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Limit for the Tau Neutrino Mass using $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0\nu_\tau$

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Abstract

In this note a method for selecting $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0$ at LEP energy is presented. The branching ratio and some resonances are studied. With this decay mode a limit for the τ neutrino mass of 77MeV at a confidence level of 95% is obtained. For the analysis both the 1989 and 1990 data are used.

Contents

1 Introduction

The multi pion states in τ decays give a good tool to measure the τ neutrino mass by looking at the mass and the energy of the hadronic system. The world best limit was given by ARGUS using five prong events [1]. They quote a limit at 35MeV. That value is mainly determined by the event with the highest hadronic mass. This means it is worthwhile to look at all possible multi pion states, in the hope of finding one clear event with a high hadronic mass.

Starting this work, it was thought, that the resolution for hadronic mass and energy is limited by the ECAL energy resolution. So one way to overcome this problem is to select the decay mode $\tau \rightarrow \omega\pi\nu$ with $\omega \rightarrow \pi^-\pi^-\pi^0$ and to take the Particle Data Group value for the ω mass as a constraint for calculating the hadronic mass. Doing so, the hadronic mass would only depend from the angle of the photons coming from the π^0 decay and from the momentum of the charged particles. But this method needs a rather clean ω sample and a deep understanding of the dynamics of the $\pi^-\pi^-\pi^+\pi^0$ states which are not produced by the ω resonance, because they contribute as background. That means that the dynamics of the $\pi^-\pi^-\pi^+\pi^0$ states has to be studied, which needs much more effort, so we give here a limit without using the ω mass as a constraint.

The branching ratio of the $\pi^-\pi^-\pi^+\pi^0$ decay channel fits into the well known "tau problem". The Particle Data Group value is $(4.4 \pm 1.6)\%$ [2]. Recently a value for the branching ratio for three charged pions and some neutral pions is published by CELLO $(5.6 \pm 0.7 \pm 0.2)\%$ [3]. In this note we present a preliminary result for the branching ratio.

2 Selection of $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0$

At first we ask for a 1–3–topology where a track must have at least 5 measured coordinates in the TPC, have momentum exceeding 200MeV, and originate from the beam–crossing within 5cm along the beam direction and 2cm in the transverse direction. By a 1–3–topology we mean that the event is divided in two hemispheres, using the plane perpendicular to the thrust axis, and one hemisphere should have only one track whereas the other contains three tracks. The total charge has to be zero. These criteria reject most of Bhabha events, μ–pairs and hadronic events. $\gamma\gamma$–events are rejected by further demanding at least one track with a momentum above 5GeV. The cosine of the angle between the two jets, where the jet axis is given by the momentum sum over the hemisphere, should be less than -0.9 and the thrust axis must have a polar angle within $|cos\theta| < 0.8$. It garantees a good track resolution. At the three prong side the cosine of the angle of each track from the jet axis has to be larger than 0.8. To get a further reduction of Bhabha events with converted photons we demand a momentum at the one prong side lower than 35GeV. In addition a special pair finder procedure was applied, searching and rejecting events with secondary vertices, that means vertices with a distance in the transverse plane from the beam crossing larger than 4cm and an invariant mass less than 15MeV.

Within an opening angle of 30° from the jet axis on the 3–prong–side we search for photons by looking at the ECAL-storey energy. The photons are defined as described by A. Rouge [4].

These photons have to form a π^0, wich may consist of one, two or three energy deposits. If only one photon is found, then either the two photons have coalesced together or one γ is lost. In this case the γ–energy has to be above 5GeV. If two photons are present then we ask for a total energy above 500MeV and a reconstructed π^0–mass between 70 and 220 MeV (see Fig. 1). For the three photon case we choose that pair which gives the best π^0–mass. The total energy should be above 1GeV and the mass should be in the interval used for the two photon case.

Events which have one π^0 and fulfill the cuts as described above give our final sample. We are left with 179 events, 110 of which are on the Z^0 peak, $91.1GeV < \sqrt{S} < 91.3GeV$.

3 Branching ratio of $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0$

Applying the same selection as discribed in section 2 on Monte Carlo data generated at the peak with KORALZ we obtain an efficiency of $(19.1 \pm 0.8_{stat})\%$. The error contains only the contribution due to the statistics of the Monte Carlo data. The background is $(13.1 \pm 1.4_{stat})\%$ of the signal which consists of A_1–decay mode of the τ (50%), ρ–decay mode (29%) and other multi–π–decay modes.

The kaon background can be neglected for the following reason: according to [2], the branching ratio for τ decay to one charged kaon, plus two charged pions and may be some neutrals is less than 0.06%, so we expect no relevant contribution from that. The K_L will not decay within the TPC so only decay modes with three charged pions, one neutral pion and a K_L contribute. We expect this cross section to be small. What is left is a decay in one K_S, one charged and one neutral pion, where the kaon decays in two charged pions. An upper limit for this ratio can be calculated using the ratio for the $K^-\pi^+\pi^-$ (plus some neutrals) channel times a factor smaller than 2 coming from the Clebsch–Gordan coefficients times the branching ratio for $K_S \to \pi^+\pi^-$. The contribution is negligible.

Subtracting the background from the data and correcting for the efficiency we have 500.5 ± 8.8 events on the Z^0 peak at a Luminosity of $4158 nb^{-1}$. Assuming a τ–cross section of $(1.50 \pm 0.03) nb$[6] we finally obtain a branching ratio of $(3.99 \pm 0.43_{stat})\%$.

Of course the efficiency and the background depend from the assumed dynamics of the multi pion state. This needs more study. The efficiency quoted above was calculated using the recently generated 30000 τ pairs with KORL03. For that sample the multi pion states are generated with LUND. No resonances are implemented. I want to show some examples of resonances, which appear in the ALEPH data.

The invariant mass distribution of $\pi^-\pi^+\pi^0$ combinations show a ω resonance which was presented by A. Rouge [4]. For studing the efficiency, a τ–decay routine, contaning the ω resonance was implemented in KORALZ. The routine generates the decay chain

$$\tau^- \to \rho^- \nu \qquad \rho^- \to \omega\pi^- \qquad \omega \to \pi^-\pi^+\pi^0$$

with a ρ–form factor containing $\rho(770)$ and $\rho(1250)$ as proposed by ARGUS [7]. A sample of 1000 events where generated with $\tau^- \to \omega\pi^-\nu$ and $\tau^+ \to X^+\nu$. The efficiency for that sample using our cuts is $(16.4 \pm 1.3)\%$. This tells us, that the correction on the branching ration due to the dynamics is of the order of 0.7%.

There are also ρ^-, ρ^+ and ρ^0 resonances as recently discovered by ARGUS [8]. These resonances can be seen by rejecting ω events, that means if there is a combination of $\pi^-\pi^+\pi^0$ states with a mass between 700MeV and 850MeV then the event will not be used for the following histograms. Fig. 2 shows the mass distribution for different pion pairs. The sign convention for the charge of the pions is $\tau^- \longrightarrow \pi^-\pi^-\pi^+\pi^0\nu$. The ρ^0 resonance is nicely evident whereas the charged ρ signal is poor. The $\pi^-\pi^-$ mass distribution is also shown, but it is clear, that this distribution cannot be used for background subtraction (imagine just a charge two resonance). These histograms give an indication for ρ resonances, which clearly influence our efficiency.

Since we have a Monte Carlo containing the omega resonance the efficency for a selection of $\tau \longrightarrow \omega\pi\nu$ can be calculated. But for getting the branching ratio, also the background has to be estimated, which depends from the dynamics of the four pion states. For instance ρ resonances, which are build up by two pions will have a "omega" mass between 1 and 1.3GeV if the three pions, taken for the "omega" mass contains the two pions from the ρ. So the main background is given by the swamp of unknown hadronic physics.

4 τ–Nutrino mass

The momentum of the three charged π's is calculated by a χ^2–fit of a helix using the coordinates measured by the TPC. The fit is constrained to the beam–crossing point. That means, that we assume the tracks originate from one unknown point and the best estimate for that point is the beam–crossing point. All ITC coordinates are ignored. The main purpose of the refitting is to reduce the number of bad measured tracks. Tracks which are reasonably well measured by the standard fitting are not improved by the constraint fit. The error on the total charged energy is for three prong τ decay of the order of 430MeV and the error on its mass is 50MeV. Fig. 3 show the reconstructed minus the Monte Carlo true energy of the hadronic system for three prong τ decays: 3a) for standard fitting using ITC and TPC, 3b) for fitting after exclusion of ITC coordinates and 3c) for fitting after exclusion of ITC coordinates but adding the vertex constraint. We see that we loose a lot in resolution by excluding the ITC coordinates but we get the good resolution back by constraining the fit to the beam–crossing point. But as said above the tail in the distribution of Fig.3 a is disappeared. The nonzero lifetime of the τ gives an error of only 30MeV to the hadronic energy. The smallness of this number is because the τ travels approximately along the helix. The spread of the beam size $300\mu m \times 60\mu m \times 10.3mm$ induce a ϕ dependence of the error where ϕ is the angle between the track and the plane in which the storage ring lies. The contribution to the error on the energy is of the order of 540MeV, 70MeV and 120MeV for the beam spread in x, y and z. I want to point out, that the contribution of the beam spread to the error on the energy of the hadronic system is reduced by a compensation: if the vertex moves perpendicular to the thrust axis one track gets a large curvature whereas the other two tracks gets a smaller curvature or viceversa.

The error on the energy of the hadronic system can be summarised by

$$\frac{\delta p}{p^2} = (0.30 + 0.17 sin^2\phi)10^{-3}(GeV/c)^{-1} \quad .$$

Similar arguments as described above hold also for the mass of the hadronic system. Of course the exact error depends strongly from the event itself.

The statistical error of the fit is tested by analysing μ–pair events, produced at the Z^0–peak. Selecting them with:

- two tracks with opposite charge
- acolinearity better then $\cos\theta = -0.9975$
- one track with a momentum above 42GeV
- total ECAL energy less then 2GeV
- reasonable pattern in HCAL.

The track for which the cut in the momentum is applied is choosen randomly. The opposite track is analysed. This gives μ–pairs which are almost free of bremsstrahlung. The difference beeween μ– and beam energy show a gaussian distribution with a mean value of -0.045GeV and a r.m.s. of 2.9GeV, which is in good agreement with the Monte Carlo data. Plotting the reconstructed minus the beam energy divided by the calculated error we obtain for ALEPH data and Monte Carlo data a gaussian distribution with a r.m.s of 1.2. This means that the calculated error should be scaled by that factor for ALEPH data and Monte Carlo data.

According to test beam data the resolution in energy, ϕ and θ of ECAL clusters is given in [5]. From that the error on the π^0–energy can be estimated. Comparing reconstructed and Monte Carlo true energy, it can be seen that the reconstructed energy depends from the reconstructed π–mass if two or three photons are found. This can be well corrected by subtracting a term like

$$\frac{\Delta E}{GeV} = 0.0205 \frac{m_\pi}{GeV} - 2.924 \qquad .$$

Plotting this new reconstructed energy minus the Monte Carlo true energy divided by the error for events showing two or three photons, we obtain a gaussian distribution with a width of 1.35. So we should scale the calculated error by that factor. Events where the π^0 is build up by only one photon need a factor 3.7, which means we have to reject these events. The π^0–momentum is calculated by fixing its mass to the Particle Data Group value.

Putting all together we obtain an energy and mass resolution for the 4–π–state of approximately 700MeV and 70MeV. Of course this error depends strongly on the particular event. For the following we also reject events which give an error in the hadronic energy larger then 1GeV or on error in its mass larger then 200MeV.

The neutrino mass is constrained by the two formulars:

$$\begin{aligned} m_\nu^2 &< (m_\tau^2 - m_h^2)(1 - \tfrac{E_h}{E_\tau}) \\ m_\nu &< \tfrac{m_\tau^2 - m_h^2}{2m_\tau} \end{aligned}$$

where h stands for the hadronic system. The τ–energy E_τ is assumed to be equal to the beam energy. The presence of bremsstrahlung can only lead to a higher neutrino mass limit. The hight hadronic mass is also esential for the first formula because the contribution of the error on the hadronic energy to the error on the neutrino mass is smaller for higher hadronic masses. Roughly speeking if $E_h/E_\tau \approx 1$ and $m_\tau - m_h < 100MeV$ the first formula gives a good limit whereas if $m_\tau - m_h < 50MeV$ and $\delta m_h < 50MeV$ the second one is better. Fig. 4 show the hadronic energy divided by the beam energy versus its mass divided by the τ mass. The kinematical limit is also drawn. The most rellevant events are numbered in this plot. There is no event outside the scale of the figure. $(3.1 \pm 1.5)\%$ of the ALEPH data and $(2.1 \pm 0.7)\%$ of the Monte Carlo data are fare outside the kinematical limit, so they well agree. Now let us study events with $E_h/E_\tau > 0.9$ because only these will give a good limit: only they have the chance to have a hight hadronic mass.

Fig. 5 show the distribution of the hadron mass divided by the τ mass for ALEPH and monte carlo data. We are left with 27 events. On our MC–sample we are left with 89 events, 10 of them are A_1–decay mode of the τ with three charged pions and one event belongs to the desiered decay mode but with a decay of one charge pion. MC–events with a hadronic energy higher than the τ mass show an error on m_h which is larger than $m_h - m_\tau$. Event 5 (from ALEPH data) has also a large error on its mass.

At first let us study the calculation of the error. Fig. 6 present the reconstructed minus MC-true energy and mass divided by its error. From the distribution we conclude that the error for the energy (mass) has to be scaled by a factor 1.49 (1.27).

The limit can be calculated as follows. Assuming we have one event with

$$m_0^2 = (m_\tau^2 - m_h^2)(1 - \frac{E_h}{E_\tau})$$

and an error of $\sigma(m_0^2)$ for that mass square. To get a limit m_{lim} at a confidence level of 95% we can choose m_{lim} in such a way that the probability $P(m_\nu^2 > m_{lim}^2)$ that m_ν^2 is greater then m_{lim}^2 is less than 5%. This probability is given by

$$P(m_\nu^2 > m_{lim}^2) = \frac{\int_{m_{lim}^2}^\infty \exp - \frac{(m^2 - m_0^2)^2}{2\sigma(m_0^2)^2} dm^2}{\int_0^\infty \exp - \frac{(m^2 - m_0^2)^2}{2\sigma(m_0^2)^2} dm^2}$$

Fig. 7 shows that probability as a function of m_{lim}^2 for some events.

The square root of m^2_{lim}, for which this probability is 5% gives our limit. Since the events are uncorrelated, the product of $P(m^2_\nu > m^2_{lim})$ of each event gives the confidence level as a function of m^2_{lim} of our data sample (see Fig. 8). From Fig. 8 we get $m^2_{lim} = 0.0059 GeV^2$, so the τ neutrino mass is, up to a confidence level of 95% lower then 77MeV.

Fig. 9 shows the same distribution using the second formula for the limit, which goes linearly in m_ν. We obtain a limit of 78MeV.

Fig. 7 shows that the limit is given by four events. The energies and masses of the hadronic systems are:

Event	$Energy/E_\tau$	$Mass/M_\tau$
1	0.963 ± 0.018	0.985 ± 0.037
2	1.000 ± 0.016	0.904 ± 0.038
3	1.012 ± 0.022	0.868 ± 0.032
4	0.914 ± 0.021	0.976 ± 0.043

Dali pictures of these four events are added at the end of this note.

5 Acknowledgements

I want to thank L. Rolandi for all the discusions about that field, L. Bauerdick for writing the fitting routine, A. Rouge for sending me the π^0–routine and R. Della Marina for studying the influence of the error in momentum resolution for $\tau \rightarrow 3\pi\nu$ coused by the beam spread and finally G. Giannini for carefully reading this note.

References

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Fig 1

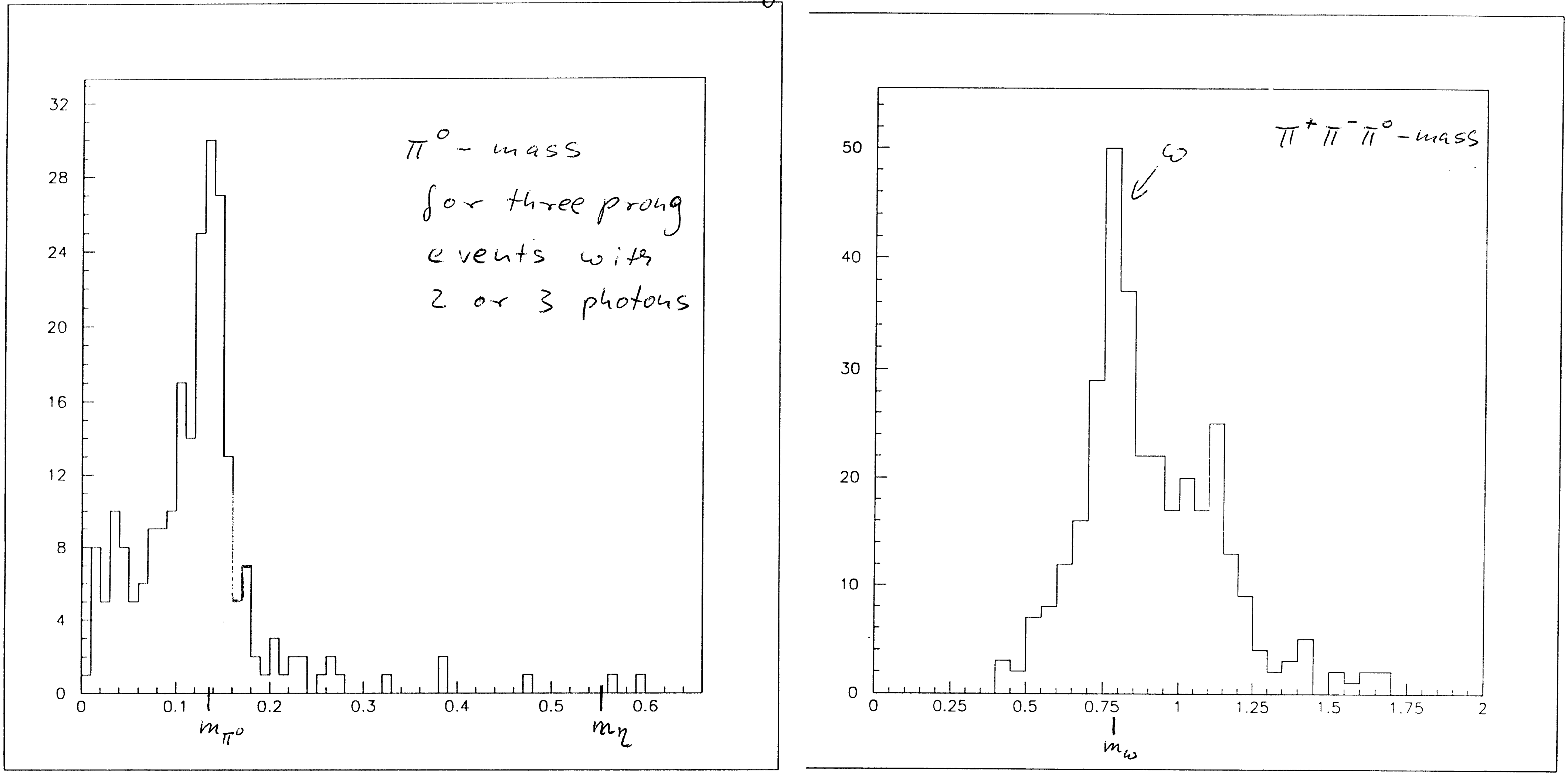

π^0 - mass
for three prong
events with
2 or 3 photons
32
28
24
20
16
12
8
4
0
0
0.1
0.2
0.3
0.4
0.5
0.6
m_{π^0}
m_η
$\pi^+\pi^-\pi^0$ - mass
ω
50
40
30
20
10
0
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
m_ω

Fig 2

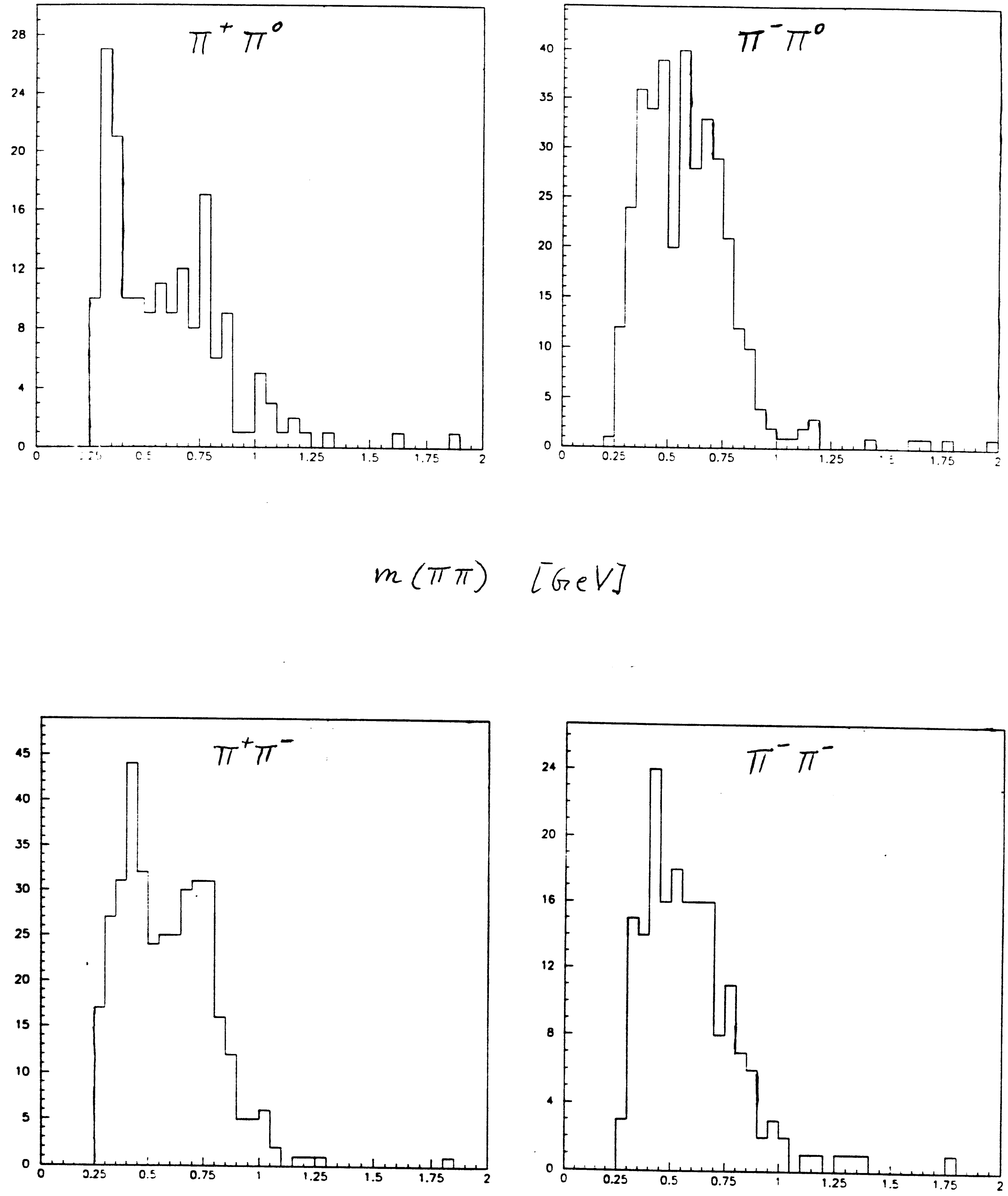
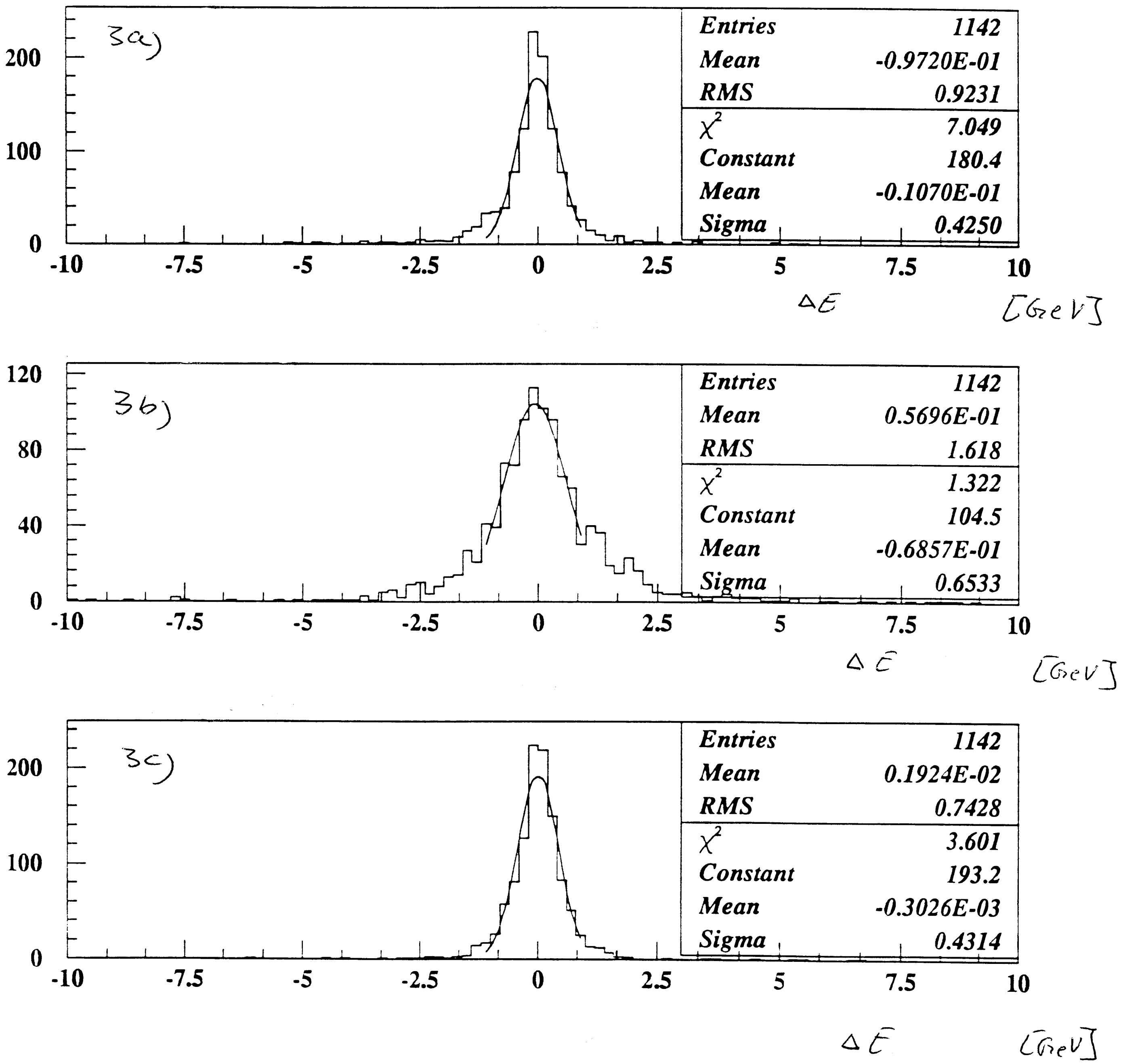

$\pi^+\pi^0$
0
4
8
12
16
20
24
28
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
$\pi^-\pi^0$
0
5
10
15
20
25
30
35
40
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
m(ππ) [GeV]
$\pi^+\pi^-$
0
5
10
15
20
25
30
35
40
45
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
$\pi^-\pi^-$
0
4
8
12
16
20
24
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2

Fig 3


3a)
200
100
0
-10
-7.5
-5
-2.5
0
2.5
5
7.5
10
Entries 1142
Mean -0.9720E-01
RMS 0.9231
χ^2 7.049
Constant 180.4
Mean -0.1070E-01
Sigma 0.4250
ΔE [GeV]
3b)
120
80
40
0
-10
-7.5
-5
-2.5
0
2.5
5
7.5
10
Entries 1142
Mean 0.5696E-01
RMS 1.618
χ^2 1.322
Constant 104.5
Mean -0.6857E-01
Sigma 0.6533
ΔE [GeV]
3c)
200
100
0
-10
-7.5
-5
-2.5
0
2.5
5
7.5
10
Entries 1142
Mean 0.1924E-02
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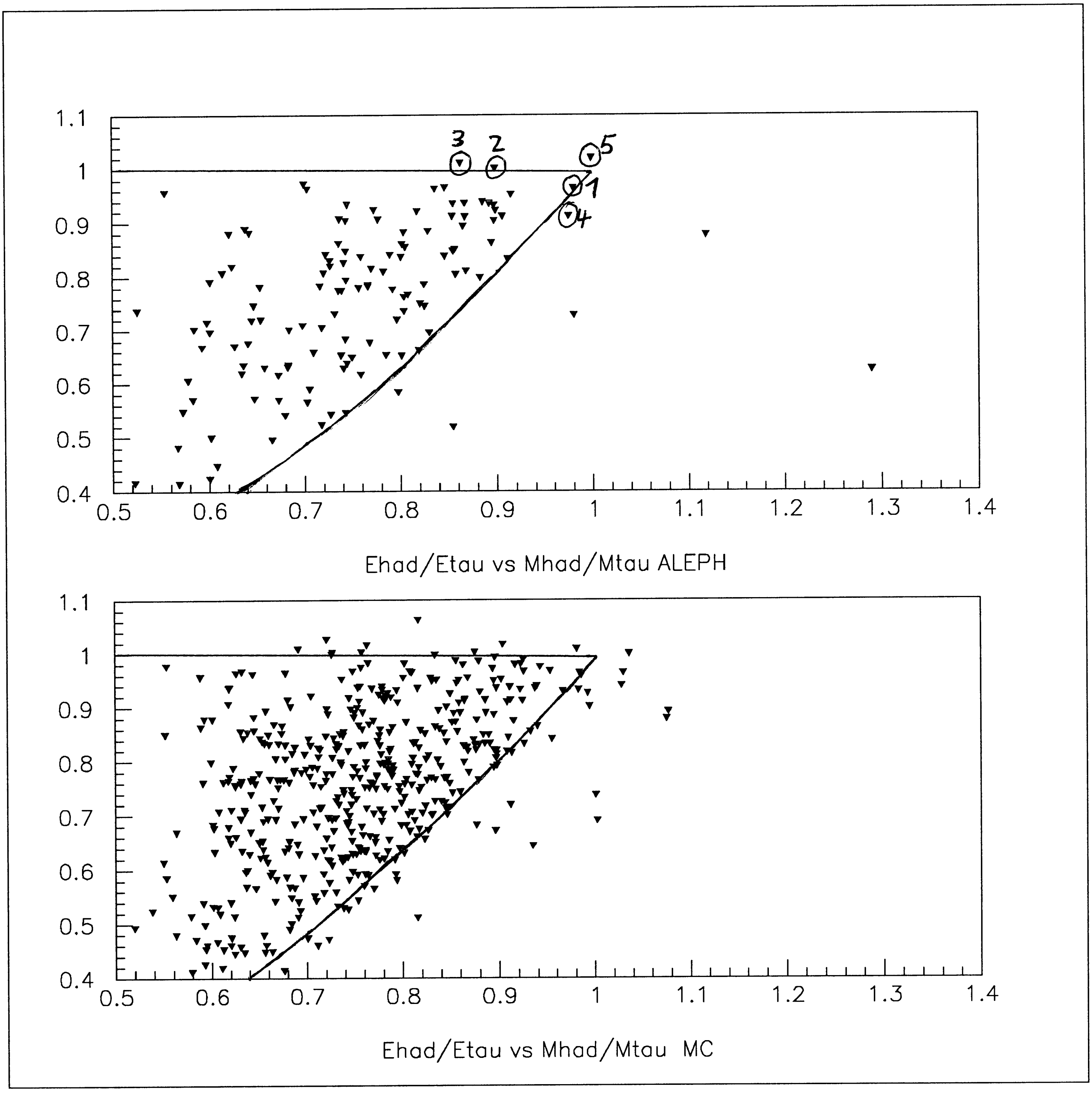
χ^2 3.601
Constant 193.2
Mean -0.3026E-03
Sigma 0.4314
ΔE [GeV]

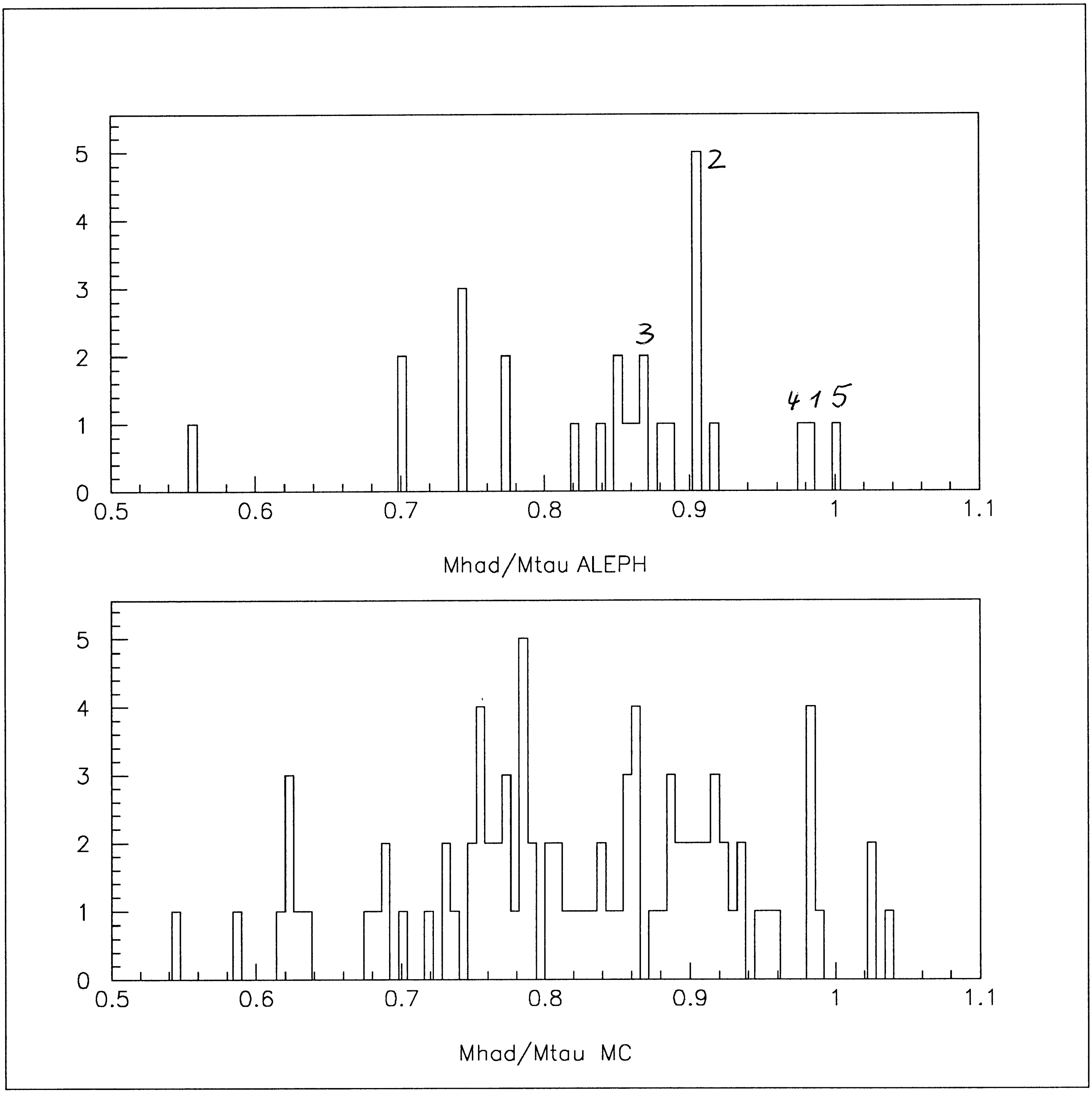
Fig 4



Ehad/Etau vs Mhad/Mtau ALEPH

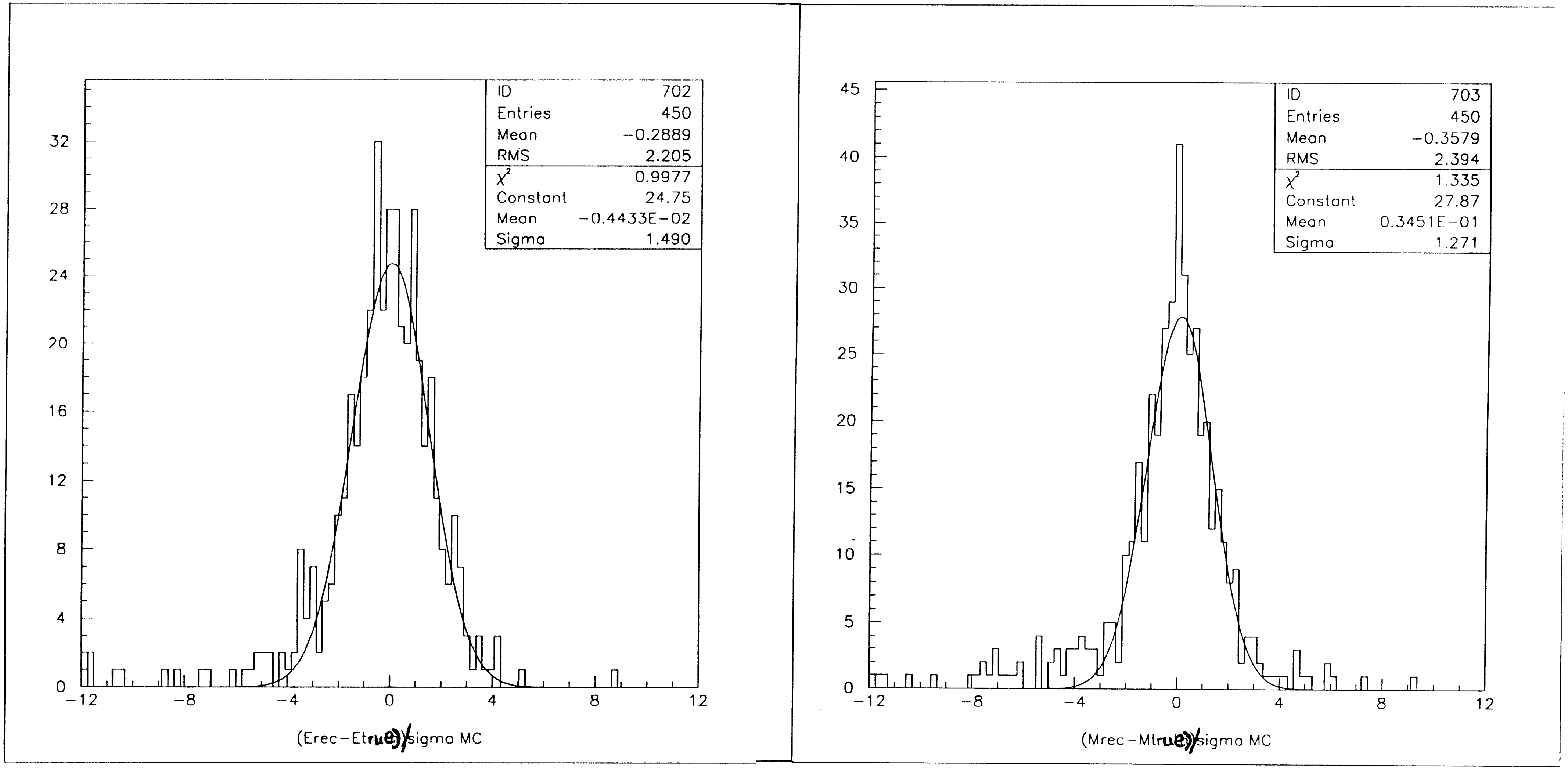
Ehad/Etau vs Mhad/Mtau MC

Fig 5



0
1
2
3
4
5
0.5
0.6
0.7
0.8
0.9
1
1.1
2
3
4 1 5
Mhad/Mtau ALEPH
0
1
2
3
4
5
0.5
0.6
0.7
0.8
0.9
1
1.1
Mhad/Mtau MC

Fig. 6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RMS 2.205
χ^2 0.9977
Constant 24.75
Mean −0.4433E−02
Sigma 1.490
32
28
24
20
16
12
8
4
0
−12
−8
−4
0
4
8
12
(Erec−Etrue)/sigma MC
ID 703
Entries 450
Mean −0.3579
RMS 2.394
χ^2 1.335
Constant 27.87
Mean 0.3451E−01
Sigma 1.271
45
40
35
30
25
20
15
10
5
0
−12
−8
−4
0
4
8
12
(Mrec−Mtrue)/sigma MC

Fig 7

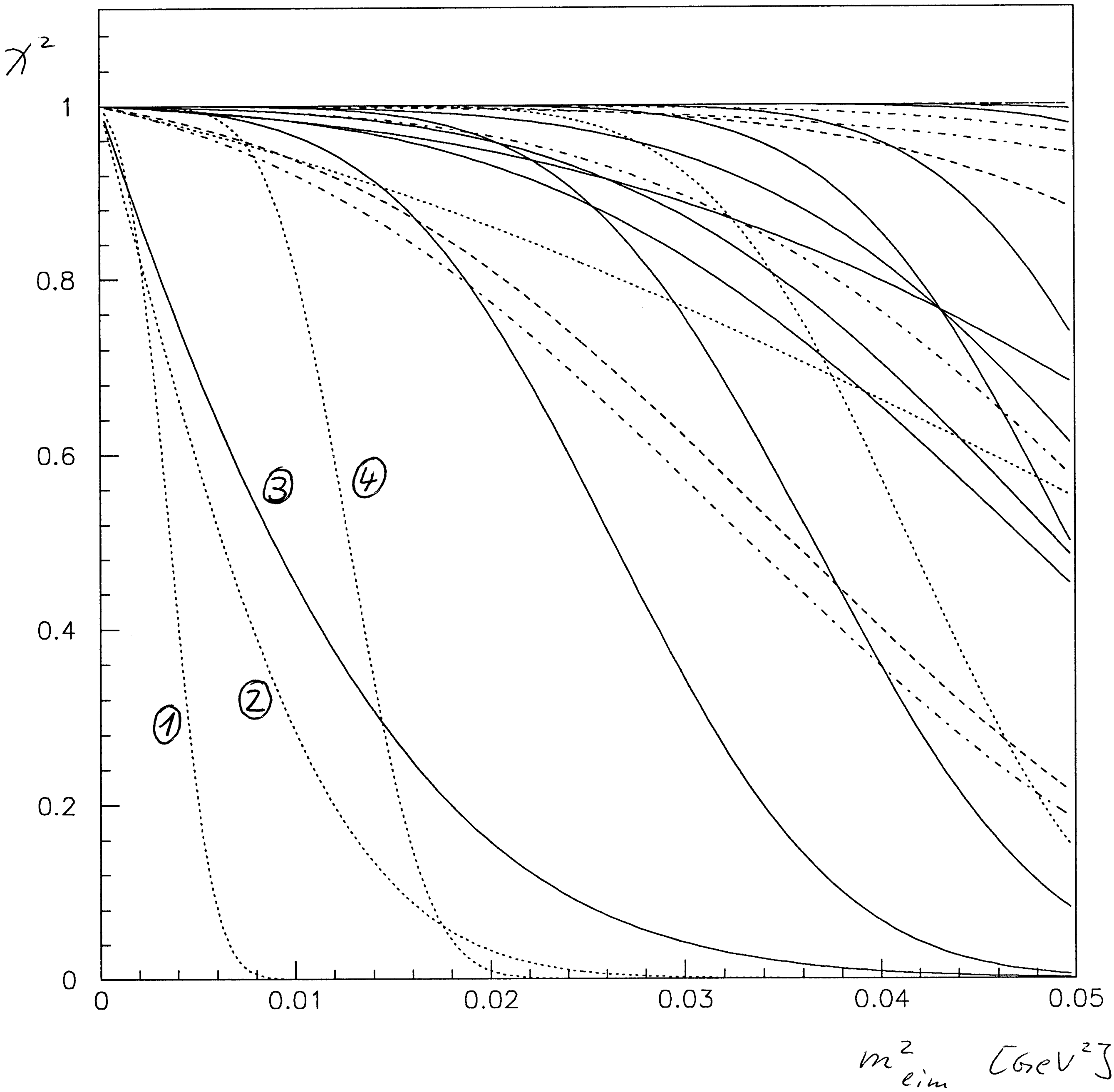
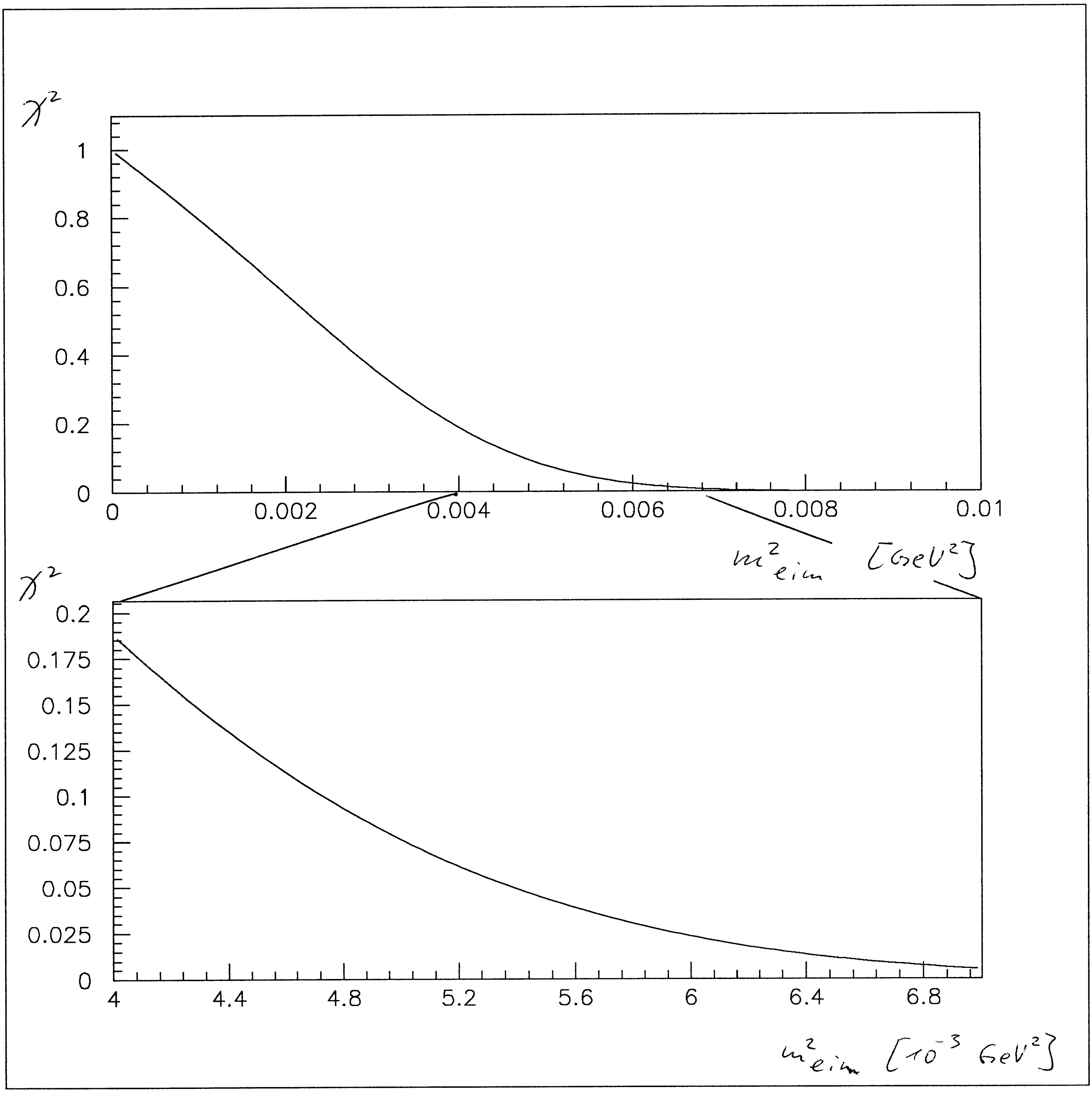
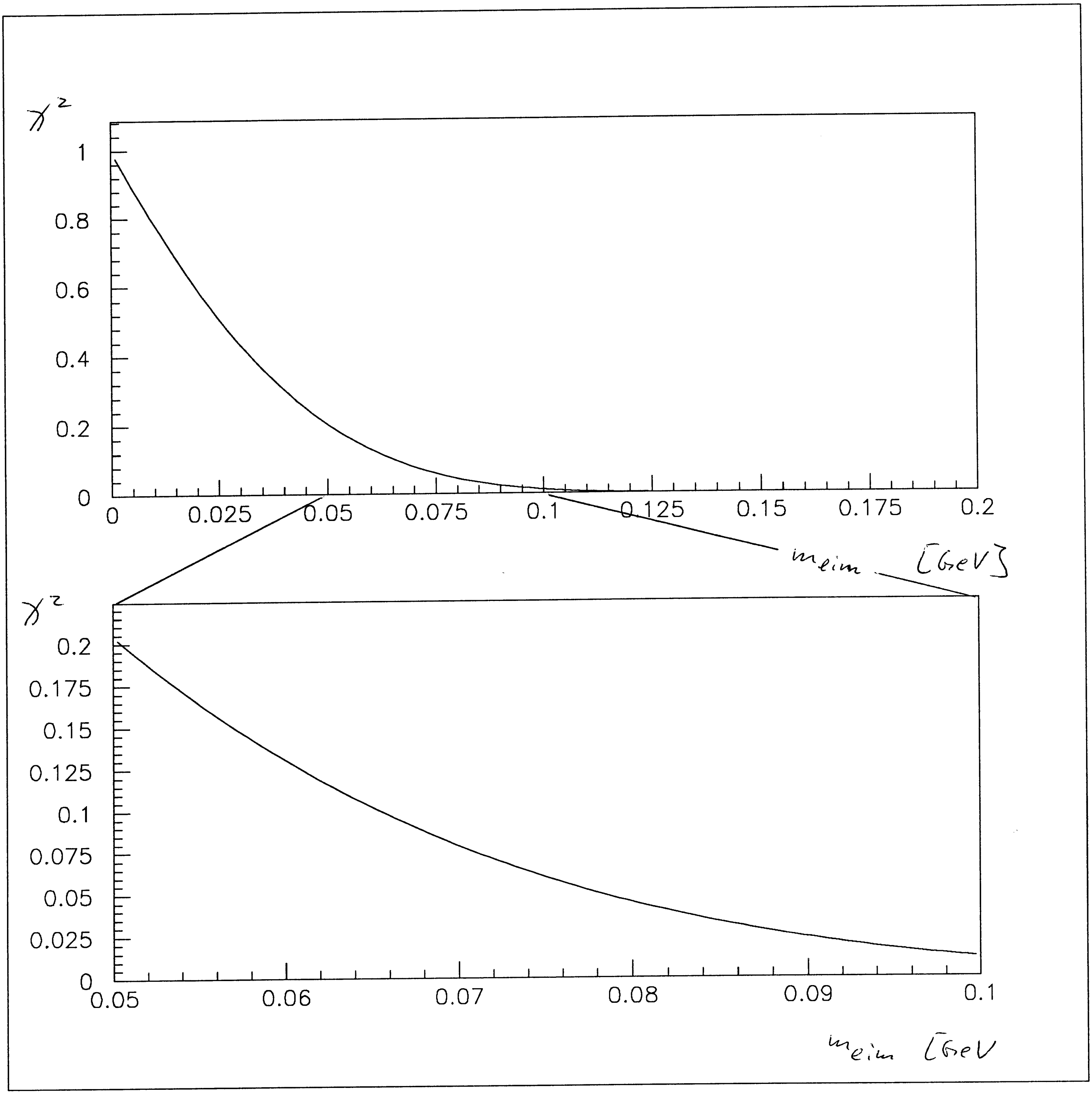


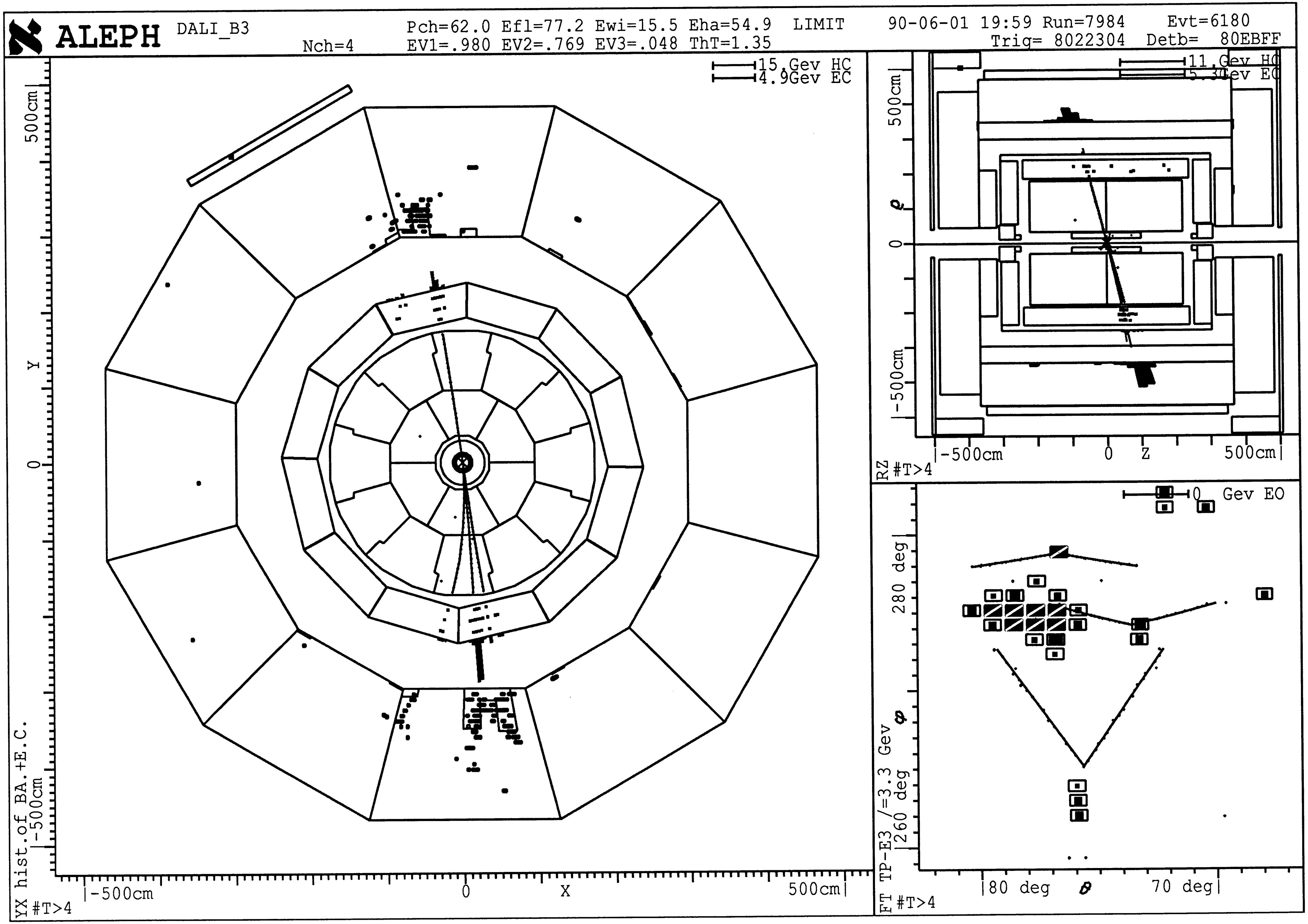
Fig 8



χ^2
1
0.8
0.6
0.4
0.2
0
0
0.002
0.004
0.006
0.008
0.01
m^2_{eim} [GeV^2]
χ^2
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
4
4.4
4.8
5.2
5.6
6
6.4
6.8
m^2_{eim} [10^{-3} GeV^2]

Fig. 9


χ^2
1
0.8
0.6
0.4
0.2
0
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
meim [GeV]
χ^2
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
0.05
0.06
0.07
0.08
0.09
0.1
meim [GeV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Pch=62.0 Efl=77.2 Ewi=15.5 Eha=54.9 LIMIT
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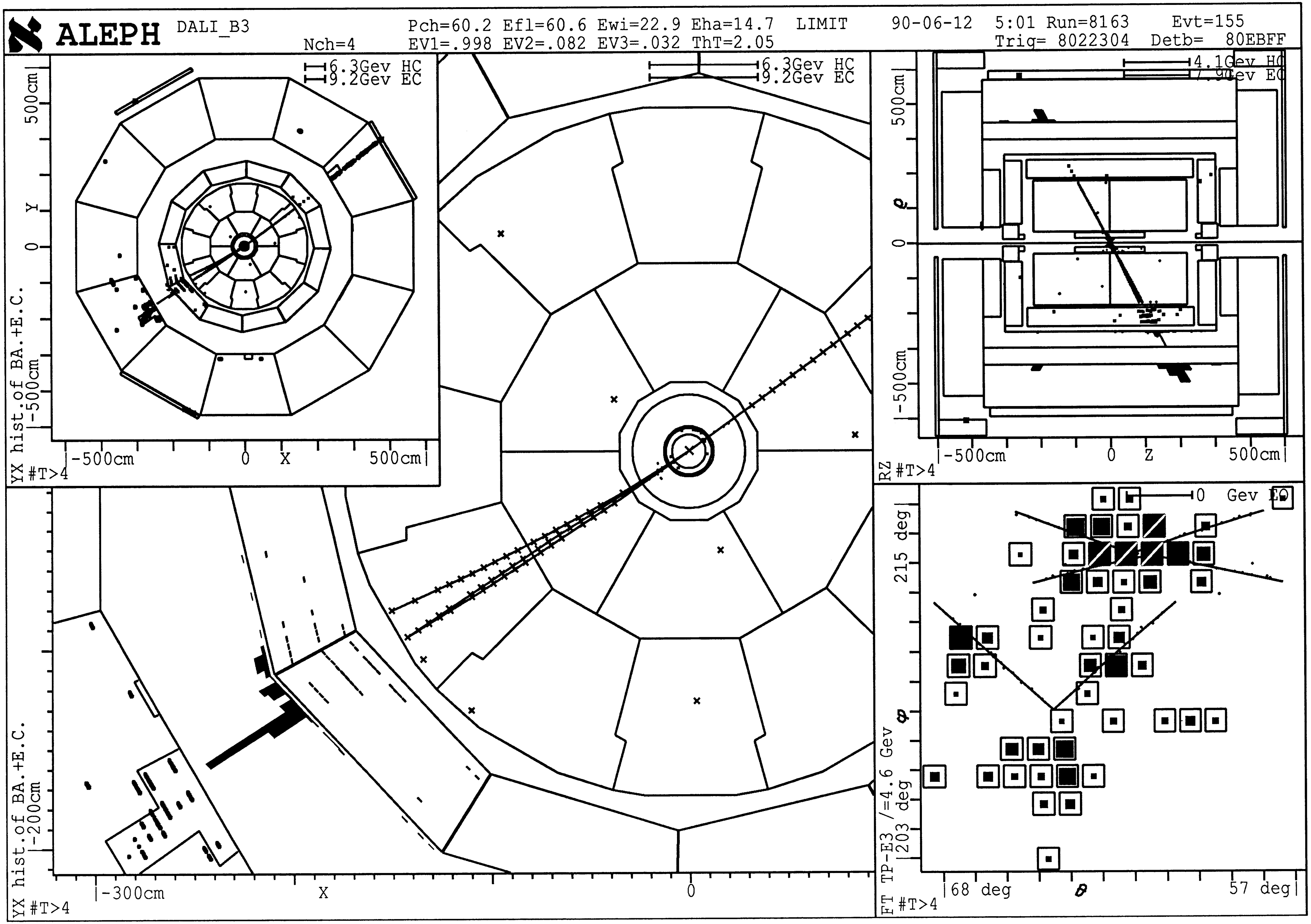
90-06-01 19:59 Run=7984 Evt=6180
Trig= 8022304 Detb= 80EBFF
15.Gev HC
4.9Gev EC
500cm
Y
0
|-500cm
YX hist.of BA.+E.C.
YX #T>4
|-500cm
0
X
500cm|
11.Gev HC
5.3Gev EC
500cm
ρ
0
|-500cm
RZ #T>4
|-500cm
0
Z
500cm|
0 Gev EO
280 deg
φ
TP-E3 /=3.3 Gev
|260 deg
FT #T>4
|80 deg
θ
70 deg|

Event 1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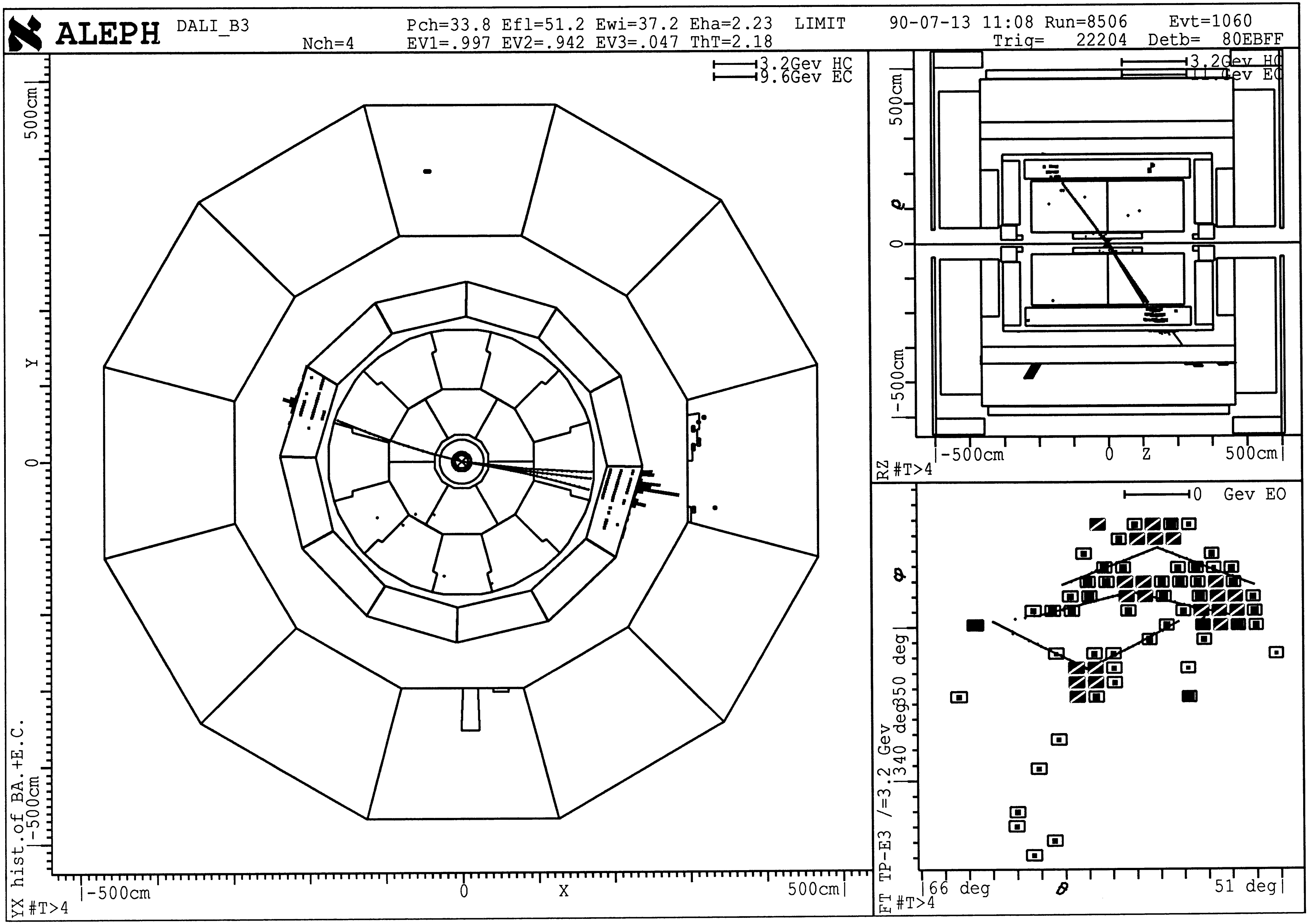
90-06-12 5:01 Run=8163 Evt=155
Trig= 8022304 Detb= 80EBFF
6.3Gev HC
9.2Gev EC
500cm
Y
0
-500cm
YX hist.of BA.+E.C.
#T>4
|-500cm
0 X
500cm|
4.1Gev HC
7.9Gev EC
ρ
RZ #T>4
Z
-200cm
|-300cm
X
0
0 Gev EO
215 deg
φ
203 deg
FT TP-E3 /=4.6 Gev
68 deg
θ
57 deg

Event 2


ALEPH
DALI_B3
Nch=4
Pch=33.8 Efl=51.2 Ewi=37.2 Eha=2.23 LIMIT
EV1=.997 EV2=.942 EV3=.047 ThT=2.18
90-07-13 11:08 Run=8506 Evt=1060
Trig= 22204 Detb= 80EBFF
3.2Gev HC
9.6Gev EC
500cm
Y
0
-500cm
YX hist.of BA.+E.C.
#T>4
-500cm
0
X
500cm
3.2Gev HC
11.6Gev EC
500cm
ρ
0
-500cm
RZ #T>4
-500cm
0
Z
500cm
0 Gev EO
φ
340 deg350 deg
FT TP-E3 /=3.2 Gev
#T>4
66 deg
θ
51 deg

Event 4