How Did We Get There:
from LEP to the LHC

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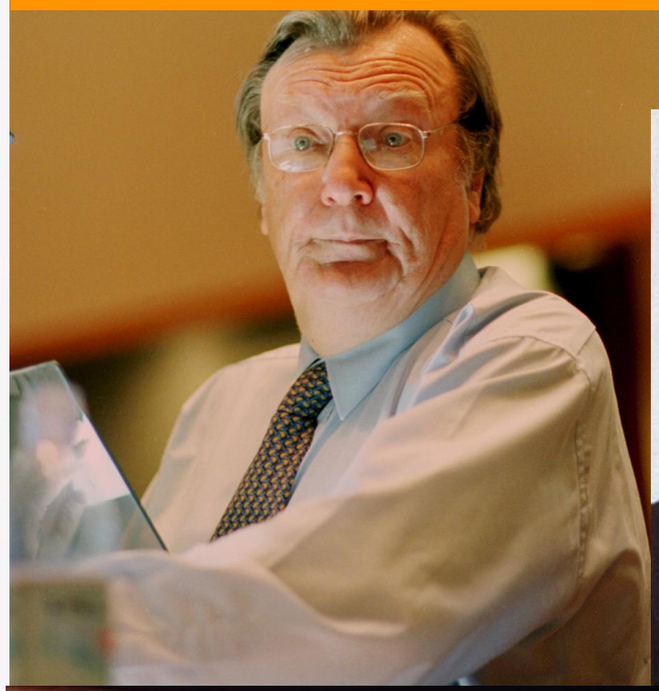
THE EUROPEAN PHYSICAL JOURNAL H

Oral history interview

The LHC timeline: a personal recollection (1980–2012)*

Luciano Maiani[1] and Luisa Bonolis[2,a]

LHC @ CERN
some protagonists



1. Prologue: the LEP tunnel

- Physicists had thought to make the tunnel wider than what was strictly needed, so as to be able to install later a proton machine with superconducting magnets
- The ECFA study (Roma 1978, chaired by A. Zichichi) had made a recommendation in this direction, nothwitstanding the resistence of those afraid that the implied cost increase would put the LEP project at risk
- As a compromise, a tunnel of 4 meters diameter was accepted. However, this was not enough for a cryogenic system with two independent magnets (such as was designed for the SSC).
- CERN was forced to develop a new advanced design: "two-in-one", more compact and less expensive
- The choice of tunnel's dimensions, all in all, is a positive story: an admirable compromise that made it possible to prolong the lifetime of CERN well above 20 years.

Two-in-one Dipole Superconducting Magnets

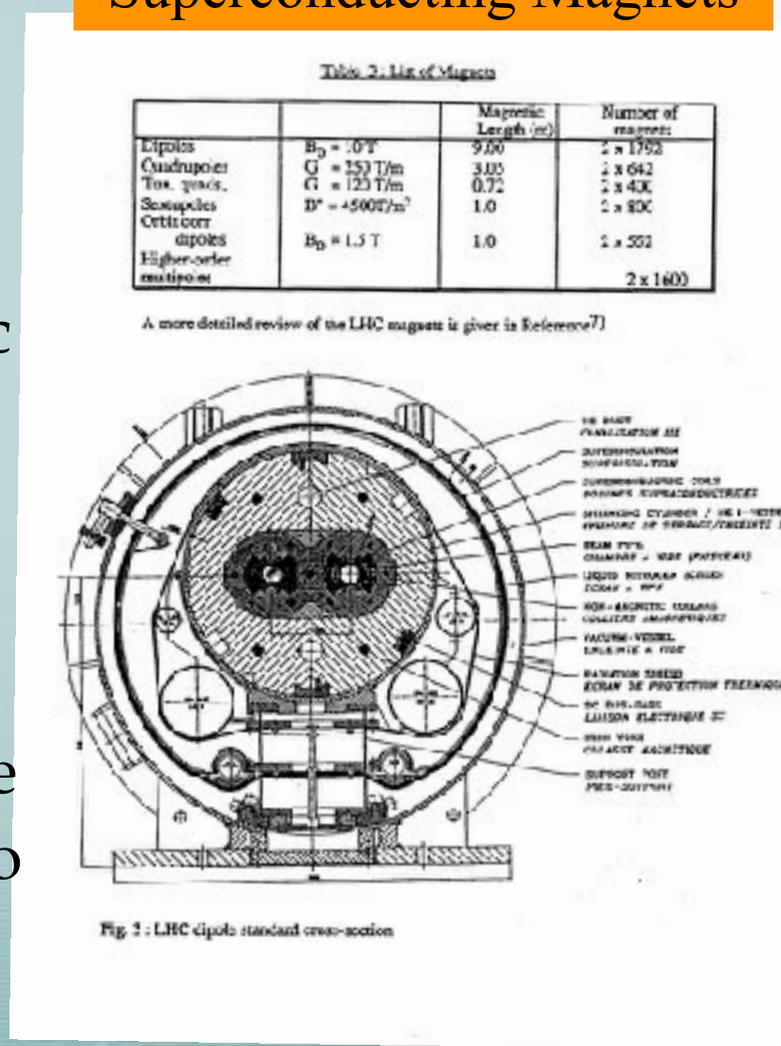


Table 2: List of Magnets

		Magnetic Length (m)	Number of magnets
Dipoles	B_0 = 9 T	9.00	2 x 1792
Quadrupoles	G = 250 T/m	3.05	2 x 642
Trim quads.	G = 123 T/m	0.72	2 x 408
Sextupoles	$D'' = 4500 T/m^2$	1.0	2 x 800
Orbit corr. dipoles	B_0 = 1.5 T	1.0	2 x 552
Higher-order multipoles			2 x 1600

A more detailed review of the LHC magnets is given in Reference 7)

Fig. 2 : LHC dipole standard cross-section

November 1988.
SSC approved at a new site: Waxahachie, Texas,
Fermilab loses the competition for hosting the SSC

- **1988** **SSC approved,** proton-proton, 20 TeV/beam, 87 km tunnel, cost 4-5 B US$;
  1989 SSC construction starts.
- **1993** SSC discontinued by the US Congress after a bitter discussion which invested all the scientific community (projected cost >10 B US$, 2 B US$ spent).

10 November 1988. Leon Lederman, wearing a Stetson hat, annoounces to the Laboratory that Fermilab has not been chosen as the SSC site. FNAL Visual Media Service.

Shaft to the SSC tunnel di SSC, located at about10 meters underground. The planned tunnel had a circumference of 87 km.

2. Early LHC chronology

- **1981** Lausanne ECFA workshop: LHC in LEP tunnel
- **1986** La -Thuile workshop: first design (G. Brianti)
- **1988** Feasibility of High Luminosity expts at LHC, Geneve meeting
- **1990** ***Aachen meeting***: main lines are delineated.
- ***G. Kalmus*** closing remarks: (The Aachen meeting) has marked a watershed, the time, when the LHC project…***graduated ..to being the way forward for European particle physics.***
- ***C. Rubbia: high luminosity makes LHC competitive with the SSC (compensating for an energy ratio 40/16)***
- A lot of wishful thinking:
  - schedule: start civil engineering in 1992, commissioning in 1998 (6 years).
  - ***In reality***…start civil engin. in 1997(+5), commiss. in 2008 (11 years).
  - It was still considered possible to install in the tunnel LHC together with LEP and run LEP and LHC concurrently.
  - The possibility was kept alive until 1995. The need to dismantle LEP was announced by C. Llewellyn Smith in Beijing… I. Mannelli asked me to protest formally, on behalf of INFN.
  - no cost mentioned.
- **1992** Council declares that the LHC ***"will be CERN's next facility"***,
- **1992** Expressions of Interest for experiments are presented in Evian; the LHC experiments Committe is created.

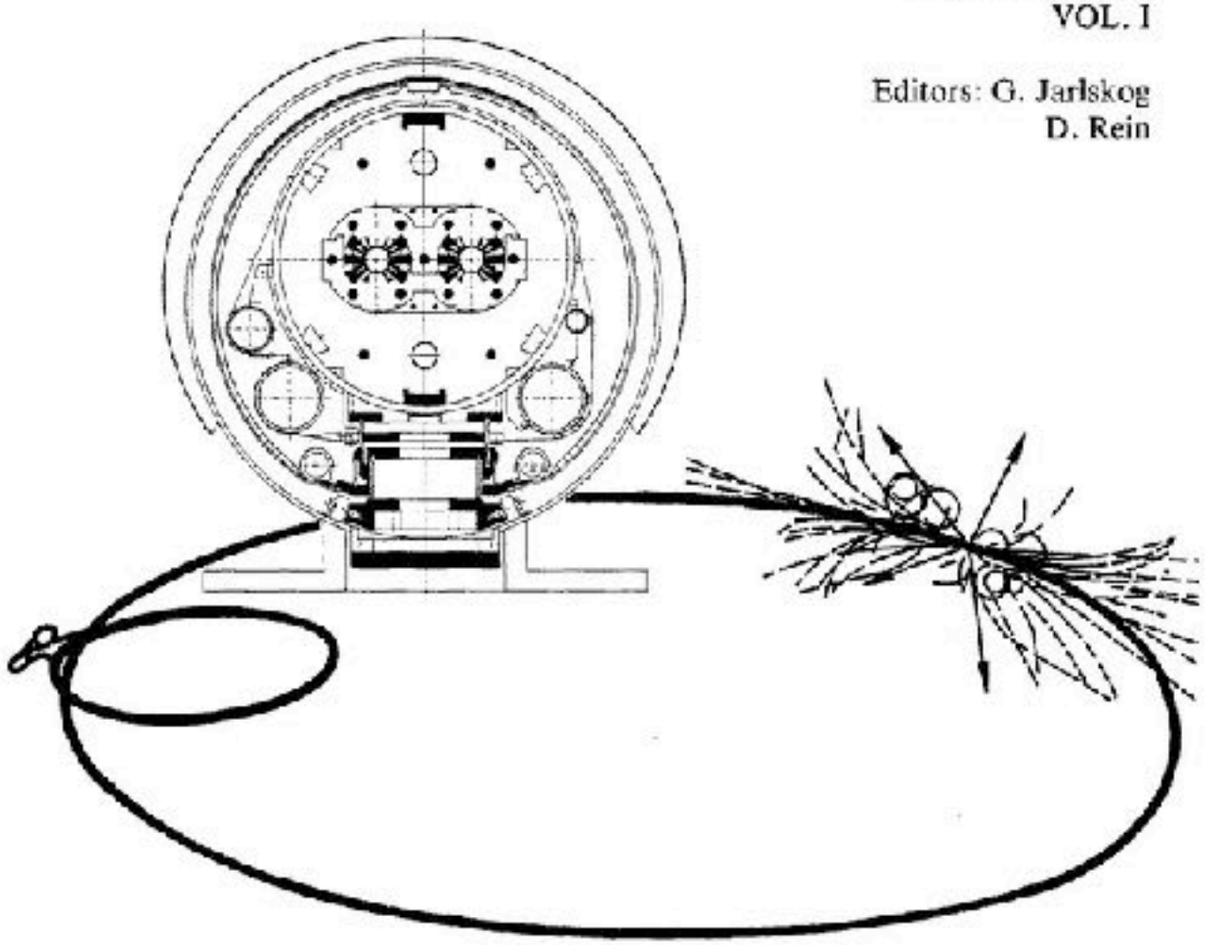
CERN 90-10
ECFA 90-133
Volume I
3 December 1990

EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

Large Hadron Collider Workshop

PROCEEDINGS
VOL. I

Editors: G. Jarlskog
D. Rein



Aachen, 4-9 October 1990

from LEP to LHC in the same tunnel

LEP, July 1989- December 2000

LHC, January 2010-

1994: LHC is approved

- the cancellation of the SSC programme (1993) made a real shock-wave in Europe, firing back on particle physics and CERN.
- Top quark discovery (1994) had a very good balancing effect (as seen from Italy)
- the first prototype of the 11 m superconducting LHC magnets was deliverd to CERN in Dec. 1993 and presented to CERN Council in March 1994, with a very positive effect
- ***On the basis of the SppbarS and LEP successes, CERN project was approved in December 1994.***

First prototype of 15 m superconducting LHC dipole by CERN-INFN-Ansaldo Energia collaboration,1998.

LHC agreements: 1995 to 1997

Chris Llewellyn Smith (right), with Hubert Curien, President of Council (center) receives a Daruma Doll from Kaoru Yosano, Japan Minister of Education, Science and Culture, June 1st 1995 at the signature of the Japan-CERN agreement for Japan participation in LHC (machine and experiments.

Agreements were made with several other countries, among them:

- Russia: warm magnets for the beam transfer line from SPS to the LHC (over 150 MCHF)
- India: hardware, software and skilled superconductor manpower
- Pakistan: detector construction (RPC); barrel yoke (35 tons) for the CMS detector

Signature of the USA-CERN agreement for the US participation in LHC (machine and experiments), Washington 8 december 1997. From left: Neil Lane, Director NSF, Federico Peña, Secretary for Energiy, Luciano Maiani, President of Council, Chris Llewellyn Smith, Director General of CERN.

The December 1996 resolution

- CERN Council came back to LHC in december 1996
- The new resolution approved to start LHC construction in 1997, in the final stage of full magnets
- At the same time, Council accepted the request of Germany ***to reduce the annual CERN budget by some 8%, a total of about 700 MCHF over the construction period***
- CERN, accepted the cut, to be reabsorbed by a general reduction of the Laboratory expenses, within 2009.
- ***The starting of LHC was fixed to 2005***.
- LHC had no more contingency and no resources for magnet R&D
- Chris had fulfilled his goal to obtain the approval, at the expense of moving the problems forward in time.

Was to fire back in 2001

- ***The community, myself included, was anyway satisfied for the approval. Physicists of all countries started preparing the detectors, leaving to CERN the problem to make the machine under financial severe conditions.***

CERN personnel protest against budget cuts requested by CERN Council to approve LHC construction. December 1996

3. Normal sufferings...ground freezing at the CMS shaft

..and major crises: LEP

Clean, startling events seen by ALEPH, september 2000

Analysed as:

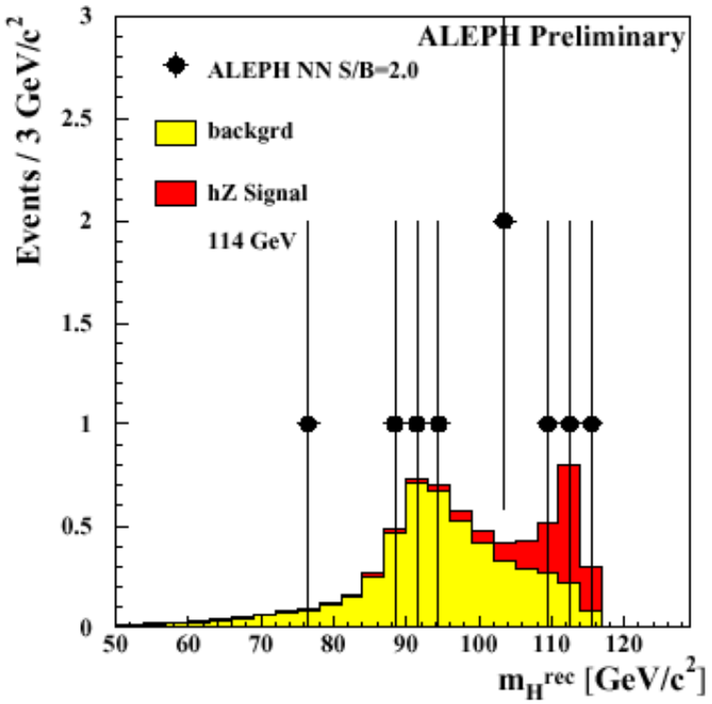
$e^+e^- \to Z + H$

$Z \to 2$ jets;

$H \to 2\ b-$ tagged jets

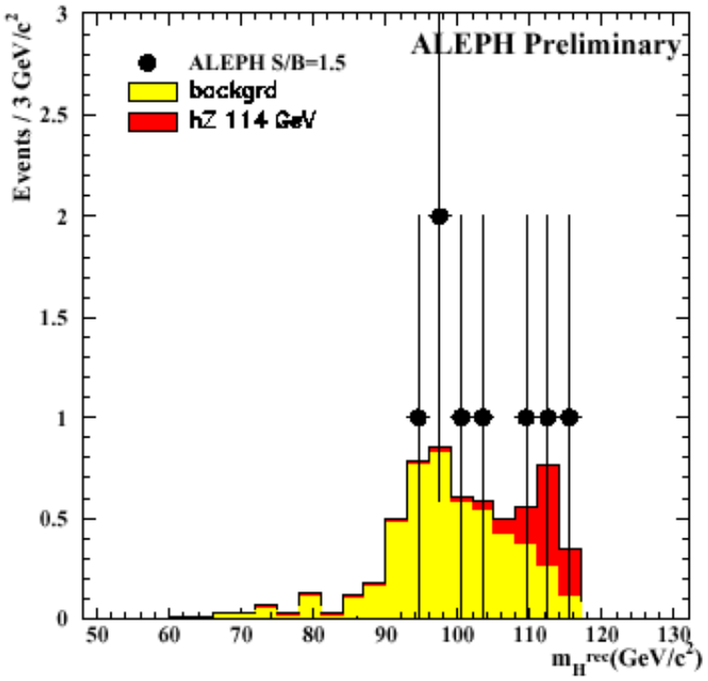
$M_{2\ b\ jets}$ compatible with M_Z

NN Analysis



When cuts are tightened, both accept the same three four jet events with $M_H > 109$ GeV/c^2

CUT Analysis



The survival of these three candidates indicates that they are indeed quite signal-like

Peter McNamara — Status of the Higgs Search at Aleph — November 3, 2000

..and major crises: LEP

LEP in the year 2000

- LEP has obtained important results in the last months of operation in the year 2000
- evidence for a Higgs particle at about 115 GeV/c^2.
- LEP Collaborations requested a further run in 2001(from May to October) in order to consolidate the data.

Agreement with SM Higgs cross-sect. for

$m_H = 115.0^{+1.3}_{-0.9}$ GeV

P. Igo-Kemenes - LEP Seminar - Nov. 3, 2000

Statistical Significance

2.2σ	September 5
2.3σ	LEP fest
2.9σ	November 2

Preliminary!!

- Run in September and October has been very beneficial: significance increased, better understanding of background

What to do next?

L.Maiani 9 Februay 2001 LEP @ICFA 4

To prolong LEP running for one year, required to stop the LHC civil works for the connection of SPS to the LHC tunnel, with an estimated cost of ~ 120 MCHF, to be added to the overall LHC budget.

Letter to G. Kalmus, Chair Scientific Policy Committee
November 4th, 2000

…an interesting evidence for the Higgs boson in LEP data. However, I am much more sceptical that a year running may allow us to get any better. ….Indeed, even the more optimistic analyses conclude that there are no golden plated events to be seen, all relying on small statistical effects accumulating here and there. This may well be the case, by the way, of LHC experiments, but when we shall be there we shall have all the time and the energy to improve the statistics as much as we want, a much more comfortable situation.

The idea that we may find ourselves in September 2001 with 3.5-4 sigmas, CERN's financial position aggravated, LHC delayed and LHC people disbanded is not very encouraging. I am not going to go along this way.

CERN Council, DG report, Dec. 15, 2000

The future of CERN is in the LHC !!!

CC Statement

"On 17th November 2000, the CERN Committee of Council held a meeting to examine a proposal by the Director-General concerning the continuation of the existing CERN programme, which foresees the decommissioning of the LEP accelerator at the end of the year 2000.

The Committee has expressed its recognition and gratitude for the outstanding work done by the LEP accelerator and experimental teams.

It has taken note of the request by many members of the CERN Scientific Community to continue LEP running into 2001 and also noted the divided views expressed in the Scientific Committees consulted on this subject.

On the basis of these considerations and in the absence of a consensus to change the existing programme, the Committee of Council supports the Director-General in pursuing the existing CERN programme."

This decision moves us definitely into the LHC era
A powerful complex, machine and detectors, to fully explore the Higgs and SUSY region

Le Roi est mort
Vive le Roi !!

15/12/2000 L. MAIANI. Status Report 2000

Epilogue: Committee of Council, Nov. 17 2000

. . . . The Committee of Council supports the Director General Luciano Maiani in pursuing the existing CERN programme, (which foresees the decommissioning of the LEP accelerator at the end of the year 2000).

At 8h00 a.m., November 2nd 2000, The LEP collider was shut down forever.

Since then in the Luciano office, I noticed (subliminal) a strange suitcase……..

May 2001 TI2 Breakthrough

June 2001
Magnets from Novosibirsk

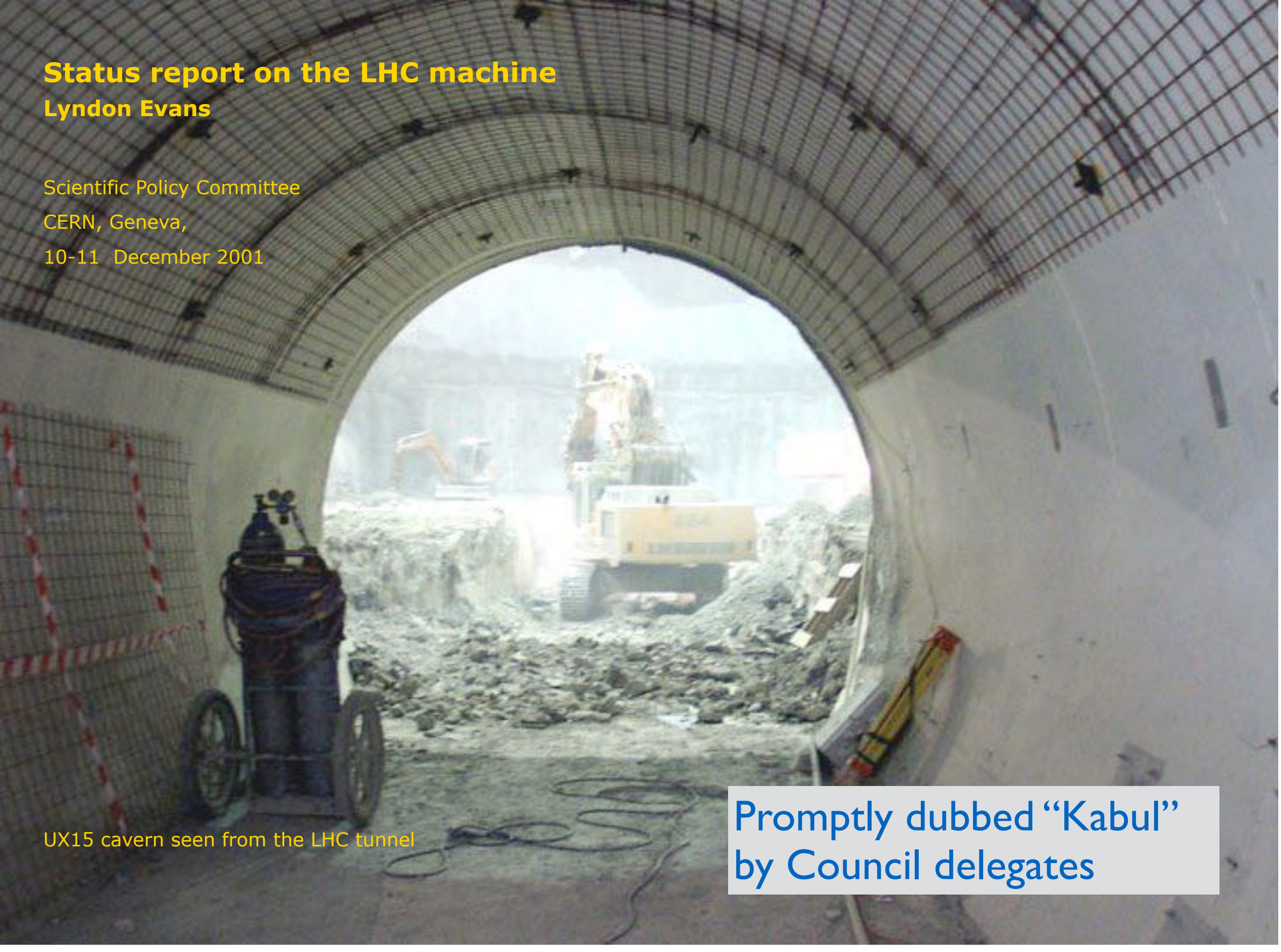
Status report on the LHC machine

Lyndon Evans

Scientific Policy Committee

CERN, Geneva,

10-11 December 2001



UX15 cavern seen from the LHC tunnel

Promptly dubbed “Kabul” by Council delegates

Dipoles in store @ CERN (and LEP magnets)

4. The cost-to-completion crisis

- In summer 2001 we received the replies to the call for making the 1232 magnetic dipoles, the biggest contract, and the cost of the escavation of the ATLAS and CMS halls could be made with good approximation
- A conference of the groups dedicated to LHC construction was made and a cost to completion could be estimated reliably
- at the same time, we could make a cost estimate for the upgrading of CERN infrastructures needed to host the LHC, obtaining a realistic cost-to-completion of the whole project.
- We presented the result to the Finance Committe, 19 Sept. 2001.
- A shortfall of money was found, with respect to the projected budget, and a big crisis started, which lasted until the end of 2002

The LHC extra cost to completion: main figures

Presented to the Finance Committe March 2002

Sept.19 talk	
480	LHC machine and areas construction
150	Prototyping
50	CERN share of detector construction and M&O
	LHC Injectors
120	LHC computing Phase II
	LHC infrastructure and support(*)(machine & detectors)
	Radioactive waste management
	Cut for LHC prototyping (over 2001-2008)
	Cut in R&D
	Cut in consolidation
40	Balance
	Missing in-kind contributions
≈10	

The model following the cost review and the assumptions above are:

LHC machine and areas construction	+ 475.0
Prototyping	+ 143.0
CERN share of detector construction and M&O	+ 56.0
LHC Injectors	+ 26.0
LHC computing Phase II	+ 120.0
LHC infrastructure and support(*)(machine & detectors)	+ 53.2
Radioactive waste management	+ 14.0
	+ 887.2
Cut for LHC prototyping (over 2001-2008)	- 143.0
Cut in R&D	- 25.8
Cut in consolidation	- 18.0
	- 186.8
Balance	+ 700.4
Missing in-kind contributions	+ 40.0
Total	**740.4**

Corresponds to the materials margin not allocated to the Remuneration Review (CERN/FC/4360/corr.) distributed so as to increase the support provided to the LHCproject and the related CERN infrastructure.

Further Assumptions:
Special Indexation of Host States stops after 2005
From 2006 onwards indexation keeps purchasing power

An opportunity for CERN

Chinese symbol for CRISIS (危机 contains two characters

That for DANGER (危险 and

That for OPPORTUNITY (机会

Present crisis should be viewed in a balanced way. Clear dangers

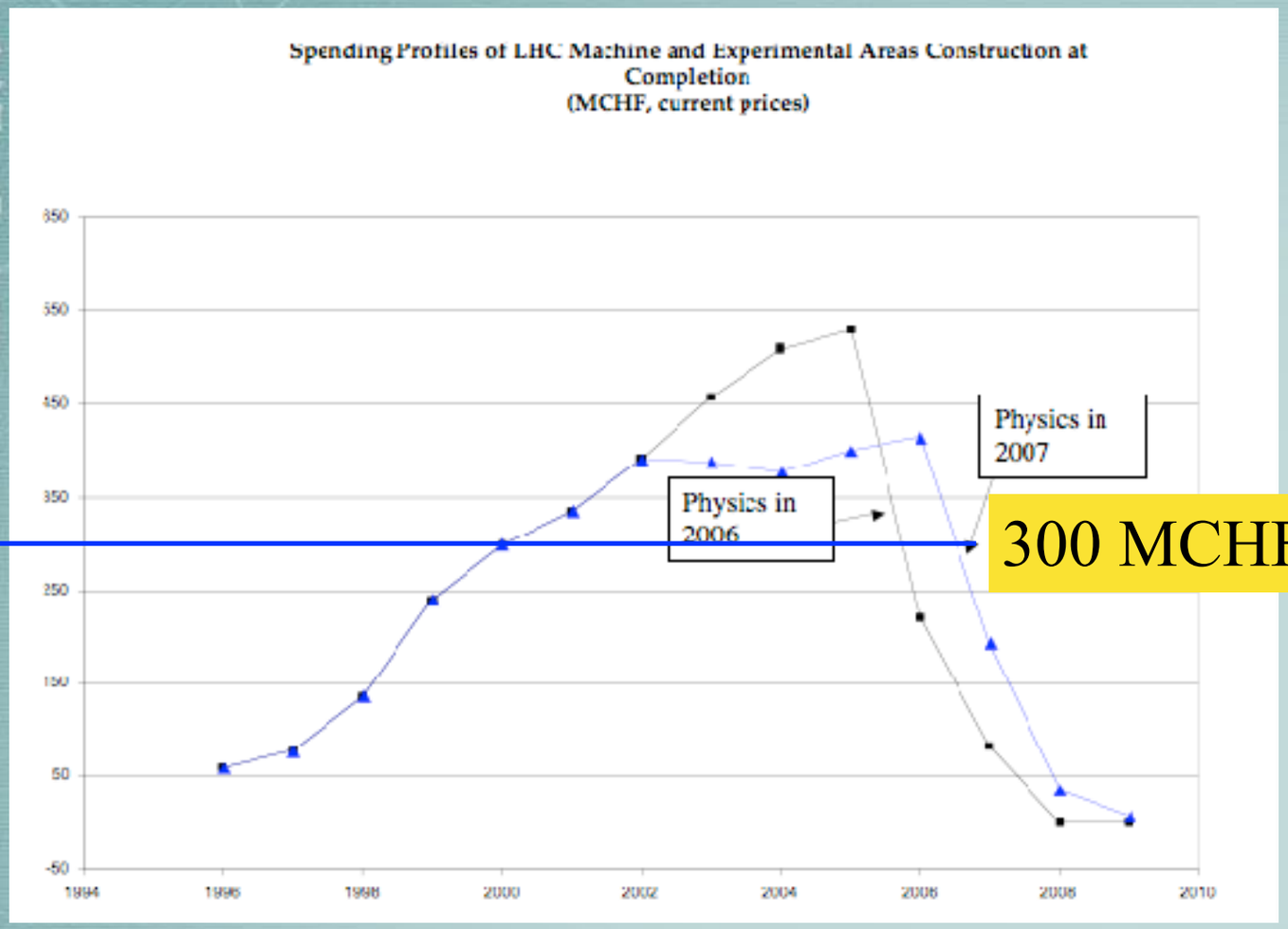
but also clearer opportunities coming to light

... a tough cure, a balanced package

In very rough figures:

- savings: ***reduction in science programme*** with recuperation of manpower, ***rescheduling*** (required anyway by cable production rate) ...more ***spending control***...(about 300 MCHF)
- extending repayment period from 2007 to 2010 (about 400 MCHF)
- CERN came out leaner but more focussed....

The last bump: the expenditure peak



…..The European Investment Bank proposed a loan of 300 millions Euro with 4% interest (the rate for a triple A Institutions) to be repaid within 2010.... the final crucial step in LHC financing.

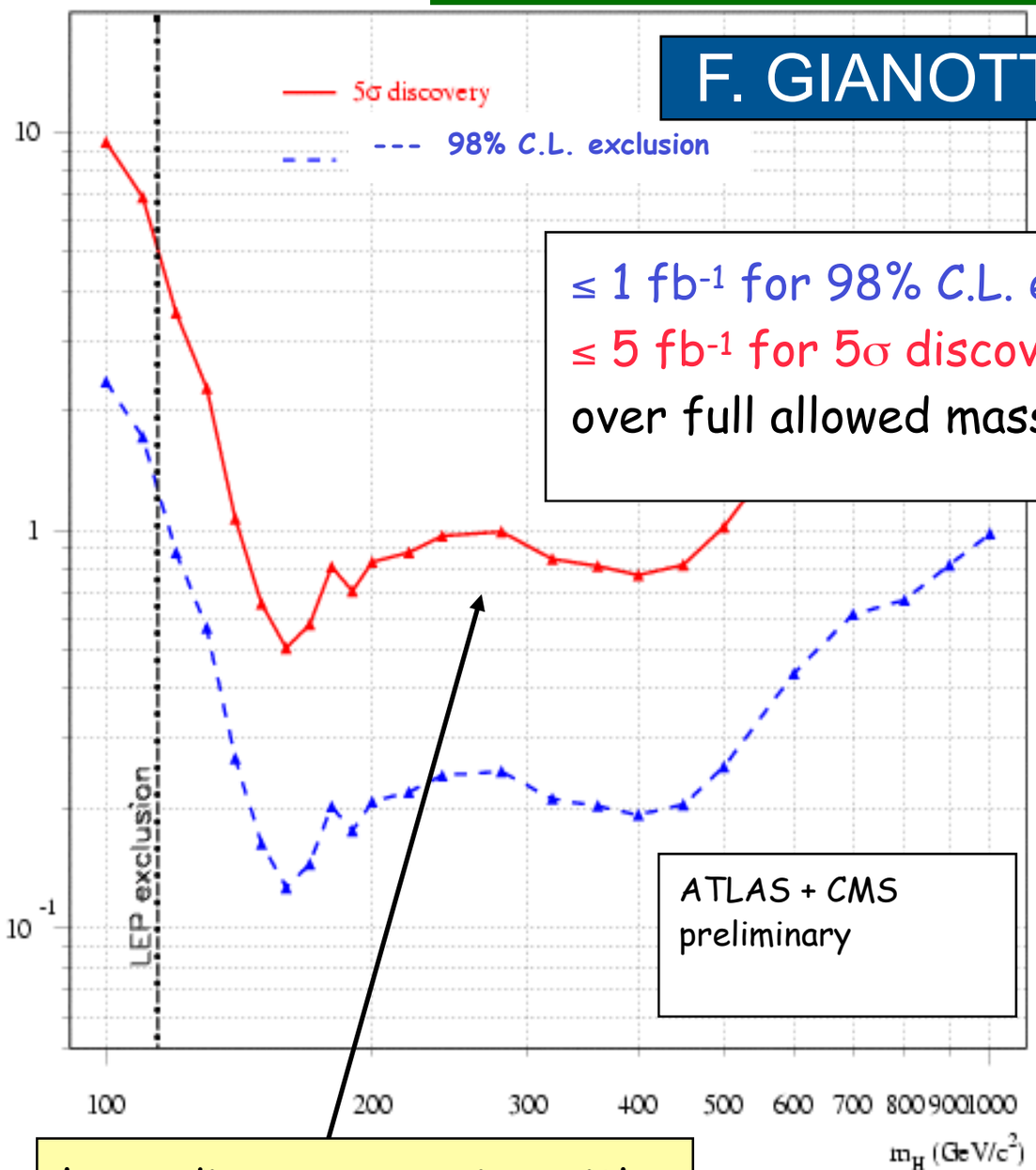
The loan to CERN was approved unanimously by Ecofin, the Council of the European Ministers of Economy and Finance.

The agreement was signed by the President of EIB and me in Bruxelles, on december 2002.

A loan for a research infrastructure was an absolute prime Europe. Commissioner Philippe Bousquin expressed that day the wish for the agreement to ‘open the way for similar initiatives, to promote the investments research and innovation in Europe’ (no follow-up, until now)

5. Higgs Boson Search at LHC (as seen in 2006)

F. GIANOTTI. ICHEP 06



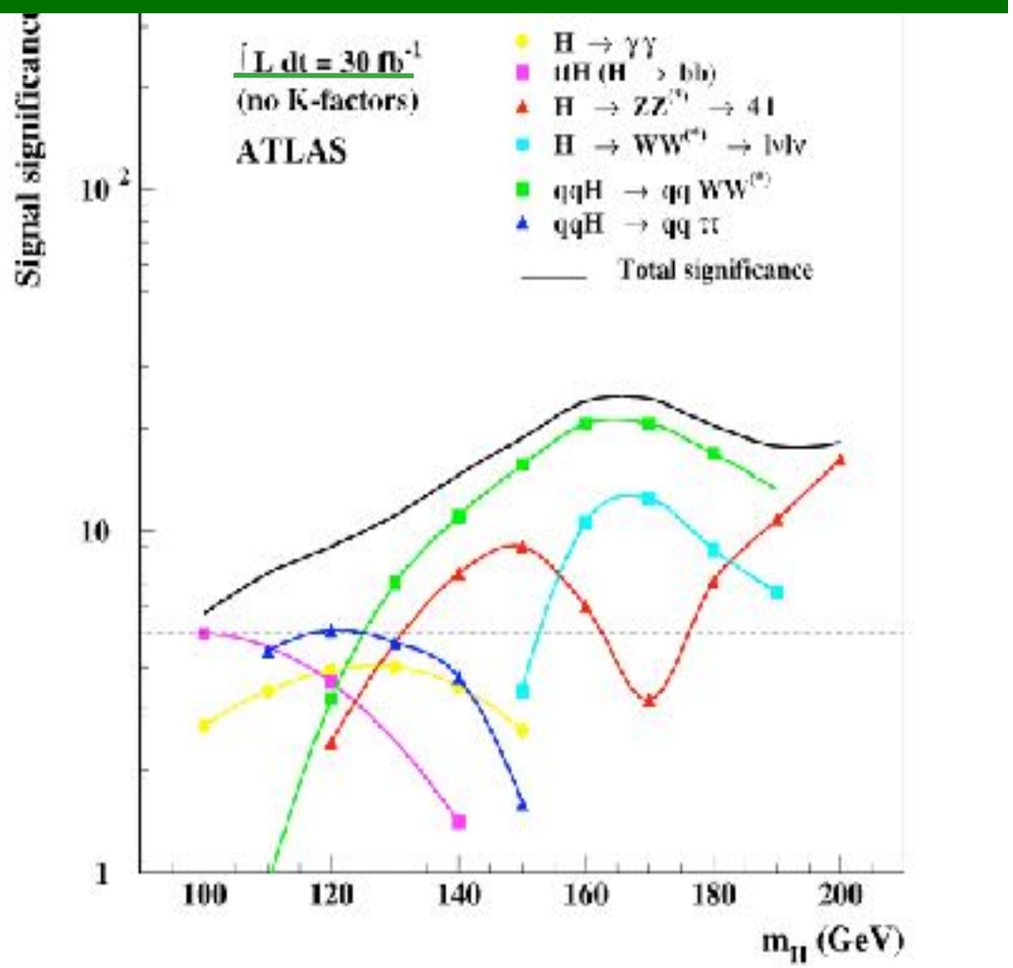
≤ 1 fb^{-1} for 98% C.L. exclusion

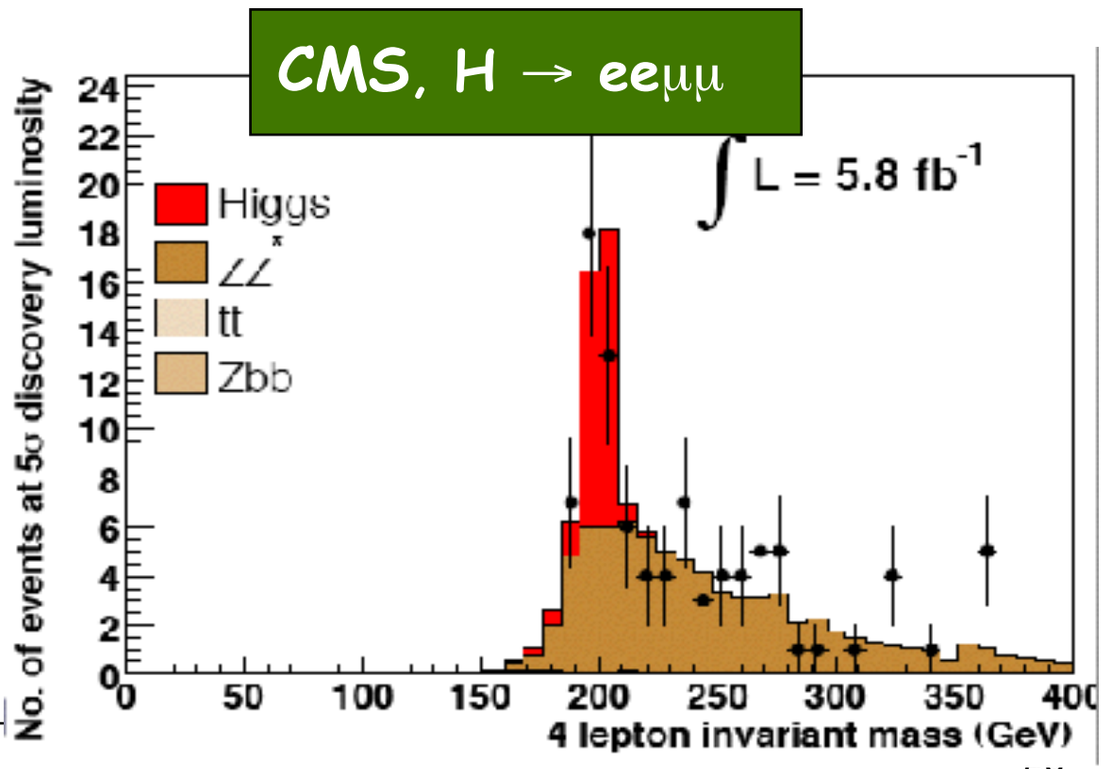
≤ 5 fb^{-1} for 5σ discovery

over full allowed mass range

here discovery easier with gold-plated H → ZZ → 4l

→ **by end 2008 ?**





H → 4l : narrow mass peak, small background

H → WW → lνlν (dominant at the Tevatron): counting channel (no mass peak)

2. ST Higgs search in the coming years: Tevatron, LHC

Summary Talk
Higgs Hunting 2006

TeVatron Highlights

Jean-François Grivaz

(LAL-Orsay)

for the CDF and DØ Collaborations

J.-F. Grivaz FRIF - November 13, 2006 1

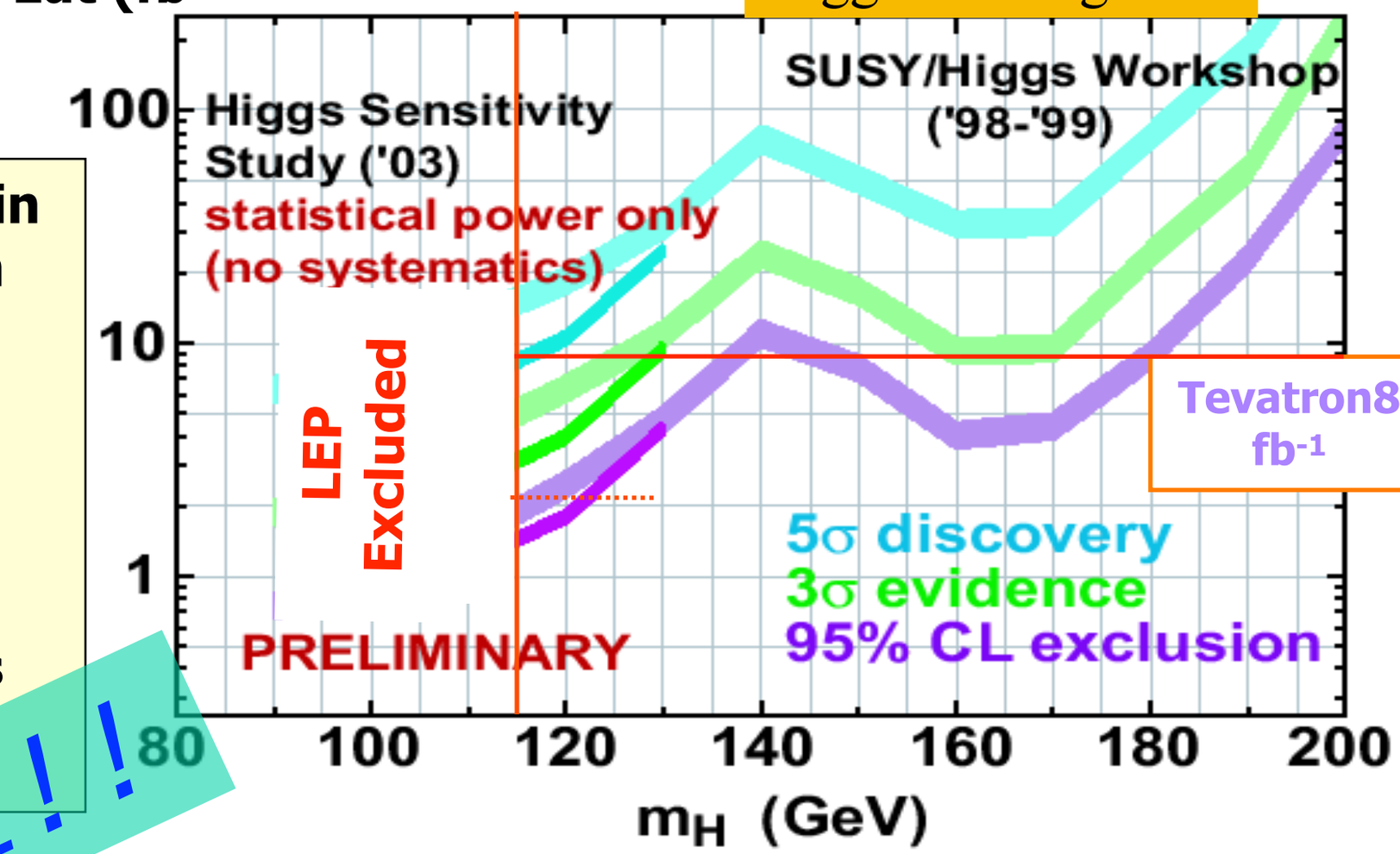
Tevatron SM Higgs Search: Outlook

Summary Talk
Higgs Hunting 2006

Prospects updated in 2003 in the low Higgs mass region

W(Z) H→ lν(νν,ll) $b\bar{b}$

→ better detector understanding
→ optimization of analysis



A SUIVRE ! !

Sensitivity in the mass region above LEP limit (114 GeV) starts at ~2 fb^{-1}
With 8 fb^{-1}: exclusion 115-135 GeV & 145-180 GeV,
5 - 3 sigma discovery/evidence @ 115 – 130 GeV

6. THE LHC TIME-LINE

Schedule redifined in March 2002

1.1. LHC Schedule

Contracts for dipole cold mass assembly are being signed;

CERN has a double role: supplier of SC cables, end-customer of the dipoles. We must be prudent in defining the dipole delivery schedule, hence the LHC schedule.

SC cable production to end mid 2005;

last dipole delivered July 1st, 2006;

Machine closed and cold: Oct. 2006;

First beam: April 2007;

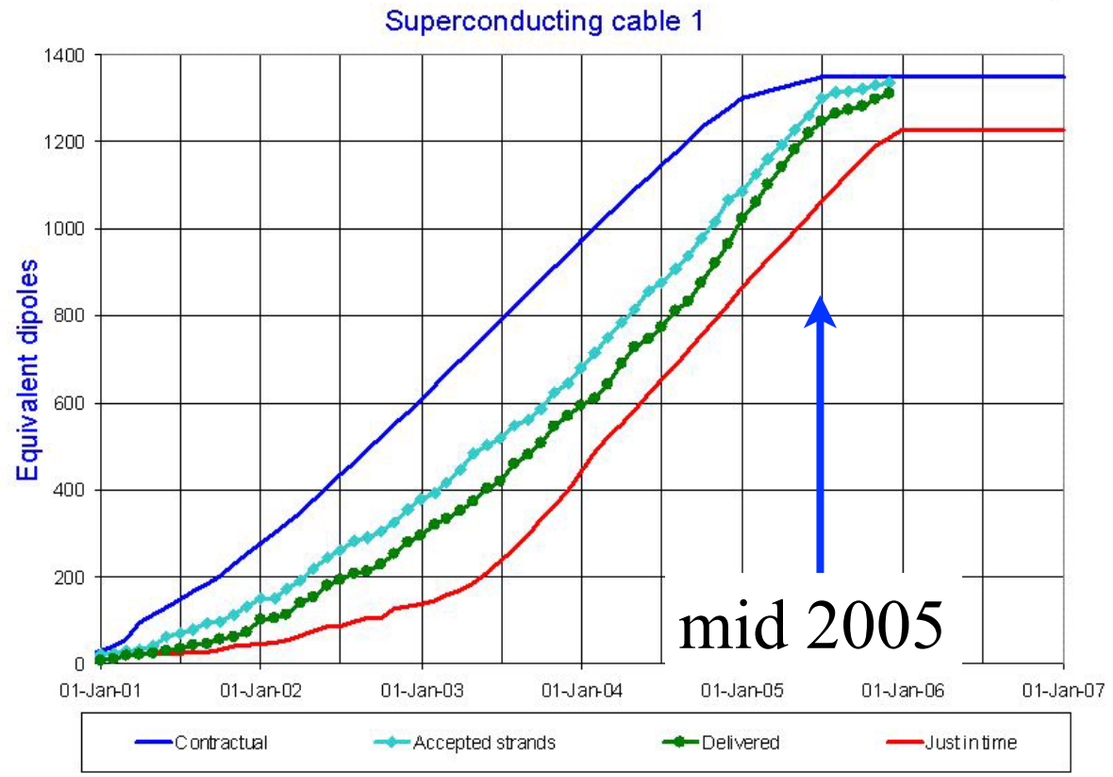
First physics: mid 2007;

Very solid foundation of the LHC confirmed by SC cable panel and Machine Advisory Committee.

L. Maiani. March 21, 2002 Committee of Council 8

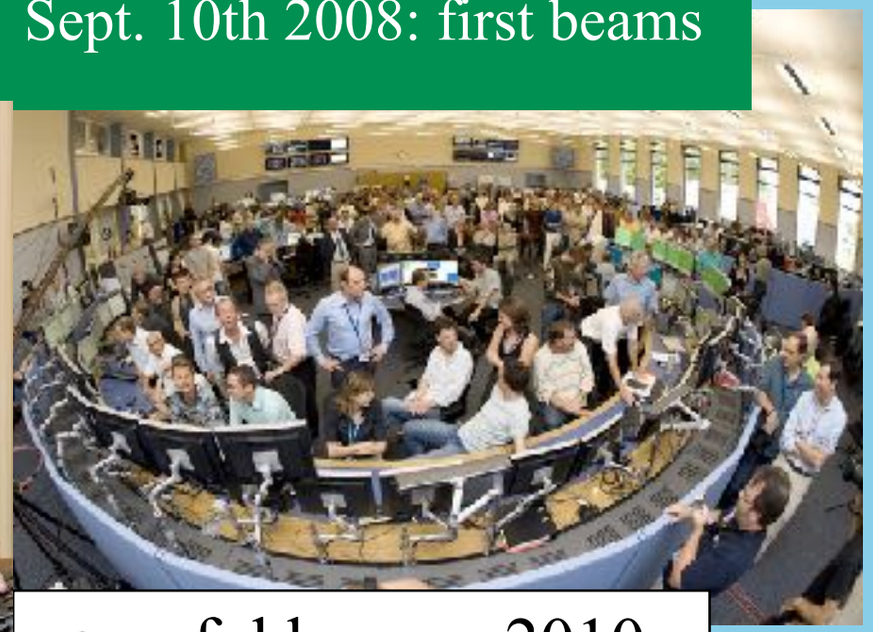
Dashboard

Department



Updated 30 Nov 2005 Data provided by A. Verweij AT-MAS

Sept. 10th 2008: first beams



- useful beams: 2010
- Higgs physics: 2011

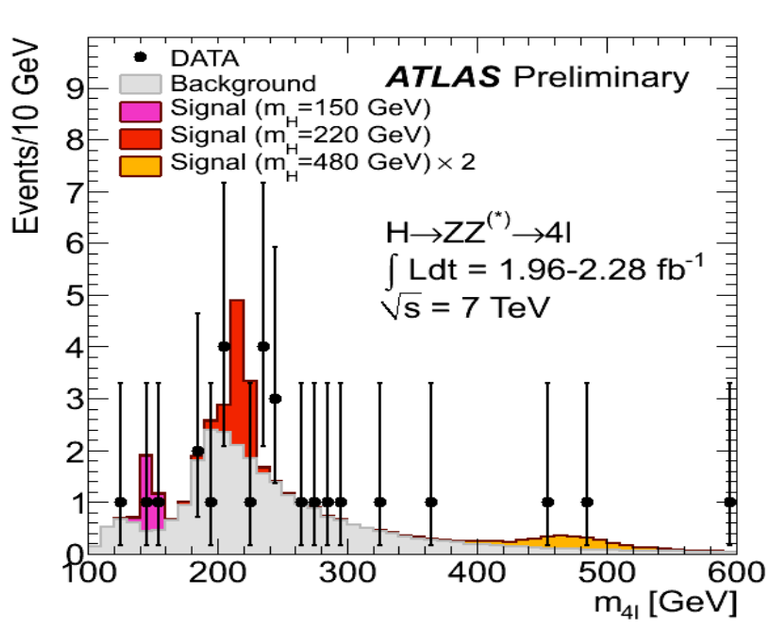
- 1.5 year delay due to problems with QRL
- another 1.5 year for the accident to SC dipoles resolved by Steve Myers

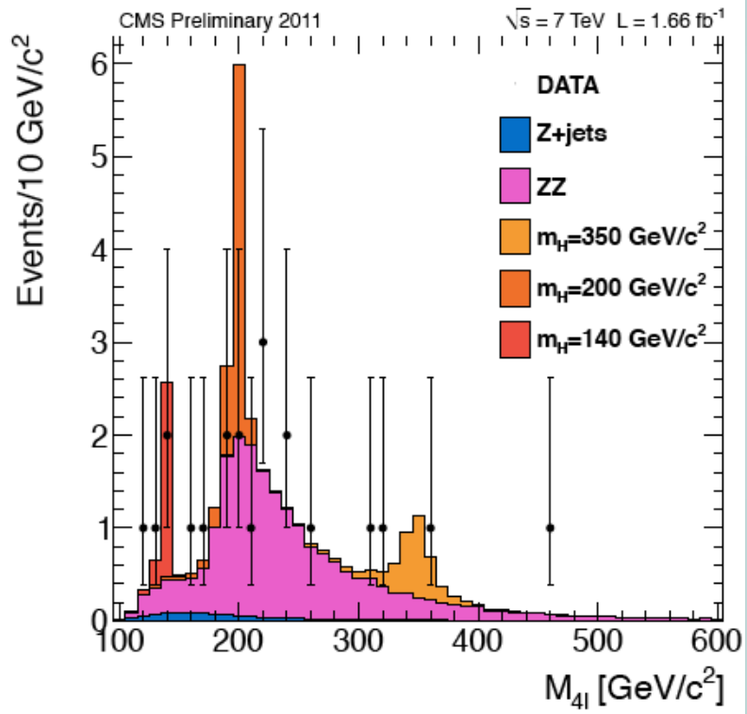
Lyn Evans and Lucio Rossi receive the last dipole at CERN

Higgs hunting: the situation in summer 2011, was summarised by Jim Virdee at the Ellis65 fest, @ ~2 fb^{-1} LHC luminosity

Imperial College London

Search for the SM H → ZZ → 4l





ATLAS
Observe: 27 events
6ee, 9eμ, 12μμ events
Expected: 28 ± 4 events

CMS
Observe: 21 events
5ee, 10eμ, 6μμ events
Expected: 21.2 ± 0.8 events

J. Ellis Colloquium-tsv 14

- Not so different from the situation at LEP, but…
- Luminosity increase to arrive in the coming year…no time limits

- At the same time…Tevatron was making a big effort to increase its luminosity
- Some worry from competition…

7. Discovery

CERN-4 july 2012

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !

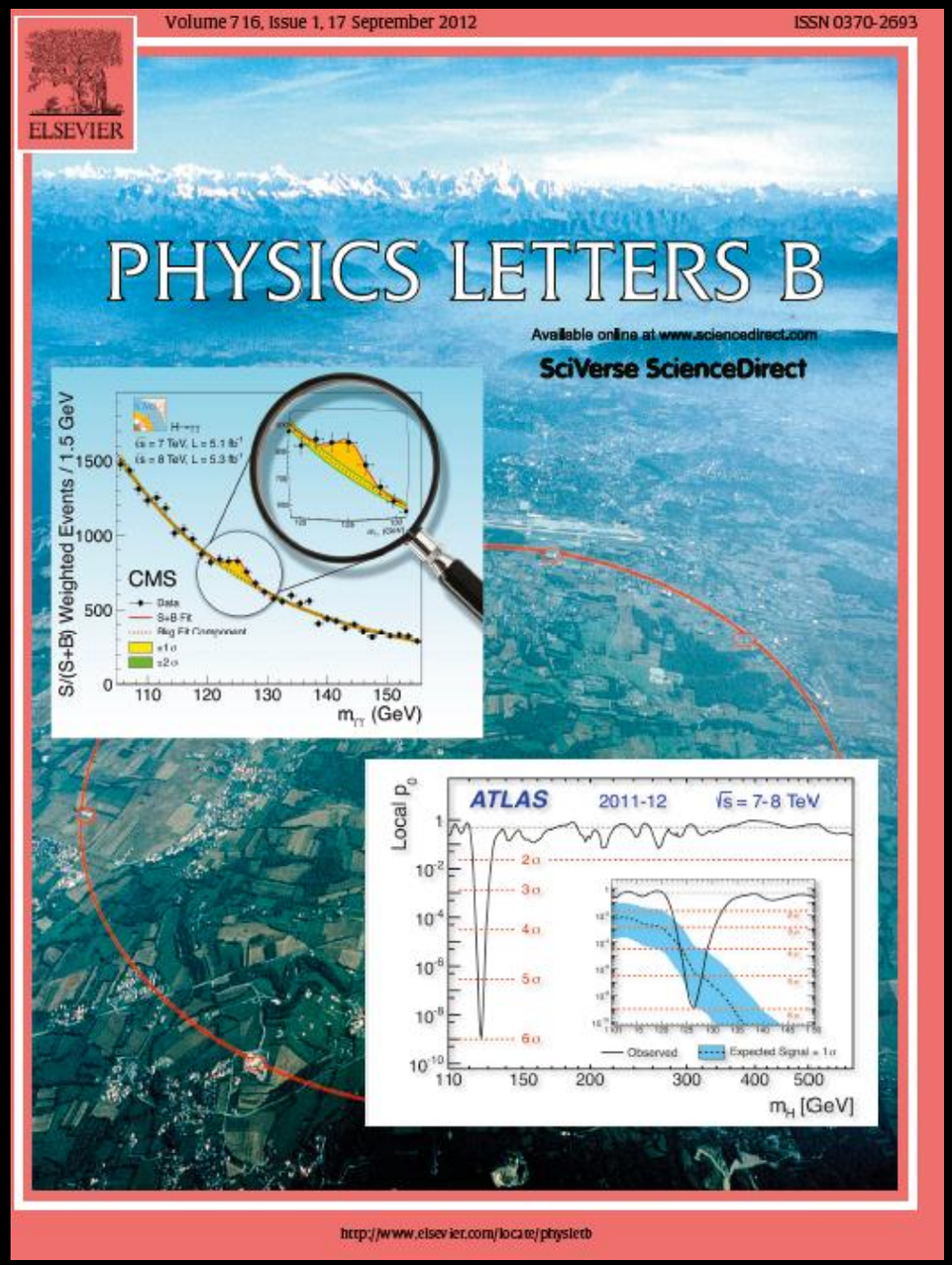
Fabiola Gianotti. ATLAS

Joe Incandela. CMS

In scientific press

The Discovery

July 2012

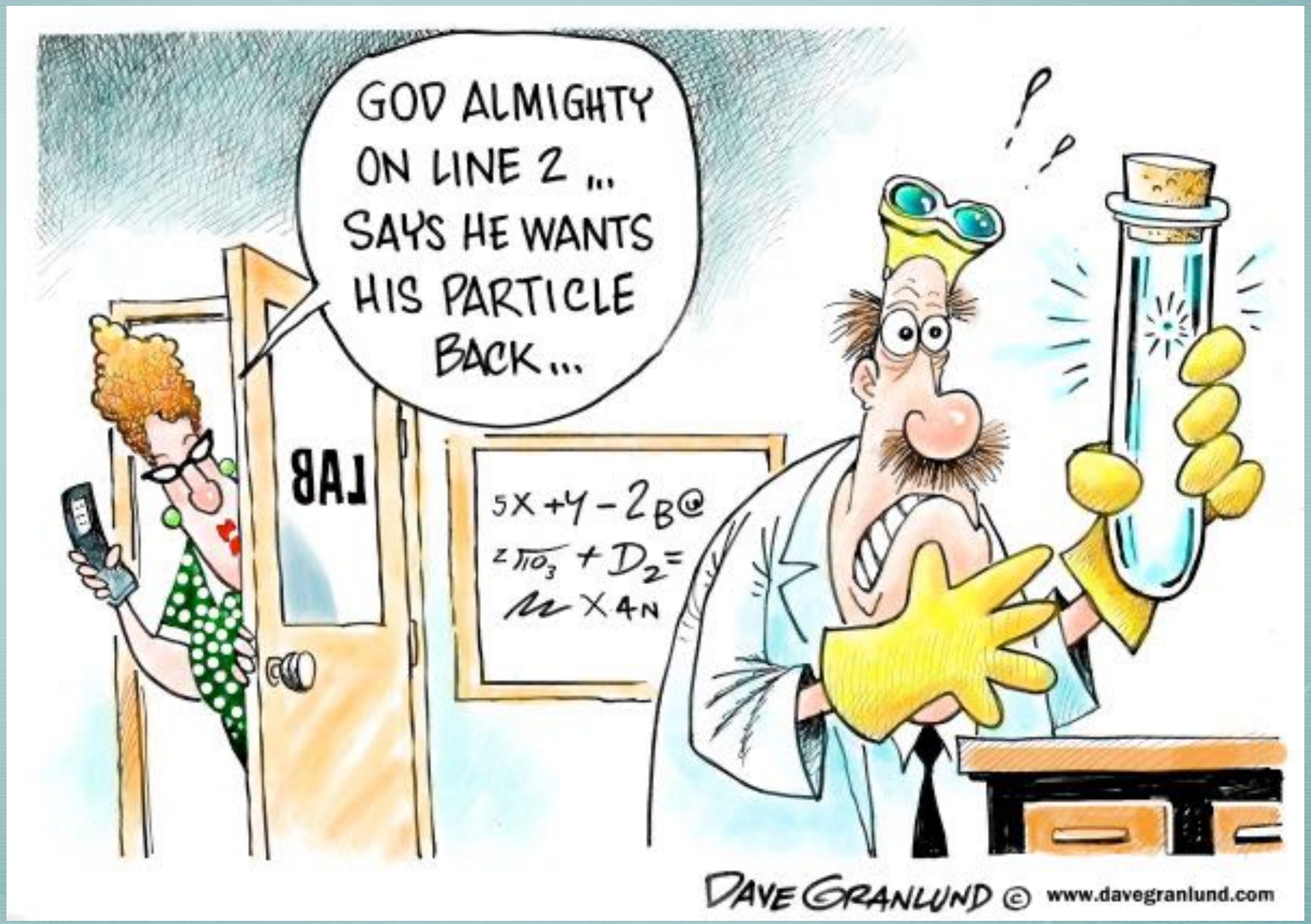


~ 3800 citations / experiment so far

October 2013

"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The “God particle”



8. The LHC has been a big industrial enterprise

- LHC used 1200 tons of superconductiong cable, for a total lenght of 7000 km
- during construction, LHC has been the largest single buyer of Niobium-Titanium cables
- one Nb-Ti bar 0 .9m long and 0.2 m diameter gives rise, after extrusion to 9000 filaments of 7 micron diameter and 30 km lenght.
- Magnets prototypes have been developed at CERN in collaboration with European research institutions (INFN for Italy) and European companies (ALSTOM, NOELL, ANSALDO (*))
- in this way it has been possible to transfer advanced technologies to European companies
- that are now using them for Nuclear Fusion facilities like ITER.

(*) now ASG Superconductors SpA, Genova

A few lessons learned

•Do not save on tunnel: a long and large tunnel has a longer lifetime than the first machine you put in;

•A global project, but centralised construction and responsibility: CERN management had the responsibility to stay within cost and, when extracosts were detected, CERN reacted coherently and responsibly;

•Starting from a big lab, already financed, not from green grass, helps!

•A fully globalised management (e.g. ITER) is more vulnerable to cost increases

•Cost-to-Completion crisis in 2001. CERN has profited from it to enforce real changes: a leaner programme, a well-focused Laboratory.

•LHC final costs to CERN:

	Personnel	Material	Total
Machine and Experimental Areas	**1 150**	**3 685**	**4 835**
Injectors	**86**	**67**	**153**
Detectors: construction, R&D	**879**	**312**	**1 191**
Detectors: test and pre-operation	**–**	**181**	**181**
LHC Computing	**86**	**93**	**179**
Grand Total	**2 202**	**4 337**	**6 539**

Table 1: Cost to CERN of LHC and associated detectors, in Millions CHF. Source: CERN/2840, May 27, 2009.

3 743 (2002 estimate)

- Global collaboration for detectors worked out very well

The result of more that 25 years of work (1984-2012) is an increadibly robust, upgradable complex, e.g. HL-LHC, that will produce physics for at least two other decades

feature article

Particle physics, from Rutherford to the LHC

Steven Weinberg

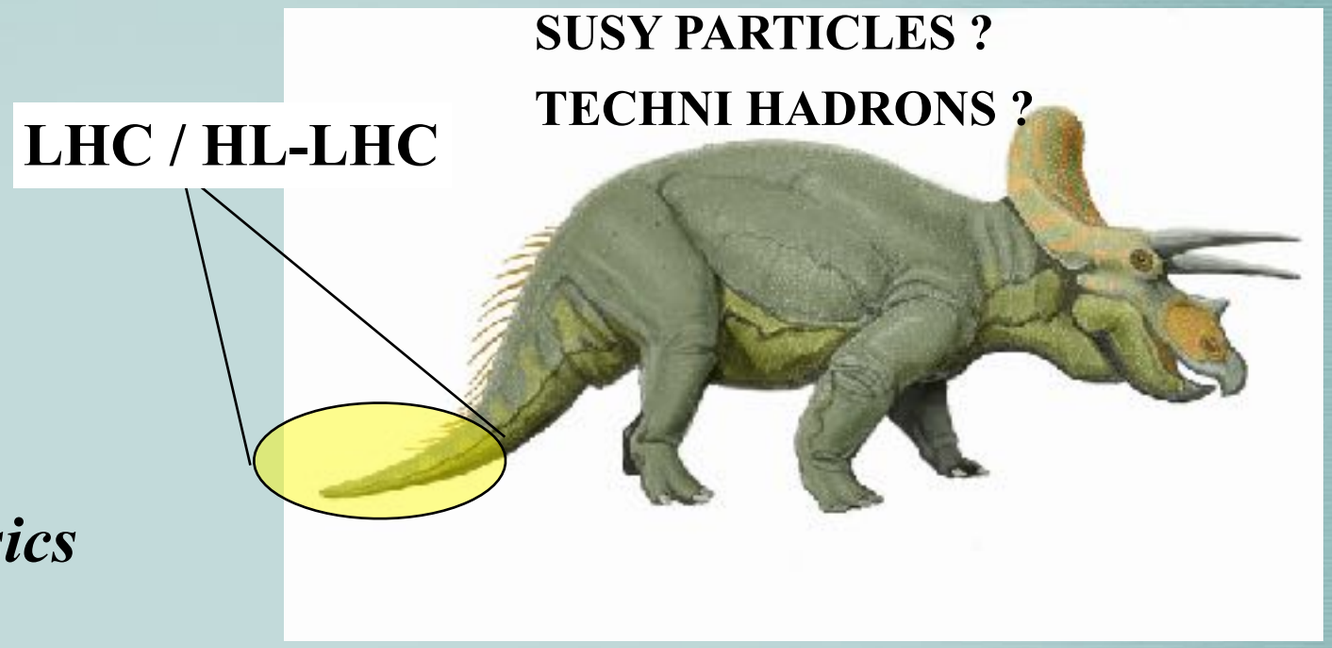
August 2011 Physics Today 33

Not the last word

It is clearly necessary to go beyond the standard model. There is a mysterious spectrum of quark and lepton masses and mixing angles that we have been staring at for decades, as if they were symbols in an unknown language, without our being able to interpret them. Also, something beyond the standard model is needed to account for cosmological dark matter.

9. What's next at High Energy?

- With the LHC / HL-HLC energy limitation, it is not likely that we can see all particles implied by SUSY or by Technicolor and find out which is the next step BEYOND the STANDARD THEORY



  - but we may be able to see the tail of the dinosaur….do not leave any possibilty untested
- ***Can we really guess what New Physics at High Energy is?***
- In the 80s we thought that the unnaturalness of ST could give the key to a complete theory of what is Beyond the Standard Theory (SUSY, GUT, then Gravity…)
- we may have guessed some real point…. compositeness, supersymmetry …but there are so many things we do not fully understand (which kind of SUSY, dark matter, hierarchy, strong interactions) that the physics we will find there will be, most likely, ***entirely new, strange and unexpected***.

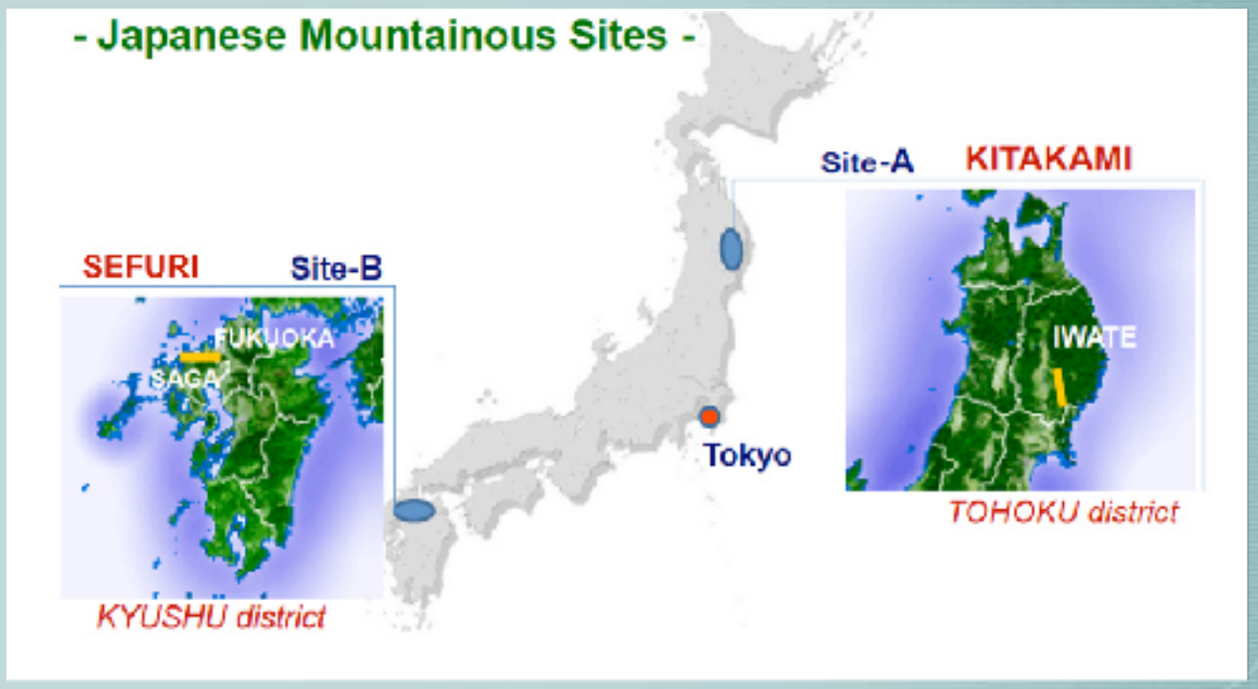
Experiments are definitely needed

Asia gets in

The electron-positron step

An $e^+ e^-$ Higgs boson factory, could aim at high precision to probe Higgs physics at high energies

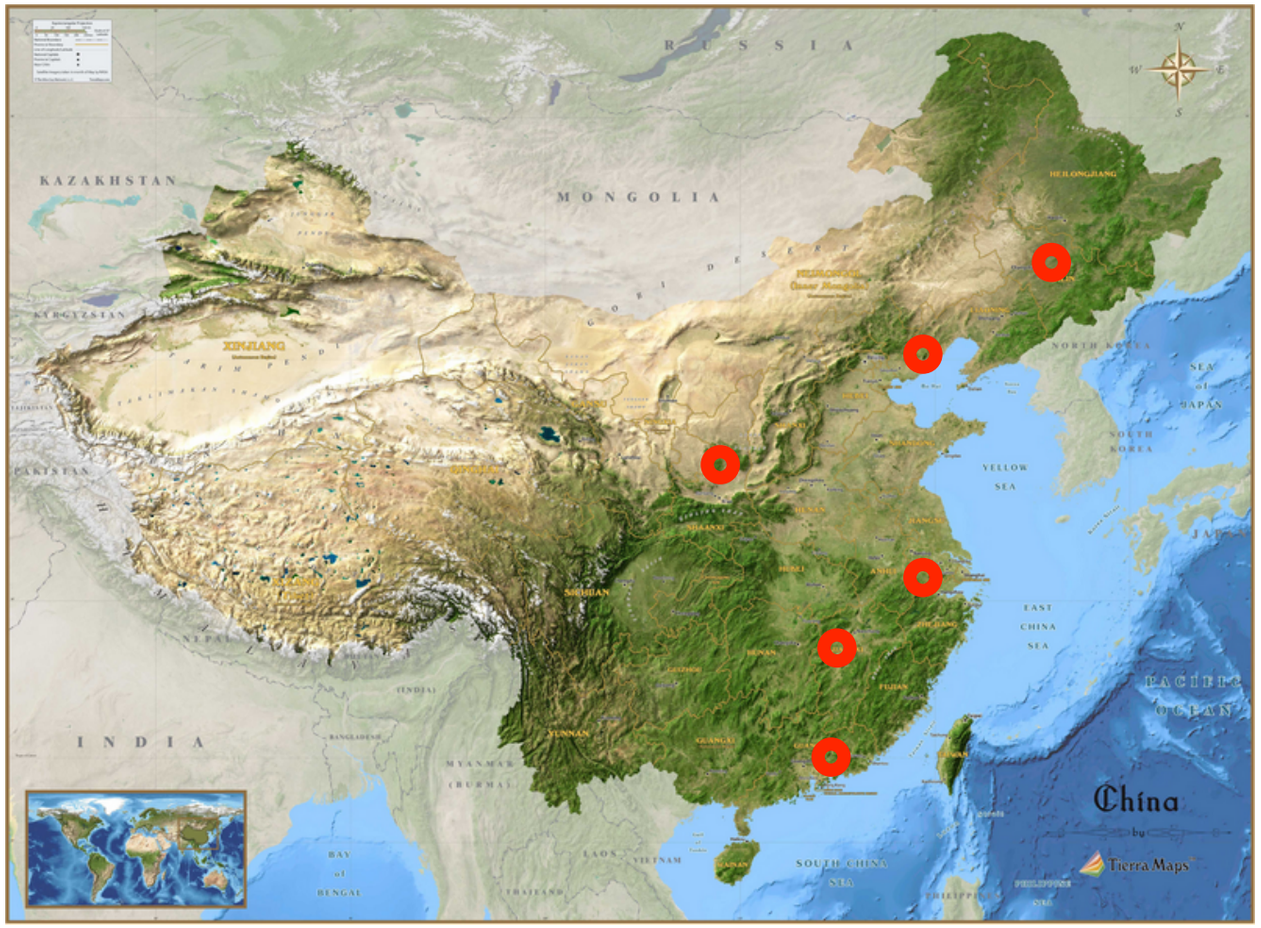
- International Linear Collider, e^+e^- @ 0.5 TeV:
  - site approved in Japan: (Kitakami)
  - a reserve site (Sefuri)



An alternative…

- Go for a circular e^+e^- @ 250-300 GeV in a large tunnel (Higgs factory)
- 70-100 km to make radiation losses acceptable,
- tunnel may host later a p-p collider @ 80-100 TeV, to explore the region left by LHC, 3 to 10 TeV
- projects are being made at CERN, (FCC-e^+e^-), and in China at IHEP (CepC)

CEPC site investigation and facility study

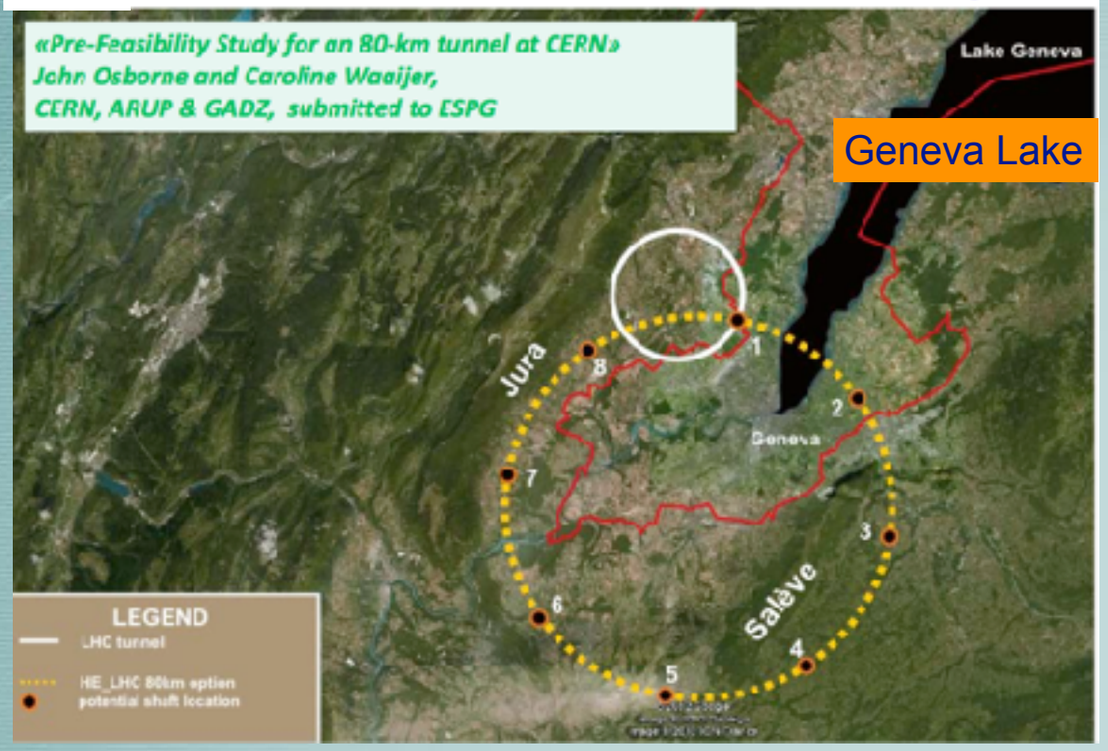


- Site selection based on geology, electricity supply, transportation, environment for foreigners, local support & economy,…
- North are better for running cost savings
- CDR study is based on Qing-Huang-Dao, 300 km towards the east of Beijing

- More invitations from local governments: Changsha, Changchun, …
- Recent visit to Shangsha: best for geology & transportation(20 km from a large city & an international airport)

Dreams about the future

FCC tunnel in the Geneva area – "best" option



A good example is Qinghungdao (秦皇岛)

- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted in the last 100 years

1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europe
1990's: Regional Laboratorie in Europe, America, Asia …
2030's: will they be able to unite in a Global Accelerator Network ? The World ??