Search for R-Parity Violation and Production of Neutral Higgs Bosons at 130 GeV $\leq \sqrt{s} \leq$ 172 GeV

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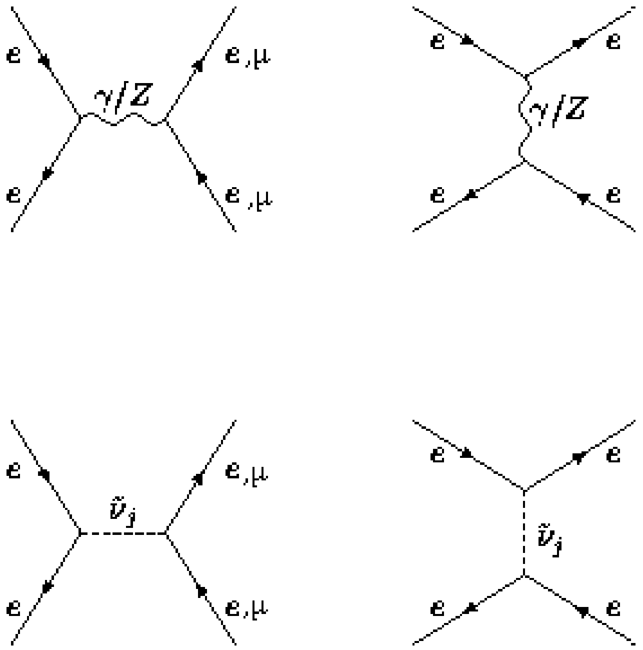
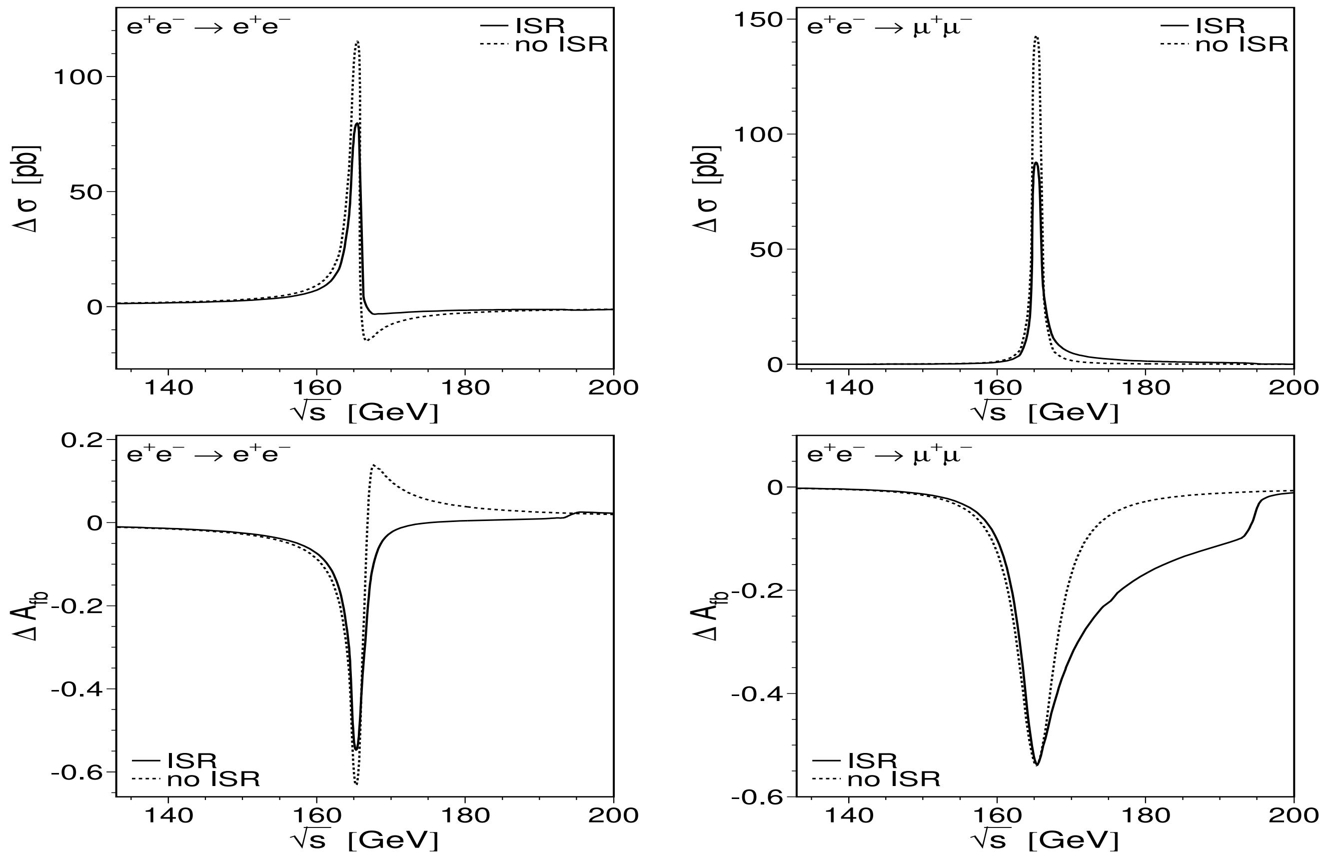
Representing the
L3 collaboration

- Search for R-Parity Violation with L3
  - Sneutrino Exchange
  - Direct Search for Chargino, Neutralino decay
- Search for Production of Neutral Higgs Bosons with L3
  - Standard Model Specific Search
  - MSSM Search for “invisible” Higgs Decays
  - MSSM Specific Search (assuming no “invisible” decays)
- Comparison to Other LEP Experiments and LEPWG Combined Results

R-Parity Violation: Motivation



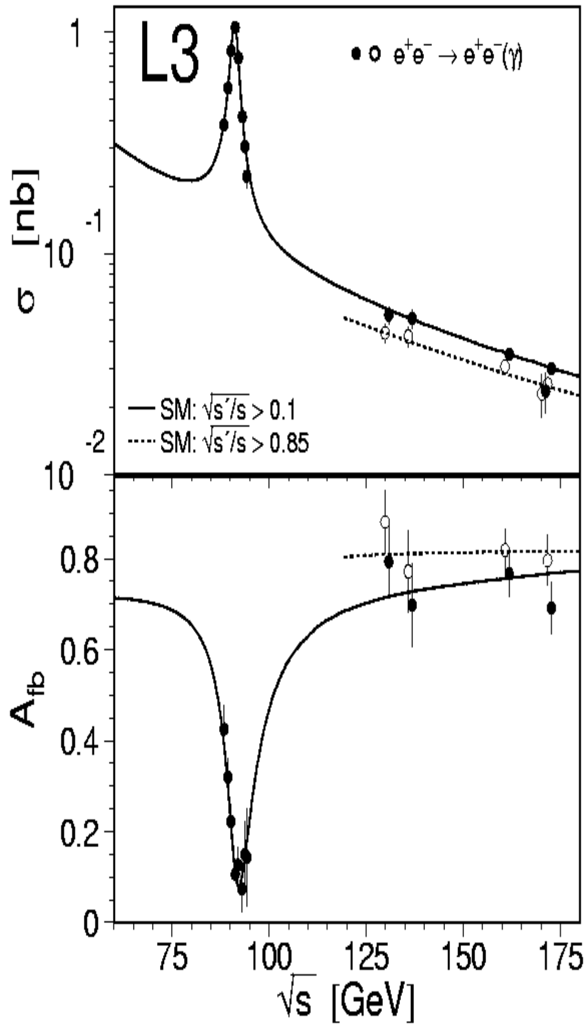
- High Q^2 events observed by H1 and ZEUS have revived interest in broken R-parity.
- L-violating Yukawa term: $\lambda_{ijk} L^i_{\mathrm{L}} L^j_{\mathrm{L}} \bar{E}^k_{\mathrm{R}}$
- Consider case where $\lambda_{131,232}$ large
- Expect deviations from SM $\mathrm{A_{fb}}$ and $e^+e^- \to e^+e^-, \mu^+\mu^-$

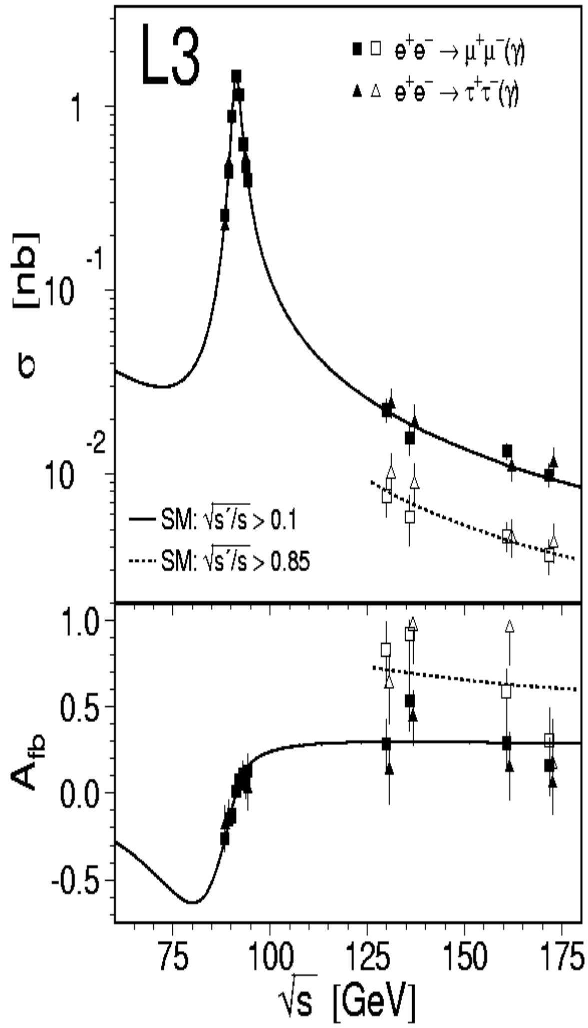


R-Parity Violation: Selection

- **Likelihood for deviations from SM is constructed as function of coupling strength, λ**
- $-\ln L = \sum_{i=1}^{n} \left(\frac{(\sigma(\mathrm{SM};\lambda,m_{\tilde{\nu}_\tau})-\sigma^{\mathrm{meas}})^2}{2\cdot\delta_\sigma^2} + \frac{(A_{\mathrm{fb}}(\mathrm{SM};\lambda,m_{\tilde{\nu}_\tau})-A_{\mathrm{fb}}^{\mathrm{meas}})^2}{2\cdot\delta_{A_{\mathrm{fb}}}^2} \right)_i$

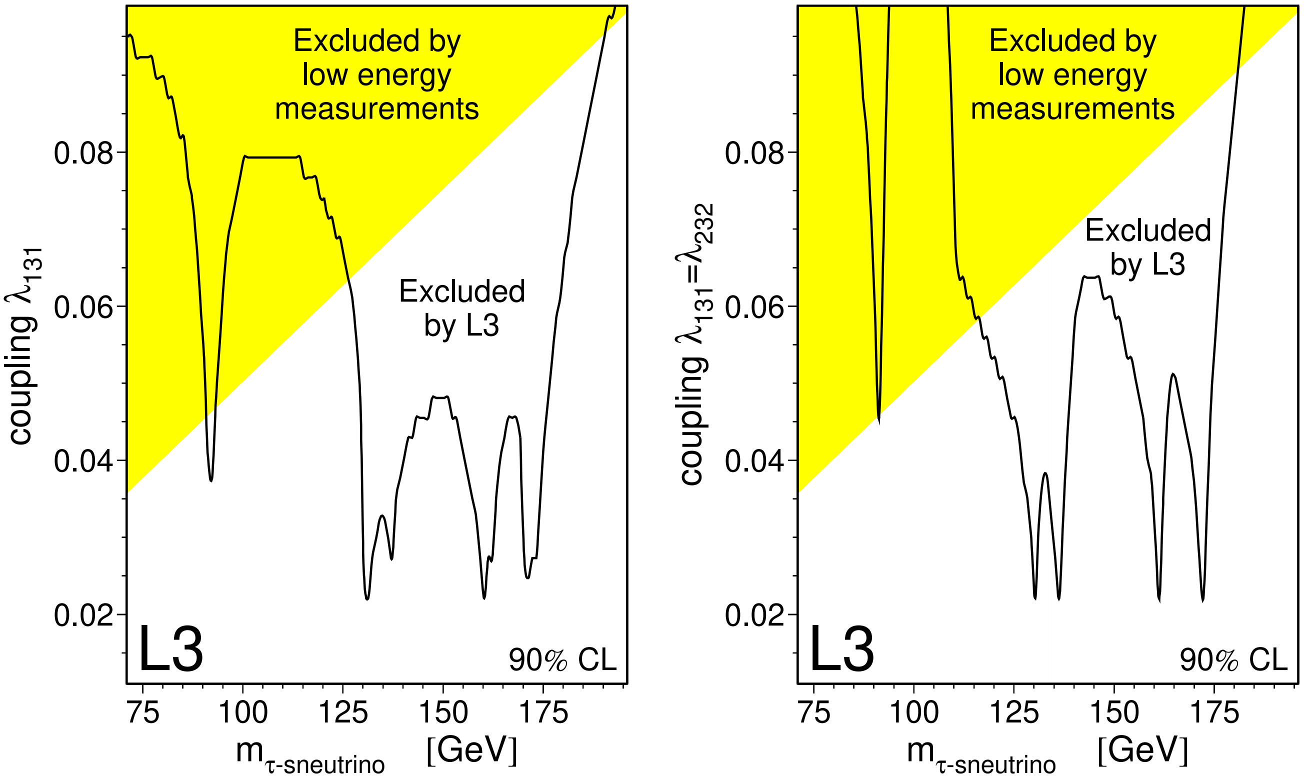
$$\delta_\sigma = \mathrm{error}(\sigma(\mathrm{SM};\lambda,m_{\tilde{\nu}_\tau}) - \sigma^{\mathrm{meas}})$$
$$\delta_{A_{\mathrm{fb}}} = \mathrm{error}(A_{\mathrm{fb}}(\mathrm{SM};\lambda,m_{\tilde{\nu}_\tau}) - A_{\mathrm{fb}}^{\mathrm{meas}})$$





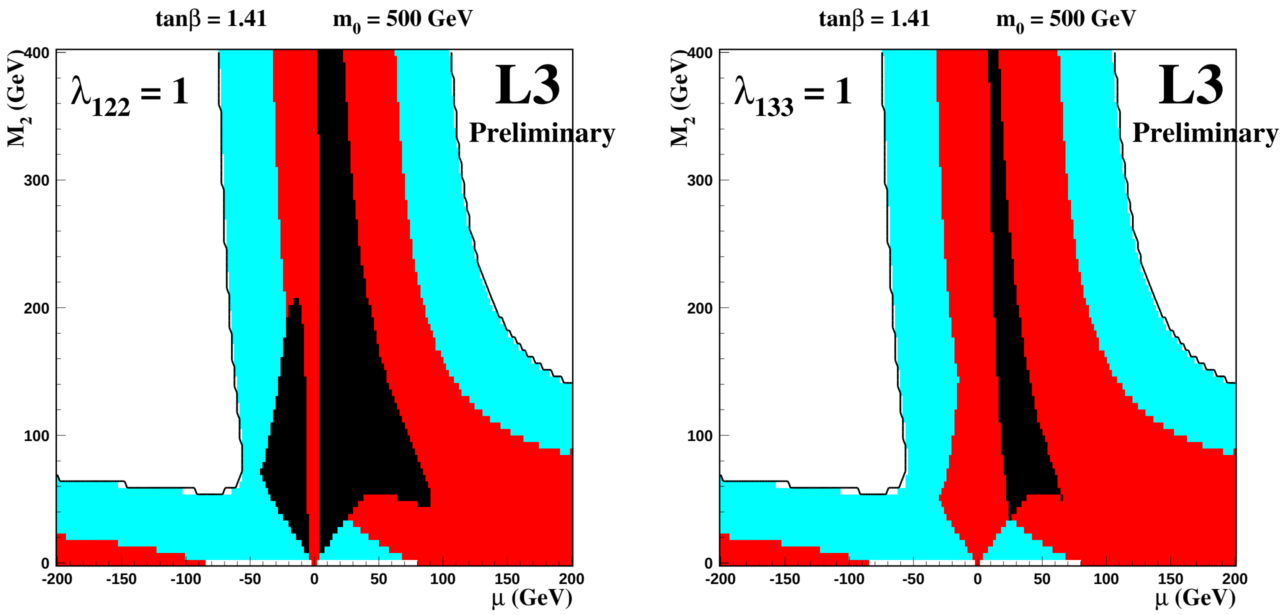
R-Parity Violation: Results

- **90% C.L. upper limits on λ_{131} are derived**
- **In order to simplify presentation in 2 dimensions, it is assumed that $\lambda_{131} = \lambda_{232}$**



R-Parity Violation: $\tilde{\chi}$ Decay

- Assume superpotential term $\lambda_{ijk} L_i L_j \overline{E}_k$
- Let $\lambda_{122}, \lambda_{133}$ dominate
- $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \ell\ell\ell\ell\nu\nu$
- $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^* W^* \rightarrow \ell\ell\ell\ell W^* W^* \nu\nu$
- **Signature:** 4 charged leptons and large missing E
- Backgrounds: 2f, 2γ, 4f
- No candidate event is found!



95% C.L. exclusion: Solid line – kinematic limit, Blue – $\tilde{\chi}^{\pm}$ search, Red – Lineshape, Black–$\tilde{\chi}^0$ search

Higgs Search: Motivation

- **Origin of mass and Spontaneous Symmetry Breaking await experimental verification.**

- **Minimal Standard Model (SM) uses 1 scalar doublet $\Rightarrow$ 1 physical neutral scalar.**

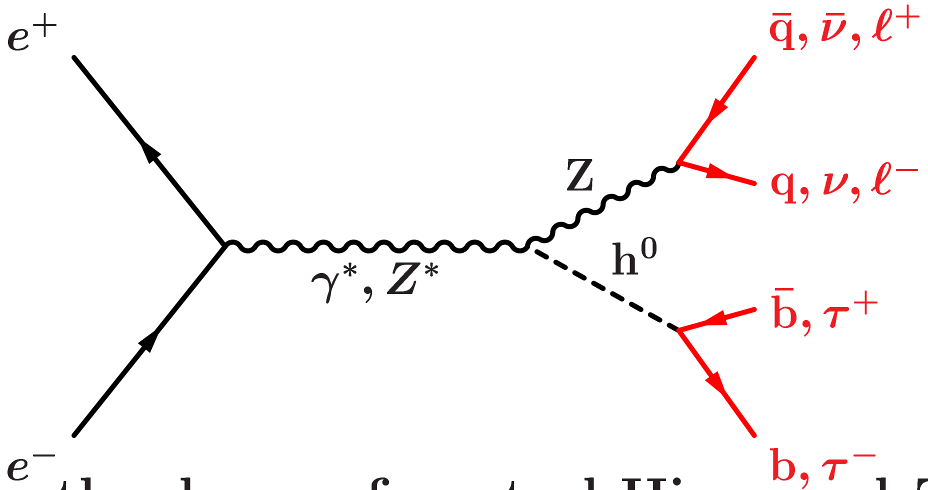
- **Minimal SUSY extensions to SM use 2 doublets $\Rightarrow$ 5 physical scalars: 2 charged; 3 neutral.**

- **$\mathrm{hZ} \to \mathrm{b\bar{b}q\bar{q}}$, $\mathrm{hZ} \to \mathrm{b\bar{b}}\nu\bar{\nu}$ and $\mathrm{hZ} \to \mathrm{b\bar{b}}\ell^+\ell^-$ expected to dominate in SM.**

- **$\mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}}$ and $\mathrm{hA} \to \mathrm{b\bar{b}}\tau^+\tau^-$ ($\mathrm{hA} \to \tau^+\tau^-\mathrm{b\bar{b}}$) decays of pair produced neutral Higgs bosons are expected to dominate in MSSM.**

hA production and decay is slightly model dependent, but the limit on m_A and m_h can be done for a few "typical" scenarios of MSSM parameters such as minimal, maximal squark mixing.

Higgs Search: SM

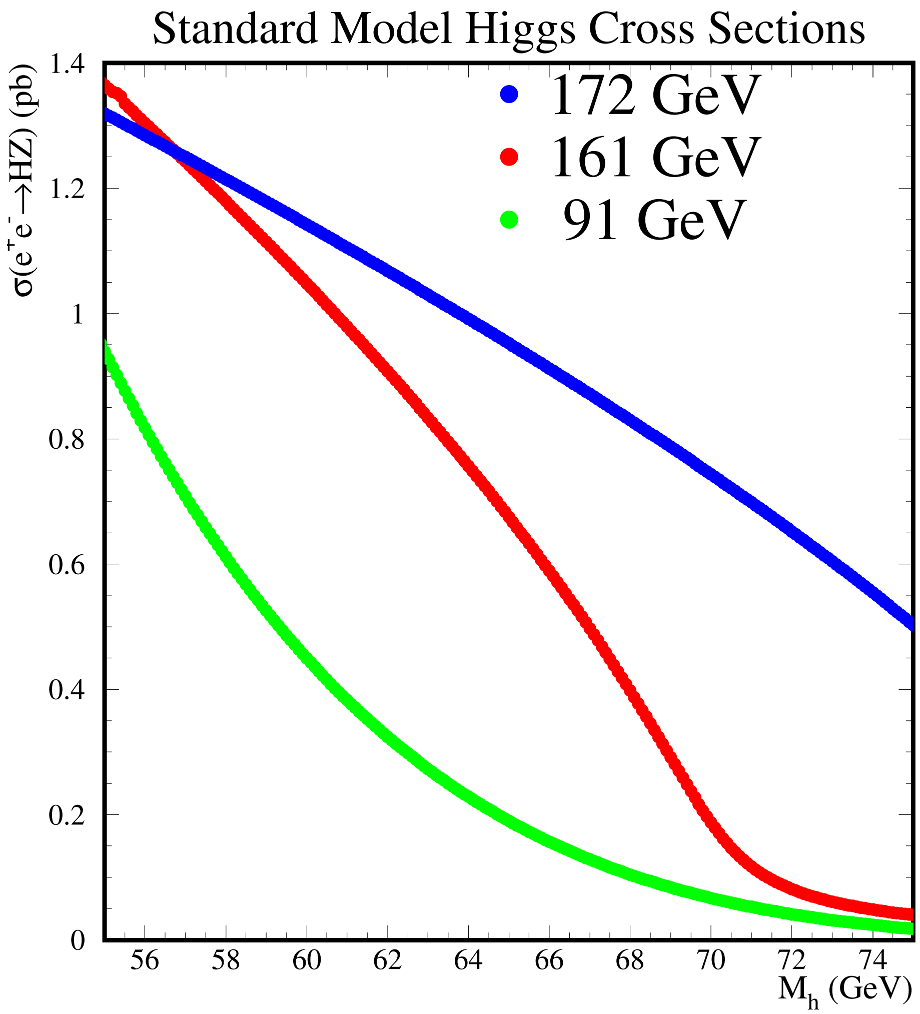


Searched for the decay of neutral Higgs and Zbosons in the following channels:

- $hZ \to b\bar{b}q\bar{q}$
- $hZ \to b\bar{b}\nu\bar{\nu}$
- $hZ \to q\bar{q}\ell^+\ell^-$
- $hZ \to q\bar{q}\tau^+\tau^-$
- $hZ \to \tau^+\tau^-q\bar{q}$
- 1996 L3 data sample

$\sqrt{s}$(GeV)	Integrated Lumi (pb^{-1})
161.3	10.8
170.3	1.0
172.3	9.2
Total	21.0

- MC: JETSET, KORALW and PYTHIA, PHOJET for ∼100 times data statistics for $e^+e^- \to qq, WW, ZZ, \gamma\gamma$ and signal of $e^+e^- \to Z^*/\gamma^* \to hZ$.
- Signal cross sections were calculated with the HZHA generator.



H decay channel	Z decay channel	Branching fraction
$q\bar{q}$	$q\bar{q}$	64.4%
$q\bar{q}$	$\nu\bar{\nu}$	18.4%
$q\bar{q}$	e^+e^-	3.1%
$q\bar{q}$	$\mu^+\mu^-$	3.1%
$q\bar{q}$	$\tau^+\tau^-$	3.1%
$\tau^+\tau^-$	$q\bar{q}$	5.5%

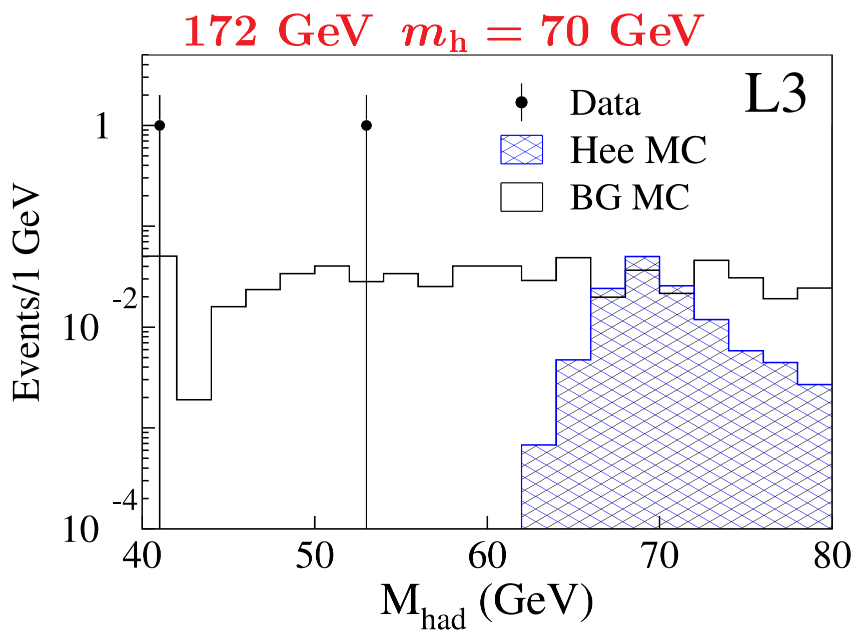
Higgs Search: Analysis Procedure

- **Final Variable:** Rather than making a final set of cuts on all variables that discriminate signal from background, the spectra for data, MC background and signal of the most powerful variable is "saved for last," after all other cuts are optimized.
- **Likelihood Technique:**
  - ◇ These spectra are used to calculate the binned likelihood for the observation to be compatible with MC background as a function of the Higgs mass.
  - ◇ $\mathcal{L}(\mu^{\mathrm{H}}) = \prod_{k=1}^{n^{\mathrm{ch}}} \prod_{i=1}^{n_k^{\mathrm{bn}}} \frac{e^{-(\mu_{i,k}^{\mathrm{H}}+\mu_{i,k}^{\mathrm{b}})}(\mu_{i,k}^{\mathrm{H}}+\mu_{i,k}^{\mathrm{b}})^{N_{i,k}}}{N_{i,k}!}$

In the absence of an observed signal, $\mathcal{L}$ is integrated to get the 95% C.L. lower limit on the Higgs mass.

$hZ \rightarrow q\bar{q}\ell^+\ell^-$, $hZ \rightarrow q\bar{q}\tau^+\tau^-$ $hZ \rightarrow \tau^+\tau^- q\bar{q}$ Channels

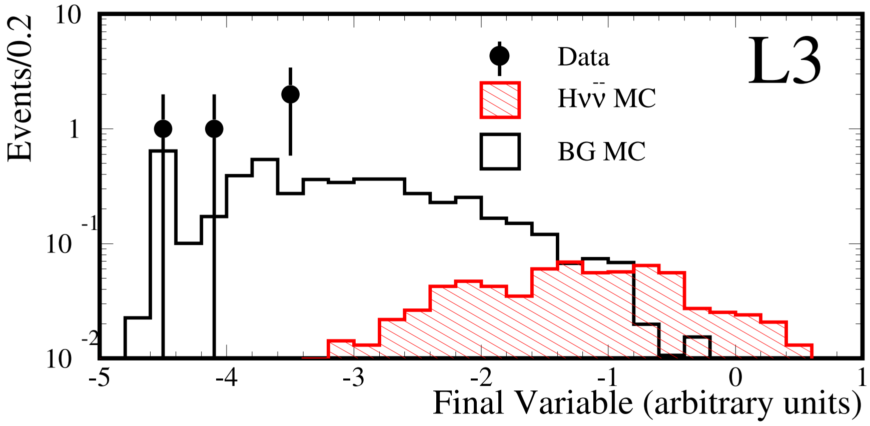
- **Backgrounds:** 4-fermion processes (and some semileptonic W decays)
- **Selection:**
  - High multiplicity hadronic events
  - A pair of prompt, isolated electrons or muons, or a well isolated pair of low multiplicity (1,2 or 3 tracks) τ-jets
  - After (4C) kinematic fit, $M_{\ell\ell}$ must be near m_Z
- **Final Variable:** No b tagging is necessary $\rightarrow$ ***Recoil hadronic mass, M_{had}***, is used as the final variable.



$hZ \to b\bar{b}\nu\bar{\nu}$ Channel

- **Backgrounds:** $\gamma\gamma$, semileptonic decays of WW and $Z^*/\gamma^* \to q\bar{q}$.
- **Selection:**
  - High multiplicity hadronic events
  - Little energy in forward calorimeters and missing energy away from beam direction
  - Large transverse momentum
  - Large jet energies
  - No prompt, isolated leptons
  - Acoplanar b-jets
- **Final Variable:** 1 final variable computed from B_{tag}, kinematics variables and visible mass is used in calculation of limit.

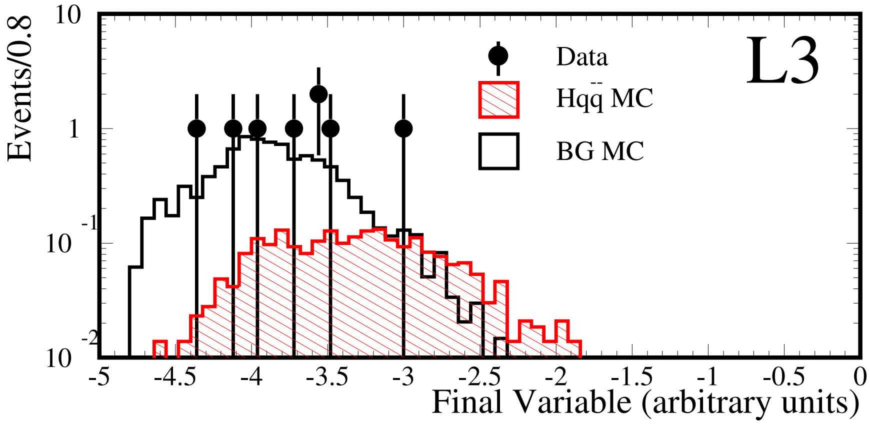
172 GeV $m_h = 70$ GeV

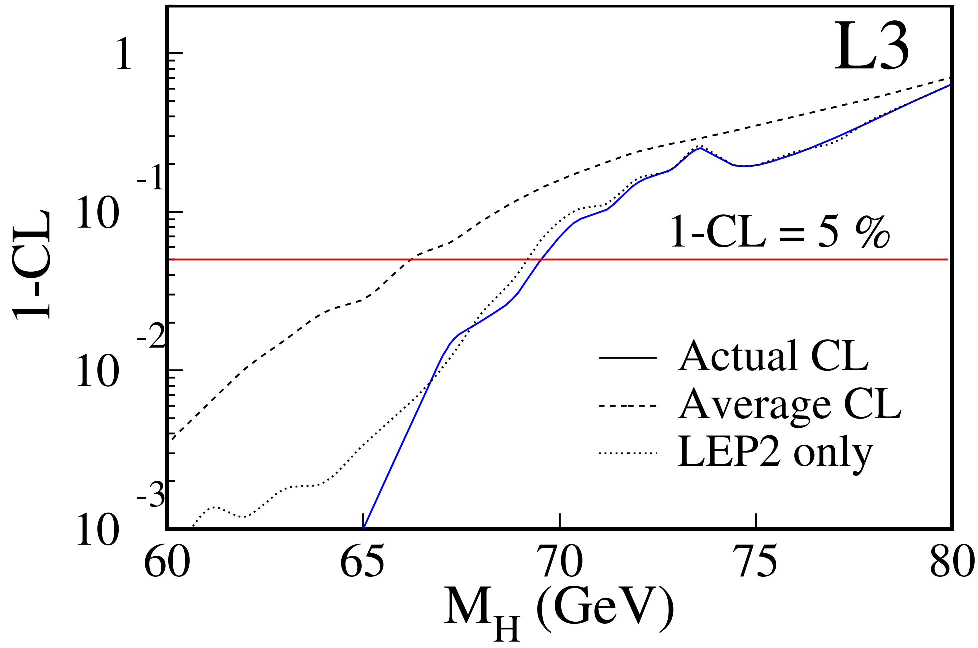


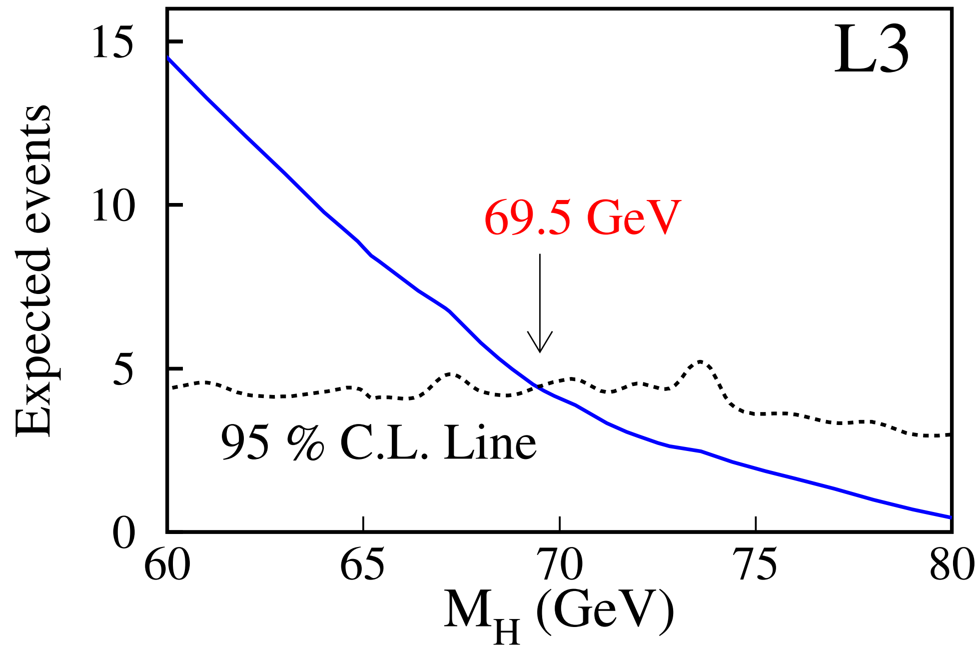
$hZ \rightarrow b\bar{b}q\bar{q}$ Channel

- **Backgrounds:** Hadronic decays of WW and multiple jet events in $Z^*/\gamma^* \rightarrow q\bar{q}$.
- **Selection:**
  - High multiplicity hadronic events
  - Large visible energy
  - No energy imbalance
  - Force event to have 4 jets exactly for kinematic fits
  - No large difference in di-jet masses or energies
  - Loose B_{tag}
- **Final Variable:** 1 final variable computed from B_{tag} , kinematics variables and mass χ^2 for the m_{h} in question.

172 GeV $m_{\mathrm{h}} = 70$ GeV

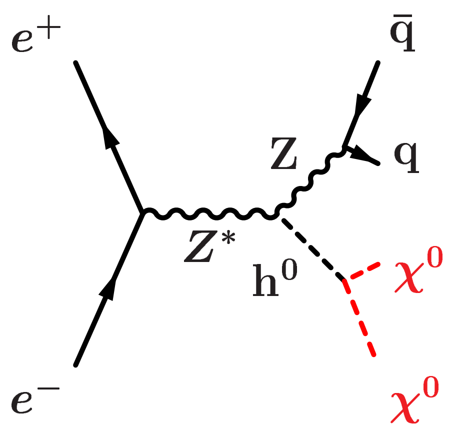






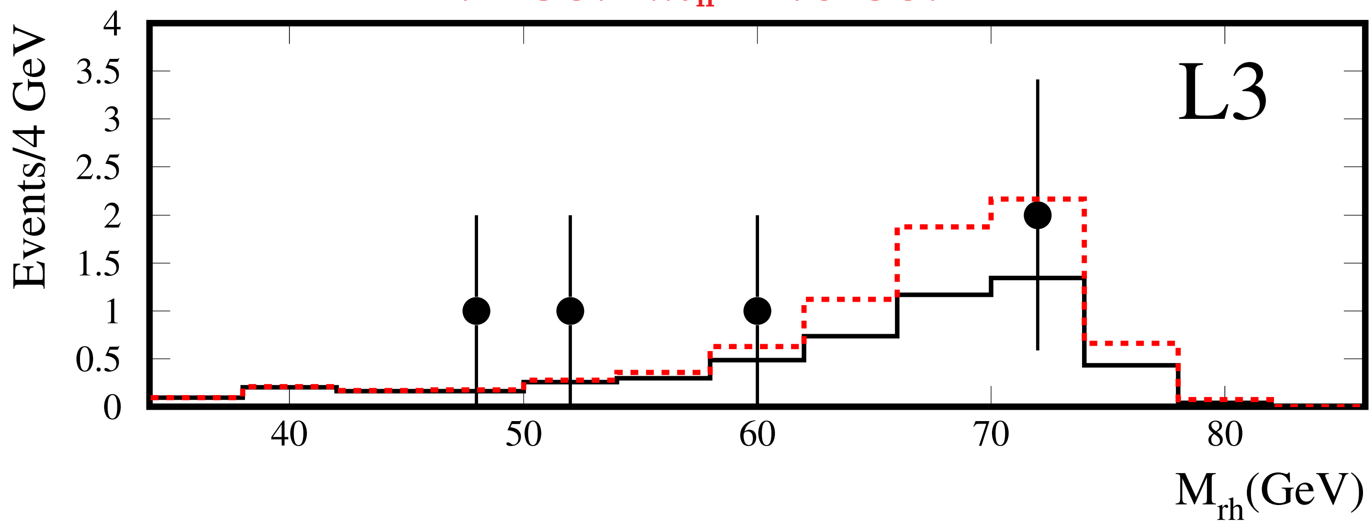
No observation of signal. **Lower limit on m_h is set including data from Higgs search at Z-peak.**

Higgs Search: Invisible

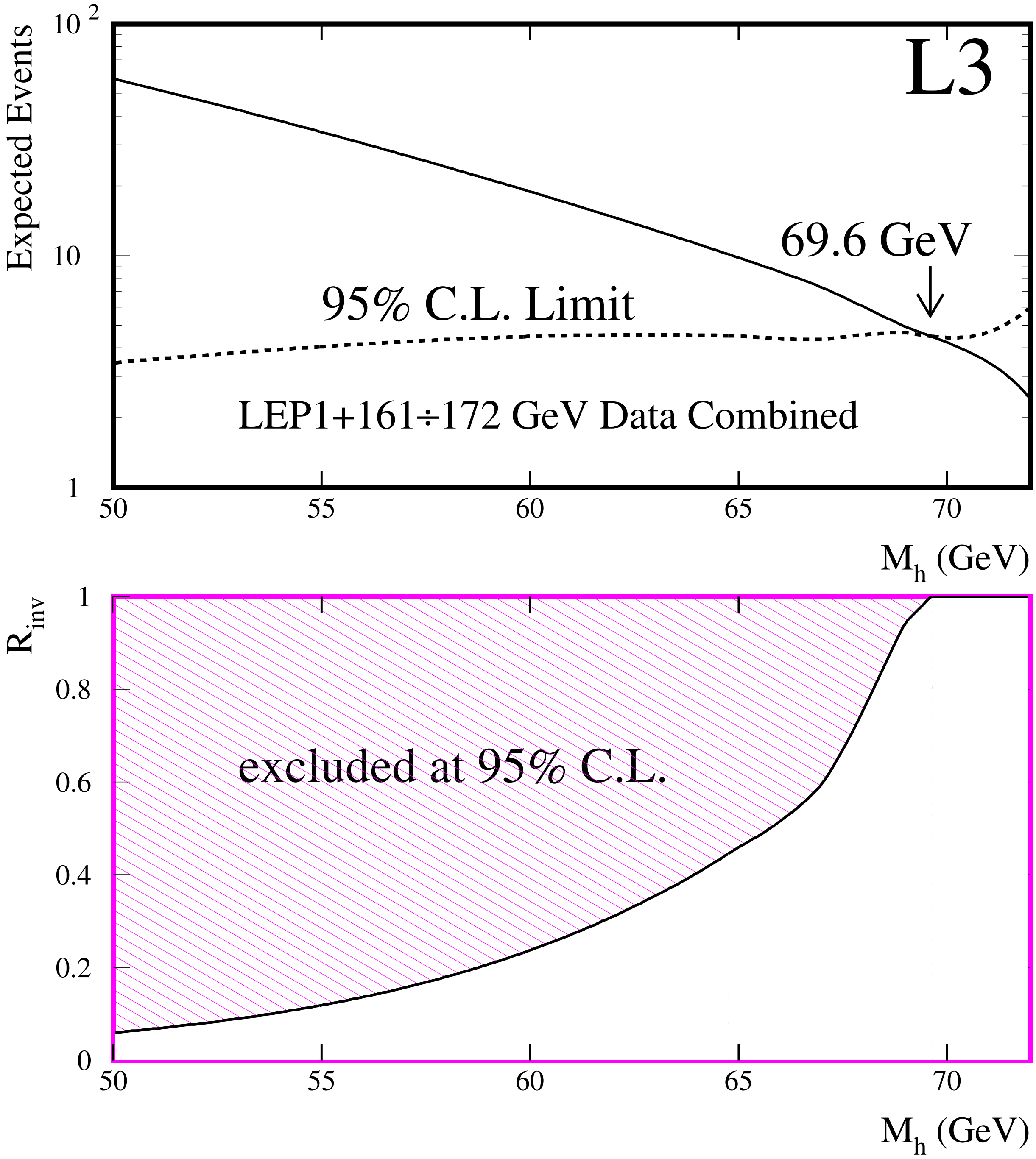


- Some weakly interacting stable particle is kinematically accessible to Higgs $\Rightarrow$ Br $\sim$ 100%.
- Higgs decays into undetected particles $\Rightarrow$ Peak in missing mass spectrum.

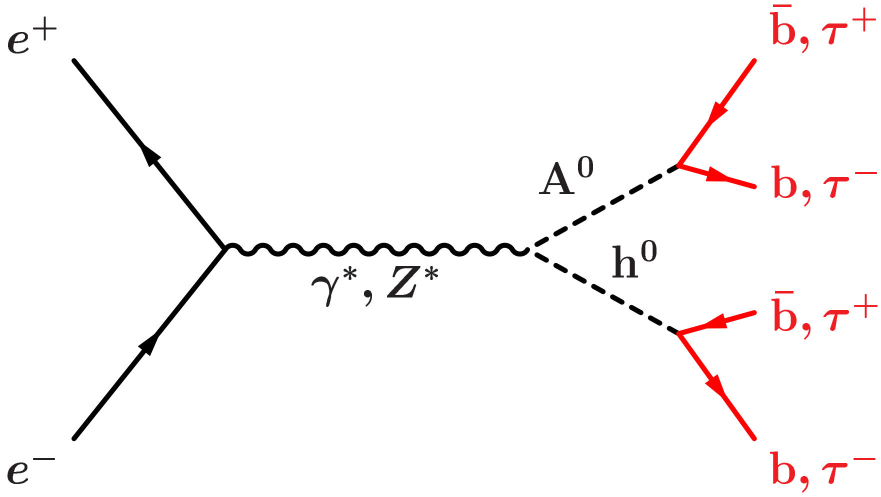
- Different from $hZ \to b\bar{b}\nu\bar{\nu}$ since visible mass $\sim m_Z$ for invisible decays.
- Constrain visible energy and momentum to come from Z and determine *missing, or Higgs mass, M_{rh}.*



Higgs Search: Invisible



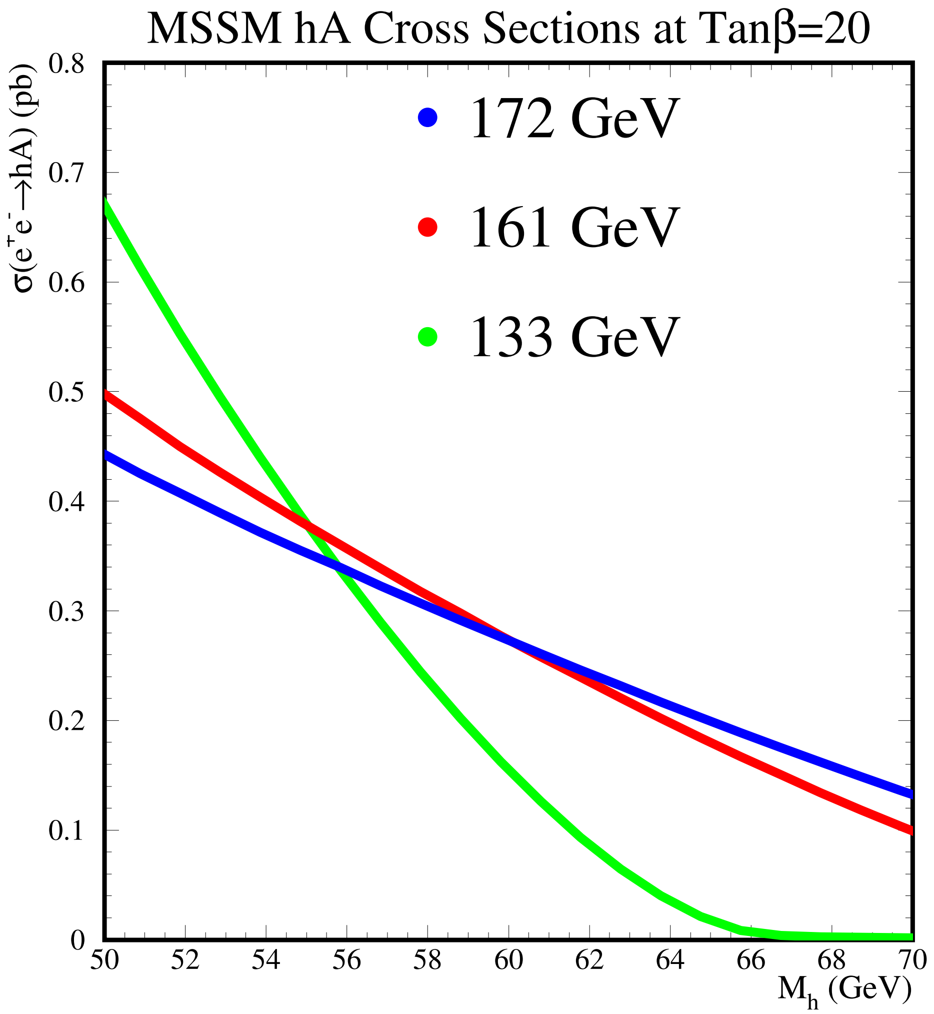
No observation of signal. **Lower limit on m_h is set including data from invisible Higgs search at Z-peak.**



Searched for the decay of neutral Higgs boson pairs in the following channels:

- $hA \to b\bar{b}b\bar{b}$
- $hA \to b\bar{b}\tau^+\tau^-$ and $hA \to \tau^+\tau^- b\bar{b}$
- Used same data from 161-172 GeV runs as in SM search but with the addition of 5 pb^{-1} from 130-136 GeV data giving a total of 25.6 pb^{-1}.
- Same MC for background as in SM Higgs search.
- Signal cross sections were calculated with HZHA. SUSY parameters were fixed to be: $m_t = 175$ GeV, $\mu = -100$ GeV, $M_{SUSY} = 1$ TeV. A_t and A_b were changed from "minimal" (0 GeV) to "maximal" ($\sqrt{6}M_{SUSY}$) mixing scenarios.

Higgs Search:MSSM Cross Section



hA decay mode	Branching fraction	Expected signal events produced
$b\bar{b}b\bar{b}$	84.3%	5.46
$b\bar{b}\tau^+\tau^-$	7.1%	0.46
$\tau^+\tau^-b\bar{b}$	7.2%	0.46

The expected signal events to be produced are with the total integrated luminosity and MSSM parameters above for $\tan\beta = 20$ and minimal mixing for $m_h = 70$ GeV.

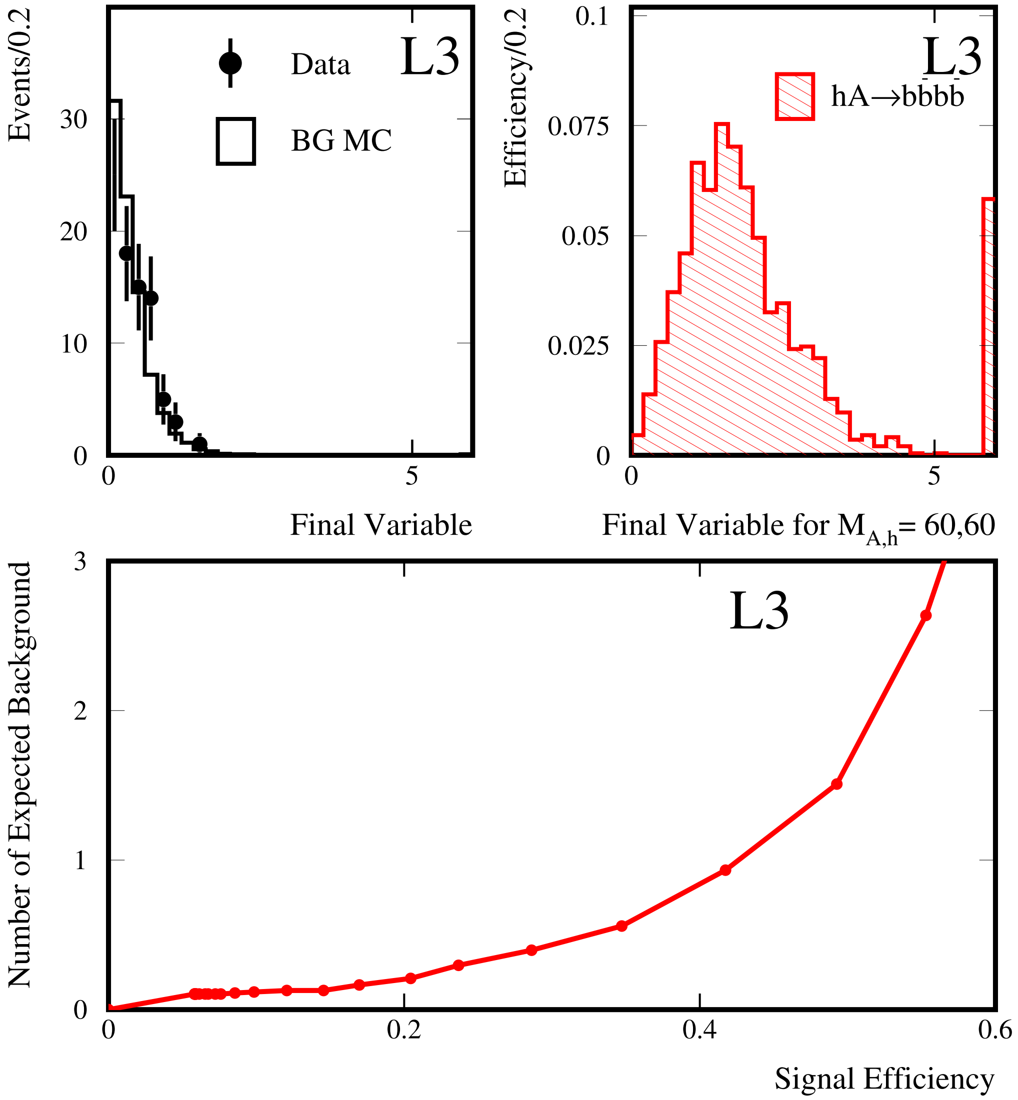
Higgs Search: MSSM

Backgrounds: WW decays into hadrons, higher order QCD processes, like $Z \to q\bar{q}gg$ and $Z \to q\bar{q}q\bar{q}$ as well as ZZ production.

Selection (very similar to HZ 4-jets search)

- **High Multiplicity**
  - Large number of calorimetric clusters
  - Large number of charged tracks
  - Large visible energy
  - No energy imbalance
- **4 Jets: Optimized variables**
  - No radiative returns
  - Reject 2-jet-like events
  - Finally, events are *forced to 4 jets* for kinematic fits and cuts.
  - 4-momentum conservation is assumed (4C fit)
  - Large di-jet masses
  - Smallish ΔM between di-jets
- **Final Variables**
  - B_{tag}
  - Prob(χ^2) for 2 di-jet masses to be consistent with either (m_Z,m_h) or (m_A,m_h). Maximum probability makes unique assignment of event (depends on m_A and $\tan\beta$).
  - B_{tag} and Prob(χ^2) combined into single final variable

$m_{\rm h} = 60$ GeV$m_{\rm A} = 60$ GeV for 172 GeV



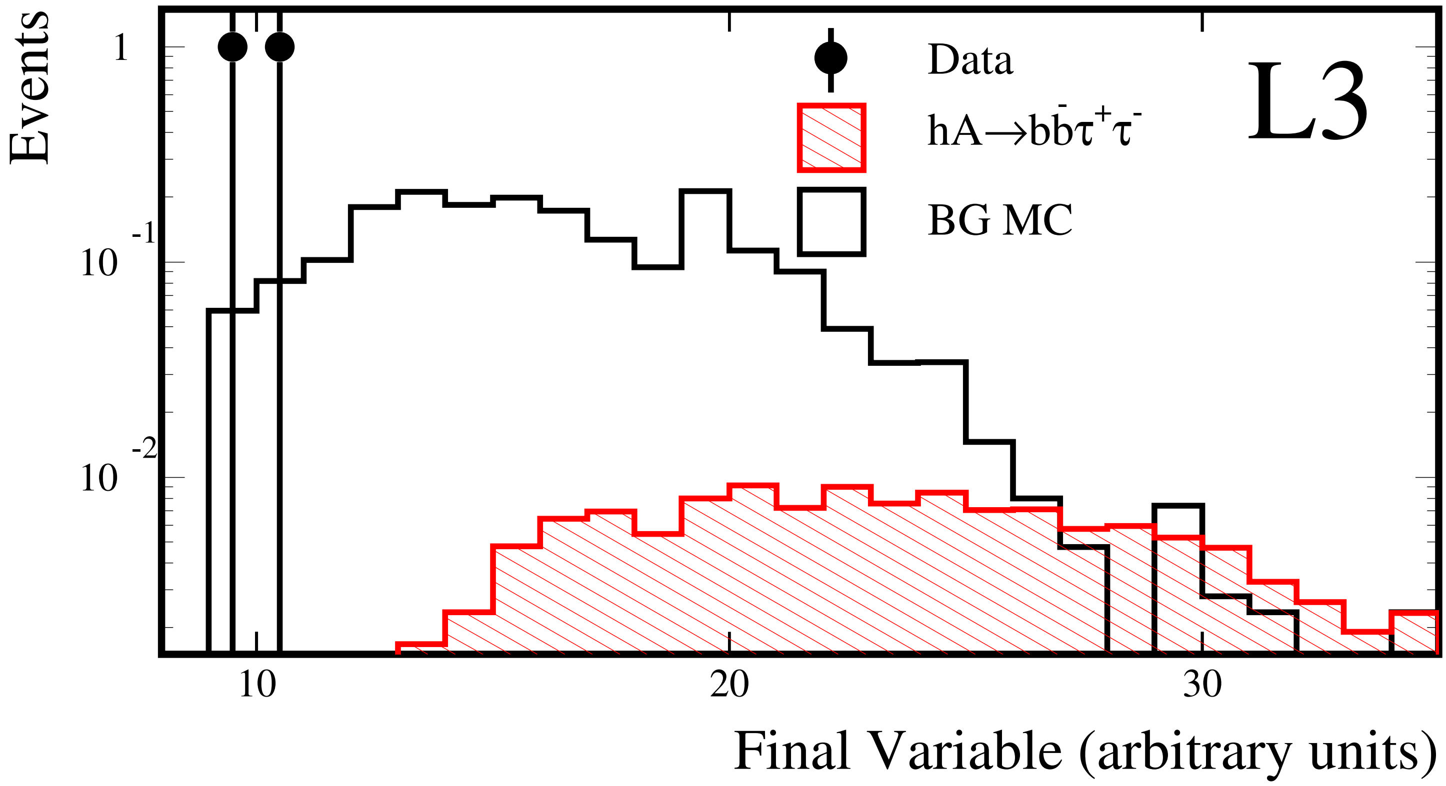
High signal efficiency and relatively large background are used for the search since the background and data candidates in the low signal/noise regions don't spoil the sensitivity or the final limit.
No significant excess or mass structure can be seen at any mass point considered.

Higgs Search: MSSM

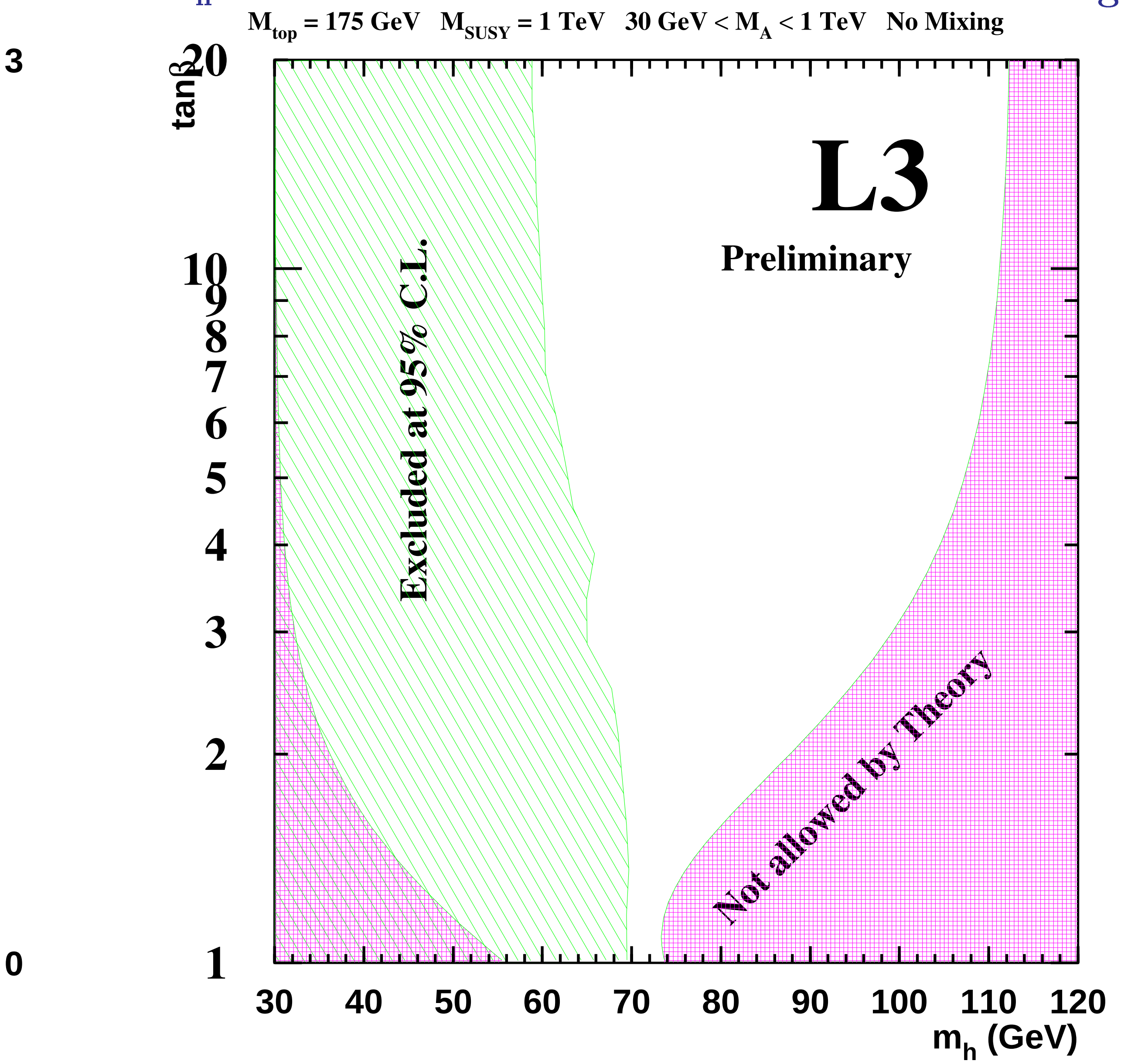
Signature: Same as $hZ \rightarrow q\bar{q}\tau^+\tau^-$ except now use B_{tag} as well.

Final Variable: Kinematic variables and B_{tag} are combined into a single final variable.

$m_h = 58$ GeV $m_A = 58$ GeV for 172 GeV



$m_{\rm h}$Mass Limit in the MSSM for Minimal Mixing

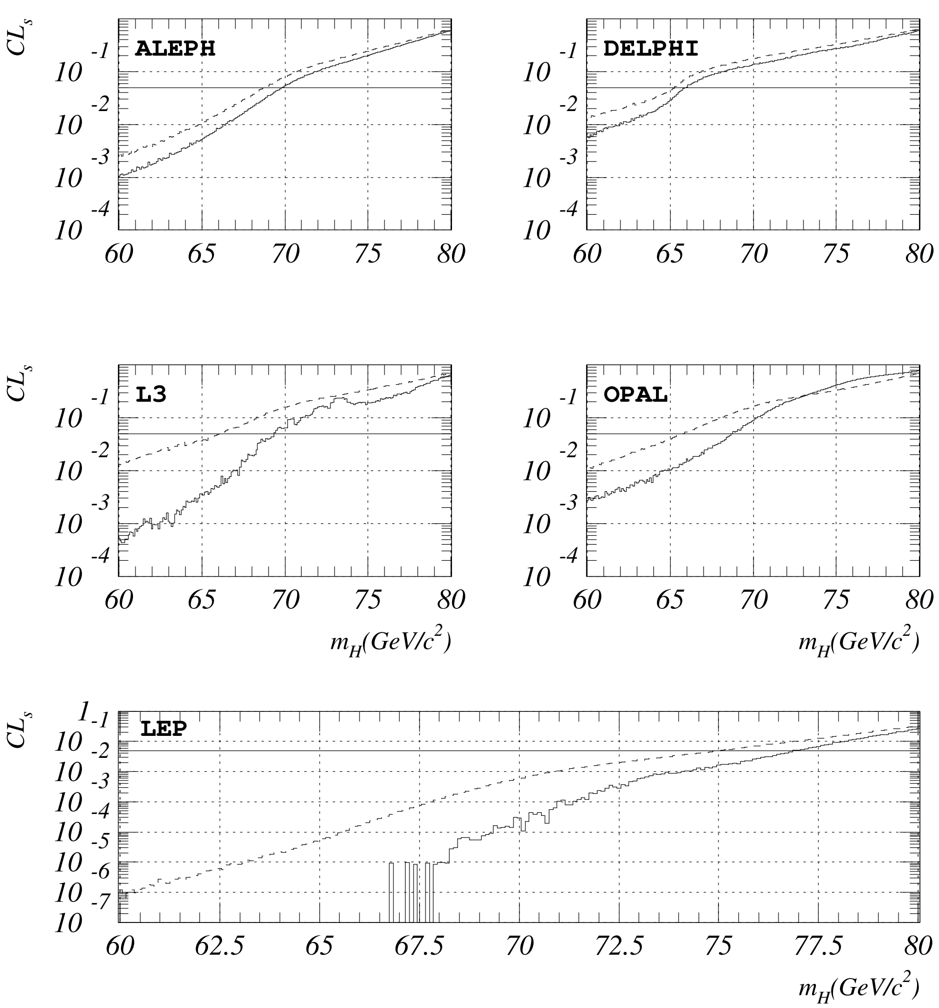


- The LEPI data were *not* included in the limit calculation.
- ***No observation of signal.*** **Lower limits on $m_{\rm h}$ and $m_{\rm A}$ are set as a function of $\tan\beta$.**

LEP Results of SM Searches

Each experiment's procedure for combination of channels can be applied to other LEP experiment's data.

CL_{s+b}/CL_b - DELPHI method



Experiment	Statistical method				Spread (MeV)
	ALEPH	DELPHI	L3	OPAL	
ALEPH	69.6	69.8	69.8	69.5	±150
DELPHI		65.9	65.8	65.3	±300
L3		69.4	69.3	68.7	±350
OPAL		68.7	68.2	69.3	±300

LEP Results of SM Higgs Searches

Experiment	Statistical method				Spread (MeV)
	ALEPH	DELPHI	L3	OPAL	
LEP	77.1	76.9	77.8	77.8	± 450

Spread: not fully understood ...

... to be compared, e.g. to the difference between the 90% c.l. and 99% c.l. limits, $\approx$ 4 GeV.

Combined limit at 95% C.L.: 77 GeV

(PRELIMINARY)

Status as of Jerusalem (EPS97)

Including Some of the New 183 GeVData

ALEPH	DELPHI	L3	OPAL
74.0	73.0	72.0	–

These numbers will be obsoleted soon!

Experiment	Lower Limit on m_{h} GeV
ALEPH	71.3
L3	69.6

No evidence of "invisible" Higgs in 161-172 GeV data

LEP Results of MSSM Higgs

Experiment	Lower Limit m_h GeV	Lower Limit m_A GeV
ALEPH	62.5	62.5
DELPHI	59.5	51.0
L3	58.6	58.6
OPAL	56.0	50.6

No evidence of MSSM neutral Higgs production in 130-172 GeV data

L3 result only for minimal mixing scenario. ALEPH quotes same result regardless of mixing parameters. DELPHI and OPAL results change slightly for different mixings.