18 April, 2001
UCSB

Searches for the Higgs Boson at LEP

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- Review of Higgs Physics in the Standard Model
  - **Why** we think there is a Higgs Boson to be Discovered
  - **Where** and **How** to look for it
- Pushing LEP to its Limits
- Search Channels
- Combining LEP Higgs Results

Preliminary, November 3 Results

Why Must There Be a Higgs Boson

- The $W^{\pm}$ and the Z^0 have large masses, m_W~80.4 GeV, m_Z~91.2 GeV; the photon is *massless*

  $SU(2)_L \times U(1)_Y$ gauge symmetry elegantly predicts all electroweak phenomena
  - Precision tests at LEP/SLC ~0.1%
  - Mass terms violate gauge symmetry

- Simplest solution -- P.W. Higgs, 1964, following an idea from Phil Anderson (solid state example -- quasiparticle mass from interactions with a background field)

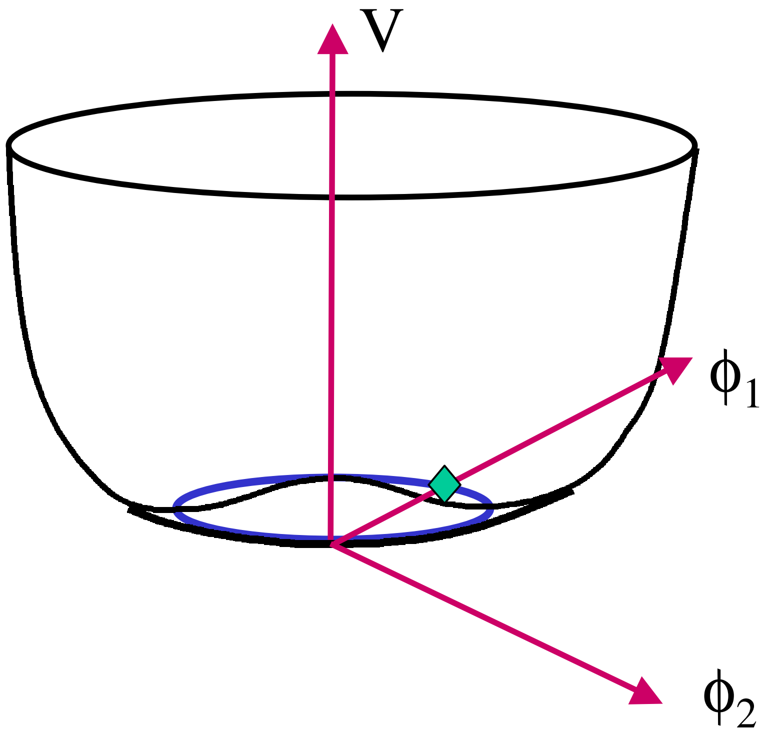
  Hypothesize a **complex doublet of scalar fields.**

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

And a term in the Lagrangian:

$$V = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \quad \text{with} \quad \mu^2 < 0,\ \lambda > 0$$

The Higgs Mechanism and Higgs Bosons



Physical minimum ◆chooses an arbitrary phase, breaking SU(2)×U(1) symmetry in the ground state with a nonzero vacuum expectation value (VEV) -- **A revival of the ether, perhaps!**

Two complex fields: 4 degrees of freedom

- One constrained by V -- Higgs scalar!
- Three massless Nambu-Goldstone Bosons
  - Appear as the longitudinal polarization components of the W^+, the W^-, and the Z^0
    $\rightarrow$ gauge boson masses (no physical Nambu-Goldstone Bosons)
- $U(1)_{EM}$ gauge symmetry unbroken -- photon remains massless.

More Reasons Why there Must be a Higgs Scalar (or something else)

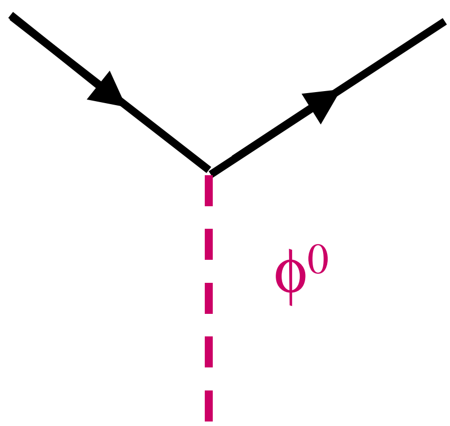
$W^{\pm}$ couples to *left-handed* fermions but *not* to right-handed ones!

Standard Model puts left-handed fermions in $SU(2)_L$ doublets, but the right-handed ones do not have such a symmetry.

So f_L and f_R have ***different quantum numbers*;**

-- a Dirac mass term in the Lagrangian violates gauge symmetry.

-- "Yukawa" couplings to the Higgs scalar field allow f_L and f_R to appear together with ϕ in the Lagrangian (Y=1/2 for the Higgs field)
Fermion masses depend on coupling strength and the Higgs VEV.

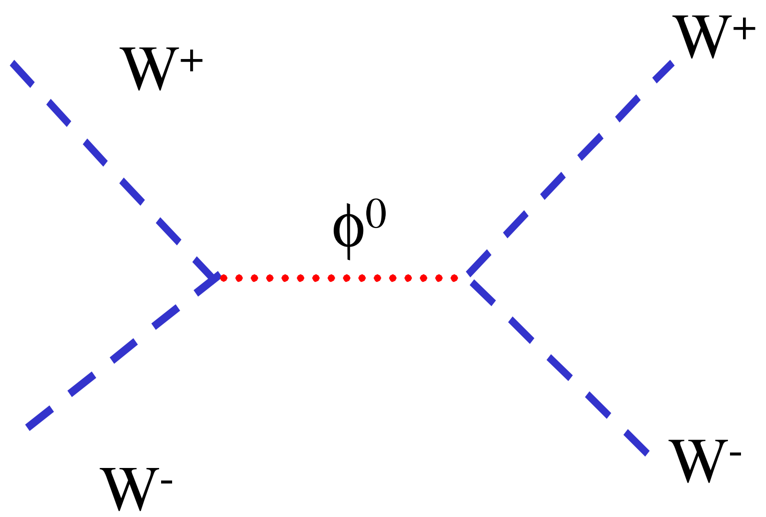


Top-quark coupling=1!
(VEV ~ M_{top})

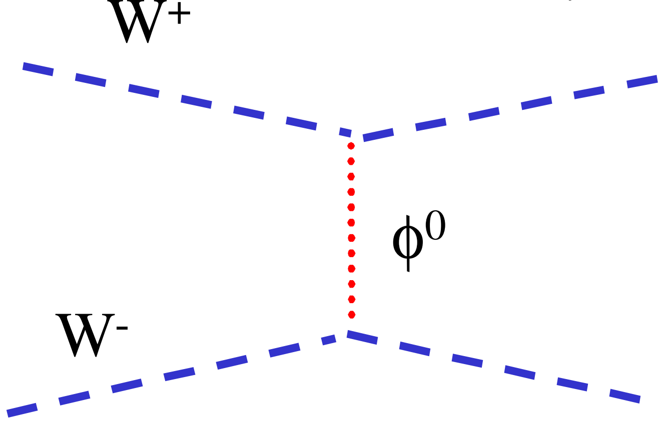
Yet Another Reason for a Higgs Scalar

Scattering of W^+W^- grows with *s* and violates unitarity without Higgs scalar exchange to cancel it.

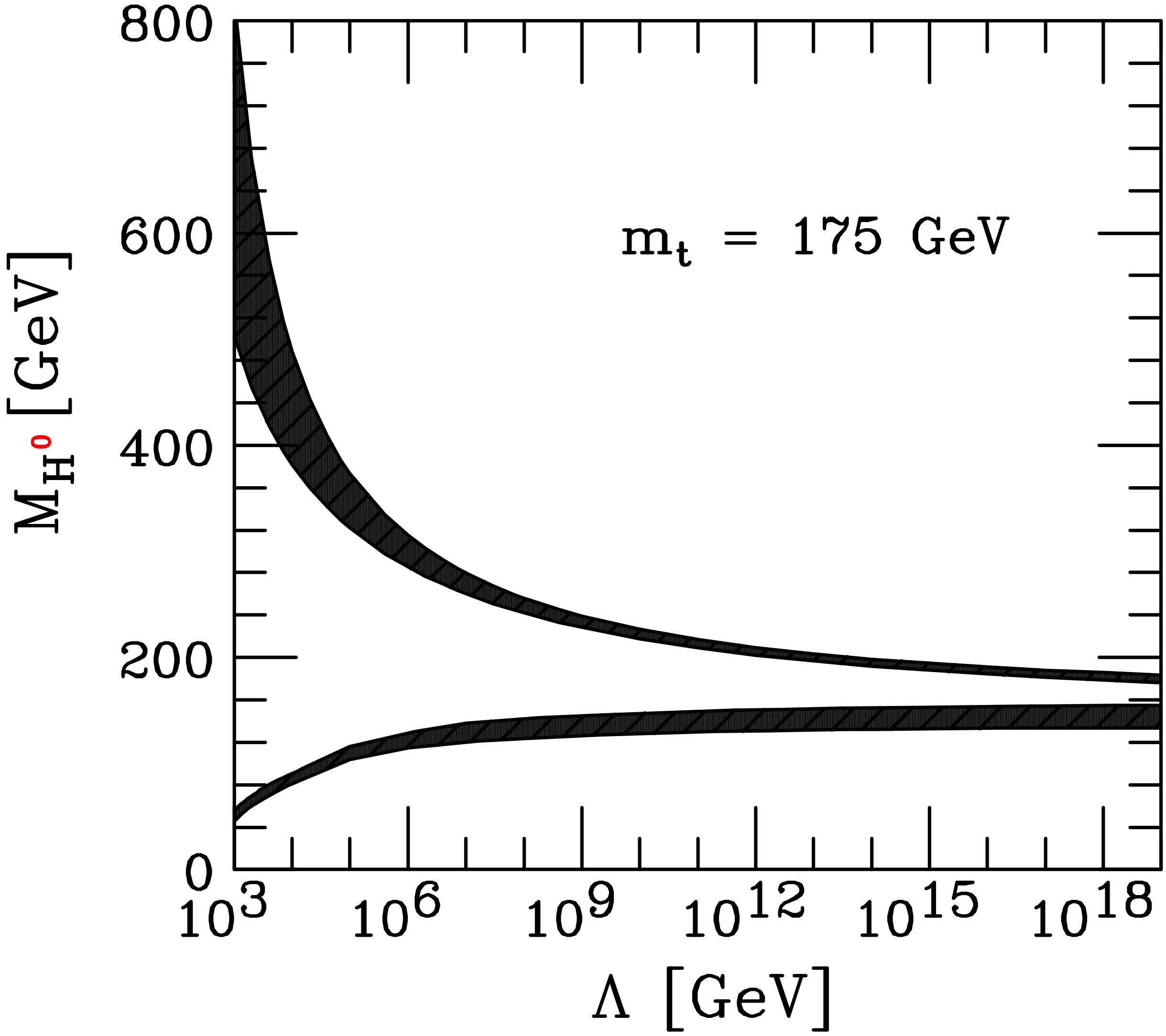
(no surprise -- theory not renormalizable without the Higgs fields)



+ γ, Z^0 exchange



Consequences of Believing the Standard Model up to the Planck Scale



hep-ph/9708416 and references therein

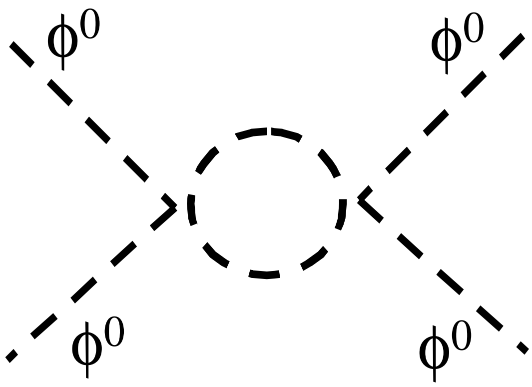
Λ is the scale at which interactions beyond the Standard Model become important

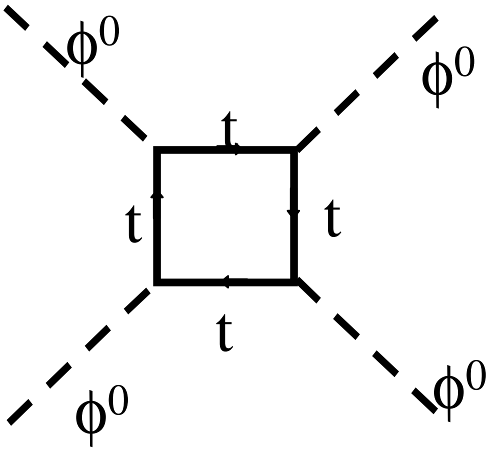
Upper Higgs mass bound -- Landau pole -- Higgs self-coupling grows without bound as the energy scale increases

Lower Higgs mass bound -- vacuum stability

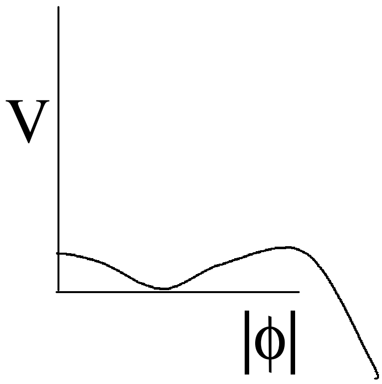
The Vacuum Stability Argument for a lower bound on the Higgs Mass

One-loop correction terms to to the quartic self-coupling:





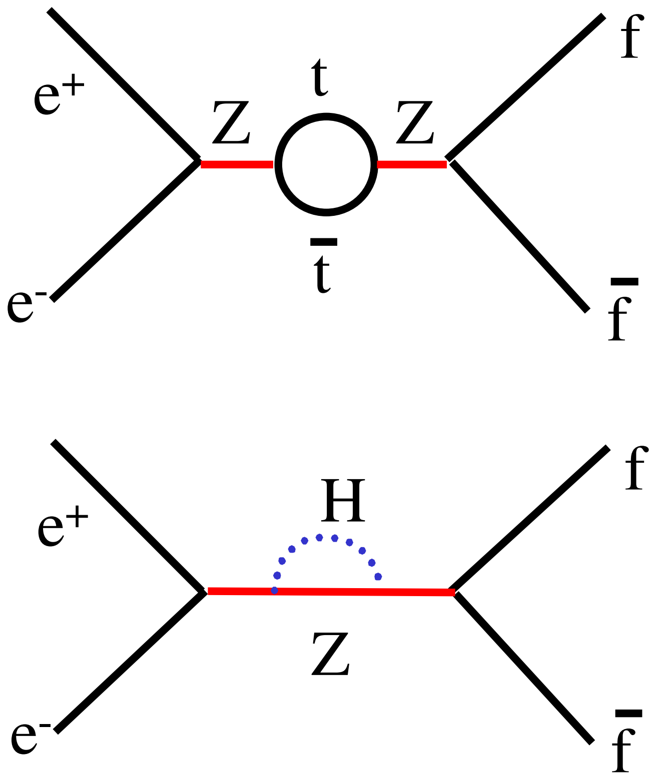
Then $V = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$ picks up an additional term proportional to $-m_t^4\phi^4$ (among other terms)
$V(\phi)$ turns negative if m_H is too light:



Review: M. Sher, Phys. Rep. 179 (1989) 273.
Calculaitons with measured m_t: Casas, Espinosa, and Quirós

Hints of a light Higgs Boson from Precision Electroweak Data from LEP/SLC

- Vacuum Polarization quantum corrections to $e^+e^- \rightarrow f\bar{f}$



Affect all Z^0 observables,

strongest: $\sin^2\theta_W$ from **asymmetries**

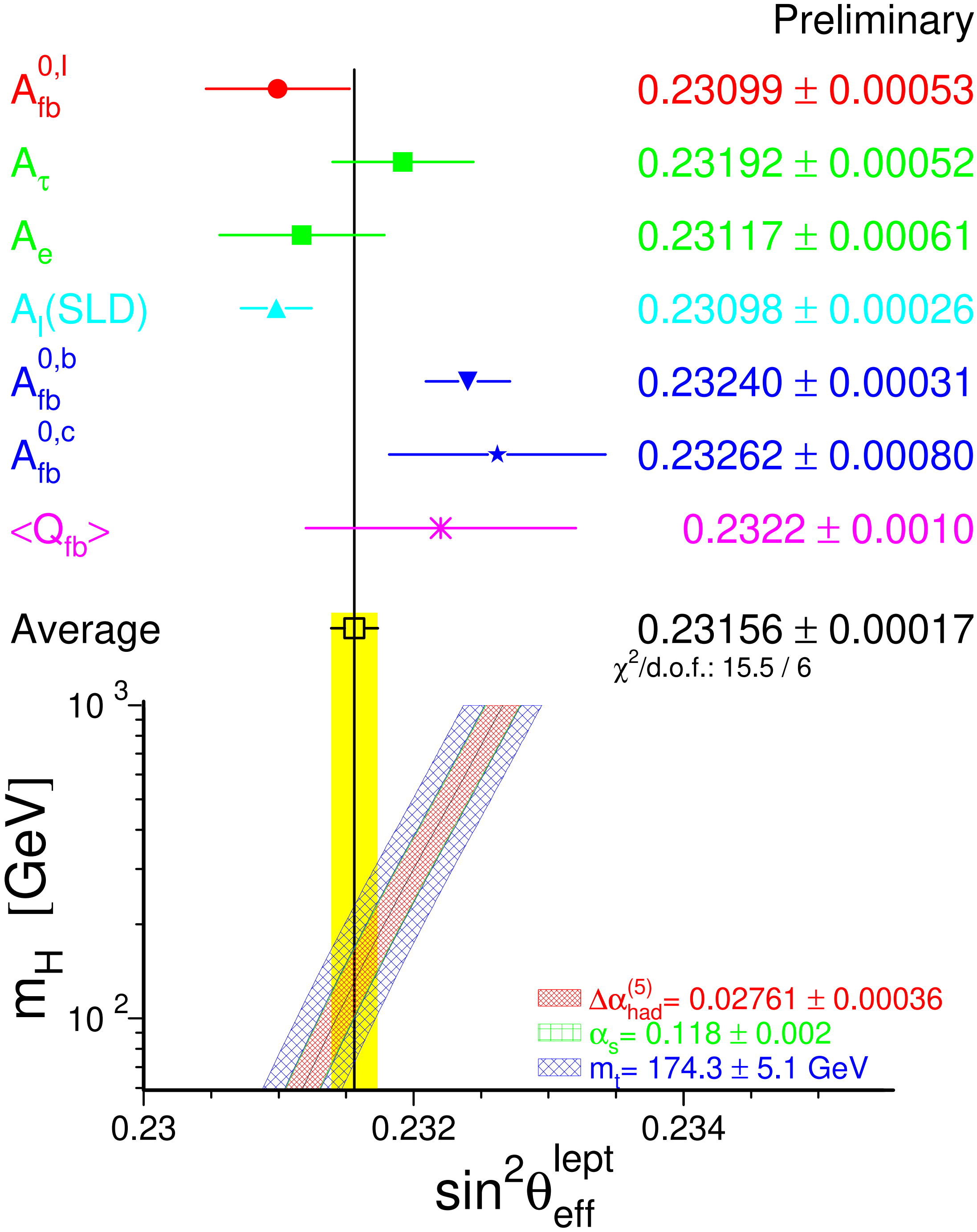
Logarithmic dependence on m_H

- LEP/SLC precision cross-sections and asymmetries -- predict m_{top}
- TeVatron measures m_{top} to ±5 GeV
- Residual precision information used to predict m_H

Electroweak Precision Data News

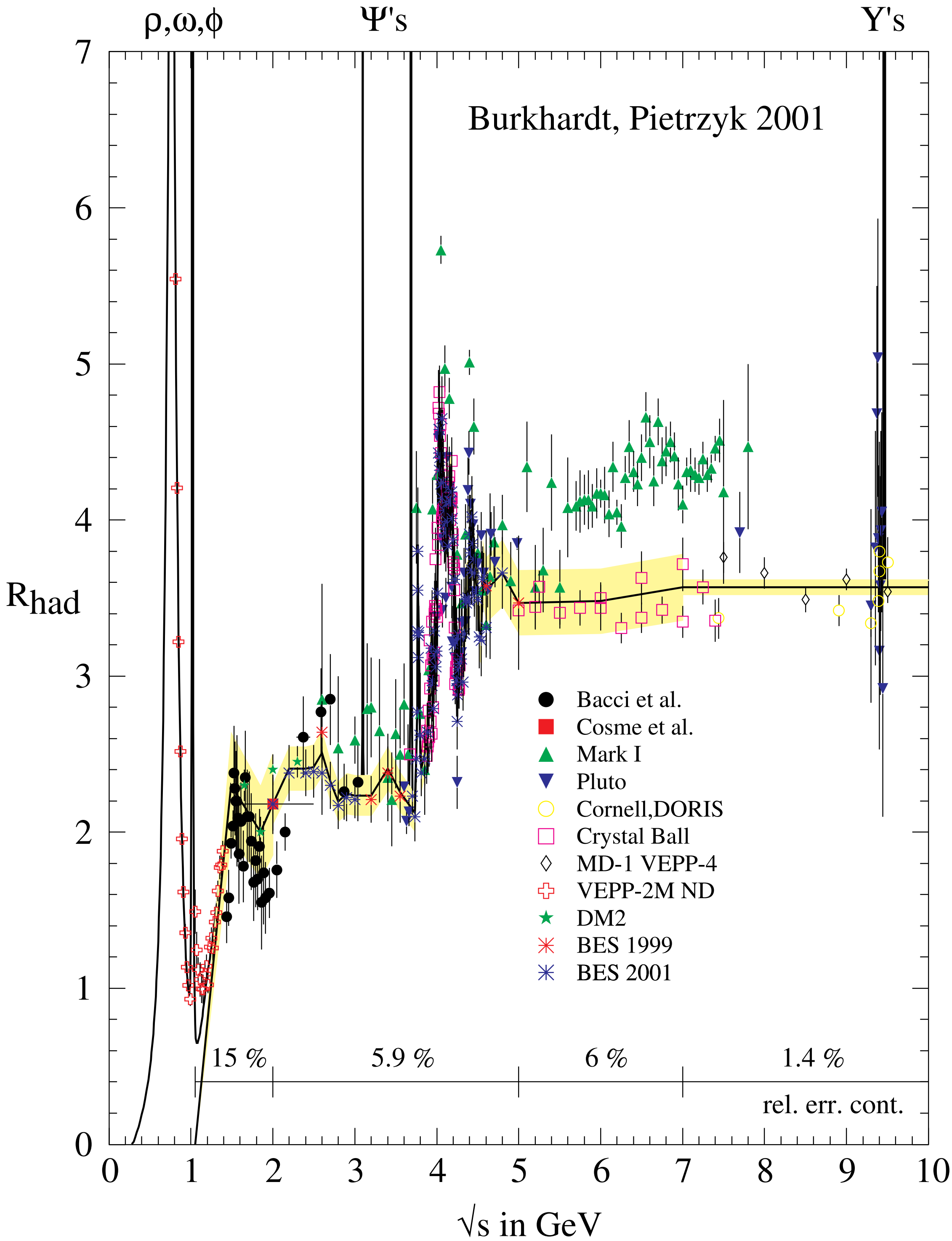
New Measurements of $A_{FB}^{0,b}$ from ALEPH and DELPHI (Moriond 2001)

Pulls m_H prediction up (and adds χ^2 to the fit)

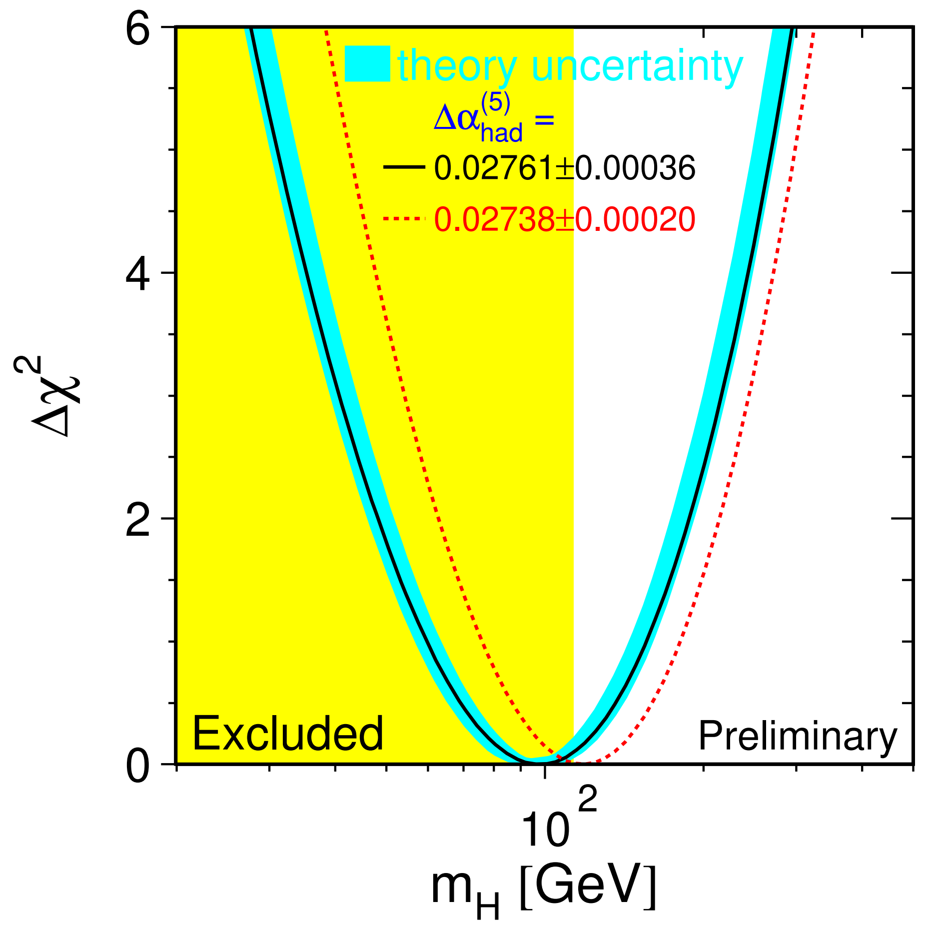


BES Measurements of R_{had}

- Used to estimate 1-loop QCD vacuum polarization corrections to $\alpha_{EM}(m_Z)$ Reduced uncertainty in the 2-5 GeV range



Electroweak Fit Constraint on m_H



- Logarithmic sensitivity to $\sin^2\theta_W$
  Current central value:

$$\boxed{m_H = 98^{+58}_{-38}\ \text{GeV}}$$

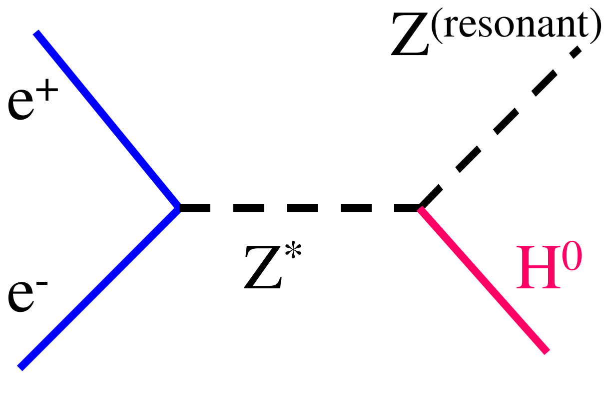
Results as of Moriond 2001

- 95% CL Upper limit

$$m_H < 212\ \text{GeV}$$

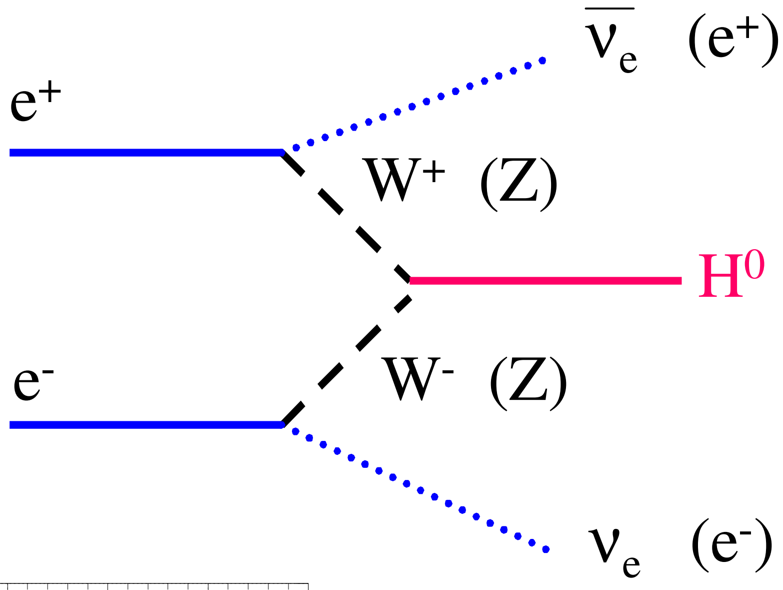
Standard Model Higgs Production

Higgsstrahlung:

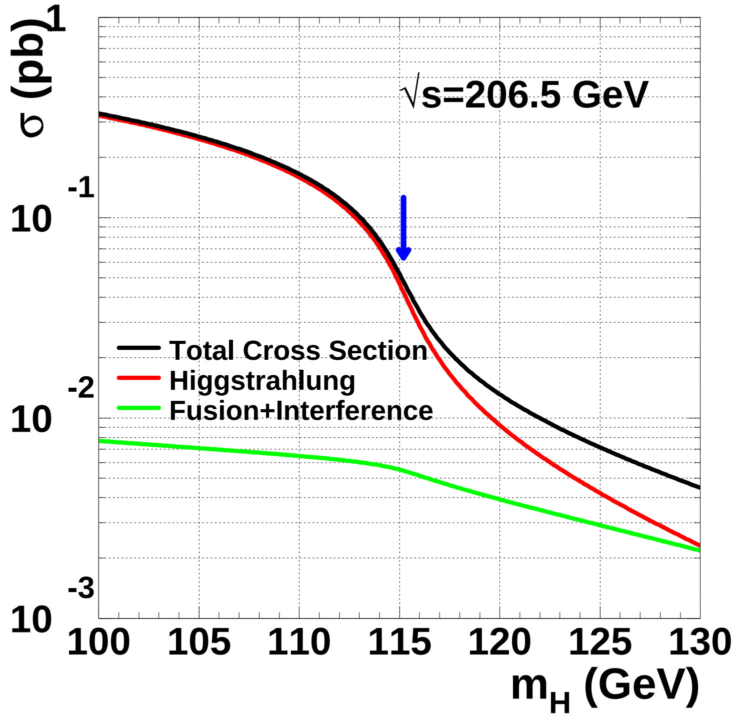


Has a kinematic "cutoff" at $\sqrt{s} - m_Z$

Fusion:



"No" kinematic cutoff, but low cross-section



Optimizing LEP Performance for Higgs Searches

- Keys to success: **Both Energy and Luminosity are important.**

- Increasing the energy pays off quicker, but several tens of pb^{-1}/experiment are needed to get the full benefit from each new energy

Raising the Energy:

The main hurdle to overcome -- synchrotron radiation.

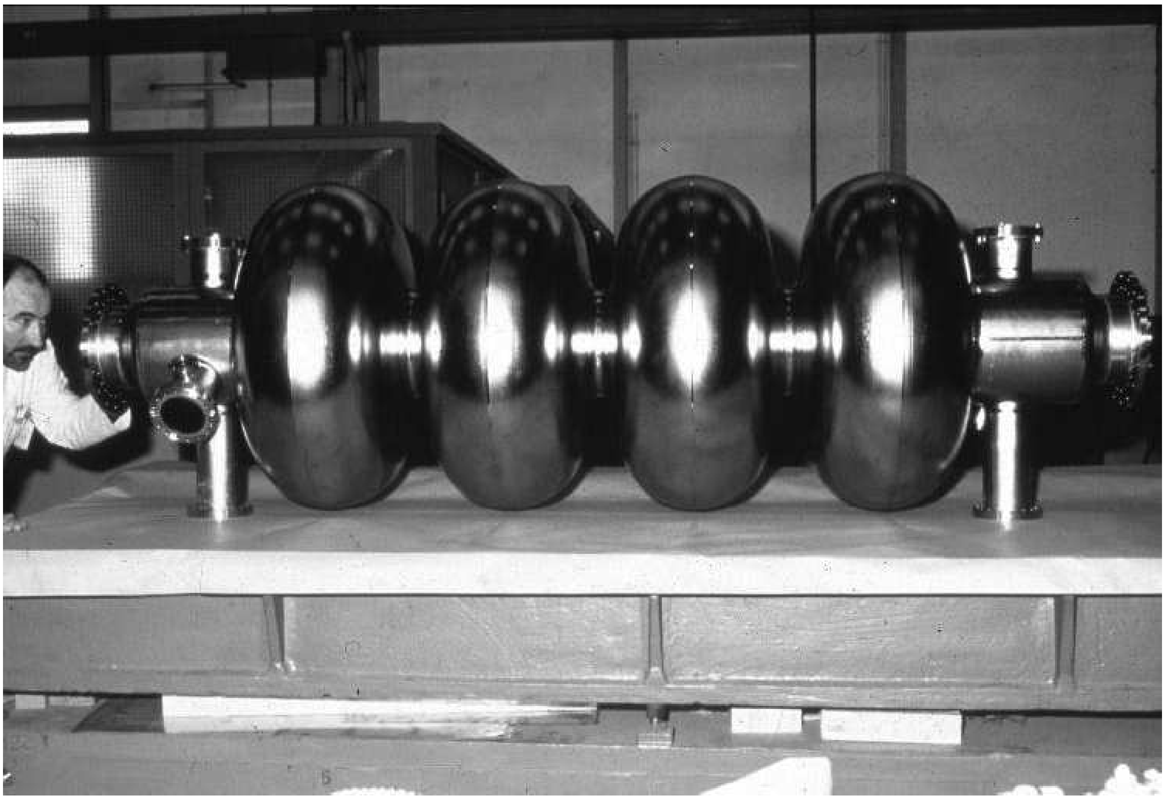
$$E_{loss} \propto E_{beam}^4 / r$$

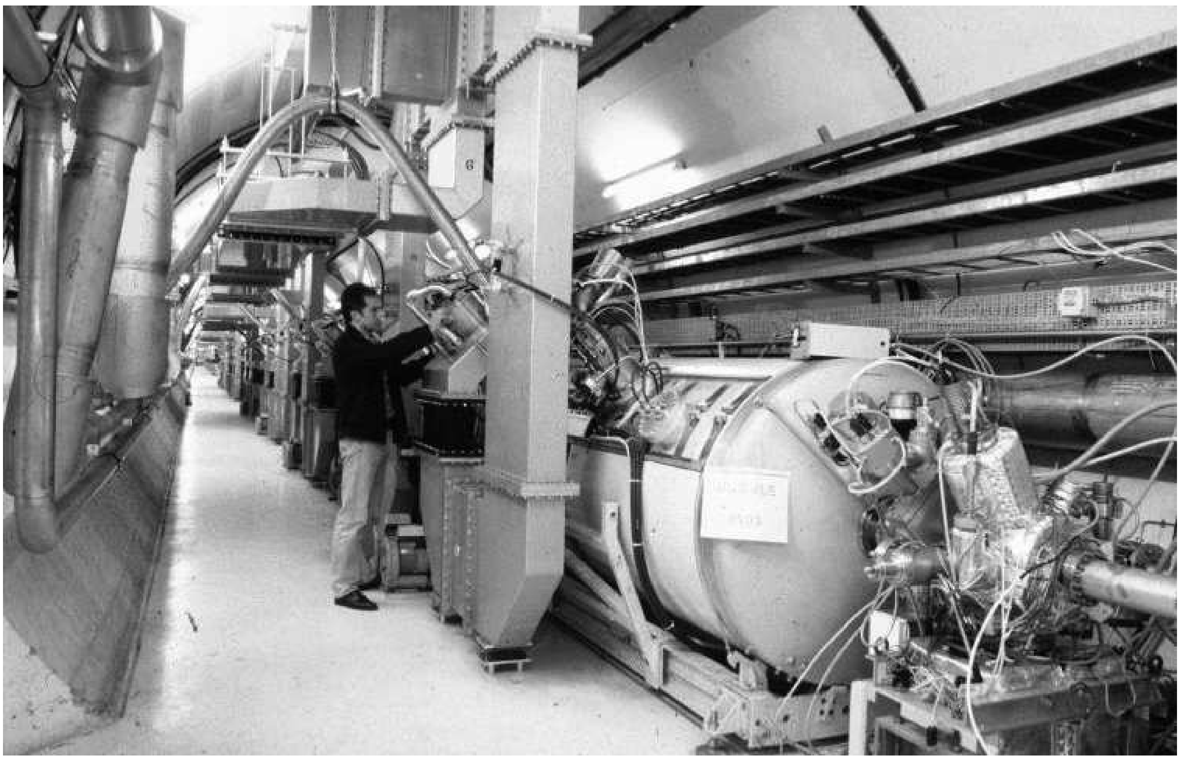
Possible solutions

- Add more energy per turn, and/or
- Make LEP bigger.

More Radio Frequency Power

288 Superconducting RF cavities installed
by the year 2000.





More Radio Frequency Power

Push the Superconducting RF as hard as it will go

- Extra conditioning of surfaces
  - 7 MV/meter **Achieved** with only
  - 6 MV/meter as Designed
- Shorter bunches -- sample a smaller phase spread in the RF across a bunch
  - Pickup antenna burnout in 1998 -- replace all RF antennas over winter 1998
- Additional Cryogenics plant
  - Buy some of the LHC cryo equipment early -- find its weak spots and fix them

Re-install 8 Copper cavities where there is space.

Running at the RF Limit

- 3600 MV of total RF power available in mid-2000

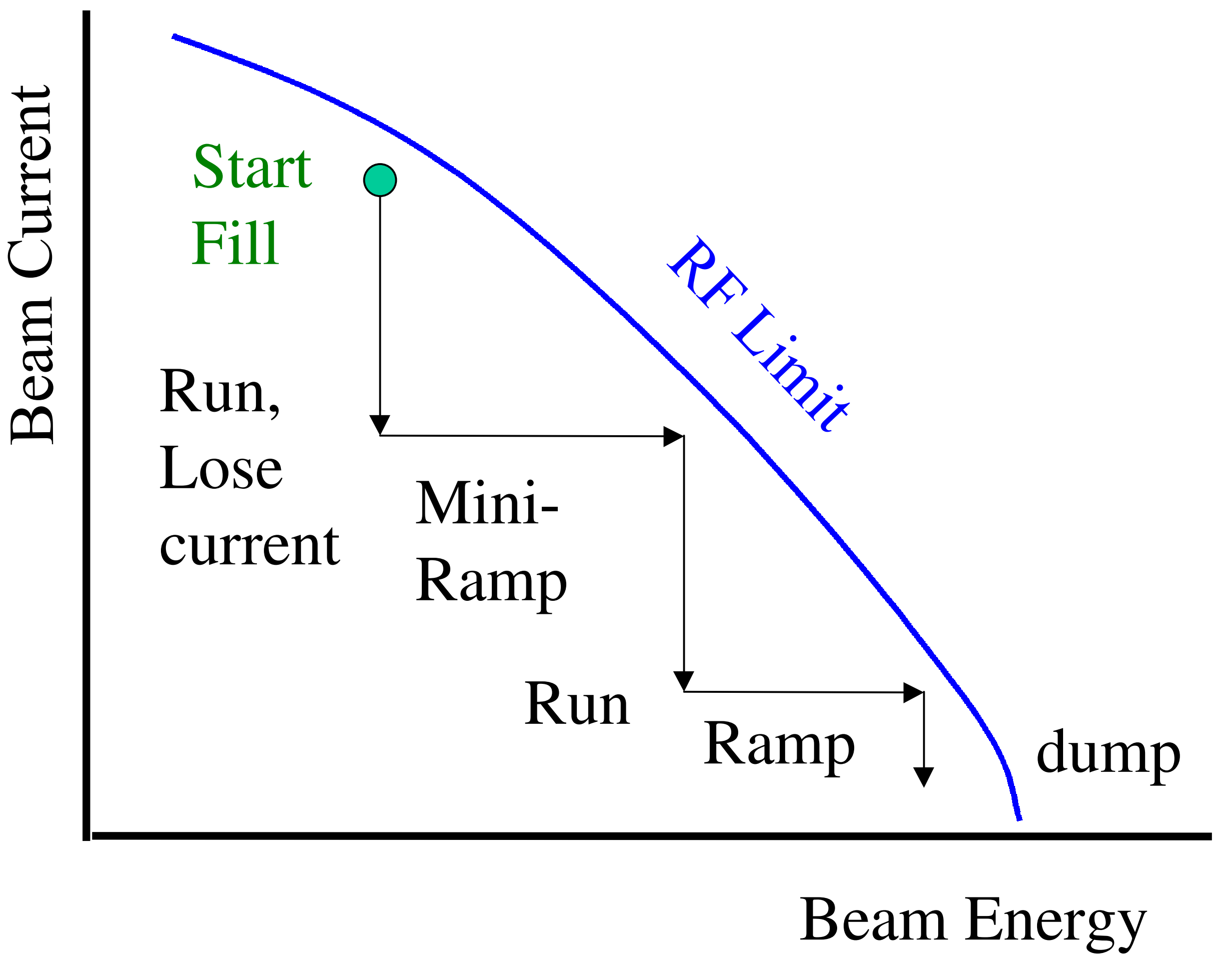
- Subject to random klystron trips, and trips correlated with the beam (one klystron trip can trigger many others because the beam moves)

- "RF Margin"= How many klystrons can trip without losing the beam.

- Mean time between klystron trips depends on
  - beam current
  - beam energy
  - condition of cavities and cryo plant
  - Averages ~15 minutes

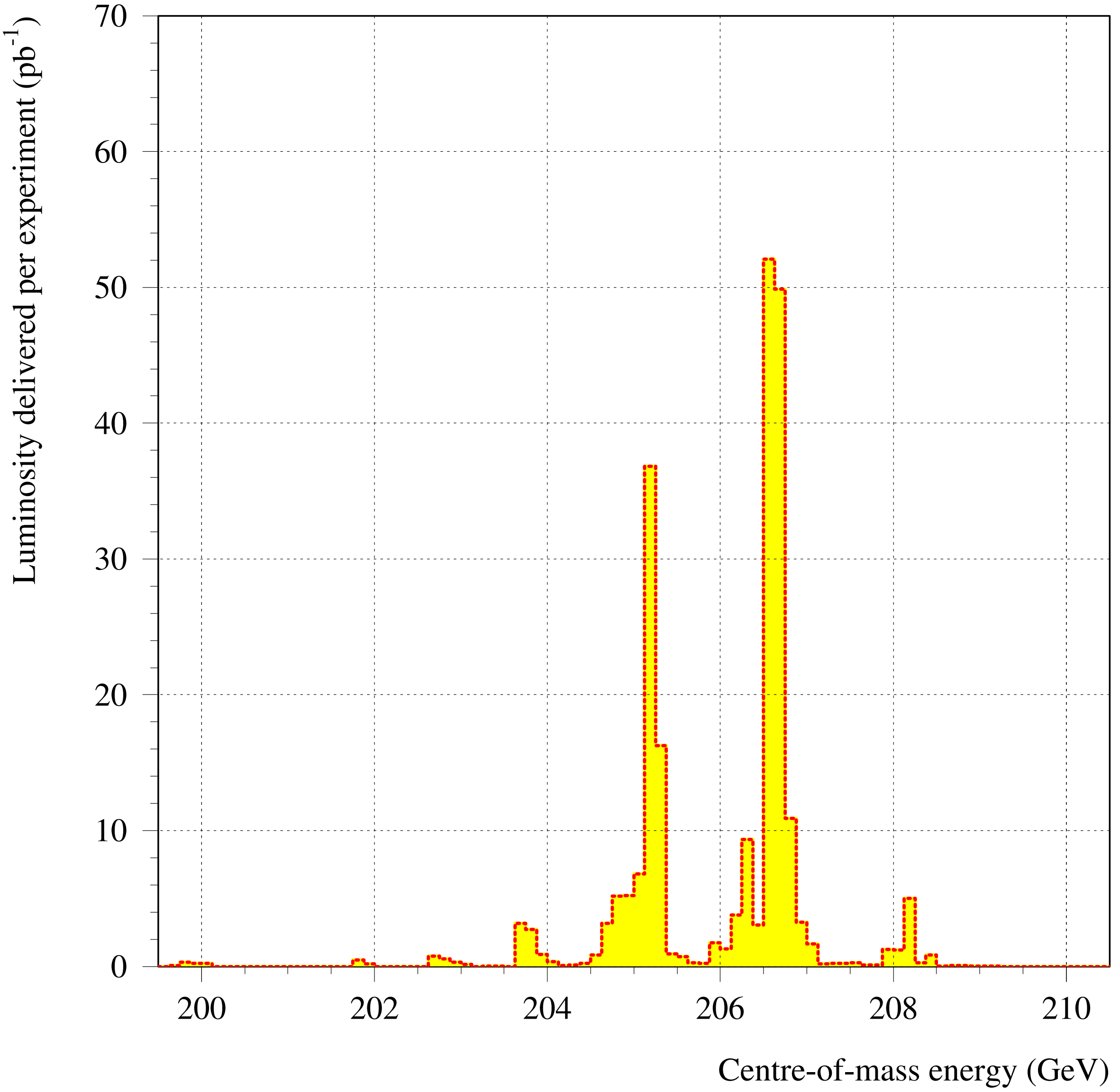
Mini-Ramps at LEP

- A strategy for maximizing the luminosity at the top energy.
- Fill turnaround -- 45 minutes. Very time-consuming to refill after 15 minutes at zero margin.
- Strategy for Higgs searches -- put in a long fill at 1 or 2 klystrons margin, then go for the top energy possible.



The Energy Delivered to the Experiments

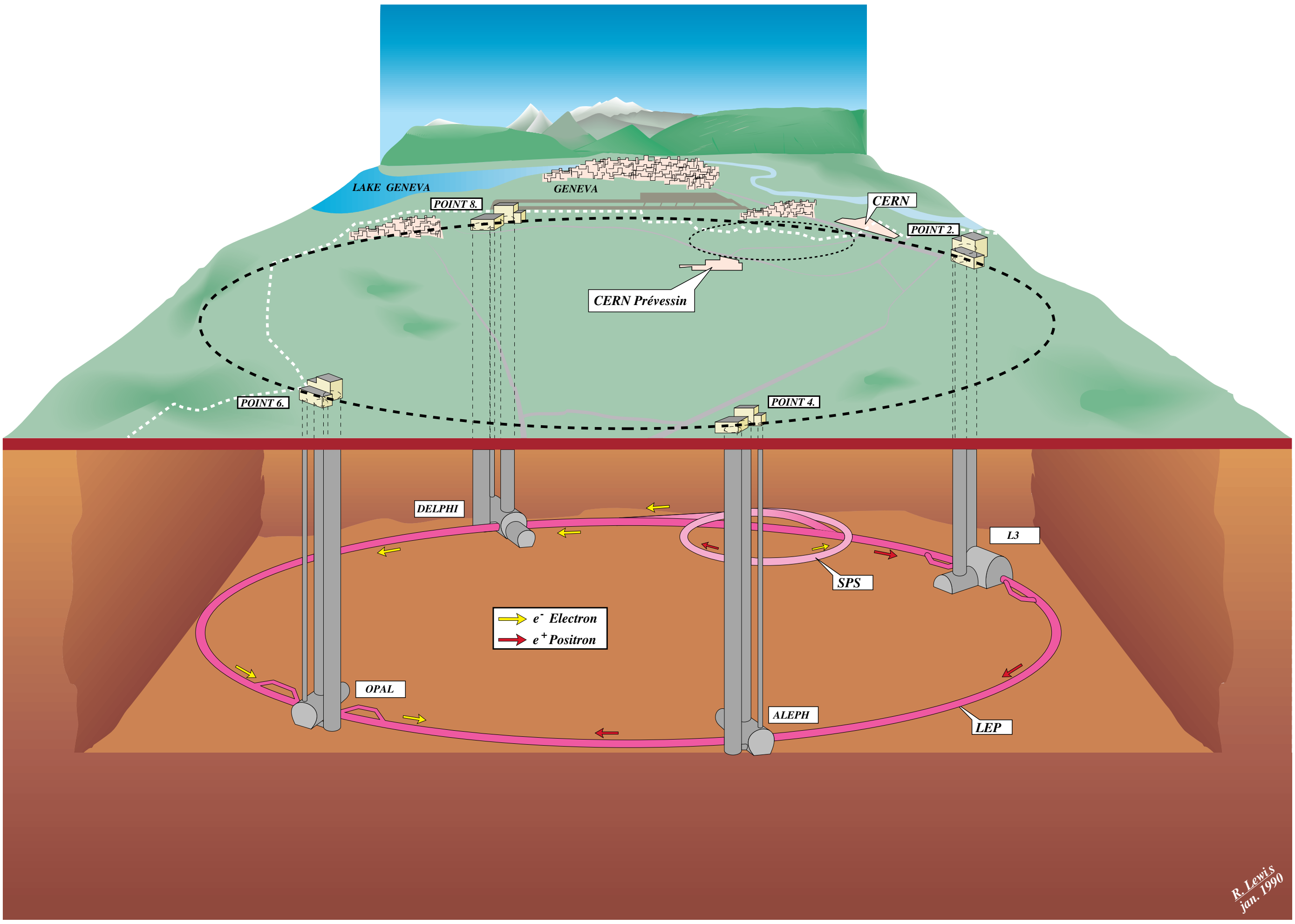
Discretized by how many klystrons are in reserve.



Average in 2000: 206 GeV. But the distribution is important (particulary what's at the top)

Making LEP BIGGER

- The tunnel is already 27 KM around...

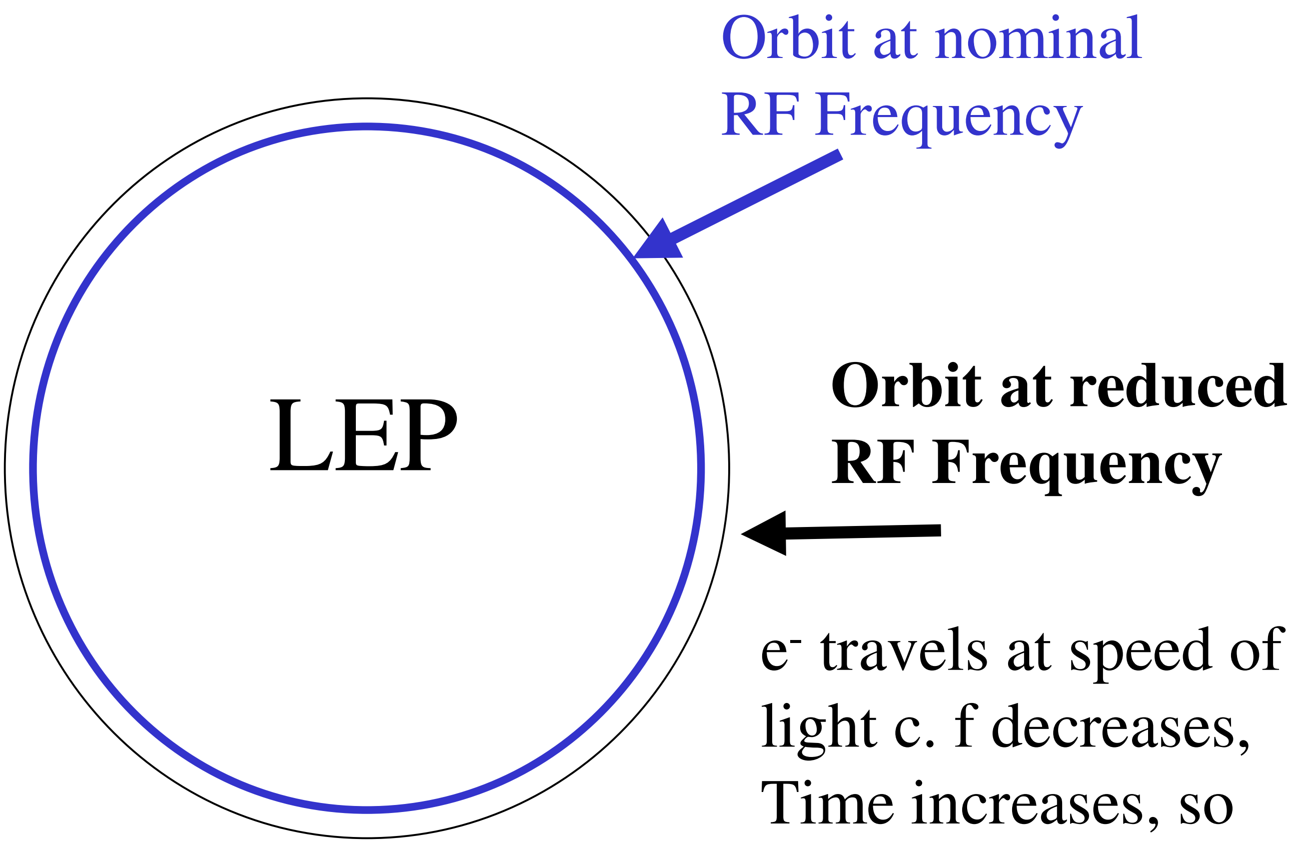


- But it is the *magnetic length* of the ring that counts to reduce synchrotron radiation.

(straight sections don't count!)

Tricks to Increase LEP's Circumference

- Trick 1: Reduce the RF Frequency (350 MHz) by ~50 Hz.



e^- travels at speed of light c. f decreases, Time increases, so the circumference increases

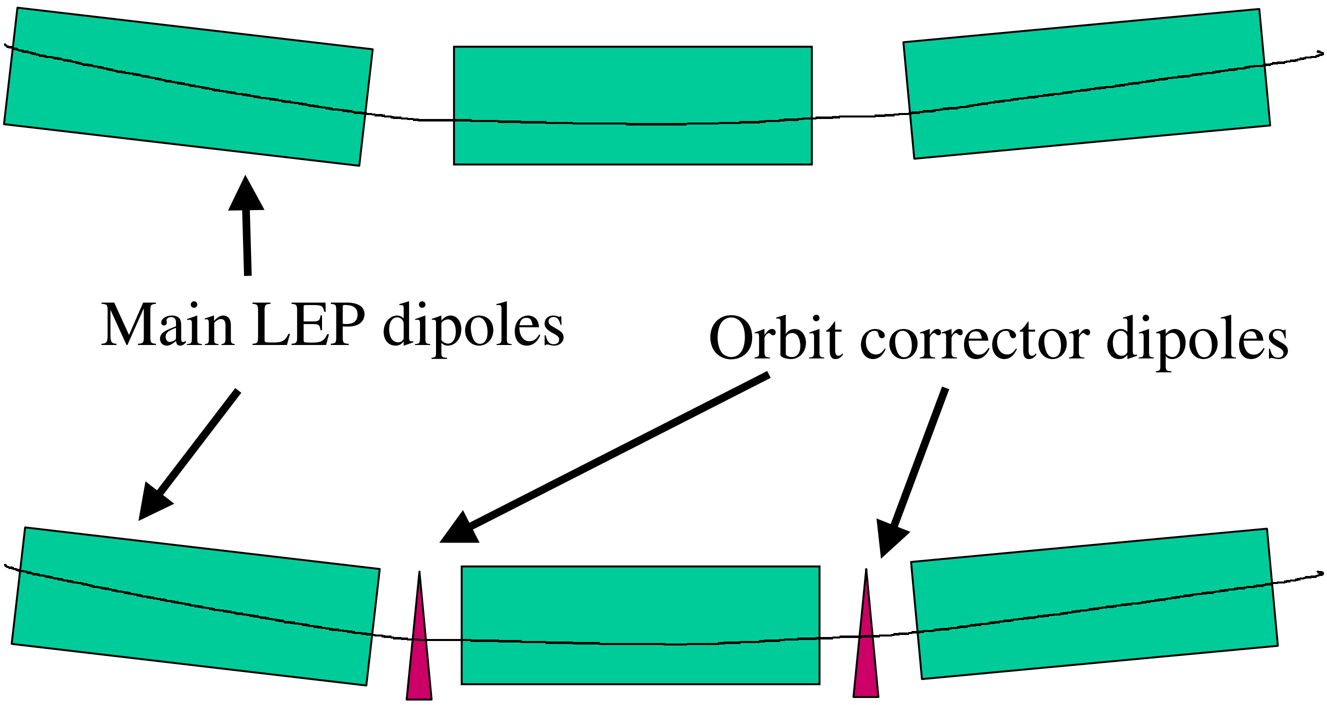
Also: e^- see larger fields in the quadrupoles

The Prices:
- Lower luminosity
- Higher backgrounds

But a little bit is worth it!

Higgs sensitivity gain: 0.5 GeV

Increasing the Bending Length



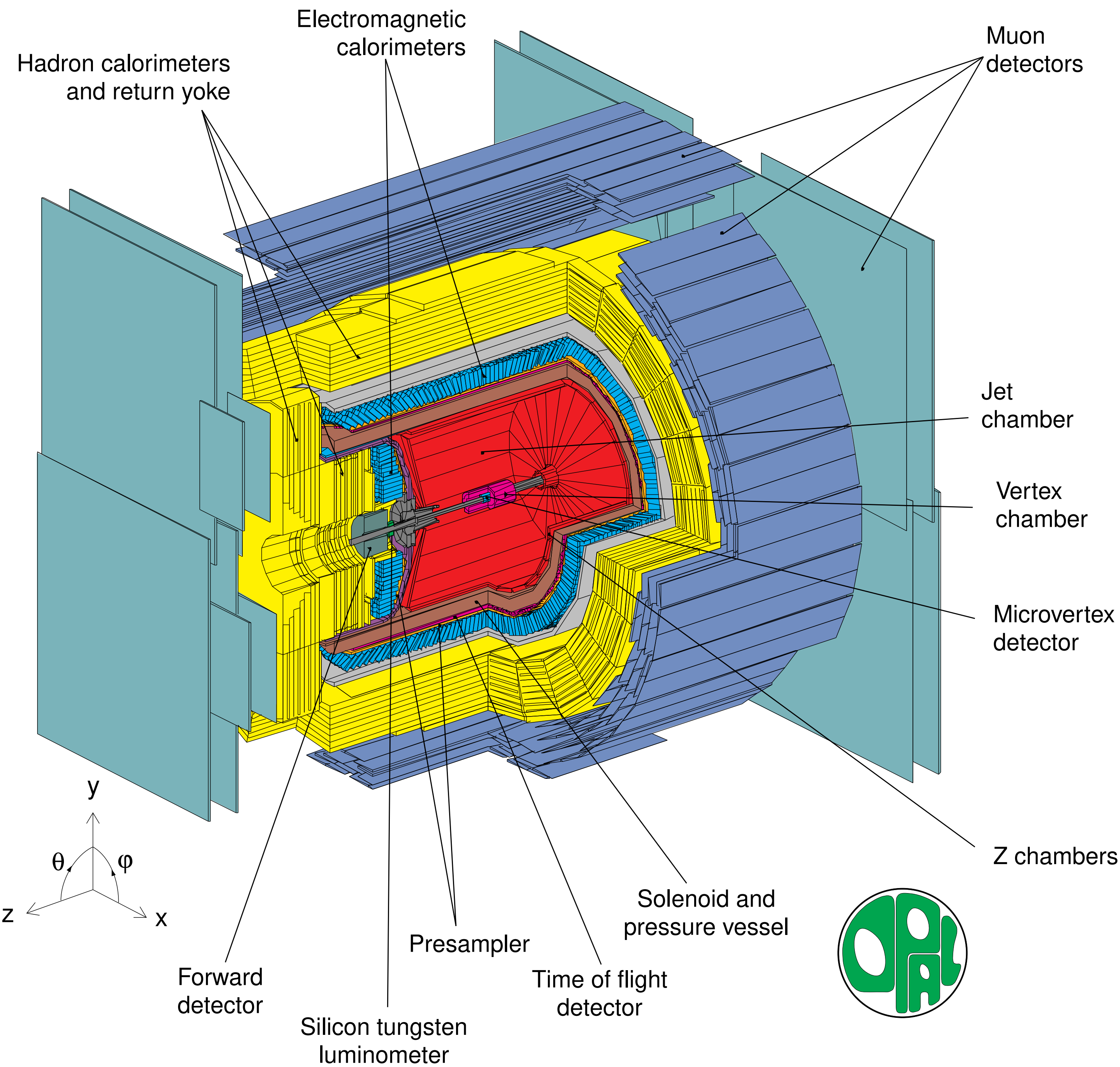
Switch on unused orbit corrector dipoles!

In 1999, 80% of the horizontal correctors were not even cabled up. In 2000, these were connected in series.

Gentler bends in the main dipoles -- less synchrotron radiation! (or more energy!)

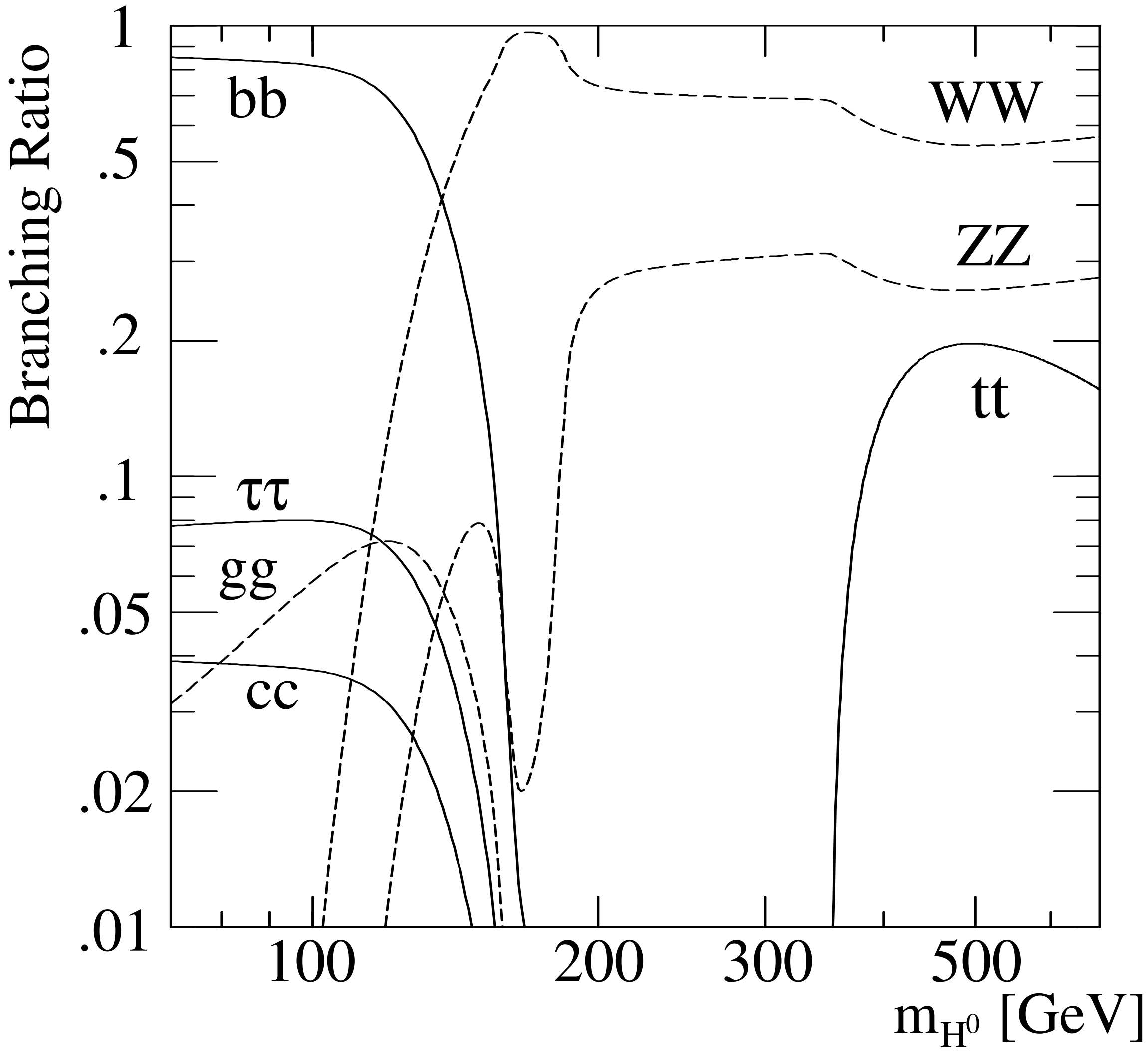
Higgs sensitivity: +0.25 GeV

A Typical LEP Dectector -- OPAL



- Solenoidal magnetic field 0.4 T
- Tracking -- particle momenta, impact parameters
- Calorimetry -- Electromagnetic and Hadronic
- Hermeticity: ECAL coverage to 25 mrad
- Muon coverage over full solid angle

Standard Model Higgs Decays



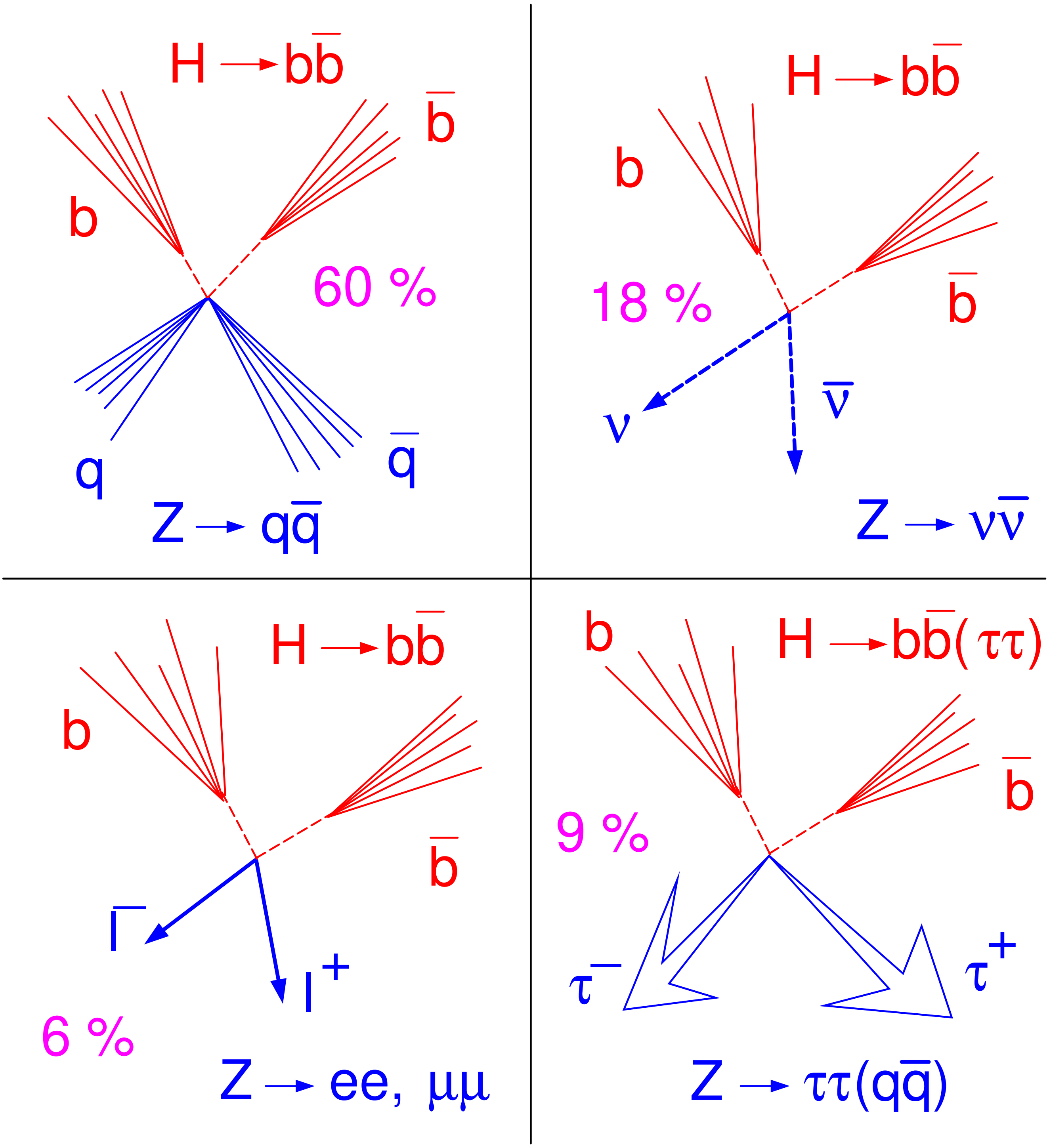
SM Higgs Decay, at 110 GeV < m_H <115 GEV

- b-quarks ~73% at m_H=115 GeV
- W^+W^- ~8% and rising quickly
- tau pairs ~7%
- charm and gluons -- the rest

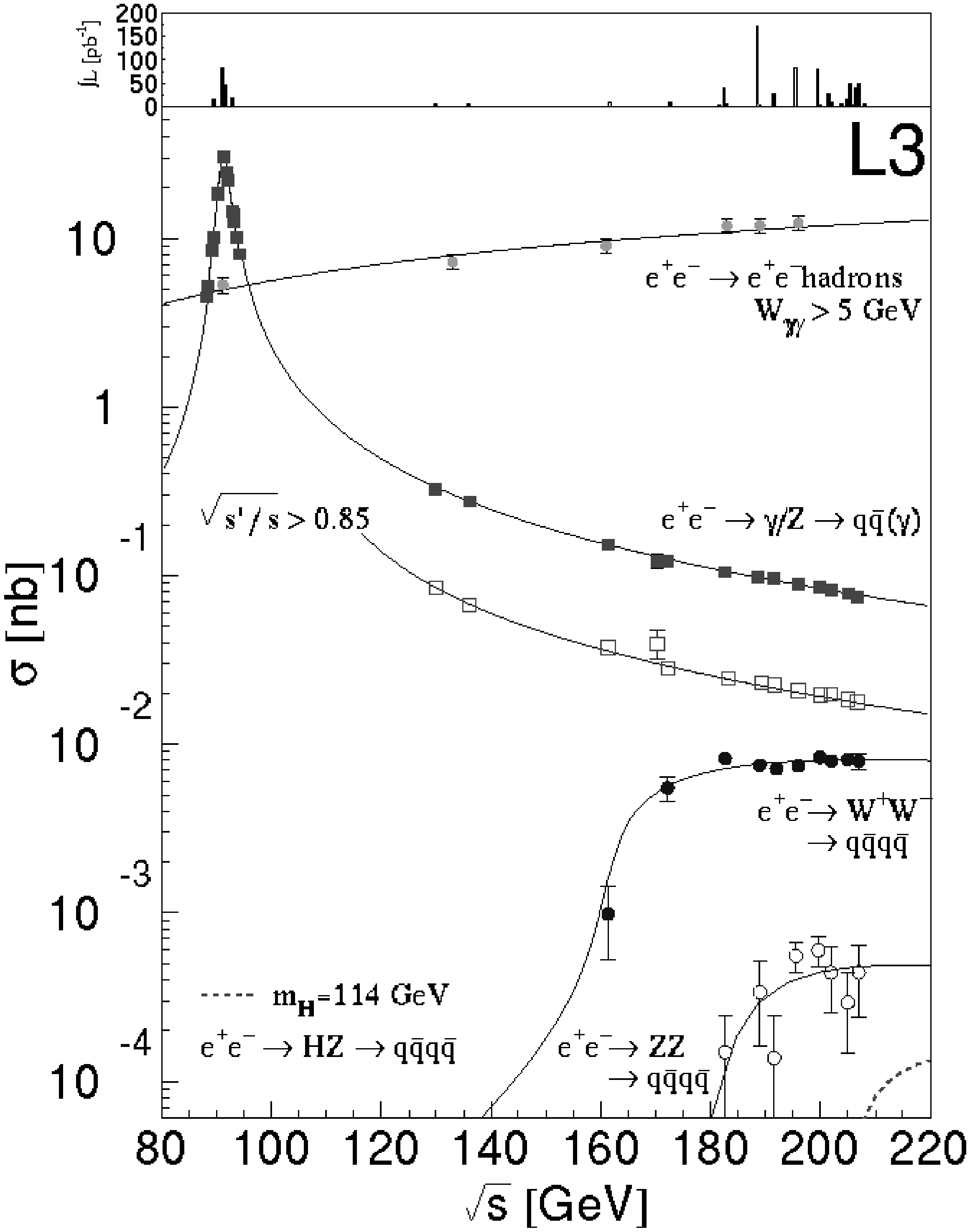
B-tags are very important

SM Higgs Search Channels

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



SM Background Processes



At LEP, SM processes are well-understood, measured electroweak interactions. Measuring luminosity is no problem.

SM Search Channels

- Four-Jet Channel
  - Strategy:
    - Preselection

      Four Clear Jets, Not Radiative

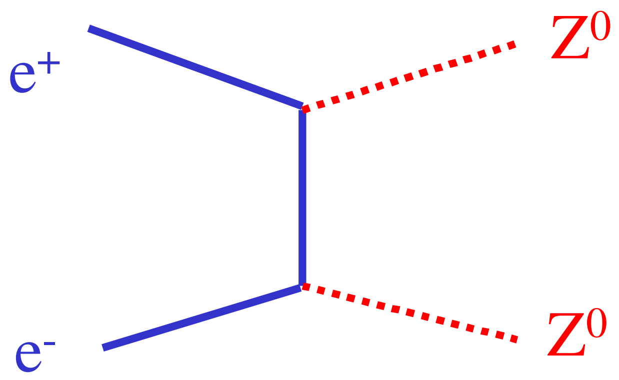
    - Likelihood selection or Neural Nets
      - b-tags
      - QCD/ZZ/WW/HZ matrix elements
      - Jet energies and angles...

    - Pick the best pairing
      - reconstructed Z mass
      - b-tags
    - Reconstruct the mass with a kinematic fit using the beam energy and momentum **(constrain E, p, and m_Z)**

      Mass resolution: About 3 GeV
    - Form a disc. var out of NN + rec. mass

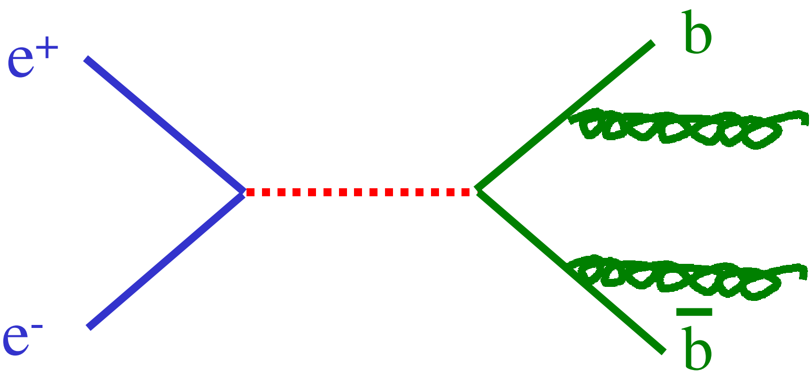
Backgrounds for the Four-Jet Channel

- Z^0Z^0 -- irreducible when searching for $m_H \approx m_Z$



- W^+W^- has more x-section, but almost never b-tags -- reducible!

- $Z^0/\gamma \rightarrow q\bar{q}$ becoming more important near threshold production for $m_H > m_Z$



•b's back-to-back, gluons back-to-back $\rightarrow$ reconstructed mass = maximum possible

SM Search Channels

- Missing-Energy Channel
  - Strategy:
    - Preselection (Recoil mass near m_Z, non-radiative)
    - Likelihood selection or Neural Nets
      - b-tags
      - E_{miss}, $\cos\theta_{miss}$, acoplanarity
    - Reconstruct the mass

      Again a beam constraint, but **missing two neutrinos!**

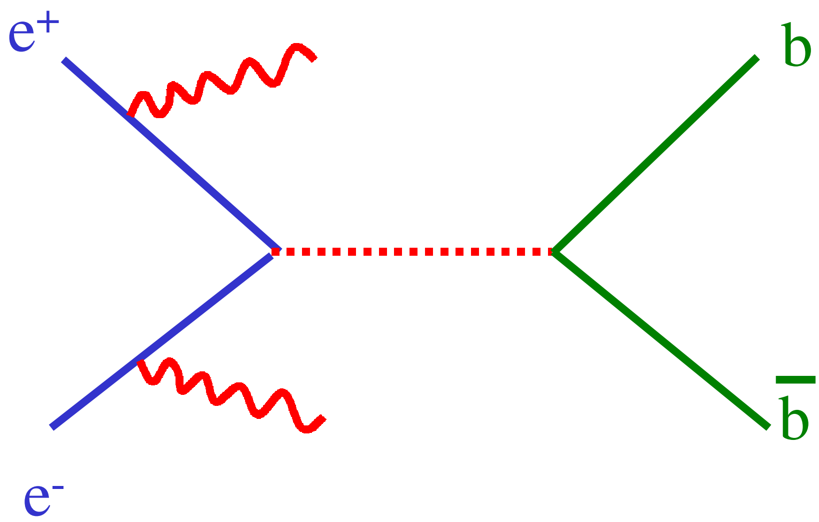
      Mass Resolution: About 7 GeV
    - Form a disc. var out of NN + rec. mass
  - Capitalize on fusion: relax preselection cuts, particularly on recoil mass

Backgrounds for the Missing-Energy Channel

For $m_H \approx m_Z$, Z^0Z^0 is irreducible -- real b's and missing energy. W^+W^- not a problem because b-tags are very pure.

For $m_H > m_Z$, then $Z^0/\gamma \rightarrow qq$ is more important again.

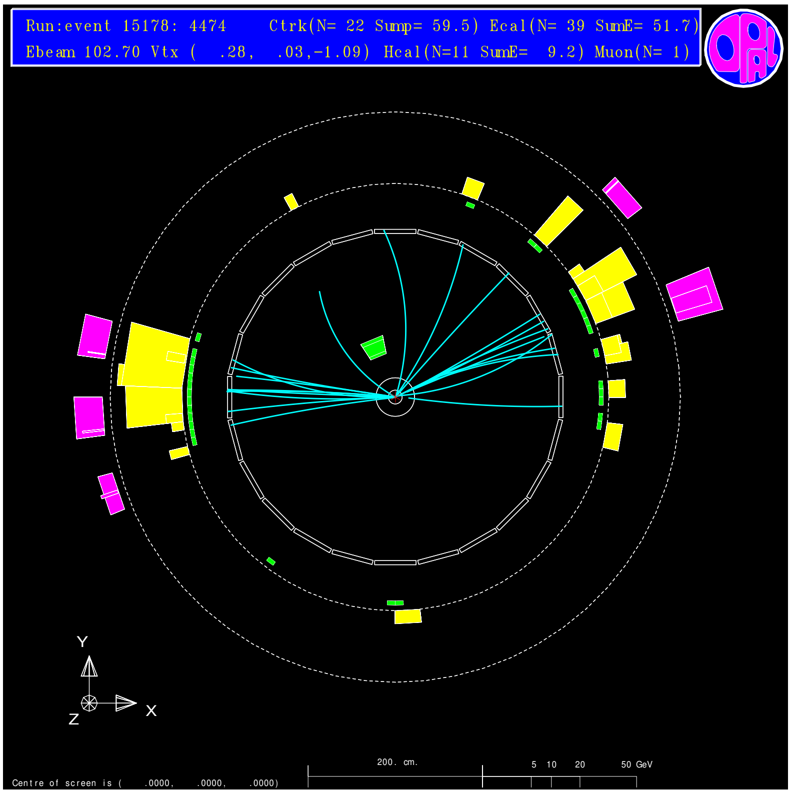
Double-ISR: (undetected photons down beampipe)



Can reduce it by requiring missing P_t, but for $m_H^{recon} = \sqrt{s} - m_Z$ P_t=0, acop.=0, and cuts reduce the signal acceptance.

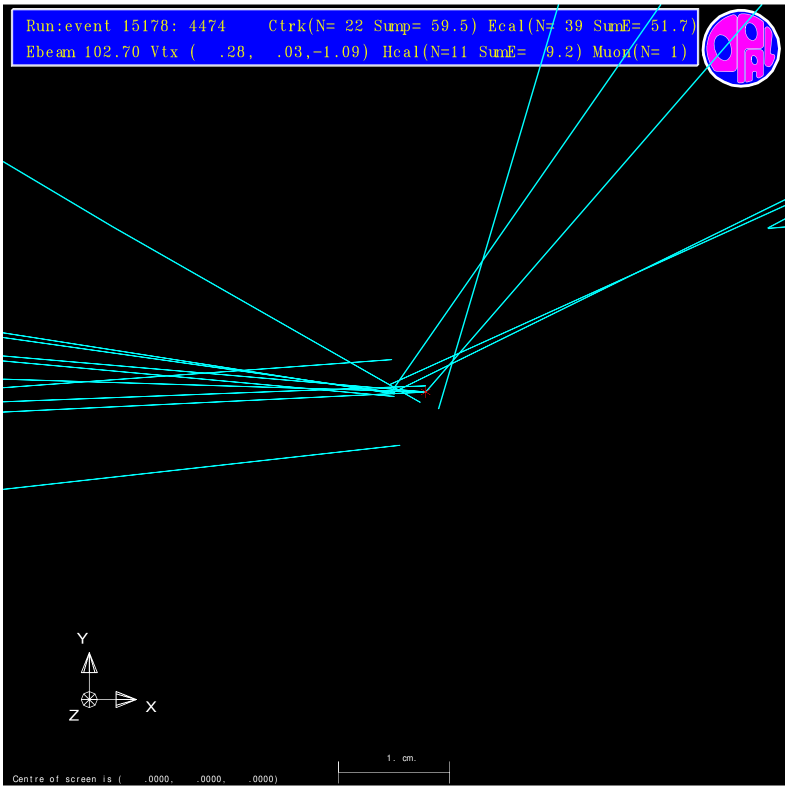
Single-W and **Single-Z production** (*t*-channel photon exchange)

An Example of a Missing-Energy Candidate from OPAL



Large missing p_T

$m_{H,rec}$=104 GeV



Solid b-tag (beam spot is red)

SM Search Channels

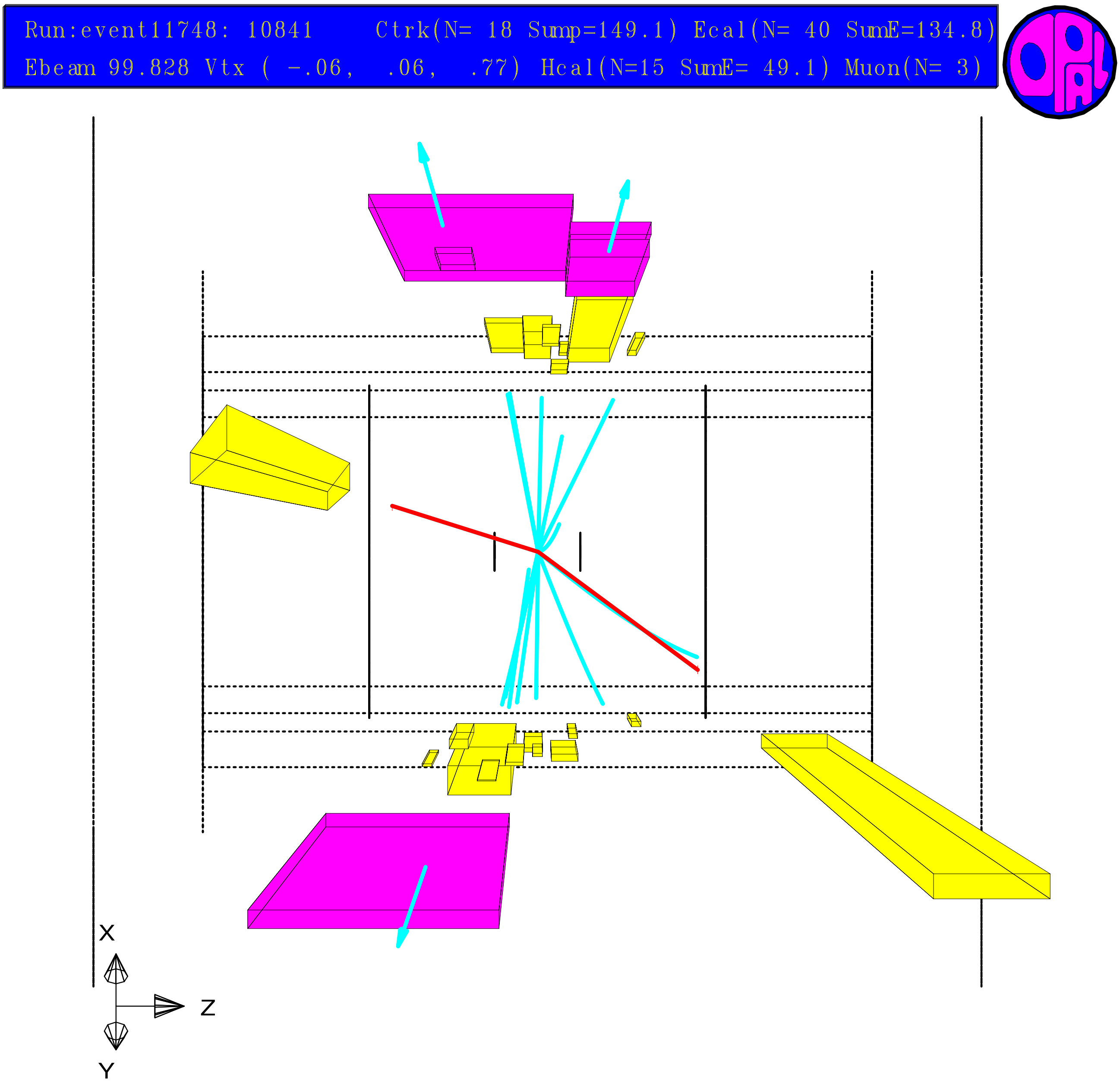
- Tau Channels HZ $\rightarrow$ H$\tau\tau$ and $\tau\tau$Z
  - *Two* selections
    different recoil mass constraints
  - Elaborate Tau ID

- Lepton channels --
  - Electron and muon ID
    - Calorimeters
    - Muon chambers
  - 5C fits done to improve m_{rec}
    resolution, particularly in muon channels

  - ZZ background irreducible

Typical efficiencies in all channels:
30-50% -- but separation of the selected signal from the selected background is what counts!

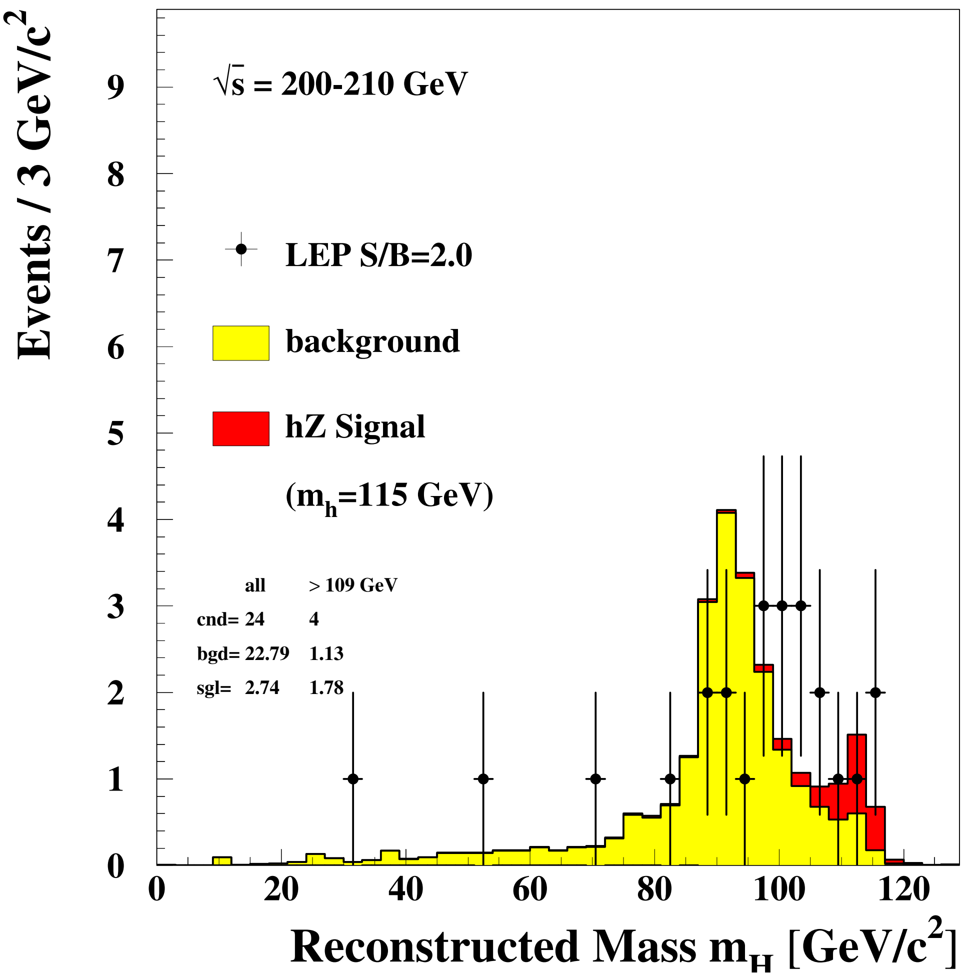
Example of a Lepton Channel Candidate



Two Electrons and Two Jets

$M_{rec} \sim 90$ GeV

Distribution of the Reconstructed Mass



Question: Where to put the cuts?
Answer: Ideally, nowhere.
Plot is to show mass resolutions
And with tight cuts, shows the
"good" candidates. But lose eff'y!

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?

- Constructed from binned search results:
- Each bin has
  - **Estimated number of signal events**
    (depends on m_H, x-sec., branching ratios)
  - **Estimated number of background events**
  - **Number of events observed in the data**
- Systematic errors included by channel by error source.

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

The Likelihood Ratio

Treat each bin as an independent counting experiment.

$$Q = \prod_i \frac{\dfrac{(s_i + b_i)^{n_i^{data}} \; e^{-(s_i+b_i)}}{n_i^{data}\,!}}{\dfrac{b_i^{\,n_i^{data}} \; e^{-b_i}}{n_i^{data}\,!}}$$

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

- Combination is very easy -- logQ's add linearly
- Contribution of an event depnds on the

  local s/b ratio. -- in the bin in which the candidate is observed.

Events are classified by their s/b ratios.
s/b depends on m_H (x-sec, branching ratios)

Confidence Levels

Use MC or analytic techniques to find the PDF of log$Q$, given the results of all bins.

The probability of missing a signal if it is there:

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

The probability of seeing the candidates we got (or more) if there were only background.

$$1 - CL_b = P\left(Q > Q_{obs} \mid background\right)$$

Discovery Criterion: 1-CL$_b$ < 5.7×10^{-7}

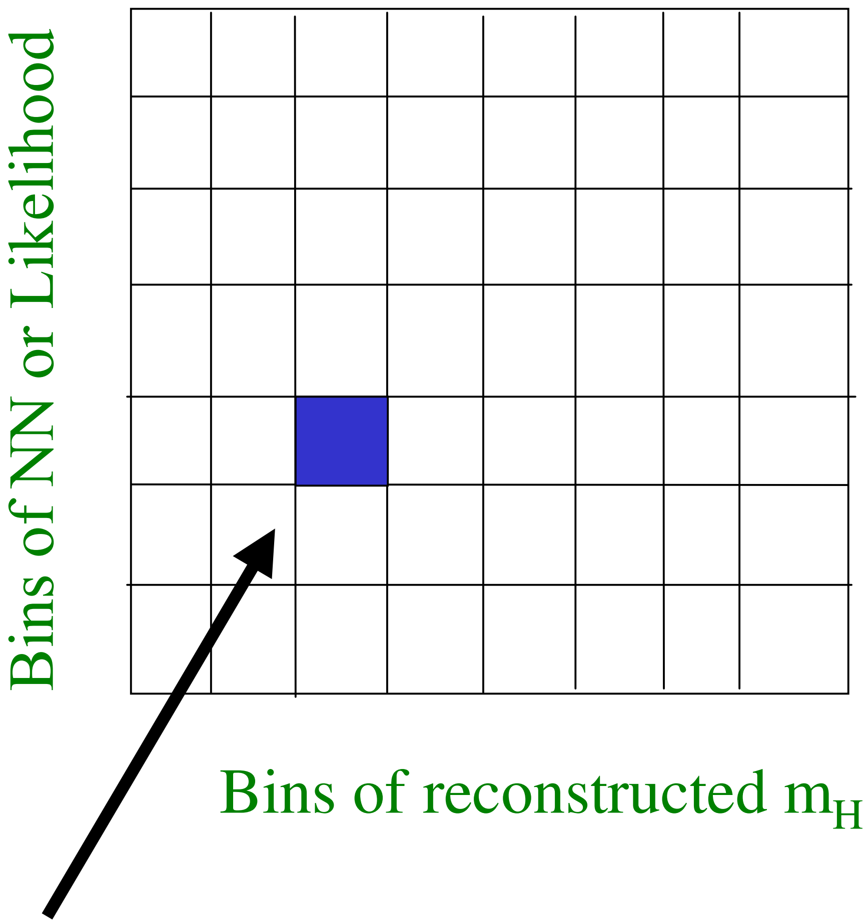
Regulated CL$_{s+b}$ so fluctuations in bg do not exclude models we are not sensitive to.

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

Two-Dimensional Results

most channels

- Reconstructed mass
- Likelihood variable or Neural net, summarizing
  - b-tags
  - kinematic information

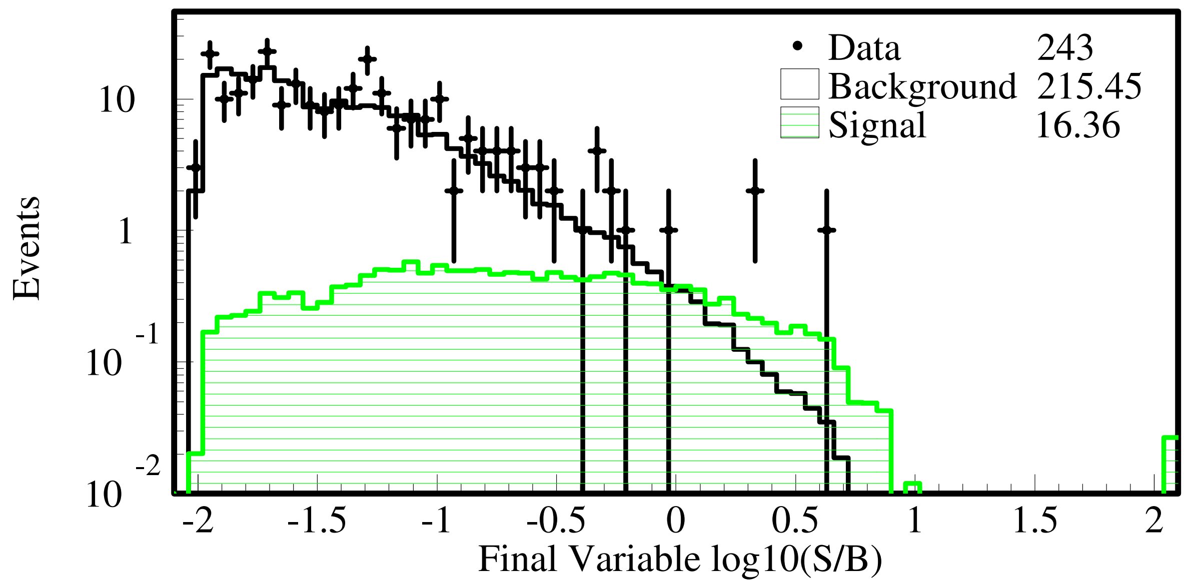


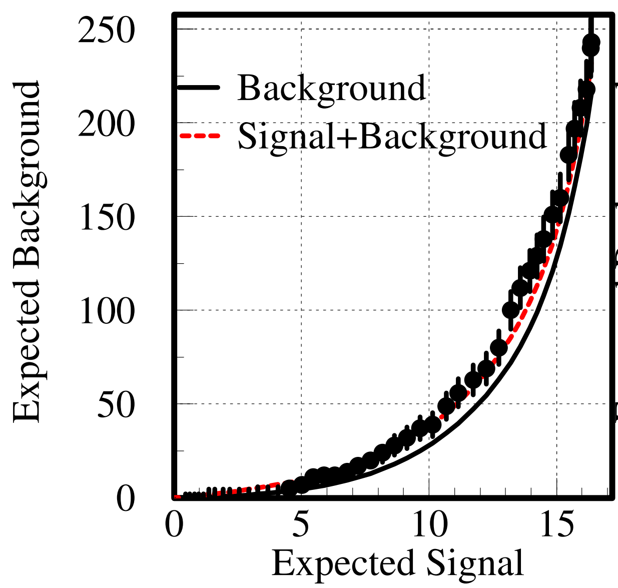
Compute s_i, b_i, and $n_{data,i}$ in each bin

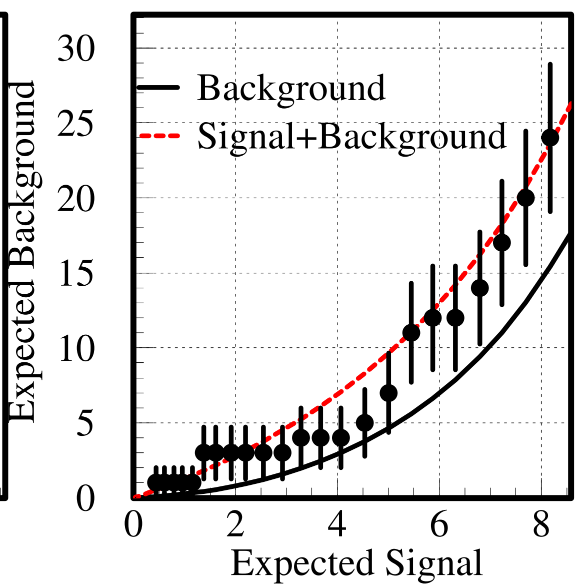
Extends sensitivity over just the mass, or cuts!

Distribution of Local s/b

Test mass: m_H=115 GeV



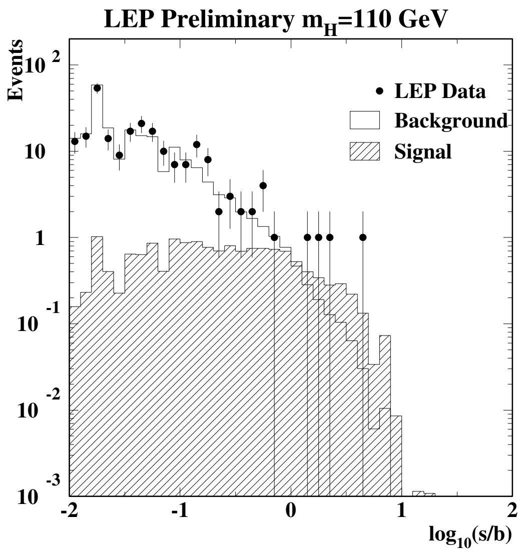


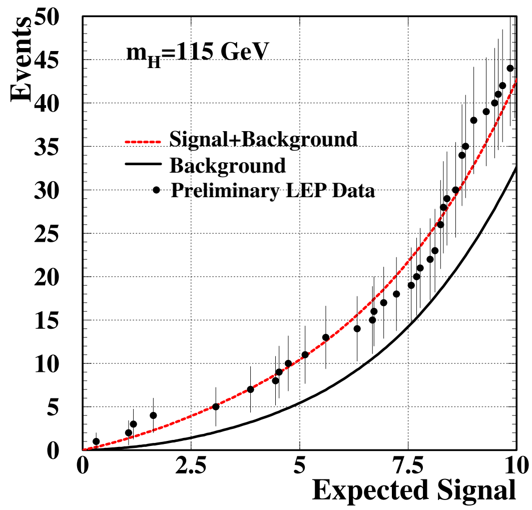


Integral is from the high s/b side.
Retains all search sensitivity information.

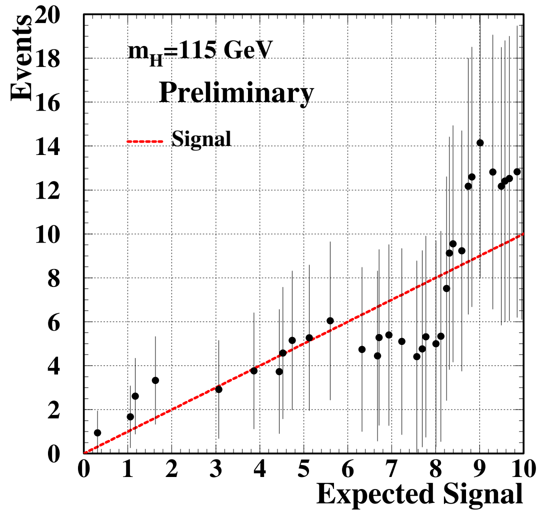
SM November 3 Results -- L3 needs more time

Sensitivity and Observations at m_H=115 and 110 GeV

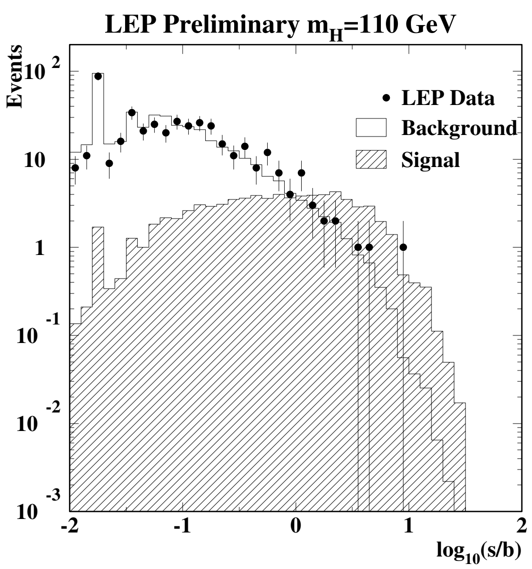


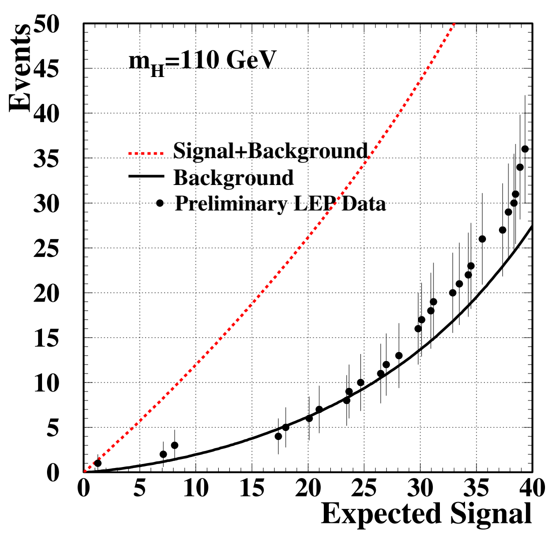


Background subtracted

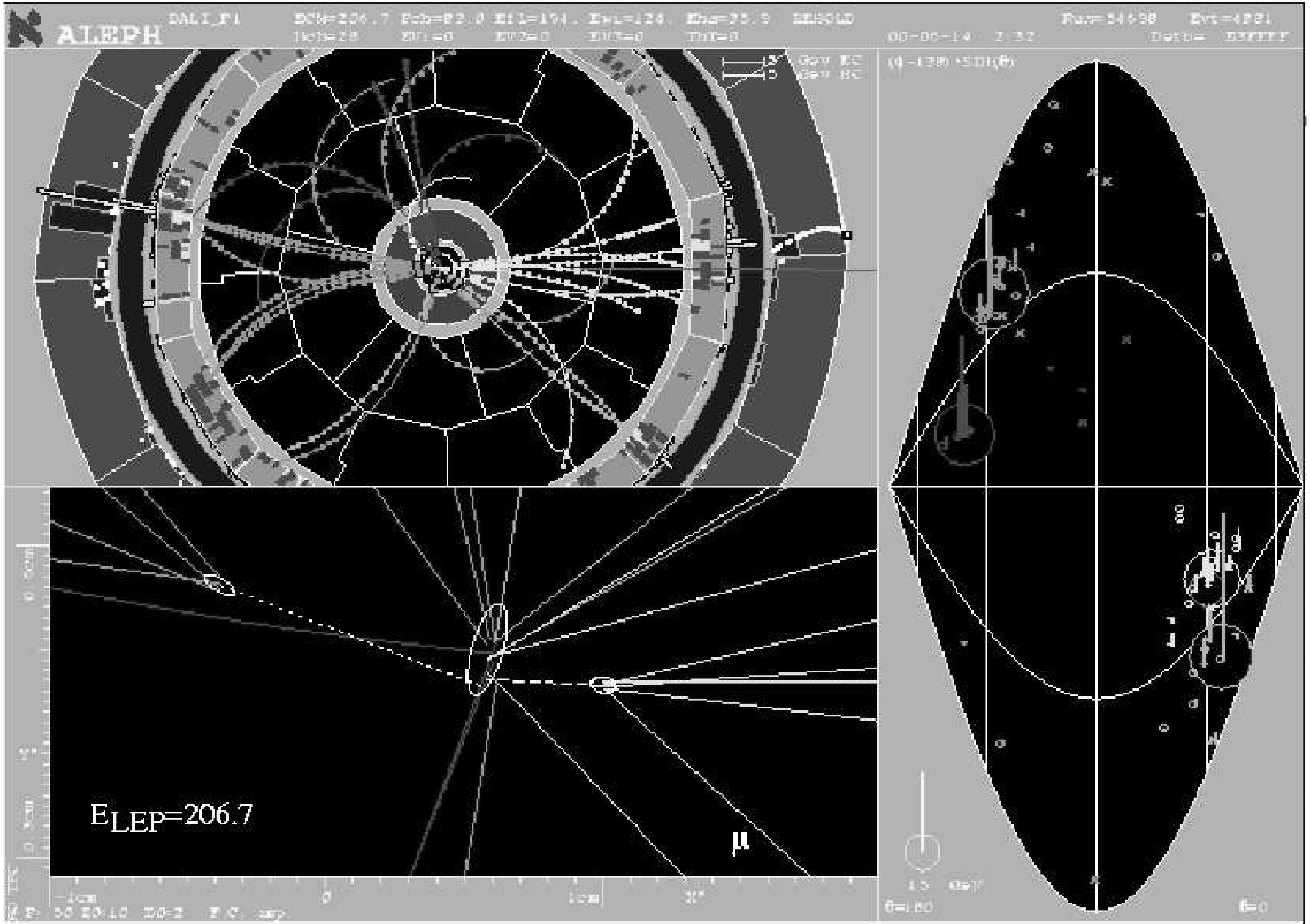


nb: uses SUSY inputs "SM-like" case.





The First Strong ALEPH 4J Candidate -- July 2000



2 b cand.

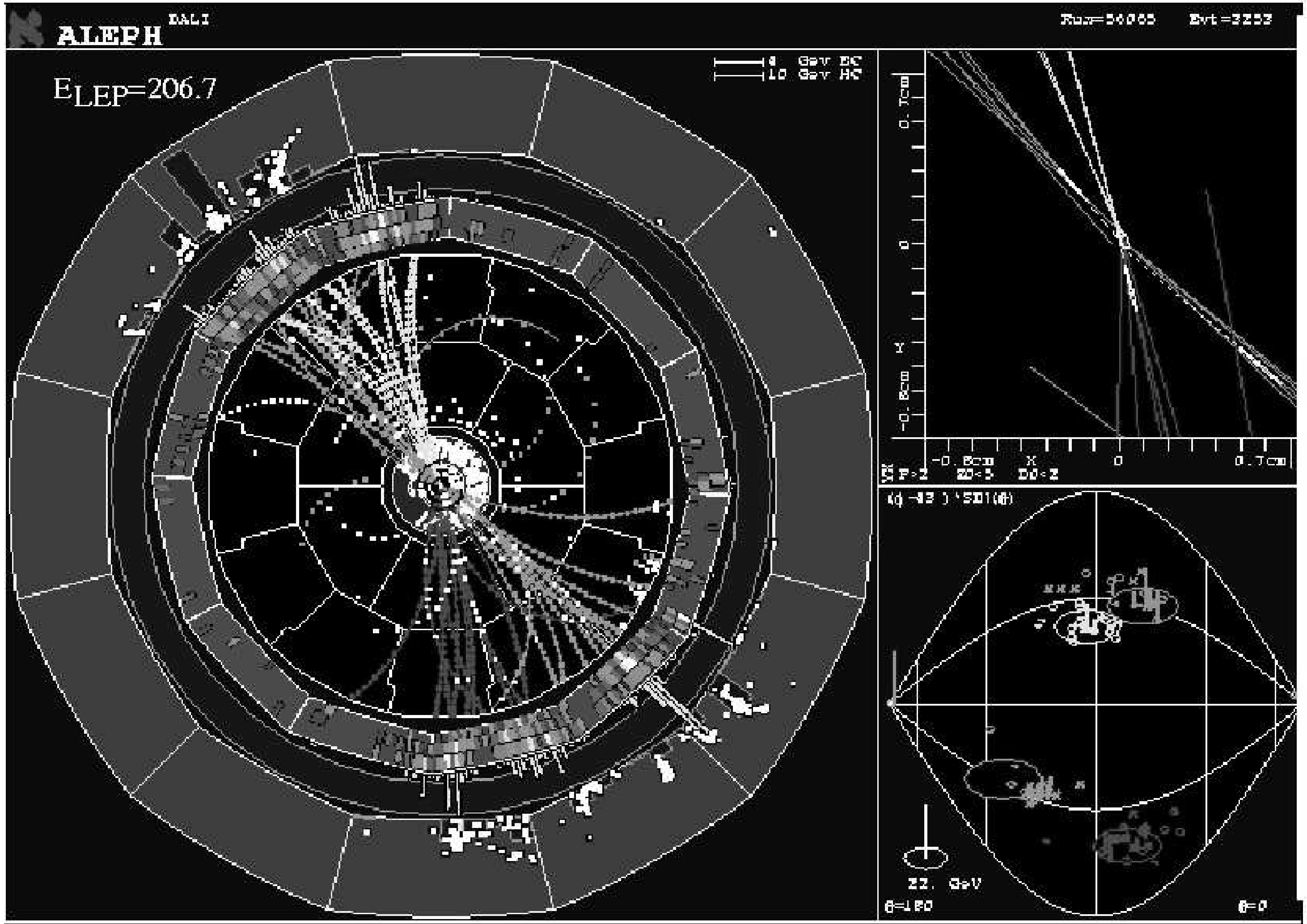
HZ hyp.

m_H=114 GeV

NN = 0.996

jet	b–tag:
	Z
1	0.14
2	0.01
	H
3	0.99
4	0.99

A Second Strong 4J Candidate from ALEPH



4 b cand.

HZ hyp.

m_H=

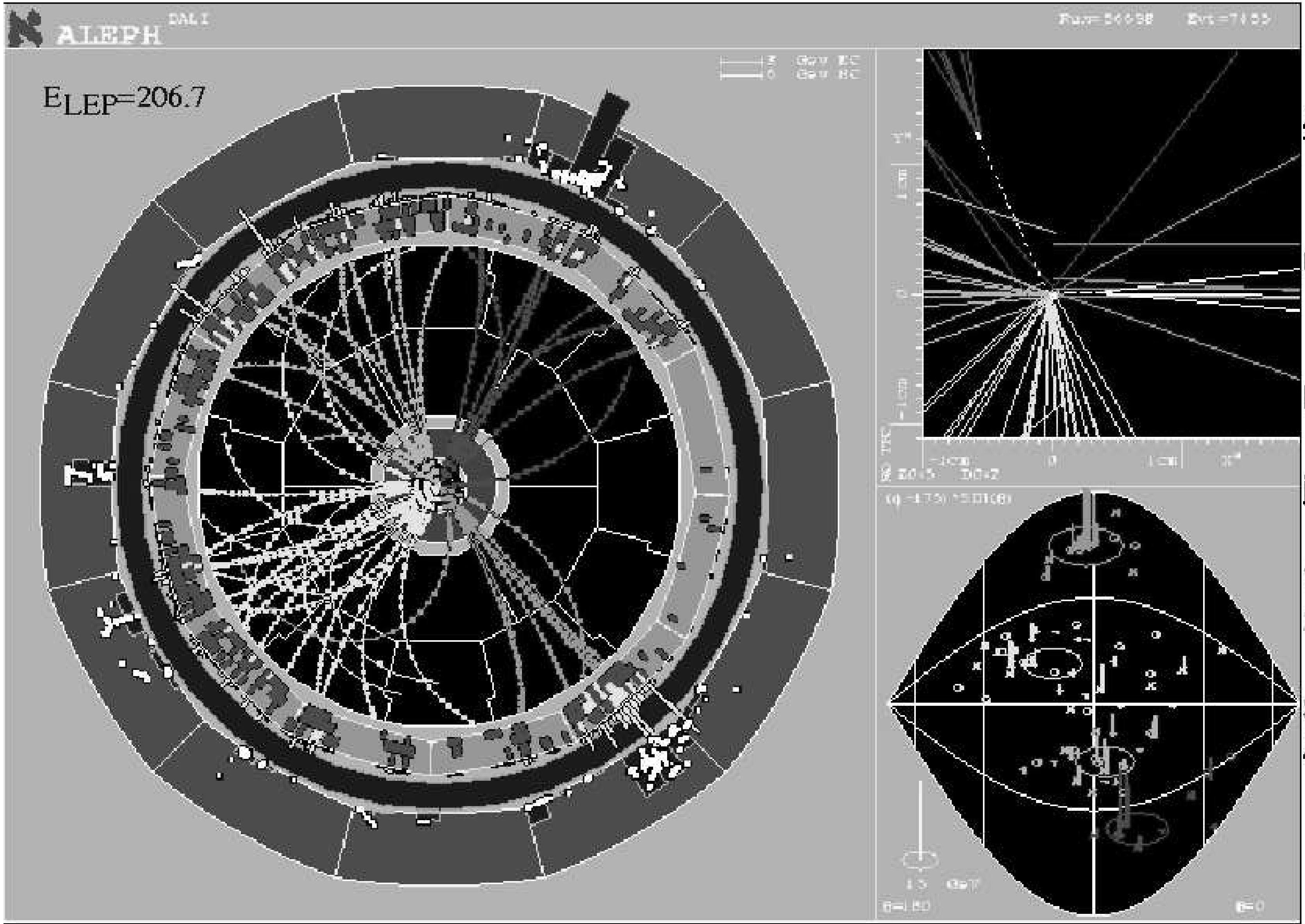
112.8 GeV

NN = 0.997

jet	b–tag:
Z	
1	0.994
2	0.78
H	
3	0.993
4	0.999

Kinematics more qq-like, but four b-tags

The Third Strong Candidate from ALEPH



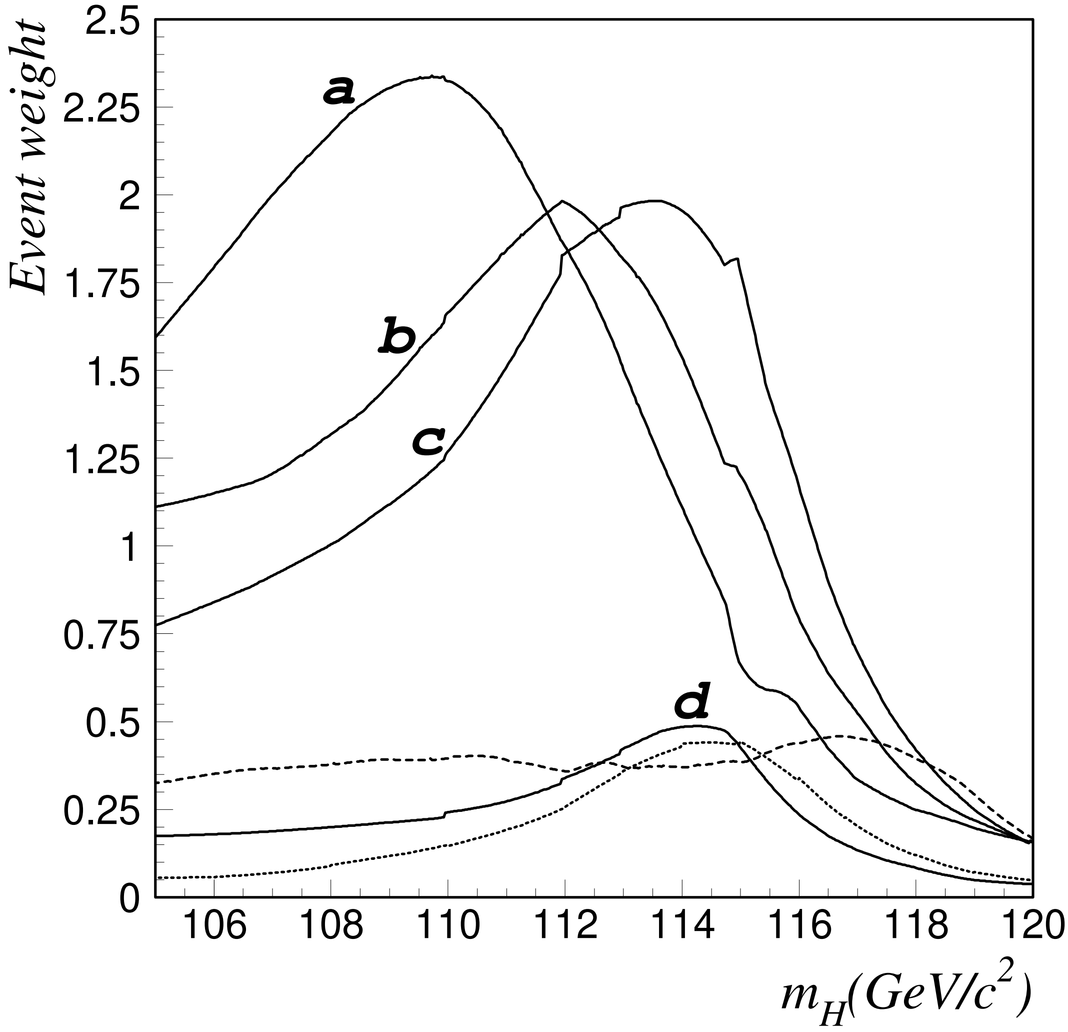
4 b cand.

m_H=110 GeV

NN = 0.999

jet	b–tag:
Z	
1	0.99
2	0.84
H	
3	0.99
4	0.21

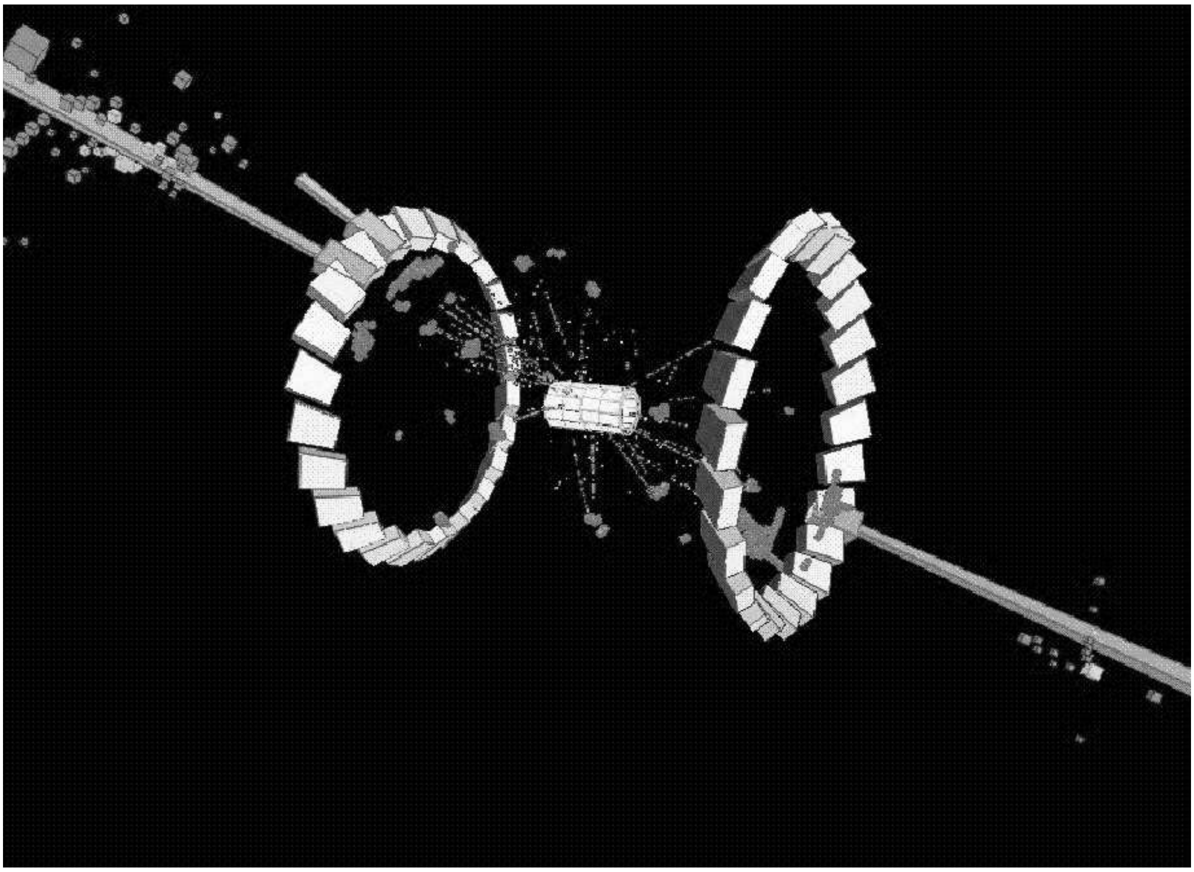
Contributions from ALEPH Candidates

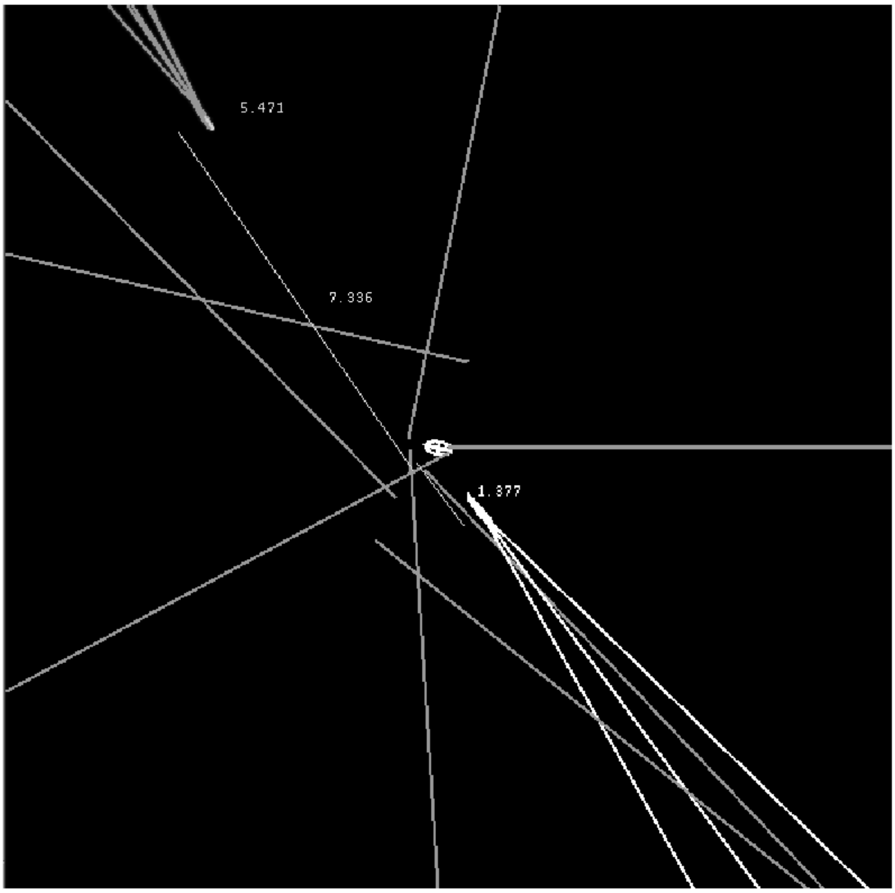


As published in Phys. Lett. B

Three most significant candidates:
in the 4-jet channel.

A Missing-Energy Candidate from L3

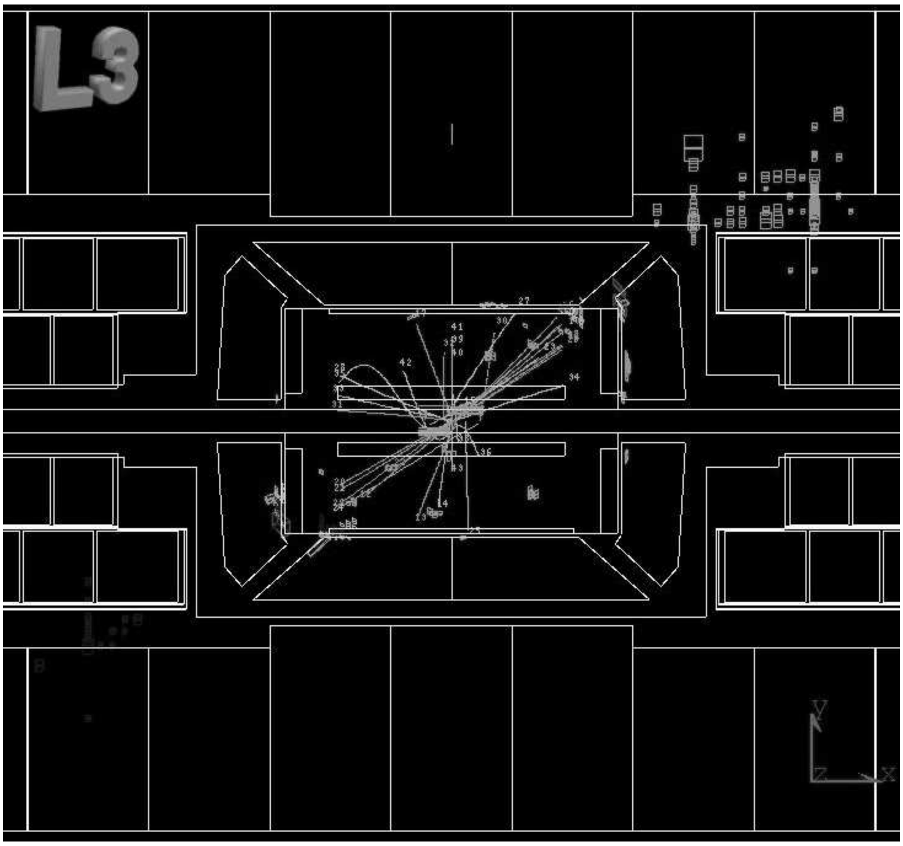


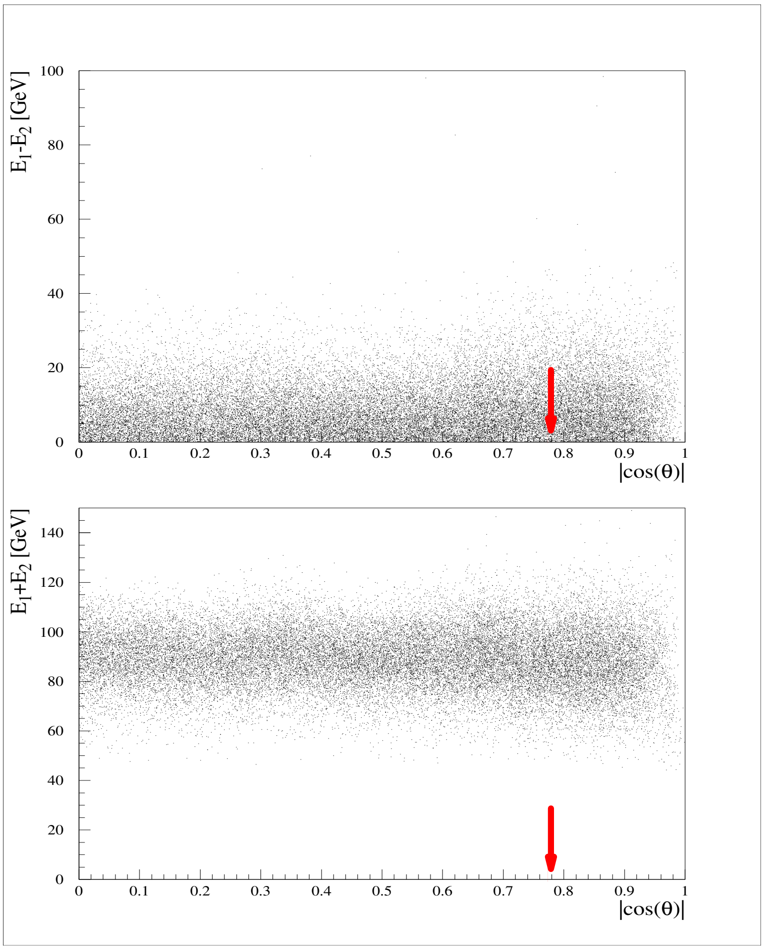


Two good b-tags!

M_{rec}=114 GeV

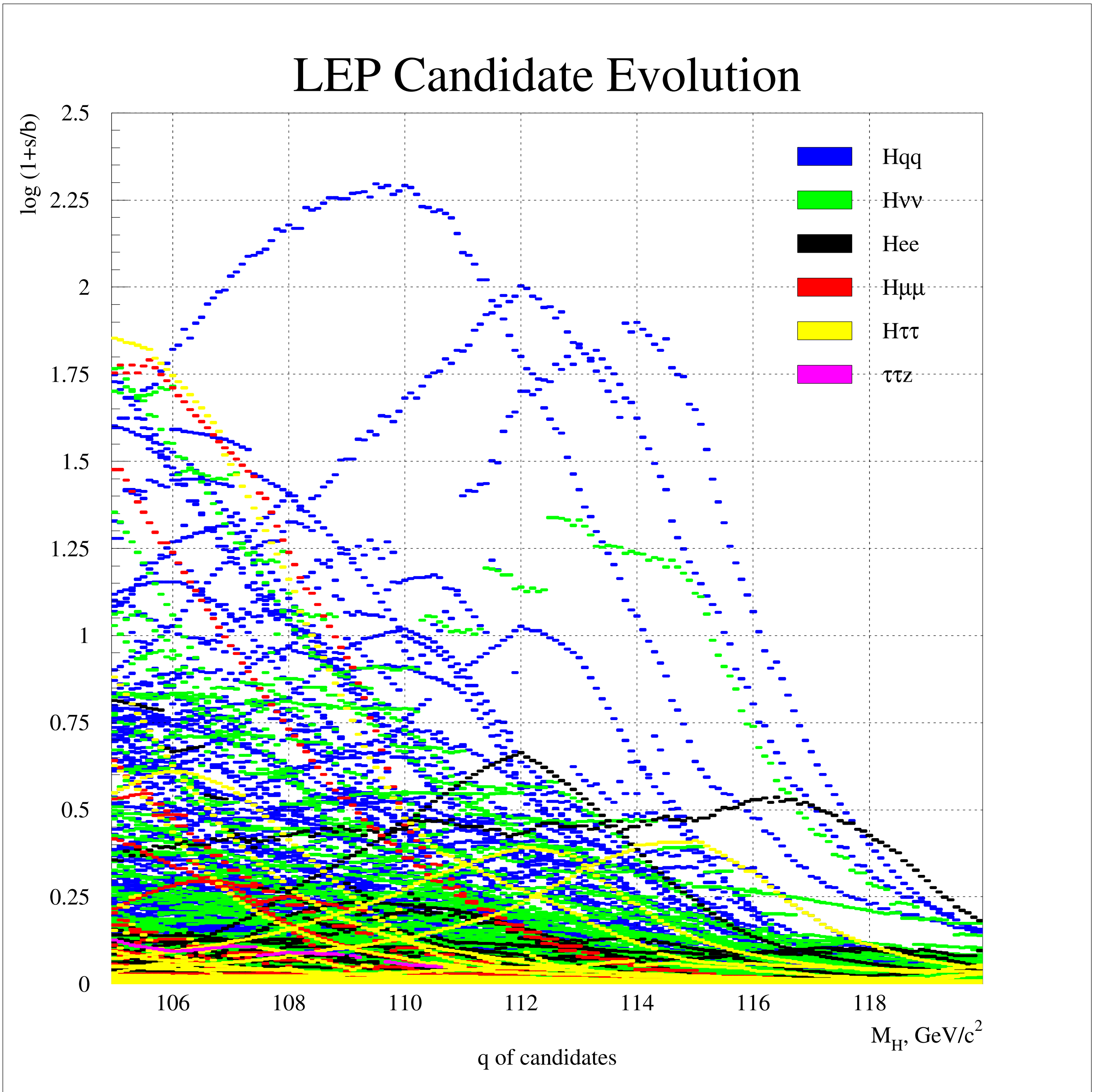
Is the L3 Event Headed for a Crack?





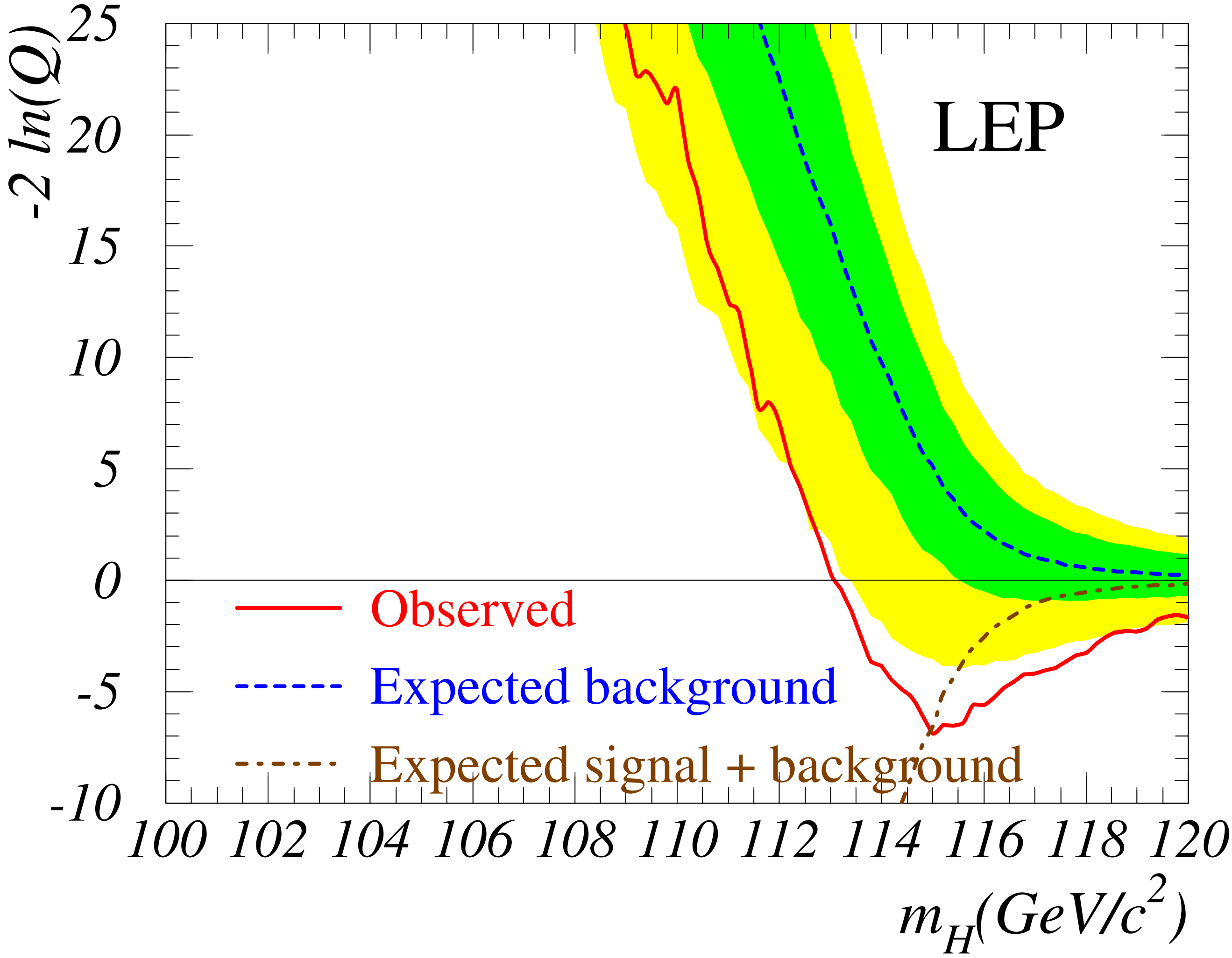
Jet energy resolution remains good even in the barrel-endcap overlap region

Contributions from All Candidates



All candidates from data taken in 2000

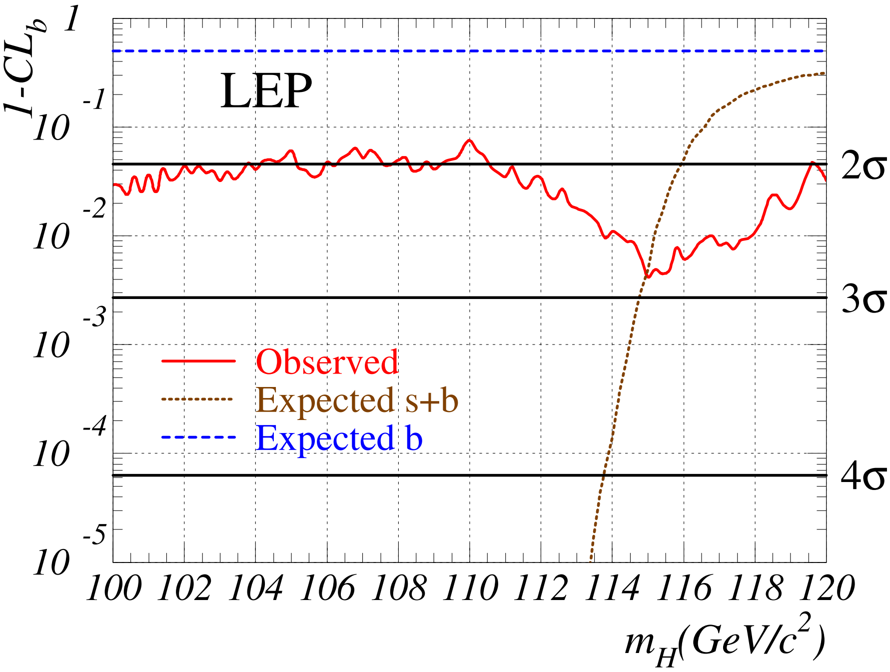
Combined Test Statistic and its Expectation



Nov. 3 LEPC Results

$1\text{-}CL_b$ is the integral of the PDF of -2lnQ from the observation to infinity. Preferred m_H is very near 115 GeV -- contains cross-section and reconstructed mass information

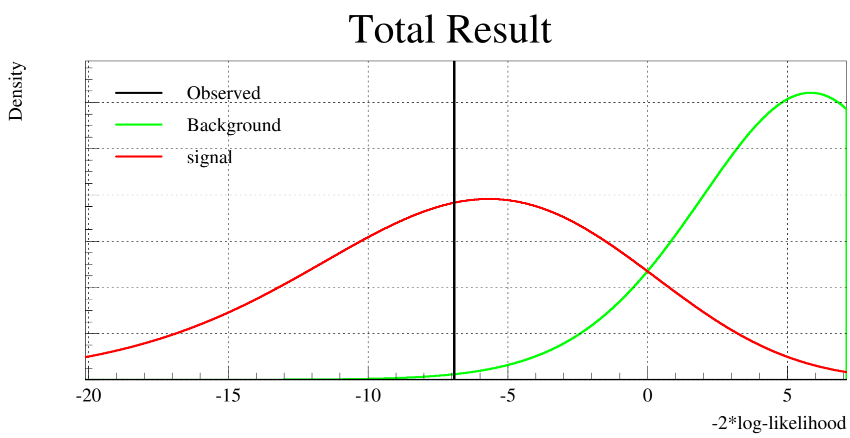
The Significance of the Excess



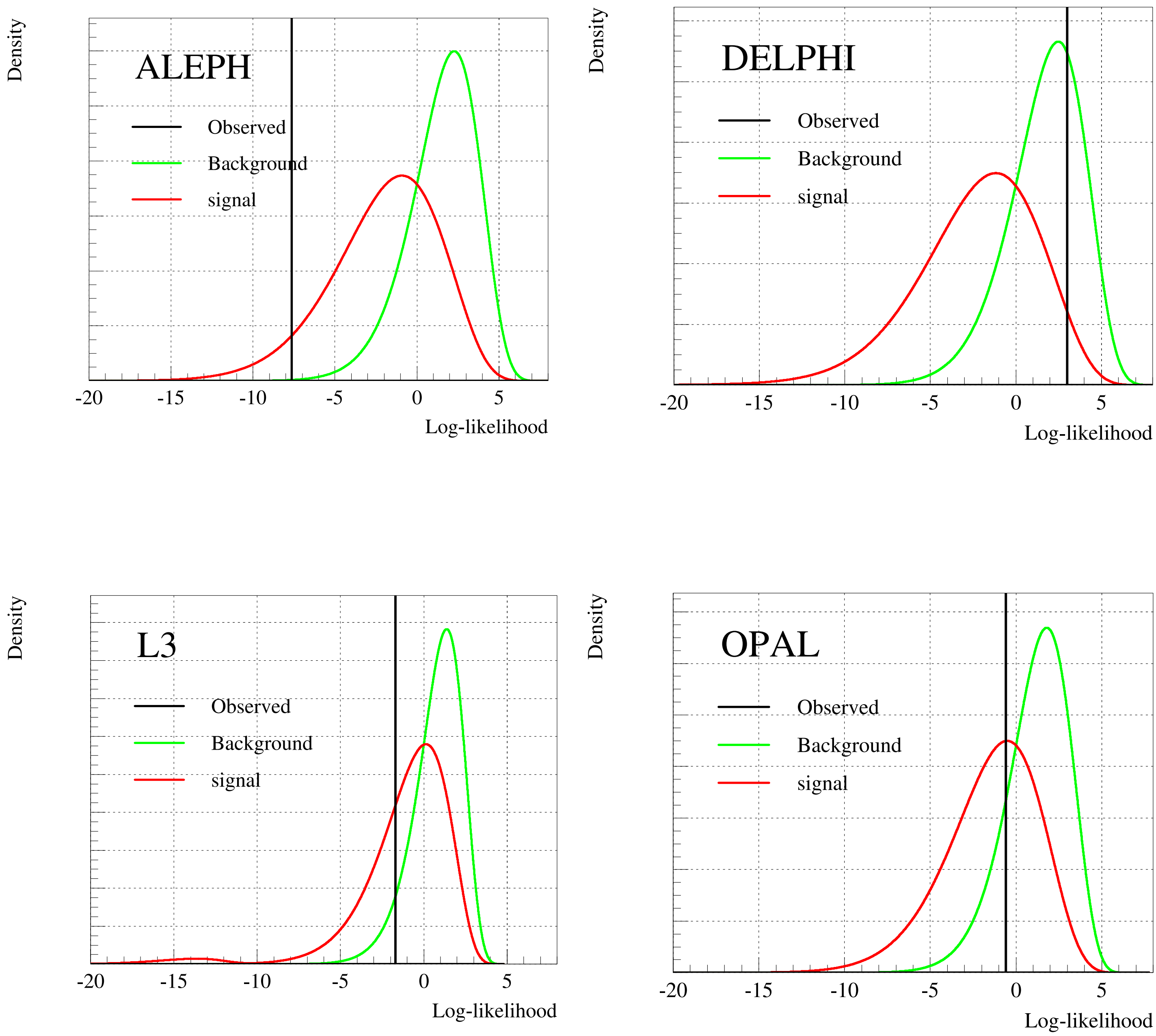
“One-Sided” “One-Tailed” sigmas indicated.
(5σ corresponds to $1\text{-}CL_b=5.7\times10^{-7}$)

$1\text{-}CL_b(m_H=115\ \text{GeV}) = 4.2\times10^{-3}$, corresponding to a 2.9σ excess.

A snapshot of the PDF’s of -2lnQ for m_H=115 GEV

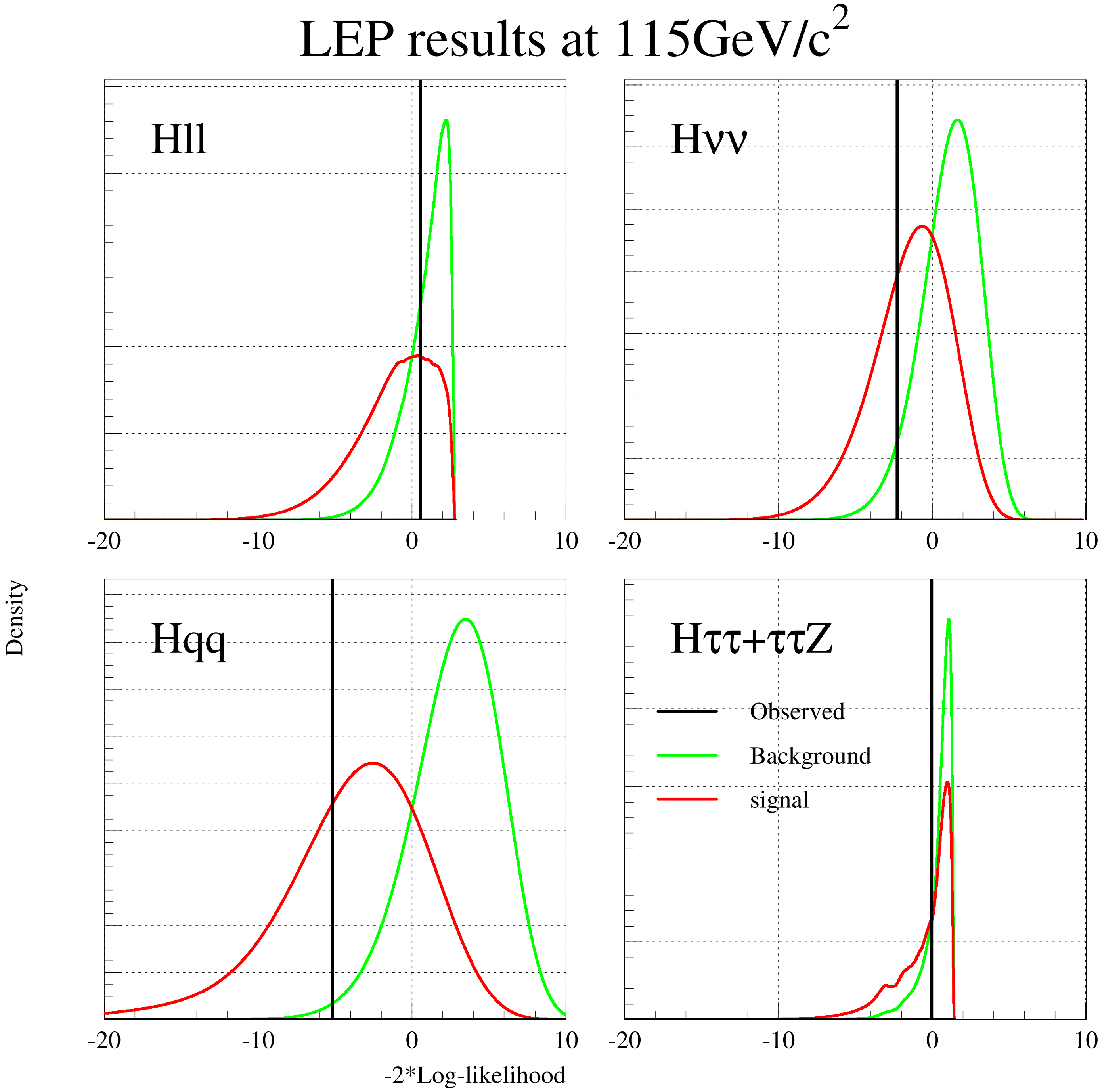


Source of the Excess -- -2lnQ by Experiment



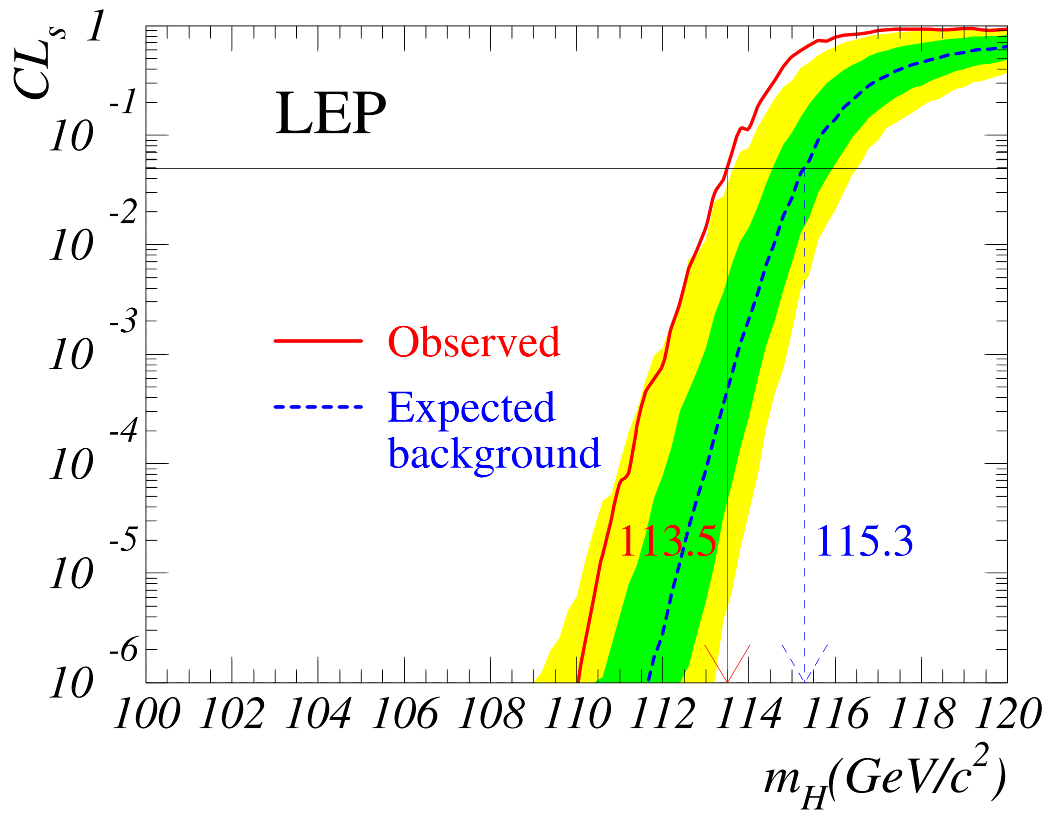
m_H = 115 GeV “Test Mass”

Source of the Excess -- -2lnQ by Search Channel



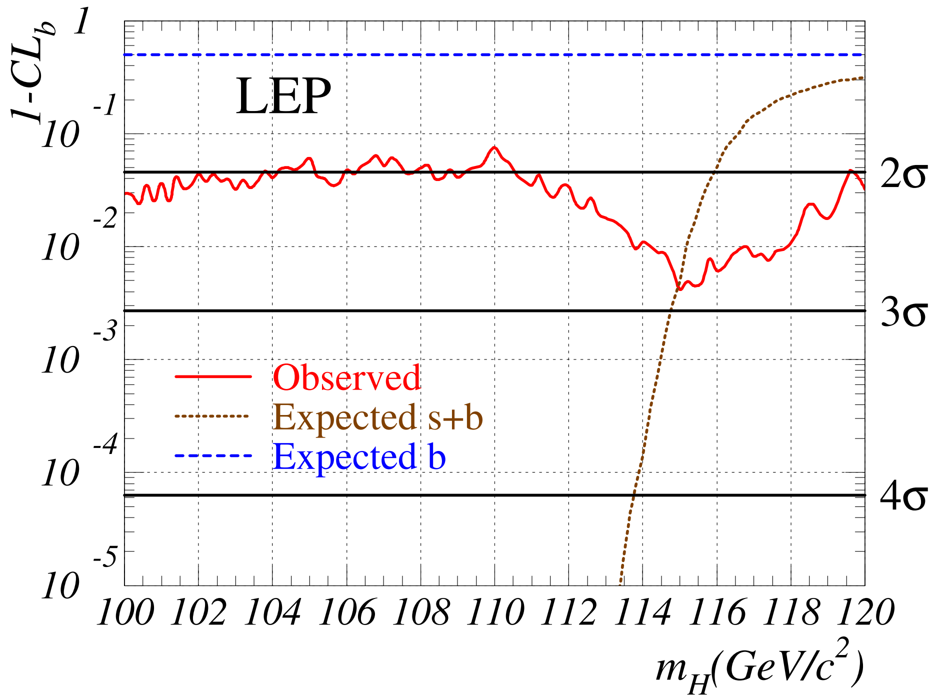
Exclusion Limits

- Even with excess candidates, LEP can still exclude some m_H test hypotheses because
  - Not enough candidates for expected signal rate, or
  - Candidate reconstructed masses (or NN values) are not correct for the signal

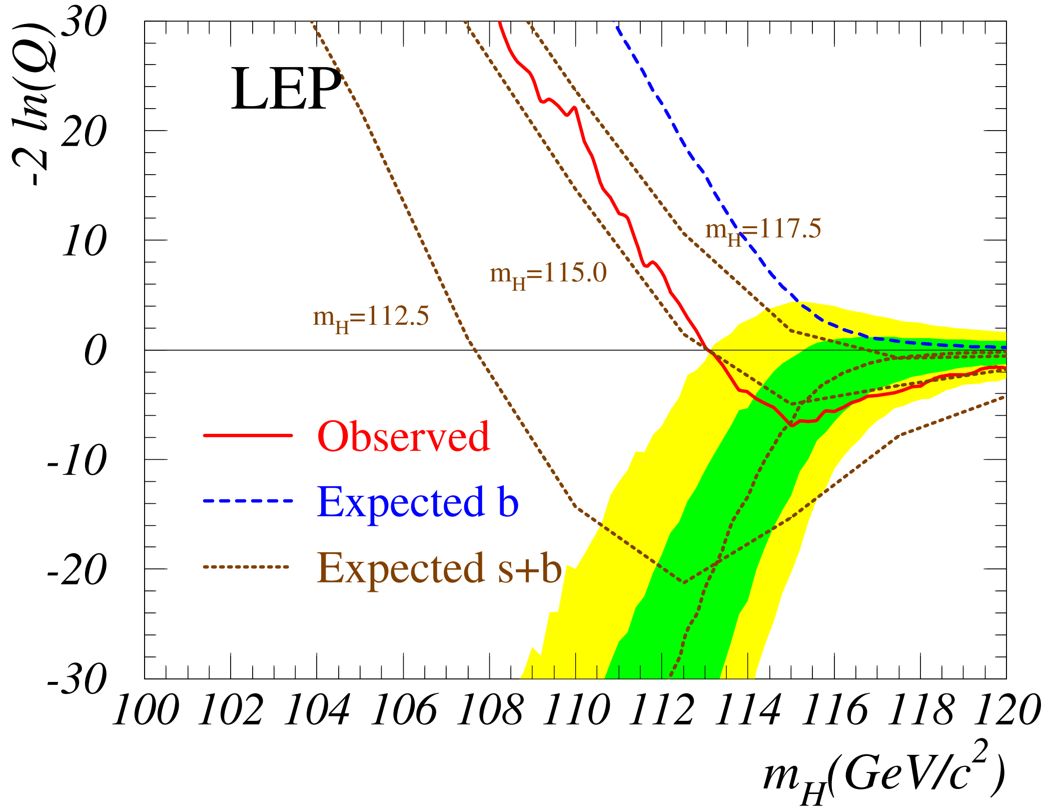


Exclusion limits are weaker than expected!

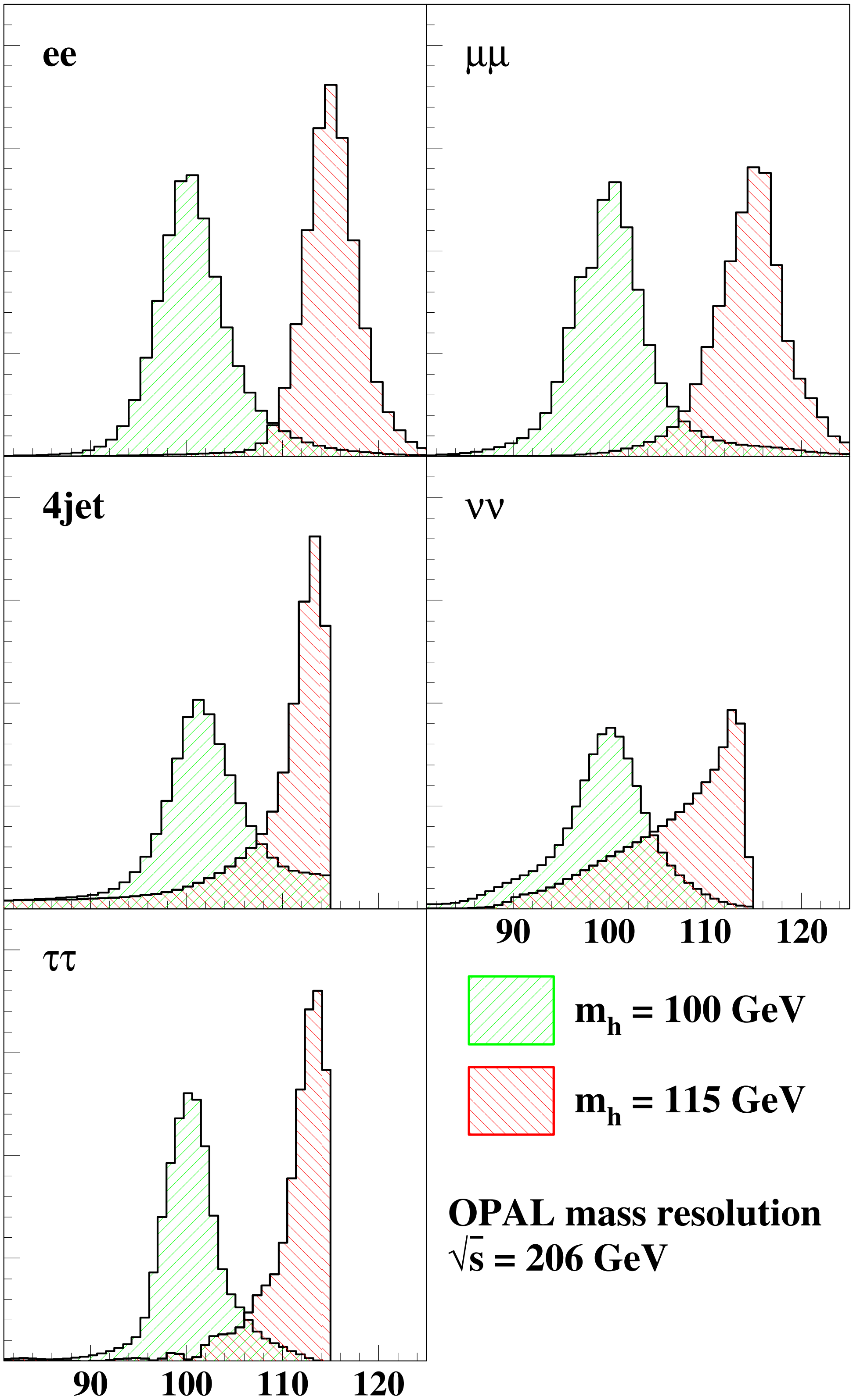
General Excess Below m_H=115 GeV?



It is expected for a true signal at m_H=115 GeV



The Reason A General Excess is Expected



Near the kinematic edge, get lower m_{rec}, not higher!

Timeline

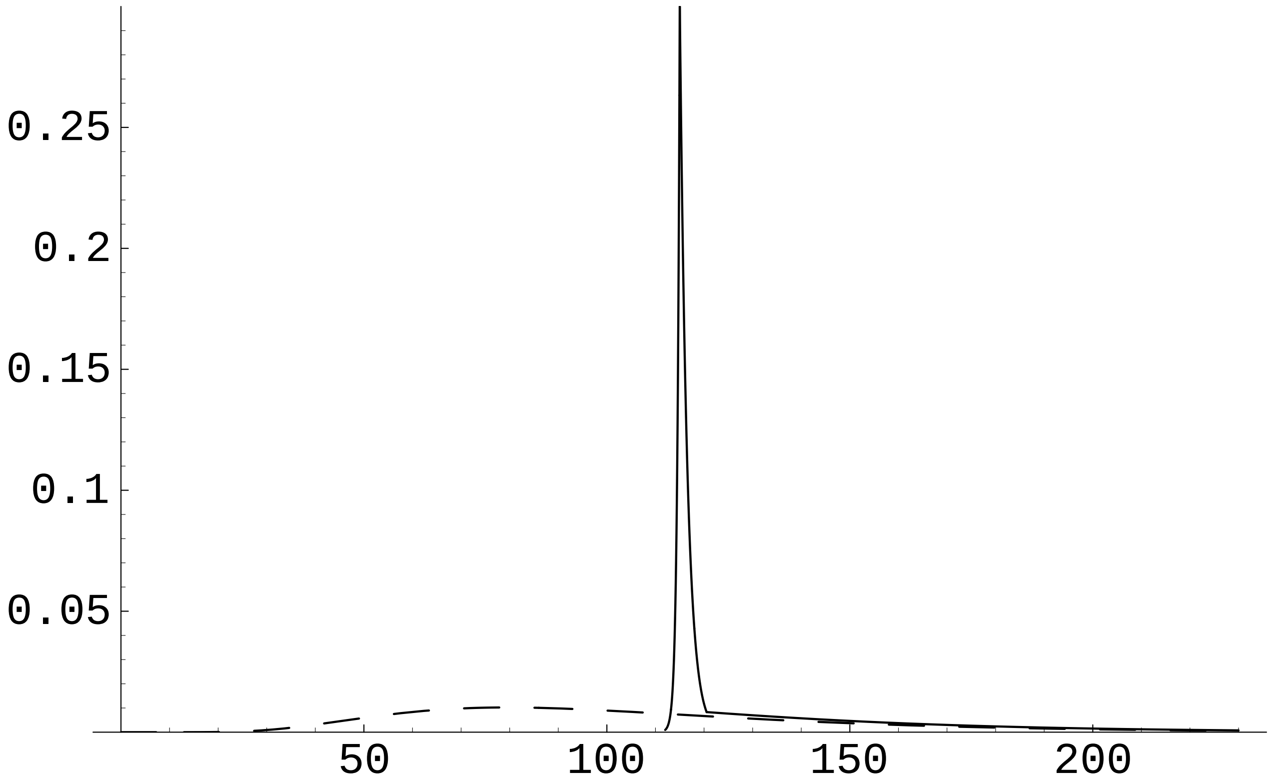
- 1976: First LEP design studies 1979: nearly final
- 1989-1995: LEP Experiments record 17 M Z^0's
- 1995 start slowly increasing the energy
- 1998: Run Request in 2000 granted
- 2000: E_{CM}=209 achieved, 206.6 routine.
- November 2, 2000 -- Last day of LEP physics
- November 3, 2000 -- LEPC presentations (mostly SM Higgs) + LEP combined SM Higgs search results. Excess reported: 2.9σ
  Experiments request run in 2001
- November 15 committee of council -- no decisions by the LEPC, research board, or committee of council. **LEP declared finished.**
- November-December -- ADLO publish results in Phys. Lett. B. LEP Dismantling starts.
- Summer-Fall 2001 -- final publications, also for extended Higgs sectors

- Quite a lot of work still to be done

Bayesian Interpretation

Includes Precision EW + LEP direct searches "PDF" (degree of **belief**) distribution, along with direct searches. No theory limits included. Uniform prior in $\ln(m_H)$

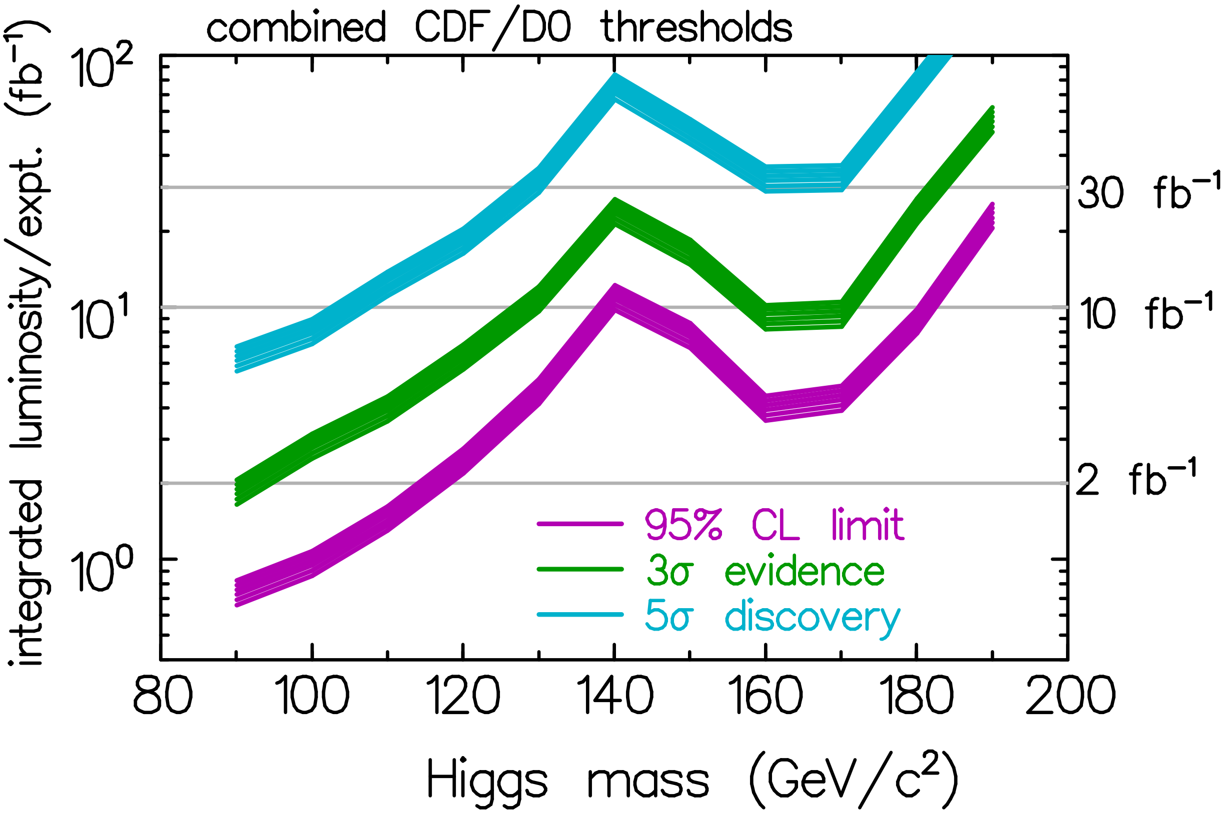
Degrassi, 2001



Approx 37% chance that it's there, m_H<116 GeV.

Very Important to follow up on this!!!

SM Higgs Reach of the TeVatron

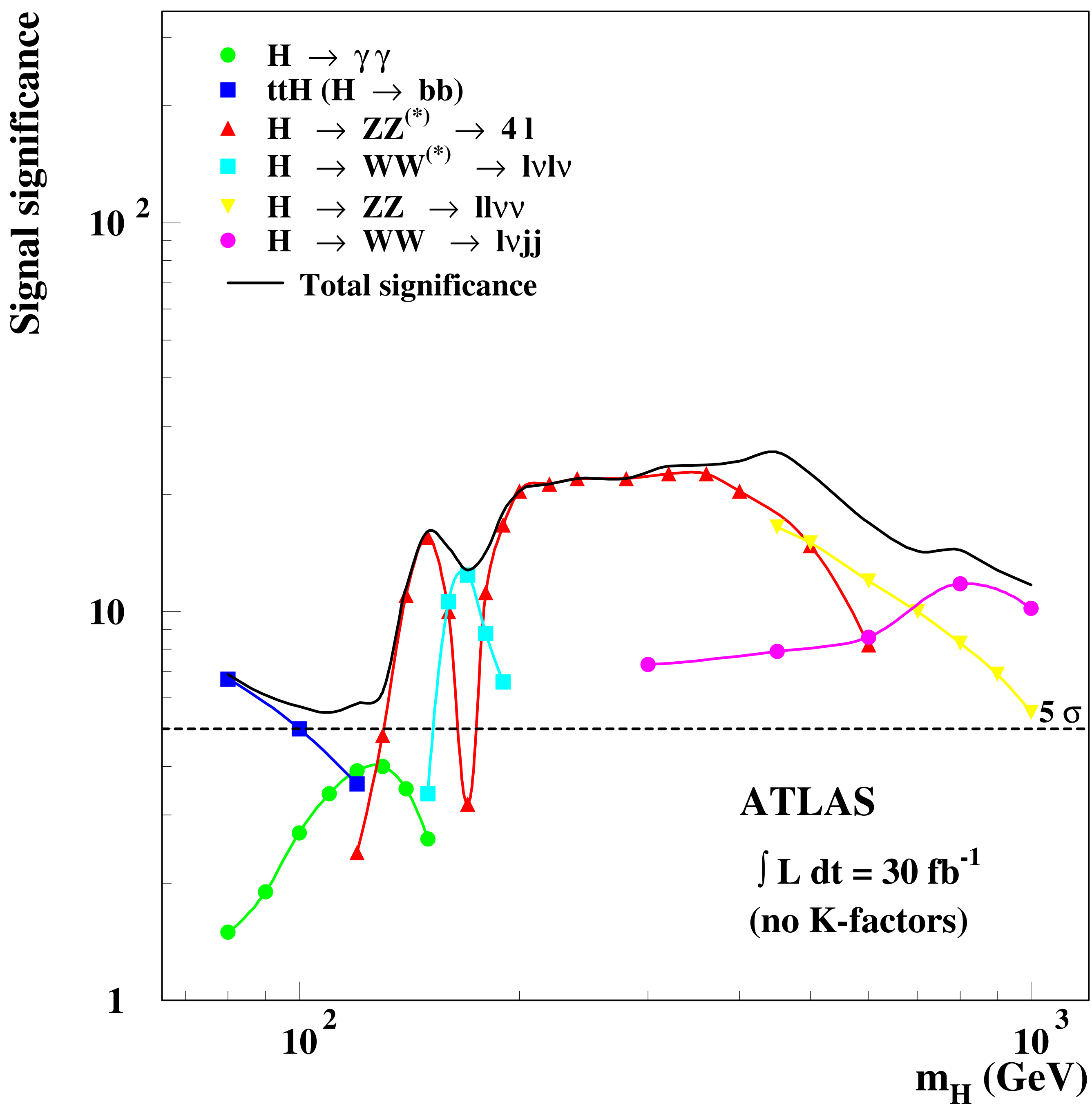


m_H below 130 GeV:
Search channels: Z^0H^0, $W^{\pm}H^0$, $t\bar{t}H^0$ with $H^0 \to b\bar{b}$

m_H above 130 GeV: $gg \to H^0$ with $H^0 \to W^{(*)}W$

Several Years' Running before fully sensitive.
-- Combine with LEP!

SM Higgs Reach at the LHC



Low-mass region to be explored by other colliders first!