned} \tag{3.10}$$

Both the Fock three quark states ($|fff\rangle$) and the scalar wave functions ($\Psi_{nnn}^{B_N}$) are described further in reference [19].

The above equations are used, along with a representation of the helicity amplitudes of the $J/\psi \rightarrow B\bar{B}$ process to determine the decay width of J/ψ into baryon pairs. Table 3.2 shows the results of this perturbation analysis when the strange quark mass has been fixed at $m_s = 350 \text{ MeV}/c^2$. The decay width into $\Xi^{*0}\bar{\Xi}^{*0}$ was not calculated as “the perturbative approach is not applicable to $J/\psi \rightarrow \Xi^{*0}\bar{\Xi}^{*0}$ decays due to almost zero momentum transfer.”[19]. The $\Omega^-\bar{\Omega}^+$ width was not calculated as it is kinematically forbidden.

	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Sigma^0\bar{\Sigma}^0$	$\Xi^-\bar{\Xi}^+$	$\Delta^{++}\bar{\Delta}^{--}$	$\Sigma^{*+}\bar{\Sigma}^{*-}$
$\Gamma_{th}(\text{eV})$	174	113	117	62.5	65.1	40.5
$\Gamma_{exp}(\text{eV})$	186 ± 4	117 ± 14	110 ± 15	78 ± 18	96 ± 26	45 ± 6

Table 3.2: Direct predictions of the width of J/ψ to dibaryon final states from the perturbative analysis by Bolz and Kroll [19]. Experimental data is from the PDG [4].

This model is extended to the decays of the ψ' by rescaling the hadronic widths by:

$$\Gamma(\psi' \rightarrow B\bar{B}) = \frac{\rho_{ps}(m_B/m_{\psi'})}{\rho_{ps}(m_B/m_{J/\psi})} \frac{\Gamma(\psi' \rightarrow e^+e^-)}{\Gamma(J/\psi \rightarrow e^+e^-)} \Gamma(J/\psi \rightarrow B\bar{B})$$

where $\rho_{ps}(z)$ is the phase space factor $\rho_{ps}(z) = \sqrt{1-4z^2}$. This rescaling is very similar to the factorization hypothesis in Section 3.1. The results of this rescaling for the $\psi(2S)$ are shown in Table 3.3, along with measurements of $\Gamma(\psi' \rightarrow B\bar{B})$. This model will be discussed further in Chapter 8.

	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Sigma^0\bar{\Sigma}^0$	$\Xi^-\bar{\Xi}^+$	$\Delta^{++}\bar{\Delta}^{--}$	$\Sigma^{*+}\bar{\Sigma}^{*-}$
$\Gamma_{th}(\text{eV})$	76.8	54.6	55.0	33.9	32.1	24.4
$\Gamma_{exp}(\text{eV})$	53 ± 15	< 111		< 55		

Table 3.3: Direct predictions of the width of ψ' to dibaryon final states from a rescaling of the J/ψ results of Bolz and Kroll [19]. Experimental data is from the PDG [4].

Chapter 4 Baryon Octet

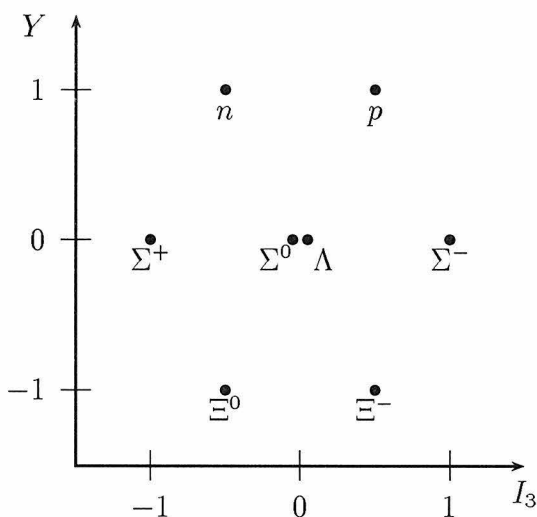


Figure 4.1: The SU(3)-flavor octet for the baryons. Vertical axis is hypercharge, defined as Baryon Number (B) plus Strangeness (S). Horizontal axis is the z projection of Isospin.

The 3 quarks which make up the lowest lying baryon states are members of the group SU(3)-flavor. This group is made up of quarks belonging to the multiplets $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$. The baryon octet, shown above, consists of the nucleons, the Λ , the Σ triplet, and the Ξ doublet. Each member of the octet has a finite lifetime, from the Σ^0 ($\tau = 7.4 \times 10^{-20}$ s), to the stable proton.

The particles to be examined in this section only include those that have strictly charged particles in the final state, after all daughters decay. This would exclude, for example, $\psi' \rightarrow n\bar{n}$ and $\psi' \rightarrow \Lambda\bar{\Lambda}$, $\Lambda\bar{\Lambda} \rightarrow n\pi^0$. For these two modes in particular, the high energy neutron would probably not interact in the detector. The $\bar{n}$ would interact hadronically, though.

4.1 General Cuts

Each analysis in the ψ' octet has a set of cuts in common. These are:

- $\min(r_{dca}) < 1.5 \text{ cm}$
- $\min(z_{dca}) < 15 \text{ cm}$
- $N_{\text{charge}} = 2, 4, 6$
- Good helix or circle fit
- $|\cos \theta_{\text{track}}| < 0.80$
- Total charge = 0

where r_{dca} is the distance of closest approach to the origin in the $x - y$ plane and z_{dca} is for the z axis. The $\cos \theta_{\text{track}}$ cut is to keep the tracks within the fiducial area covered by the drift chamber (Section 2.2.2).

4.2 $\psi' \rightarrow p\bar{p}$

In the decay $\psi' \rightarrow p\bar{p}$, the protons are collinear, each with momentum 1.586 GeV/ c . In a perfect world, we would be able to simply make a kinematic fit to the hypothesis $\psi' \rightarrow p\bar{p}$ and examine the efficiency with Monte Carlo. However, when this is done, large backgrounds contaminate the final sample. This is illustrated in Figure 4.2. For this test, 40000 two prong events were generated, uniform in momentum from 1.4 to 1.8 GeV/ c , essentially mimicking pure noise over the signal region. These events were passed through a kinematic fit to the above hypothesis; those that passed with a $P_{\text{fit}} > 0.2$ are plotted in Figure 4.2. The plot of measured momenta is slightly non-gaussian, with high shoulders. With low statistics (<200 events) this signal shape would fit a gaussian fairly well.

As it is not feasible to use a kinematic fit in my analysis of $\psi' \rightarrow p\bar{p}$, a more general sort of analysis chain must be used. Figure 4.3 shows the collinearity of two prong candidates. A cut is made at $\cos \theta < -0.9995$, or within 1.8 degrees of collinear.

The shower counter energy deposition as a function of momentum for positively charged tracks is shown in Figure 4.4. The faint cluster near $p = 1.6 \text{ GeV}/c$, $E_{SC} = 0.3 \text{ GeV}$ is the proton signal. A cut is made at $E_{SC} < 0.7 \text{ GeV}$. The other features on the graph are due to Bhabhas, (large concentration at $p \approx 1.8 \text{ GeV}/c$,

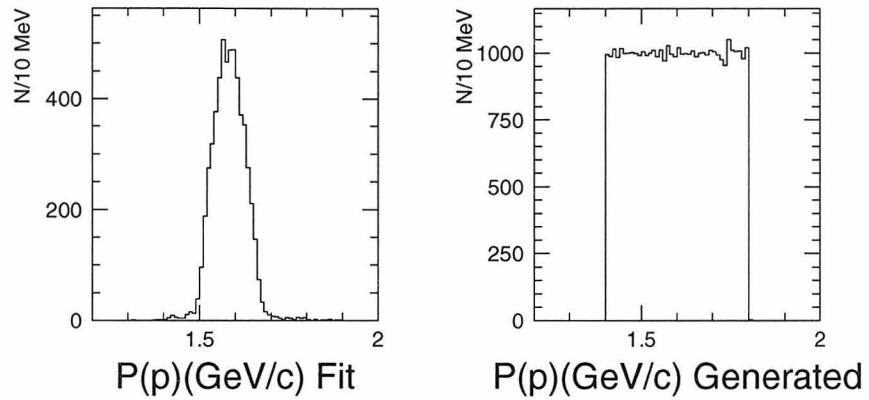


Figure 4.2: Average p momentum from kinematic fit to the hypothesis $\psi' \rightarrow p\bar{p}$. Left plot is measured momentum, right is generated.

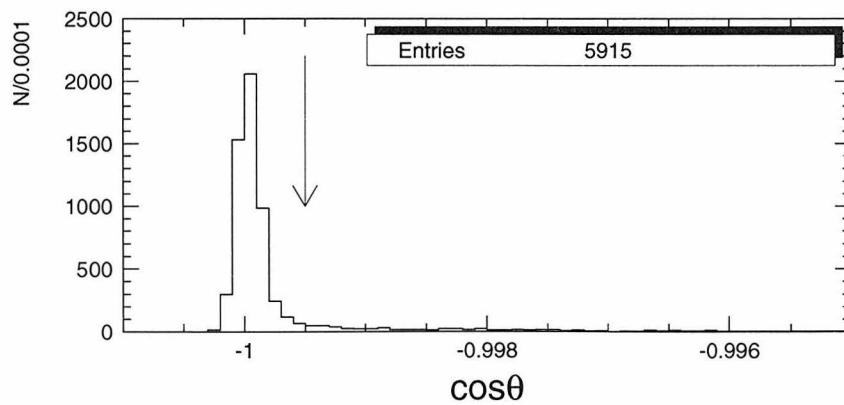


Figure 4.3: Cosine of the angle between two $p\bar{p}$ candidates. A cut is made at $-.9995$.

$E_{SC} \approx 1.5$ GeV), muons (vertical stripe at $p \approx 1.8$ GeV/c), $E_{SC} < 1$ GeV and radiative Bhabhas (trailing cluster at $p < 1.6$ GeV, $E_{SC} \approx p$). Due to possible muon contamination, tracks are also required to be identified as “not a muon” by the muon subsystem. As the muon counters cover a smaller region in solid angle than the BSC (Section 2.2.5), a tighter restriction on $\cos \theta_{\text{track}}$ of 0.6 is added.

As the shower counter ribs, discussed in Section 2.2.4, degrade the measured energy of tracks, tracks which enter the BSC near the ribs are removed from the sample. Tracks may not enter the shower counter in the regions: $-.95 < z_{SC} < -.75$ m; $-.05 < z_{SC} < .05$ m; or $.75 < z_{SC} < .95$ m. This is illustrated in Figure 2.7.

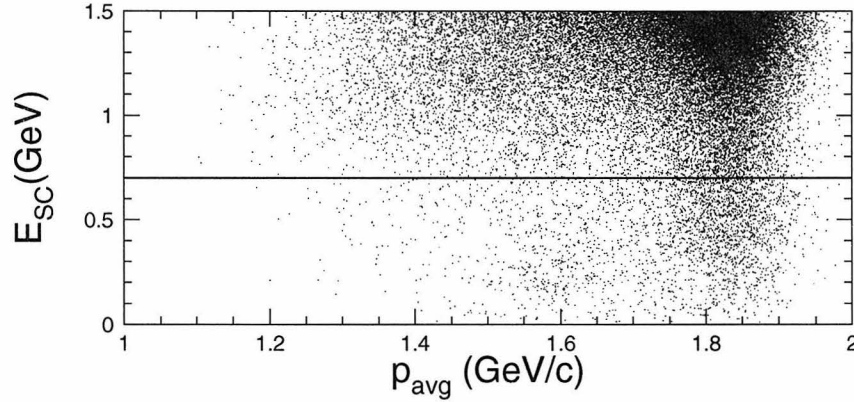


Figure 4.4: Shower counter energy *vs.* momentum for positively charged tracks.

An additional handle on the identification of protons is gained from the dE/dx system. Figure 4.5 shows the reduced $\chi_{dE/dx}$ for candidate events that pass the above cuts. Reduced $\chi_{dE/dx}$ is defined as $\chi_{dE/dx}/DOF$. The vertical axis is for the $\bar{p}$ hypothesis, and the horizontal refers to the p hypothesis. The cluster near (0,0) contains true $p\bar{p}$ events, and the cluster near (5,5) is a mixture of event types such as radiative Bhabhas and dimuons. A cut is made on the combined χ^2 , $(\chi_p^2 + \chi_{\bar{p}}^2)^{1/2} < 3$.

The weighted average momentum of the remaining candidate events is shown in Figure 4.6. To construct p_{avg} , I average the measured drift chamber quantities

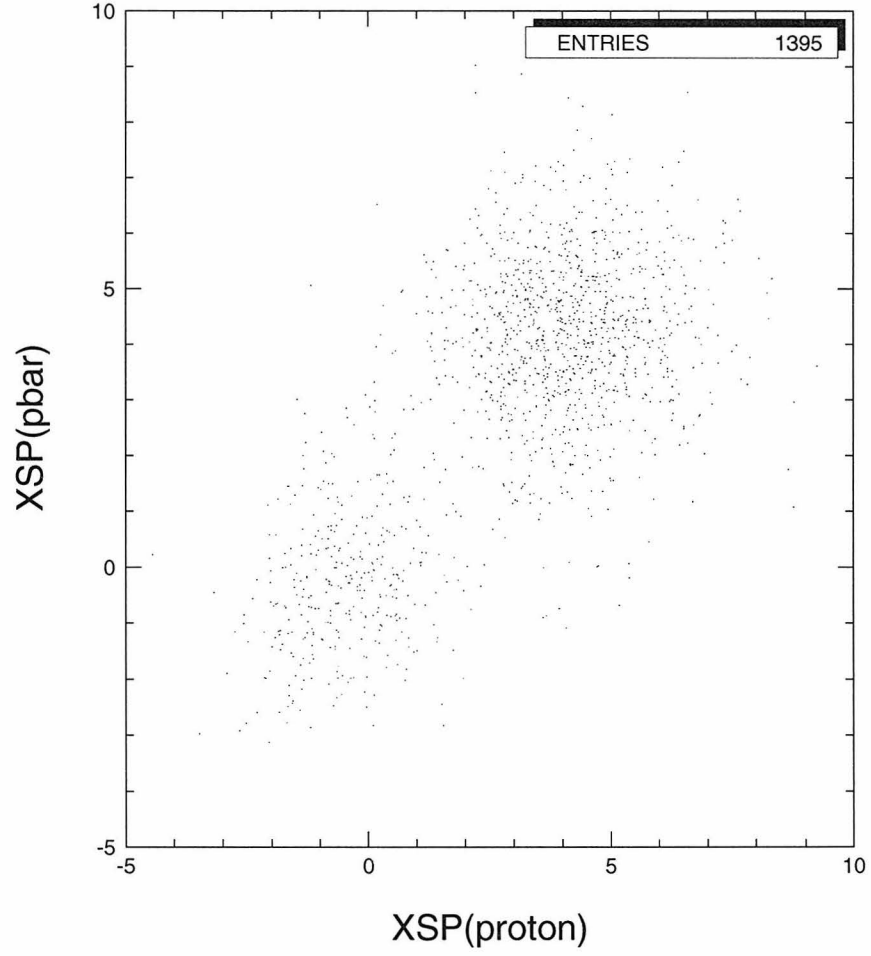


Figure 4.5: dE/dx reduced χ for diproton candidates. Vertical axis is for $\bar{p}$ candidates, horizontal is for p candidates. A cut is made on the combined χ^2 , $(\chi_p^2 + \chi_{\bar{p}}^2)^{\frac{1}{2}} < 3$.

κ (curvature), and $\tan \lambda$ (dip angle) as shown in Equation 4.1 and construct the momentum in Equation 4.2.

$$\kappa_{\text{avg}} = \frac{\frac{\kappa_1}{\sigma_{\kappa_1}^2} + \frac{\kappa_2}{\sigma_{\kappa_2}^2}}{\frac{1}{\sigma_{\kappa_1}^2} + \frac{1}{\sigma_{\kappa_2}^2}}; \quad \tan \lambda_{\text{avg}} = \frac{\frac{\tan \lambda_1}{\sigma_{\tan \lambda_1}^2} + \frac{\tan \lambda_2}{\sigma_{\tan \lambda_2}^2}}{\frac{1}{\sigma_{\tan \lambda_1}^2} + \frac{1}{\sigma_{\tan \lambda_2}^2}} \quad (4.1)$$

$$p_{\text{avg}} = \frac{\sqrt{1 + (\tan \lambda_{\text{avg}})^2}}{\kappa_{\text{avg}}}; \quad pz_{\text{avg}} = \frac{\tan \lambda_{\text{avg}}}{\kappa_{\text{avg}}} \quad (4.2)$$

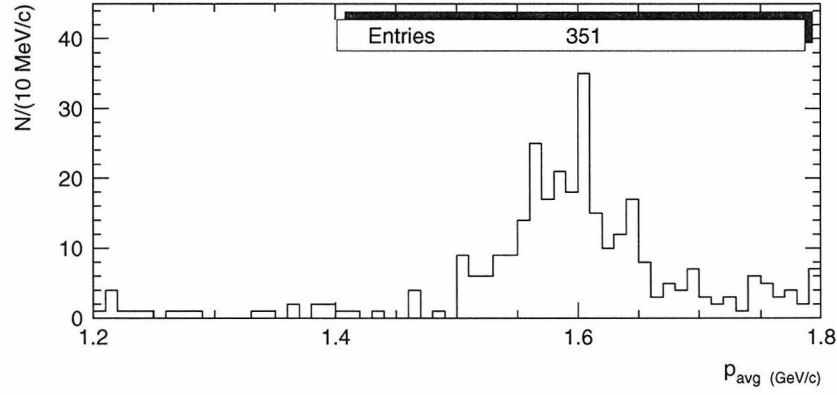


Figure 4.6: Weighted average of track momenta in $p\bar{p}$ candidate events. p_{avg} is constructed in Equation 4.2.

The average momentum spectrum is fit to a gaussian plus a quadratic background function. The centroid of the gaussian is fixed at the theoretic momentum of the p in the decay, 1.586 GeV/ c . The width and height are allowed to vary. From the fit, $N_{p\bar{p}} = 225 \pm 15 \pm 21$, where the first error is statistical and the second is the error on the fit.

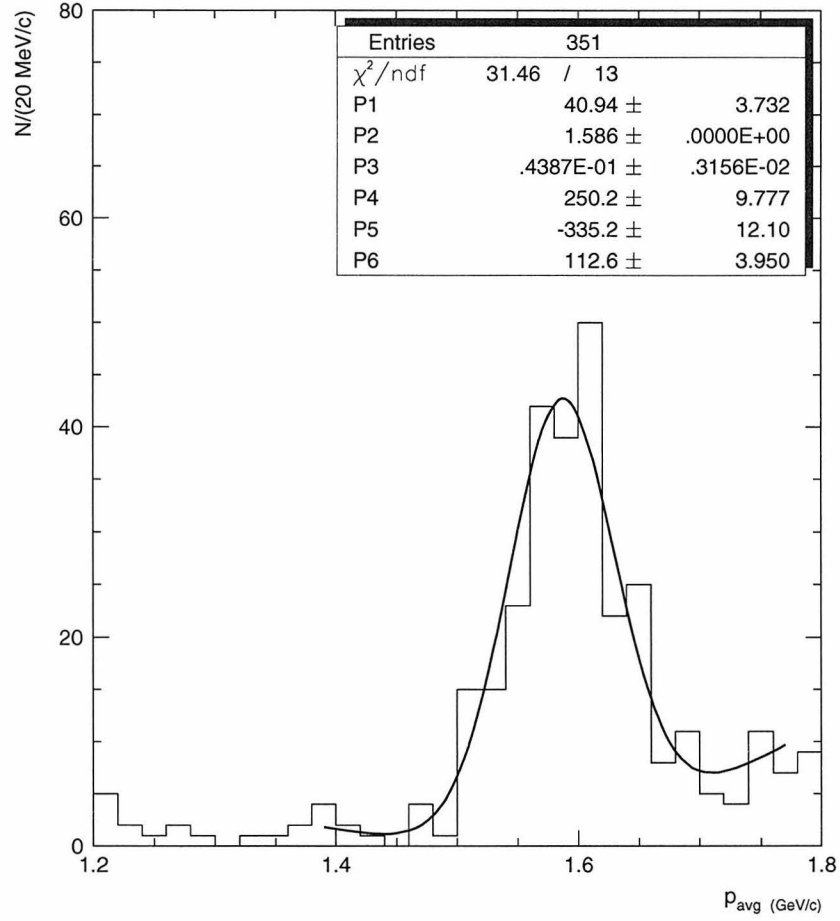


Figure 4.7: Weighted average of track momenta in $p\bar{p}$ candidate events, fit to a gaussian plus a quadratic background function. $N_{p\bar{p}} = 225 \pm 15.0 \pm 21.4$.

4.3 $\psi' \rightarrow \Lambda \bar{\Lambda}$

The decay $\psi' \rightarrow \Lambda \bar{\Lambda}$ produces two back-to-back Λ s, each with momentum 1.467 GeV/ c . Of the two major decay modes of the Λ ($p\pi^-$ and $n\pi^0$), we only consider the charged mode with a branching ratio of 63.9 percent, and the final state of interest is $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. In this decay, the momentum of the p ($\bar{p}$) ranges from 1.075 to 1.407 GeV/ c , and the momentum of the π^- (π^+) ranges from 0.060 to 0.392 GeV/ c . Thus, the proton (antiproton) is always the highest momentum positive (negative) track in the event.

Events which pass the general selection cuts (Section 4.1) are 5-C kinematic fit to the hypothesis $\psi' \rightarrow p\bar{p}\pi^+\pi^-$, with the fifth constraint being $M_{p\pi^-} = M_{\bar{p}\pi^+}$. The $p\pi$ candidates are processed through a displaced vertex finder. The χ^2 confidence level, P_{fit} , is calculated for each candidate event. A cut of $P_{fit} > 0.01$ is applied to events which pass the kinematic fit; these are shown in Figure 4.8. The $\pi^+\pi^-$ recoil spectrum is examined for evidence of cascade decays of the form $\psi' \rightarrow J/\psi\pi^+\pi^-$, $J/\psi \rightarrow p\bar{p}$ (Figure 4.9). While J/ψ production is seen when $M_{p\pi}$ is unrestricted, there is none evident where values of $M_{p\pi}$ are confined $\Lambda\bar{\Lambda}$ signal region.

An examination of the $p\pi$ mass spectrum in the Λ mass region gives 84 events in the plot. Roughly extrapolating the two events in the region above 1.13 GeV to the area under the mass peak, I find that there are four background events in the plot. I conservatively assign this number a 100% error and determine $N_{\Lambda\bar{\Lambda}}$ to be $80 \pm 9 \pm 4$.

4.4 $\psi' \rightarrow \Sigma^0 \bar{\Sigma}^0$

The decay $\psi' \rightarrow \Sigma^0 \bar{\Sigma}^0$ produces two monoenergetic Σ^0 s with momentum 1.405 GeV/ c . These will decay to $\Lambda\gamma$ 100% of the time. As in Section 4.3, only the charged mode decay of the Λ s will be considered. (This will be true for the remainder of this thesis.) The final state is thus $p\bar{p}\pi^+\pi^-\gamma\gamma$. Most of the Σ^0 's momentum is taken by the Λ (1.203 to 1.433 GeV/ c), and the Λ s momentum is transferred to the proton (0.869 to 1.375 GeV/ c). The π^- and γ have momenta of 0.0376 to 0.385 GeV/ c and 0.0273

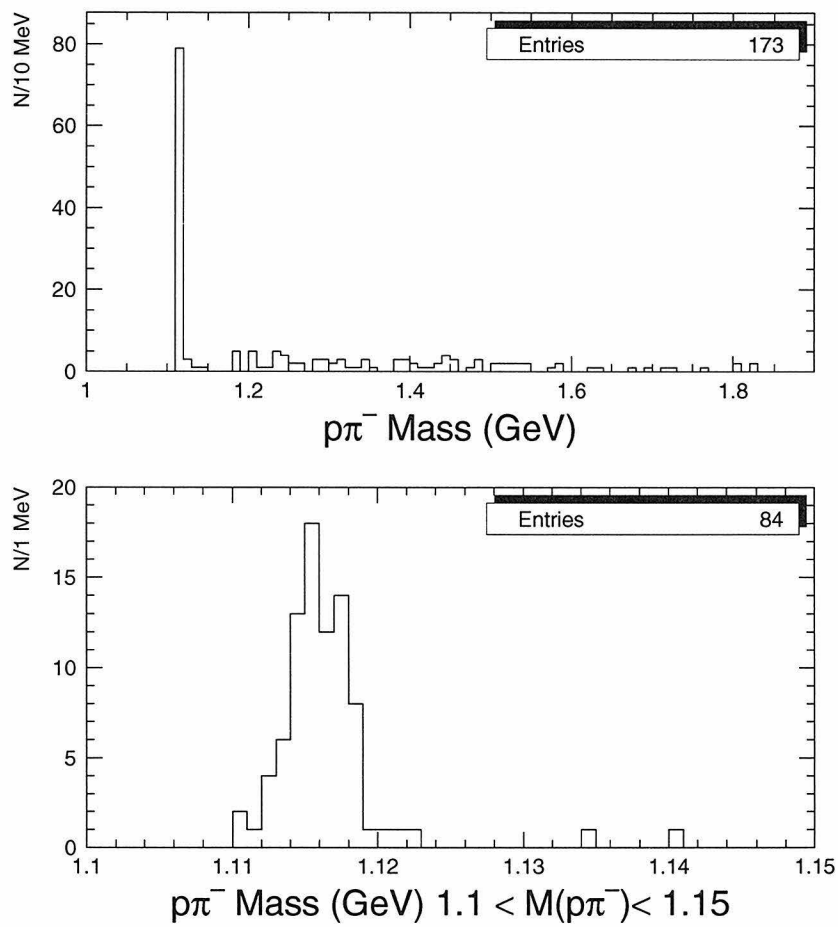


Figure 4.8: $p\pi$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$, $M_{p\pi^-} = M_{\bar{p}\pi^+}$. Upper plot is all data ($P_{fit} > 0.01$). Lower is $1.1 < M_{p\pi} < 1.15$ GeV/ c , showing the Λ peak.

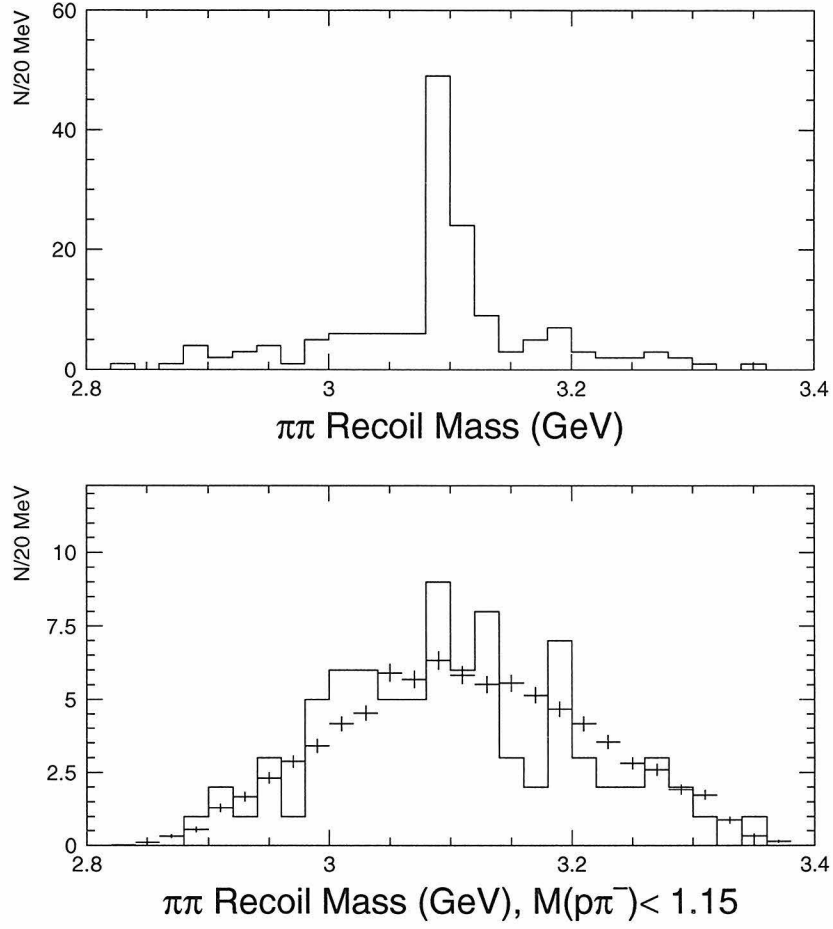


Figure 4.9: $\pi^+\pi^-$ recoil mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$, $M_{p\pi^-} = M_{\bar{p}\pi^+}$. Upper plot is all data ($P_{fit} > 0.01$). Lower is for $1.1 < M_{p\pi^-} < 1.15$ GeV/c. Histogram is data, error bars are MC.

to 0.203 GeV/ c respectively. The protons are the highest momentum particles in the final state.

Events which pass the basic selection cuts (Section 4.1) and which have more than two neutral clusters are passed into a kinematic fitting routine with the constraints $\psi' \rightarrow p\bar{p}\pi^+\pi^-\gamma\gamma$ with $M_{p\pi-\gamma} = M_{\bar{p}\pi^+\gamma}$. The $p\pi$ combinations are processed through a displaced vertex finder. All combinations which pass the fit with a P_{fit} of greater than one percent are kept for further examination.

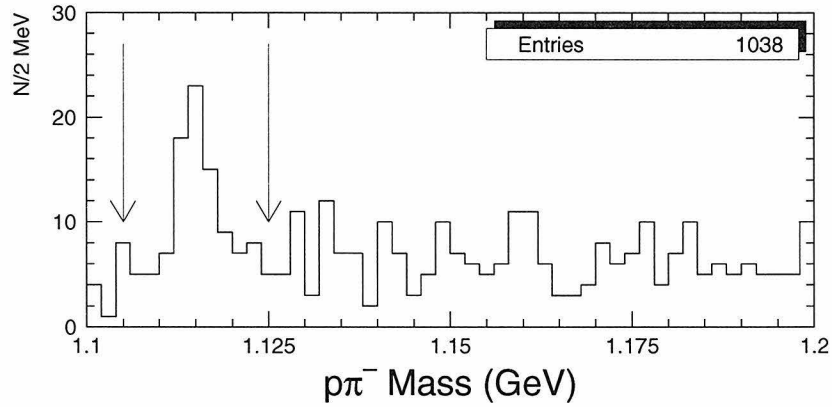


Figure 4.10: $p\pi$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\gamma\gamma$, $M_{p\pi-\gamma} = M_{\bar{p}\pi^+\gamma}$. Arrows are 10 MeV/ c^2 on either side of the Λ peak.

Figure 4.10 shows a spectrum of $p\pi$ masses from the above fit. A clear peak at the Λ is seen. Events which do not have a $p\pi^-$ or $\bar{p}\pi^+$ candidate within 10 MeV/ c^2 of the Λ are excluded. A 60 MeV minimum energy cut is placed on the photons, as the BSC is not efficient below this energy. Also, the photons are required to be isolated, or more than 12.8° ($\cos \theta_{isol} < .975$) away from the intercept of the charged tracks with the shower counter, Figure 4.11. Events which pass these cuts and have $M_{p\pi\gamma} < 1.3$ GeV/ c^2 are fit to a gaussian signal plus a linear background, Figure 4.12. The peak is fixed to the mass of the Σ^0 , 1.192 GeV/ c^2 . From the fit, $N_{\Sigma^0\bar{\Sigma}^0} = 8 \pm 3 \pm 2$. The first error is statistical, and the second is the error on the fit.

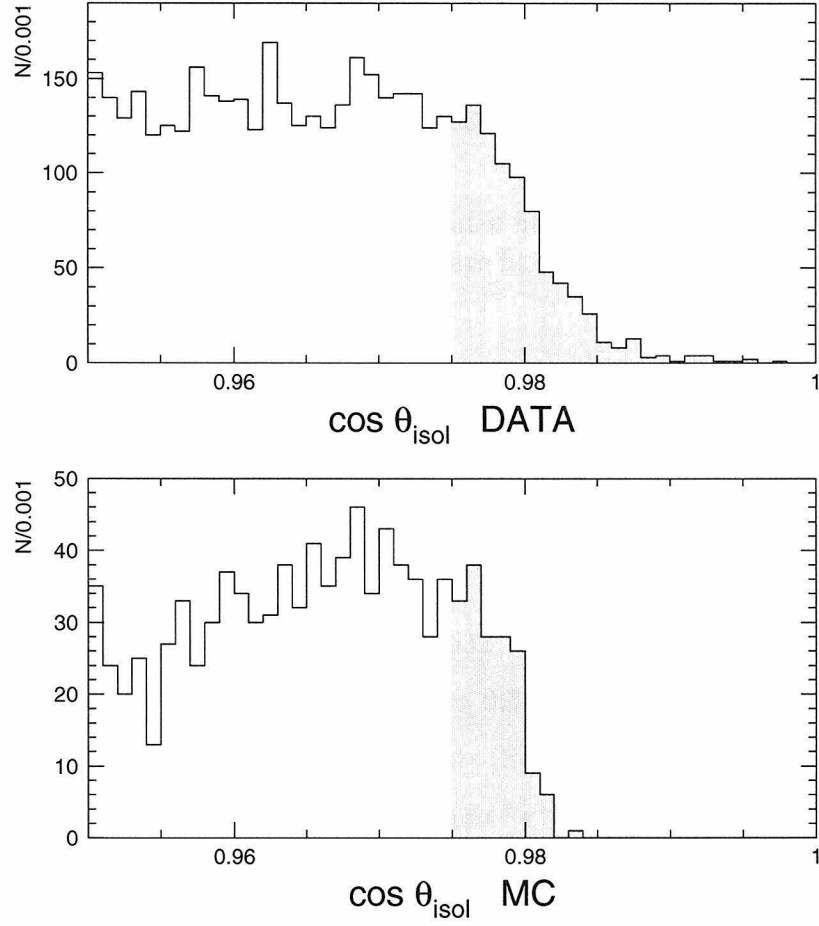


Figure 4.11: $\cos \theta_{isol}$ for data (upper plot) and Monte Carlo (lower plot). A cut is made at $\cos \theta_{isol} < 0.975$, or 12.8° .

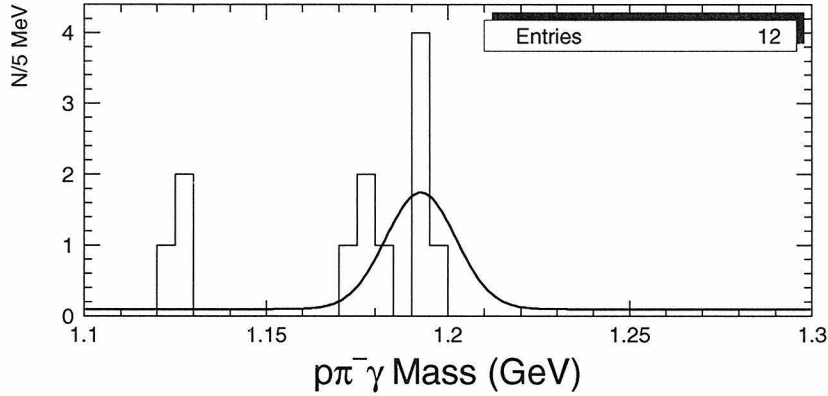


Figure 4.12: $p\pi\gamma$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\gamma\gamma$, $M_{p\pi^-\gamma} = M_{\bar{p}\pi^+\gamma}$. $p\pi\gamma$ masses below $1.3 \text{ GeV}/c^2$ are fit to a gaussian signal plus a linear background.

4.5 $\psi' \rightarrow \Xi^- \bar{\Xi}^+$

The Ξ s from $\psi' \rightarrow \Xi^- \bar{\Xi}^+$ are back-to-back with momentum $1.288 \text{ GeV}/c$. These decay to $\Lambda\pi^-$ 99.89% of the time; the final state of interest is $p\bar{p}\pi^+\pi^-\pi^+\pi^-$. Momentum ranges for the final state particles are: 0.632 to $1.242 \text{ GeV}/c$ for protons, 0.0024 to $0.386 \text{ GeV}/c$ for direct pions, and 0.0095 to $0.352 \text{ GeV}/c$ for pions from Λ s.

Events which pass the basic selection cuts (Section 4.1) are passed into a kinematic fitting routine with the constraints $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$ with $M_{p\pi^-\pi^-} = M_{\bar{p}\pi^+\pi^+}$. As the highest momentum particles in the event are the protons, four combinations of $(p\pi^-\pi^-)(\bar{p}\pi^+\pi^+)$ are fit to the above hypothesis, with the $p\pi$ combinations passed through a displaced vertex finder. All combinations which pass the fit with a P_{fit} of greater than one percent are kept for further examination.

Figure 4.13 shows the $\Lambda\bar{\Lambda}$ candidate mass distribution for hypotheses which pass the above kinematic fit. A clear peak at the J/ψ is seen, indicating contamination from cascade events of the type $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$. Events within $20 \text{ MeV}/c^2$ of the J/ψ are excluded. Further discrimination is achieved by cutting

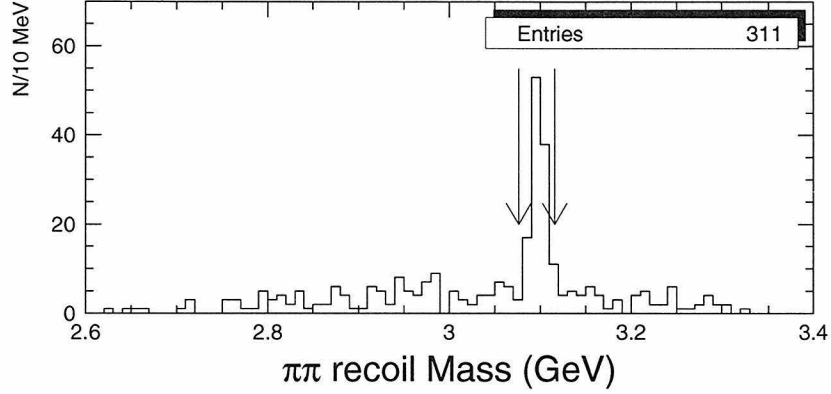


Figure 4.13: $\Lambda\bar{\Lambda}$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, $M_{p\pi^-\pi^-} = M_{\bar{p}\pi^+\pi^+}$. Λ s ($\bar{\Lambda}$ s) are chosen from combinations of $p\pi^-$ ($\bar{p}\pi^+$). Arrows are $20 \text{ MeV}/c^2$ on either side of the J/ψ peak.

close on the Λ resonance, Figure 4.14. Events with both $p\pi^-$ and $\bar{p}\pi^+$ masses within $10 \text{ MeV}/c^2$ of the Λ mass are kept.

The $M_{p\pi^-\pi^-}$ spectrum of events which remain is plotted in Figure 4.15. There are 12 ± 3.4 events in the Ξ^- peak. Averaging the five events outside the peak region over the entire plot and multiplying by the width of the signal gives 0.15 background events. A conservative error of 100 percent is applied, giving $12 \pm 3.4 \pm 0.2$ $\psi' \rightarrow \Xi^-\bar{\Xi}^+$ events detected.

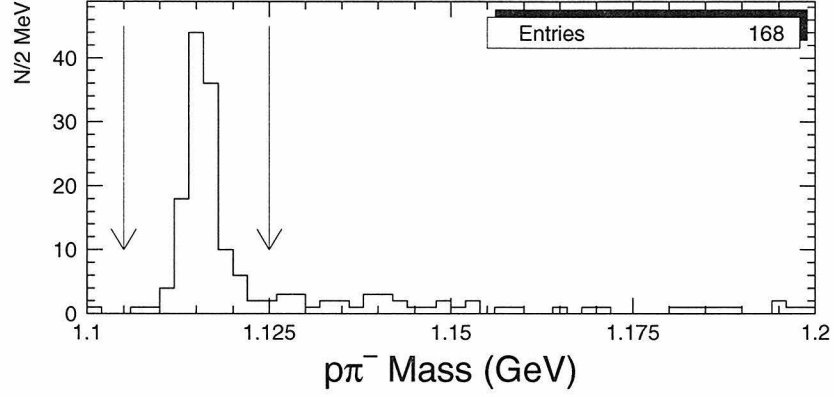


Figure 4.14: $p\pi$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, $M_{p\pi^-\pi^-} = M_{\bar{p}\pi^+\pi^+}$. Arrows are shown at $M_\Lambda \pm 10 \text{ MeV}/c^2$.

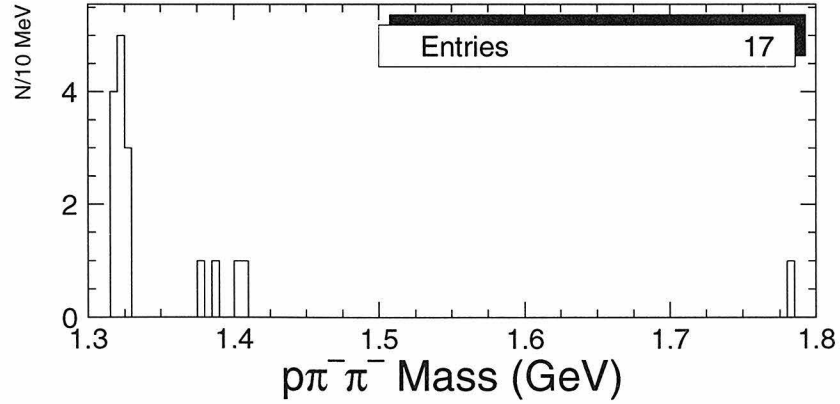


Figure 4.15: $p\pi^-\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, $M_{p\pi^-\pi^-} = M_{\bar{p}\pi^+\pi^+}$. There are $12 \pm 3.4 \pm 0.2$ events in the Ξ^- peak.

Chapter 5 Baryon Decuplet

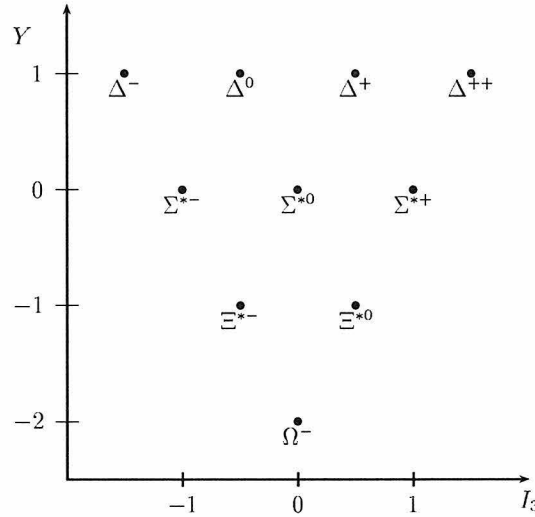


Figure 5.1: The SU(3)-flavor decuplet for the baryons. Vertical axis is hypercharge, defined as Baryon Number (B) plus Strangeness (S). Horizontal axis is the z projection of Isospin.

The SU(3)-flavor decuplet shown above consists of the $\Delta(1232)$ quadruplet, the $\Sigma(1385)$ triplet, the $\Xi(1580)$ doublet and the $1.632 \text{ GeV}/c^2$ Ω^- . Of these, only the Ω^- has a directly measurable lifetime, 82 ps. Widths of the others run from $111 \text{ MeV}/c^2$ for Δ^{++} , to about $10 \text{ MeV}/c^2$ for the $\Xi(1580)$ pair.

As in Chapter 4, the modes to be examined have only charged particles in the final states.

5.1 General Cuts

Each analysis for ψ' decuplet modes has a set of cuts in common. These are:

- $\min(r_{dca}) < 1.5 \text{ cm}$
- $\min(z_{dca}) < 15 \text{ cm}$
- $N_{\text{charge}} = 4, 6, 8$
- Good helix or circle fit
- $|\cos \theta_{\text{track}}| < 0.80$
- Total charge = 0

where r_{dca} is the distances of closest approach to the origin in the $x - y$ plane and z_{dca} is for the z axis. The $\cos \theta_{\text{track}}$ cut is to keep the tracks within the fiducial area covered by the drift chamber (Section 2.2.2).

5.2 $\psi' \rightarrow \Delta^{++}\bar{\Delta}^{--}$

The Δ^{++} s from $\psi' \rightarrow \Delta^{++}\bar{\Delta}^{--}$ are produced back to back in the ψ' rest frame. However, as they are broad ($110 \text{ MeV}/c^2$) resonances, the primary hyperons do not have well-defined momenta. The dominant decay mode for Δ^{++} s is $\Delta^{++} \rightarrow p\pi^+$, with a branching fraction of $> 99\%$. Thus the final decay chain of interest is $\psi' \rightarrow p\bar{p}\pi^+\pi^-$.

Events which pass the basic selection cuts (Section 5.1) are passed into a kinematic fitting routine with the constraints $\psi' \rightarrow p\bar{p}\pi^+\pi^-$ (4C). No other kinematic constraints are used. All combinations which pass the fit with a P_{fit} of greater than one percent are kept for further examination.

One of the possible backgrounds in $\Delta^{++}\bar{\Delta}^{--}$ decays is $\Lambda\bar{\Lambda}$ from ψ' . This background would appear as a peak in the $p\pi^-/\bar{p}\pi^+$ invariant mass distributions. Figure 5.2 shows the $p\pi^-$ mass distributions for hypotheses which fit the above 4C fit. A peak at the Λ mass, $1.116 \text{ GeV}/c^2$, is seen. The background is removed by requiring that $M_{p\pi^-}$ be greater than $1.14 \text{ GeV}/c^2$.

Another background in $\Delta^{++}\bar{\Delta}^{--}$ decays is the cascade decay $\psi' \rightarrow \pi^+\pi^-J/\psi$ where J/ψ decays to $p\bar{p}$. Figure 5.3 shows the $p\bar{p}$ invariant mass distribution (kinematically equivalent to the $\pi^+\pi^-$ recoil mass). A clear peak is seen at the J/ψ mass, $3.096 \text{ GeV}/c^2$. This background is removed by requiring $|M_{p\bar{p}} - M_{J/\psi}| > 60 \text{ MeV}/c^2$.

Events which pass all above cuts are fit to a spin-1 Breit-Wigner plus a 4-body phase-space background histogram. The spin-1 Breit-Wigner used was parameterized

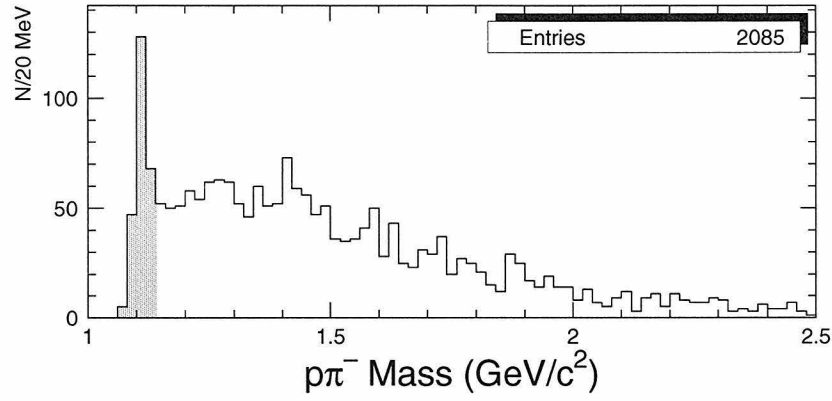


Figure 5.2: $p\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. Notice the peak near the Λ mass, $1.116 \text{ GeV}/c^2$. A cut is made at $M_{p\pi^-} > 1.14 \text{ GeV}/c^2$ to remove $\Lambda\bar{\Lambda}$ background.

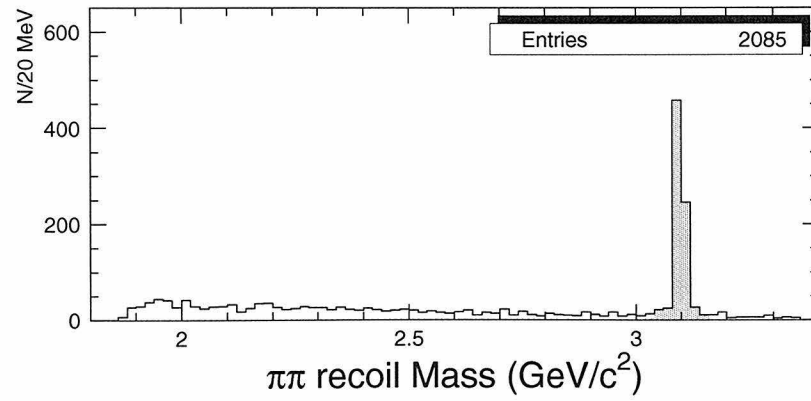


Figure 5.3: $\pi^+\pi^-$ recoil masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. The peak near 3.1 GeV is background from $\psi' \rightarrow J/\psi\pi^+\pi^-$, $J/\psi \rightarrow p\bar{p}$. A cut is made at $|M_{p\pi^-} - M_{J/\psi}| > 60 \text{ MeV}/c^2$ to remove J/ψ contamination.

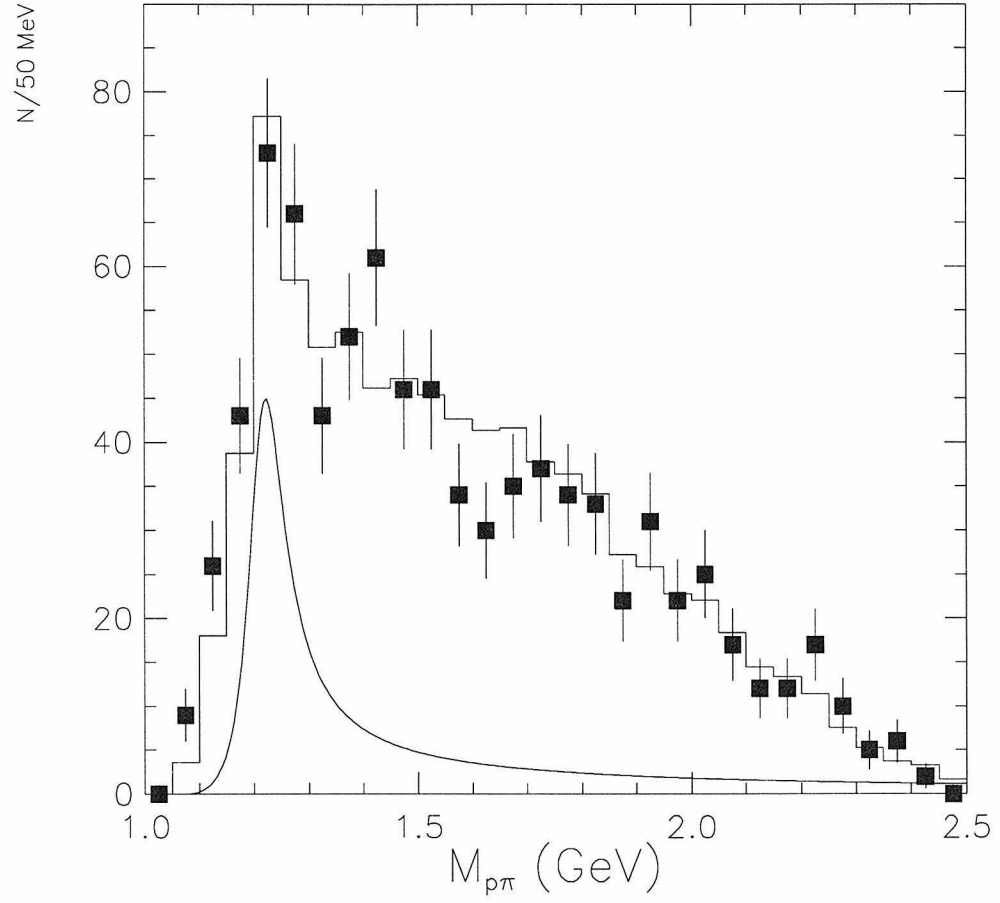


Figure 5.4: $p\pi^+$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. Data is fit to a spin-1 Breit-Wigner plus a 4-body phase-space background. $N_{\Delta^{++}\bar{\Delta}^{--}} = 157 \pm 13 \pm 34$.

as:

$$\begin{aligned}
q_0 &\equiv \frac{1}{2}M_{\Delta^{++}}\sqrt{(M_{\Delta^{++}}^2 - (M_{\pi^-} + M_p)^2)(M_{\Delta^{++}}^2 - (M_{\pi^-} - M_p)^2)} \\
q &= \frac{1}{2}M_{p\pi^+}\sqrt{(M_{p\pi^+}^2 - (M_{\pi^-} + M_p)^2)(M_{p\pi^+}^2 - (M_{\pi^-} - M_p)^2)} \\
\Gamma' &\equiv \frac{\Gamma_0 M_{\Delta^{++}}}{M_{p\pi^+}} \left(\frac{q}{q_0}\right)^3 \\
BW &\propto \frac{q^3}{(M_{p\pi^+}^2 - M_{\Delta^{++}}^2) - (M_{\Delta^{++}}\Gamma')^2}
\end{aligned} \tag{5.1}$$

with $M_{\Delta^{++}}$ fixed at 1.234 GeV/ c^2 , Γ_0 fixed at 0.111 GeV/ c^2 , and the masses of the proton and pion fixed at the PDG values.

Figure 5.4 shows the output of the fit; there are 849 total events in the plot. The fit parameter varied is the relative proportions of the phase space background and the Breit-Wigner signal to the total number of events in the plot. $N_{\Delta^{++}\bar{\Delta}^{--}}$ is $157 \pm 13 \pm 34$, where the first error is statistical and the second is the systematic error from the fitting procedure.

5.3 $\psi' \rightarrow \Sigma^{*+}\bar{\Sigma}^{*-}$

The Σ^* s from $\psi' \rightarrow \Sigma^{*+}\bar{\Sigma}^{*-}$ are produced back to back in the ψ' rest frame. However, as they are broad (35 MeV/ c^2) resonances, the primary hyperons do not have well-defined momenta. The dominant decay mode for Σ^{*+} is $\Sigma^{*+} \rightarrow \Lambda\pi^+$, with a branching fraction of $> 88\%$. Λ s decay as in Section 4.5 to $p\pi^-$. Thus the final decay chain of interest is $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$.

Events with six charged tracks which pass the general acceptance cuts of Section 5.1 are kinematically fit to the hypothesis $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$ (4C). $p\pi$ candidates for Λ s are sent through a displaced vertex finder. Events with a P_{fit} greater than 0.01 are kept and examined further.

Figure 5.5 shows the Λ signal in the $p\pi^-$ invariant mass spectrum. To enhance the signal, a loose cut is made around the Λ mass, $|M_{p\pi} - M_\Lambda| < 15$ MeV/ c^2 . This cut is made for both $p\pi^-$ and $\bar{p}\pi^+$.

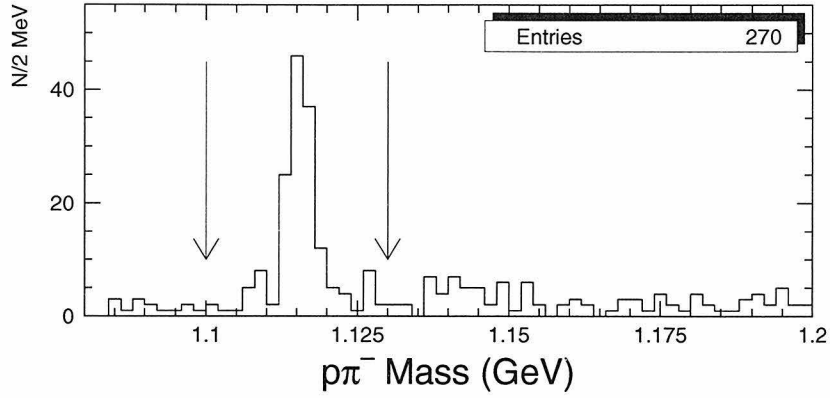


Figure 5.5: $p\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$. The peak near 1.115 GeV is Λ signal from $\Sigma^{*+} \rightarrow \Lambda\pi^+$. A loose cut (15 MeV/ c^2) is made around the Λ peak to remove background.

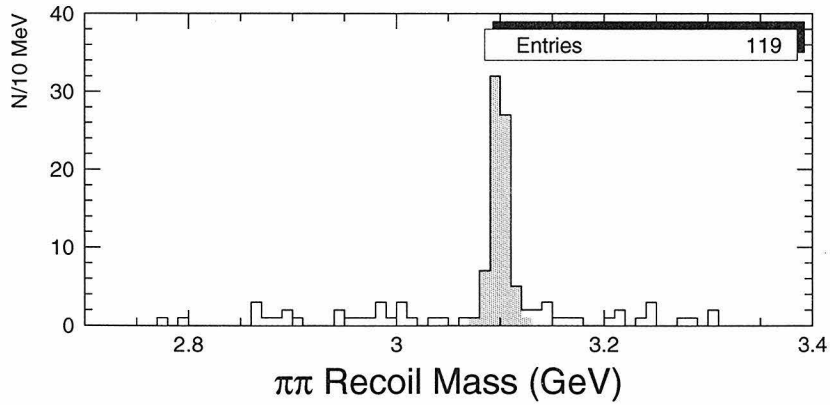


Figure 5.6: $\pi^+\pi^-$ recoil masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$. The peak near 3.1 GeV is background from $\psi' \rightarrow J/\psi\pi^+\pi^-$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$. A cut is made at $|M_{\Lambda\bar{\Lambda}} - M_{J/\psi}| > 30 \text{ MeV}/c^2$ to remove J/ψ background.

The dominant background in the $\Sigma^{*+}\bar{\Sigma}^{*-}$ decays are from $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$, and combinatorics from $\psi' \rightarrow \Xi^-\bar{\Xi}^+$. Figure 5.6 shows the $\pi^+\pi^-$ recoil mass (kinematically equivalent to $\Lambda\bar{\Lambda}$ invariant mass), with a strong peak at the J/ψ . The J/ψ signal is removed by requiring $|M_{\Lambda\bar{\Lambda}} - M_{J/\psi}| > 30 \text{ MeV}/c^2$. Figure 5.7 shows the background from $\Xi^-\bar{\Xi}^+$ combinatorics. A cut of $M_{p\pi^-\pi^-} > 1.35 \text{ GeV}/c^2$ is made to remove this background.

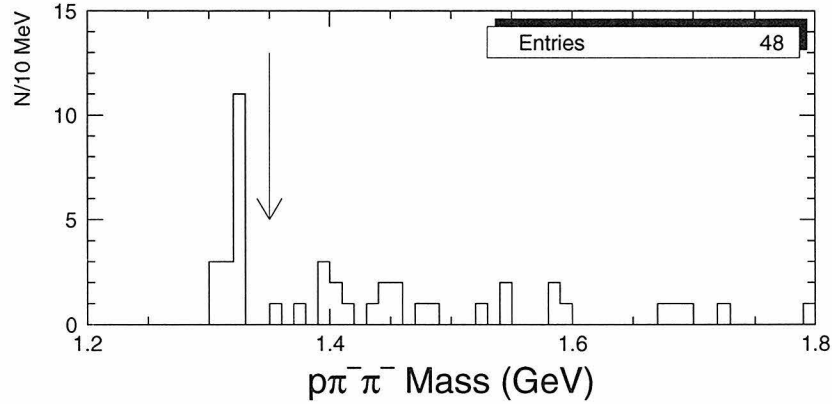


Figure 5.7: $p\pi^-\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$. The peak near 1.3 GeV is background from $\psi' \rightarrow \Xi^-\bar{\Xi}^+$. A cut is made at $M_{p\pi^-\pi^-} > 1.35 \text{ GeV}/c^2$ to remove $\Xi^-\bar{\Xi}^+$ combinatoric background.

To determine $N_{\Sigma^{*+}\bar{\Sigma}^{*-}}$, I constrain the $\bar{p}\pi^+\pi^-$ combination ($\bar{\Sigma}^{*-}$ candidate) to be within 107.4 MeV ($3 \times \Gamma$) of the nominal PDG value in order to enhance the Σ^{*+} signal. Events which pass the above cuts are fit to a Breit-Wigner with a constant background, with the mass and width fixed to the PDG values ($M = 1382.8 \text{ GeV}/c^2$, $\Gamma = 35.8 \text{ MeV}/c^2$). This fit is shown in Figure 5.8; from the fit, $N_{\Sigma^{*+}\bar{\Sigma}^{*-}} = 14 \pm 4 \pm 3$.

5.4 $\psi' \rightarrow \Xi^{*0}\bar{\Xi}^{*0}$

In the decay $\psi' \rightarrow \Xi^{*0}\bar{\Xi}^{*0}$ the Ξ^{*0} s are produced back to back in the ψ' rest frame. The dominant decay mode of Ξ^{*0} baryons is $\Xi^{*0} \rightarrow \Xi^-\pi^+$, with a branching fraction

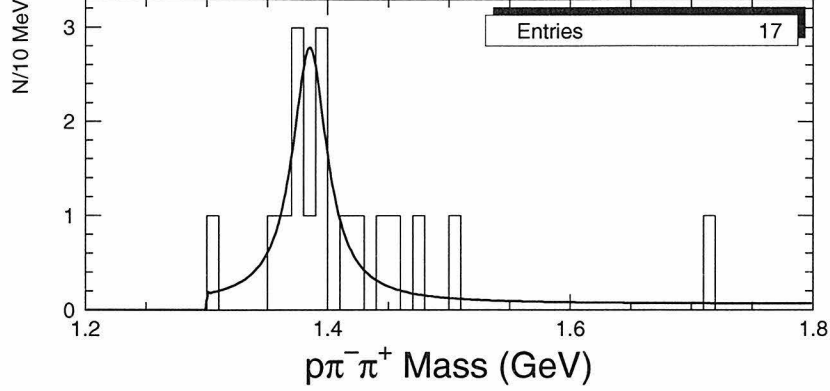


Figure 5.8: $p\pi^-\pi^+$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, where the recoil $\bar{p}\pi^+\pi^-$ mass is within 107 MeV ($3 \times \Gamma$) of the $\bar{\Sigma}^{*-}$ mass. The peak near 1.4 GeV is Σ^{*+} signal from $\psi' \rightarrow \Sigma^{*+}\bar{\Sigma}^{*-}$. Data is fit to a Breit-Wigner plus a constant background. $N_{\Sigma^{*+}\bar{\Sigma}^{*-}} = 14 \pm 4 \pm 3$.

of 0.66. The Ξ^- decays as in Section 4.5 to $\Lambda\pi^-$, and the Λ decays to $p\pi^-$. As the Ξ^{*0} is a narrow resonance ($\Gamma = 9.1 \text{ MeV}/c^2$), it has a reasonably well defined momentum of 1.026 GeV/ c . The daughter protons range in momentum from about 250 MeV/ c to 1.1 GeV/ c , and the daughter pions range from 20 to 350 MeV/ c . The final state of interest is $p\bar{p}\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$.

Eight-prong events which pass the general selection cuts of Section 5.1 are kinematically fit to the hypothesis $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ (4C). $p\pi$ candidates for Λ s are sent through a displaced vertex finder. Events which pass the fit with a P_{fit} greater than 0.01 are kept and examined further.

As the dominant decay mode in Ξ^{*0} decays includes a Λ in the decay chain, a loose cut is placed on the $p\pi^-$ mass ($|M_{p\pi^-} - M_\Lambda| < 20 \text{ MeV}/c^2$) to enhance the signal fraction (see Figure 5.9). Due to π combinatorics, each event that passes the kinematic fit is counted four times in this plot.

Similarly, as there is a Ξ^- in the decay chain, a cut is made on the $p\pi^-\pi^-$ invariant mass; $M_{p\pi^-\pi^-}$ is required to be less than 20 MeV/ c^2 , as shown in Figure 5.10. Due

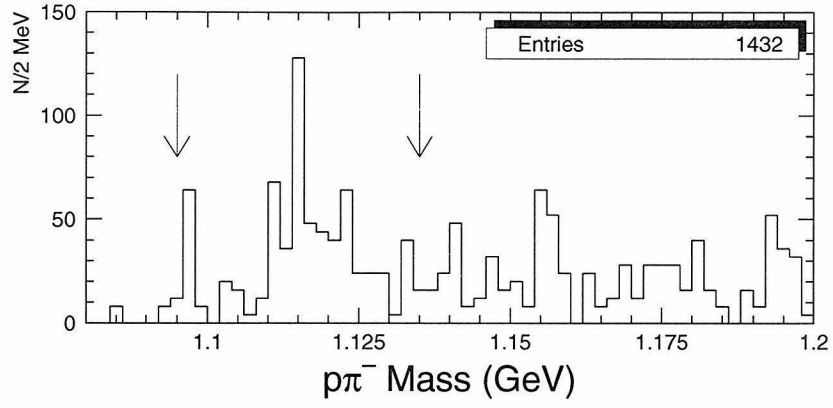


Figure 5.9: $p\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$. The peak near 1.115 GeV is Λ signal from $\Xi^- \rightarrow \Lambda\pi^-$. A loose (20 MeV) cut is made around the Λ peak to enhance signal. Each event is counted $\times 4$ because of π combinatorics.

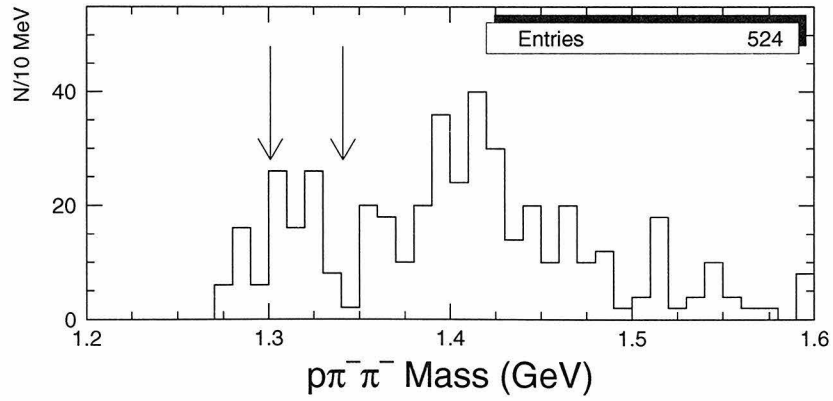


Figure 5.10: $p\pi^-\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$. The area near 1.32 GeV is the theoretic location of the Ξ signal from $\Xi^{*0} \rightarrow \Xi^-\pi^+$. A loose (20 MeV) cut is made around the Ξ peak location to remove background. Each event is counted $\times 2$ because of π combinatorics.

to π combinatorics, each event is counted twice in this plot.

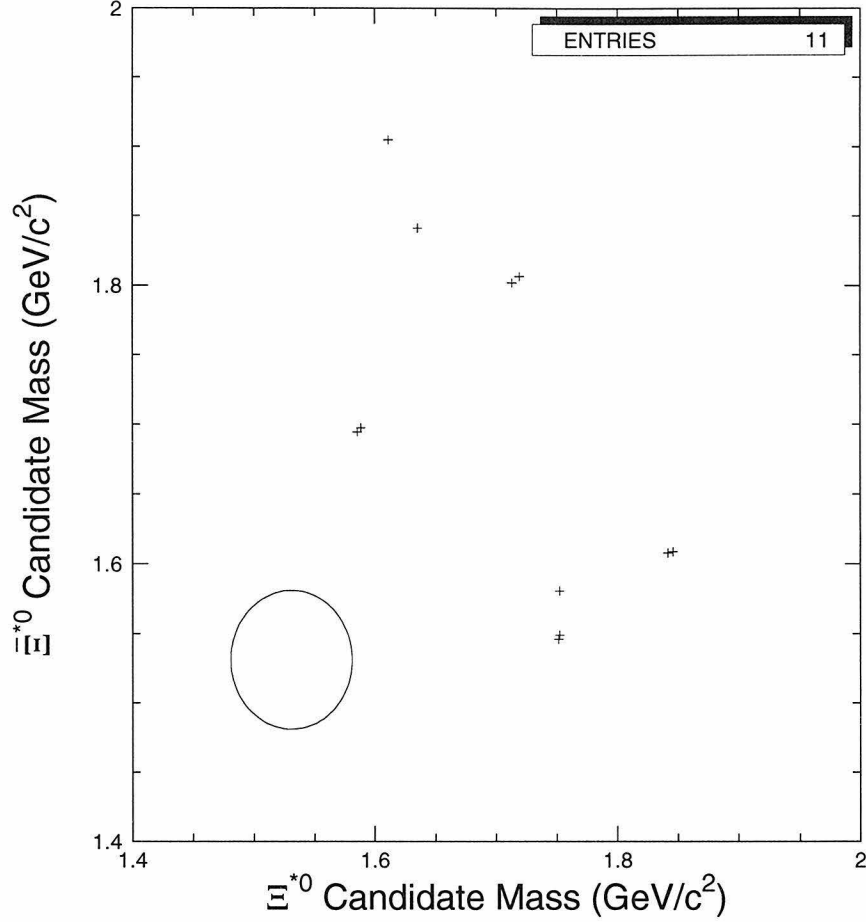


Figure 5.11: Ξ^{*0} candidate mass *vs.* $\bar{\Xi}^{*0}$ candidate mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$. The circle near (1.5,1.5) shows the location of the $\Xi^{*0}\bar{\Xi}^{*0}$ signal. No events fall in or near the signal region. An upper limit of 2.3 is set for $N_{\Xi^{*0}\bar{\Xi}^{*0}}$ at 90% CL.

The events that remain after the above cuts are graphed in Figure 5.11 with $M_{\bar{p}\pi^+\pi^+\pi^-}$ on the vertical axis and $M_{p\pi^-\pi^-\pi^+}$ on the horizontal. The signal region is shown as a circle at (1.531,1.531). No events fall within the signal region defined as a 50 MeV/c² radius from the central value. I set an upper limit of 2.3 events at 90% CL for $N_{\Xi^{*0}\bar{\Xi}^{*0}}$.

5.5 $\psi' \rightarrow \Omega^- \bar{\Omega}^+$

The Ω^- s from $\psi' \rightarrow \Omega^- \bar{\Omega}^+$ are back-to-back with momentum 0.774 GeV/ c . These decay to ΛK^- 67.8% of the time; the final state of interest is $p\bar{p}\pi^+\pi^-K^+K^-$. Momentum ranges for the final state particles are: 0.144 to 0.763 GeV/ c for protons, 0.016 to 0.481 GeV/ c for the direct kaons, and 0.0047 to 0.239 GeV/ c for pions from Λ s.

Events which pass the basic selection cuts (Section 5.1) are passed to a kinematic fitting routine with the constraints $\psi' \rightarrow p\bar{p}\pi^+\pi^-K^+K^-$, and $M_{p\pi-K^-} = M_{\bar{p}\pi^+K^+}$. Those events passing the fit with a probability of greater than 1% are examined further.

As the Ω^- decay mode we are interested in is ΛK^- , I make a cut at 10 MeV/ c^2 on either side of the nominal Λ and $\bar{\Lambda}$ masses. This is shown in Figure 5.12, where the histogram is data, and crosses are Monte Carlo, which has been normalized to 60 detected events.

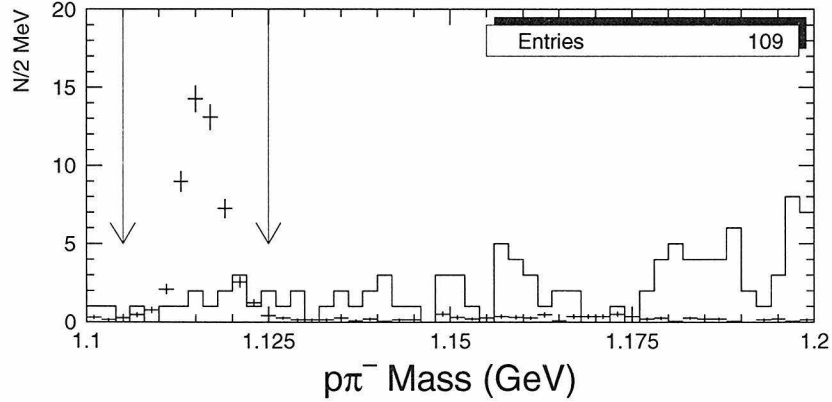


Figure 5.12: $p\pi^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-K^+K^-$, $M_{p\pi-K^-} = M_{\bar{p}\pi^+K^+}$. Histogram is data, crosses are Monte Carlo, normalized to sixty events. Arrows are cuts at 10 MeV/ c^2 on either side of the nominal Λ mass.

Candidates which pass the above cuts are plotted in Figure 5.13. For reference,

Monte Carlo events are also shown, normalized to three total events. There are no candidates within three sigma of the nominal Ω^- peak, thus I quote upper limit of 2.3 events observed at the 90 percent confidence level.

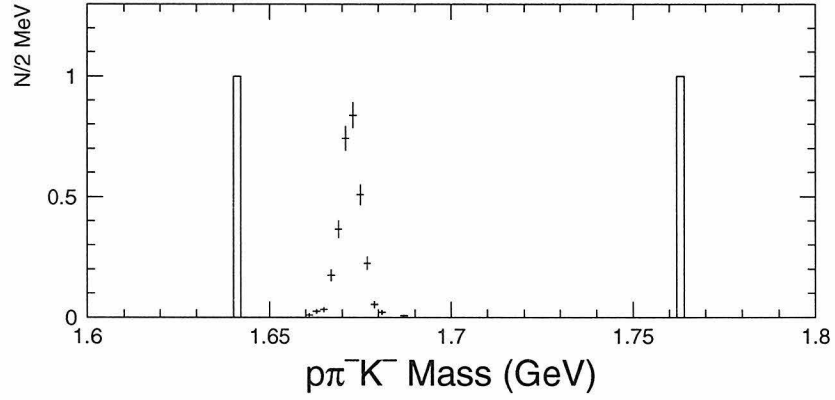


Figure 5.13: $p\pi^-K^-$ masses from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-K^+K^-$, $M_{p\pi^-K^-} = M_{\bar{p}\pi^+K^+}$. Histogram is data, crosses are Monte Carlo, normalized to three events. No $\Omega^-\bar{\Omega}^+$ candidates are evident.

Chapter 6 J/ψ Decays to Baryons

A useful check on the methods used in Chapters 4 and 5 is to examine the same baryonic decay modes in the J/ψ system. The $J/\psi \rightarrow p\bar{p}$ mode is additionally interesting, in that it provides a clean sample of $p\bar{p}$ pairs to examine the efficiency of the cuts used in the $\psi' \rightarrow p\bar{p}$ analysis, Section 4.2.

6.1 $J/\psi \rightarrow p\bar{p}$

The decay $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow p\bar{p}$ produces two approximately back-to-back protons with the invariant mass of the J/ψ , with two pions associated with the ψ' decay. The general selection cuts of Chapters 4 and 5 are modified for this mode to increase the acceptance. For the kinematic fit, the $|\cos\theta|$ cut of 0.8 is removed. The kinematics of the event are such that all true π tracks will have momenta less than 500 MeV/c, and all true p tracks will have momenta higher than 1 GeV/c. All four charged track candidates which pass the momentum criteria are fed to the 4-C kinematic fit to $\psi' \rightarrow \pi^+\pi^-p\bar{p}$. Events which pass the fit with a χ^2 confidence level of greater than 0.01 are booked into an n-tuple and examined further.

The dominant backgrounds to this mode are $\psi' \rightarrow \Lambda\bar{\Lambda}$, $\psi' \rightarrow \Delta^{++}\bar{\Delta}^{--}$, and non-resonant $\pi^+\pi^-p\bar{p}$ production. Figure 6.1 shows a spectrum of $p\pi^-$ invariant masses from the above kinematic fit. A peak is seen at the mass of the Λ . This background is removed with a cut at $M_{p\pi^-} > 1.15$ GeV/c². As Δ^{++} is a rather broad resonance, efficiency will be hurt too much trying to remove this background. In any case $\Delta^{++}\bar{\Delta}^{--}$ production only contributes a small, relatively constant background under the J/ψ peak, as shown in Figure 5.3.

As the $|\cos\theta|$ criterion for all tracks was relaxed for this analysis, the dependence on this variable must be examined. Figures 6.2 and 6.3 show the dE/dx dependence on $\cos\theta$ for proton candidates. In the central region, $|\cos\theta| < 0.8$, the XSP variable

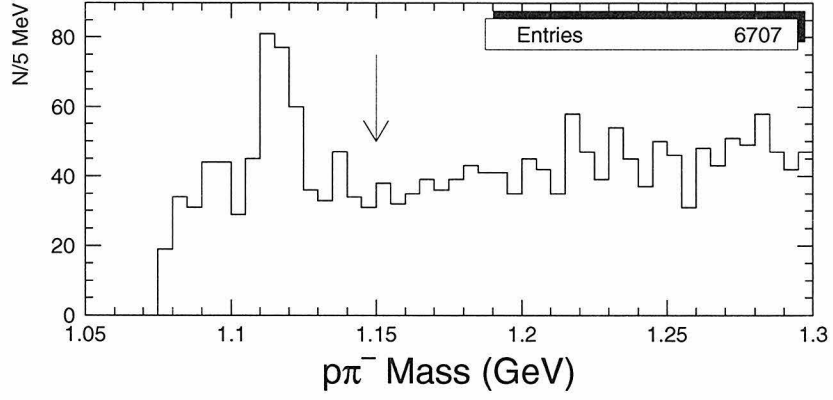


Figure 6.1: $p\pi$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. A cut is made at $M_{p\pi^-} > 1.15 \text{ GeV}/c^2$ to remove $\Lambda\bar{\Lambda}$ background.

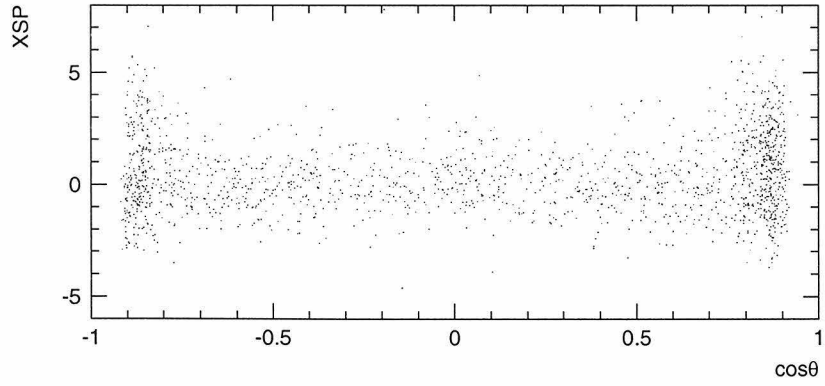


Figure 6.2: XSP vs. $\cos\theta$ for protons from J/ψ . Notice the large change in the dE/dx response outside $|\cos\theta| = 0.8$.

projects to a unit gaussian, centered at the origin (Figure 6.3, left). Outside the central region, XSP projects to a much wider functional form, no longer centered at the origin (Figure 6.3, right).

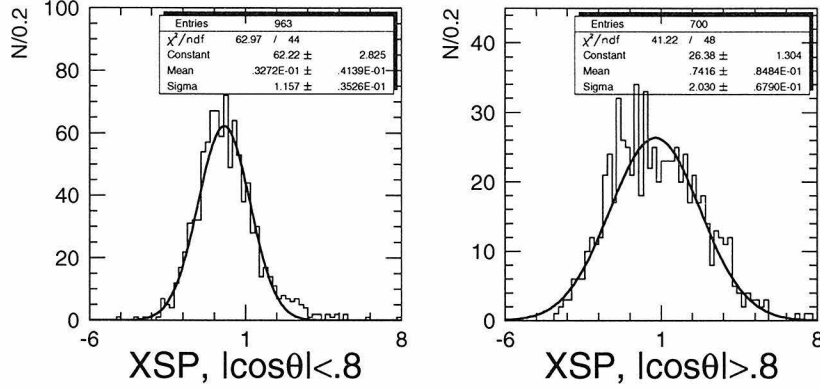


Figure 6.3: **left:** Projection onto XSP axis of Figure 6.2, $|\cos \theta| < 0.8$. **right:** Projection onto XSP axis of Figure 6.2, $|\cos \theta| > 0.8$.

Figure 6.4 shows the dependence on $\cos \theta$ of the energy deposited by the particle in the BSC. Notice that the Monte Carlo $\bar{p}s$ do not model the data, and that there are a large number of high E_{SC} hits for p and $\bar{p}$ candidates outside $|\cos \theta| = 0.8$. These energies (1–2 GeV) are in the general range for electrons produced by J/ψ . For further analysis, proton and antiproton candidates are required to be within a $|\cos \theta|$ of 0.8.

The invariant $p\bar{p}$ mass of each event which passes the kinematic fit, the Λ rejection cut, and the $\cos \theta$ cut on the protons is plotted in Figure 6.5. This spectrum is fit to a gaussian plus a linear background, with centroid fixed to the J/ψ mass. From the fit, $N_{J/\psi \rightarrow p\bar{p}} = 705 \pm 27 \pm 13$, where the first error is statistical and the second is the error from the fit.

As an independent check on this analysis method, this decay mode was explored without a kinematic fit. All four charged track modes with a $\pi^+\pi^-$ recoil mass within $75 \text{ MeV}/c^2$ of the J/ψ were examined for $p\bar{p}$ pairs. The pairs were selected

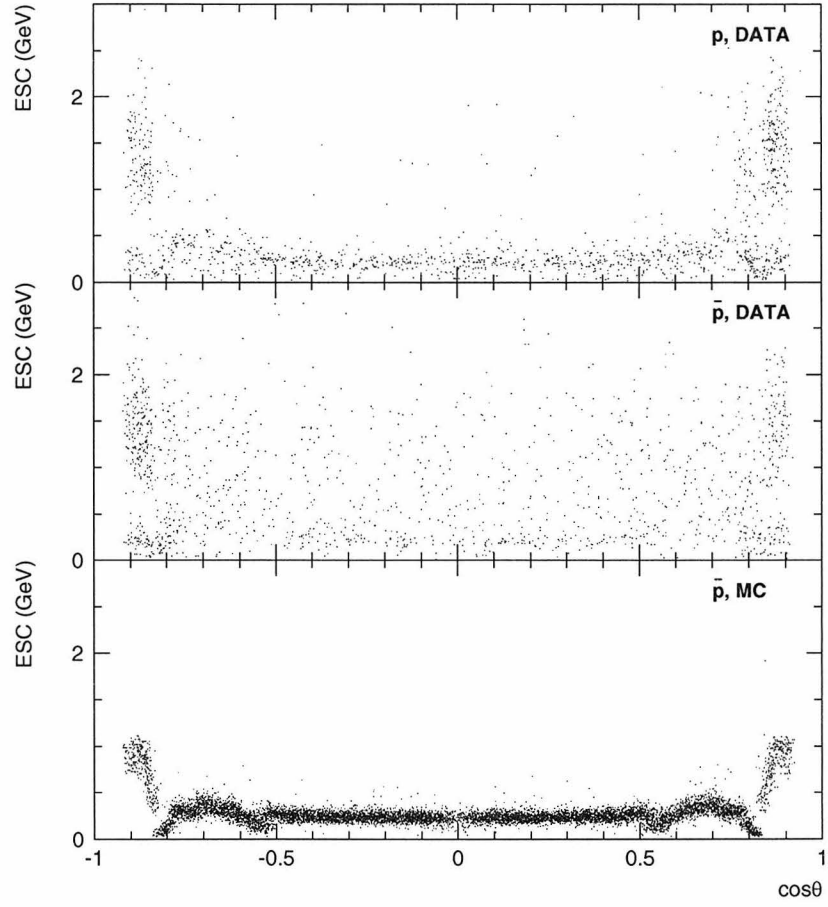


Figure 6.4: E_{SC} vs. $\cos\theta$ for protons and antiprotons. Top plot is from $J/\psi \rightarrow p\bar{p}$ kinematic fit to data for charge +1 objects (p), center is for charge -1 objects ($\bar{p}$). Bottom plot is from $J/\psi \rightarrow p\bar{p}$ Monte Carlo for charge -1 objects ($\bar{p}$).

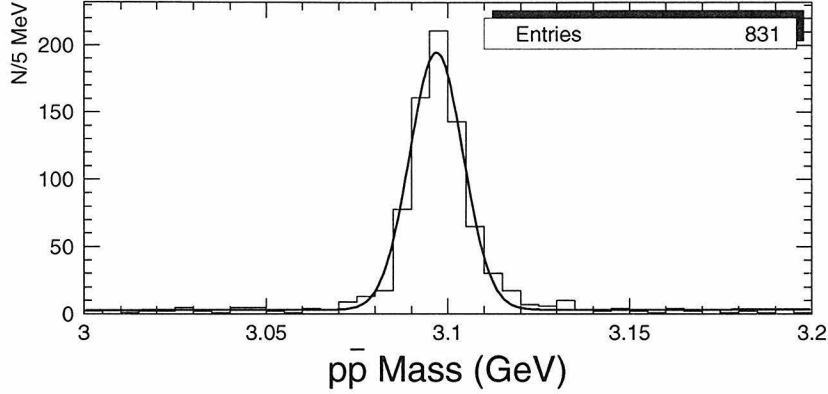


Figure 6.5: $p\bar{p}$ invariant mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-$. Data is fit to a gaussian plus a linear background. From the fit, $N_{J/\psi \rightarrow p\bar{p}} = 705 \pm 27 \pm 13$.

by requiring the confidence level for Time-Of-Flight identification to be 0.1 for the proton hypothesis for both tracks. Average momentum of the proton and antiproton candidate tracks in the J/ψ rest frame is plotted in the upper portion of Figure 6.6. The lower portion is all events which do *not* pass the kinematic fit detailed above. The lack of a clear signal in the signal-subtracted plot shows that the kinematic fit is picking up most of the $p\bar{p}$ pairs from J/ψ .

6.2 $J/\psi \rightarrow \Lambda\bar{\Lambda}$

The decay $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$ is analyzed similarly to the ψ' mode. I make a kinematic fit to $\pi^+\pi^-\pi^+\pi^-p\bar{p}$, with the mass of one of the $p\pi^-$ pairs constrained to be the mass of one of the $\bar{p}\pi^+$ pairs (5 constraint). The $p\pi$ pairs are sent through a displaced vertex finder. All combinations with a fit confidence level greater than 1 percent are examined further. To increase acceptance for this analysis, the $\cos\theta_{\text{track}}$ cut is partially relaxed. Although the direct $\pi^+\pi^-$ pair is not required to be within $|\cos\theta| < 0.8$, the particles which make up the Λ candidates retain the requirement.

Figure 6.7 shows the results of the $p\pi$ mass constraint from the above fit. The

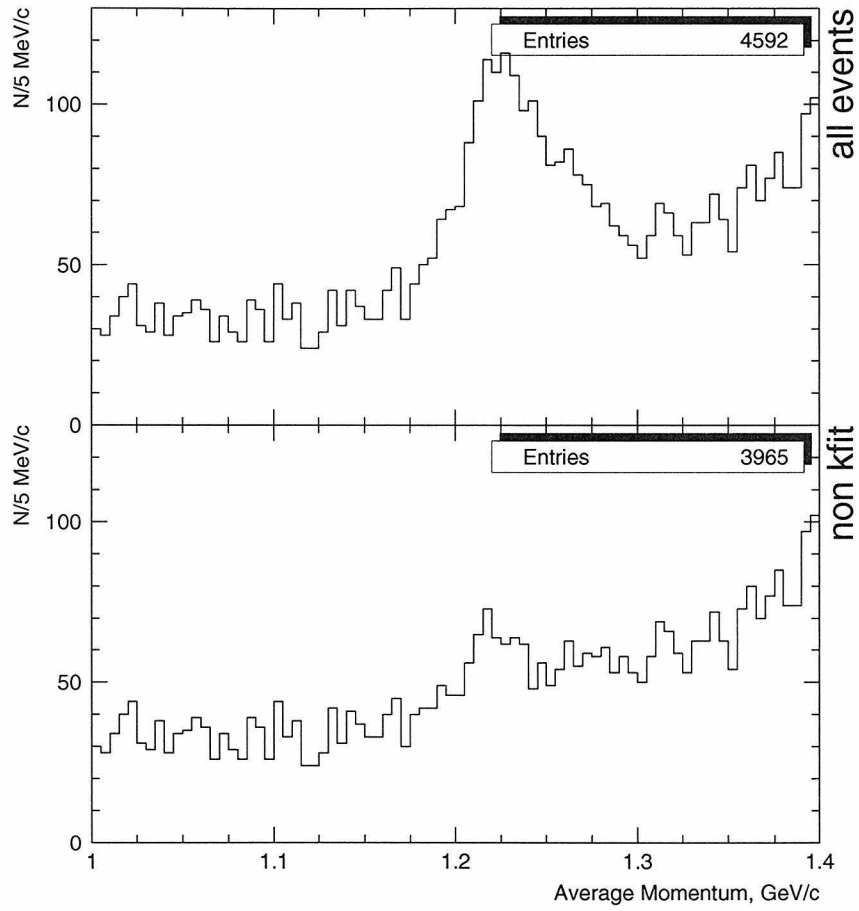


Figure 6.6: Average momentum of p and $\bar{p}$ candidate tracks in the J/ψ rest frame that pass TOF cuts. Upper plot is all events which pass TOF. Lower plot is all events which do *not* pass the kinematic fit. Little, if any, remaining $p\bar{p}$ signal is seen.

upper plot is all $p\pi$ candidates, enhanced by a $100 \text{ MeV}/c^2$ cut on the $\pi^+\pi^-$ recoil mass. The lower plot details the $p\pi$ spectrum in the Λ mass region, showing a clear peak near the nominal Λ mass. All events satisfying $|M_{p\pi} - M_\Lambda| < 30 \text{ MeV}/c^2$ are retained for further analysis.

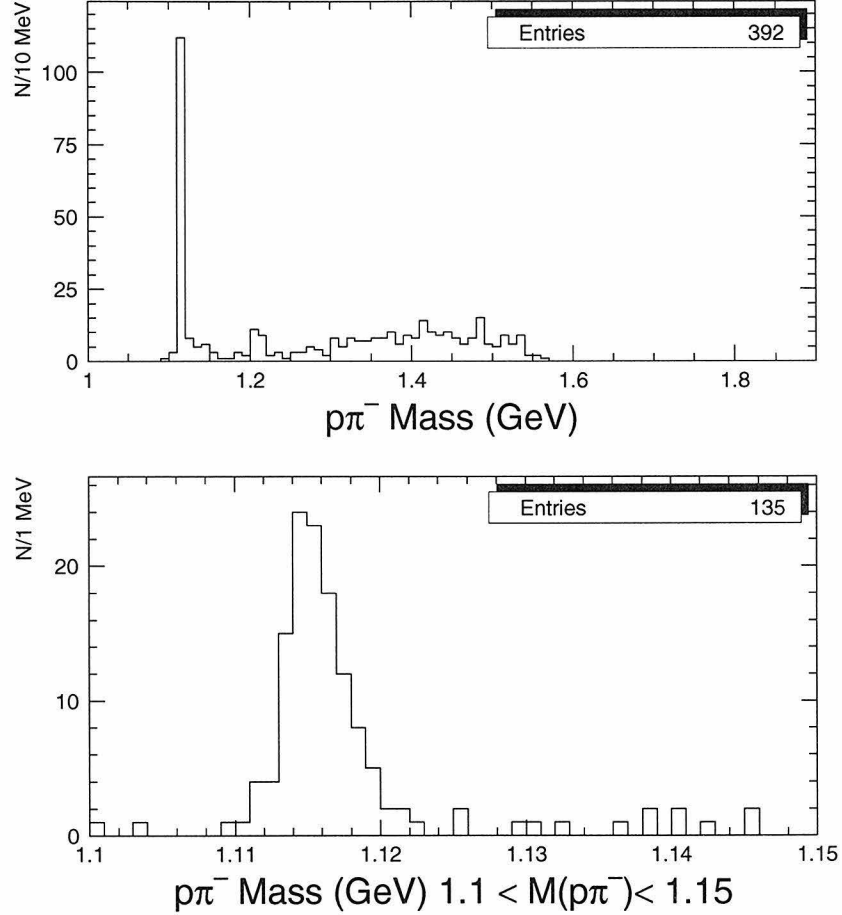


Figure 6.7: $p\pi$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, $M_{p\pi^-} = M_{\bar{p}\pi^+}$. Upper plot is all data ($P_{fit} > 0.01$), with a $100 \text{ MeV}/c^2$ cut on the J/ψ mass. Lower is $1.1 < M_{p\pi} < 1.15 \text{ GeV}/c^2$, showing the Λ peak.

Figure 6.8 shows the $\Lambda\bar{\Lambda}$ candidate masses that pass the above cuts. The peak is fit to a gaussian plus a linear background function. From the fit, $N_{J/\psi \rightarrow \Lambda\bar{\Lambda}} = 102 \pm 10.3 \pm 6.0$ where the first error is statistical and the second is the systematic

error on the fit.

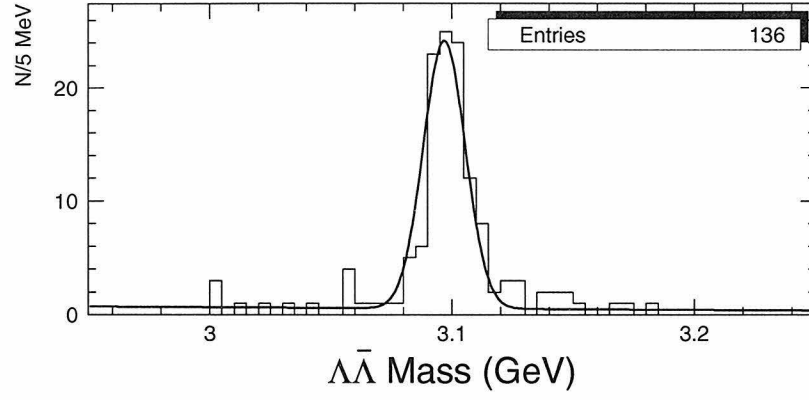


Figure 6.8: $\Lambda\bar{\Lambda}$ mass from a kinematic fit to $\psi' \rightarrow p\bar{p}\pi^+\pi^-\pi^+\pi^-$, $M_{p\pi^-} = M_{\bar{p}\pi^+}$. The peak is fit to a gaussian plus a linear background. From the fit, $N_{J/\psi \rightarrow \Lambda\bar{\Lambda}} = 102 \pm 10.3 \pm 6.0$.

Chapter 7 Monte Carlo and Systematics

7.1 Efficiencies

In order to determine detector and cut efficiencies, a set of Monte Carlo events was generated for each mode. Events were generated in a $1 + \alpha_d \cos \theta$ distribution. The α_d values simulated are shown in Table 7.1. For the octet, the values used were those measured in the J/ψ system by MarkII [20] and DM2 [21][22]. However, as the value measured for $\Xi^- \bar{\Xi}^+$ had extremely large error bars ($\alpha_d = -.13 \pm .59$ [20]), I chose 0.5 ± 0.5 for α_d . For the decuplet modes, I chose 0.6 as a central value, and similarly varied to determine the effect on efficiency. Due to the low statistics and systematic fit errors in $\Sigma^0 \bar{\Sigma}^0$ and $\Sigma^{*+} \bar{\Sigma}^{*-}$, α_d was not varied for these modes.

The one-sigma error bar on the central value of each α_d was used to determine the effects on efficiency. For the $p\bar{p}$ and $\Lambda\bar{\Lambda}$ modes, a flat distribution ($\alpha_d = 0$) was also simulated in order to measure the angular distribution. Each baryon data set was generated with only the final state of interest. For example, $\Lambda\bar{\Lambda}$ was generated with $\Lambda \rightarrow p\pi^-$ with no other decay modes active.

Each set detailed above is sent through the relevant analysis described in Chapters 4 and 5. Efficiencies determined for all modes other than $p\bar{p}$ are summarized in Table 7.2. The $p\bar{p}$ mode is discussed separately in Section 7.2 as the cuts for that mode depend on both the shower counter and the dE/dx subsystems, and BES Monte Carlo system does not model $\bar{p}$ hadronic interactions very well. (*N.B.*, As all modes other than $p\bar{p}$ are investigated purely via kinematic fit; therefore, hadronic interactions are not used as part of their analysis chains.)

Mode	α_d	$N_{\text{simulated}}$
$p\bar{p}$	$0.61 \pm 0.20, 0.0$	20000
$\Lambda\bar{\Lambda}$	$0.67 \pm 0.21, 0.0$	20000
$\Sigma^0\bar{\Sigma}^0$	0.22	20000
$\Xi^-\bar{\Xi}^+$	0.5 ± 0.5	20000
$\Delta^{++}\bar{\Delta}^{--}$	1, 0.6, 0.0	20000
$\Sigma^{*+}\bar{\Sigma}^{*-}$	0.6	20000
$\Xi^{*0}\bar{\Xi}^{*0}$	0.6	20000
$\Omega^-\bar{\Omega}^+$	0.6	20000
$\pi^+\pi^-p\bar{p}$	phase-space	20000

Table 7.1: Number of events simulated in each mode for the polar angle distribution $1 + \alpha_d \cos \theta$. The phase-space $\pi^+\pi^-p\bar{p}$ sample was generated in order to examine the background shape in the $\Delta^{++}\bar{\Delta}^{--}$ mode.

Mode	Efficiency
$\Lambda\bar{\Lambda}$	0.273 ± 0.009
$\Sigma^0\bar{\Sigma}^0$	0.043 ± 0.003
$\Xi^-\bar{\Xi}^+$	0.078 ± 0.007
$\Delta^{++}\bar{\Delta}^{--}$	0.312 ± 0.024
$\Sigma^{*+}\bar{\Sigma}^{*-}$	0.104 ± 0.005
$\Xi^{*0}\bar{\Xi}^{*0}$	0.041 ± 0.001
$\Omega^-\bar{\Omega}^+$	0.042 ± 0.001

Table 7.2: Measured efficiencies for all modes other than $p\bar{p}$.

7.2 $p\bar{p}$ Detection Efficiency

The BES Monte Carlo system is of limited use in modeling the mode $\psi' \rightarrow p\bar{p}$. Geometric effects are modeled well, but the hadronic interactions between the proton/antiproton and the detector are not. Those cuts which are based on hadronic effects must be corrected for by examining the real data.

Fortunately there is a subset of events which will allow the effects of these cuts to be determined. As shown in Section 6.1, a clean sample of $p\bar{p}$ pairs can be acquired by a kinematic fit to $\psi' \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow p\bar{p}$. This gives us several hundred $p\bar{p}$ pairs to examine the effects of the shower counter cuts.

The general acceptance cuts on the $p\bar{p}$ analysis from Section 4.1 are purely geometric and can be modeled solely by the BES Monte Carlo. Out of 20000 events generated, 14857 events survive these cuts. This efficiency is thus 0.743. The collinearity cut is also purely geometric, and has an efficiency of 0.999.

Other cuts are examined using either both Monte Carlo and the $J/\psi \rightarrow p\bar{p}$ sample, or just the data. The effects of these cuts are summarized in Table 7.3.

Cut	MC	ϵ_{MC}	J/ψ	$\epsilon_{J/\psi}$	Avg	Syst
None	20000					
General	14857	.743	847		.743	.006
Muon ID	10335	.696	662	.782	.739	.043
BSC Geom	7942	.768	418	.631	.700	.069
$E_{SC} < 0.7$			404	.610	.610	
$ XSP < 3$			391	.968	.968	.047
Collinearity	7937	.999			.999	.011

Table 7.3: Relative efficiencies for cuts in the mode $\psi' \rightarrow p\bar{p}$, as modeled by Monte Carlo and J/ψ data. Avg column denotes efficiency used in the analysis.

The muon ID cut and the BSC geometry cut were examined in both data and Monte Carlo, giving different results. As there is no *a priori* reason to prefer one method over the other, I averaged the efficiencies, using the spread in values as a

systematic error. The systematic errors on the other cuts were determined both by the statistics of the cuts, and by varying the cuts. The systematic error on the E_{SC} and XSP cuts are combined.

The total efficiency for the $p\bar{p}$ mode is the product of the “Avg” column of Table 7.3, $\epsilon = 0.227 \pm 0.032$.

7.3 Acceptances

As each baryon data set is simulated only in the dominant decay mode, the data must be corrected for the finite branching fractions of the simulated modes. Table 7.4 summarizes the acceptances required by each analysis. Due to space constraints, the error on each branching fraction is only reported in the first column.

Mode	η_1	η_2	η_3	$(\prod_i \eta_i)^2$
$\Lambda\bar{\Lambda}$	$0.639 \pm .005$ (Λ)			$0.408 \pm .005$
$\Sigma^0\bar{\Sigma}^0$	1.0 (Σ^0)	0.639 (Λ)		$0.408 \pm .005$
$\Xi^-\bar{\Xi}^+$	$0.999 \pm .001$ (Ξ^-)	0.639 (Λ)		$0.407 \pm .005$
$\Delta^{++}\bar{\Delta}^{--}$	> 0.99 (Δ^{++})			$1.00 \pm .01$
$\Sigma^{*+}\bar{\Sigma}^{*-}$	$0.88 \pm .02$ (Σ^{*+})	0.639 (Λ)		$0.316 \pm .011$
$\Xi^{*0}\bar{\Xi}^{*0}$	$0.650 \pm .001$ (Ξ^{*0})	0.999 (Ξ^-)	0.639 (Λ)	$0.172 \pm .001$
$\Omega^-\bar{\Omega}^+$	$0.678 \pm .007$ (Ω^-)	0.639 (Λ)		$0.187 \pm .003$

Table 7.4: Acceptances for the baryon channels due to finite branching fractions of decaying particles. Parentheses indicate which daughter particle creates the acceptance.

The decay of the Δ is listed by the PDG [4] as having a branching fraction to $N\pi$ of greater than 0.99. Due to charge conservation, Δ^{++} can only go to $p\pi^+$. I quote the uncertainty on this branching ratio as a conservative 1 percent. Similarly, the decay of the Ξ^{*0} is listed as proceeding via $\Xi\pi$ 100 percent of the time. Taking into account isospin and phase space corrections, Ξ^{*0} will decay to $\Xi^-\pi^+$ 65 percent of the time. I also quote the uncertainty as a conservative one percent.

7.4 Number of ψ'

The determination of the number of ψ' mesons produced by the BES experiment during the two ψ' runs is extensively discussed in reference [23]. The method used was to examine the inclusive $\pi^+\pi^-$ recoil mass spectrum for the cascade decay $\psi' \rightarrow \pi^+\pi^- J/\psi$, Figure 7.1.

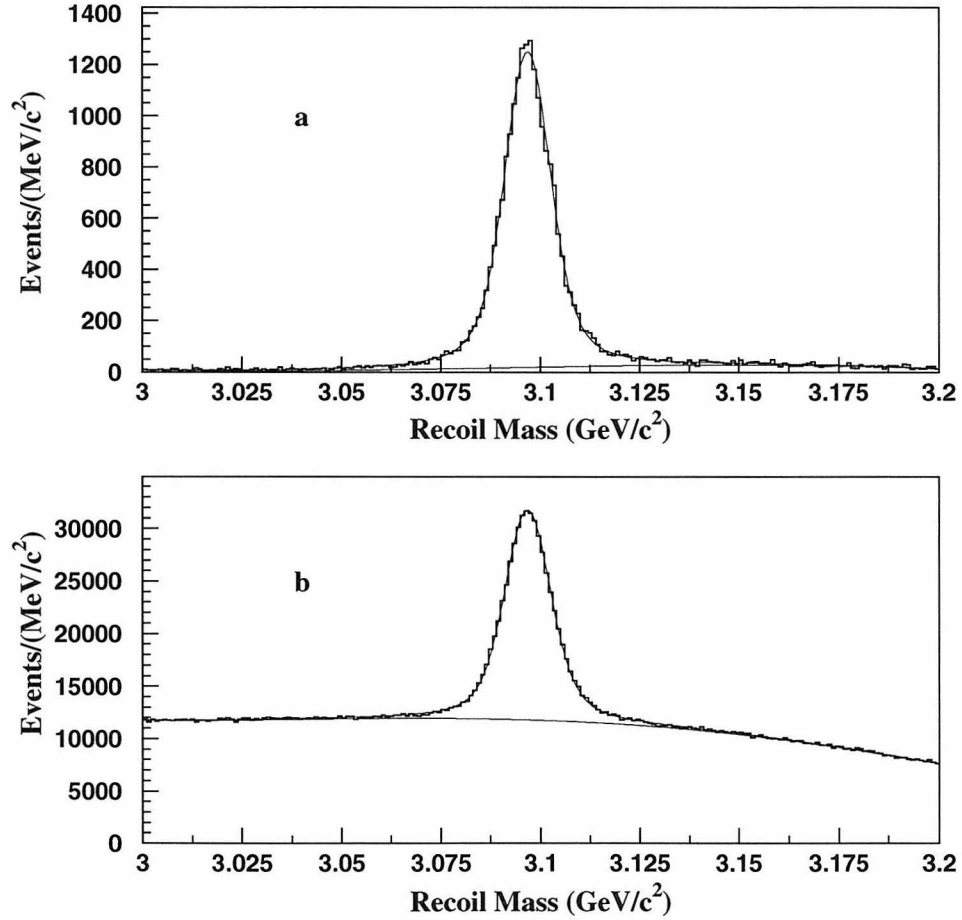


Figure 7.1: **a:** Number of events *vs.* $\pi^+\pi^-$ recoil mass for $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$. Histogram is data, curve is a Breit-Wigner-Gaussian “signal” plus a cubic polynomial “background”. **b:** Number of events *vs.* $\pi^+\pi^-$ recoil mass for inclusive events. Histogram is data, curve is a Breit-Wigner-Gaussian “signal” (parameters derived from **a:**) plus a quartic “background”.

The $\pi^+\pi^-$ recoil spectrum was examined in two ways. First, in the decay $J/\psi \rightarrow l^+l^-$, the spectrum was fit to a cubic polynomial “background” plus a Breit-Wigner convoluted with a gaussian “signal”. Leptons were selected using kinematic and dE/dx information, along with the BSC and muon systems. Detailed cuts are discussed in [23]. The fit parameters gained via this method are used to fit the inclusive $\pi^+\pi^-$ recoil spectrum to determine the total number of J/ψ observed in this mode, $(5.481 \pm .007) \times 10^5$. This number is corrected for the $\pi^+\pi^-$ acceptance, and the total number of J/ψ mesons produced by BES in the two running periods is thus $(1.227 \pm .003 \pm .017) \times 10^6$. If this number is divided by $\mathcal{B}(\psi' \rightarrow \pi^+\pi^- J/\psi)$, the total number of ψ' covered by these analyses is $(3.79 \pm .01 \pm .31) \times 10^6$. If this is split up by run period, the first ψ' data set contains $(1.33 \pm .01 \pm .11) \times 10^6$ ψ' s, while the second data set contains $(2.46 \pm .01 \pm .20) \times 10^6$ ψ' s.

7.5 J/ψ Monte Carlo

For each of the two J/ψ decay modes examined, 20000 events were generated with the topology $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow B\bar{B}$. According to Pham, Pire and Truong, [24], the orbital angular momenta between the $\pi^+\pi^-$ system and the J/ψ is zero, as is that between the π^+ and π^- . The $\pi^+\pi^-$ mass distribution is then:

$$\begin{aligned} \frac{d\sigma}{dm_{\pi^+\pi^-}} &\propto (\text{Phase Space}) \times (M_{\pi^+\pi^-}^2 - 4m_\pi^2)^2 \\ &\propto (M_{\pi^+\pi^-}^2 - 4m_\pi^2)^2 (M_{\pi^+\pi^-}^2 - 4m_\pi^2)^{1/2} \times \\ &\quad [(M_{\psi(2S)}^2 - m_{J/\psi}^2 - m_{\pi^+\pi^-}^2)^2 - 4m_{J/\psi}^2 m_{\pi^+\pi^-}^2]^{1/2}. \end{aligned} \quad (7.1)$$

The decay chain is generated as a set of sequential two body decays, $\psi' \rightarrow X J/\psi$, $X \rightarrow \pi^+\pi^-$, and $J/\psi \rightarrow B\bar{B}$. An isotropic angular distribution is used for both the J/ψ in the lab frame, and the pions in the X rest frame. The baryons from the J/ψ are produced in the J/ψ rest frame with the $1 + \alpha_d \cos^2 \theta$ distribution described in Section 7.1. The Monte Carlo efficiencies for the $J/\psi \rightarrow p\bar{p}$ and $\Lambda\bar{\Lambda}$ modes are given in column two of Table 7.5. Column three contains the acceptance for the decay

$J/\psi \rightarrow B\bar{B}$. In addition, there is an additional acceptance correction for both modes due to the branching fraction $\mathcal{B}(\psi' \rightarrow \pi^+\pi^- J/\psi) = 0.324 \pm 0.026$.

Mode	Efficiency	Acceptance
$J/\psi \rightarrow p\bar{p}$	0.437 ± 0.005	1.0
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	0.145 ± 0.003	$0.408 \pm .005$

Table 7.5: Monte Carlo efficiencies and acceptances for $J/\psi \rightarrow B\bar{B}$.

Chapter 8 Results

From Chapters 4 and 5, the number of produced particles in each $\psi' \rightarrow B\bar{B}$ mode are:

$$N_{p\bar{p}} = 225 \pm 15 \pm 21$$

$$N_{\Lambda\bar{\Lambda}} = 80 \pm 9 \pm 4$$

$$N_{\Sigma^0\bar{\Sigma}^0} = 8 \pm 3 \pm 2$$

$$N_{\Xi^-\bar{\Xi}^+} = 12 \pm 3.4 \pm 0.2$$

$$N_{\Delta^{++}\bar{\Delta}^{--}} = 157 \pm 13 \pm 34$$

$$N_{\Sigma^{*+}\bar{\Sigma}^{*-}} = 14 \pm 4 \pm 3$$

$$N_{\Xi^{*0}\bar{\Xi}^{*0}} < 2.3; \quad \text{CL}=90\%$$

$$N_{\Omega^-\bar{\Omega}^+} < 2.3; \quad \text{CL}=90\%$$

The branching fractions from these numbers are obtained by correcting for efficiency and acceptance, and dividing by the total number of ψ' s (Section 7.4), Equation 8.1.

$$\mathcal{B}(\psi' \rightarrow B\bar{B}) = \frac{N_{B\bar{B}}}{\epsilon_{B\bar{B}} \times \eta_{B\bar{B}} \times N_{\psi'}} \quad (8.1)$$

Inserting the above measurements along with the acceptances and efficiencies of Chapter 7 into the above equation generates the following branching ratios for the $\psi' \rightarrow B\bar{B}$ modes:

- $\mathcal{B}(\psi' \rightarrow p\bar{p}) = (26.2 \pm 1.7 \pm 5.5) \times 10^{-5}$
- $\mathcal{B}(\psi' \rightarrow \Lambda\bar{\Lambda}) = (18.9 \pm 2.1 \pm 2.1) \times 10^{-5}$
- $\mathcal{B}(\psi' \rightarrow \Sigma^0\bar{\Sigma}^0) = (12 \pm 4 \pm 3) \times 10^{-5}$

- $\mathcal{B}(\psi' \rightarrow \Xi^- \bar{\Xi}^+) = (10 \pm 3 \pm 1) \times 10^{-5}$
- $\mathcal{B}(\psi' \rightarrow \Delta^{++} \bar{\Delta}^{--}) = (13.4 \pm 1.1 \pm 3.3) \times 10^{-5}$
- $\mathcal{B}(\psi' \rightarrow \Sigma^{*+} \bar{\Sigma}^{*-}) = (11 \pm 3 \pm 3) \times 10^{-5}$
- $\mathcal{B}(\psi' \rightarrow \Xi^{*0} \bar{\Xi}^{*0}) < 8.5 \times 10^{-5}$ (90% CL)
- $\mathcal{B}(\psi' \rightarrow \Omega^- \bar{\Omega}^+) < 7.7 \times 10^{-5}$ (90% CL)

The first error is statistical on $N_{B\bar{B}}$, and the second is the result of propagating the systematics on η , ϵ , and $N_{\psi'}$.

Of these branching ratios, only $\psi' \rightarrow p\bar{p}$ has been previously measured, and then with poor statistics. The combined Mark I [25] and DASP [26] measurement is $\mathcal{B}(\psi' \rightarrow p\bar{p}) = (1.9 \pm 0.5) \times 10^{-4}$, which is consistent with the above result. The upper limits given for $\Lambda\bar{\Lambda}$ and $\Xi^- \bar{\Xi}^+$ are also consistent with my measurements.

The branching ratios for $J/\psi \rightarrow \{p\bar{p}, \Lambda\bar{\Lambda}\}$ can be determined from the measurements of Chapter 6. Using $N_{J/\psi \rightarrow p\bar{p}} = 705 \pm 27 \pm 13$, $N_{J/\psi \rightarrow \Lambda\bar{\Lambda}} = 102 \pm 10 \pm 6$ and the equation

$$\mathcal{B}(J/\psi \rightarrow B\bar{B}) = \frac{N_{J/\psi \rightarrow B\bar{B}}}{\epsilon_{J/\psi \rightarrow B\bar{B}} \times \eta_{J/\psi \rightarrow B\bar{B}} \times \mathcal{B}(\psi' \rightarrow \pi^+ \pi^- J/\psi) \times N_{\psi'}},$$

I get the following branching ratios for the J/ψ modes:

- $\mathcal{B}(J/\psi \rightarrow p\bar{p}) = (1.31 \pm .05 \pm .13) \times 10^{-3}$
- $\mathcal{B}(J/\psi \rightarrow \Lambda\bar{\Lambda}) = (1.41 \pm .14 \pm .16) \times 10^{-3}$

While the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ result is consistent with previously measured values [4], the $J/\psi \rightarrow p\bar{p}$ is only 61 percent of the current world average, $2.14 \pm .10 \times 10^{-3}$. This is a 6σ discrepancy. As shown in Figure 6.6, two completely different analysis methods pick up approximately the same number of events. Thus, as there is no inefficiency in the kinematic fit, the reason for the difference is unclear.

8.1 Theoretic Comparison

What would an experimental result be if it weren't compared with theoretical predictions? The following graph (Figure 8.1) shows the ratio of branching ratios $\mathcal{B}(\psi' \rightarrow B\bar{B})/\mathcal{B}(J/\psi \rightarrow B\bar{B})$. The horizontal dotted line is the 12 percent ratio expected from naïve factorization. Each branching fraction is consistent with the

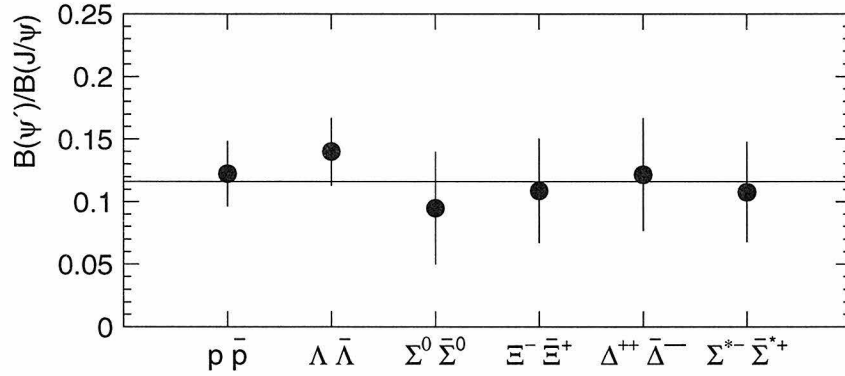


Figure 8.1: The ratio $\mathcal{B}(\psi' \rightarrow B\bar{B})/\mathcal{B}(J/\psi \rightarrow B\bar{B})$. J/ψ results are from [20], [21], [22], [27], [28] and [29]. Horizontal line is the 12 percent ratio expected from factorizing the $\psi' \rightarrow B\bar{B}$ Feynman diagram.

factorization hypothesis.

Next, I examine the predictions from SU(3)-flavor. Under this symmetry, the reduced branching fraction, $\mathcal{B}(\psi' \rightarrow B\bar{B})/p_B$, should be a constant. The values for $p_{\Delta^{++}}$, $p_{\Sigma^{*+}}$, and $p_{\Xi^{*0}}$ are obtained using the central value of the particle mass. This ratio is shown in Figure 8.2. Each branching ratio is also consistent with this model, within two sigma.

The last theoretic model is the perturbative QCD model of Bolz and Kroll [19]. Using the values in Table 3.3, the ratio $\Gamma(\psi' \rightarrow B\bar{B})_{ex}/\Gamma(\psi' \rightarrow B\bar{B})_{th}$ is constructed and graphed in Figure 8.3. The values for $\Gamma(\psi' \rightarrow B\bar{B})$ are obtained by multiplying $\mathcal{B}(\psi' \rightarrow B\bar{B})$ by $\Gamma(\psi') = 277 \pm 31$ keV. [4]

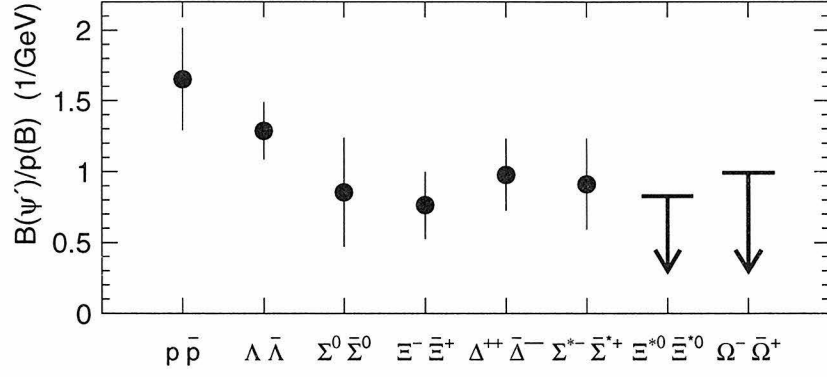


Figure 8.2: The ratio $\mathcal{B}(\psi' \rightarrow B \bar{B}) / p_B$. Under SU(3)-flavor, this ratio should be a constant.

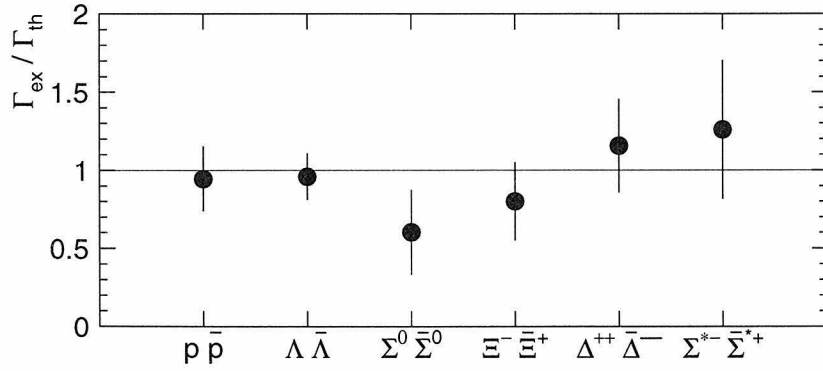


Figure 8.3: Comparison of $\psi' \rightarrow B \bar{B}$ to predictions from perturbative QCD. Horizontal line is $\Gamma_{ex} / \Gamma_{th} = 1.0$.

8.2 Angular Distributions

In $J/\psi \rightarrow B\bar{B}$, several of the modes had angular distributions that were distinctly different from the expected $1 + \cos^2 \theta$ of spin-1/2 systems. The J/ψ angular distributions were used for Monte Carlo generation in the ψ' system, and the uncertainty in the distribution was used as part of the systematic error on efficiency (Section 7.1). Of the six modes that have a definite measurement, only two, $p\bar{p}$ and $\Lambda\bar{\Lambda}$ have enough signal/noise to examine the angular distribution. This is shown in Figure 8.4. The plots are fit to $\beta + \gamma \cos^2 \theta$. $\alpha_{B\bar{B}}$ is obtained by dividing γ by β . From this fit, $\alpha_{p\bar{p}} = .27 \pm 1.0$ and $\alpha_{\Lambda\bar{\Lambda}} = .66 \pm .89$. The error bars essentially cover the entire possible range of distributions, thus very little can be said. More statistics are required to improve these measurements.

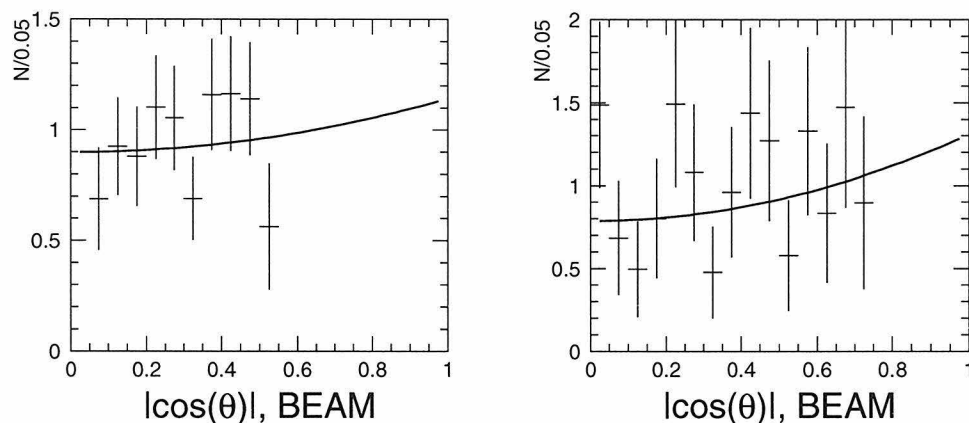


Figure 8.4: $|\cos \theta|$ in **left:** the $p\bar{p}$ system, and **right:** the $\Lambda\bar{\Lambda}$ system. Both distributions are fit to $\beta + \gamma \cos^2 \theta$.

8.3 Conclusions

The branching ratios for $\psi' \rightarrow \{p\bar{p}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0, \Xi^-\bar{\Xi}^+, \Delta^{++}\bar{\Delta}^{--}, \text{ and } \Sigma^{*+}\bar{\Sigma}^{*-}\}$ have been measured with varying statistical precision. Upper limits are quoted for $\psi' \rightarrow$

$\{\Xi^{*0}\bar{\Xi}^{*0}$ and $\Omega^-\bar{\Omega}^+\}$. The results obtained agree with the factorization hypothesis, with SU(3)-flavor predictions, and with predictions from perturbative QCD.

Appendix A The CODEMAN Code Management System

In any collaborative physics effort, the maintenance of the simulation and analysis code-base is difficult. When a collaboration grows to include ~ 150 physicists at a dozen institutions in two hemispheres, code maintenance can become a sysiphean task.

The code management system for the BES collaboration was developed to allow code updates to be tested on the various computing platforms in use by the collaboration. Over the years 1991 – 1998, the platforms in use included: IBM-AIX, DEC-OSF, VMS, ULTRIX, IBM-VM, HP-UX, and LINUX. Code updates had to be tested on each working system, and only after all tests were passed were the updates allowed into the working code-set.

As users do not normally have access to all the various systems in use in the collaboration, it was unreasonable to expect each user to test his or her modification on all possible systems. To this end, the CODEMAN system was developed. CODEMAN allows users to submit a modification via e-mail, and coordinates the tests on the various computing platforms.

The actual path of a code update is shown in Figure A. The links in the figure are as follows:

1. The user sends an update to the Primary CODEMAN server, hereafter called the Primary.
2. The Primary sends a copy of the proposed modification to each of several Secondary servers, with the instruction to test-compile the update.
3. Each Secondary test-compiles the update and sends the result back to the Primary. In the case where compilation fails, a full traceback is returned along

with the status message.

4. If all Secondaries have replied that the proposed update has compiled without error, the Primary sends a message to instruct the Secondaries to install the update into the working code-set.
5. The Secondaries, having installed the update, reply to the Primary, indicating completion.
6. Once the Primary has received an affirmative on installation from each Secondary, the original user is notified that the code has been installed into the working code-base.

If, however, one or more of the Secondaries experience a failure in compilation in step 3, the Primary skips steps 4 and 5, notifies the user of the failure, and provides the traceback sent by each system where compilation has failed. The user must then fix the problem and re-submit the code.

A.1 Communicating with the Primary

Users can communicate only with the primary server. All communication between users and the CODEMAN system is via RS-232 format mail messages. Each of these messages can contain multiple requests, placed sequentially. All requests are in the body of the mail message; the subject line is ignored entirely. Requests consist of one or more lines in the message, the first line of the request beginning with a colon ":" followed by a request keyword.

The request keywords allowed by the CODEMAN system are as follows:

NEW Create an entry for the $\langle \text{filespec} \rangle$ code module in the primary's database and reserve the file for the user. The $\langle \text{Package} \rangle$ and $\langle \text{Comment} \rangle$ fields are required.

Format: `:NEW  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

CO (Mnemonic for CHECKOUT) Attempt to reserve a code module for modification.

If the $\langle \text{filespec} \rangle$ module is not already reserved, the user will receive a copy of

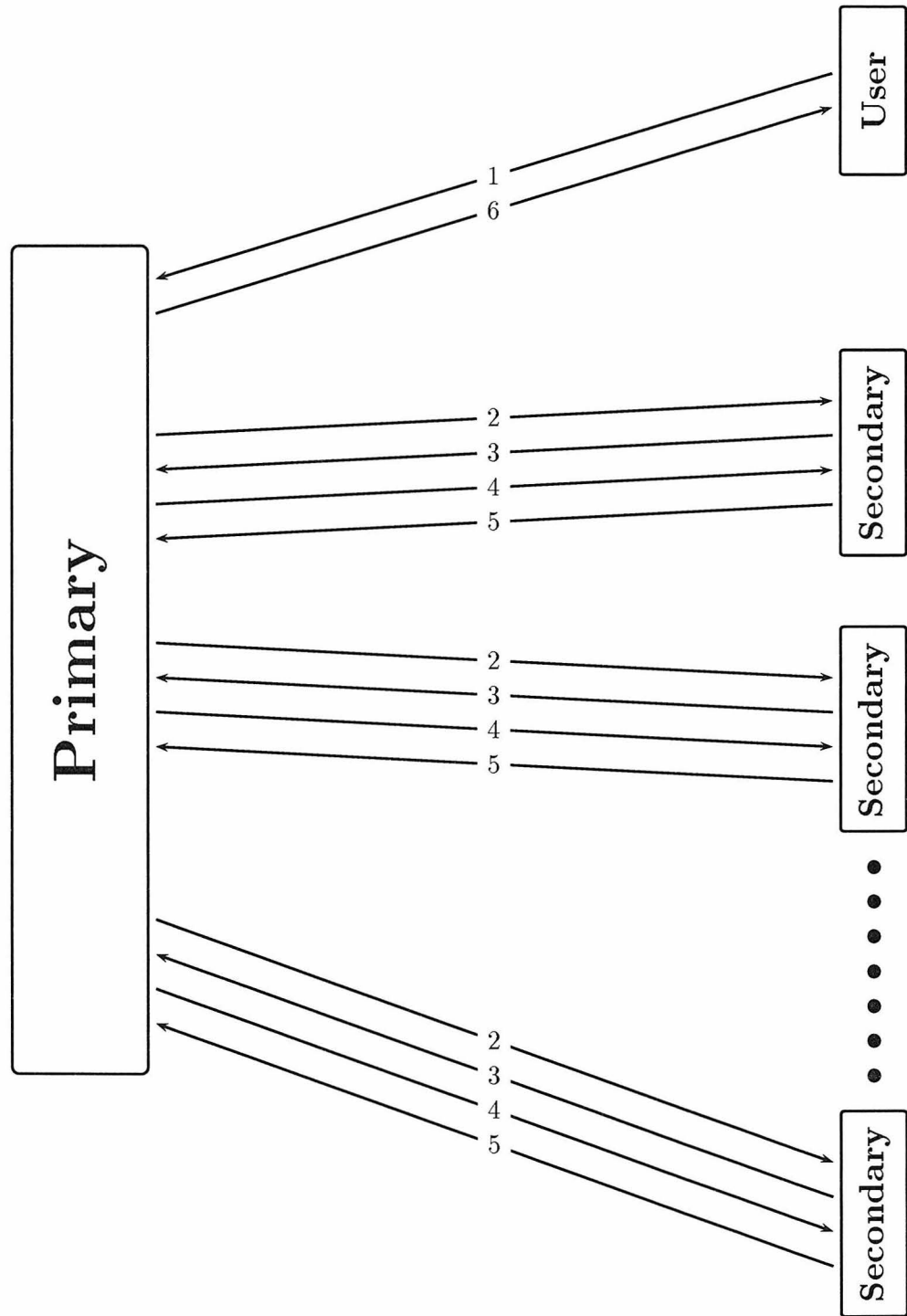


Figure A.1: The message paths for an update to the BES working code-set. Path numbers are discussed in the text.

the module from the master server. If the module is reserved by another user, the first user will be informed of the fact. The $\langle \text{Package} \rangle$ and $\langle \text{Comment} \rangle$ fields are required.

Format: `:CO  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

FETCH Retrieve a copy of the latest version of the $\langle \text{filespec} \rangle$ module from the primary server. This does *not* reserve the file. The $\langle \text{Package} \rangle$ field is required.

Format: `:FETCH  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

CI (Mnemonic for CHECKIN) Submit the $\langle \text{filespec} \rangle$ module to the primary system for test-compilation and eventual installation. The $\langle \text{Package} \rangle$ and $\langle \text{Comment} \rangle$ fields are required.

Format: `:CI  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

`:BEGIN`

as many random lines of
badly structured code as needed
go in here

`:END`

KILL Delete a file from the primary server. If $\langle \text{Package} \rangle$ is either BESCDE or UPGRADE, the module is removed from the object library. The $\langle \text{Package} \rangle$ and $\langle \text{Comment} \rangle$ fields are required.

Format: `:KILL  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

CANCEL Un-reserve the $\langle \text{filespec} \rangle$ module. This is the opposite of CI. The $\langle \text{Package} \rangle$ and $\langle \text{Comment} \rangle$ fields are required.

Format: `:CANCEL  $\langle \text{filespec} \rangle$  :PACKAGE  $\langle \text{Package} \rangle$   $\langle \text{Comment} \dots \rangle$`

QUERY Query the status of portions of the CODEMAN system. Users can examine the status of the CODEMAN queue, the status of any file in the CODEMAN system, or any pending actions for a particular user.

Format: :QUERY JOBS

Format: :QUERY NAME $\langle$ filespec $\rangle$ [$\langle$ filespec $\rangle$...]

Format: :QUERY USERID $\langle$ user $\rangle$

Format: :QUERY STATUS NOT_RESERVED

Format: :QUERY STATUS RESERVED

Format: :QUERY STATUS PENDING

HELP Receive a copy of the CODEMAN system's user documentation

Valid $\langle$ Package $\rangle$ s will be listed in the next section.

A.2 Internal CODEMAN Communication

All internal messages between the Primary and the Secondaries are tagged through the subject line of the email message. The Primary communicates to the Secondaries with a subject line of the following format:

Subject: :U $\langle$ username $\rangle$ $\langle$ Directive $\rangle$:PACKAGE $\langle$ Package $\rangle$

The $\langle$ username $\rangle$ tag is there mainly for the Secondary site administrator's information. Valid $\langle$ Directive $\rangle$ s are:

:COMPILE $\langle$ groupid $\rangle$ Test-compile a set of updates and report on the results to the Primary. $\langle$ groupid $\rangle$ is a unique name that defines the code update.

:INSTALL $\langle$ groupid $\rangle$ Install a previously compiled set of updates into the correct library.

:NEW $\langle$ filespec $\rangle$ Create an entry for $\langle$ filespec $\rangle$ in the correct library structure.

:KILL $\langle$ filespec $\rangle$ Delete $\langle$ filespec $\rangle$ from the appropriate library structure.

The current valid $\langle$ Package $\rangle$ identifiers are BESBIN (executable scripts), BESCONS (constants files), BESDOC (documentation), BESLEX (lexical parsers), BESLUM (luminosity monitor code), BWFIT (curve fitting package), JETSET (event simulation package), BESCODE (main codeset for BES system) and UPGRADE (codeset for the upgraded BES detector, post 1996).

A.3 CODEMAN UNIX Secondary

The UNIX Secondary server for the CODEMAN system was written over the period 1993–1995 at Caltech. The main engine is written in the Korn Shell, a standard tool shipped with UNIX operating systems. The main aspects of the server were set with the following design considerations:

1. The server should be modular and relatively easy to debug.
2. The server should contain *only* tools shipped with a certain “standard” UNIX operating system. “Standard” in this case means those tools defined in O’Reilly’s *Unix in a Nutshell* guide [30].
3. The server should work *without change* on any of the UNIX systems currently in use by the BES collaboration.

The first consideration is what prompted the programming of the secondary in the Korn Shell. The Korn Shell, or `ksh`, is a scripting language shipped with most standard UNIX systems (the only notable exception being Sun’s Solaris). Unlike other standard shells, `ksh` has the benefit of being a modular language. It accepts the definition of functions and subroutines, which greatly aided the development of this project.

The following definitions will be in effect for the rest of this appendix:

`$CMHOME` The working directory of the CODEMAN Secondary server.

`$BESROOT` The top level directory of the BES code-set.

A.3.1 codeman

`codeman` is a `cs`h script built as a wrapper to `codeman.main`. This routine must be located in the `$CMHOME` directory. It takes one argument, the name of the sender of the incoming message. It takes the sent e-mail message as standard input.

On startup, `codeman` sources `.cshrc` to set environment variables. This file is provided mainly for managers who are not familiar with the Korn shell. It then

passes standard input and `$argv` to `codeman.main` (see Section A.3.3). No other commands should be contained in this file.

A.3.2 `codeman.loc`

`codeman.loc` contains the local environment variables that control the behavior of the CODEMAN secondary. In general, these values should be customized for each secondary site. The variables defined here are:

Primary The internet e-mail address of the CODEMAN Primary server. In general use, this should be set to `codeman@slac.stanford.edu`.

local_czar The internet e-mail address of the local CODEMAN manager. This is to be set to the person who administrates the local secondary. It can, however, be set to point to more than one person by setting it as: `manager1@host1,manager2@host2`.

CODEMAN_DEBUG The current level of logging for the local secondary. In general use, this should be set to 0, no logging. Valid values for CODEMAN_DEBUG and their effects are:

- 0** no logging, and delete groups and temporary files when finished with them.
- 1** logging is enabled, temporary files and groups are kept, and a copy of the results of any action requested by the Primary are sent to `local_czar`.
- 2** logging is enabled, program trace is enabled, temporary files and groups are kept, and a copy of the results of any action requested by the Primary are sent to `local_czar`.
- > 3** logging is enabled, trace is enabled, and the location of Primary is changed to `local_czar`. This CODEMAN_DEBUG level is for testing of the CODEMAN secondary only, and should not be set in general use.

ver The current working release level of the BES code-set, *e.g.*, v85, v88.

BESVUP The current working release level of the BES code-set for the upgraded detector, *e.g.*, v100.

vax2unix Command alias for conversion system from VMS code format to local UNIX format. *e.g.*, **vax2rs**, **vax2osf**.

unix2vax Command alias for conversion system from local UNIX code format to VAX format. *e.g.*, **vax2rs**, **vax2osf**.

listext Extension for code listings produced by the local FORTRAN compiler. *e.g.*, **lst**, **l**.

A.3.3 **codeman.main**

The **codeman.main** file is by far the most complicated module in the CODEMAN UNIX Secondary system. On startup, this script creates a number of useful environment variables, executes **codeman.loc** and creates a safe execution **\$path**. The safe path is created to prevent the execution of some common Trojan Horse types of attacks. In 1998, the safe **\$path** is set to:

```
PATH=/bin:/usr/bin:$cmhome:/usr/local/bin:$BESROOT/bin
```

After setup, the incoming mail message subject line is parsed according to the rules detailed in Section A.2, and the proper action is determined. The messages which correspond to a Checkout, Cancel, Query, and Fetch are ignored. Only Compile, Install, New, and Kill are recognized by the UNIX secondary.

Also determined is the proper destination of the directive. This is determined by the **:PACKAGE** tag on the Subject line. If the destination is invalid, the script terminates, and keeps all relevant log files.

Compile On the receipt of a Compile directive, **codeman.main** creates a new directory for test compilation of the code under the **\$CMHOME/groups** directory. The directory name is the tracking number for the current code group. The incoming message is parsed into code modules, and these are converted from the standard VAX

format to the local UNIX format with the `vax2unix` alias defined above. The code is now test-compiled.

Test compilation can be relatively complicated. Any include file that is being checked in must be cross-compiled against *every* code module that includes it. For some include files in the BES code-set, the number could reach to over one hundred. If any submitted or cross-compiled module causes a fail in compilation, the entire code group is rejected, and compile logs are returned to the CODEMAN Primary.

A.3.4 `mail.parse`

`mail.parse` separates an RFC-822 mail folder into single messages and passes them to the `codeman` command. Several environment variables are defined in `mail.parse`:

`primes` Defines who is an authorized user of the CODEMAN system. Normally `primes` is set to include the primary server, and a few different local managers. Regular users should *not* be included in this environment variable.

`besmgr` The e-mail address of the local manager. This is used when the script detects an error situation: *e.g.*, a message is sent to the CODEMAN secondary by an unauthorized user.

`mailfile` The file to check for incoming mail to the codeman secondary. Typically, this is defined as `/usr/spool/mail/codeman`.

`codepath` The location of `$CMHOME`.

`infile` The place to store the working copy of the incoming `mailfile`.

`maillock` The location of `mail.lock`, defined above.

`codelock` The location of the `codeman.lock` file, defined below.

`statfile` The location of the CODEMAN status file, defined in Section A.3.6.

`errorlog` The location of the `mail.parse` error log.

`autooff` File, that if present, switches the CODEMAN system to manual operation.

This should only be used for testing purposes.

At startup and after the instantiation of the environment variables detailed above, `mail.parse` determines the existence of the `maillock` file. If this file is detected, the script will immediately exit. This is to prevent the attempted execution of more than one CODEMAN process at a time.

Immediately thereafter, the BES environment variables are instantiated by sourcing the `$BESROOT/site/cshrc.loc` file. The contents of this file vary from site to site. Other bookkeeping work is now done, including updating the `statfile` log and determining whether CODEMAN is in manual mode. If CODEMAN is in manual mode, the script notes the fact in `statfile` and exits.

The script then checks for the existence of an incoming mail message by determining the existence of the file pointed to by the `mailfile` variable. If this file does not exist, `mail.parse` deletes the `mail.lock` file and exits. If there is an incoming message, the script moves `mailfile` to `infile` and starts processing. Each message in `infile` is extracted, checked for valid primary source, and sent to the `codeman` script. If the incoming mail message either comes from an inappropriate source, or is in an incorrect format for the CODEMAN system, an error message is generated and sent to the `besmgr`.

If the message is valid, it is passed to `codeman` script. `mail.parse` then waits until `codeman` is finished processing and deals with the next message, if any.

When `mail.parse` completes the processing of `infile`, the `mail.lock` and `infile` files are removed and `mail.parse` exits.

A.3.5 `mail.cron`

`mail.cron` is an interface with the UNIX `cron` facility. In practice, it executes the `mail.parse` script every five minutes, sending standard output and standard error to `$CMHOME/tmp/mail.log`. For information on the `cron` facility, see the relevant UNIX man pages.

A.3.6 Directories

As detailed above in Section A.3.3, there are two directories that must be contained in the `$CMHOME` structure.

`$CMHOME/tmp` This directory is where all temporary files used by the CODEMAN system are stored. If neither a `codeman.lock` nor a `mail.lock` file is present in the `$CMHOME` directory, the contents of `$CMHOME/tmp` can be purged.

`$CMHOME/groups` This directory is where all code that is being processed by the CODEMAN system is stored. Subdirectories are named as the code group that was received. If neither a `codeman.lock` nor a `mail.lock` file is present in the `$CMHOME` directory, the contents of `$CMHOME/groups` can be purged.

All other directories in the `$CMHOME` directory are present at the discretion of the local manager.

Bibliography

- [1] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).
- [2] J. E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974).
- [3] J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974).
- [4] R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).
- [5] C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions* (Addison-Wesley, Menlo Park, CA, 1983).
- [6] G. S. Abrams *et al.*, Phys. Rev. Lett. **33**, 1452 (1974).
- [7] The Beijing Electron-Positron Collider, Institute for High Energy Physics, promotional literature.
- [8] M. Sands, Technical Report No. SLAC-121, SLAC (unpublished).
- [9] M. H. Ye and Z. P. Zheng, in *Proceedings of the 1989 International Symposium on Lepton and Photon Interactions at High Energies*, Stanford University, edited by M. Riordan (World Scientific, Stanford, California, 1989), p. 122.
- [10] M. H. Ye and Z. P. Zheng, Int. J. Mod. Phys. A **2**, 1707 (1987).
- [11] M. E. B. Franklin *et al.*, Phys. Rev. Lett. **51**, 963 (1983).
- [12] G. Trilling, J. Phys (Paris) **43 C3**, 81 (1982).
- [13] E. Bloom, J. Phys (Paris) **43 C3**, 407 (1982).
- [14] W.-S. Hou and A. Soni, Phys. Rev. Lett. **50**, 569 (1983).
- [15] S. J. Brodsky, G. P. Lepage, and S. F. Tuan, Phys. Rev. Lett. **59**, 621 (1987).

- [16] Y. Chen, BES Analysis Memo (unpublished).
- [17] S. J. Brodsky and M. Karliner, Phys. Rev. Lett. **78**, 4682 (1997).
- [18] M. Chaichian and N. A. Törnqvist, Nucl. Phys. **B323**, 75 (1988).
- [19] J. Bolz and P. Kroll, Eur. Phys. J. **C2**, 545 (1998).
- [20] M. W. Eaton *et al.*, Phys. Rev. D **29**, 804 (1984).
- [21] D. Pallin *et al.*, Nucl. Phys. **B292**, 653 (1987).
- [22] P. Henrad *et al.*, Nucl. Phys. **B292**, 670 (1987).
- [23] J. Z. Bai *et al.*, (1998), submitted to Phys. Rev. D.
- [24] B. P. T.N. Pham and T. Truong, Phys. Lett. B **61**, 183 (1976).
- [25] G. J. Feldman and M. L. Perl, Phys. Rep. **33**, 285 (1977).
- [26] R. Brandelik *et al.*, Z. Phys. **C1**, 233 (1979).
- [27] A. Antonelli *et al.*, Phys. Lett. B **301**, 317 (1993).
- [28] H. J. Besch *et al.*, Z. Phys. **C8**, 1 (1981).
- [29] I. Peruzzi *et al.*, Phys. Rev. D **17**, 2901 (1978).
- [30] D. Gilly *et al.*, *UNIX in a Nutshell* (O'Reilly & Associates, Inc., Sebastopol, CA, 1992).