Searches at LEP

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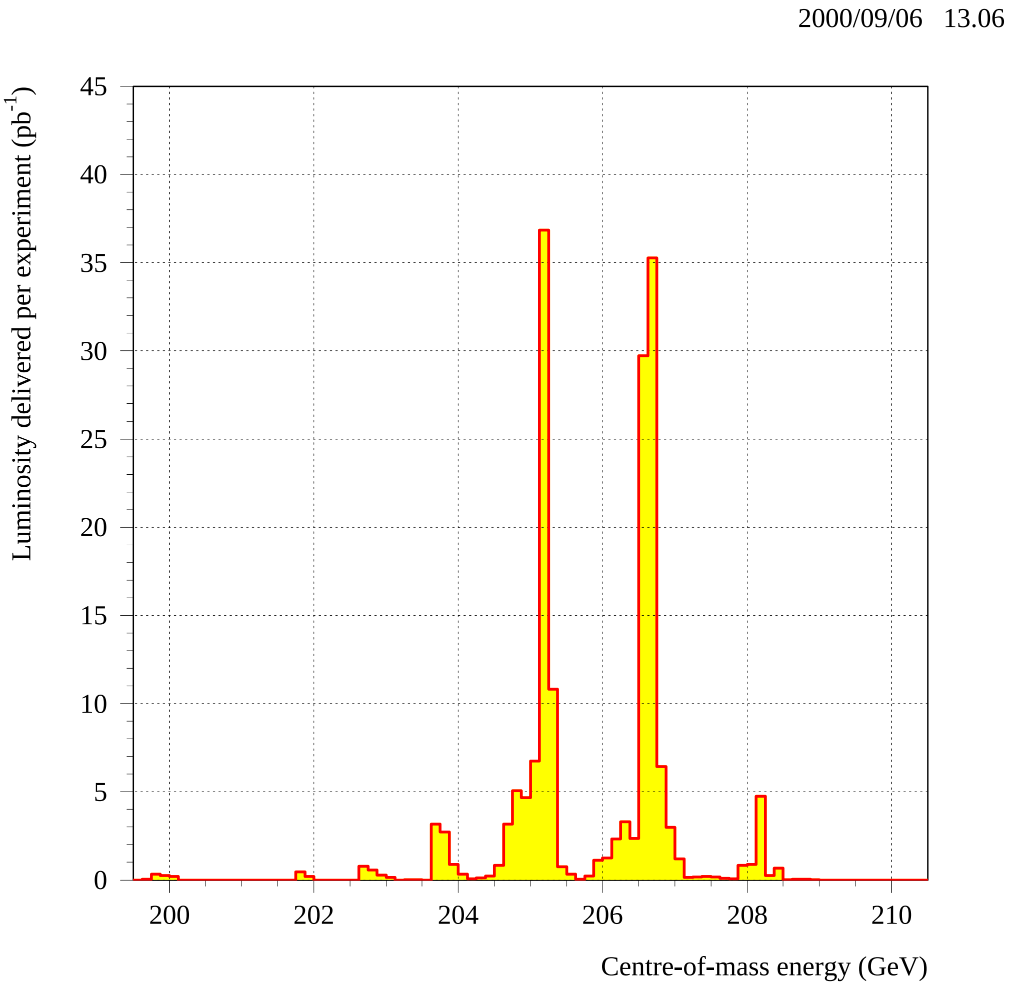
With many thanks to the ALEPH, DELPHI, L3, and OPAL collaborations, and the Accelerator Divisions at CERN

- Introduction and Context
- Higgs Searches
  - SM, MSSM, $H^{\pm}$, $H\rightarrow$invisible, $H\rightarrow\gamma\gamma$
- 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

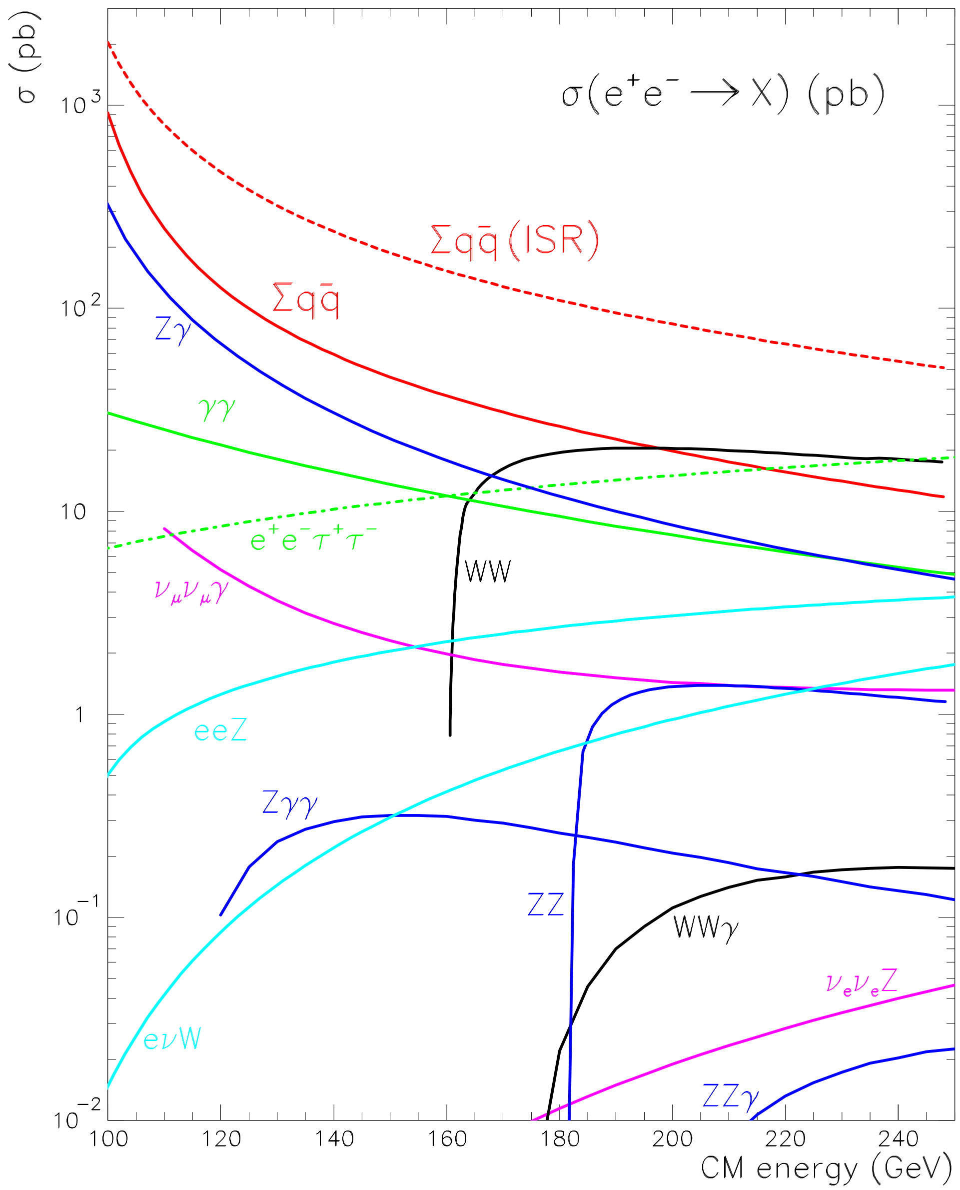
Bending-Field Spreading with Correctors

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. σ~20 pb (W^+W^-), 1 pb (Z^0Z^0)
- Two-photon processes have *large* cross-sections -- more important for SUSY searches with small Δm (to be explained later)

The SUSY Spectrum

SM Particles +Higgs $R_P = 1$	SUSY Partners $R_P = -1$
★ γ, 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, μ, τ	★ sleptons $\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$
ν_e ν_μ ν_τ	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

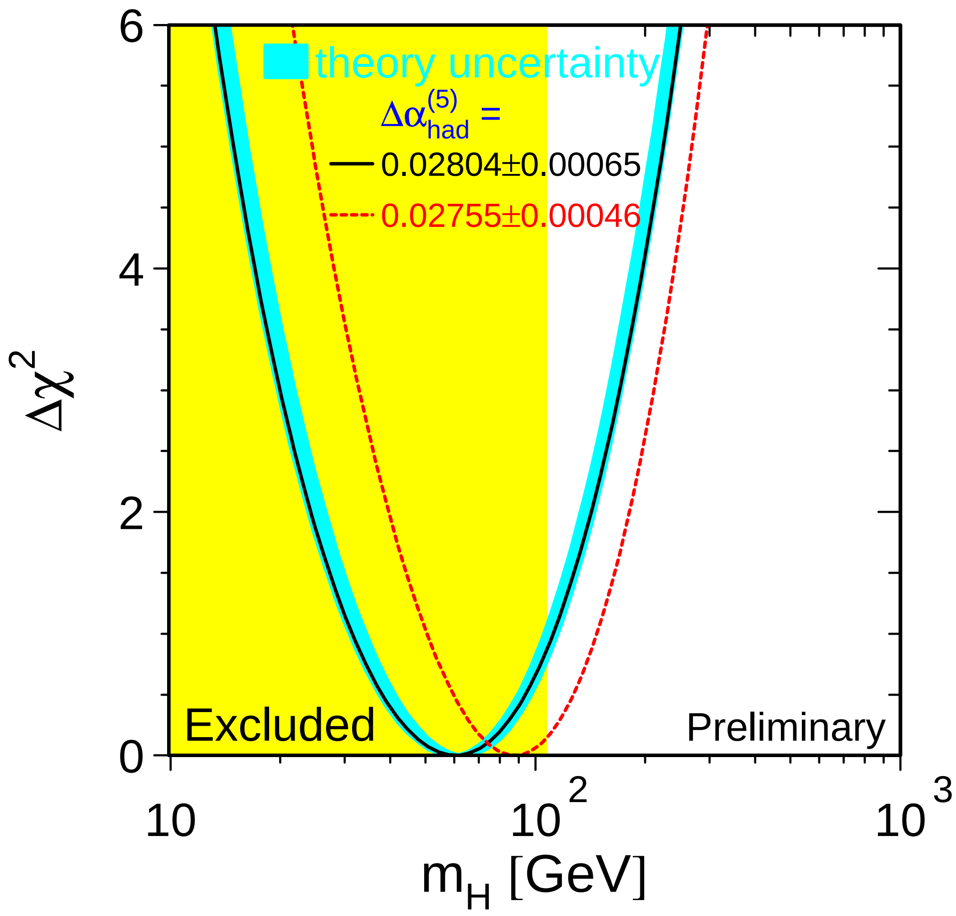
Use MC or analytic techniques to find the PDF of log$L$, given the results of all bins. --
Easy to combine many searches for the same particle -- different analyses, ECM, and experiments all can be combined for more search power.

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

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

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

Electroweak Fit Constraint on m_H



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

  Current central value:

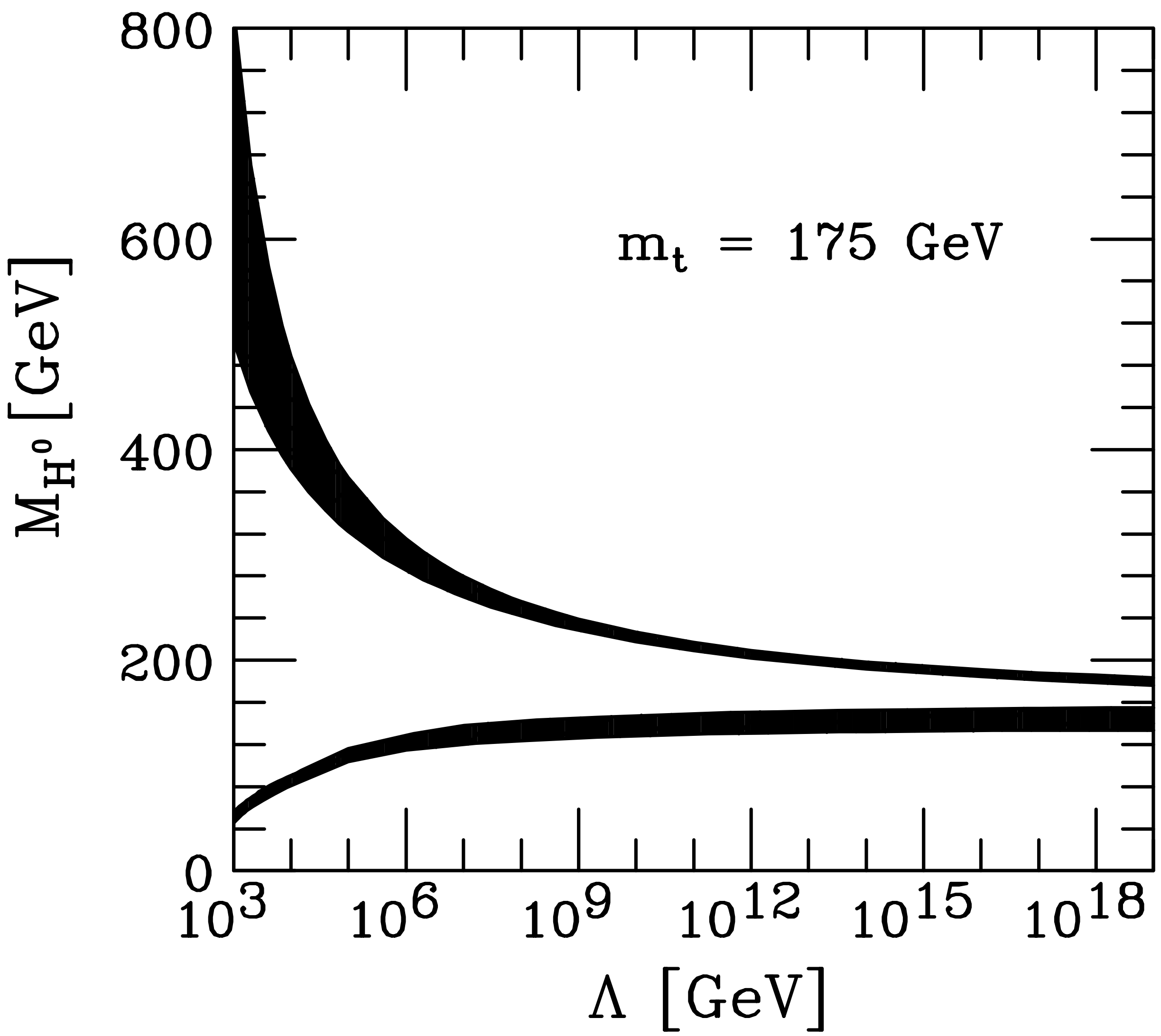
$$m_H = 62^{+53}_{-39}\ \text{GeV}$$

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

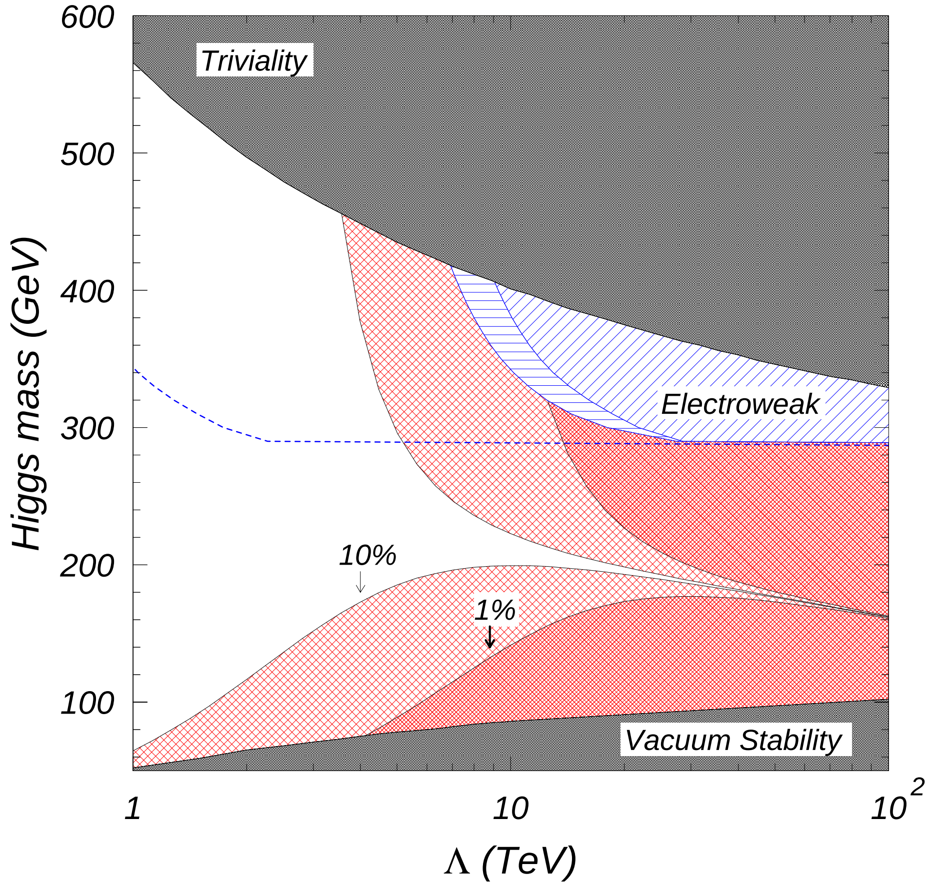
Upper Higgs mass bound -- Landau pole
Lower Higgs mass bound -- vacuum stability

Fine-Tuned Radiative Corrections in the SM

Kolda and Murayama, hep-ph/0003170

One-loop correction to μ^2 is proportional to Λ^2, which destabilizes the weak scale, unless m_h is exquisitely chosen.

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

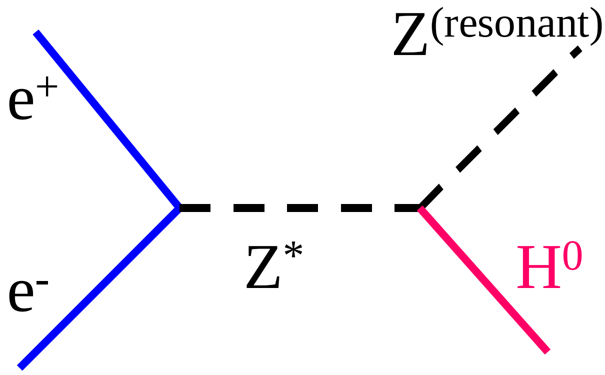


Provocative, but experimentalists don't believe pretty theories until the particles show up.

Standard Model Higgs Production

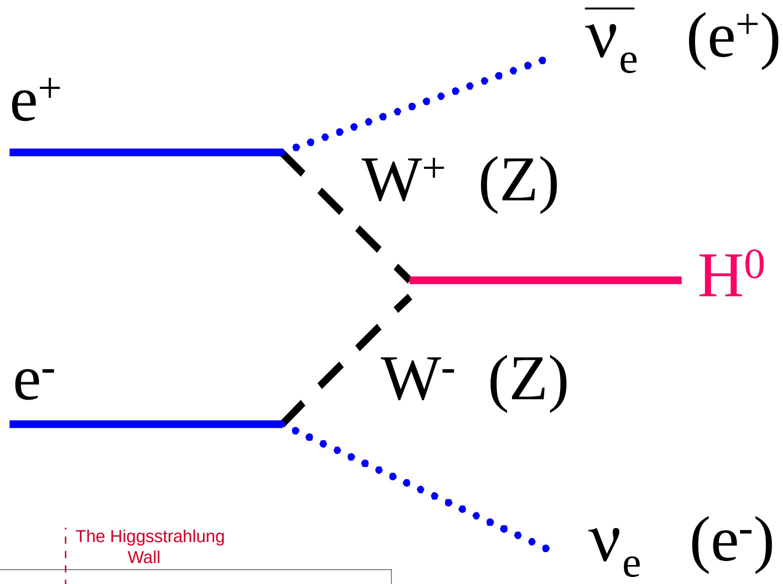
"Higgs-Strahlung"
(BJ process)

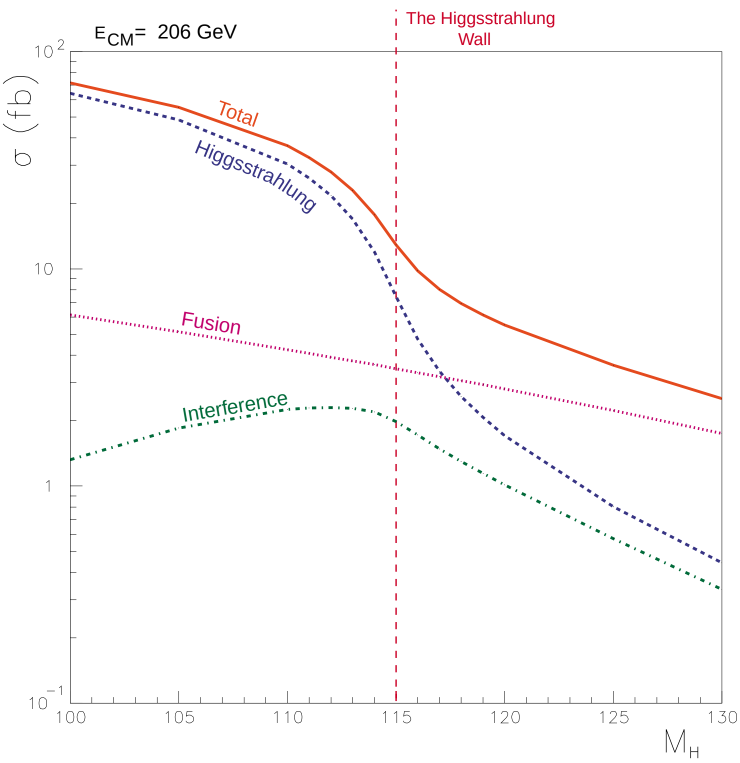
Has a kinematic "cutoff" at $\sqrt{s} - m_Z$



"Fusion"

"No" kinematic cutoff, but low cross-section

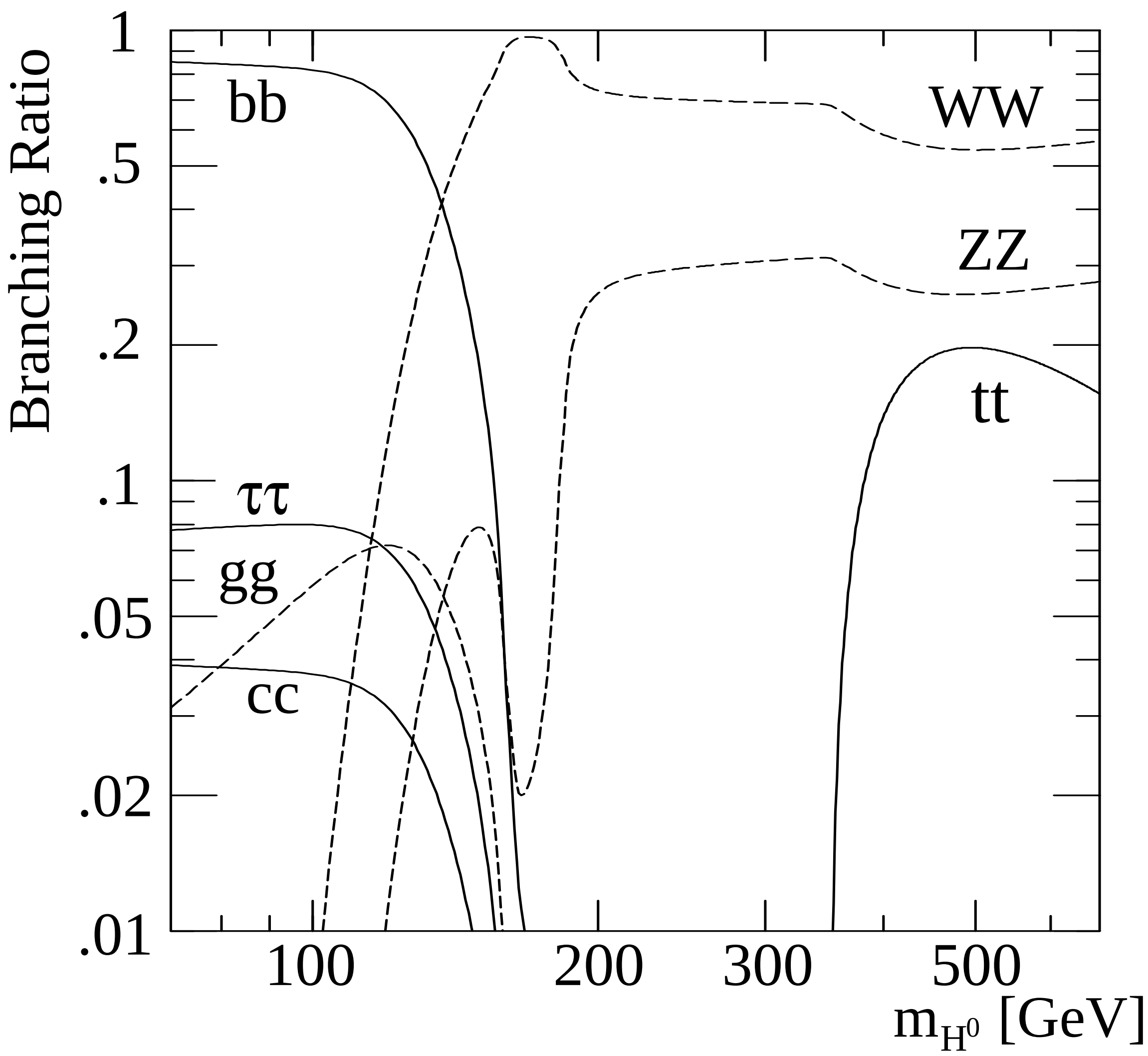




Note: only $H\nu\nu$ x-sect shown.

Multiply HZ by ~5 to get total.

Standard Model Higgs Decays



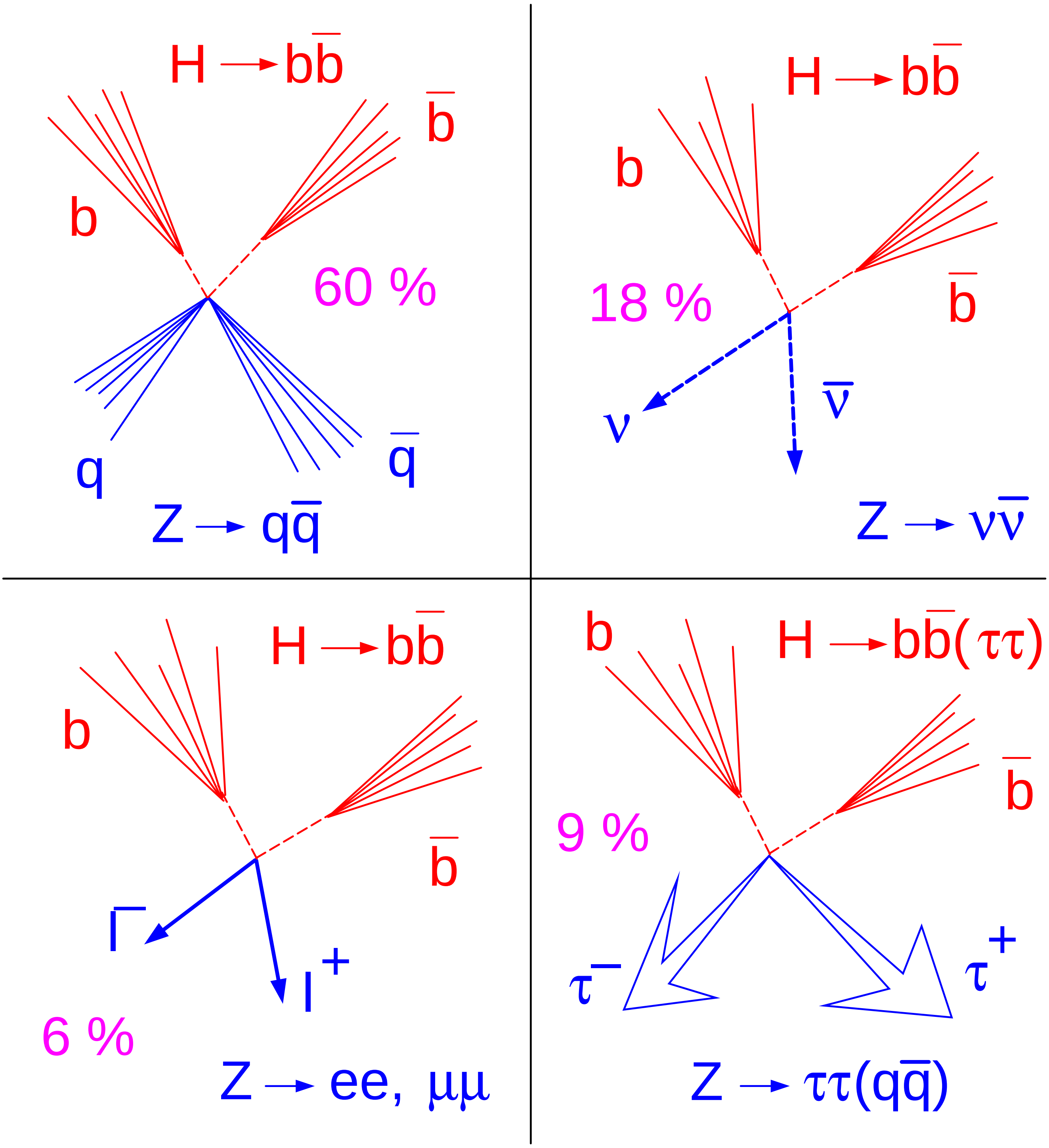
SM Higgs Decay, at 110 GeV < m_H <115 GEV

- 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.

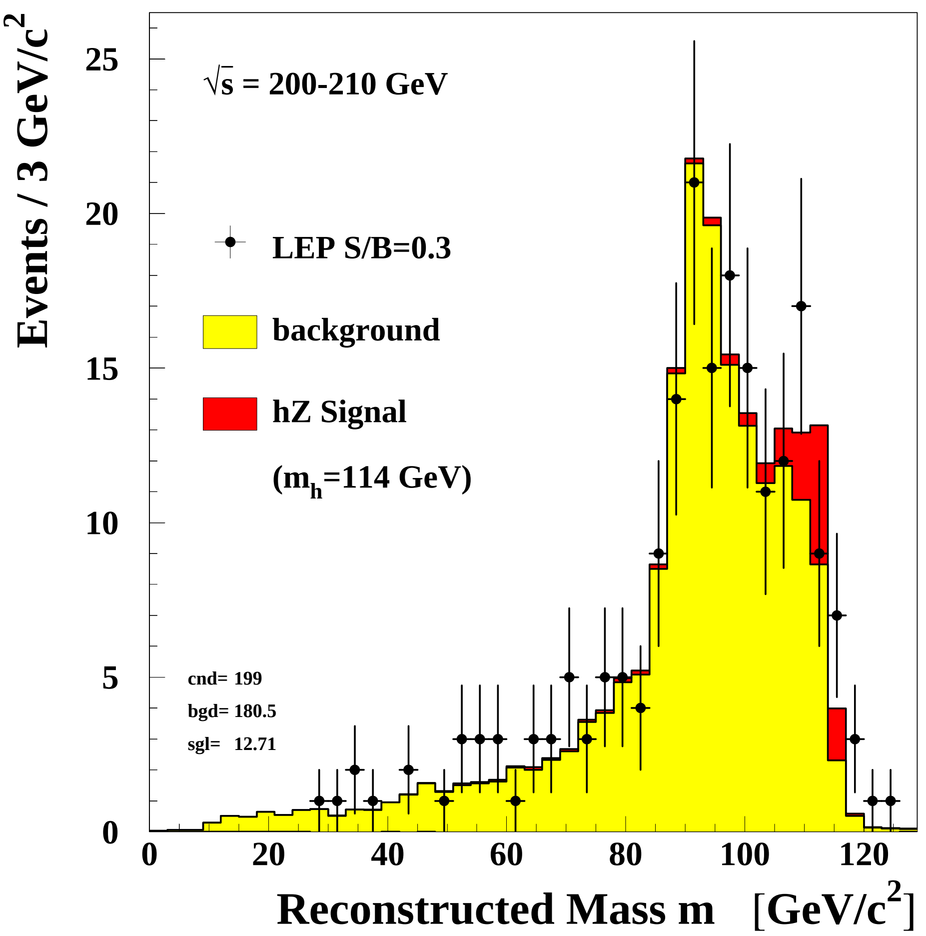


Exchanging LEP Higgs Results for Combination

- 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!**

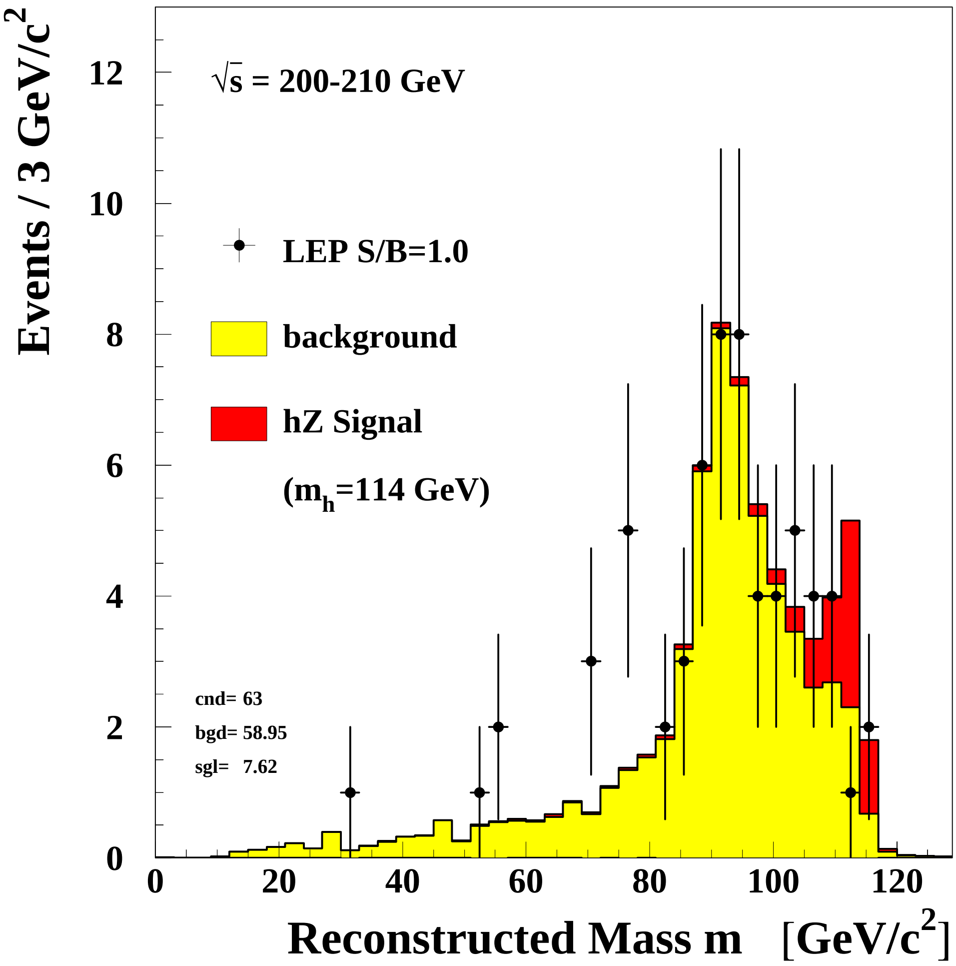
Distributions of the Reconstructed m_H



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

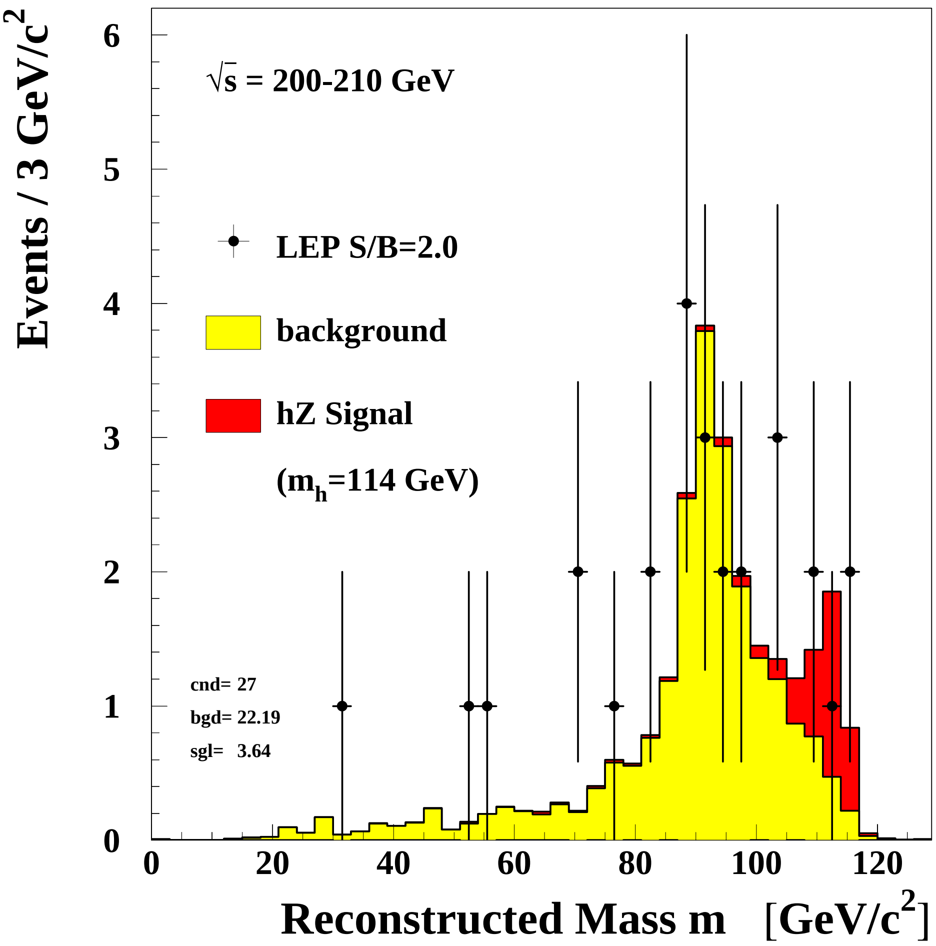


Tighter Cuts: s/b=1.0 for $m_{h,rec}$>109 GeV

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**

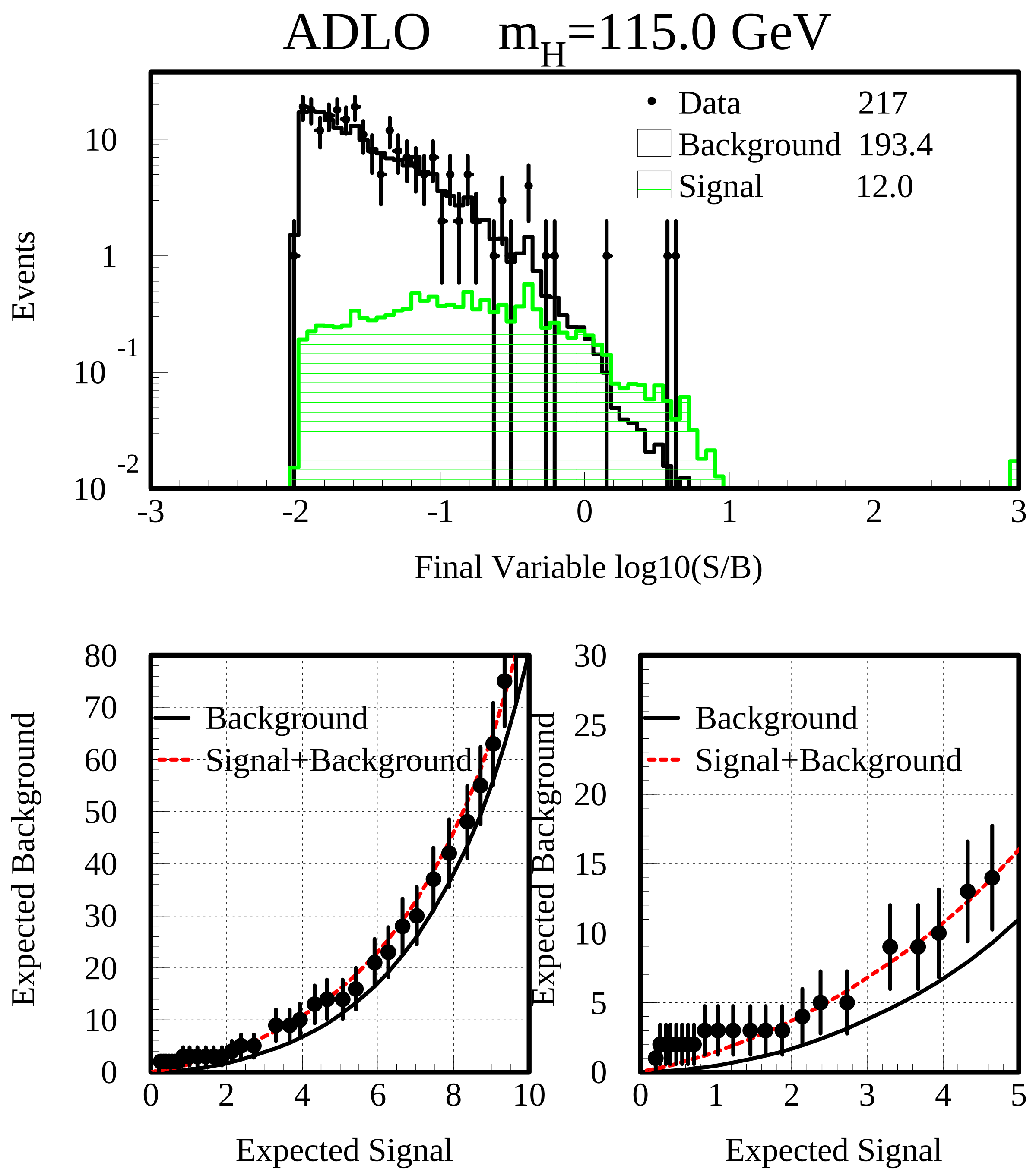
Distributions of the Reconstructed m_H



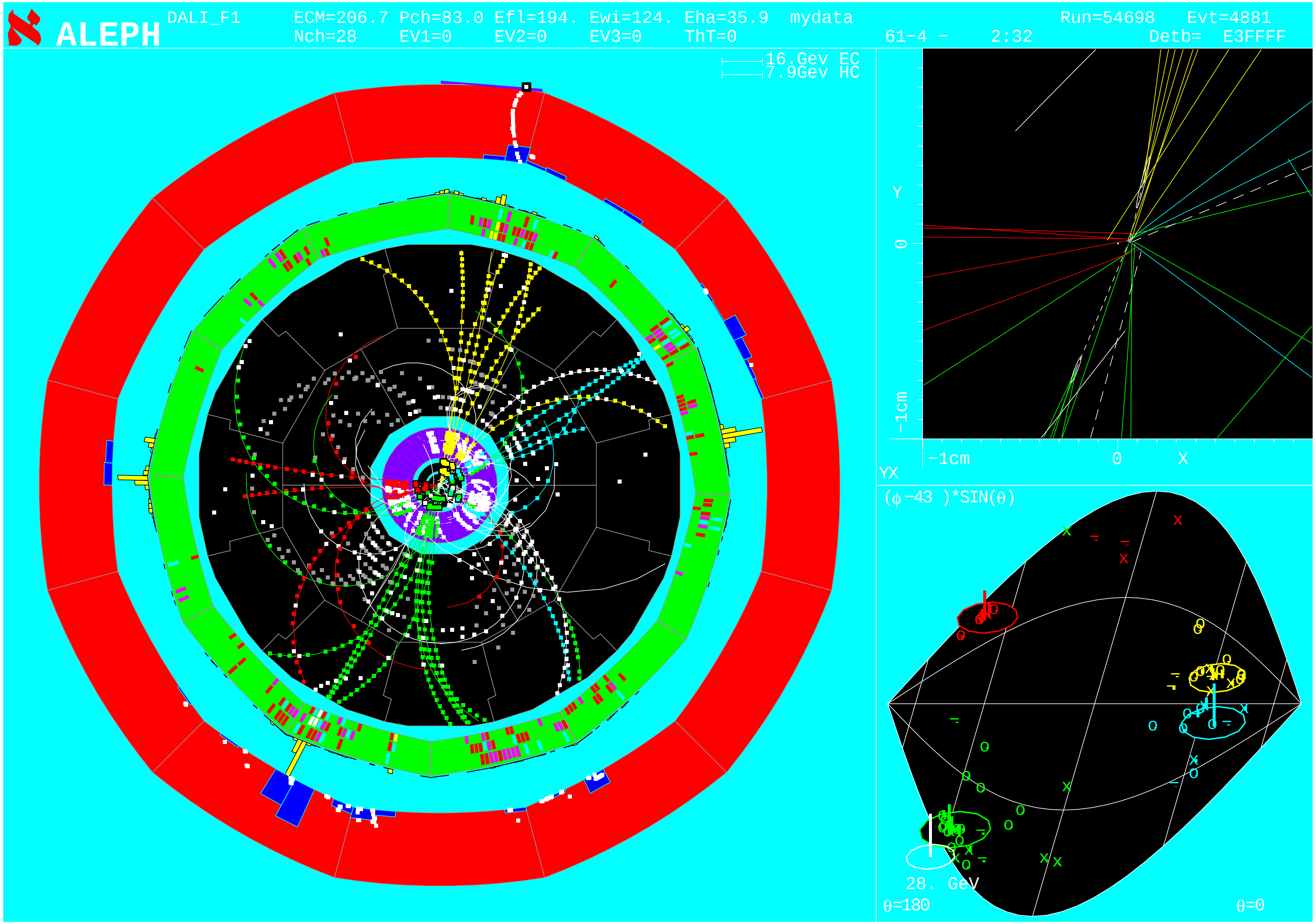
Very Tight Cuts: s/b=2.0 for $m_{h,rec}$>109 GeV
Signal model: m_h=114 GeV

	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

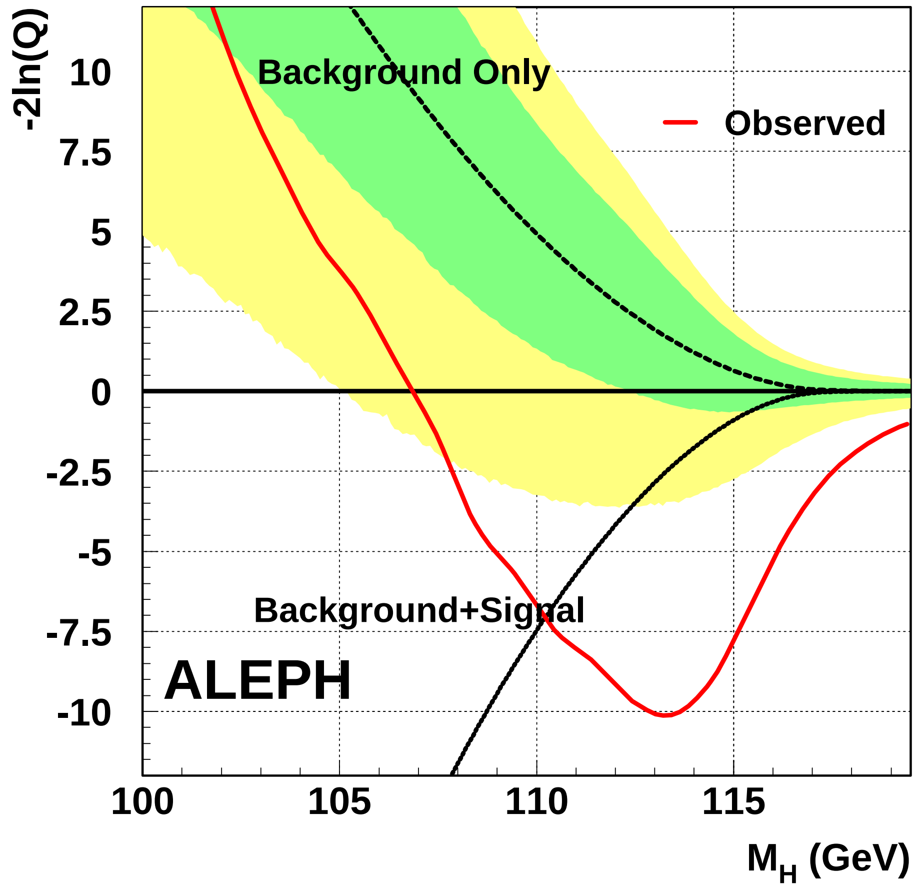


Three most significant candidates -- ALEPH four-jet channel taken at the highest ECM's. Two fairly significant DELPHI four-jet events too.



An ALEPH Four-Jet Candidate

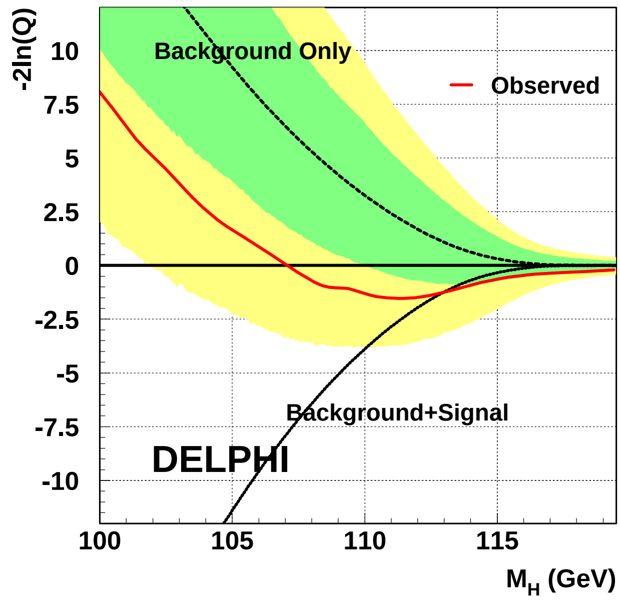
Excess is mostly in the ALEPH 4-Jet Channel



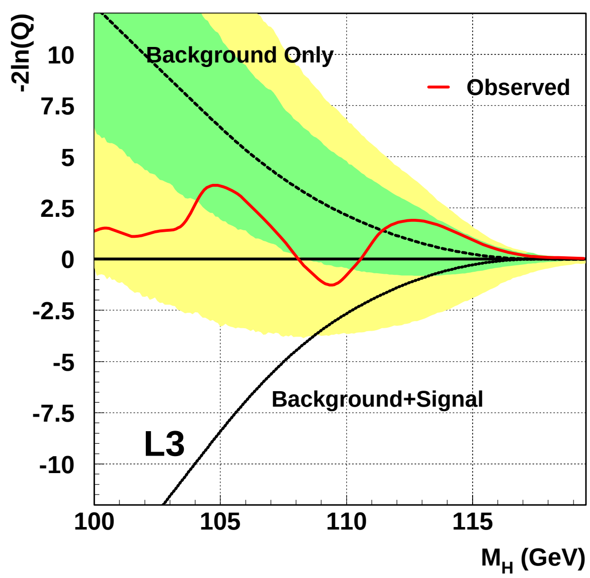
Systematic checks done:

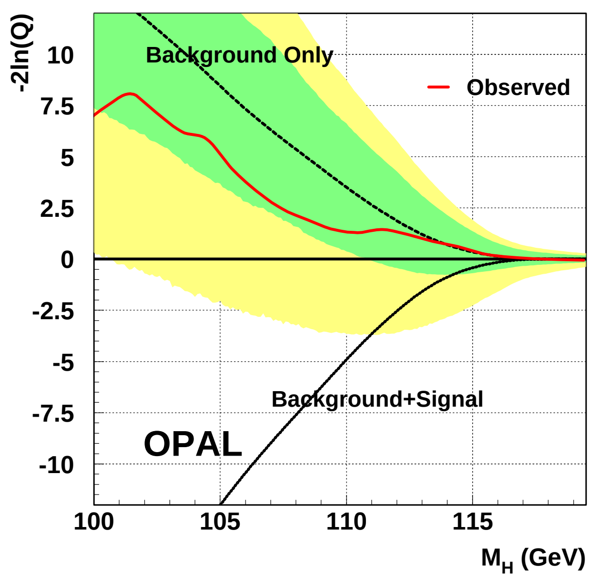
- Cut-based vs. NN analysis
- Test of m_{rec} bias towards kinematic endpoint (no effect seen at lower E_{CM})
- B-tag modeled well, NN modeled well.
- Excess goes away when one cuts out events with a pairing consistent with Z^0Z^0 or W^+W^-, but this does not separate signal from background.

Also a small excess in the DELPHI Four-Jet Channel

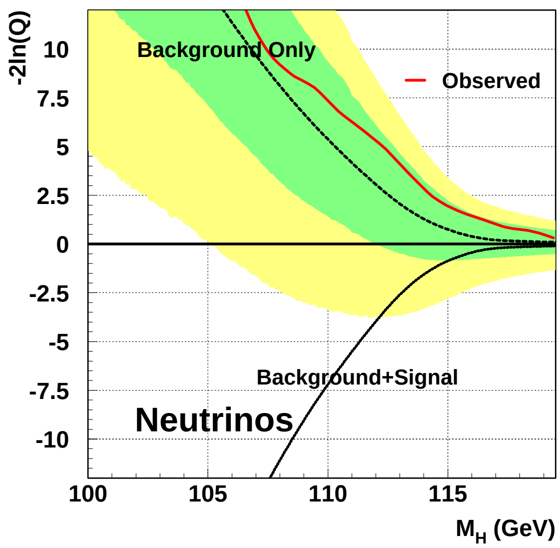


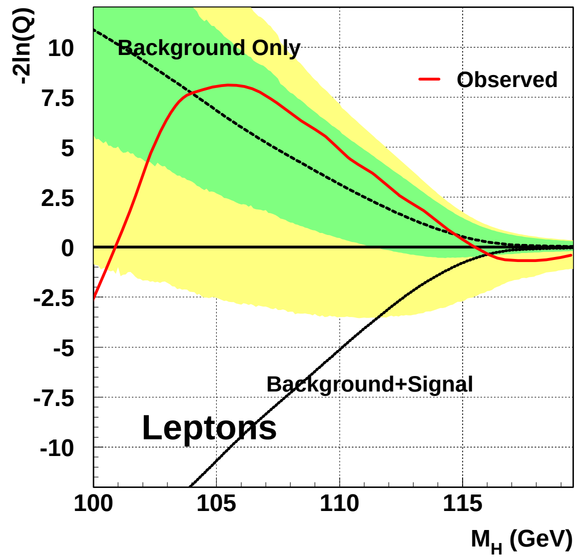
But not in L3 or OPAL's four-jet channels

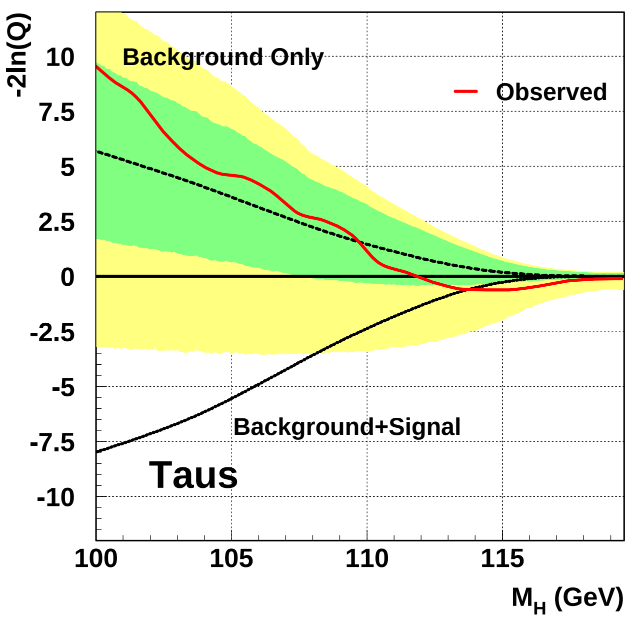


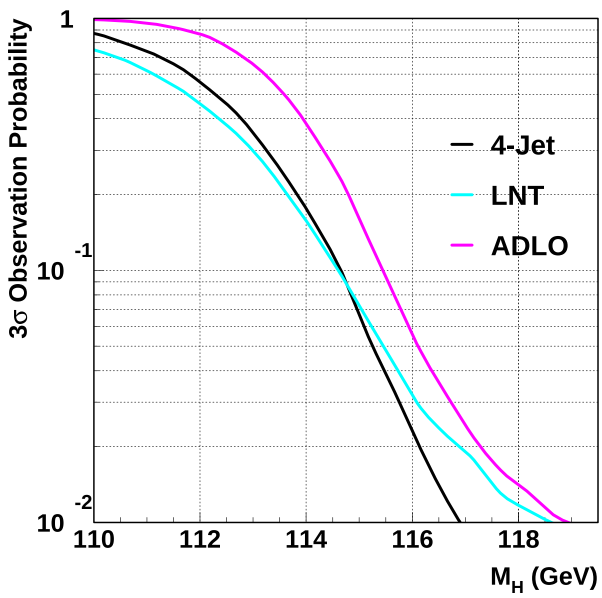


Missing-Energy, Lepton, and Tau Channels





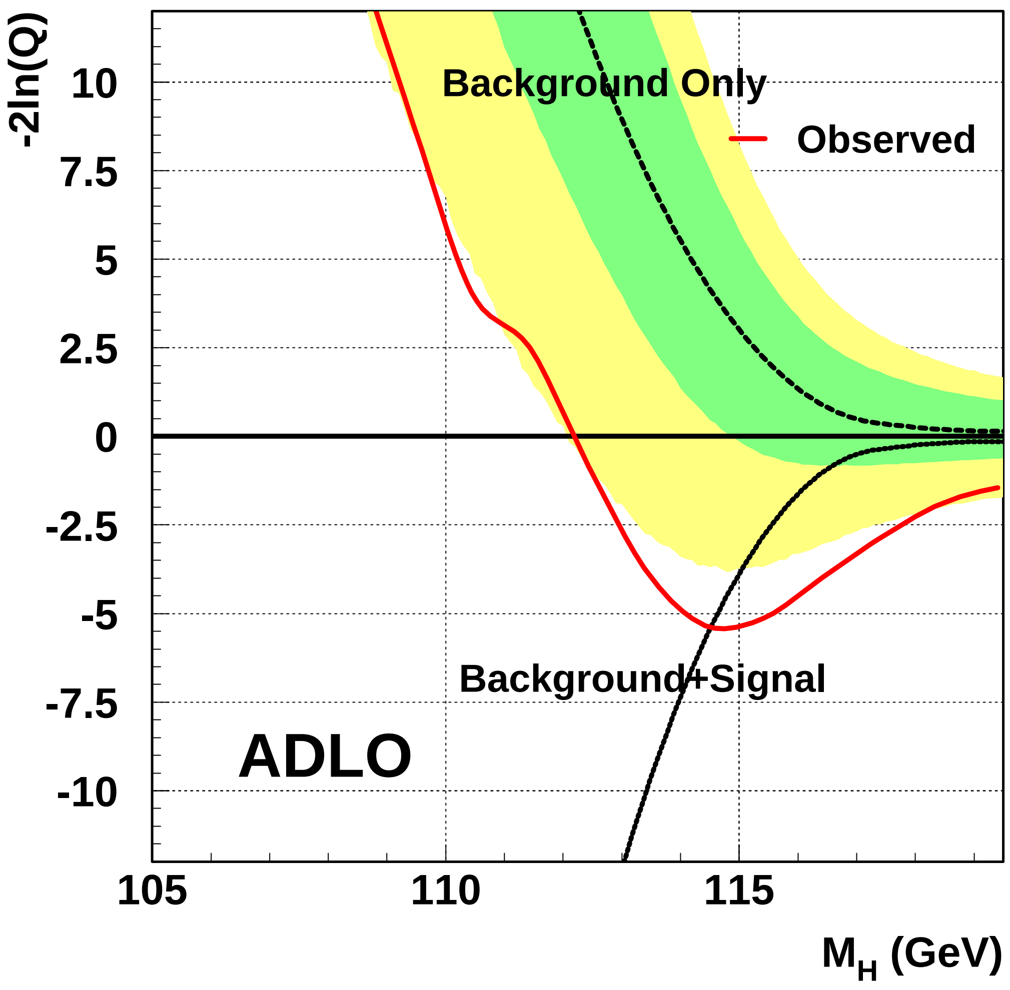




Combined Missing-Energy, Lepton, and Tau channels fairly powerful!

The Combined Likelihood Ratio

All the information that's available!

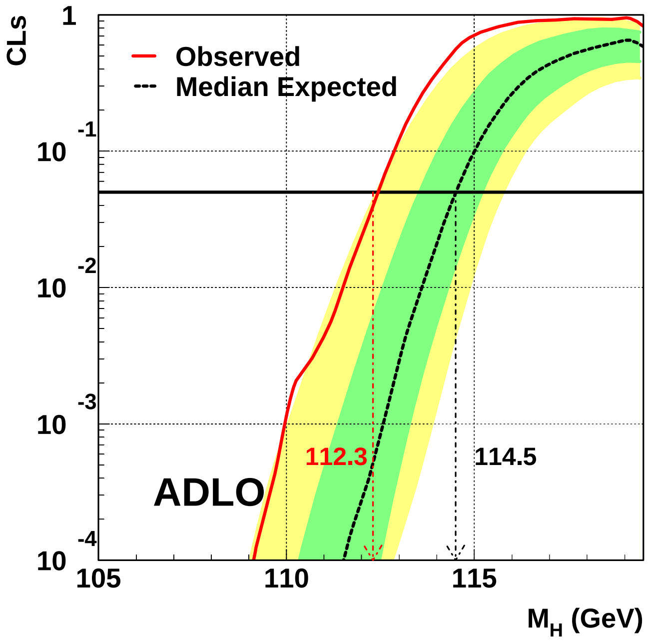


Higgs boson of mass 114 GeV preferred over the background hypothesis by 2.6σ

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

Confidence Levels CL_s and $1\text{-}CL_b$

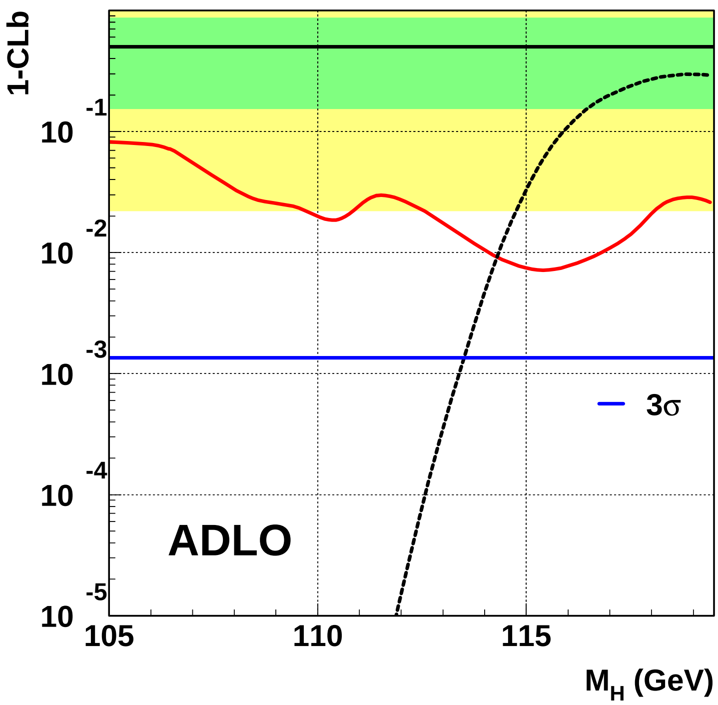
For the combination of all Higgs search results



Exclude up to 112.3 GeV

Median Expectation: 114.5 GeV

DLO only: 114.2 obs
113.8 exp.



$1\text{-}CL_b$ 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

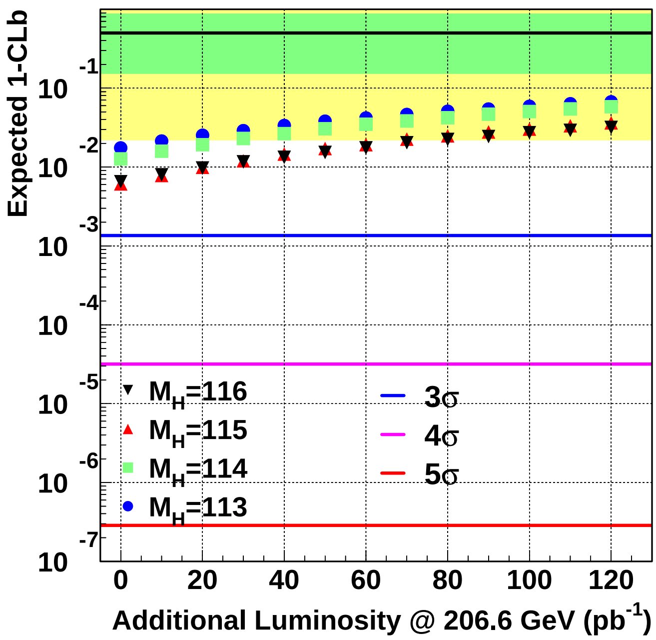
(*) Small unexcluded region below 100.7 GeV

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

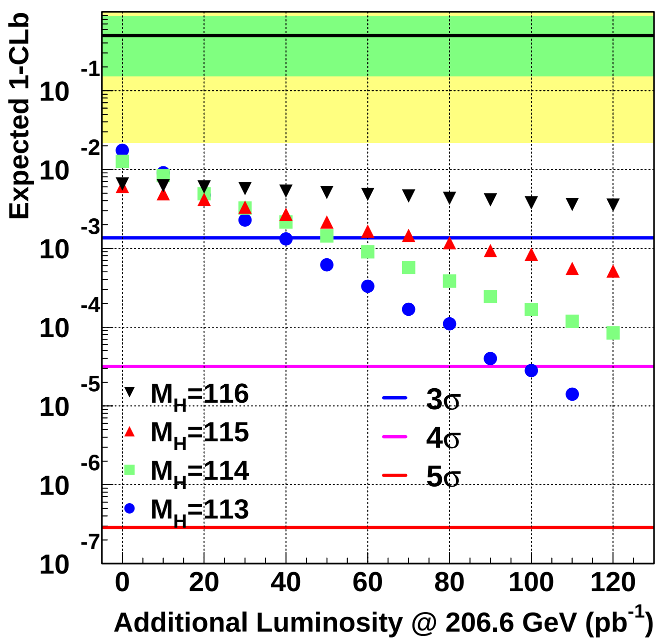
LEP Extension Scenarios

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

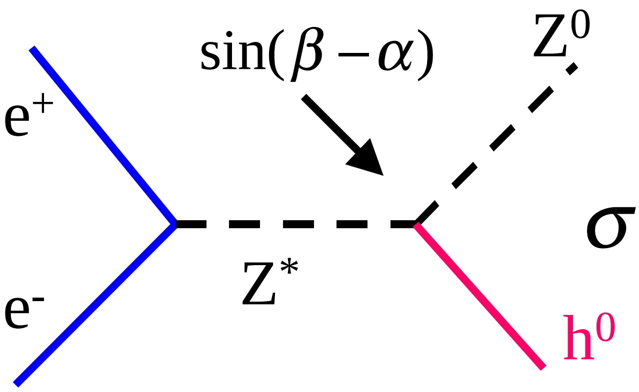


The Neutral Higgses of the MSSM

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

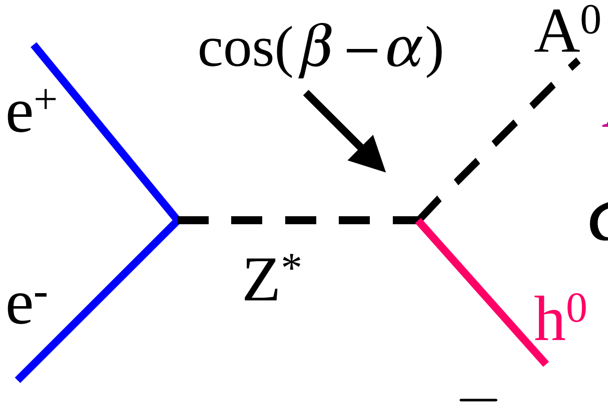
$$m_{h^0} < \sim 135 \text{ GeV}$$



Higgs-strahlung

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

And fusion processes too!



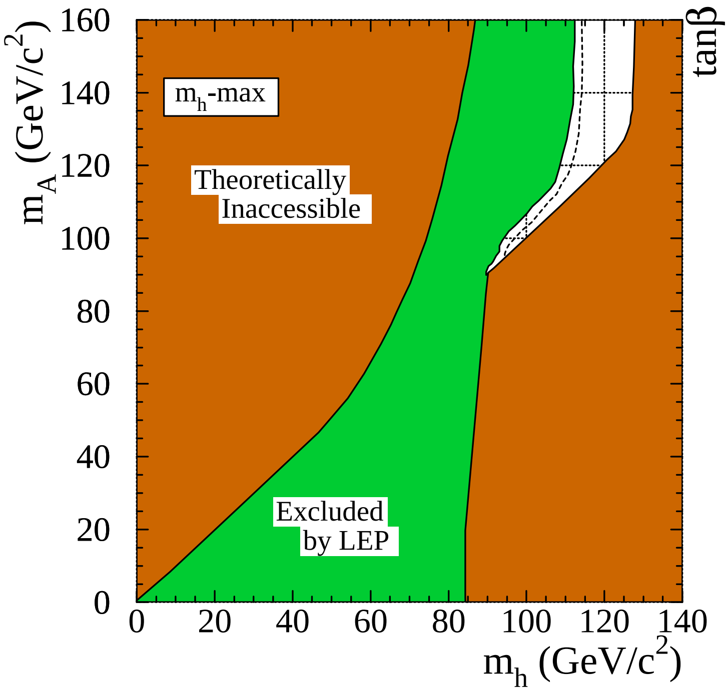
Associated Production

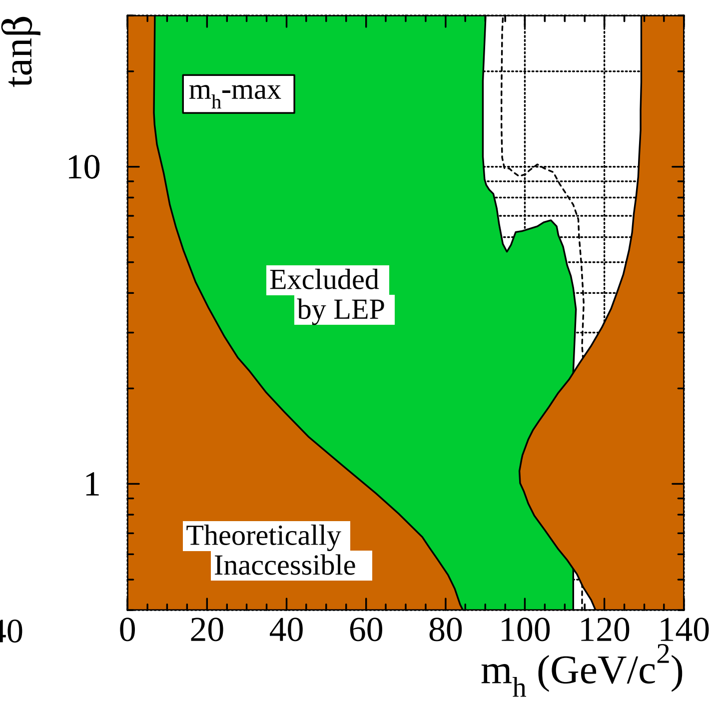
$$\sigma_{hA} = \cos^2(\beta-\alpha)\bar{\lambda}\sigma_{hZ}^{SM}$$

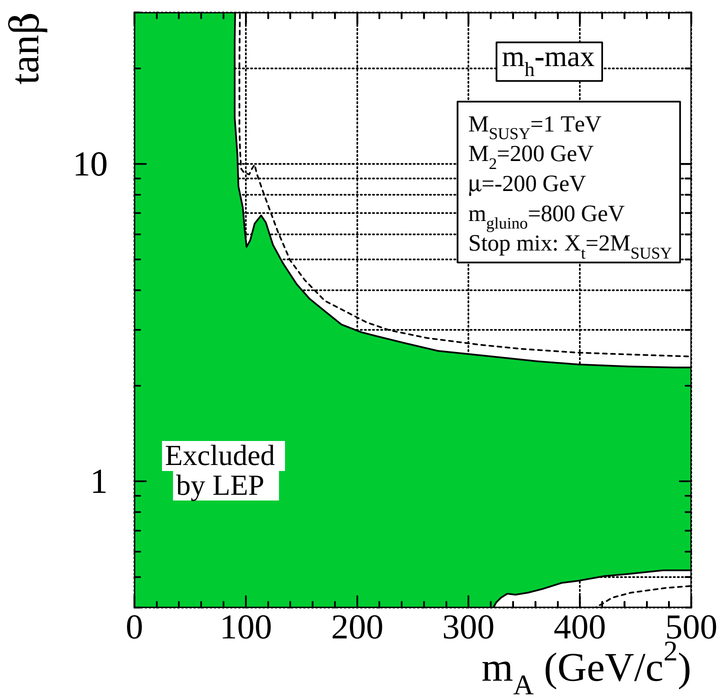
$\bar{\lambda}$: kinematic factor $(m_h, m_A, \sqrt{s})$

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)

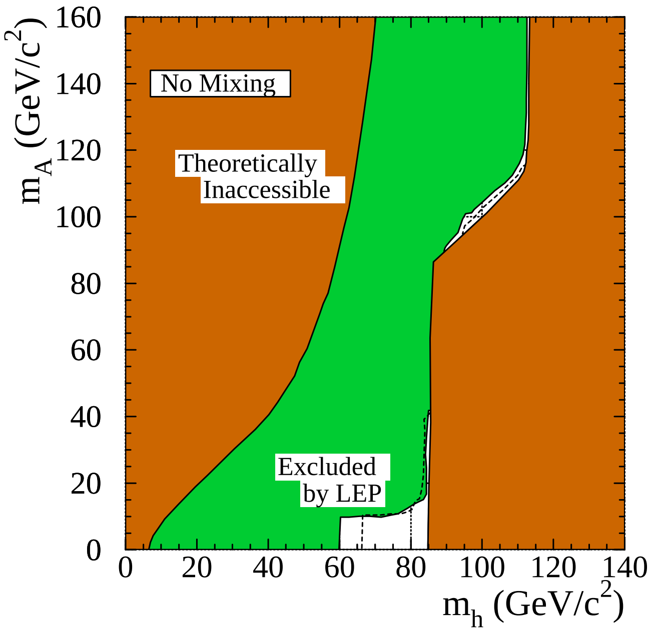
	obs.	exp.
$m_h >$	89.5	93.8
$m_A >$	90.2	94.1

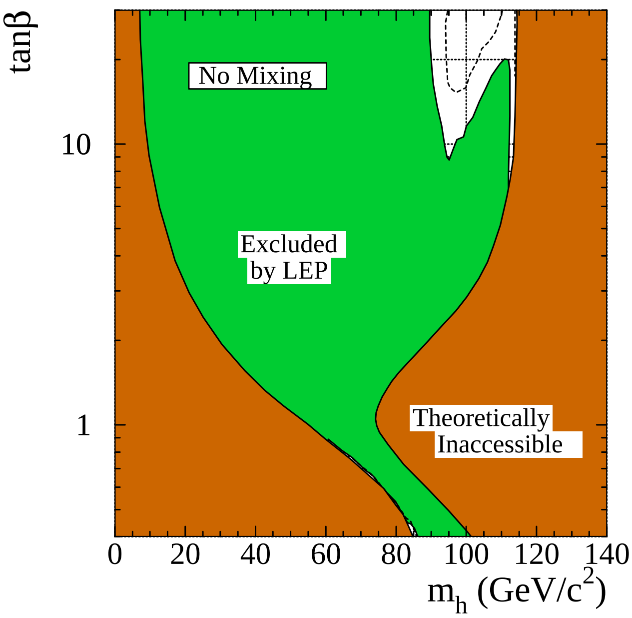
tanβ exclusion

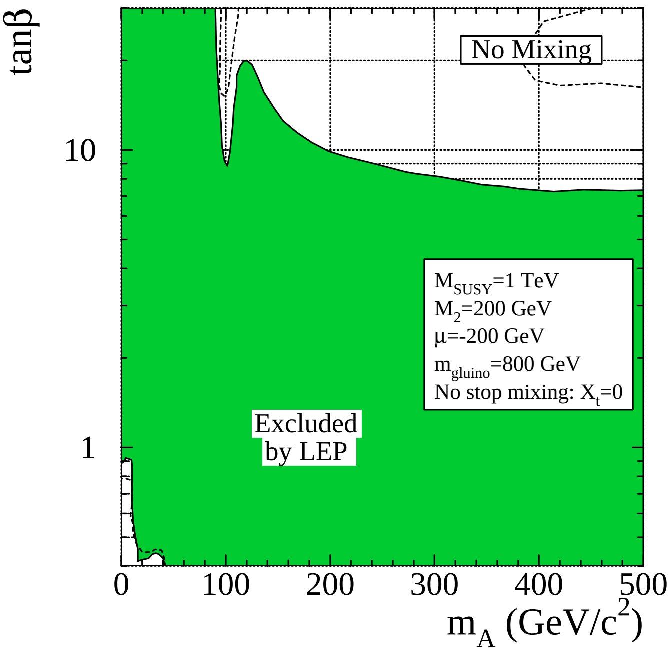
obs	exp.
0.53-2.25	0.48-2.48

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

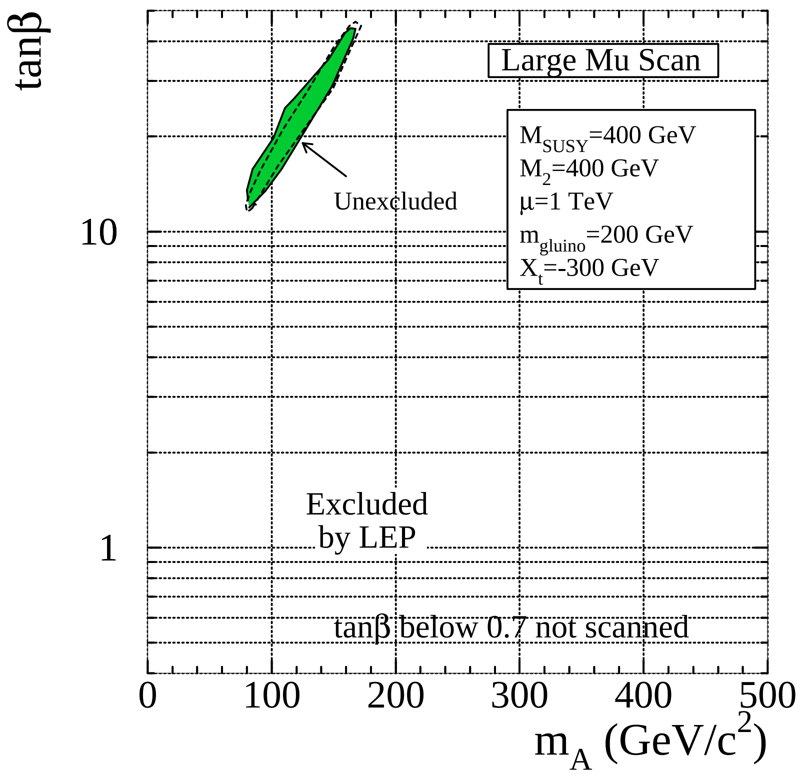
Large-μ Scenario -- Uses Subhpole2 by Carena and Wagner --RG-improved 1-loop calculation. More reliable for high tanβ and large μ.

Designed to be challenging!

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

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.

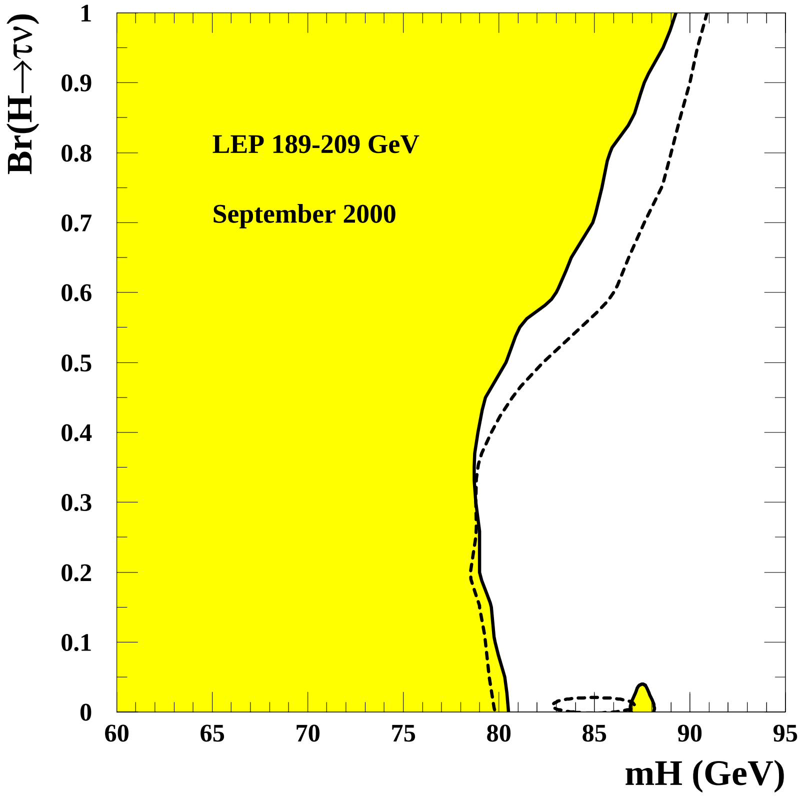
-- LEP has these, but we need to combine them.



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.

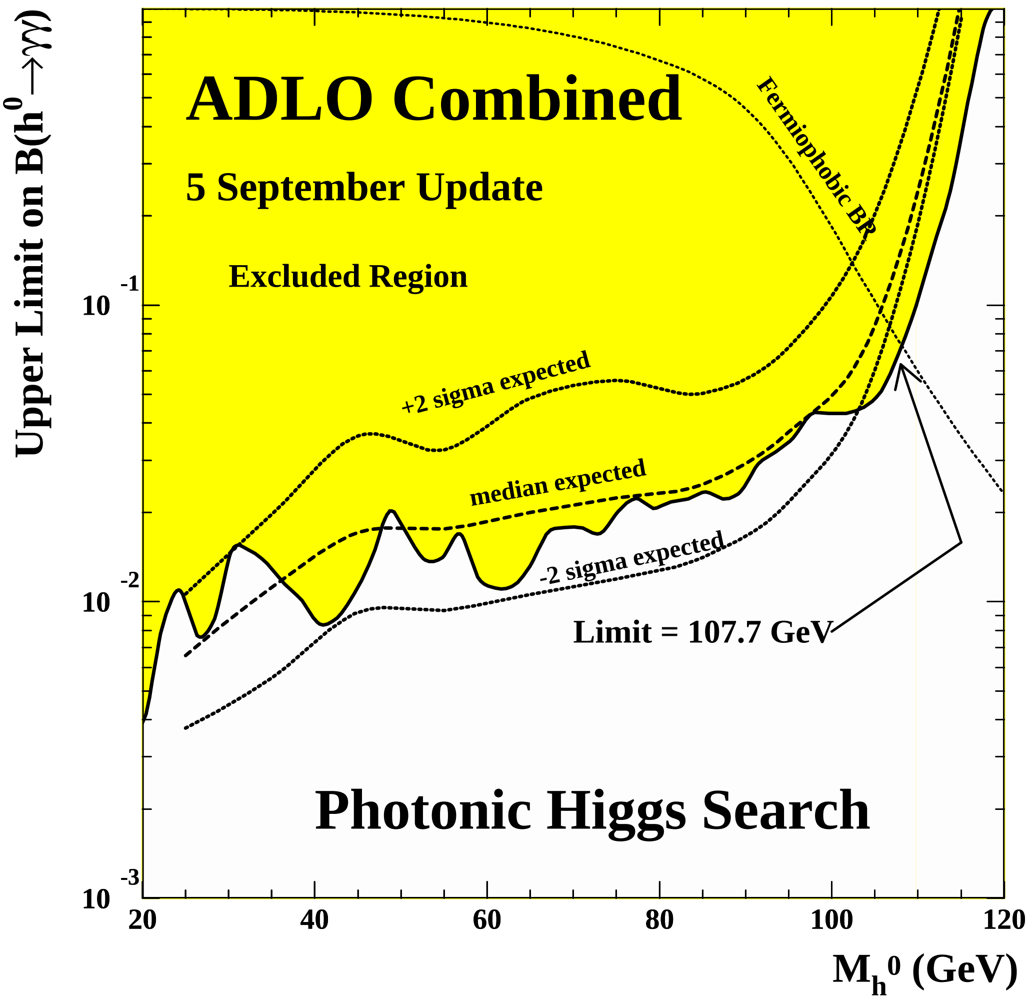
Assume $Br(H^+ \rightarrow \tau^+\nu_\tau) + Br(H^+ \rightarrow c\bar{s}) = 1$
for the limits.



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

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 $Br(H \rightarrow \gamma\gamma) = 1$, normalized to the SM x-sect

Can derive a mass limit assuming $Br(H \rightarrow \mathit{fermions}) = 0$

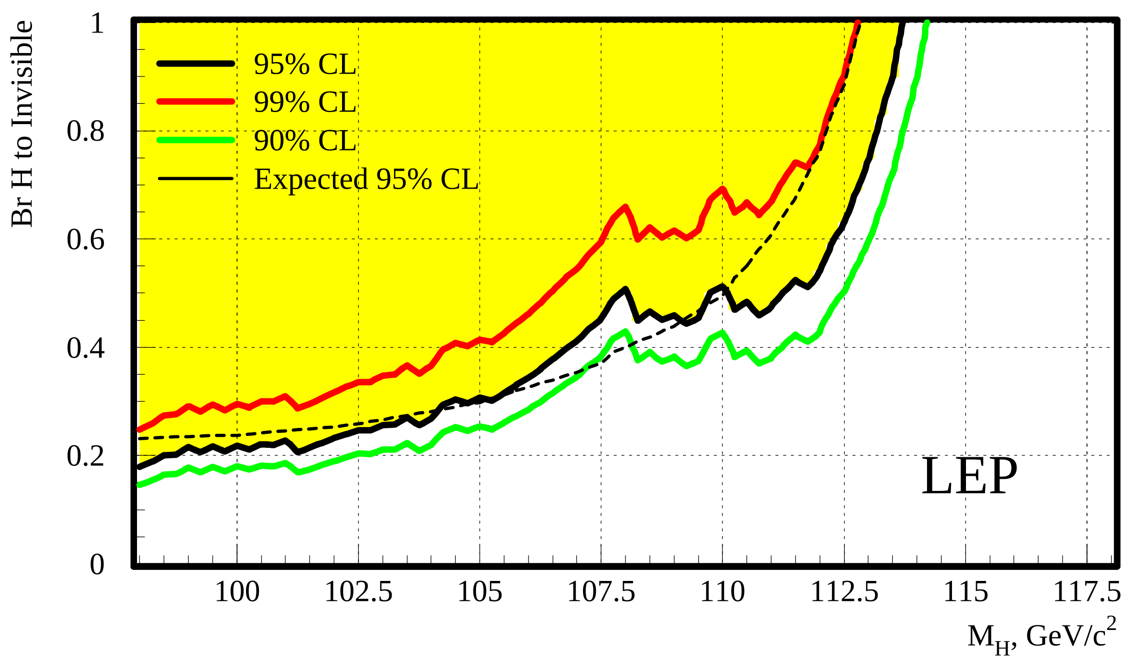
Observed limit: 107.7 GeV

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.



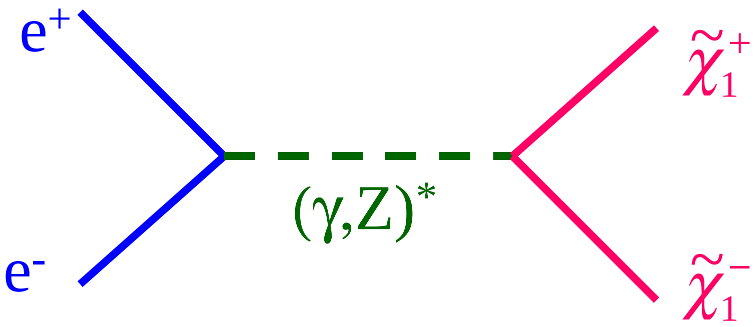
Assuming SM production x-section and 100% invisible decays, obtain the limits

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)



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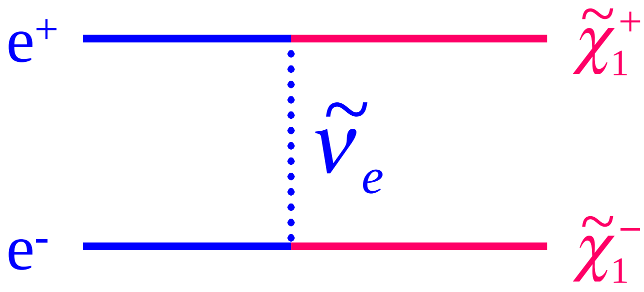


Destructive interference!

Diagram important for small m_0

Decays:

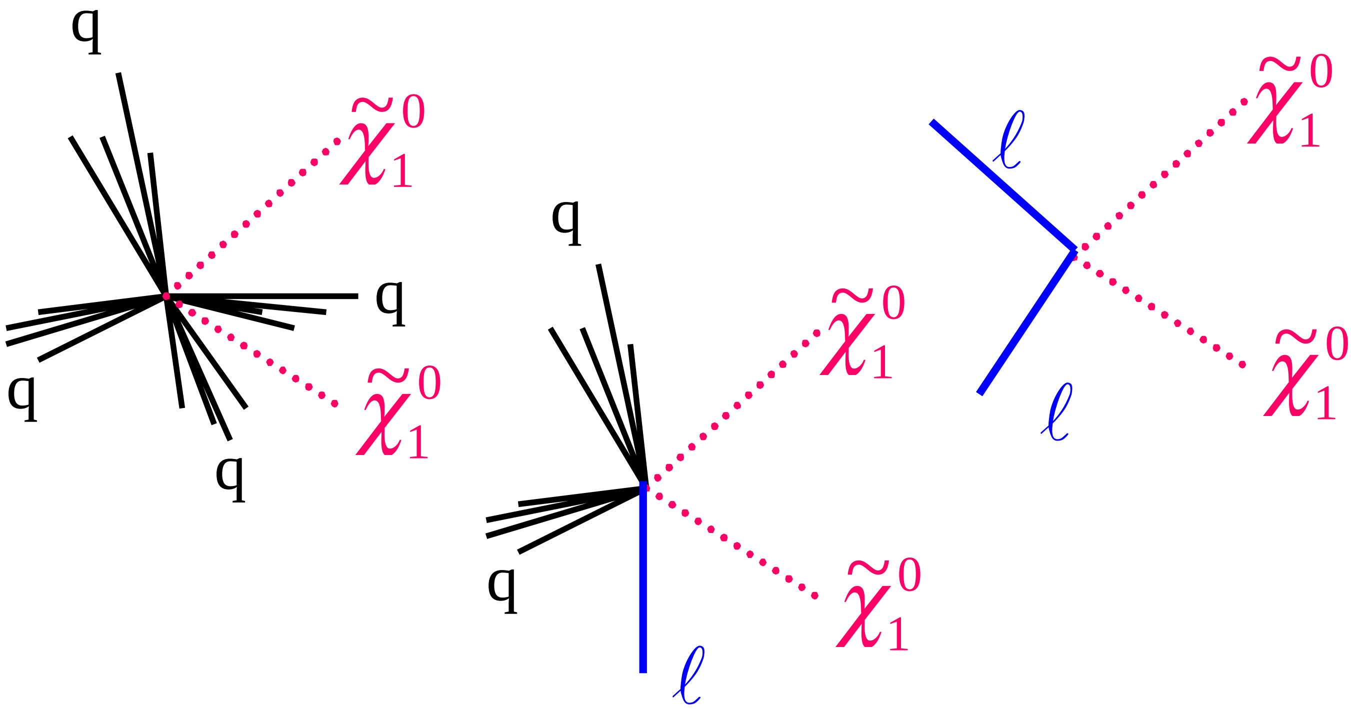
$$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^+ \qquad \textit{or}$$

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

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

Chargino Search Modes

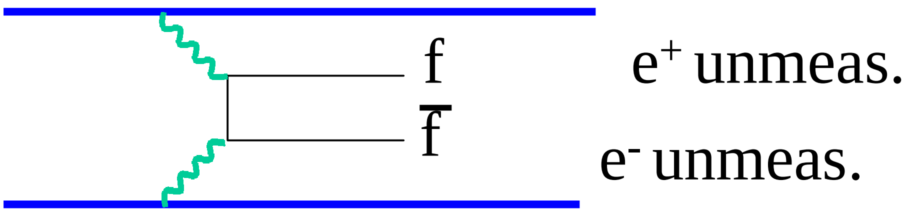
Same as W^+W^- channels, but with missing energy



Kinematics depend strongly on

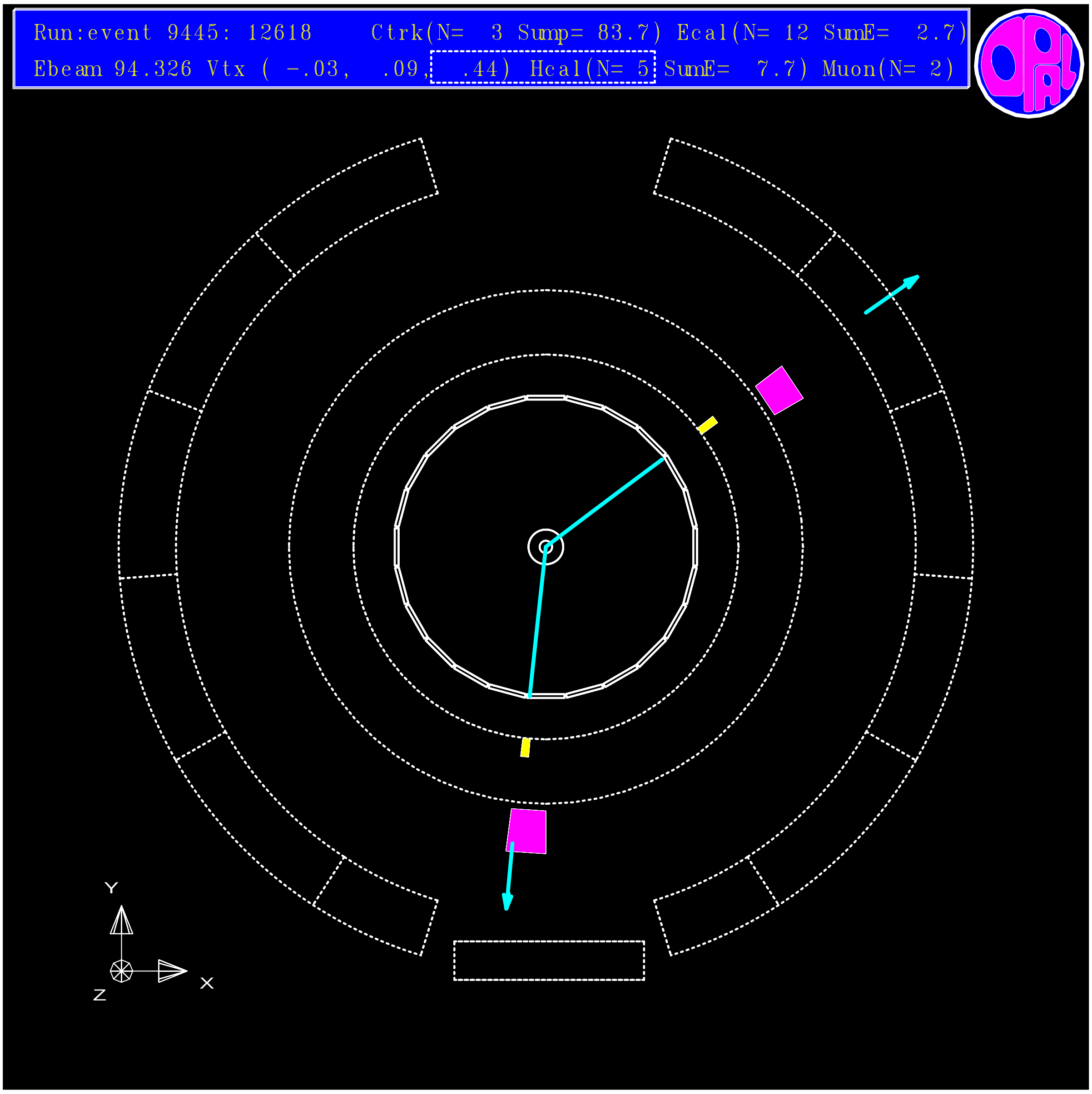
$$\Delta M = M_{\chi_1^+} - M_{\chi_1^0}$$

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



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

An "Acoplanar Dilepton"

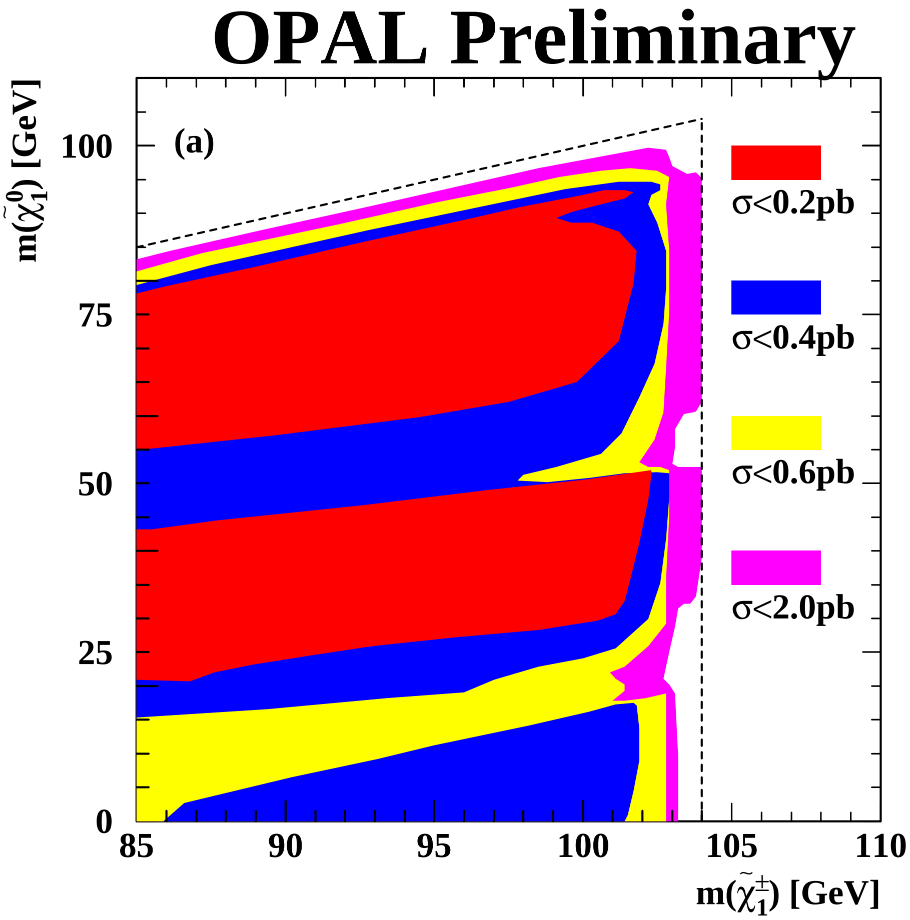


$\mu^+\mu^-$ with large missing p_t

SM interpretation:

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

Chargino Production Limits



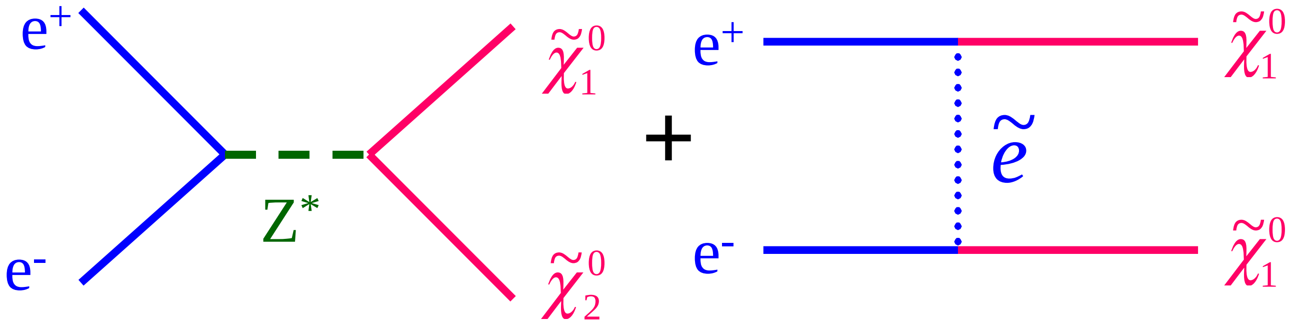
Plot does not assume CMSSM

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!

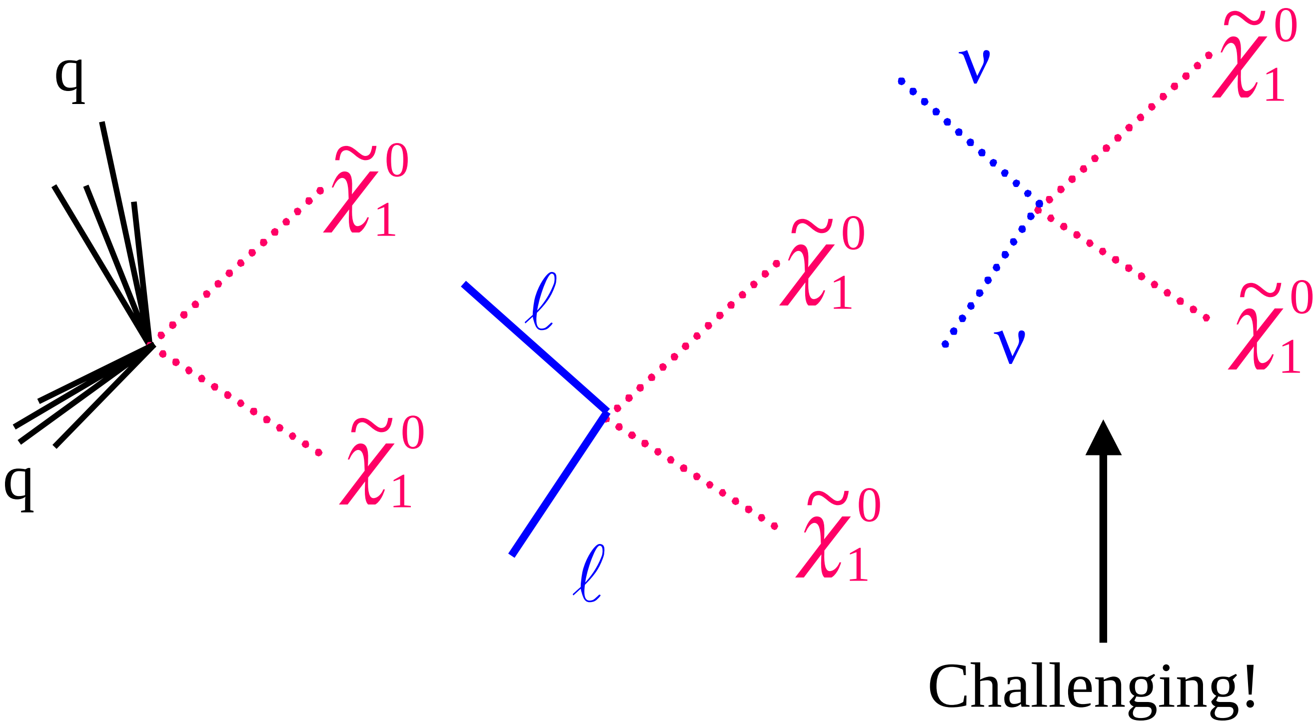
Neutralino Production and Decay

- 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

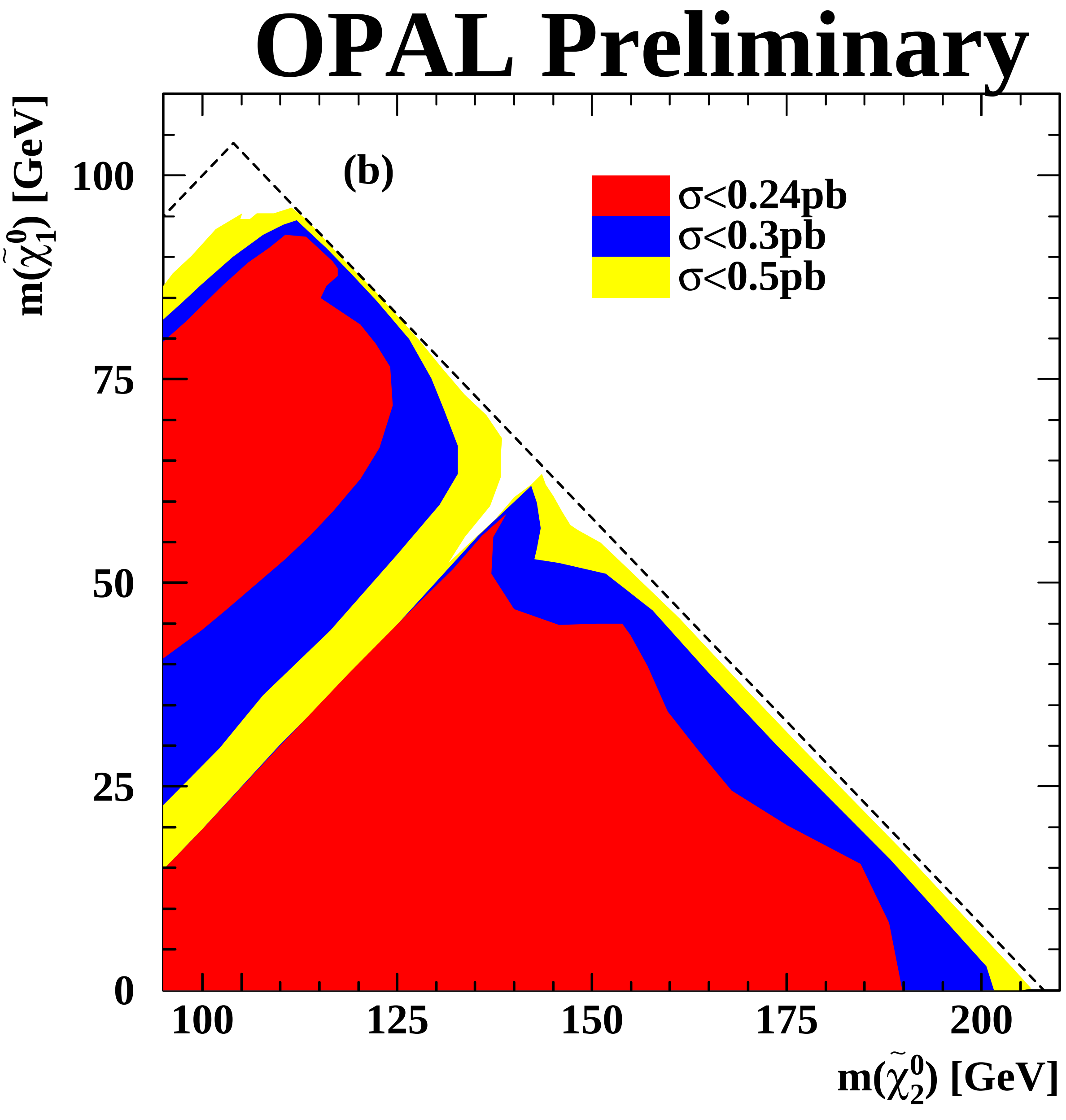


- Decays:

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



Neutralino Production Limits

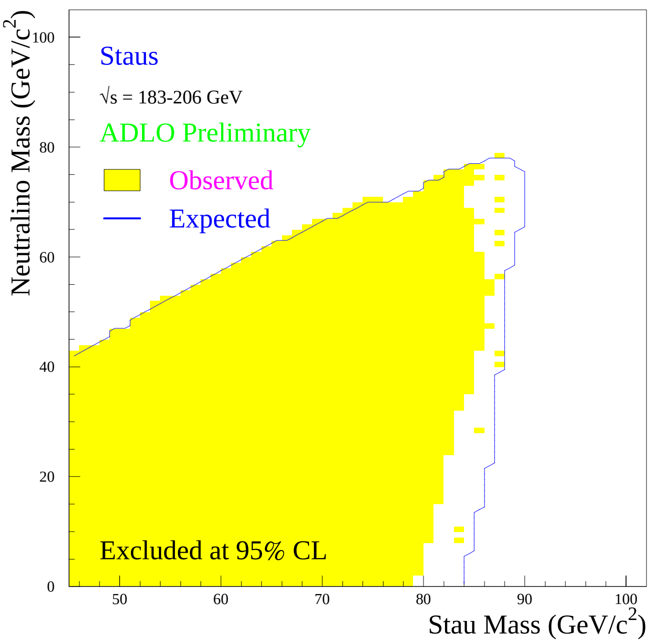


Slepton Searches

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

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

ADLO Y2K data (Osaka)



Limits for Δm > 15 GeV

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

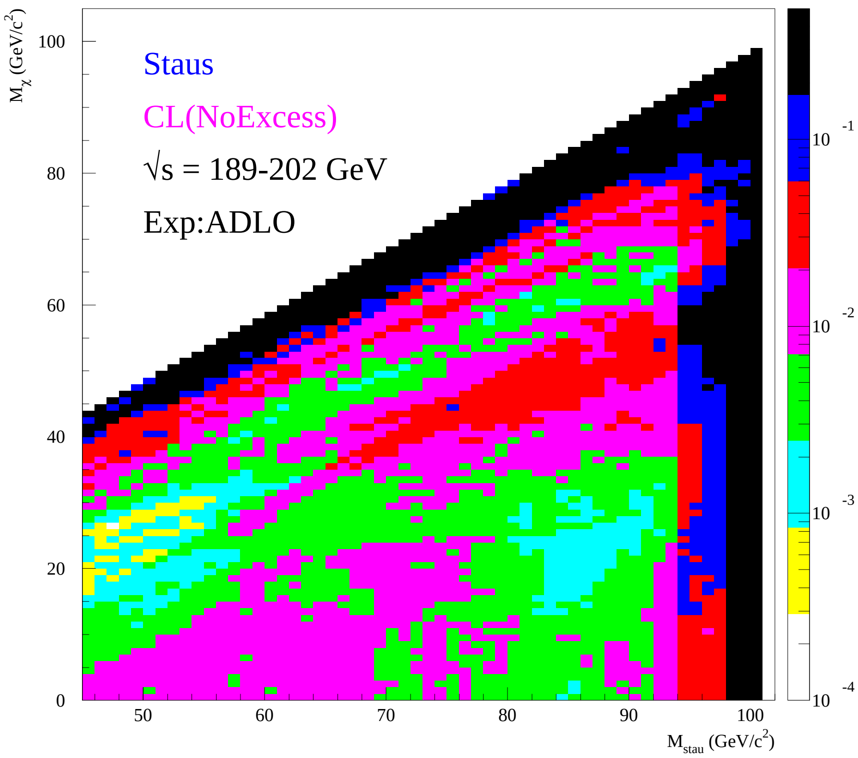
$$m_{\tilde{\mu}} > 94 \text{ GeV}$$

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

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

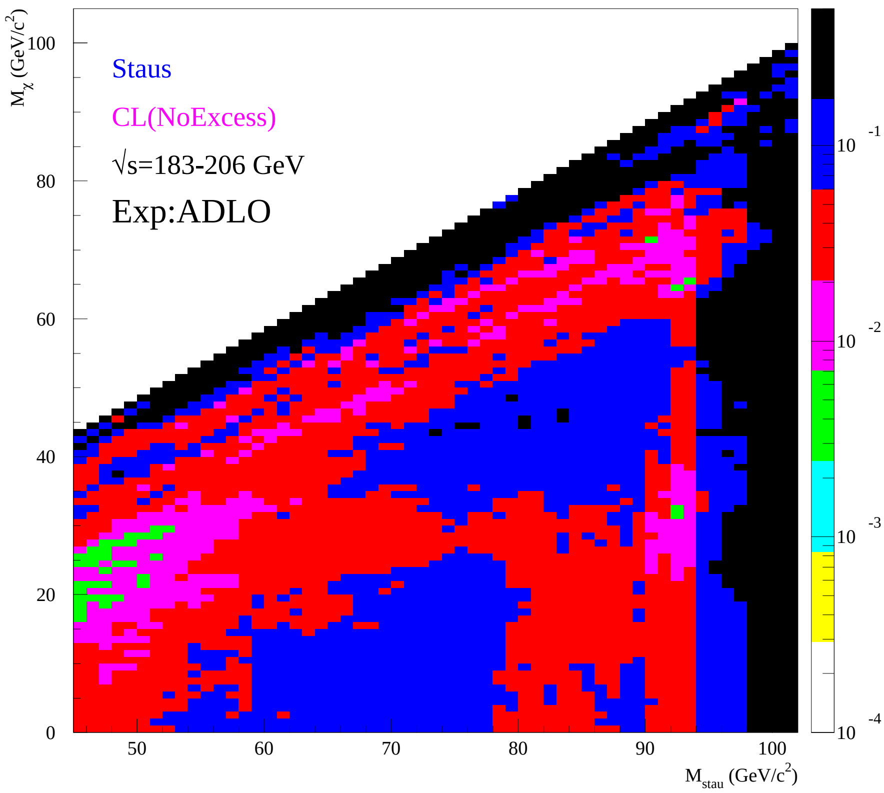
"Stau excess" in 1999 data not confirmed in 2000 data.

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

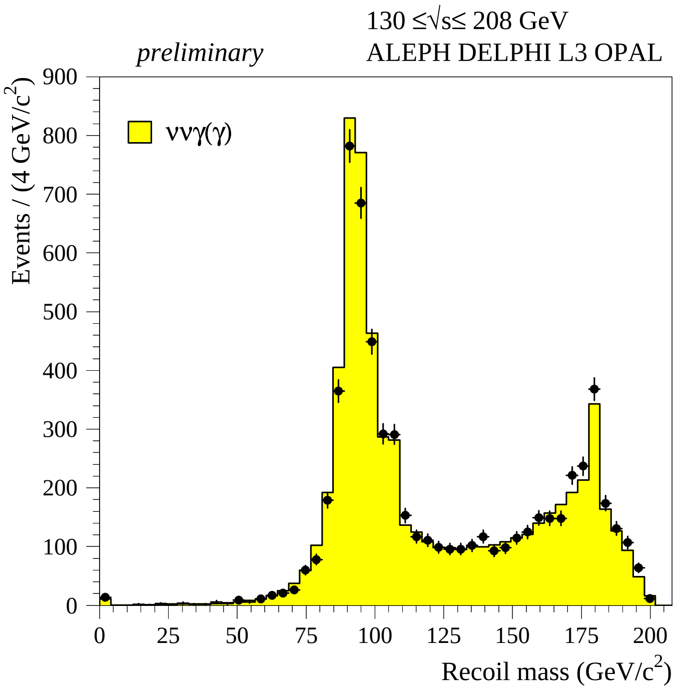
Sensitive to a variety of new signals

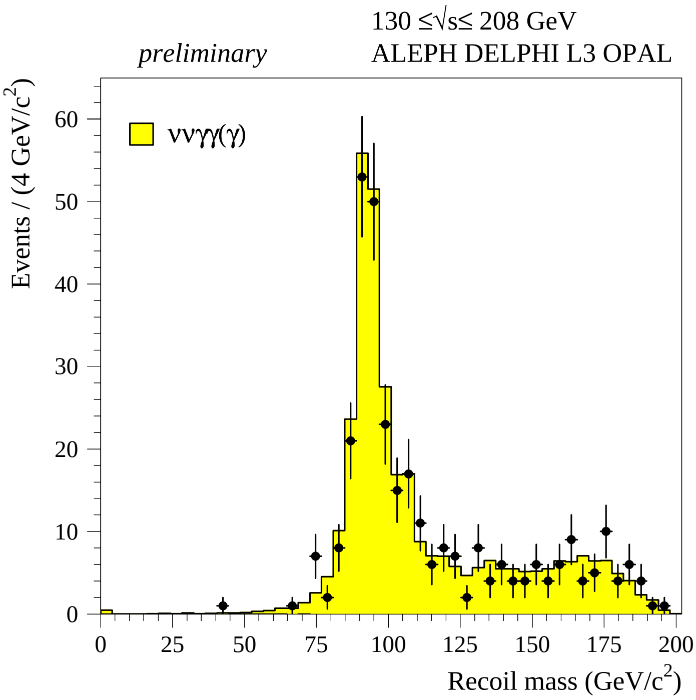
$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$ possible, and can be dominant in the MSSM, depending on params

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

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

Anything invisible + ISR.



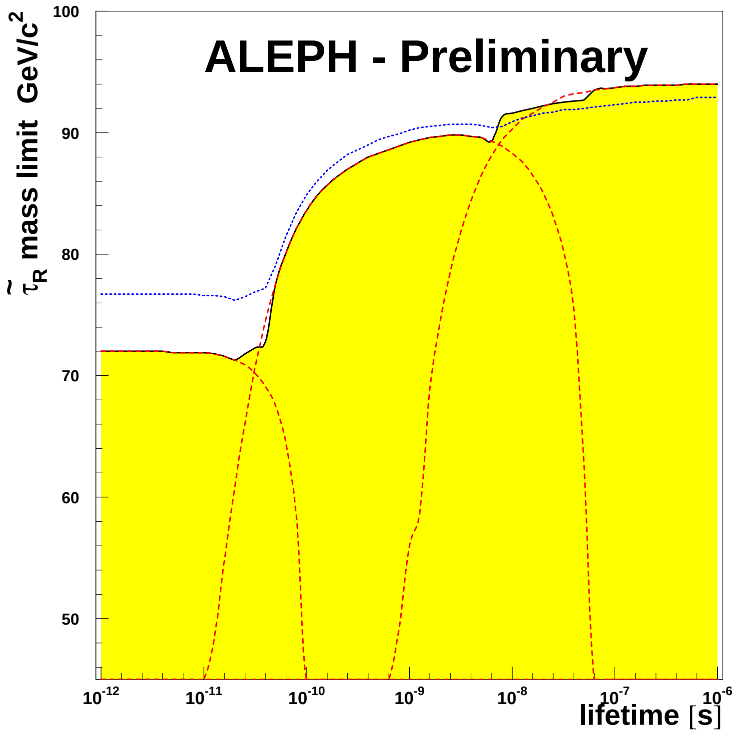


Interesting Signatures of GMSB

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 council on 14 September to decide.**