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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Measurement of B-$\bar{\mathrm{B}}$ Mixing at the Z

The ALEPH Collaboration*

Abstract

From more than 175,000 hadronic Z decays observed with the ALEPH detector at LEP, we select 823 events with pairs of leptons in the final state. From these we measure χ, the probability that a b hadron which is observed to decay originated as a $\bar{b}$ hadron. We find $\chi = 0.132^{+0.027}_{-0.026}$.

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19 December 1990

The ALEPH Collaboration

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1 Introduction

The level of mixing of b hadrons is sensitive to some of the remaining unmeasured parameters of the Standard Model, such as the mass of the top quark and elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix involving the coupling of the top quark [1,2]. Previous observations of B-$\bar{\text{B}}$ mixing [3,4] provided early indications that the top is heavy and have provided limits on unknown CKM matrix elements. This letter describes a measurement using the ALEPH detector of B-$\bar{\text{B}}$ mixing in 175,000 multihadronic events from e^+e^- annihilations at the Z resonance.

In e^+e^- annihilation b hadrons are always produced in pairs, such that initially there is one b hadron and one $\bar{b}$ hadron. Since it is not known which of the hadrons initially contained the b or $\bar{b}$ quark, one can select events in which both b hadrons are tagged at their decay time. This is done here by requiring that both b hadrons decay semileptonically, in which case a negative (positive) lepton indicates that a b ($\bar{b}$) hadron has decayed. Then if neither the b nor the $\bar{b}$ hadron has mixed (or if both have), one observes two leptons of opposite charge (*unlike-sign* dileptons), whereas if one of the b hadrons mixes, a *like-sign* lepton pair results. There are background processes, in which one (or both) of the leptons is from a charm decay or is a misidentified hadron, which also can produce events with lepton pairs of like and unlike-sign charges. The hard fragmentation and large mass of the b quark give separation between leptons from b hadron decay and background processes in both the momentum p and transverse momentum $p_\perp$ with respect to the nearest jet. An excess above background of hadronic events with two like-sign lepton candidates in the region of the p-$p_\perp$ plane dominated by leptons from b-hadron decays is a signal for B-$\bar{\text{B}}$ mixing.

2 The ALEPH Detector and Lepton Identification

The ALEPH detector has been described in detail elsewhere [5]. Here we present only a brief description of the parts of the apparatus used in this analysis. Charged tracks are measured over the range $|\cos\theta| < 0.95$, with θ the polar angle, by an inner cylindrical drift chamber (ITC) and a large cylindrical time projection chamber (TPC). These are immersed in a magnetic field of 1.5 Tesla and together measure the momenta of charged particles with a resolution, determined from dimuon events, of $\delta p/p^2 = 0.0008\,(\text{GeV/c})^{-1}$. The TPC also provides up to 330 measurements of the specific ionization ($\mathrm{d}E/\mathrm{d}x$) of each charged track. For electrons in hadronic events, the $\mathrm{d}E/\mathrm{d}x$ resolution which has been obtained is 4.6% for 330 ionization samples. The electromagnetic calorimeter (ECAL), which surrounds the TPC but is inside the coil of the superconducting solenoid, is used, together with the TPC, to identify electrons. It is a lead-proportional-tube calorimeter with cathode-pad readout which has a resolution for electromagnetic showers of $\delta E/E = 0.18/\sqrt{E}$, with E in GeV. It covers the angular region $|\cos\theta| < 0.98$ and is finely segmented into projective towers, each subtending an angle of less than 1° by 1°, which are read out in three stacks corresponding to thicknesses of 4, 9, and 9 radiation lengths. Muons are identified by the hadron calorimeter (HCAL), composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes, and the muon chambers, an additional 2 layers of streamer tubes surrounding the calorimeter. The tubes of the HCAL have a pitch of 1 cm and measure in 2 dimensions tracks from penetrating particles within the angular range $|\cos\theta| < 0.985$. The muon chambers cover the same angular range as the HCAL and provide a single 3-dimensional coordinate for charged tracks which penetrate the 7.5 interaction lengths of material between the chambers and the interaction point.

The selection of hadronic events is based on charged tracks. We require each event to have at least 5 "good" charged tracks, where a "good" charged track is one that passes through a cylinder of 2 cm radius and 20 cm length around the interaction point, has $|\cos\theta| < 0.95$, and has at least 4 TPC coordinates. The sum of the energies of these good charged tracks must be greater than 10% of the center-of-mass energy. This selection has an efficiency of 97.5%, and the background from $\tau\bar{\tau}$ and two-photon events has been estimated to be less than 0.25%. A total of 175,468 events pass the selection, with 23,705 from the 1989 data set and the remainder from the 1990 data set. The muon chambers and endcaps of the HCAL were not operational during the 1989 data taking period.

Jets are found using the scaled-invariant-mass clustering algorithm [6].[1] The inputs to the clustering algorithm are the good charged tracks with $p > 200\,\mathrm{MeV/c}$. We only accept events with at least two jets. The $p_\perp$ of a lepton is defined as the transverse momentum of the lepton with respect to the axis of the jet excluding the lepton.

The identification of leptons with the ALEPH detector has been discussed in detail elsewhere [7]. In this analysis electrons and muons are both required to have momenta greater than 3 GeV/c. Electrons are identified by comparing the ECAL energy deposits in the 4 towers around the extrapolation of each charged track with that expected for electrons of the measured momentum. The average depth of the energy deposition in the ECAL is also measured and required to be consistent within 3σ of the value expected for an electron. If at least 50 TPC ionization samples are available for an electron candidate, the candidate is rejected if the $\mathrm{d}E/\mathrm{d}x$ is more than 2.5 standard deviations below the expected value. The same algorithm as presented in Ref. 7 is used to remove photon conversions and Dalitz pairs from the prompt electron signal. Muons are identified using the pattern of fired planes in the HCAL and, for the 1990 data, the 3-dimensional coordinate of the muon chambers,

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[1] We use a value of $y_{\mathrm{cut}} = 0.02$ for the clustering algorithm.

which is considered by the algorithm as an additional layer of the HCAL. The technique of mapping the efficiency of the HCAL planes with $Z \to \mu^+\mu^-$ events used in Ref. 7 has been extended to the full angular range, and the same method has been employed to measure the muon-chamber efficiency in the 1990 data.

3 The Dilepton Sample

Events containing pairs of lepton candidates are selected and divided into two samples. Those for which the angle between the two lepton candidates is greater than 90° in space form the opposite-jet sample, and the others form the same-jet sample. The same-jet sample is not sensitive to B-$\bar{\mathrm{B}}$ mixing and is only considered further as a cross check of our understanding of the dilepton sample. There are five sources of observed two lepton events:

[PB-PB] both leptons are from the direct decay of b hadrons (primary b),

[PB-SC] one lepton is from direct b decay and the other is from the decay of a c hadron produced in the decay of a b hadron (secondary c),

[SC-SC] both leptons are from secondary c decays,

[PC-PC] both leptons are from the direct decay of a c hadron that does not result from a b hadron decay (primary c), and

[BACK] either one or both of the two lepton candidates is not from the decay of a heavy hadron or is a misidentified hadron.

The first three sources (PB-PB, PB-SC, SC-SC) are sensitive to B-$\bar{\mathrm{B}}$ mixing, while the remaining two (PC-PC, BACK) are not. As a measure of the mixing of b hadrons to $\bar{b}$ hadrons, one defines the probability χ that a hadron initially containing a b ($\bar{b}$) quark decays to a positive (negative) lepton:

$$\chi \equiv \frac{\Gamma(\bar{b}\,\mathrm{hadron} \to \ell^- X)}{\Gamma(\bar{b}\,\mathrm{hadron} \to \ell^\pm X)} = \frac{\Gamma(b\,\mathrm{hadron} \to \ell^+ X)}{\Gamma(b\,\mathrm{hadron} \to \ell^\pm X)}, \tag{1}$$

where Γ is the time-integrated rate. This definition includes all produced b mesons, neutral and charged, and baryons, and it assumes that CP violation in the B^0-$\bar{\mathrm{B}}^0$ system is negligible. The fraction of like-sign events in the PB-PB sample is then $2\chi(1-\chi)$, where it is assumed that the two b hadrons are produced incoherently[2] and therefore undergo mixing without interference. Similarly the fraction of like-sign events in the PB-SC sample is $0.91 \cdot (1 - 2\chi(1-\chi)) + 0.09 \cdot (2\chi(1-\chi))$,

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[2] In each event, the quantum numbers of the pair of b hadrons are arbitrary. This is in contrast to the situation in $\Upsilon(4S) \to B^0\bar{B}^0$, in which the two mesons are in the state $C = -1$, $J = 1$.

where it is assumed that the number of c hadrons produced per b-hadron decay is 1.08 ± 0.14 [8] and that 9% of these contain $\bar{c}$. The SC-SC sample behaves similarly to the PB-PB sample although a small correction due to $\bar{c}$ production is taken into account. The PC-PC events are assumed to contribute only to unlike-sign events, as D^0-$\bar{D}^0$ mixing is negligible [9]. Events containing background leptons (the BACK sample) contribute to both the like and the unlike-sign samples.

Figure 1(a) shows the distribution of the lower of the two lepton momenta in the opposite-jet dilepton event sample together with a Monte Carlo prediction[3] decomposed into the contributions of the five sources mentioned above. Figure 1(b) shows a similar distribution for the lower of the two $p_\perp$ of each event in the same sample after the requirement of $p > 5.0$ GeV/c for both leptons.

Those parts of the lepton p-$p_\perp$ spectrum with the highest purity in primary b-hadron decays contain the most information on B-$\bar{\text{B}}$ mixing. The probability, $Prob(p, p_\perp)$, that a lepton candidate originated in the primary decay of a b hadron has been determined by a fit, similar to that of Ref. 7, of the p-$p_\perp$ distribution of the lepton candidates, in which the semileptonic branching ratio of the b hadrons and fragmentation parameters of the b-quark were allowed to vary freely. The Monte Carlo simulation was used to predict the shapes of the p-$p_\perp$ distributions for the various components of the lepton spectrum, Standard-Model production rates were assumed for $b\bar{b}$ and $c\bar{c}$, and the branching ratios for $b \to c \to \ell$ and $c \to \ell$ were taken from experiments at lower energies [11,12]. The results of this fit are in good agreement with our earlier result [7]. Figure 1(c) shows the distribution in opposite-jet dilepton events versus the smaller of the two probabilities $Prob_1$ and $Prob_2$, comparing data with the Monte Carlo simulation.

The probabilities for the single lepton candidates to be from each of the four sources (PB, SC, PC, background) are used to infer the composition of the dilepton sample. To a first approximation, the probability function for the dileptons factorizes into a product of the probabilities of the individual lepton candidates. For example, within any region in the plane $Prob_1$-$Prob_2$ (or equivalently, for any region delineated by cuts on p and $p_\perp$ of the two lepton candidates), the number of dilepton events in the PB-PB class is predicted by

$$N_{\text{PB-PB}} = \left(\sum_j Prob^s_j / N_{\text{had}} \right)^2 N_{\text{had}} \cdot C_{PB-PB} \,, \qquad (2)$$

where $Prob^s$ is the probability that the lepton in a single lepton event is from primary b decay, and the sum runs over all single lepton candidates in the region of interest. N_{had} is the number of hadronic events, and C_{PB-PB} is a correction factor that takes into account correlations in acceptance and production which has been

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[3] We use a Monte Carlo event generator based on the JETSET-6.3 program, with the parton-shower option, of Ref. [10].

Leptons	Sample	Unlike-Sign			Like-Sign		
		Data	Prediction		Data	Prediction	
			$\chi = 0$	$\chi = 0.13$		$\chi = 0$	$\chi = 0.13$
ee	Opposite Jet	76	83	69	22	19	33
ee	Same Jet	20	21	21	0	1	1
$e\mu$	Opposite Jet	131	162	137	71	45	70
$e\mu$	Same Jet	44	49	49	11	10	10
$\mu\mu$	Opposite Jet	87	93	83	53	42	52
$\mu\mu$	Same Jet	33	29	29	11	8	8
Total	Opposite Jet	294	338	289	146	106	155
Total	Same Jet	97	99	99	22	19	19

Table 1: The number of hadronic events with two leptons, where each lepton is required to have $p > 5.0\,\mathrm{GeV/c}$ and $p_\perp > 1.0\,\mathrm{GeV/c}$. The samples are broken down according to the number with like and unlike-sign charges. Also shown is the prediction of the number of dilepton events in each category, as derived from Eqn. 2 for $\chi = 0$ and $\chi = 0.13$.

estimated from a sample of 400,000 fully simulated Monte Carlo events. There are different correction factors for each of the five dilepton classes and all are in the range between 0.6 and 1.6. This method has been found to predict well the size and composition of the dilepton sample in independent Monte Carlo samples.

4 Measurement of χ

A value for χ can be extracted from the data by considering only lepton candidates with high p and high $p_\perp$ and subtracting the predicted background. By selecting lepton pairs in which both lepton candidates satisfy the cuts $p > 5.0\,\mathrm{GeV/c}$ and $p_\perp > 1.0\,\mathrm{GeV/c}$, we obtain a sample with a PB-PB purity of 65%. Table 1 shows the number of events in the opposite and same-jet samples with a breakdown according to lepton type and the number with like and unlike-sign charges. Also shown are the predictions made according to Eqn. 2 with the assumptions $\chi = 0$ and $\chi = 0.13$. The excess of like-sign events in the opposite jet sample in the data as compared to the $\chi = 0$ prediction is clear evidence for B-$\bar{\mathrm{B}}$ mixing.

To subtract the background (the BACK sample), it is necessary to know how it contributes to the unlike and like-sign samples. The majority of background events results from pairing one heavy-flavor lepton with one background track. We consider events with one lepton candidate with $p > 5.0\,\mathrm{GeV/c}$ and $p_\perp > 1.0\,\mathrm{GeV/c}$

Source	high p-$p_\perp$	$Prob_i > 0.1$
PB-PB	63.7%	50.5%
PB-SC	18.0%	19.9%
SC-SC	2.3%	2.4%
PC-PC	2.5%	5.8%
BACK	13.5%	21.4%

Table 2: The prediction for the fractions of dileptons from the various sources.

and count the number of tracks in the opposing jets which satisfy the same cuts on p and $p_\perp$, and all of the kinematical acceptance cuts for either e or μ identification, but are explicitly not identified as leptons. Of these background tracks, $(41.7 \pm 1.0)\%$ have the same sign as the lepton candidate. We assume that the proportion of unlike-sign to like-sign pairs in the BACK sample follows this prediction. We also take into account the fact that a positive hadron has a 6% higher probability than a negative hadron to be misidentified as a muon. This difference has been measured from our data using late showering hadrons identified in the HCAL.

With the background subtracted, and using the prediction of Eqn. 2 for the composition of the remaining event sample, χ can be derived from the number of like and unlike-sign pairs. The prediction of the fractions of dilepton events from the various sources is shown in Table 2. We find $\chi = 0.120 \pm 0.030$, where the error is statistical only.

The statistical accuracy on χ can be enhanced by considering the joint probability that both leptons result from primary b decay. We make a subdivision in the plane $Prob_1$-$Prob_2$ and extract the value of χ from a binned maximum-likelihood fit to the like-sign and unlike-sign distributions. This method allows the amount of data to be increased without diluting the weight of those bins with the highest purity in PB-PB events. The log likelihood as a function of χ is given by

$$\log\mathcal{L} = \sum_{ee,e\mu,\mu\mu} \left\{ \sum_j^{\text{like sign}} \log\left[\frac{x_j(\chi)^{n_j} e^{-x_j(\chi)}}{n_j!}\right] + \sum_j^{\text{unlike sign}} \log\left[\frac{x_j(\chi)^{n_j} e^{-x_j(\chi)}}{n_j!}\right] \right\}, \quad (3)$$

where n_j is the observed number of dileptons in bin j of the probability plane and $x_j(\chi)$ is the expected number of events in bin j for a given value of χ. To reduce the level of background, we restrict the fit to the region $Prob_i > 0.1$. This cut rejects 69% of the BACK events but only 13% of the PB-PB events, as can be seen in Figure 1(c), and the remaining sample contains 50% PB-PB events. We use 36 bins of equal size in the plane. Table 3 shows the numbers of observed like and unlike-sign dilepton events in this region together with the predicted numbers of events for two assumptions on χ. Shown in Table 2 is the prediction for the fractions of

Leptons	Unlike-Sign			Like-Sign			Fitted χ
	Data	Prediction		Data	Prediction		
		$\chi = 0$	$\chi = 0.13$		$\chi = 0$	$\chi = 0.13$	
ee	143	151	133	67	54	72	$0.109^{+0.036}_{-0.034}$
$e\mu$	245	286	260	136	125	150	$0.128^{+0.034}_{-0.029}$
$\mu\mu$	132	144	160	100	75	92	$0.177^{+0.069}_{-0.054}$
Total	520	597	537	303	254	314	0.132 ± 0.022

Table 3: The numbers of dileptons observed in the region $Prob_1 > 0.1$, $Prob_2 > 0.1$. Also shown are the predictions with $\chi = 0$ and $\chi = 0.13$. The last column is the result of the maximum likelihood fit over this region for each of the lepton subsamples and the total sample.

dileptons from the different sources in this sample. This procedure for measuring χ has been cross-checked by fitting Monte Carlo event samples generated with three different values of χ=0, 0.13 and 0.25, which give in all cases results which agree well with the input value.

The result of the fit is $\chi = 0.132 \pm 0.022$, where the error is statistical only. The fit results are summarized in Table 3 for the sum over all flavors of dileptons and separately for the ee, $e\mu$, and $\mu\mu$ dilepton samples. To check the sensitivity of the fit to the prediction of the backgrounds, we repeat the fit for $Prob_i > 0.35$. In this restricted region 74% of the dileptons are of the type PB-PB. The result is $\chi = 0.120 \pm 0.024$ in good agreement with the fit in the larger region. Both fit results agree well with that obtained from counting events at high p-$p_\perp$.

5 Systematic Errors

Systematic errors on χ result from errors in the prediction of the composition of the dilepton sample, which arise from uncertainties in the lepton identification efficiency and background, the semileptonic branching ratios of the c and b hadrons, and the fragmentation functions of the c and b quarks. The relative contributions of these systematic effects are estimated by varying each within its estimated error, producing in each case a new prediction for the composition of the dilepton sample and a new fitted value of χ. Correlations are accounted for which result from the fact that the sum of the predictions for the classes of dileptons must always add up to the number of observed events. The results of these effects on the value of χ are summarized in Table 4.

For the b semi-leptonic branching ration we use our own measurement of the

Source	Effect on χ
BR($b \to \ell\nu X$)	± 0.003
BR($b \to c \to \ell\nu X$)	$^{+0.014}_{-0.011}$
BR($c \to \ell\nu X$)	± 0.002
BR($\mathrm{b} \to \bar{\mathrm{c}}$)	± 0.0003
b fragmentation	± 0.004
c fragmentation	± 0.002
e, μ identification efficiency	± 0.0005
background	± 0.006
BACK charge distribution	± 0.001

Table 4: Sources of systematic errors and their contributions to the error on χ.

observed number of leptons. This gives a statistical error on BR($b \to \ell\nu X$) of ± 0.002; systematic effects, which also enter into the measurement of the b semileptonic branching ratio, such as background, fragmentation, and efficiency are accounted for separately in Table 4. For the other branching ratios we use BR($b \to c \to \ell\nu X$) $= 0.102 \pm 0.010$ [4] and BR($c \to \ell\nu X$) $= 0.090 \pm 0.013$.[5] The backgrounds to the lepton sample were varied according to their uncertainties as estimated in Ref. 7. The number of electrons from non-heavy flavor sources was varied by ±20%,[6] the number of hadrons misidentified as electrons was varied by ±20%, the number of muons from non-heavy flavor sources was varied by ±10%, and the number of hadrons misidentified as muons was varied by ±40%. The uncertainties in the fragmentation of heavy quarks were taken into account by varying the b and c fragmentation parameters according to our measurements from the single-lepton spectrum [7]. We also considered the uncertainties in the identification efficiencies for electrons (±3%) and muons (±3%), uncertainties in the proportions of like and unlike-sign dilepton events in the BACK sample, and a 10% uncertainty in the branching ratio of $b \to \bar{c}$. The probability that charged tracks in this sample have an incorrectly measured charge has been estimated from our data to be less than 10^{-4} per track, and the effect is negligible.

Adding all contributions to the systematic error, with correlations taken into

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[4] For the branching ratio $b \to c \to \ell\nu X$, we use the CLEO result obtained from their fit to the lepton spectrum from the $\Upsilon(4S)$ [11]. We introduce an additional systematic error of 7% by considering the expected differences in the B-meson mixture between Z decays and $\Upsilon(4S)$ decays, as explained in Ref. 7.

[5] For the c semileptonic branching ratio, we calculate an average of the electron and muon results from several experiments at PEP and PETRA [12].

[6] This differs from Ref. 7 due to the introduction of a vertex detector in ALEPH at the beginning of the 1990 run, which resulted in a larger uncertainty in the background from photon conversions.

account, we obtain

$$\chi = 0.132 \pm 0.022\,^{+0.015}_{-0.012}\,. \tag{4}$$

The systematic errors are similar in the analysis based on counting dilepton events for $p > 5.0\,\mathrm{GeV/c}$ and $p_\perp > 1.0\,\mathrm{GeV/c}$, from which we obtain $\chi = 0.120 \pm 0.030\,^{+0.017}_{-0.014}$. Note that the division of the sample into bins in the fit analysis results in a slightly smaller systematic error on χ, as compared to the counting analysis, despite the lower average purity of the total sample.

6 Conclusion

Using multihadronic Z events with pairs of lepton candidates, we have measured the probability χ that a hadron initially containing a $b(\bar{b})$ quark decays to a positive (negative) lepton to be $\chi = 0.132^{+0.027}_{-0.026}$. This observed value of χ is a combined effect of mixing of the B_d^0 and B_s^0 mesons according to

$$\chi = f_d\chi_d + f_s\chi_s\,, \tag{5}$$

where f_d and f_s are the fractions of leptons from B_d^0 and B_s^0 present in the sample. We assume, $f_u = f_d = 0.375$, $f_s = 0.15$, and $f_{\mathrm{baryon}} = 0.10$, which derives from the default parameters of the JETSET 6.3 program [10], assuming that the semileptonic branching ratios of the b hadron species are equal. Figure 3 displays, in the χ_d-χ_s plane, the range allowed by our measurement of χ for this assumption on f_d and f_s. Also plotted is the combined measurement on B_d^0 mixing from the ARGUS and CLEO experiments, $\chi_d = 0.17 \pm 0.04$ [4], and the prediction of the Standard Model. From our measurement of χ combined with the measurement of χ_d by ARGUS and CLEO we find $\chi_s = 0.46 \pm 0.27$, under the assumption that $f_d = 0.375 \pm 0.05$ and $f_s = 0.150 \pm 0.05$ and that the semileptonic branching ratios of the B_d^0 and B_s^0 are equal within 20%. This result for χ_s is close to the maximum allowed value, $\chi_s = 0.5$, and excludes $\chi_s = 0$ at the 95% confidence level.

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Figure 1: The number of hadronic events with two leptons in opposite jets versus (a) the minimum of the momenta of the two leptons, (b) the minimum of the transverse momenta of the two leptons (with $p > 5\,\mathrm{GeV/c}$ for both leptons), and (c) the minimum of the two probabilities that the lepton are from the primary decay of a b hadron. Also shown are the predictions of the Monte Carlo for the various components of signal and background.

Figure 2: The distribution of $Prob_1$ versus $Prob_2$ for (a) PB-PB events, (b) PB-SC events, (c) PC-PC events, and (d) BACK events. The cut $Prob_i > 0.1$ is indicated in the figure.

Figure 3: χ_d versus χ_s for our value of χ, assuming $f_d = 0.375$ and $f_s = 0.15$. Also shown are the combined result of ARGUS and CLEO, and in grey the region allowed by Standard Model, as given in Ref. [2].

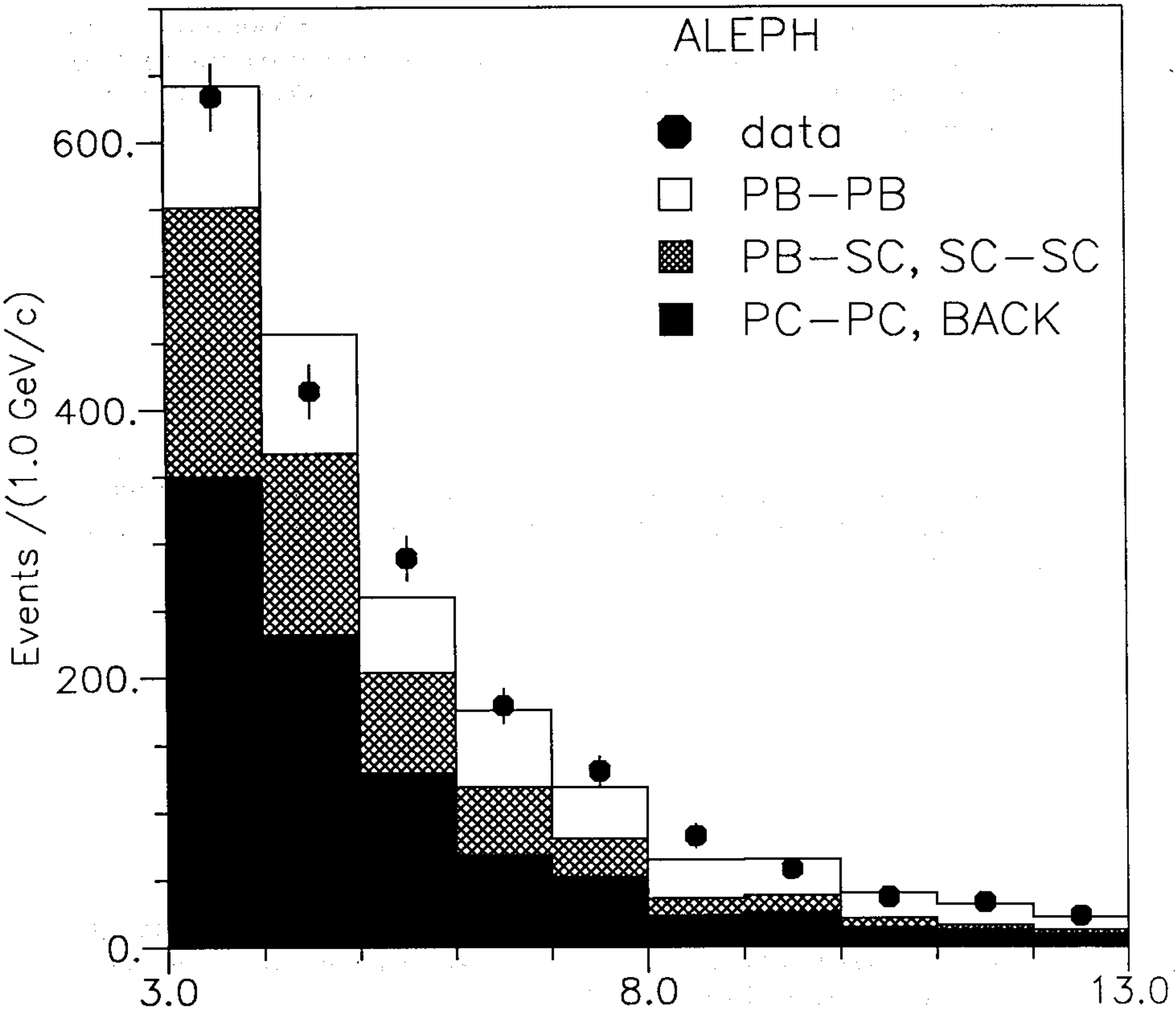
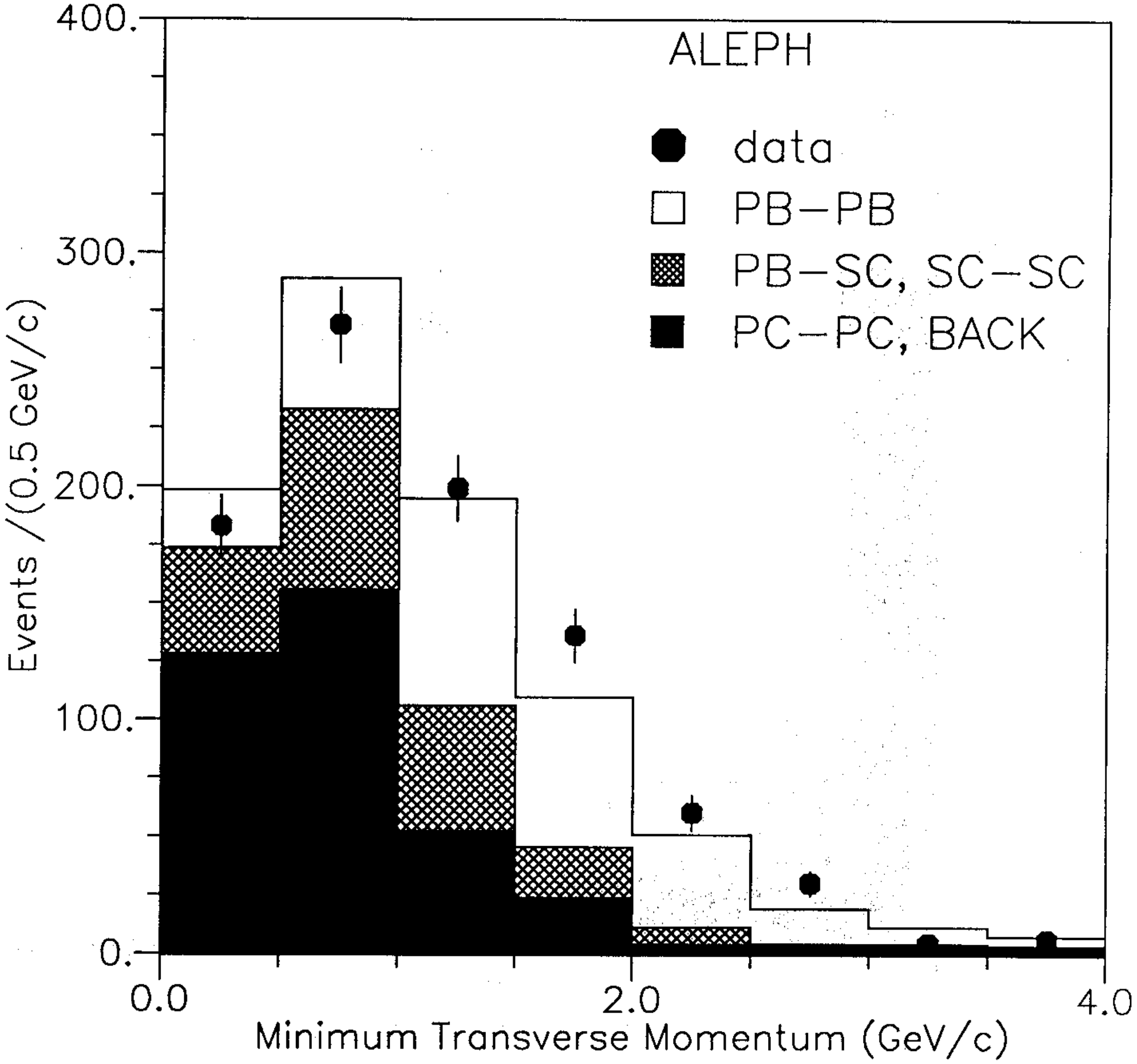

ALEPH
● data
☐ PB−PB
▨ PB−SC, SC−SC
■ PC−PC, BACK
Events /(1.0 GeV/c)
600.
400.
200.
0.
3.0
8.0
13.0
Minimum Momentum (GeV/c)

Fig. 1(a)


ALEPH
data
PB−PB
PB−SC, SC−SC
PC−PC, BACK
Events /(0.5 GeV/c)
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200.
100.
0.
0.0
2.0
4.0
Minimum Transverse Momentum (GeV/c)

Fig. 1(b)

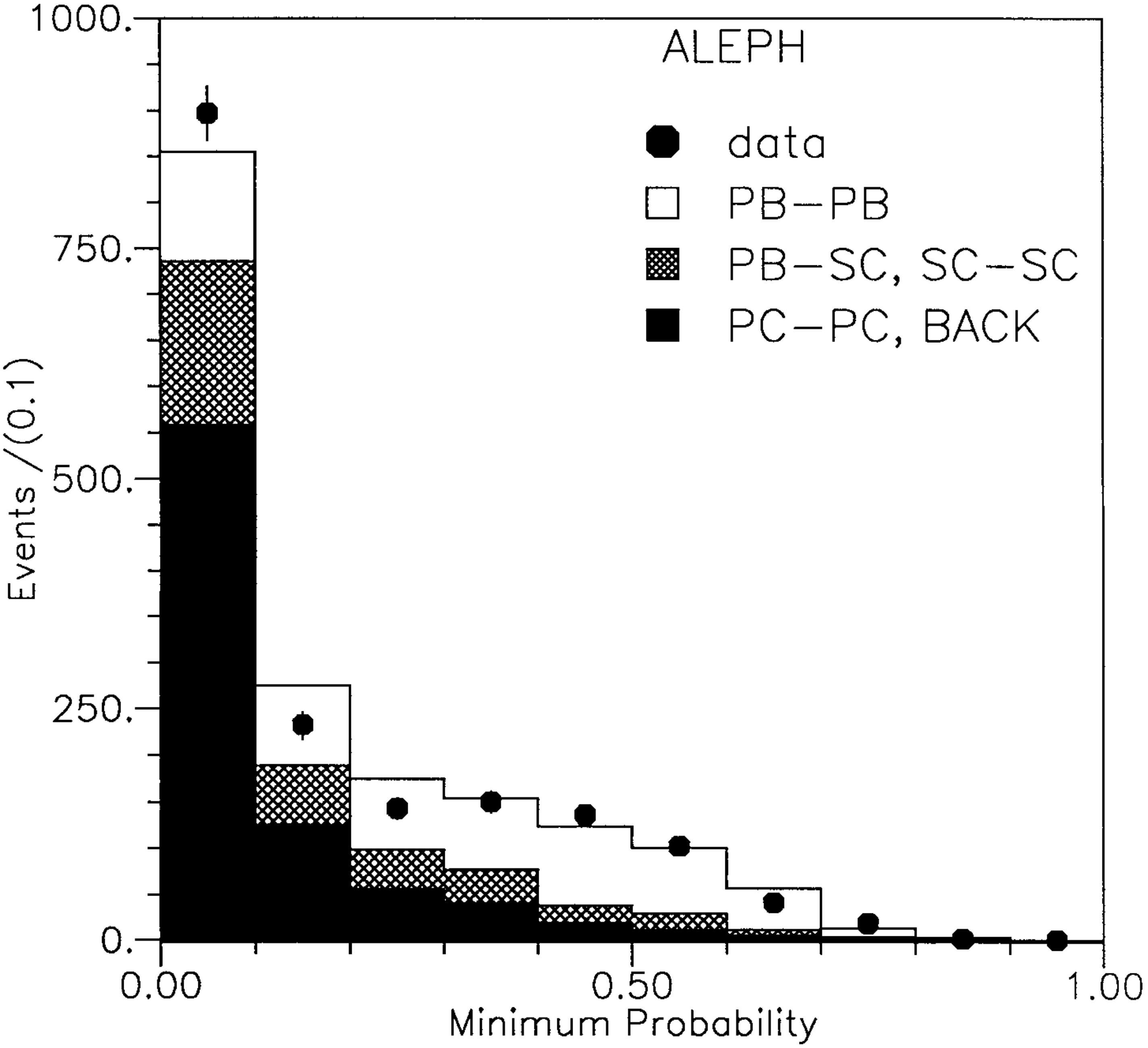
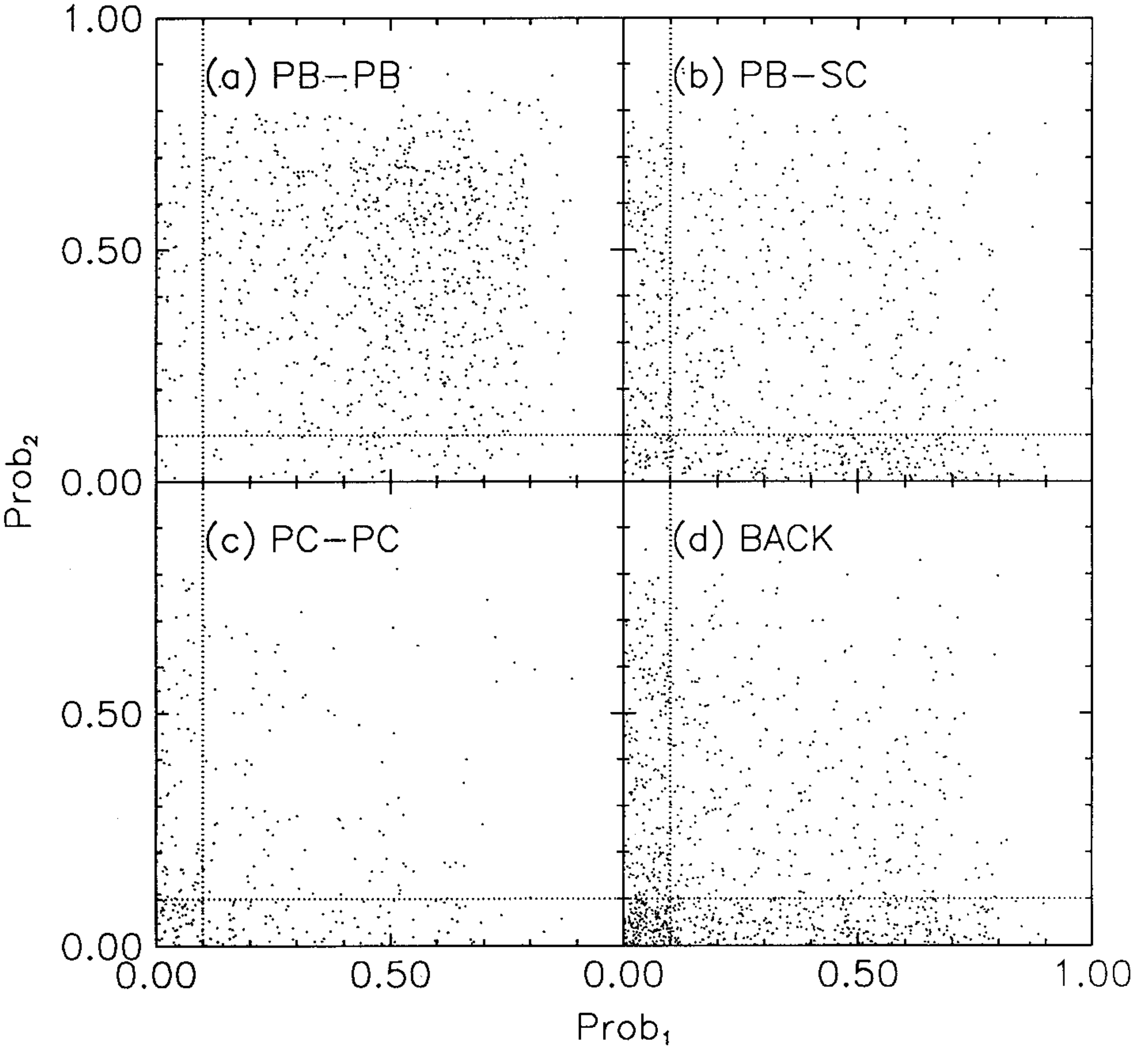

ALEPH
data
PB−PB
PB−SC, SC−SC
PC−PC, BACK
Events /(0.1)
1000.
750.
500.
250.
0.
0.00
0.50
1.00
Minimum Probability

Fig. 1(c)



(a) PB−PB
(b) PB−SC
(c) PC−PC
(d) BACK
1.00
0.50
0.00
0.50
0.00
0.00
0.50
0.00
0.50
1.00
Prob$_2$
Prob$_1$

Fig. 2

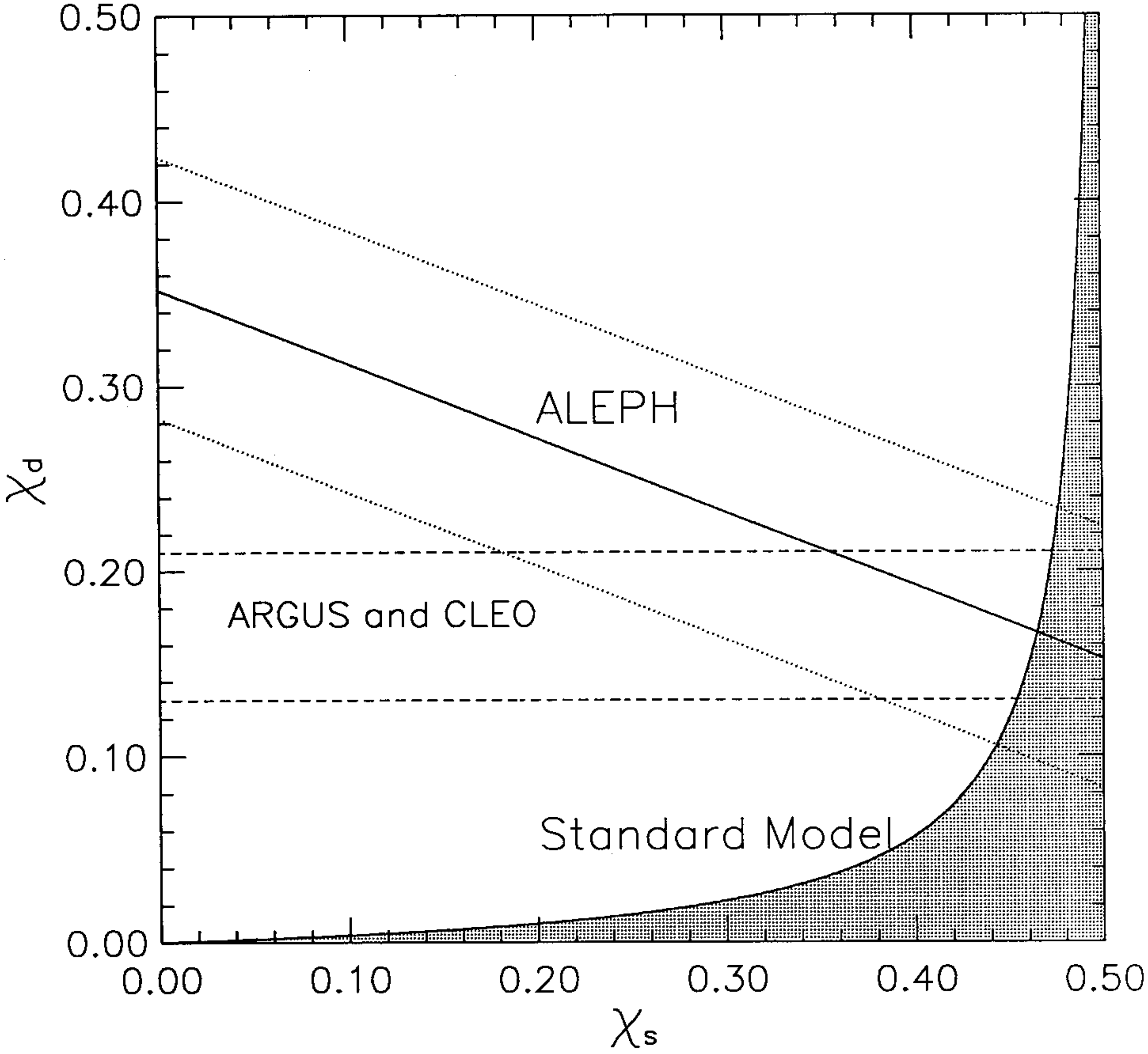


Fig. 3

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