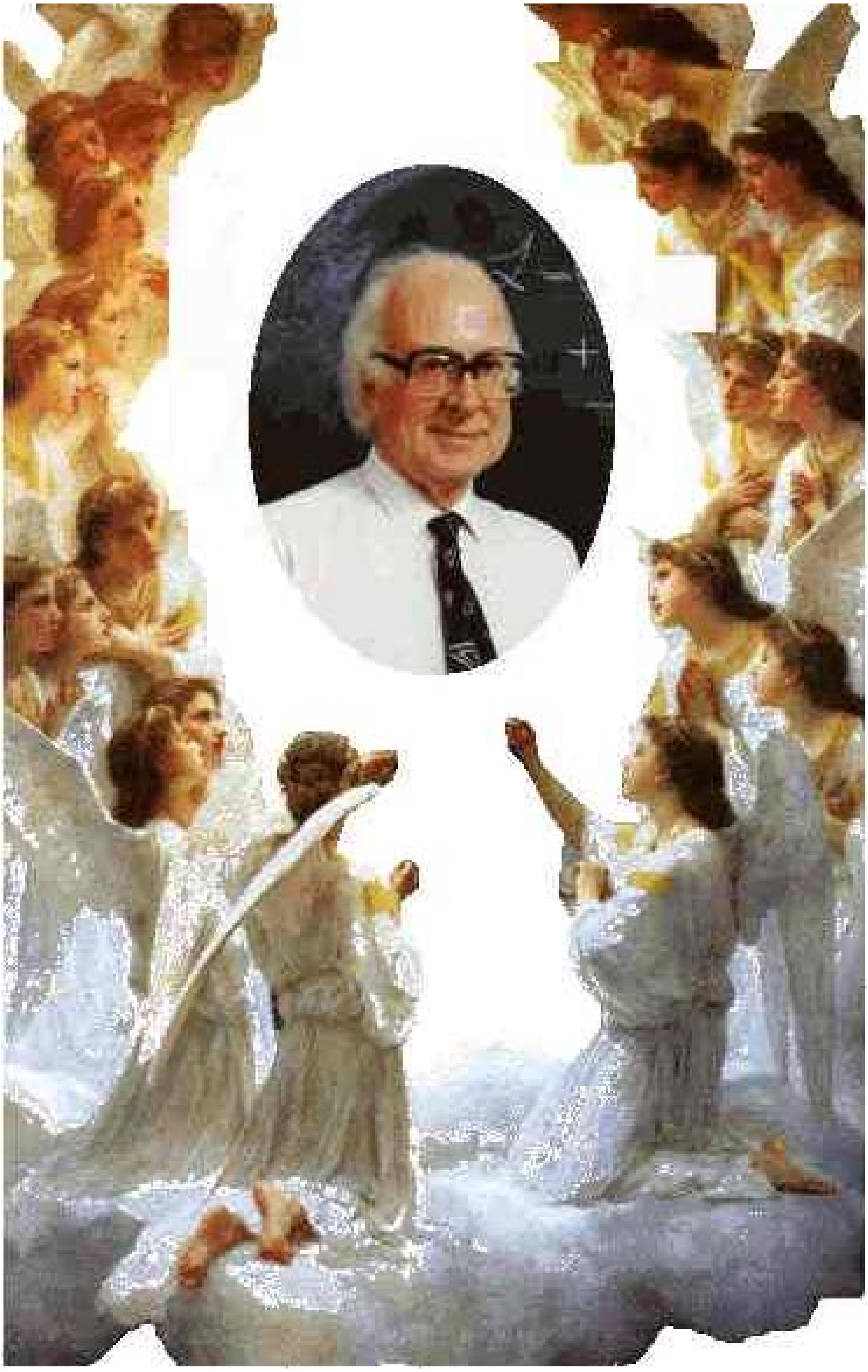
Have We Caught a Glimpse of the Higgs Boson?



Has the “God Particle” Been Discovered?

(Comments by a cautious participant)

Mark Oreglia
The Enrico Fermi Institute,
The University of Chicago

Outline:

The Standard Model; Higgs Boson
Higgs Production at LEP2
Hints of a Signal
Future Prospects

Oh, Leon!!!...

The Sunday Times September 10 2000 EUROPE

Scientists find 'God's particle'

Jonathan Leake, Science Editor

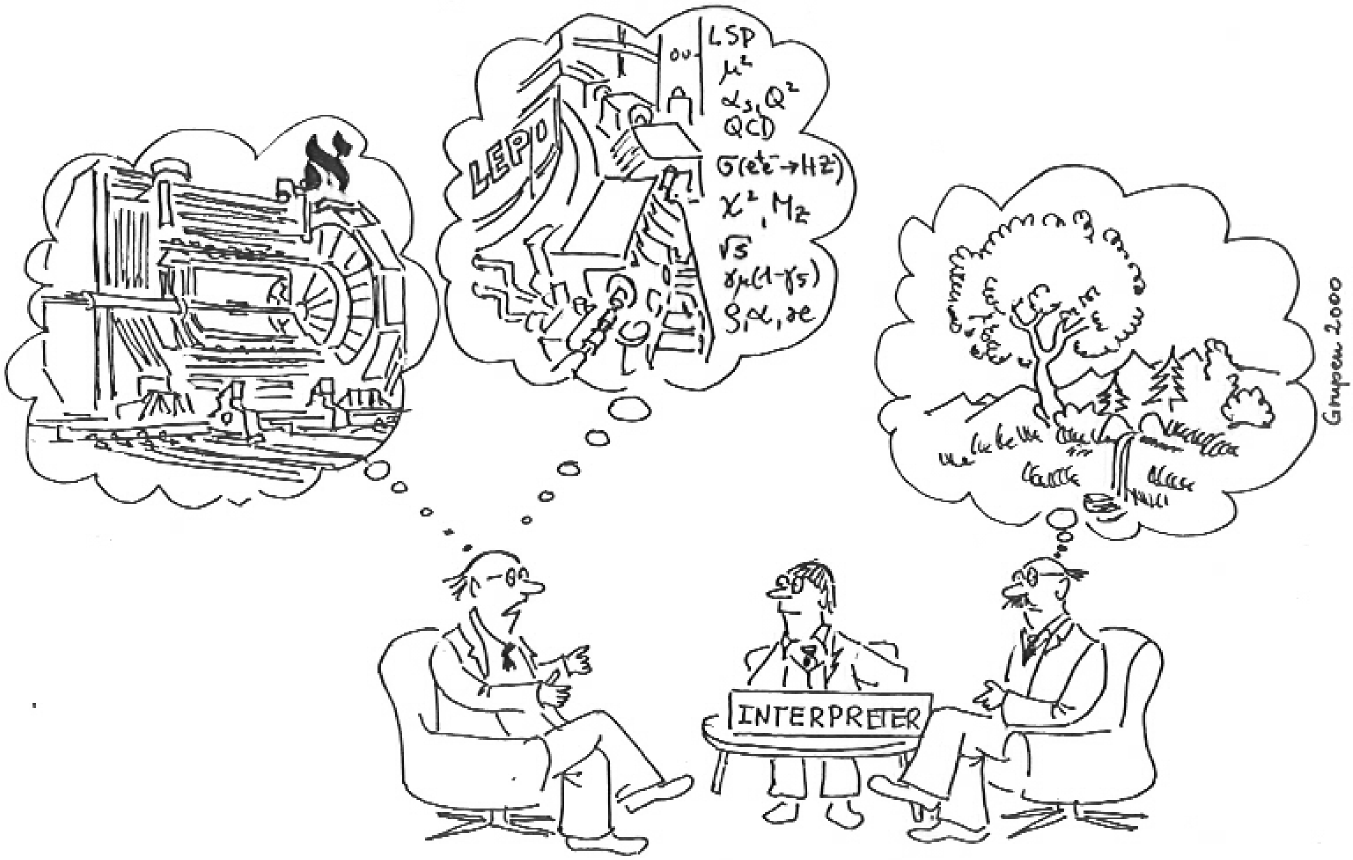
AFTER a search lasting three decades, scientists may have tracked down the most sought-after prize in particle physics.
The Higgs boson, nicknamed "God's particle" by some researchers, has been detected in experiments carried out by researchers in Geneva.

One of Chicago's illustrious former faculty feels the Higgs boson is so important it deserves the moniker "God particle".

That's because the Higg's particle is a manifestation of a field which could explain the mechanism by which all particles get mass.

It is not yet clear that the Higgs boson exists.

Explaining the Standard Model



An ALEPH expert explains the Higgs evidence to a layman.

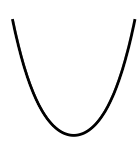
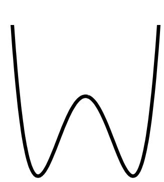
(thanks to Claus Grupen!)

The Standard Model

- It was so simple before 1968:
  - QED: massive fermions $m\bar{\psi}\psi$
  - massless photon; no $\frac{1}{2}A^{\mu}A_{\mu}$ because it violates Gauge invariance …
  - …which we like because it gives rise naturally to conserved charges
- Attempt to unify QED w/ Weak Force:
  - additional bosons known to exist
  - but can't just add boson mass terms
  - The trick of Weinberg and Salam:
    - add scalar field ϕ

$$L \to L_{QED} + |D_{\mu}\phi|^2 - V(\phi)$$

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

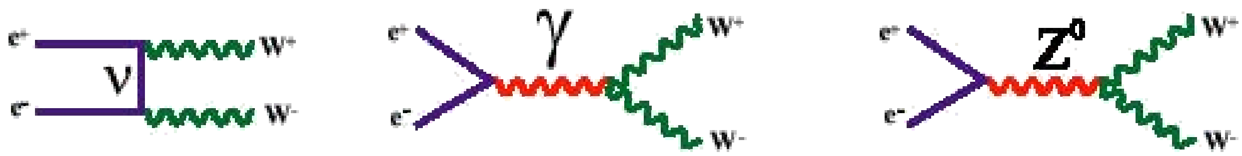
  - Two cases:
    - $\mu^2 > 0$:  not interesting
    - $\mu^2 < 0$  remarkable!

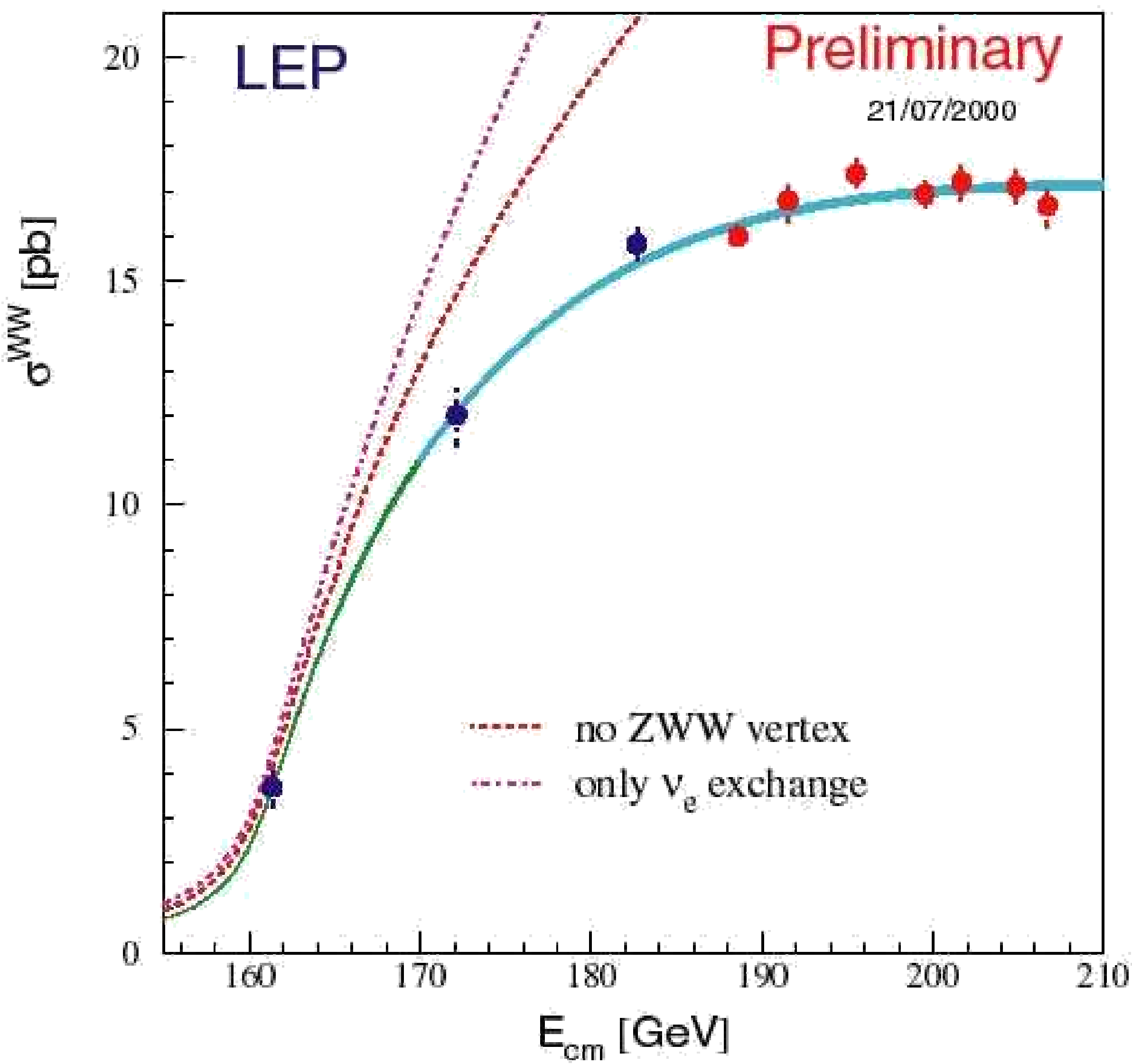
Symmetry Breaking

- For $\mu^2<0$, min V at $\sqrt{\frac{-\mu^2}{2\lambda}} = v$
- Expanding ϕ about this minimum gives rise to new structure:
  - bosons: 1 massless neutral (γ)
    1 massive neutral (Z^0)
    2 massive charged ($W^\pm$)
  - and a left-over scalar: H
  - boson masses show the sym. breaking!
- Lagrangian now has mass terms:
  - $M^2_W = \frac{1}{4} g^2 v^2$
  - $M^2_Z = \frac{1}{4} (g^2+g'^2) v^2$
  - $M_\gamma = 0$
  - $M^2_H = 2 v^2 \lambda$
  - … and $v = 246$ GeV
- Fermion masses $\lambda_i v$ (Yukawa couplings)
- H-fermion coupling $v^{-1} m_f h \bar{\psi}\psi$
  - Higgs field is a mass generator!

Compelling Evidence for SM

- WW cross section alone shows the need for W, Z:





The Wonderful Higg's Properties

- H field couples to mass
  - creates a mechanism for generating masses in the theory
- H boson cancels divergences
  - SM without Higgs boson has WW scattering cross section violating unitarity
- Unifies EM and weak forces

- Things are even better in a theory having 2 Higgs fields (and with SUSY!) … MSSM
  - with SUSY, get exact cancellations without fine tuning problem
  - family of 5 Higgs particles or more
- The MSSM model, e.g., gives masses and rates in terms of a fairly small set of fundamental parameters
  - 5 or >100, depending on symmetry!

The Higgs Mass

- Not specified explicitly … but
- restrictions are imposed by the structure of gauge couplings
- λ is a running coupling (i.e., function of the energy scale Q)
  - large-λ: $Q\frac{\partial\lambda}{\partial Q} \propto \lambda^2$
  - and so λ can be calculated if you fix a high energy cutoff scale Λ:

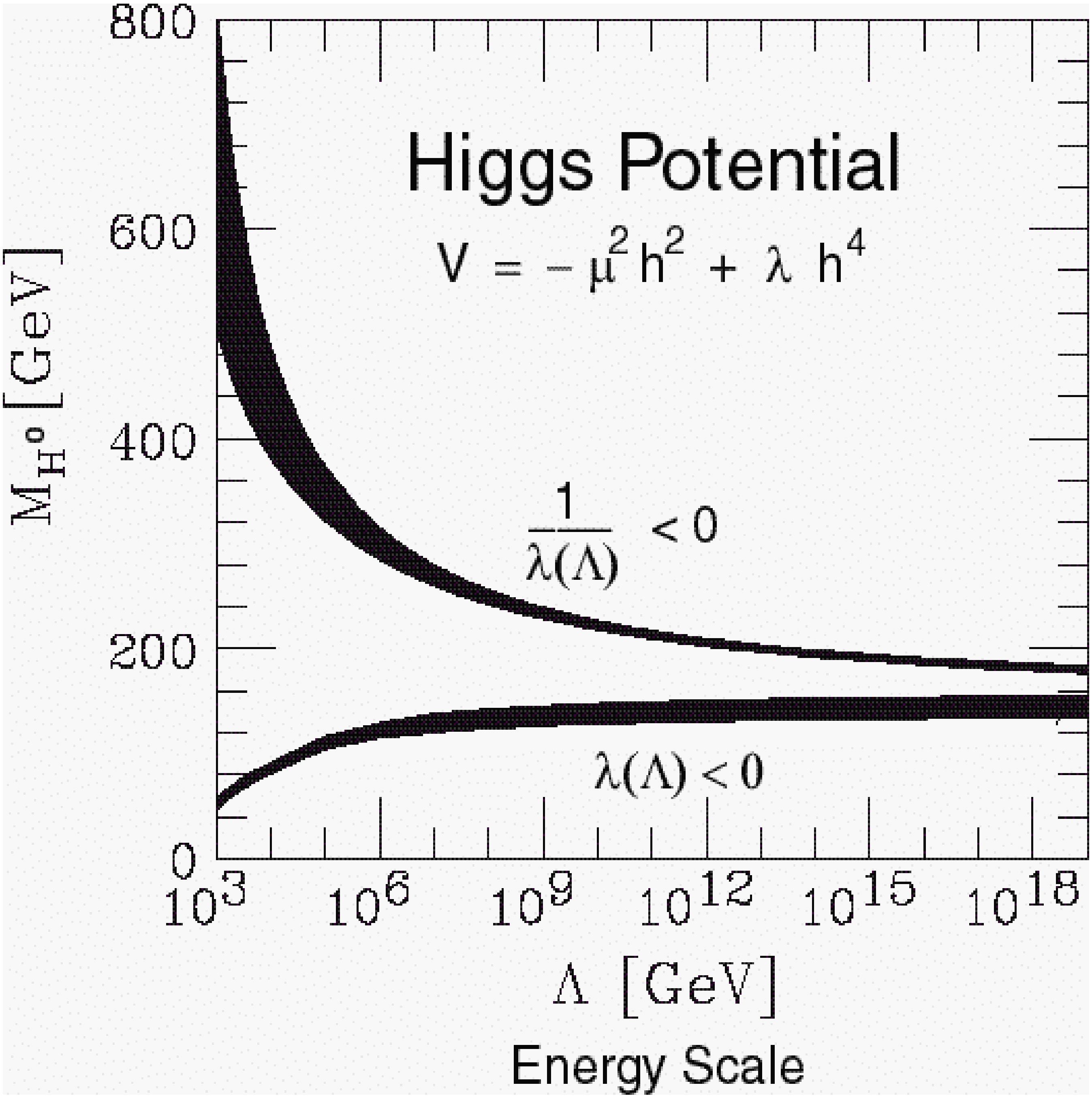
$$\lambda^{-1}(Q) = \lambda^{-1}(\Lambda) - \frac{3}{4\pi^2}\ln(Q/\Lambda)$$

  - λ finite gives an upper bound on m_H ("Landau Pole")

  - small-λ: $Q\frac{\partial\lambda}{\partial Q} \propto \left[g_{SU2}^4 + 2g_{SU2}^2 g_{U1}^2 + 3g_{U1}^4 - g_t^4\right]$
  - the t-quark Yukawa coupling is large
  - quartic coupling positive gives a lower bound on m_H
- Thus m_H = 180 GeV at $\Lambda \to \infty$, unless:
  - there is new physics on the way

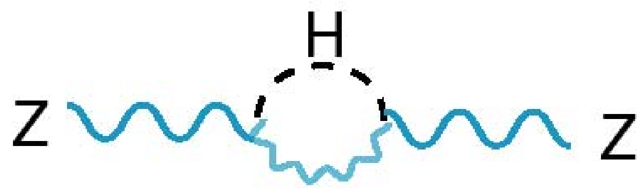
Theoretical Mass Bounds

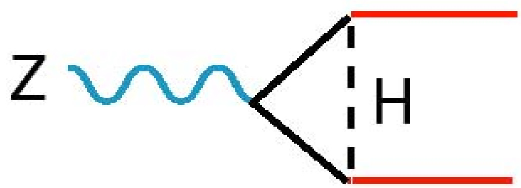
At current energy scale, m_H can cover a large range



Indirect Evidence of the Higgs

• The existence of a Higgs-like object with mass on the order of 100 GeV is suggested by several precision electroweak measurements





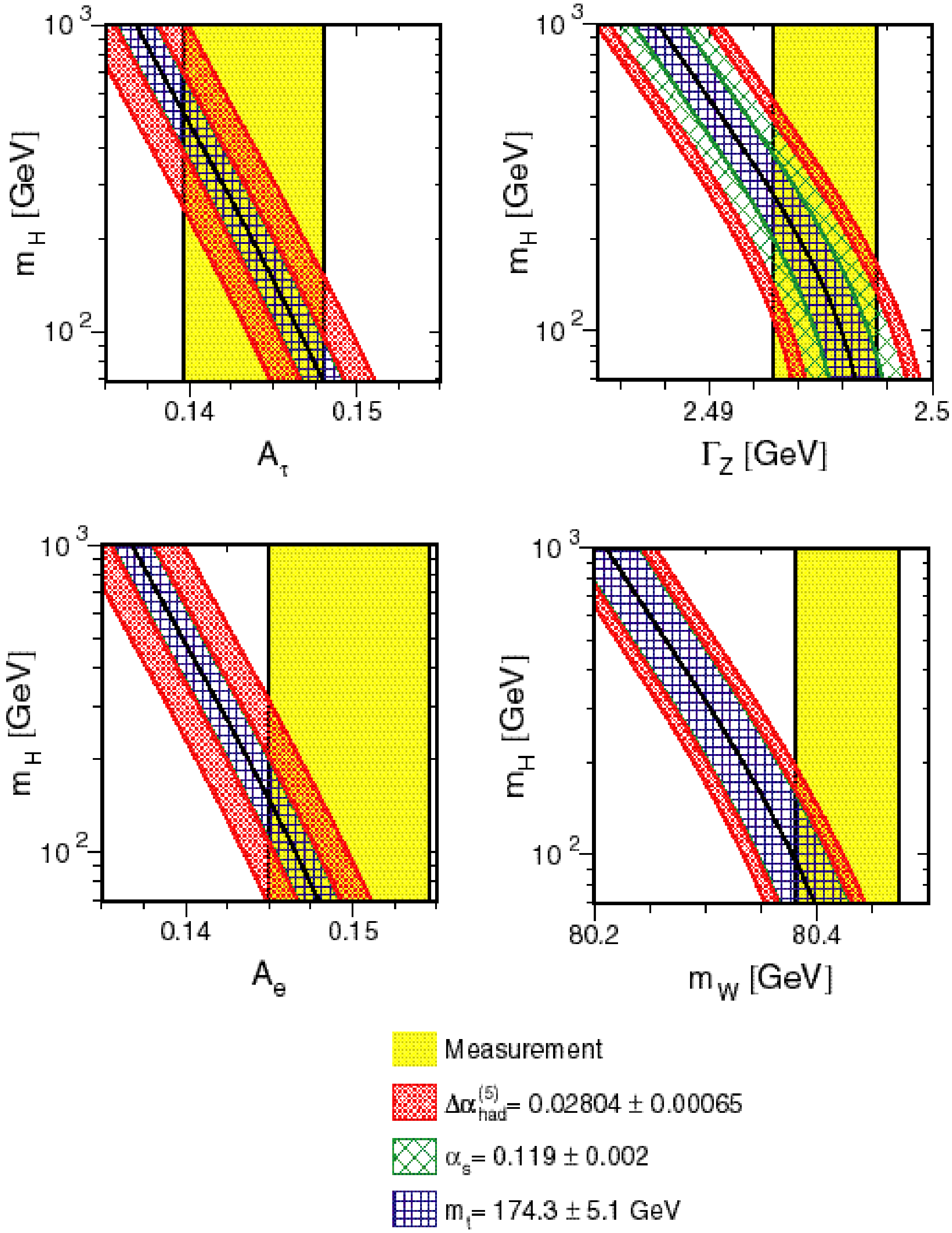
• Higgs boson modifies the Z propagator
• … and decay vertices

- small correction (~ 0.1%) ~ ln(m)
- largest effect in angular distributions of Z-decay products

•The WW cross section also requires the existence of a Higgs-like object

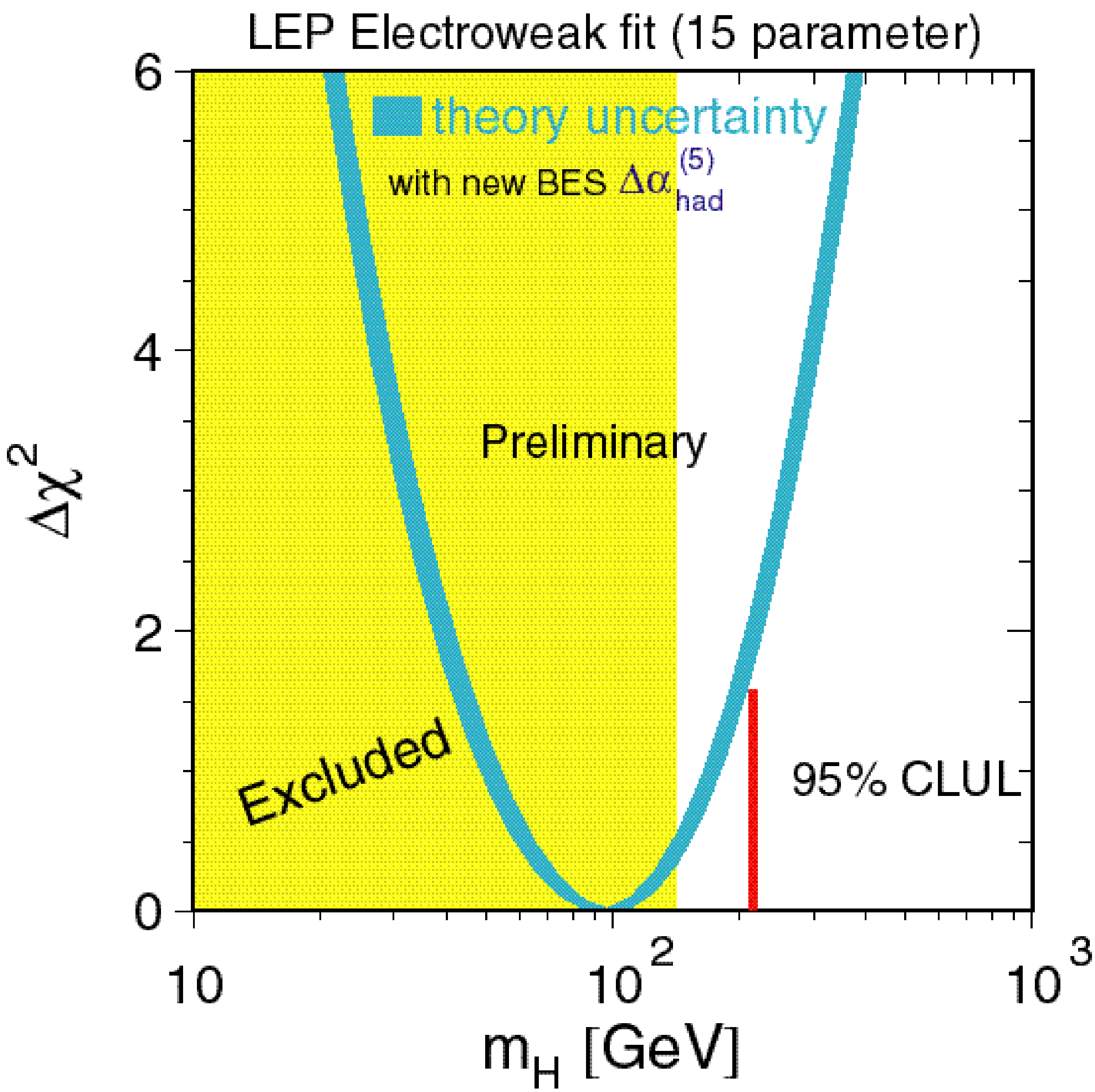
• We are psyched for a Higgs discovery!

Electroweak Observables



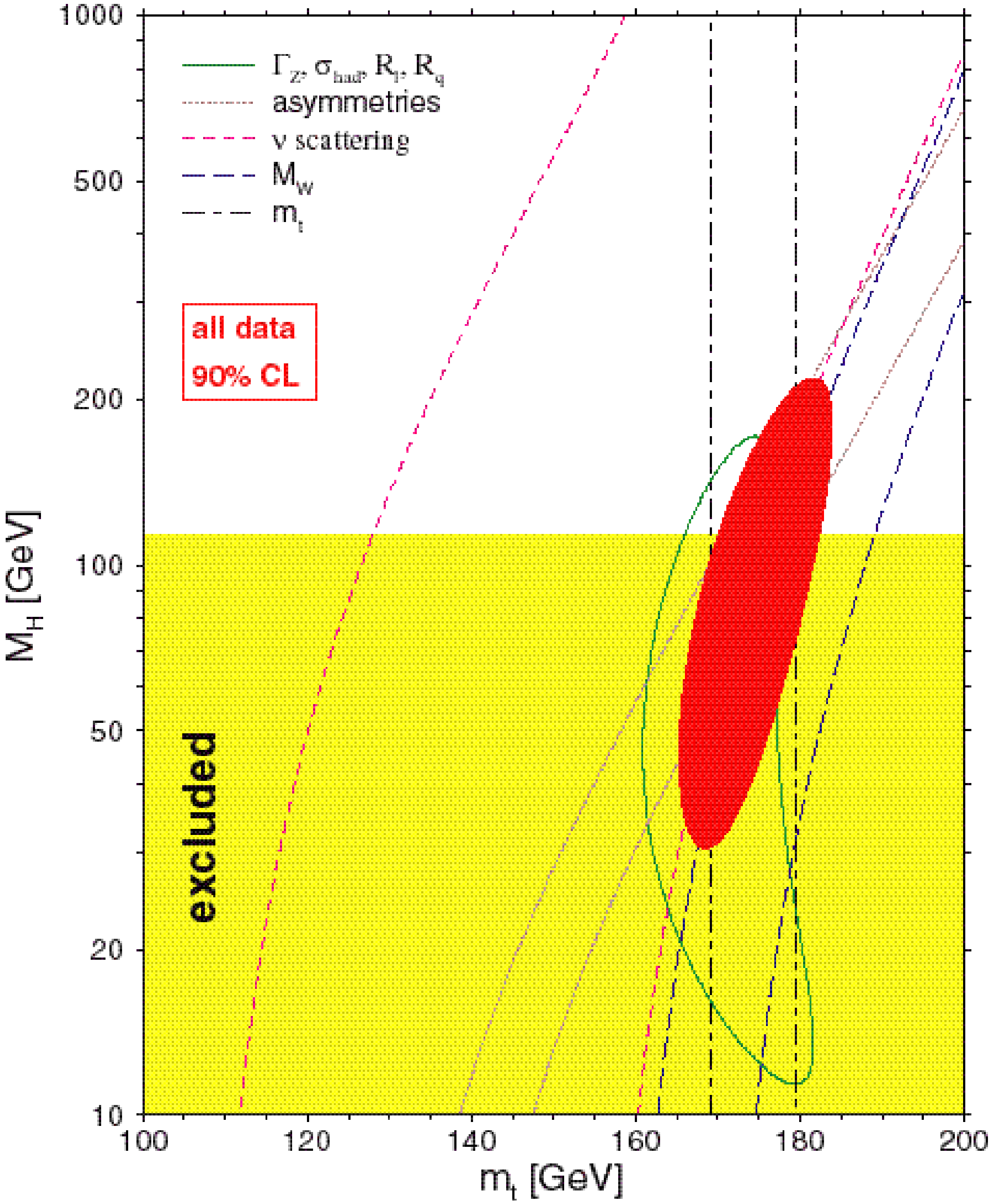
Direct and Indirect Limits

Radiative corrections imply m_H = 94 GeV
… or m_H < 210 GeV at 95% CL



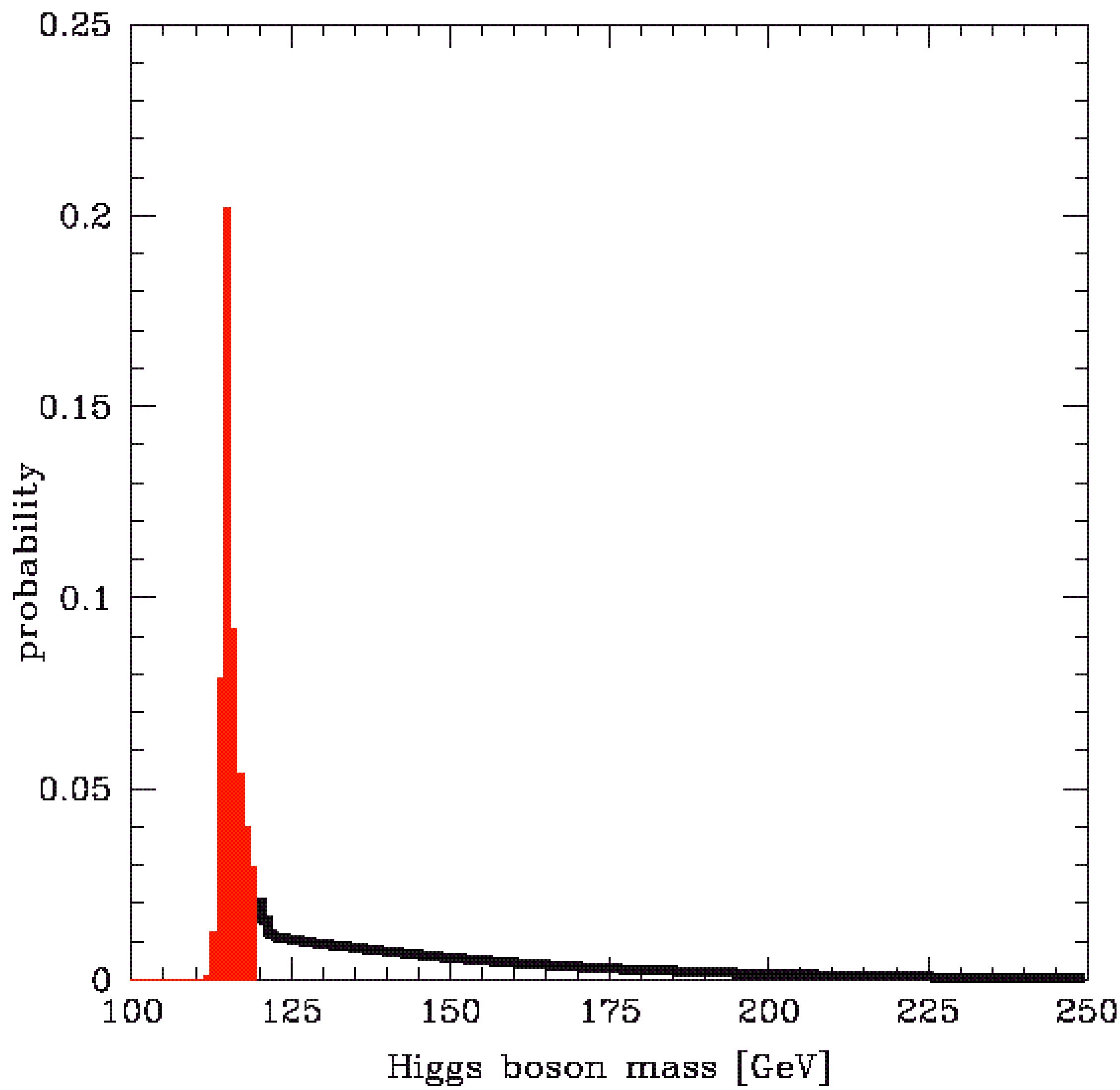
Another Way to Assess EW Data

- Jens Erler has been compiling all the EW data:



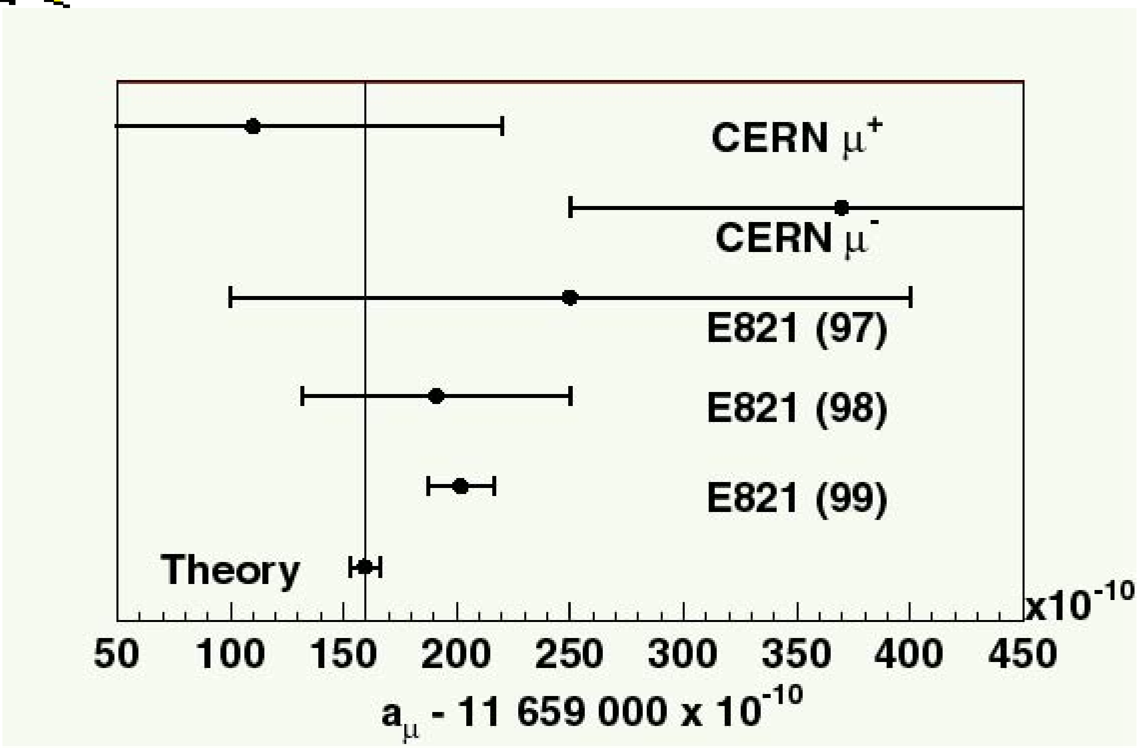
Summary: m < 200 GeV!!!

Because the Higgs mass dependence is weak, half the probability lies between 120 and 200 GeV



And Hot Off Feb's Press...

NEW!



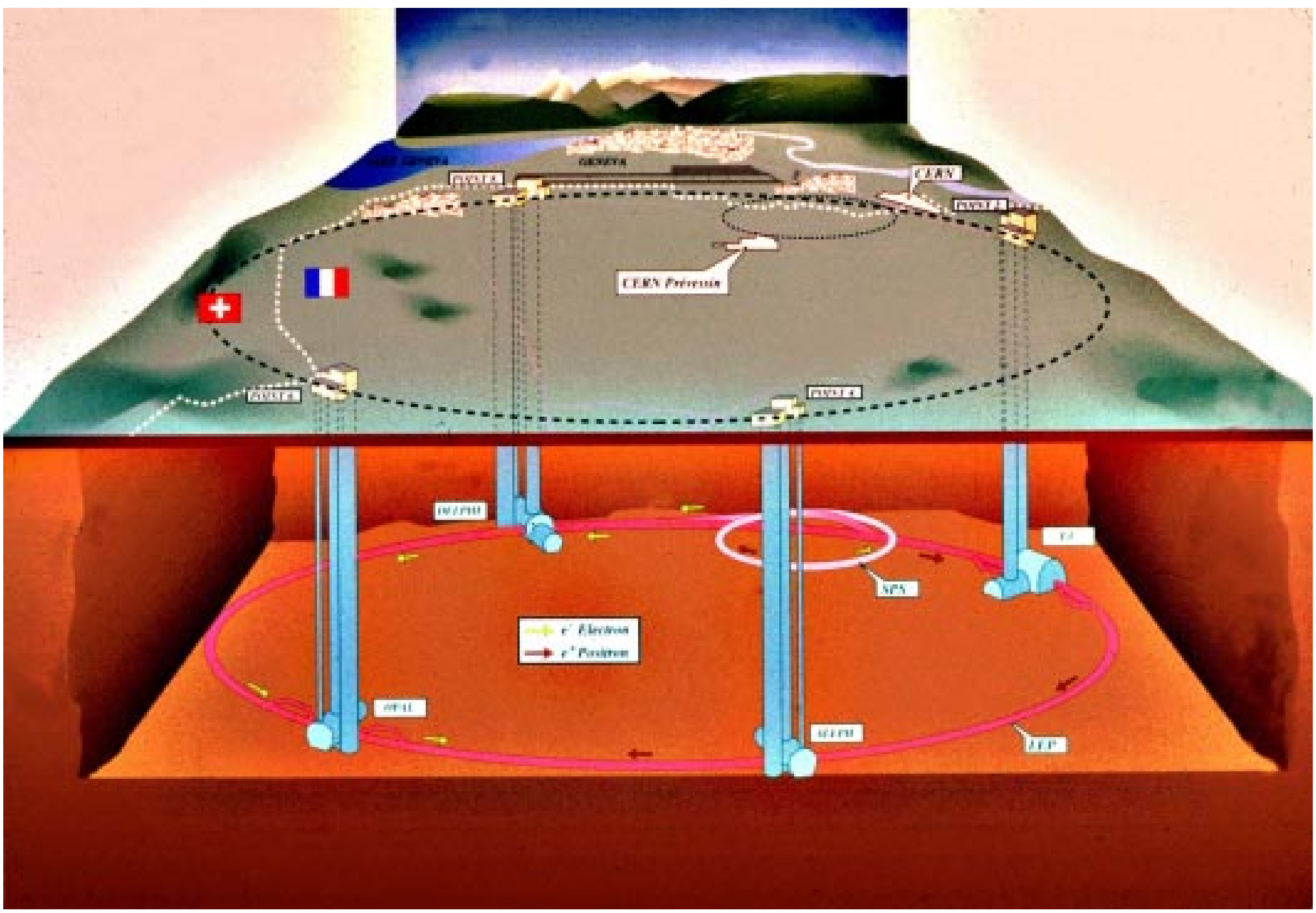
- E821 (BNL) has announced a new measurement of g-2 for the muon
- They get a value 2.5 sigma above that predicted by the Standard Model
- There are various types of new physics which could modify g-2 …
- But if you use SUSY, the g-2 value suggests a SUSY mass scale of ……… 120-400 GeV !!!

LEP --The Large Electron Positron Collider

- 27 km circumference electron synchrotron
- supports 4 experiments simultaneously
- initiated in 1989 at E_{cm} = 91 GeV …
- upgraded over the years with additional superconducting RF cavities ...
- has reached 209 GeV this summer …
    - and is now being dismantled

LEP Interaction regions

- Accelerator 100-200 m underground for stability
- We are sensitive to:
  - tidal forces (yes … the moon!)
  - ground water content
  - Swiss electric trains (!)
- … but its all under control



The 4 Logos

ALEPH
fine grained

DELPHI
high tech

L3
hi-res photon

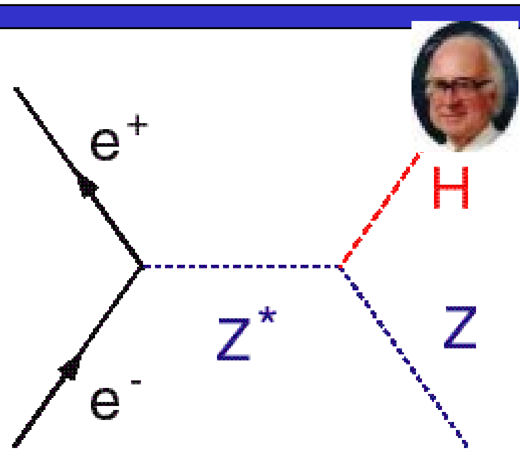
OPAL
general purpose,
conservative group
quite superb, really

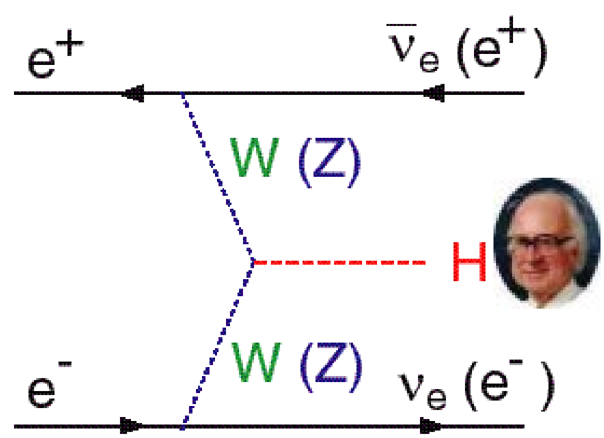
Each Expt is Major Facility

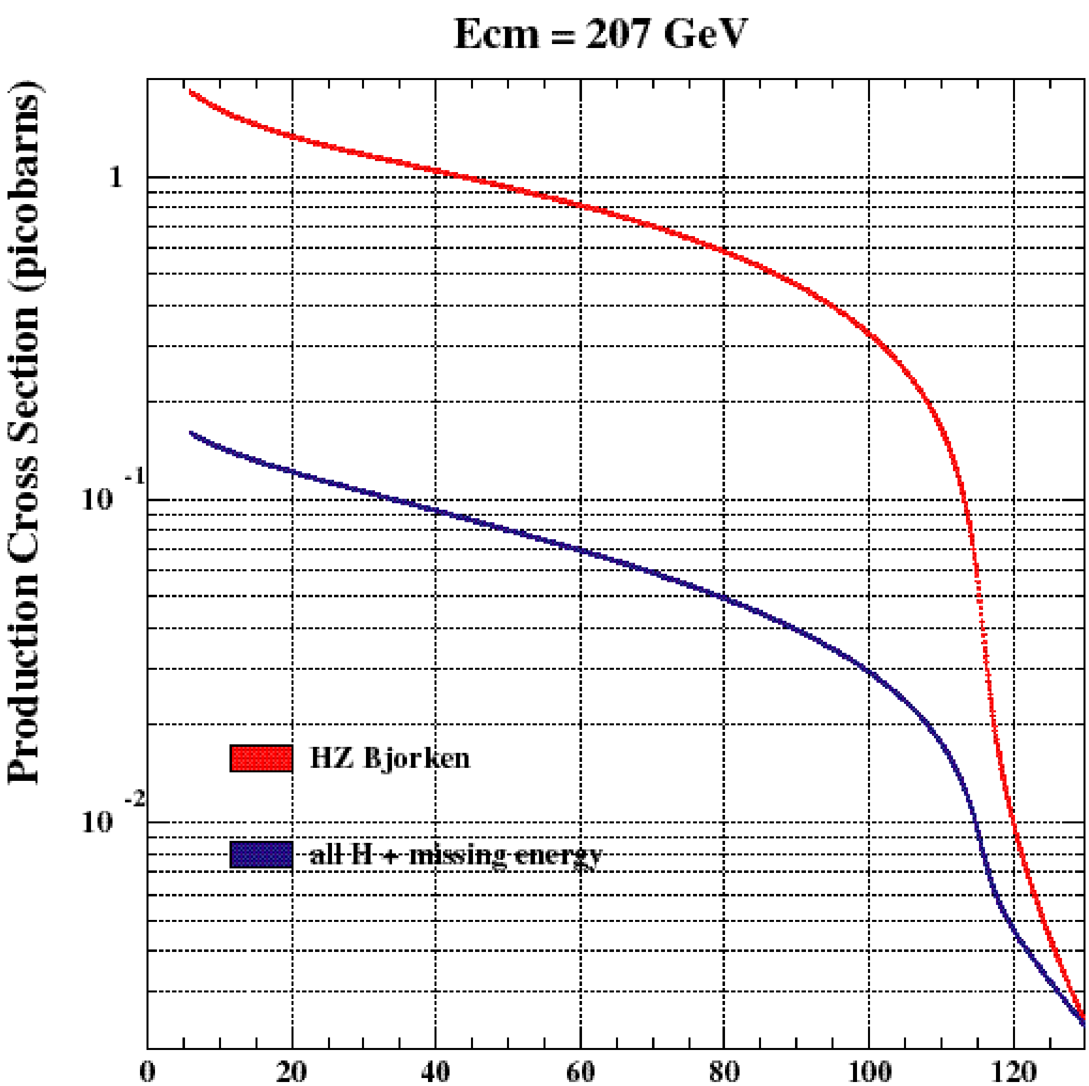
• The support structure for a single experiment
• Generally, about 200,000 electronic channels

• The Large Hadron Collider will take over the LEP tunnel and interaction regions

Higgs Production at LEP

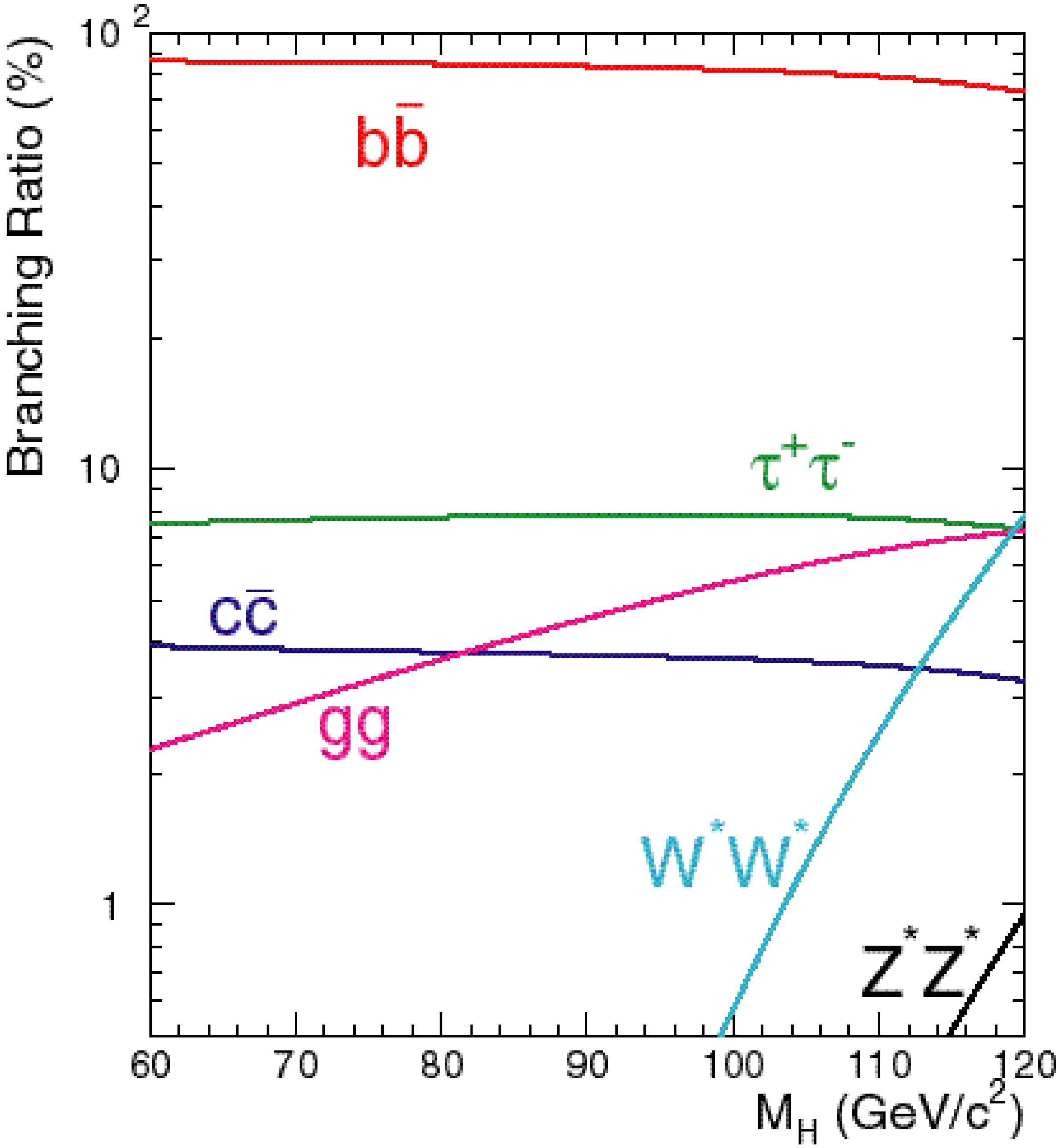




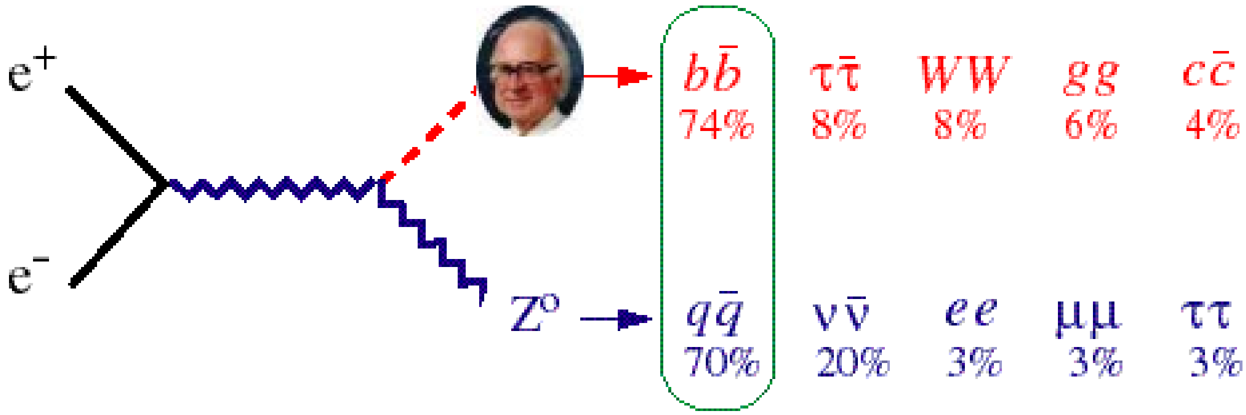


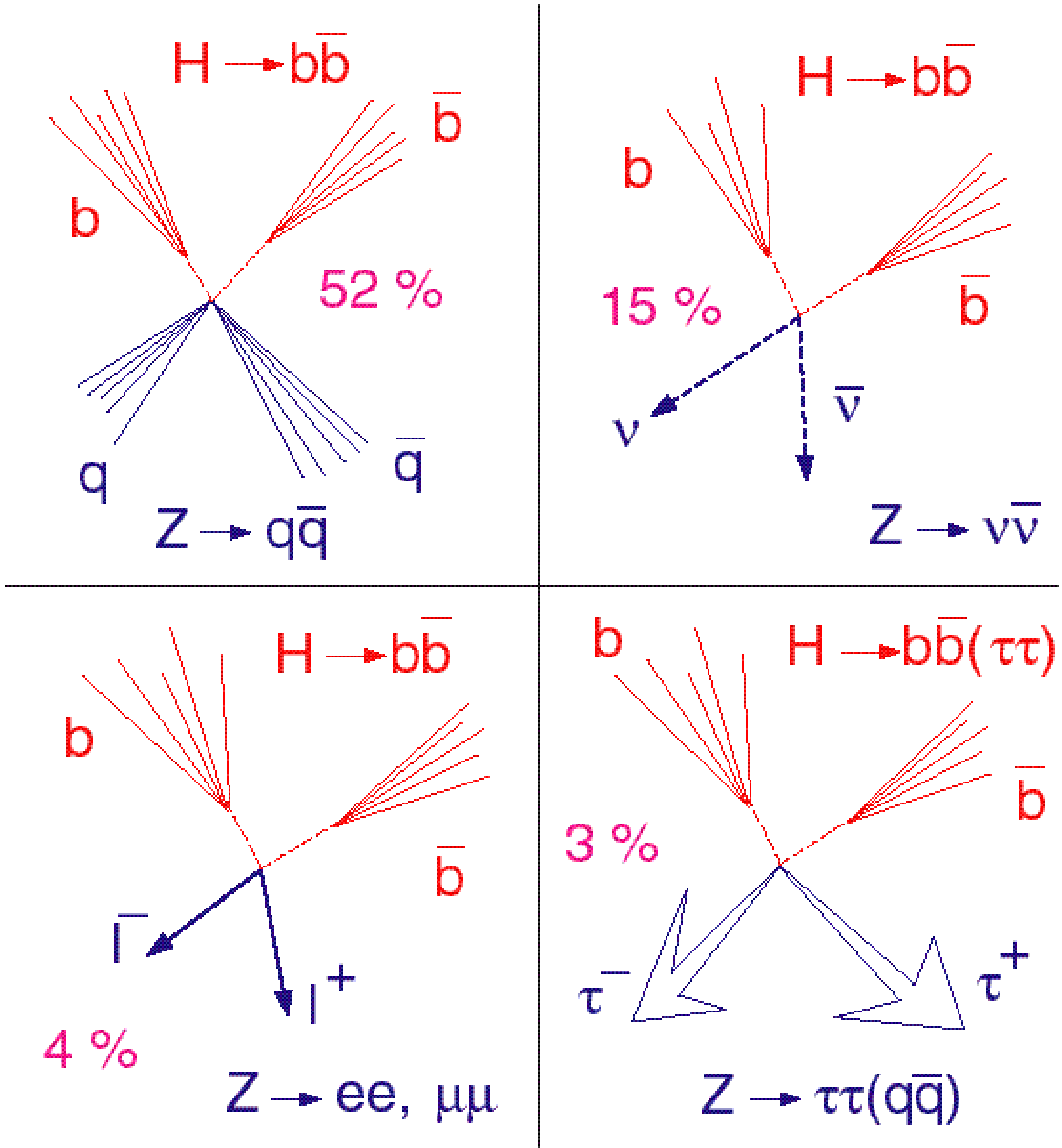
MSM Higgs Decays

Remember … H couples to mass!
It predominantly decays to the heaviest particles



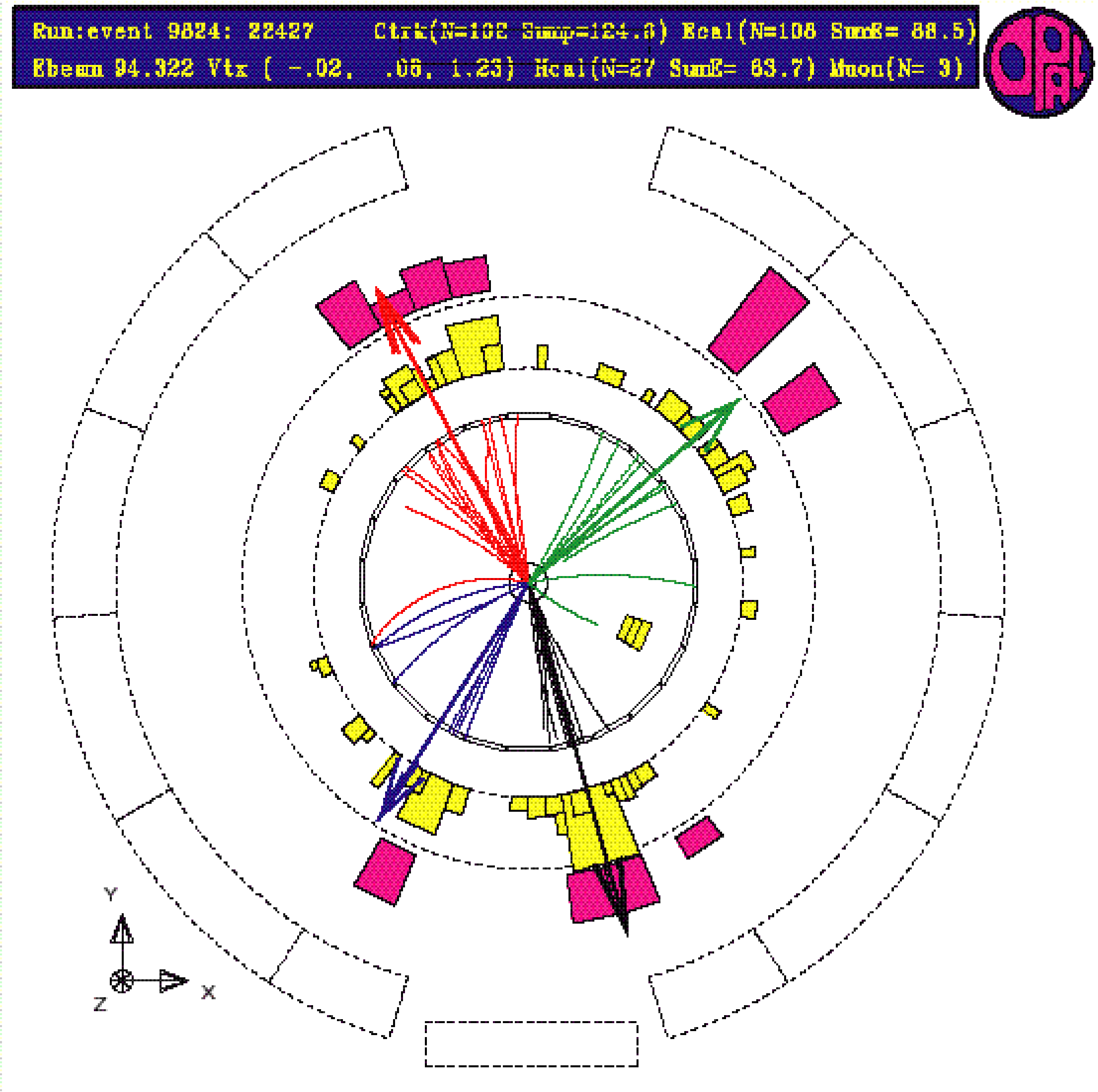
Decay Topologies





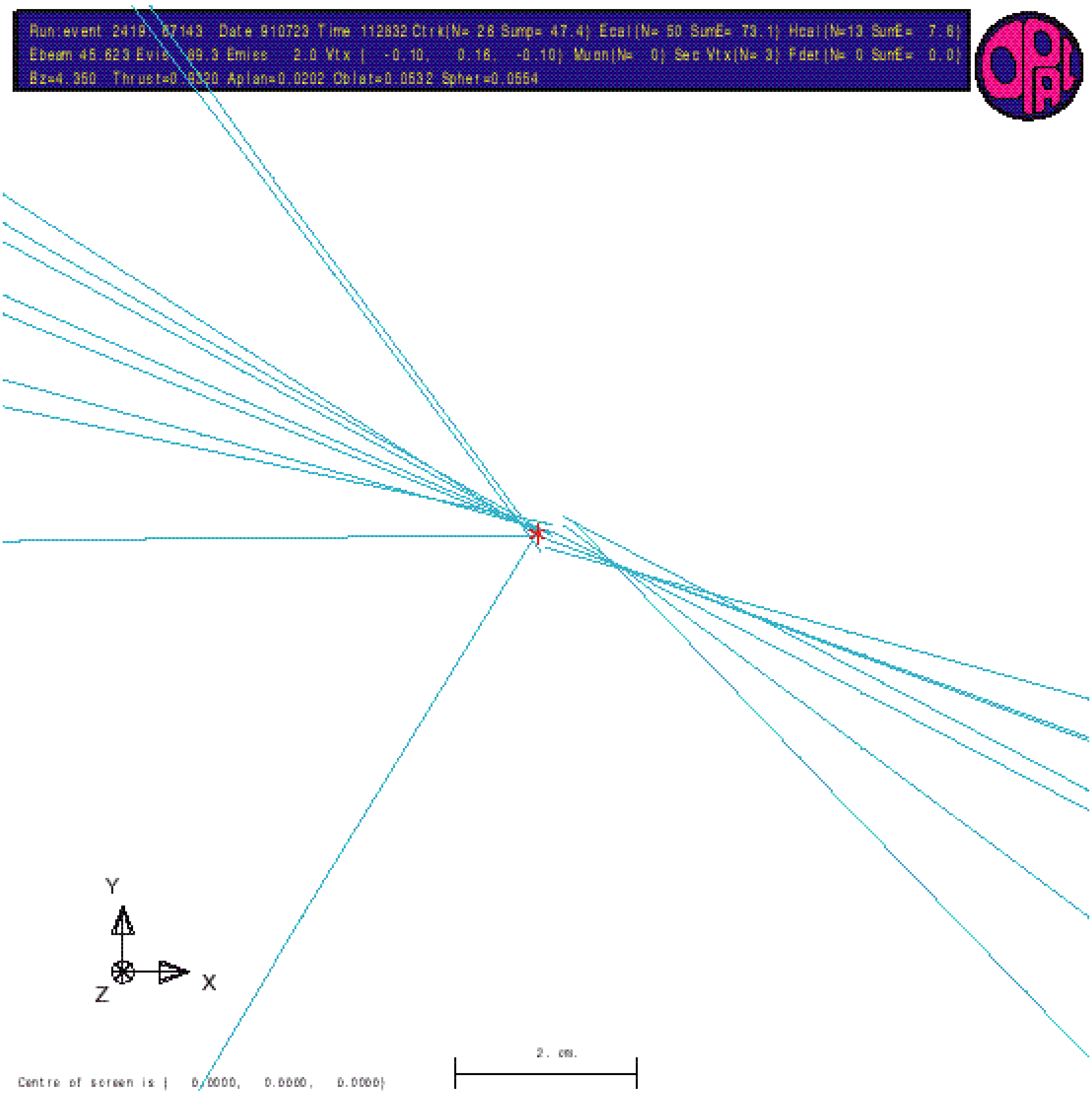
Most Common Event Expected

$$e^{+}e^{-} \rightarrow Z^{0}H^{0}, Z^{0} \rightarrow q\bar{q}, H^{0} \rightarrow b\bar{b}$$



B-Tagging

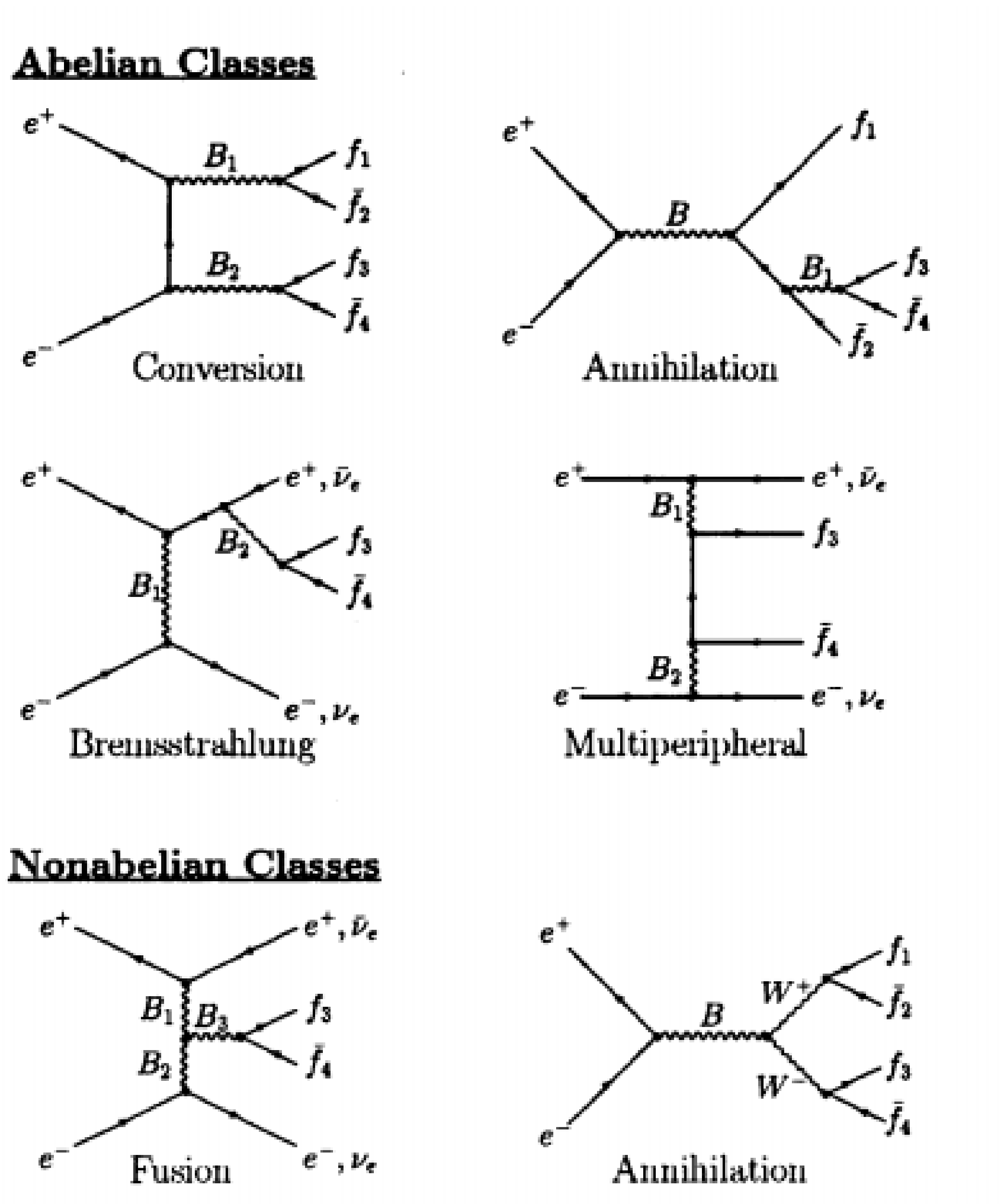
The heavy b decay products have long lifetime, and can travel centimeters before decaying



4-fermion Backgrounds

$e^+e^- \to Z^0 Z^* \to f\bar{f}f\bar{f}$ is an irreducible background for m_H near m_Z, and it caused trouble in 1998.

Beyond m=100 GeV, backgrounds are low.



LEP Has Benefited from Many Higgs Discoveries!

Warning! This slide is tactless in the extreme.

- ALEPH, 1992, E_{cm}= 90 GeV
  - M_h=58 GeV
- L3, 1992, E_{cm}= 90 GeV
  - M_h=60 GeV
- ALEPH, 1996, E_{cm}= 133 GeV
  - M_h+M_A=105 GeV
- ALEPH, 1998, E_{cm}= 189 GeV
  - M_h=102 GeV
- ALEPH, 1999, E_{cm}=196 GeV
  - M_h=105
- L3, 2000, E_{cm}=206 GeV
  - M_H+=68 GeV
- … and worst of all ...

Even OPAL Should Know Better

NEWS FOCUS

A Tentative Nondiscovery of the Higgs

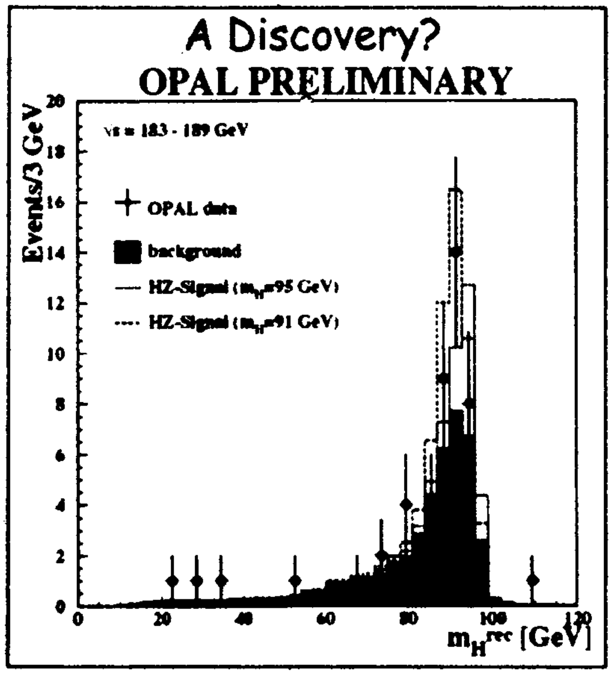
BATAVIA, ILLINOIS—Don't think of elephants. Now, are you thinking of elephants?

This classic psychological ploy captures the dilemma facing one scientific collaboration at the Large Electron-Positron collider (LEP), a particle accelerator at CERN in Geneva, Switzerland. The subject of the "don't think of" scenario is the Higgs boson, the hypothetical particle that is thought to explain how everything else in the universe—including all the particles in elephants—acquired its mass. The collaboration, called OPAL, is trying to dampen speculation that a handful of unexplained events in its data point to a Higgs discovery. The result is to fuel the rumors.

"It's not an effect—but may be interesting," said Eilam Gross of OPAL and the Weizmann Institute of Science in Rehovot, Israel, during the SUSY99 conference here last week. Gross's disclaimer, given as he presented a viewgraph on the data, drew knowing titters from the audience. He explained that the gap between the data points and the green peak of expected "background" counts could either represent a statistical fluctuation or the first hints of a Higgs with a mass of about 91 billion electron volts (GeV), or 97 times the mass of a proton. "It's exactly the right sort of Higgs mass," said Gordon Kane, a theorist at the University of Michigan, Ann Arbor, who adds that the signal should soon be either "golden or gone" as more LEP data stream in.

LEP has been smashing together electrons and their antimatter counterparts, positrons, at gradually increasing energies, and Gross said that the intriguing data came from runs since 1997 at collision

energies from 183 to 1
debris of those collisions
to a bottom quark and a
manifested as a "jet" of
tector. Because other pa
Z boson, which mediates
ilar events, their expecte



Don't even think it. A viewgraph shows a slight excess of events over the expected background (green), at a plausible Higgs mass.

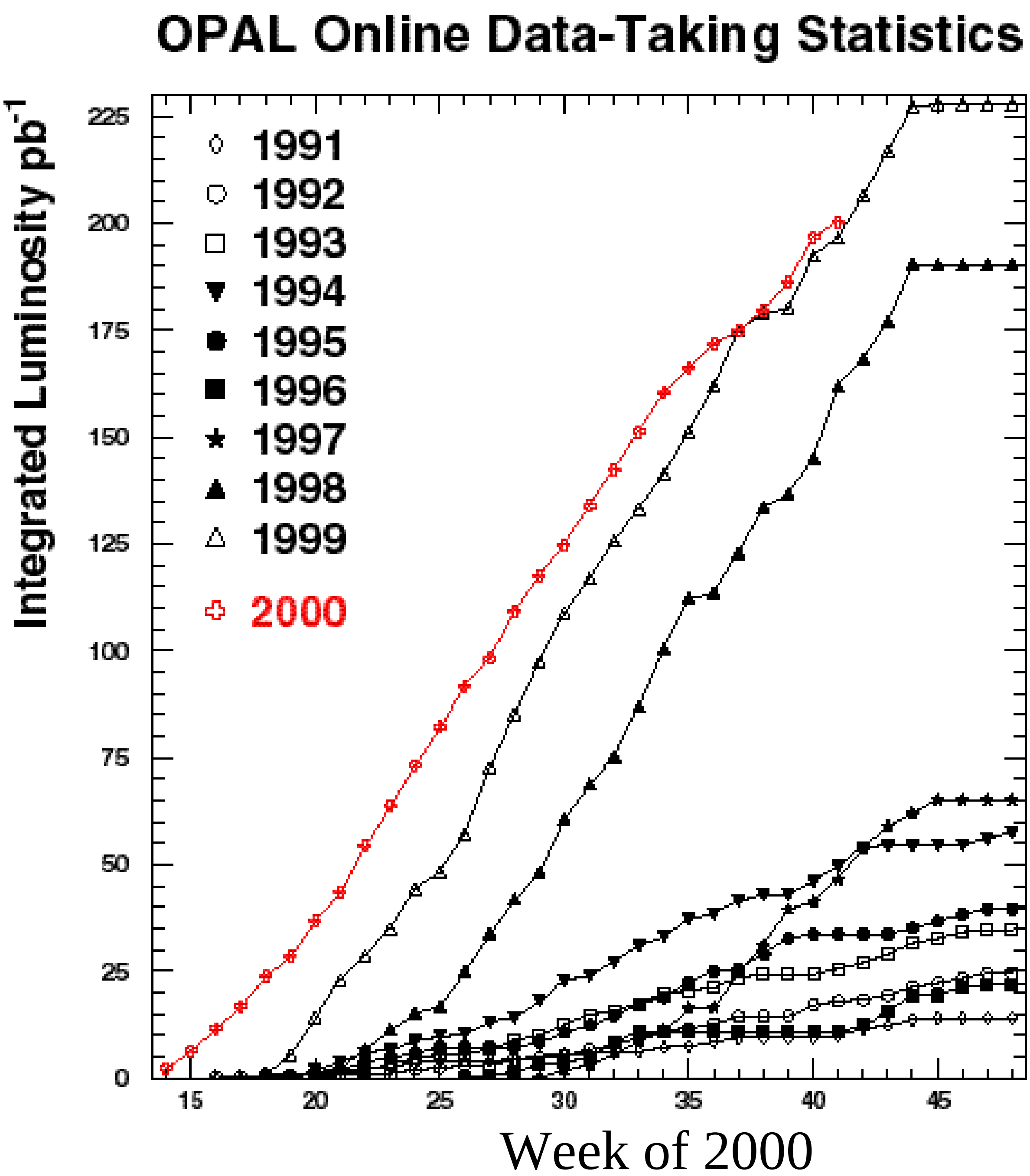
Higgs if its mass is anyw
ergy goes into creating
has a shot at the discov
main text). "If God is o
theological significance
"let Higgs appear this ye

Y2K LEP Performance

- This year the maximal LEP upgrade done
- Two run modes:
  - Maximum Energy Mode
    - 209.14 GeV attained
    - but no klystrons in reserve; if a klystron trips (every 15-60 minutes), the beam is lost
    - refill time: 20-90 minutes
  - Maximum Production Mode
    - keep 1 klystron in reserve
    - 205-207 GeV
    - fills last 3 hours
    - yields 2-4 pb^{-1} per week
- HE running stresses LEP:
  - severe pitting in RF cavities
  - … but reconditioning works

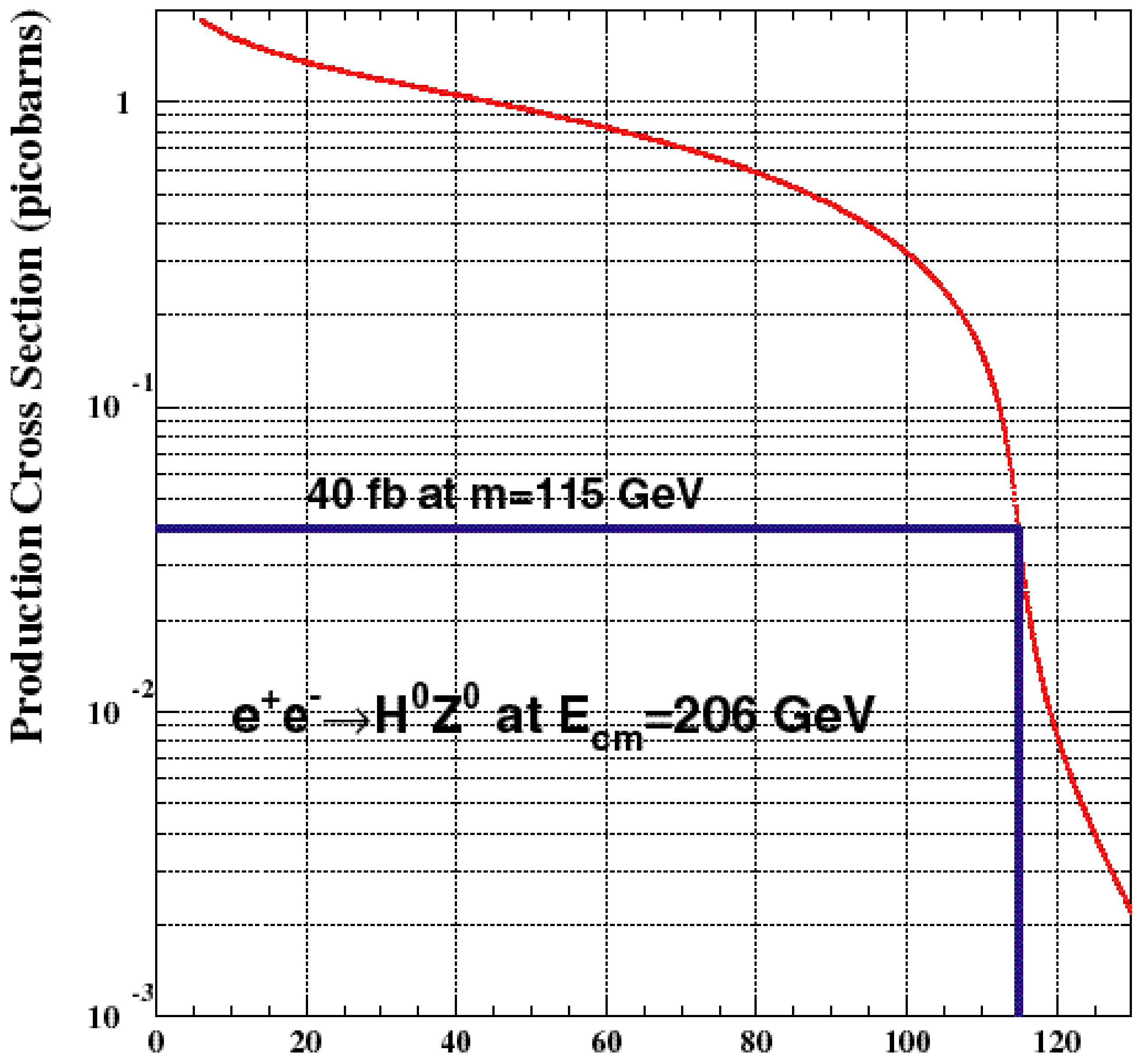
OPAL Integrated Luminosity

OPAL recorded 210 inverse pb at E_{cm} = 200-209 GeV



SM Higgs Cross Section

For m=115 GeV, L=150 pb^{-1}:
about 6 events/expt for 100% efficiency.
More like 3 really!



Higgs Mass (GeV)

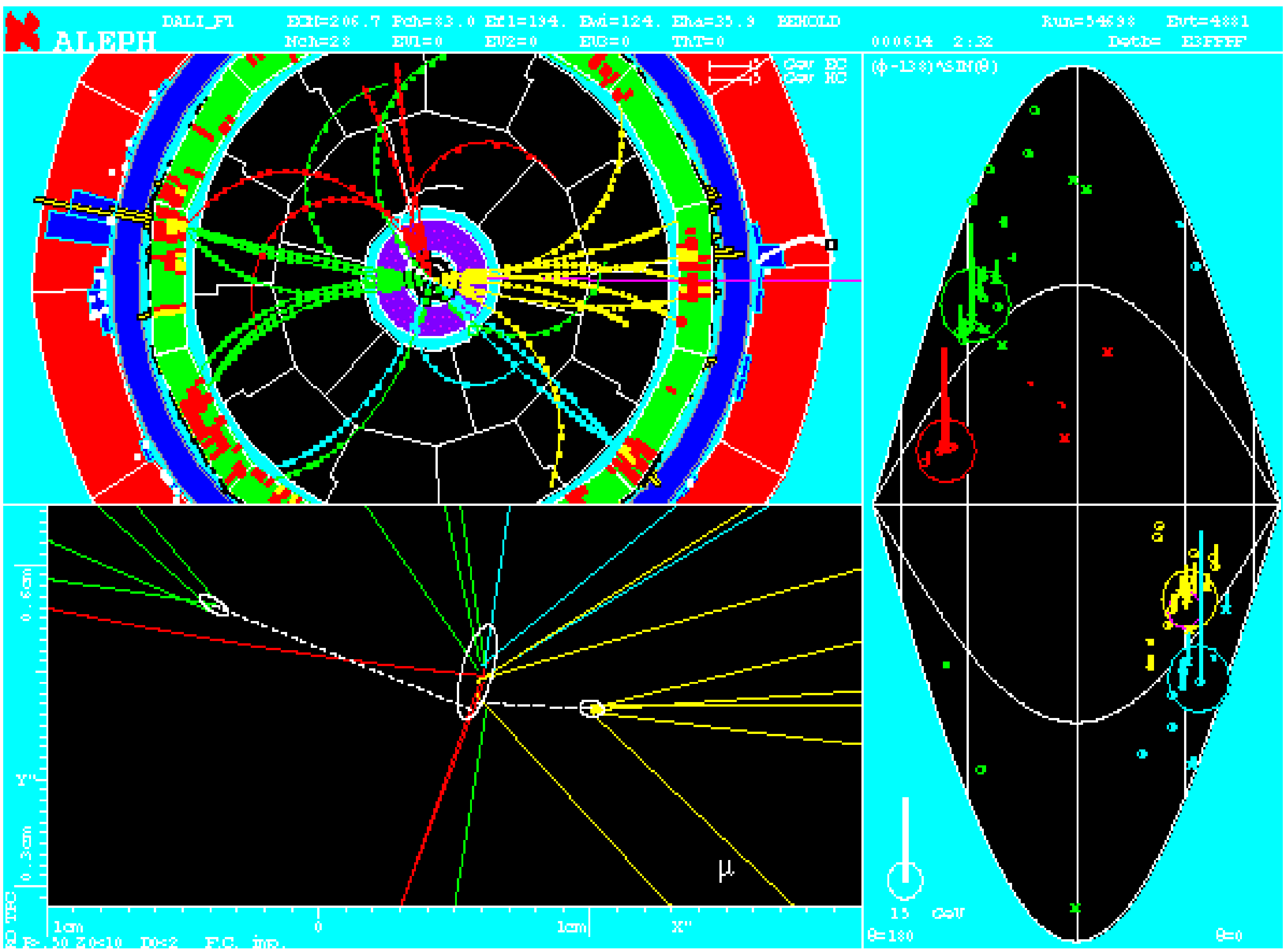
How We Spent The Summer

- The LEP accelerator was scheduled to close down at beginning of September
- run extended to 30 Sept after a LEPC meeting held on 20 July
- a meeting of the LEPC was scheduled for 5 Sept to decide if any hint of new physics could justify an extension. 4 events (3 from ALEPH, 1 from DELPHI) were recorded between 20 July and 5 Sept. Three events are perfect candidates for Higgs boson decays.
  Run extended to 2 Nov.
- 10 Oct LEPC: No new candidates
  - LEP shuts 2 Nov … for this year.
- 3 Nov LEPC: Big decision time
  - hoped that HE data would double
  - … but -1 new candidates
  - DG declares LEP will be dismantled

Best ALEPH event

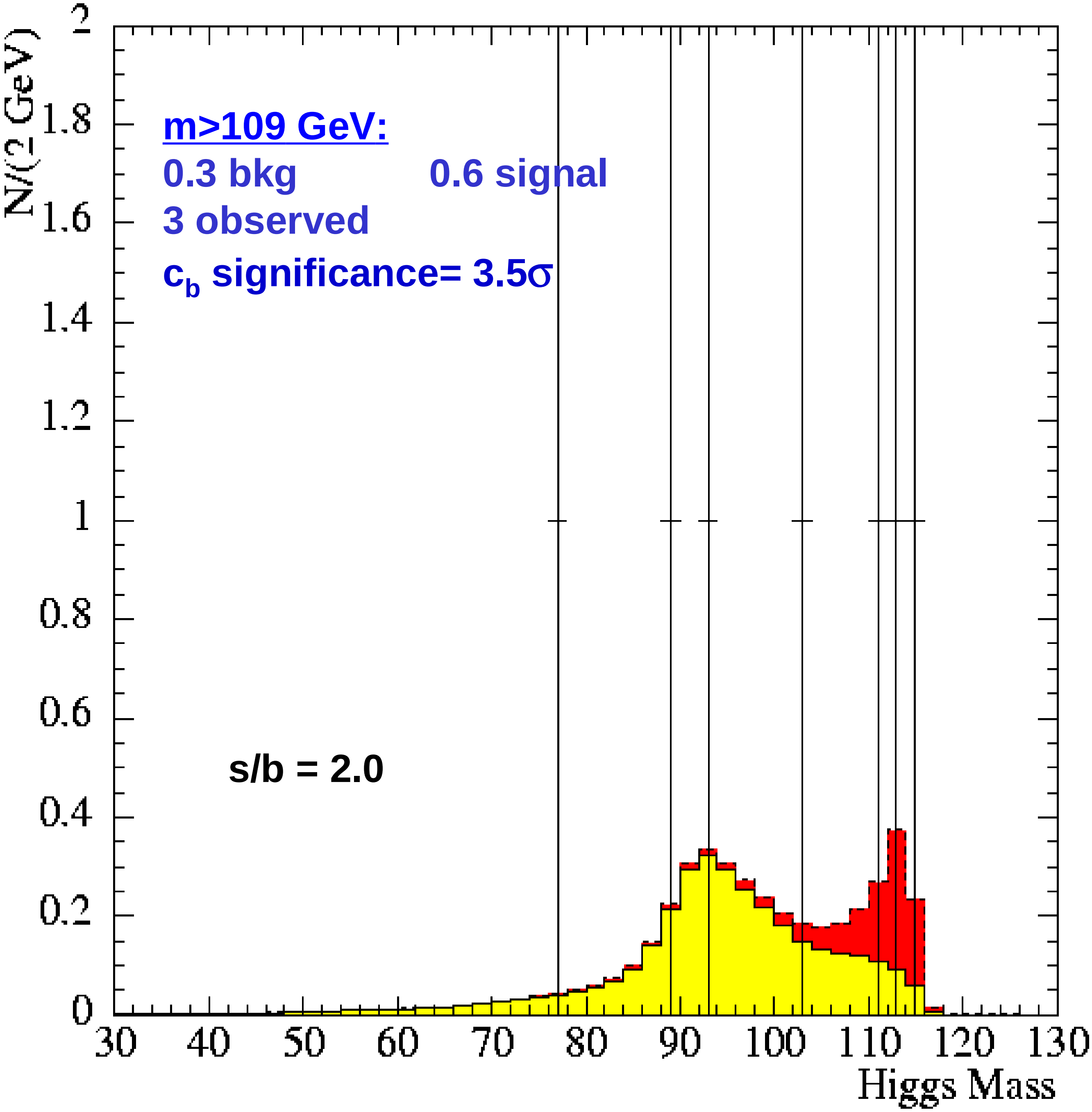
$e^+e^- \to Z\,H,\;\; Z \to qq,\;\; H \to bb$ (85%)

$m_H = 115$ GeV



What ALEPH saw Sept 5

(one representative plot)



The mass plot does not tell the whole story …
… as I will now elucidate

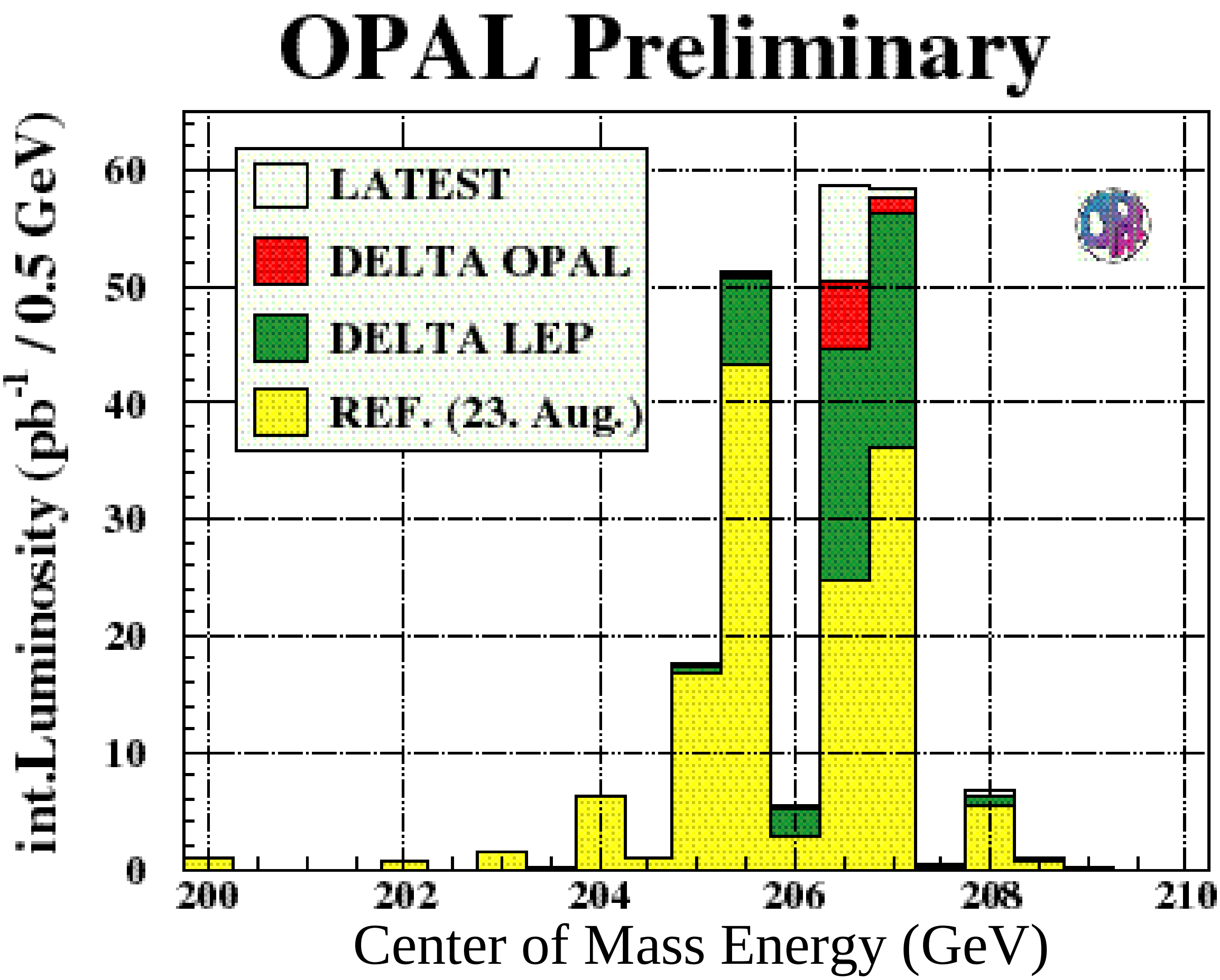
The Next Steps

- The events are only in one channel (4-jet)
  - ok ... low statistics
- Mostly from one experiment
  - again, low statistics
- Weighted by the significance of the b-tagging
  - 2 of the ALEPH events are “gold plated”
- At this high mass, very little background is expected, but just how well modelled is it?
  - more to the point, have enough MC events been processed to get smooth background and signal curves ?
- It was hoped that we could double the data at E_{cm}=207 by running an additional month
- The LEP-wide HIGGS working group (PIK!) was instructed to create a team which could combine the data from 4 experiments rapidly, and cross-check results

The E_{cm}>206Y2K Data (pb^{-1})

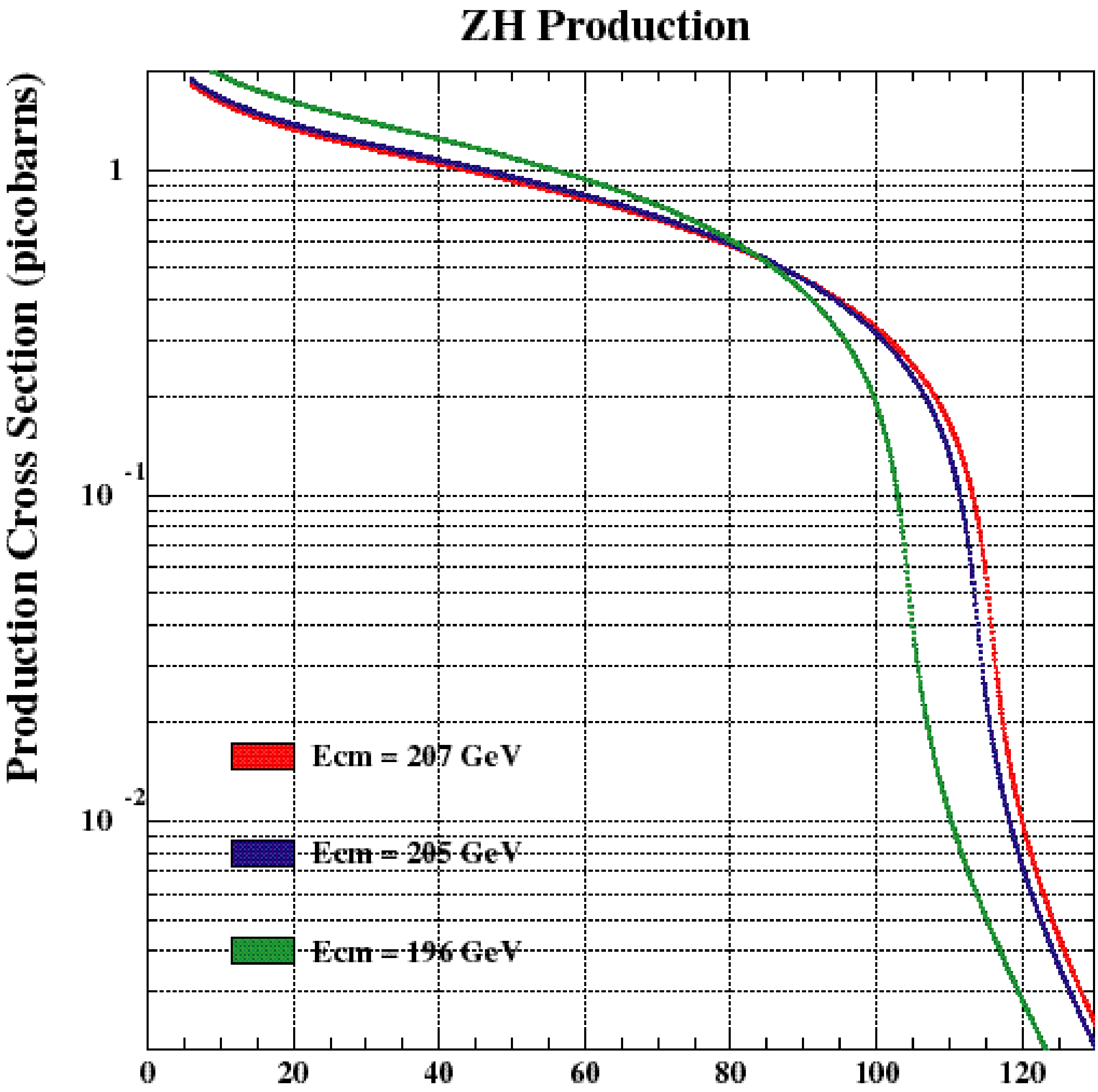
Expt:	Sept. 5	Nov. 2	Δ
ALEPH	72	119	47
DELPHI	74	122	48
L3	66	118	52
OPAL	67	119	52

(we were hoping for twice Δ)



How E_{cm} Helps

Shifting <E> from 205 to 206 GeV boosts the production rate for m_H=115 considerably



Higgs Mass (GeV)

Effect of 11 Years of LEP Operation

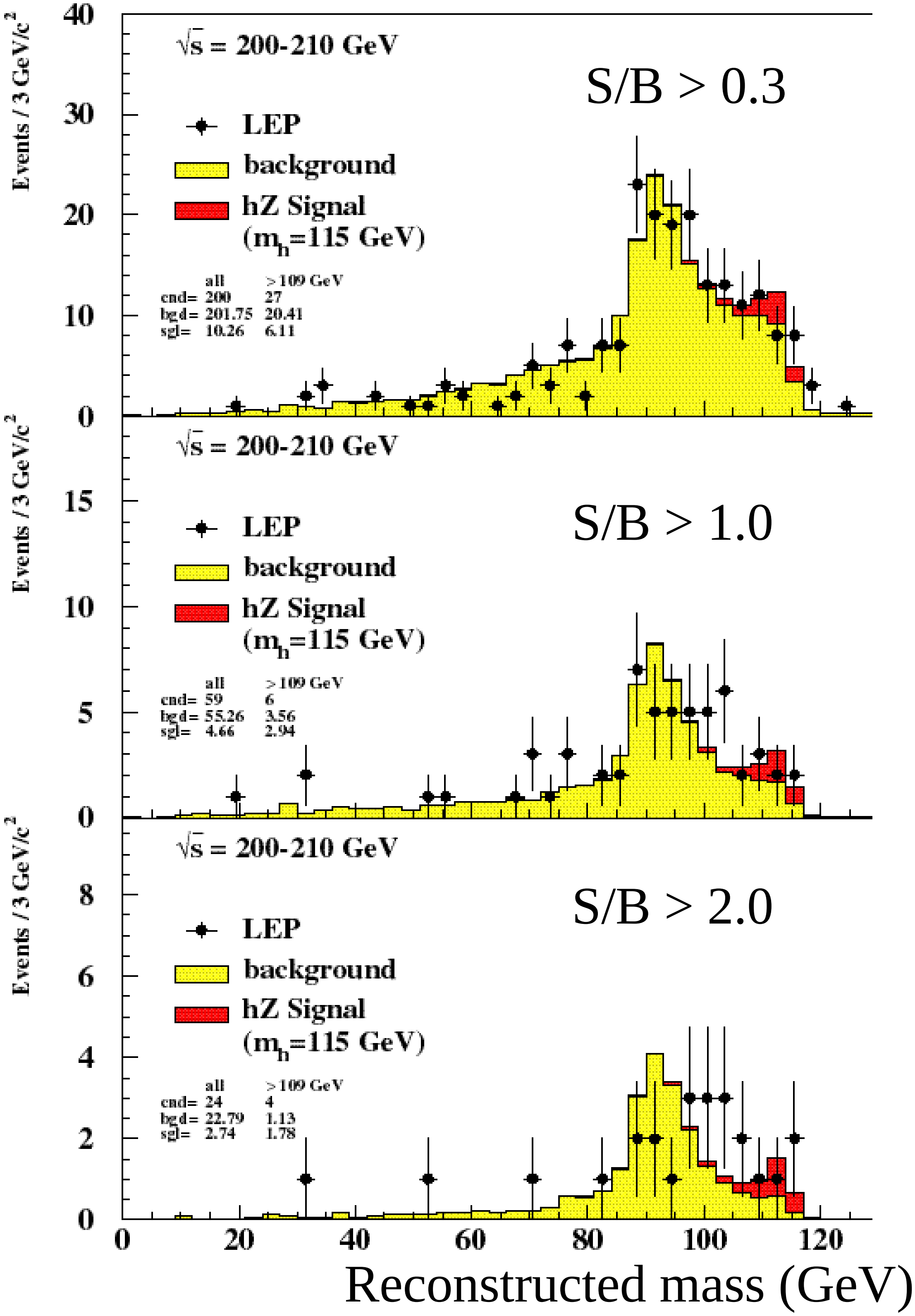
- All of the LEP experiments show signs of stress from age and radiation
  - ALEPH also had a short during a beam loss in July … and then the problem went away with another beam loss!
  - L3 has had inner tracker problems
  - OPAL lost efficiency in a sector of its b-tagging tracker
  - DELPHI suffered a short in their TPC
- But the good news is that corrections in software and redundancies in the apparatus mean the overall performance of the detectors is still excellent

Analysis Procedure

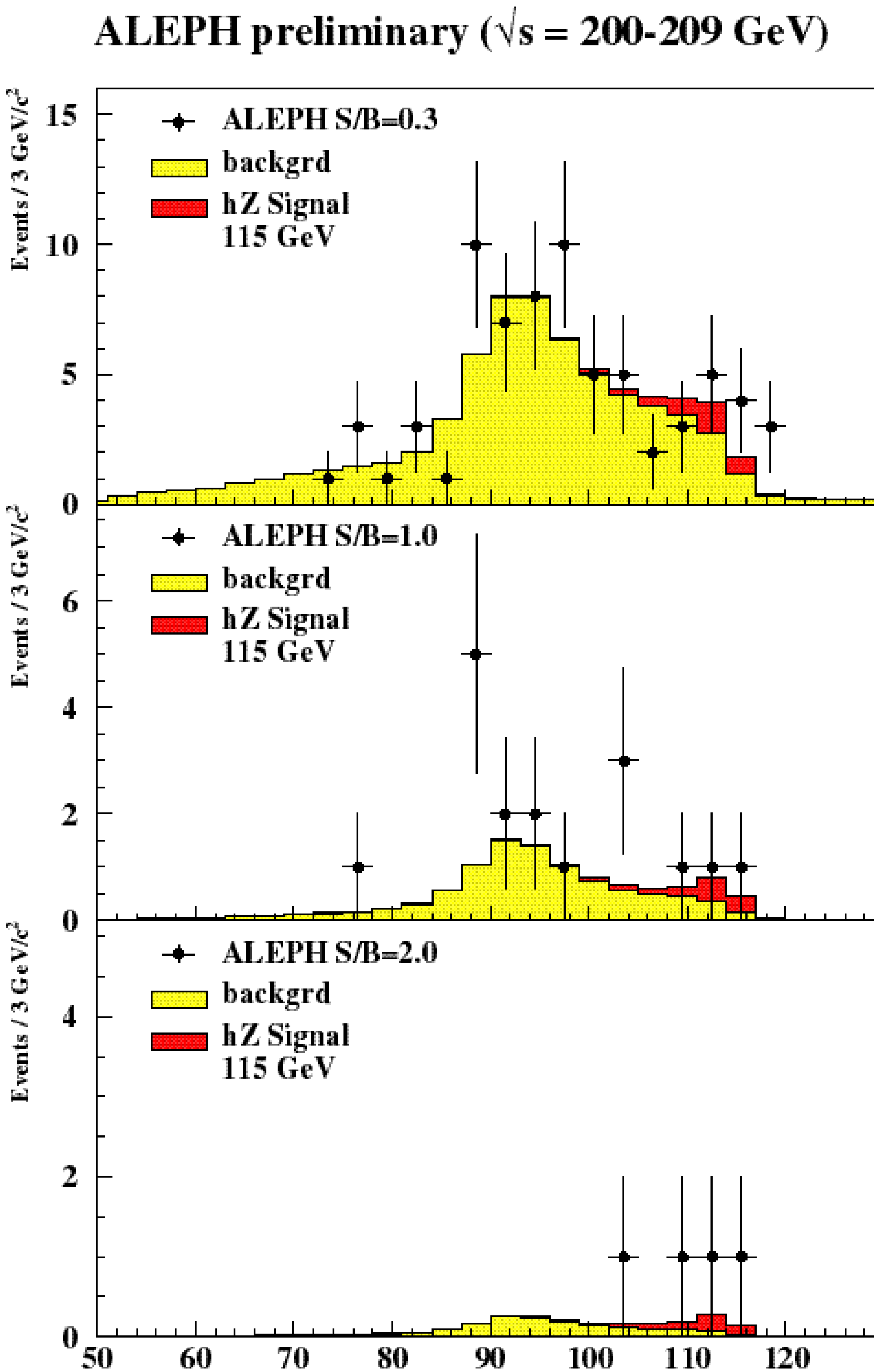
- The plot of candidate masses only shows a part of the total information
- In searching for the H^0 in the context of the Standard Model theory, we also have distributions in the various decay channels
- Each channel has different:
  - backgrounds
  - mass resolutions
- Individual events should be weighted for quality and systematic uncertainty
  - the likelihood of the b-tag quantified
  - mass reconstruction quality
  - likelihood of kinematic cuts
  - … and the S/B
- All this info should go into CL
- But everybody wants to see mass plots, so we show them for variations of the cuts which yield different minimum S/B

ADLO Mass Plot

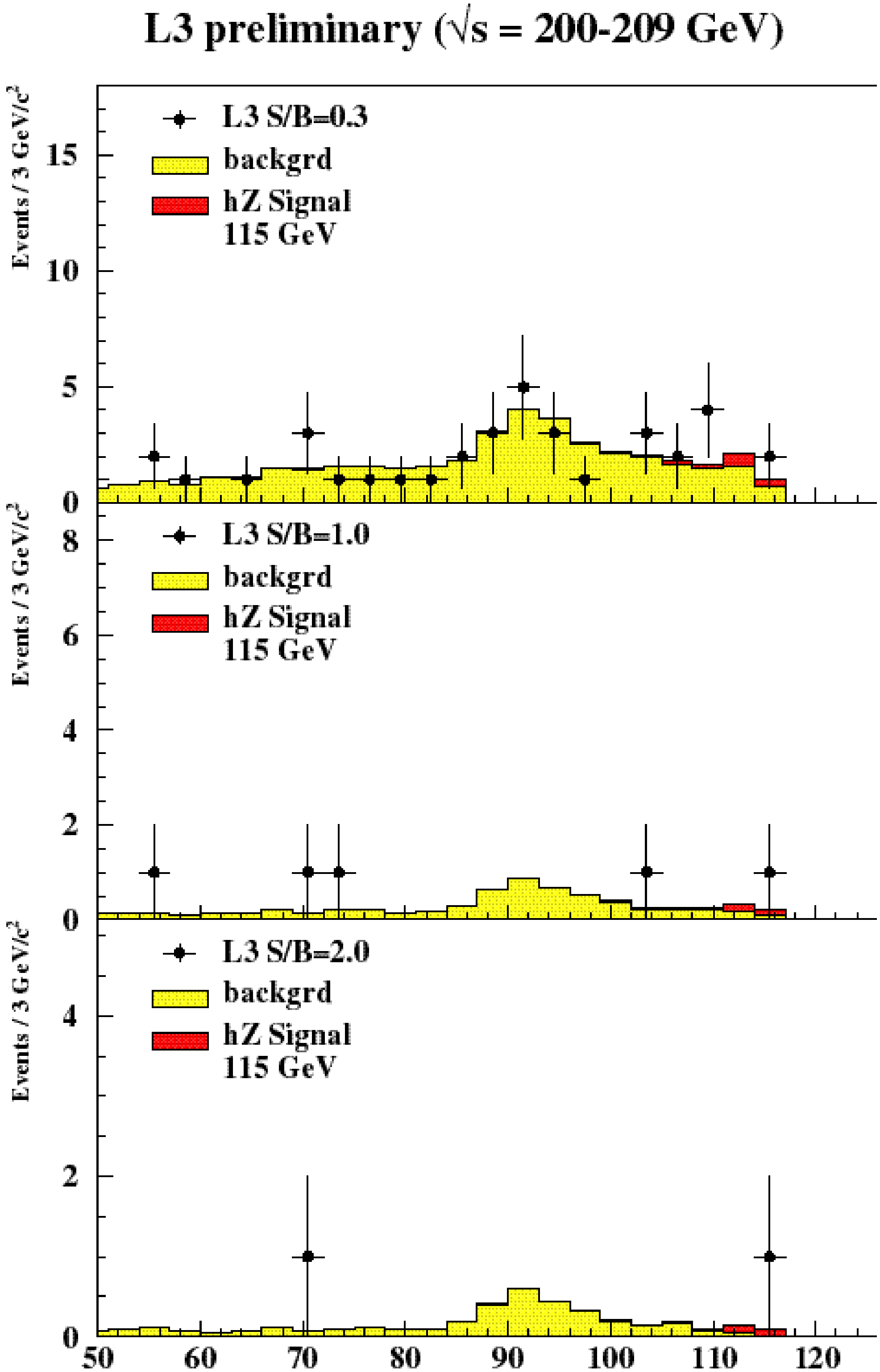
2 November ***PRELIMINARY***



ALEPH:


ALEPH preliminary ($\sqrt{s}$ = 200-209 GeV)
Events / 3 GeV/c²
ALEPH S/B=0.3
backgrd
hZ Signal
115 GeV
ALEPH S/B=1.0
backgrd
hZ Signal
115 GeV
ALEPH S/B=2.0
backgrd
hZ Signal
115 GeV
0
5
10
15
2
4
6
50
60
70
80
90
100
110
120

L3


L3 preliminary (√s = 200-209 GeV)
Events / 3 GeV/c²
L3 S/B=0.3
backgrd
hZ Signal
115 GeV
L3 S/B=1.0
backgrd
hZ Signal
115 GeV
L3 S/B=2.0
backgrd
hZ Signal
115 GeV
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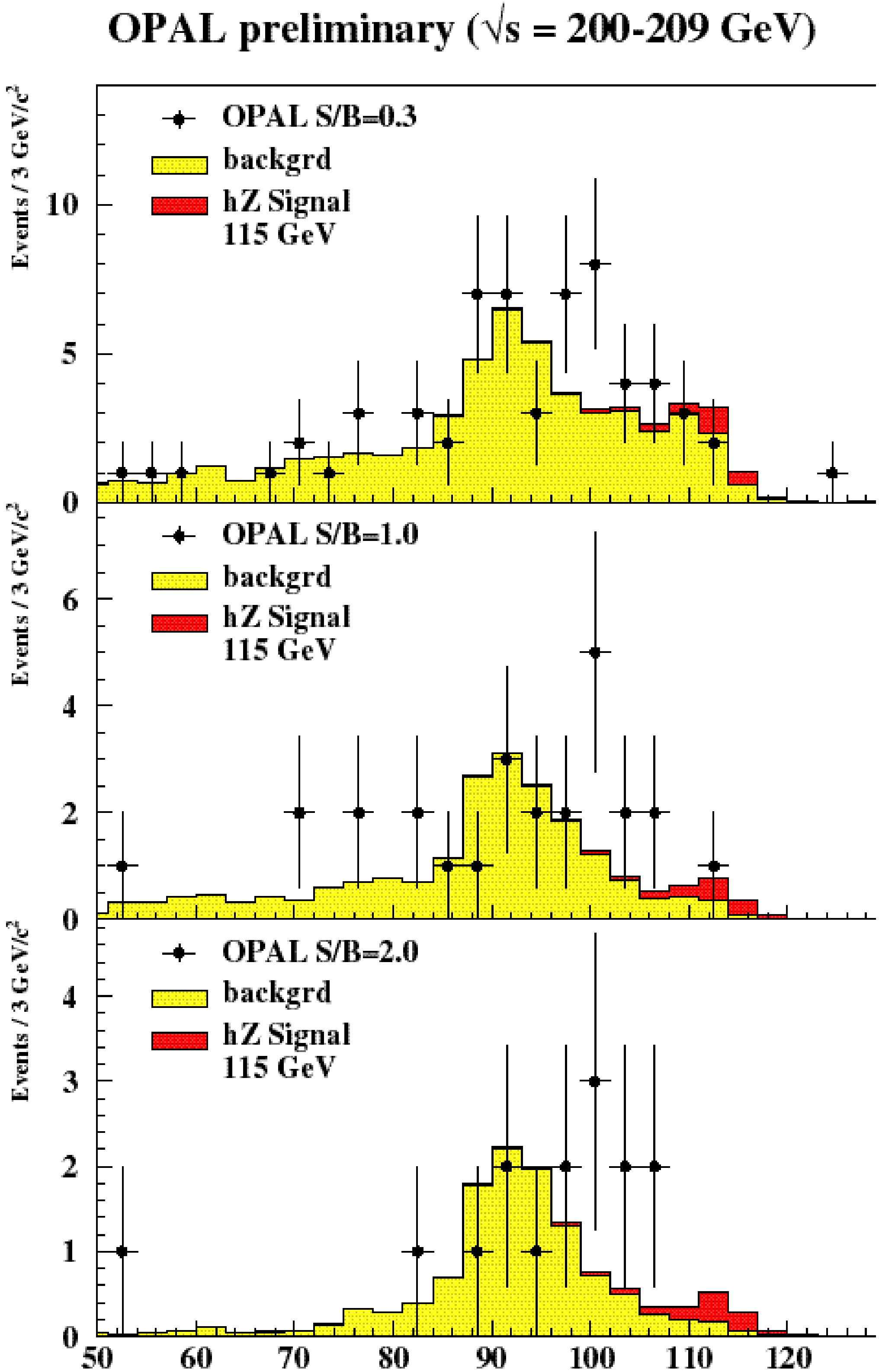
OPAL


OPAL preliminary (√s = 200-209 GeV)
Events / 3 GeV/c²
OPAL S/B=0.3
backgrd
hZ Signal
115 GeV
OPAL S/B=1.0
backgrd
hZ Signal
115 GeV
OPAL S/B=2.0
backgrd
hZ Signal
115 GeV
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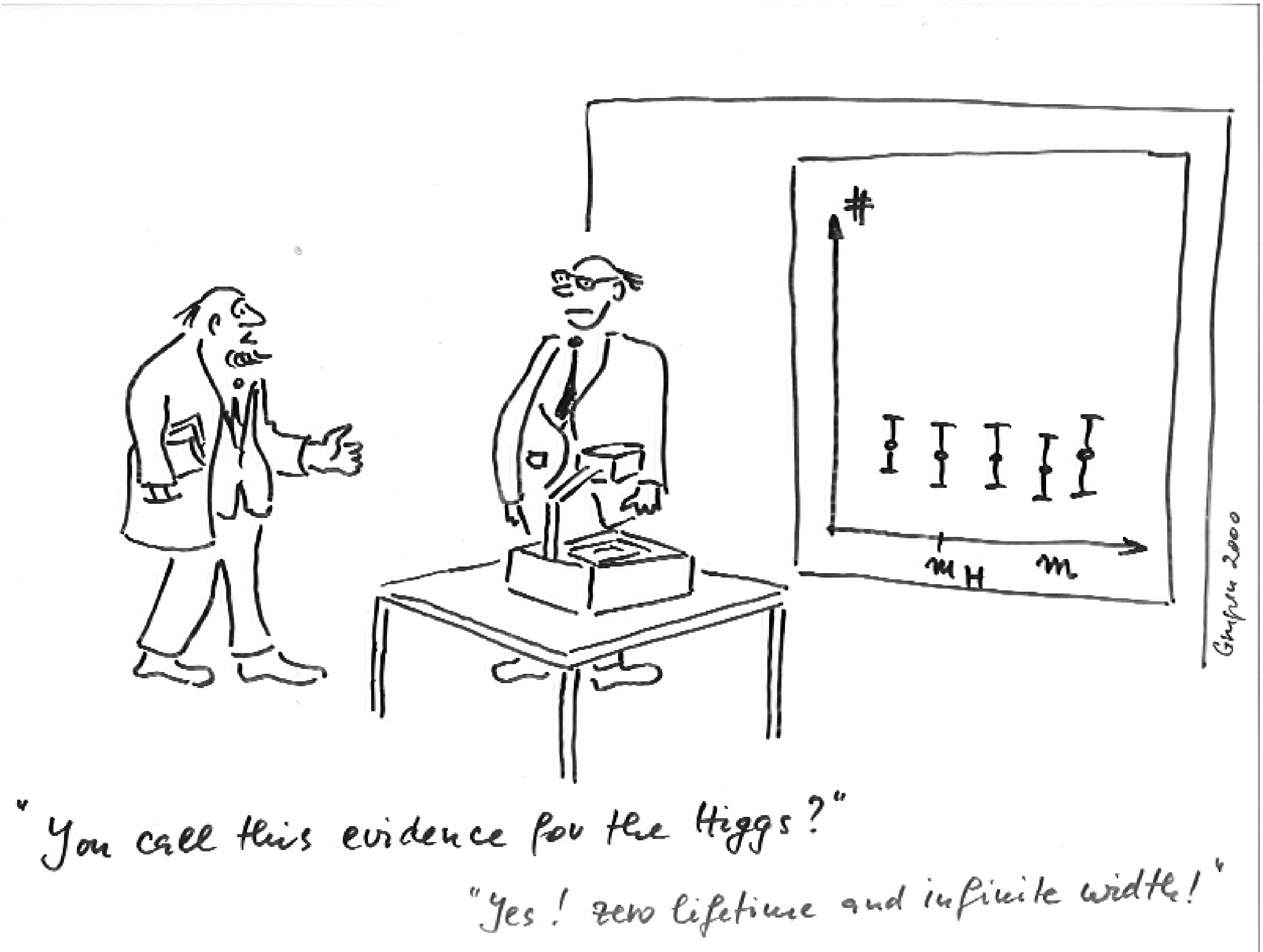
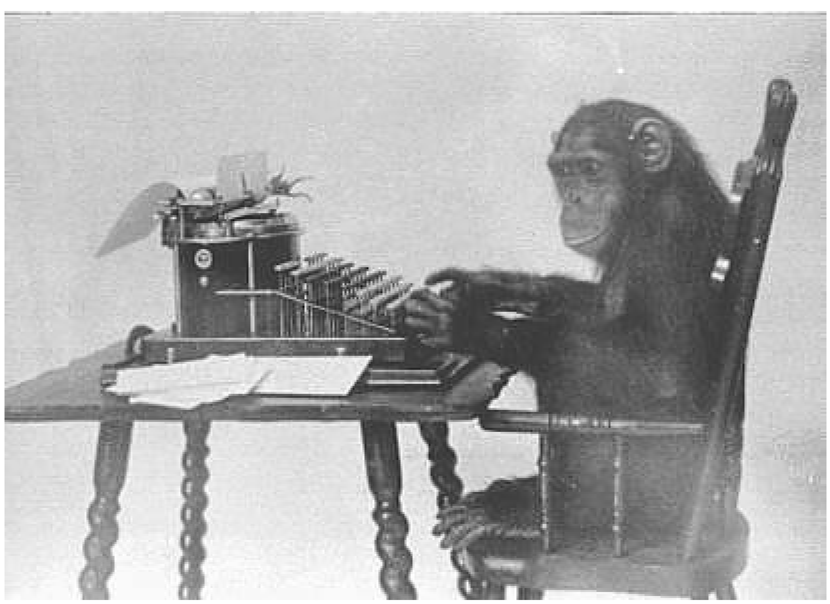
Even Some ALEPH Skeptics!



(Thanks again, Claus Grupen!)

Statistical Procedures

• We are looking for the Higgs within a very specific theory
• The mass plot does not convey all information (i.e., separate decay channels, amount of background, etc)
• So we need a statistical treatment



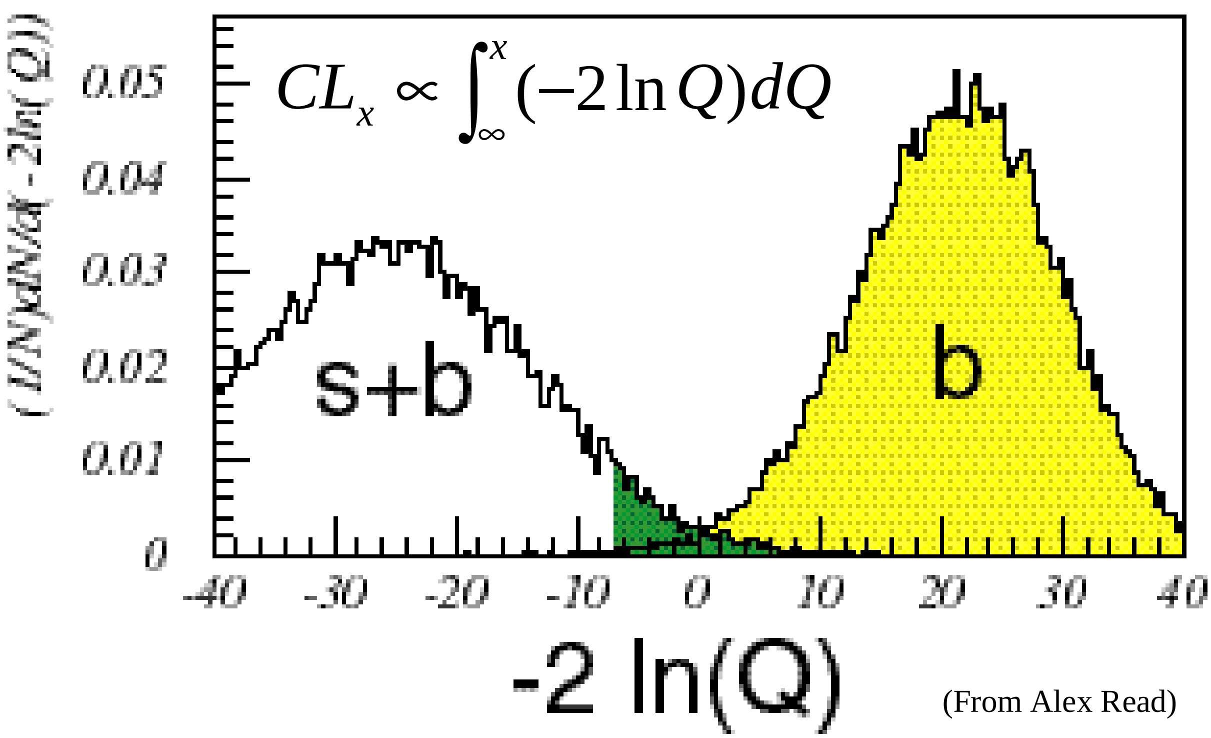
Signal, Background Hypotheses

• Construct a parameter that orders outcomes as more signal-like, or less signal-like

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

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

For hi-stat, -2lnQ is distributed like χ^2

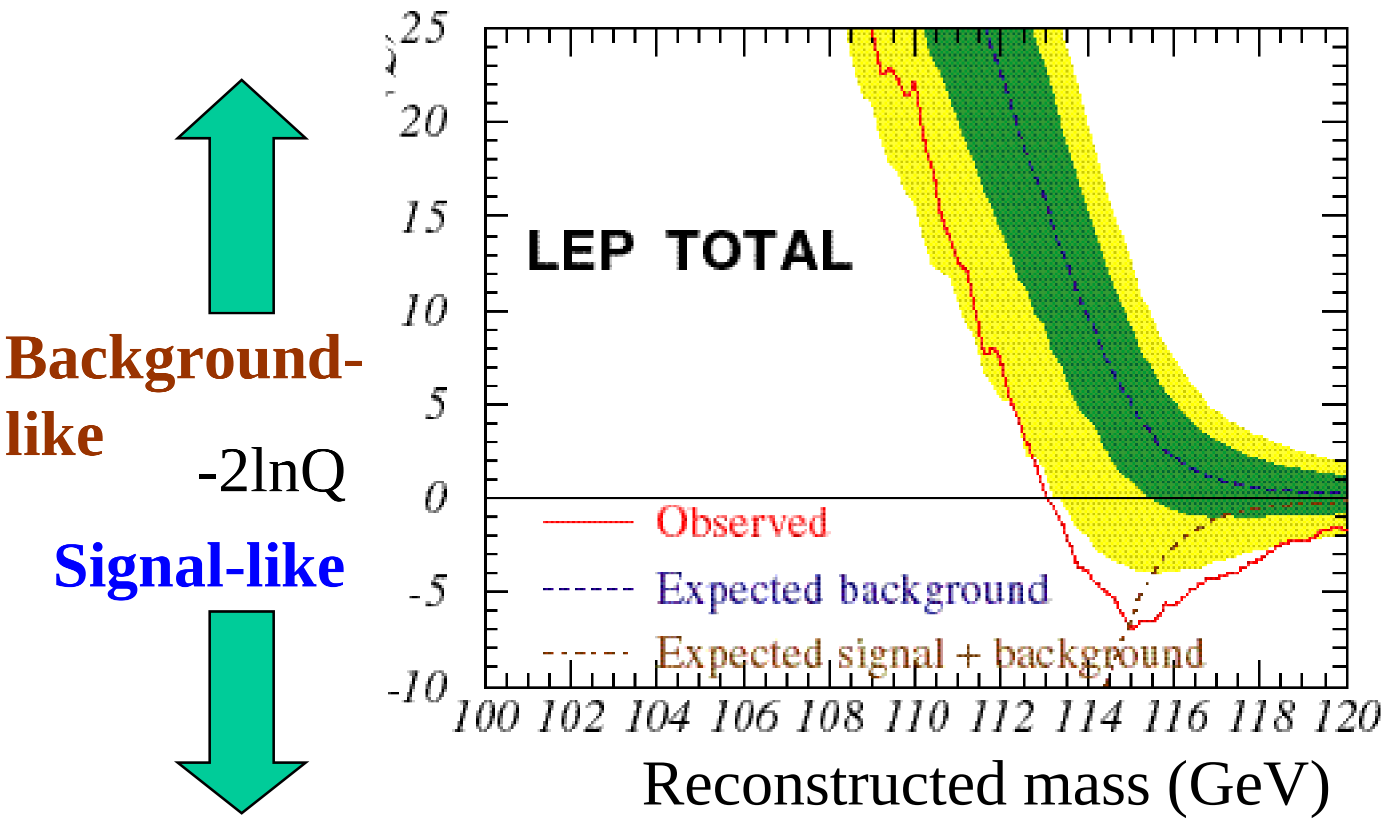


(From Alex Read)

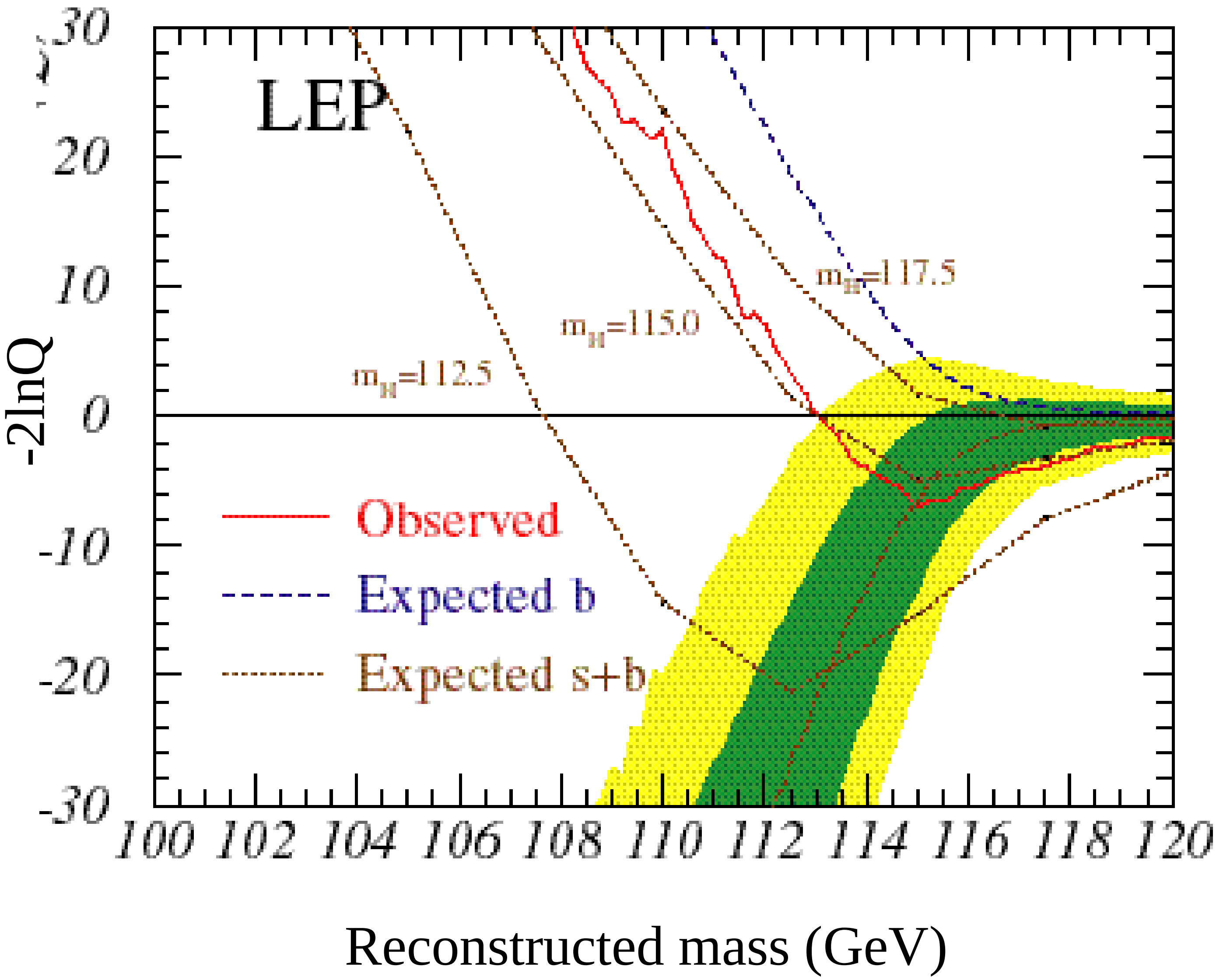
In Terms of Test Statistic:

- The data, expected background, and signal are binned in reconstructed mass
- "channels" for the likelihood computation include:
    - each decay channel
    - each experiment
    - each signal mass hypothesis
- NB: analyses, cuts *may* be m_H dependent

ADLO Nov 2 LEPC plot ***PRELIMINARY***:



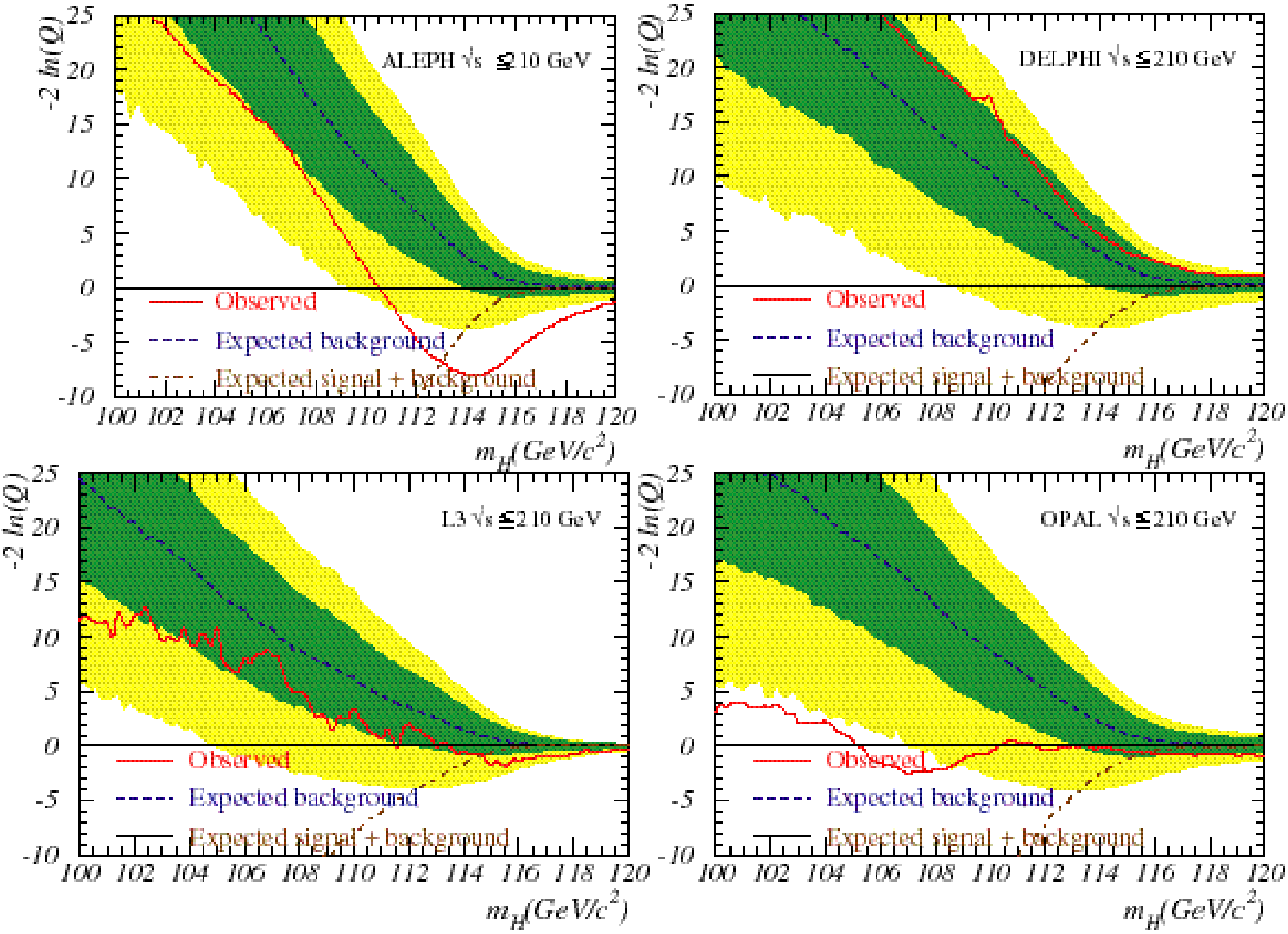
With Model Signals:



For Individual Experiments:

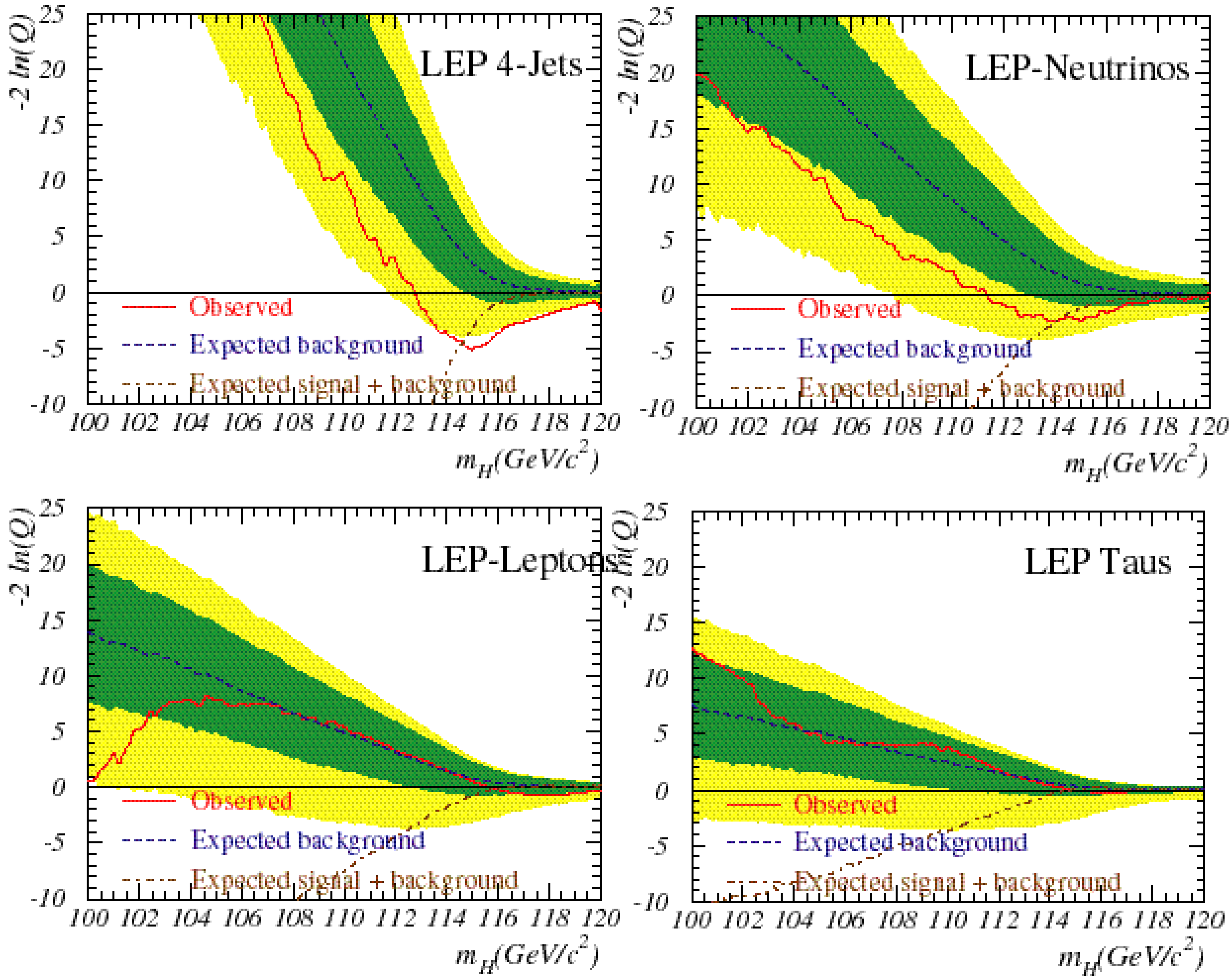
2 Nov ADLO LEP-combined data

PRELIMINARY



For Individual Channels

2 Nov data: ***PRELIMINARY***



How to ascribe Significance

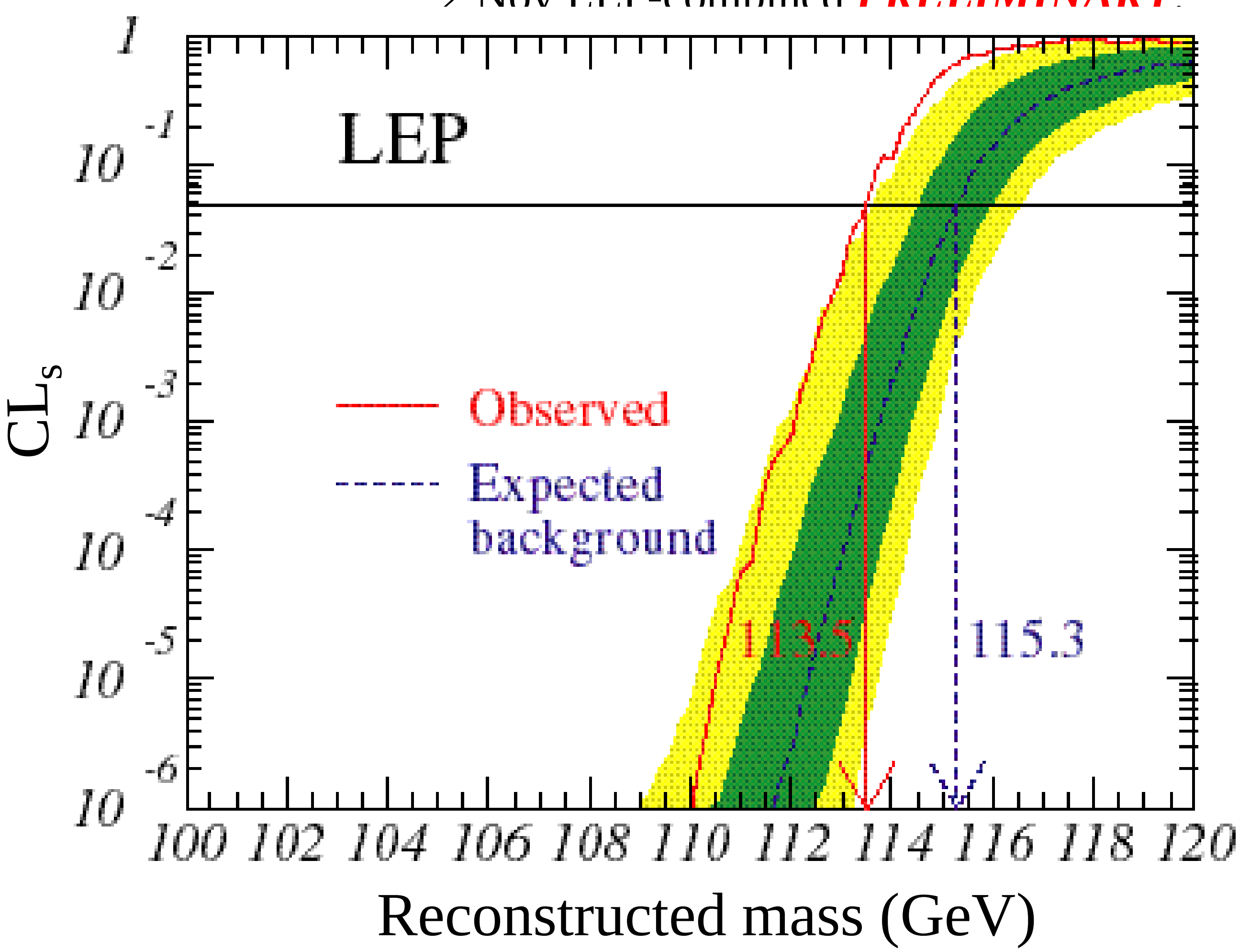
- **CL_s** -- compatibility with signal hyp.
  $CL_s < 0.05$: Signal hypothesis ruled out at the 95% CL.

We use CL_s to set mass limit

- **CL_b** -- compatibility with background hyp.
  $1\text{-}CL_b < 5.7\times10^{-7}$ is a 5σ discovery

We use CL_b for discovery

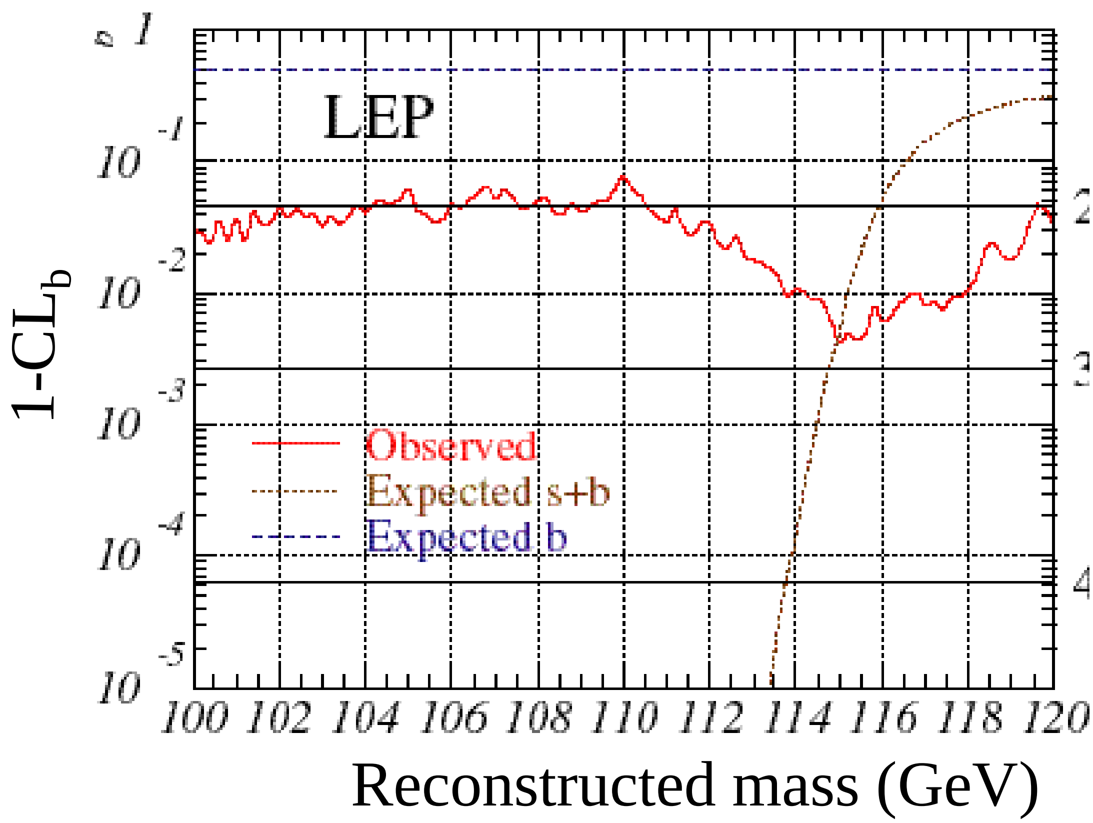
2 Nov LEP-combined ***PRELIMINARY***:



If You Are An Optimist ...

The pip at 115 GeV drops down to 0.004 in $1\text{-}CL_b$
If taken as a signal, this has a significance of 2.9σ

NB: no look-elsewhere dilution, since we have excluded to 112 and are only sensitive to 115



Where Do We Go From Here?

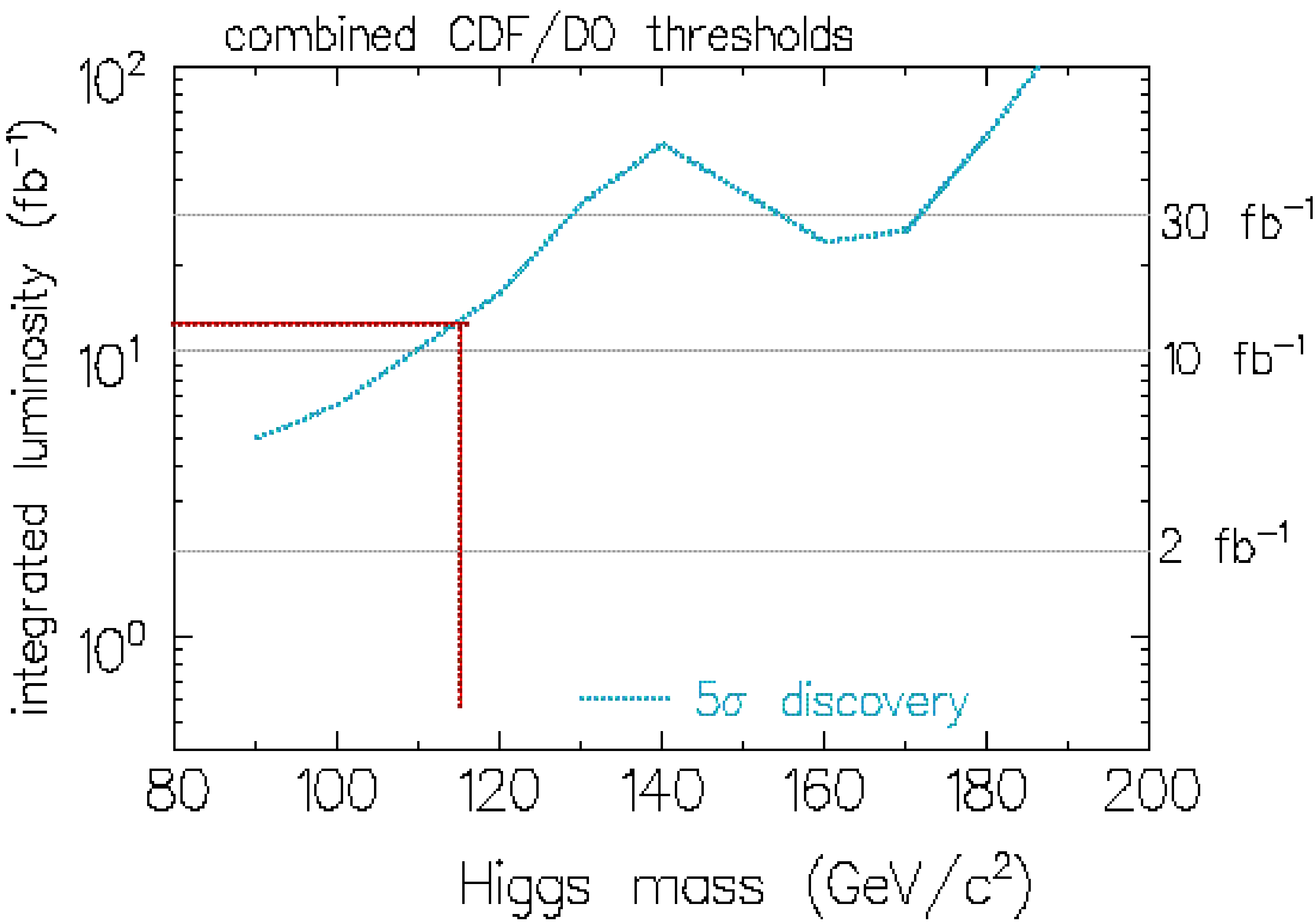
•On 3 November, the CERN director decided there will NOT be LEP running in 2001

- •*VERY* expensive: LHC contractor penalties
- •The Large Hadron Collider is delayed by more than 1 year

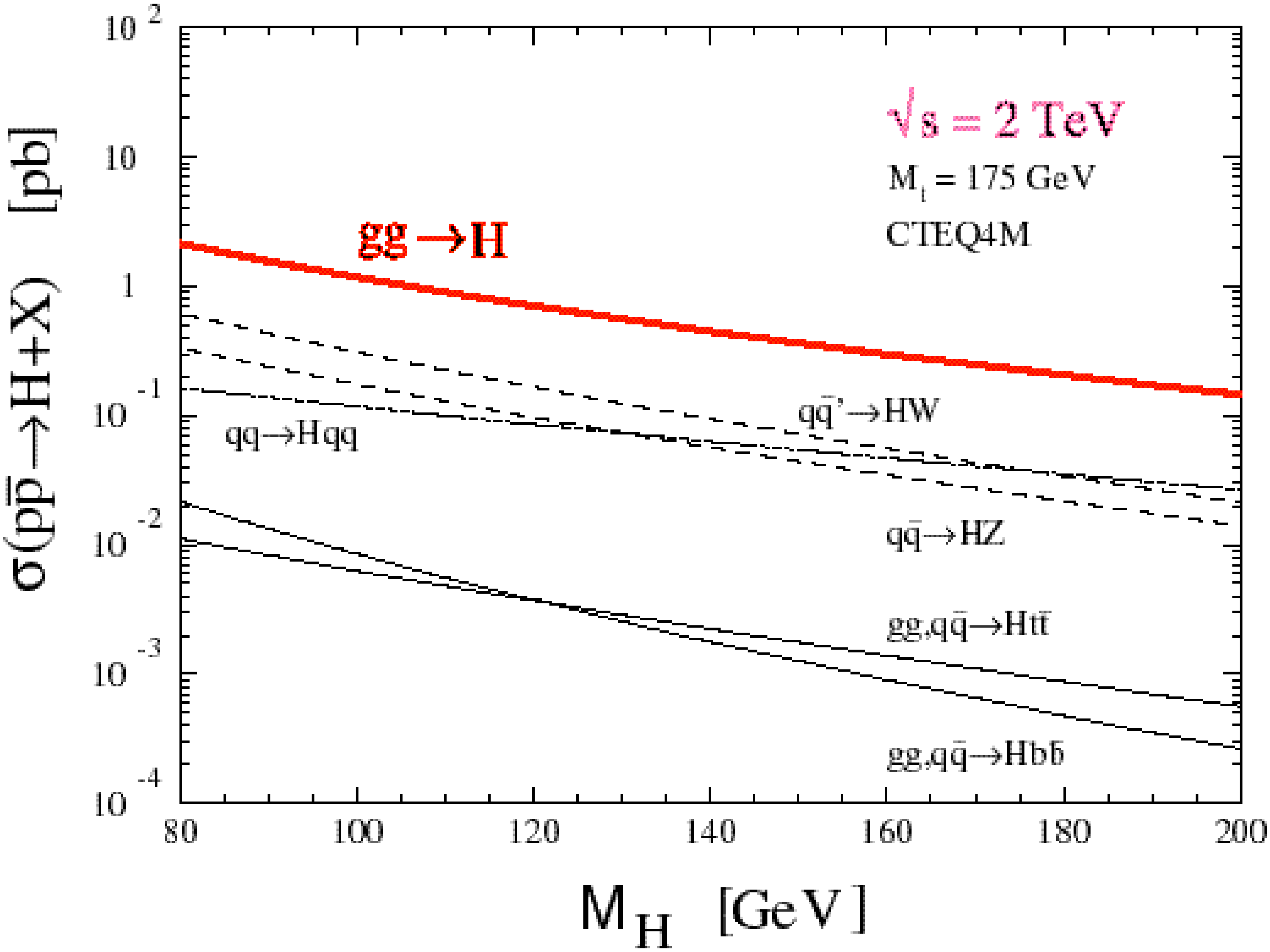
- Next experiments:
  - Fermilab TeVatron run II
    - higher luminosity than before
      - 15 inverse fb by 2004?
    - upgraded detectors (2)
  - CERN Large Hadron Collider
    - high field magnets in LEP tunnel
    - pp collisions at E_{cm} = 14 TeV
    - Turn-on in 2006: 1 inverse femtobarn
    - x10 luminosity in 2007

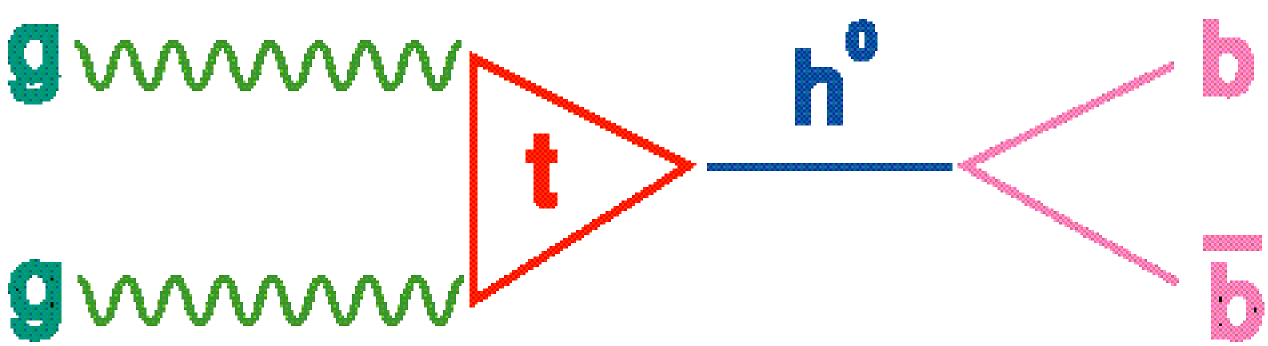
LEP's Difficult Legacy

- A 115 GeV Higgs is difficult to see
- Fermilab TeVatron and LHC: large backgrounds
- 2-3 years (2004?) for CDF/D0
- Not so easy for LHC either … 2007?



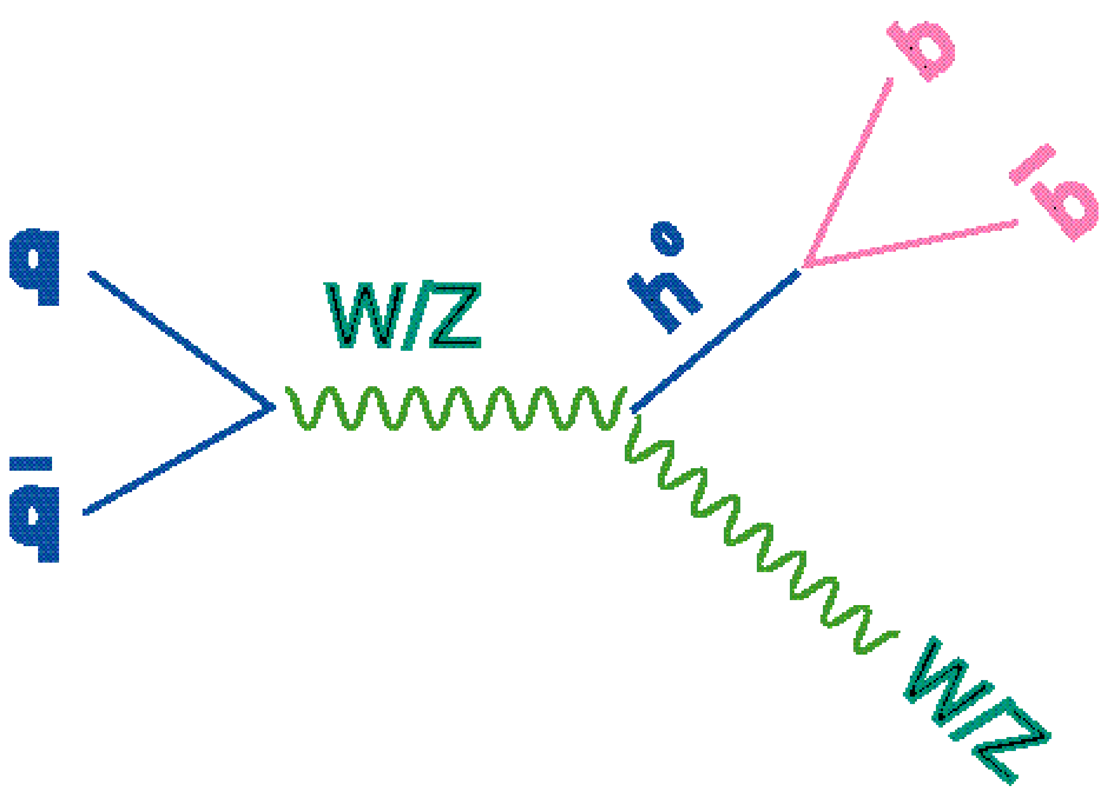
Hadron Collider Dominant Process





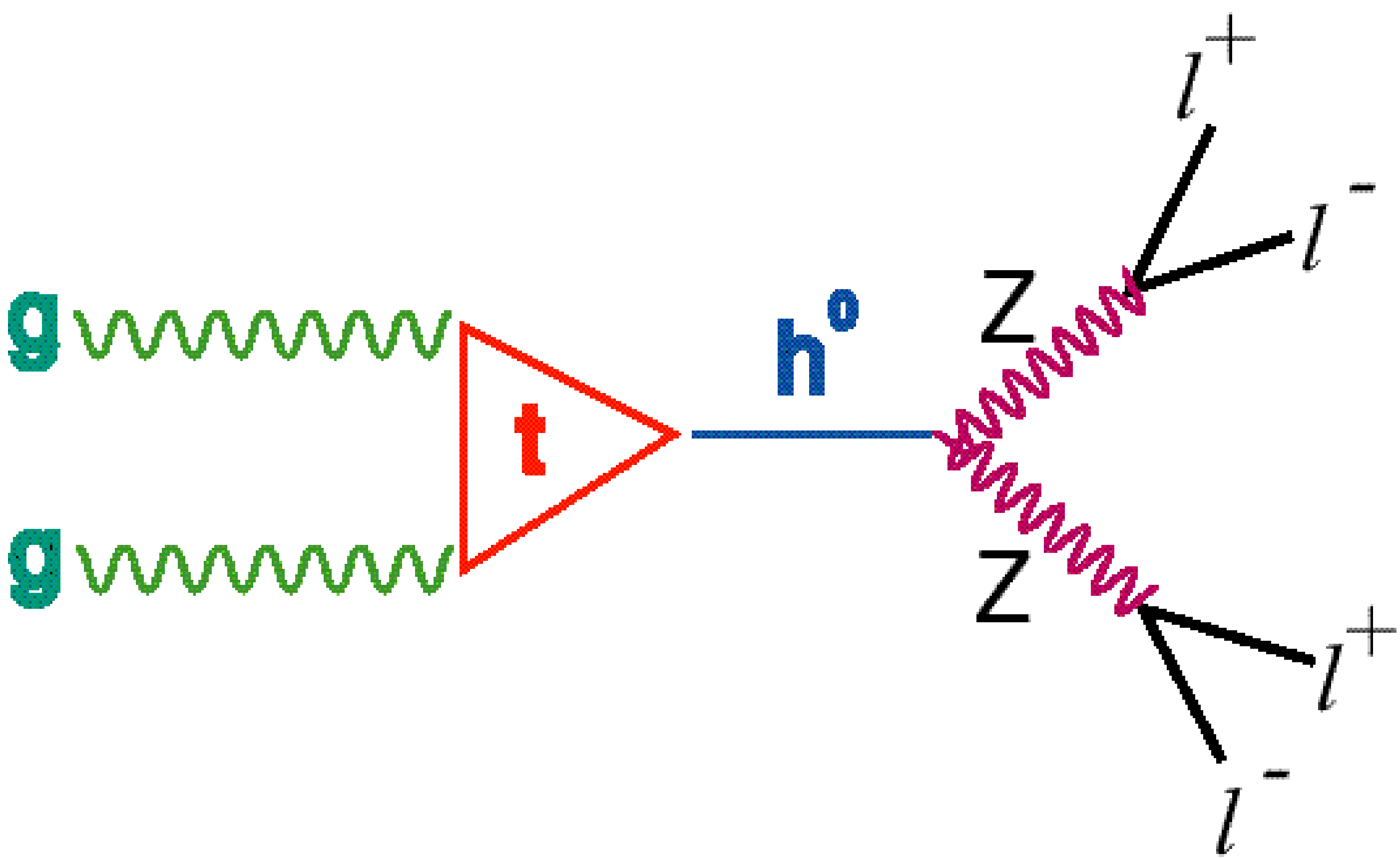
TeVatron Best bet

- While σ_{gg}=1pb, the QCD baclground is 10^6
- The hW and hZ allow mass-tag of W,Z
- Using all channels, they can probably just get up to 115 GeV mass reach in 4-5 years



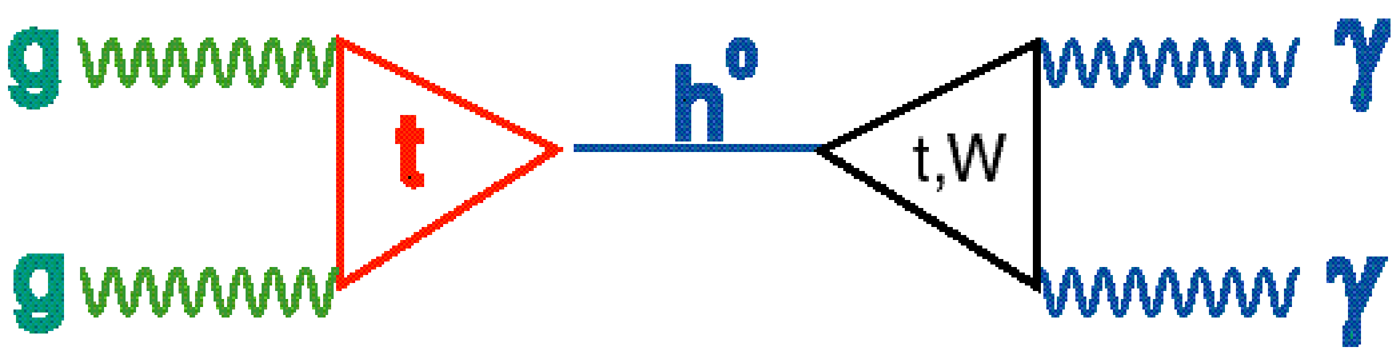
LHC Golden Process

- The rates at LHC’s higher energy are larger, but so are the backgrounds
- Can afford to tag on very clean Z decays
- In this way, mass reach is up to 1 TeV



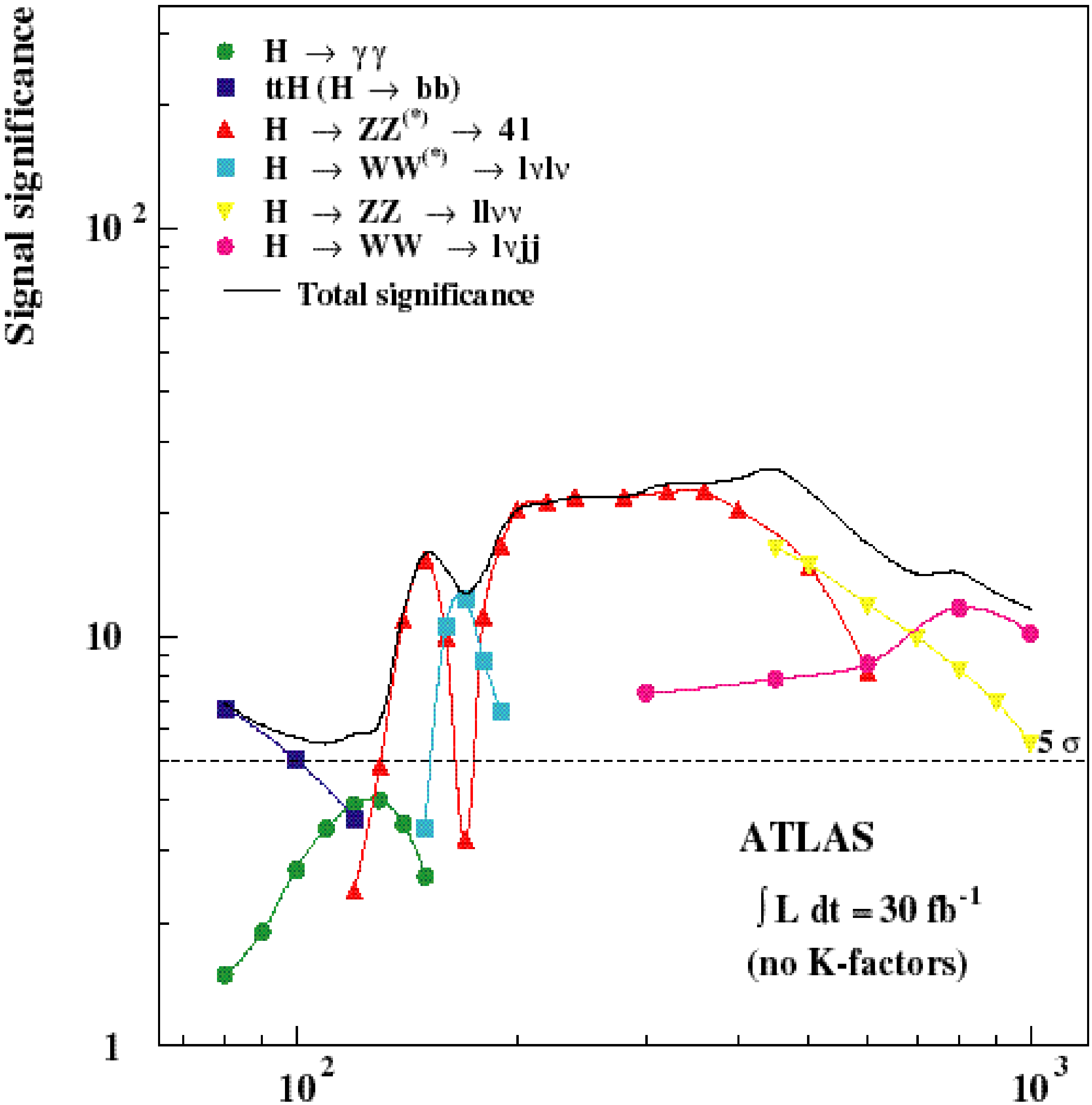
LHC m=115 Clean Process

- The low 115 GeV Higgs mass is a problem for LHC (below ZZ threshold).
- Make some use of the relactively clean diphoton decays of the Higgs
- But there is background from QCD here too



What LHC Can Do

2006-2007: 20-40 fb^{-1}



Conclusions

- We might be seeing the Higgs
- …but not at a “discovery” level
- Indirect evidence strongly suggests new physics in the energy range 100-200 GeV
- FNAL has just started, LHC is on the horizon

I am confident that this new energy scale of ~100-200 GeV will be revealed by the end of this decade!

This decade will see tremendous excitement in High Energy Physics!