ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Trieste

M. Caccia, N. Demaria, E. Gross, Ch. Petridou and M. Prest

A FEASIBILITY STUDY OF THE MEASUREMENT OF B^0 - $\bar{B}^0$ MIXING BY USING Λ^0's AND LEPTONS TO TAG THE b-DECAY

A Feasibility Study of the Measurement of $B^0 - \bar{B}^0$ Mixing by using Λ^0's and Leptons to tag the b-decays

M. Caccia, E. Gross
CERN, PPE Division

N. Demaria
Dipartimento di Fisica dell'Universita di Torino, Italy and
Sezione INFN di Torino

Ch. Petridou
Sezione INFN di Trieste

M. Prest
Dipartimento di Fisica dell'Universita di Trieste, Italy and
Sezione INFN di Trieste

Abstract

A tagging of b-quarks is pursued using Λ^0 and leptons in opposite jets, requiring one b-quark to decay semileptonically and the other to a final state containing a Λ^0. A purity in $b\bar{b}$ of about 60% is achieved at the Monte Carlo level by retaining about 40% of the signal. Furthermore an attempt was made to use this type of b-tagging in order to measure $B^0 - \bar{B}^0$ mixing. The results look rather encouraging.

1 Introduction

One of the consequences of the flavour changing weak current is to transform a neutral meson to its antiparticle. In the Standard Model, this transformation can only happen via box diagrams as it is known for the $K^0 - \bar{K}^0$ system. Similarly the B^0 meson can oscillate via box diagrams which involve virtual top quarks. Measurement of this mixing provides information about the CKM matrix elements V_{td} and V_{ts}, while the mixing depends on the top quark mass as well. The importance of measuring the mixing in the $B^0 - \bar{B}^0$ system has been stressed in several detailed theoretical studies performed in the past and at present [1], [2].

On the experimental side there is an ongoing effort to actually measure the $B^0 - \bar{B}^0$ mixing. From the measurement of B_d^0 mixing by ARGUS and CLEO [3] it is possible to extract a value for V_{td} (dependent on the top-quark mass), and therefore the importance of measuring V_{ts} is evident. At LEP and at hadron collider machines both B_s^0 and B_d^0 mesons are produced and there have been already attempts to measure the average $B^0 - \bar{B}^0$ mixing, see for example [4], [5].

In $e^+ e^-$ colliders two methods have been usually employed to measure the $B^0 - \bar{B}^0$ mixing. One involves looking for like sign dileptons from the semileptonic b-quark decays. The other requires the tagging of a lepton from the b-decay and the measurement of the charge of the other b-jet by a jet-charge method [6].

In the present note we report on the feasibility of a different method to study the $B^0 - \bar{B}^0$ oscillations. In particular it is explored the possibility of measuring $B^0 - \bar{B}^0$ mixing using $\Lambda^0 l$ pairs produced in $b\bar{b}$-decays.

It is required one b quark to have a semileptonic decay and the other $\bar{b}$ quark to decay to c-baryon, itself decaying to a Λ^0 baryon. Charge conjugate states are implied.

$$
\begin{aligned}
b &\to l^- \bar{\nu}_l X \\
\bar{b} &\to \bar{\Lambda}_c X; \quad \bar{\Lambda}_c \to \bar{\Lambda}^0 X'
\end{aligned}
\tag{1}
$$

The baryon number of the Λ_c (by Λ_c we refer to any c-baryon) is preserved and the final Λ^0 carries baryon number which is a signature of the original b-quark ($b \to \Lambda_c \to \Lambda^0$). So given the b-quark charge the lepton charge is fixed and similarly for a given b-quark charge, the baryon number of the $\Lambda^0(\bar{\Lambda}^0)$ to which it decays is also fixed. In consequence, if there are no other sources of $\Lambda^0 l$ pairs a change in the relative charge between the Λ^0 and the lepton can be only caused by oscillation of a $B^0(\bar{B}^0)$ to $\bar{B}^0(B^0)$ before decaying. To summarize, with no oscillations a $\Lambda^0 l$ final state has either baryon number (+1) and lepton charge (+1), or its conjugate, i.e baryon number (-1) and lepton charge (-1). Oscillations will produce instead (+-) or (-+) $\Lambda^0 l$ pairs. This again holds when the only source of Λ^0 pairs in opposite jets is $b\bar{b}$ events. In this paper this two kinds of pairs will be called *like sign* $\Lambda^0 l$ pairs (++ and --) and *opposite sign* pairs (+- and -+).

What is measured experimentally is the ratio R^- of $\Lambda^0 l$ pairs of opposite sign to the total. In the case of $B^0 - \bar{B}^0$ oscillations and in the ideal situation of no other source of $\Lambda^0 l$ pairs, this ratio:

$$R^- = \frac{\Lambda^{\pm} l^{\mp}}{\Lambda^{\pm} l^{\mp} + \Lambda^{\pm} l^{\pm}} \tag{2}$$

is a function of the mixing parameter χ which is defined as:

$$\chi = \chi_s f_s + \chi_d f_d \tag{3}$$

where χ_s and χ_d are respectively the probabilities for a B_s^0 and B_d^0 meson to oscillate and f_s, f_d are the respective fractions of B_s^0 and B_d^0 mesons in the total of the produced b-flavoured hadrons.

In the case of a Λ^0 coming from the decay of a b-quark there are the following three possibilities:

      1. b-quark $\rightarrow b - baryon X \rightarrow \Lambda_c X \rightarrow \Lambda^0 X$

      2. b-quark $\rightarrow B^{\pm} X \rightarrow \Lambda_c X \rightarrow \Lambda^0 X$

      3. b-quark $\rightarrow B^0 X \rightarrow \Lambda_c X \rightarrow \Lambda^0 X$

From the above three only in the last case we can have oscillations. Similarly, we can have leptons from primary b-decays from the following cases:

      1. b-quark $\rightarrow b - baryon X \rightarrow \Lambda_c l$

      2. b-quark $\rightarrow B^{\pm} X \rightarrow l X$

      3. b-quark $\rightarrow B^0 X \rightarrow l X$

Note that the BR for the semileptonic decay of the b-quark is the same for all three production mechanisms, ($\cong 10\%$), which is not the case for a Λ^0 from a b-decay. When all these are taken into account the ratio R^- as defined in equation 2 for $\Lambda^0 l$ pairs originated from b-decays only is given by the formula:

$$R^- = 2\chi(1 - \chi)\frac{f_{B\Lambda}}{f_{\Lambda}} + \chi f_b \left(\frac{f_{b\Lambda} - f_{B\Lambda}}{f_{\Lambda}}\right) \tag{4}$$

where χ is defined in equation 3 and f_b is the branching fraction of b-quark to b-baryons, $f_{b\Lambda}$ and $f_{B\Lambda}$ the BR's of b-baryons and B-mesons (charged or neutral) to Λ^0 respectively and f_{Λ} the total BR of a b-quark to Λ^0.

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2 Signature

The aim is to tag first a $b\bar{b}$ decay of the Z^0. In order to achieve it, we exploit the fact that in the semileptonic decay of the b-quark the momentum P of the lepton and its transverse momentum P_T (with respect of the jet axis) are high. Furthermore we require a Λ^0 in the opposite jet of *relatively* high momentum. So the signature of a $b\bar{b}$ decay will be high P and high P_T lepton in one jet and a *high* P Λ^0 in the opposite jet. (The P_T of the lepton is computed with respect to the jet axis to which it belongs.)

3 Procedure

In this note the study of the feasibility of the method was carried out at Monte Carlo generation level and therefore no detector effects were included. We used the JETSET algorithm for all but $b\bar{b}$ events. JETSET, with default decay tables, does not include the recently measured branching fraction of $B-mesons \rightarrow \Lambda^0 X$ [7]. This is found to be about 5% and is included in the EURODEC Monte Carlo generator. As a consequence, whenever a B-meson is found among the particles produced by JETSET, is forced to decay according to the EURODEC decay tables. It has been found that this trick introduces biases (asymmetries) which are not present if only the JETSET generator is used. At this stage, the purpose of the study is the feasibility of the method, which, as it will become clear later, is not strongly affected by these Monte Carlo uncertainties. At a later stage (analysis) these effects should be considered and taken into account in the systematic error of the oscillation measurement.

In what follows the term primary b-decay (PB) signifies for either the lepton or the Λ^0 one of the production mechanisms discussed in section 1. (We do characterize the Λ^0 as coming from a primary b (PB) because it actually carries the information about the initial b-quark, i.e. a Λ^0 is originated by a b-quark while a $\bar{\Lambda}^0$ by a $\bar{b}$). The actual decay for the Λ^0 refered to as PB can be summarized as : $b \rightarrow (B - meson$ or $b - baryon)X \rightarrow \Lambda_c X \rightarrow \Lambda^0 X$.

However $\Lambda^0 l$ pairs can be obtained as well from other (than $b\bar{b}$) hadronic decays of the Z^0. We consider here all the possible sources of $\Lambda^0 l$ pairs which can be summarized as follows:

1. PB-PB as explained above.

2. PB-SC, where the Λ^0 originated from a primary b-decay while the lepton from a secondary c-decay (i.e $b \rightarrow c \rightarrow lX$)

3. PC-PC, where both the Λ^0 and the lepton were originated from a primary c-quark decay. In the case of the Λ^0 we have: $c \rightarrow \Lambda_c X \rightarrow \Lambda^0 X$

4. In the fourth category we include the cases in which: a) the Λ^0 comes from fragmentation (in which case carries no information about the initial quark) and the lepton from a primary b or c-decay; b) the lepton originated from (uds) fragmentation, in which we also include the decay of any meson (but c) to lepton(s) and the Λ^0 from PB or PC decay; c) both lepton and Λ^0 originated from fragmentation.

In the case of real data this fourth category of events will also include background from misidentified leptons or Λ^0's.

In what follows we study each of these backgrounds and their contribution to the measurement of oscillations. The first category will be refered to, from now on, as signal. A basic requirement, in order to consider a $\Lambda^0 l$ pair, is that the two particles should not belong to the same jet. (The jet reconstruction and particle assignment is done according to LUCLUS algorithm). Note that from b-decays, if there are no oscillations, we expect only same sign $\Lambda^0 l$ pairs. Oscillations will be manifested as excess of opposite sign $\Lambda^0 l$.

On the contrary, background events, depending on their origin, contribute differently to same and opposite sign $\Lambda^0 l$ pairs. The background from PB-SC, if no oscillations, will produce opposite sign pairs, while oscillations of this background will create same sign $\Lambda^0 l$. The PC-PC background does not oscillate and gives opposite sign pairs. That means that this background simply gives a fixed contribution to the ratio.

Finally the background of type 4. is expected to be symmetric, that is, should consist of similar number of $\Lambda^0 l^+$ and $\Lambda^0 l^-$ pairs.

Experimentally we measure the ratio R_t^- which is:

$$R_t^- = \frac{(\Lambda^\pm l^\mp)_{signal} + (\Lambda^\pm l^\mp)_{BKG}}{(\Lambda^\pm l^\mp + \Lambda^\pm l^\pm)_{signal} + (\Lambda^\pm l^\mp + \Lambda^\pm l^\pm)_{BKG}} = \frac{R^- S + \alpha B}{S + B} \quad (5)$$

where R^- is the probability that a $b\bar{b}$ with a $\Lambda^0 l$ pair will oscillate and is given by equation 4. S is the signal as defined here (i.e. PB-PB events) and B is the background, that is all the other sources of $\Lambda^0 l$ pairs. Finally α is the fraction of $\Lambda^0 l^-$ (and their charge conjugate) in B. The equation 5 rewritten in terms of the signal to background ratio $n = S/B$ becomes:

$$R_t^- = R^- \frac{1}{(n+1)} (n + \frac{\alpha}{R^-}) \quad (6)$$

From equation 6 one sees that the measurement of R^- is diluted by a factor. The ideal case will be to either have this factor equal to 1 (that is the fraction of opposite sign background events α to be approximately equal to R^- and n large), or to have $B = 0$. If the background is symmetric $\alpha = 0.5$, in which case the difference $R_t^+ - R_t^-$ is a better quantity:

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$$R_t^+ - R_t^- = (1 - 2R^-)\frac{1}{(n+1)}(n + \frac{1 - 2\alpha}{1 - 2R^-}) \tag{7}$$

where R^+ is the ratio of like sign $\Lambda^0 l$ to the total. For a completely symmetric background, the dilution factor becomes: $n/(n + 1)$ and for large enough n approaches one.

The general strategy, therefore, in what follows, will be to eliminate (if possible) the contributions of the three types of backgrounds.

4   Results and Discussion

Figure 1 shows the momentum distribution (P_l) of the lepton for the four types of events, before any selection cuts. It is clear that P_l is a good variable to discriminate signal from background which steeply peaks at zero for fragmentation events and is soft for leptons from SC and PC decays.

In Figure 2 is shown the P_T distribution of the lepton with respect to its jet axis. The leptons from primary b-decays, (due to the large b-quark mass), have large P_T with respect to their jet axis. Leptons from primary or secondary c-quark decay are soft while leptons from fragmentation have even softer P_T spectrum.

The Λ^0 momentum distributions, P_Λ, are shown in Fig.3. For both PB-PB and PB-SC types of events the P_Λ does not differ, as expected, since in both cases the Λ^0's are originated from a b-quark. On the contrary, Λ^0's from the primary c-decay have much harder momentum spectra while those from fragmentation are very soft.

The angle between the direction of flight of the Λ^0 and the direction of the other jet (where the lepton belongs) is peaking at 180^0 for event types 1-3 but not for type 4 (i.e. fragmentation), see Fig. 4.

Since P_l and P_Λ are two good variables to separate signal from background, their correlations for the four event-types are shown in Figure 5. One can clearly see the different behaviour for signal and background events.

The total number of generated events is 300K hadronics. Before applying any selection criteria for signal, by simply selecting $\Lambda^0 l$ pairs where the Λ^0 and the lepton dont belong to the same jet, the background is overwhelming. This can also be seen in Table 1. In Table 1 there is a small contribution of opposite sign pairs in the signal events although there are no oscillations. These events contain both Λ^0 and $\bar{\Lambda}^0$ in the same B-meson decay. This means that we have actually lost the information of the initial quark and therefore such events contribute to the background. In JETSET the BR of $B \to \Lambda^0 \bar{\Lambda}^0 X$ is about 10^{-3}.

Before any selection the signal is only about 6% of the total $\Lambda^0 l$ pairs produced from the hadronic Z^0 decays. This is basically what we expect considering the measured branching ratios of $b \to \Lambda^0 X$, see also [7], and $b \to lX$.

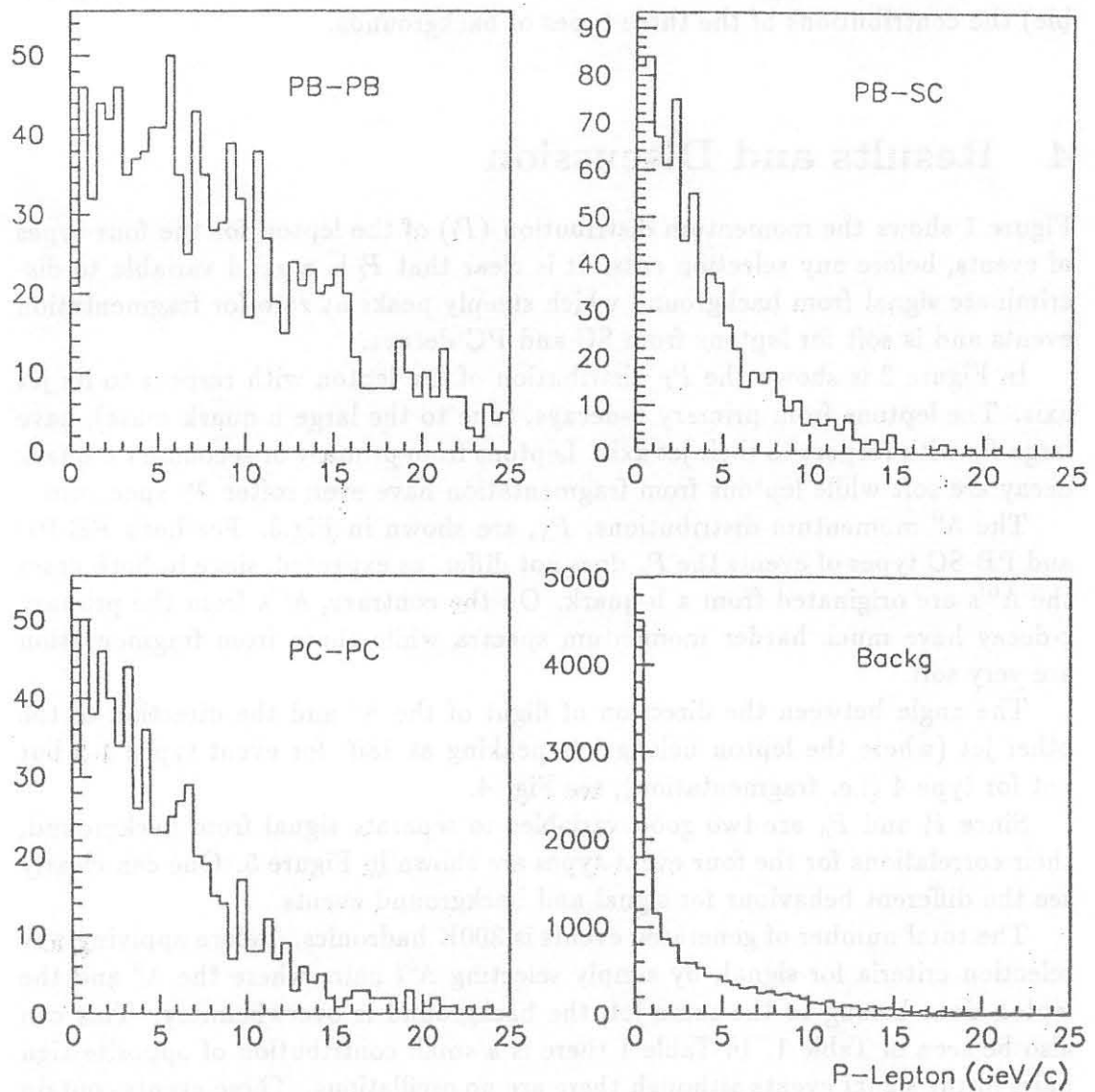$$R - \bar{R}_{\rm max} = (1 - 2\xi)\left(\frac{1}{n+1}\right)\frac{1-2\alpha}{1-2\xi} \qquad (1)$$

where $\bar{R}^*$ is the ratio of the sign Λ_b^* to the total. For a completely symmetric its background, the dilution factor becomes $\alpha(=1)$ and for large enough n approaches one.

The general strategy therefore, in what follows, will be to eliminate (i) maximize the contributions of the three terms of the equation.

4 Results and Discussion

Figure 1 shows the momentum distribution (P_l) of the lepton for the four types of events, before any selection cuts. It is clear that P_l is a good variable to eliminate signal from background, which steeply peaks for π or K or fragmentation events and is soft for leptons from SC and PC decays.

In Figure 2 is shown the P_l distribution of the lepton with respect to its jet axis. The lepton is primarily emitted. To the large π quark mass, it carries away a large fraction of the beam energy, at the same it acquires a large transverse momentum with respect to the jet axis.

The π momentum distributions, P_π, are shown in Fig. 3. For both PB-PB and PB-SC type of events the P_π distributions differ appreciably, because the Λ_b's are originated from a b-quark. Of the contrary, π's from the primary reaction have much harder momenta, while π's from fragmentation are very soft.

The angle between the direction of flight of the π and the momentum of the other jet (where the lepton is found) according as for the event topology that expect for type 4 (i.e. fragmentation), see Fig. 4.

Since P_l and P_π are two good variables to separate signal from background, their correlations for the four types of events are shown in Figure 5. It can clearly see the different behaviour for signal and background events.

The total number of generated events is 800k hadronic events representing a... selection criteria for signal by simply selecting Λ_b^* pairs where the Λ_b^* and the...

In Figure 1 (label 1) it is found there is a sizeable contribution of oscillations... indeed events although there are no oscillations. These events contain both Λ_b^* and Λ_b^* in the same hemisphere. This happens that we have actually lost the information of the initial quarks and therefore such events contribute to the background. In 1.3157% the BR of $R = -\Lambda_b^* X$ is about 10^-4.

before any selection the signal is only about 5% of the total $b\bar{b}$ pairs produced from the inclusive Λ_b^* decays. This is basically what we expect considering the measured branching ratio of $b \to \Lambda_b^* X$, see also [7], and $b \to l X$.
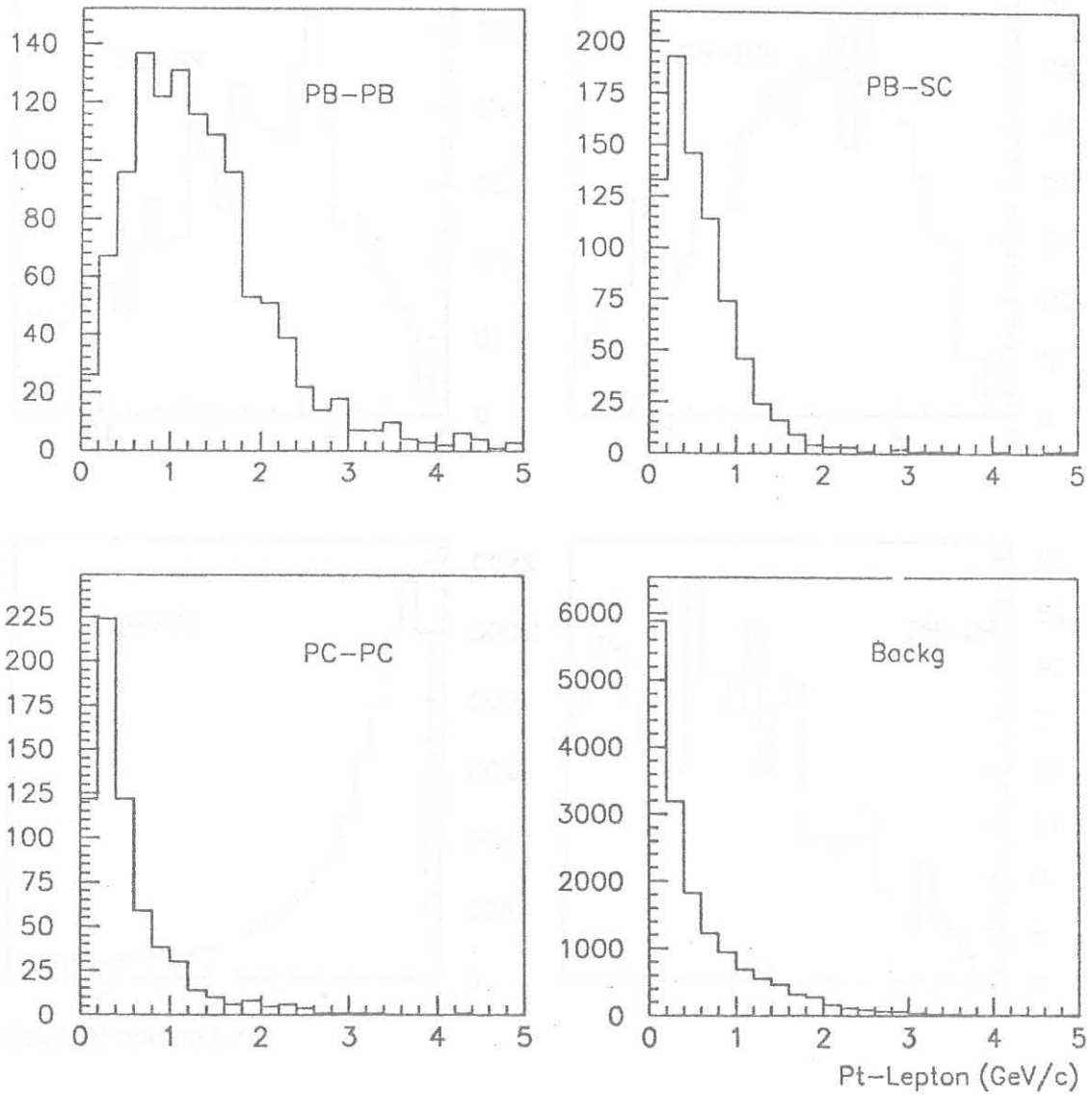

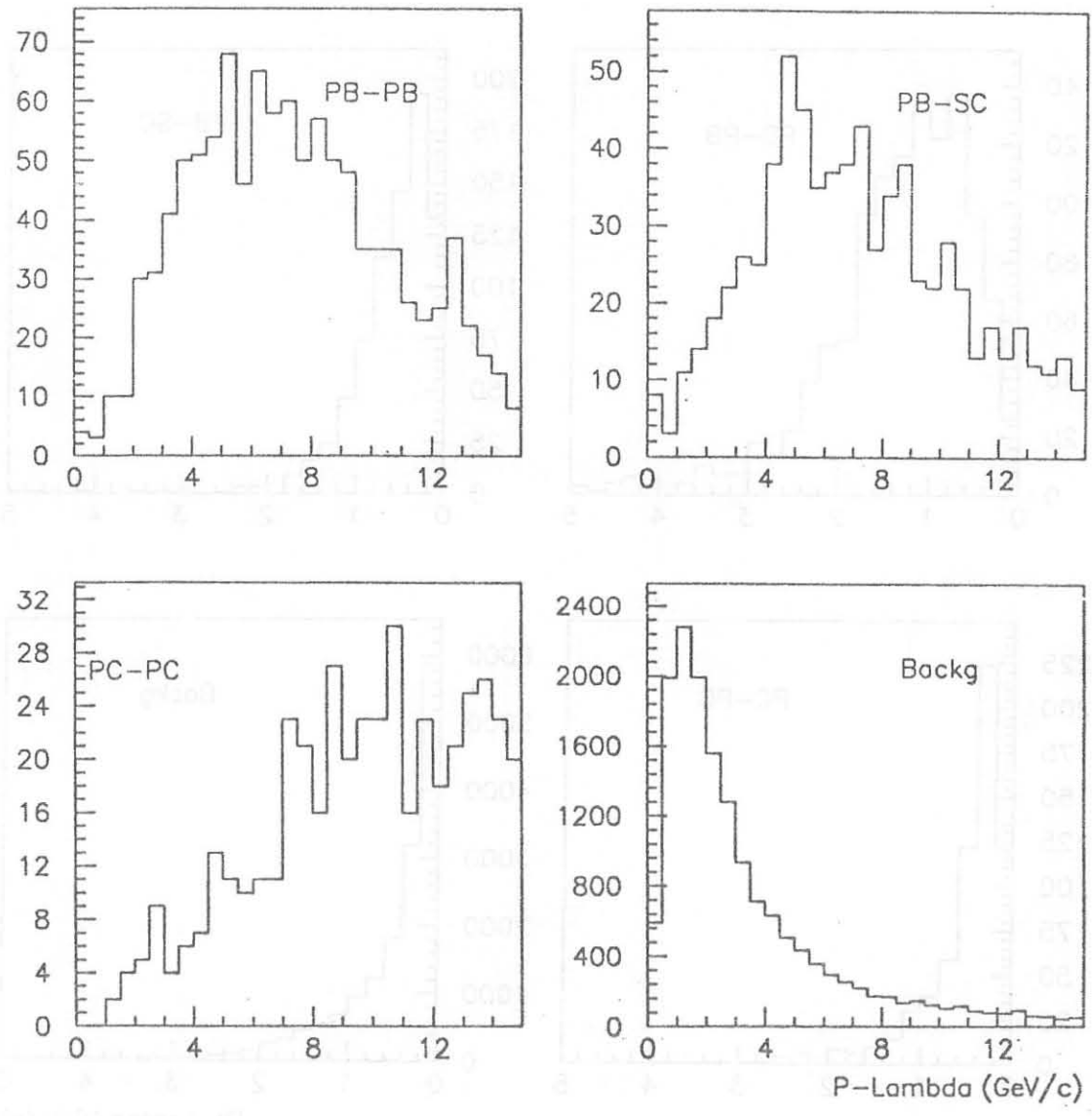**Fig. 1 - P lepton distributions.**

Fig. 2 - Pt lepton distributions.

Fig. 3 - P Lambda distributions.

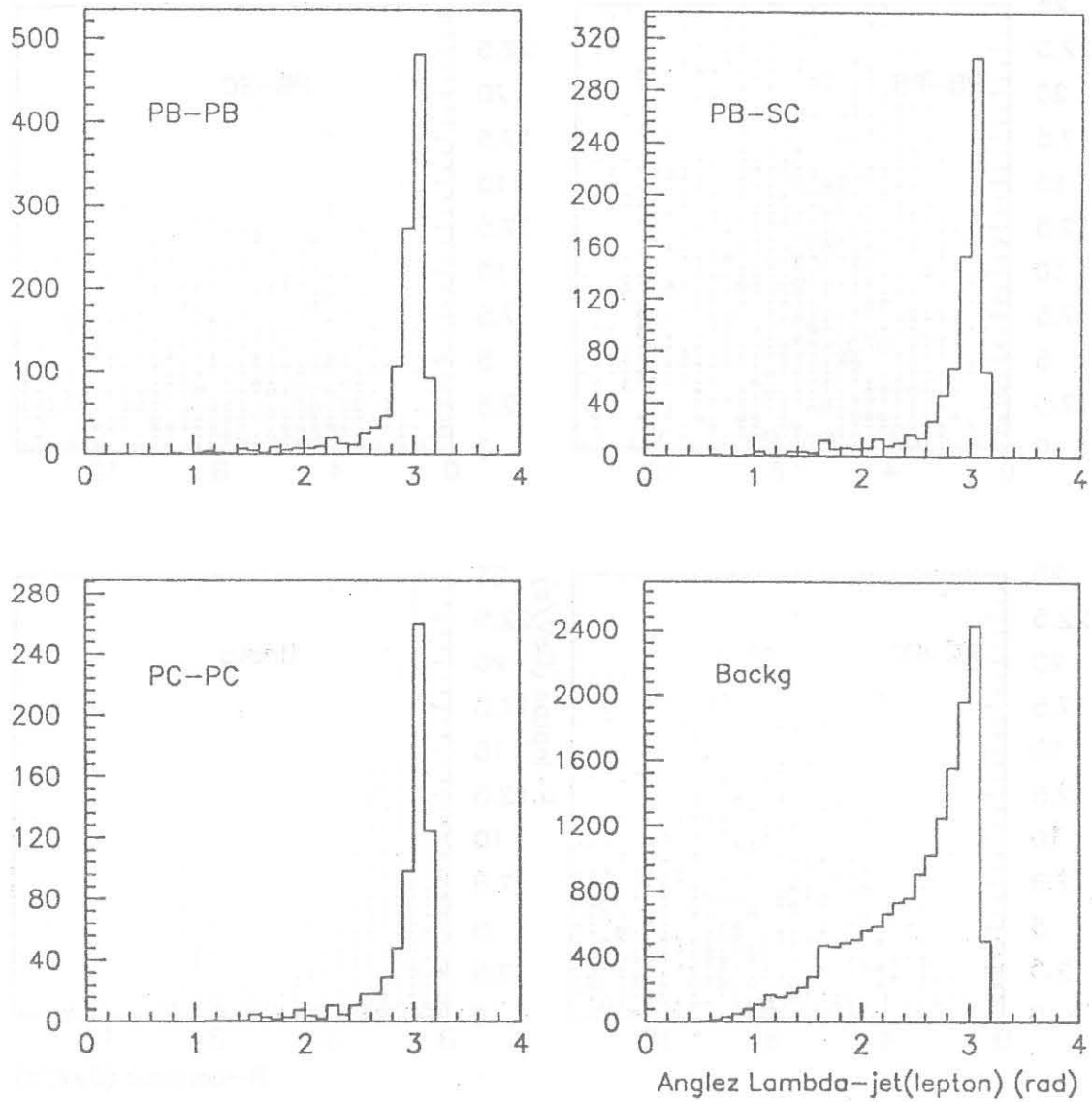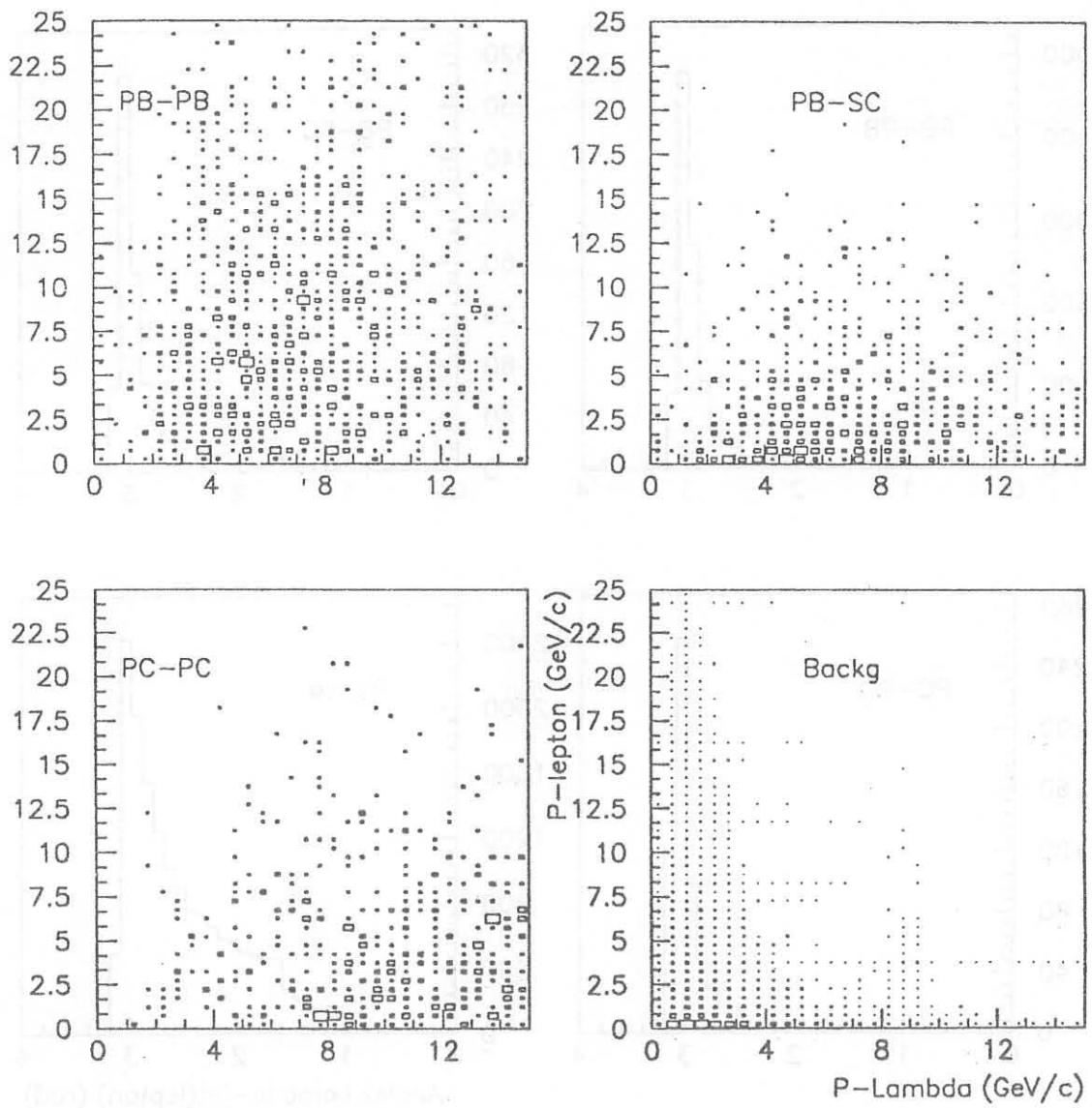**Fig. 4** - Angle between Lambda and lepton jet-axis.

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Fig. 5 - P-lepton versus P-Lambda.

$EventType$	$\Lambda^0 l^+$	$\Lambda^0 l^-$	$Total$	%
$PB - PB$	1094	57	1151	6.1
$PB - SC$	163	615	778	4.2
$PC - PC$	10	642	652	3.5
$Backg$	7973	8150	16123	86.2

Table 1: Number of $\Lambda^0 l$ pairs before any cuts on 300K hadronics, with no oscillations.

$EventType$	$\Lambda^0 l^+$	$\Lambda^0 l^-$	$Total$	%
$PB - PB$	356	6	362	60.3
$PB - SC$	9	45	54	9.
$PC - PC$	0	30	30	5.
$Backg$	58	96	154	25.7

Table 2: Number of $\Lambda^0 l$ pairs after cuts on 300K hadronics, no oscillations.

To achieve a purity of about 60% in signal, which is mainly required in order to be sensitive in oscillations, several set of cuts have been tried.

A set which optimizes the purity of the signal and the actual number of remaining signal-events after the cuts is:

- i) $P_l \geq 5 GeV/c$

- ii) $P_T^l \geq 0.8 GeV/c$

- iii) $5.5 \leq P_\Lambda \leq 14 GeV/c$

- iv) $\Theta_{\Lambda jet-l} \geq 2.8 rad$

The results obtained with these cuts are shown in Table 2: the signal is about 60% of the total and corresponds to about 400 $\Lambda^0 l$ pairs from PB decays.

The opposite sign $\Lambda^0 l$ pairs in PB-PB events have been basically eliminated, while the previously symmetric background (fourth event type) has become asymmetric. This background consists of the following event categories:

1. Λ^0 from b-quark fragmentation and lepton from PB decay.

2. Λ^0 from b or c-quark fragmentation and lepton from SC or PC respectively.

3. Lepton from b-quark fragmentation and Λ^0 from PB decay.

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$EventCategory$	$\Lambda^0 l^+$	$\Lambda^0 l^-$
1.	21(7837)	58(7850)
2.	31(2803)	35(2364)
3.	1(3917)	0(3854)
4.	0(738)	0(742)
5.	5(240)	3(238)

Table 3: Contributions to event type 4 in $\Lambda^0 l^+$, $\Lambda^0 l^-$ pairs after all cuts, from its different categories. In parenthesis the values of the same backgrounds are given before the cuts.

4. Lepton from c-quark fragmentation and Λ^0 from PC decay.

5. Both Λ^0 and lepton from fragmentation.

In Table 3 the detailed composition of this general background is given. As can be seen, categories 3 and 4 have been eliminated by our cuts, while 2 and 5 are symmetric. Finally category 1. is rather asymmetric. For an S/B ratio of about 5, equations 6 and 7 show that some asymmetry in the background will not particularly affect the dilution factor, especially when using the difference $\delta = R_t^+ - R_t^-$ between the two ratios. Therefore the study of the symmetric/asymmetric backgrounds and their Monte Carlo dependence will be pursued farther when from real data a value for χ is extracted.

Figures 6-8 show the behaviour of the good kinematical variables: P_l, P_T^l, P_Λ respectively, for the four types of events after cuts and Fig.9 the correlations between P_l and P_Λ for signal and backgrounds. One sees clearly that in all three variables the background drops significantly as we move to larger values. To benefit from the differences between signal and background in all three variables (which are highly uncorrelated), one should use a maximun likelihood method. This approach was also followed by other LEP experiments in the case of dileptons; see [4].

In the present note we study the signal to background ratio for two variables. One is the P_Λ (momentum of the Λ^0), and the second is combining the P_l and P_T of the lepton into one variable, P_{comb}, which is defined by the equation:

$$P_{comb} = \sqrt{(P_l/2 - 2.5)^2 + (P_T^l - 0.8)^2} \qquad (8)$$

Figure 10 shows the behaviour of this new variable (P_{comb}) for the four event categories and Fig.11 the correlation between P_{comb} and P_Λ for signal and each of the three backgrounds. In Figure 12 the distribution of P_{comb} for the total number of events is given, with the curve for signal only superimposed to it (hatched region). One clearly sees that going towards high values of P_{comb} the
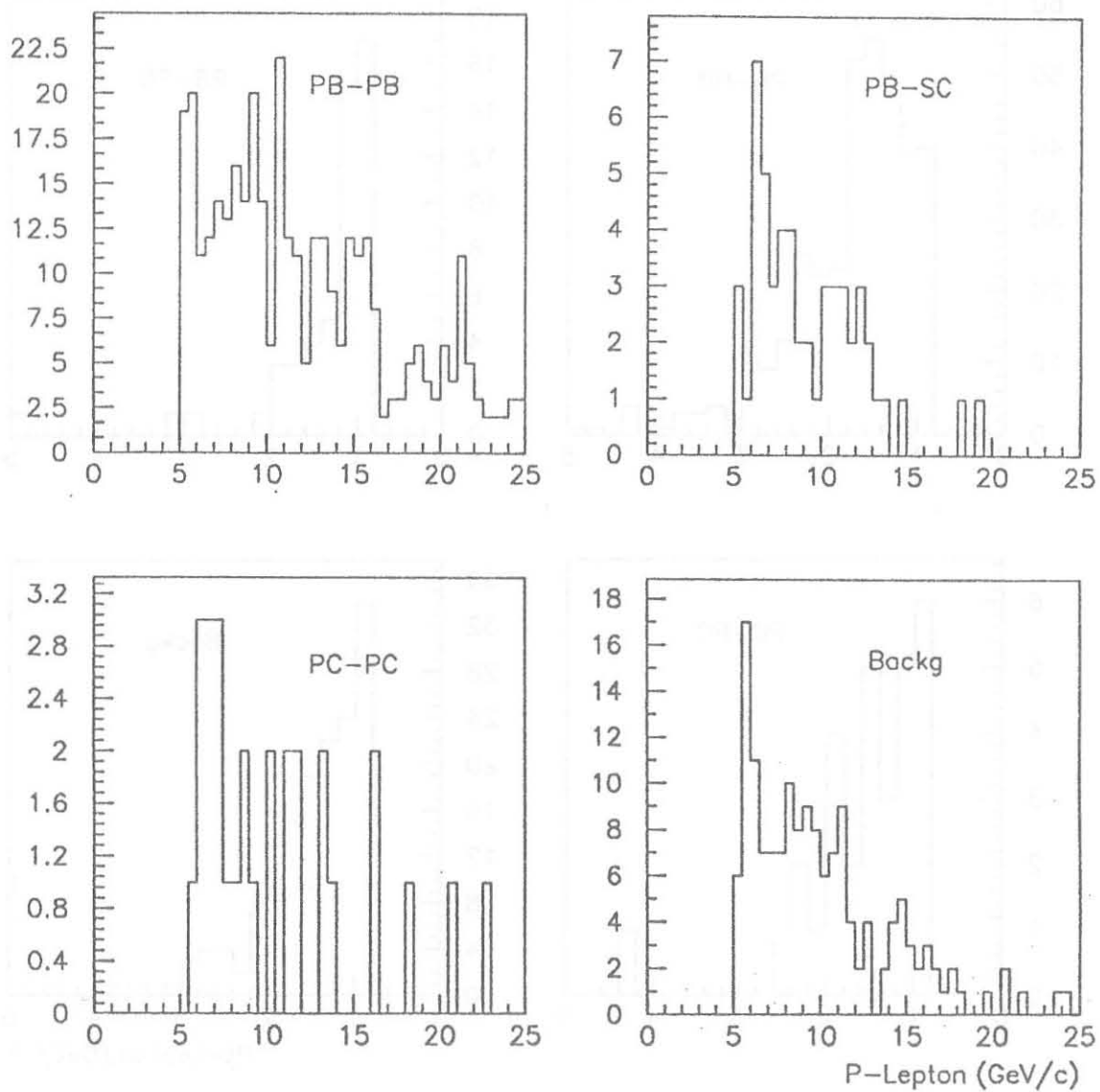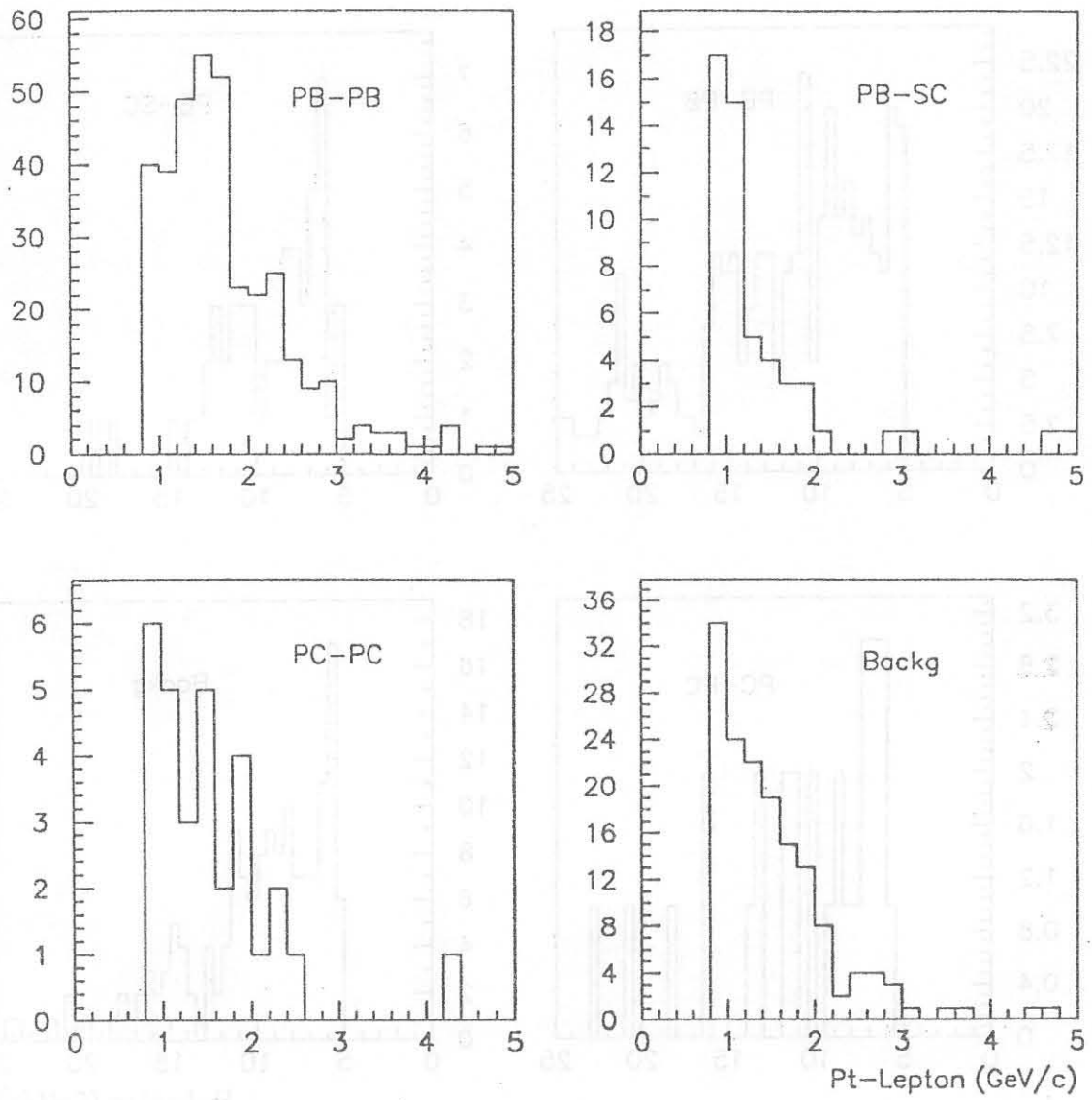
Fig. 6 - P lepton distributions after cuts.

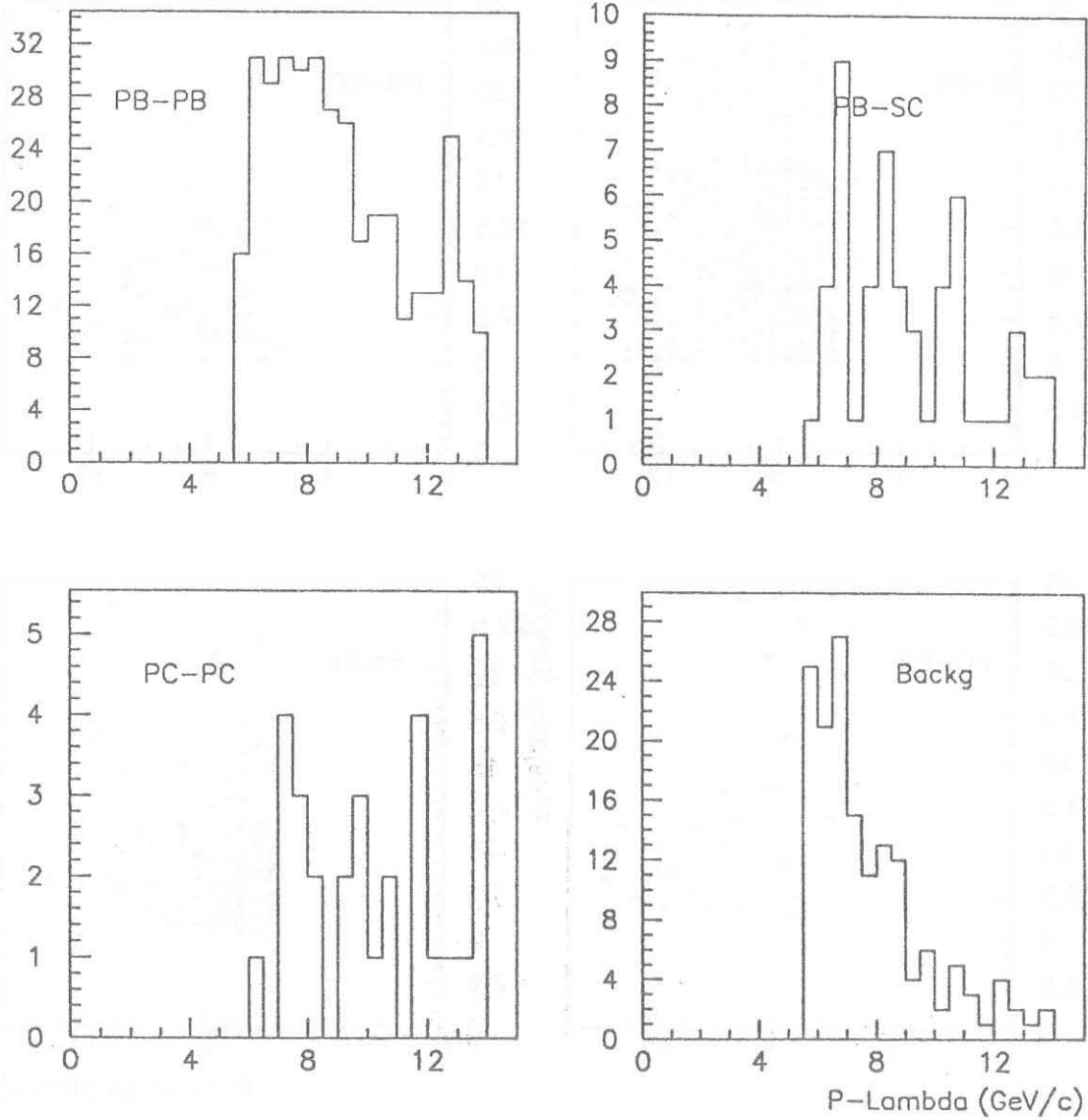**Fig. 7** - Pt lepton distributions after cuts.

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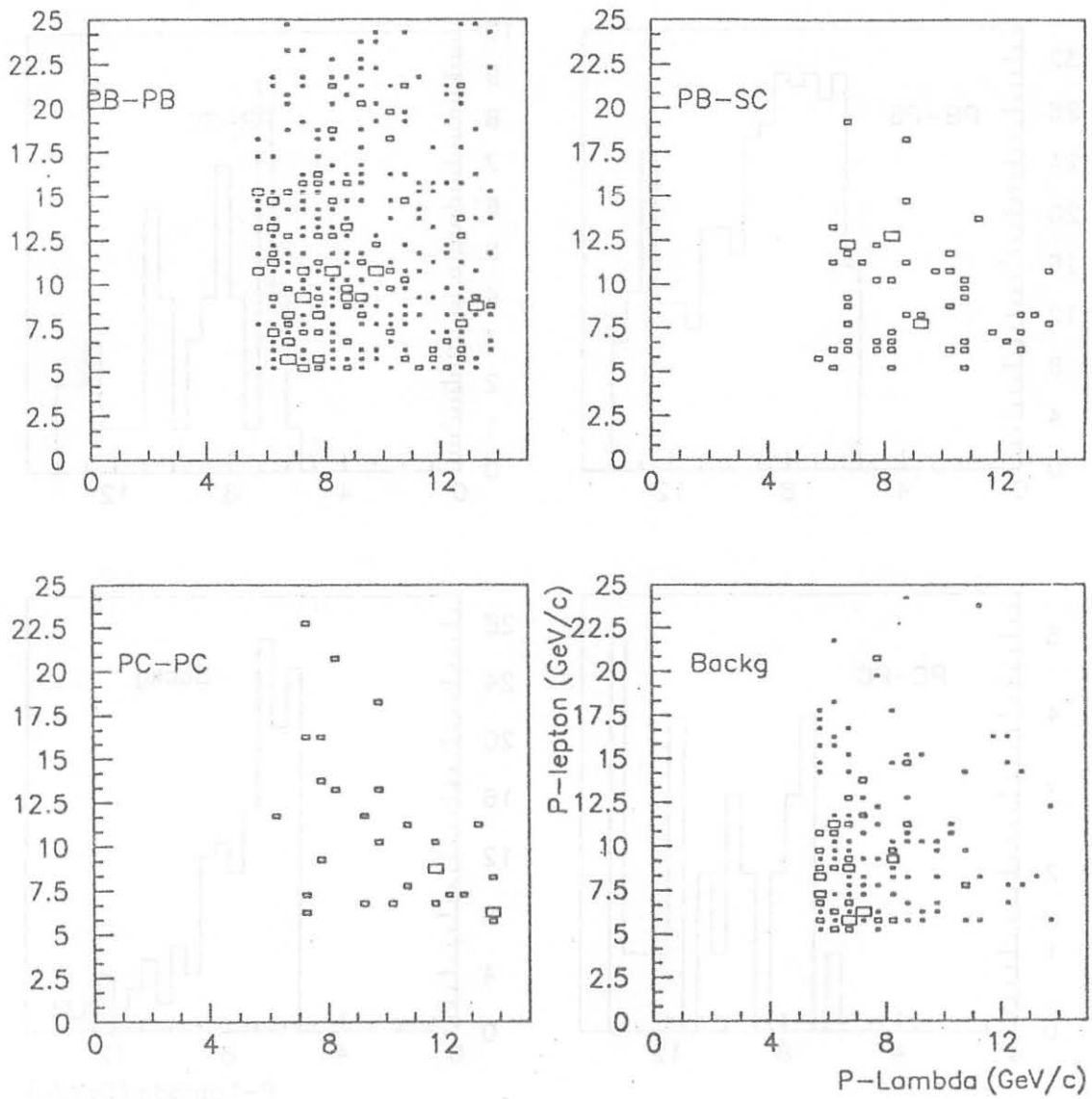
Fig. 8 - P Lambda distributions after cuts.

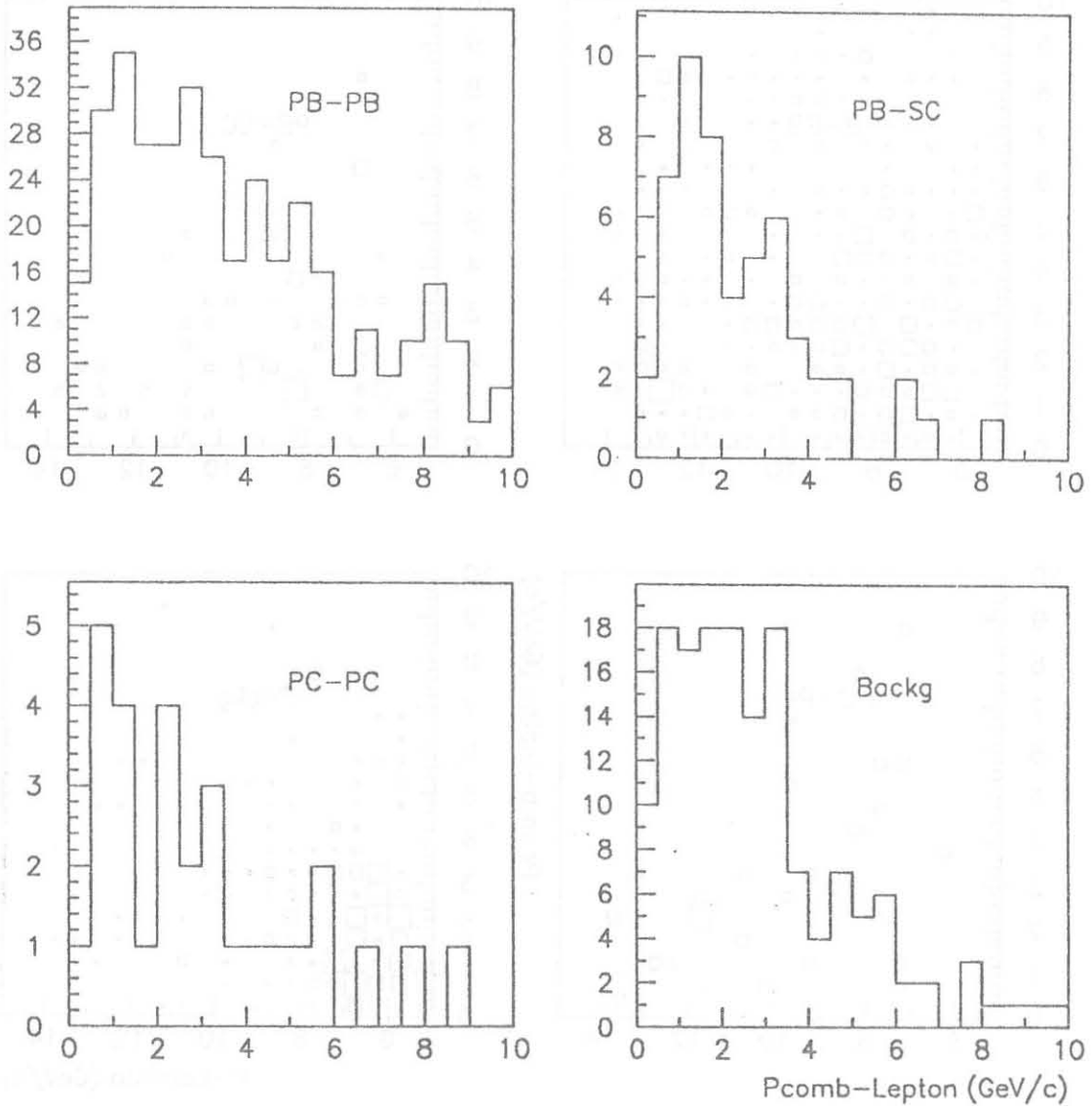Fig. 9 - P lepton versus P Lambda after cuts.
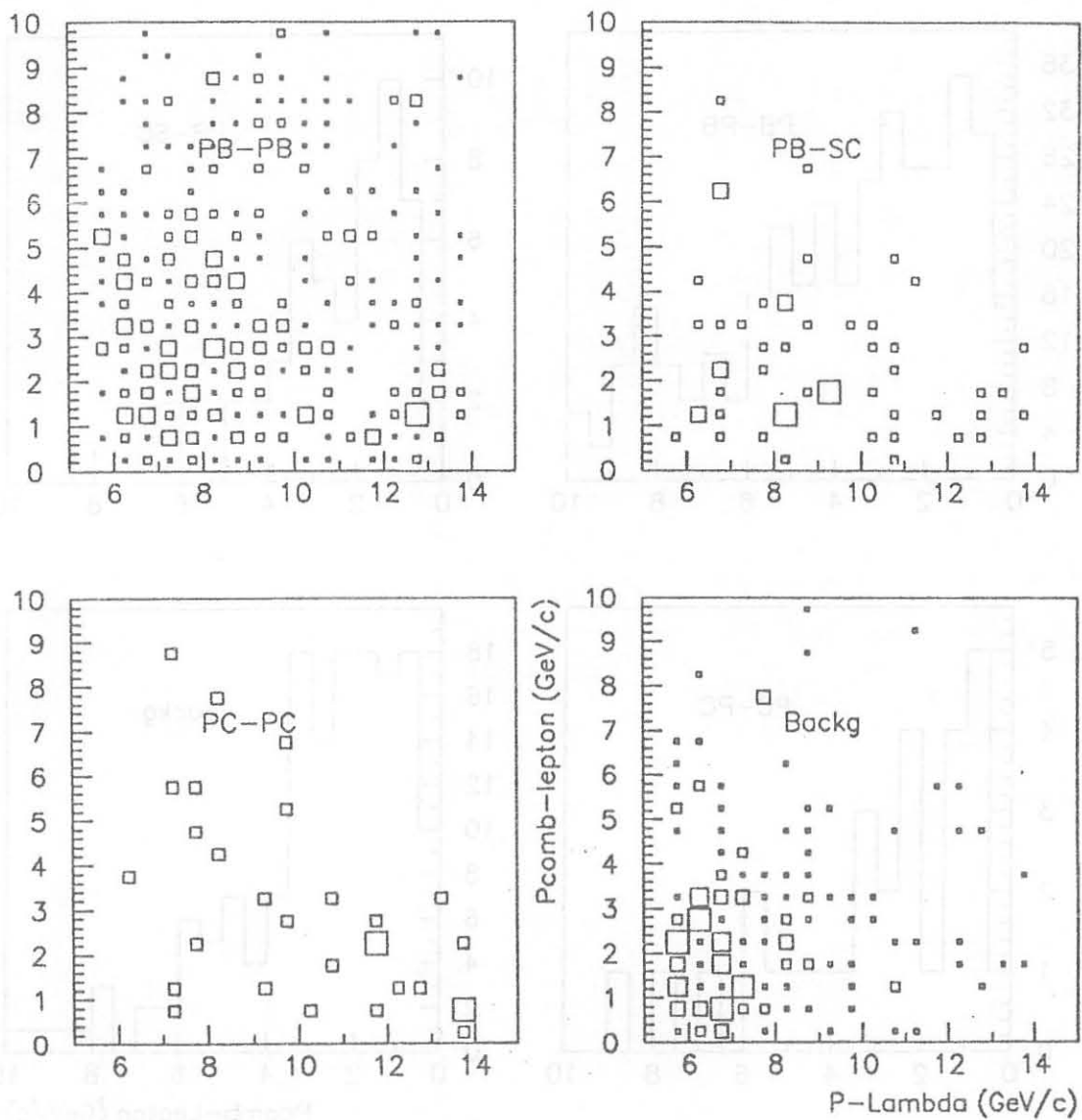
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Fig. 10 - Pcomb of lepton after cuts.
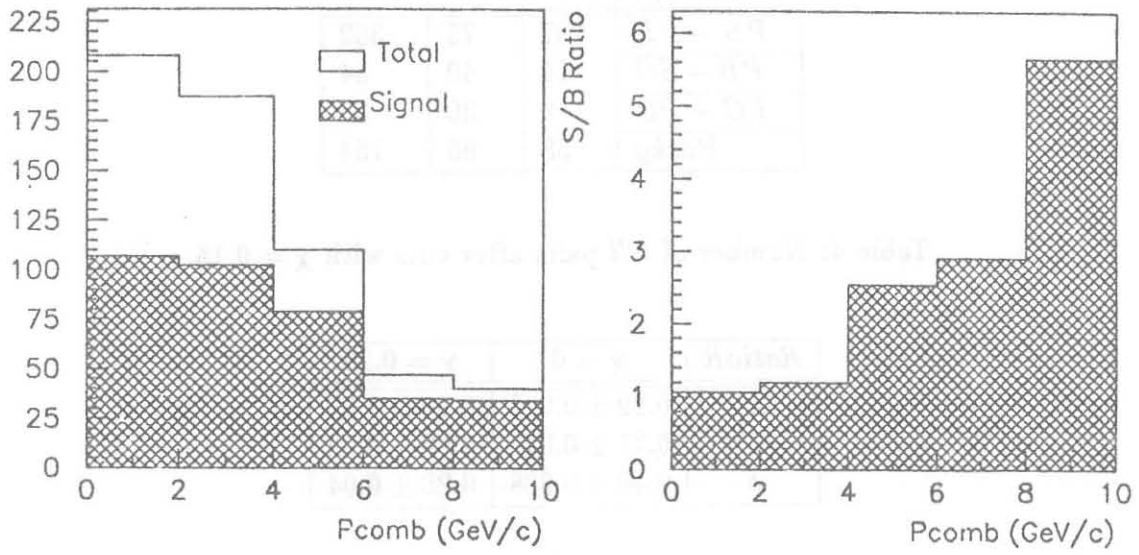
Fig. 11 - Pcomb Lepton versus P Lambda after cuts.
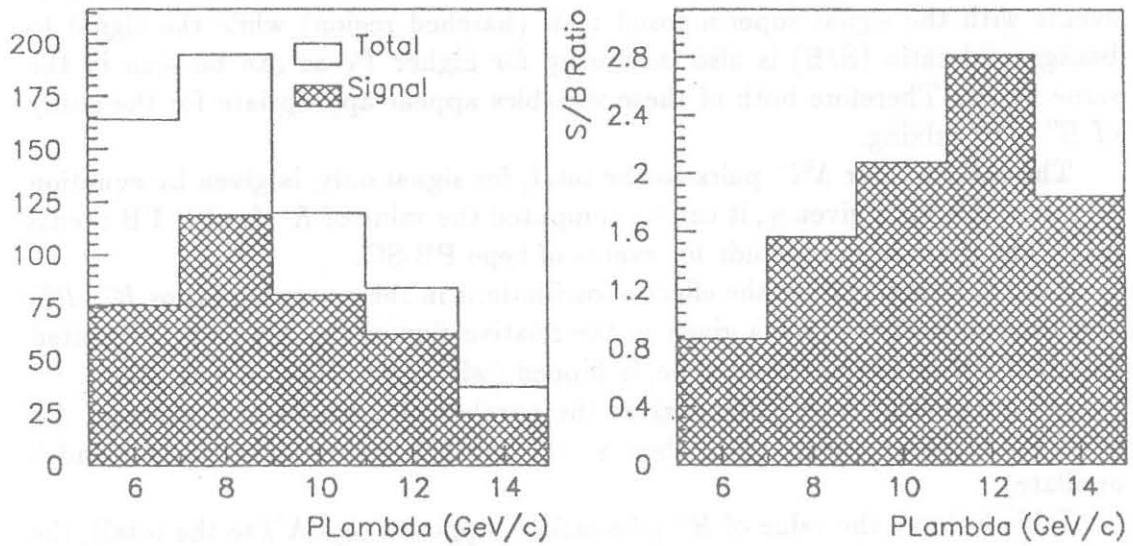
Fig. 12 - Pcomb-Lepton total and signal after cuts.

Fig. 13 - PLambda-Lepton total and signal after cuts.

$EventType$	$\Lambda^0 l^+$	$\Lambda^0 l^-$	$Total$
$PB - PB$	287	75	362
$PB - SC$	14	40	54
$PC - PC$	0	30	30
$Backg$	58	96	154

Table 4: Number of $\Lambda^0 l$ pairs after cuts with $\chi = 0.15$

$RatioR$	$\chi = 0$	$\chi = 0.15$
R^-	0.29 ± 0.019	0.40 ± 0.02
R^+	0.71 ± 0.019	0.60 ± 0.02
δ	0.40 ± 0.038	0.20 ± 0.04

Table 5: Ratios of $\Lambda^0 l^+$, $\Lambda^0 l^-$ and their difference for $\chi = 0$ and $\chi = 0.15$

sample is almost entirely composed by signal. In the same figure the signal to background ratio (S/B) is shown as a function of P_{comb}.

Similarly the P_Λ distribution is shown in Figure 13 for the total number of events with the signal superimposed to it (hatched region) while the signal to background ratio (S/B) is also increasing for higher P_Λ as can be seen in the same figure. Therefore both of these variables appear appropriate for the study of $B^0 - \bar{B}^0$ mixing.

The ratio R^- for $\Lambda^0 l^-$ pairs to the total, for signal only, is given by equation 4. From, this for a given χ, it can be computed the value of R^- for PB-PB events only. The same formula holds for events of type PB-SC.

Finally, in order to see the effect of oscillations in the measured ratios R_t^-, R_t^+, and their difference δ, for a given χ, the relative sign of the $\Lambda^0 l$ pairs originated from PB-PB or PB-SC event type, is flipped (with probability R^- as it is

computed from χ). Table 4 gives the number of opposite and like sign $\Lambda^0 l$ pairs for the four event types when $\chi = 0.15$. (Of course only types 1 and 2 oscillate).

Table 5 shows the value of R^- (the ratio of opposite sign $\Lambda^0 l$ to the total), the value of the ratio of same sign to the total (R^+) and their difference $\delta = R^+ - R^-$ for both $\chi = 0$ and $\chi = 0.15$.

One should note that already in the average value of these ratios (R_t^+, R_t^-) there is a change of about 10% when we switch on the oscillations with a χ (as defined by equation 3), of 0.15 and a change of about 20% in their difference δ for the same χ. This is rather encouraging.

In Figure 14 each of these ratios $(R^-, R^+, \text{and } \delta)$ are presented as a function
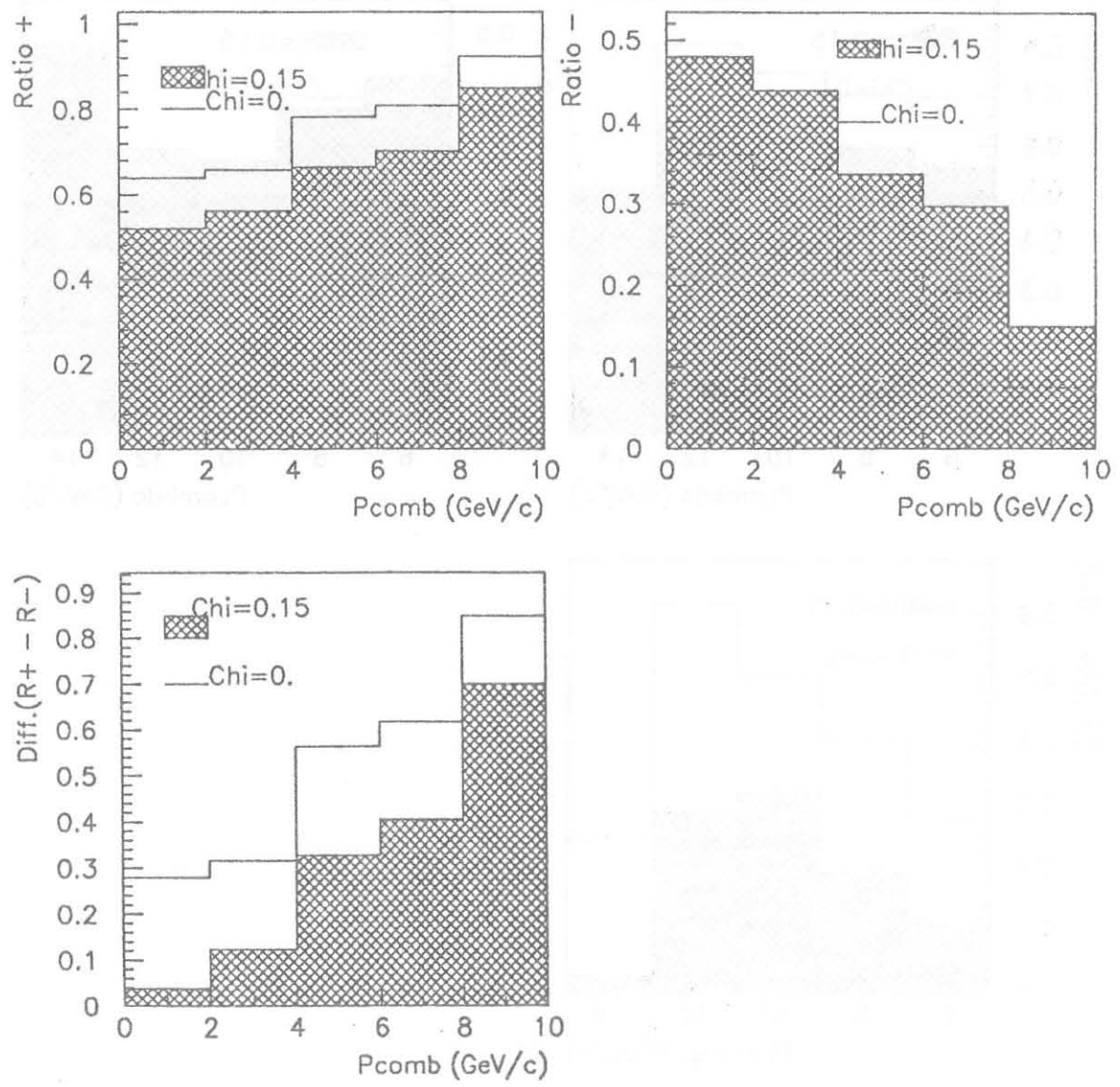
Fig. 14 - The R+ R- and R+ - R- versus Pcomb.

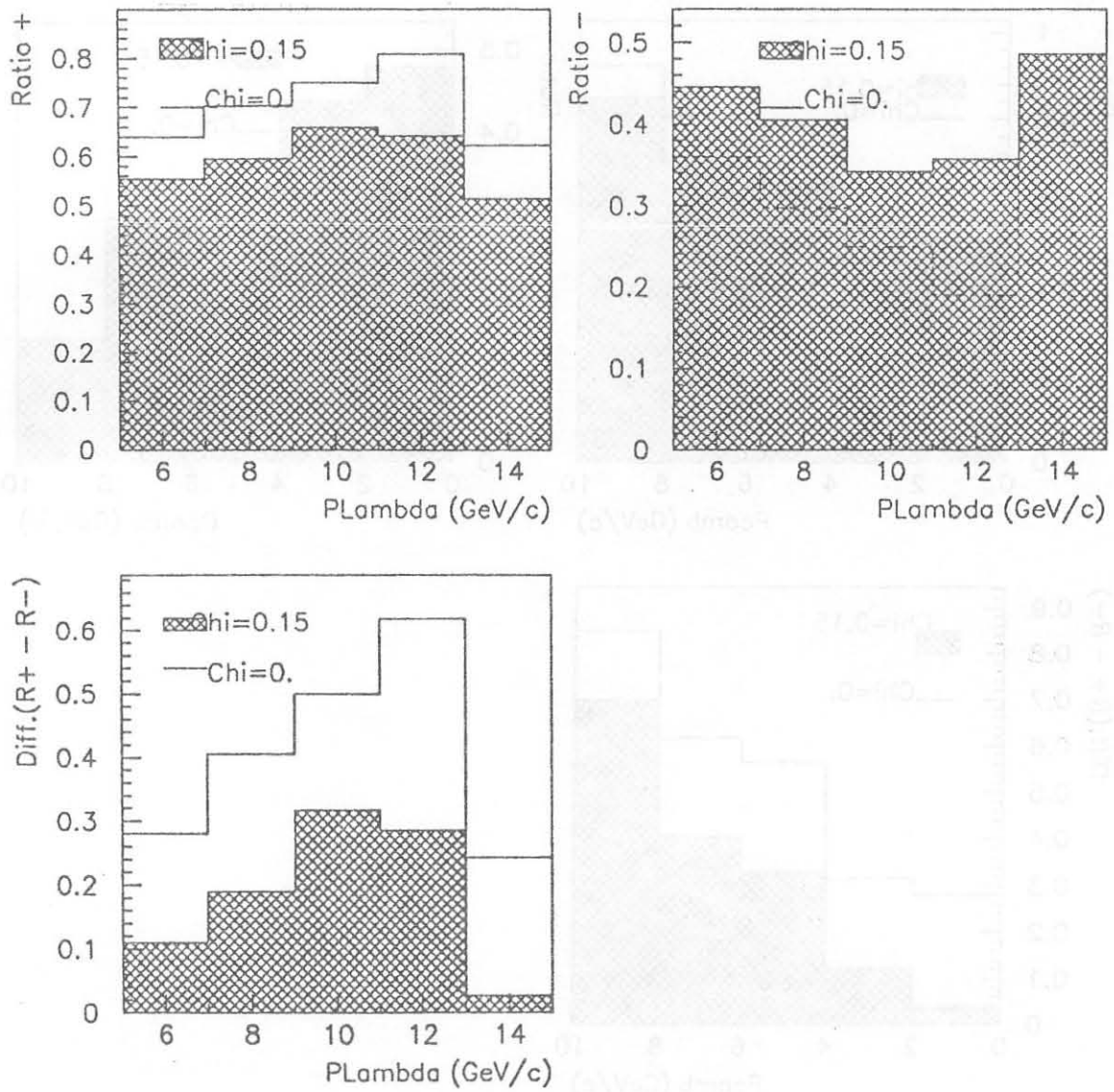Fig. 15 - The R+ R- and R+ - R- versus PLambda.

of the P_{comb} variable, and similarly in Figure 15 the same ratios as a function of P_Λ. The line which is defined by the hatched region corresponds to $\chi = 0.15$ while the continuous one indicates the same ratios when $\chi = 0$.

These curves are statistics limited. To obtain smooth curves for different values of χ one should run with large statistics. On the other hand, starting for this study from 300K hadronics gives an idea of what one can expect from real data. Of course, in order to get a rough estimate of the signal events expected from the data, the numbers resulted here for signal and background have to be scaled by the approximate detection efficiencies for Λ^0's in this momentum range and leptons. Assuming an average efficiency of 20% for Λ^0's and 50% for electron and muons about 40 events from PB-PB decays are expected from 300K hadronics.

With the rapidly increasing data collected by LEP we feel that it is worthwhile to pursue the method as a different approach to the $B^0 - \bar{B}^0$ mixing measurement.

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