Higgs searches at LEP – techniques and results

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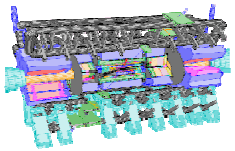
Third Nordic LHC Physics Workshop − Oslo

Outline



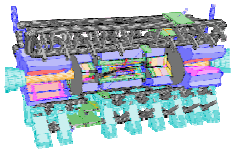
I. Analysis of search results

- Likelihood ratio
- Modified (almost) frequentist
- Widely used at LEP for combining searches
- Consequences for event selection/analysis

II. Application to SM Higgs search at LEP (all results prelim.)

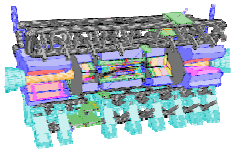
III. Other Higgs searches (all results prelim.)

Questions

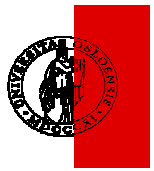


- What we do mean by exclusion, observation, discovery?
- What is a confidence level?
- What is a discovery limit?
- How can we combine searches?
- How do we optimize a search?
- What does it mean, "The lower mass bound on the SM Higgs is 113.5 GeV at the 95% CL"?
- Have we seen the SM Higgs at LEP or not??

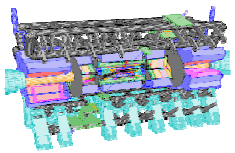
Goals



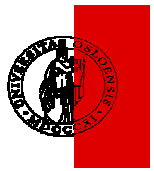
- Exclude, observe, measure in a common framework as much as possible.
- Maximize potential for exclusion of false signals and discovery of true ones.
- Don’t exclude or discover things which the experiment isn’t sensitive to.
- Take experimental errors into account.
- Leave combination with indirect evidence, theoretical preference, etc. for a later stage: search result should be as objective and accessible for later combination as possible.



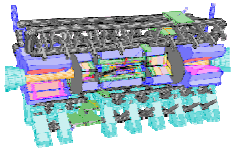
Search rules



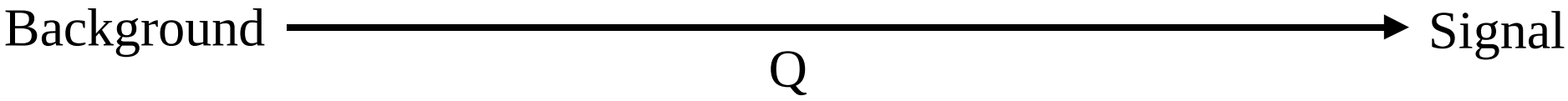
- Formulate search as hypothesis test
  - Exclusion: The signal is absent (or perhaps tiny)
  - Discovery: It looks like a signal and not at all like the background
- Select observables
  - Number of candidates
  - Model−related feature (e.g. mass)
  - Discriminant variable (e.g. b−tag)



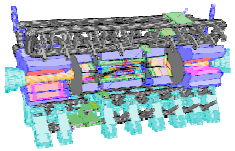
Ordering



- Select a test−statistic (ordering principle): Any function of the observables and model parameters
  - Many proposed at Confidence Limits workshop
  - Several studied in detail by LEP Higgs Working Group
- The test−statistic Q should order the experiments according to the degree to which they support one or the other hypotheses.



Search rules



- Define how to reach a quantitative conclusion
  - Exclusion: incompatibility with signal+background

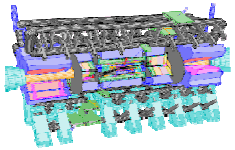
$$CL_{s+b} = P(Q_{s+b} \leq Q_{obs}) \leq 0.05 \qquad CL \equiv 1 - CL_{s+b}$$

  - Discovery: incompatibility with background (in direction of signal)

$$1 - CL_b = P(Q_b > Q_{obs}) \leq 5.73 \times 10^{-6} \ (5\sigma)$$

- This gives frequentist coverage (correct false exclusion and discovery rates) but we want to test signal−only hypothesis!

Modified Frequentist

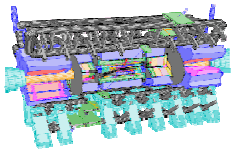


- Confidence in signal−only hypothesis: an approximation (conservative) one might obtain if the background could be removed entirely.
  - ALEPH (Jin and McNamara) less conservative:

$$CL_s = CL_{s+b} + (1 - CL_b) \times e^{-s}$$

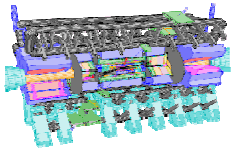
  - HWG: $CL_s = CL_{s+b} / CL_b$
    - Looks like a combined probabilty: $CL_{s+b} \sim CL_s \cdot CL_b$
    - *Happens* to coincide with Bayes (Helene) for counting with flat prior
    - Contains no global parameters

Confidence workshops



- No consensus of what is best or most correct
  - F&C has support of PDG but practical problems
  - Bayes criticised as subjective for reporting results
- CL_s neither strict Bayes nor Frequentist
  - Widely used at LEP (as last step of exclusion)
  - Is robust
  - Is not the main point of the method
- Consensus to publish LR w.r.t. background−only
  - HWG does this (plus mostly obj. interpretation)
  - Combine experiments (difficult for frontier searches)
  - Input to subjective Bayesian analyses

Event counting

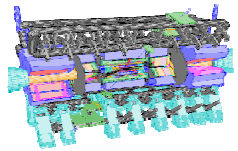


$$CL_{s+b} = P(n \le n_{obs}) = \sum_{n=0}^{n_{obs}} e^{-(s+b)} \frac{(s+b)^n}{n!} \qquad CL_b = P(n_{bg} \le n_{obs}) = \sum_{n=0}^{n_{obs}} e^{-b} \frac{b^n}{n!}$$

$$CI = 1 - \int_0^s g(\mu | n_{obs})\, d\mu = 1 - \frac{\int_0^s \frac{e^{-(\mu+b)}(\mu+b)^{n_{obs}}\, d\mu}{n_{obs}!}}{\int_0^\infty \frac{e^{-(\mu+b)}(\mu+b)^{n_{obs}}\, d\mu}{n_{obs}!}} = \frac{\sum_{n=0}^{n_{obs}} e^{-(s+b)} \frac{(s+b)^n}{n!}}{\sum_{n=0}^{n_{obs}} e^{-b} \frac{b^n}{n!}}$$

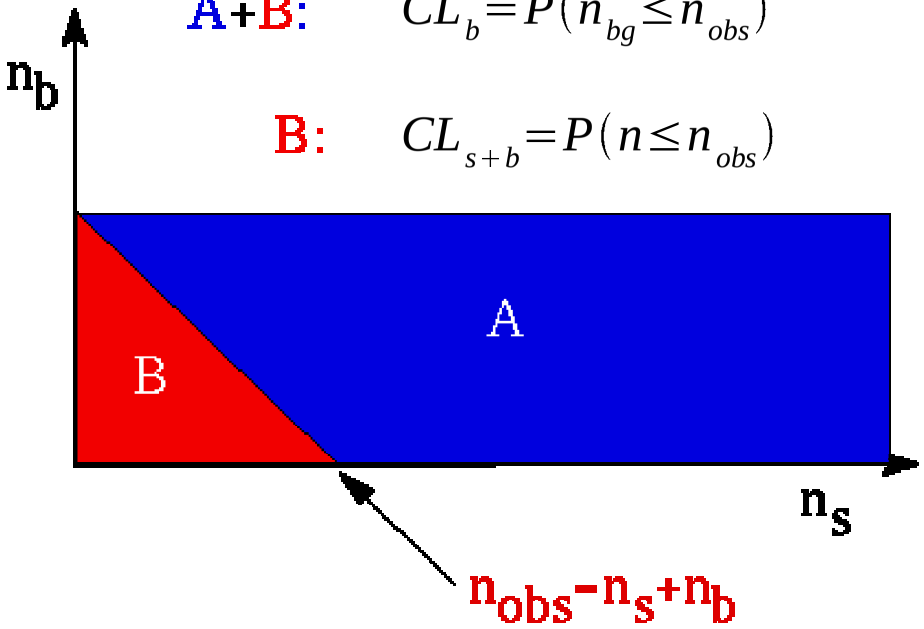
- Modified frequentist $CL_s = CL_{s+b}/CL_b$ **accidently** same as Bayes confidence interval (CI) with uniform prior!

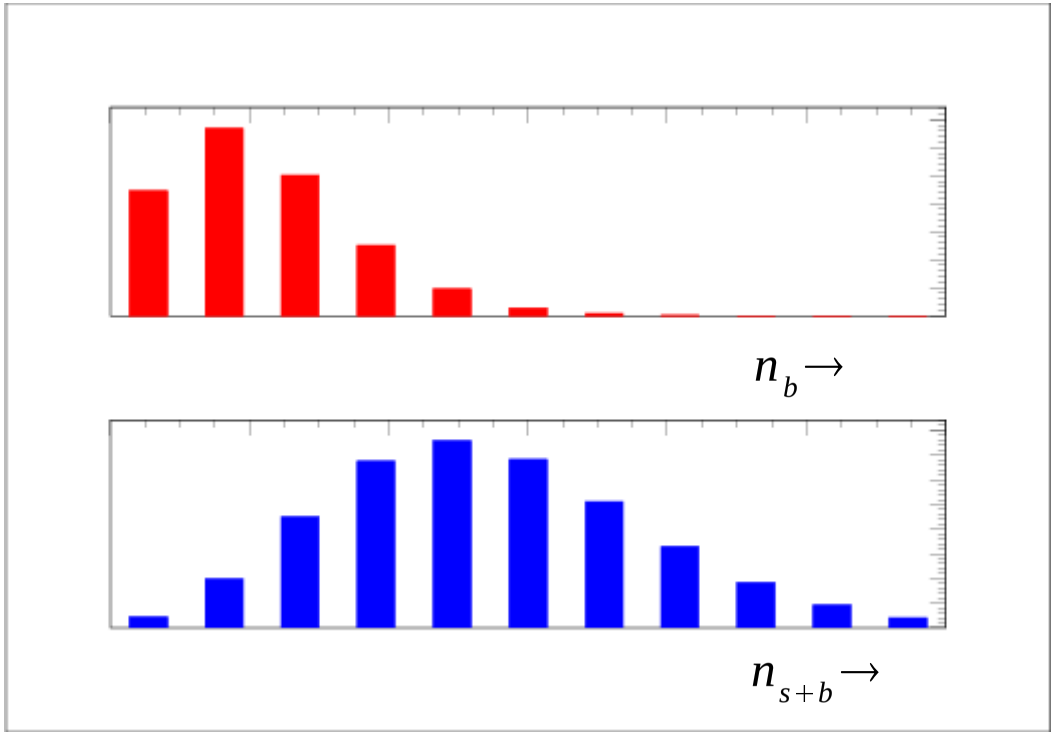
Event counting II



A+B: $CL_b = P(n_{bg} \leq n_{obs})$

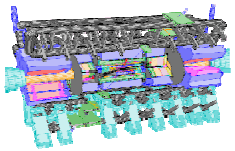
B: $CL_{s+b} = P(n \leq n_{obs})$





- No problems if $n_{obs} >> n_b$

Likelihood ratio

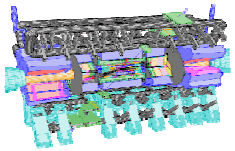


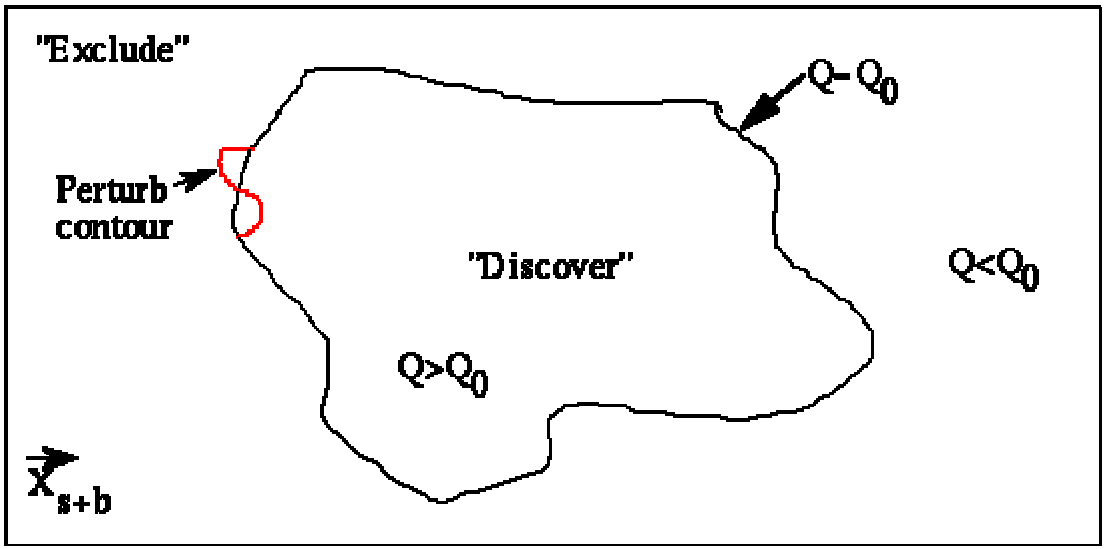
- Appropriate for searches: $Q = \mathscr{L}(s+b)/\mathscr{L}(b)$
- Appropriate for measurements (PDG, Feldman and Cousins): $Q = \mathscr{L}(s+b)/\mathscr{L}(\hat{s}+b)$
- Single channel counting: $\mathscr{L}(s+b) = \frac{e^{-(s+b)}(s+b)^n}{n!}$
- Multichannel/multibin counting:

$$\mathscr{L}(s+b) = \prod_{i=1}^{n_{chan/bin}} \frac{e^{-(s+b)}(s+b)^{n_i}}{n_i!}$$

- s is function of physics model (e.g. Higgs mass)

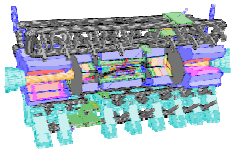
Why likelihood ratio?





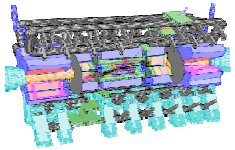
- Neyman−Pearson theorem: argument for searches related to maximum likelihood for measurements.
- Any perturbation of LR contour that separates the exclusion and discovery regions leads to weakened discovery and exclusion potentials.

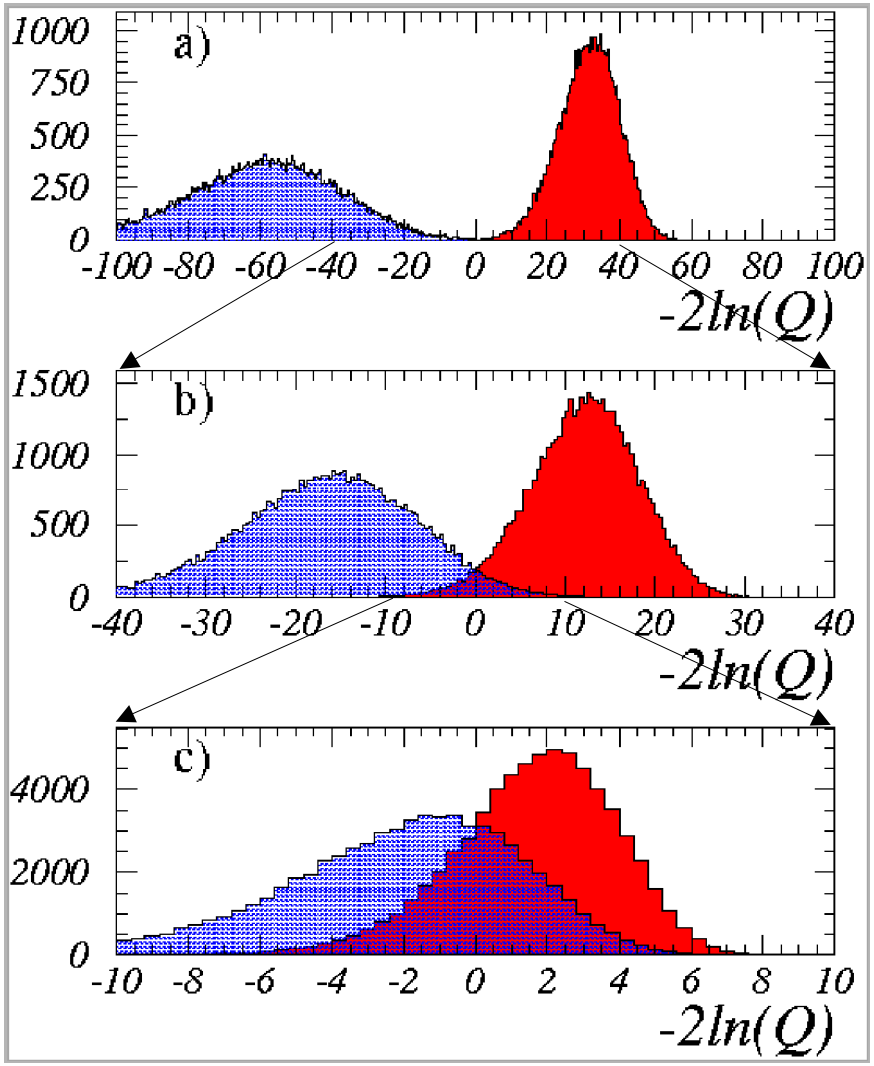
Properties of LR



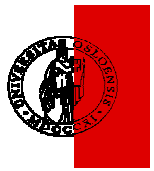
- Maximizes probability to exclude the signal hypothesis when it is false (for specified false exclusion rate, e.g. 5% for exclusion at 95% CL)
- Maximizes probability to exclude the background hypothesis (in favor of the signal) when the signal hypothesis is true (for a specified false discovery rate, e.g. 5.7E−7 for "5 sigma")
- Any other test−statistic (ordering principle) is less sensitive. HWG has studied this empirically.

Likelihood ratio pdf's

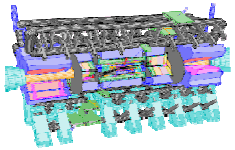




- High sensitivity (e.g. low Higgs mass, large cross−section)
- Moderate sensitivity
- Poor sensitivity (e.g. high Higgs mass)

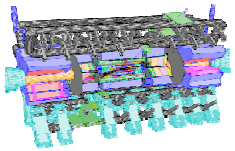


Technical details

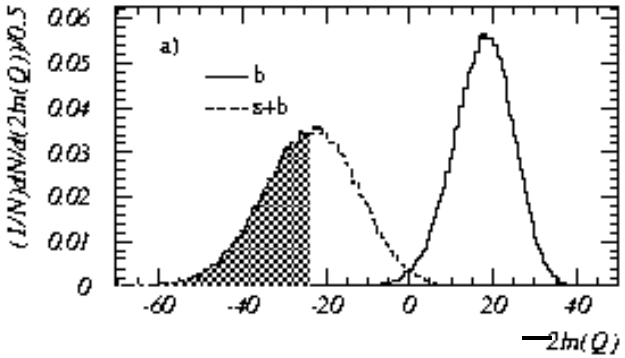


- Different ways to compute pdf's of LR (Gedanken expts.)
  - Sometimes fully analytic (Poisson counting, normal dist.)
  - Analytic with fixed pdf for bg (Janot & LeDiberder)
  - FFT convolution of 1−event pdf (Hu & Nielsen)
  - Iterative, binned convolution (Junk, Schiøtz)
  - Approximate, analytic convolution (Bock)
  - Binned, stratified sampling (Murray)
  - Weighted MC (Read)
- In HWG initialization tends to dominate CPU time.
- Weighted MC fast enough when precision counts, simplest to introduce systematic uncertainties, no tuning required.

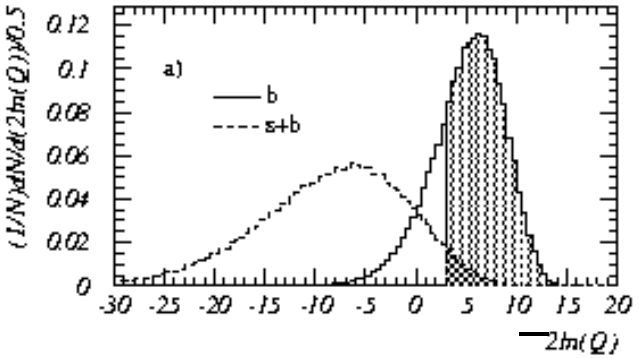
Weighted MC



Discovery

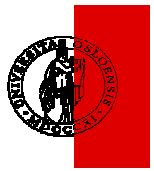


Exclusion

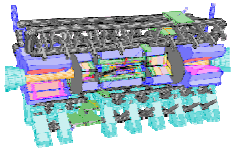


$$2ln(Q)<0:\quad \rho_b(Q)=\frac{\rho_{s+b}(Q)}{Q}$$

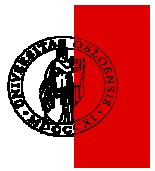
$$2ln(Q)>0:\quad \rho_{s+b}(Q)=\rho_b(Q)\cdot Q$$



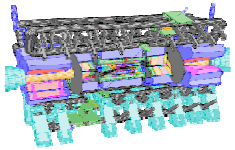
Systematic uncertainties



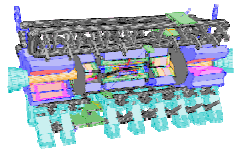
- Background rate, efficiencies, theoretical inputs often uncertain
- Bayesian inference of likelihood distribution for uncertain parameters (and distributions)
  - Gedanken experiments "smeared" by these distributions, experiment by experiment
  - Generalization of Cousins and Highland NIM **A316** (1992) 388 (the MC they used to verify their analytic approx.)
- LR pdf’s are broadened
  - Sensitivities and significances are weakened



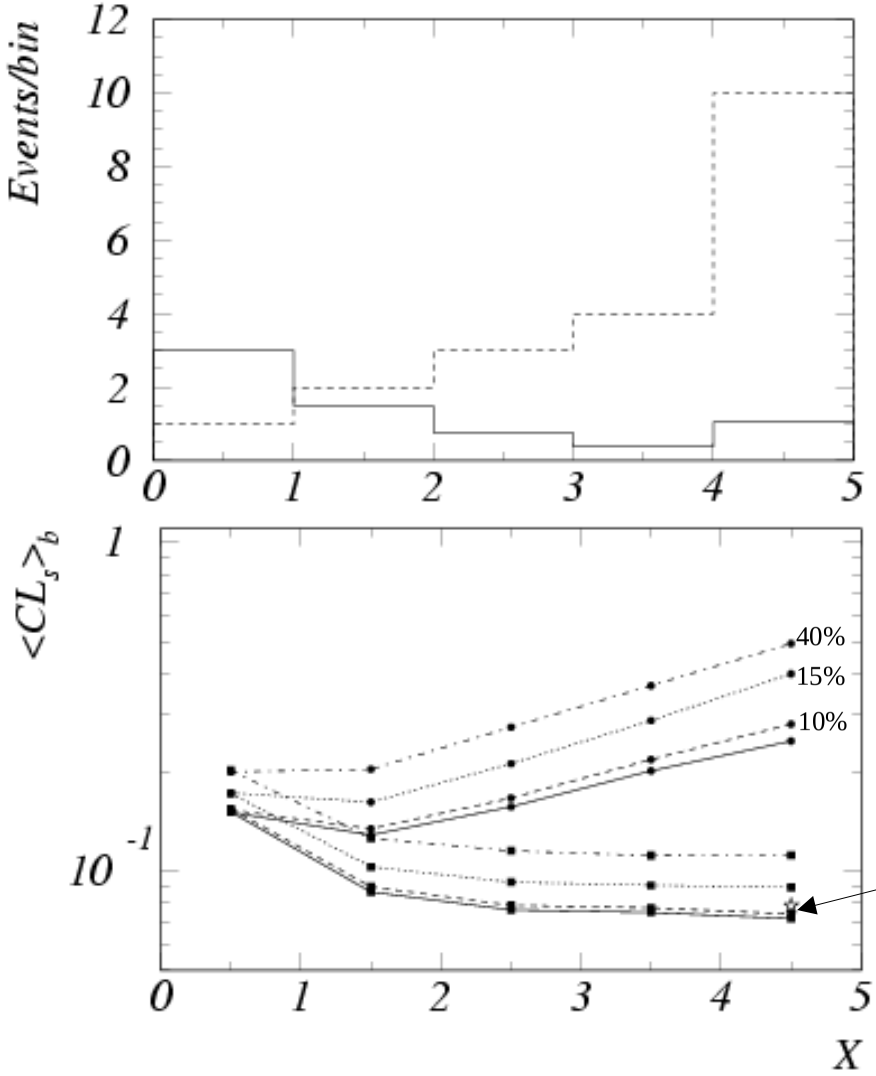
Definitions (sensitivity)



- Exclusion potential: Probability of correctly excluding a false signal (typically at 90 or 95% CL).
- Exclusion limit: The value of a model parameter (e.g. Higgs mass) for which the exclusion potential is 50%.
  - Often called expected limit (and sometimes still computed as mean)
- Discovery potential: The probability of correctly confirming the existance of a true signal and excluding the background−only hypothesis (typically at the 5σ confidence level).
- Discovery limit: The value of a model parameter for which the discovery potential is 50%.

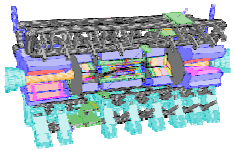


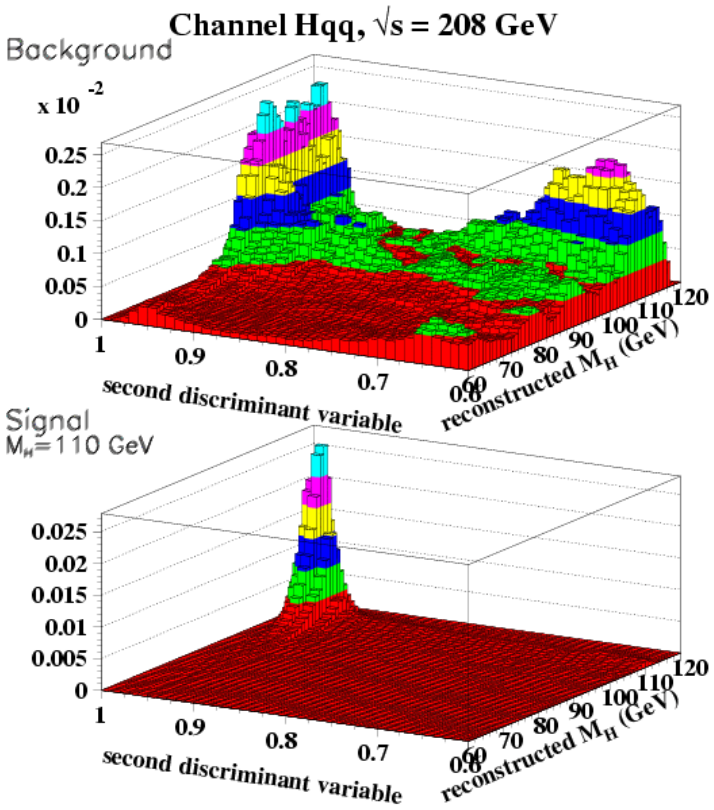
Optimization

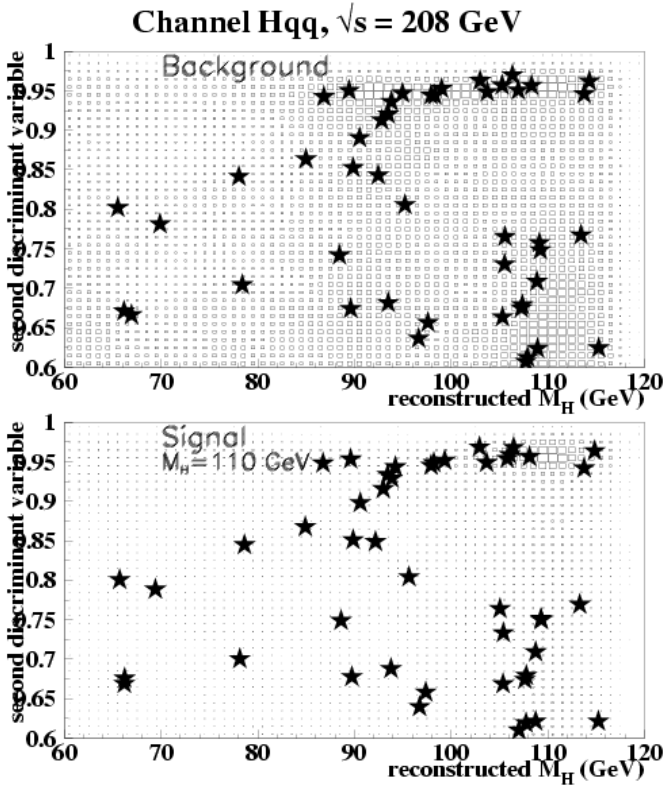


- Binned signal (solid) and background (dashed).
- Adding additional bins
  - Optimal cut for naïve sum
  - No cut best when bins treated independently
  - Remove temptation to tune on data
- Optimization should include syst. Uncertainties: 10%, 40% last bin

2D discriminants

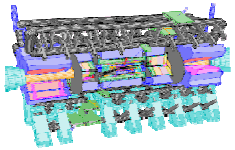




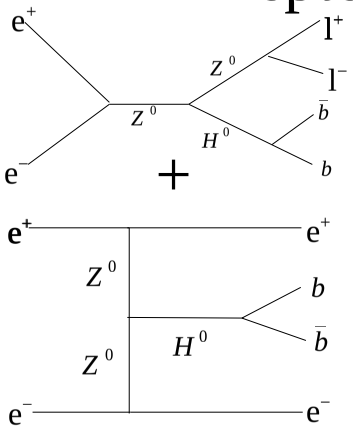


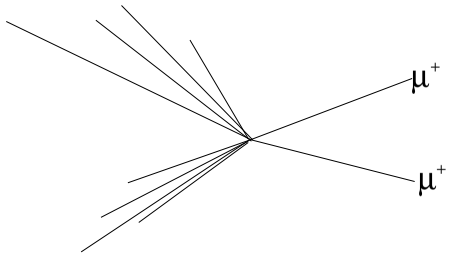
- Take advantage of 2D differences between signal and background (DELPHI gained ~0.5 GeV in exp. Limits).

Higgs search channels

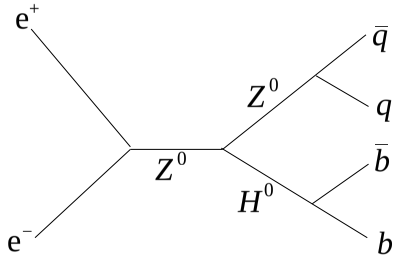


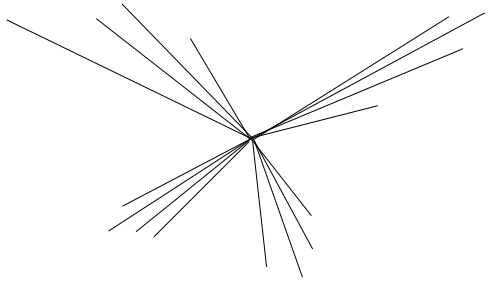
Leptonics (light)



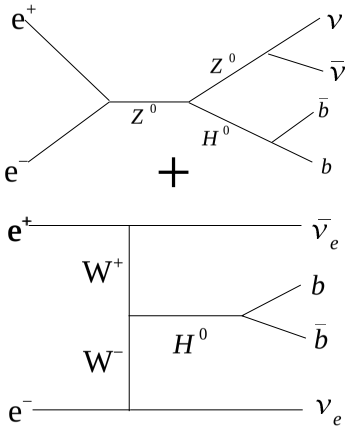


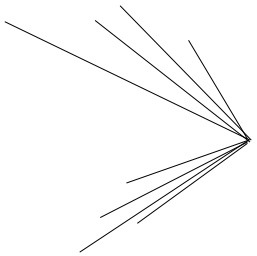
4 Jets



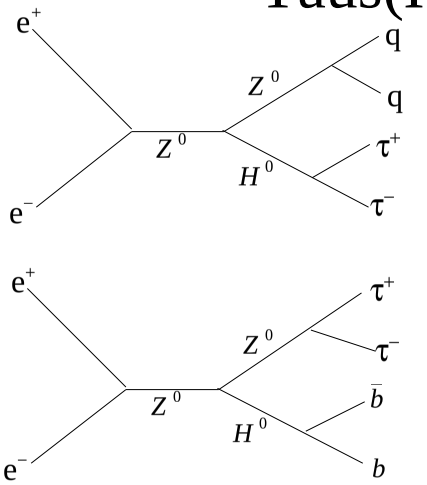


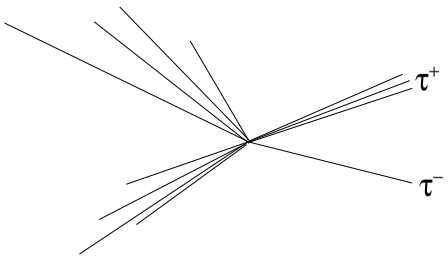
Missing energy



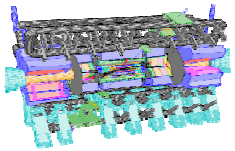


Taus(H or Z decay)





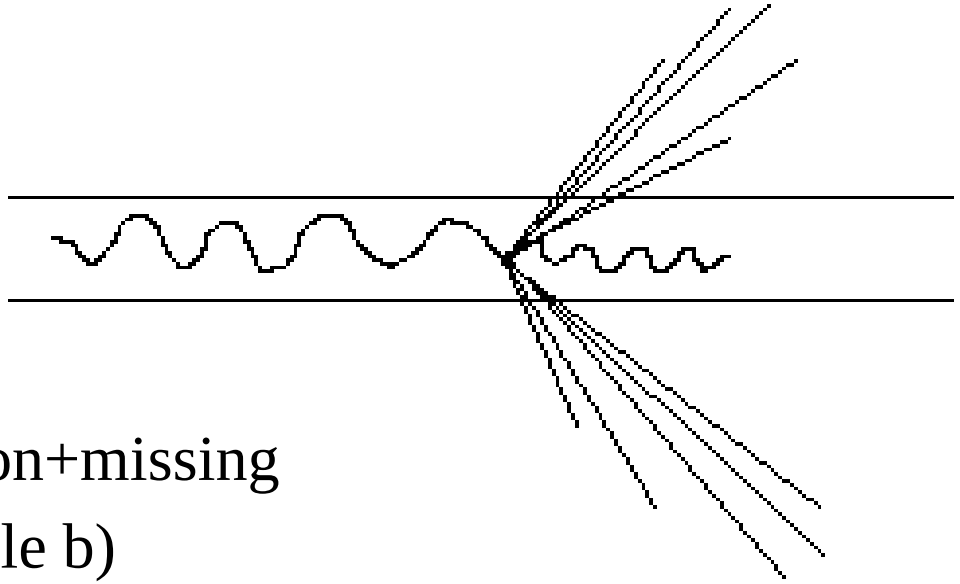
Higgs backgrounds



$e^+e^- \rightarrow Z^0Z^0$ (Z^0bb) : Irreducible (except mass)

$e^+e^- \rightarrow Z^0 \rightarrow$ 4 jets

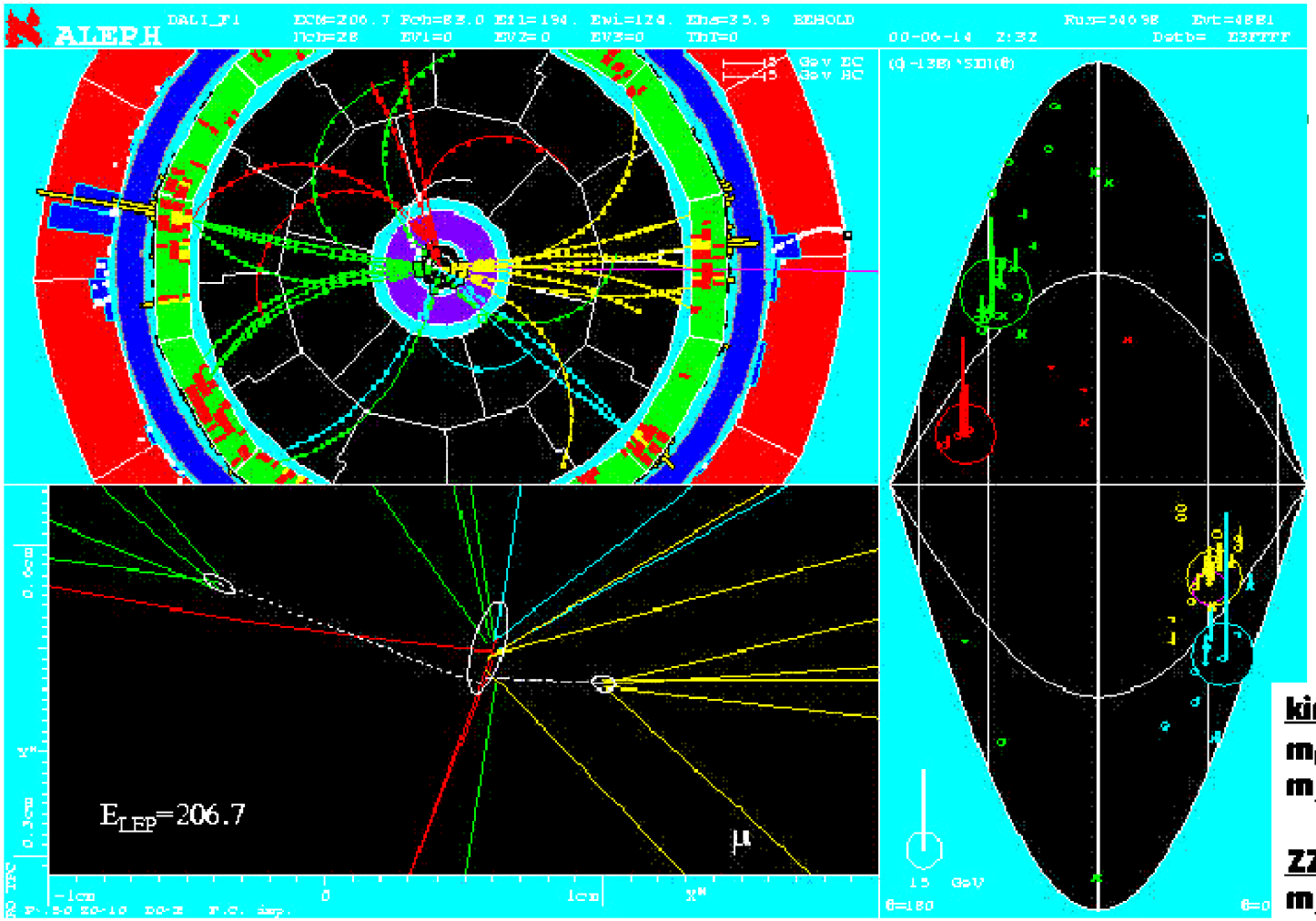
$e^+e^- \rightarrow Z^0\gamma(\gamma) \rightarrow$ 2 jets+missing



$e^+e^- \rightarrow W^+W^- \rightarrow$ 4 jets, 2 jets+lepton+missing

(but extremely little b)

ALEPH 2b candidate



2 b cand.

HZ hyp.
m_H=114 GeV
±3 GeV

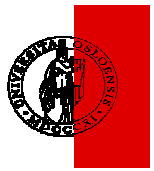
NN = 0.996

jet b-tag:

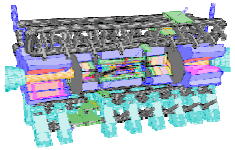
	Z
1	0.14
2	0.01
	H
3	0.99
4	0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

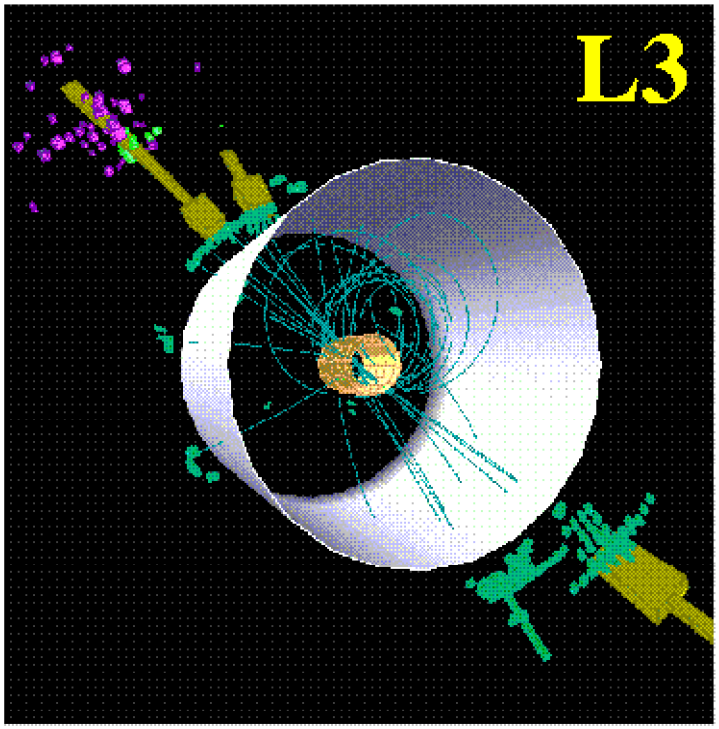
ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV



L3 bbνν candidate

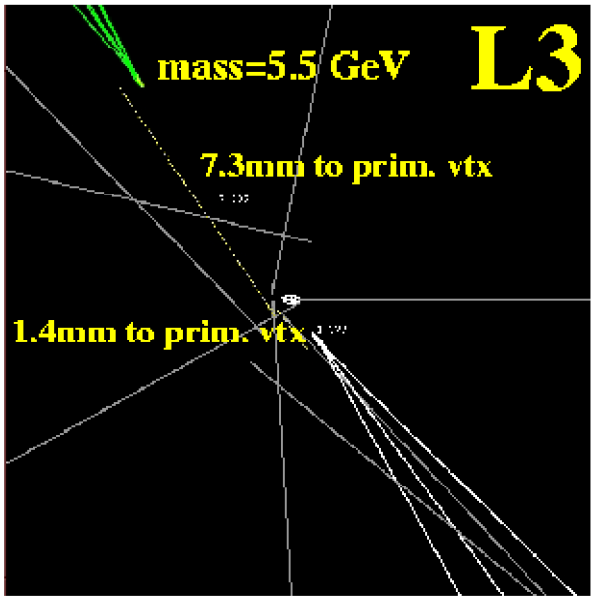


most significant Hνν candidate



measured H mass=114.4 GeV
H mass resolution ~3 GeV

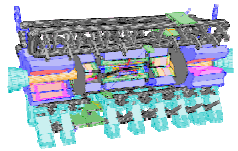
Secondary vtx's view

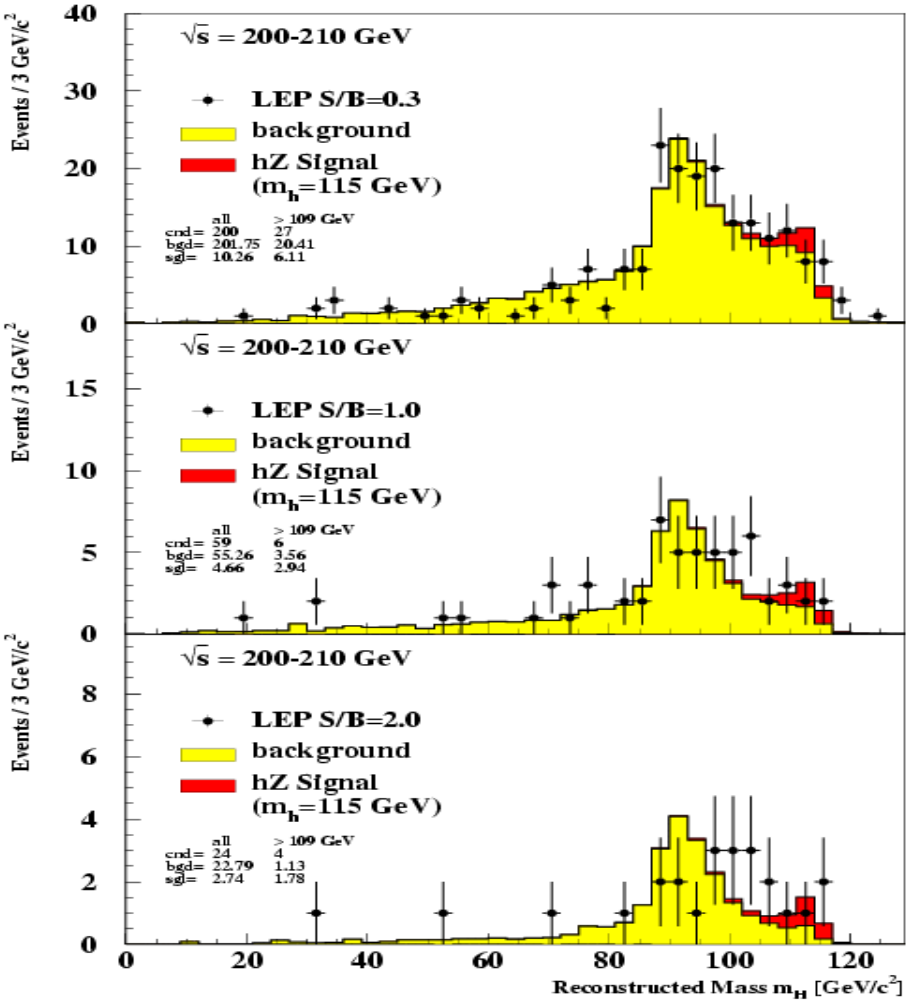


M. Felcini

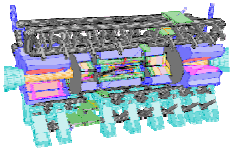
LEPC Meeting, CERN, November 3, 2000

Mass plot for SM Higgs

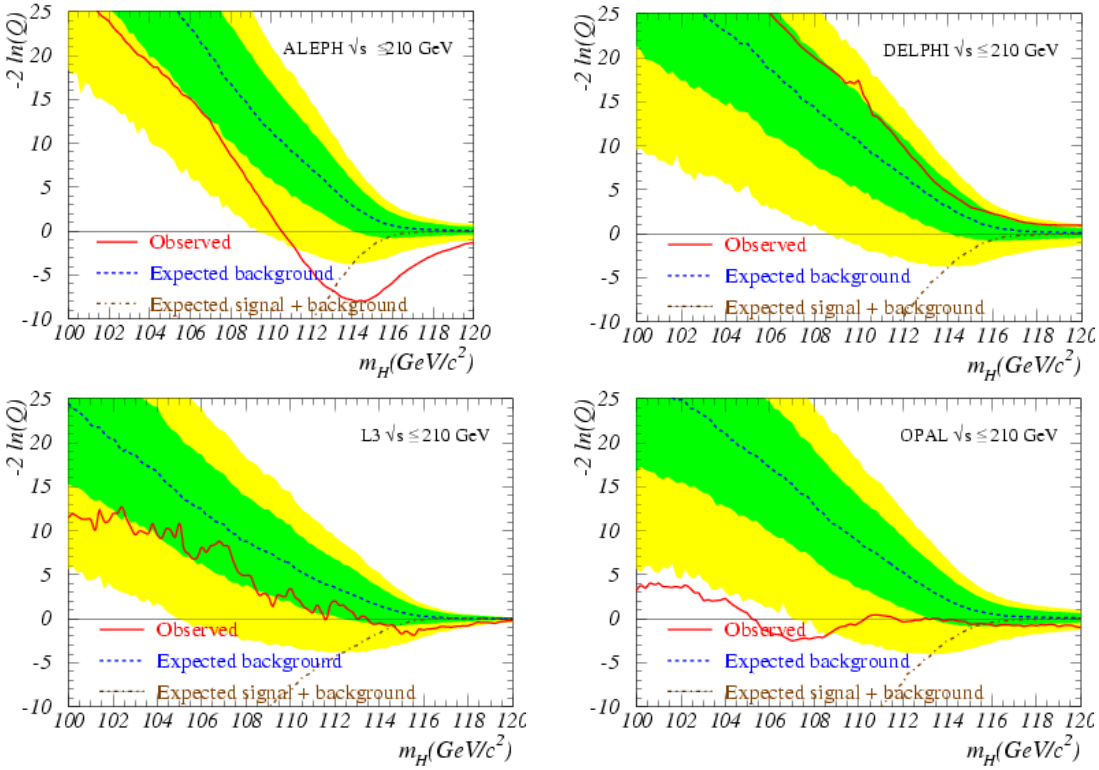




- S/B is integral of mass distribution after cut on Higgs discriminant
  - Naïve combination of channels, experiments
  - So not direct correspondence to −2lnQ



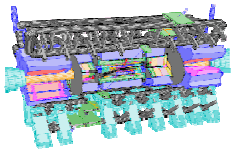
−2lnQ for 4 LEP expts.

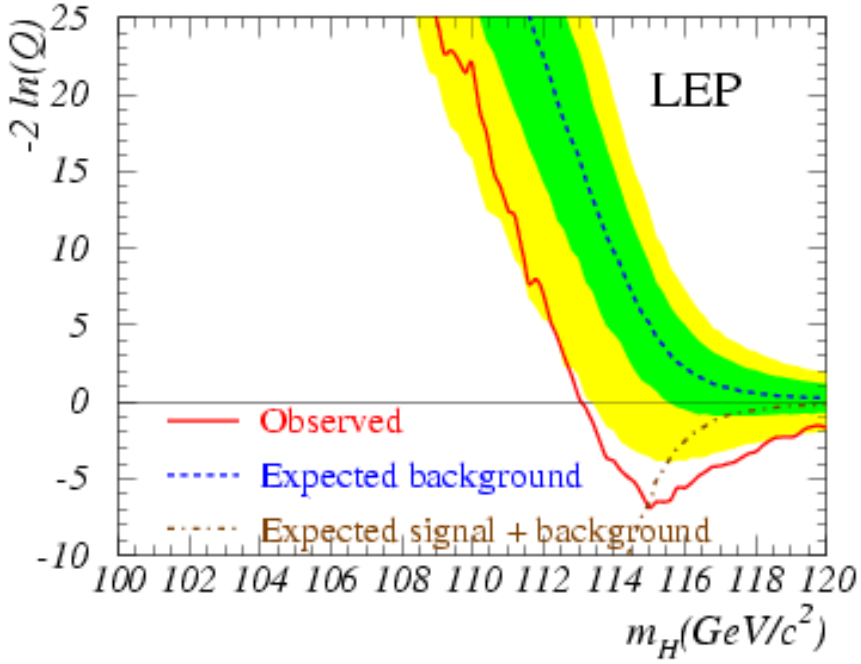


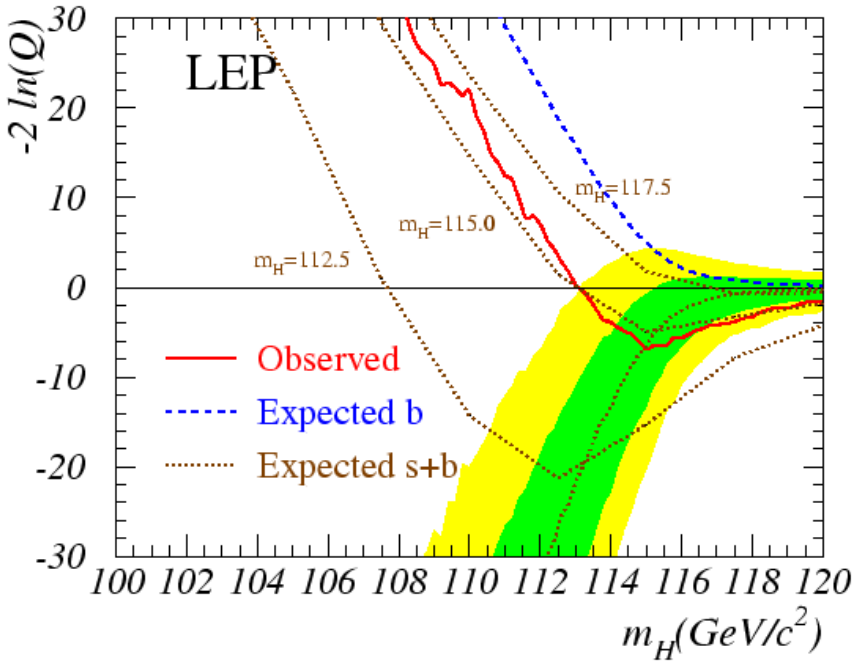
- Below 0 means signal favored
- Bands show +−1,2 σ
- Observed results add linearly (bands, no)

- For large statsistics $-2\ln Q \rightarrow \chi^2$ but we are far from
- Position of minimum is estimator of m_H

Combined −2lnQ

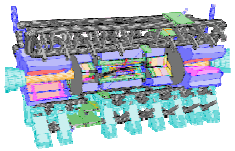


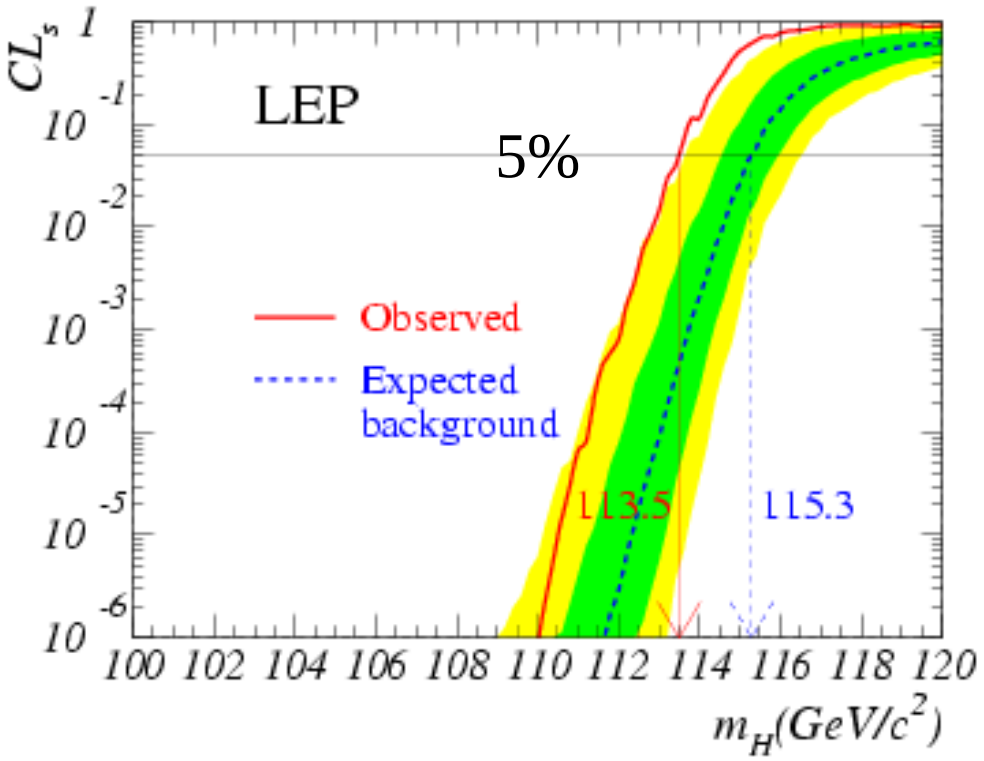




- Long tail of observed result not unexpected for a true signal
  - Recall that mass reconstruction has long tails
  - Observation consistent with 115 GeV Higgs

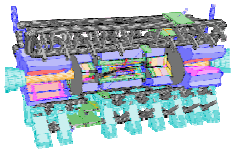
Confidence in signal

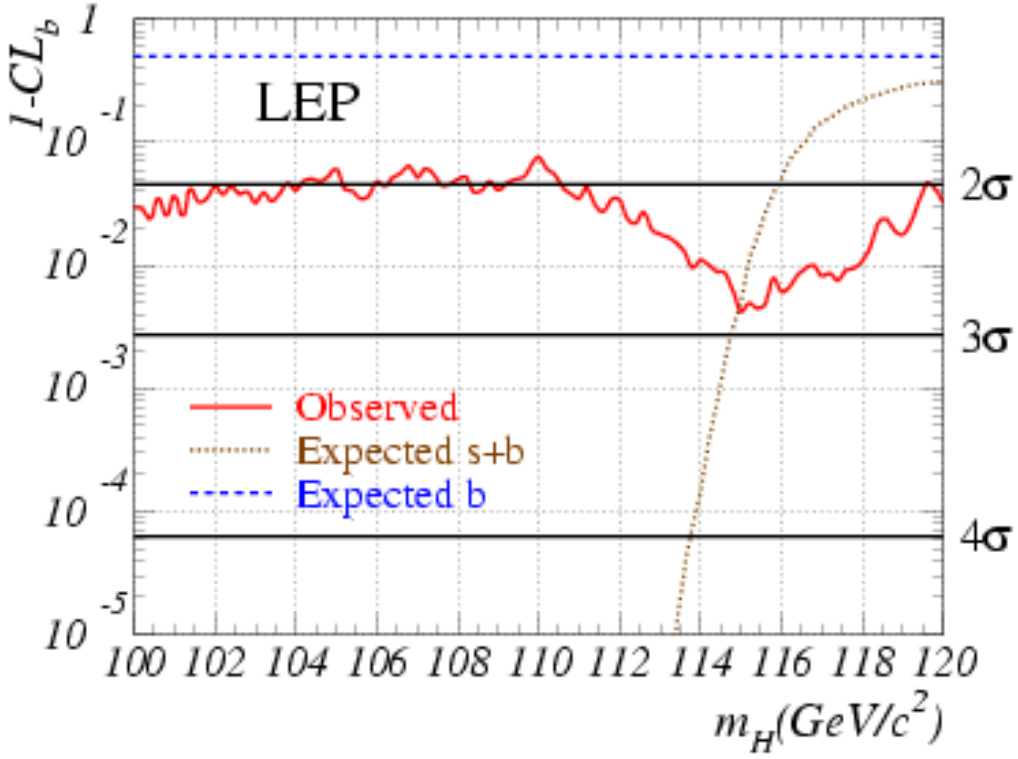




- 95% CL's where CL_s's cross 5%
- 1−to−1 relation between all curves and bands in −2lnQ plot
- Observed limit: 113.5 GeV
- Expected limit: 115.3 GeV
  - Median (50%)

Significance

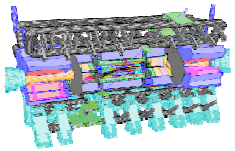


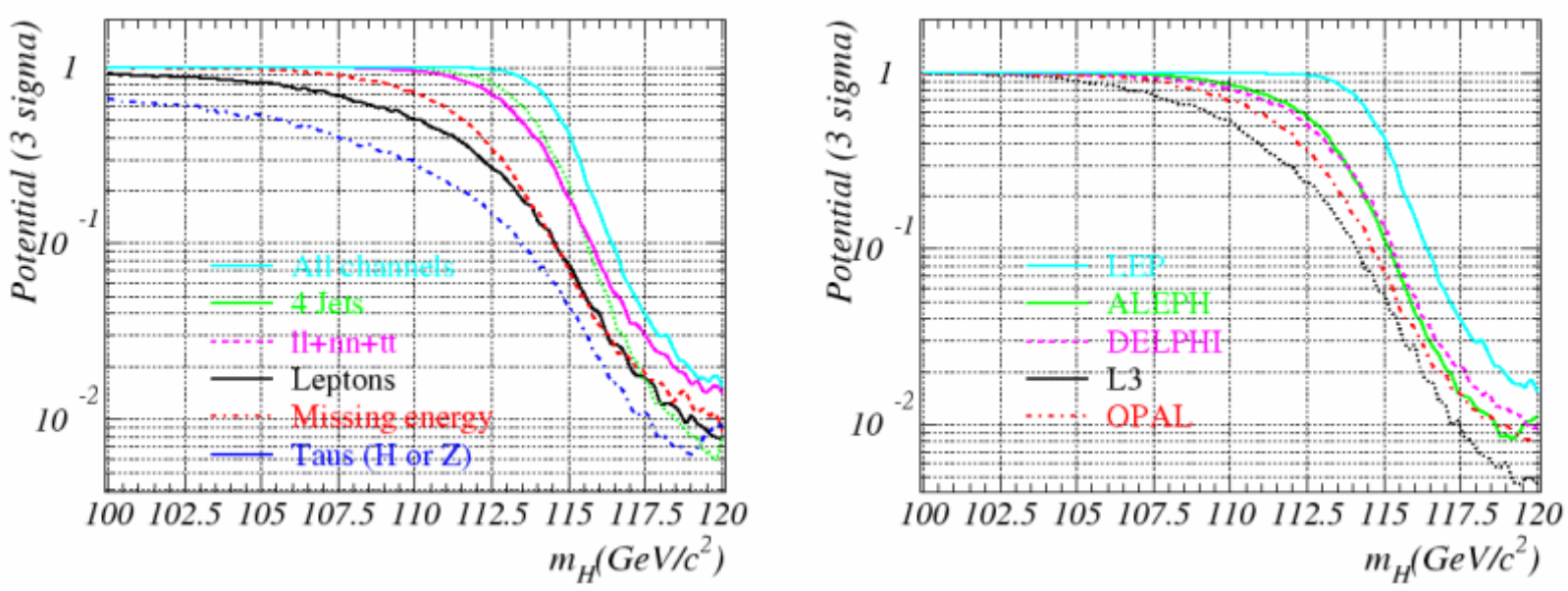


- Read 1−CLb at ML value of m_H
- Look−elsewhere effect!

- 1−CLb indicates degree of background incompatibility (significance of signal)
  - Expect 0.5 for background
- We are looking for fluctuation on 1 side of −2lnQ pdf
  - Single tail of χ^2
  - Double tail of Gaussian
- Expect signal tail

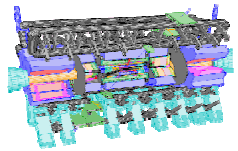
Search potentials (3σ)

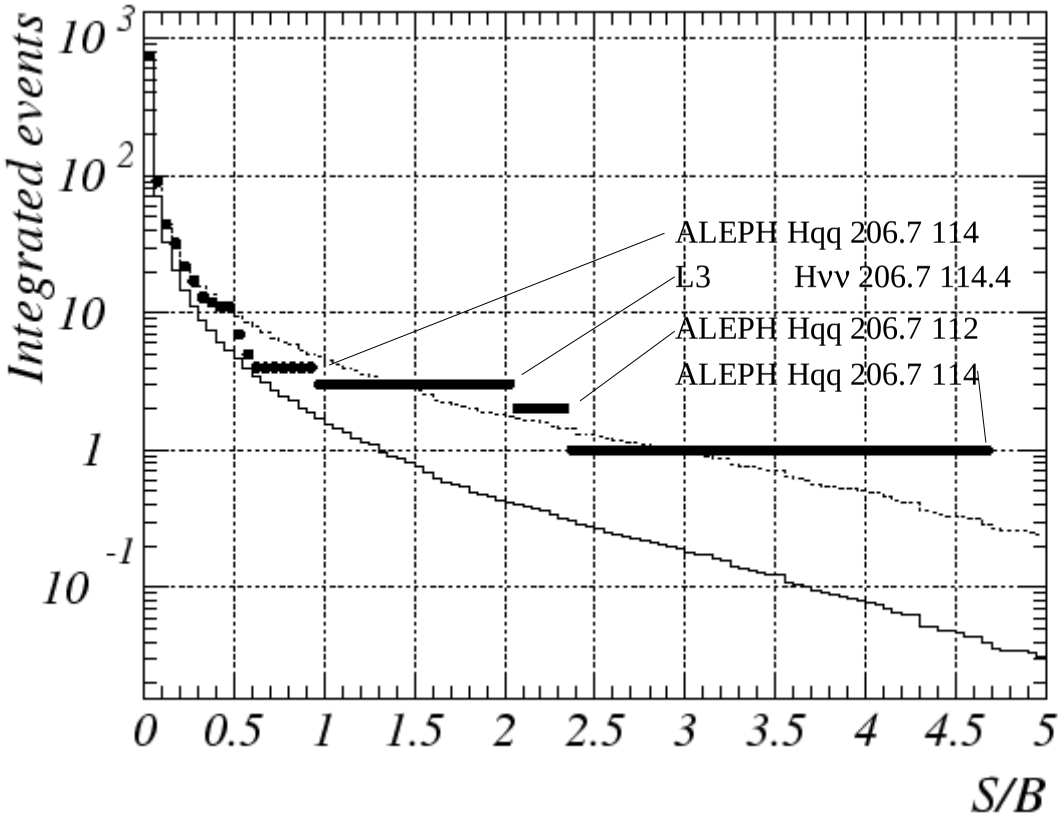




- ~40% probability to observe combined 3σ at 115
- Not surprising that strongest signal observed in 4−jets
- 5−15% probability for individual experiment to observe 3σ
  - Not surprising that not all 4 experiments signal−like

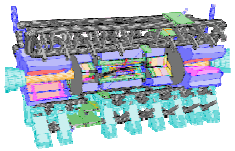
Event weights

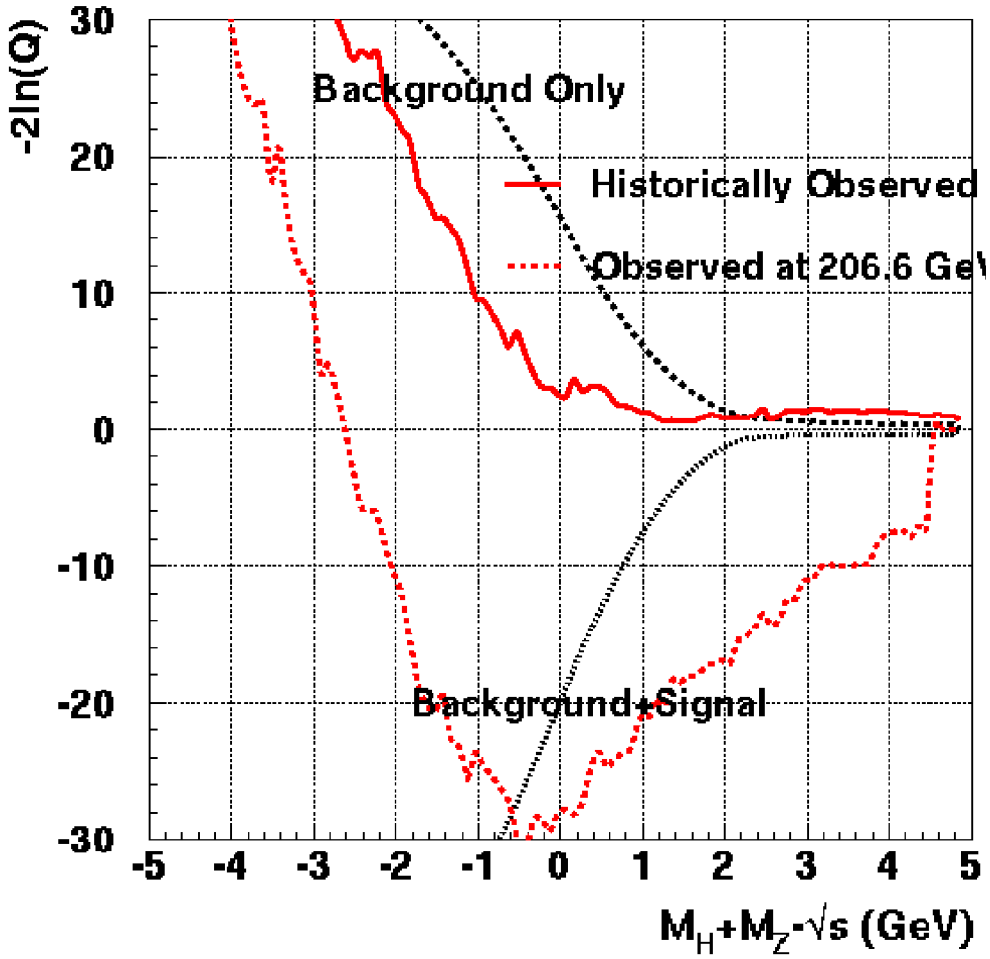




- The integration is from the right
- Each candidate brings a contribution or weight to −2lnQ of −2ln(1+S/B)
- The "arrival" of the candidates is consistent with a 115 GeV signal

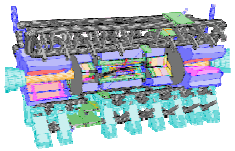
Threshold effect?

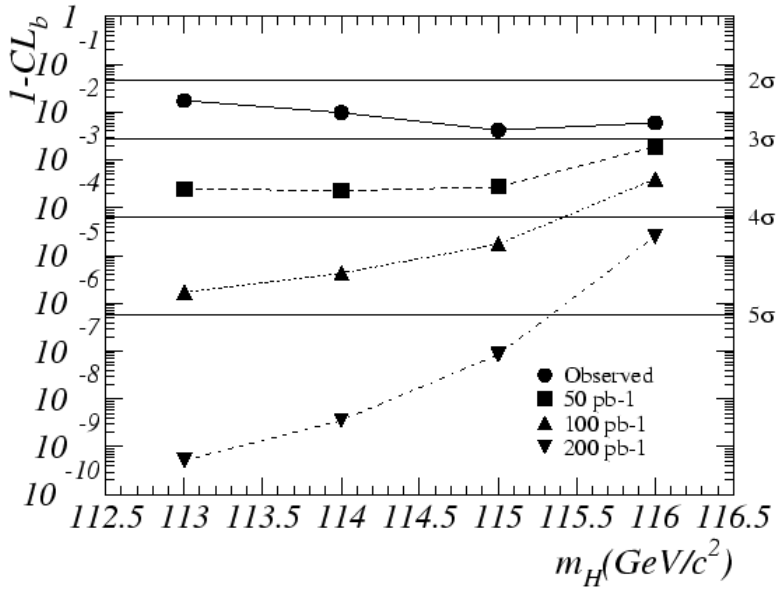




- Data from √s=189−205 GeV show no evidence of signal at kinematic limit.
- Scaling of data from √s=206−210 GeV to same luminosity would give >5σ effect.
- We showed a ~2σ excess at Tampere in 189 − reflection in ALEPH mass recon−struction since corrected

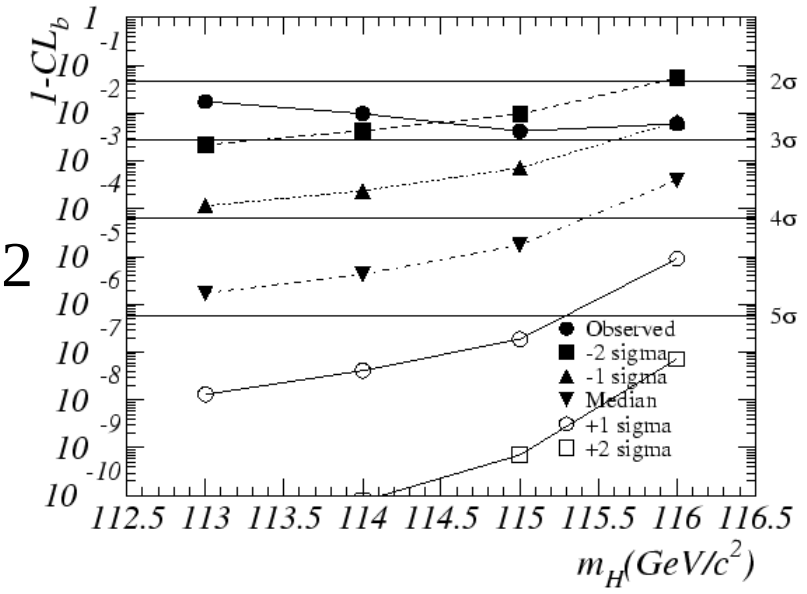
Prospects at LEP?



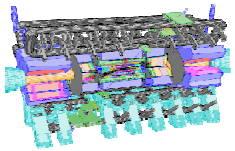


Expected significance vs. lumi at 208.2

Expected significance for 200 pb^{-1} at 208.2



Prospects not at LEP!

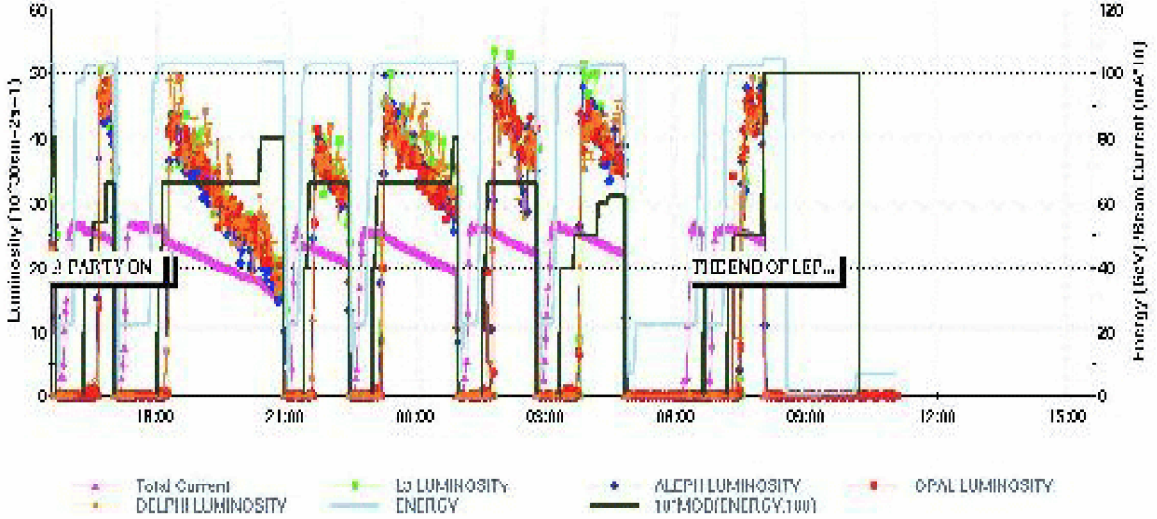


Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

PR14.00
08.11.00

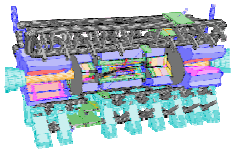
PRESS RELEASE

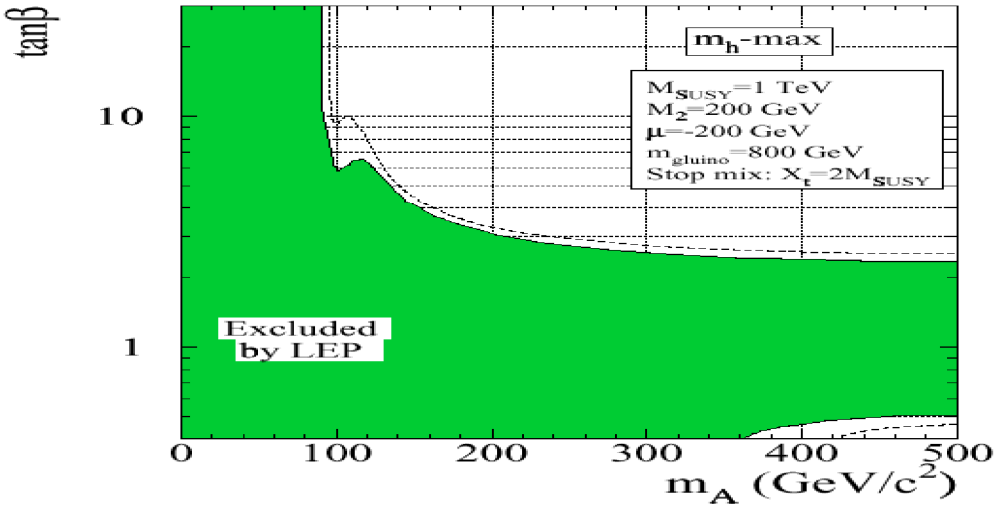
LEP shuts down after eleven years of forefront research

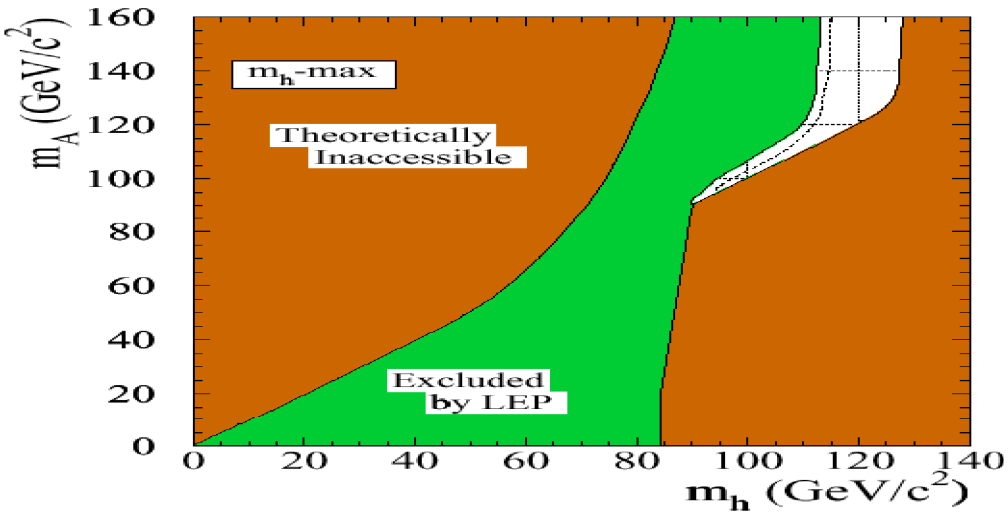


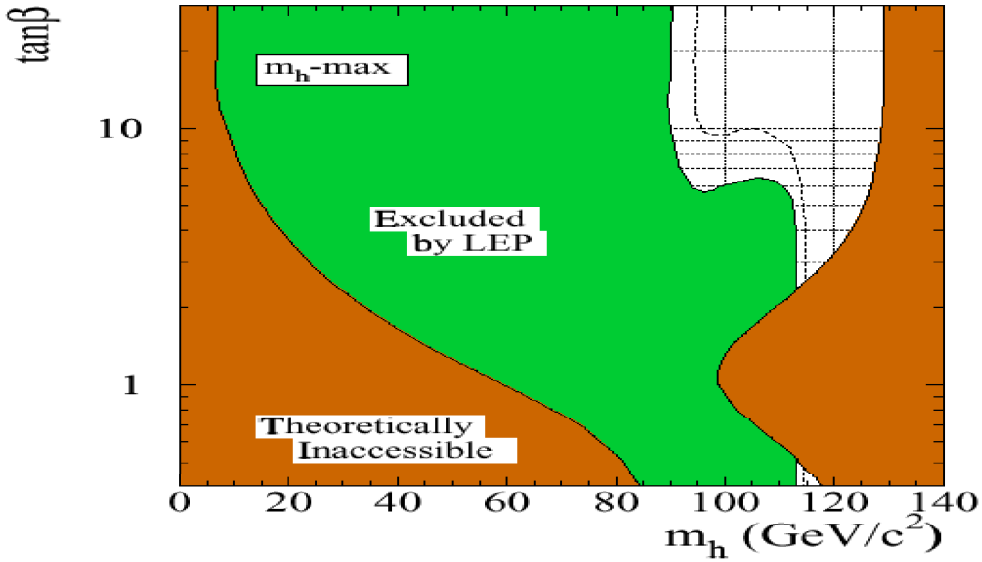
These are the measurements taken of LEP's final beam. The accelerator was switched off for the last time at 8:00 am on 2 November. (Click on photo for enlargement)

MSSM Higgs search





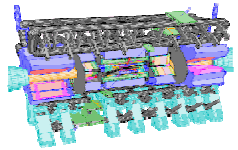


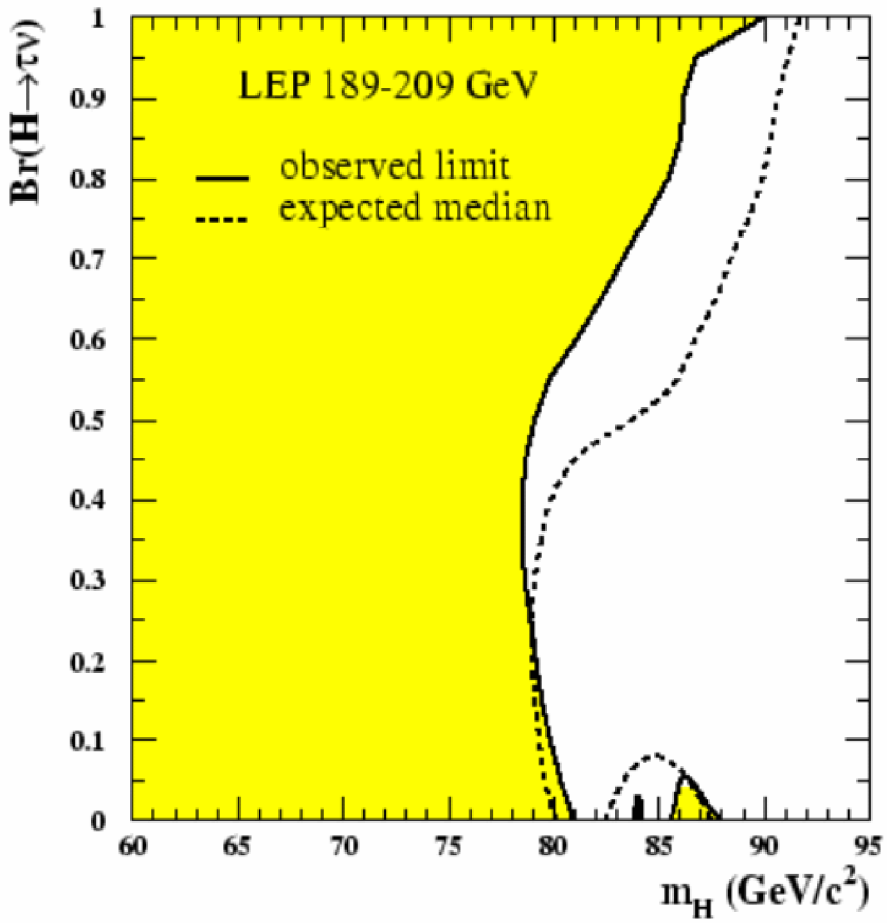


	Observed	***Expected***
m_h> (GeV)	89.9	93.8
m_A> (GeV)	90.5	94.1
tanβ exclusion	0.5−2.3	0.5−2.5

(*missing last month of data*)

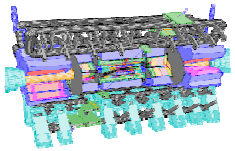
Charged Higgs search

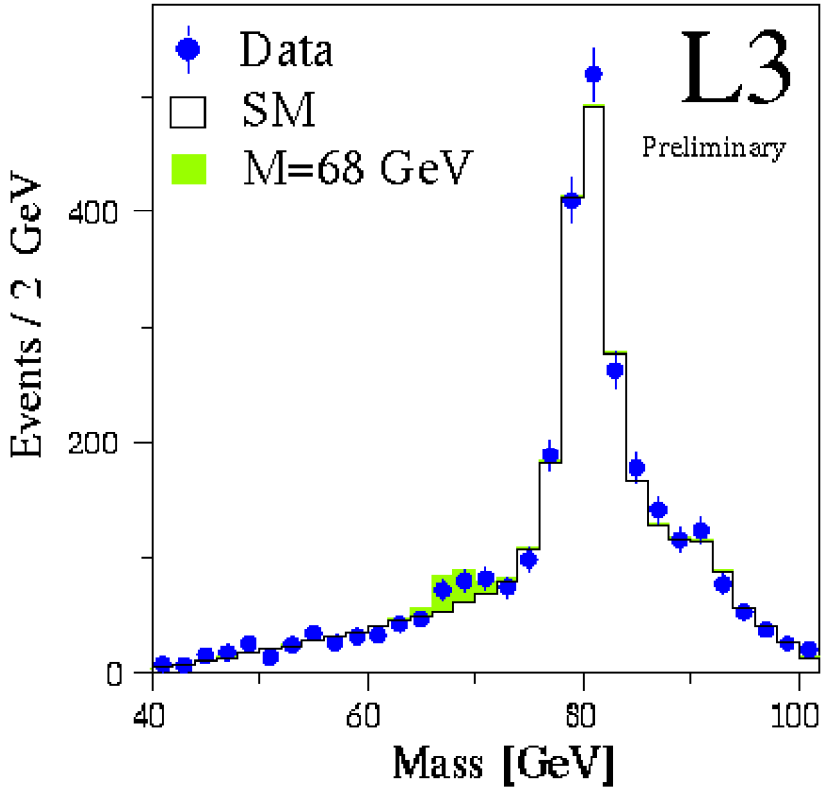


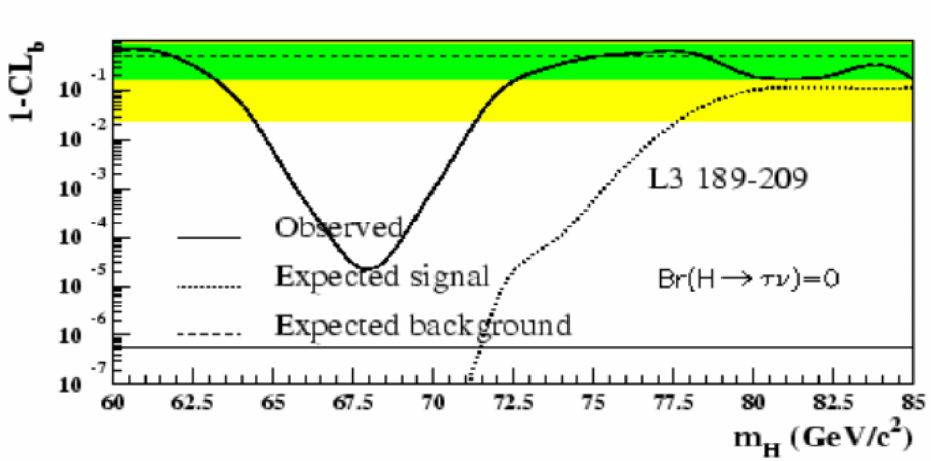


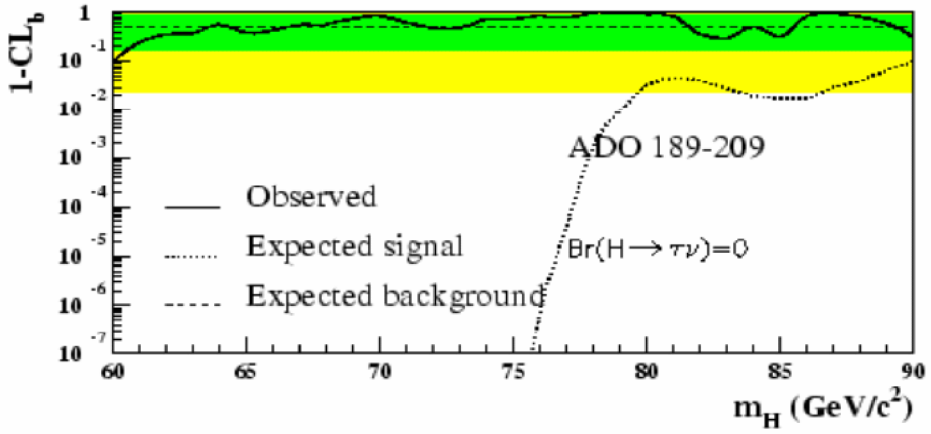
- In context of general 2HDM
  - Ignore MSSM $m_{H+} > m_W$ at tree level
  - Cross−section determined by the unknown mass
  - Assume cs and $\tau\nu_\tau$ exhaust decays (otherwise model−ind.)
- W^+W^- is irreducible background
  - Just starting to have sensitivity beyond m_W
- Lower mass bound 78.5 GeV

Charged Higgs search



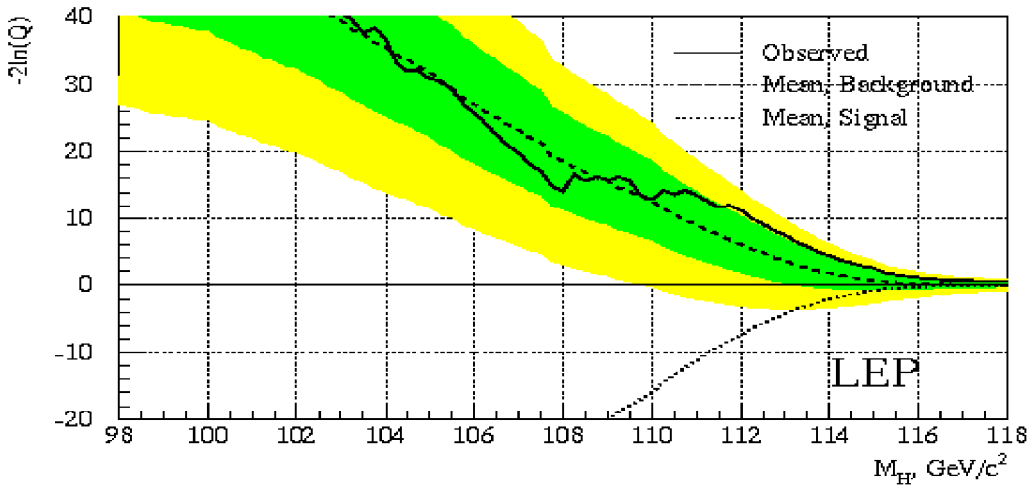


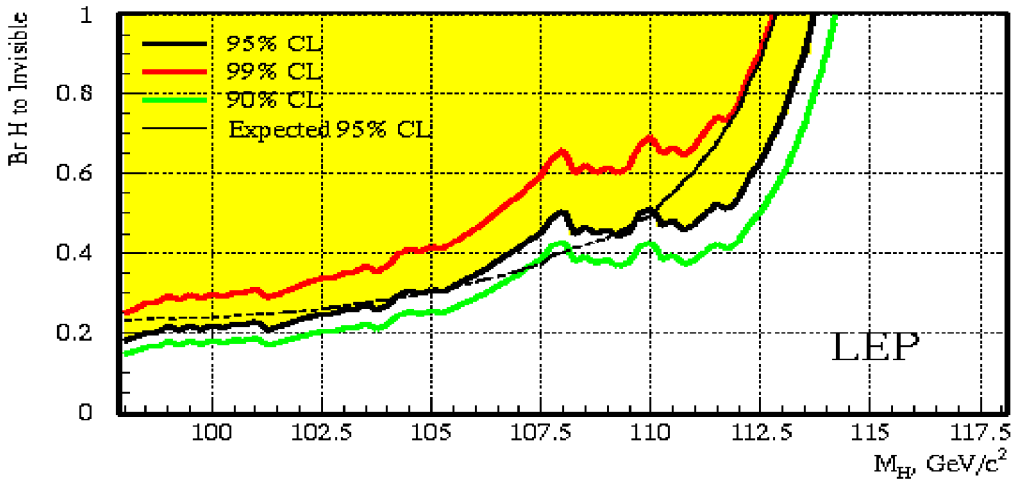




- L3 sees structure around 68 GeV in 4j final state (flavor ind.) that the others don't...

Invisible Higgs search

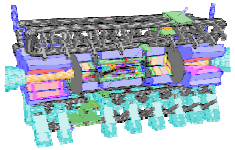


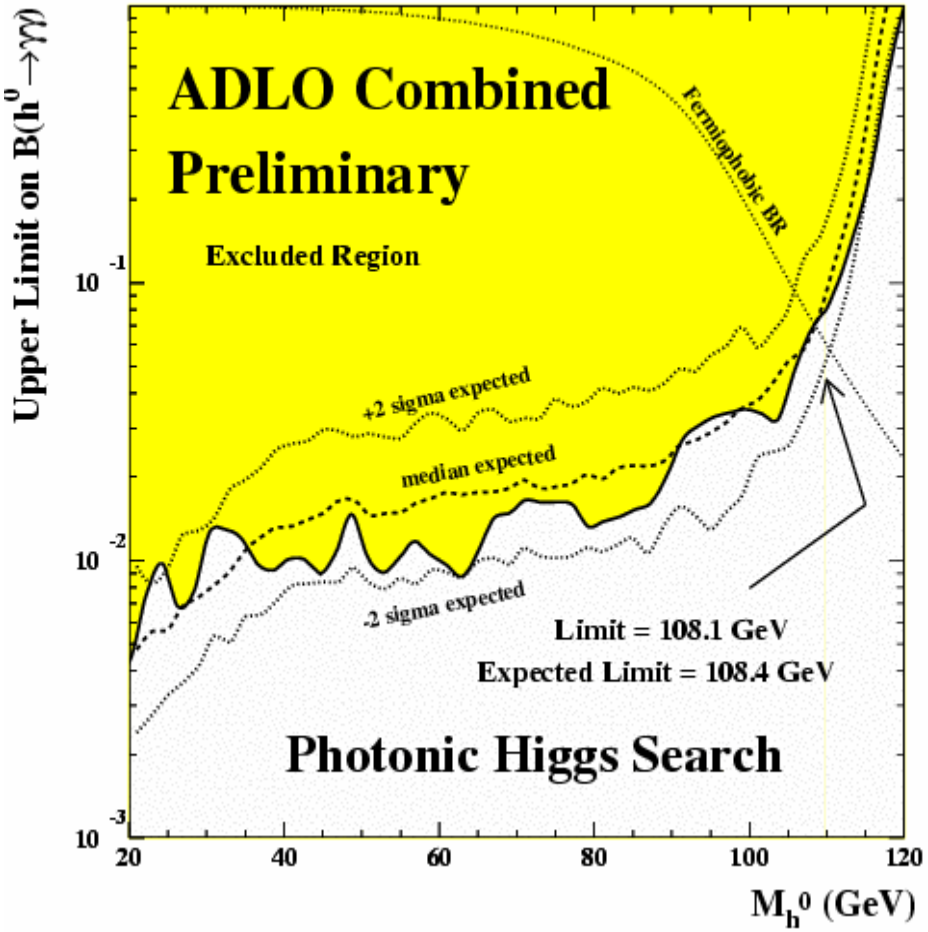


- Production as in SM but decays to stable, noninteracting particles (neutralinos, Majorons)

Observed limit: 113.7 GeV
Expected limit: 112.8 GeV

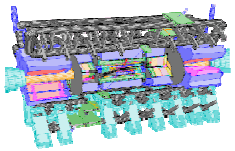
Fermiophobic Higgs search





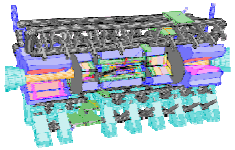
- 2HD model type I
  - only one of Higgs doublets couples to fermions
  - cosα gives mixing between h^0 and H^0 and coupling of h^0 to fermions − and can be 0
- BR(η→γγ) falls as WW^* opens up
- Includes all Y2K data
  - Combination with WW^* search in the works

Conclusions



- The MFLR method of analysing search results is widely used at LEP (even though the CLs business is not rigorous and is not supported by PDG).
  - LR w.r.t. background/insensitivity−bound becoming standard
  - Should also be useful at LHC
- There is a ~2.9σ effect for mH~115 GeV (still preliminary) in the search for the SM Higgs boson.
- There is no evidence for MSSM or more exotic Higgs production at LEP.
  - Plenty of excluding and hopefully some discovery to do at LHC

Exam question 1

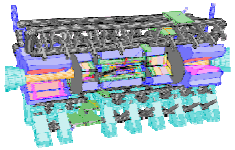


- Suppose you have a particle detector. You take it to a testbeam and measure:
  - P(counter says π | particle is π) = 90%
  - P(counter says not π | particle is π) = 10%
  - P(counter say π | particle is not π) = 1%
  - P(counter sat not π | particle is not π) = 99%

- Then you put your detector in an experiment and select a track which the detector says is a π. Question: What is the probability this track is a pion?

Source: R.D. Cousins

Exam question 2



- Suppose you have a LEP detector. You do years of work to find out:
  - P(Higgs tag | Higgs event) = 90%
  - P(no Higgs tag | Higgs event) = 10%
  - P(Higgs tag | background event) = 1%
  - P(no Higgs tag | background) = 99%
- Then you put your detector in an experiment and select an event which the detector gives a Higgs tag. Question: What is the probability this event contains a Higgs?

Source: R.D. Cousins