40 Years of the Higgs Boson

M. E. Peskin
SSI 2012
July 2012

The organizers of the SSI asked me to review the 40 years of history of the Higgs Boson that parallel the 40 years of the SSI.

I am not a historian.   This survey will be anectodal.   I do not promise that it will be "fair and balanced".

I will emphasize topics close to my own experience, and those that actually appeared in the SSI.

Iliopoulos at Higgs Hunting 2012:

"Never read old papers with today's knowledge."

He meant, for the purpose of assigining credit. It is very illuminating to read the old papers to glean insights.

So I will begin at ICHEP 1972, held at NAL (now called Fermilab).

From the lecture of Benjamin Lee on the theory of weak interactions

symmetry. The basic strategy of this construction appears first in Weinberg's[1] paper published in 1967 and also in Salam's,[2] published in 1968. In these papers, weak interactions and electromagnetic interactions are unified in a Yang-Mills gauge theory with the intermediate vector bosons $W^{\pm}$ and the photon as gauge bosons. This idea by itself was not new, having previously been discussed by Schwinger,[3] Glashow,[4] Salam and Ward,[5] and others. What was new in the Weinberg-Salam strategy was to attribute the observed dissimilarities between weak and electromagnetic interactions to a spontaneous breakdown of gauge summetry (which is known as the Higgs mechanism).

This mechanism was studied by Higgs,[6] Kibble,[7] Guralnik, Hagen, and others[8] since 1964. The Higgs mechanism takes place in a gauge theory in

At the Amsterdam conference last year, a young Dutch physicist, G. 't Hooft, not yet out of graduate school, presented a paper which would change our way of thinking in gauge field theory in a most profound way.[26,27] In addition to rediscovering the Higgs mechanism and the Weinberg-Salam theory by himself, he presented a formulation of spontaneously broken gauge theories which is manifestly renormalizable, i.e., all Feynman graphs are finite except for a small number of primitively divergent vertices. The formulation takes advantage of the gauge freedom afforded in such a theory. In this formulation Green's

In the fall of 1972, I was an undergraduate at Harvard. I was hustled to a lecture by a new assistant professor, Alvaro de Rujula, who explained the newly resurgent unified theory of weak and electromagnetic interactions.   He included Lee's locution:

"Higgs" is an abbreviation for Higgs, Kibble, Guralnik, Hagen, Brout, Englert.

In 1972, the properties of the Higgs boson were a neglected corner of the electroweak theory.   People were interested in more immediate questions:

Were there weak neutral currents ?

What was the gauge group ?

This did not change until 1975, with the pathbreaking paper:

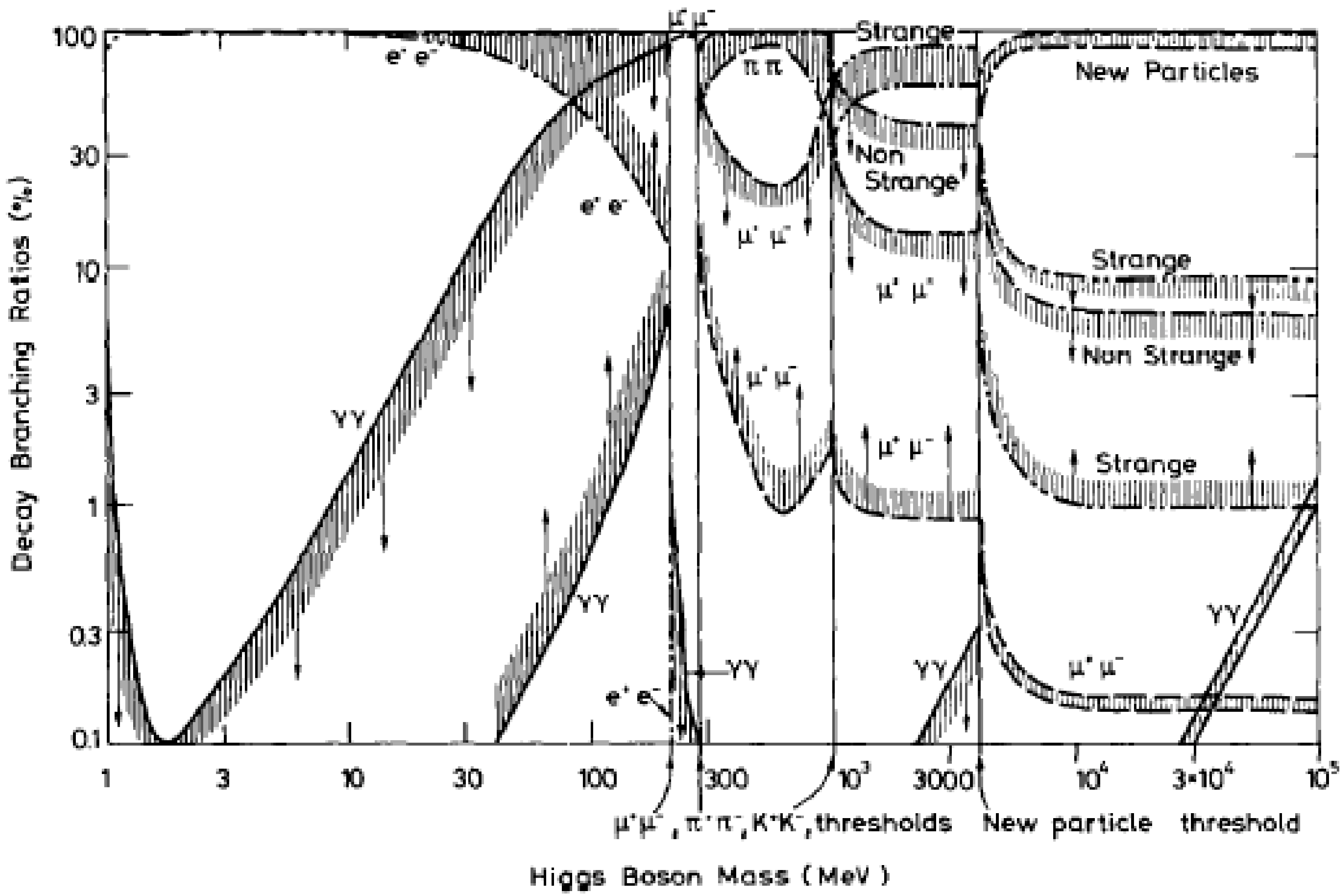
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

Here are some figures from the paper:

The first comprehensive accounting of Higgs branching fractions (up to a mass of 100 GeV):



The first calculation of

$$\Gamma(h \to \gamma\gamma)$$

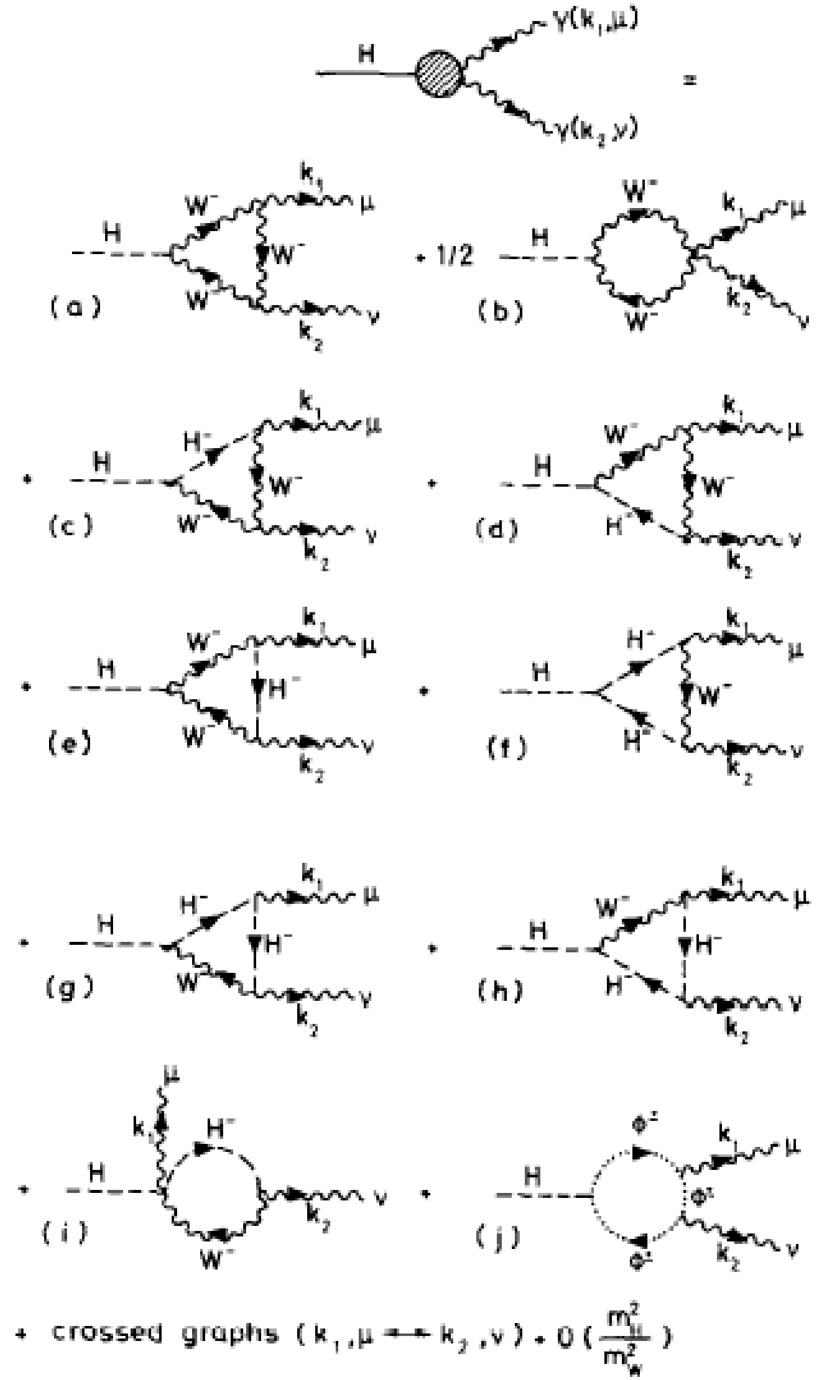


Fig. 17. Feynman diagrams for I_W.

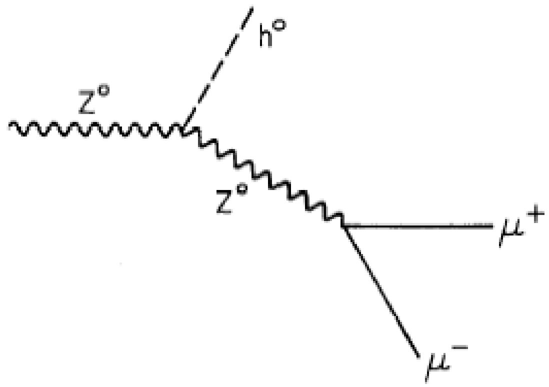
The Higgs boson made its first appearance at the SSI in 1976, in a now-classic set of lectures by Bjorken.

> To fix up this situation without reverting to a previous case involving large phase-shifts, it is necessary to introduce J=0 particles coupled principally to the gauge-bosons W. Such particles, the so-called Higgs particles,[33,34] also play a role in the more fundamental field-theoretical approach. Just as in

Is there hope of finding real Higgs bosons experimentally? It appears to be very difficult.[42] The coupling of Higgs bosons to fermions is proportional to fermion mass: the Yukawa coupling to a fermion of mass m_f is typically

$$\mathscr{H}' \sim e \frac{m_f}{m_W} \bar{\psi} \psi \phi \qquad (2.20)$$

The Higgs bosons are coupled more substantially to gauge bosons. There is a quadratic coupling similar to the $A^2\phi^2$ seagull in scalar electrodynamics. In addition there is a trilinear $B_\mu B^\mu \phi$ coupling proportional to $e\, m_W$. One hope for entering the Higgs sector is to resonantly produce some neutral Z^o in e^+e^- collisions, and look for the Higgs boson h in the decay $Z^o \rightarrow h e^+ e^-$ or $Z^o \rightarrow h\mu^+\mu^-$ (Fig. 4). There are other ideas as well,[43] but they are also futuristic and difficult. More thought on these general issues might well be fruitful.



"Bjorken process"

The years 1976-77 saw the first limits on the mass of the Higgs boson in the now-established Standard Model.

Both limits came from theory.

Linde and Weinberg computed the radiative corrections to the Higgs potential and found that the potential could not actually be flat at the minimum without being unstable.

Mass of the Higgs Boson*

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 15 December 1975)

The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest $SU(2) \otimes U(1)$ model, this lower bound is $1.738\alpha G_F^{-1/2}$, or 3.72 GeV.

ON THE VACUUM INSTABILITY AND THE HIGGS MESON MASS

A.D. LINDE
Lebedev Physical Institute, Moscow, USSR

Received 10 July 1977

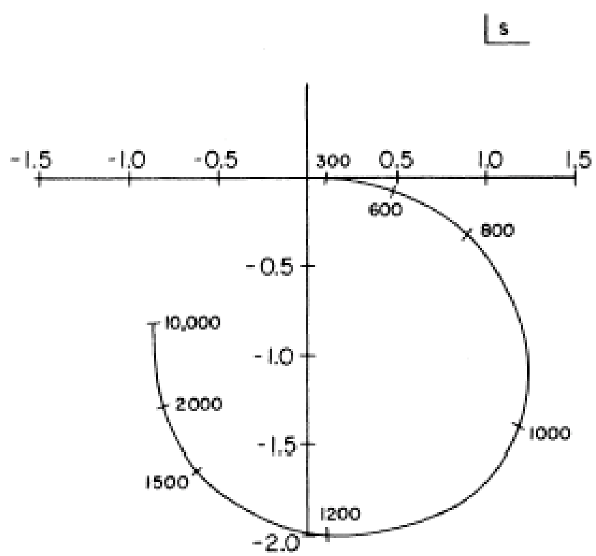
A theory of the decay of a metastable vacuum state is investigated. As an application it is shown that if the Universe is not enormously charge asymmetric, then the Higgs meson mass in the Weinberg model should exceed 6.9 GeV.

At the same time, there is an upper bound on the Higgs mass. Large Higgs mass is associated with strong Higgs coupling. This strong coupling should not violate unitarity.

Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

Benjamin W. Lee, C. Quigg,* and H. B. Thacker
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 28 February 1977)

It is shown that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$ partial-wave unitarity is not respected by the tree diagrams for two-body reactions of gauge bosons, and the weak interactions must become strong.



from Lee, Quigg, Thacker II.

Shortly after this paper was submitted, Ben Lee was killed in an auto accident.

By 1978, with the SLAC-Yale parity violation experiment, the Standard Model of weak interactions was established. It required the Higgs boson, but the Higgs was nowhere to be found.

In 1981, Lev Okun presented this situation in his concluding talk at the Lepton-Photon conference:

> It seems to me that the problem No.1 of high energy physics are scalar particles. The search for these particles is extremely important mainly because of their vital role in symmetry breaking. The whole picture of the physical world consists of two parts, which are complementary like yin and yang brought in another context into quantum physics by Niels Bohr:

The 1980’s were the era of the CESR and DORIS b-factories and the run-up to the Superconducting SuperCollider.

In this context, two types of Higgs bosons were in fashion, those light enough to be produced in Upsilon decays, and those so obese that only the SSC could find them.

Since the Higgs couples to heavy quarks, it is naturally found (if light enough) in quarkonium annihilation, e.g.

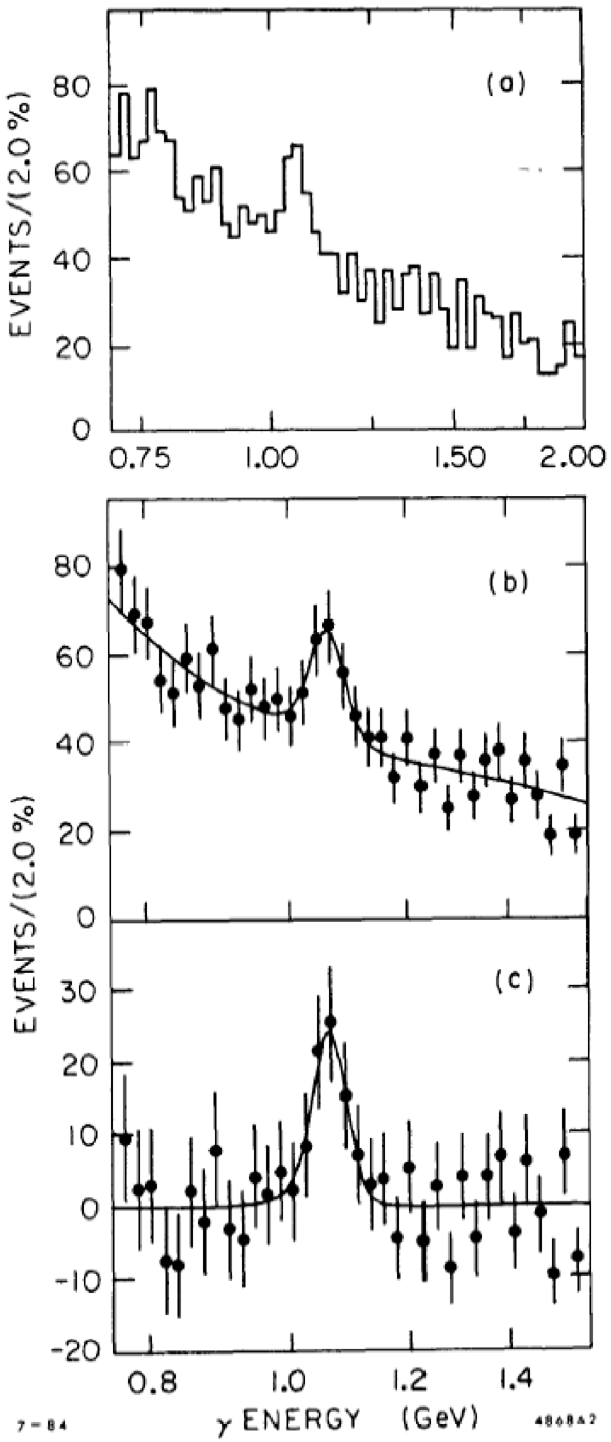
$$\Upsilon \to h + \gamma$$

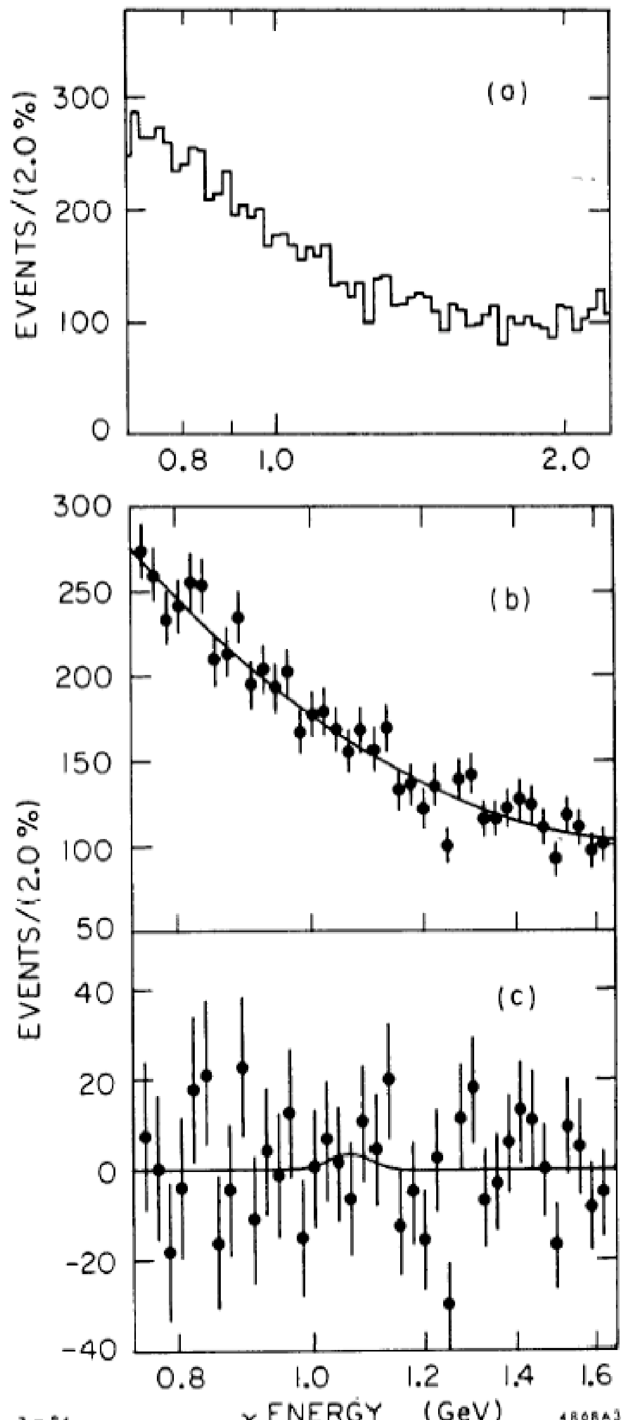
Many searches were carried out, both at ψ and Υ. None were successful. Except (SSI 1984),

Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon*

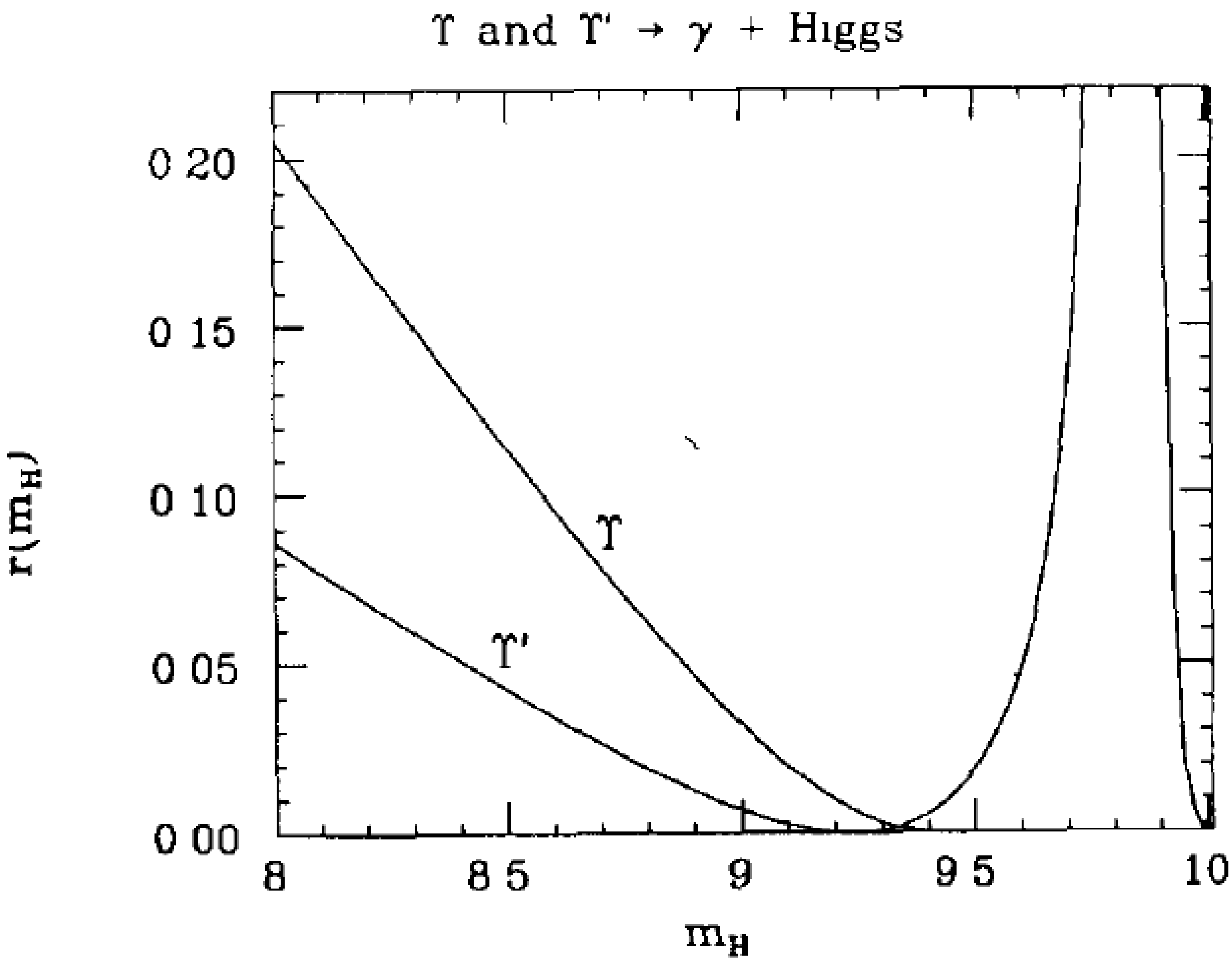
Crystal Ball Collaboration

Υ





Υ'



Pantaleone, Peskin, and Tye 1984

meanwhile, the study of very heavy Higgs bosons was spearheaded by the work of Chanowitz and Gaillard,

THE TeV PHYSICS OF STRONGLY INTERACTING W's AND Z's*

Michael S CHANOWITZ

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

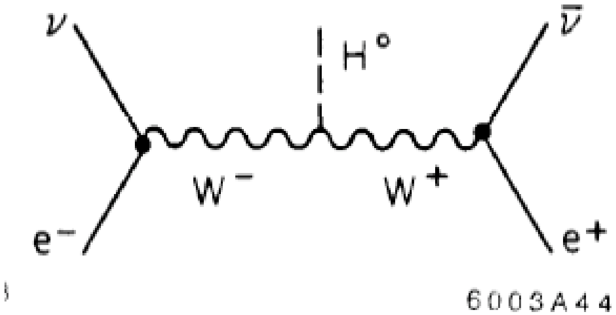
Mary K GAILLARD

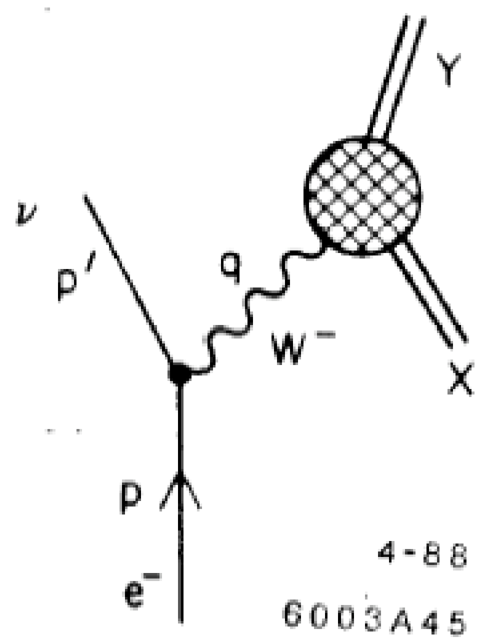
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, USA

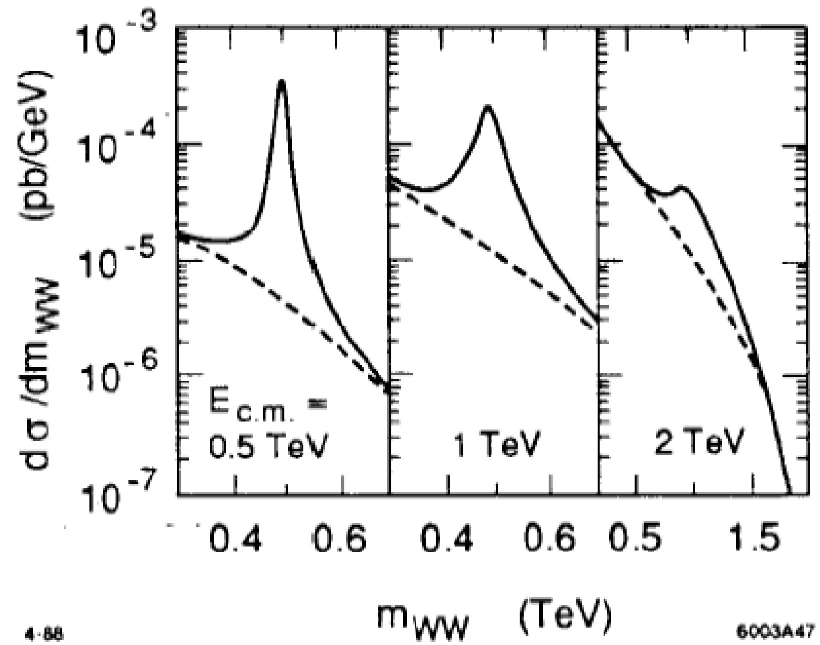
Received 24 June 1985

There are two possibilities for electroweak symmetry breaking either there is a scalar particle much lighter than 1 TeV or the longitudinal components of W and Z bosons interact strongly at center of mass energies of order 1 TeV or more We study the general signatures of a strongly interacting W, Z system and conclude that these two possibilities can be unambiguously distinguished by a hadron collider facility capable of observing the enhanced production of WW, WZ and ZZ pairs that will occur if W's and Z's have strong interactions Detection of the enhanced signal over background requires hadron collisions at a center of mass energy of order $\sqrt{s} = 40$ TeV and an integrated luminosity of order 10^{40} cm^{-2} With these parameters we predict 3800 to 6000 gauge boson pairs satisfying cuts for which only 2600 pairs would be produced in the absence of strong interactions

This was an important theme of my SSI lectures in 1987.
Here are some figures from the lectures:







Dawson

Gunion and
Tofighi-Niaki

Unfortunately, there was a regime that we missed.

SEARCH TECHNIQUES FOR CHARGED AND NEUTRAL INTERMEDIATE-MASS HIGGS BOSONS*

J.F. GUNION

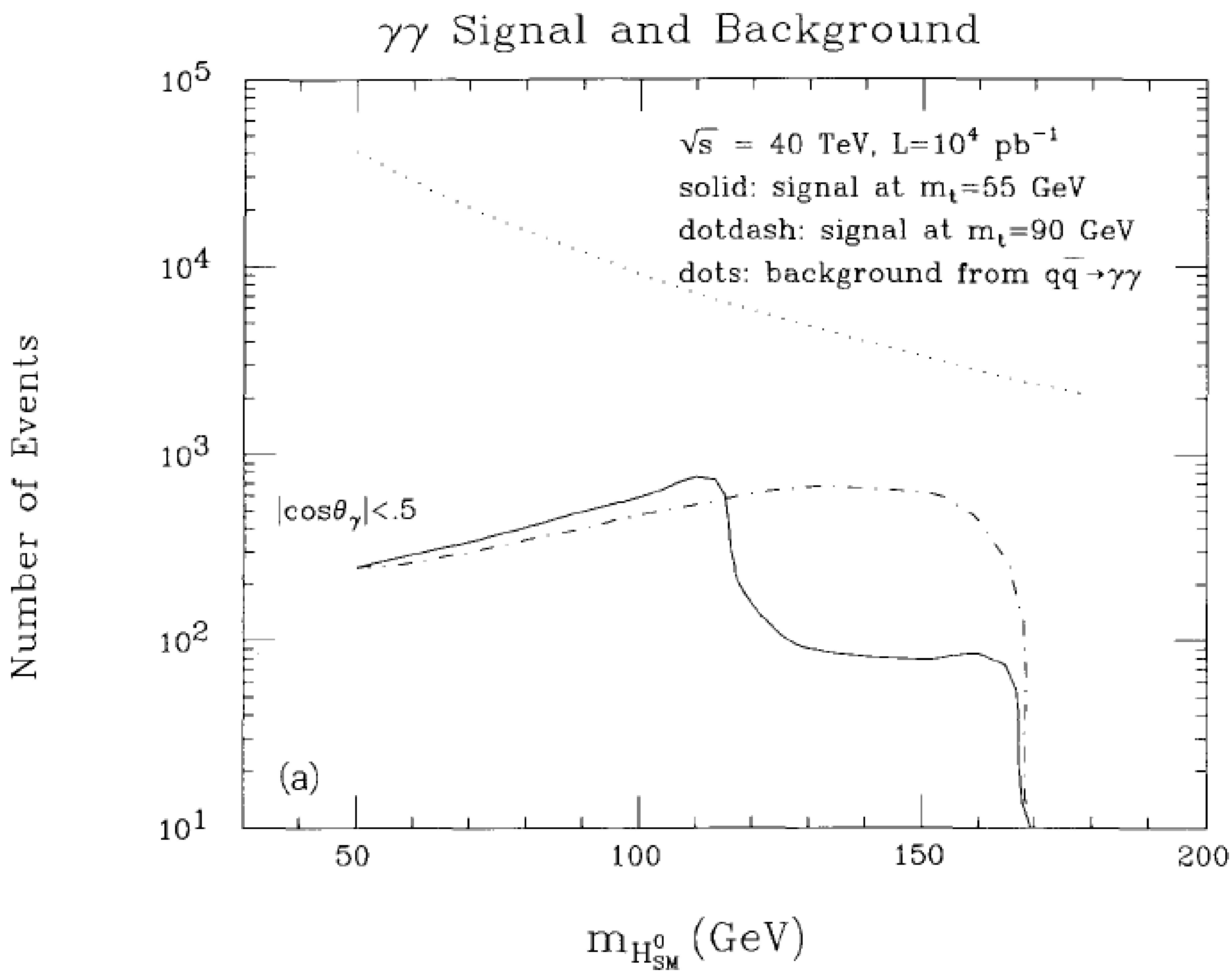
Department of Physics, U.C. Davis, Davis, CA 95616, USA

G.L. KANE and Jose WUDKA

Randall Laboratory of Physics, University of Michigan, Ann Arbor, MI 48104, USA

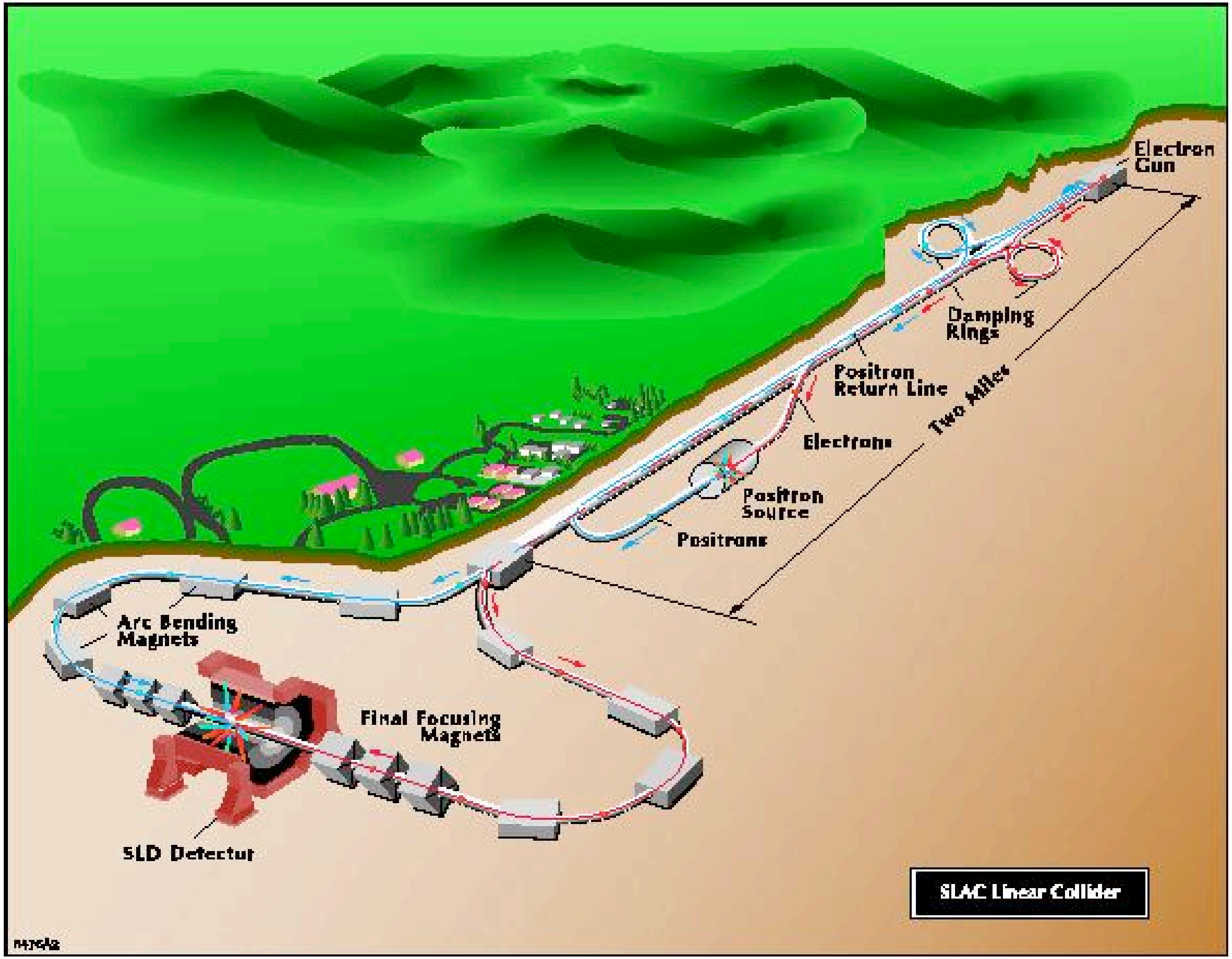
Received 12 October 1987

If fundamental scalar bosons exist, a natural implication of theories based on supersymmetry or superstrings, Higgs boson masses are likely to be of order m_Z within roughly a factor of two. We term this the intermediate mass range. We study how such Higgs bosons could be detected at e^+e^- and, particularly, at hadron colliders. At a hadron collider it appears to be necessary to use rare decay modes of the Higgs boson, and we examine $H^0 \to \gamma\gamma$, $\tau^+\tau^-$, $Z\gamma$, $Z\ell^+\ell^-$, $\Theta\gamma$, and $b\bar{b}$. Since charged scalars also occur in all theories beyond the minimal Standard Model, we examine ways to find the $H^\pm$, concentrating on $H^\pm \to \tau^\pm\nu$, $W^\pm H^0$, $W^\pm H^0\gamma$, $W^\pm\gamma$, and $W^\pm Z$. Because obtaining data about the spectrum of Higgs bosons is so essential, our approach is to ask what facilities would be sufficient to cover the entire intermediate mass range.



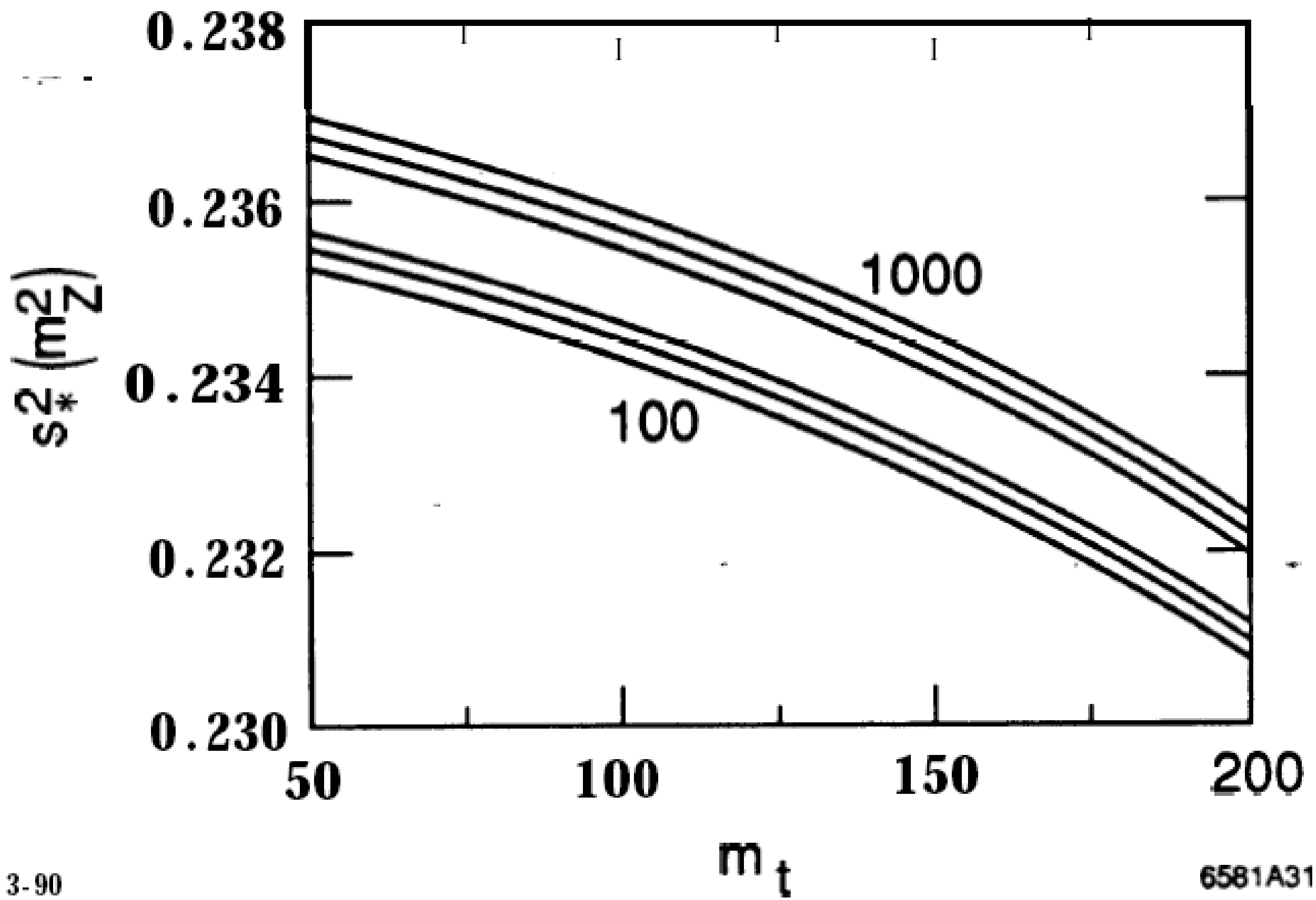
γγ Signal and Background
$\sqrt{s}$ = 40 TeV, L=10^4 pb^{-1}
solid: signal at m_t=55 GeV
dotdash: signal at m_t=90 GeV
dots: background from $q\bar{q}\to\gamma\gamma$
$|\cos\theta_\gamma|<.5$
(a)
Number of Events
10^1
10^2
10^3
10^4
10^5
50
100
150
200
$m_{H^0_{SM}}$ (GeV)

1989 brought the start of the SLC and LEP precision electroweak experiments. Morris Swartz will review these in more detail.

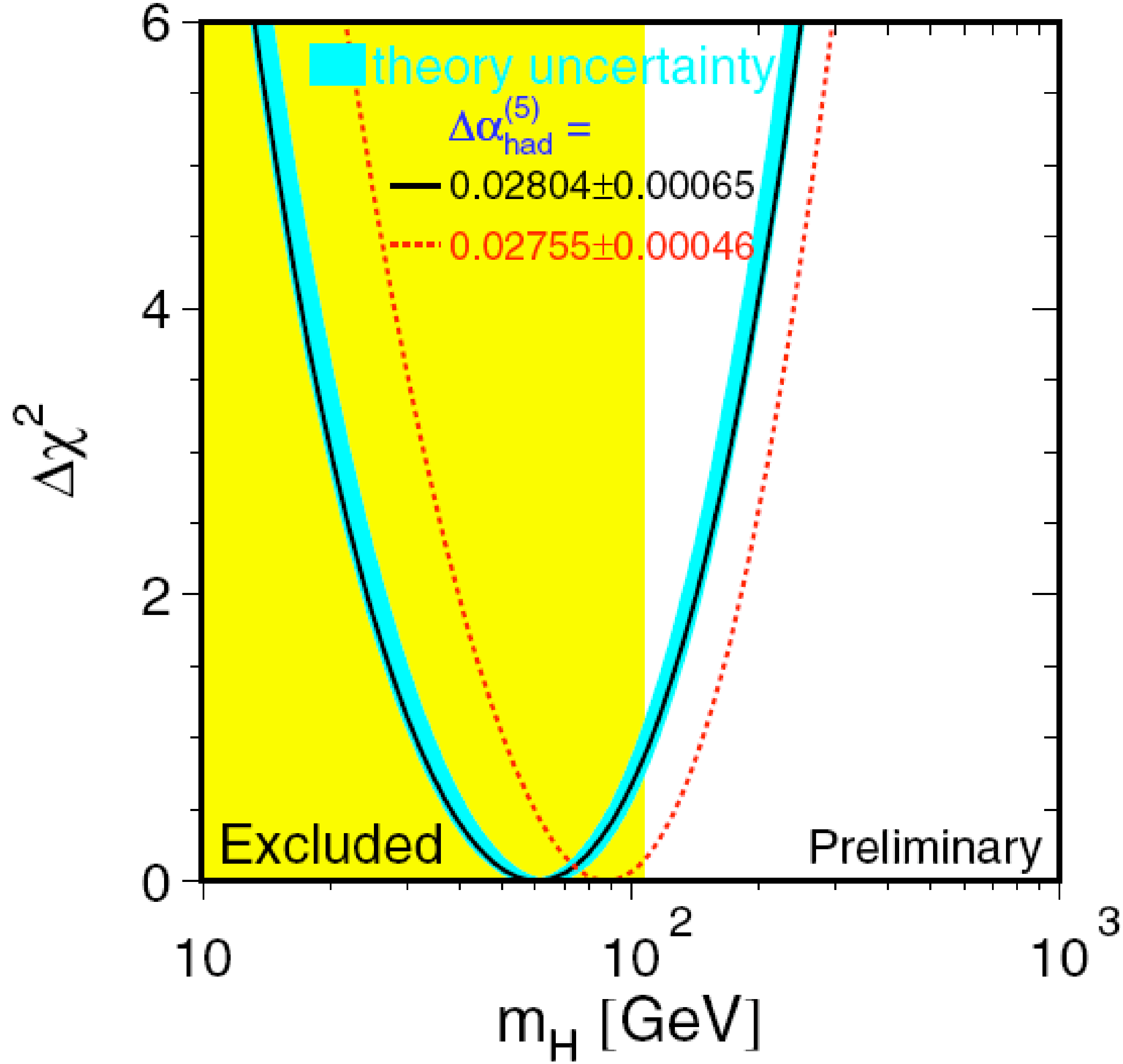


The important point for this lecture is that these precision observables depend signficantly on the Higgs boson mass.

Here is a slide from my 1989 SSI lectures on precision electroweak.

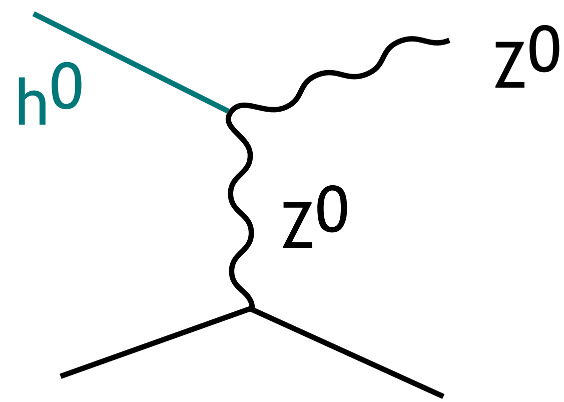


This constraint on the Higgs mass was soon captured by the LEP Electroweak Working Group in their “blueband plot”.

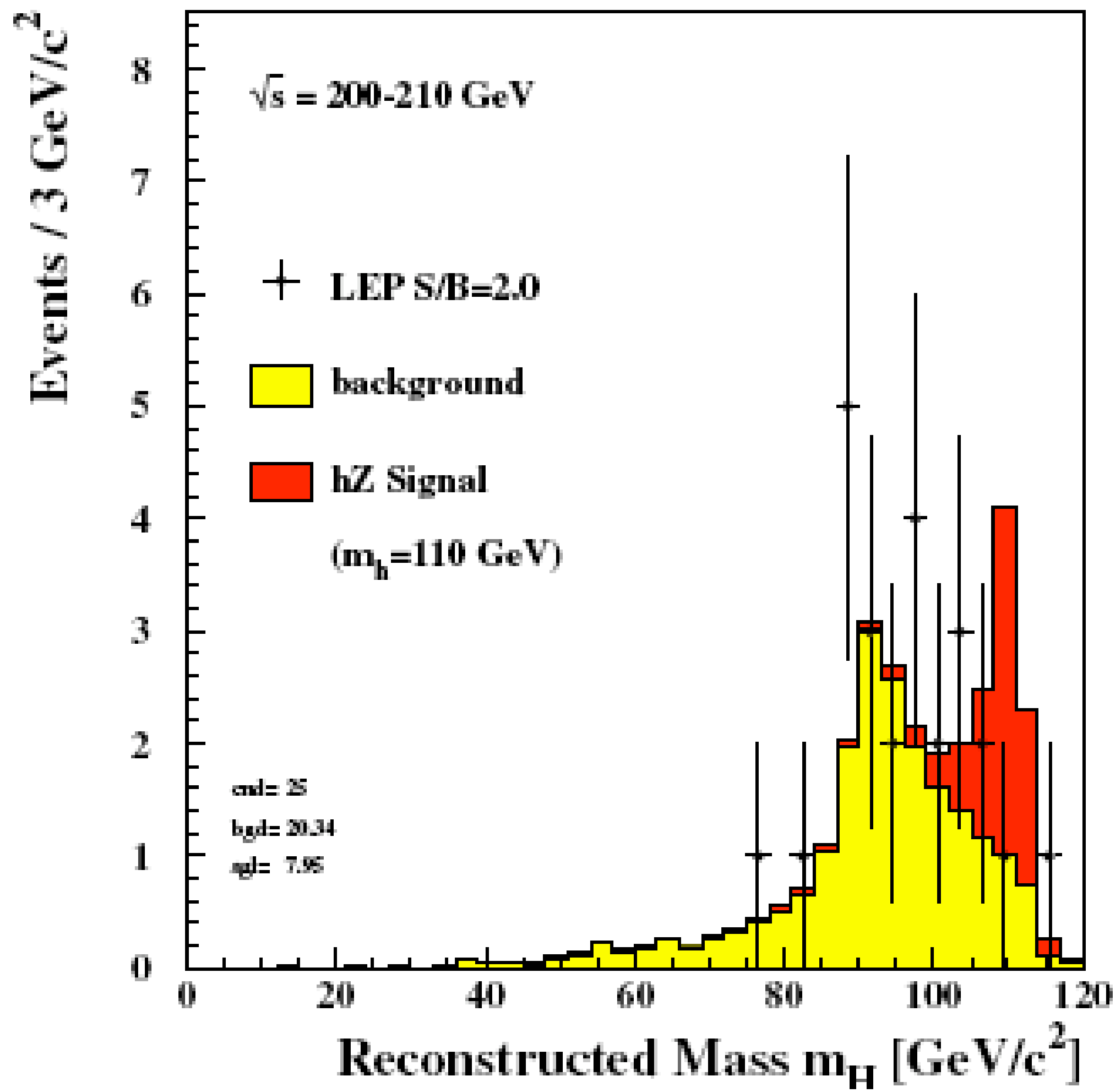


In the late 1990's, as the energy of LEP was raised toward 200 GeV, the LEP experiments became sensitive to Higgs through the process

$$e^+e^- \rightarrow Z^0 h^0$$

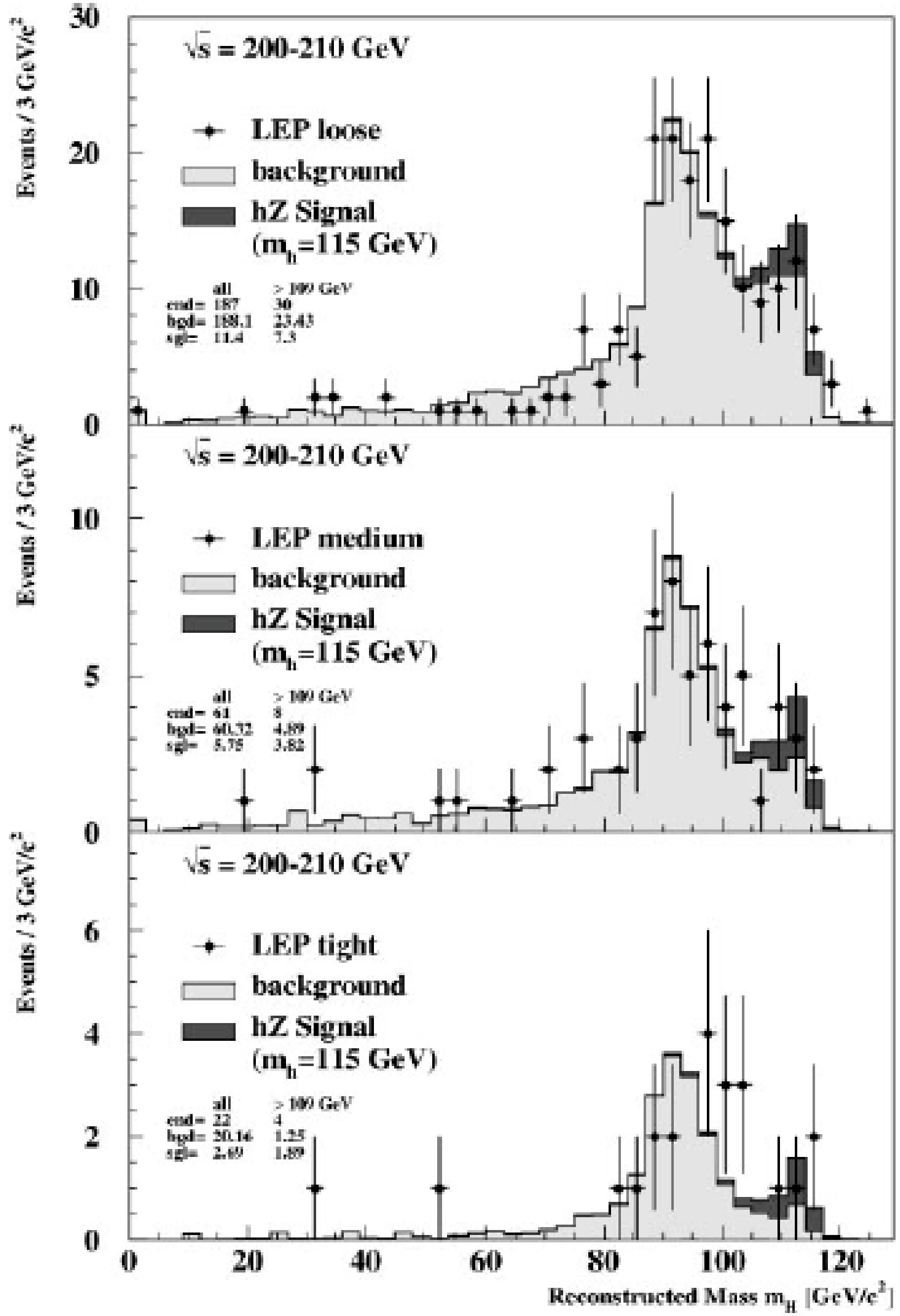


For several years, speakers from LEP would present delicious pictures of Higgs candidate events, always, however, consistent with background.



Chiara Mariotti, SSI 2000

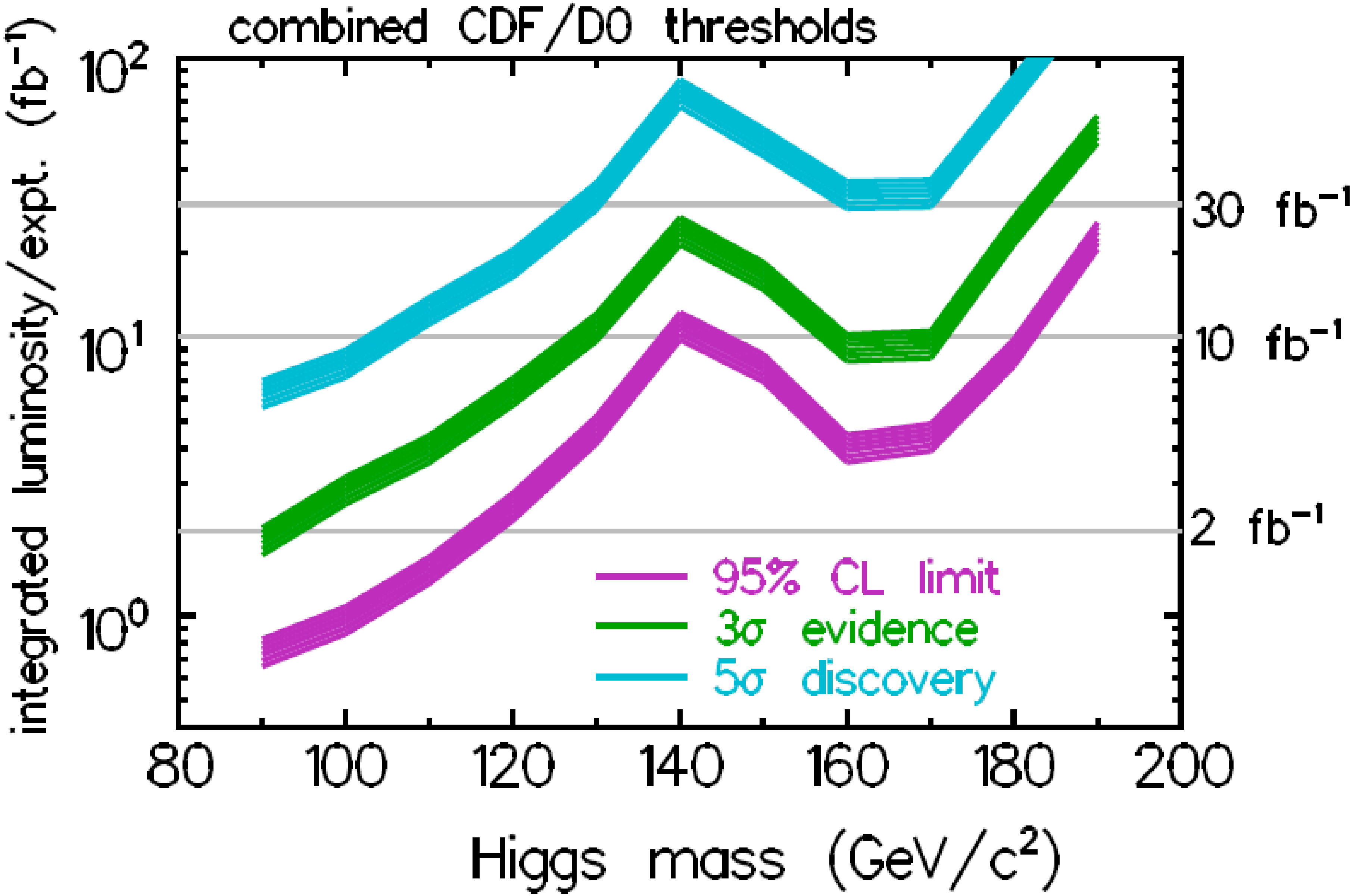
find LEP exclusions, from Kado and Tully, Annual Reviews 2002



This left the search for Higgs, unfortunately, to the domain of hadron colliders.

Report of the Tevatron Higgs Working Group, October 2000

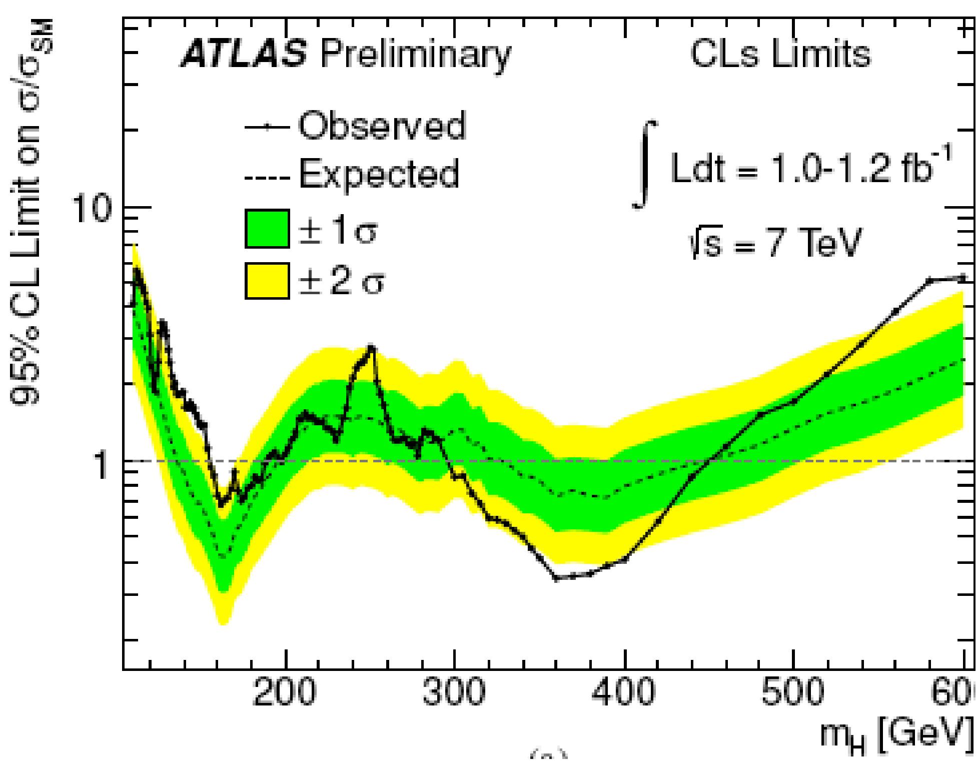
Carena, Conway, Haber, Hobbs, convenors

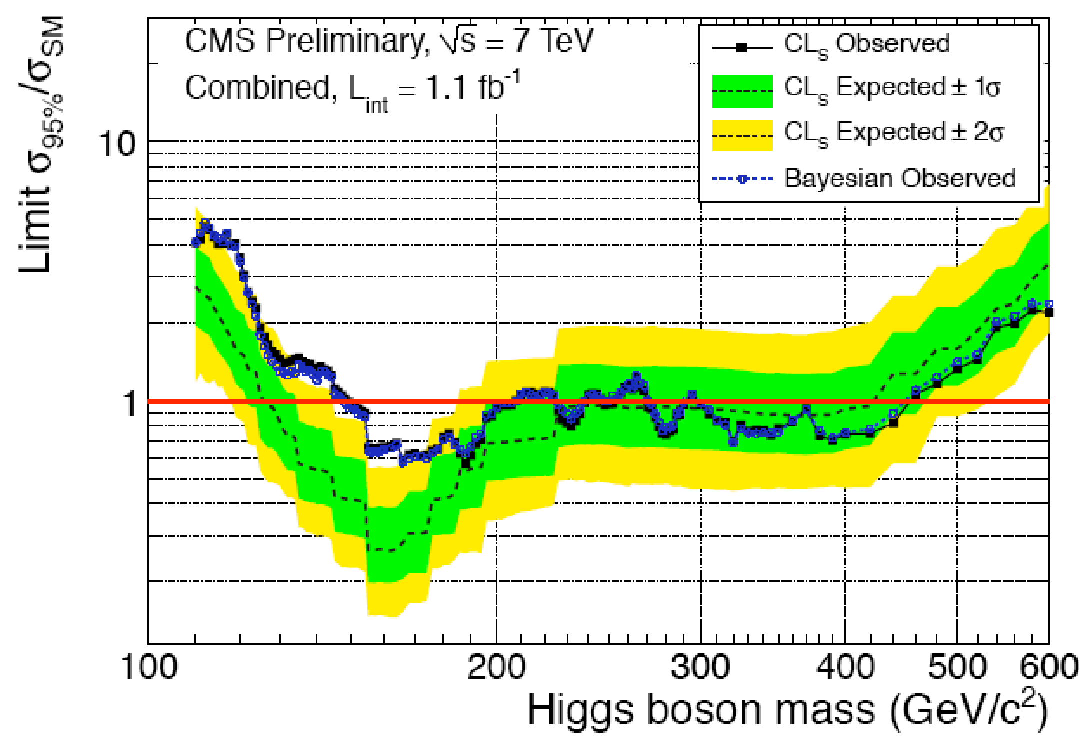


Now we come close to the present time.

The Tevatron Run II had initial difficulties but eventually achieved 10 fb-1/expt.

The LHC finally began its colliding beam run in 2009. By the summer of 2011, ATLAS and CMS had, between bursts of optimism, excluded the Higgs over most of its mass range.





from the Bombay Times August 22, 2011

during Lepton-Photon 2011 in Mumbai

God particle may not exist after all: Experts

A particle believed to have played a key role in the creation of the universe might not exist after all, a media report said on Tuesday quoting experts. Scientists said last month that they were close to cornering the elusive Higgs boson or 'God particle' — a vital element in the construction of life.

fortunately, after July 4, 2012, everything has changed ...

from the Borowitz Report in the New Yorker: July 3, 2012
an interview with the Higgs boson

O.K., be honest, and no false modesty here: Is there anything the Higgs boson can't do?

A: Honest answer? I want to be considered the Michael Jordan of subatomic particles. By that I mean, Michael Jordan might not have been the most physically gifted player in the history of the N.B.A., but nobody worked harder at his game than he did. That's what I'm all about. Whether it's giving mass to matter, breaking electroweak symmetry, or explaining the origin of the universe and whatnot, I believe I can do it all.

After 40 years of theory and simulation, we have now entered the era of Higgs boson experimental physics.

I hope that this lasts another 40 years, giving us unexpected insights into the deep structure of the universe.