Waiting for Higgs - a personal perspective

Chris Llewellyn Smith
Director of Energy Research Oxford University
President SESAME Council

Outline

- Decade of neglect 1964-73
- Moving up the agenda 1973-83
- Big searches - LEP, LHC - to discovery
- Concluding reflections

Early History Highlights
(The Whig/Textbook version)

Theory

1954 Yang Mills

-beautiful idea, but $M_v = 0$

1961 Nambu Goldstone

-beautiful idea, but $M_0 = 0$

1964 Englert Brout, Higgs, GHK, ..

Y-M + N-G $\rightarrow M_v \neq 0$

+ (P H) at least one massive scalar

1967 Kibble - Non-Abelian generalisation

1971 't Hooft - Y-M + Higgs renormalizable

Models

1961 Glashow

- SU(2)xU(1)

1967 Weinberg

1968 Salam-Ward

- SU(2)xU(1) + Higgs

1973 Neutral Currents

Some Details of the Whig History 1

Theory

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"Isotopic Spin and Isotopic Gauge Invariance"

…………

In electrodynamics, by the requirement of electric charge conservation, it is argued that the mass of the photon vanishes. Corresponding arguments in the **b** field case do not exist even though the conservation of isotopic spin still holds. We have therefore not been able to conclude anything about the mass of the **b** field.

A conclusion about the mass of the **b** field is of course very important in deciding whether the existence of the **b** field is consistent with experimental information……

Some Details of the Whig History 2

Theory

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Murray Gell-Mann 1961

The Eightfold way

The vector mesons are introduced in a very natural way, by an extension of the gauge principle of Yang and Mills

Schwinger 1962

Gauge Invariance and Mass

It is argued that the gauge invariance of the vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong. This situation may permit a deeper understanding of nucleonic charge conservation as a manifestation of gauge invariance, without the obvious conflict with experience that a massless particle entails.

Some Details of the Whig History 3

Theory

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1961 Nambu Goldstone

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1964 Englert Brout, Higgs, GHK ..

Y-M + N-G $\rightarrow M_v \neq 0$

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1971 't Hooft - Y-M + Higgs renormalizable

Ancestry:

Heisenberg 1928
Bogoliubov 1947
Ginzburg & Landau 1950
Nambu 1960

Anderson 1963 noted that in a superconductor the Goldstone mode becomes massive because of its e-m coupling, and that this effect also renders the photon massive:

The Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang-Mills zero-mass problem

Some Details of the Whig History 4

Theory

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1964 Englert Brout, Higgs, GHK ..

Y-M + N-G $\rightarrow M_v \neq 0$

+ (P H) at least one massive scalar

1967 Kibble - Non-Abelian generalisation

1971 ‘t Hooft - Y-M + Higgs renormalizable

Differing motivations

Schwinger - local baryon number conservation without $M_v = 0$

Englert, Brout – avoid $M_v = 0$

Higgs, GHK avoid $M_0 = 0$

How to understand approximate hadronic symmetries?

Some Details of the Whig History 5

Theory

1954 Yang Mills

-beautiful idea, but $M_v = 0$ **??**

1961 Nambu Goldstone

-beautiful idea, but $M_0 = 0$

1964 Englert, Brout, Higgs, …

Y-M + N-G → $M_v \neq 0$

+ (P H) at least one massive scalar

1967 Kibble - Non-Abelian generalisation

1971 ‘t Hooft - Y-M + Higgs renormalizable

"It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons. It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields."

- *Technicolour!!*

1966 Veltman - Divergence conditions: Studying scattering of real or hypothetical vector bosons → most results of current algebra without Schwinger terms

Quantization rules, ghosts, gauge invariant regularization… ….

Some Details of the Whig History 6

Theory

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Models

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- SU(2)xU(1)

1967 Weinberg

1968 Salam-Ward

-SU(2)xU(1) + Higgs

1970 GIM (Bj & G 1964)

1972 – Heavy leptons, as well or instead of neutral currents?

1973 Neutral Currents

Why Neglect?

Big questions in the 60s:

Nature of hadrons (bootstrap?)

Nature of strong force?

Nature of weak interactions??

Attention mostly on hadrons/strong force, SU(3)?, bootstrap..

Theorists 'forming groups or dispersing', or working on Regge, current algebra,..

Quarks: born 1964, **but** only taken seriously by very a small minority

Distractions – relativistic combination of internal and space time symmetries

Yang Mills - only in Schweber (1961) as reference for 'e-m gauge invariance of the second kind'. No mention in Bjorken & Drell (1964/5)

Doubts about field theory:

G Chew "Field theory, like an old soldier, will not die but simply fade away…"

Deep inelastic scattering claimed to indicate that 'nature reads books on free field theory'

HIGH-ENERGY NEUTRINO-NUCLEON SCATTERING, CURRENT ALGEBRA AND PARTONS

David J. GROSS * and C. H. LLEWELLYN SMITH
CERN, Geneva

Received 11 July 1969

— — — — —

A serious objection has been raised to the use of the Bjorken limit to derive sum rules such as eqs. (11) and (17) by Adler and Tung [14], and by Jackiw and Preparata [15]. They show that the Bjorken limit breaks down, and the resulting sum rules are untrue in second-order perturbation theory. However, there is no reason to assume that perturbation theory is relevant to the discussion of high energy behaviour. In particular, in second-order perturbation theory all the limits,

$$\lim_{q^2 \to \infty} F_i(q^2, \omega)$$

are infinite, due to logarithmic factors log q^2/m^2. Even when these are removed the sum rules given by eq. (11) diverge. In the case of electron-nucleon scattering, this contradicts experiment. Thus, the real world seems to be less divergent than perturbation theory indicates.

Alternatively, one can say that the sum rules are certainly correct (and trivial) to lowest order in perturbation theory (no interaction). If, as is suggested by the 'parton' model, leptons, at high energies and large momentum transfer, interact with hadrons as if the latter were bare particles, then the sum rules could be valid. This is certainly the case in the parton model for the relations (15) and (16).

Moving up the Agenda

Discovery of neutral currents did not clinch matters –

- doubts about initial claim
- data only converged on SU(2)xU(1) at end of 1980

Big doubts about standard model sown by first (late 1994) **SPEAR data** (charm threshold mistaken for constant cross section)

Meanwhile:

Higgs necessary as well as sufficient

First systematic study of Higgs phenomenology

1976 discovery of charm – SM could be right!

1978 LEP Summer Study – Higgs a highlight

1983 discovery of W and Z. NY Times "Europe 3 - US Not Even Z-Zero". S M → orthodox

1973 Higgs necessary as well as sufficient

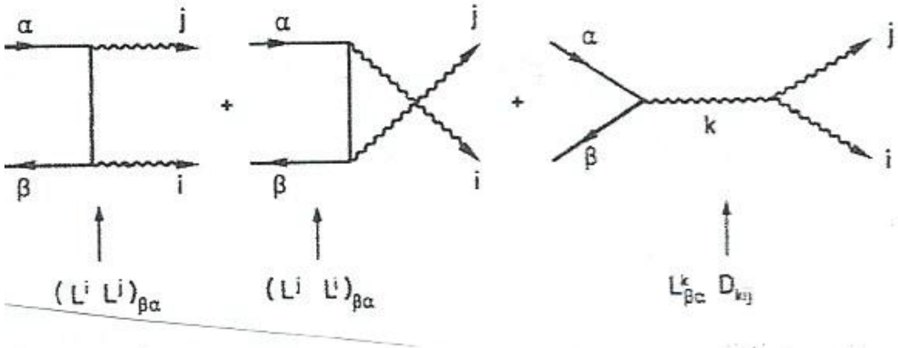
Proof that (apart from the U(1) case) the only theories with massive vector bosons in which amplitudes are 'well behaved' order by order at high energy*, are gauge theories with masses generated by the Higgs mechanism

* A condition known to be intimately connected to renormalizabilty

Consider now $F\bar{F} \to WW$. Given that the 3W vertex has the Yang-Mills form, the leading (E^2) pieces cancel if and only if the coupling constants represent a Lie algebra [5, 6]:

$$[L^i, L^j] = iD_{ijk}L^k, \qquad [R^i, R^j] = i\,D_{ijk}R^k. \qquad (4)$$

The relevant diagrams are shown in fig. 1, where the



origin of each term is indicated for the case of left-handed leptons. Non-leading ($\sim E$) terms necessarily remain unless either all fermions are massless or all fermions in a given irreducible multiplet are degenerate and parity is conserved [this can be inferred from eq. (6) below], which would not be interesting for physics. Additional particles must therefore be exchanged and, if we wish to avoid the vicious problems associated with particles with spin $\geqslant \frac{3}{2}$, they must have spin zero† 5 . .

First Systematic (49 Pages!) Look at Phenomenology

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [lo] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [111 model, and experimental lower limits [1 Z-14] on its mass are around 15 MeV, piffling compared with the intermediate vector boson masses expected to be O(50 to 100) GeV.

Ellis, Gaillard and Nanopoulos cont..

Most of this paper is phenomenological, however, and we discuss ways of looking directly for the Higgs boson, pushing the experimental lower mass limit up to a few hundred MeV or a few GeV.

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

LEP Summer Study 1978

Extracts from theoretical summary talk **'e+e- Physics Beyond PETRA Energies'** (CHLIS)

Note: LEP approved 1981

8) Beyond the W; Higgs?

The interactions of vector bosons (W's and Z's) and fermions are well-behaved when the couplings are those of a gauge theory. However, there is still a residual sickness which shows up, for example, in W W scattering for which the lowest order Feynman diagrams are shown in fig. 10. With arbitrary couplings (with dimensionless coupling constants) the amplitude for longitudinal W's grows like $E^6_{c.m}$; with gauge theory couplings this is reduced to $E^2_{c.m.}$ – still two powers faster than allowed by unitarity as $E_{c.m.} \to \infty$ [26]. In a well-behaved renormalizable theory which can be treated perturbatively there must be some new ingredient which cancels the $E^2_{c.m.}$ term. This is provided by the exchange of a spin zero Higgs meson (fig. 11).

. . . . . .

. . . . . . in fact unitarity is violated unless[27)]

$$M_H < \frac{8\pi\sqrt{2}}{3G_F} \simeq 1.2 \text{ TeV.}$$

Presumably, therefore, unless M_H is small compared to 1.2 TeV there will be large corrections to the lowest order diagrams, e.g. there will be big final state interactions in $e^+e^- \to W^+W^-$ and the diagrams in fig. 3 will not give the right answer.

LEP Summer Study 1978 (cont.)

It is hard to be precise about the critical mass/energy but clearly this is a powerful argument for pushing for the highest possible energy at LEP.

The reason for the intense theoretical interest in the Higgs sector (or whatever piece of theoretical ignorance it parameterises[29]) is that it is intimately connected with the fundamental problem of the mass spectrum of elementary particles, their mixing angles and CP violating phases. In the unbroken theory, the vector bosons are massless and members of fermion multiplets are degenerate (being also massless in most models). The coupling to Higgs mesons induces symmetry breaking and generates the mass spectrum - if we understood the Higgs sector we would understand the origin of mass!

LEP Summer Study 1978 (cont.)

The decays $Z \to H\mu\bar{\mu}$ and $Z \to He\bar{e}$ (fig. 13) provide a way to search for H.

With $M_Z \sim 90$ GeV,

$$\frac{\Gamma(Z \to He\bar{e})}{\Gamma(Z \to e\bar{e})} \sim 10^{-3} \text{ for } M_H = 10 \text{ GeV}$$

$$\sim 10^{-5} \text{ for } M_H = 50 \text{ GeV}$$

(see ref 34). Given the huge rate on the Z^0 pole, this should provide a way to find H if $M_H \lesssim 45$ GeV.

At high energies the cross-section $e\bar{e} \to ZH$ is substantial. The ratio

$$\frac{\sigma(e\bar{e} \to ZH)}{\sigma_{point}}$$

is about one at $\sqrt{s} = 140$ Gev for $M_H < 50$ GeV (dropping very rapidly for $M_H > 50$) and about 0.5 at $\sqrt{s} = 200$ GeV for $M_H < 90$ GeV (dropping very rapidly for $M_H \gtrsim 90$)[35)]

Final LEP 1 limit – 65.6 GeV

LEP Summer Study 1978 (cont.)

4) What questions will remain unanswered when LEP is available?

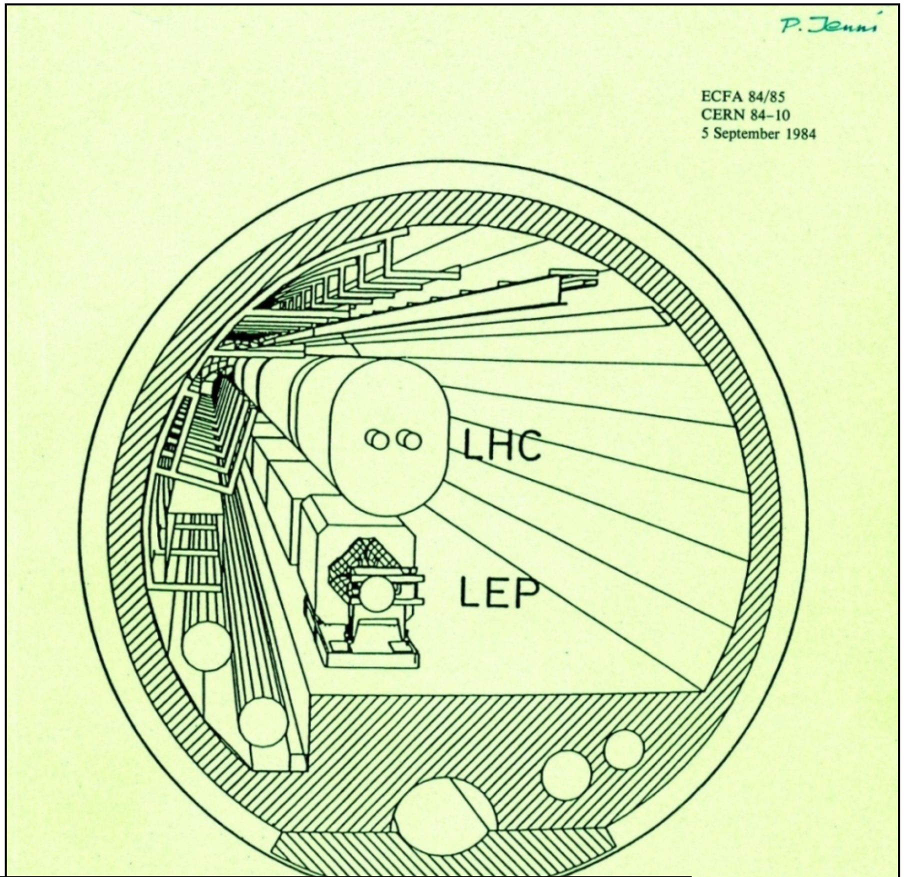
It seems clear that experiments at PETRA (and PEP) will teach us a great deal more about the neutral current. However, although ungraded versions of PETRA and PEP should give hints about the mass scale on which the predictions of L_{eff} are modified, they will not answer the most essential questions about weak interactions at high energy. Experiments at these machines may also discover new flavours of quarks and leptons (there certainly seems to be a good chance that PETRA will discover the top quark - but I know of no theoretical predictions of its mass and the discovery may have to wait for LEP) and they can make many tests of QCD. !

Either the $p\bar{p}$ collider or Isabelle should discover the $Z,^0$ but apart from measuring its mass (with considerable errors) they will not allow us to investigate its properties in detail (they may also discover the $W^\pm$ but this looks more difficult).

It therefore seems certain that LEP will be needed to study the behaviour of weak interactions at high energy. Presumably LEP will also be needed to extend our knowledge of the spectrum of quarks and leptons.

For the experimental community "it all started with the CERN – ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel"

This workshop was organized in preparation for the 1984 ICFA workshop at KEK, which witnessed a big SSC-LHC shoot out



CHAPTER I

THE PHYSICS CASE

Physics with a Multi-TeV Hadron Collider

C.H. Llewellyn Smith

11. SUMMARY AND CONCLUSIONS

A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

Lausanne Workshop (cont.)

PHYSICS WITH A MULTI-TeV HADRON COLLIDER

C.H. Llewellyn Smith,

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1. INTRODUCTION

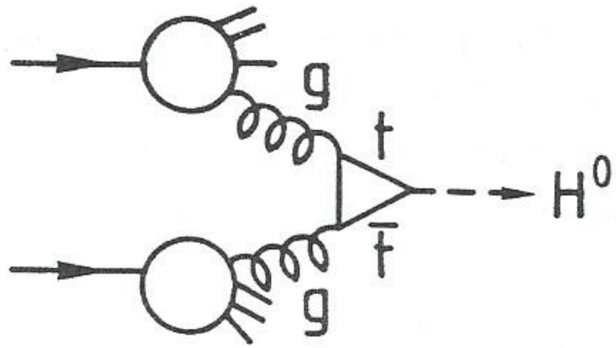
A large hadron collider (LHC) has always seemed an obvious option to follow LEP and it is clearly becoming time to start R and D on suitable magnets. It is less clear that it is sensible to discuss the physics which might be studied with such a machine without more complete results from the SPS collider, let alone data from LEP, SLC and HERA. All we can do is identify the questions which seem most pressing now and ask how they could be addressed by experiments at an LHC, whose centre of mass energy we take to be 10 to 20 TeV. This crystal gazing is unusually hazardous following the recent tantalizing hints of new discoveries from UA1[1)] and UA2[2)], which remind us that it runs the risk of rapid redundancy.

Lausanne Workshop (cont.)

7. HIGGS BOSONS

Extensive studies of Higgs boson production were reported at Lausanne[15,16] which lead to the conclusion that discovering a conventioanl heavy Higgs boson will be difficult even at 20 TeV., the energy we assume in the following discussion. Four mechanisms have been investigated:

1. Gluon fusion:[17]



… 1 ½ pages on Higgs phenomenology, 2 pages on SUSY,…..

1991: 1st Complete Presentation of the LHC to the CERN Council at a special open session. I presented the scientific case, as Chair of the SPC:

- Further progress needs higher energy – 1 TeV is next major goal
- Proton-proton collisions are the only open road to 1 TeV now
- LHC – most cost effective route
  – heavy ion and ep collisions as bonus

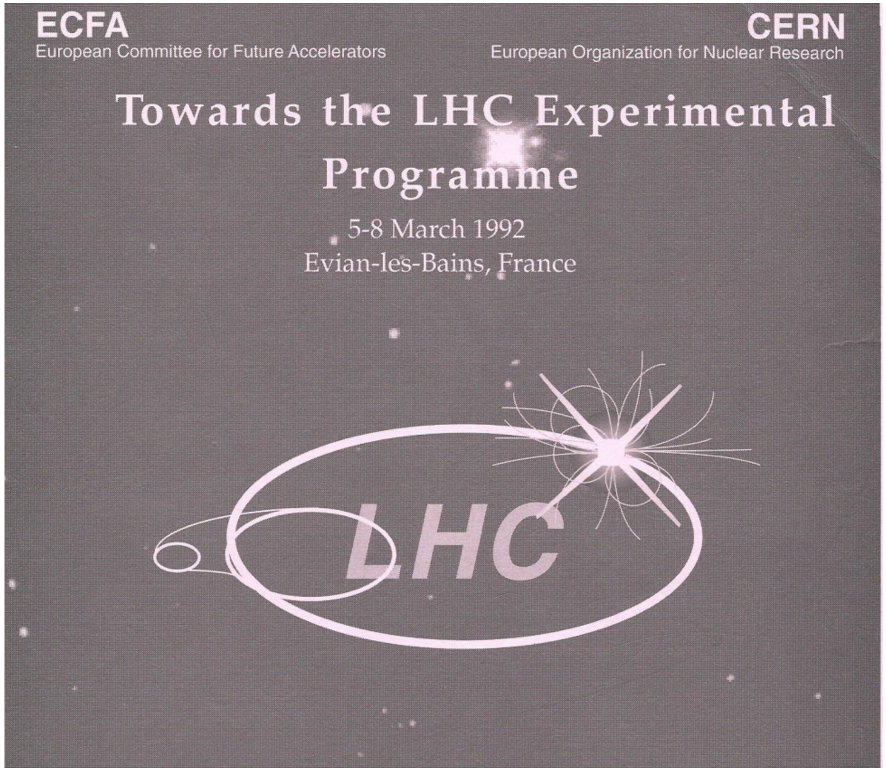
> LHC must be the next project for CERN

Council concluded: 'LHC is the right machine for the advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia + Chair of Council Bill Mitchell) **and asked** for more detailed information on the project before the end of 1993 "so that Council may move towards a decision on the LHC"

Foundations of the Experimental Programme Laid at 1992 Evian Meeting

My introductory talk ‘Physics with proton beams’ contained 24/40 slides on Higgs –’instructions from the organisers/ benchmark process’

Presentations by CMS, and by EAGLE and ASCOT – soon after merged to form ATLAS’



Aside (1): Statement by Mr William Waldegrave (UK Minister at office of Public Service and Science) 20 April 1993:

It would be easier to win money for research if taxpayers and Ministers understood the scientists' quest. To provide a little spurt of this, I will offer a bottle of vintage champagne (at my own expense) to anyone who can write down on a single sheet of A4 paper, what the Higgs boson is and why you would like to find it.

Aside (2): Private letter from an official at the Science and Engineering Research Council

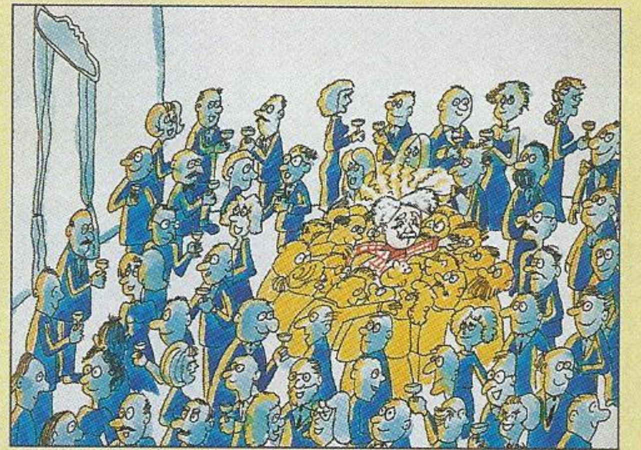
It is a prime example of the English problem (not ‘British’): can you envisage a similar jocular challenge requiring a one-page answer on, say, Shakespeare's historiographical debt to Plutarch? No, of course not. Gentlemen are expected to have a natural grasp of that sort of thing. On our scale of social values, it is the Higgs, the carburettor and the tap-washer that are defined as arcane and the natural province of some other sector of the population.

Illustration of the Winner* (David Miller)

How the Higgs Field Generates Mass

"Empty" space, which is filled with the Higgs field, is like a roomful of people chatting quietly.

A particle crossing that region of space is like a celebrity arriving …



… and attracting a cluster of admirers who impede his progress—he acquires "mass."

How Higgs Particles Are Created

Energy from a particle collision can be like a rumor crossing the room …

… creating a similar cluster that is self-sustaining, analogous to a Higgs particle itself.

* Scientific American version. In the original version of the cartoon, the celebrity was Mrs Thatcher

Aside (4): Letter to the Daily Telegraph 24/4/93

I observed with interest that William Waldegrave, the Public Service Minister, is offering a bottle of vintage champagne to anyone who can tell him what and where is the Higgs Boson. He should be asking who?

I knew Higgs well when serving as a deckhand on the China seas in the 1920s. Born in County Clare of Franco-Irish parents, he was christened to his enormous chagrin Amadee Maria and ran away to sea at the age of 13 to escape the derision of his schoolmates.

There, to conceal his hated given names and having ambitions to personal preferment, he gave his first name as ‘Bosun’, his strong Irish accent giving exaggerated emphasis to the second vowel, and so it was is duly entered in the books as Higgs Boson, which nomenclature remained with him throughout his long and eventful career in the Far East where he did eventually attain the coveted title of Bosun. Sad to relate he was killed by pirates in the Celebes in about 1930. I trust this brief account will put Mr Waldegrave's mind at rest.

December 1993

Presentation of a proposal to build the LHC in the context of a complete long-term plan for CERN (preparation and presentation delegated to me by C Rubbia)

“The LHC will provide unique insights into the nature of matter and the structure of the universe, and ensure that CERN maintains a leading position in the decades to come.”

LHC Proposal (cont.)

3) There are compelling arguments that, beyond the ranges currently being studied at LEP and at the proton-antiproton collider (Tevatron) at Fermilab, fundamental new physics will appear in the domain of energy that will be opened up by the LHC *(II)*. A high-luminosity proton-proton collider is currently the only realistic choice for exploring this energy domain, and LHC is now the only possibility for such a collider after the cancellation of the SSC. A high-energy electron-positron collider would be appropriate for detailed studies above any previously-identified energy threshold for new physics, once the technology to build such a machine is available.

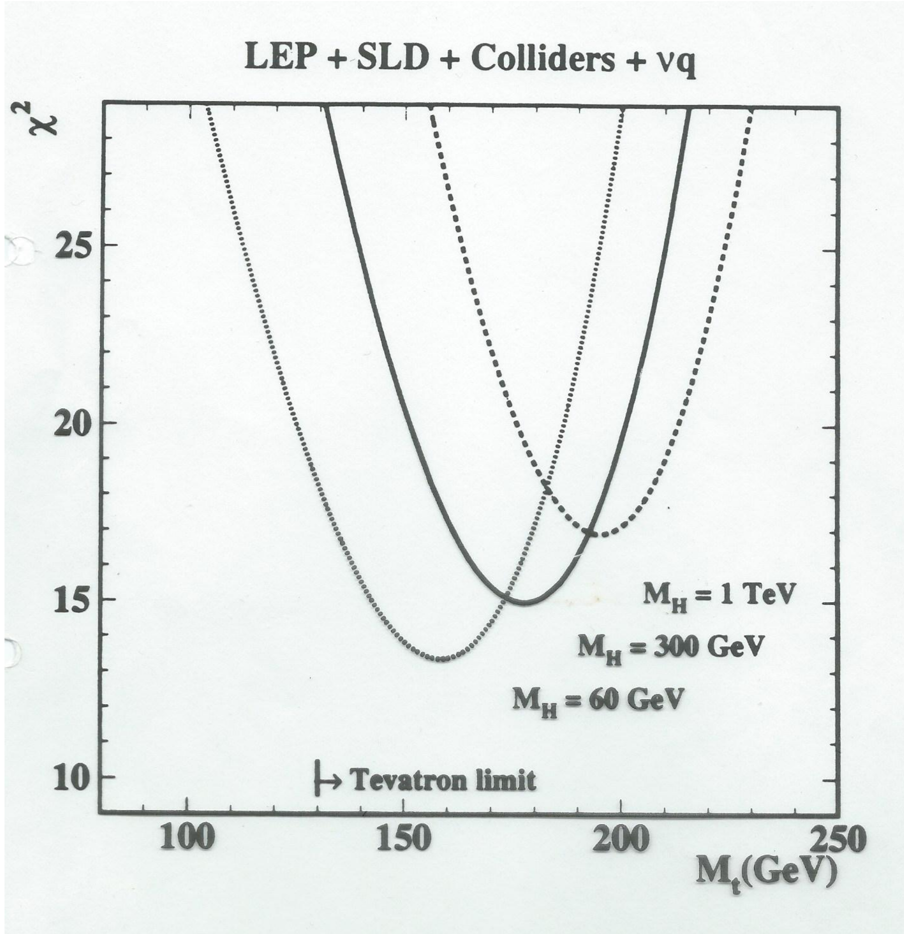
4) The LHC *(II* and *III)* will be the centrepiece of the CERN programme in the first two decades of the next century. It will provide an unparalleled "reach" in the search for new fundamental particles and interactions between them, and it is expected to lead to new, unique insights into the structure of matter and the nature of the Universe *(II)*. Studies of proton-proton collisions at LHC will provide the opportunity to find the so-called Higgs boson, or bosons, and thus should answer the question why some particles are massive while others are not. These experiments should find "supersymmetric" particles, if they exist, thereby revealing a

More colloquially (Scientific American, July 2000)

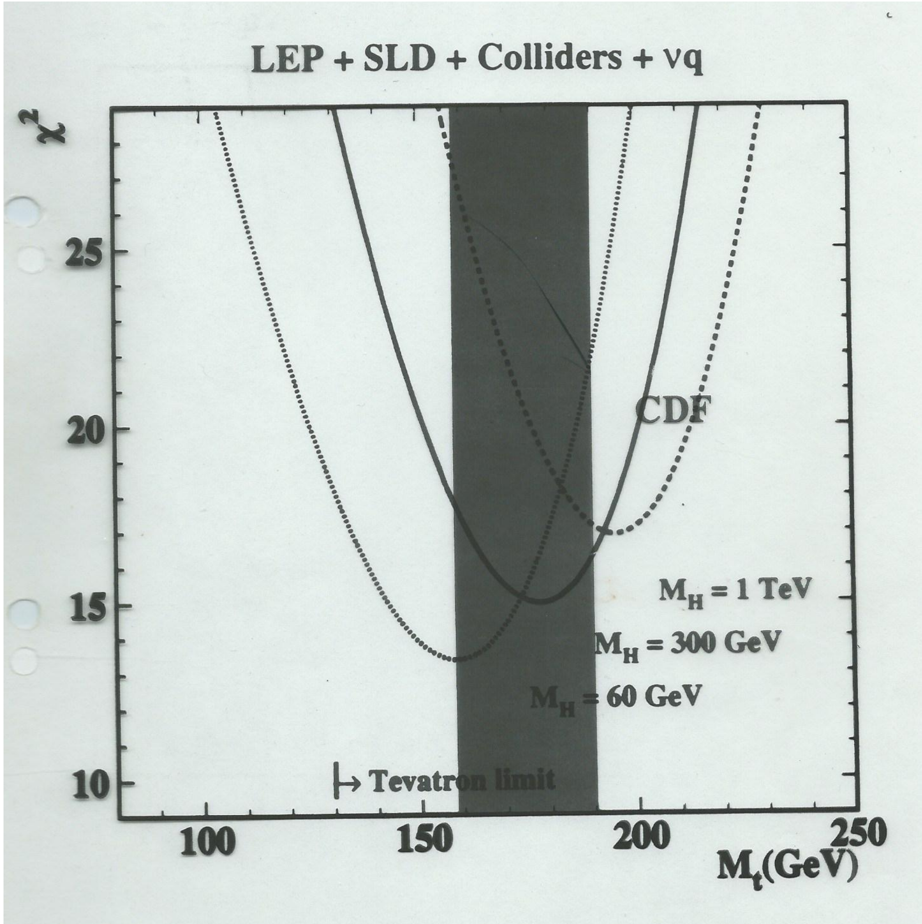
“The LHC’s projectiles will penetrate even deeper into the heart of matter, down to 10^{-19} metre. This alone would be enough to whet scientific appetites, but pulses are really set racing by compelling arguments that the answers to major questions must lie in this new domain that the LHC data will illuminate”.

The CERN Council set tough conditions and asked for further economies. Meanwhile science moved ahead:

Fit to precision data March 1994



Fermilab top quark range April 1994



December 1994

After very tough negotiations the Council approved the LHC*

- for construction in two stages, with the condition that ‘any contributions form non-Members with be used to speed up and improve the project, not to allow reductions in the members Sates’ contributions’ (a pledge which was not kept)

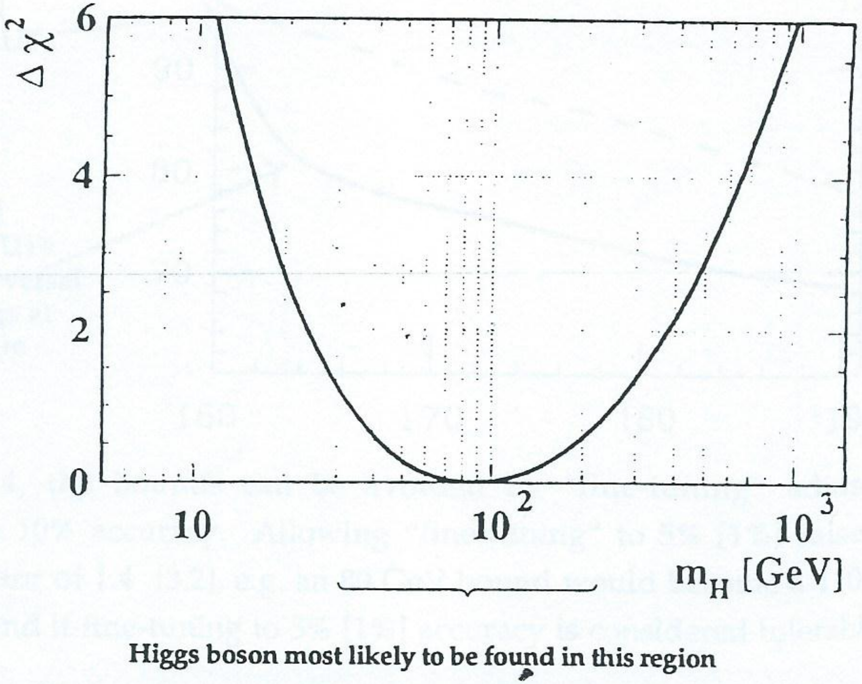
* For the political battle (1994-98) see Nature 281, 448, 2007

" . . . and we can save 700 lire by not taking soil tests."

In December 1995, the CERN Council (although very nervous of new initiatives following the approval of the LHC) accepted a proposal to add more superconducting cavities (32 new + equip 16 spares) on the grounds that 1) this would provide a good chance of finding the Higgs boson

Various experimental and theoretical considerations support the *a priori* guess that the Higgs boson might be in the region that could be explored by LEP2 operating at 192 GeV. First, precision data from LEP and other facilities are sensitive to the mass of the Higgs boson through "virtual" processes. These are processes in which, utilising the quantum mechanical possibility of "borrowing" energy for infinitesimal time intervals as allowed by Heisenberg's uncertainty principle, Higgs bosons can be temporarily emitted – even if this violates energy conservation – and then reabsorbed. This subtle effect has a small influence on the real processes that are observed, and the data therefore can be analysed to determine M_H within errors, which however are large since the effect is small. This determination is represented in terms of a quantity called $\Delta\chi^2$ shown in Figure 1.

Figure 1 - The existing data are indirectly sensitive to the mass of the Higgs boson (M_H). The figure shows the quantity $\Delta\chi^2$ obtained from a fit to the best available data. The Higgs boson is most likely to be found in the region where $\Delta\chi^2$ is smallest



The most likely value of M_H is at the minimum of $\Delta\chi^2$ which is in the LEP2 region, although it should be cautioned that there is a 32% [5%] probability that the Higgs mass is in the region where $\Delta\chi^2$ is greater than 1 [4]. It is worth noting that a similar analysis was used by CERN to successfully predict the mass of the top quark (m_t) before it was observed in a real process – see the Director-General's Status Report for 1994 (CERN/2079).

and 2) a good chance of finding SUSY

Supersymmetry

Supersymmetry connects fermions ("constituent particles") to bosons ("force carrying particles") and is aesthetically very appealing, as well as perhaps being required to underwrite the stability of the Standard Model. When combined with the equally appealing idea of "grand unification" between the nuclear and electroweak force, supersymmetry successfully explains the strength of the nuclear force – see Figure 2 – and must therefore be taken very seriously.

• • • •

If supersymmetry is correct, electrically charged supersymmetric particles ("charginos" or "sleptons") must exist which could be discovered by LEP2. In fact, a class of attractive grand-unified supersymmetric models leads to the expectation that charginos lie in the LEP2 region, as shown in Figure 4.

In Figure 4, the bounds can be avoided by "fine-tuning" adjustable parameters to 10% accuracy. Allowing "fine-tuning" to 5% [1%] raises the limits by a factor of 1.4 [3.2], e.g. an 80 GeV bound would become a 110 GeV [250 GeV] bound if fine-tuning to 5% [1%] accuracy is considered tolerable.

Conclusion

The above arguments should be treated with due caution as they are rather theoretical in nature and depend on a number of assumptions and hypotheses which, while plausible, have not been tested. Nevertheless, they show that the completed LEP2 will have a spectacular discovery potential, and that, at the least, completion of the LEP upgrade will provide significant tests of leading models, and ensure a comfortable and safe overlap of the capabilities of LEP and the LHC

December 1996: Single Stage Construction of LHC Approved

- albeit accompanied by cuts in the budget (after an onslaught from Germany and the UK)

(see Nature 281, 448, 2007 for the politics)

June 1998

Council agreement to run LEP for an additional year (2000)

4.— CONCLUSIONS

The scientific case for operating LEP in the year 2000 is very compelling. The extra energy that will be available in 1999 combined with an additional year of operation would increase very significantly the exciting prospect of discovering a Higgs boson,[1] which would unblock progress to a deeper understanding of nature, and/or supersymmetry, which would radically alter our view of the microstructure of matter. An early decision is very desirable for *i)* CERN, in order to allow the planning that is needed to minimise the costs and optimise the overall use of CERN's resources, *ii)* the outside funding agencies that support the LEP experiments, and *iii)* the scientists involved.

Member States and non-Member States that are willing to consider making additional contributions to allow the operation of LEP in the year 2000 are asked to inform the CERN Management as soon as possible.

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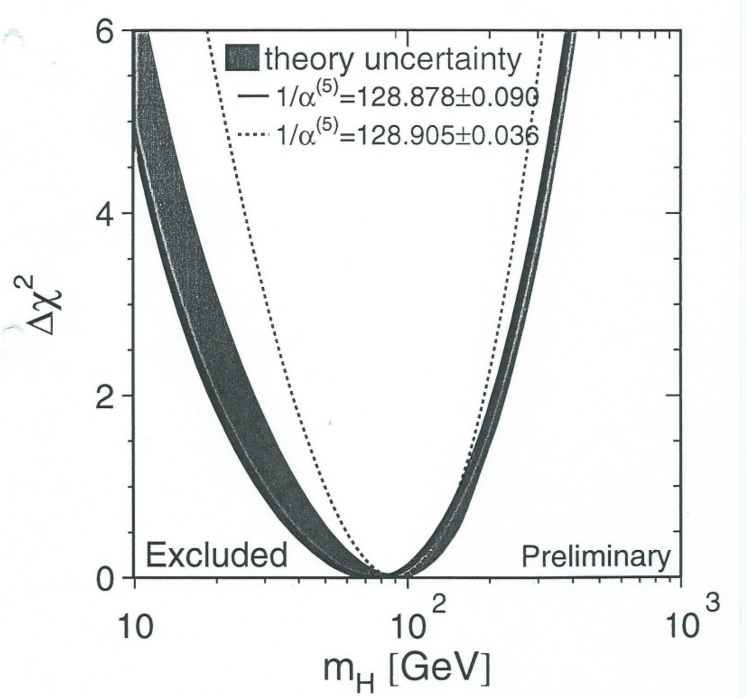
1 The discovery of a Higgs boson, or of supersymmetry, at LEP would strengthen the case for the LHC. In the absence of any new physics ("beyond the Standard Model") below the ("Planck") energy scale where the effects of quantum gravity become important, the Higgs boson must have a mass *greater than* 130 GeV. Discovery of a Higgs boson at LEP (i.e. *below* 104 GeV) would therefore indicate the existence of new physics at a relatively nearby energy scale, probably(?) supersymmetry and probably below 1000 GeV, i.e. in reach of the LHC. If supersymmetry is correct, the LHC will be essential for studying and understanding this whole new aspect of nature (even if LEP discovers one or more supersymmetric

December 1998

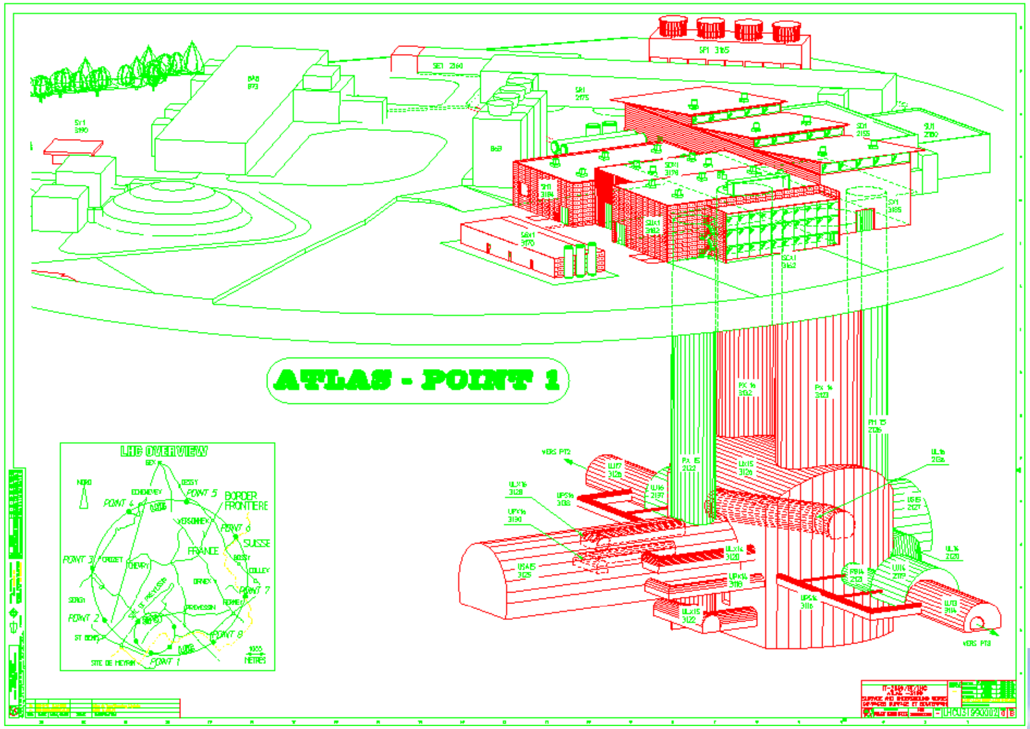


What else would have been needed to find a 125 GeV Higgs at LEP?

Final upgrade: 95 → 104.5 GeV/beam

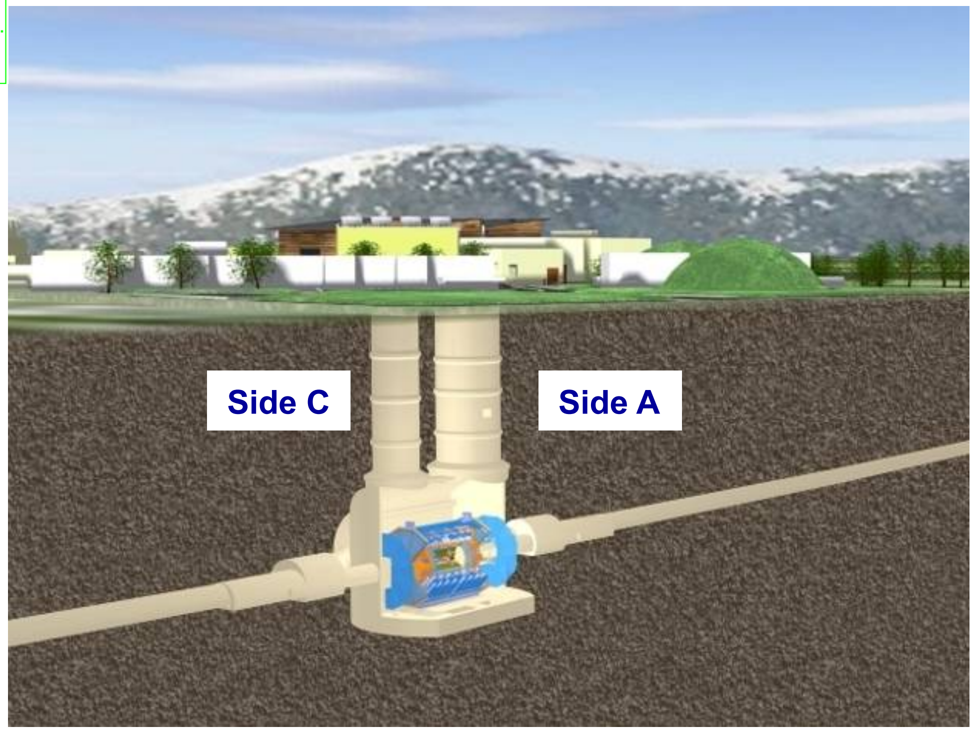
The technical limit with Nb-film cavities was 111 – just enough?

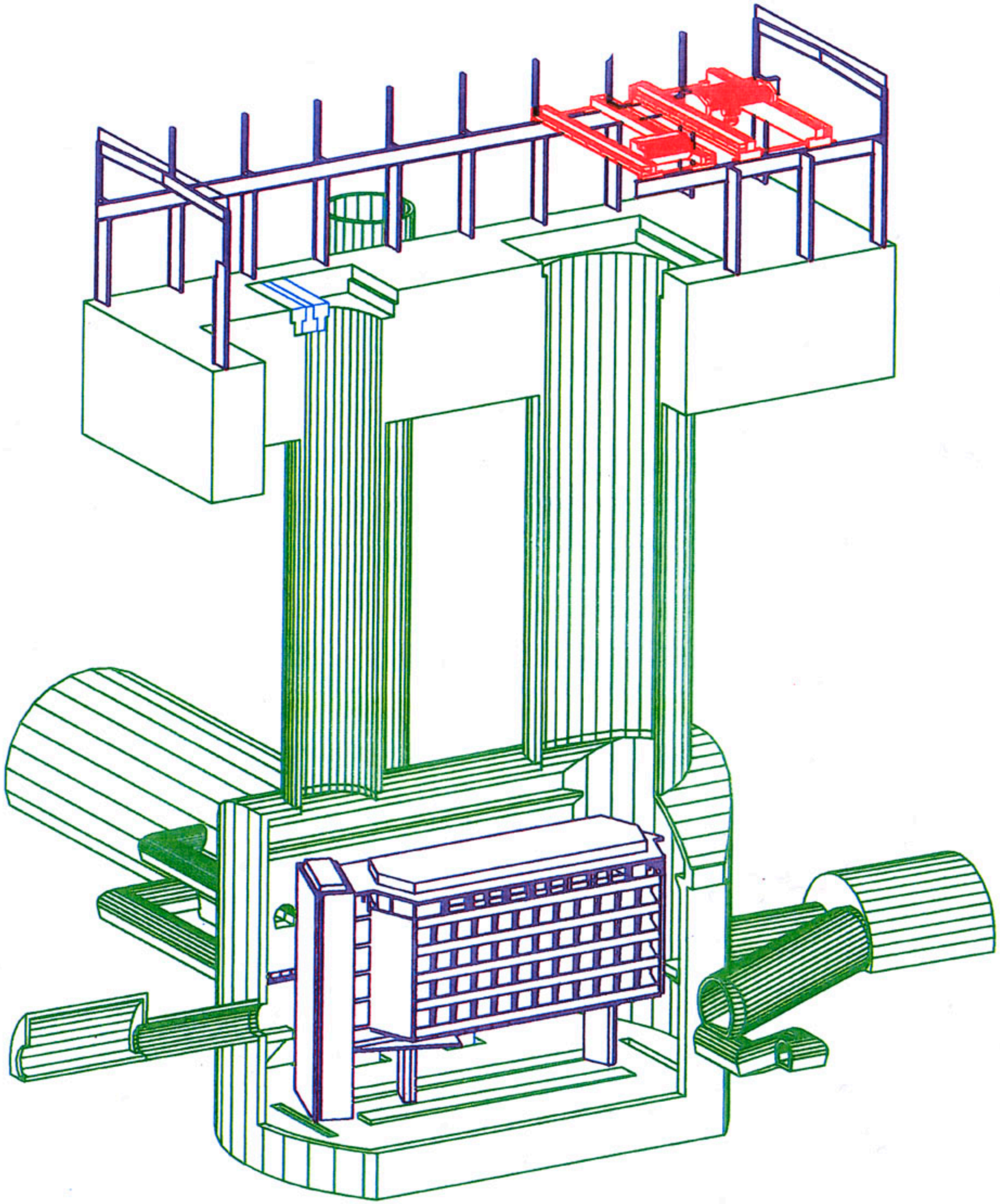
But we would never have found the support or money to buy the extra cavities and the extra time needed to exploit them

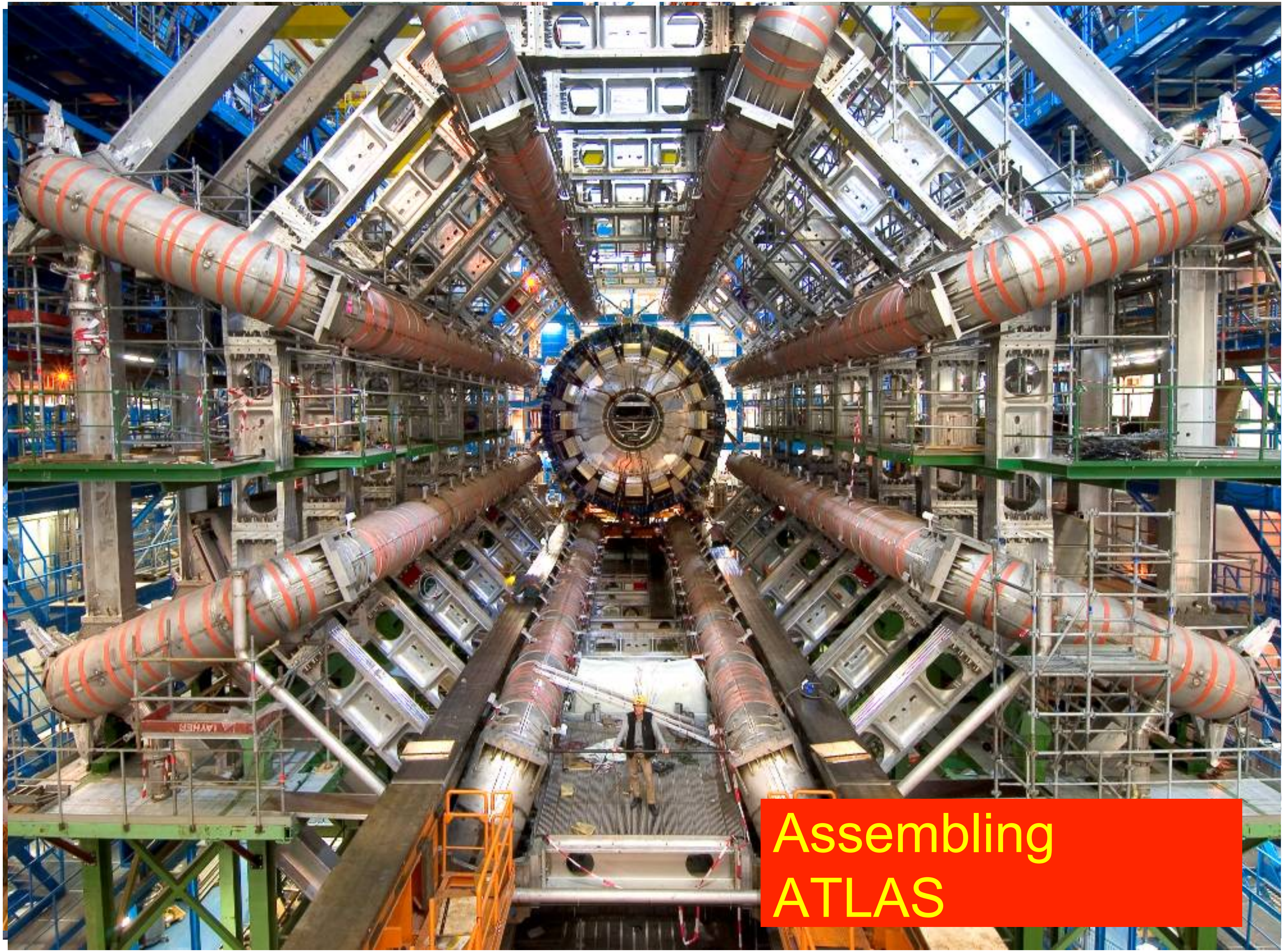


The Underground Cavern at Point-1 for the ATLAS Detector

Length = 55 m
Width = 32 m
Height = 35 m



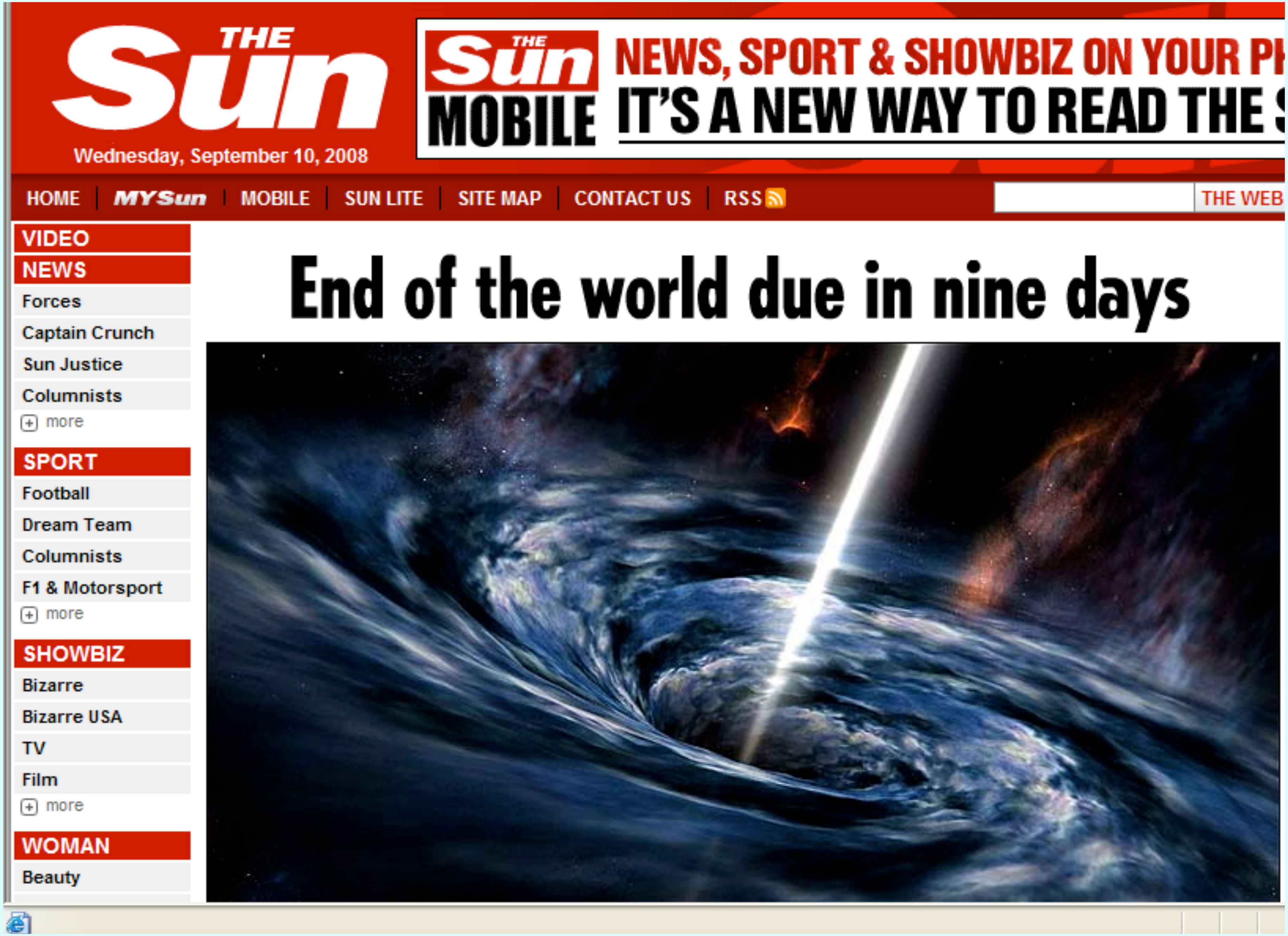




Assembling ATLAS

CMS Site

Excavation of CMS Pit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Wednesday, September 10, 2008
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Beauty
End of the world due in nine days

By PAUL SUTHERLAND
Sun Spaceman

Published: 01 Sep 2008

ADD YOUR COMMENTS

SCIENTISTS are trying to stop the most powerful experiment ever – saying the black holes it will create could destroy the world.

Dubbed by some the Doomsday test, it will be carried out next week in the Large Hadron Collider (LHC), located 300ft underground near the French-Swiss border.

The machine is 17 miles long and cost £4.4billion to create.

When its switch is pulled on September 10, this atom-smasher will become a virtual time machine, revealing what happened when the universe came into existence 14 billion years ago.

New particles of matter are expected to be discovered, new dimensions found beyond the four known, as scientists re-create conditions in the first **BILLIONTHS** of a second after the Big Bang.

Don't panic, there's time to try out every position in the Kama Sutra

WITH just nine days to go until the end of the world, here's what you could get up to before it's too late ...

1. Eat 27 Big Mac meals. Who's counting the calories?

2. Visit all seven continents.

3. Try out all 64 Kama Sutra positions.

4. Watch the entire box sets of Lost, Heroes and Prison Break.

5. Cruise the River Nile.

6. Drive to Switzerland for a ringside seat of doomsday.

7. Complete Super Mario: The Lost Levels.

8. Catch England's World Cup qualifiers against Andorra on Saturday and – if we're still alive – England v Croatia on September 10 If we lose, it'll feel like the end of the world anyway!

9. Cancel the milk and papers.


10 September 2008

The LHC entered Popular Culture:

But unfortunately (before any collisions) an electrical fault 9 days later had catastrophic knock-on effects. Repairs and improvements took until November 2009, when the LHC re-started

But then it worked

All hail those who built

- the machine: working way beyond expectations
- the detectors working way beyond expectations
- the grid etc.: working way beyond expectations

Concluding Reflections

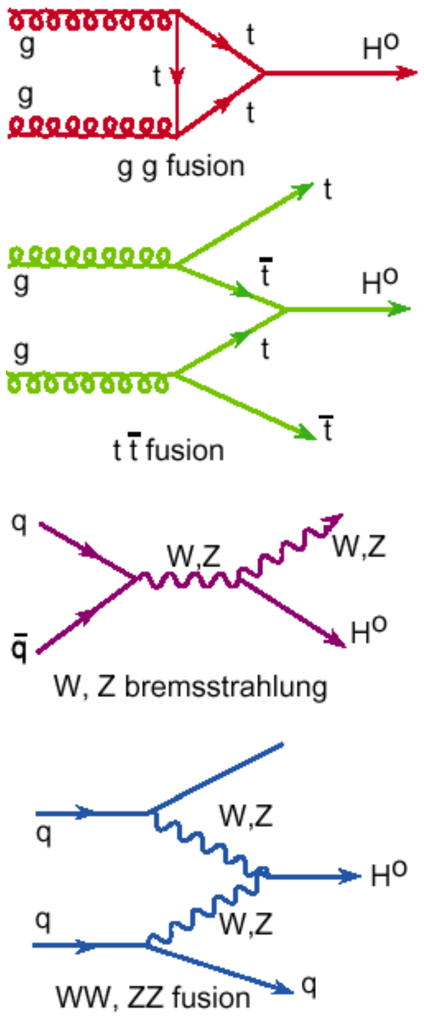
- **M_H ~ 125 GeV is good news** as there is sensitivity to many production mechanisms and decay modes, as needed to answer the question – is the discovery the end of an old chapter (appears to be the case?), or the opening of a new?

- **Looking further ahead**

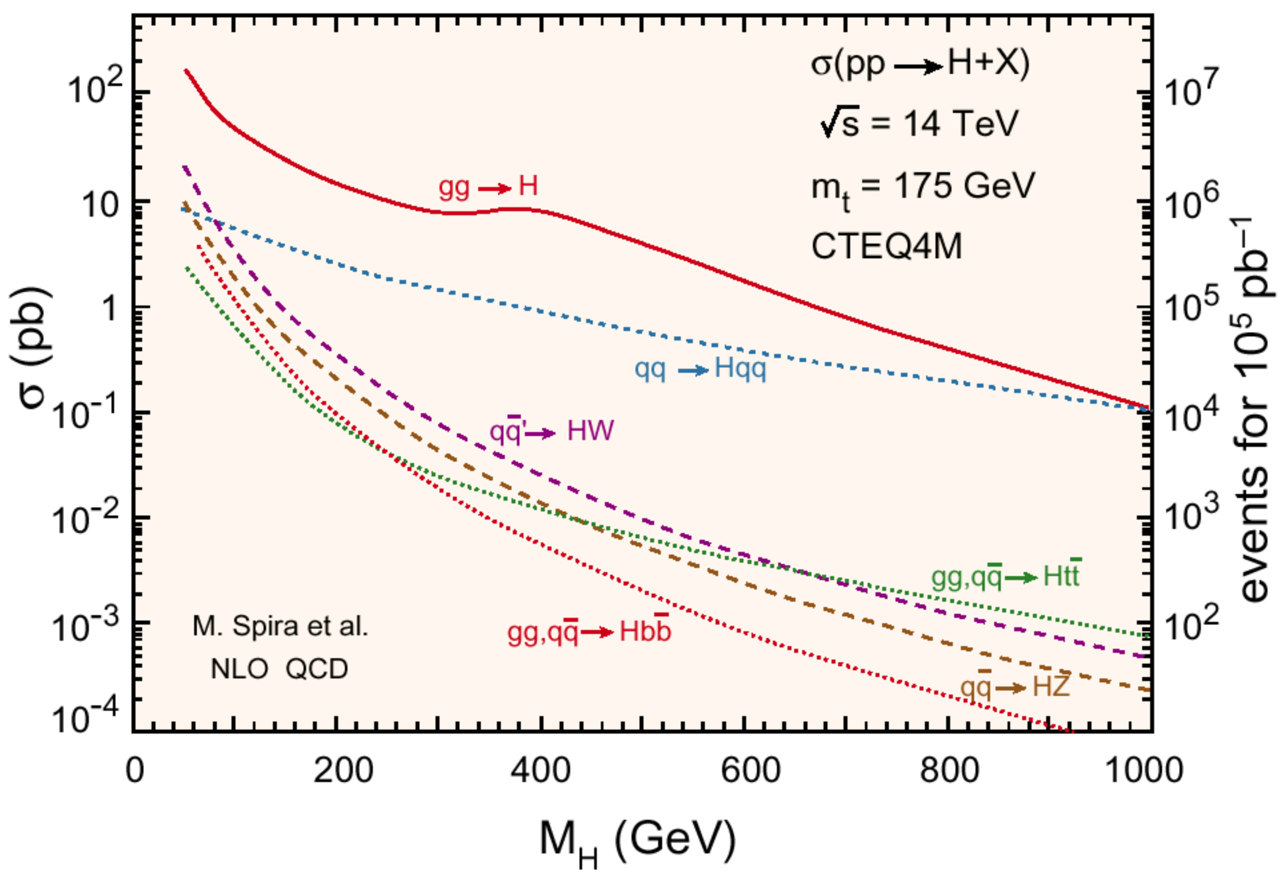
- barring a big breakthrough, the days of building machines simply to look at a new domain are over: the extra reach is too small compared to the cost
- but speculation about next machines is very premature pending collection of a large data set at full LHC energy

LHC still has a large discovery potential: there is lots to do

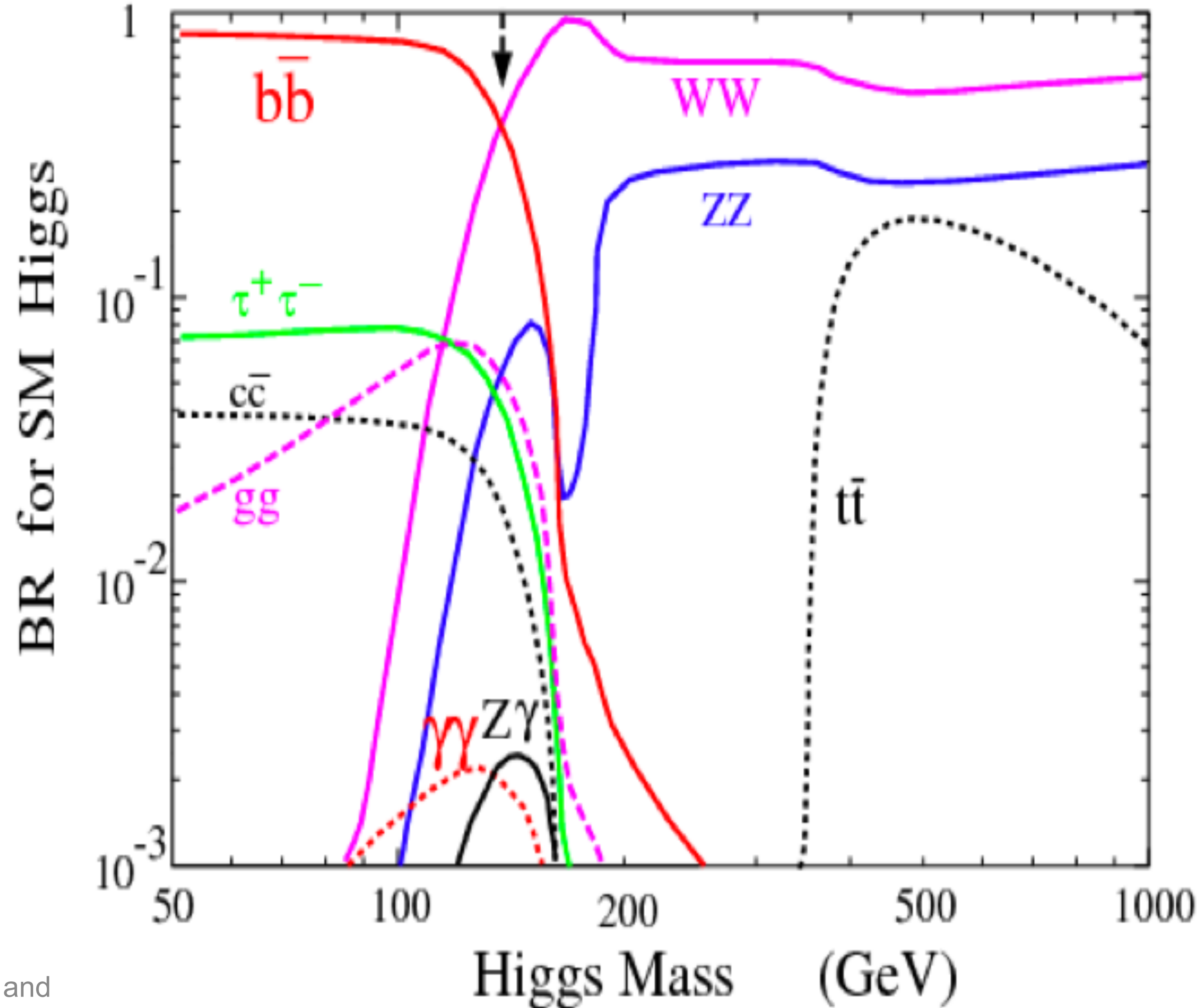
The Higgs Hunt at the LHC



Higgs production cross sections at LHC

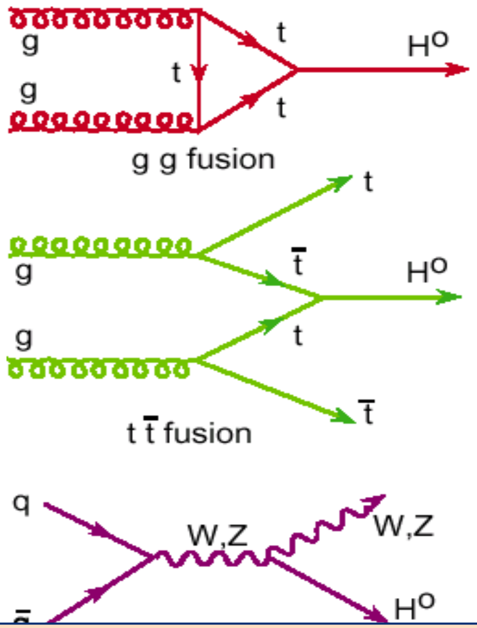


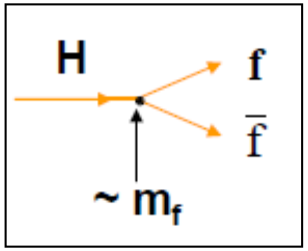
Higgs decay branching ratios

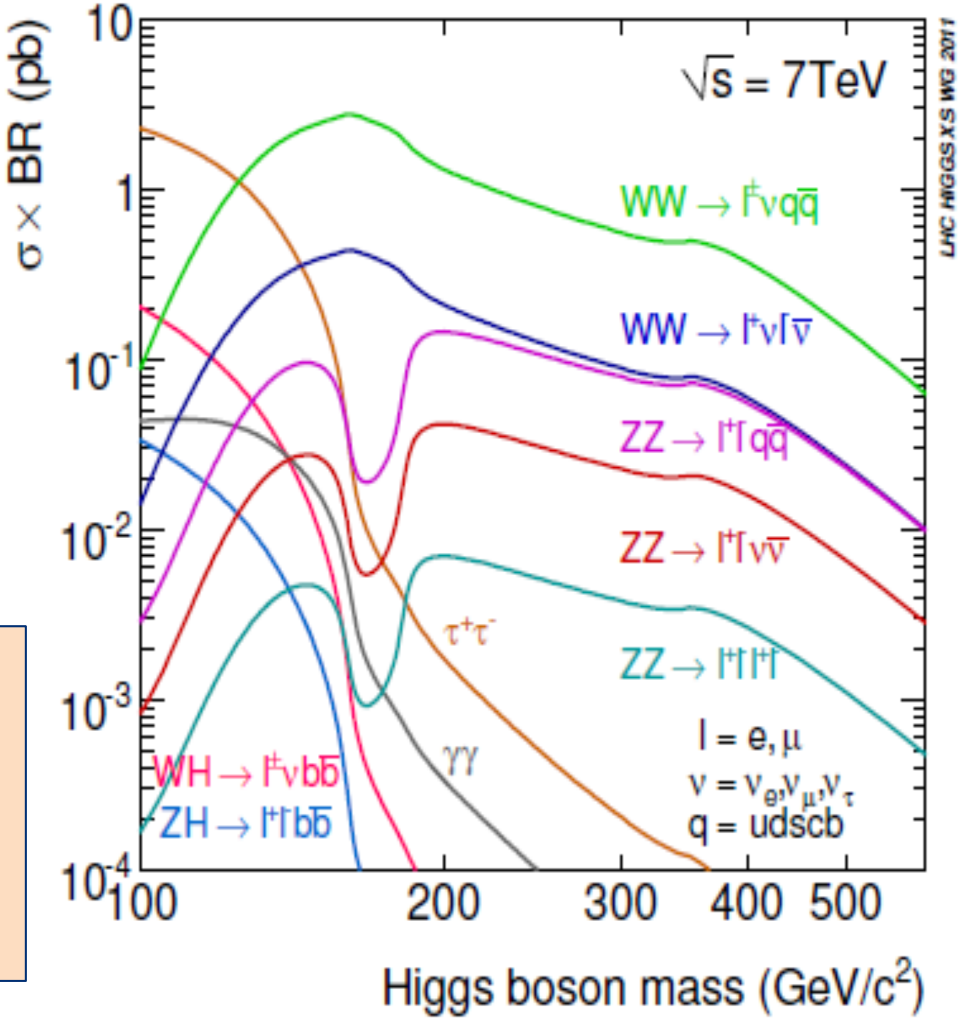


Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 7 TeV







Best channels at the LHC:

< 130 GeV	H→ γγ
125-180 GeV	H → $WW^{(*)}$→ lνlν
125-300 GeV	H→ $ZZ^{(*)}$→ llll
300-600 GeV	H→ ZZ→ llνν

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LHC still has a large discovery potential: there is lots to do


Meanwhile lots to celebrate