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Measurement of the angular distribution in $\bar{p}p \to \psi(2S) \to e^+e^-$

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Abstract

We present the first measurement of the angular distribution for the exclusive process $\bar{p}p \to \psi(2S) \to e^+e^-$ based on a sample of 6844 events collected by the Fermilab E835 experiment. We find that the angular distribution is well described by the expected functional form $\frac{dN}{d\cos\theta^*} \propto 1 + \lambda \cos^2\theta^*$, where θ^* is the angle between the

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antiproton and the electron in the center of mass frame, with $\lambda = 0.67 \pm 0.15$ (stat.) $\pm$ 0.04 (sys.) The measured value for λ implies a small but non zero $\psi(2S)$ helicity 0 formation amplitude in $\bar{p}p$, comparable to what is observed in J/ψ decays to baryon pairs.

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1 INTRODUCTION

The angular distribution of final state electrons from the process $\bar{p}p \to \psi(2S) \to e^+e^-$ can be written as

$$\frac{dN}{d\cos\theta^*} \propto 1 + \lambda\cos^2\theta^* \tag{1}$$

where θ^* is the angle between an electron and the $\overline{p}$ direction in the center-of-mass (CM) system.

The value of the angular distribution parameter, λ, is determined by the $\psi(2S)$ helicity formation amplitudes in $\bar{p}p$

$$\left|\frac{C_0}{C_1}\right| = \sqrt{\frac{1-\lambda}{1+\lambda}} \tag{2}$$

with the normalization condition $|C_0|^2 + 2|C_1|^2 = 1$.

In the limit of infinitely heavy charm mass, the hadron helicity conservation rule implies $\lambda = 1$ [1] for both J/ψ and $\psi(2S)$ decays to octet baryon anti-baryon pairs. Small but not negligible deviations from this prediction are expected based on constituent quark[3–5] or hadron mass effect[2] from $\mathcal{O}(v^2)$ and higher twist corrections to the QCD effective lagrangian, while electromagnetic corrections are expected to be negligible[3].

There are several measurements of λ in J/ψ decays to baryon anti-baryon pairs [6–10]. Only an indirect measurement (with large error) based on $\psi(2S) \to J/\psi\, X$, has been reported for λ at the $\psi(2S)$[11], and the uncertainty in $\psi(2S)$

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helicity formation amplitudes is the major source of systematic error on the $\psi(2S)$ branching ratios measured in E760 and E835[12].

The measurement of λ at the $\psi(2S)$ presented here is based on a sample of 6844 fully reconstructed $\bar{p}p \to \psi(2S) \to e^+e^-$ events with negligible ($< 1.5\%$) background.

2 E835 DETECTOR

The detector and the experimental technique are described in detail in [13]. Here we recall only the features relevant to the present work.

The experiment was located in the Antiproton Accumulator (AA) ring at Fermilab. The stochastically cooled antiproton beam ($\Delta p/p \approx 10^{-4}$) circulating in the AA passed through an internal hydrogen gas-jet target. The energy of the beam could be tuned to the charmonium resonance of interest, in this case the $\psi(2S)$. The E835 detector was a nonmagnetic spectrometer with cylindrical symmetry about the beam axis. The inner part of the detector contained a system for precise tracking of charged particles and four scintillator hodoscopes used variously for triggering and dE/dx measurement. Outside the inner detectors was a 16 cell threshold Čerenkov counter to identify electrons at the trigger level and offline; the Čerenkov covered the polar angle range from 15° to 65°. Two electromagnetic calorimeters used to measure the angles and energies of photons and electrons completed the detector. The Central Calorimeter (CCAL), composed of 1280 lead-glass Čerenkov counters arranged in a pointing geometry, covered the polar angle region from 11° to 70°. The energy resolution of the CCAL was $\sigma(E)/E = 6\%/\sqrt{E}(GeV) + 1.4\%$. Given the size of the target region (≈ 0.6 cm $\times\, 0.6$ cm $\times\, 0.6$ cm), the angular resolution for photons and electrons was 6 mrad in polar angle (θ) and 11 mrad in azimuth (ϕ). The Forward Calorimeter which covered the region from 3° to 11° is not used in this analysis. The luminosity was measured by a set of solid state detectors which counted recoil protons from elastic scatters at 90°.

The calorimeter channels were equipped with both ADC's to record pulse height and TDC's to record the time with respect to the trigger. The latter allowed signals from accidentals within the ADC gate to be ignored thus maintaining analysis efficiency at high luminosity. Signals were labelled ‘in-time’ if they were within ± 10 ns of the trigger, ‘out-of-time’ if they were outside this range. Channels with no timing information (the TDC threshold for small energy deposits was ≈ 50 MeV) were labelled ‘undetermined’.

3 EVENT SELECTION

Two sets of $\psi(2S)$ data from different data taking periods (1996-1997 and 2000) were used for this analysis.

The total luminosity for these data sets is 22.57 pb^{-1}: 10.09 pb^{-1} for the 1996-1997 run and 12.48 pb^{-1} for the 2000 run. The typical instantaneous luminosity during data taking was $\approx 2 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The hardware trigger was designed to accept events with a large-mass e^+e^- pair within the acceptance of the central calorimeter. It required two "electron tracks", defined by the appropriate coincidence of the inner and outer scintillator hodoscopes and the corresponding cell of the Čerenkov counter, and independently two large energy deposits (clusters) in CCAL separated by $> 90°$ in azimuth, with an invariant mass > 2.2 GeV.

Offline reconstruction of electron showers in the CCAL was performed clustering all hits in a 5×5 grid around a central block (*seed*) with at least 50 MeV energy deposit. If the "cluster mass" defined as

$$M_{cl} \equiv \sqrt{\left(\sum_{i=1}^{N_{blk}} E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2} \tag{3}$$

exceeded $M_{cl} > 120$ MeV, the cluster is considered as originating from two overlapping e.m. showers and it is split into two distinct clusters. The values for the seed energy (50 MeV) and the cluster splitting mass (120 MeV) are specific to the $\psi(2S) \to e^+e^-$ channel and were chosen to ensure reasonably uniform efficiency over the angular acceptance.

A preliminary selection, aimed at generic $e^+e^- X$ channels, required the two highest energy clusters in the calorimeter to have $M_{e^+e^-} >$2.6 GeV and to be associated to hits in the Čerenkov and in at least two of the three scintillators. To reject background, largely due to Dalitz decay or photon conversions of π^0s misidentified as single electrons, we calculate the likelihood ratio (EW) of the electron and background hypothesis (described in detail in [13]) and require that $EW_1 \times EW_2 > 10^{-4}$.

A four constraint kinematic fit to the hypothesis $\bar{p}p \to e^+e^-$ is performed on all events with two high energy clusters (candidate electron-positron pair). Events with no extra clusters were retained if the nominal χ^2 probability $Prob(\chi^2) > 10^{-5}$. Events with up to two extra clusters (either on-time or undetermined) were also retained if the $Prob(\chi^2) > 10^{-2}$. This was done to retain events where the high energy electron shower was not contained within

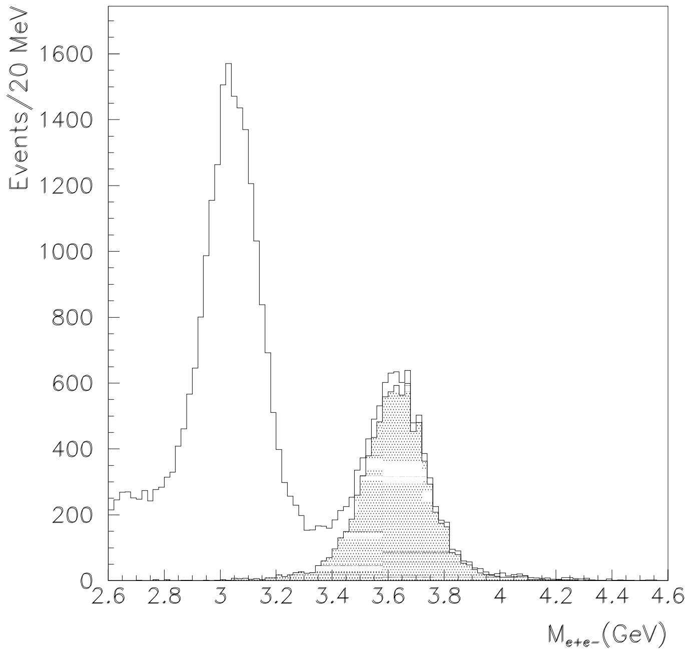

Fig. 1. Invariant mass distributions of $\bar{p}p \rightarrow e^+e^-\ (X)$ candidates. The shaded area represents events in the $\bar{p}p \rightarrow \psi(2S) \rightarrow e^+e^-$ sample.

the 5x5 grid or the electron had radiated a bremsstrahlung photon in the material in front of the calorimeter.

To avoid possible contamination from $\psi(2S) \rightarrow J/\psi\, X$ events, we finally require that $M_{e^+e^-} > 3.4$ GeV (see fig. 1).

The amount of material in front of the calorimeter and the size of the calorimeter counters both varied with angle. This means that the probability of bremsstrahlung and the number of low energy satellite clusters distinct from the high energy cluster could vary with angle.

A full Monte Carlo (MC) detector simulation based on GEANT [14] was performed to evaluate the efficiency correction as a function of $\cos\theta^*$ (shown in fig. 2).

With the cuts chosen, the efficiency is essentially independent of angle.

To ensure uniform efficiency we limit our acceptance to $|\cos\theta^*| < 0.58$, where the efficiency ranges between 0.83 and 0.93. The bin by bin differences depend mainly on the CCAL counters' geometry (including two dead channels) that are accurately modelled in the MC.

The statistical error on the efficiency due to the size of the MC sample (330,000 events) is negligible given the size of our data sample.

The final sample has 2391 and 4457 events from the 1996-1997 and 2000 runs,

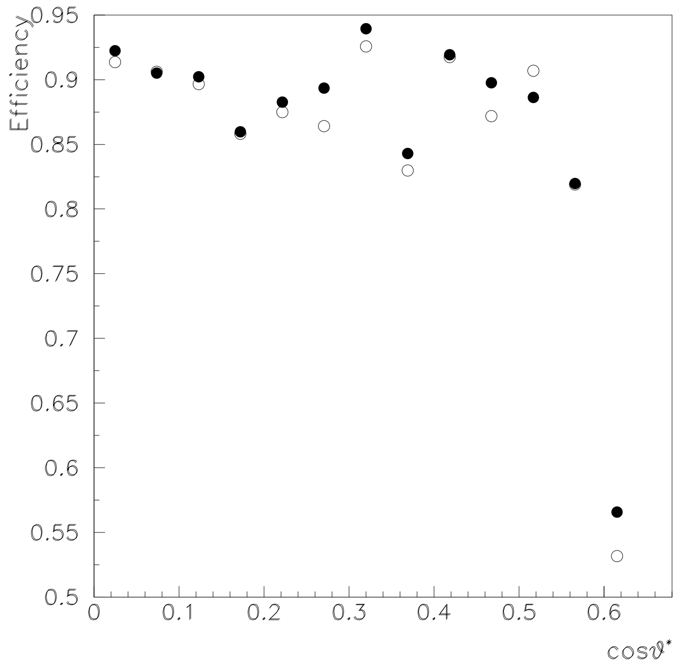

Fig. 2. Selection efficiency as a function of $\cos\theta^*$ for the 1996-1997 (open circles) and 2000 (filled circles) data sets.

respectively.

There are two possible sources of background events, the first from genuine electrons and positrons from $\psi(2S) \to J/\psi\, X$ events mis-classified as exclusive $\psi(2S) \to e^+e^-$ decays, the second from events where the electron and positron candidates are from non resonant hadronic events with π^0 Dalitz decays or photon conversions in the beam pipe.

The backgrounds from mis-classified events is estimated performing the same analysis on Monte Carlo samples of 100,000 $\psi(2S)$ decays to J/ψ η, J/ψ $\pi^0\pi^0$ and J/ψ π^+ π^-. We expect less than 1 % contamination and no subtraction is performed.

The background from mis-identified electron-positron pairs is measured using samples of data taken off-resonance, at center of mass energies 3576 MeV $< \sqrt{s} <$ 3660 MeV in 1996-1997 and $\sqrt{s}$=3666, 3705 and 3526 MeV in 2000. The mis-identified background contamination is less than 0.4 % in both runs, and also in this case no background subtraction is performed.

4 RESULTS

Binned likelihood fits were performed on the 1996-1997 and the 2000 data sets separately. Data were binned in bins of 2.1^o, corresponding to the average

	1996-1997 Data	2000 Data
Candidate events (0< $\cos\theta^*$ <0.58)	2391	4453
λ	0.59 ± 0.24	0.71 ± 0.18
Sources of systematic error		
Cluster seed threshold	±0.01	
$Prob(\chi^2)$	±0.01	
EW cut	–	
Cluster mass	±0.01	
$M_{e^+e^-}$	±0.04	
Total systematic	±0.04	

Table 1
Results for the two data sets.

CCAL block polar coverage ($1.52^o \sim 4.80^o$).

The angular dependence of the efficiency correction was taken into account on a bin by bin basis.

Results are summarized in table 1 and shown in fig. 3 for each data set.

The systematic errors were estimated by varying the cluster seed threshold and the cluster mass value used in electron shower reconstruction, the kinematic fit χ^2 probability, the EW cut, and the invariant mass cut used in event selection. The systematic error, expected to be common to both data sets, has been estimated separately on the two samples for each of the above sources to verify this assumption. No significant correlation was found between the systematics from different sources, and the total systematic error (0.04) has been evaluated adding in quadrature the contribution from all sources.

The bin by bin differences in efficiency are smaller than the statistical uncertainty of data in each bin, and the contribution to the systematic error due to the uncertainty in the efficiency correction is negligible compared to other sources.

Further details on the analysis and on the systematic error evaluation can be found in [16].

While the CCAL and Čerenkov remained the same for both sets of data, the amount of material in the inner detectors was about half as much for the 2000 data as for the 1996-1997 data, resulting in a small difference in the angle dependent efficiency correction (see fig. 2) between the two data sets.

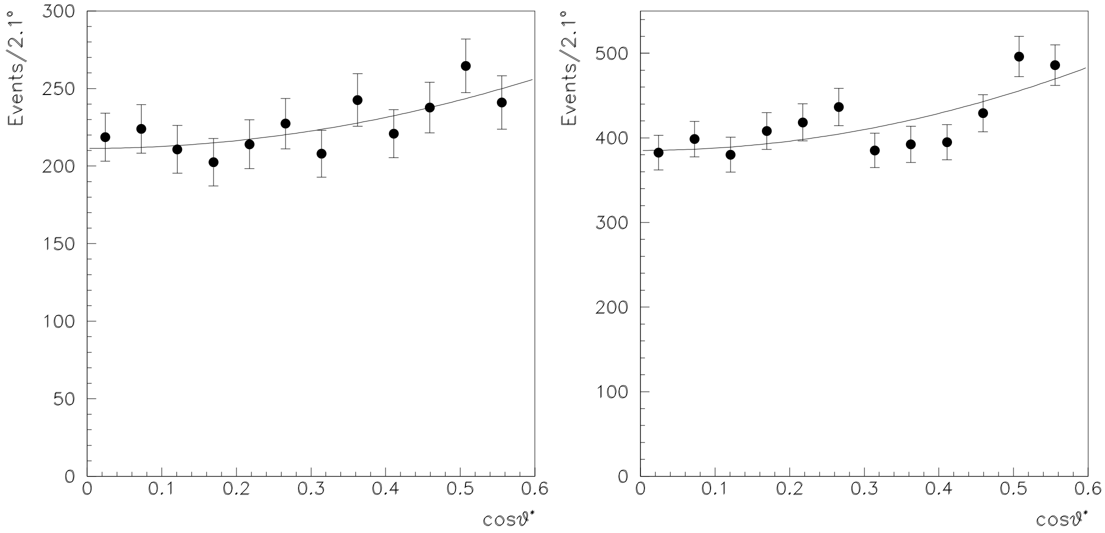

Fig. 3. Angular distributions after efficiency correction for the 1996-1997 (left) and 2000 data (right). The lines represent the likelihood fit to data.

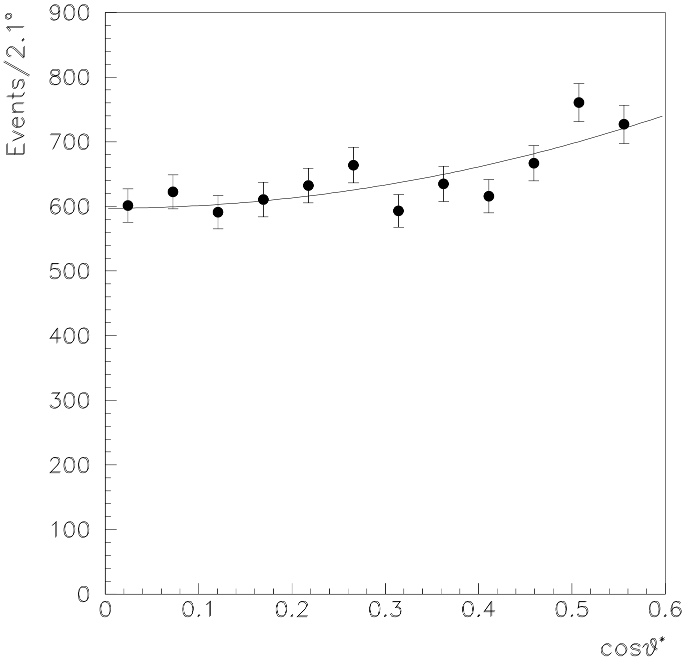

Fig. 4. Angular distribution from the combined data set. The line represents the fit result $\lambda = 0.67$.

Based on the Kolmogorov-Smirnov test [15] the probability for the $\cos\theta^*$ distributions measured in the two periods of data taking to be compatible with the same angular distribution is 74.4%. We therefore perform the likelihood fit to the combined data sets (shown in fig. 4) and obtain $\lambda = 0.67 \pm 0.15$(stat.)± 0.04 (sys.).

The corresponding ratio of the $\psi(2S)$ helicity formation amplitudes is $\left|\frac{C_0}{C_1}\right|_{\psi(2S)} = 0.44 \pm 0.12 \pm 0.03$.

Reference	$\lambda_{(J/\psi)}$	$\lambda_{(\psi(2S))}$
Predicted		
Claudson et al.[2] (eq. 9)	0.46	0.58
Carimalo[3] (eq. 24)	0.69	0.80
Measured		
MARK-II[8]	0.61 ± 0.23	–
DM2[9]	0.62 ± 0.11	–
BES[10]	$0.676 \pm 0.036 \pm 0.042$	–
This experiment	–	$0.67 \pm 0.15 \pm 0.04$

Table 2
Experimental results and theoretical predictions for the parameter λ in $J/\psi, \psi(2S) \to p\bar{p}$.

5 CONCLUSIONS

We have presented the first measurement of the angular distribution parameter λ at the $\psi(2S)$.

From this measurement we determine that the helicity amplitude ratio at the $\psi(2S)$ is

$$\left|\frac{C_0}{C_1}\right|_{\psi(2S)} = 0.44 \pm 0.12 \pm 0.03.$$

The value of λ measured at the J/ψ (table 2) is 0.66 ± 0.05 , which results in $\left|\frac{C_0}{C_1}\right|_{J/\psi} = 0.45 \pm 0.04$.

The ratio of the helicity amplitudes is the same within the errors at the J/ψ and $\psi(2S)$.

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