26 June, 2000
SUSY2K

Searches for HIGGS Bosons at LEP

Tom Junk

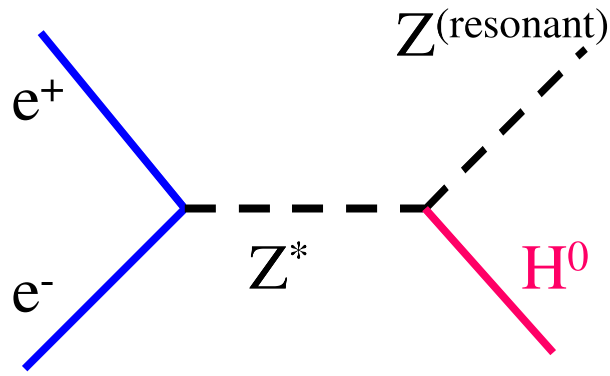
on behalf of the ALEPH, DELPHI, L3, and OPAL collaborations and the LEP Higgs WG

- Context
  - Higgs production and decay
  - Theory bounds
- Combining LEP Higgs Search Results
  - Exchange of Data, Errors, and Models
  - Combinations
    - Standard Model, MSSM, $H^{\pm}$
  - Future combinations: invisible and $\gamma\gamma$ decays
- Optimizing LEP Performance for Higgs Searches
- This year's schedule
  - Plans for searches and combinations

Standard Model Higgs Production

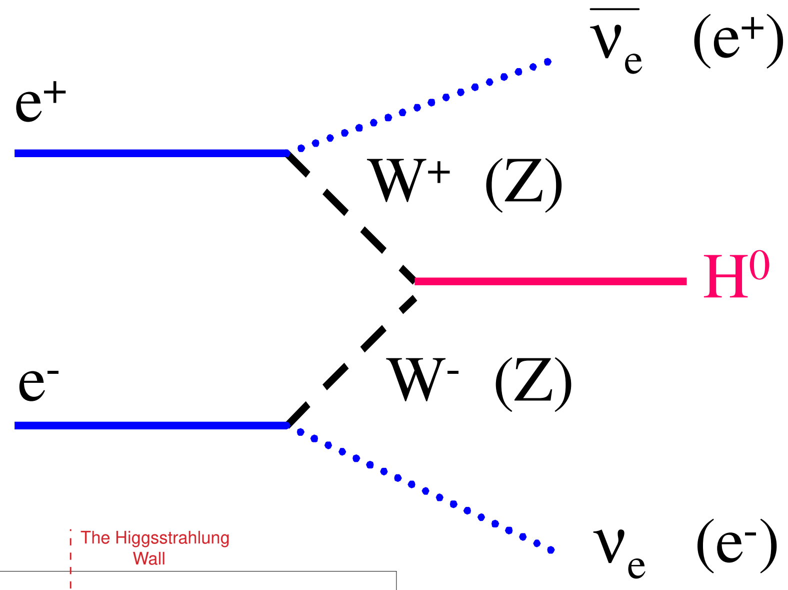
"Higgs-Strahlung"
(BJ process)

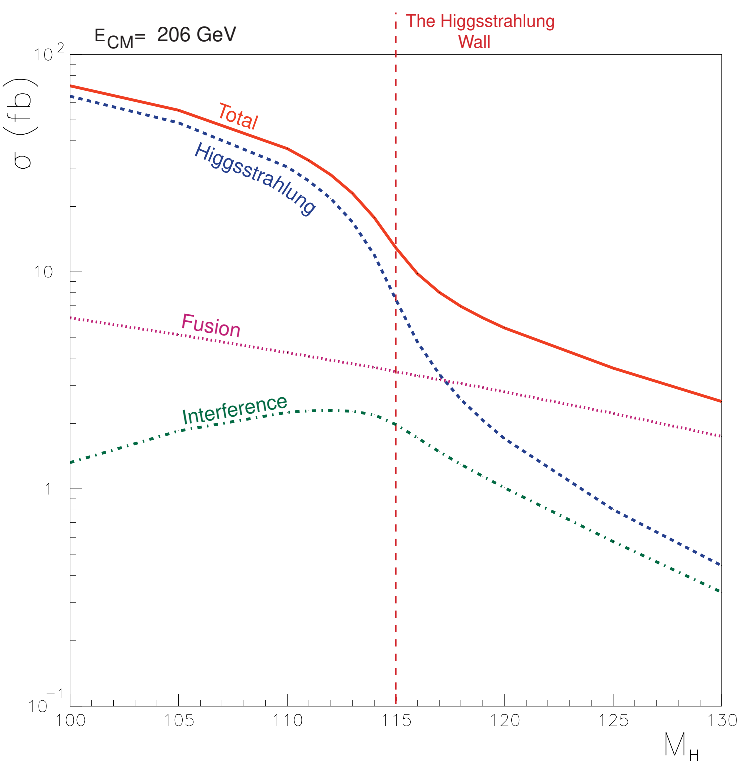
Has a kinematic "cutoff" at $\sqrt{s} - m_Z$



"Fusion"

"No" kinematic cutoff, but low cross-section

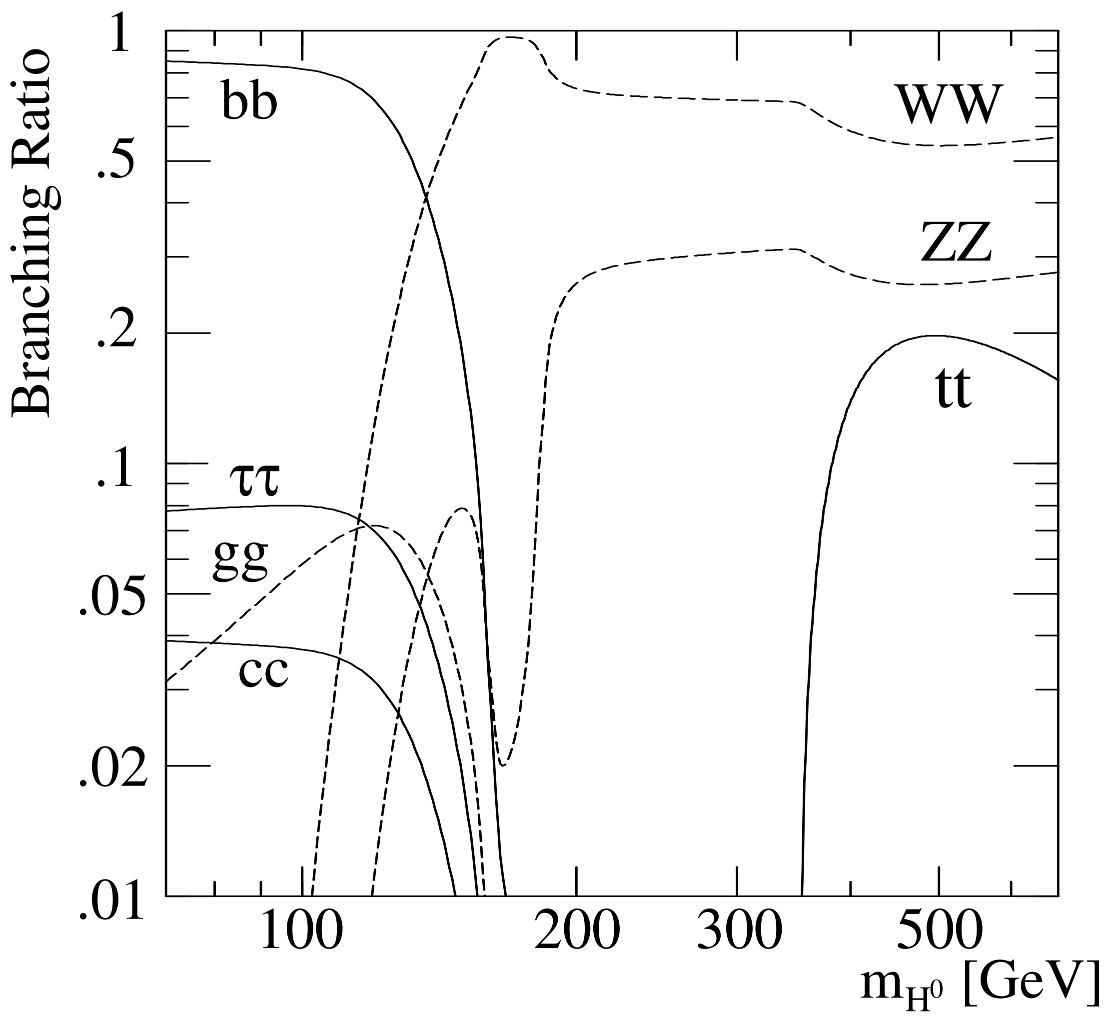




Note: only $H\nu\nu$ x-sect shown.

Multiply HZ by ~5 to get total.

Standard Model Higgs Decays



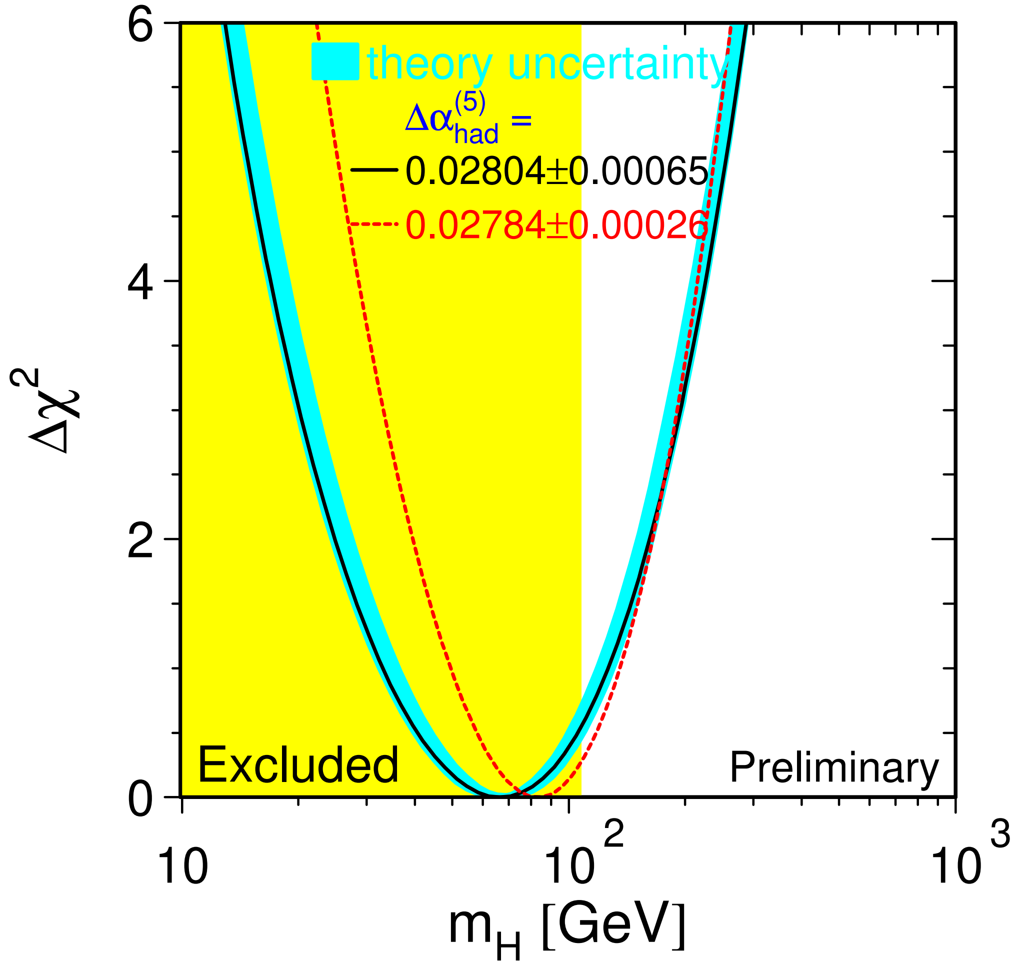
Dominated by $H^0 \rightarrow b\bar{b}$

at accessible Higgs Boson masses

$H^0 \rightarrow \tau^+\tau^-$ ~8%,

$H^0 \rightarrow W^+W^-$ beginning to switch on at high m_H

Electroweak Fit Constraint on m_H



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

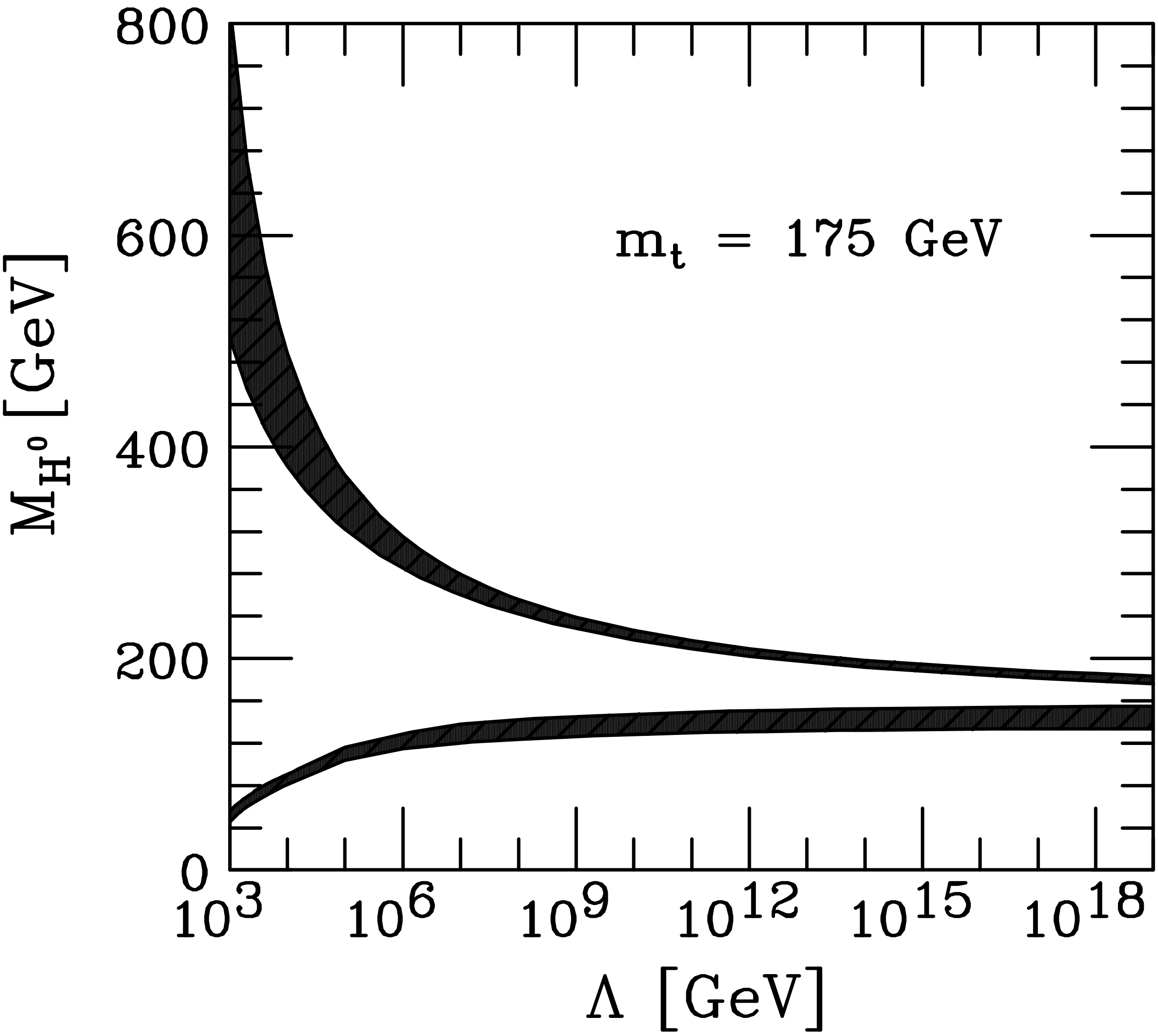
  Current central value:

$$\boxed{m_H = 77^{+69}_{-39}\ \text{GeV}}$$

- 95% CL Upper limit

$$m_H < 215\ \text{GeV}$$

Consequences of Believing the Standard Model up to the Planck Scale



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

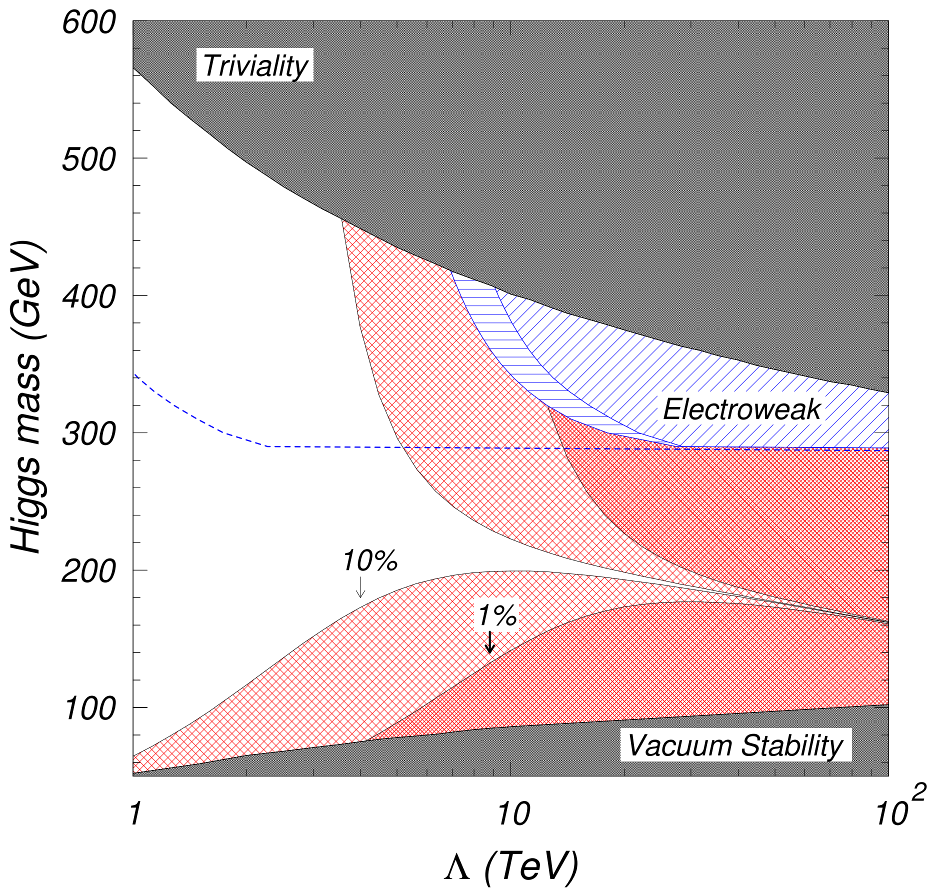
Upper Higgs mass bound -- Landau pole
Lower Higgs mass bound -- vacuum stability

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.

CMSSM Parameters

"Low-energy effective SUSY"
Seven Parameters to specify it:

M_2: EW scale SU(2) Gaugino mass. Assume Gaugino masses unified at GUT scale

M_{SUSY}: Common sfermion mass (squark, slepton, sneutrino) at the EW scale, except for squark mixing splitting the L and R states

$\tan\beta$: Ratio of the VEV's of the two Higgs doublets

μ: Higgs mixing parameter

A_0: Common trilinear coupling (parameterizes squark mixing)

M_A: Mass of the CP-odd Higgs Boson

$m_{\tilde{g}}$: Gluino mass -- only important via loops

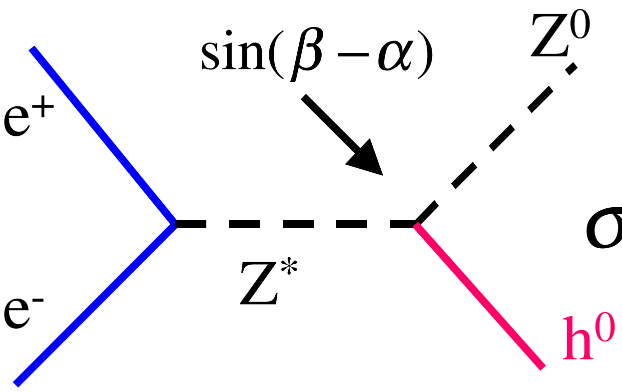
Can derive: m_h, m_H, α: mixing between the two doublets

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

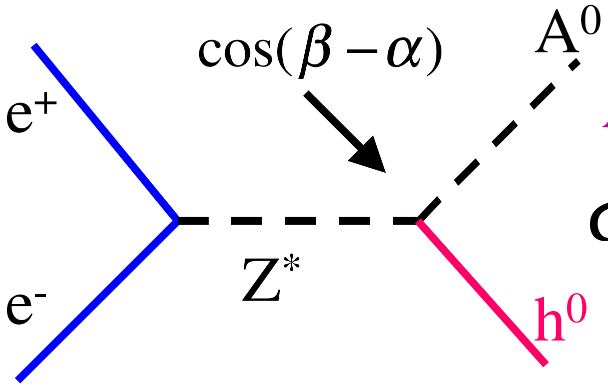
$$\boxed{m_{h^0} < \sim 135 \ \ \text{GeV}}$$



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 $(\mathrm{m_h}, \mathrm{m_A}, \sqrt{\mathrm{s}})$

Decay Modes of MSSM Higgses

Branching Fractions:

$$\left.\begin{array}{l} \mathrm{Br}(h^0 \to b\bar{b}) \\ \mathrm{Br}(h^0 \to \tau^+\tau^-) \end{array}\right\} \text{similar to SM } H^0$$

$\mathrm{Br}(A^0 \to b\bar{b}) \sim 92\%$

$\mathrm{Br}(A^0 \to \tau^+\tau^-) \sim 8\%$

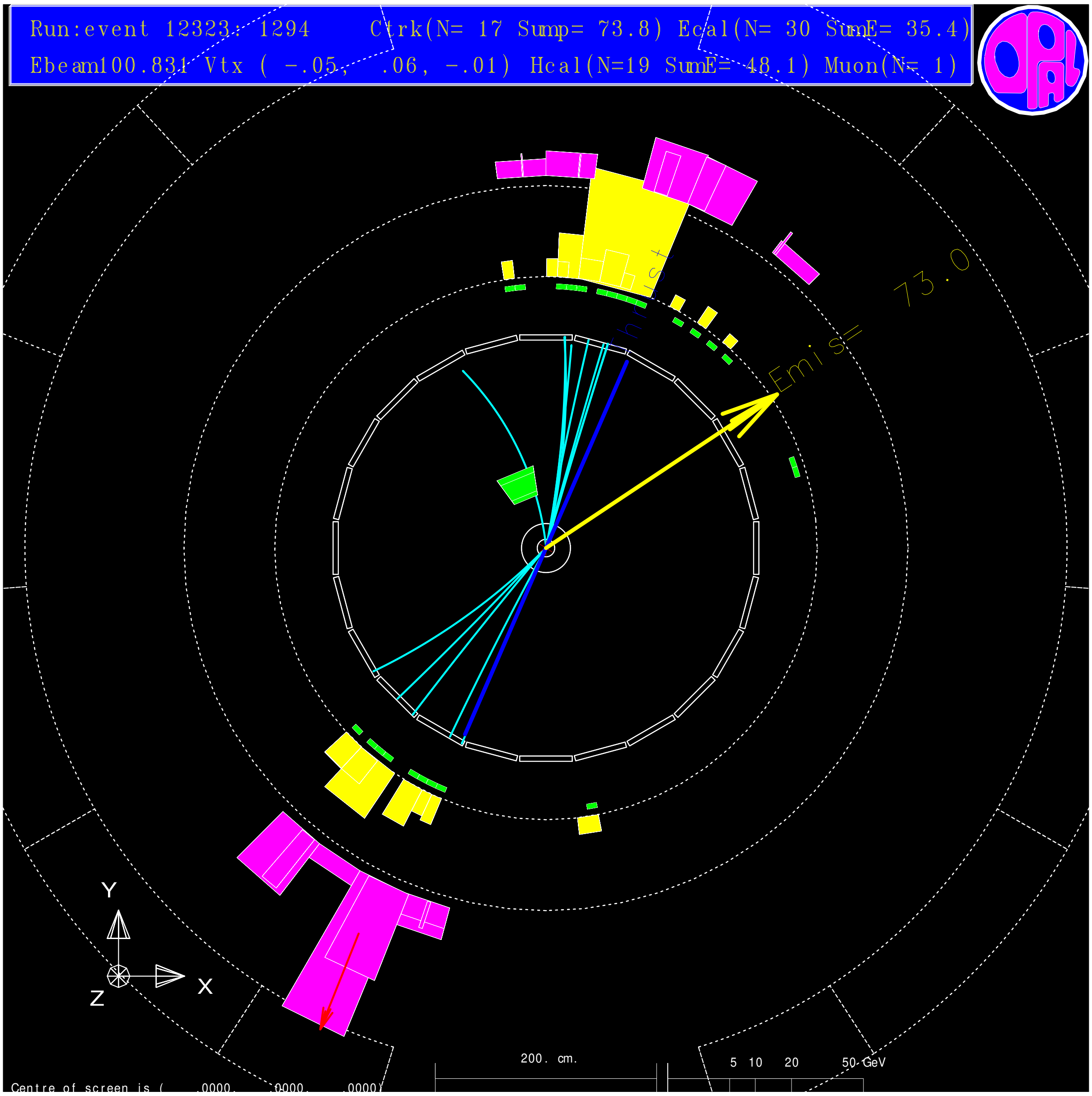
over much of parameter space, **but $h^0 \to A^0A^0$ can be dominant** when kinematically allowed.

- ## h^0Z^0 Searches
  - Reuse SM H^0Z^0 analyses
  - Find Efficiency for processes with $h^0 \to A^0A^0$ with $A^0 \to bb$
- ## h^0A^0 Searches
  - No Z^0 mass constraint! Rely more on the b-tag: bbbb and bbττ are main channels.
  - More ambiguities in interpretation
    Six combinations in 4-jet
    Two combinations in bbττ
  - Also a dedicated $A^0A^0A^0 \to 6b$ search
  - Use H^0A^0 production when allowed

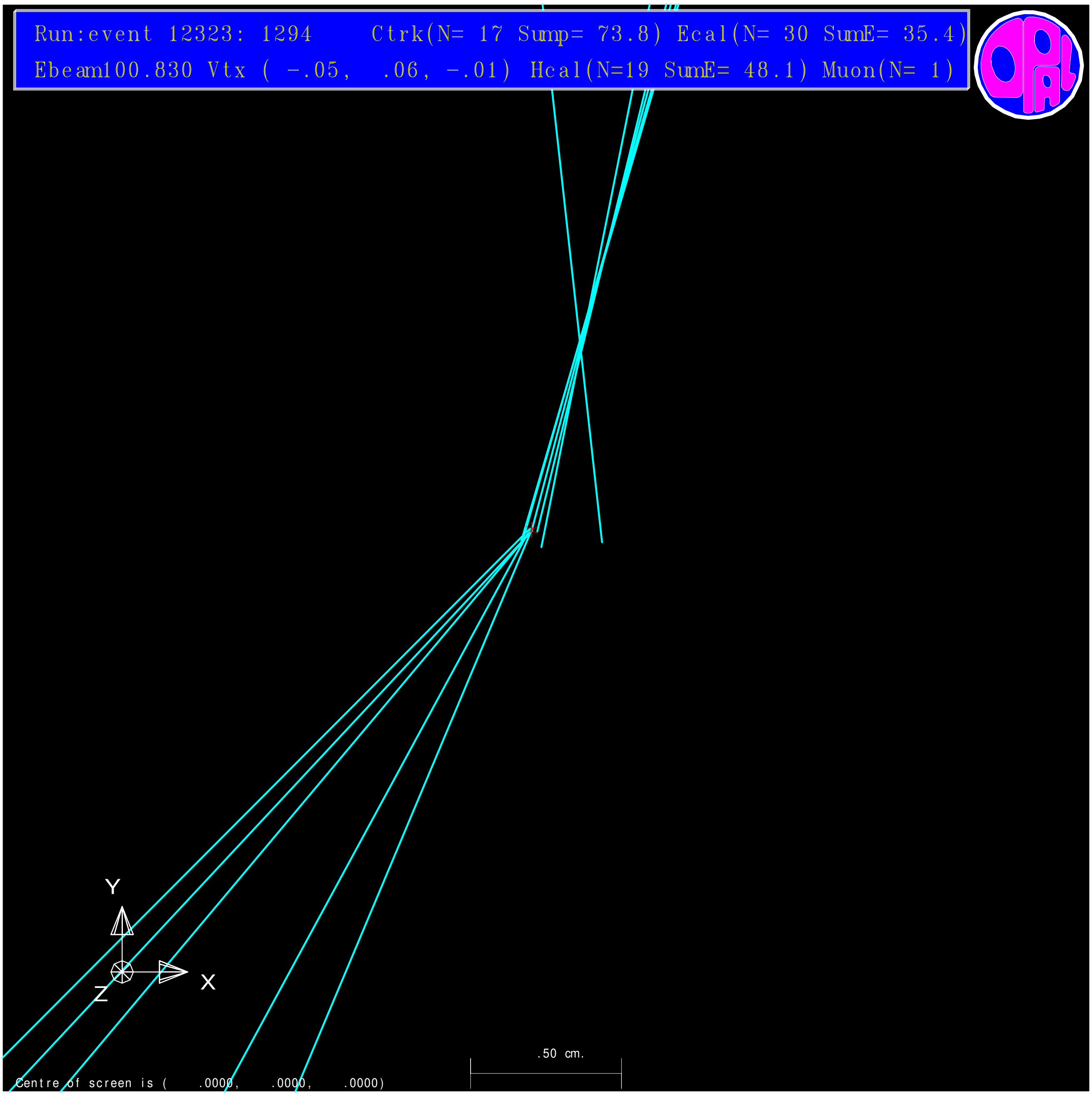
A Missing-Energy Channel Candidate

$$\sqrt{s} = 202\,\text{GeV}$$

$$m_{rec} = 106.9\ \text{GeV}$$



B-tag for the Missing-Energy Cand.



Confidence Levels

Two hypotheses "signal+background" and "background" Use experiment to distinguish between them.

A spectrum of experimental outcomes

Need a ***Test-Statistic*** for ordering experimental outcomes -- Likelihood Ratio =

$$Q = P(\text{data}|s+b)/P(\text{data}|b)$$

$CL_{s+b} = P_{s+b}(Q \leq Q_{data})$ $CL_b = P_b(Q \leq Q_{data})$

"Cousins and Feldman with only two hypotheses"

Protection against downward fluctuations: (possible exclusions of signals to which we are not sensitive)

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

$CL_s < 0.05 \rightarrow$ 95% Exclusion

$1\text{-}CL_b < 5.7\times10^{-7} \rightarrow$ 5σ Discovery

SM Search Results for Each Experiment

Moriond results.
Preliminary, data up to 202 GeV

	Integrated Lumi [pb^{-1}]	SM Higgs limit [GeV]	Median expected [GeV]
ALEPH	237.0	107.7*	107.7*
DELPHI	222-228	106.3	103.9
L3	232.4	105.3	105.2
OPAL	213-217	105.2	103.0

*ALEPH defines CL_s differently, for a difference of about 0.5 GeV

Cross-section still not zero for higher Higgs masses, and smaller amounts of data were collected at higher energies -- Much to be gained from combination.

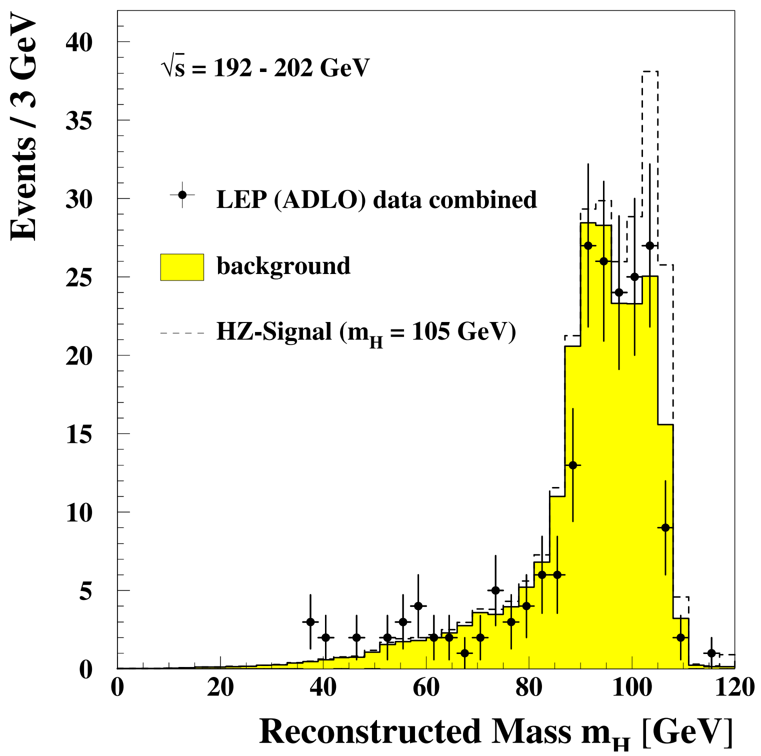
Exchanging LEP Higgs Results for Combination

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

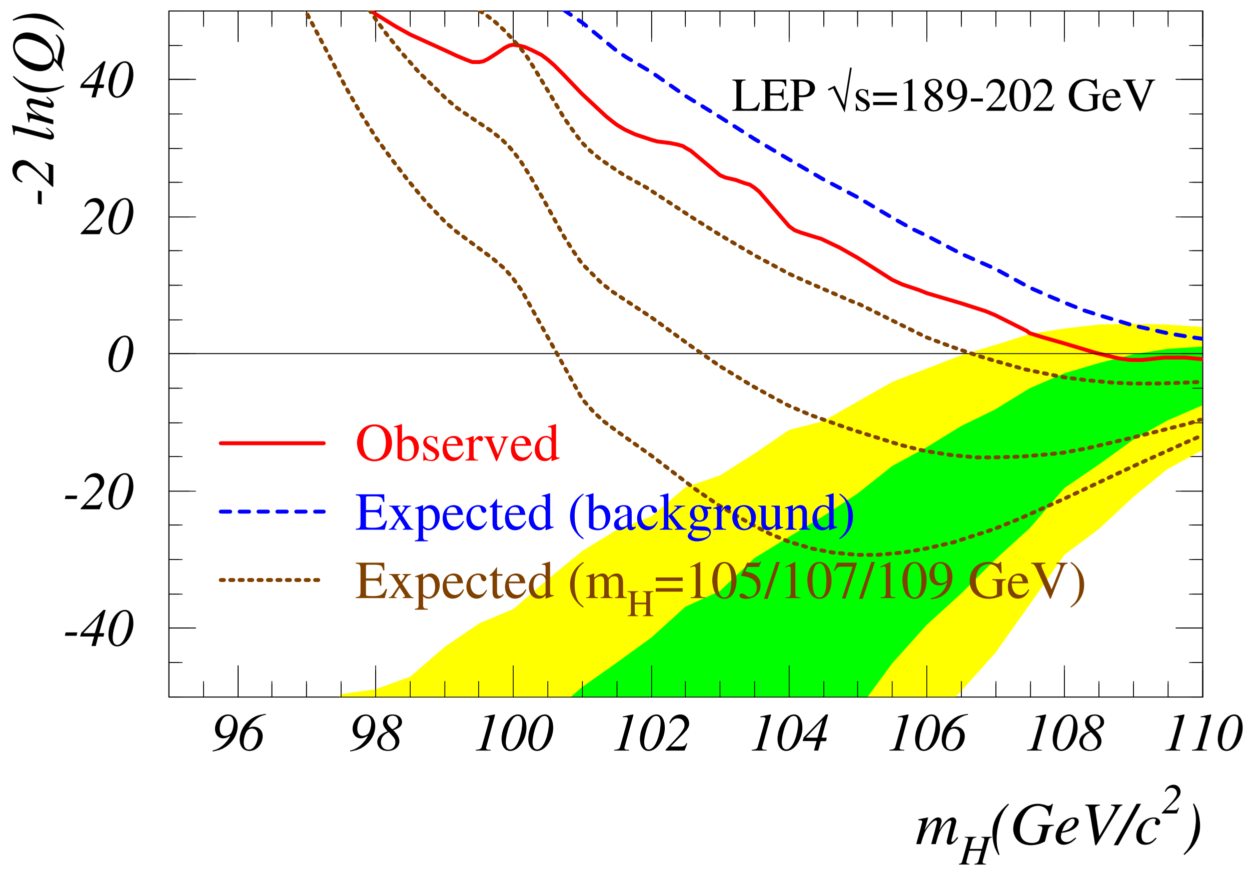
- For each bin:
  - signal estimation
  - background estimation
  - data counts
- For each search analysis channel:
  - **signed relative error on the signal and background** itemized *by named source*
  - examples: B decay modeling, ZZ x-sect, MC comparisons
- Effect of including errors
  - Uncorrelated: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

LEP SM Higgs Results

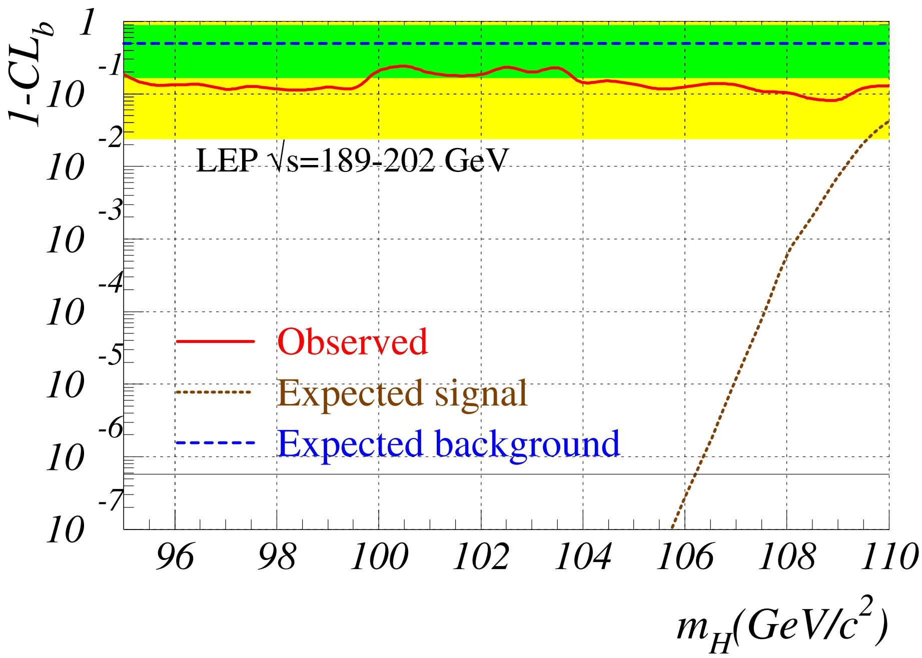
CERN-EP-2000-055



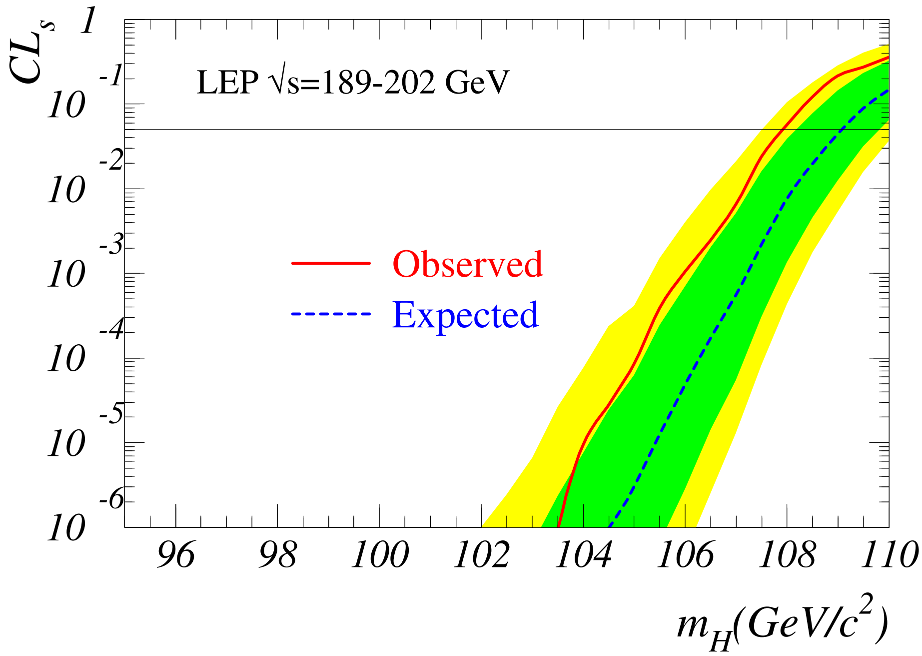
For m_H=105 GeV, expect 40.7 signal, 220 backg, observe 201 (cut to keep s/b similar - not used for limits)



LEP-Combined Higgs Limits



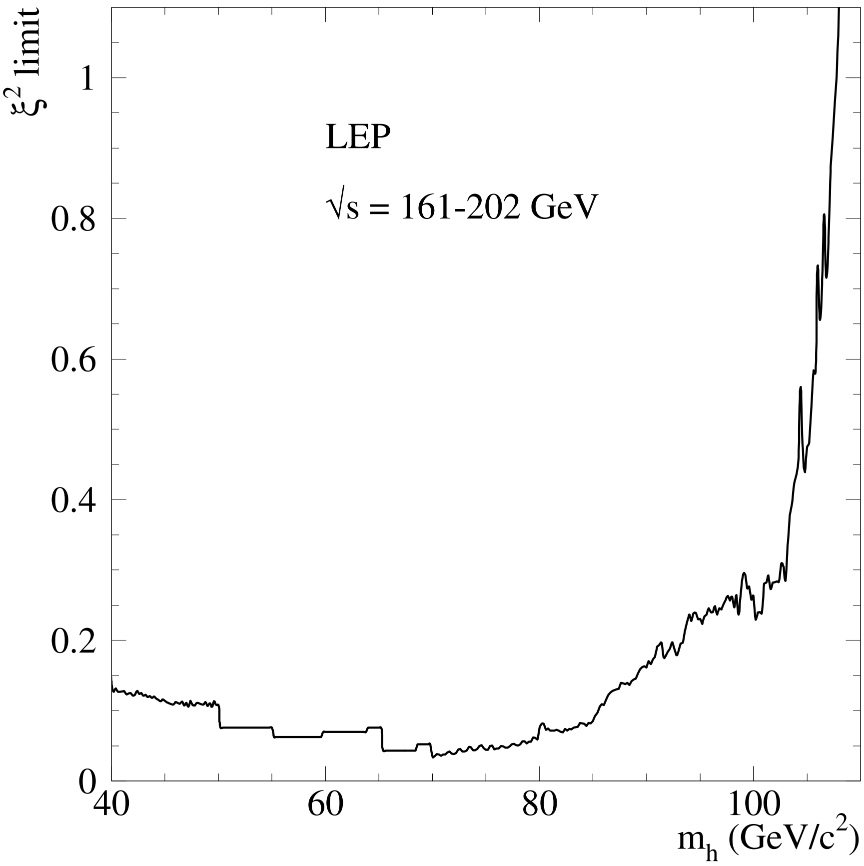
CL_b: No discovery, but we could have discovered an SM Higgs boson if m_H < 106 GeV (at least 50% of experiments)



Obtained limit: 107.9 GeV

Median Expected limit: 109.1 GeV if no signal

Placing Limits on the ZZH Coupling Strength



$$\xi = \frac{g_{HZZ}}{g_{HZZ}^{SM}}$$

SM H decay branching ratios assumed.

MSSM Combinations

- An important ingredient -- Model calculations -- masses, b.r.'s, and production cross sections
- SM is easy -- just one unknown parameter: m_H. Agreed calculations with fusion and interference.
- MSSM more involved. Seven parameters in our model.
- Need to combine data rapidly, so need a precomputed, shared model database

Three Scenarios

- No stop-quark mixing scenario
  generous exclusion
- Max-m_h scenario
  conservative limits on tanβ
- Large-μ scenario
  branching to b quarks suppressed
  "pathological" points

Some Recent Progress on the Theory Front

- Full two-loop calculation of m_h in the MSSM:
  Weiglein, Heinemeyer, Hollik hep-ph/9909540

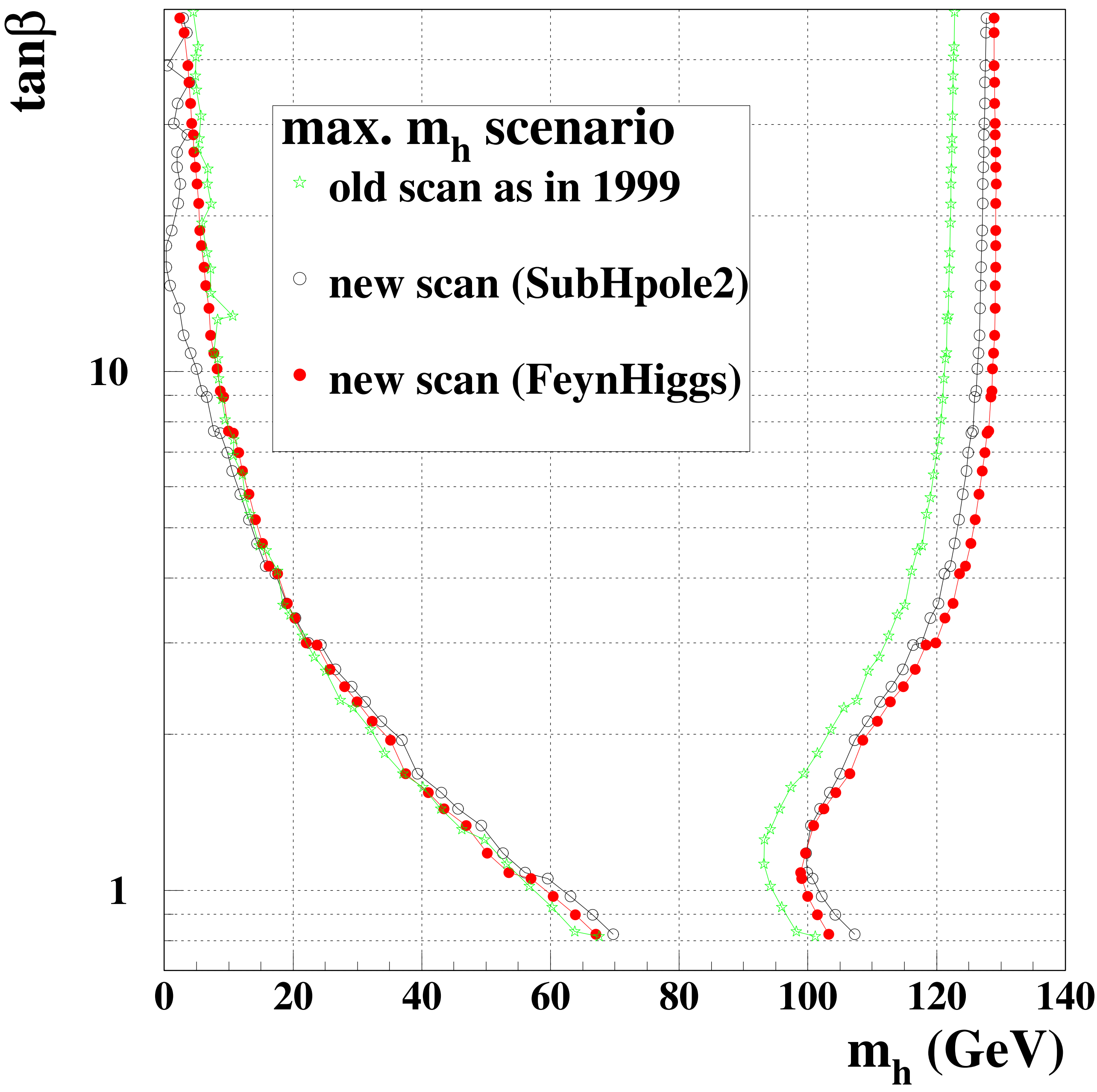
- One-loop renormalization-group improved
  calculation: Carena, Quiros, Wagner
  Nucl. Phys. **B461** (1996) 407.

- Reconciliation of differences in calculation hep-ph/0001002
  Carena, Haber, Heinemeyer, Hollik, Wagner, Weiglein

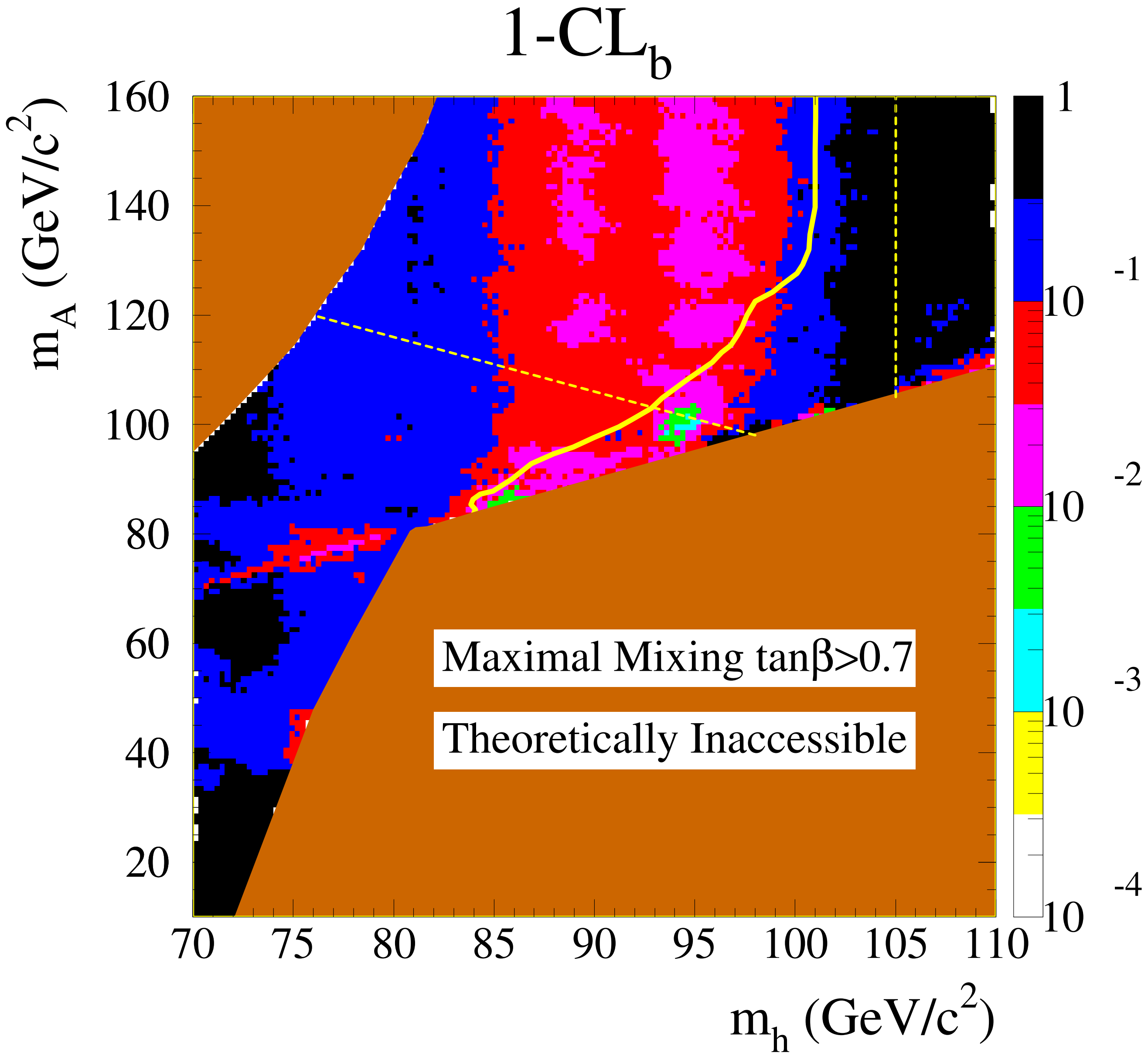
- Outcome is the best of all worlds
  - Genuine 2-loop terms
  - Resummation of higher-order effects
  - Differences absorbed in the running top quark mass at the apropriate scale.

- Two-loop calculation used for no-mixing and max-m_h scenarios -- conservative limits on $\tan\beta$. RG-improved 1-loop more stable for large μ.

Two-Loop Allowed Regions vs. Old Models

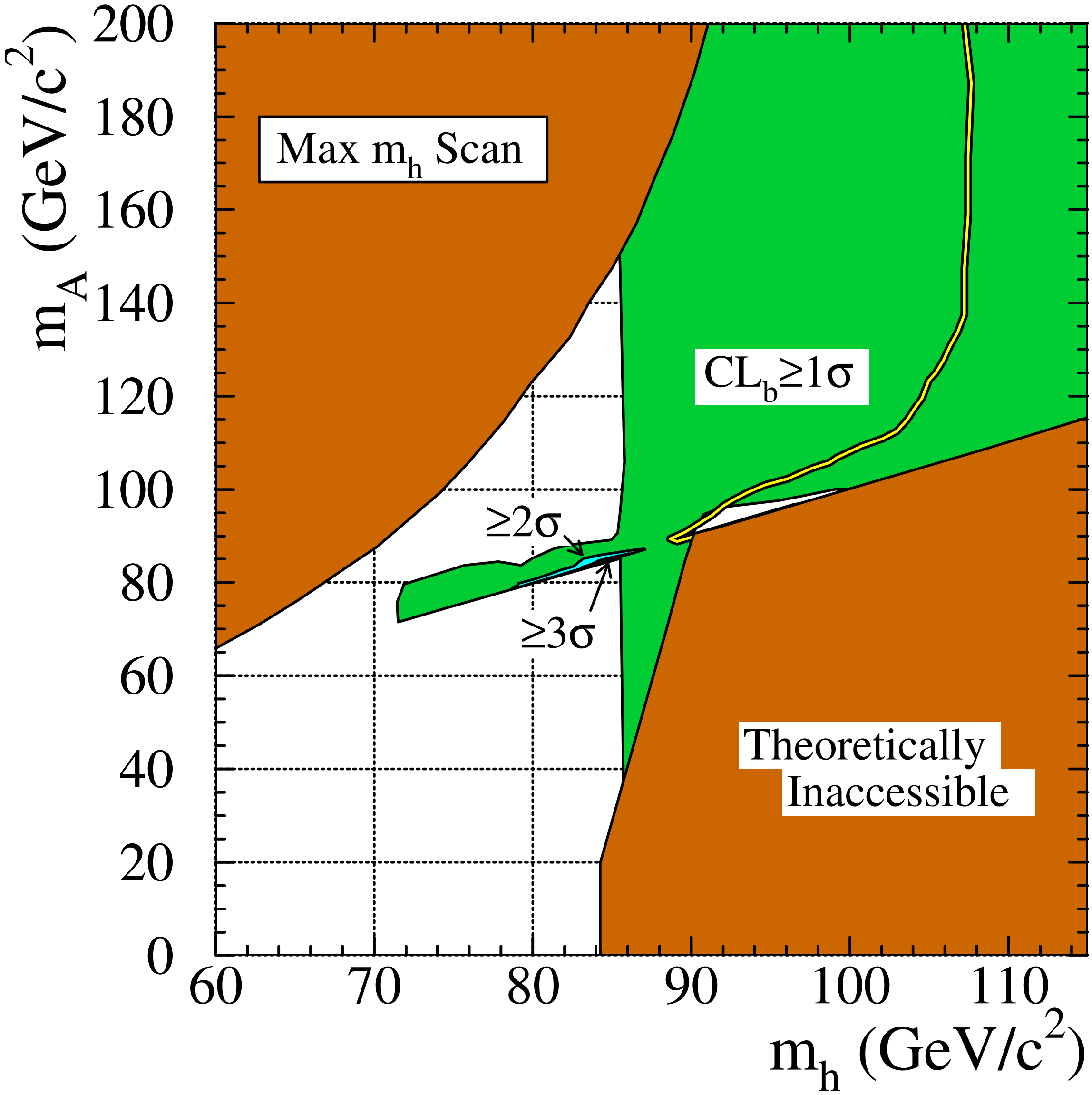


A Hint of Something from Last Summer?



Combining ADLO with 192, 196 GeV data.
Bump at (84,84) is OPAL bbττ only (189 GeV).
Bump at (95,100)?? Just inside sensitivity?
Shared by four experiments. Don't start rumors!

The Full Combination up to 202 GeV

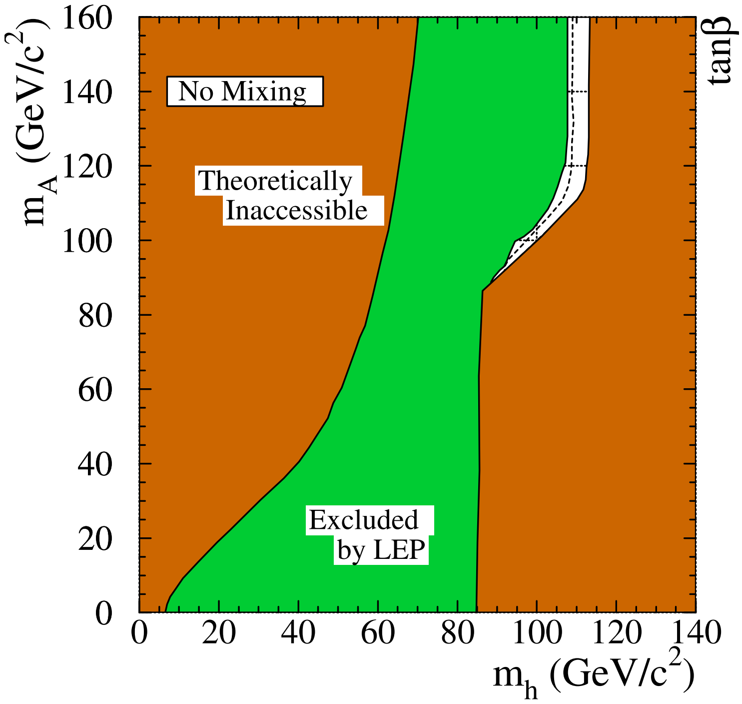


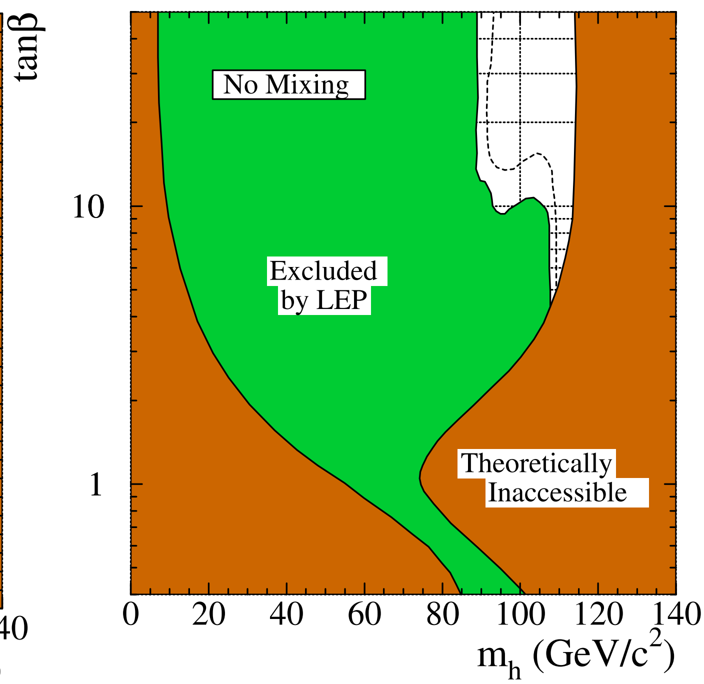
(much) more expected signal, no new candidates there. CL_b back to normal.

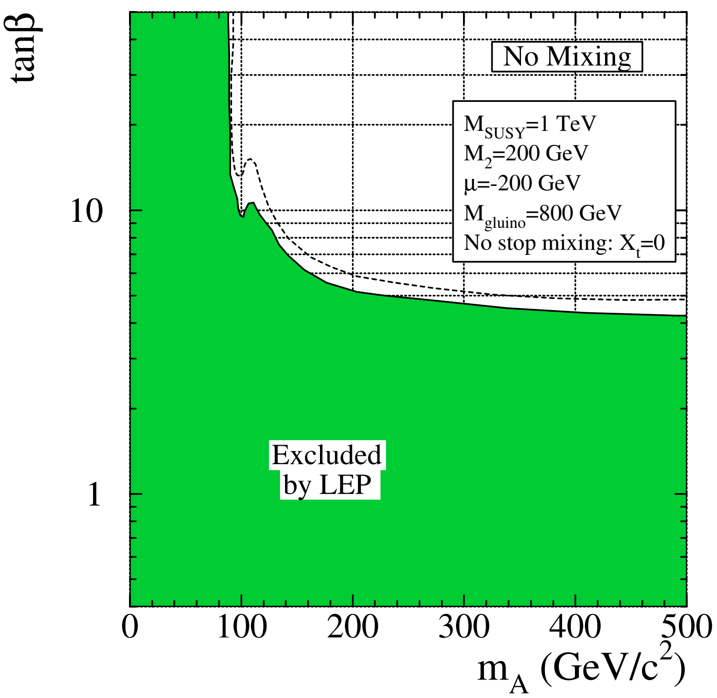
No discovery, but still hopeful!

Still large CL_b at (84,84) -- same 189 GeV candidates. Point is now excluded!

Exclusions in the No-Mixing Scenario







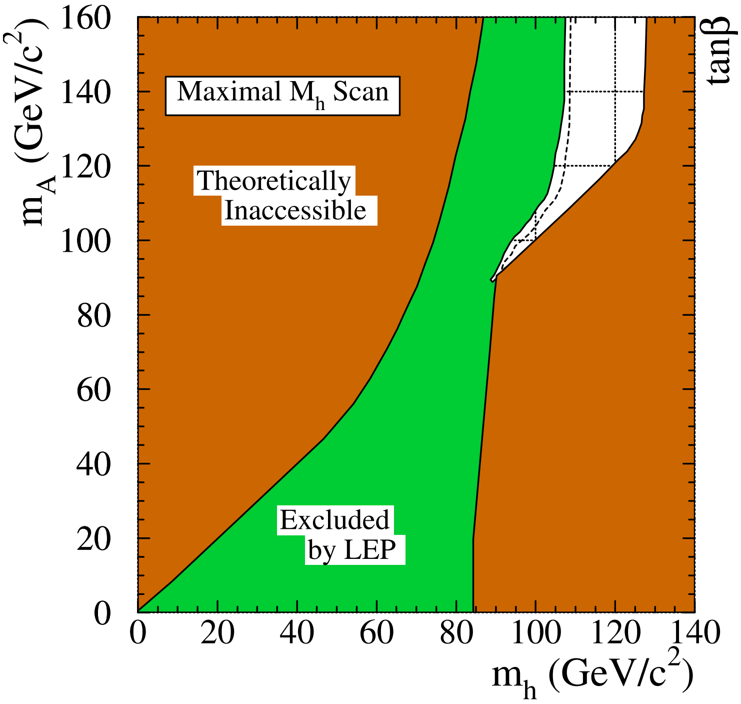
m_h > 88.3 GeV
m_A > 88.4 GeV

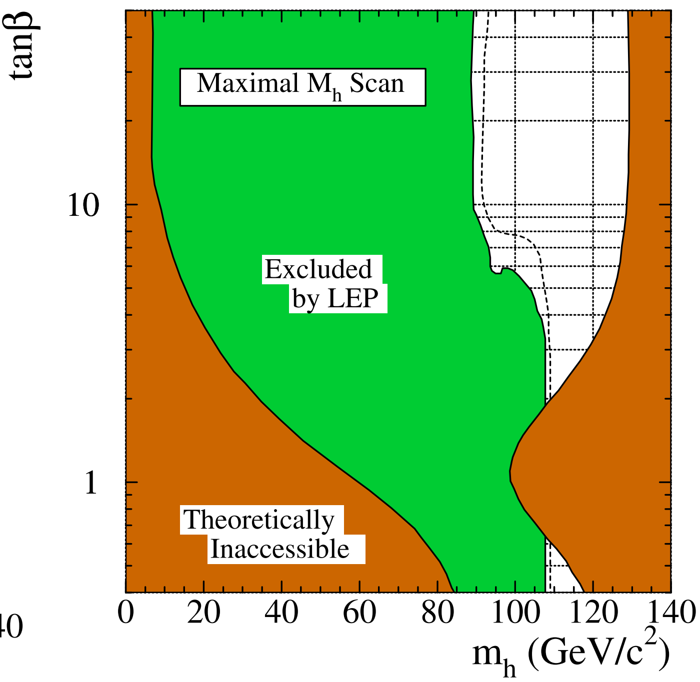
median expectation:
m_h>90.8, m_A>91.1

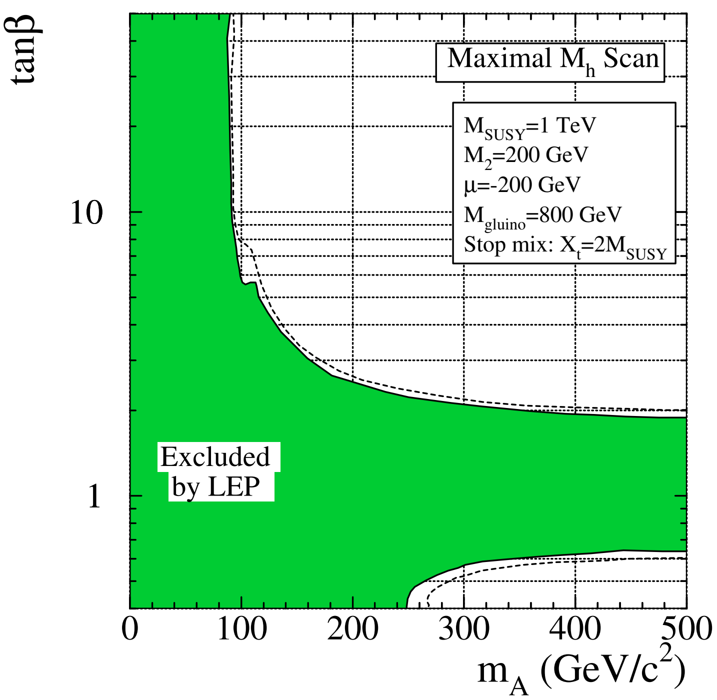
tanβ between 0.4
and 4.1 excluded

Zero stop mixing a casualty soon?

Exclusions in the Max-m_h Scenario







m_h > 88.4 GeV
m_A > 88.7 GeV

median expectation:
m_h>90.8, m_A>91.1

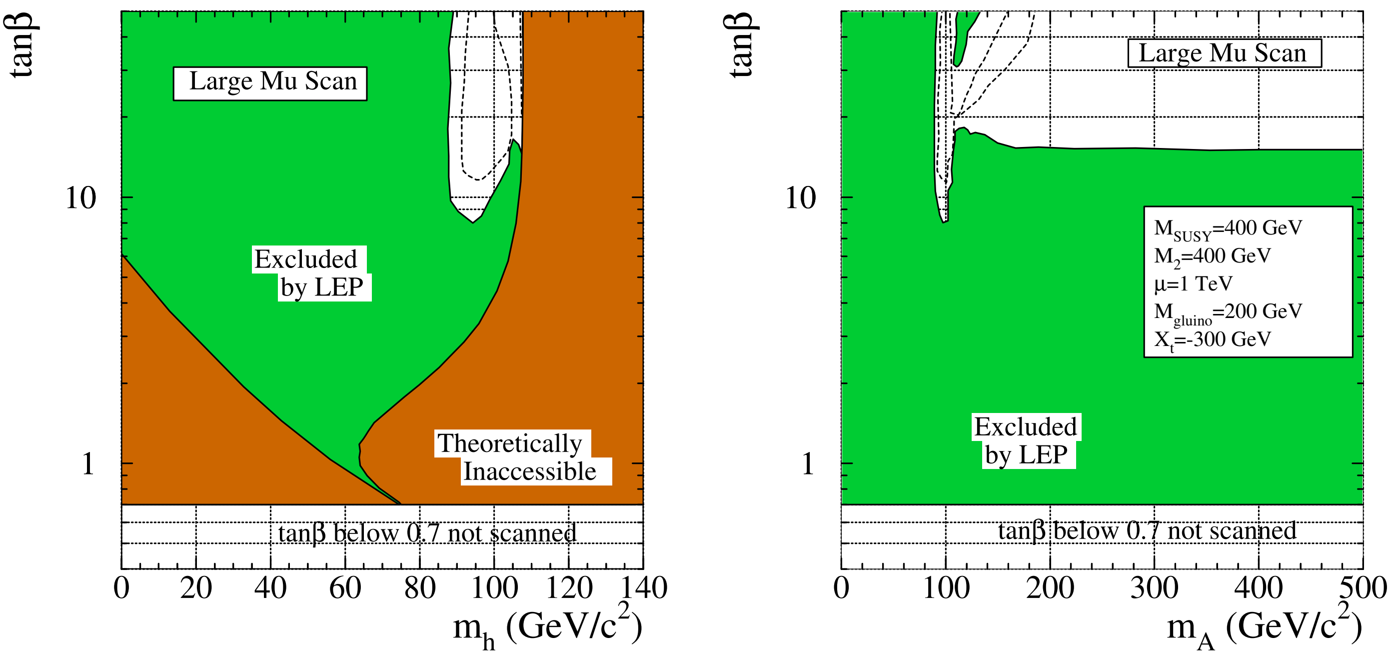
tanβ between 0.7
and 1.8 excluded

Still exclude 0.8-1.5
even if m_t=179.4 GeV
(+1σ of msmt).

The Large-μ Scenario

M_h < 108 GeV through most of param. space.

Easy to exclude most of this! But low $Br(h^0 \to b\bar{b})$ points from cancellation of tree-level and 1-loop sbottom-gluino processes.



A Challenge! How to be sensitive?

- More and more data
- tagless analyses
- Limits by search process -- tau channels help!

Charged Higgs Searches at LEP

Production via s-channel γ/Z^0 exchange.

Assume: $Br(H^+ \rightarrow c\bar{s}) + Br(H^+ \rightarrow \tau^+\nu_\tau) = 1$

and provide results as a function of

$$Br(H^+ \rightarrow \tau^+\nu_\tau)$$

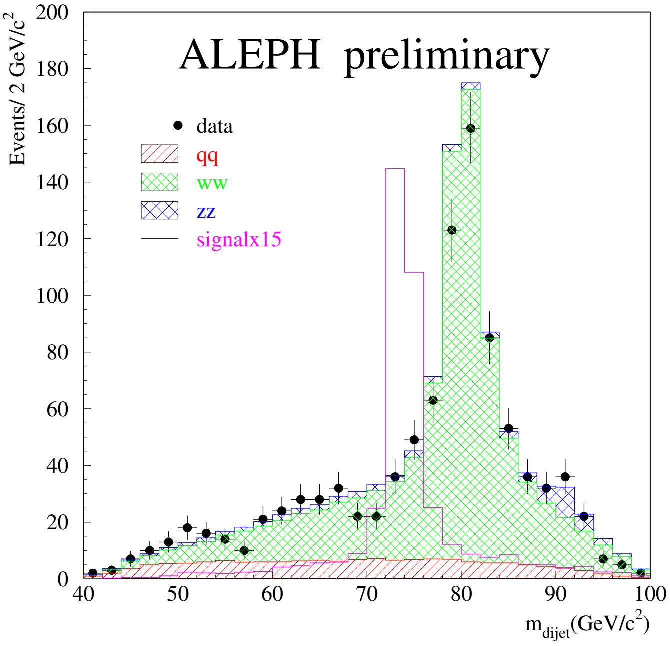
Three search channels:

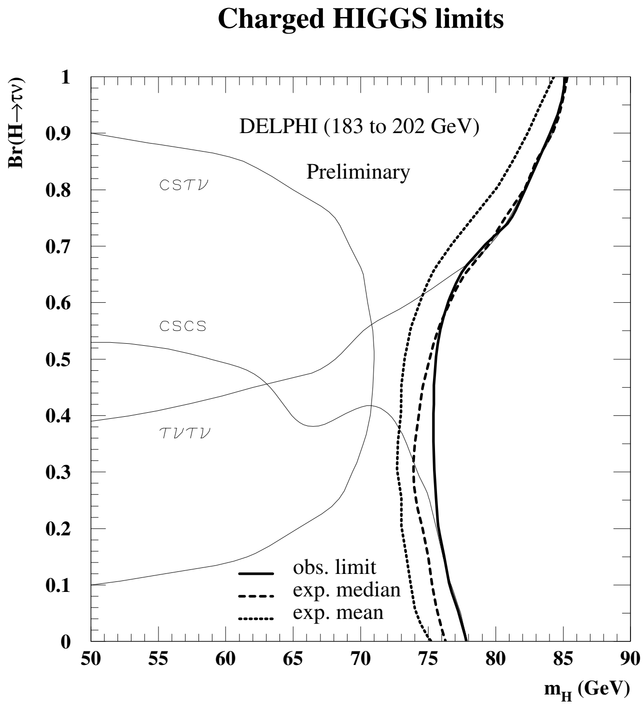
"Hadronic"	four-jets, no b-tagging
"Semileptonic"	two jets, lepton, missing energy
"Leptonic"	two leptons + missing energy
	-- Acoplanar dilepton searches used to look for $H^\pm$

Main Background: W^+W^- production

Can exploit kinematic distributions, known W^+W^- production and decay.

Experiment Charged Higgs Results





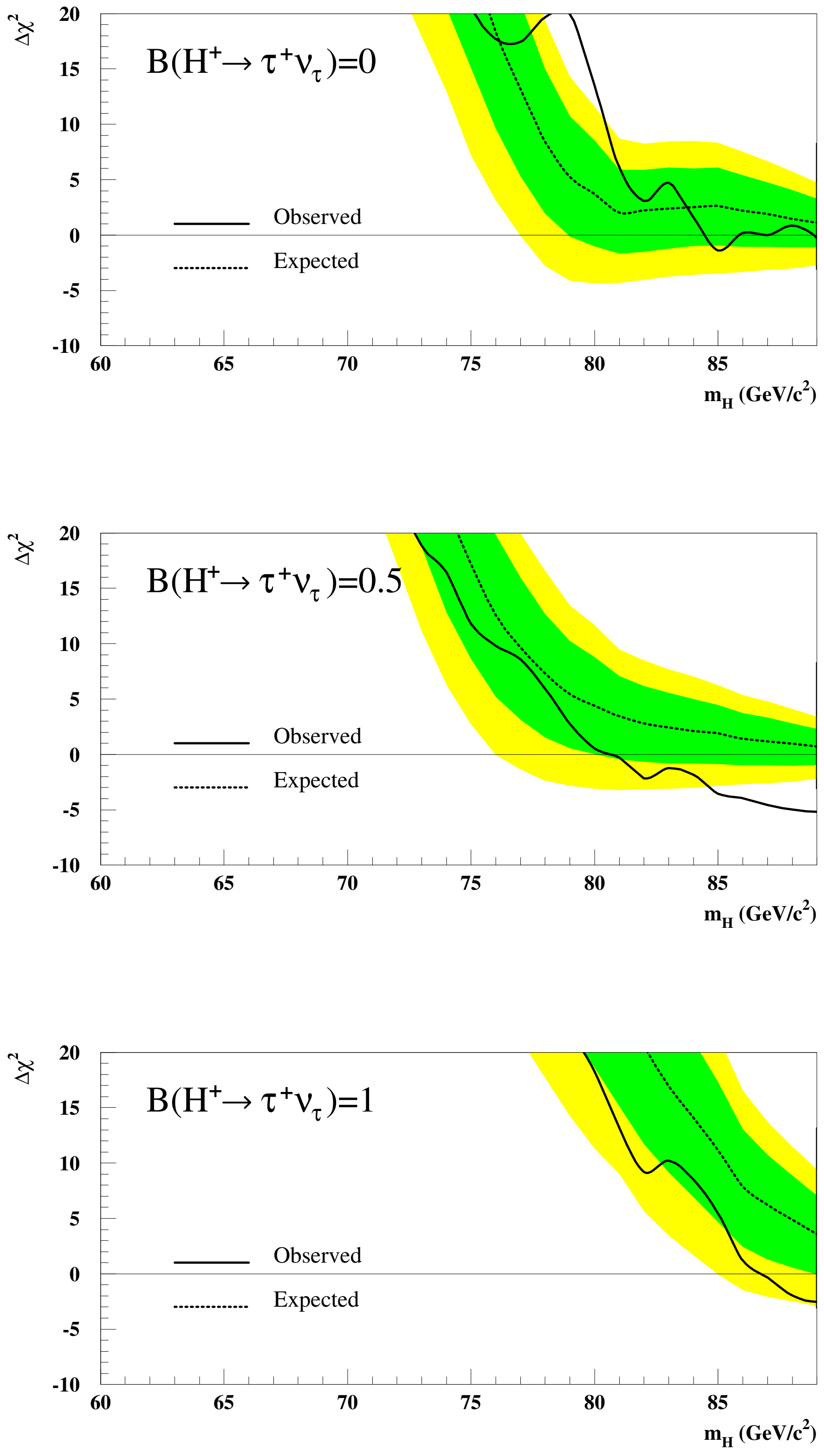
Observed (and median expected) Limits [GeV]

$Br(H^+ \to \tau^+ \nu_\tau) = 0.0$		1.0	Any *Br*
ALEPH	81.2(78.1)	81.8(84.6)	77.7(76.4)
DELPHI	77.8(76.3)	85.1(85.3)	75.4(73.9)
L3	74.0(74.1)	79.3(79.2)	65.0(73.2)
OPAL	70.7(73.0)	74.7(79.0)	70.7(72.5)

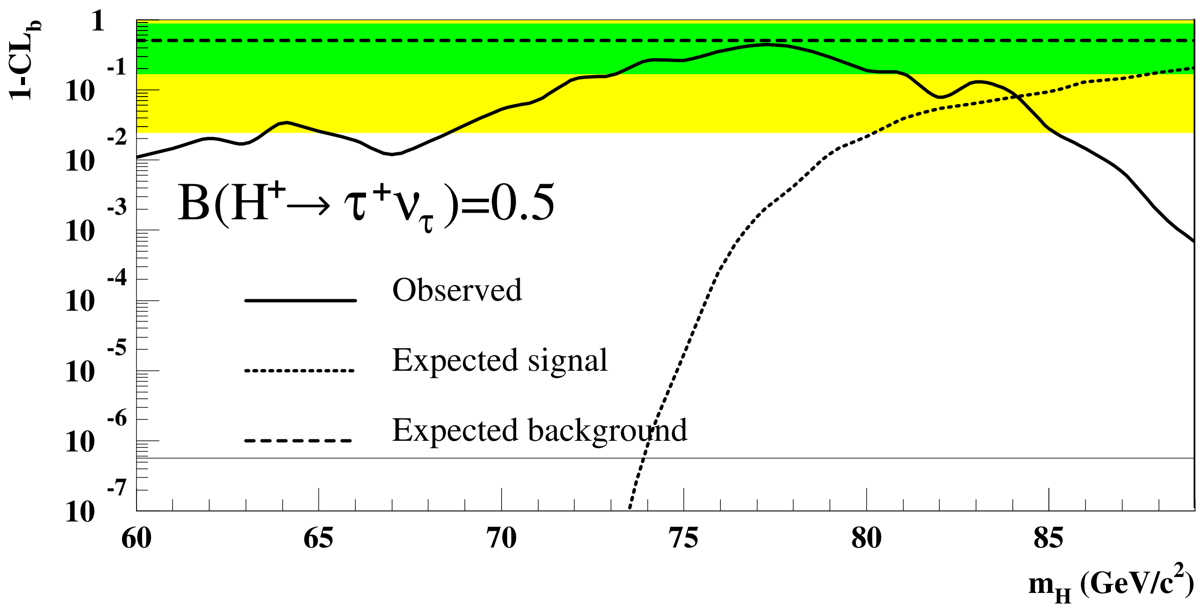
Note: OPAL gives *mean* expected limits.

Not kinematically limited (background limited)
-- can gain sensitivity from combination!

LEP-Combined Charged Higgs Search Test-Statistic



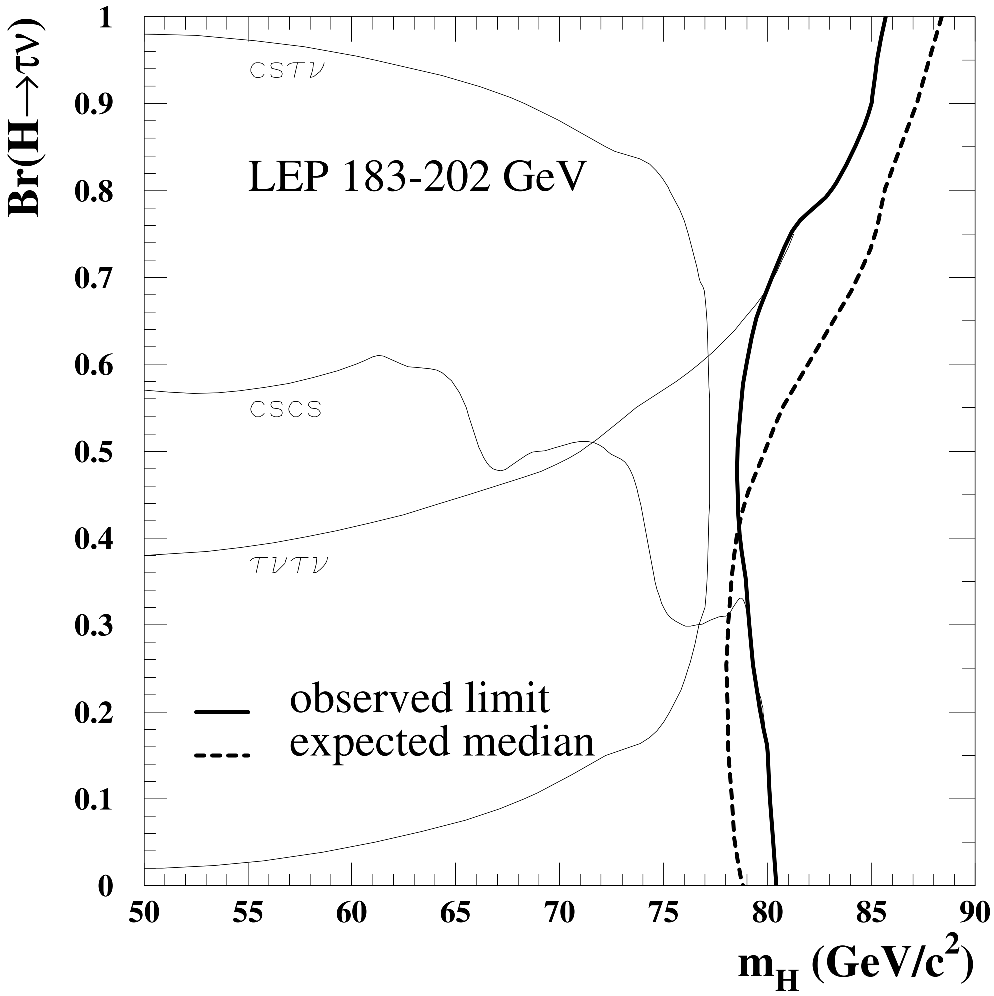
An Excess in the Charged Higgs Combination?



Excess seen for $Br(H^+ \to \tau^+ \nu_\tau) = 0.5$
in the $\Delta\chi^2$ distribution -- but the signal expectation
is too small to expect that excess even if there
is a signal. Still only a 3-ish sigma effect.

We'll keep an eye on it!

LEP-Combined Charged Higgs Limits



Observed (and median expected) Limits [GeV]

$Br(H^+ \rightarrow \tau^+ \nu_\tau) = 0.0 \quad 1.0$ Any Br

80.4 (78.8) 85.7 (88.4) 78.6 (78.0)

2-7 GeV increase in sensitivity

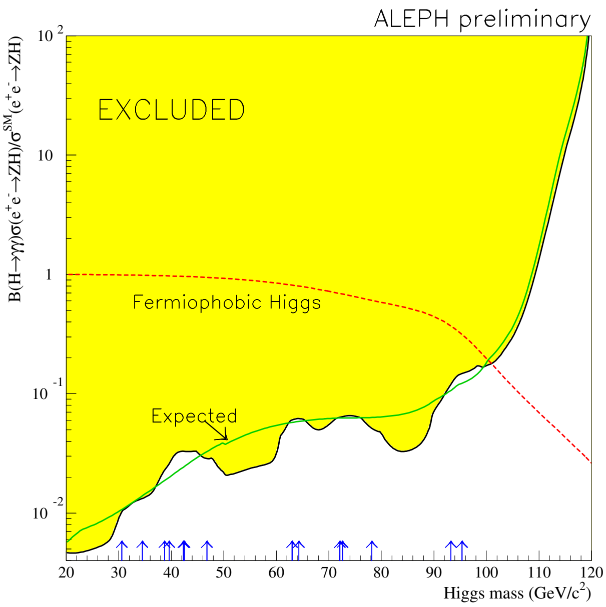
Searches for $H^0 \to \gamma\gamma$

Small SM branching ratio, but very clean search: $qq\gamma\gamma$, $ll\gamma\gamma$ and $\nu\nu\gamma\gamma$ channels.

Main Background: double ISR

Limits: assume SM production x-section, place limits on branching ratio.

Mass limit: assume Fermiophobia, sensitivity limited by turnon of $H^0 \to W^+W^-$



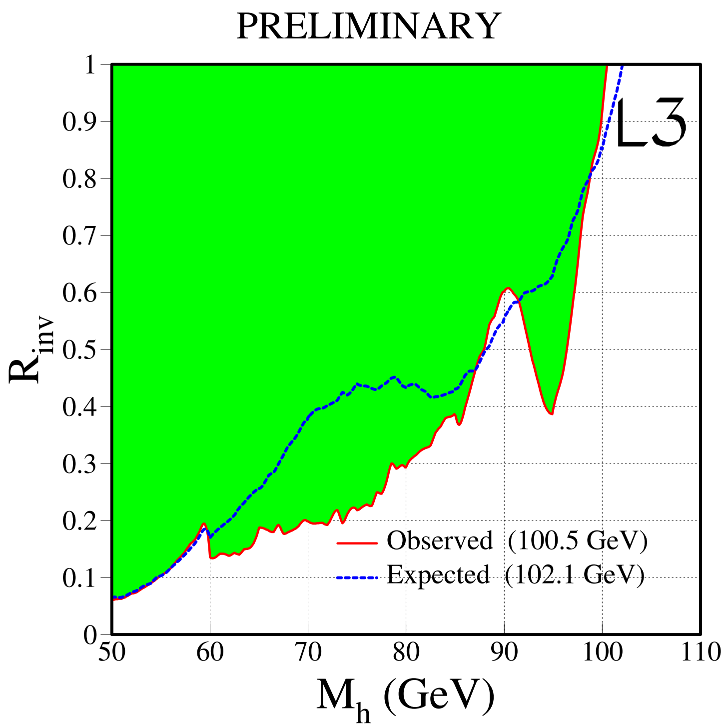
LEP combination of $H^0 \to \gamma\gamma$ scheduled for the near future

Experiment	Fermiophobic limit [GeV]	
ALEPH	101.0	
DELPHI	96.0	($\leq$189 GeV data)
L3	98.8	
OPAL	97.8	

Searches for $H^0 \to$ Invisible Particles

e.g., $h^0 \to \chi_1^0 \chi_1^0$ 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.



To be combined soon!

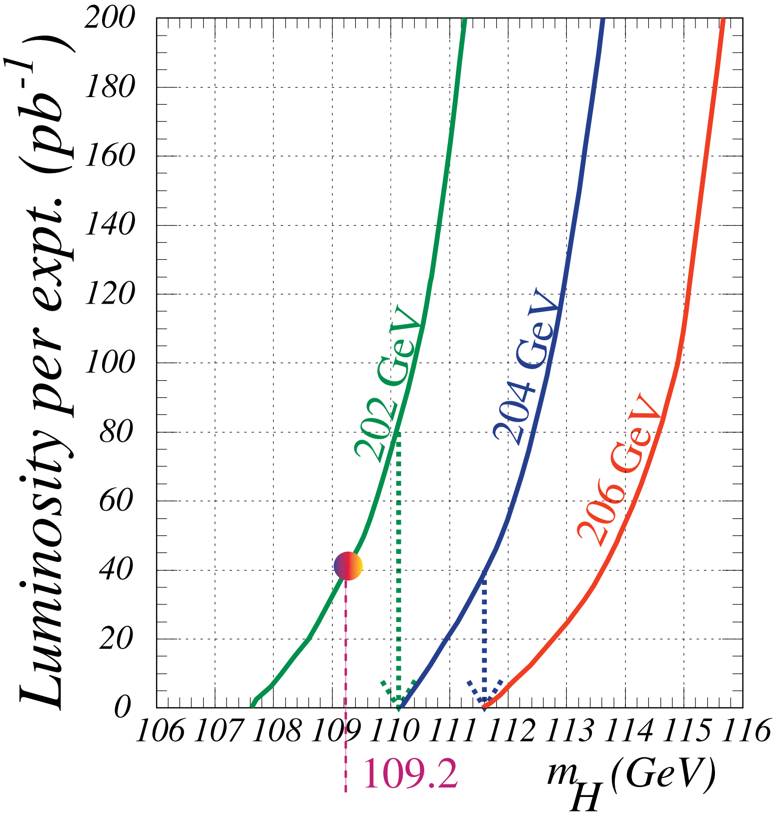
Assuming SM production x-section and 100% invisible decays, obtain these limits [GeV].

ALEPH	106.4	
DELPHI	92.3	(≤189 GeV data)
L3	100.5	
OPAL	94.4	

Optimizing LEP Performance for Higgs Searches

- Increasing energy is most important -- see the effect after only a few pb^{-1}/experiment
- Need to run for a few tens of pb^{-1}/experiment to get full benefit from the new energy
- LEP improvements this year:
  - More RF cavities (old CU ones put back in)
  - Corrector magnets used to spread the bending to reduce synch. radiation
  - Mini-Ramps

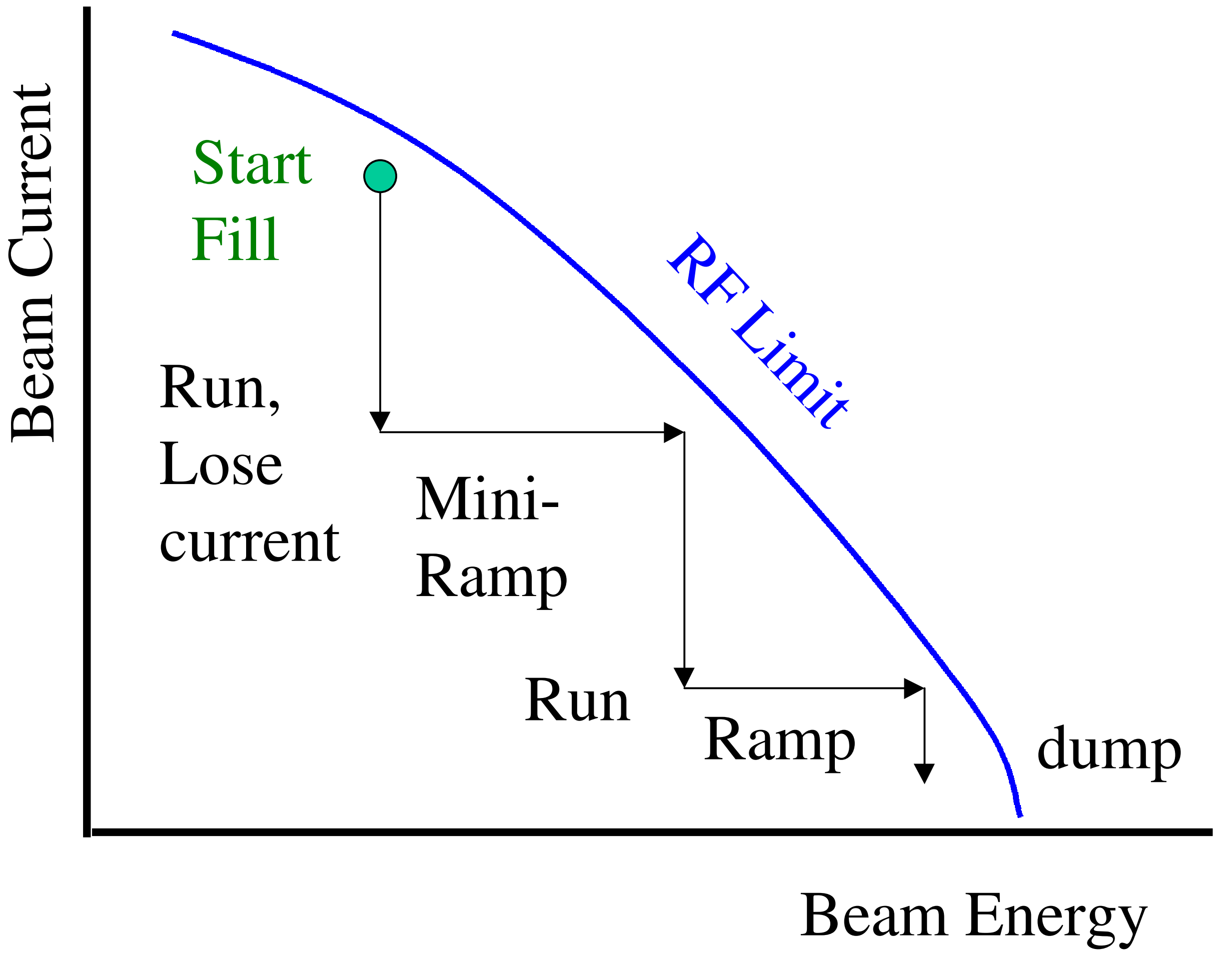
Gross+ Read:



Mini-Ramps at LEP

RF power is limited

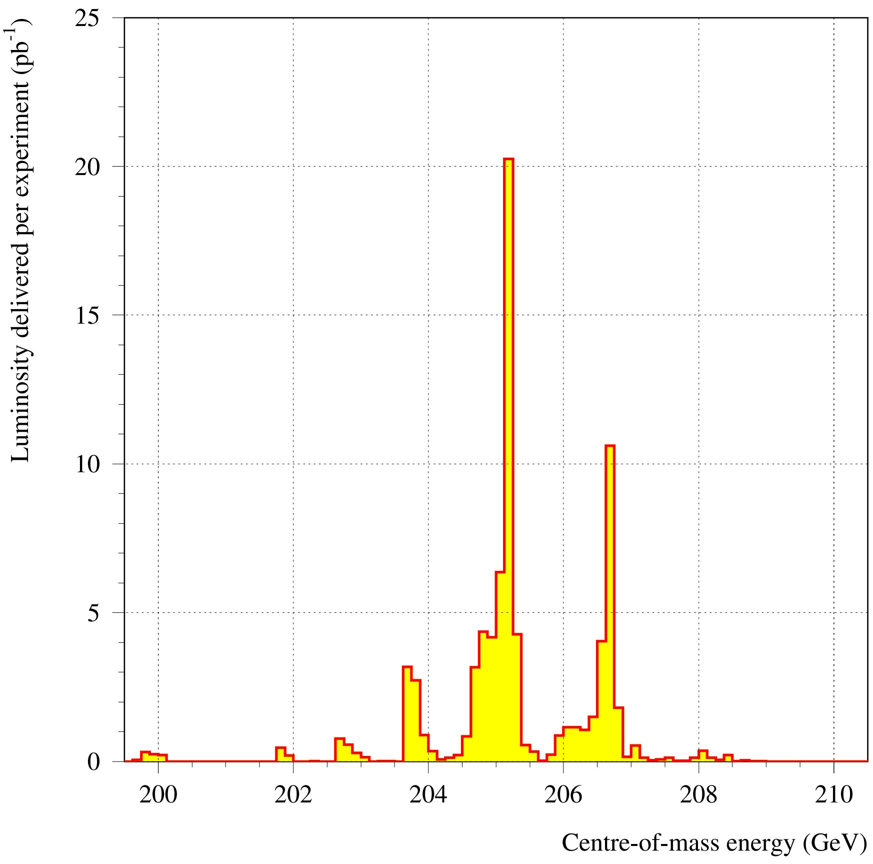
- Cryogenic load (mostly solved with early LHC cryo plant installation)
- RF Trip probability increases with energy and beam current



Energy Samples Collected by Experiments

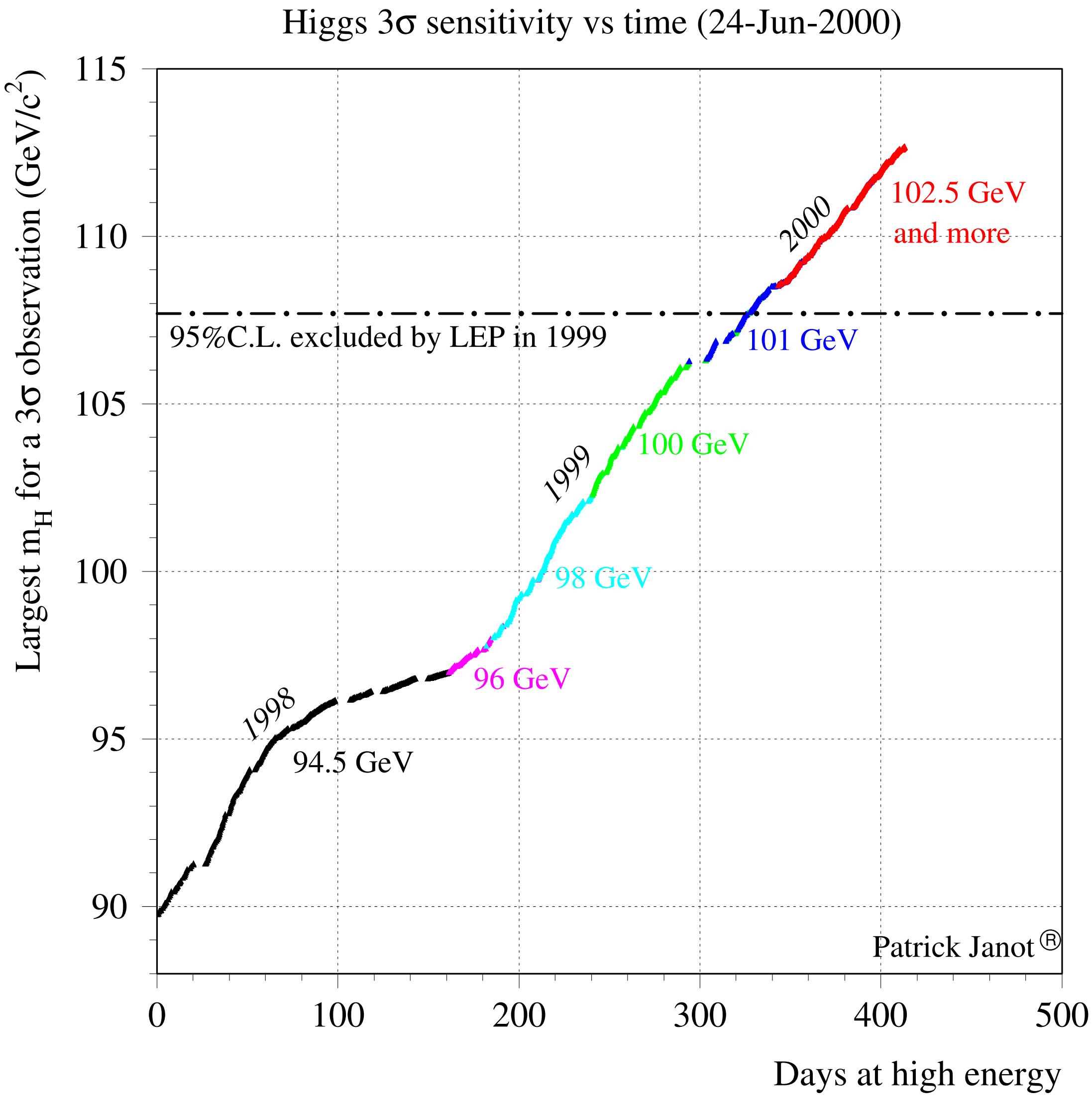
LEP Performance plots updated daily
by Patrick Janot

http://alephwww.cern.ch/~janot/LEPCO/



Approx 75 pb^{-1}/experiment so far this year at high energy (as of 24 June).
Top energy so far: 208.7 GeV (only 0.2 pb^{-1} total for the four experiments, though!)

3σ Sensitivity Increase for SM Higgs as the Run Progresses



3σ Sensitivity still increasing at a rate of 1.0 GeV every 15-20 days of running

LEP2 Potential not fully exploited yet.
Need to run longer, and push the energy

LEP Higgs WG
Plans for This Year

- First preliminary exchange of results 19 June
- Bugs fixed, all MC results frozen, test combinations 3 July
- Last data update and exchange 10 July
- Combination 10-17 July
- Review by collaborations 17 July
- Open LEPC session **20 July**

Decide on Run Extension
if anything interesting is seen

- Same results for Osaka (experiment update?)
- Another exchange and combination at the end of August -- "Last Chance!"
- September, 2000 Scheduled end of LEP run, start dismantling, if no hints of new particles
- Combine Non-Standard and Model-Independent search results (general 2HDM, CP violating, $\gamma\gamma$, invis., widened MSSM parameter scans ....)

Openness and cooperation among the experiments has been superb!