# Searches at LEP

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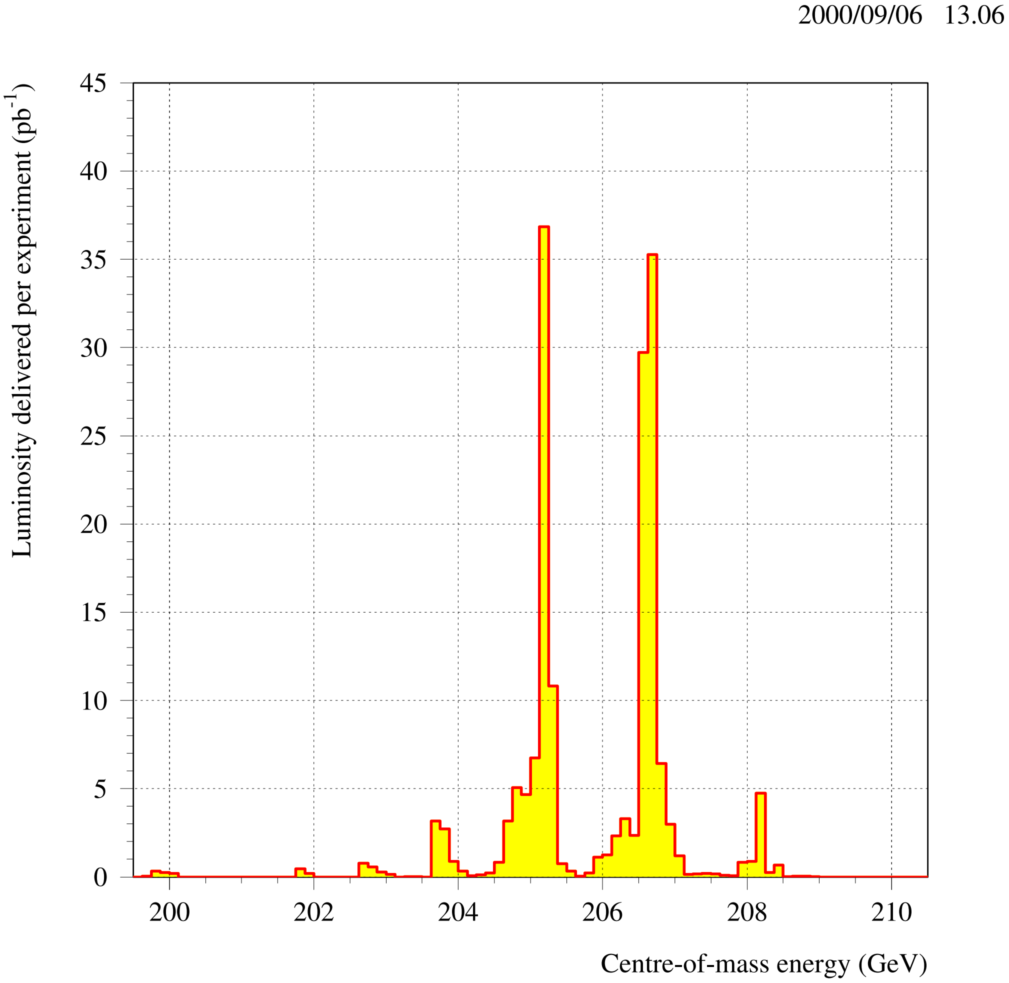
*With many thanks to the ALEPH, DELPHI, L3, and OPAL collaborations, and the Accelerator Divisions at CERN*

- Introduction and Context
- Higgs Searches
  - SM, MSSM, $H^{\pm}$, $H \to$invisible, $H \to \gamma\gamma$
- SUSY Searches
  - Gauginos, squarks, sleptons, GMSB
- Beyond the SM
  - Check of the photon recoil
- Prospects

# *Performance of LEP in 2000*




Follow the news at http://alephwww.cern.ch/~janot/LEPCO/

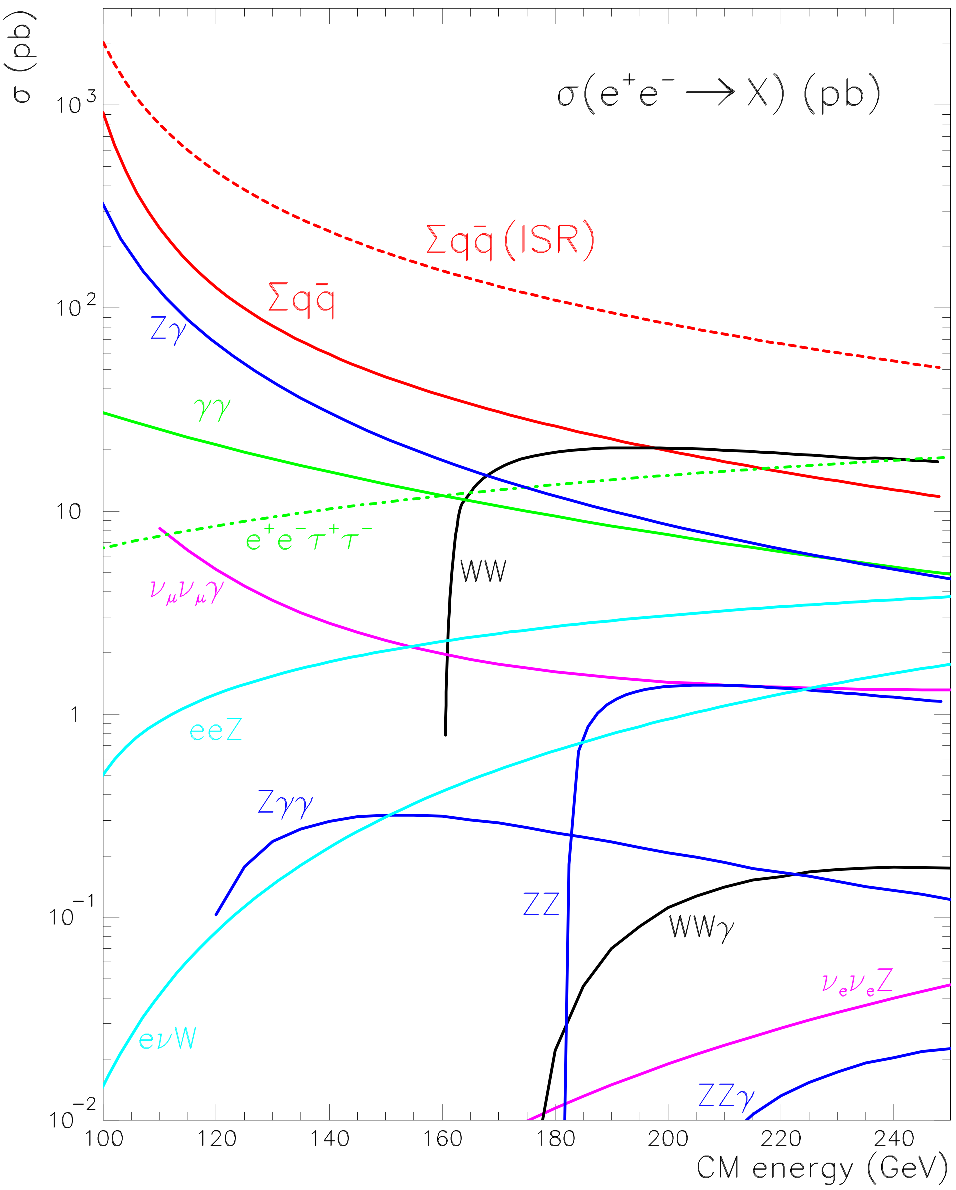
What's new in 2000

- More RF volts: 3650 MV
- Bending-Field Spreading with Correctors
- Mini-Ramps at the ends of fills

Approximately **150 pb$^{-1}$/experiment** in 2000 analyzed and combined for this presentation (results as of 5 Sept. LEPC)

**Average $E_{CM}$: 205.9 GeV.** 6.4 pb$^{-1}$/experiment above 207.5 GeV

# *The Standard Model Landscape at LEP2: "Backgrounds"*




- Four-Fermion Backgrounds, $W^+W^-$ and $Z^0Z^0$ are important to Higgs/SUSY searches. $\sigma$~20 pb ($W^+W^-$), 1 pb ($Z^0Z^0$)
- Two-photon processes have *large* cross-sections -- more important for SUSY searches with small $\Delta m$ (to be explained later)

# *The SUSY Spectrum*

| SM Particles +Higgs $R_P = 1$ | SUSY Partners $R_P = -1$ |
|---|---|
| ★ $\gamma, Z^0,$ **$H^0, h^0, A^0$** | ★ Four Neutralinos $\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_3$ $\tilde{\chi}^0_4$ |
| $W^\pm$, $H^\pm$ | ★ Two Charginos $\chi^\pm_1$ $\chi^\pm_2$ |
| gluon | gluino |
| graviton | gravitino |
| udscbt | ★ squarks $\tilde{u}$ $\tilde{d}$ $\tilde{s}$ $\tilde{c}$ $\tilde{b}$ $\tilde{t}$ |
| e, $\mu$, $\tau$ | ★ sleptons $\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ |
| $\nu_e$ $\nu_\mu$ $\nu_\tau$ | sneutrinos $\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$ |

★: Search presented in this talk

# *Confidence Levels and the Likelihood Ratio*

First: Select a hypothesis of new physics to test.

One parameter to order experimental outcomes

Does the experiment look

Signal-like: more candidates

Background-like: fewer candidates

or Somewhere in Between?

Sometimes: Too many candidates even for signal! or

Too few candidates even for background

- Constructed from binned search results:
- Each bin has
  - **Estimated number of signal events**
  - **Estimated number of background events**
  - **Number of events observed in the data**

$$L = \frac{P_{poiss}(data \mid signal + background)}{P_{poiss}(data \mid background)}$$

$$\log L = -s_{tot} + \sum_{bins} n_i^{data} \log\left(1 + \frac{s_i}{b_i}\right)$$

# *Confidence Levels and the Likelihood Ratio*

Some searches just count events -- one bin!

Other searches reconstruct masses, tag B's etc --
Many bins with different s/b's. Each bin is an independent counting experiment (a "separate analysis with different cuts")

Can add bins with the same s/b

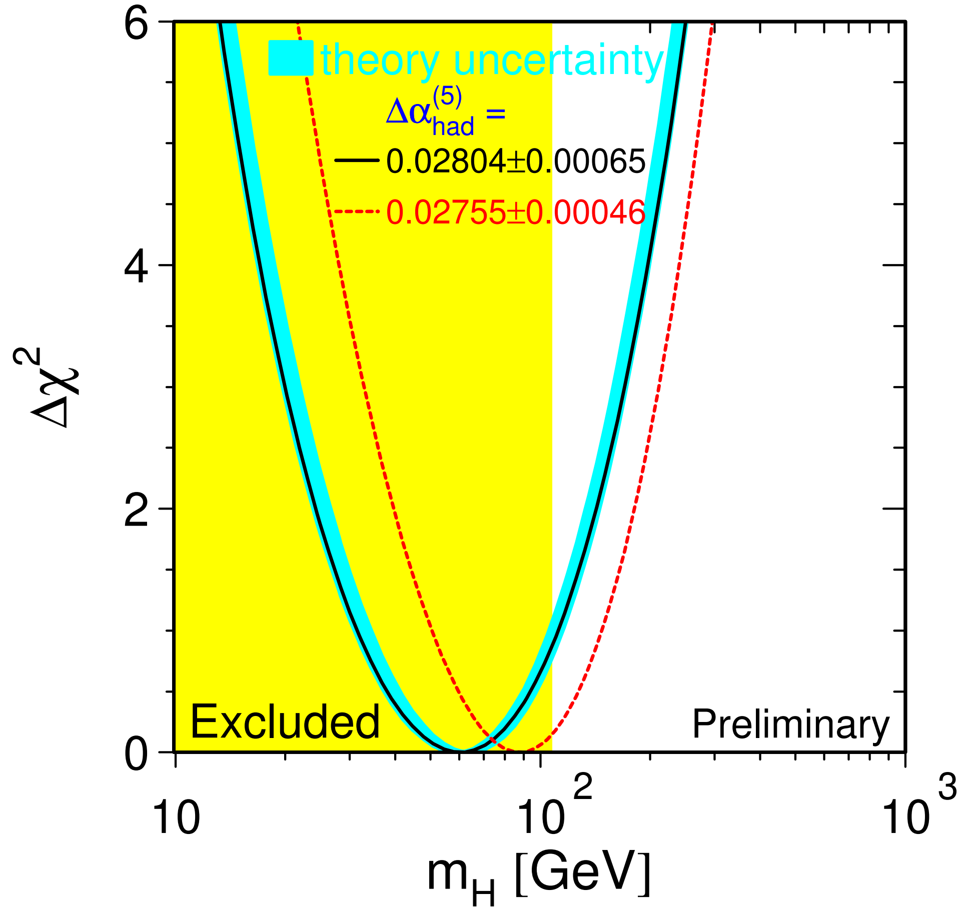
Use MC or analytic techniques to find the PDF of log$L$, given the results of all bins. --
Easy to combine many searches for the same particle -- different analyses, ECM, and experiments all can be combined for more search power.

$$CL_{s+b} = P\left(L \leq L_{obs} \mid signal + background\right)$$

$$CL_b = P\left(L \leq L_{obs} \mid background\right)$$

$$CL_s = CL_{s+b} / CL_b$$

# *Electroweak Fit Constraint on $m_H$*




- Logarithmic sensitivity to $\sin^2\theta_W$

  Current central value:

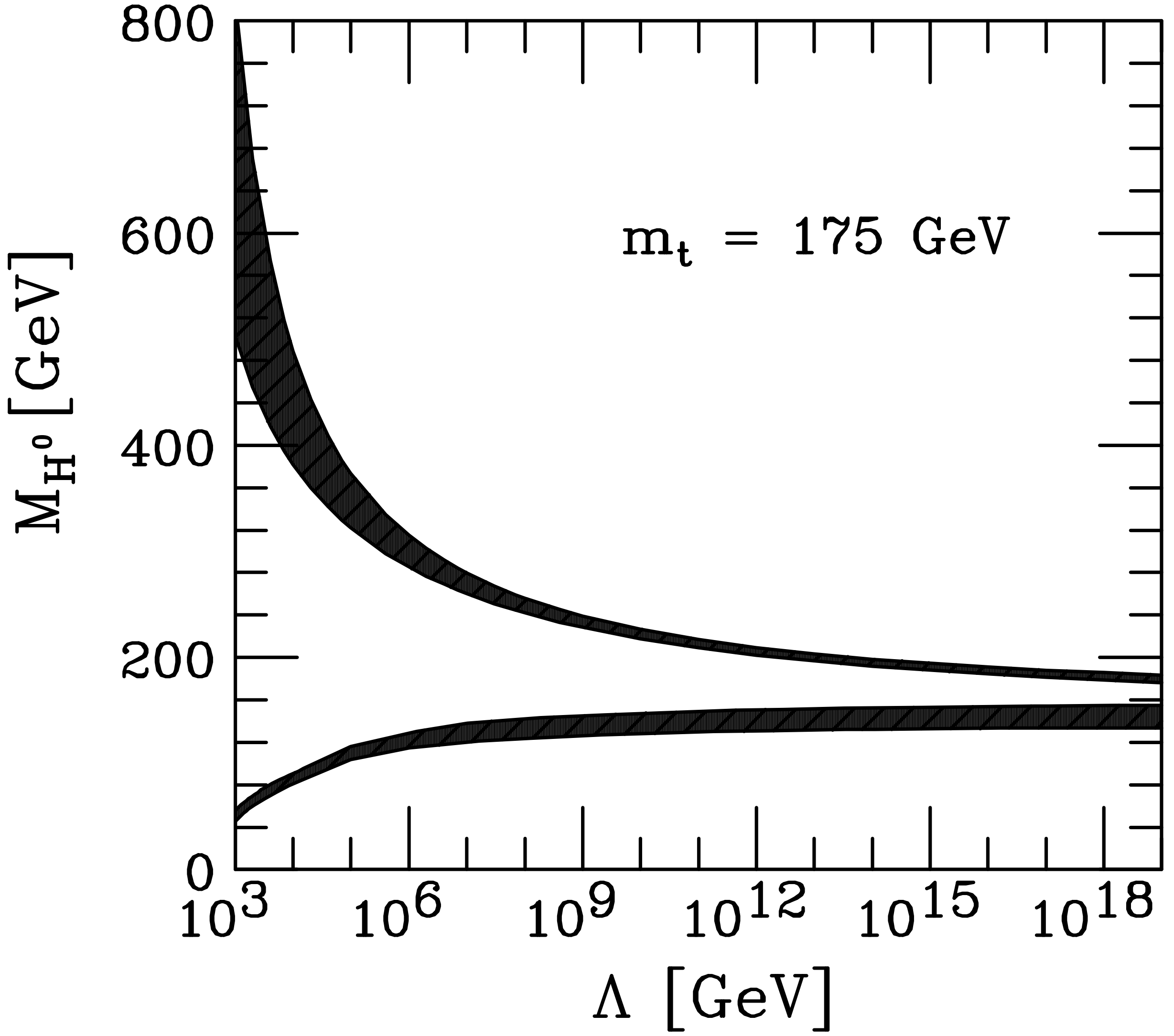
$$\boxed{m_H = 62^{+53}_{-39}\ \text{GeV}}$$

*Results as of ICHEP 2000*

- 95% CL Upper limit

$$m_H < 170\ \text{GeV}$$

*Consequences of Believing the Standard Model up to the Planck Scale*




Λ is the scale at which interactions beyond the Standard Model become important

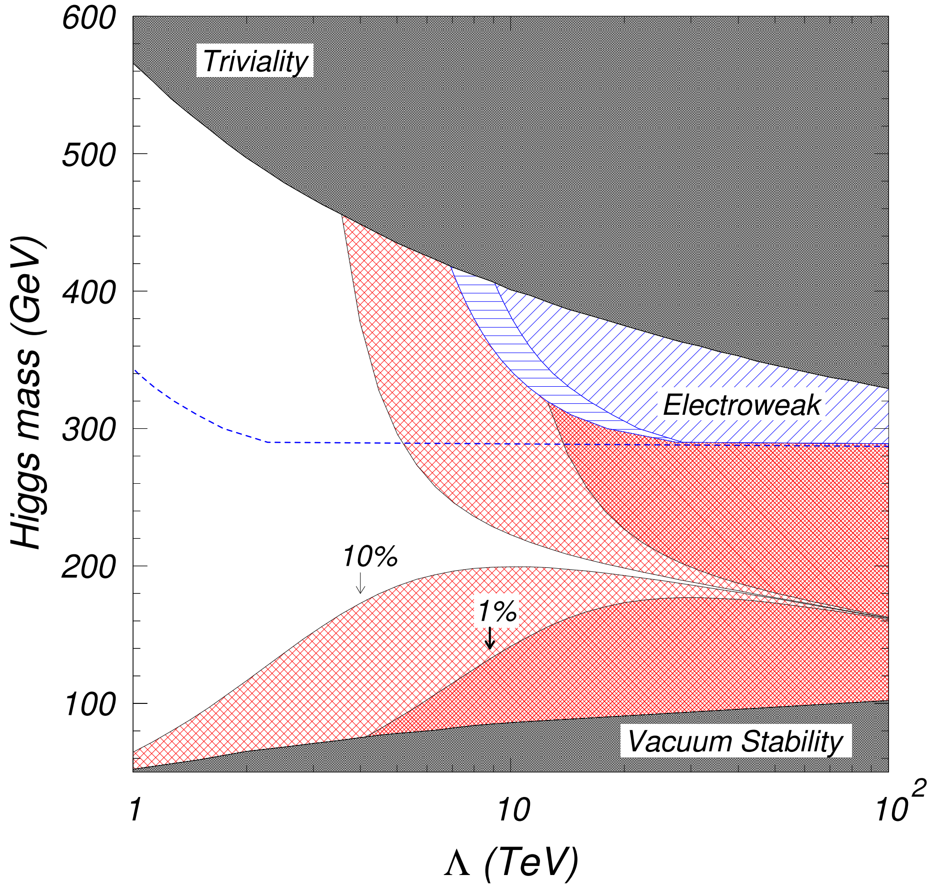
Upper Higgs mass bound -- Landau pole
Lower Higgs mass bound -- vacuum stability

# *Fine-Tuned Radiative Corrections in the SM*

Kolda and Murayama, hep-ph/0003170

One-loop correction to $\mu^2$ is proportional to $\Lambda^2$, which destabilizes the weak scale, unless $m_h$ is exquisitely chosen.

$$\mu^2 \to \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}\left(2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2\right)$$

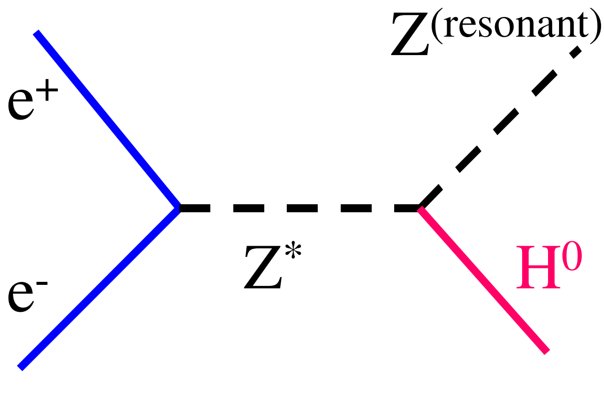



Provocative, but experimentalists don't believe pretty theories until the particles show up.

# *Standard Model Higgs Production*

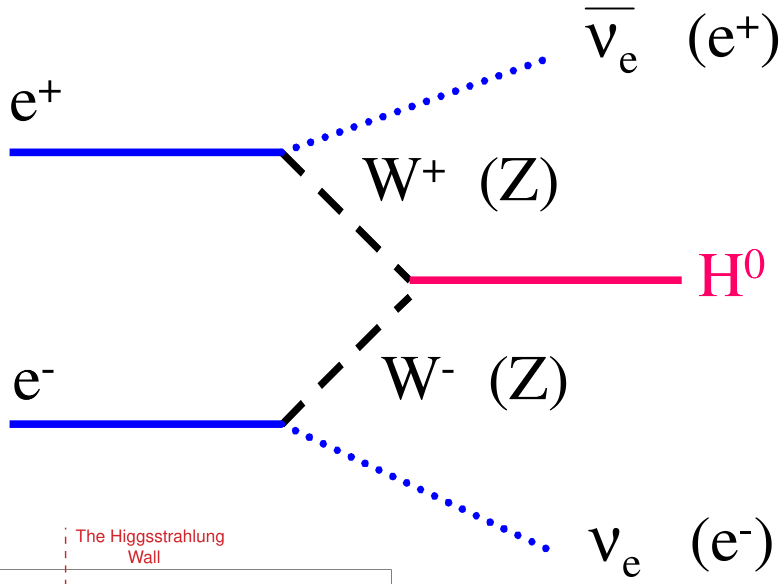
"Higgs-Strahlung"
(BJ process)

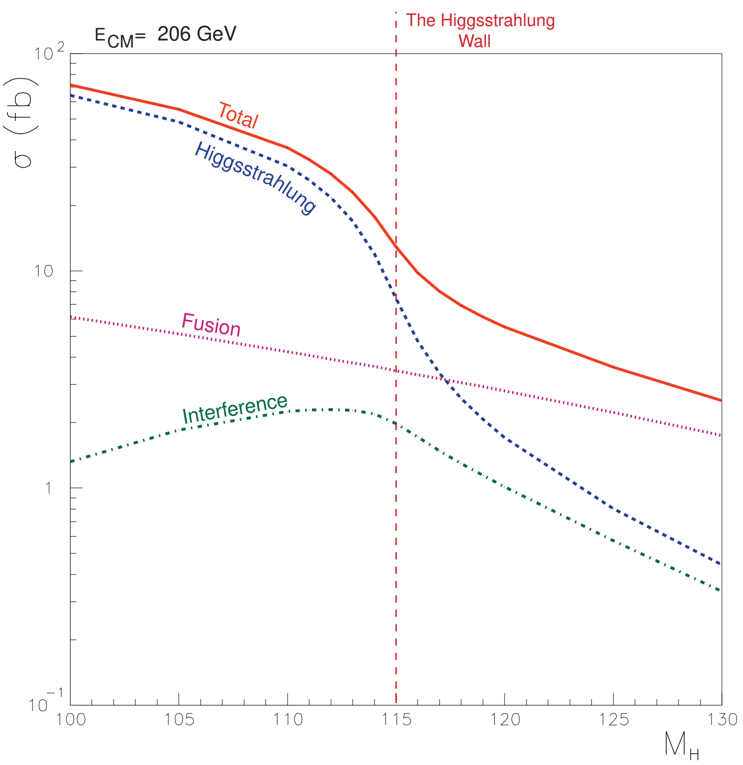
*Has a kinematic "cutoff" at $\sqrt{s}-m_Z$*




"Fusion"

*"No" kinematic cutoff, but low cross-section*

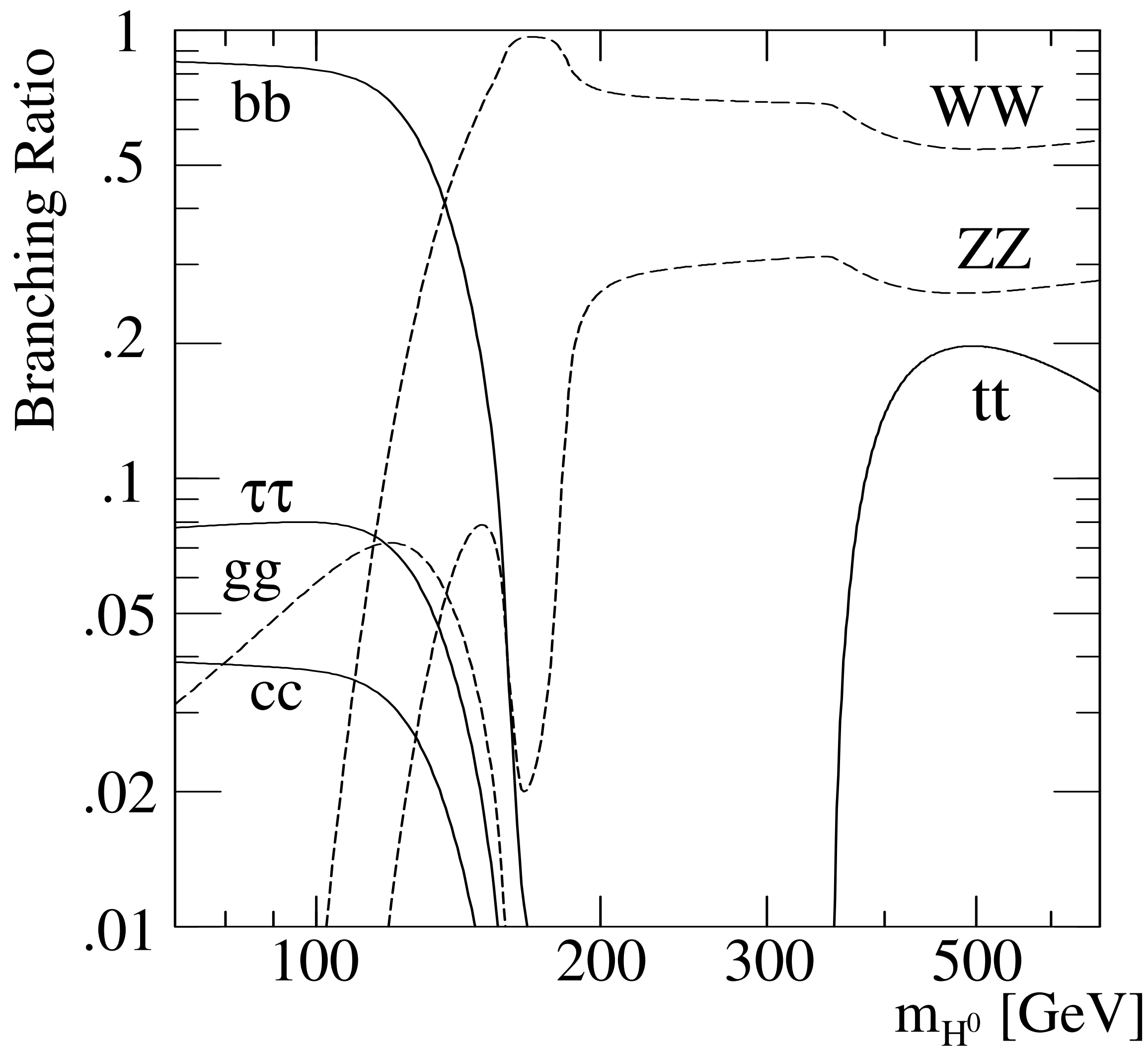



Note: only $H\nu\nu$ x-sect shown.

Multiply HZ by ~5 to get total.

# *Standard Model Higgs Decays*



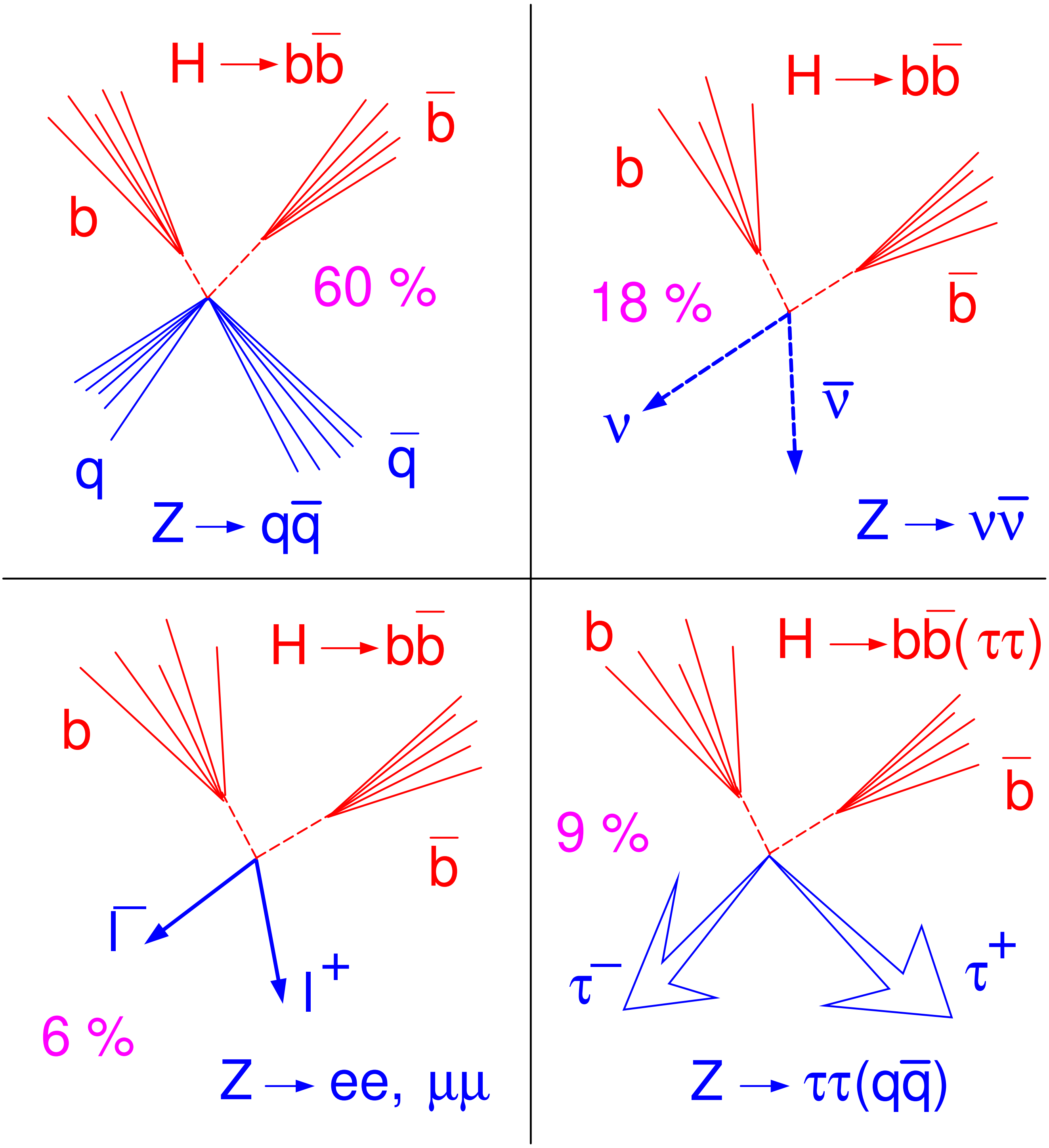

SM Higgs Decay, at 110 GeV < $m_H$ <115 GEV

- b-quarks ~80%
- $W^+W^-$ ~8% and rising quickly
- tau pairs ~7%
- charm and gluons -- the rest

B-tags are very important

# *SM Higgs Search Channels*

Each Higgs search channel is named after the $Z^0$ decay mode.

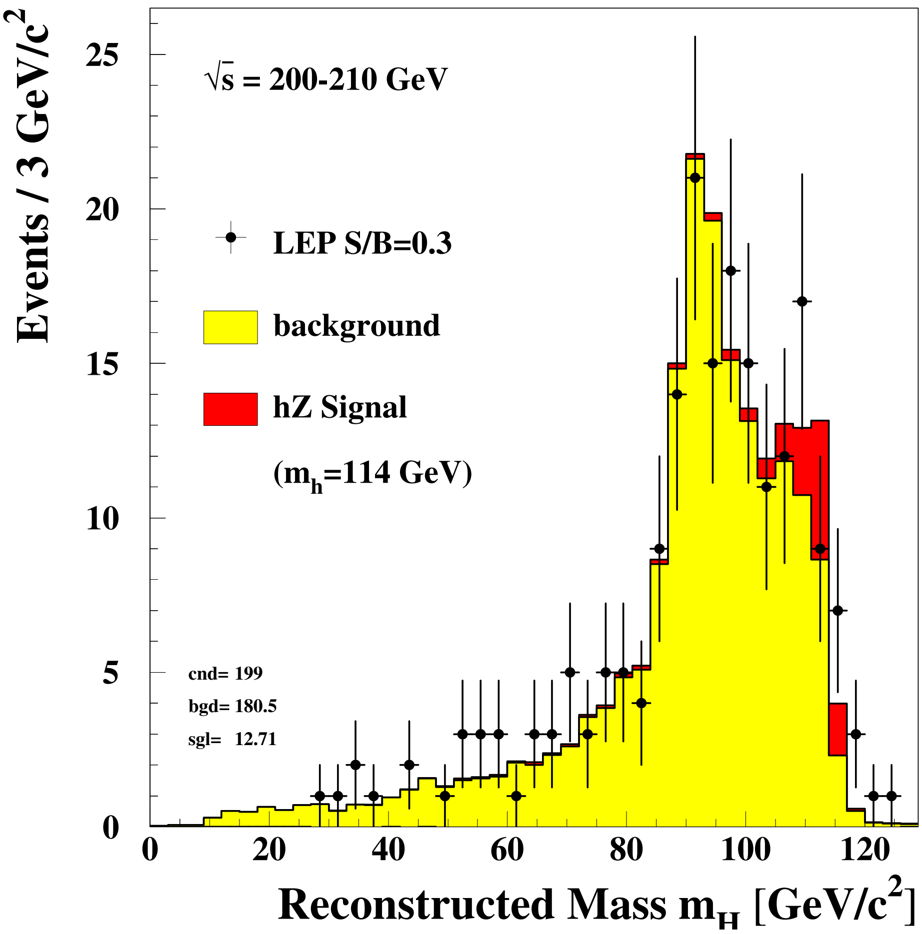


# *Exchanging LEP Higgs Results for Combination*

- Results are binned in an experiment's choice of discriminant variables (reconstructed mass, b-tag, kinematic variables, or a combination of these)

- For each bin:
  - signal estimation
  - background estimation
  - data counts
- For each search analysis channel:
  - **signed relative error on the signal and background** itemized *by named source*
  - examples: B decay modeling, ZZ x-sect, MC comparisons
- Effect of including errors
  - Uncorrelated: Almost no effect on limits
  - 100% Correlated: 200-300 MeV lower expected SM limit
  - Properly correlated: ~100 MeV lower expected SM limit
  - **We have prepared for a discovery!**

# *Distributions of the Reconstructed $m_H$*

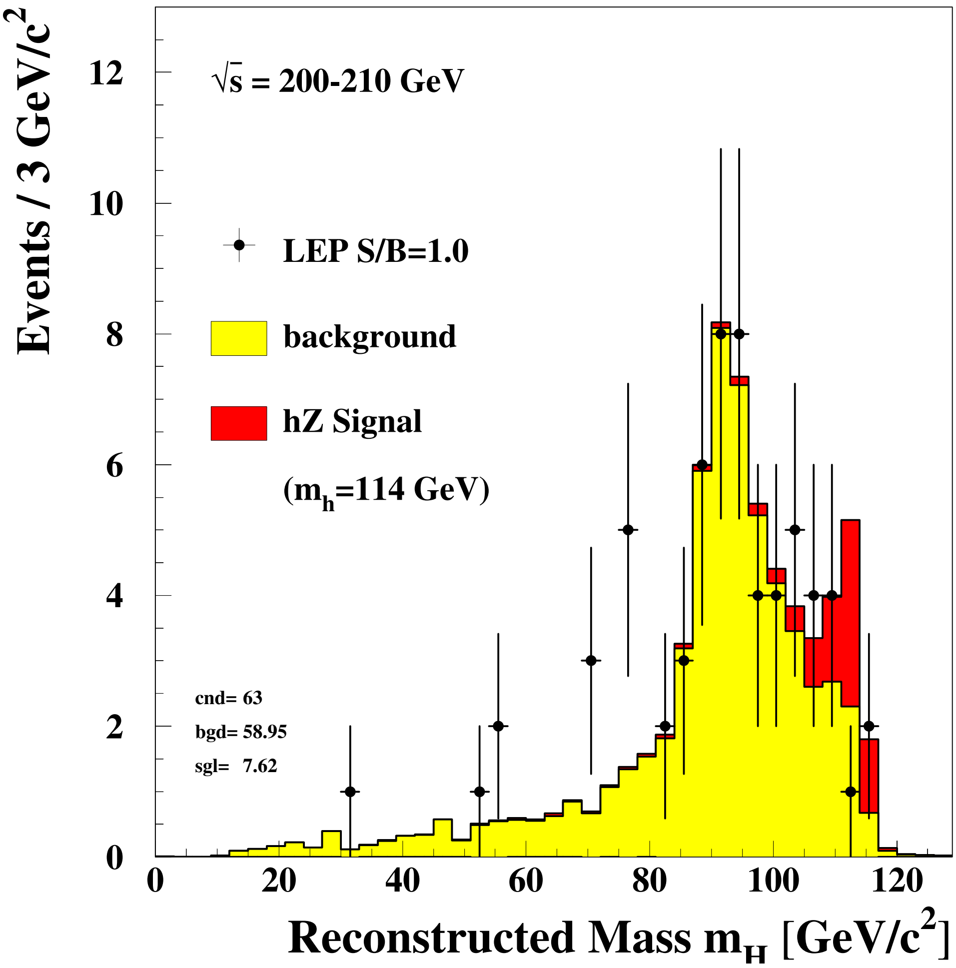



**Loose Cuts:** Def'n: **s/b=0.3** for $m_{h,rec}$>109 GeV

Signal model: $m_h$=114 GeV

| | Data | Background | Signal |
|---|---|---|---|
| ALEPH | 62 | 56.4 | 3.9 |
| DELPHI | 38 | 36.8 | 3.4 |
| L3 | 31 | 34.7 | 2.1 |
| OPAL | 68 | 52.7 | 3.4 |
| **LEP** | **199** | **180.5** | **12.7** |

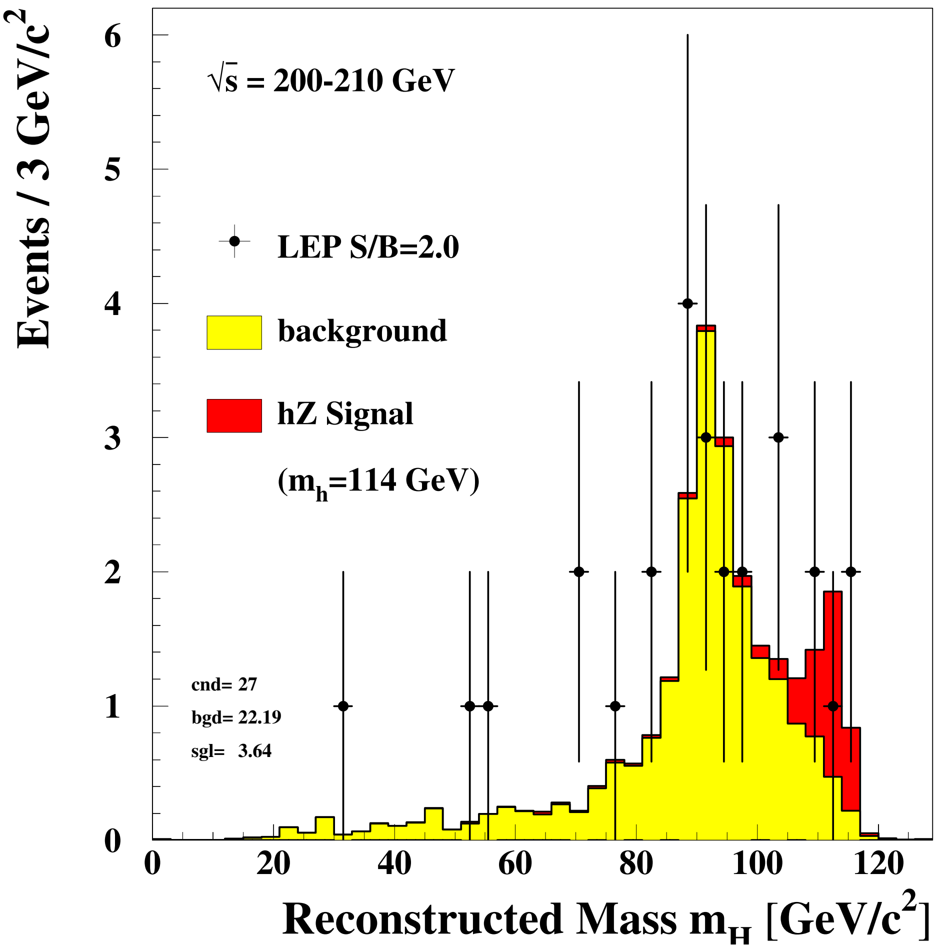
# *Distributions of the Reconstructed $m_H$*




**Tighter Cuts: s/b=1.0** for $m_{h,rec}$>109 GeV
Signal model: $m_h$=114 GeV

| | Data | Background | Signal |
|---|---|---|---|
| ALEPH | 16 | 14.3 | 2.4 |
| DELPHI | 14 | 14.7 | 2.6 |
| L3 | 11 | 9.7 | 0.7 |
| OPAL | 22 | 20.3 | 2.0 |
| **LEP** | **63** | **59.0** | **7.6** |

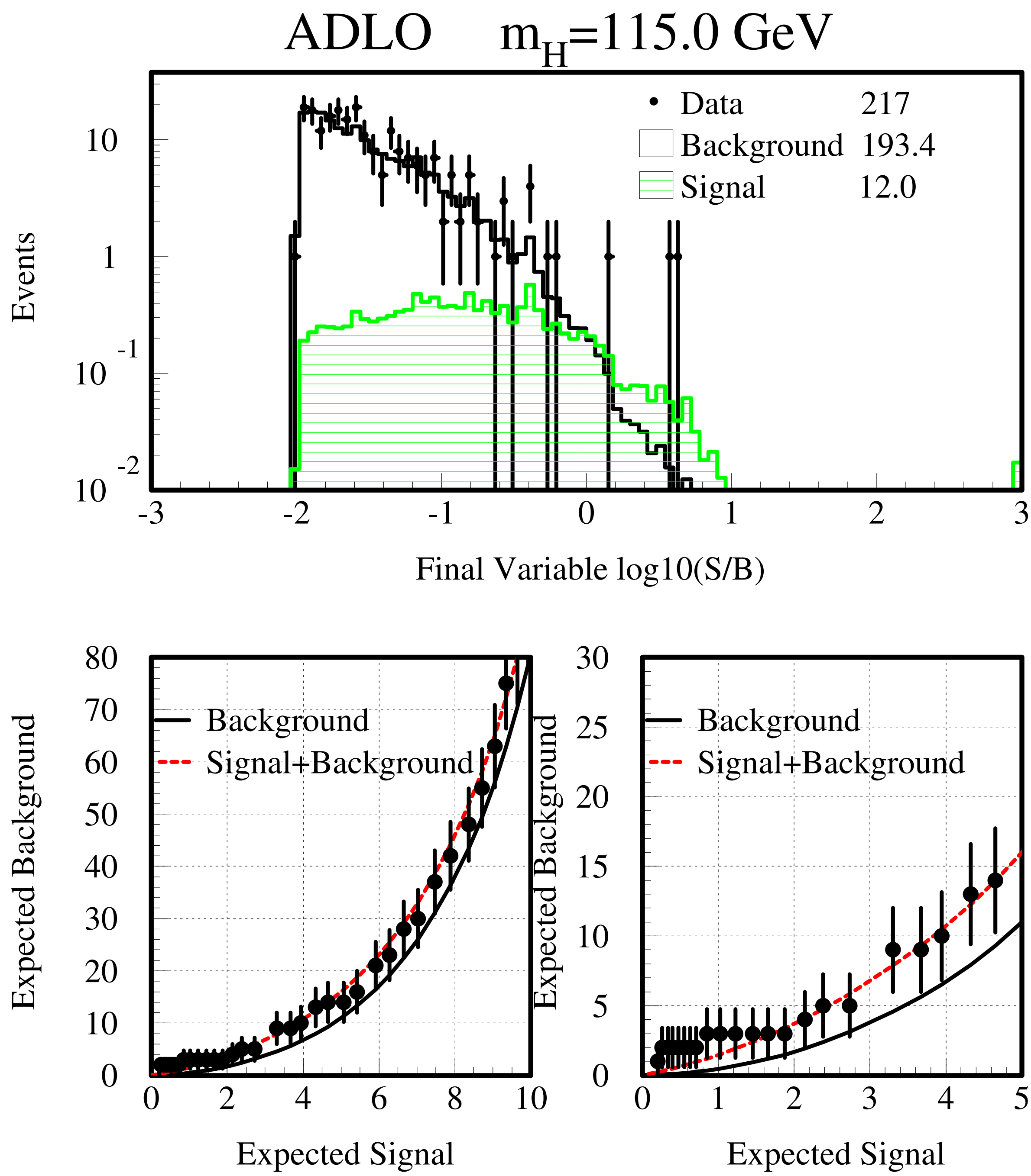
# *Distributions of the Reconstructed $m_H$*




**Very Tight Cuts: s/b=2.0** for $m_{h,rec}$>109 GeV
Signal model: $m_h$=114 GeV

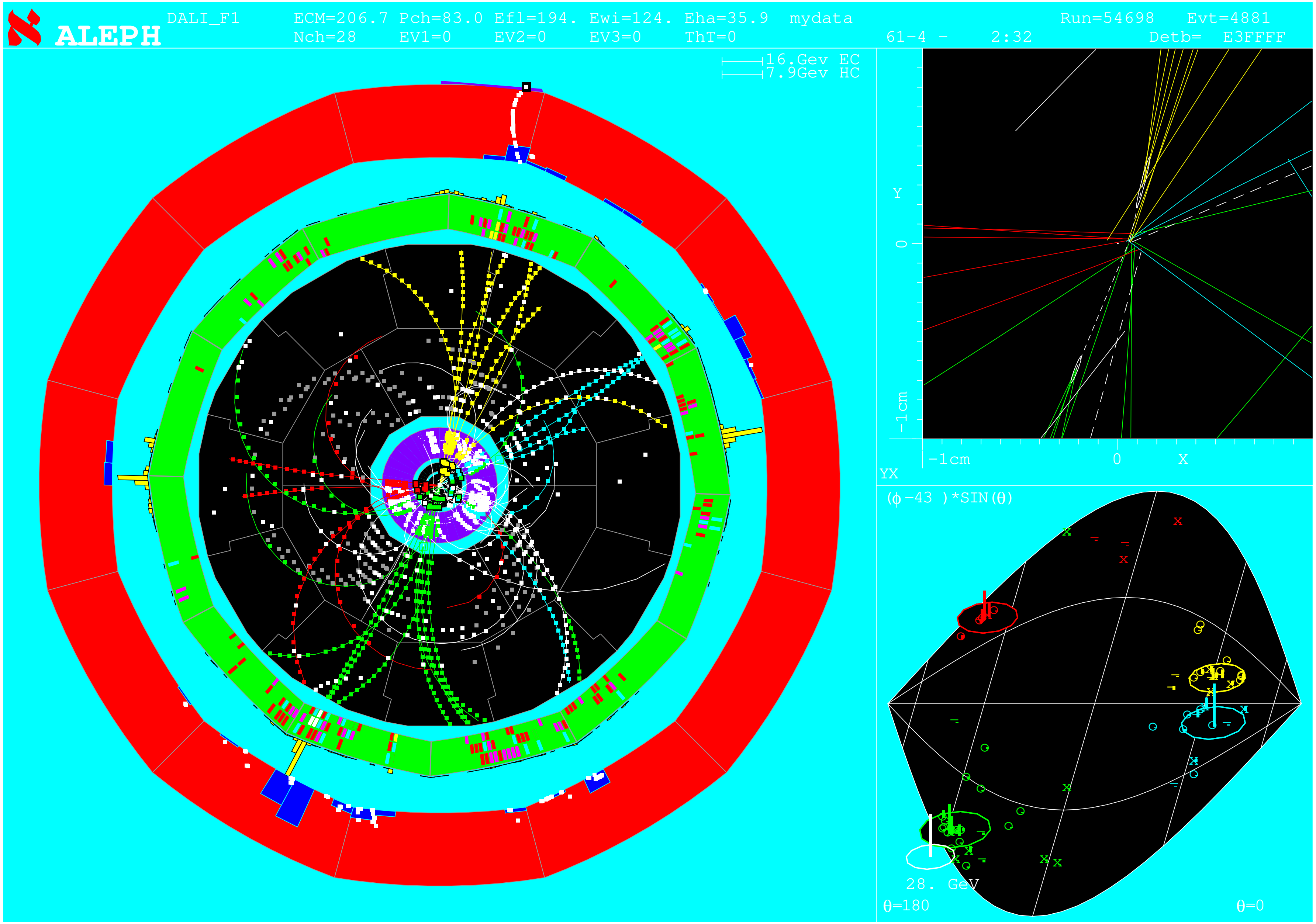
| | Data | Background | Signal |
|---|---|---|---|
| ALEPH | 7 | 3.3 | 1.0 |
| DELPHI | 5 | 5.4 | 1.3 |
| L3 | 4 | 4.0 | 0.3 |
| OPAL | 11 | 9.6 | 0.9 |
| **LEP** | **27** | **22.2** | **3.6** |

# *Signal, Background, and Candidates as a function of s/b*

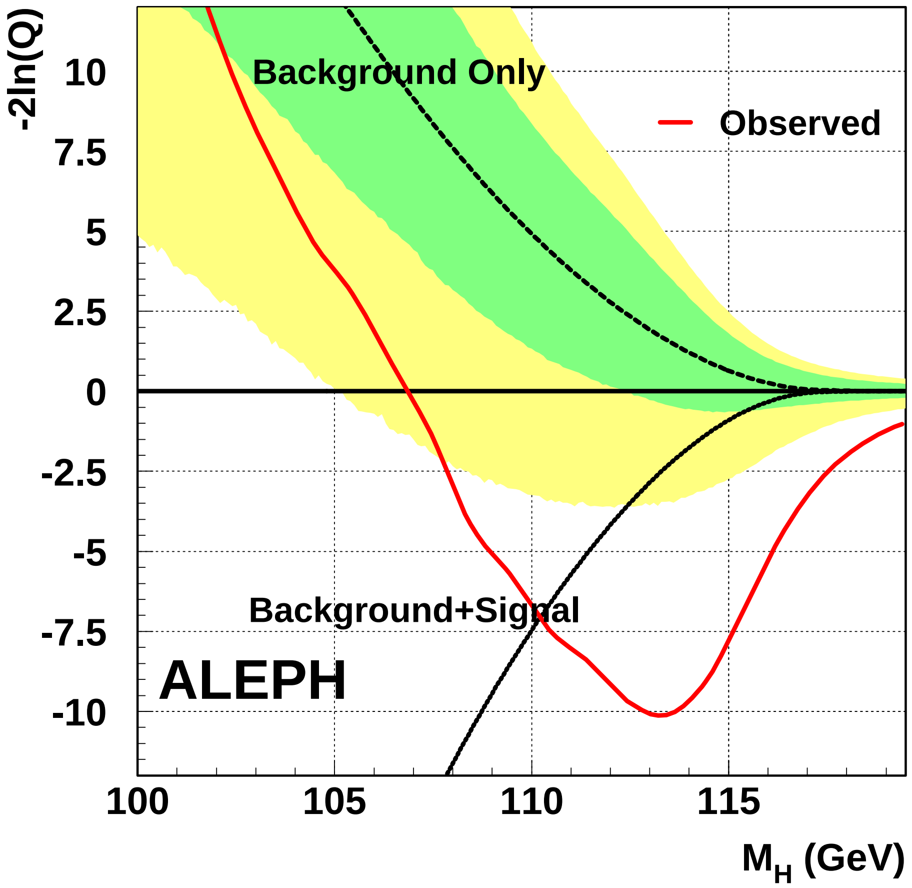



Three most significant candidates -- ALEPH four-jet channel taken at the highest ECM's. Two fairly significant DELPHI four-jet events too.

# An ALEPH Four-Jet Candidate



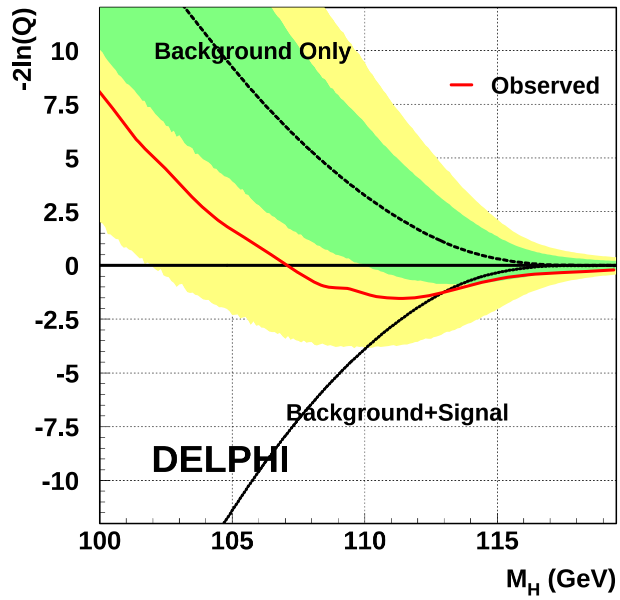
# Excess is mostly in the ALEPH 4-Jet Channel



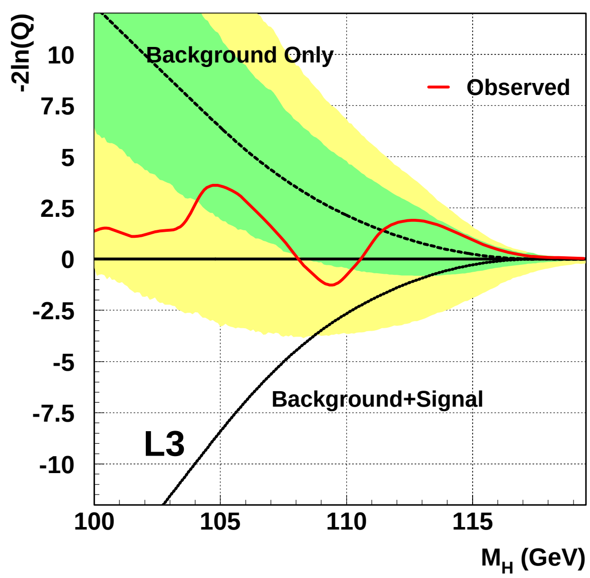

Systematic checks done:

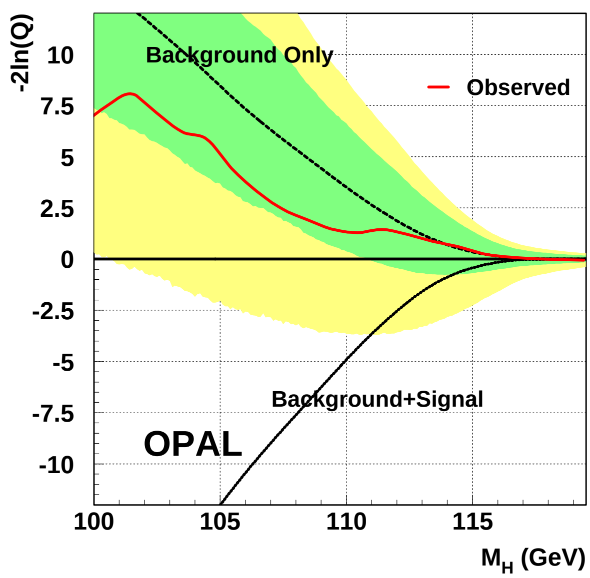
- Cut-based vs. NN analysis
- Test of $m_{rec}$ bias towards kinematic endpoint (no effect seen at lower $E_{CM}$)
- B-tag modeled well, NN modeled well.
- Excess goes away when one cuts out events with a pairing consistent with $Z^0Z^0$ or $W^+W^-$, but this does not separate signal from background.

# *Also a small excess in the DELPHI Four-Jet Channel*

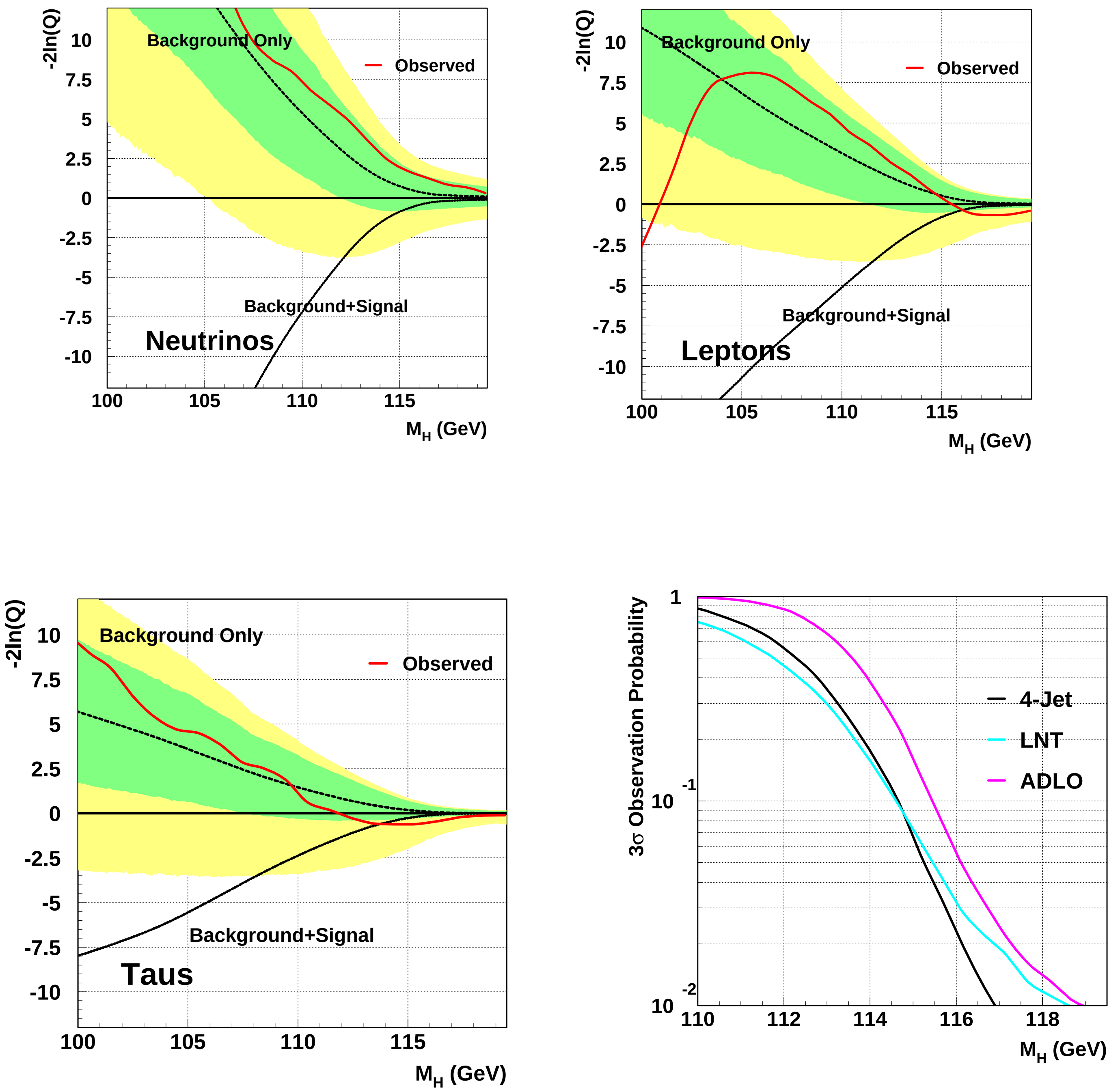



## But not in L3 or OPAL's four-jet channels



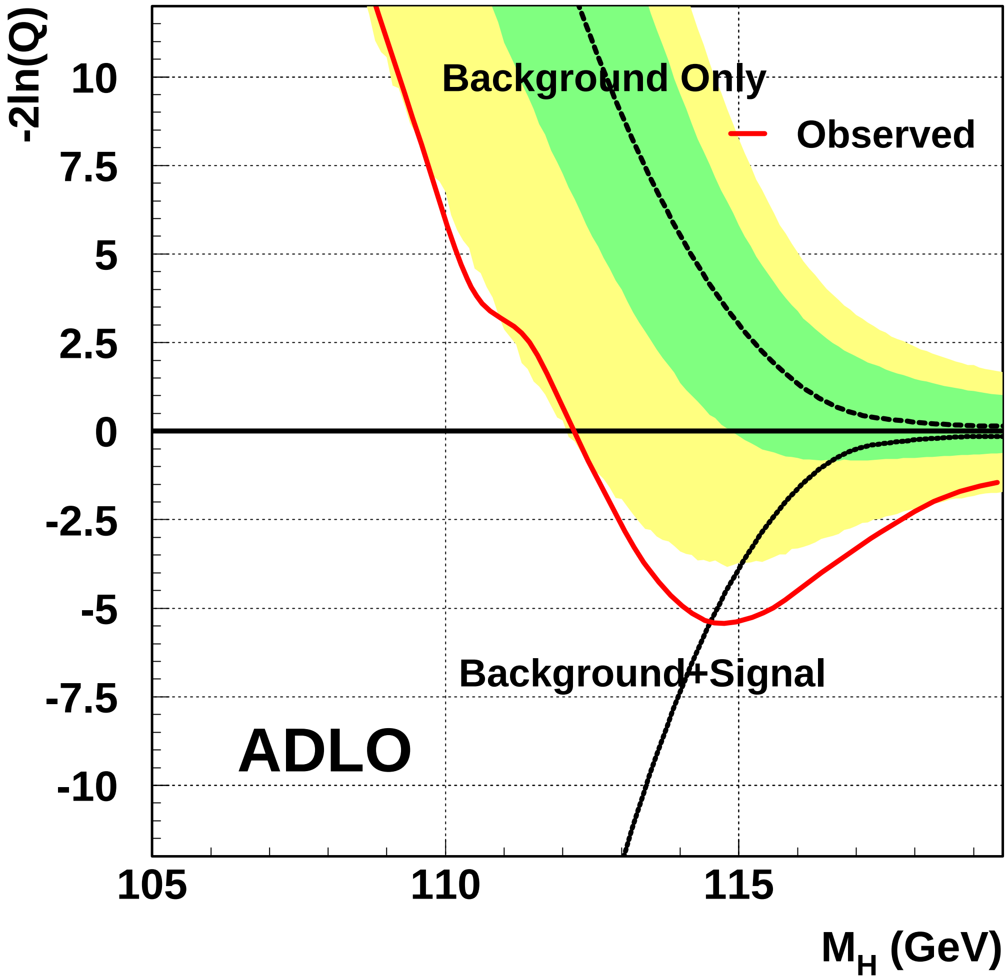
# *Missing-Energy, Lepton, and Tau Channels*




Combined Missing-Energy, Lepton, and Tau channels fairly powerful!

# *The Combined Likelihood Ratio*

*All the information that's available!*

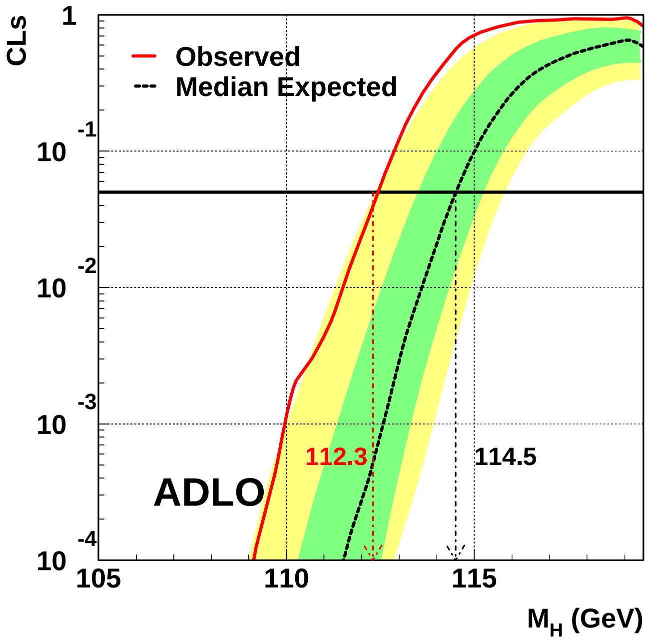



Higgs boson of mass 114 GeV preferred over the background hypothesis by 2.6σ

-- approximately the level of significance expected for a 114 GeV signal.

# *Confidence Levels $CL_s$ and 1-$CL_b$*

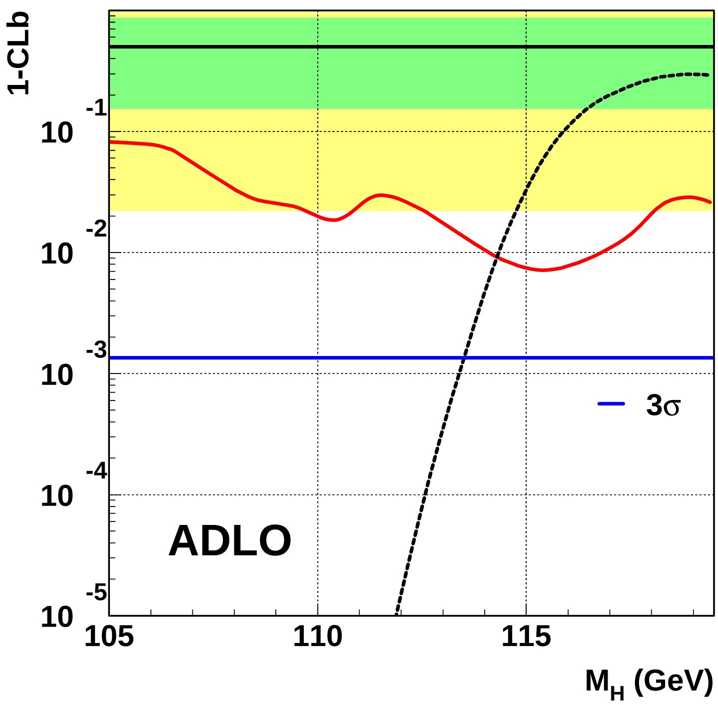
For the combination of all Higgs search results




**Exclude up to 112.3 GeV**

**Median Expectation: 114.5 GeV**

DLO only: 114.2 obs
113.8 exp.




**1-$CL_b$ Minimum at 2.6σ significance at 115.5 GeV -- but -2lnL minimum at 114.9 GeV**

# *Standard Model Limit Summary*

| Experiment | Observed (GeV) | Expected (GeV) |
|---|---|---|
| **ALEPH** | **109.1** | **112.5** |
| **DELPHI** | **110.5** | **110.9** |
| **L3** | **108.8** | **110.2** |
| **OPAL** | **109.5** | **111.7** |
| **Leptons** | **109.9*** | **108.8** |
| **Neutrinos** | **112.1** | **110.7** |
| **Taus** | **105.4** | **104.2** |
| **Four Jets** | **109.0** | **113.5** |
| **LEP** | **112.3** | **114.5** |

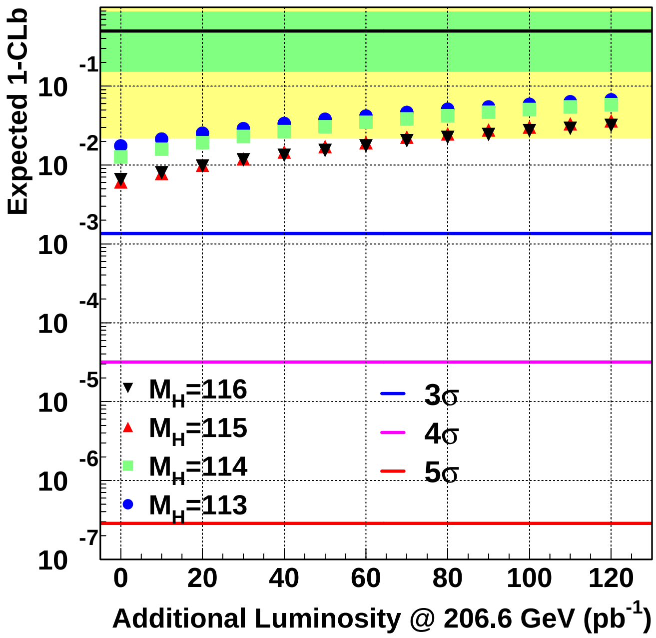
(*) Small unexcluded region below 100.7 GeV

All results are preliminary, but they are computed consistently between experiments and channels from exchanged results. Individual experiments' limits differ slightly.

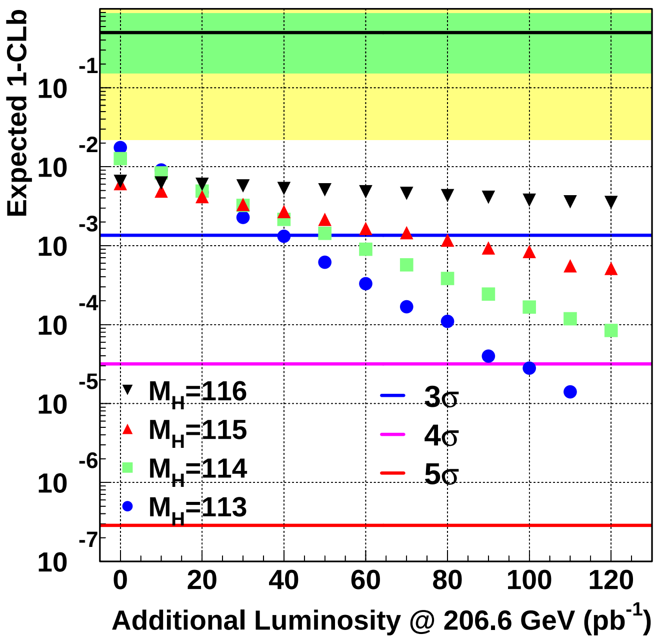
# LEP Extension Scenarios

As functions of the luminosity collected at $\sqrt{s} = 206.6$ GeV, i.e., one klystron margin

## *Case 1: Assuming no signal*




## *Case 2: Assuming a signal is present*

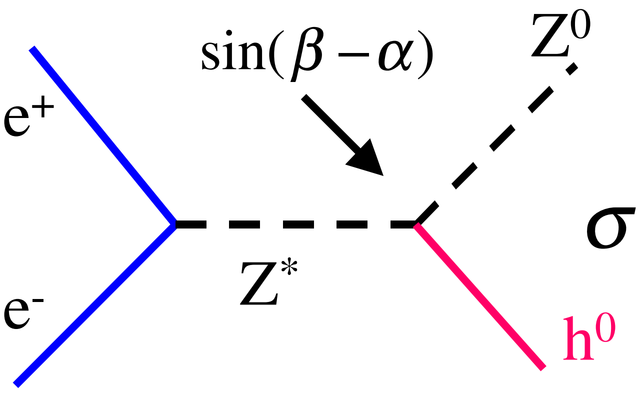


# *The Neutral Higgses of the MSSM*

## Two Higgs Doublets: 5 Higgses

| | |
|---|---|
| **$h^0$** | light CP-even Higgs |
| **$H^0$** | heavy CP-even Higgs |
| **$A^0$** | CP-odd Higgs |
| **$H^+$, $H^-$** | Charged Higgs |

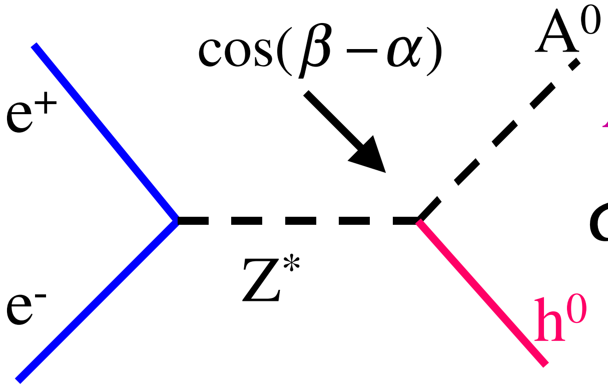
$$\boxed{m_{h^0} < \sim 135 \;\; \text{GeV}}$$




*Higgs-strahlung*

$$\sigma_{hZ} = \sin^2(\beta-\alpha)\sigma_{hZ}^{SM}$$

And fusion processes too!



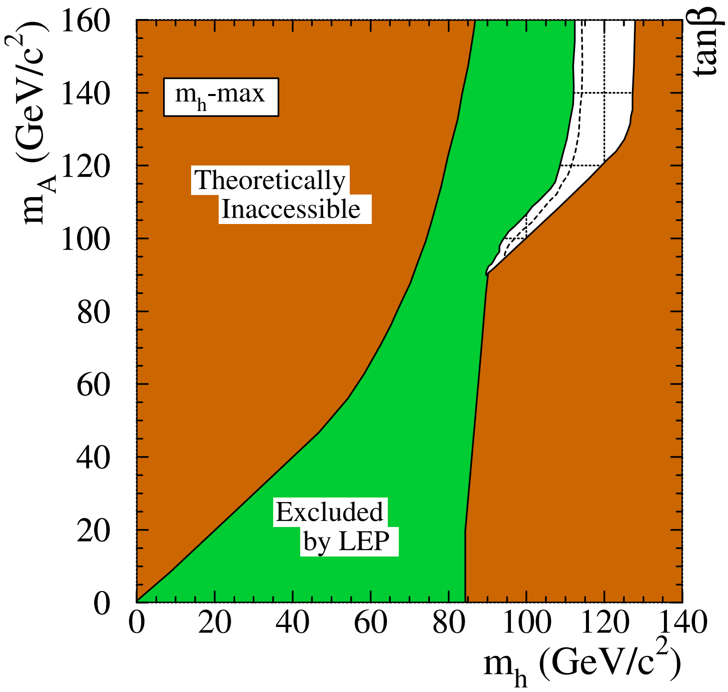

*Associated Production*

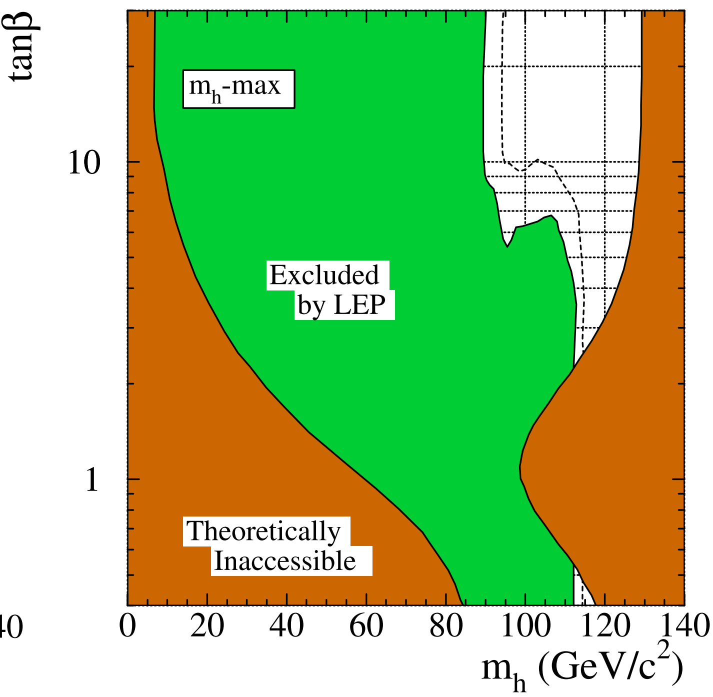
$$\sigma_{hA} = \cos^2(\beta-\alpha)\bar{\lambda}\sigma_{hZ}^{SM}$$

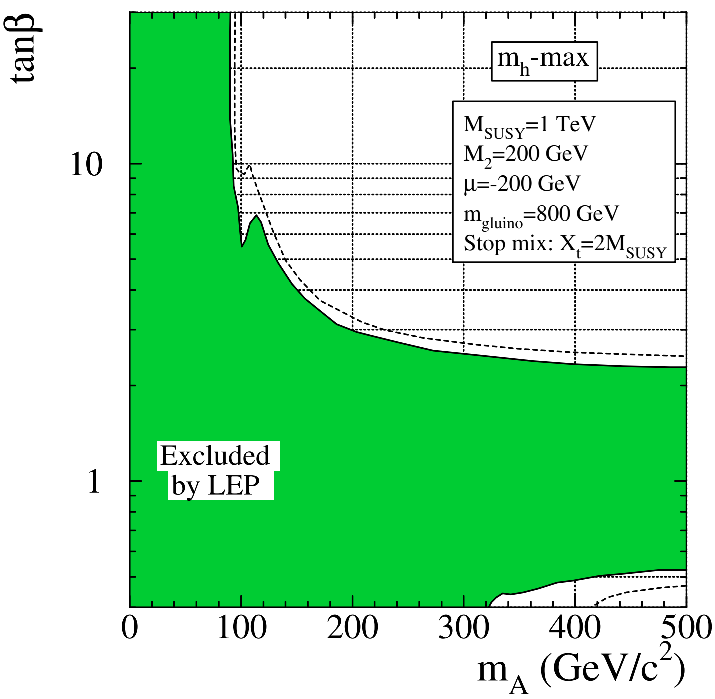
$\bar{\lambda}$ : kinematic factor $(\mathrm{m_h}, \mathrm{m_A}, \sqrt{\mathrm{s}})$

# *MSSM Higgs Limits*

**$m_h$-max scenario** -- using FeynHiggs calculations courtesy of Heinemeyer, Hollik, Weiglein including leading two-loop contributions to $m_h$.




## Mass Limits (GeV)

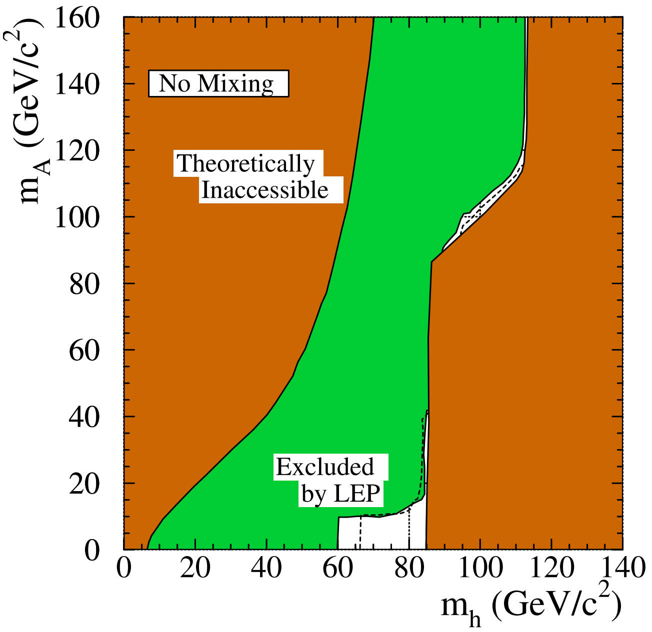
| | obs. | exp. |
|---|---|---|
| $m_h >$ | 89.5 | 93.8 |
| $m_A >$ | 90.2 | 94.1 |

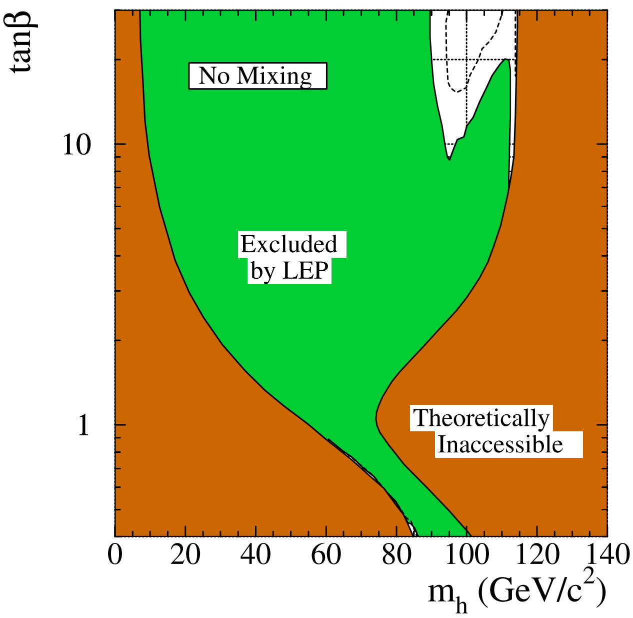
## $\tan\beta$ exclusion

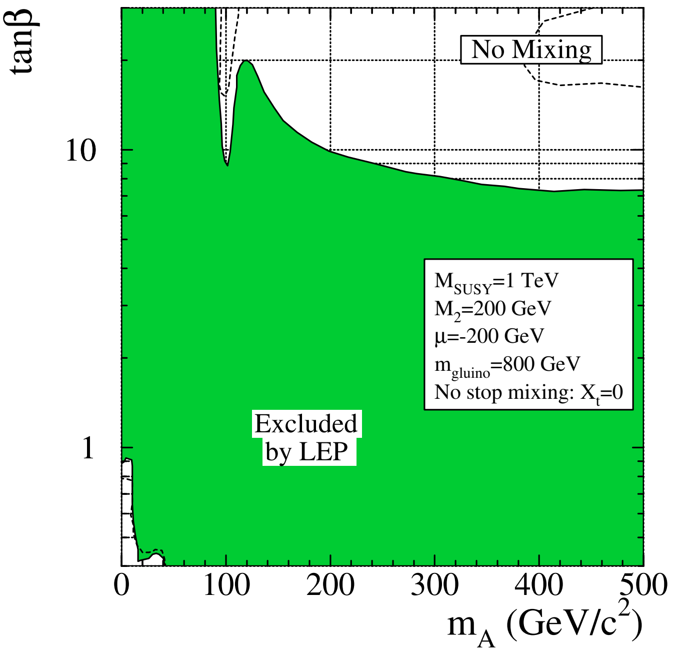
| obs | exp. |
|---|---|
| 0.53-2.25 | 0.48-2.48 |

# *MSSM Higgs Limits*

**No stop mixing scenario** also with FeynHiggs. Soon a casualty? Or maybe not! Interesting features at low and high tanβ




## Mass Limits (GeV)

| | obs. | exp. |
|---|---|---|
| $m_h$ > | 89.4 | 94.3 |
| $m_A$ > | 89.6 | 94.6 |

## tanβ exclusion

| obs | exp. |
|---|---|
| 0.9-7.2 | 0.8-15 |

# *MSSM Higgs Limits*

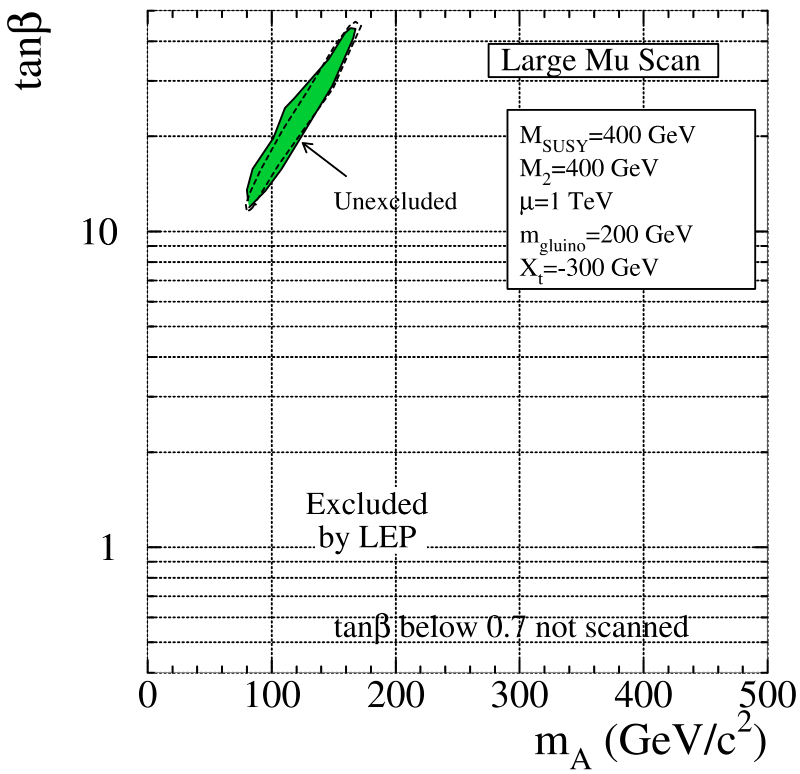
**Large-μ Scenario** **--** Uses Subhpole2 by Carena and Wagner --RG-improved 1-loop calculation. More reliable for high tanβ and large μ.

**Designed to be challenging!**

$$Br(h^0 \to b\bar{b}) \to 0$$

for some points, and the tau b.r. is not enhanced. $W^+W^-$, charm, and gluons make up the difference. Need to combine flavor-independent searches.

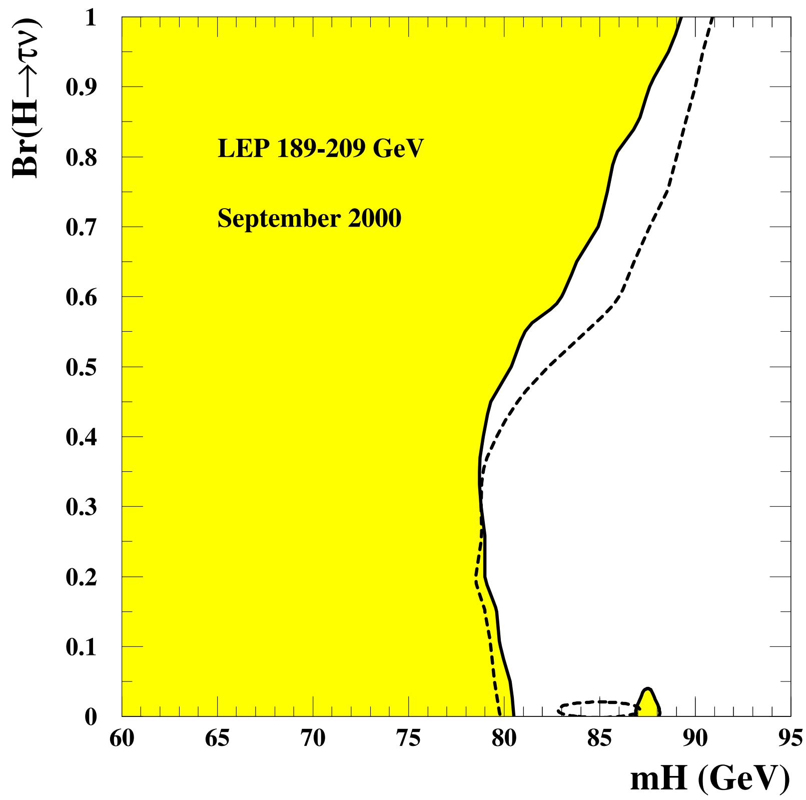
-- LEP has these, but we need to combine them.



# *Limits on Charged Higgs Production from Combining LEP Searches*

Large background from $W^+W^-$ production -- easiest to overcome in the $\tau\nu\tau\nu$ channel.

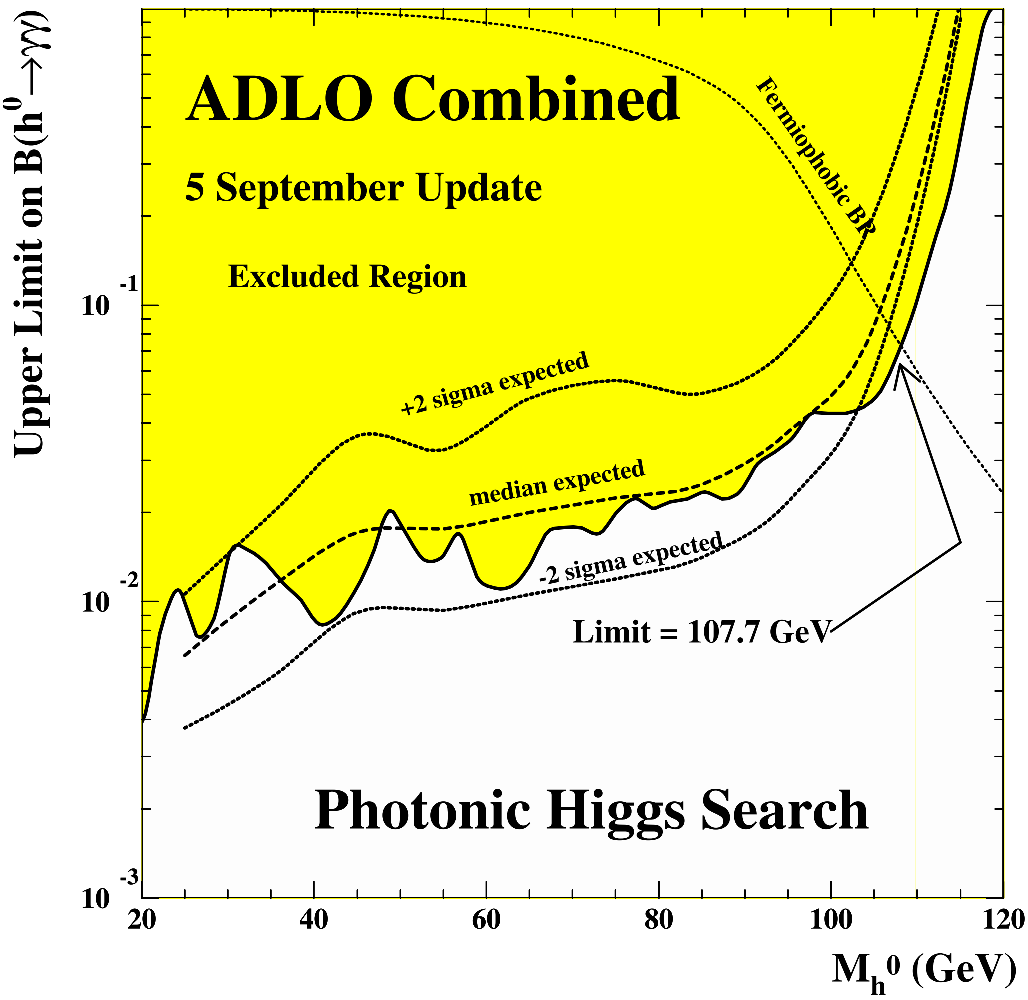
Assume $Br\left(H^+ \to \tau^+\nu_\tau\right) + Br(H^+ \to c\bar{s}) = 1$ for the limits.




Observed (median expected) Limits (GeV) vs. $Br\left(H^+ \to \tau^+\nu_\tau\right)$

| Br = 0 | Br = 1 | Any Br |
|---|---|---|
| 80.5 (79.8) | 89.2 (90.9) | 78.7 (78.5) |

# *Combination of H→γγ Searches*




Really the cross-section limits assuming $Br(H \to \gamma\gamma) = 1$, normalized to the SM x-sect

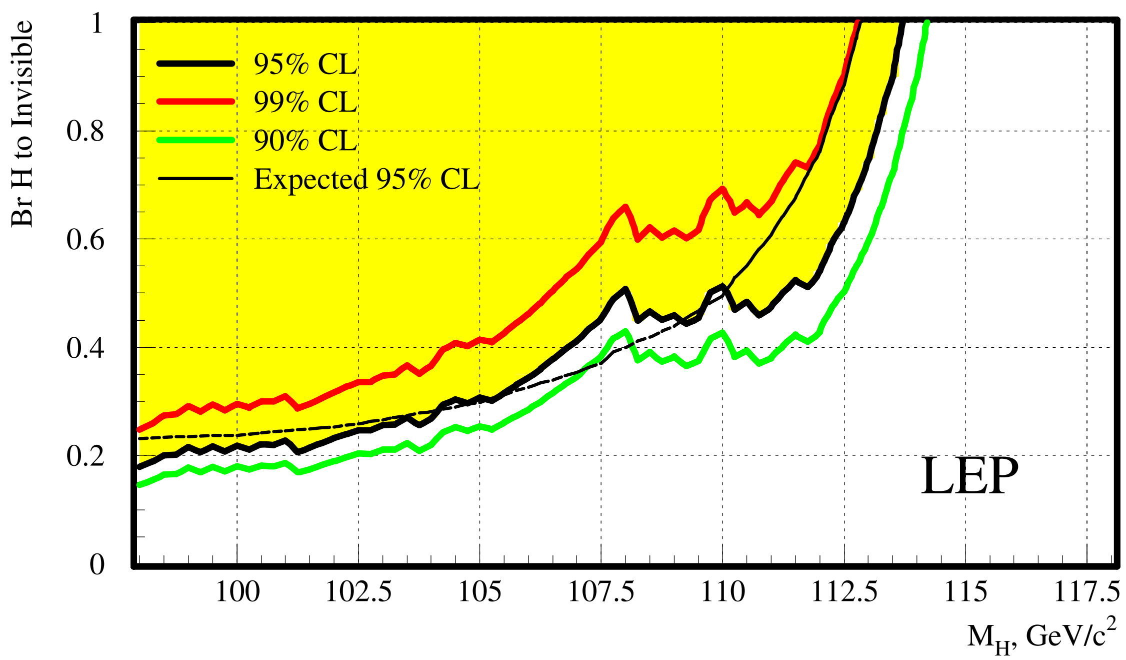
Can derive a mass limit assuming
$Br(H \to fermions) = 0$

**Observed limit: 107.7 GeV**
**Median expected: 105.8 GeV**

# *Searches for $H^0 \rightarrow$ Invisible Particles*

e.g., $h^0 \rightarrow \chi_1^0 \chi_1^0$ with $\chi_1^0 = \text{LSP}$

but no restrictions on the model.
Search: similar to the SM missing-energy channel, but the visible system has mass $M_Z$.



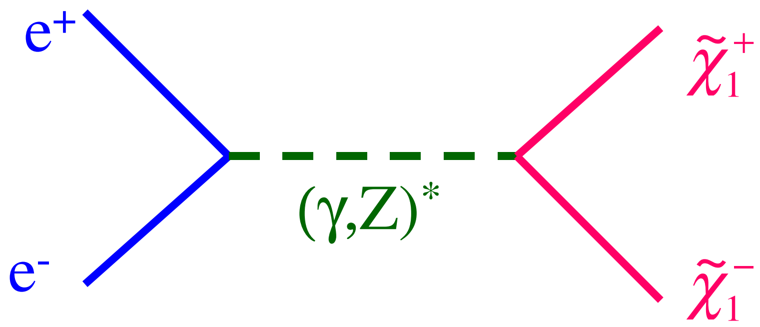

Assuming SM production x-section and 100% invisible decays, obtain the limits

**Observed Limit: 113.7 GeV**
**Median Expected: 112.8 GeV**

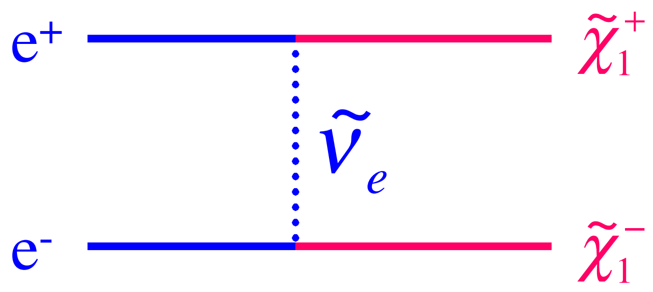
# *Chargino Search*

Assume: $\tilde{\chi}_1^+$ has a short lifetime, R-parity conserving decays, $\tilde{\chi}_1^0$ is the LSP

***Production:*** (similar to $W^+W^-$ CC03 diagrams)




**+**




Destructive interference!

Diagram important for small $m_0$

***Decays:***

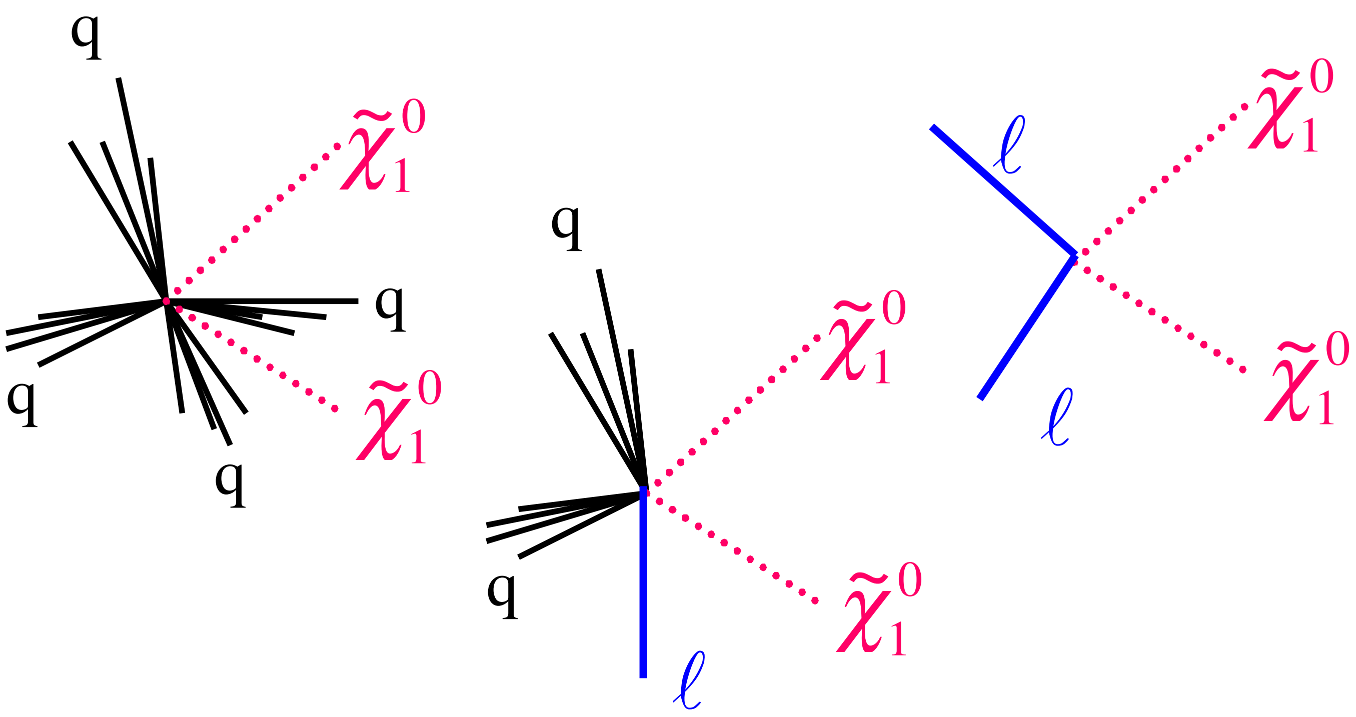
$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^+ \qquad \textit{or}$$

$$\tilde{\chi}_1^+ \rightarrow \tilde{\ell}^+ \nu_\ell, \qquad \tilde{\ell}^+ \rightarrow \tilde{\chi}_1^0 \ell^+$$

B.R.'s depend on slepton masses, $m_0$

# *Chargino Search Modes*

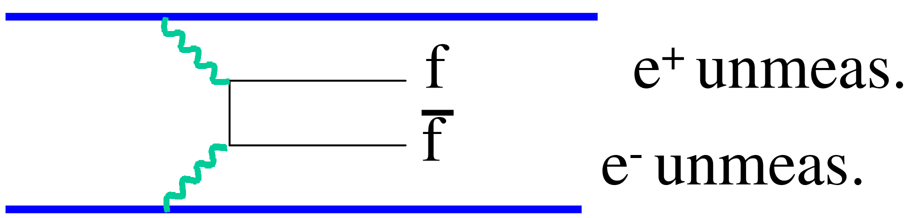
Same as $W^+W^-$ channels, but with missing energy




Kinematics depend strongly on

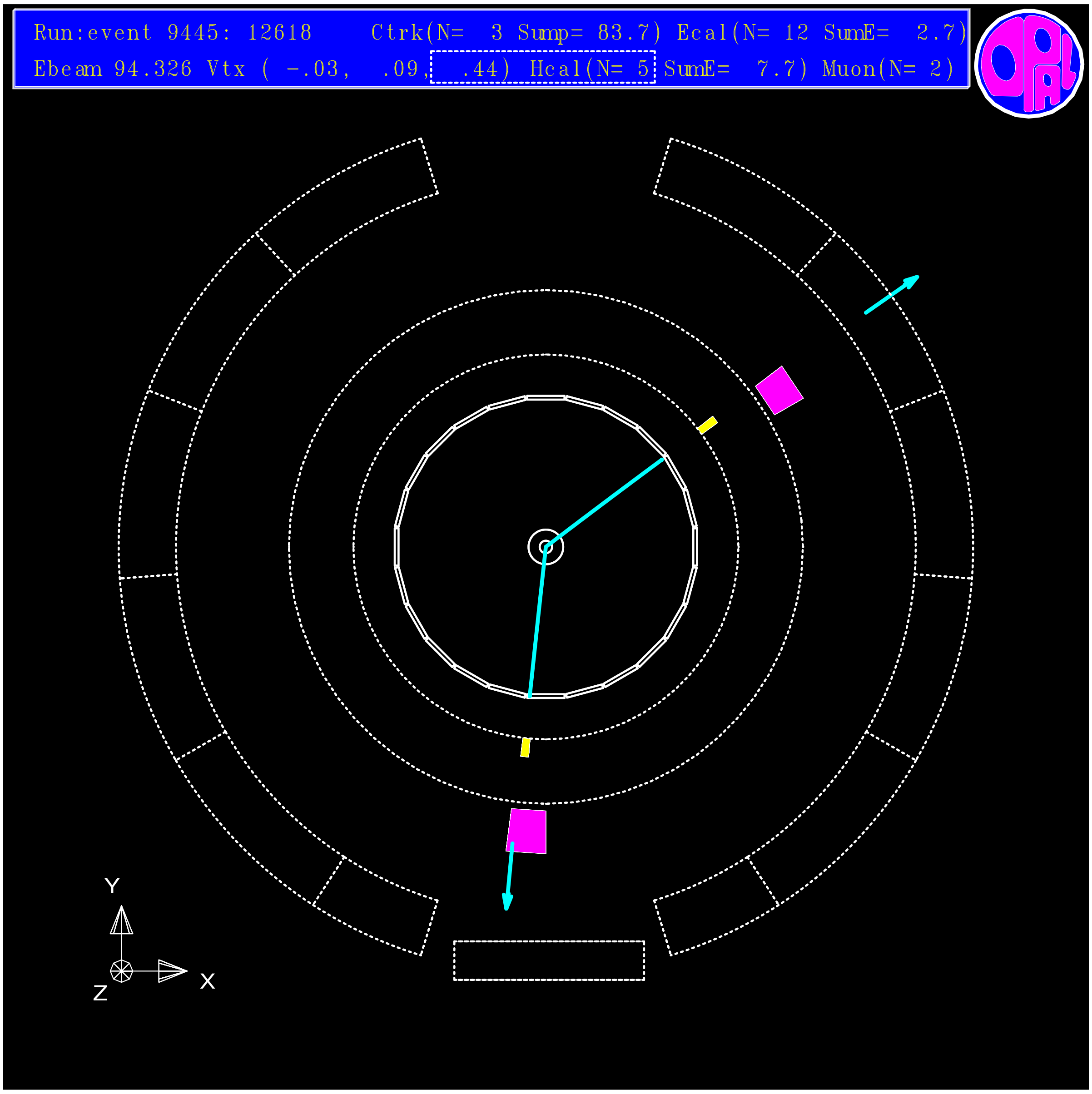
$$\Delta M = M_{\chi_1^+} - M_{\chi_1^0}$$

Low *ΔM:* Background dominated by untagged two-photon processes




High *ΔM:* Background dominated by $W^+W^-$ production.

# *An "Acoplanar Dilepton"*

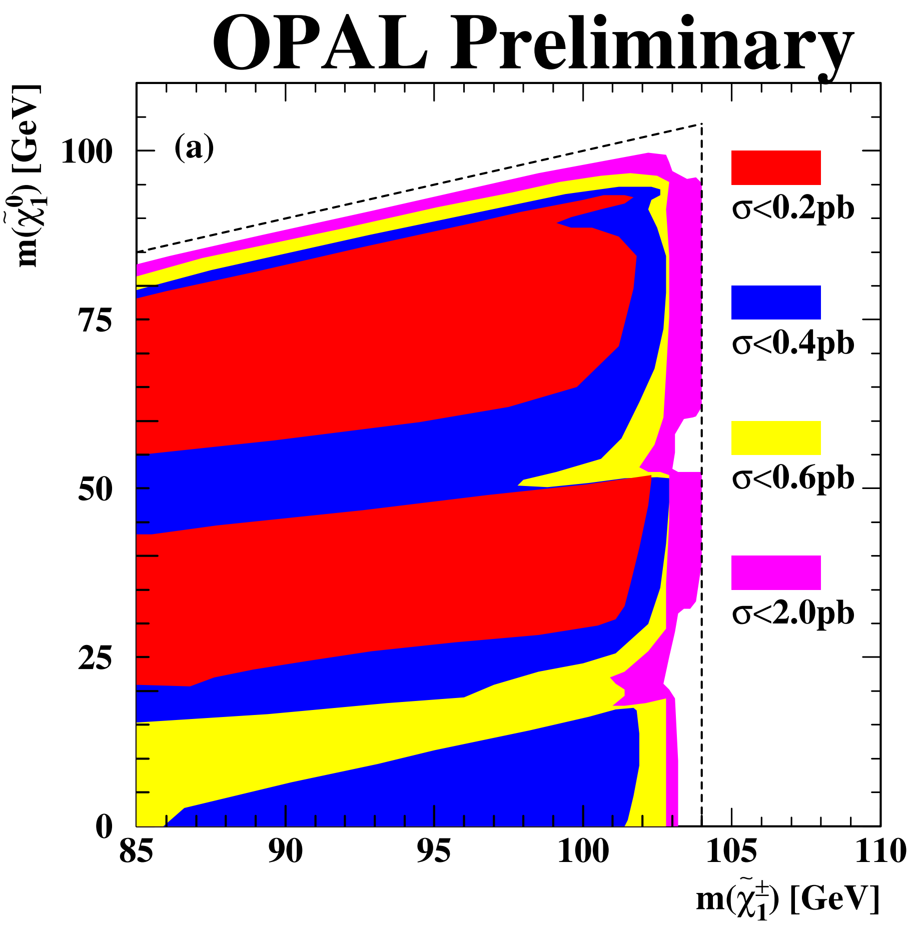



$\mu^+\mu^-$ with large missing $p_t$

SM interpretation:

$$W^+W^- \to \mu^+\nu_\mu\mu^-\overline{\nu}_\mu$$

# *Chargino Production Limits*



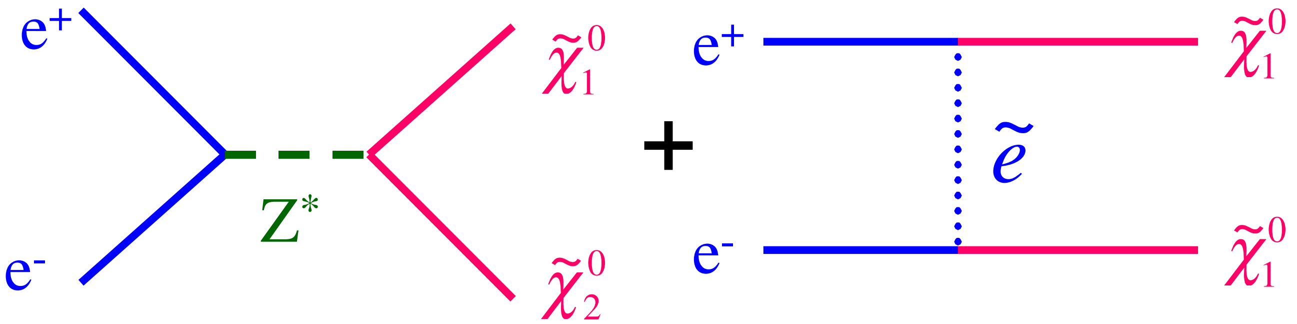

Plot does not assume CMSSM

Best sensitivity away from very low, very high ΔM

Extra data at 208 GeV makes a lot of difference! OPAL has an excess of 5 obs/0.74 bg for the ΔM~10 GeV search in the highest energy data, but it is not confirmed by the other experiments. Would like to keep looking!

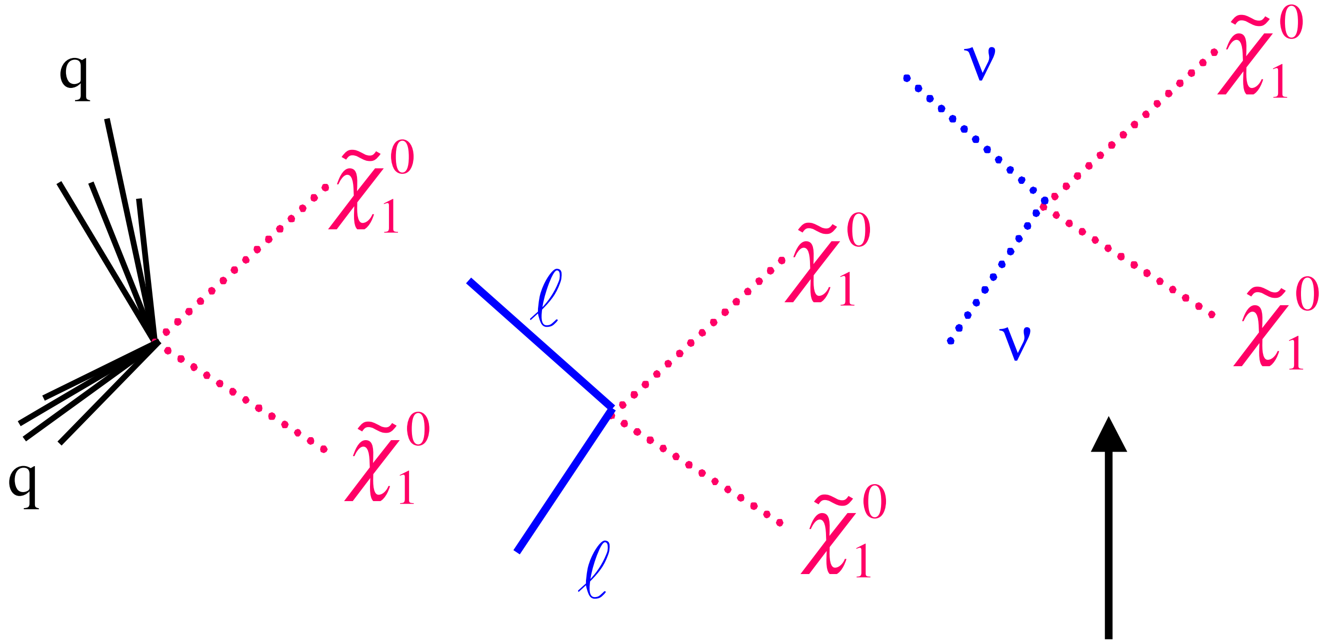
# *Neutralino Production and Decay*

- Still assume $\tilde{\chi}_1^0$ is the LSP
- Seach for associated production of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ in s-channel $Z^0$ exchange



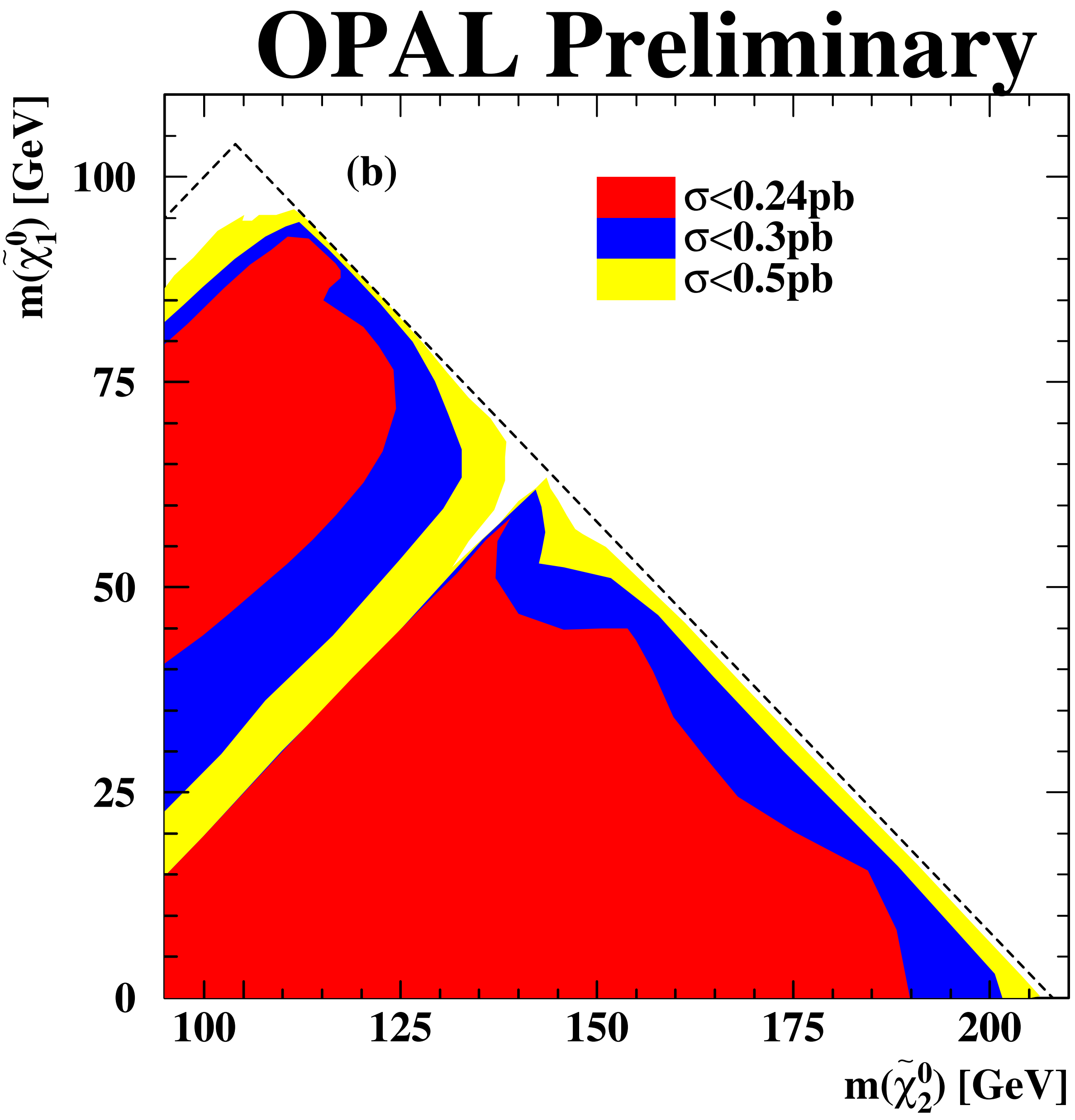

- Decays:

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^0$$




Challenging!

# *Neutralino Production Limits*

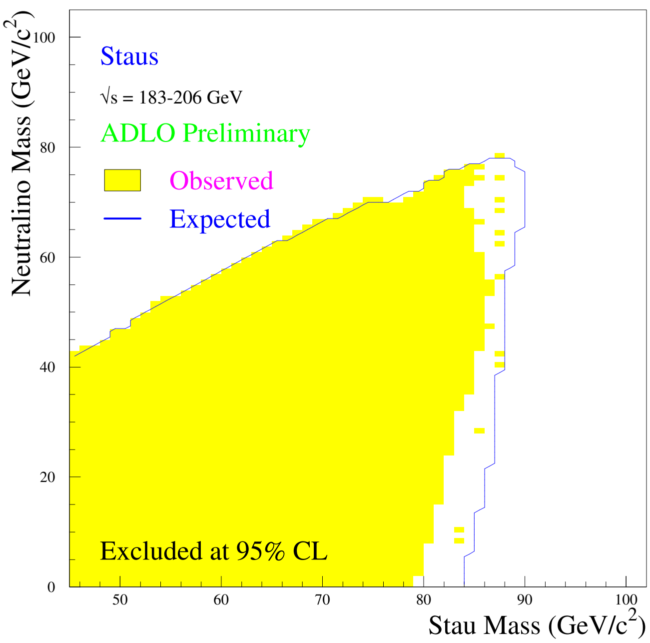


# *Slepton Searches*

$$e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^- \qquad \tilde{\ell}^+ \rightarrow \tilde{\chi}_1^0$$

$$\text{Experimental signature:} \quad \ell^+\ell^- + \not{E}_T$$

ADLO Y2K data (Osaka)




Limits for Δm > 15 GeV

$$m_{\tilde{e}} > 98 \text{ GeV}$$

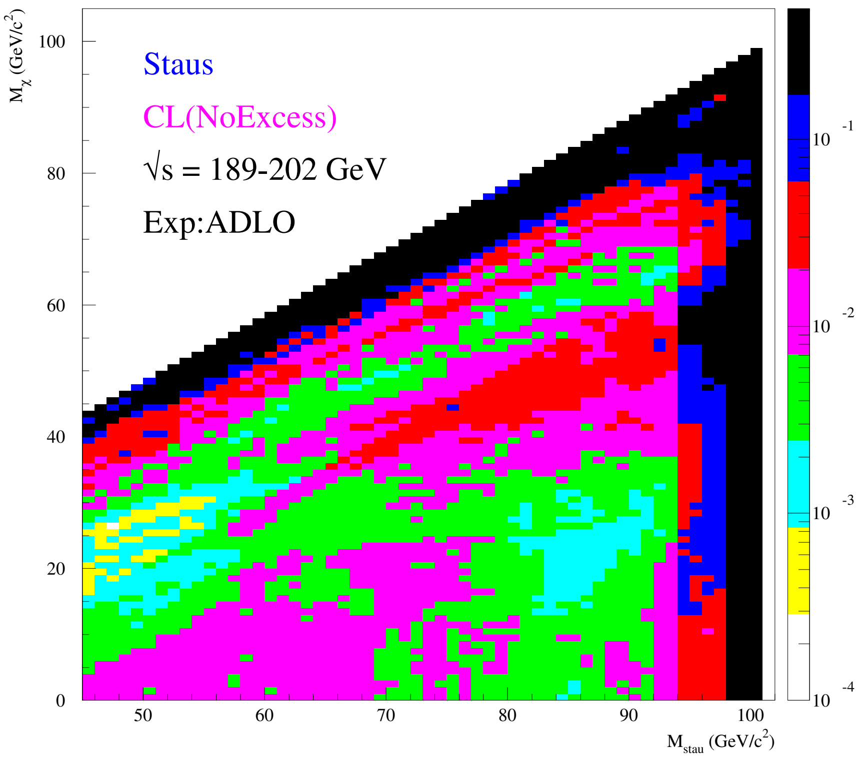
$$m_{\tilde{\mu}} > 94 \text{ GeV}$$

$$m_{\tilde{\tau}} > 79 \text{ GeV}$$

assuming tanβ=1.5,
μ=-200 GeV,
$m_{\tilde{\ell}_L} >> m_{\tilde{\ell}_R}$

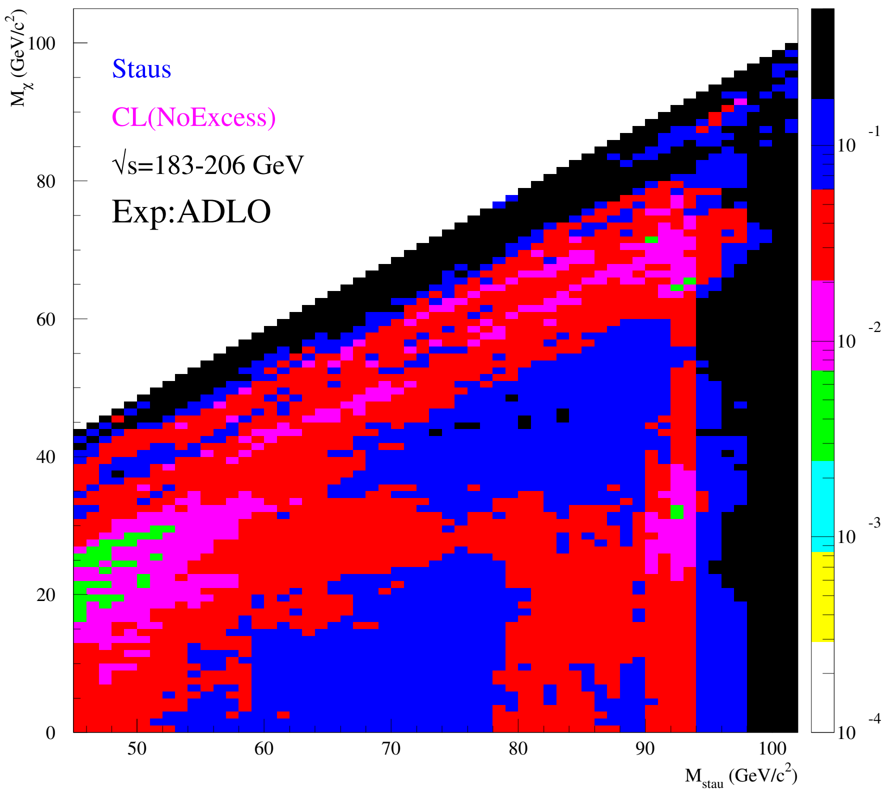
"Stau excess" in 1999 data not confirmed in 2000 data.

# *Stau $CL_b$ 1998+1999 and also 2000*




**1998 and 1999 data**

0.1% CL "no signal"




1997-
2000 data
(Osaka result)

CL now fine.

# *Check of Light Sbottom Searches*

**July 20 LEPC**: Very very very preliminary request from ALEPH to DLO to check a fresh analysis.

b-jets with leptons at LEP2:
56 obs/33.6 expected in 580 $pb^{-1}$
or 39 obs/23.0 expected in 411 $pb^{-1}$ check analysis.

Since then, OPAL and DELPHI have sought the same signal.

OPAL sees a deficit: 15/20.5, somewhat lower efficiency: 15% (vs. ALEPH ~25%)

DELPHI also does not see an excess.

ALEPH updated with new study with more appropriate lepton ID for leptons in jets, finds no excess for September 5 LEPC
24 obs/20 expected in 411 $pb^{-1}$

**Rumors travel too quickly!**

and leptons in jets are hard to identify and model

# *Model-Independent Check of the Photon Recoil Distribution*

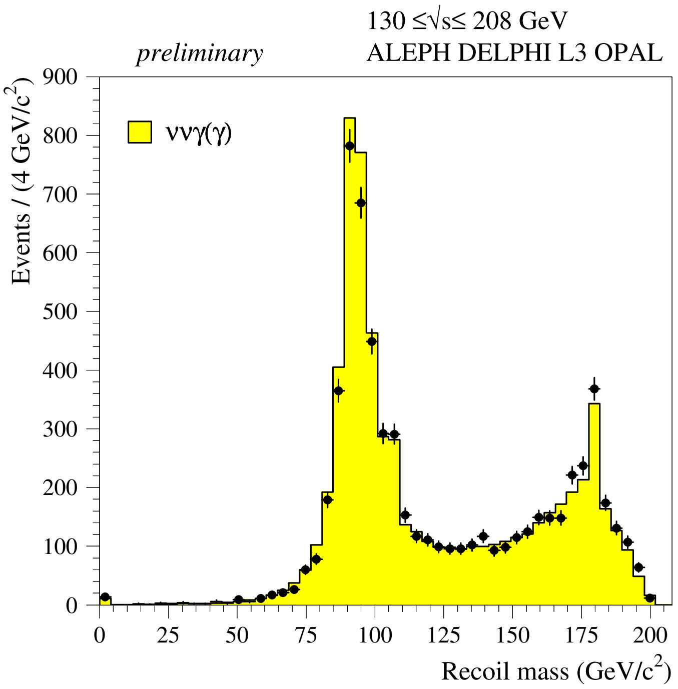
Sensitive to a variety of new signals

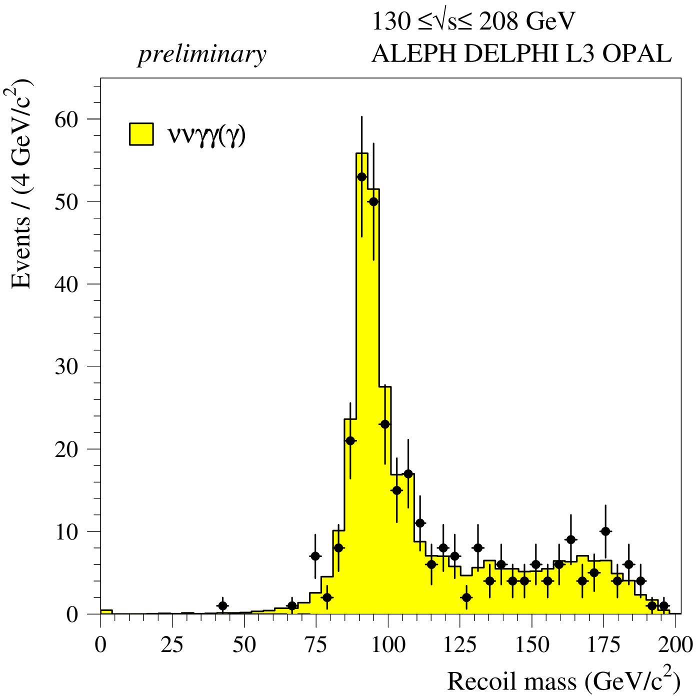
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ possible, and can be dominant in the MSSM, depending on params

$\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$ With GMSB, the Gravitino can be LSP

$\nu^* \rightarrow \nu\gamma$ Radiatively decaying excited neutrinos

Anything invisible + ISR.



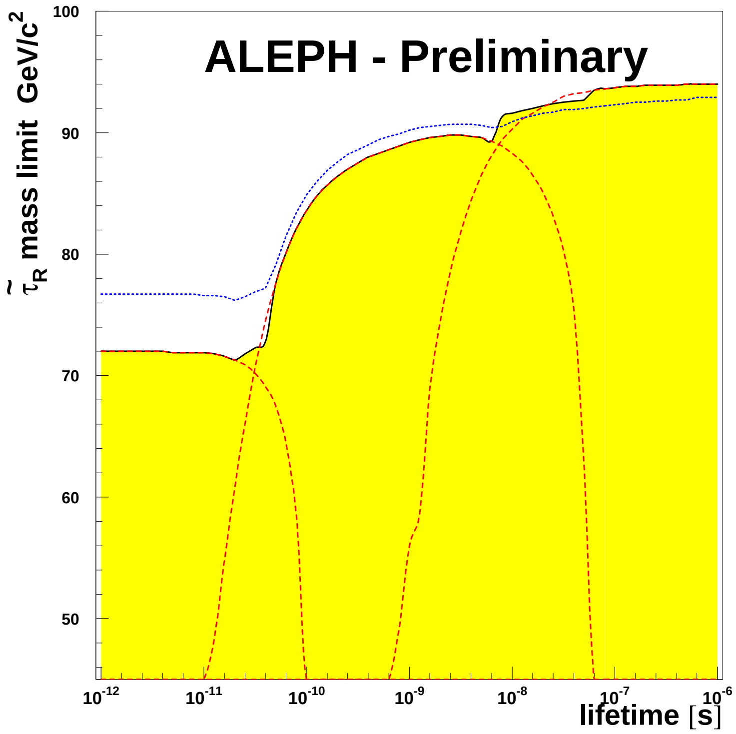



# *Interesting Signatures of GMSB*

Gravitino LSP -- Search for the NLSP

NLSP lifetime is arbitrary!

- Prompt decays -- reinterpret standard SUSY searches
- Delayed decays -- interesting class of new analyses:
    - Tracks with large impact parameter
    - Kinked tracks
    - non-pointing photons
    - Anomalous ionization of stable particles




Combination of searches $\rightarrow$ NLSP mass limits

$$m_{\tilde{\chi}_1^0} > 95 \text{ GeV}$$

$$m_{\tilde{\tau}} > 75 \text{ GeV}$$

# *LEP Extension Plans*

- **Uncertain!**

- September 16 to Oct 1 is already an extension over the original LEP plan. Granted shortly after the July 20 LEPC meeting. Dismantling scheduled to start Oct 1.

- Four experiments and the LEP Higgs Working Group jointly request an extension to double the integrated luminosity at 206.6 GeV, and review the situation then.

- Accelerator division says the request can be fulfilled by the beginning of November (we already have some of this luminosity)

- LHC Schedule would be affected by a LEP extension as requested.
  Delayed contracts→increased costs

- **Meeting with the CERN research board on 14 September to decide.**