Searches for Higgs and SUSY particles at LEP

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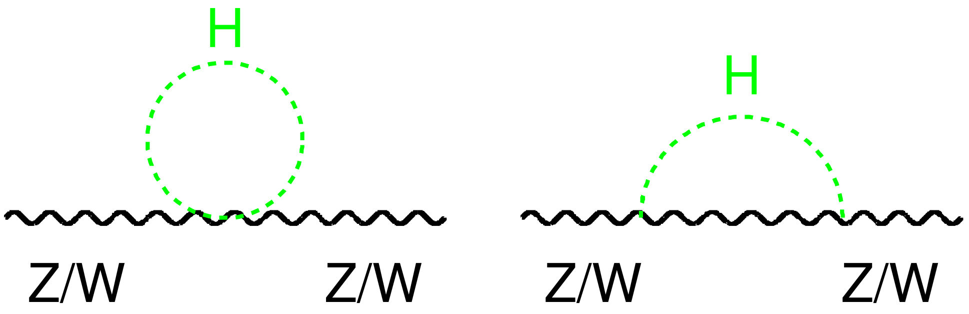
OUTLINE:

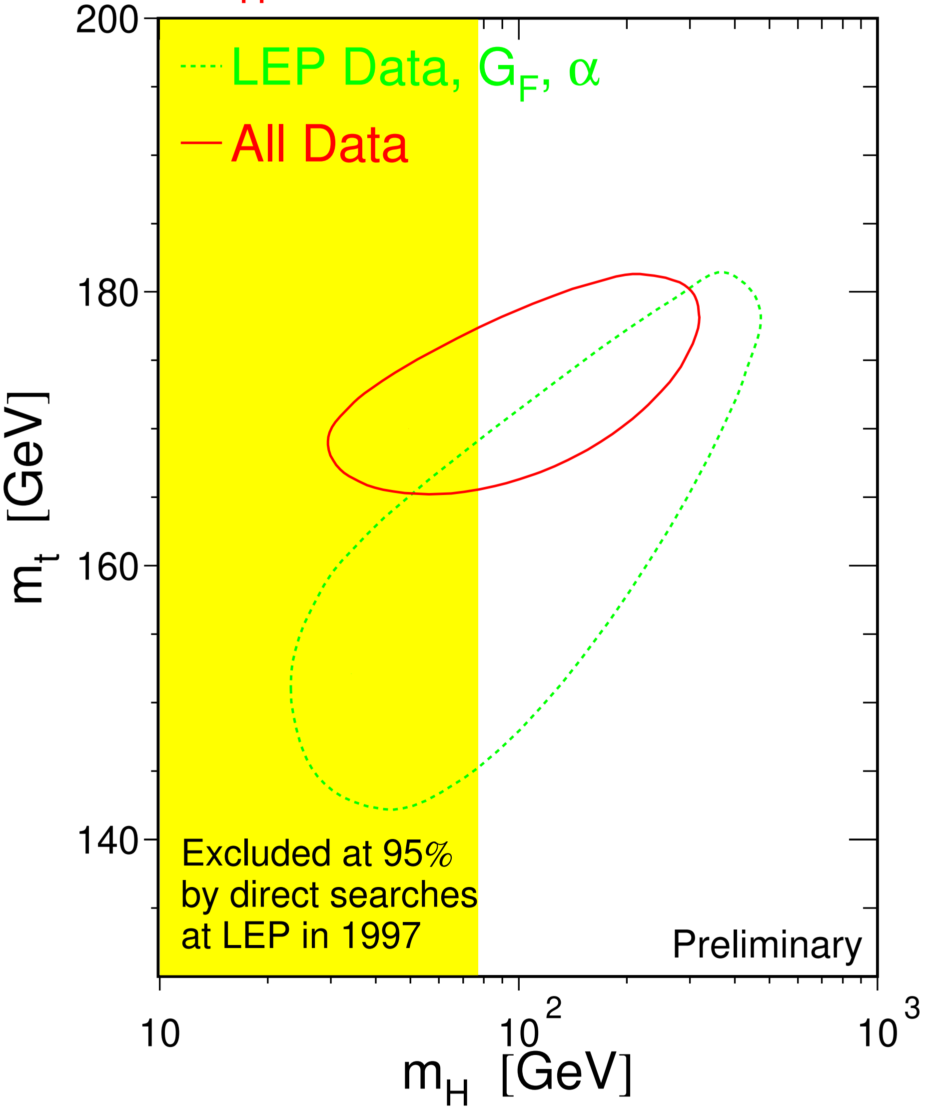
- Higgs Boson searches
  - 183 GeV results
  - Higgs inspired searches
- SUSY searches
  - Higgs sector
  - Limits on SUSY
  - Photonic final states
- Conclusions

Indirect Higgs searches

Electroweak measurements from
LEP, Tevatron and SLAC:

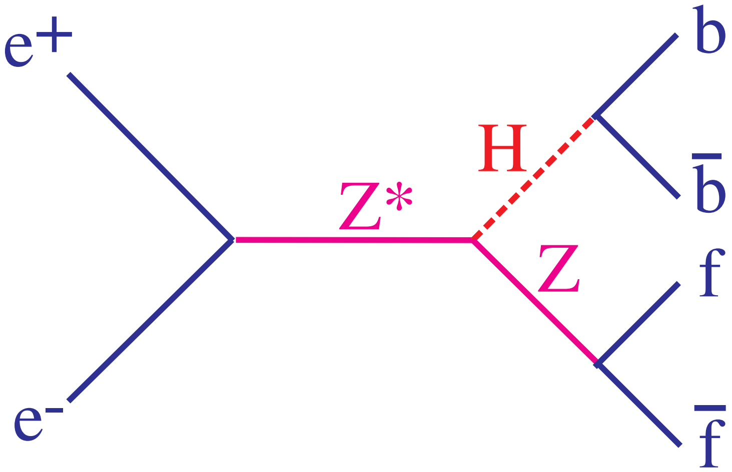


$M_H < 420$ GeV at 95% CL

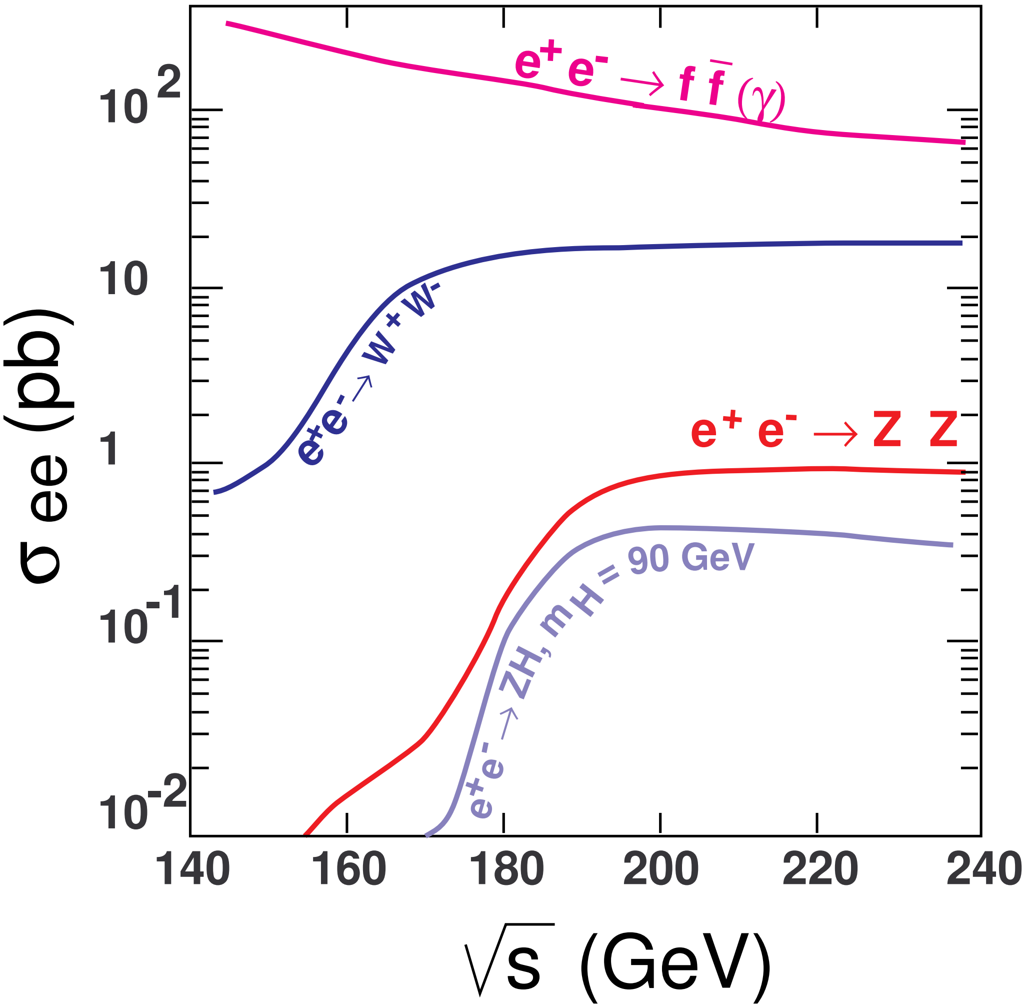


Higgs production cross-section

Direct Higgs searches at LEP:



Requires $\sqrt{s} > M_Z + M_H$



SM Higgs searches - results from L3

Four distinct topologies:

$\mathrm{Hq\bar{q}}$	-	4 jets
$\mathrm{H}\nu\bar{\nu}$	-	2 acoplanar jets
$\mathrm{H}\ell^+\ell^-$ $\ell = e, \mu$	-	2 leptons, 2 jets
$\tau^+\tau^-\mathrm{q\bar{q}}$	-	2 taus, 2 jets

Main background sources:

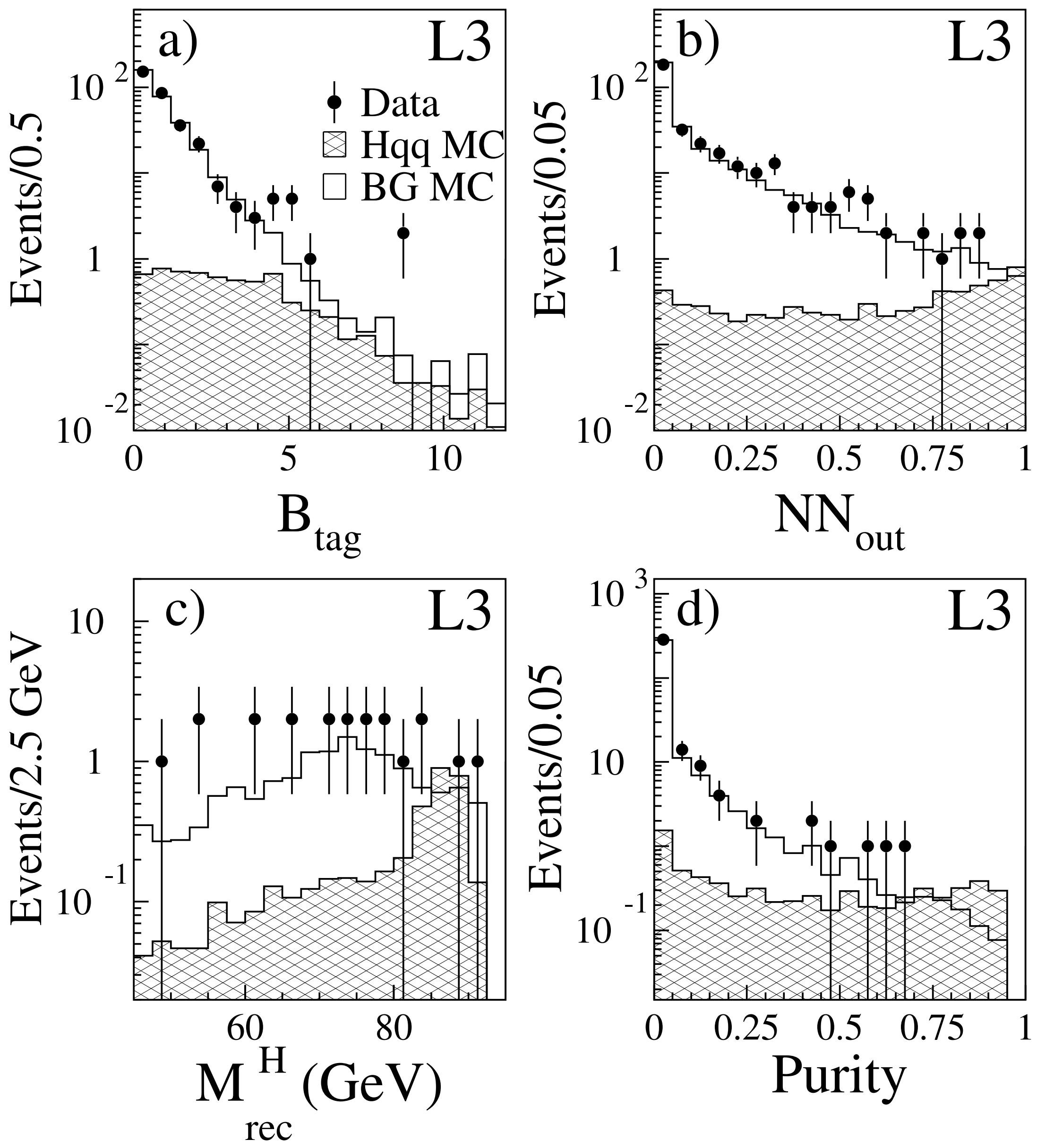
Two-fermion ($e^+e^- \to Z/\gamma \to q\bar{q}(\gamma)$) and four-fermion ($e^+e^- \to WW, ZZ$) final states for all the channels. For the $\mathrm{H}\nu\bar{\nu}$ channel the process $e^+e^- \to \mathrm{We}\nu$ in addition.

Analysis scheme:

- Loose preselection
- Mass-independent discriminant variable that combines $\mathrm{B_{tag}}$ and topological variables.
- Kinematic fit imposing energy-momentum conservation and $\mathrm{M_Z}$ constraint gives the best estimate of $\mathrm{M_H^{rec}}$
- Test of a given Higgs mass hypothesis using the discriminant variable and $\mathrm{M_H^{rec}}$.

SM Higgs searches - results from L3

Search for $Hq\bar{q}$ at 183 GeV with 55.3pb^{-1}:



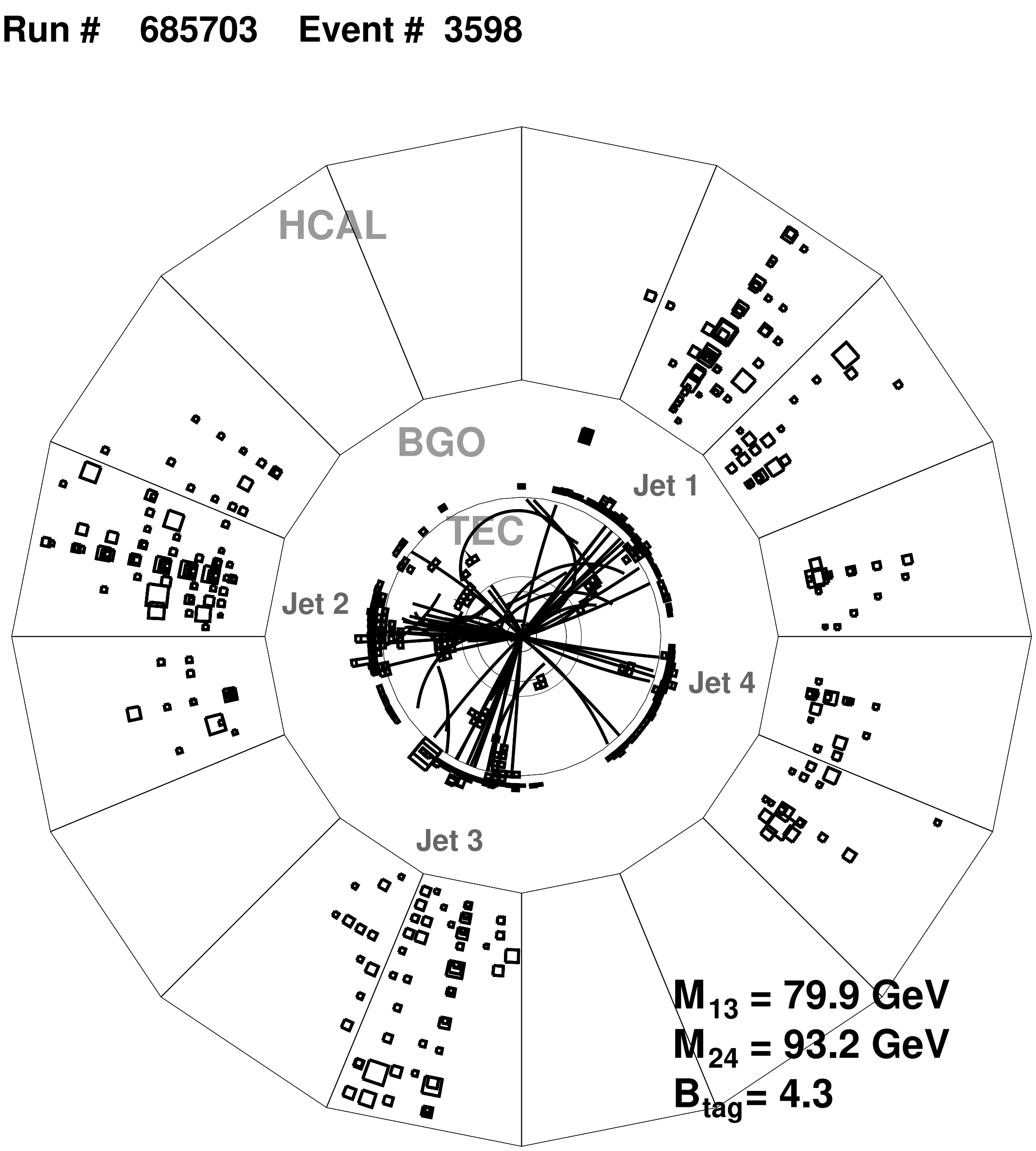
The purity variable:

$$P_{M_H} = \frac{f_s(M_H^{rec}, M_H) \cdot g_s(NN)}{f_s(M_H^{rec}, M_H) \cdot g_s(NN) + f_b(M_H^{rec}, M_H) \cdot g_b(NN)}$$

tests a given mass hypothesis.

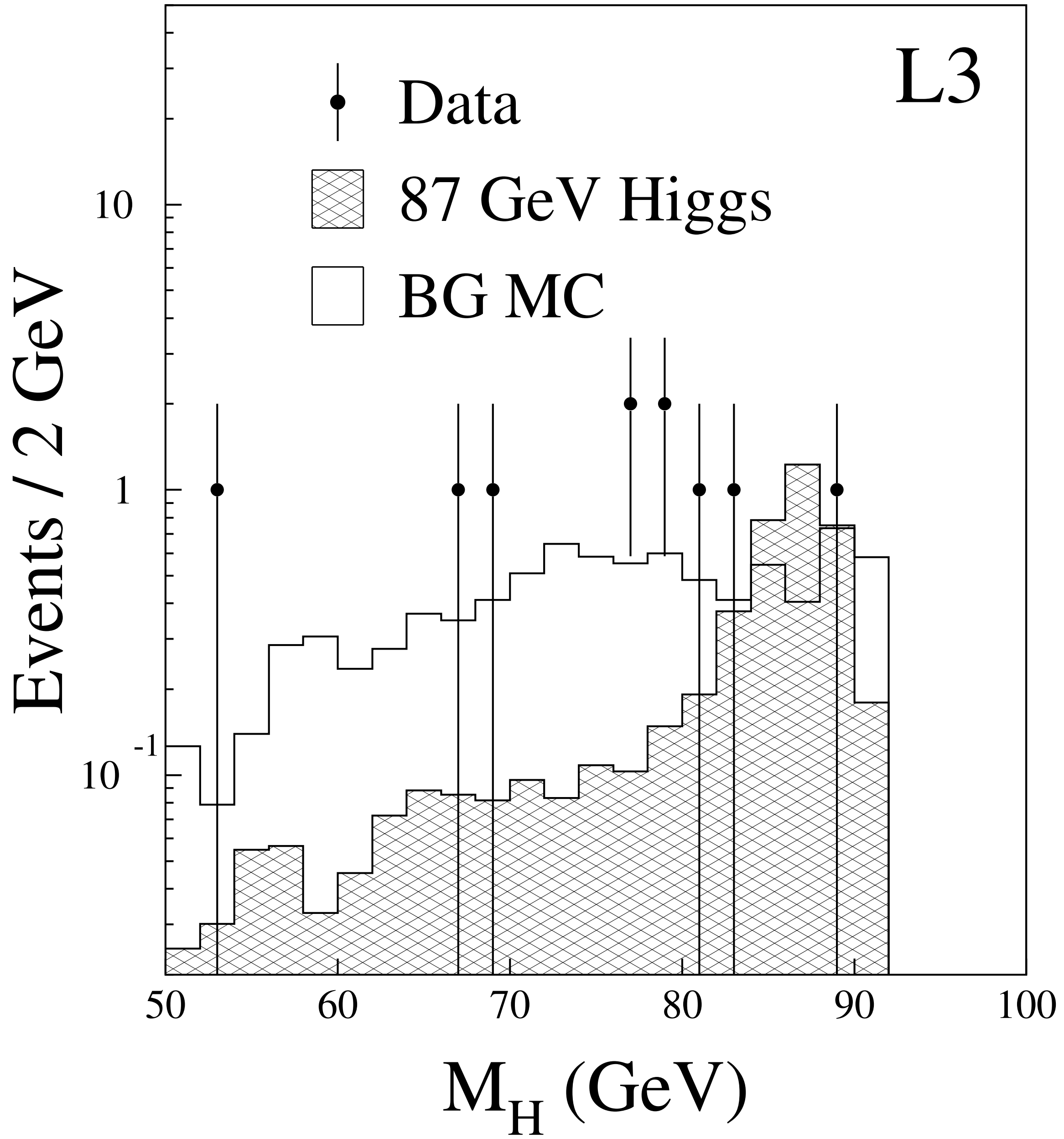
SM Higgs searches - results from L3

The most significant $Hq\bar{q}$ candidate:



SM Higgs searches - results from L3

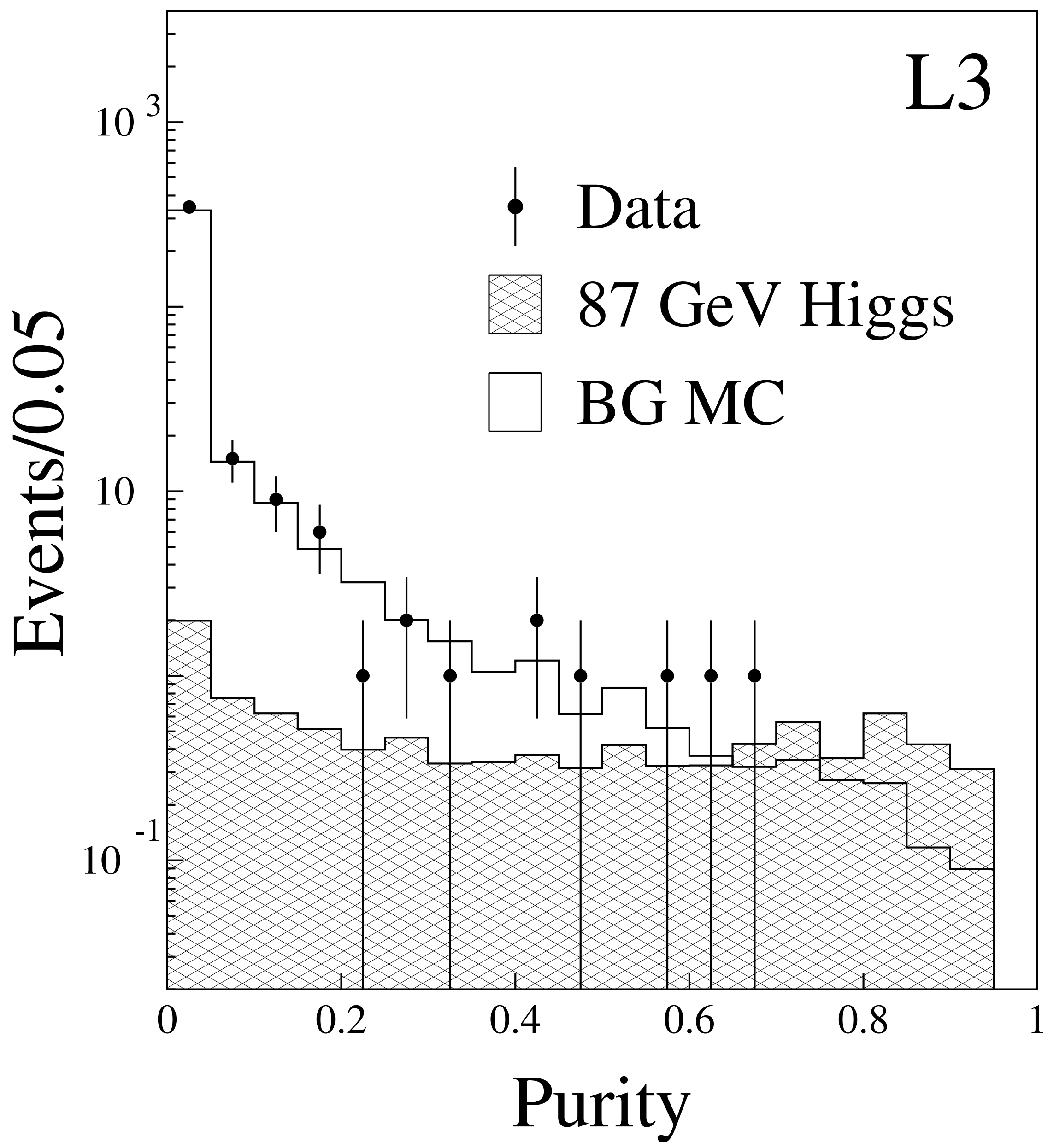
Mass spectrum of top ten candidates:



Mass resolution is typically 2-3 GeV (5C kinematic fit)

SM Higgs searches - results from L3

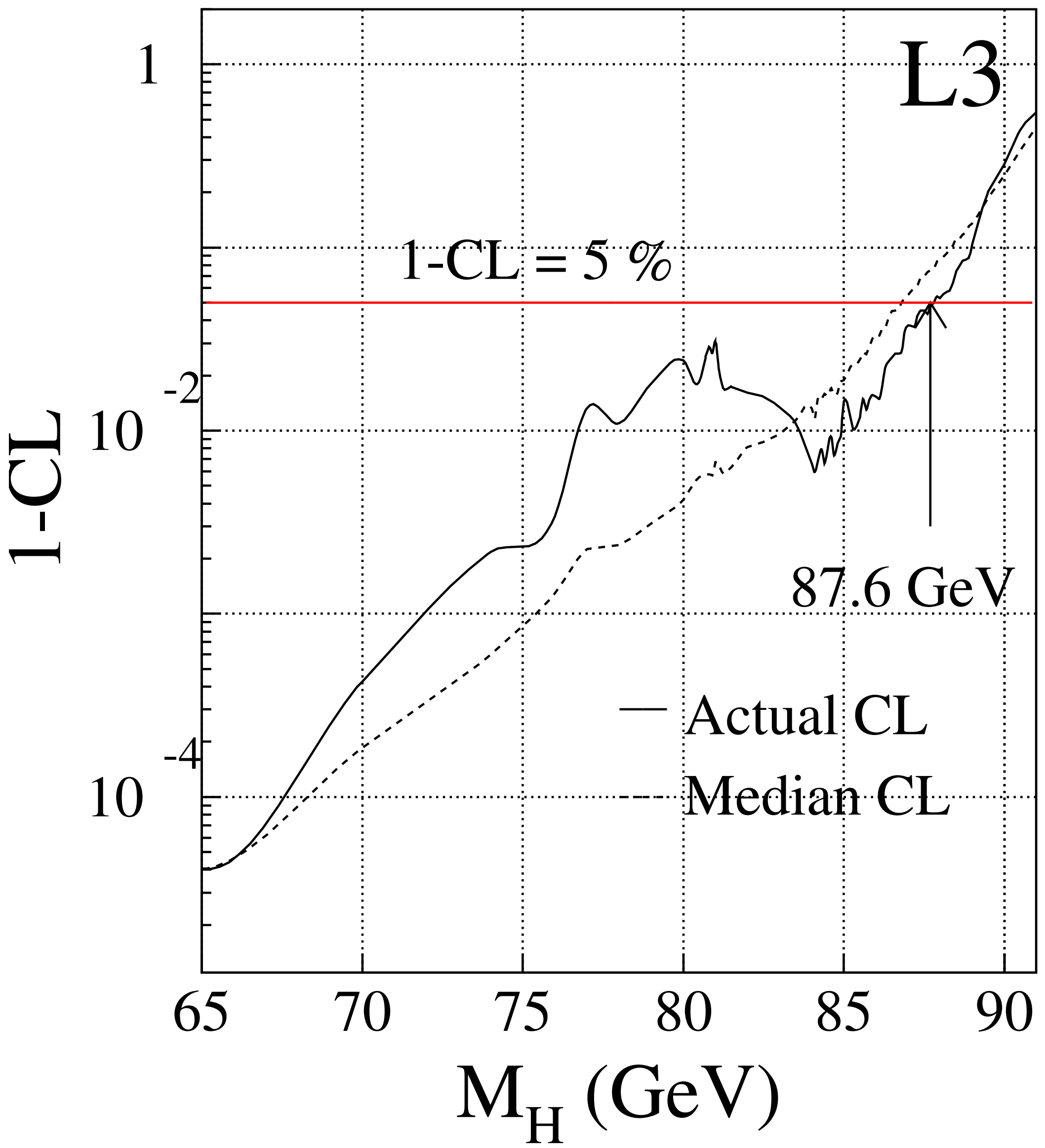
Final discriminant variable:



All search channels are combined

SM Higgs searches - results from LEP

Limits on SM Higgs Boson from the 183 GeV run

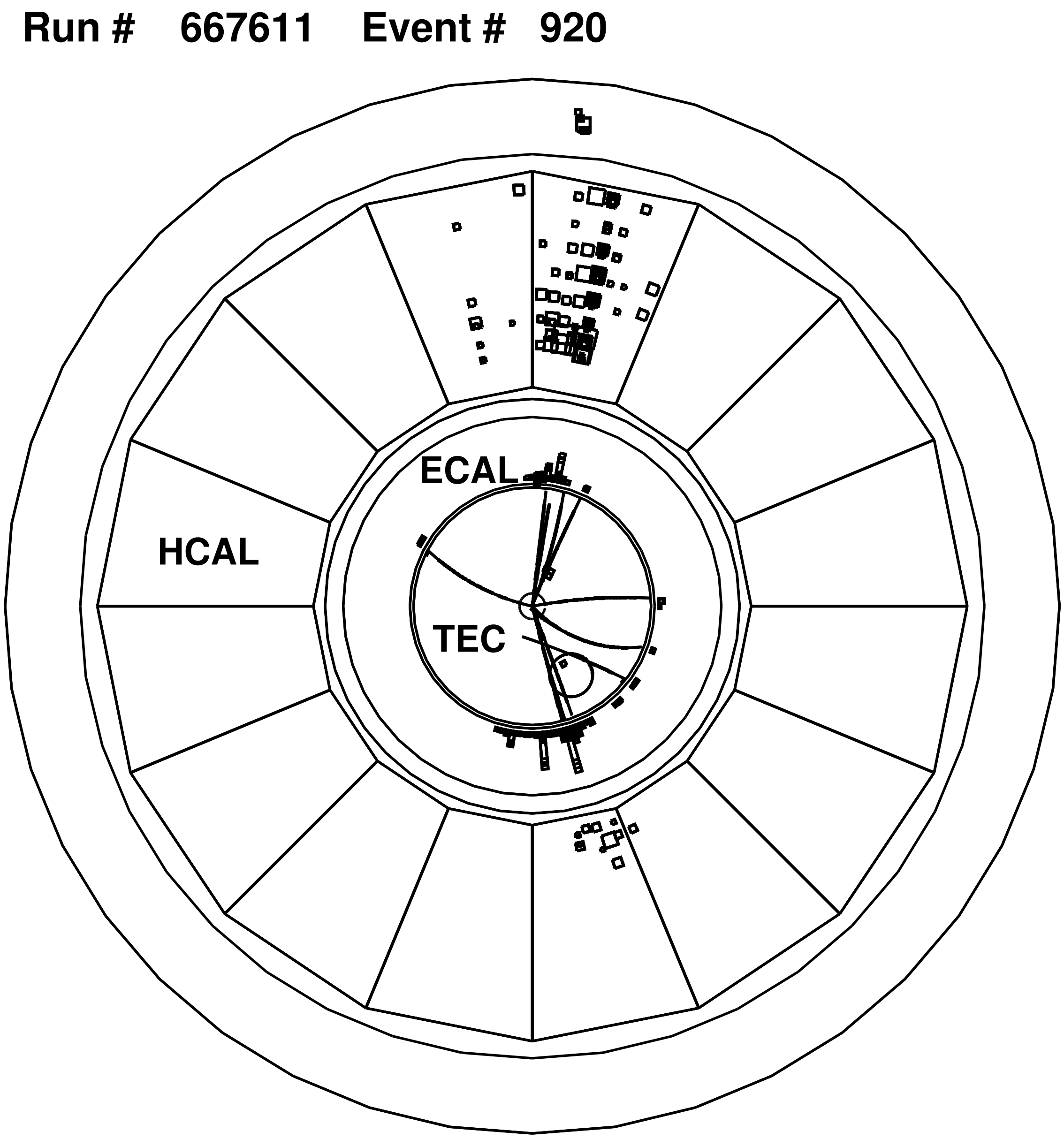


ALEPH: $M_H > 88.$GeV
DELPHI: $M_H > 83.6$GeV
OPAL: $M_H > 82.0$GeV

LEP combined (91-172 GeV): $M_H > 77.5$ GeV

Higgs inspired searches - results from L3

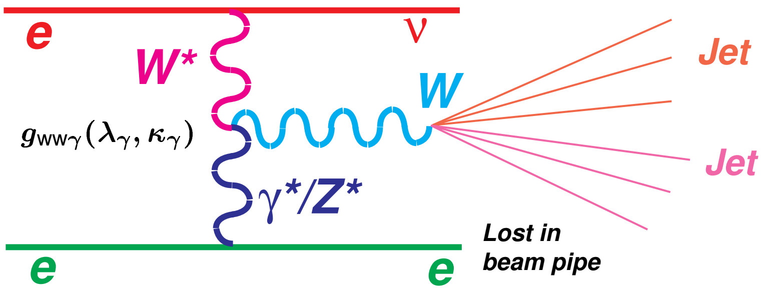
Several $\nu\bar{\nu}q\bar{q}$ candidates at 161 GeV

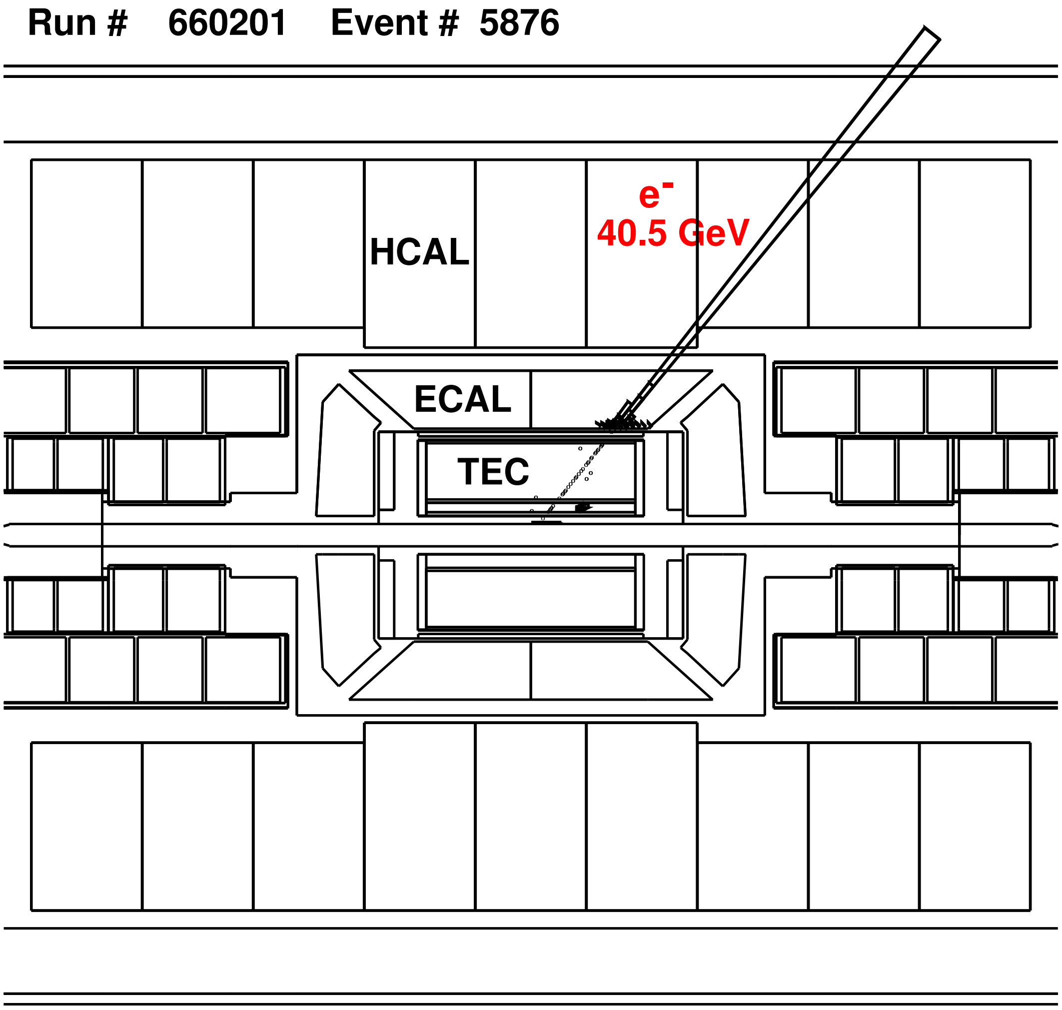


Discovery?

Higgs inspired searches - results from L3

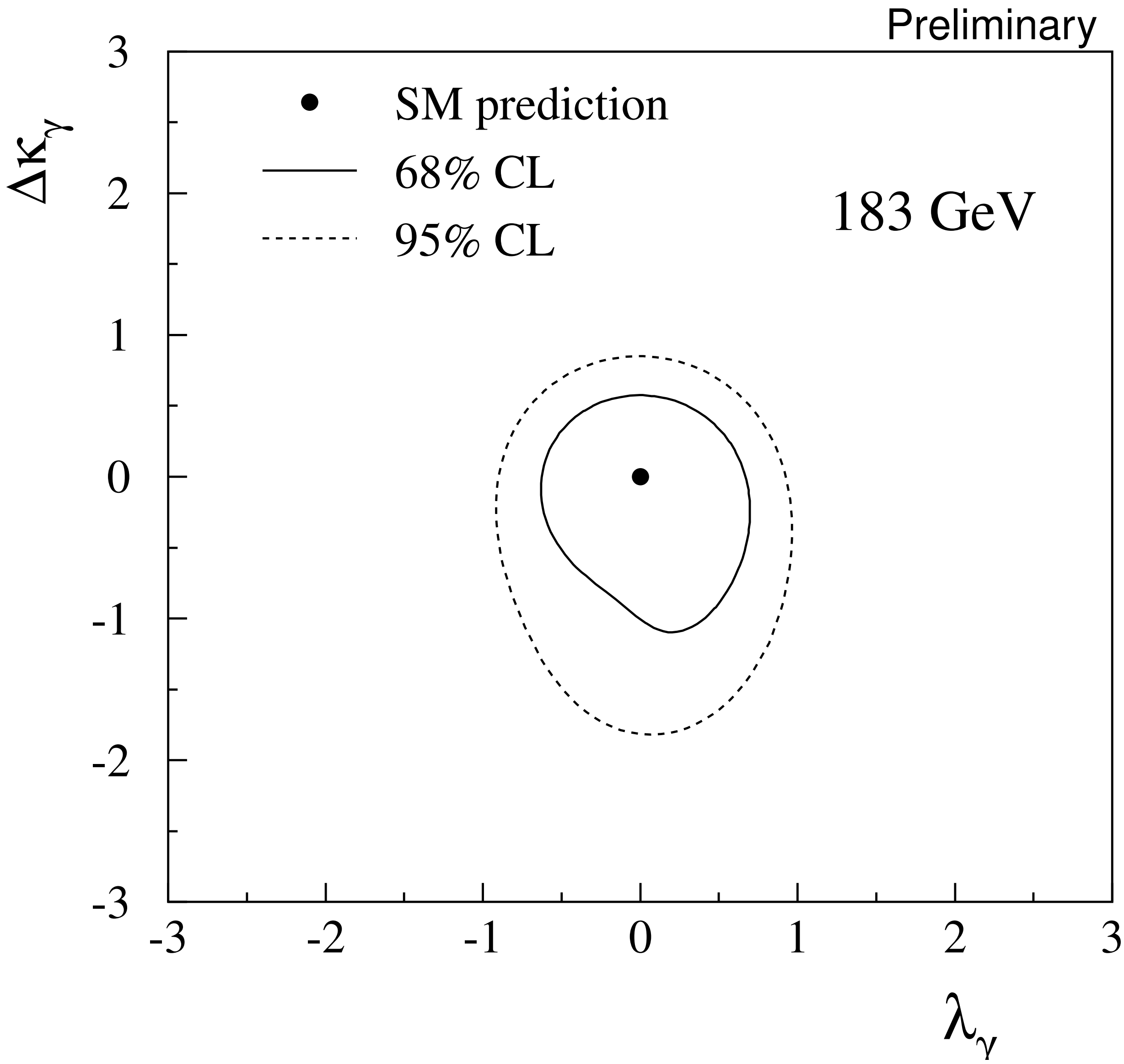
Explanation: $e^+e^- \to W^-e^+\nu_e$





Higgs inspired searches - results from L3

Single W production at LEP -
stringent test of WWγ couplings



This measurement becomes competitive with the analogous measurements from Tevatron

Minimal SUSY extension of the Standard Model

Why SUSY?

- Hierarchy problem ($\delta \mathrm{M}_{\mathrm{H}}^2 \sim \Lambda_{\mathrm{NP}}^2$)
- Grand unification

Price to pay:

- Five fundamental scalars: H^+, H^-, H, h and A
- Realm of supersymmetric partners of conventional particles: $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$, $\tilde{l}$ and $\tilde{\mathrm{q}}$
- New parameters of the model: M, μ, tanβ, m_0 and A.

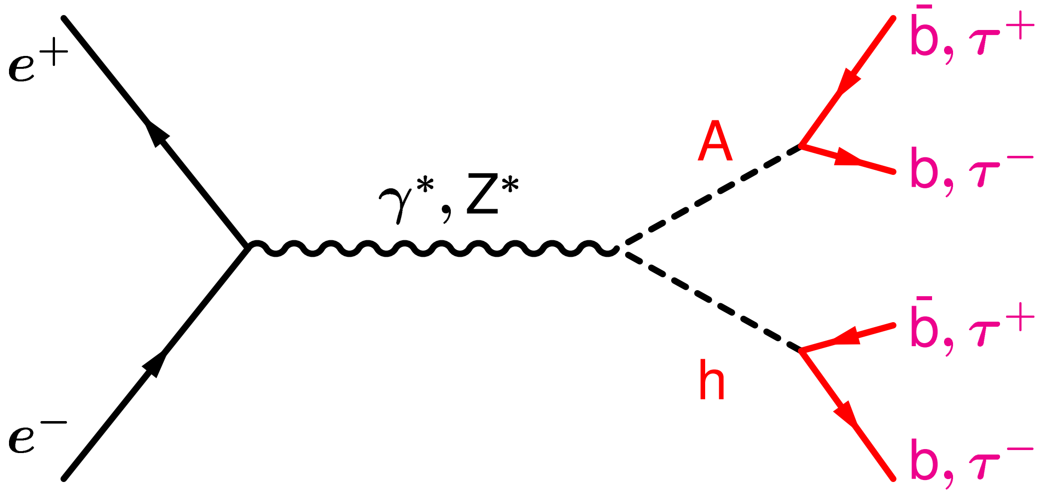
Search for Higgs particles

Search for SUSY particles

Any SUSY particle decays into χ_1^0 and conventional particles. Therefore a signature of any SUSY decay is missing energy accompanied by leptons, photons or hadrons.

hA searches

New channels in addition to $e^+e^- \to hZ$:



Cross section

- $\sigma_{hZ} = \sin^2(\beta - \alpha) \cdot \sigma_{HZ}^{SM}$
- $\sigma_{hA} = \cos^2(\beta - \alpha) \cdot \bar{\lambda} \cdot \sigma_{\nu\nu}^{SM}$

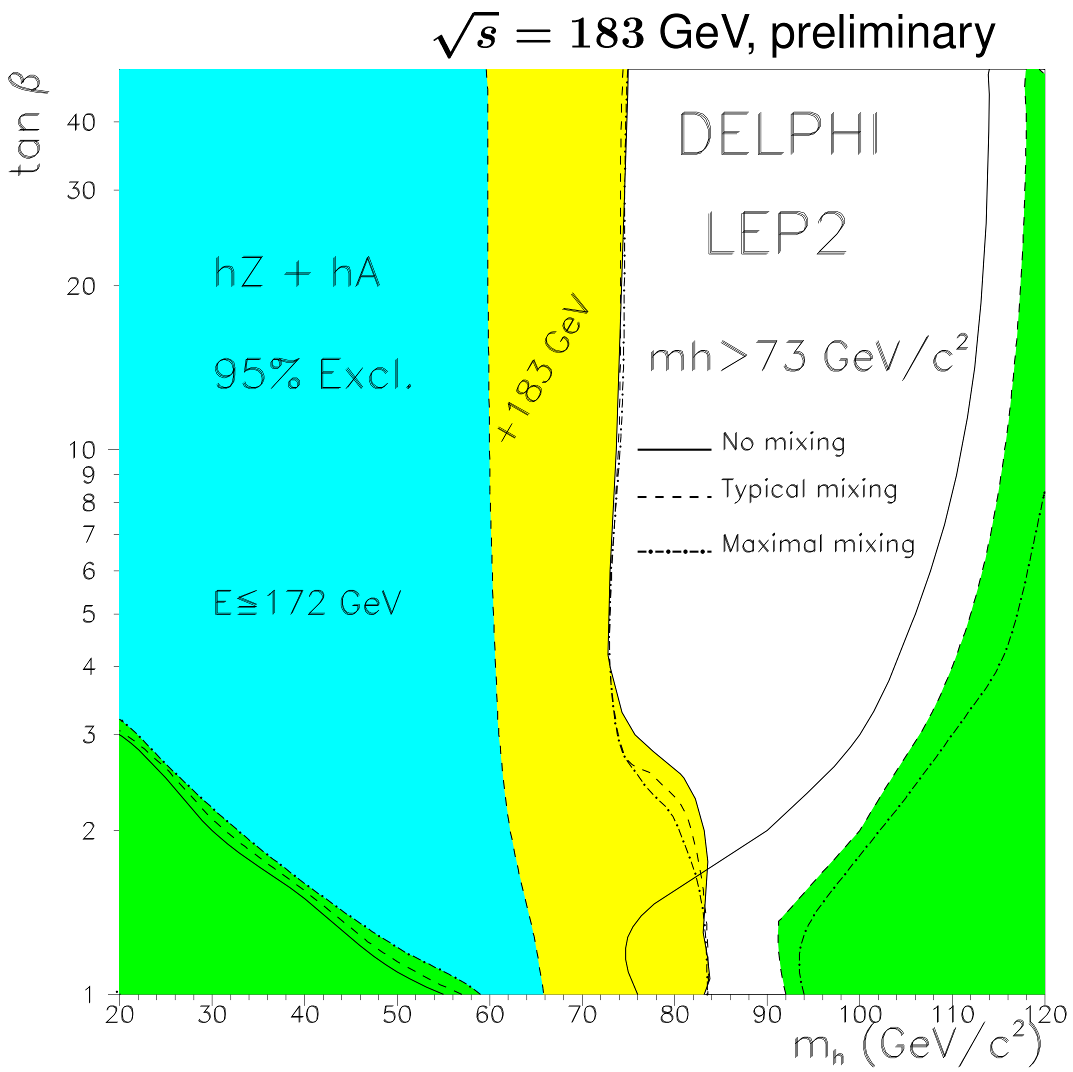
Decay modes

- $hA \to b\bar{b}b\bar{b}$
- $hA \to b\bar{b}\tau^+\tau^-$ and $hA \to \tau^+\tau^- b\bar{b}$
- $hA \to AAA \to 6b$, $4b + 2\tau$, $2b + 4\tau$ and 6τ

M_h and M_A are not independent, but are related to one another via MSSM parameters ($\tan\beta$ and A in the first place).

hZ and hA searches - results from DELPHI

Combination of hZ and hA searches:



ALEPH: $M_h > 73.$GeV

L3: $M_h > 58.6$GeV

OPAL: $M_h > 59.0$GeV

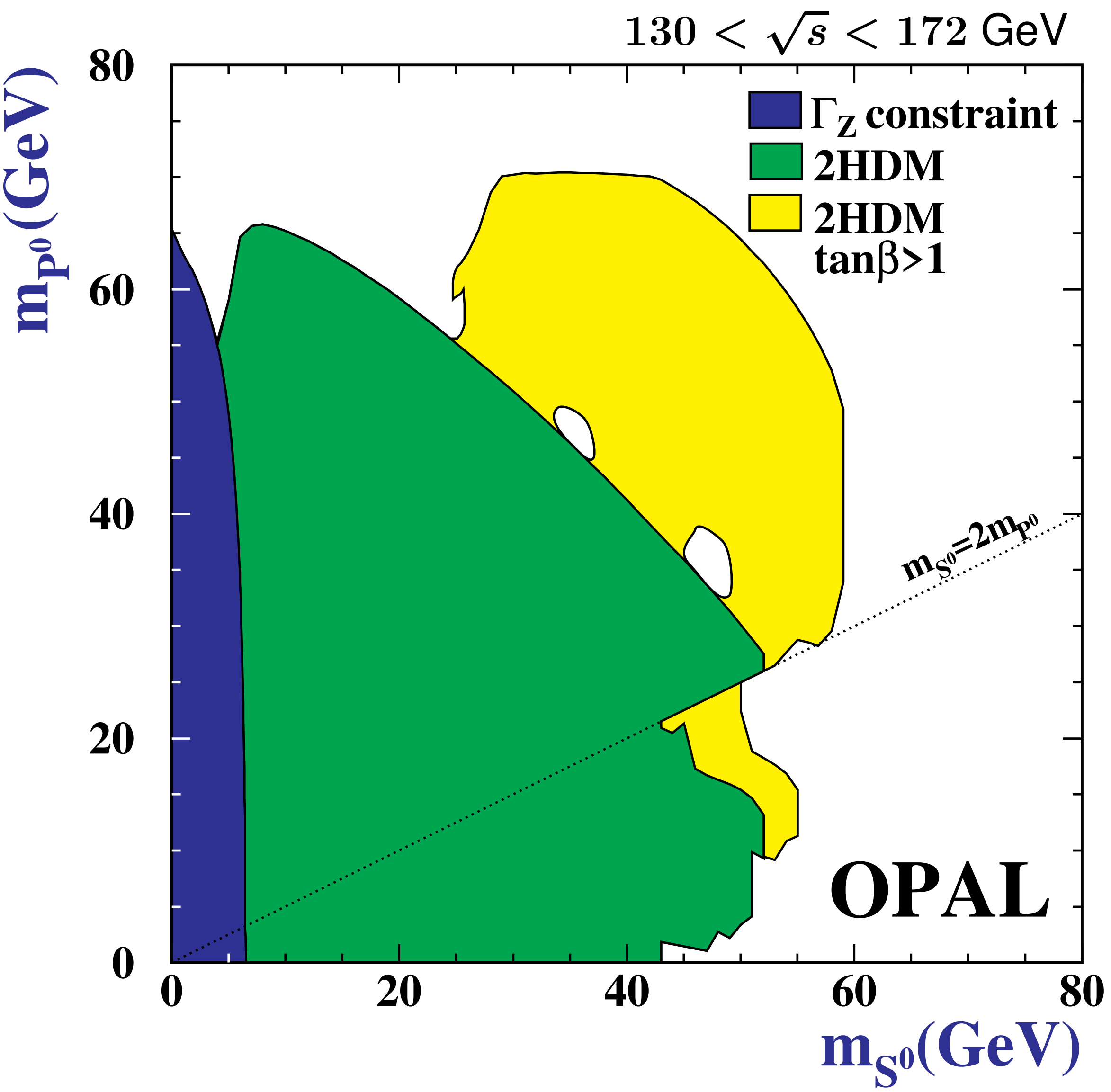
L3 and OPAL have not yet analysed 183 data sample

hZ and hA searches - results from OPAL

Generic search for S^0 and P^0 bosons:

- $e^+e^- \to S^0Z$, $\sigma = s^2 \cdot \sigma_{HZ}^{SM}$
- $e^+e^- \to S^0P^0$, $\sigma = c^2 \cdot \bar{\lambda} \cdot \sigma_{\nu\nu}^{SM}$

"Casper the friendly but shy ghost":



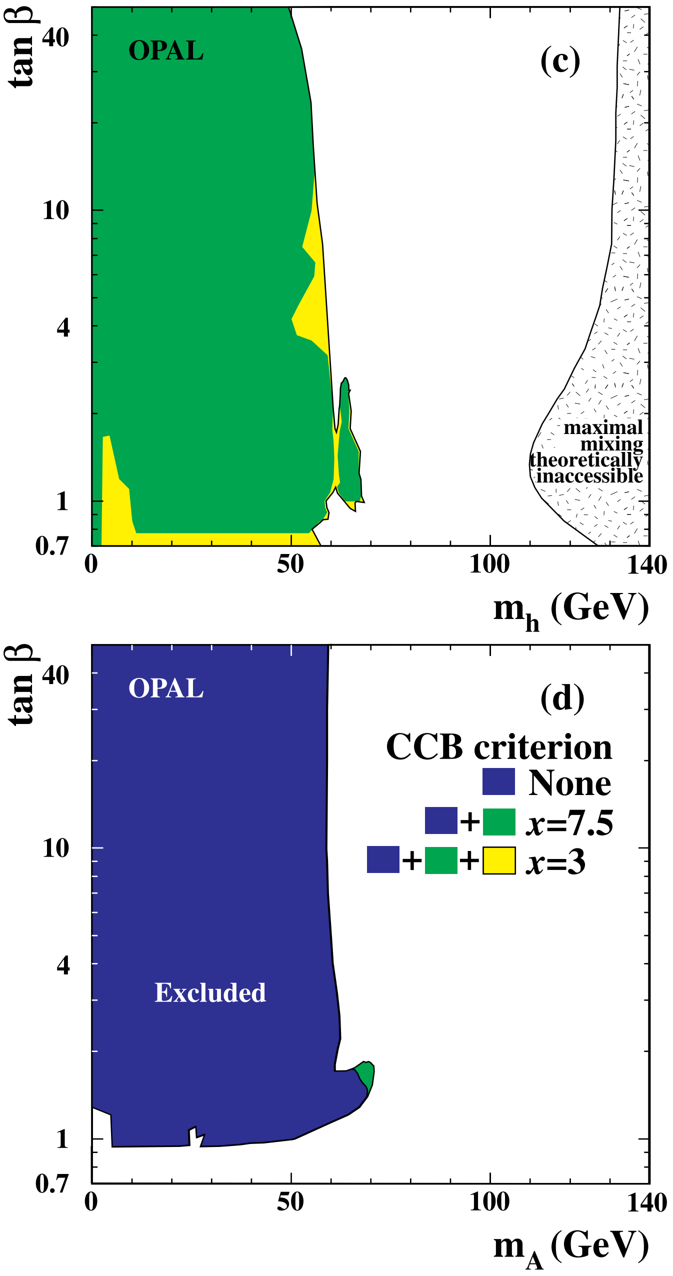
hZ and hA searches - results from OPAL

General 2HDM analysis includes effects of $\tilde{t}$ condensate

Effects of Charge- and Colour-breaking minima in MSSM lagrangian are not yet fully understood

A simple approximative criterion to avoid minima:

$$A^2 + 3\mu^2 < x(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R})$$

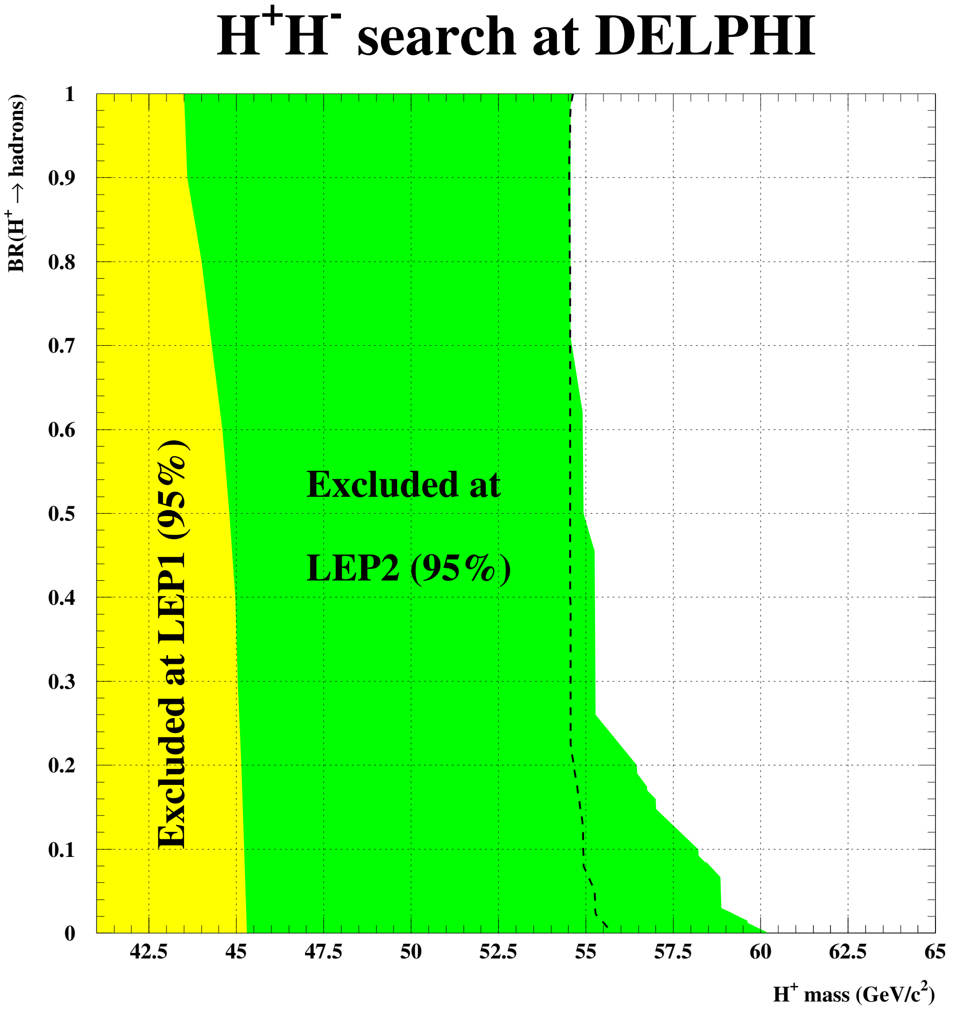


$\mathrm{H^+H^-}$ searches - results from DELPHI

At tree level $M^2_{\mathrm{H}^\pm} = M^2_{\mathrm{W}} + M^2_{\mathrm{A}}$ -
production at LEP2 is not likely

However, possible decay modes

- $\mathrm{H^+H^-} \to \mathrm{c\bar{s}s\bar{c}}$
- $\mathrm{H^+H^-} \to \mathrm{c\bar{s}}\tau^-\bar{\nu}_\tau$ and $\mathrm{H^+H^-} \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$

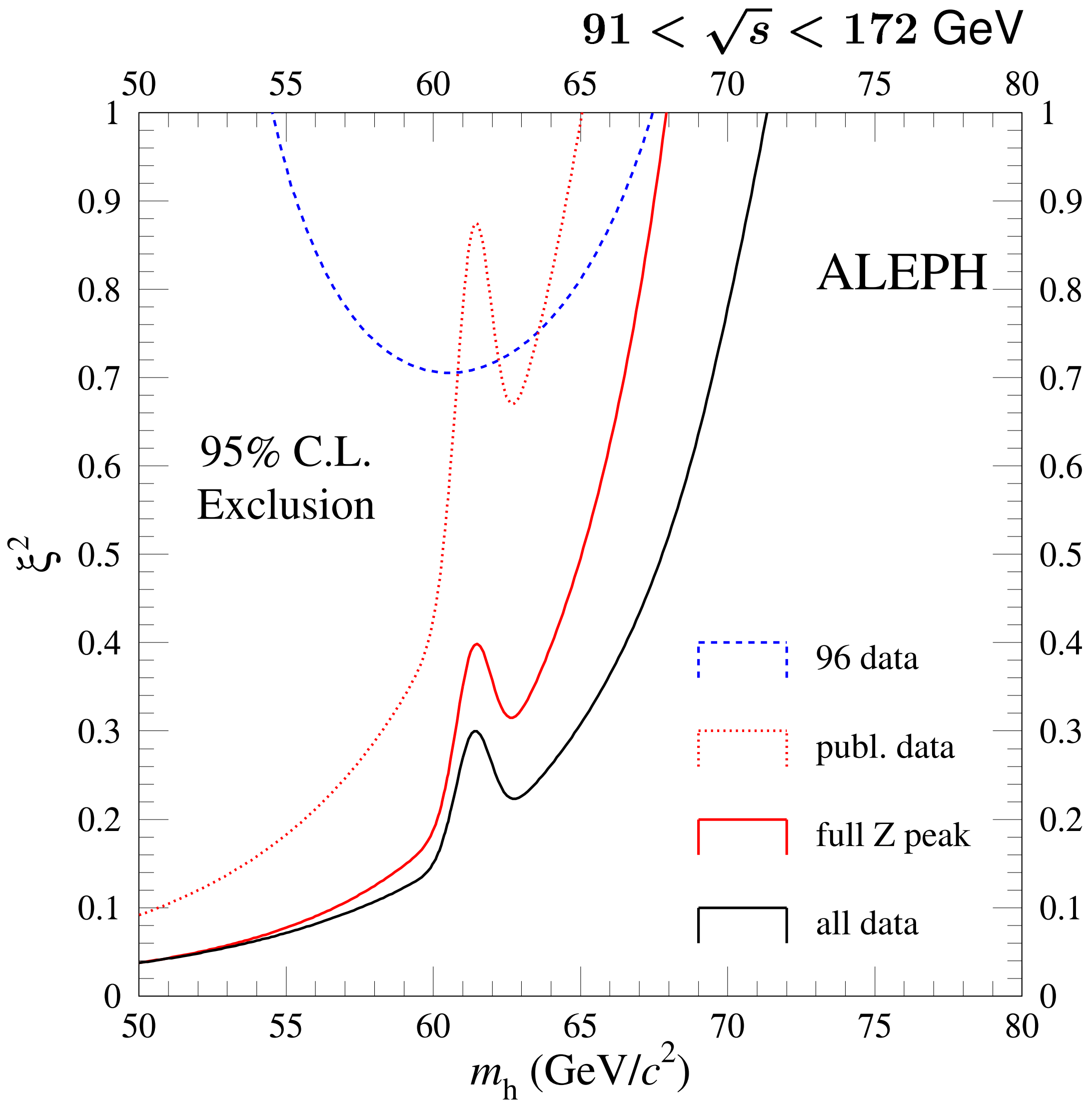


ALEPH: $M_{\mathrm{H}^\pm} > 52.\mathrm{GeV}$
DELPHI: $M_{\mathrm{H}^\pm} > 54.5\mathrm{GeV}$
OPAL: $M_{\mathrm{H}^\pm} > 52.0\mathrm{GeV}$

Invisible Higgs - results from ALEPH

If Higgs boson is heavy enough, the channel H $\rightarrow \chi^0\chi^0$ may be open

The signature HZ $\rightarrow \chi^0\chi^0 q\bar{q}$



ALEPH: $M_H > 71.2$GeV
L3: $M_H > 69.6$GeV

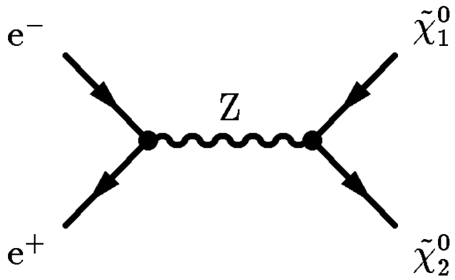
Possible SUSY scenarios

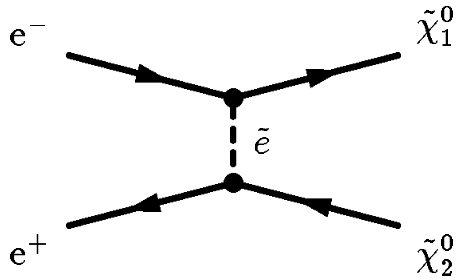
Candidates for LSP:

- χ_1^0 - gravity mediated SUSY breaking (heavy $\tilde{\mathrm{G}}$)
- $\tilde{\mathrm{G}}$ - gauge mediated SUSY breaking (light $\tilde{\mathrm{G}}$)
- R-parity violating SUSY - unstable LSP

Production of SUSY particles at LEP:

- $e^+e^- \to \chi^0\chi^0$
- $e^+e^- \to \chi^+\chi^-$
- $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$





Decays of SUSY particles:

- $\chi^\pm \to \chi_1^0 q\bar{q}', \chi_1^0 \ell \nu_\ell$
- $\chi_k^0 \to \chi_1^0 f\bar{f}, \chi_1^0 \gamma$
- $\tilde{\ell}^+ \to \ell^+ \chi_1^0$

Mass relations

Higgsino region

- Large M_2, $\mu << M_2$
- Sneutrino masses are large
- Search for charginos and neutralinos

Gaugino region I - large m_0

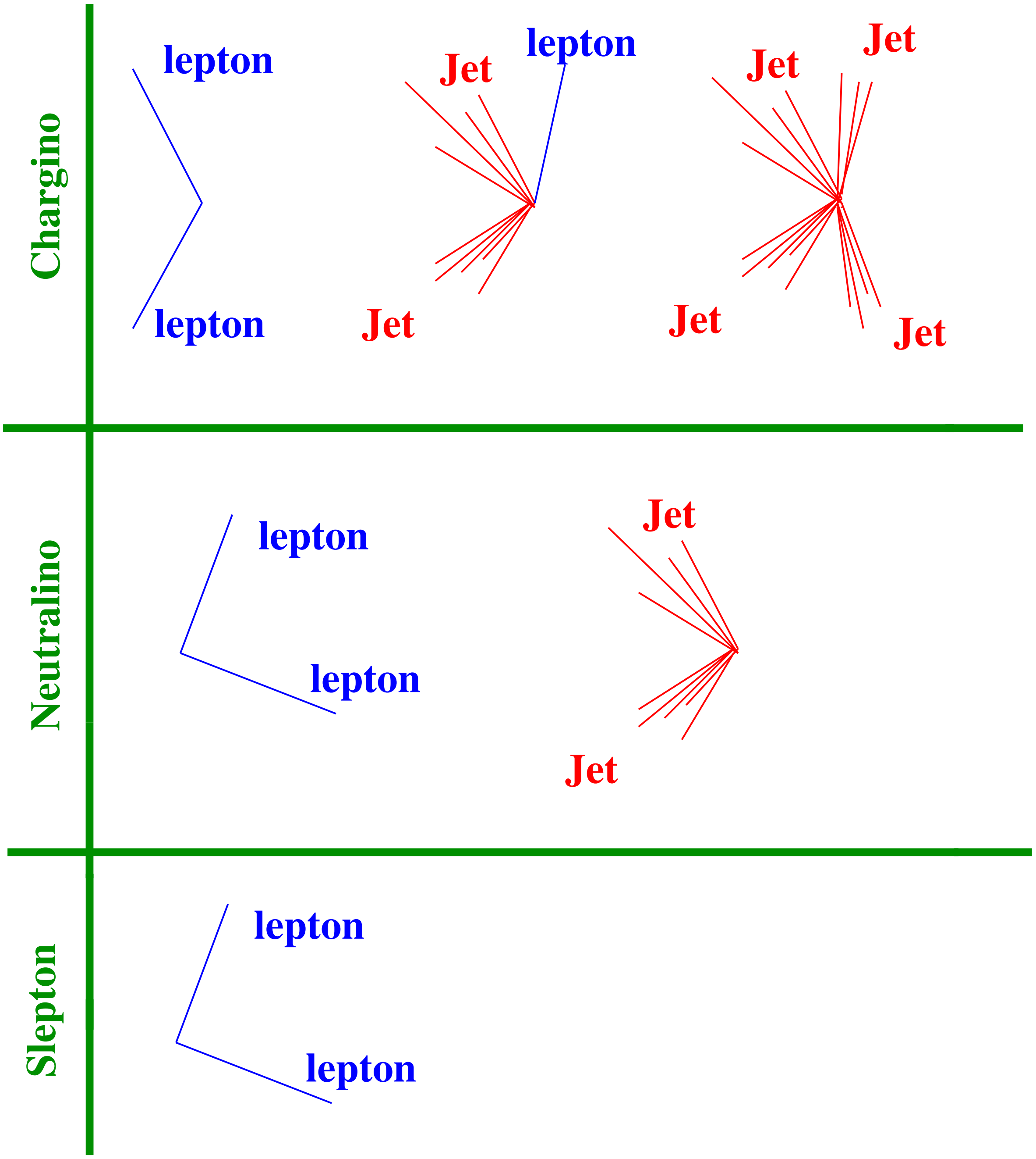
- Small M_2, $\mu >> M_2$
- Sneutrino masses are large
- t-channel $\tilde{\nu}$ exchange does not contribute
- Search for charginos and neutralinos

Gaugino region II - low m_0

- Small M_2, $\mu >> M_2$
- Sneutrino masses are small
- t-channel $\tilde{\nu}$ exchange interferes destructively
- Chargino production cross-section vanishes
- Search for scalar leptons

SUSY signatures

Typical signal topologies at $\sqrt{s} = 183$ GeV:



Dominant background to SUSY searches

$$\Delta M \simeq E_{\text{vis}}$$

Low ΔM region ($\delta \sim 3 - 10$ GeV)

- Background: $e^+e^- \to e^+e^- f\bar{f}$
- Discriminant variables: transverse momentum, acoplanarity

Medium ΔM region ($\delta \sim 30$ GeV)

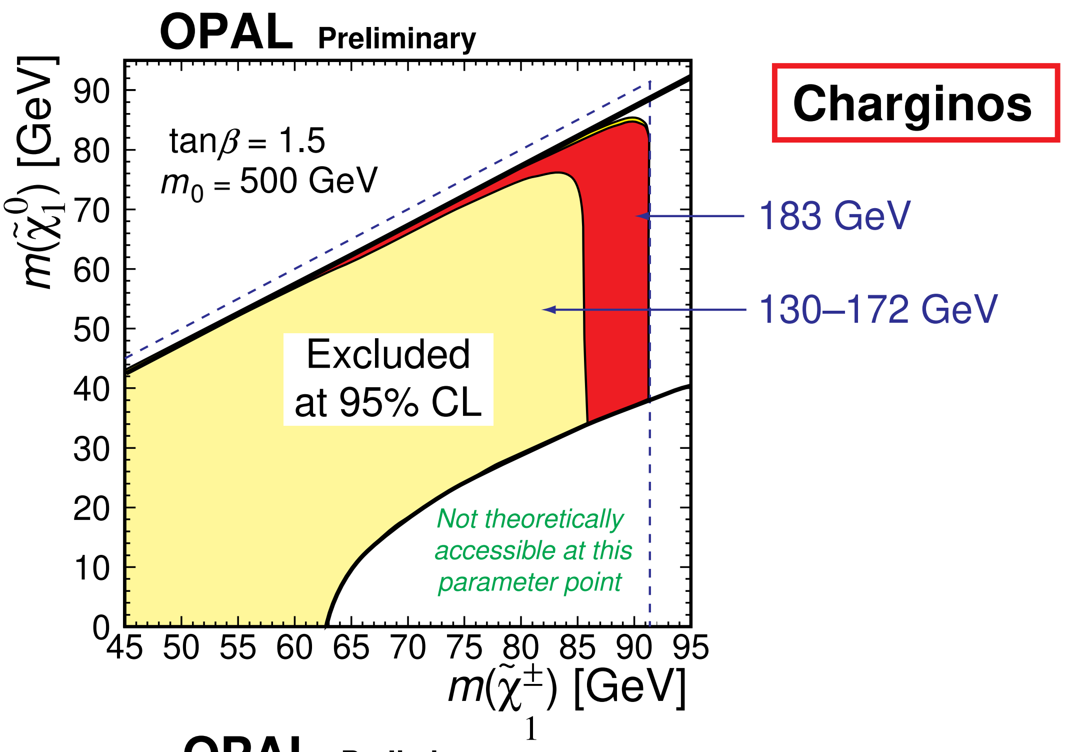
- Background: $e^+e^- \to Z/\gamma \to f\bar{f}\gamma$
- Discriminant variables: direction of missing momentum, acoplanarity

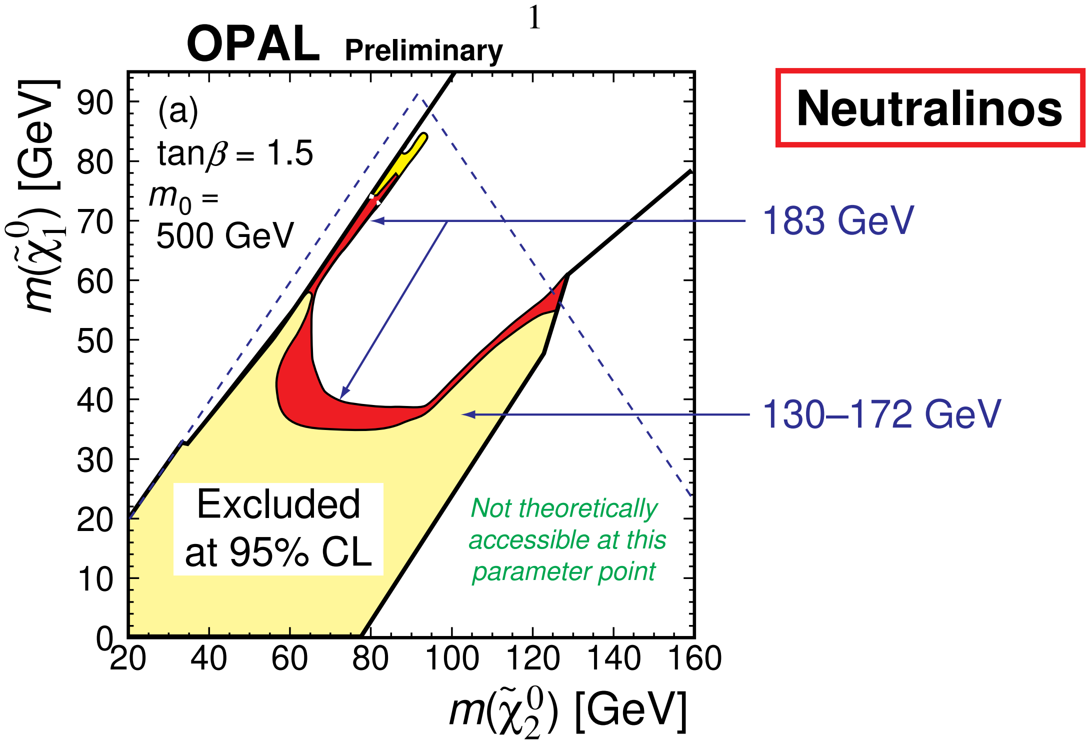
Low ΔM region ($\delta > 50$ GeV)

- Background: WW, Weν, ZZ
- Discriminant variables: lepton momentum, recoil mass, visible energy

Gaugino region I - results from OPAL

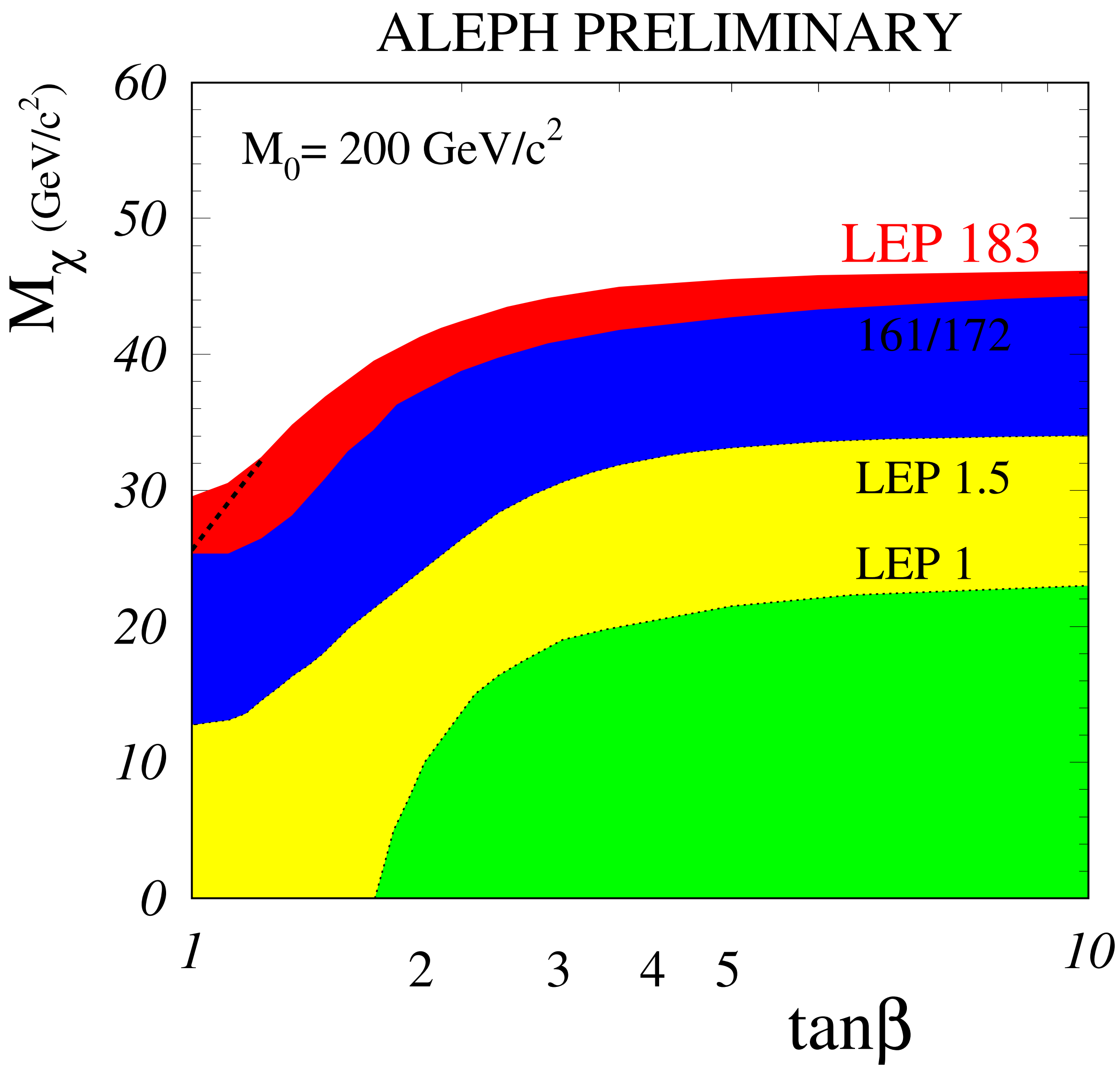
Search for charginos and neutralinos





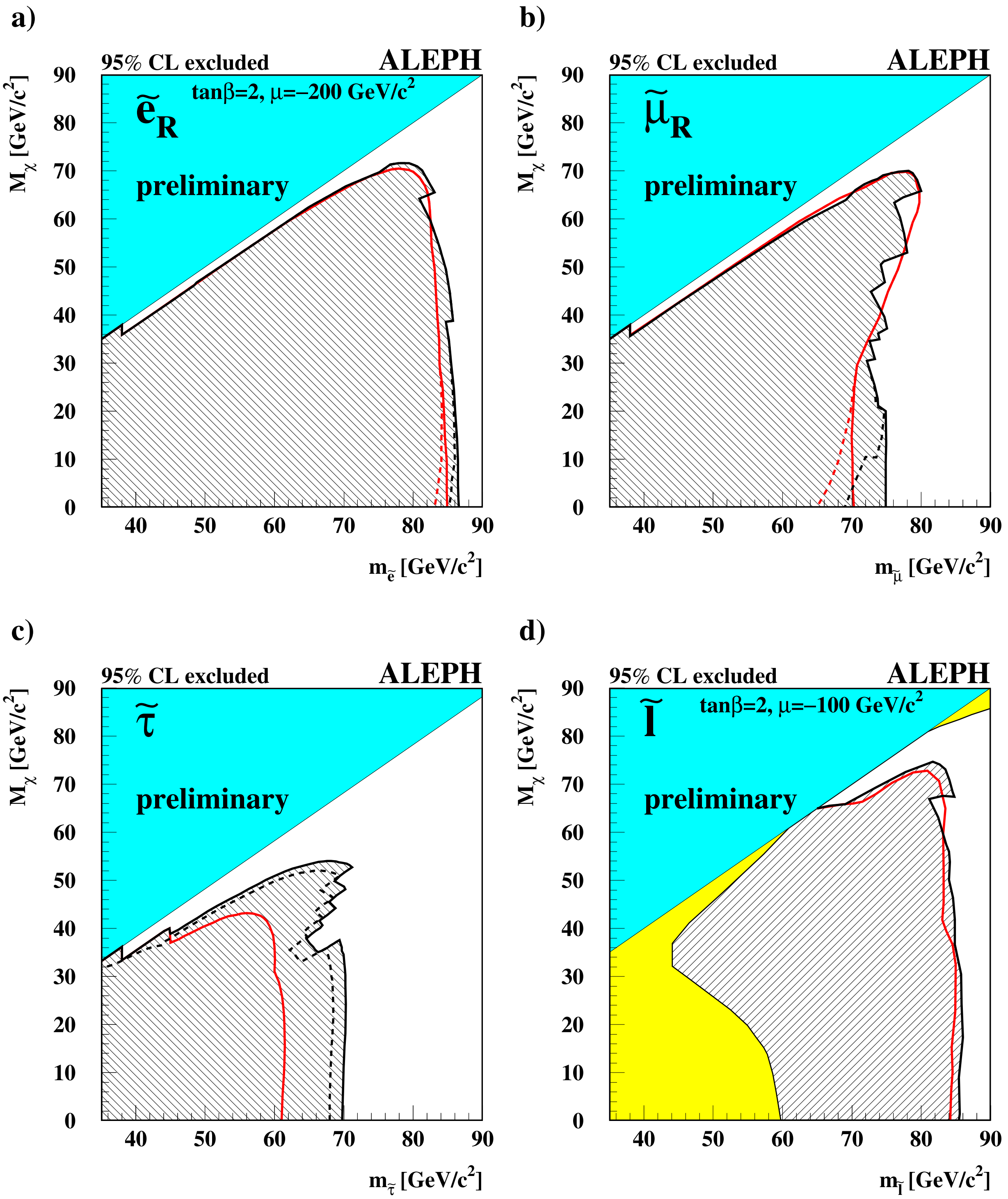
Higgsino region - results from ALEPH

Exclusion for large m_0:



Gaugino region II - results from ALEPH

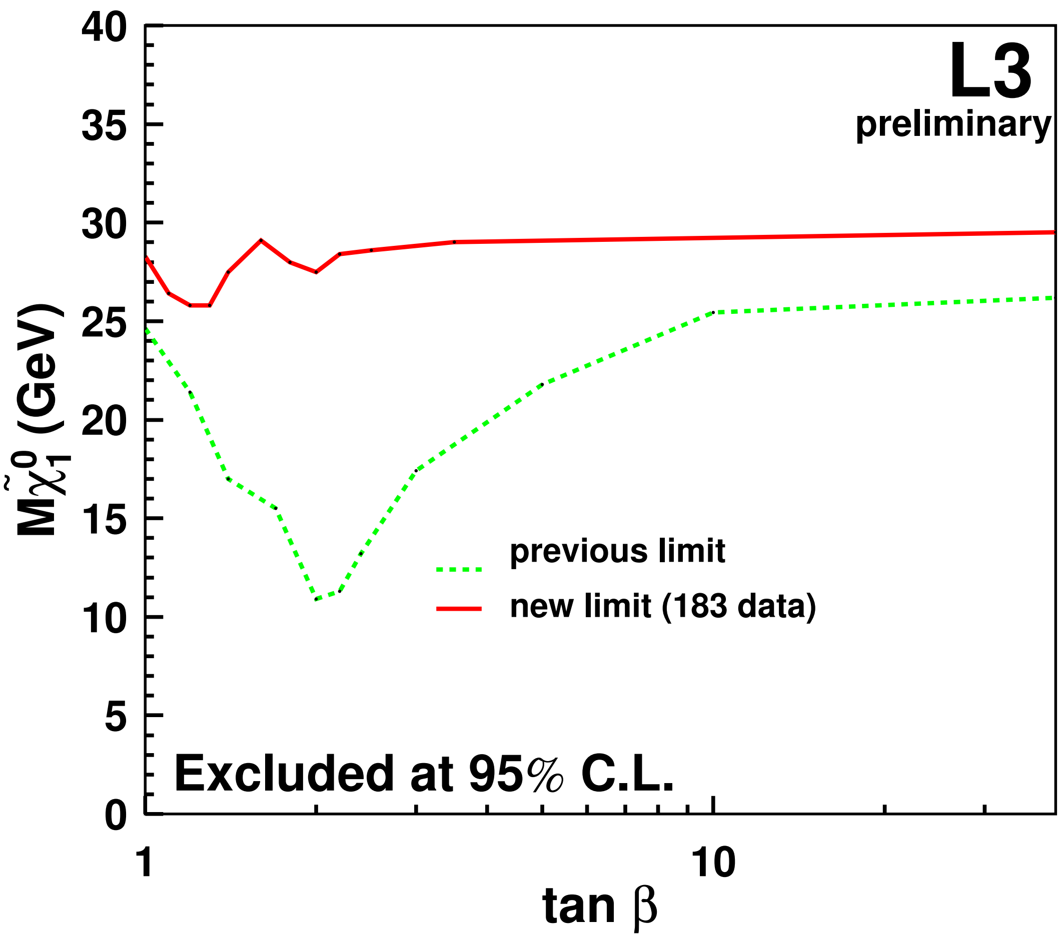
Search for scalar leptons



MSSM summary - results from L3

Preliminary $\sqrt{s} = 183$ GeV results (55.4 pb^{-1})

L3	N_{data}	N_{exp}
$\chi^+\chi^-, \chi^0\chi^0$	15	20.2 ± 7
$\tilde{e}$	3	7.1 ± 1.5
$\tilde{\mu}$	4	6.4 ± 1.8
$\tilde{\tau}$	8	7.9 ± 2.8
Overall	27	32.4 ± 9



ALEPH: $M_{\chi^0_1} > 14.0$GeV

L3: $M_{\chi^0_1} > 25.8$GeV

ALEPH has not yet analysed 183 data sample

Photons and missing energy

Very rich physics:

- Neutrino counting
- Sensitivity to WWγ vertex
- Sensitivity to anomalous Zγ couplings
- Sensitivity to light gravitino production $e^+e^- \to \tilde{G}\tilde{G}\gamma$
- Sensitivity to neutrilino decays $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$

Implications for SUSY searches:

- $e^+e^- \to \chi_2^0\chi_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$
- $e^+e^- \to \tilde{G}\tilde{G}\gamma$
- $e^+e^- \to \chi^0\tilde{G} \to \tilde{G}\tilde{G}\gamma$
- $e^+e^- \to \chi_2^0\chi_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma\gamma$
- $e^+e^- \to \chi^0\chi^0 \to \tilde{G}\tilde{G}\gamma\gamma$

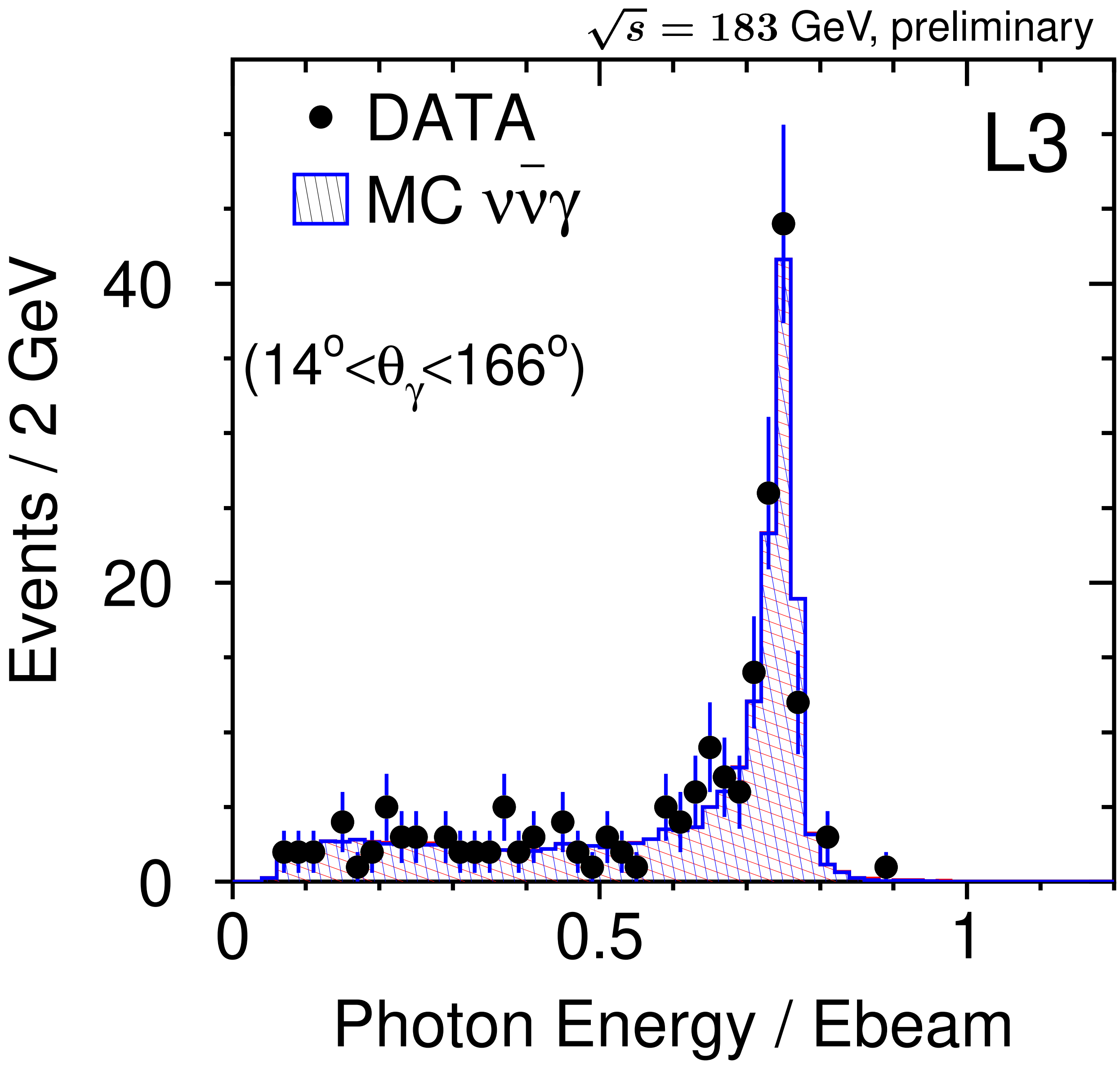
Background sources:

- $e^+e^- \to \nu\bar{\nu}\gamma$
- $e^+e^- \to e^+e^-\gamma$

Photons and missing energy

Sensitive to new physics

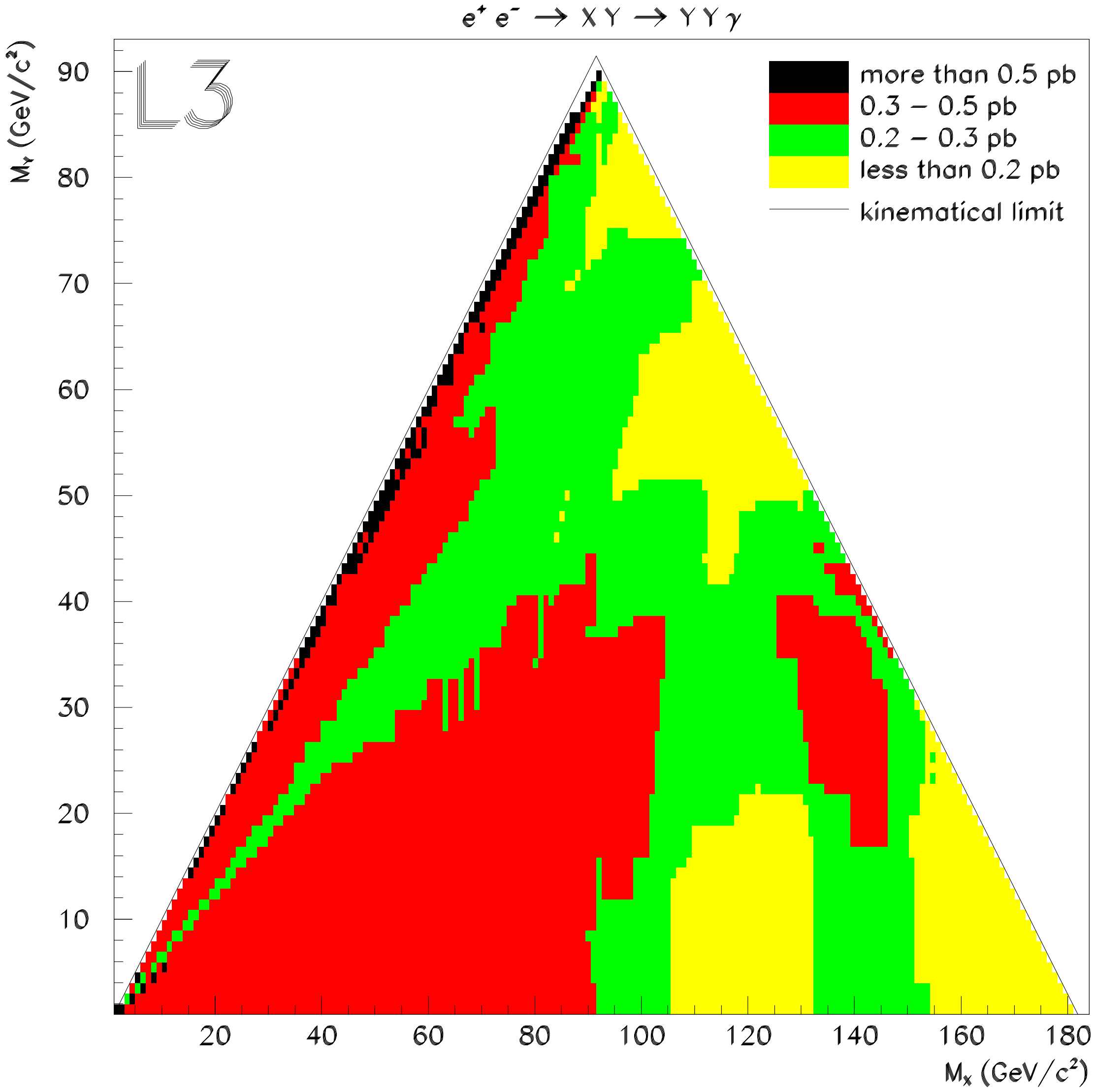
$$e^+e^- \to XY \to XX\gamma$$
$$YY \to XX\gamma\gamma$$



Photons - results from L3

Cross-section limits

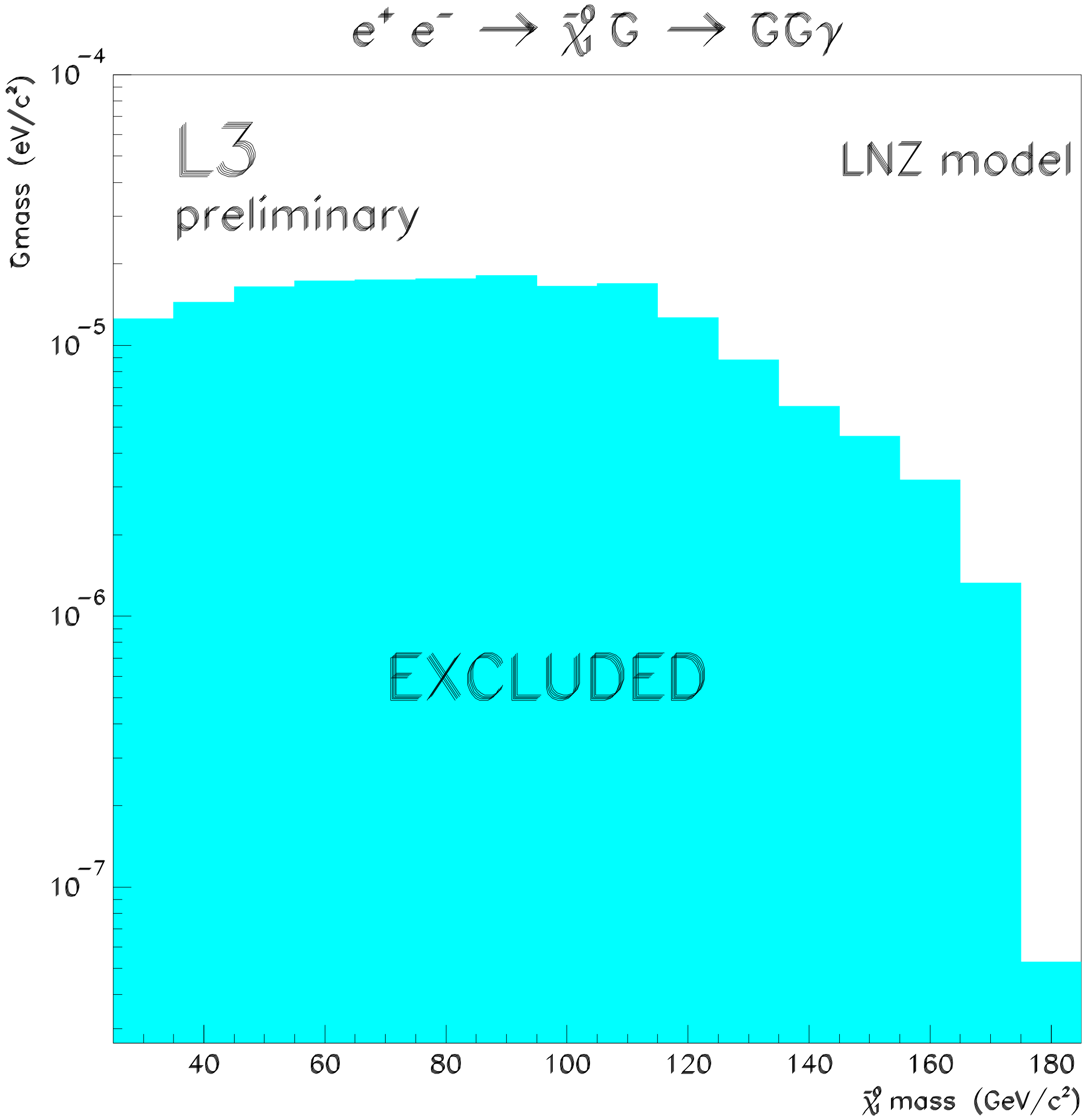
$$e^+e^- \to XY \to XX\gamma$$



Photons - results from L3

No-scale supergravity SUSY:

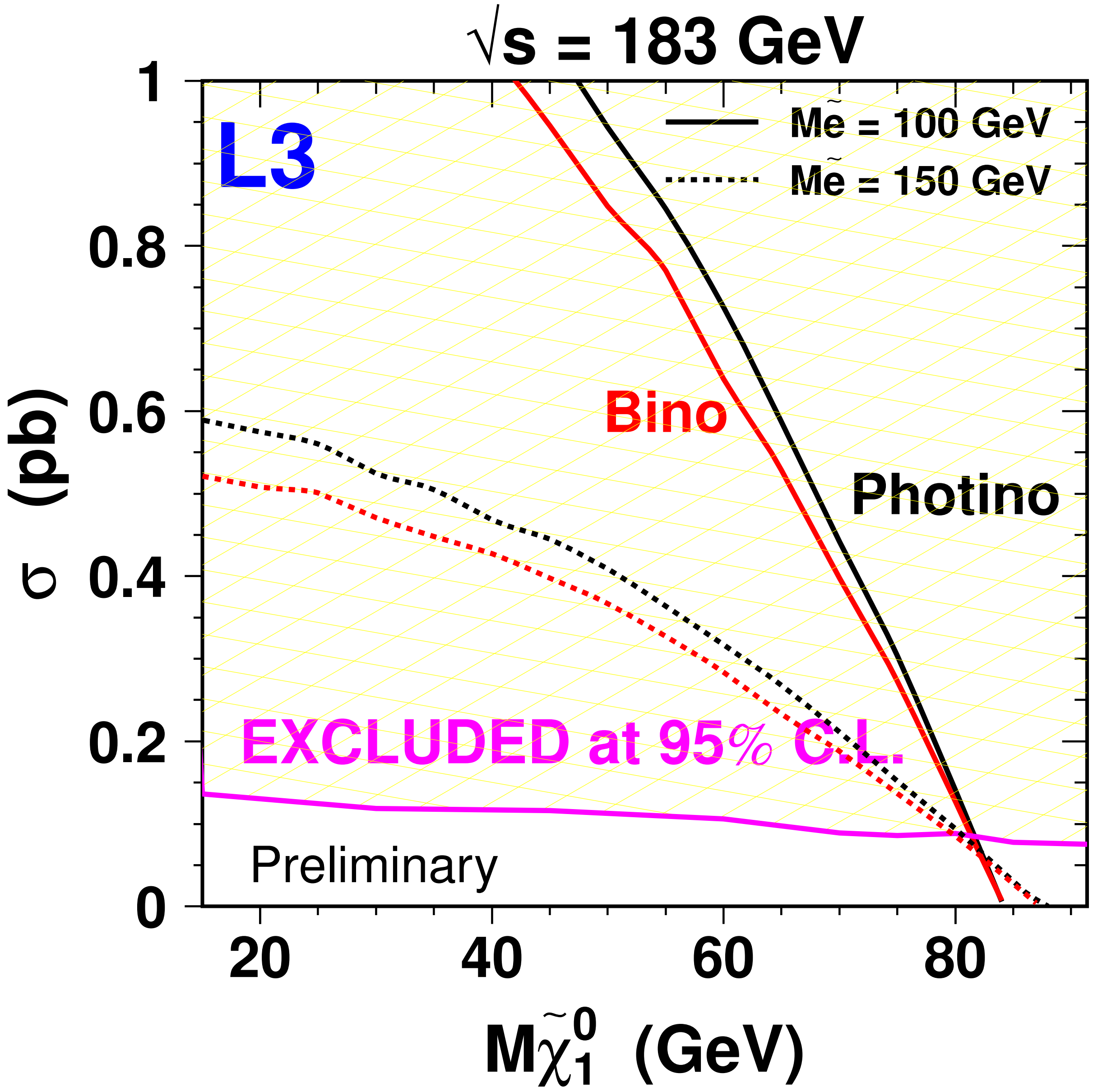
$$m_{\tilde{\mathrm{G}}} = \mathrm{O}((\frac{m_{\mathrm{W}}}{m_{\mathrm{P}}})^{p}) \cdot m_{\mathrm{P}}, \;\; p > 1$$



Photons - results from L3

No-scale supergravity SUSY:

$$e^+e^- \to \chi^0\chi^0 \to \tilde{G}\tilde{G}\gamma\gamma$$

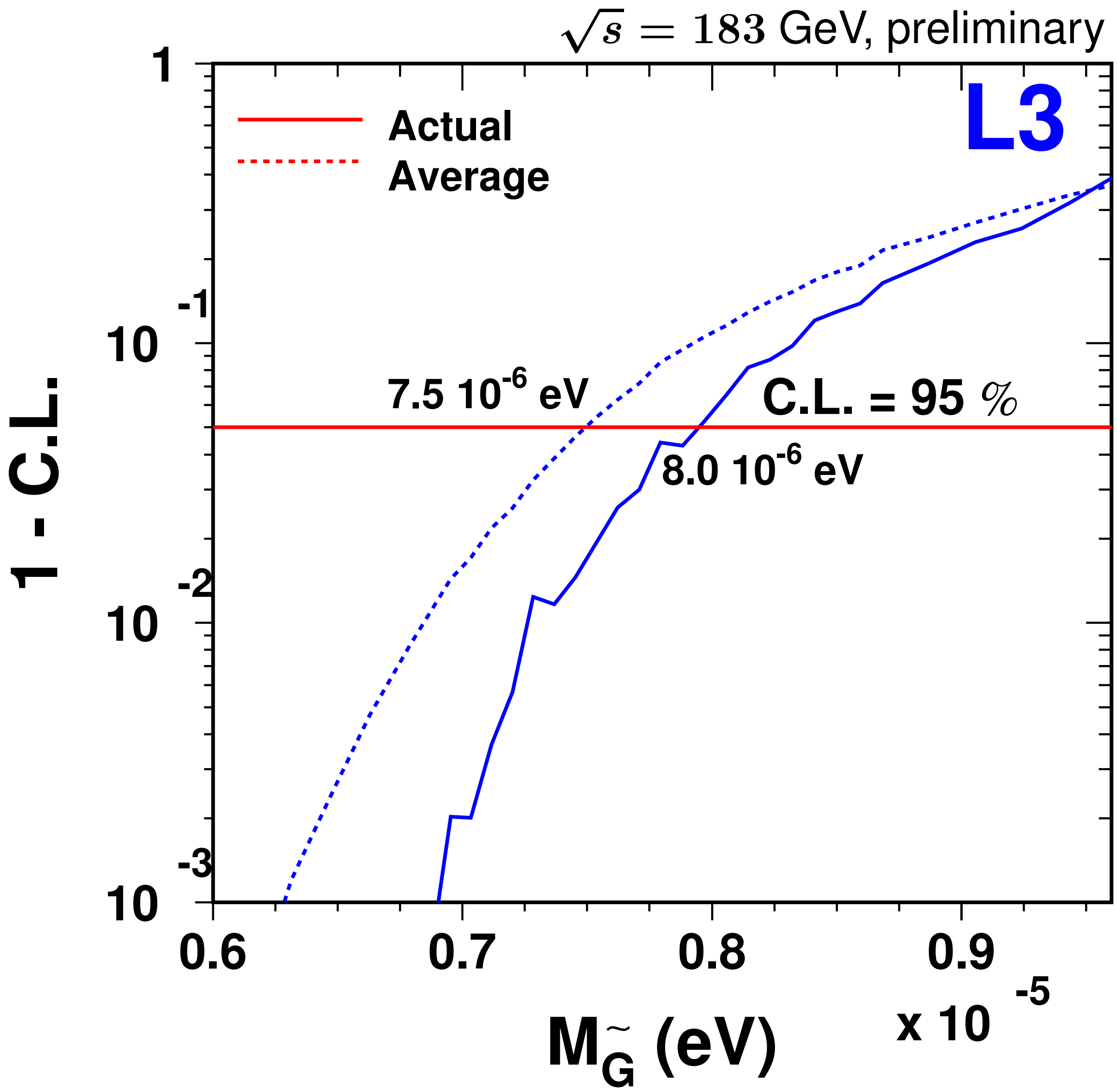


Photons - results from L3

Gauge mediated SUSY breaking

$$e^+e^- \rightarrow \tilde{G}\tilde{G}\gamma$$

$$\sigma = \frac{\alpha s^3}{320\pi^2|F|^4} \cdot I(E_\gamma, \cos\theta_\gamma)$$

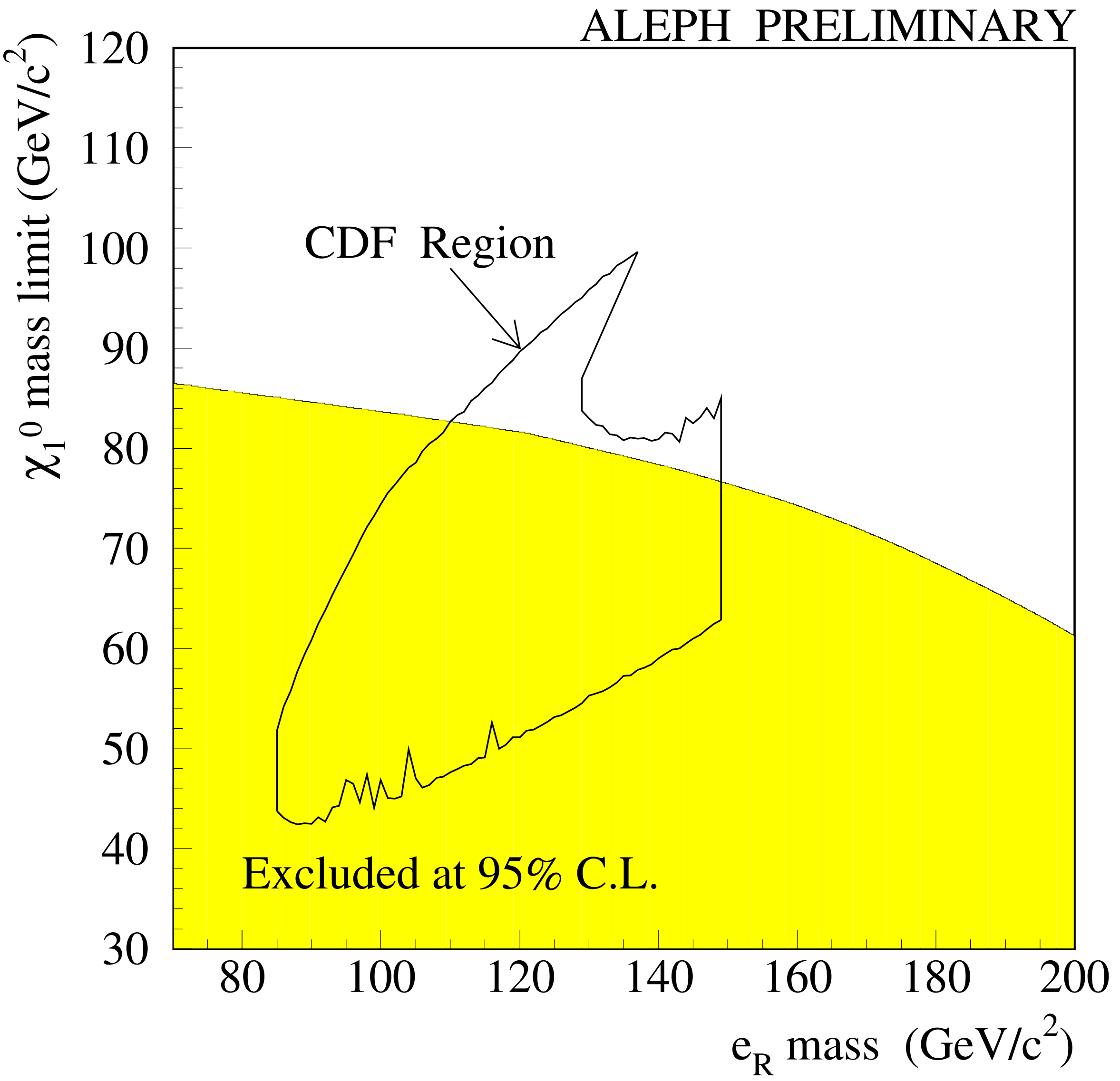


DELPHI: $M_{\tilde{G}} > 6.6 \cdot 10^{-6}$eV
L3: $M_{\tilde{G}} > 8.0 \cdot 10^{-6}$eV

Photons - results from ALEPH

Interpretation of the CDF event using Gauge mediated SUSY breaking:

$$q\bar{q} \rightarrow \tilde{e}\tilde{e} \rightarrow ee\chi_1^0\chi_1^0 \rightarrow ee\tilde{G}\tilde{G}\gamma\gamma$$



Conclusions

- no indication for New Physics yet, Standard Model still rules
- light Higgs Boson is preferred by electroweak data
- energy frontier will be crossed 2-3 more times in 1998-2000
- we eagerly waiting for new data

June 1996	161 GeV $(4 \cdot 11$ pb$^{-1})$
October 1996	172 GeV $(4 \cdot 11$ pb$^{-1})$
1997	183 GeV $(4 \cdot 55$ pb$^{-1})$
1998	190 GeV
1999	195 GeV
2000	try for 200 GeV