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Update on the Search for Excited Leptons at $\sqrt{s} = 170$ and 172 GeV

The OPAL Collaboration

Abstract

We have searched for excited states of charged and neutral leptons, e^*, μ^*, τ^*, ν_e^*, ν_μ^* and ν_τ^*, using an integrated luminosity of 10.4 pb^{-1} in $\mathrm{e}^+\mathrm{e}^-$ collisions at $\sqrt{s} = 170$ and 172 GeV using the OPAL detector at LEP. No evidence for their existence was found. With the common coupling assumptions which favour photonic $\ell^{*\pm}$ and forbid photonic ν^* decays, the topologies from excited lepton pair production include $\ell^+\ell^-\gamma\gamma$ and $\ell^+\ell^-\mathrm{W}^+\mathrm{W}^-$, with the subsequent decay of the virtual W bosons. From the analysis of these topologies, 95% confidence level lower mass limits of 85.1 GeV for e^*, 85.1 GeV for μ^*, 84.1 GeV for τ^*, 84.0 GeV for ν_e^*, 83.9 GeV for ν_μ^* and 79.5 GeV for ν_τ^* are inferred. From the analysis of the $\mathrm{W}^+\mathrm{W}^-$ and $\gamma\gamma$ with missing energy topologies and using alternative coupling assignments which favour charged $\ell^{*\pm}$ and photonic ν^* decays, 95% confidence level lower limits of 80.6 GeV for each $\ell^{*\pm}$ flavour and 85.1 GeV for each ν^* flavour are inferred. From the analysis of the $\ell^+\ell^-\gamma$, $\ell^\pm\mathrm{W}^\mp$ and single γ topologies expected from excited lepton single production, upper limits on the ratio of the coupling to the compositeness scale, f/Λ, are determined for excited lepton masses up to the kinematic limit.

This note describes preliminary OPAL results to be submitted to the XVIII International Symposium on Lepton-Photon Interactions, Hamburg, 28 July - 1 August 1997

This note is an update of the 161 GeV results, and should be read along with CERN-PPE/96-138, and also the photonic events (PN272) and heavy lepton (PN282) notes.

1 Introduction

The OPAL search for excited leptons at $\sqrt{s} = 161$ GeV [1] has been updated for the recent LEP run at $\sqrt{s} = 170$ and 172 GeV. The integrated luminosity used for the analysis is 1.0 ± 0.1 pb^{-1} at $\sqrt{s} = 170.3$ GeV and 9.3 ± 0.2 pb^{-1} at $\sqrt{s} = 172.3$ GeV. The new experimental results in the $\ell^+\ell^-\gamma(\gamma)$ and acoplanar lepton pair topologies presented here use almost identical analyses to those presented in References [1] and [2], and only updated tables and figures are presented. The results for pair production of excited leptons with charged decays are obtained using the analysis from the search for heavy leptons [3]. The excited neutrino photonic decay channels use the recent photonic events with missing energy results [4]. No signal is apparent, and the updated limits are computed by combining the new data with that from 161 GeV, and also taking into account the background expected from 4-fermion and di-lepton production.

The interpretation of charged excited lepton single production with the coupling assignment $f = f'$ (and of neutral excited leptons with $f = -f'$) has changed since Reference [1]. Previously, only the γ decay modes were used when setting limits with that coupling assignment; however, the $\mathrm{W}^\pm$ decay mode branching ratios become significant for large excited lepton masses, exceeding 50% for excited leptons with $M > 130$ GeV. In this note, the photonic and charged decay modes are used together to increase the sensitivity in those cases. Some example branching ratios are listed in Table 1.

Decay	$M_* = 80$ GeV		$M_* = 80$ GeV	
	$f = f'$	$f = -f'$	$f = f'$	$f = -f'$
$\ell^{*\pm} \to \ell^\pm\gamma$	100	0	39	0
$\ell^{*\pm} \to \ell^\pm\mathrm{Z}^0$	0	0	8	35
$\ell^{*\pm} \to \nu\mathrm{W}^\pm$	0	100	53	65
$\nu^* \to \nu\gamma$	0	100	0	39
$\nu^* \to \nu\mathrm{Z}^0$	0	0	35	8
$\nu^* \to \ell^p m\mathrm{W}^\mp$	100	0	65	53

Table 1: The branching ratios, in percent, for the example coupling assignments chosen for the interpretations in this note.

2 Charged excited leptons, photonic decays: $\ell^+\ell^-\gamma\gamma$ and $\ell^+\ell^-\gamma$ topologies

After the preselection, the energy distribution for the two most energetic leptons in events with at least two identified leptons of the same flavour are plotted in Figures 1, 2 and 3 for events with two identified electron, muon and tau leptons respectively. In those figures, (a) is for all events, (b) is for events with at least one identified photon with an energy greater than 1 GeV, and (c) is for events with at least two identified photons with energies greater than 1 GeV. In Figure 3, events with two identified electrons or two identified muons are excluded, and the visible energy of the two most energetic tau lepton jets is plotted. The energy distribution of the two most energetic photons is plotted in Figure 4 for events with

Topology	Cut	Data	Total BG
$ee\gamma\gamma$	1	3	2.3
	2	3	1.9
	3	0	0.6
$\mu\mu\gamma\gamma$	1	1	1.4
	2	0	1.1
	3	0	0.2
$\tau\tau\gamma\gamma$	1	10	6.1
	2	0	0.7
	3	0	0.1

Table 2: Number of events surviving each cut in the search for $\ell^{*+}\ell^{*-} \to \ell^+\ell^-\gamma\gamma$. The "Total BG" entry is the sum of all Standard Model processes, normalized to 10.4 pb^{-1}. The cuts are described in Reference [1]. The statistical error on the background Monte Carlo is small compared to that for data.

Mass (GeV)	e^*e^* (%)	$\mu^*\mu^*$ (%)	$\tau^*\tau^*$ (%)
70	56.4 ± 1.1	59.3 ± 1.1	30.8 ± 1.0
75	54.2 ± 1.1	57.2 ± 1.1	31.1 ± 1.0
80	53.8 ± 1.1	55.5 ± 1.1	32.3 ± 1.0
85	56.0 ± 1.1	57.6 ± 1.1	35.0 ± 1.0

Table 3: The efficiency for observing the pair creation of charged excited leptons with photonic decays at four selected mass points. The errors are due to Monte Carlo statistics.

(a) two identified electrons, (b) two identified muons and (c) two identified taus. The energy distributions show good agreement between data and Standard Model Monte Carlo for leptons and photons above a few GeV, which represent the background for the excited leptons search. There is disagreement between data and Monte Carlo for events with two relatively low-energy leptons and a low energy photon, which may be due to the absence of radiative corrections in the leptonic two-photon Monte Carlo generator.

In the search for the pair production of charged excited leptons with photonic decays, the invariant mass of each lepton-photon pair is plotted against the other after requiring two leptons of the same flavour and two photons with no missing energy (cut 2 in Section 3.1 of Reference [1]) in Figures 5, 6 and 7 for $ee\gamma\gamma$, $\mu\mu\gamma\gamma$ and $\tau\tau\gamma\gamma$, respectively. The figures show (a) data, (b) the most important background Monte Carlo and (c,d) examples of signal Monte Carlo. The analysis is summarized in Table 2; no events are selected in any channel. The total selection efficiency for the three $\ell^{*+}\ell^{*-} \to \ell^+\ell^-\gamma\gamma$ channels is summarized in Table 3.

In the search for the single production of charged excited leptons with photonic decays, the $\ell^\pm\gamma$ invariant mass distributions are plotted in Figure 8(a), (c) and (d) for e^*, μ^* and τ^*, respectively. In the search for the single production of excited electrons in the missing electron topology, the $e\gamma$ invariant mass distribution is plotted in Figure 8(b). The analysis is

Topology	Cut	Data	Total BG
eeγ	1	19	25.3
	2	18	23.9
	3	7	6.7
	4	4	4.6
$\mu\mu\gamma$	1	6	9.2
	2	6	7.8
	4	4	3.1
$\tau\tau\gamma$	1	12	11.2
	2	9	9.0
	3	5	4.7
	4	1	2.0
eγ	1	491	505.4
	2	483	496.0
	3	30	25.6
	4	28	24.4

Table 4: Number of events surviving each cut in the search for $\ell^{*\pm}\ell^{\mp} \rightarrow \ell^+\ell^-\gamma$. The "Total BG" entry is the sum of all Standard Model processes, normalized to 10.4 pb^{-1}. The cuts are described in Reference [1]. The statistical error on the background Monte Carlo is small compared to that for data.

summarized in Table 4, and the observed number of events is compatible with the expectation from Standard Model sources. The total selection efficiency for the three $\ell^{*\pm}\ell^{\mp} \rightarrow \ell^+\ell^-\gamma$ channels is summarized in Table 5.

When computing limits for an excited lepton with mass M_*, all events with at least one lepton-photon mass combination, $M_{\ell\gamma}$, satisfying $|M_{\ell\gamma} - M_*| < \Delta$ were considered signal candidates, and the number of events expected from 4-fermion and di-lepton production within the same window were considered as the expected background level. The mass half-window, Δ, is 4 GeV, 8 GeV and 8 GeV for e*, μ^* and τ^*, respectively. The values chosen for Δ are about 2σ of the mass resolution estimated from Monte Carlo. For the excited electron search, events which pass either the eγ or eeγ selections are considered as signal candidates.

Mass (GeV)	e*e (%)	$\mu^*\mu$ (%)	$\tau^*\tau$ (%)
80	30.6 ± 1.0	46.4 ± 1.1	27.6 ± 1.0
110	46.6 ± 1.1	48.9 ± 1.1	28.7 ± 1.0
140	46.7 ± 1.1	50.0 ± 1.1	30.7 ± 0.9
170	77.8 ± 1.0	64.2 ± 1.1	13.6 ± 1.0

Table 5: The efficiency for observing the single creation of charged excited leptons with photonic decays at four selected mass points. The errors are due to Monte Carlo statistics.

Topology	Data	Total BG
$e^+e^-W^+W^-$	0	0.57
$\mu^+\mu^-W^+W^-$	0	0.40
$\tau^+\tau^-W^+W^-$	2	1.78
$\nu\overline{\nu}W^+W^-$	2	3.68

Table 6: Number of events surviving in the heavy lepton search in the topologies used for the excited leptons analysis. The "Total BG" entry is the sum of all Standard Model processes, normalized to 10.4 pb^{-1}. The statistical error on the background Monte Carlo is small compared to that for data.

Mass (GeV)	$\nu^*_e\nu^*_e$ (%)	$\nu^*_\mu\nu^*_\mu$ (%)	$\nu^*_\tau\nu^*_\tau$ (%)	$\ell^*\ell^*$ (%)
70	62.7 ± 1.1	50.0 ± 1.1	27.2 ± 1.0	–
75	61.9 ± 1.1	52.2 ± 1.1	27.9 ± 1.0	25.9 ± 1.0
80	58.3 ± 1.1	47.8 ± 1.1	21.9 ± 1.0	21.8 ± 0.9
85	45.0 ± 1.1	42.5 ± 1.1	–	–

Table 7: The efficiency for observing the pair creation of excited leptons with charged decays at four selected mass points.

3 Charged and neutral excited leptons, charged decays: $\nu\overline{\nu}W^+W^-$, $\ell\ell W^+W^-$ and $\nu\ell^\pm W^\mp$ topologies

The search for charged decays of pair produced excited leptons uses the same analysis as the search for the production of unstable heavy leptons (L^0 and $L^\pm$) with "flavour mixing" decays described in Reference [3]. The topologies $e^+e^- \to L^0\overline{L^0} \to \ell^+\ell^-W^+W^-$ and $e^+e^- \to L^+L^- \to \nu\overline{\nu}W^+W^-$ are almost identical to neutral and charged excited lepton pair production with charged decays, respectively. The search results are summarized in Table 6. The total selection efficiency for the charged decays of pair produced excited leptons is summarized in Table 7.

The search for charged decays of singly produced excited leptons looks only for leptonic decays of the $W^\pm$, which may be real or virtual depending on the mass of the ℓ^*. The topology is a pair of leptons which are not coplanar with the beam direction. In addition to the cuts described in Reference [1], electrons are required to satisfy $|\cos\theta| < 0.9$ to be considered as candidate tracks for the analysis. The $\phi^{\mathrm{ACOP}}_{\ell\ell}$ distribution for data and the sum of all Standard Model background Monte Carlo is plotted immediately before this final cut is applied in Figure 9. The analysis is summarized in Table 8. The surviving events are consistent with the expected background. The total selection efficiency for the charged decays of singly produced excited leptons is summarized in Table 9.

Topology	Cut	Data	Total BG
$e\ell$	1	1377	1344.3
	2	1356	1330.8
	3	1297	1272.7
	4	1208	1202.1
	5	852	833.0
	6	3	4.7
$\mu\ell$	1	192	189.8
	2	185	184.1
	3	163	156.0
	4	136	129.0
	5	50	55.7
	6	3	5.0
$\tau\ell$	1	1646	1621.6
	2	1623	1603.5
	3	1536	1513.7
	4	1415	1407.8
	5	930	913.6
	6	4	7.5

Table 8: Number of events surviving each cut in the search for the single production of $\ell^{*\pm}$ and ν^* with charged decays in the acoplanar di-lepton channel. The "Total BG" entry is the sum of all Standard Model processes, normalized to 10.4 pb^{-1}. The cuts are described in Reference [1]. The three selections are not independent; in particular, the $\tau\ell$ selection completely includes both the $e\ell$ and $\mu\ell$ selections. The statistical error on the background Monte Carlo is small compared to that for data.

Mass (GeV)	$\mathrm{e}^*\mathrm{e}$ (%)	$\mu^*\mu$ (%)	$\tau^*\tau$ (%)	$\nu^*_\mathrm{e}\nu_\mathrm{e}$ (%)	$\nu^*_\mu\nu_\mu$ (%)	$\nu^*_\tau\nu_\tau$ (%)
80	14.8 ± 0.8	14.4 ± 0.8	12.5 ± 0.7	16.9 ± 0.9	17.0 ± 0.9	11.2 ± 0.7
110	18.1 ± 0.9	17.4 ± 0.9	16.0 ± 0.8	18.3 ± 0.9	20.2 ± 0.9	15.9 ± 0.8
140	18.1 ± 0.9	21.6 ± 0.9	14.7 ± 0.8	19.8 ± 0.9	19.9 ± 0.9	19.1 ± 0.9
170	17.1 ± 0.9	19.1 ± 0.9	5.3 ± 0.5	19.7 ± 0.9	21.2 ± 0.9	18.1 ± 0.9

Table 9: The efficiency for observing the single creation of excited leptons with charged decays at four selected mass points. The errors are due to Monte Carlo statistics. The efficiencies include the 33% $\mathrm{W}^\pm \to \ell^\pm\nu$ branching ratio.

Topology	Extra Requirements	Data	Total BG
A	1 γ and $M_{\rm miss} < 75$ GeV	0	0.05
C	$M^{\rm max}$ classification	2	3.8

Table 10: Number of events surviving in the two photonic events topologies. The "Total BG" entry is the sum of all Standard Model processes, normalized to 10.4 pb^{-1}. The statistical error on the background Monte Carlo is small compared to that for data.

Mass (GeV)	$\nu^*\nu^*$ (%)
75	78.7 ± 0.9
80	79.8 ± 0.9

Table 11: The efficiency for observing the pair creation of neutral excited leptons with photonic decays at two selected mass points. The efficiencies include the maximum mass consistent with the event classification, described in the photonic events analysis. The errors are due to Monte Carlo statistics.

4 Neutral excited leptons, photonic decays: $\nu\bar{\nu}\gamma\gamma$ and $\nu\bar{\nu}\gamma$ topologies

The search for excited neutrino production with photonic decays uses the OPAL photonic events with missing energy analysis [4]. That analysis has three search topologies (called A, B and C), and the two with the higher sensitivities for excited neutrinos with photonic decays are used. The search results are summarized in Table 10.

The topology A single photon search is used for the excited neutrino single production search. No events are selected, which is consistent with the expected background level of 0.05 events

The topology C photon pair selection is used for the excited neutrino pair production search. Two events are selected at $\sqrt{s} = 172$ GeV, consistent with the background expectation of 3.8 events. As described in Reference [4], the energies of the photons are used to classify the events as consistent with excited neutrino pair creation up to a maximum mass, $M^{\rm max}$, and the maximum excited neutrino mass consistent with either event is 64.6 GeV. While the events are fully incorporated in the excited neutrino results, the masses are sufficiently low that they do not affect the limits inferred with these data (for example, 37 events would be expected from a 70 GeV excited neutrino with $f = -f'$ using this photonic events selection).

The total selection efficiency for photonic decays of pair produced excited neutrinos is summarized in Table 11, and of singly produced excited neutrinos in Table 12.

Mass (GeV)	$\nu^*_{\mathrm{e}}\nu_{\mathrm{e}}$ (%)	$\nu^*_{\mu}\nu_{\mu}$ or $\nu^*_{\tau}\nu_{\tau}$ (%)
80	13.6 ± 0.7	12.8 ± 0.7
110	18.4 ± 0.9	17.0 ± 0.9
140	31.3 ± 1.0	27.8 ± 1.0
170	54.5 ± 1.1	55.2 ± 1.1

Table 12: The efficiency for observing the single creation of neutral excited leptons with photonic decays at four selected mass points. The errors are due to Monte Carlo statistics.

5 Results

The systematic errors in the total numbers of expected signal events are estimated from: the statistical error on the Monte Carlo estimate of the detection efficiency (typically 1%), including an additional error (5%) for the interpolation between excited lepton mass points; the error on the integrated luminosity (2%); uncertainties in the modelling of the particle identification cuts (2.5% if one identified lepton is required, 5% if two are required); uncertainties in the modelling of the photon conversion finder used in the $\ell^+\ell^-\gamma(\gamma)$ analyses (1% per photon in the event). The errors are considered to be independent and are added in quadrature for the total systematic error, which is typically about 7%. The systematic error is incorporated into the limits using the method described in Reference [5]. The backgrounds from 4-fermion and lepton pair production have been studied (in References [6] and [7], respectively), and are found to be well-modelled in the OPAL experiment. These two processes are by far the most serious backgrounds, and their expected levels are incorporated in the limits[1] computed with these data using the method advocated in the Review of Particle Physics [8]. The limits include the full 161-172 GeV data set.

The production cross-sections from Reference [9] (corrected for the effects of initial state radiation [10]), branching ratios from References [9] and [11], and measured efficiencies are used to calculate the number of events expected for an excited lepton of a given mass. Poisson statistics for the number of observed events are used to set limits on the maximum number of events in each analysis.

For the pair production searches, limits on the excited lepton masses are inferred. For the example coupling assumptions chosen, the expected branching ratios are almost 100% into either the γ or $\mathrm{W}^{\pm}$ channel for excited lepton masses up to $\sqrt{s}/2$; thus, the different channels are not combined in the pair creation mass limits. The number of events expected from charged excited lepton pair production with photonic decays is plotted in Figure 10, from excited neutral lepton pair production with charged decays in Figure 11, from excited charged lepton pair production with charged decays in Figure 12(a), and from excited neutral lepton pair production with photonic decays in Figure 12(b). The 95% confidence level lower mass limits are listed in Table 13, along with the coupling assumptions which are used for the branching ratio calculation for each topology.

For the single production searches, limits on the ratio of the coupling to the compositeness

[1] In cases where the background expectation exceeds the number of observed candidates, the background expectation is set equal to the number of observed events.

Flavour	Decays	Coupling	Mass Limit $\sqrt{s} = 161$ (GeV)	Mass Limit $\sqrt{s} = 172$ (GeV)
e^*	Photonic	$f = f'$	79.9	85.1
μ^*	Photonic	$f = f'$	80.0	85.1
τ^*	Photonic	$f = f'$	79.1	84.1
e^*	Charged	$f = -f'$	77.1	80.6
μ^*	Charged	$f = -f'$	77.1	80.6
τ^*	Charged	$f = -f'$	77.1	80.6
ν_e^*	Charged	$f = f'$	78.3	84.0
ν_μ^*	Charged	$f = f'$	78.9	83.9
ν_τ^*	Charged	$f = f'$	76.2	79.5
ν_e^*	Photonic	$f = -f'$	77.8	85.1
ν_μ^*	Photonic	$f = -f'$	77.8	85.1
ν_τ^*	Photonic	$f = -f'$	77.8	85.1

Table 13: 95% confidence level lower mass limits for the different excited leptons from the pair creation searches. The coupling assumption is necessary for the branching ratio calculation. The limits at $\sqrt{s} = 172$ GeV include the $\sqrt{s} = 161$ GeV data.

scale, f/Λ, are inferred. Since the branching ratio of excited leptons with masses approaching $\sqrt{s}$ can have significant contributions in both γ and $W^\pm$ modes, these channels are combined in the limits where appropriate. Limits on f/Λ for charged excited leptons with $f = f'$ from the photonic and charged decay mode searches are plotted in Figure 13(a), for charged excited leptons with $f = -f'$ from the $W^\pm$ decay mode search in Figure 13(b), for neutral excited leptons with $f = f'$ from the $W^\pm$ decay mode search in Figure 13(c), and for neutral excited leptons with $f = -f'$ from the γ and $W^\pm$ decay mode searches in Figure 13(d).

6 Conclusion

We have analysed a data sample with an integrated luminosity of 10.4 pb^{-1} at 170 and 172 GeV, collected with the OPAL detector at LEP, to search for the production of excited leptons. No evidence for excited leptons was found, and limits on masses and couplings are established within the framework of the model in Reference [9]. From the search for pair production, lower mass limits are established. From the search for single production, upper limits on the ratio of the coupling to the compositeness scale are presented.

References

[1] OPAL Collaboration, K. Ackerstaff *et al.*, Phys. Lett. B 391 (1997) 197.

[2] OPAL Physics Note 251: "Continued Search for Excited Leptons in e^+e^- Collisions at $\sqrt{s} = 161$ GeV."

[3] OPAL Physics Note 282: "Search for Unstable Neutral and Charged Heavy Leptons in e^+e^- Collisions at $\sqrt{s} = 170$ GeV and 172 GeV."

[4] OPAL Physics Note 272: "Search for Anomalous Production of Photonic Events with Missing Energy in e^+e^- Collisions at $\sqrt{s} = 130$-172 GeV."

[5] R. D. Cousins and V. L. Highland, Nucl. Instr. Meth. A 320 (1992) 331.

[6] OPAL Physics Note 273: "Production of W^+W^- in e^+e^- collisions at $\sqrt{s} = 172$GeV."

[7] OPAL Physics Note 271: "Production of Fermion-pair Events in e^+e^- Collisions at 172 GeV Centre-of-Mass Energy."

[8] "Review of Particle Physics," Phys. Rev. D54 (1996), p166 formula 28.40.

[9] F. Boudjema, A. Djouadi, J. L. Kneur, "Excited fermions at e^+e^- and ep colliders," Z. Phys. C57 (1993) 425.

[10] The initial state radiation is implemented according to the formulae in F. A. Berends, R. Pittau and R. Kleiss, Nucl. Phys. B 426 (1994) 344.

[11] F. Boudjema and A. Djouadi, Phys. Lett. B 240 (1990) 485.

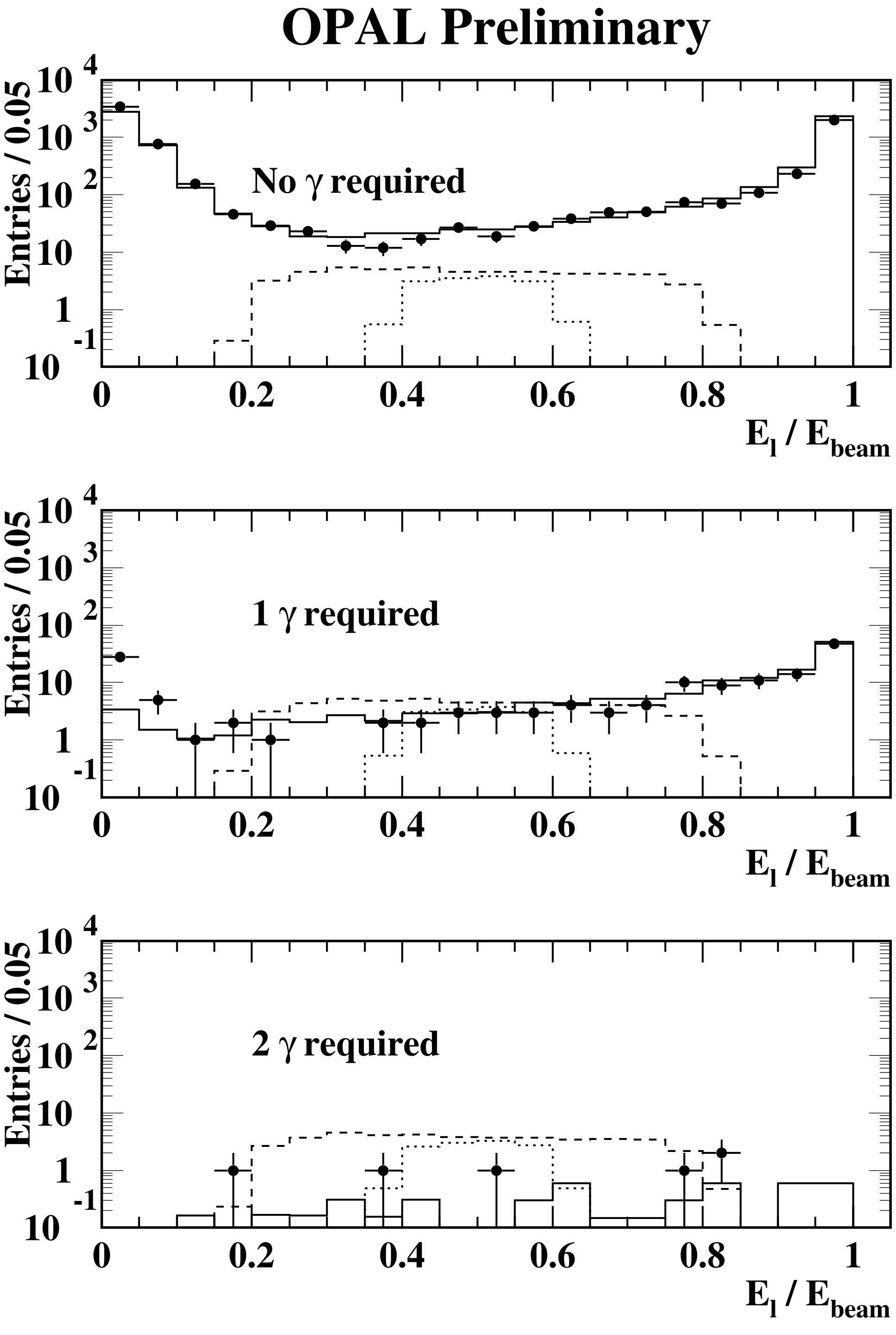

Figure 1: The energies of the two most energetic electrons in events with two identified electrons and (a) no photon requirements, (b) at least one photon with an energy greater than 1 GeV and (c) at least two photons with energies greater than 1 GeV. The data are the filled circles, the solid line is the sum of all Standard Model background Monte Carlo, while the dashed and dotted lines are $\ell^*\ell^*$ Monte Carlo with masses of 70 GeV and 85 GeV, respectively.

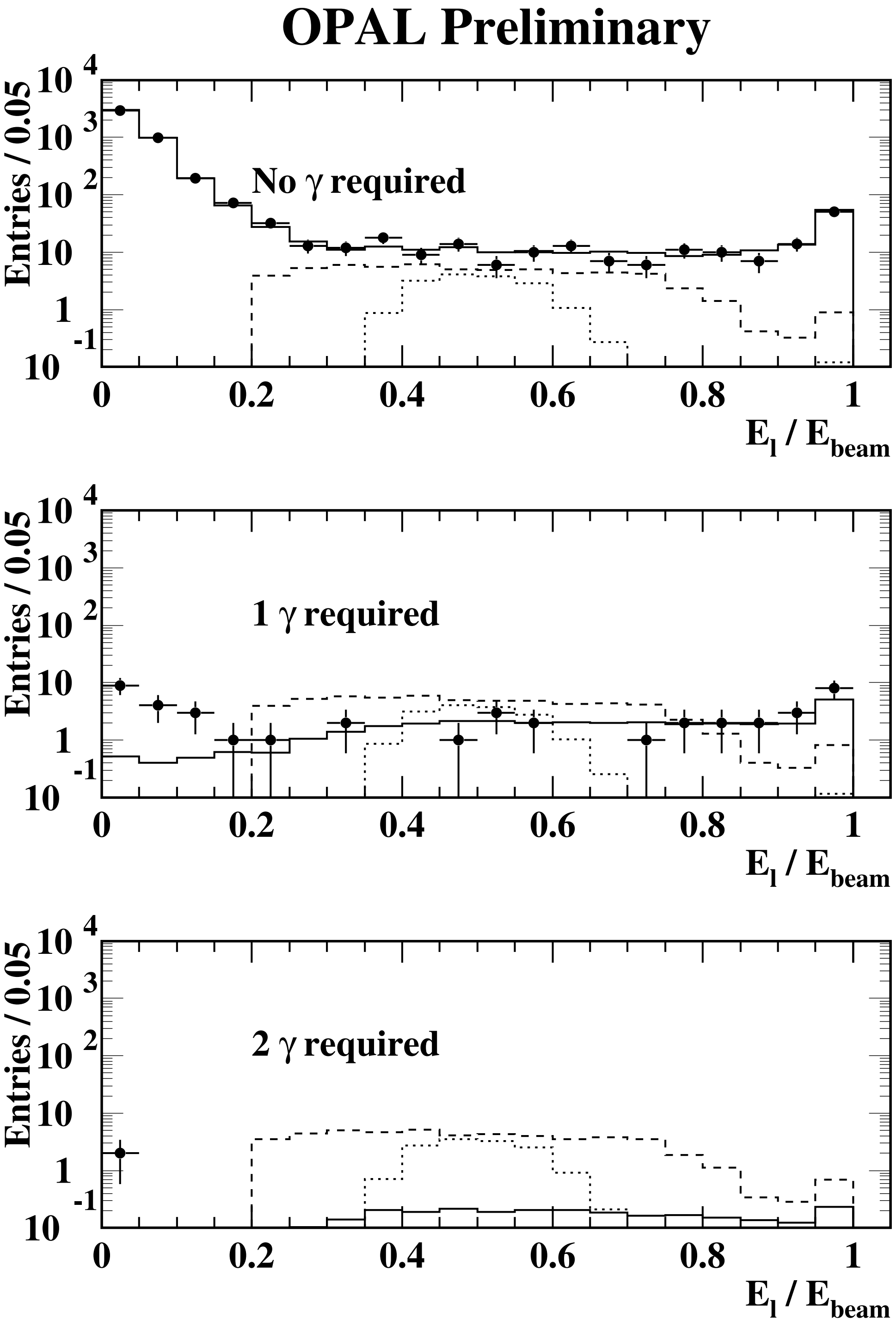

Figure 2: The energies of the two most energetic muons in events with two identified muons and (a) no photon requirements, (b) at least one photon with an energy greater than 1 GeV and (c) at least two photons with energies greater than 1 GeV. The data are the filled circles, the solid line is the sum of all Standard Model background Monte Carlo, while the dashed and dotted lines are $\ell^*\ell^*$ Monte Carlo with masses of 70 GeV and 85 GeV, respectively.

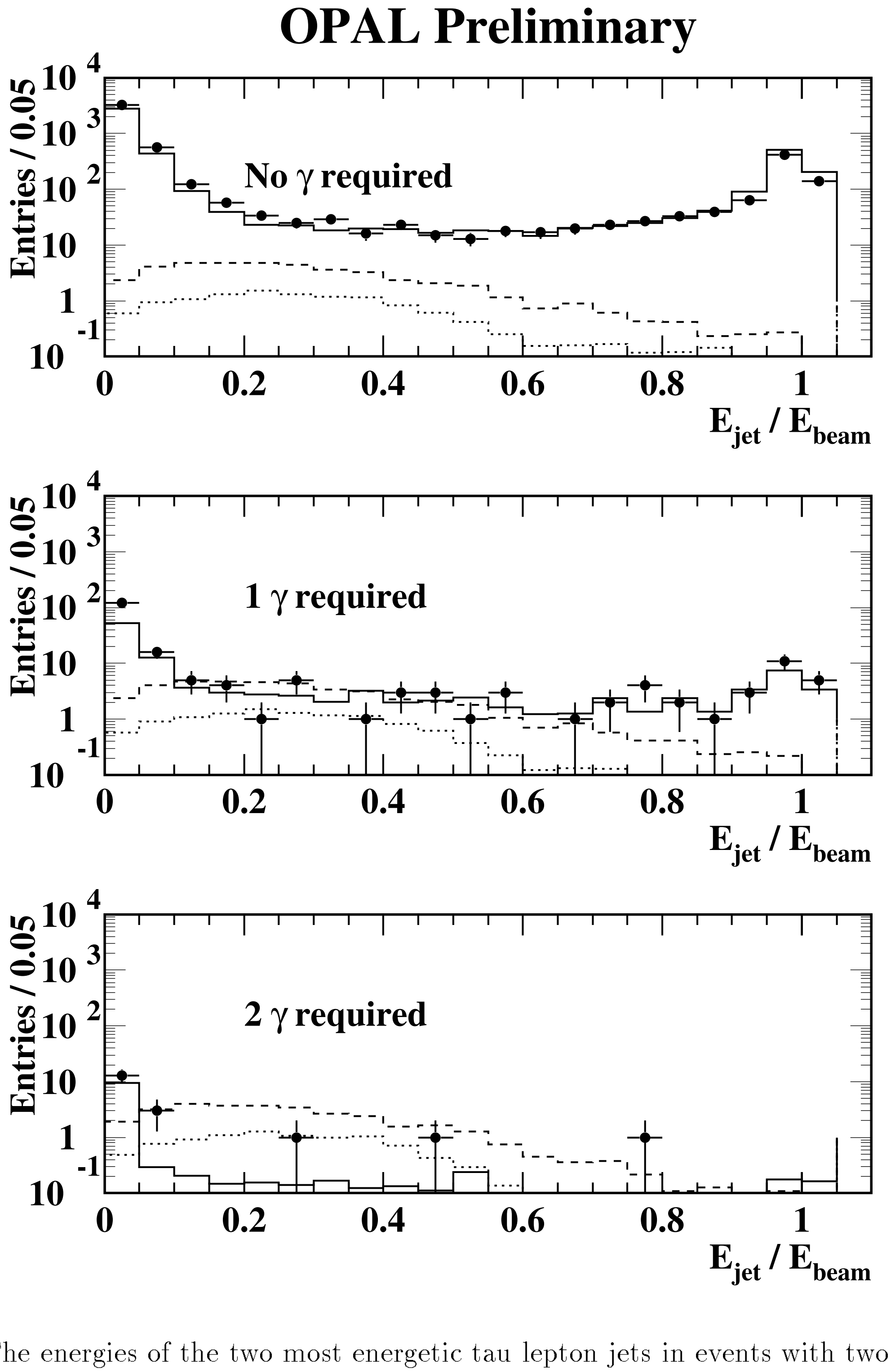

Figure 3: The energies of the two most energetic tau lepton jets in events with two identified taus and (a) no photon requirements, (b) at least one photon with an energy greater than 1 GeV and (c) at least two photons with energies greater than 1 GeV. The data are the filled circles, the solid line is the sum of all Standard Model background Monte Carlo, while the dashed and dotted lines are $\ell^*\ell^*$ Monte Carlo with masses of 70 GeV and 85 GeV, respectively.

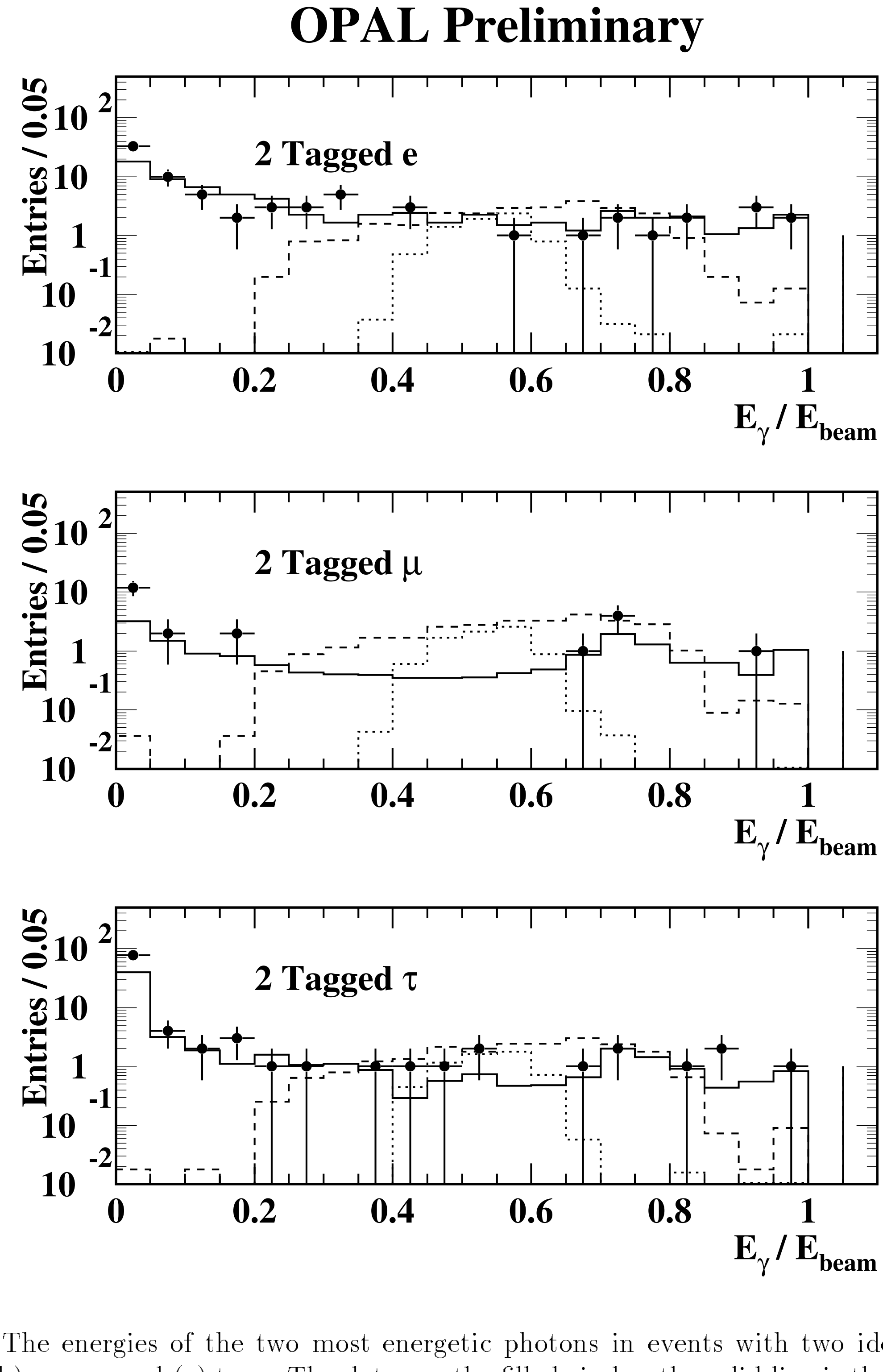

Figure 4: The energies of the two most energetic photons in events with two identified (a) electrons (b) muons and (c) taus. The data are the filled circles, the solid line is the sum of all Standard Model background Monte Carlo, while the dashed and dotted lines are $\ell^*\ell^*$ Monte Carlo with masses of 70 GeV and 85 GeV, respectively.

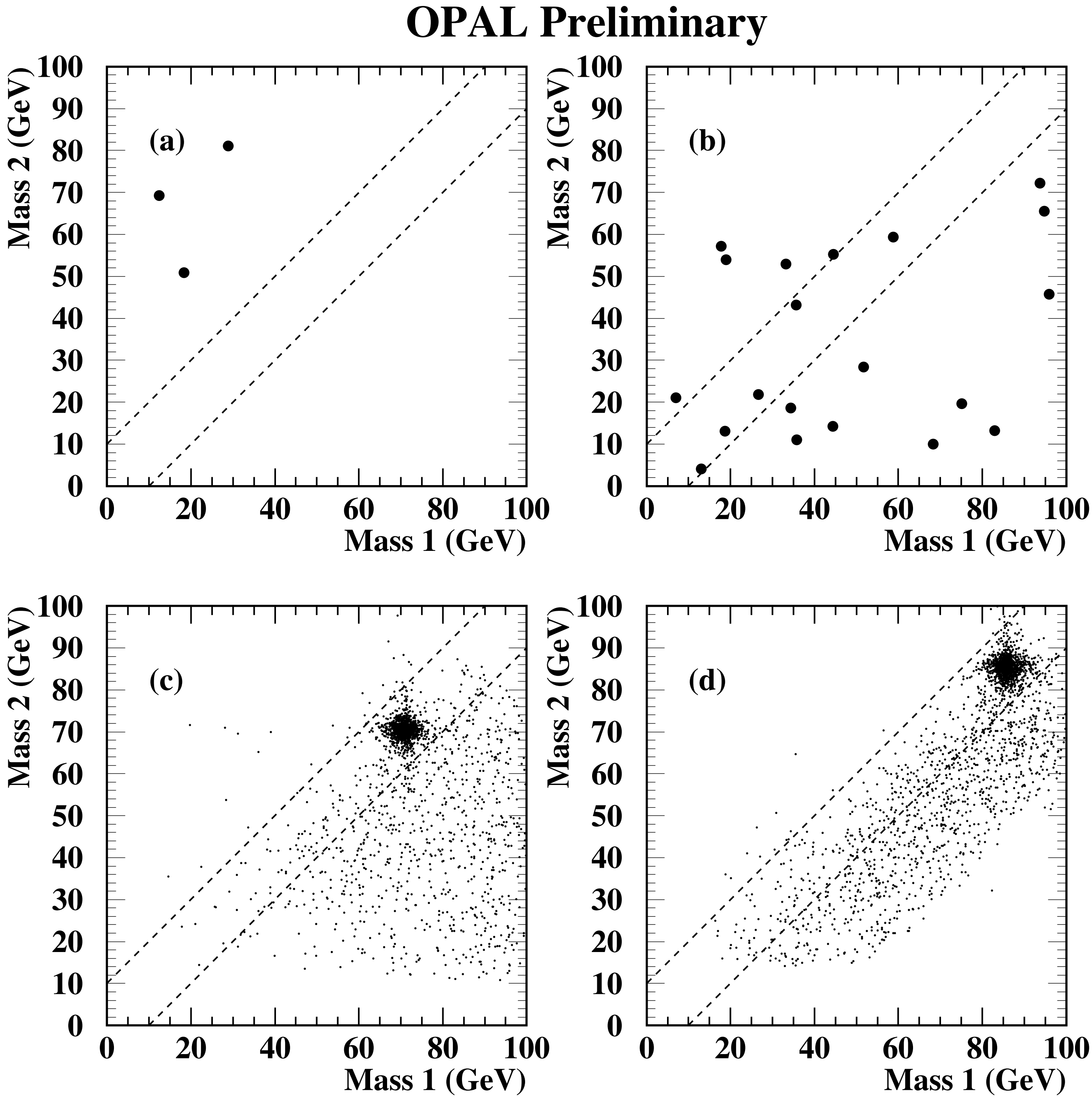

Figure 5: e* pair production, photonic decays: both lepton-photon invariant mass combinations for each event surviving cut 2. (a) is for data, (b) is for BHWIDE Bhabha scattering Monte Carlo corresponding to an integrated luminosity of about 70 pb^{-1}, and (c) and (d) are for signal Monte Carlo with masses of 70 and 85 GeV, respectively. Mass 1 corresponds to masses computed with the higher energy lepton, and mass 2 to masses computed with the lower energy lepton. The dashed line corresponds to the allowed mass region, cut 3. Both mass combinations are plotted for each event (the three events in (a) have the other combination off the plot scale, with large mass 1 and mass 2 near zero). No candidates are selected.

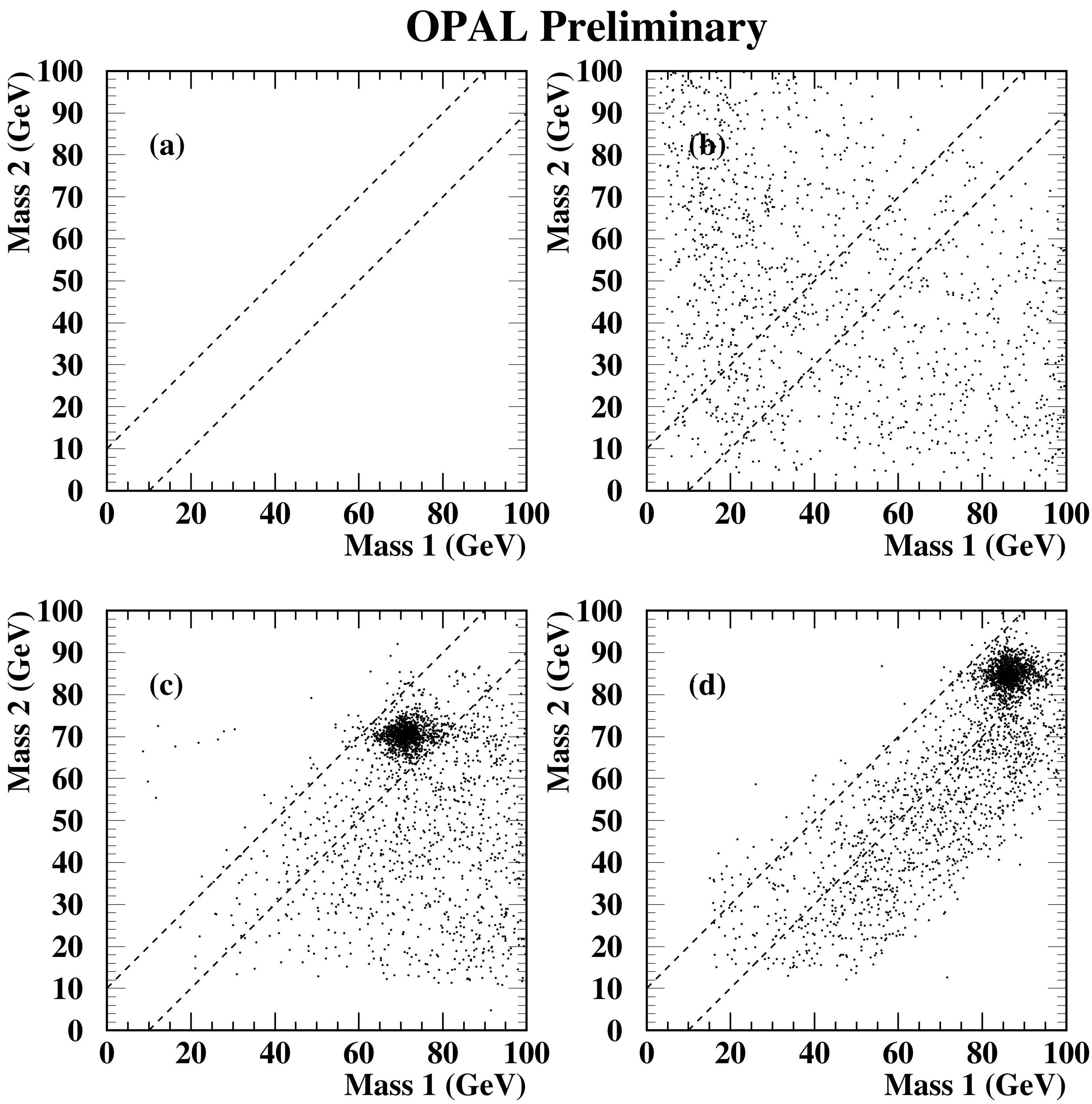

Figure 6: μ^* pair production, photonic decays: both lepton-photon invariant mass combinations for each event surviving cut 2. (a) is for data (no events in plot), (b) is for KORALZ muon pair events corresponding to an integrated luminosity of about 9000 pb^{-1}, and (c) and (d) are for signal Monte Carlo with masses of 70 and 85 GeV, respectively. Mass 1 corresponds to masses computed with the higher energy lepton, and mass 2 to masses computed with the lower energy lepton. The dashed line corresponds to the allowed mass region, cut 3. Both mass combinations are plotted for each event. No candidates are selected.

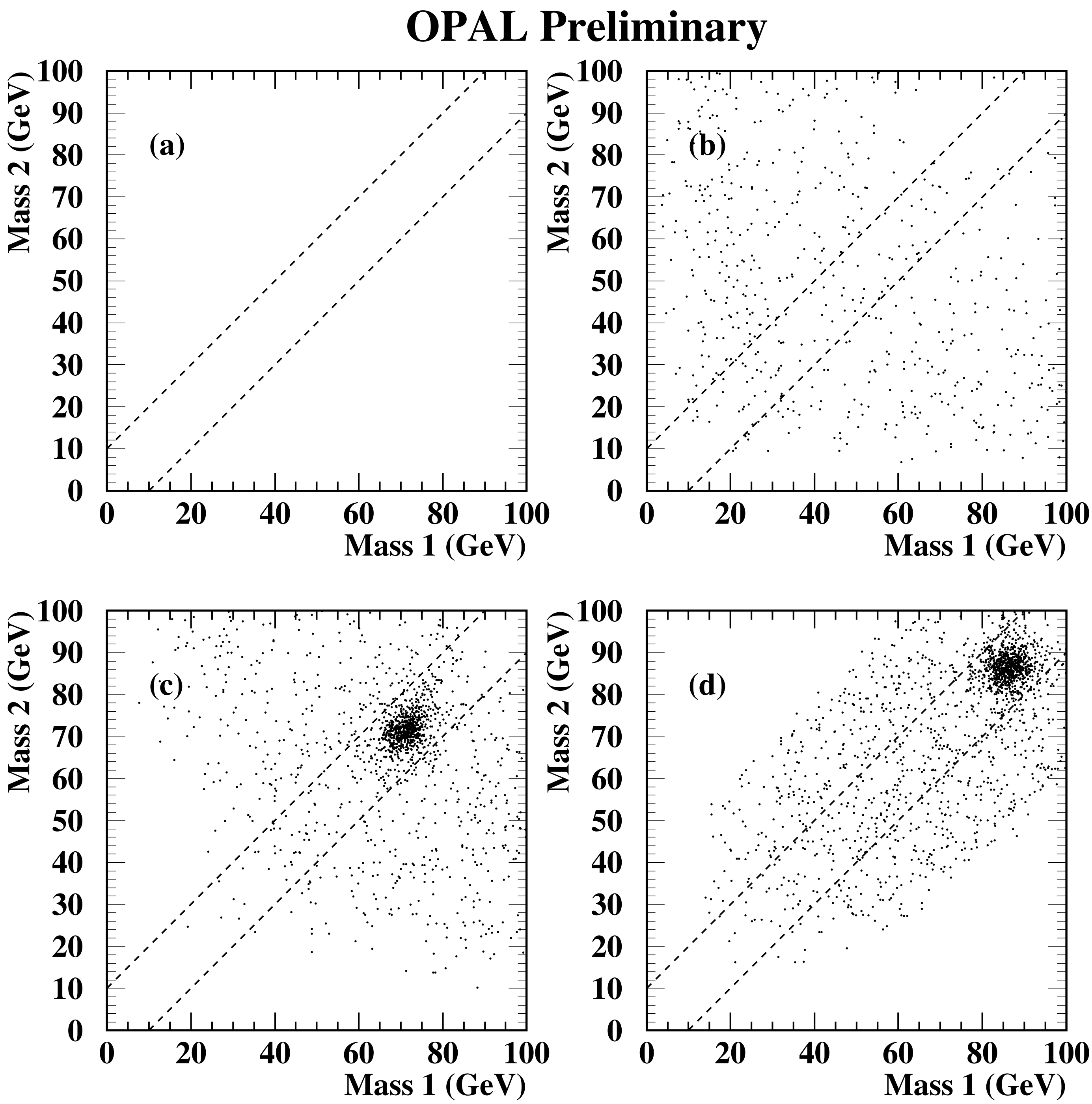

Figure 7: τ^* pair production, photonic decays: both lepton-photon invariant mass combinations for each event surviving cut 2. (a) is for data (no events in plot), (b) is for KORALZ tau pair events corresponding to an integrated luminosity of about 9000 pb^{-1}, and (c) and (d) are for signal Monte Carlo with masses of 70 and 85 GeV, respectively. Mass 1 corresponds to masses computed with the higher energy lepton, and mass 2 to masses computed with the lower energy lepton. The dashed line corresponds to the allowed mass region, cut 3. Both mass combinations are plotted for each event. No candidates are selected.

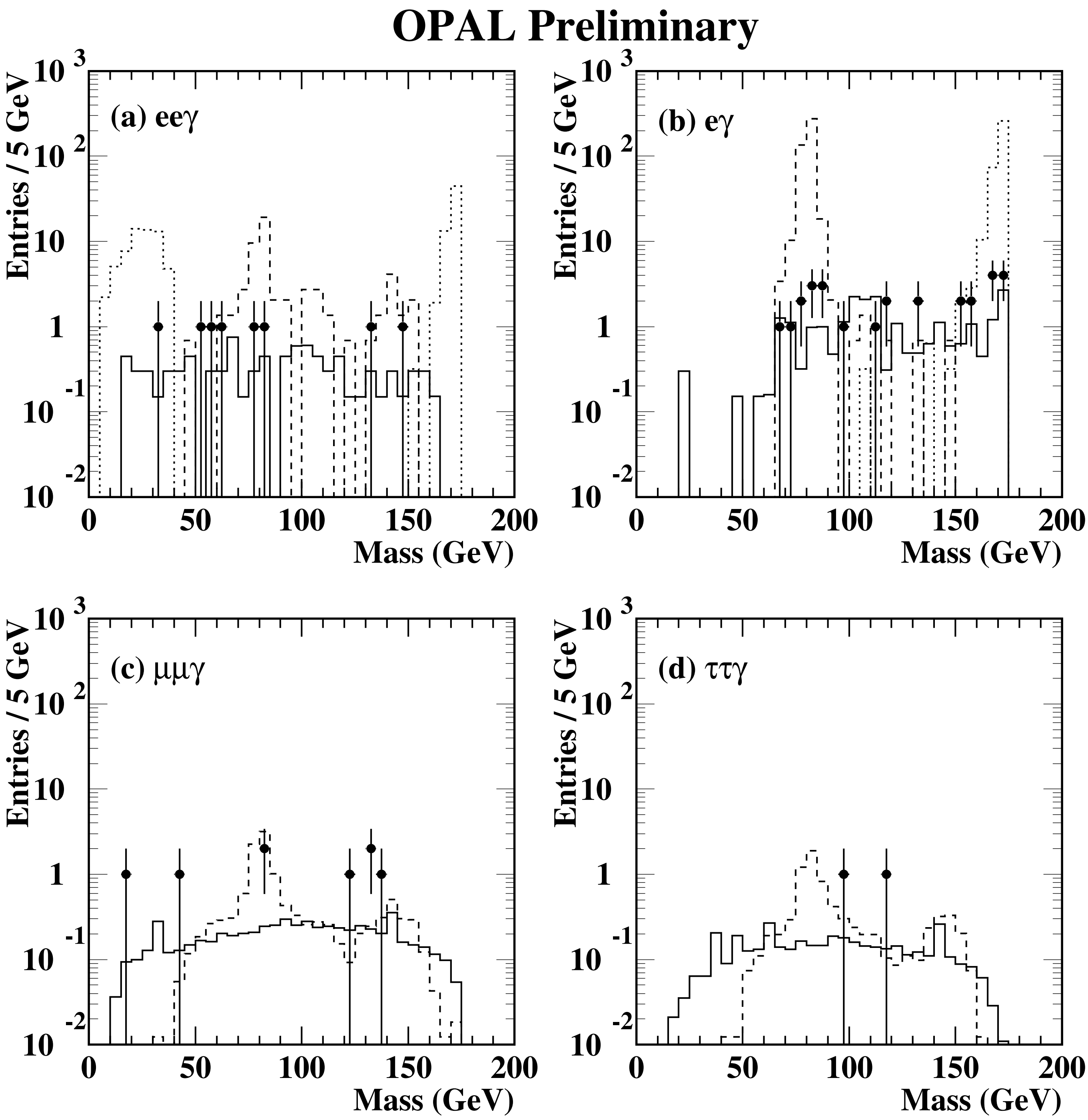

Figure 8: $\ell^{*\pm}$ single production, photonic decays: lepton-photon invariant mass distribution after all cuts. (a) is for e^* with two visible final state electrons, (b) is for e^* with one visible final state electron, (c) is for μ^* and (d) is for τ^*. The data points are the filled circles, the solid line is the sum of all Standard Model background Monte Carlo, while the dashed and dotted lines are $\ell^*\ell$ Monte Carlo with masses of 80 GeV and 170 GeV, respectively, normalized to $f/\Lambda = (200\ \mathrm{GeV})^{-1}$ (the distribution for the 170 GeV mass is only visible in (a) and (b)). (a), (c) and (d) have both mass combinations plotted for each event.

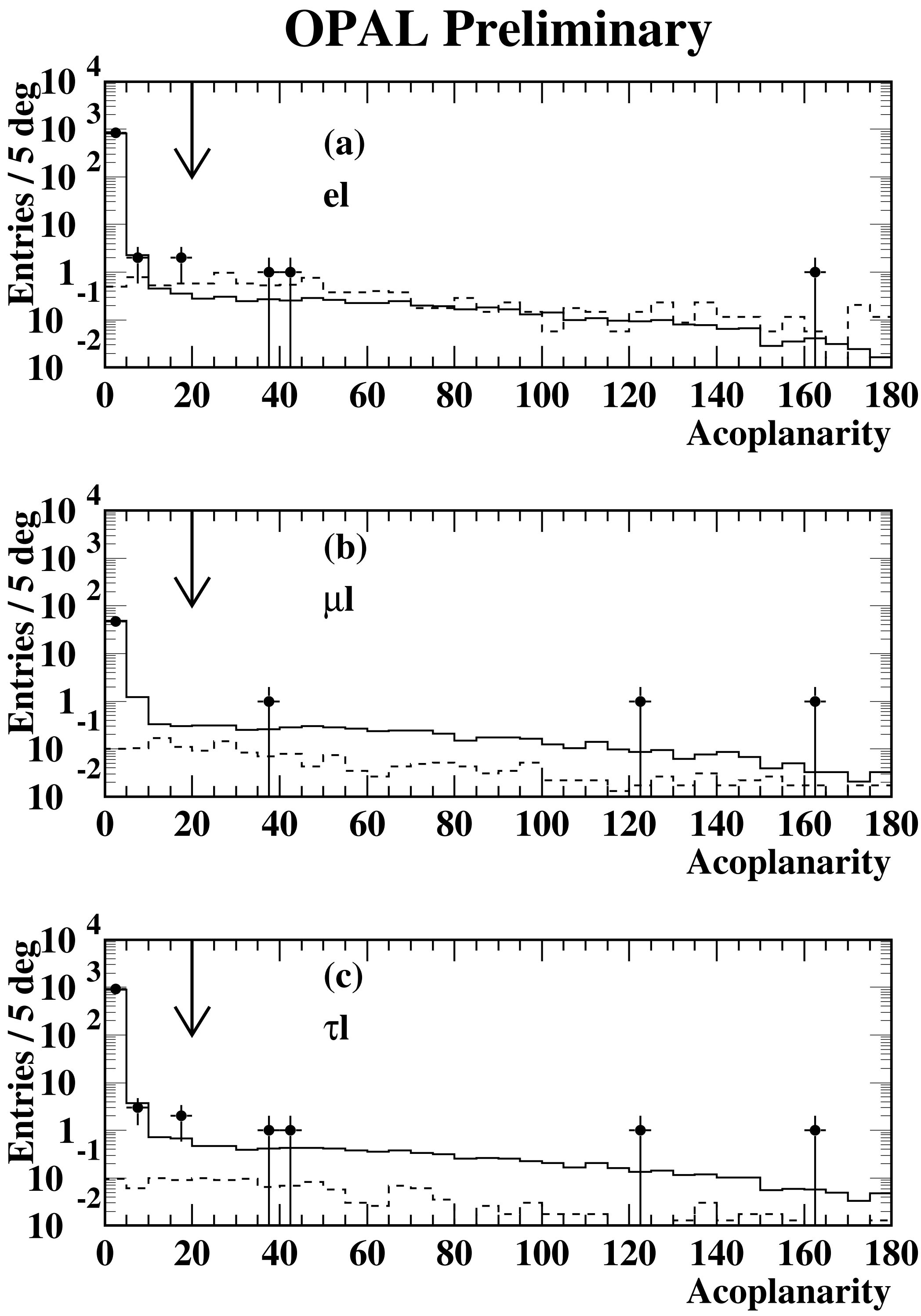

Figure 9: ℓ^* single production, charged decays: the acoplanarity angle between the two observed leptons, before the cut on acoplanarity angle (cut 6) of the acoplanar lepton pair selection in Section 3. (a) is for e* and ν_e^*, (b) is for μ^* and ν_μ^* and (c) is for τ^* and ν_τ^*. The solid line is the sum of all Standard Model background Monte Carlo, the dashed lines are $\ell^*\ell$ (charged decay) Monte Carlo with a mass of 80 GeV normalized to $f/\Lambda = (200\text{ GeV})^{-1}$, and the filled circles are the data. The arrows show the cut value of 20°.

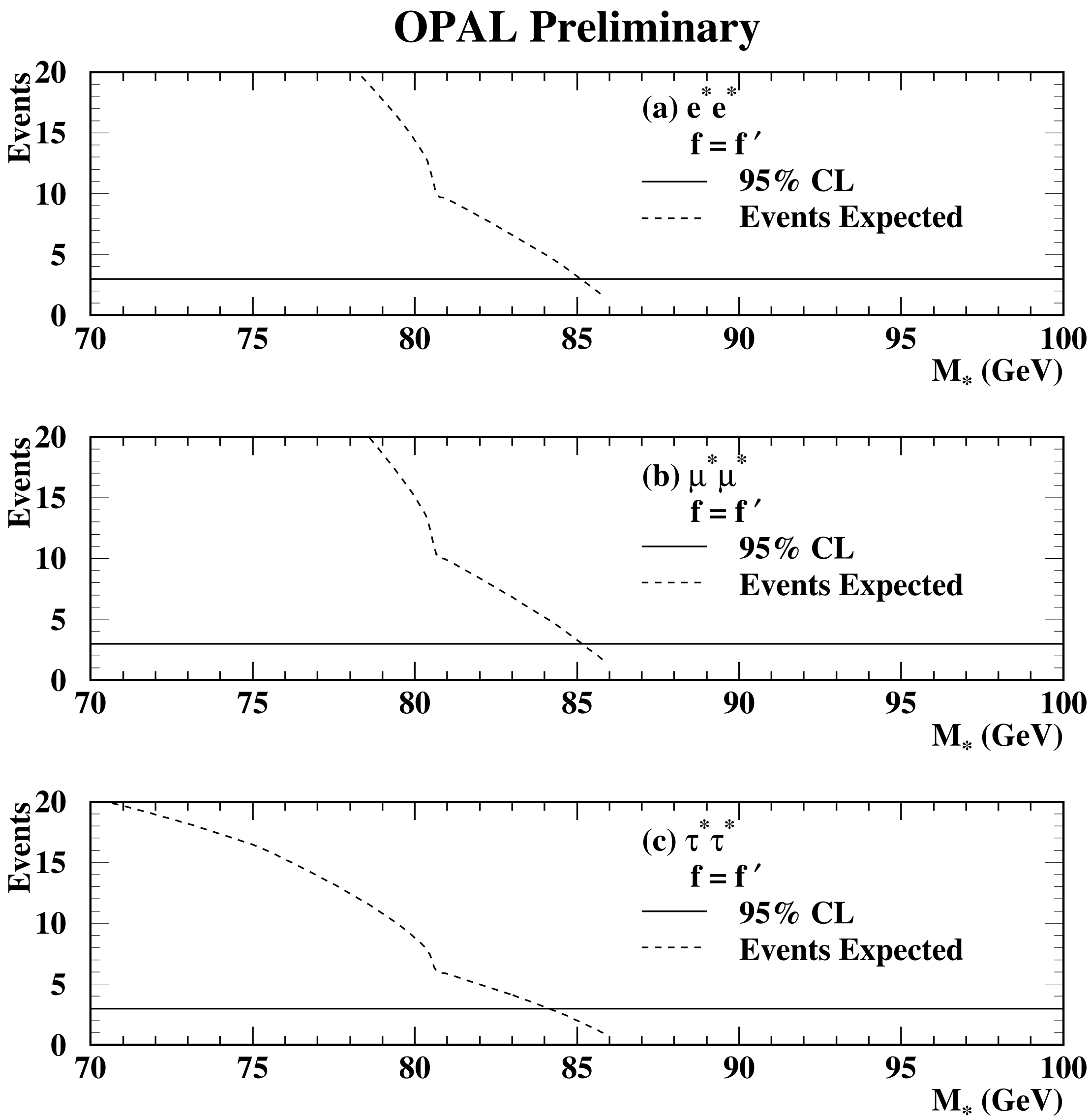

Figure 10: Expected number of observed events for the pair production of charged excited leptons with photonic decays for each lepton flavour, as a function of the excited lepton mass, M_*. Intersecting the 95% confidence level upper limit on the number of observed events with these curves gives the 95% confidence level mass limits. (a) is for $\mathrm{e}^*\mathrm{e}^*$, (b) is for $\mu^*\mu^*$ and (c) is for $\tau^*\tau^*$. The discontinuity at around 80 GeV is due to the combination of the $\sqrt{s} = 161$ GeV and 172 GeV data sets.

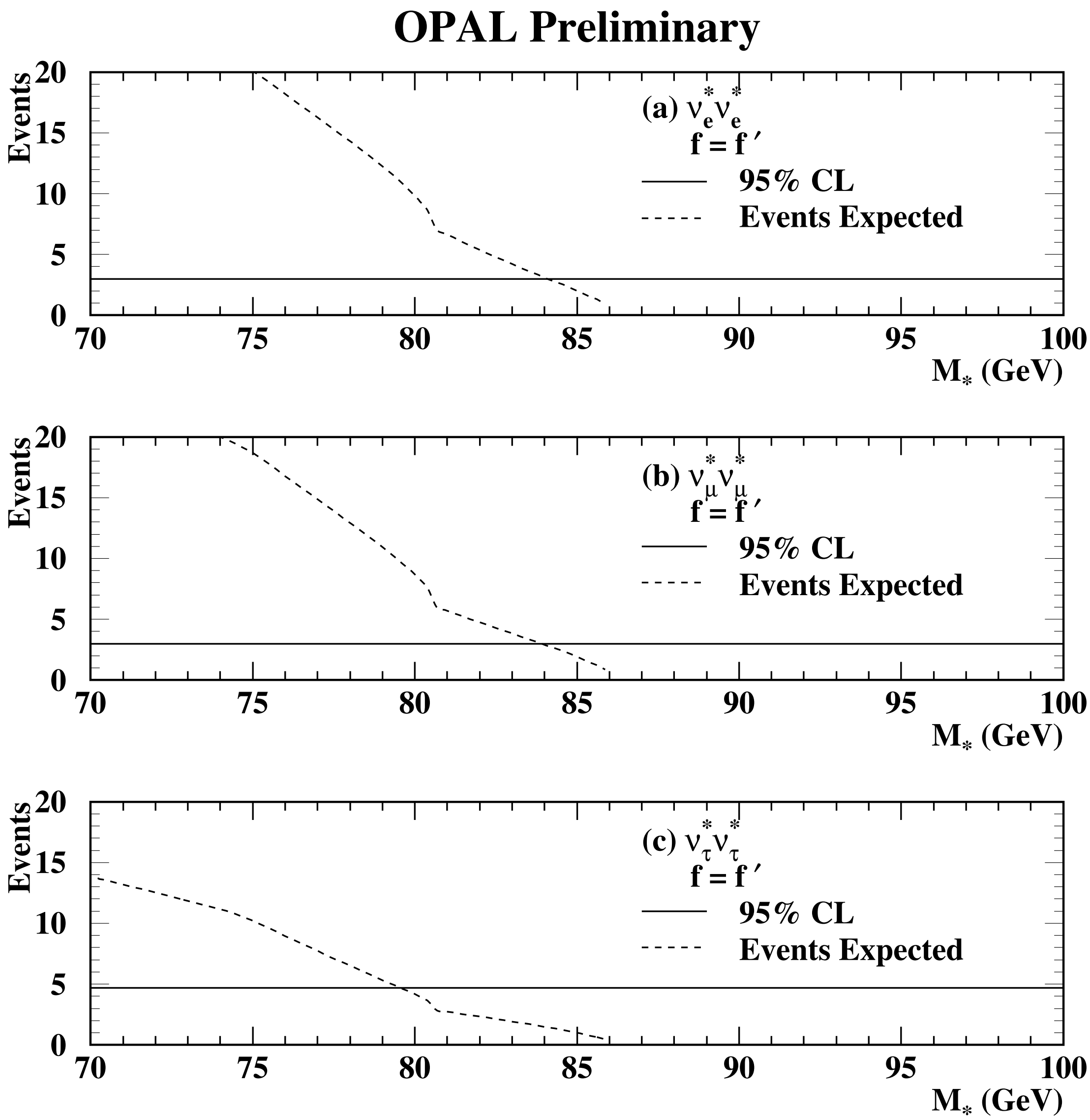

Figure 11: Expected number of observed events for the pair production of neutral excited leptons with charged decays for each lepton flavour, as a function of the excited lepton mass, M_*. Intersecting the 95% confidence level upper limit on the number of observed events with these curves gives the 95% confidence level mass limits. (a) is for $\nu_e^* \nu_e^*$, (b) is for $\nu_\mu^* \nu_\mu^*$ and (c) is for $\nu_\tau^* \nu_\tau^*$. The discontinuity at around 80 GeV is due to the combination of the $\sqrt{s} = 161$ GeV and 172 GeV data sets.

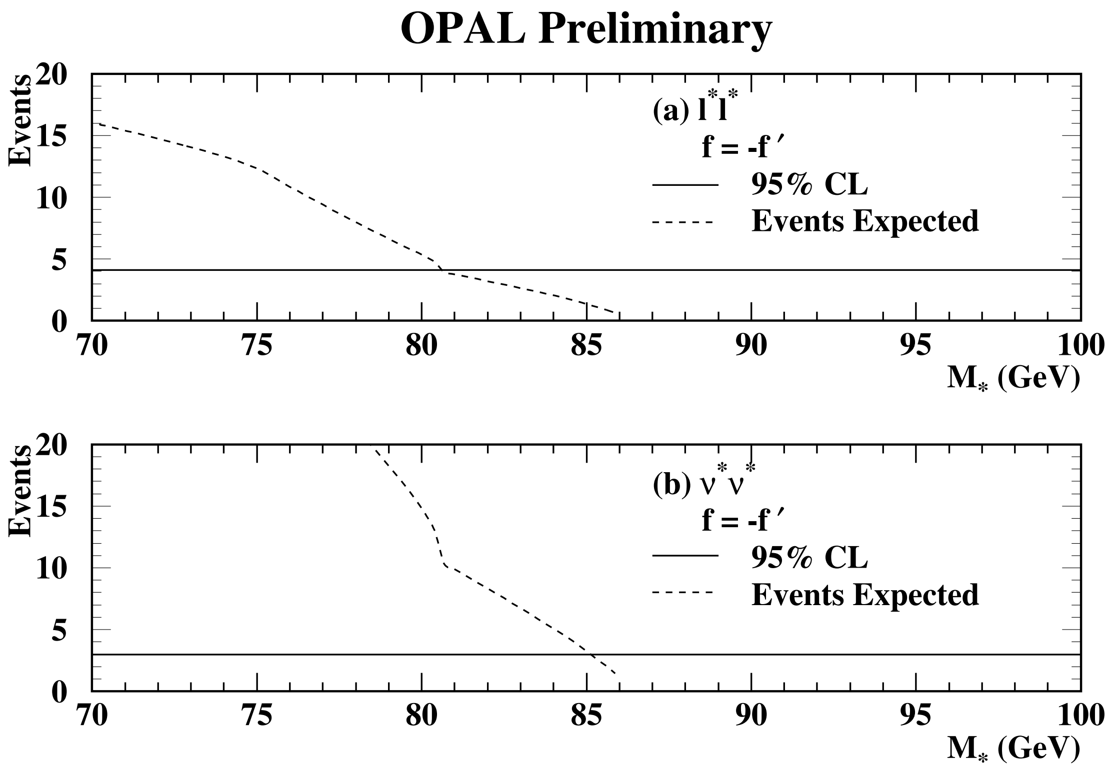

Figure 12: Expected number of observed events for the pair production of (a) charged excited leptons with charged decays, and (b) neutral excited leptons with photonic decays as a function of the excited lepton mass, M_*. Intersecting the 95% confidence level upper limit on the number of observed events with these curves gives the 95% confidence level mass limits. The (s-channel) production cross-section and branching ratios are the same for all flavours. The discontinuity at around 80 GeV is due to the combination of the $\sqrt{s} = 161$ GeV and 172 GeV data sets.

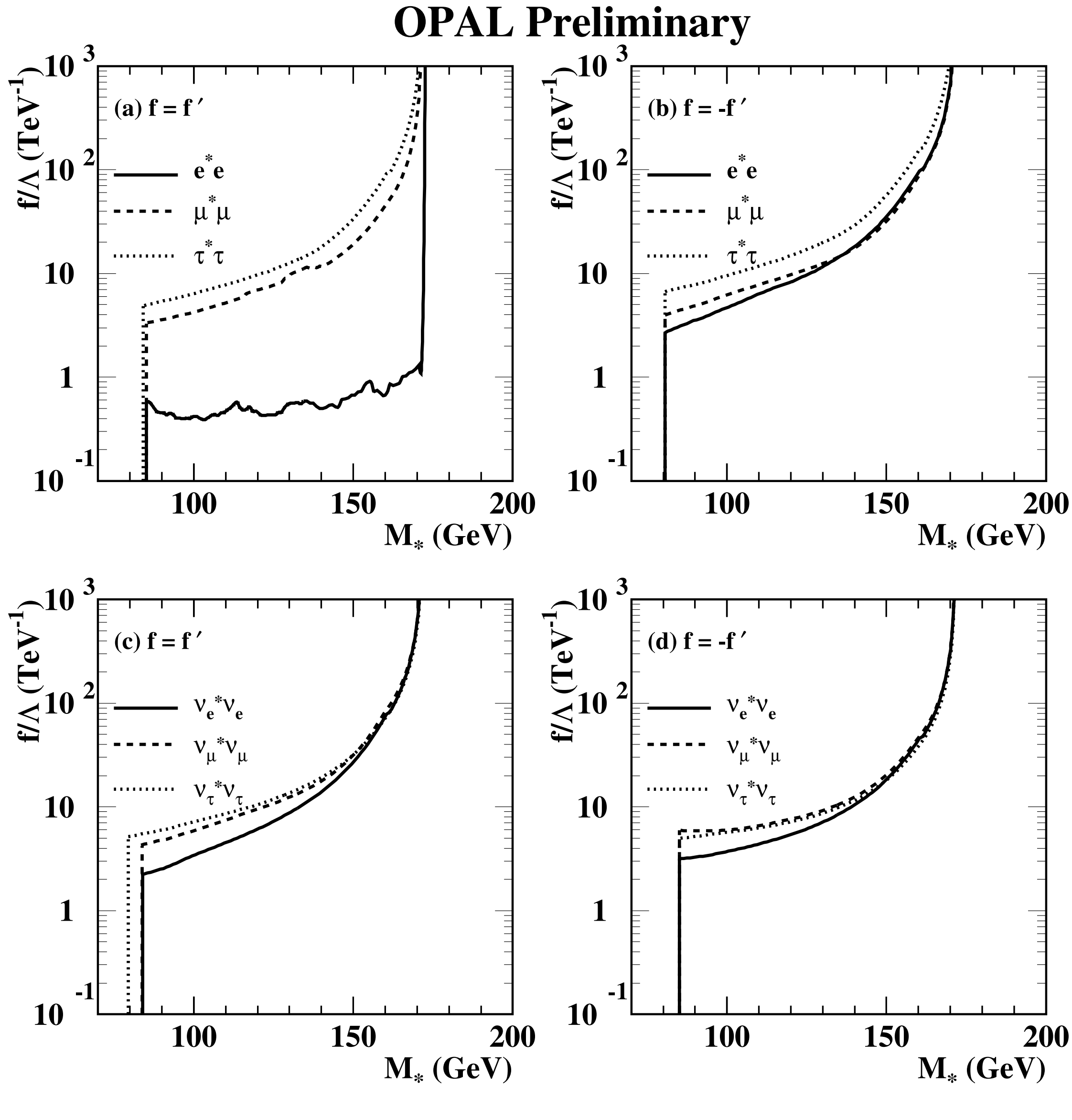

Figure 13: 95% C.L. upper limits on the ratio of the coupling to the compositeness scale, f/Λ, as a function of the excited lepton mass, M_*. (a) is for charged excited leptons with $f = f'$ from photonic and charged decays, (b) is for charged excited leptons with $f = -f'$ from charged decays, (c) is for neutral excited leptons with $f = f'$ from charged decays and (d) is for neutral excited leptons with $f = -f'$ from photonic and charged decays. The region above and to the left of the curves is excluded by the single and pair production searches, respectively.