Genesis of the LHC

Chris Llewellyn Smith

Outline

- 1st thoughts & background < 1984
- Gestation 1984 – 1993
- Approval & adolescence 1994-98
- Coming of age ≤ 2012
- Concluding remarks

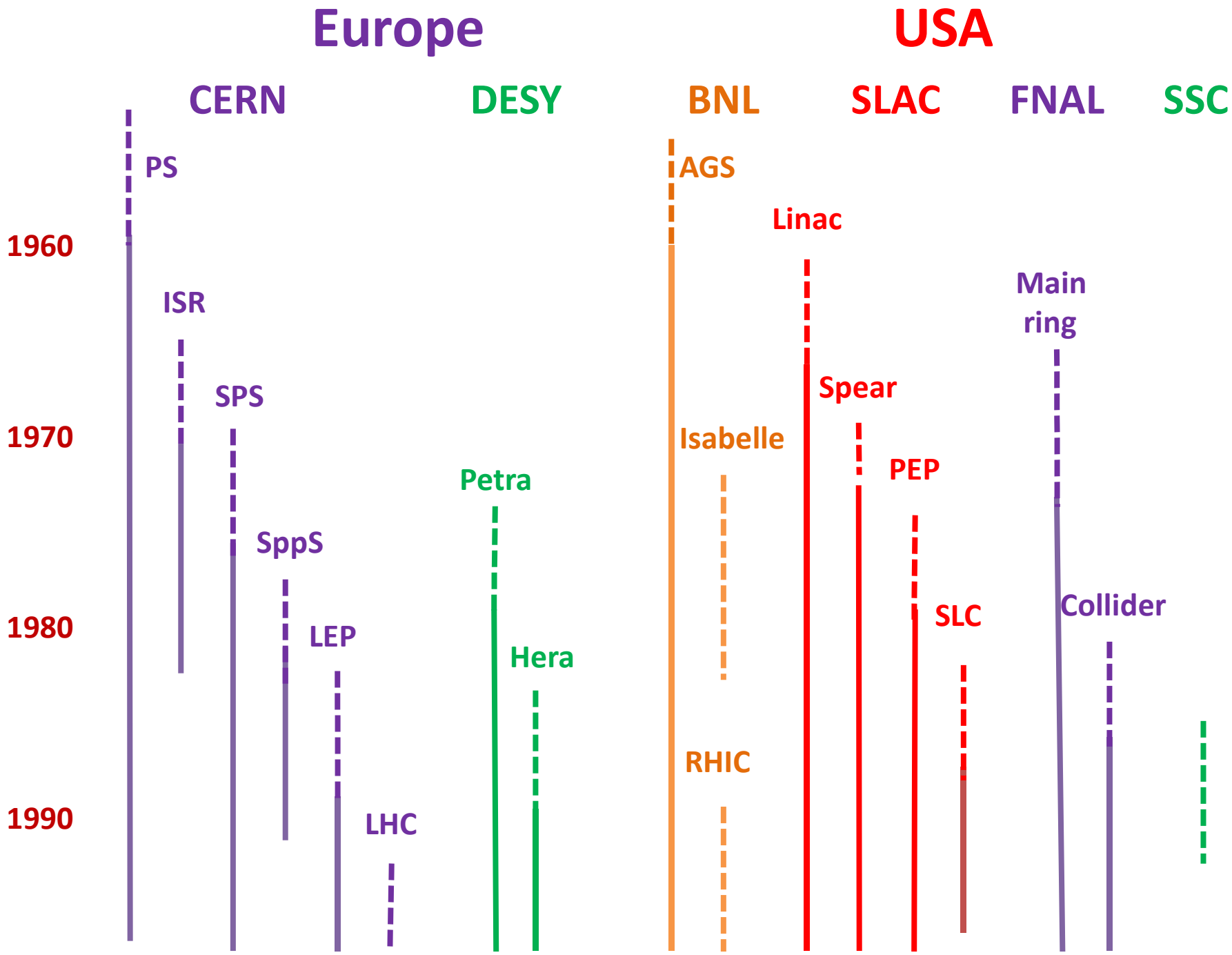
1st thoughts & background < 1984

- In 1977 John Adams (Technical DG of CERN), bowing to pressure to push for the Large Electron Positron Collider (LEP), argued that if LEP were built the tunnel should be made large enough to accommodate a ring of superconducting magnets able to accelerate protons to at least 3 TeV

- In 1970 Adams had proposed that the CERN Super Proton Synchrotron (SPS) should be built (underground) at CERN, using the PS as injector and existing infrastructure – rather than elsewhere (on the surface, no space in Geneva) as had been universally assumed

  The upshot was that Europe had all its high energy physics eggs in 1 1/2 baskets – not 3-4 as in the USA (see next slide)

- This underwrote Europe's rise to pre-eminence, and - with the construction and successful operation of the ISR and the triumphant adaptation of the SPS to become a proton-antiproton collider (SppS) - enabled the construction of the LHC, with an annual CERN budget lower in real terms than in the early 1970s


Europe
USA
CERN
DESY
BNL
SLAC
FNAL
SSC
1960
1970
1980
1990
PS
ISR
SPS
SppS
LEP
LHC
Petra
Hera
AGS
Isabelle
RHIC
Linac
Spear
PEP
SLC
Main ring
Collider

Developments 1978-83

CERN

- 1978 - decision to adapt SPS to collide protons with anti-protons – Sp$\bar{p}$S
- LEP approved 1981
- Sp$\bar{p}$S operation 1982
  Discovery of W and Z, 1983

USA

- Problems with 2 in 1 magnets for Isabelle, 200 GeV x 200 GeV proton-proton collider under construction at Brookhaven
- NY Times headline: 'Europe W, USA not even Z^0'
- Decision (summer 1983) to cancel Isabelle and push for a 40 TeV Superconducting Super Collider to 'regain US leadership', encouraged by Reagan's science advisor

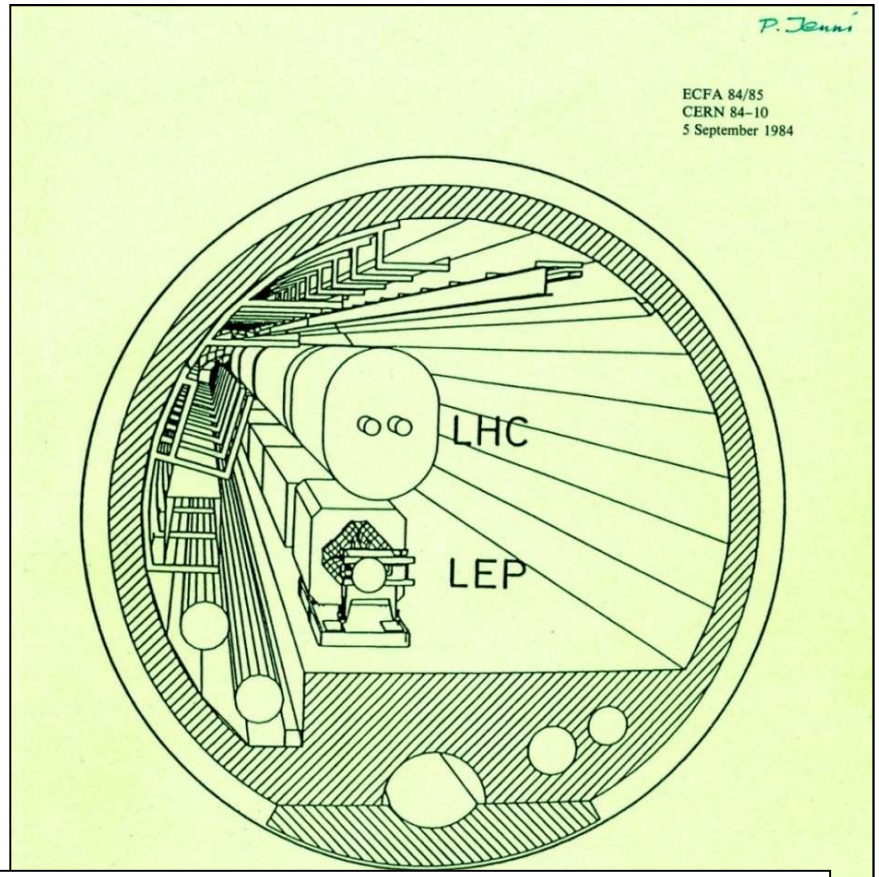
Late 1983 Herwig Schopper (CERN DG) initiated LHC studies in preparation for the International Committee on Future Accelerators (ICFA) seminar in Japan in May 1984

Gestation 1984 – 1993

- Lausanne Workshop March 1984
- ICFA Seminar at KEK May 1984
- CERN Long Range Planning Group
- Magnet R&D and evolution of LHC
- Detector R&D and evolution of experimental programme
- Engagement of the CERN Council
- Towards the proposal
- The proposal

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. → discussion of Luminosity-Energy trade off (14 TeV vs. 40 TeV), 1 ½ pages on Higgs phenomenology, 2 pages on SUSY,…..

Lausanne Workshop & ICFA Seminar

- Physics case for LHC (much developed by John Ellis and collaborators) and SSC
  - surprisingly: essentially unchanged for over 30 years

- Luminosity/energy trade-off understood – but questions whether even 10^{33} cm ^{2} s^{-1} could be used. Quotes from ICFA seminar proceedings:

  "Consensus at Lausanne Workshop that the number of events per bunch crossing should not exceed one"

  "C Rubbia also expressed doubts with regards to the usefulness of luminosities as high as 10^{33} cm^{-2} s^{-1}". R Schwitters: "Increase in cost for the detector when going from 10^{32} to 10^{33} had been estimated to be a factor 3 to 4"

- SSC presented as national project

- LHC presented by Brianti

  Based on 2-in-1 magnets but almost everything else changed subsequently: 10T magnets, 2x9 TeV, "conceivable that luminosity could eventually approach or even exceed 10^{33}" , 8 crossing points, magnets + cryo-line above LEP….

Long Range Planning Group 1985-87
Chaired by Carlo Rubbia

- Recommended 13-15 TeV proton-proton (not antiproton) collider, with 8-10 T magnets, luminosity of 10^{33}, as next option for CERN – 'first collisions possible in 1995 if decision to proceed taken 1989'!

  2 TeV electron-positron collider would have comparable reach, and could enable detailed study of phenomena discovered at LHC or SSC – but not technically feasible

- "Lesser energy of LHC [relative to SSC] can be partially 'recovered' with the help of a larger luminosity", but experiments at more than 10^{32} "will require novel instrumentation"

- Recommended intensify R&D on high field magnets

Magnet R&D and Evolution of the Machine

- **Magnet R&D**

  Started 1986 (Brianti, Perin, Leroy, Rossi…)

  1988 single bore 1 m magnet designed at CERN built by Anslado reached 9 T at 1.8K

  2-in-1 1-1.3 m magnets reached 9 T 1991-92

  10 m 2-in-1 magnet successfully operated March 1994 (good field quality)

  2-in-1 quadruples developed in parallel by CERN-CEA collaboration

  String including three 10 m magnets successfully operated November 1994

- **Machine**

  March 1992: Still 10 T envisaged 2x7.7 TeV, L = 1.6 x 10^{34} cm^{-2} s^{-1} , parameters also presented for ep and Pb-Pb

  December 1993 converging towards machine that was built - 2x7 TeV, 8.65 T, 2.5 x10^{34} cm^{-2} s^{-1}

  Conceptual Design report October 1995 – essentially machine that was built

Detector R&D

- From 1986, vigorous CERN programme with 40 MCHF funding from Italian government (Zichichi's LAA Project)
- CERN Detector R&D Committee set up mid 1990. By March 1992: 35 proposals, 24 approved – involving 800 people in 170 institutes

Engagement of the CERN Council

- CERN Council (which set up the Long Range Planning Group) kept informed of plans, which were met with varying degrees of enthusiasm, and scepticism as the Council was aware that the SSC was under construction
- Push by Carlo Rubbia, and Bill Mitchell – President of CERN Council (1990-93), kept the LHC on the agenda, and built up support in the community
- Presentation of the project to a special open Council session in December 1991

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' 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'

Evolution of the Experimental Programme

- 1987 La Thuile Workshop
- 1989 Barcelona Workshop
- 1990 Aachen Workshop
- **1992 ECFA*-CERN** Evian Worksop**:

  Expressions of Interest presented:

  ASCOT (central solenoid + outer toroid)

  EAGLE (central solenoid + outer toroid)

  CMS (large solenoid)

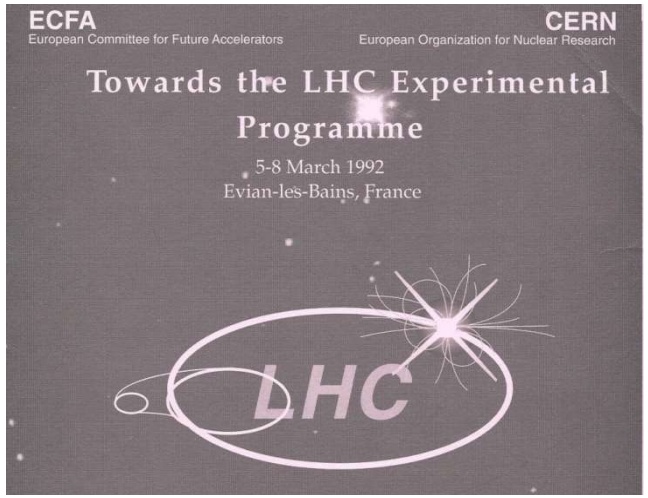
  Upgraded L3 detector (large solenoid)

  Plus: two heavy ion experiments, three CP violation/B physics experiments, two neutrino experiments

  Not presented but EOIs summarised in the proceedings : p_t physics, Total cross section etc. + physics with a jet target

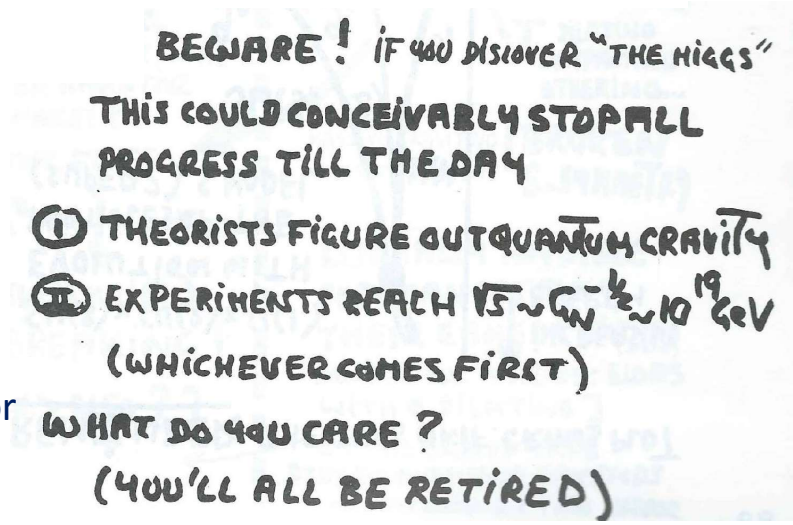
- Newly formed LHCC asked for formal LOIs by 1 October 1992, by which time ASCOT and EAGLE has merged to form ATLAS

*G Flügge ** W Hoogland - set up the LHCC, oversaw Detector R&D, and laid foundations for the LHC programme



Physics with proton beams 1
C. Llewellyn Smith (Oxford)

Physics with proton beams 2
A. De Rújula (CERN):



Towards the Proposal

- **May 1993**. New (private) cost estimates from Giorgio Brianti - higher than hoped. Carlo Rubbia handed me responsibility for putting together the LHC proposal in the context of a complete long-term plan for CERN and presenting them to Council in December.
- **Summer 1993**. Intense work i) by Lyn Evans (by then appointed as LHC Project Leader Designate) to reduce cost, and ii) with Horst Wenninger on manpower and other aspects of the long-term plan
- **October 1993.** Cancellation of SSC – next slide
- **November 1993**. External Review (Aymar):
  - Design goals (E and L) are reasonable and realistic
  - There is no doubt that 8.65 T can be achieved with an adequate safety margin
  - The technical choices (2 in 1, 1.8 K) are the only appropriate ones
  - The cost estimates are accurate…enough potential savings to avoid the need for contingency
  - Schedule OK

This when R&D still underway; no long 2-in-1 dipole tested!

Rise and Fall of the SSC

- 1987. Project approved – cost estimate $4.4 billion
- May 1990 – cost $7.9 billion: Congress voted to limit federal contribution to $5 billion
- 1992. Cancellation by House of Representatives, restoration after vote in Senate
- Final cancellation October 1993, estimated cost then $11 billion

  Factors in demise – cost increase, green field site, schizophrenia national/international ,…

Impact on LHC

- Much easier to make the case for the LHC
- Emergency ICFA meetings:

  November 1993 – calls to put LHC on hold and develop world programme not supported

  January 1994 - 'LHC now offers the only realistic opportunity to study multi-TeV hadron collisions… LHC will remain a unique facility for the foreseeable future and ICFA considers that it is now the correct next step for particle physics at the high-energy frontier'
- Early Summer 1994 – 'Drell Panel', set up by HEPAP to advise on the way forward following the demise of the SSC, recommended that the USA should join other nations in building the LHC, with a maximum contribution (machine + detectors) of $400 million – less if a proposed 'bump' in the budget did not materialise (it did not).

  Lorenzo Foa played a key role as the external member of the Drell panel, and as Research Director from mid 1994 got the LHC experimental programme underway

Presentation of complete plan to the Council (December 1993)

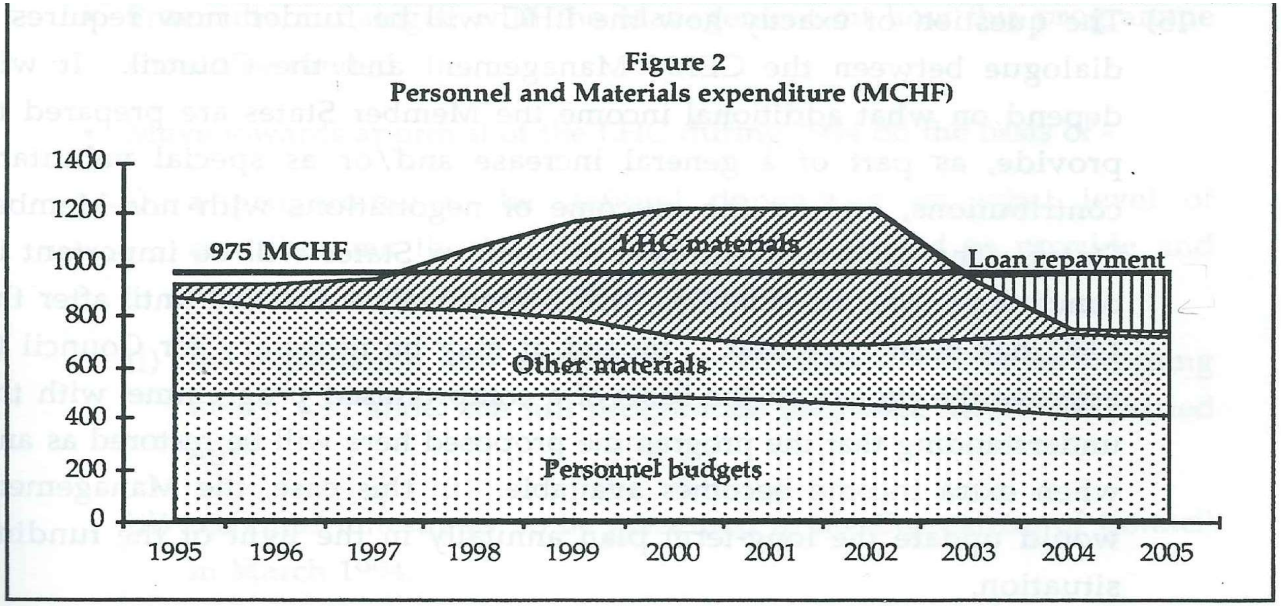
"The LHC will provide unique insights into the nature of matter and the structure of the universe, and ensure that CERN maintains a leading position in the decades to come……."

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 deep connection between constituent particles and particles that mediate the forces between them. They could reveal the existence of new

Council's reaction to the December 1993 proposal

was generally positive, but it was clear that Germany and the UK would not approve the requested hump in the budget:



14) Figure 2 shows that support of the programme proposed here will require:

i) extra income, and perhaps also

ii) advances from Member States, or loans, to provide the necessary cash-flow.[1]

and we were asked to look for further savings/cost reductions

Approval & Adolescence 1994-98

- Revised plan (proposed commissioning date delayed from 2002 to 2003 or later depending on what contributions could be found outside Europe, detectors to be staged, further cuts in rest of the programme) presented in June 1994
- 17 Members voted to approve the project but Germany and the UK wanted further cost savings and substantial contributions from France and Switzerland
- Pressure to further reduce the cost was resisted:
- Autumn 1993 – Germany and UK say they will only approve the project on the basis of planning for 2% inflation to be (under compensated) by 1% indexation of the CERN budget, with no loans

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

- Missing magnet idea* (used by Adams at one stage to sell SPS) developed and deployed as only way to build LHC on budget declining in real terms

* 1st stage with every third magnet missing

December 1994

After very tough negotiations, and pledges of special contributions from France and Switzerland, the Council approved the LHC*

- for construction in two stages (as a missing magnet machine), with the condition that ‘any contributions from non-Members with be used to speed up and improve the project, not to allow reductions in the Members States’ contributions’ (a pledge which was very helpful in asking non-Members to contribute, but was not kept) and a review of the time-table in 1997

* For the political battle see Nature 281, 448, 2007

1995-6*

- Negotiated contributions from Canada, India, Japan, Russia, USA (albeit following the election of a Republican majority in the House of Representatives, this was not approved until late 1997)
- June 1996: decided to bring forward 1997 review and ask for approval of single stage construction, but then
- August 1996: Germany (suffering from financial impact of re-unification) asked for a 10% cut in its contribution – this was seized on the by UK to ask for a 10% cut for all despite assurances on 29/12/1994 from David Hunt, UK Minister of Science that

  'We believed it was essential that the project was founded on a realistic, fair and sustainable basis. I believe that the planning and financial framework agreed unanimously by the CERN member states fulfils those necessary conditions which will ensure the LHC will be carried through to completion...Now it is down to you and the CERN staff to make this project a great success'
- Only way ahead – large loan, previously considered anathema by Germany

*meanwhile requests for final LEP upgrade approved 1995, and for one more year of operation approved in 1998

December 1996: Single Stage Construction of LHC Approved

- Accompanied by cuts in the budget (after an onslaught from Germany and the UK)
- On the basis of loans

I repeatedly stressed the risks and that Council should be ready to help and bear the consequences should they materialise. Reassuringly this seemed to be accepted, e.g. the Head of the German Delegation stated that 'a greater degree of risk would inevitably have to accompany the LHC'

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

By the end of 1998, when I handed over to Luciano Maiani as DG, the LHC was well past the point of no return – agreement signed with USA, around half (by value) of the contacts signed (overall, in line with estimates), although the situation was clearly fragile

ATLAS and CMS

- July 1993 Three letters of intent evaluated by the LHCC. ATLAS & CMS selected to proceed to technical proposals.
- 1996 ATLAS & CMS technical proposals approved
- July 1997. Formal approval to move to construction (475 MCHF material expenditure cost ceilings. Lots of controls, Resource Review Boards etc.)

Coming of age ≤ 2012

Will not elaborate or dwell on developments and difficulties* in the decade leading up to switch-on

*large cost over-run announced 2002, problems with cryo-line….

THE Sun
Wednesday, September 1, 2008

End of the world due in nine days

By PAUL SUTHERLAND
Sun Spaceman

Published: 01 Sep 2008

ADD YOUR COMMENTS

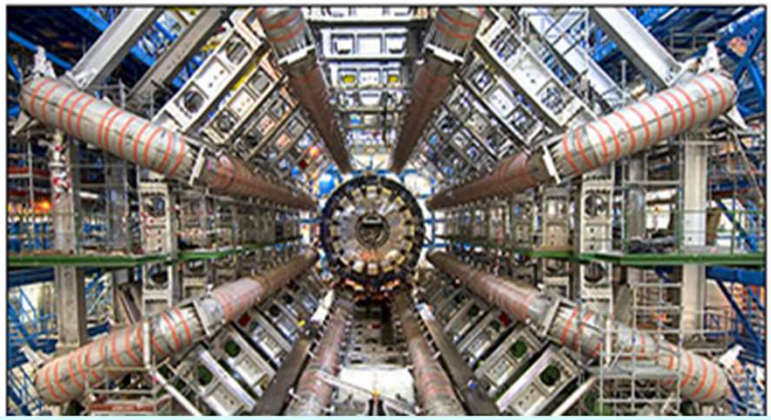
SCIENTISTS are trying to stop the most powerful experiment ever – saying the black holes it will create could destroy the world.

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!

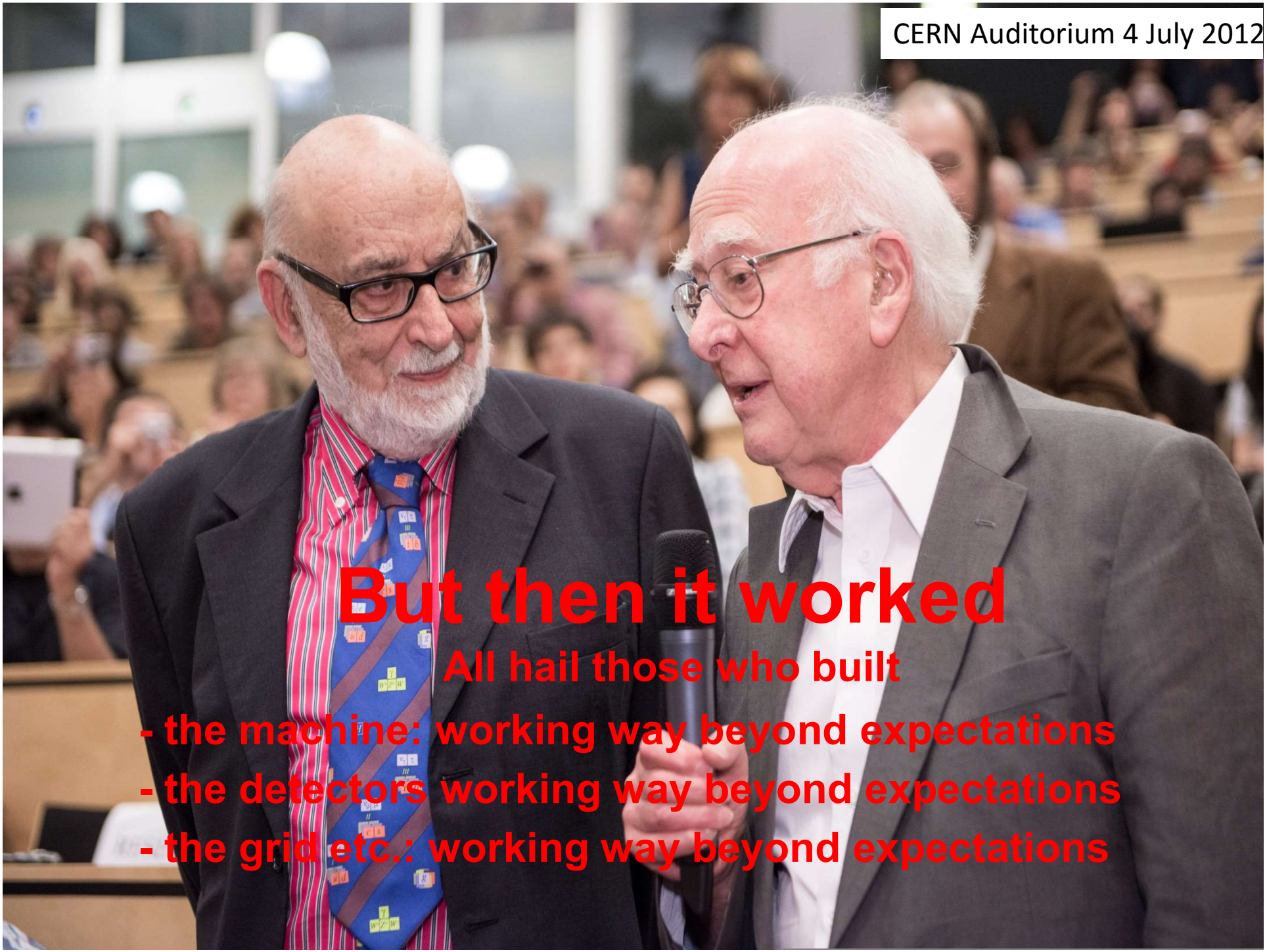
9. Cancel the milk and papers.


10 September 2008

The LHC entered Popular Culture:

Headline, afternoon of 10 September 2010:

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


CERN Auditorium 4 July 2012
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 Remarks

- **Approval of the LHC was a collective effort, which involved many people. It depended on**
  - Robust scientific case (exploration of large new domain, with good reasons to expect discoveries)
  - Uniqueness
  - Unanimous support of world particle physics community
  - Technical success of CERN
  - No budget bump (imposed)

- **Approval of future major projects will require**
  - Robust scientific case
  - Major discoveries at the LHC
  - Unanimous support of world particle physics community
  - Continued technical success
  - 'Reasonable' budget envelope

  Public support could help (previously not a factor as CERN was relatively unknown prior to the LHC)

REFERENCES

- How the LHC came to be, *Nature* **444** 28 (2007)
- Large Hadron Collider: Lessons Learned and Summary, talk at a Royal Society Discussion Meeting, *Phil Trans Roy Soc* ***A*** **370**, 995 (2012)
- Genesis of the LHC, Phil Tran Roy Soc **A373**:20140037 (2016), talk at a Royal Society Discussion Meeting January 2014 http://dx.doi.org/10.1098/rsta.2014.0037
- Planned book 'LHC – the Inside Story'