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Search for Single Top Production in e^+e^- Annihilations at $\sqrt{s} = 189\ GeV$

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Search for Single Top Production in e^+e^- annihilations at $\sqrt{s} = 189\ GeV$

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Abstract

A search for events with two jets and at least one isolated lepton was performed using data taken at LEP-2 by the DELPHI detector. These data were accumulated at a center-of-mass energy of 189 GeV and correspond to an integrated luminosity of 153.0 pb^{-1}. A search for top-charm flavour changing neutral currents ($e^+e^- \rightarrow t\bar{c}, t\bar{u}$ or charge conjugate) used the semileptonic decay channel. A limit on the flavour changing cross-section via neutral currents was set at 95% confidence level.

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1 Introduction

In e^+e^- colliders such as LEP, searches for new physics can be made with high sensitivity in places where the expected Standard Model (SM) contributions are small. Single top production via Flavour Changing Neutral Currents ($e^+e^- \to t\bar{c}(t\bar{u})$) is a good example of such processes. In this note we report on a topological search for events in this channel.

In the SM, Flavour Changing Neutral Currents (FCNC) are absent at tree level. Neutral currents such as $e^+e^- \to t\bar{c}(\bar{u})$ can be present at the one loop level, but the rates are severely supressed [1].

Flavour changing vertices are present in many extensions of the SM like supersymmetry [2], multi-Higgs doublet models [3] and anomalous t-quark production [4], which could enhance the production of top quarks. For instance, in the SM the $t \to cZ$ branching ratio is around 10^{-13} while in the context of a two Higgs doublet model without natural flavour conservation the rates can be higher by more than six orders of magnitude [3], depending on the chosen parameters.

At tree level, single top production is possible via FCNC anomalous couplings ($e^+e^- \to t\bar{c}(\bar{u})$) [4]. The corresponding Feynman diagram is shown in figure 1. The $t \to cZ$ and $t \to c\gamma$ vertices are described by two anomalous coupling constants k_Z and k_γ respectively. Present constraints from LEP–2 data were set [4] at ($m_t = 175$ GeV/c^2) $k_\gamma^2 < 0.176$ and $k_Z^2 < 0.533$.

In single top production at LEP, the $t\bar{c}(\bar{u})$ pair should be produced almost at rest once the top mass is close to the centre-of-mass energy. The top quark decays subsequently to a b quark and a W. Only leptonic decays of the W are searched for in this report. The searched signal is an almost background free signature characterised by two jets with one isolated charged lepton. At the present centre of mass energy one of the jets should be of low momentum (the $c(u) - quark$) and the other one energetic (the $b - quark$).

2 The DELPHI Detector and Data Samples

A detailed description of the DELPHI detector, its performance, the triggering conditions and the readout chain can be found in reference [5]. This analysis relies on the charged particle detection provided by the tracking system and energy reconstruction provided by the electromagnetic and hadronic calorimeters.

The main tracking detector of DELPHI is the Time Projection Chamber, which covers the angular range $20^\circ < \theta < 160^\circ$, where θ is the polar angle defined with respect to the beam direction. Other detectors contributing to the track reconstruction are the Vertex Detector (VD), the Inner and Outer Detectors and the Forward Chambers. The VD consists of three cylindrical layers of silicon strip detectors, each layer covering the full azimuthal angle.

Electromagnetic shower reconstruction is performed in DELPHI using the barrel and the forward electromagnetic calorimeters, including the STIC (Small angle TIle Calorimeter), the DELPHI luminosity monitor. Hadronic energy reconstruction is performed by the hadronic calorimeter which covers both the barrel and forward regions.

The effects of experimental resolution, both on the signal and on backgrounds, were studied by generating Monte Carlo events for the $t\bar{c}(\bar{u})$ signal and for the SM processes, and passing them through the full DELPHI simulation and reconstruction chain.

Three different sets of Monte Carlo data were generated for the signal assuming a top quark mass of $170 GeV/c^2$, $175 GeV/c^2$ and $180 GeV/c^2$ respectivelly. Initial state radiation (ISR) was taken into account at the generation level.

Bhabha events were simulated with the Berends, Hollik and Kleiss generator [6]. PYTHIA [7] was used to simulate $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to Z\gamma$, $e^+e^- \to W^+W^-$, $e^+e^- \to W^\pm e^\mp \nu$, $e^+e^- \to ZZ$, and $e^+e^- \to Ze^+e^-$ events. In all four fermion channels, studies with the EXCALIBUR generator [8] were also performed. The two-photon ("$\gamma\gamma$") physics events were simulated using the TWOGAM [9] generator for quark channels and the Berends, Daverveldt and Kleiss generator [10] for the electron, muon and tau channels.

Data corresponding to an integrated luminosity of 153.0 pb^{-1} were collected at a centre-of-mass energy $\sqrt{s}$ of 189 GeV.

3 Event Selection

This analysis looks for events with two jets. One of the jets is considered to be energetic and the other one is assumed to be of low momentum. The $t\bar{c}(\bar{u})$ decays also require an isolated charged lepton (from the W decay) to be present in the event.

Charged particles were considered only if they had momentum greater than 0.1 GeV/c and impact parameters in the transverse plane and in the beam direction below 4 cm and 10 cm respectively. Neutral clusters were defined as energy depositions in the calorimeters unassociated with charged particle tracks. All electromagnetic (hadronic) neutrals of energy above 100 MeV (1 GeV) were selected. In the present analysis the minimum required charged multiplicity was seven.

Charged particles were considered isolated if, in a double cone centred on their track with internal and external half angles of 5° and 25°, the total energy associated to charged and neutral particles was below 1 GeV and 2 GeV respectively. The energy of the particle was redefined as the sum of the energies of all the charged and neutral particles inside the inner cone. This energy was required to be greater than 4 GeV. No other charged particle was allowed inside the inner cone.

Energy clusters in the electromagnetic calorimeters were considered to be from photons if there were no tracks pointing to the cluster, there were no hits inside a 2° cone in more than one layer of the Vertex Detector and if at least 90% of any hadronic energy was deposited in the first layer of the hadron calorimeter. Photons were considered to be isolated if, in a double cone centred on the cluster and having internal and external half angles of 5° and 15°, the total energy deposited was less than 1 GeV. The energy of the photon was redefined as the sum of the energies of all the particles inside the inner cone and no charged particles above 250 MeV/c were allowed inside this cone.

All charged and neutral particles (excluding any isolated charged lepton or photon) were forced into two jets using the Durham jet algorithm [11]. A jet was classified as charged if it contained at least one charged particle.

A detailed description of the basic selection criteria can be found in reference [12]. Isolated charged particles were identified as leptons if there were associated hits in the Vertex Detector. No sellection criteria was applied to distinguish among the different lepton flavours.

The following criteria were applied to the events (level 1):

- the total visible energy was required to be larger than $0.2\sqrt{s}$;
- the momentum of the most energetic jet, required to be a charged one, had to be larger than 30 GeV/c;
- the momentum of the most energetic isolated charged lepton had to be greater than 5 GeV/c.

In Figure 2 is represented after level 1, the most energetic lepton momentum (a), the most energetic jet momentum (b) and the angle between them (c), together with the SM simulation and the expected signal behaviour. The dots show the data (1159 events), the shaded region the SM simulation (1122.50 $\pm$ 17.73) and the dark region the expected signal behaviour (for a $175 GeV/c^2$ top quark mass).

After this selection, more specific criteria (level 2) were applied to the events. For each cut a comparison between data and Monte Carlo is shown (from Figure 3 to Figure 8) together with the expected signal behaviour, after all previous cuts were applied to the events (and before applying the specific cut under study). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) the expected signal behaviour for a $175 GeV/c^2$ top quark mass. These criteria were (level 2):

- The ratio between the most energetic jet electromagnetic energy and its total energy had to be smaller than 0.95. This removes most Bhabha events. In Figure 3 is represented this ratio (just before the cut).
- The most energetic jet polar angle had to be between 10° and 170°. In Figure 4 is represented the jet polar angle (just before the cut).
- The polar angle of the least energetic jet (required to be a charged jet) had to be between 10° and 170° and its momentum had to be lower than 20.0 GeV/c. In Figure 5 (Figure 6) is represented the jet polar angle (the momentum distribution) just before the cut.
- The polar angle of the missing momentum had to be between 15° and 165°. In Figure 7 is represented the missing momentum polar angle just before the cut.
- Events with a B hadron decay were selected by requiring the event b-tag variable [13] to be below 0.10. In Figure 8 is represented the b-tag variable (just before the cut).

In Figure 9 is represented after level 2, the most energetic lepton momentum (a), the most energetic jet momentum (b) and the angle between them (c), together with the SM simulation and the expected signal behaviour. The dots show the data (39 events), the shaded region the SM simulation (41.49$\pm$3.41 events) and the dark region the expected signal behaviour (for a $175 GeV/c^2$ top quark mass). The background is essentially dominated by WW (21.48$\pm$2.51) and $q\bar{q}$ (15.59$\pm$2.23) events.

A kinematical fit to the events was performed assuming they were compatible with a topology of two jets, one lepton and one neutrino. Just for the sake of comparison, in Figure 10 (Figure 11) is represented the chi-square distribution for the tested hypothesis (mass of the two jets, after a loose chi-square cut of 7) after level 1. The dots show the data, the shaded region the SM simulation and the dark region (top right picture) the expected signal behaviour for a $175 GeV/c^2$ top quark mass. One can clearly see the WW contribution for the overall background.

Additional criteria (level 3) were applied in order to further reduce the contamination from background events, mostly $q\bar{q}$ and WW. For each cut a comparison between data and Monte Carlo is shown (from Figure 12 to Figure 15) after applying level 2 selection criteria. The dots show the data, the shaded region the SM simulation and the dark region (top right picture) the expected signal behaviour for a $175 GeV/c^2$ top quark mass. These criteria were the following:

- The value of the kinematical fit chi-square was required to be lower then 7 and the two jet invariant mass had to be lower then 60 GeV/c^2. In Figure 12 (Figure 13) is represented the chi-square distribution for the tested hypothesis (mass of the two jets, after a loose chi-square cut of 7) after level 2.
- The polar angle of the most energetic lepton had to be between 20° and 160°, and the angle between the lepton and the most energetic jet had to be lower than 165°. In Figure 14 (Figure 15) is represented the most energetic lepton polar angle (the angle between the lepton and the most energetic jet) after level 2.

In table 1 the number of events which survived the different levels of selection is shown, together with the expected SM background.

No events were found on data after the selection of level 3. The number of expected background events is 1.00 ± 0.45. The highest background contribution is due to WW events (see table 2).

	FCNC *ChargedDecay* *Data(SM)*
Level 1	1159 (1122.50 ± 17.73)
Level 2	39 (41.49 ± 3.41)
Level 3	0 (1.00 ± 0.45)

Table 1: Number of selected data events and expected SM contributions at different levels of selection criteria.

The signal efficiencies for the three simulated top quark mass values ($170 GeV/c^2$, $175 GeV/c^2$ and $180 GeV/c^2$) are represented in table 3.

4 Results for Single Top Production via FCNC

In the present analysis no events were found while the expected SM background is 1.00 ± 0.45. The detection efficiency convoluted with the W leptonic branching ratio is $6.23 \pm 0.55\%$, $6.62 \pm 0.57\%$ and $7.14 \pm 0.59\%$ for a top quark mass of $170 GeV/c^2$, $175 GeV/c^2$ and $180 GeV/c^2$ respectivelly.

	Events	Error
W^+W^-	0.59	0.42
Ze^+e^-	0.19	0.11
$\tau^+\tau^-$	0.12	0.12
$We\nu$	0.11	0.06
$Total$	1.00	0.45

Table 2: Standard Model background contributions for the FCNC search at level 3.

m_{top} (Gev/c^2)	$\epsilon \times \Gamma_{W \to l\nu}$ (%)	Error (%)
170	6.23	0.55
175	6.62	0.57
180	7.14	0.59

Table 3: Signal efficiencies (convoluted with the W leptonic decay width) assuming different top quark masses. Initial state radiation is taken into account at the generation level.

With the present luminosity of 153.0 pb^{-1} it is possible to set a conservative upper limit on the $e^+e^- \to t\bar{c}(\bar{u})$ Flavour Changing Neutral Current cross section at 0.3pb (95% confidence level).

5 Conclusions

A search for $e^+e^- \to t\bar{c}(\bar{u})$ flavour changing neutral currents was performed using the W leptonic decay channel ($t \to bW, W \to l\nu_l$). No signal was found in the data. The expected SM background is 1.00 ± 0.45 mostly due to WW events.

A conservative limit on the FCNC cross-section was set at 0.3pb (95% confidence level).

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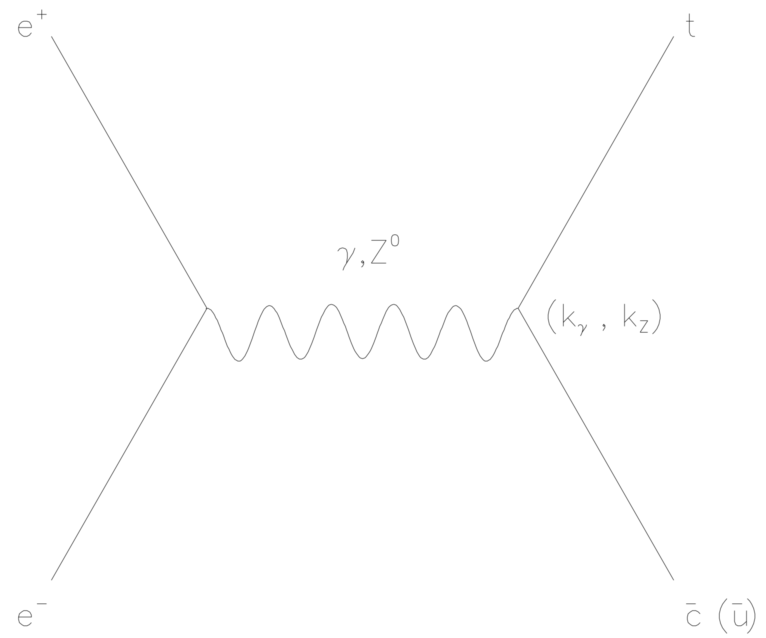

Figure 1: The single top production via FCNC in e^+e^- collisions.

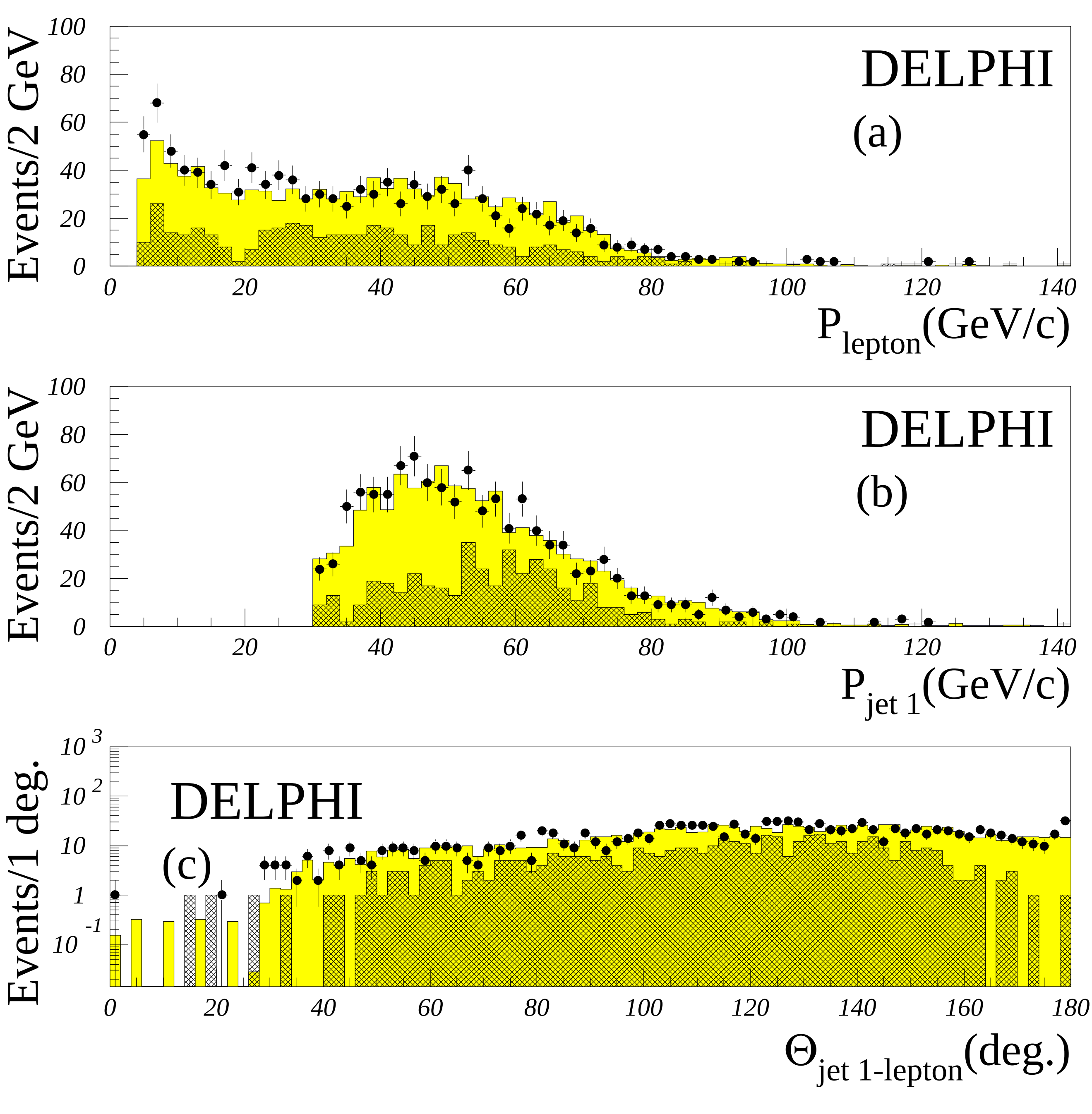

Figure 2: FCNC search after Level 1: the most energetic lepton momentum (a), the most energetic charged jet momentum (b) and the angle between them (c). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

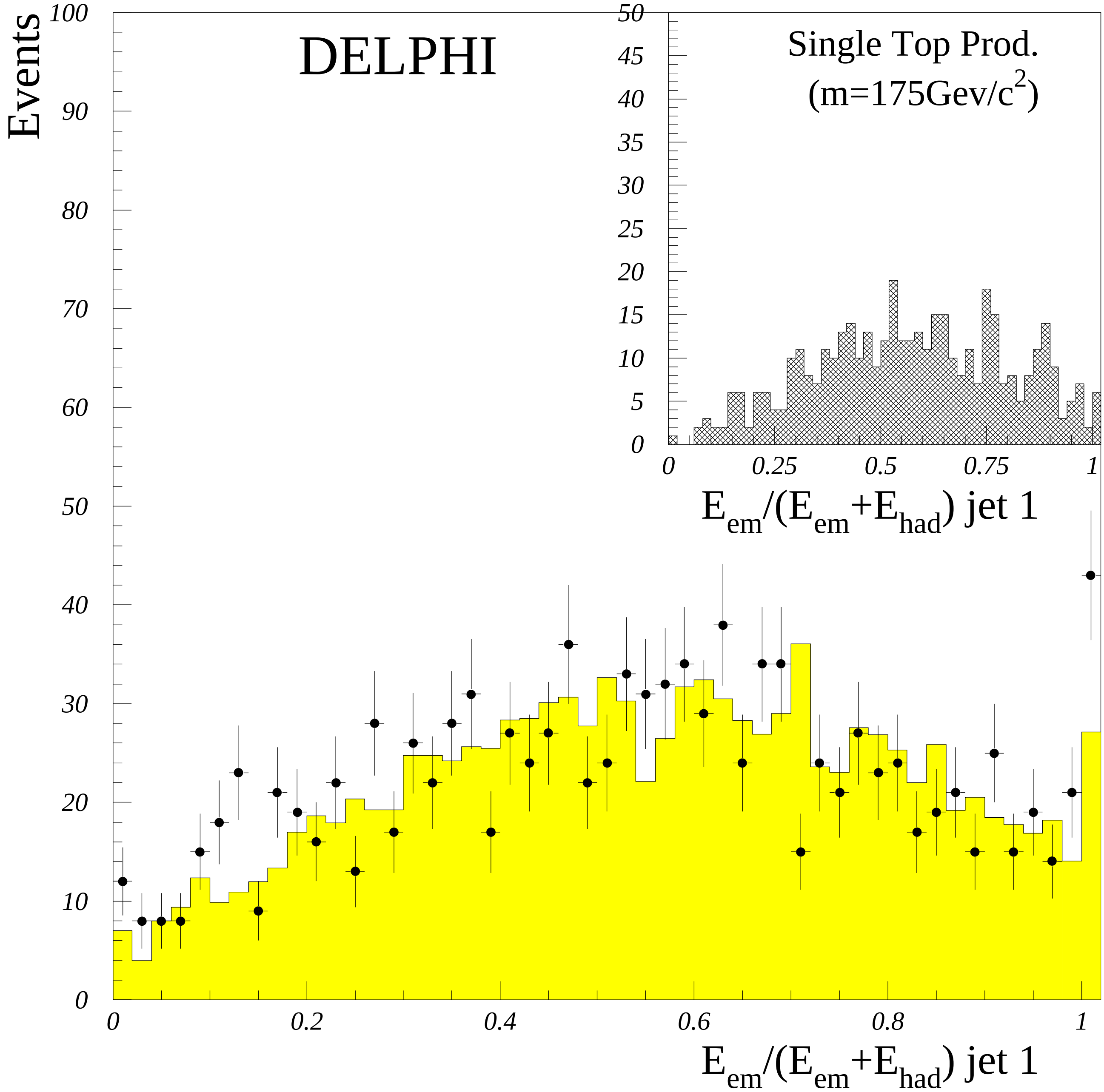

Figure 3: FCNC search: the ratio between the jet electromagnetic energy and its total energy for the most energetic jet (just before the sellection, see text). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

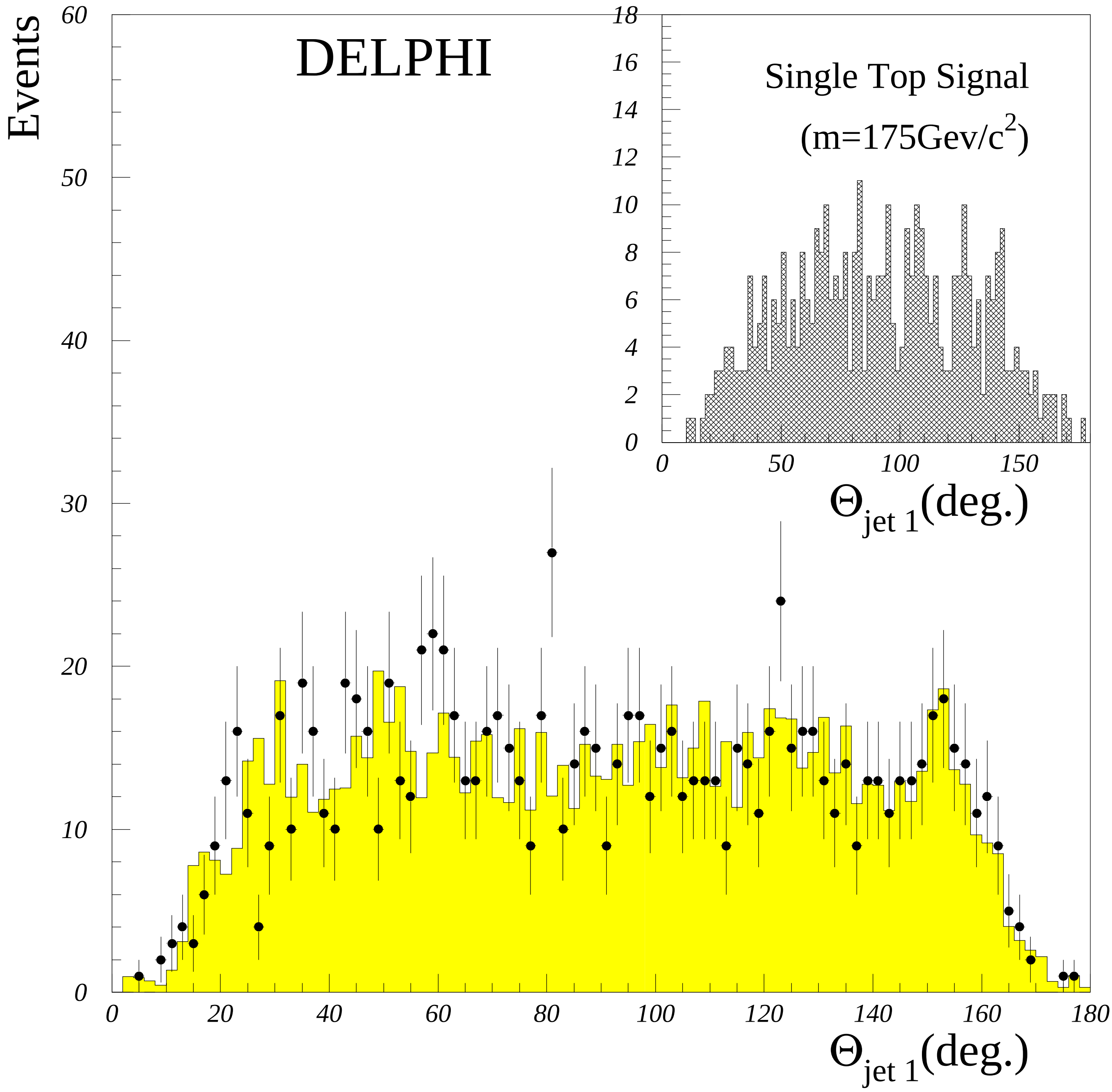

Figure 4: FCNC search: the most energetic jet polar angle (just before the sellection, see text). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

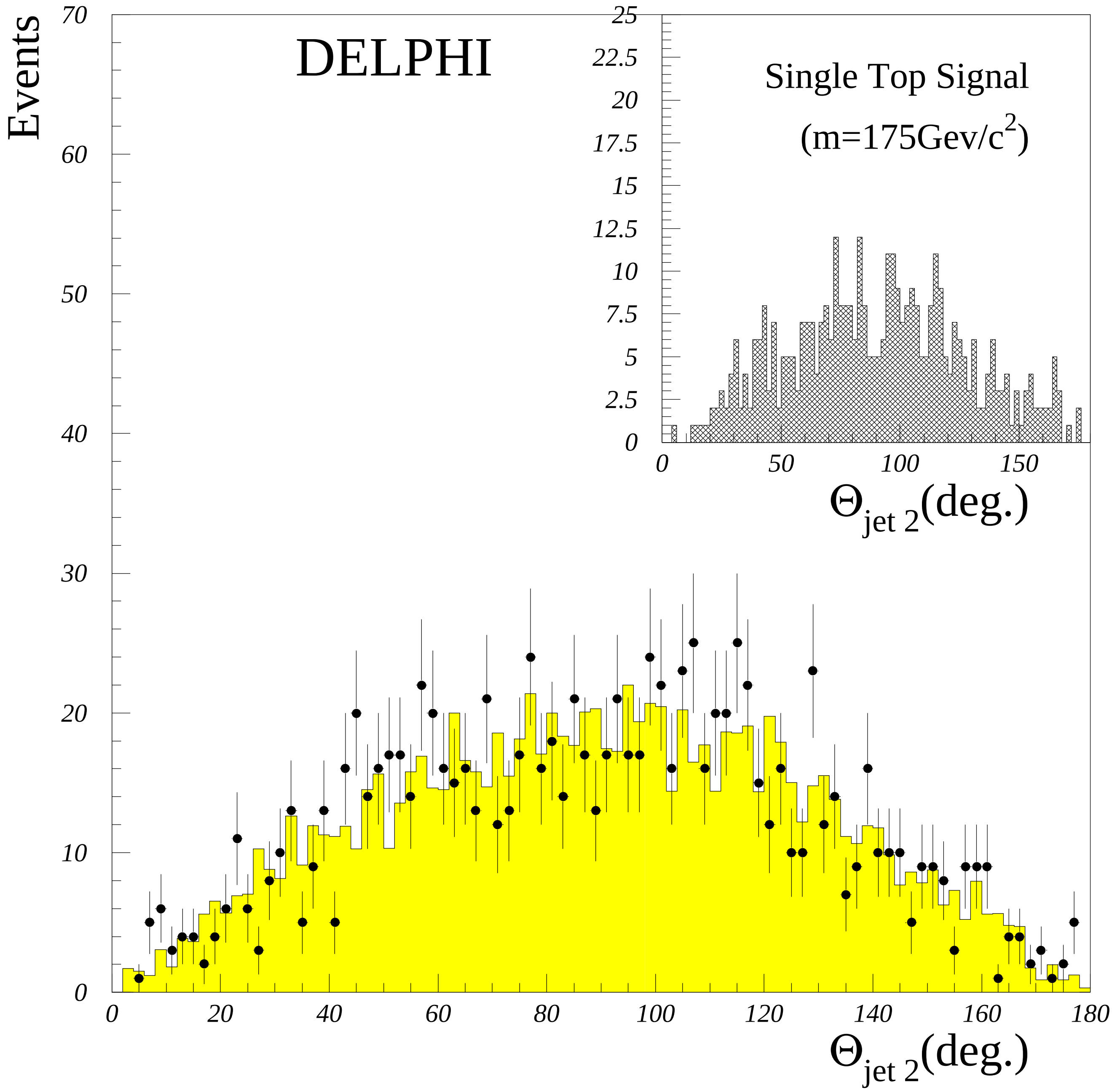

Figure 5: FCNC search: the least energetic jet polar angle (just before the sellection, see text). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

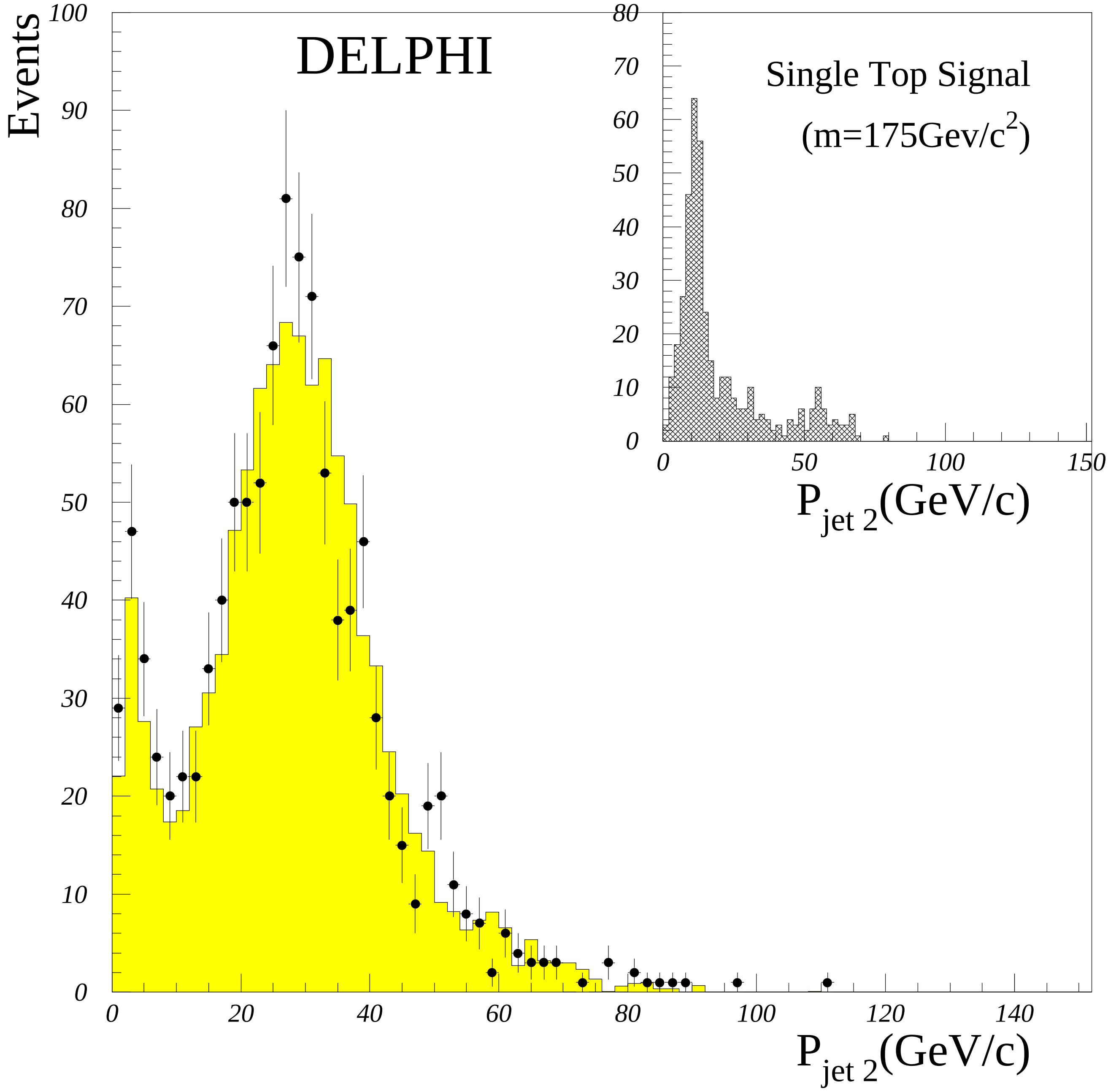

Figure 6: FCNC search: the least energetic jet momentum (just before the sellection, see text). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

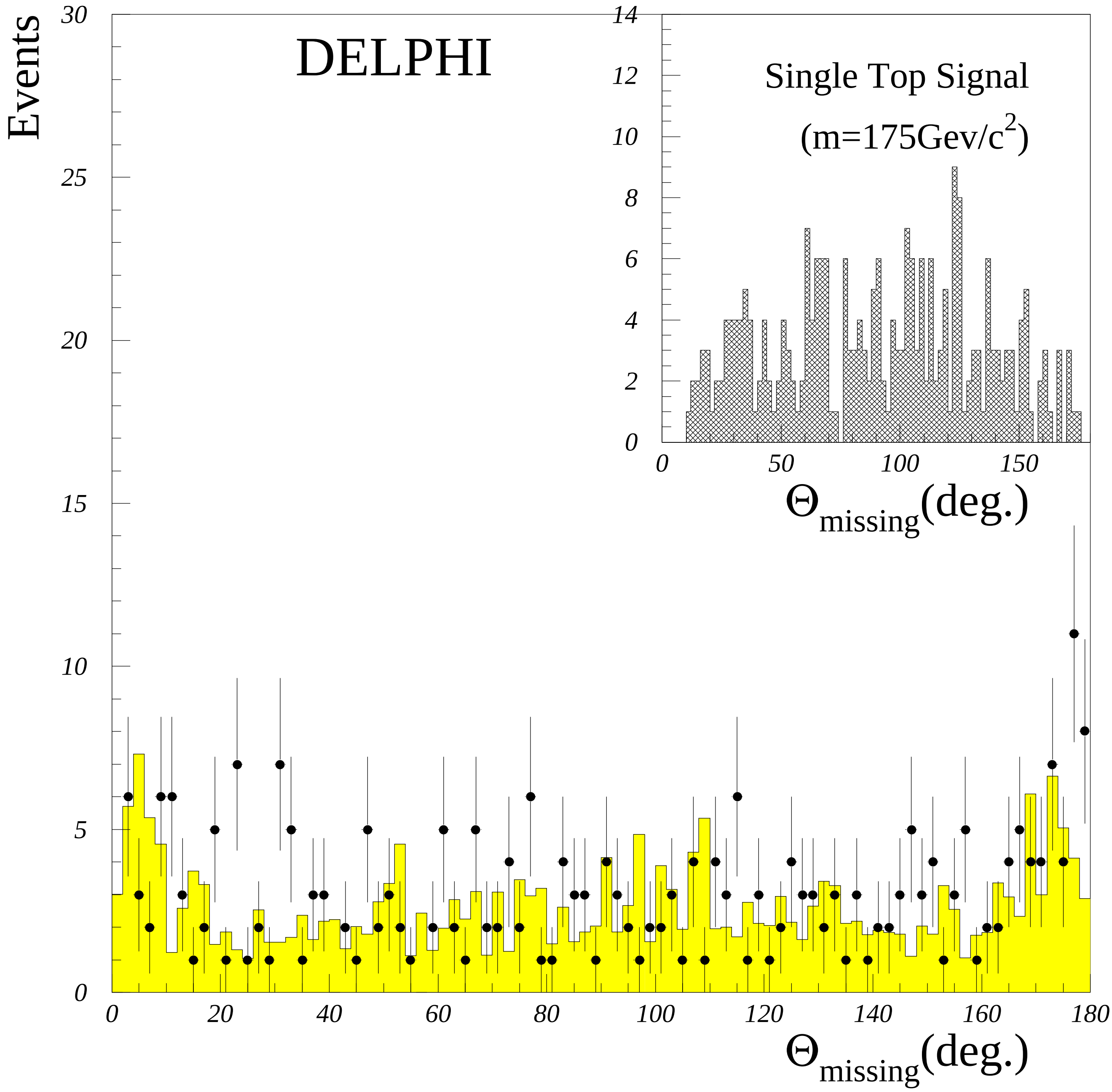

Figure 7: FCNC search: the missing momentum polar angle. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

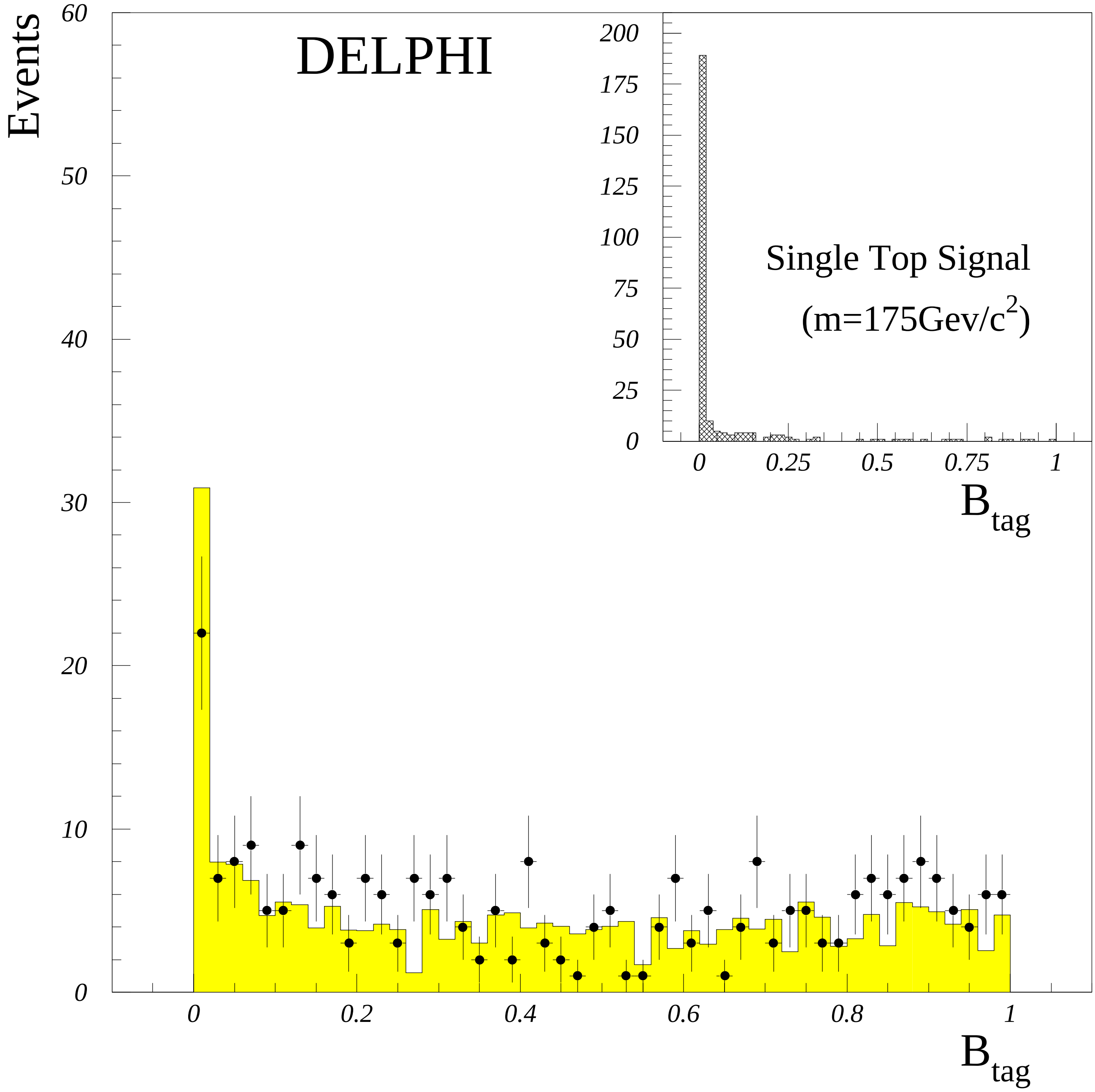

Figure 8: FCNC search: the event b-tag variable [13] (just before the sellection, see text). The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

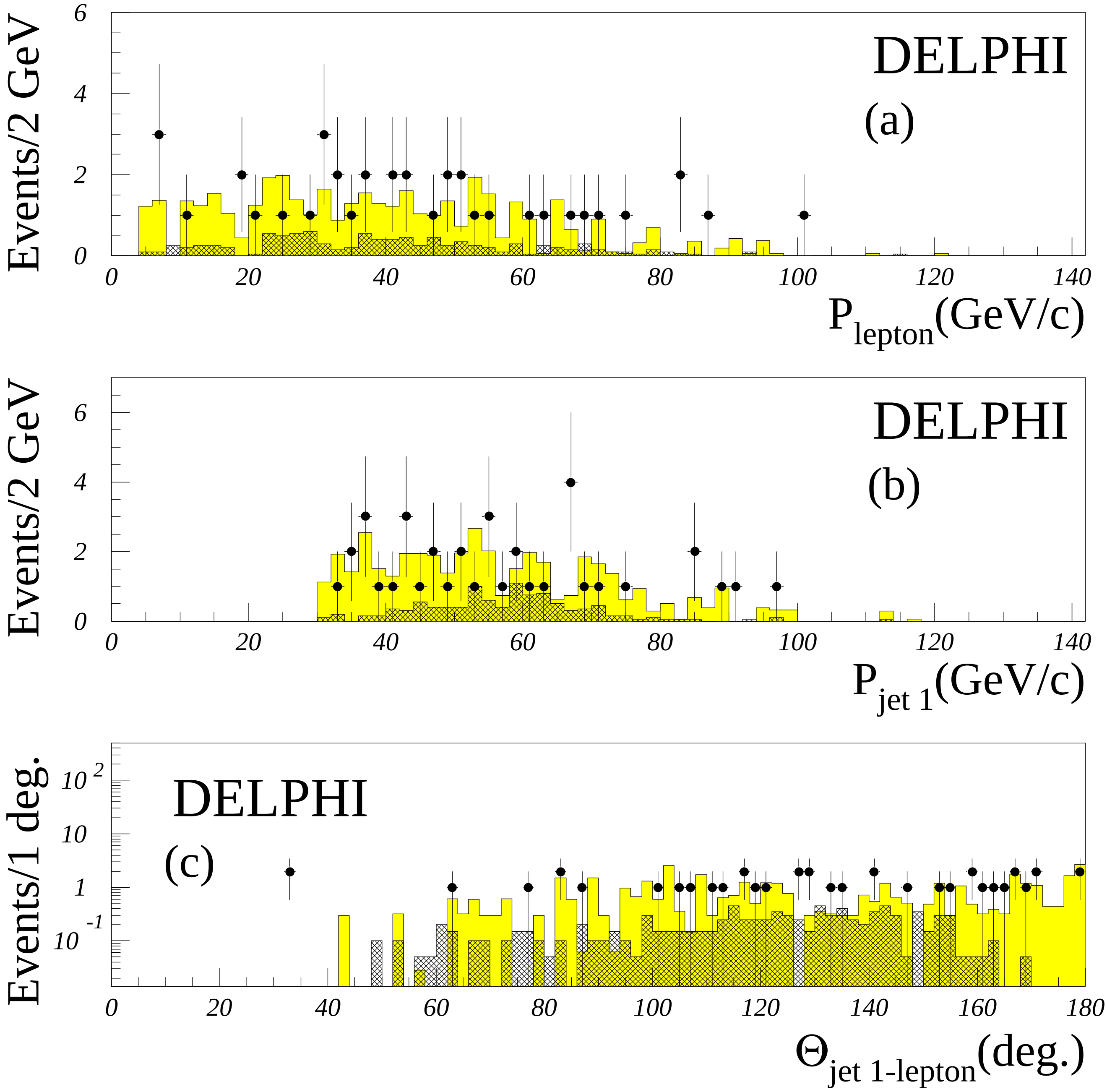

Figure 9: FCNC search after Level 2: the most energetic lepton momentum (a), the most energetic charged jet momentum (b) and the angle between them (c). The dots show the data, the shaded region shows the SM simulation and the dark region is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

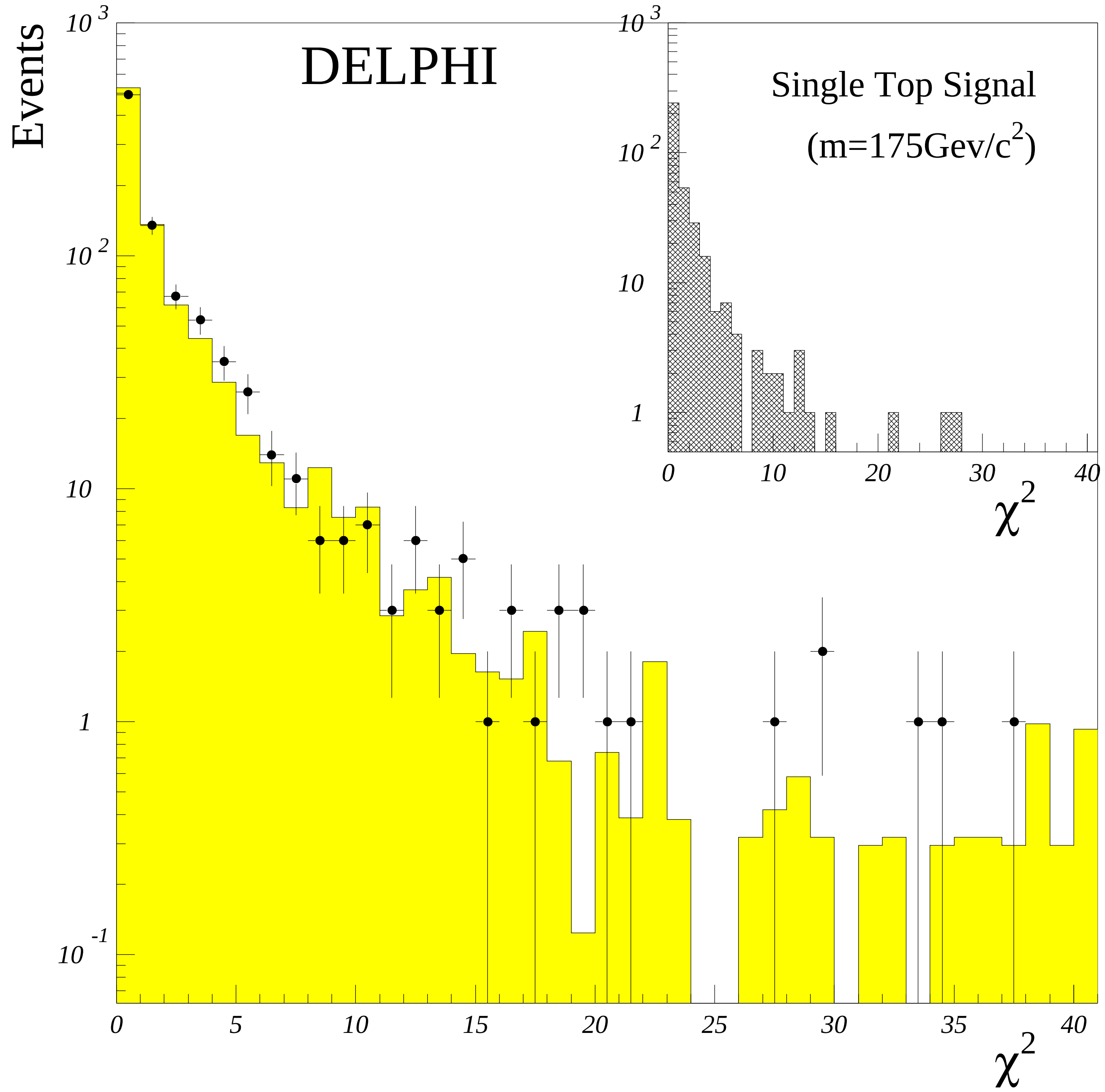

Figure 10: FCNC search after Level 1: the chi-squared distribution assuming the events were compatible with a topology of two jets, one lepton and one neutrino. The overall four-momentum conservation was imposed to the events. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

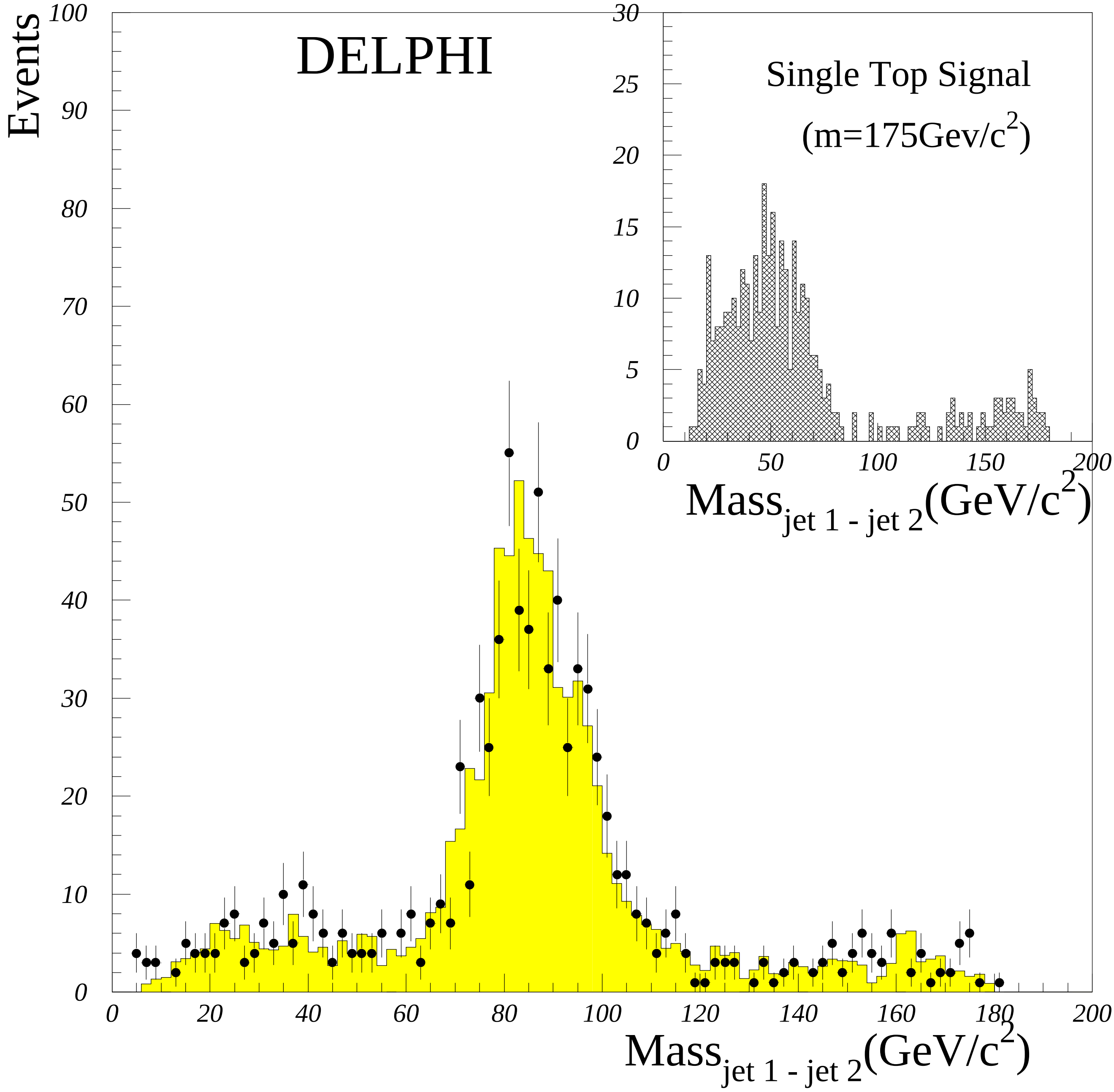

Figure 11: FCNC search after Level 1: the two jets invariant mass distribution, assuming a loose chi-squared cut of 7. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

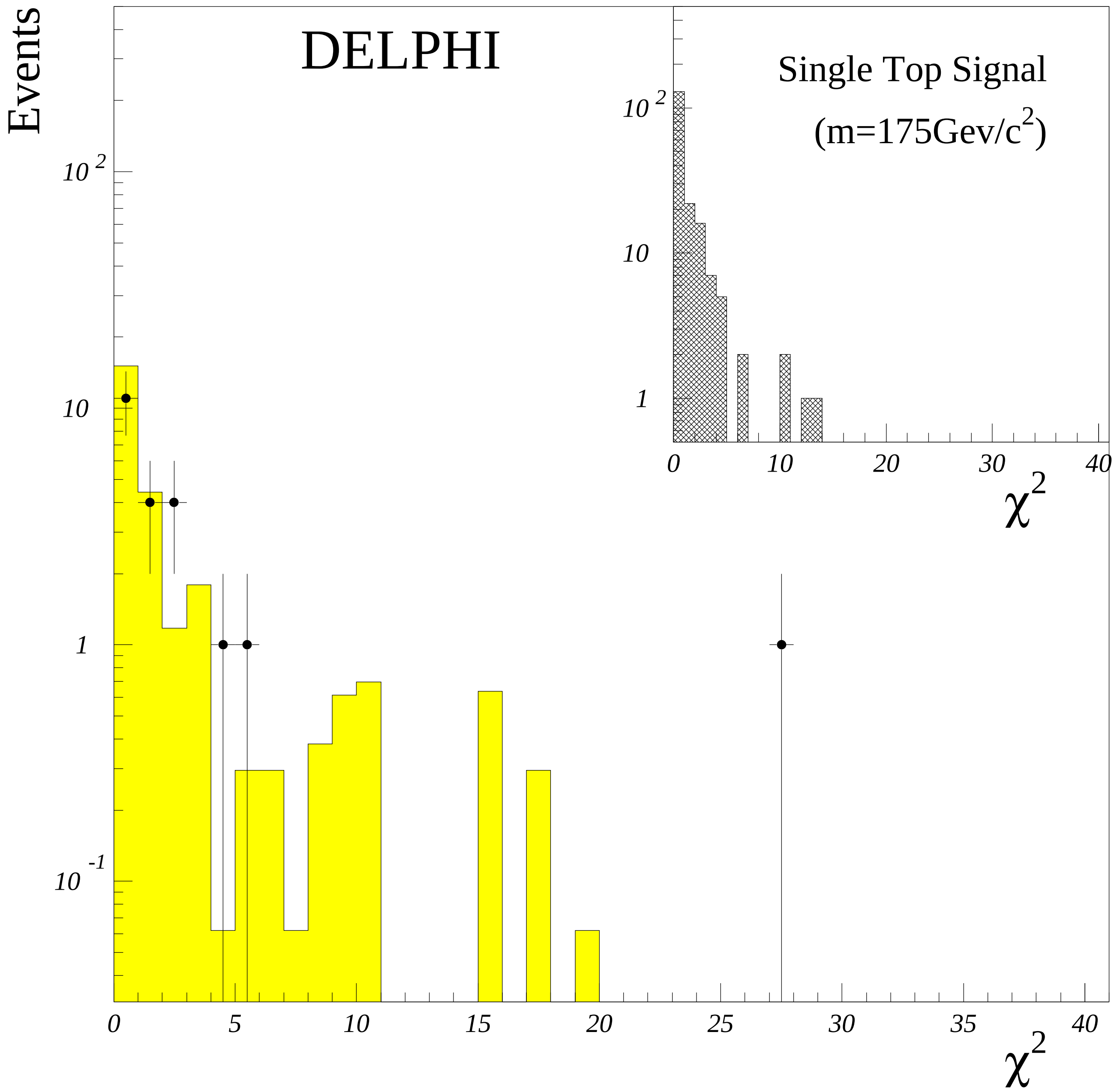

Figure 12: FCNC search after Level 2: the chi-squared distribution assuming the events were compatible with a topology of two jets, one lepton and one neutrino. The overall four-momentum conservation was imposed to the events. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

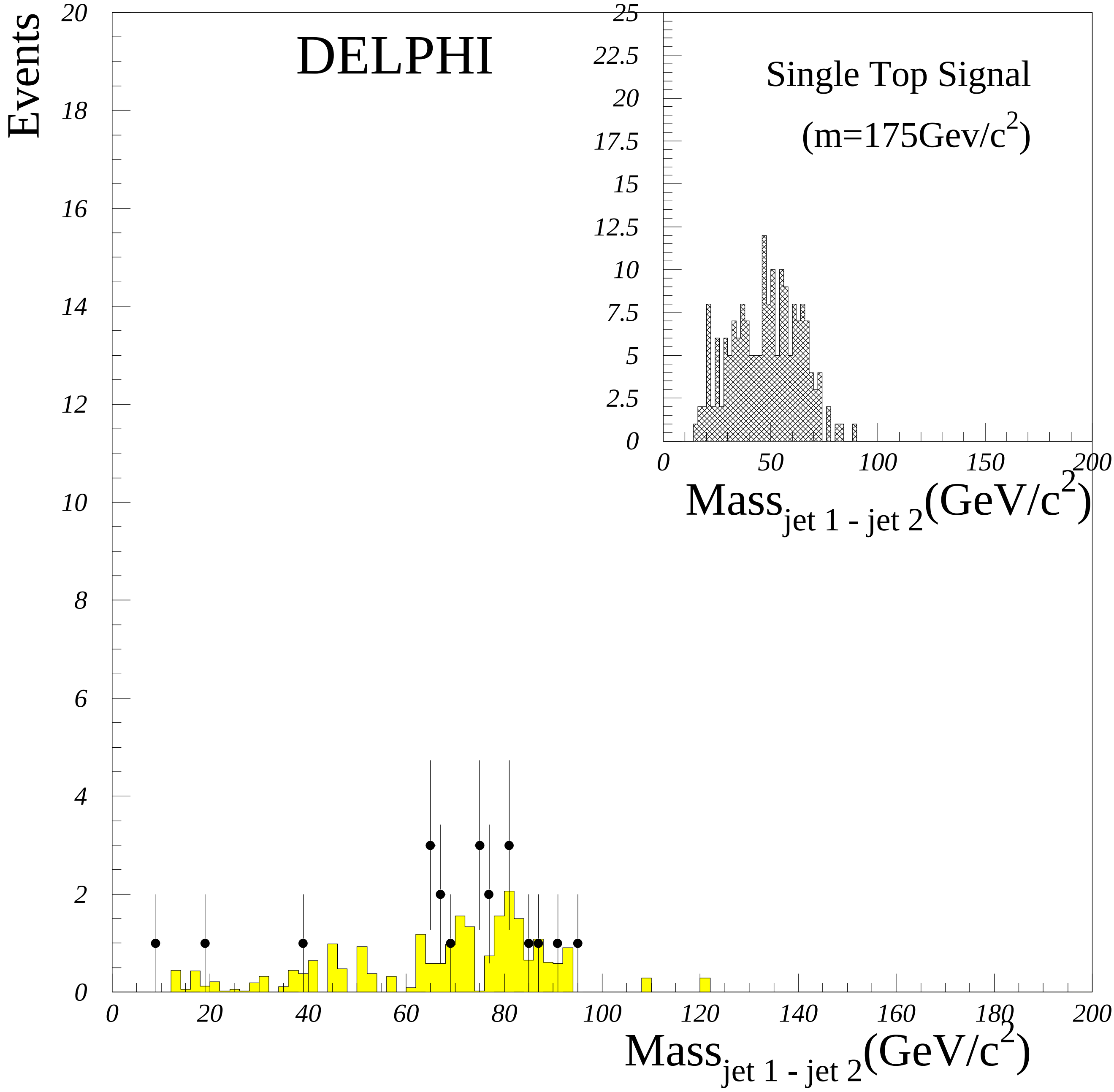

Figure 13: FCNC search after Level 2: the two jets invariant mass distribution, assuming a loose chi-squared cut of 7. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

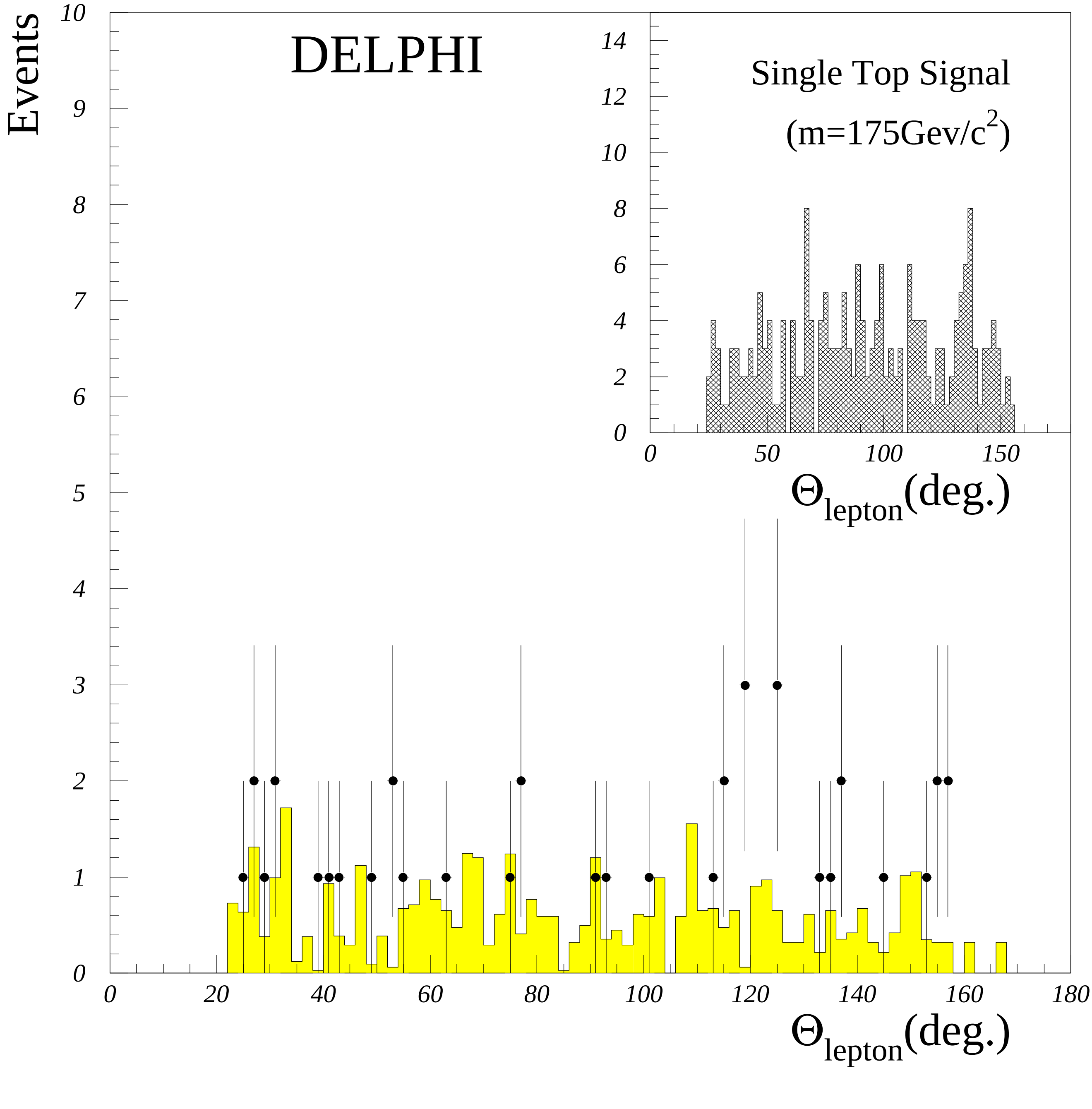

Figure 14: FCNC search after level 2: the most energetic lepton polar angle. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.

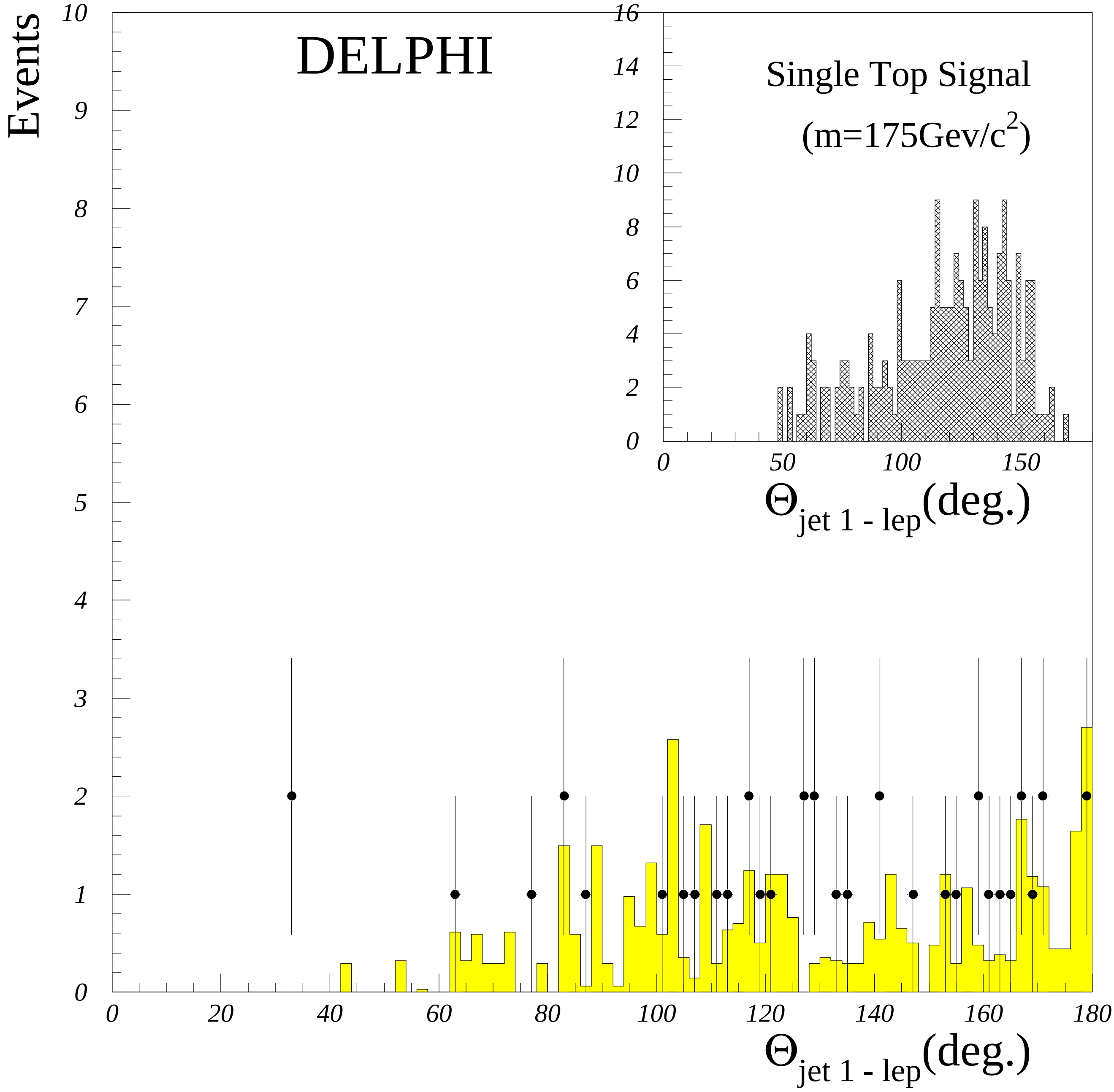

Figure 15: FCNC search after level 2: the angle between the most energetic lepton polar angle and the most energetic jet. The dots show the data, the shaded region shows the SM simulation and the dark region (top right picture) is the expected signal behaviour for a top quark mass of 175 GeV/c^2.