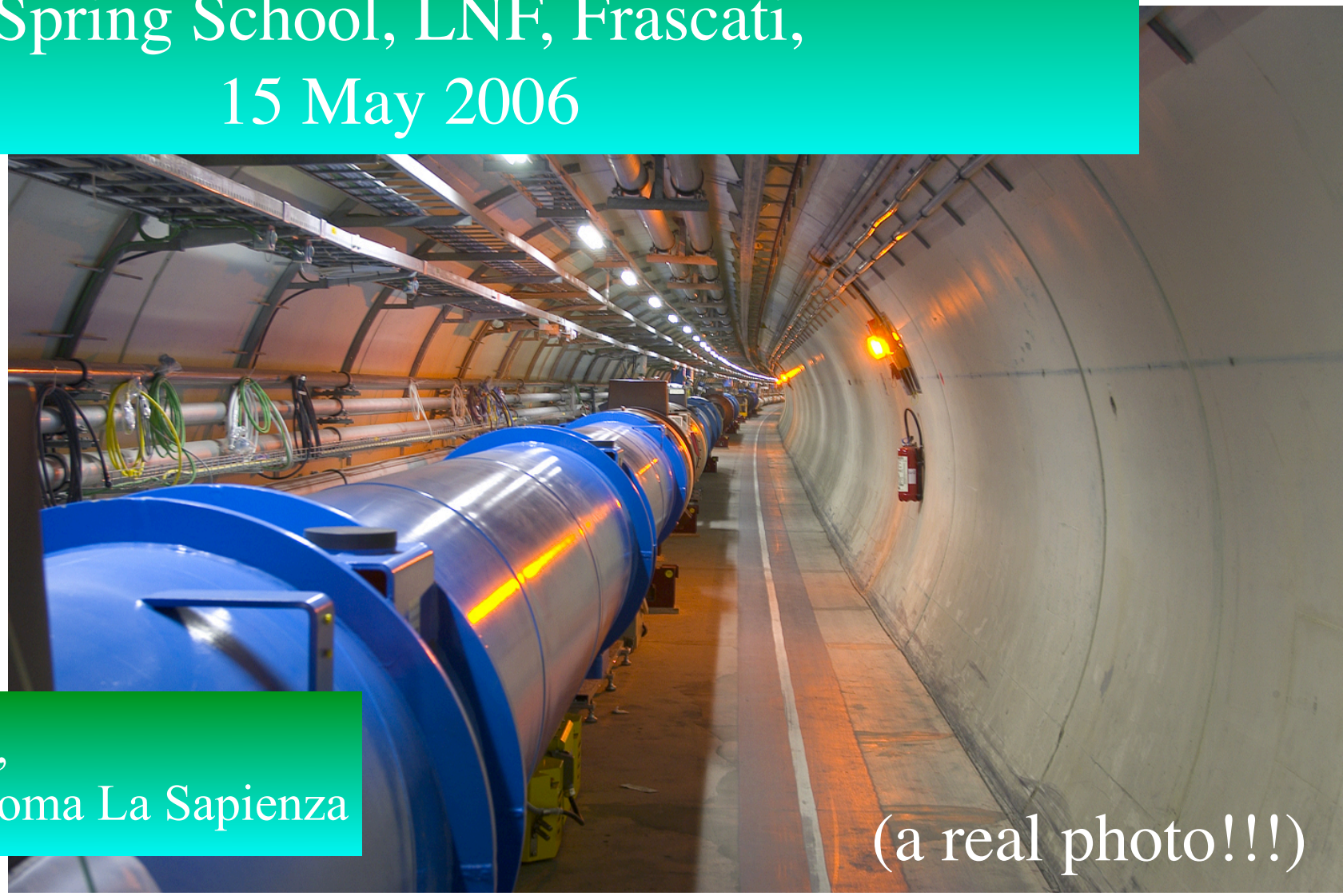
From LEP to the Large Hadron Collider @ CERN
Spring School, LNF, Frascati,
15 May 2006



Luciano Maiani,
Universita' di Roma La Sapienza

A revolutionary tool: Collision Rings

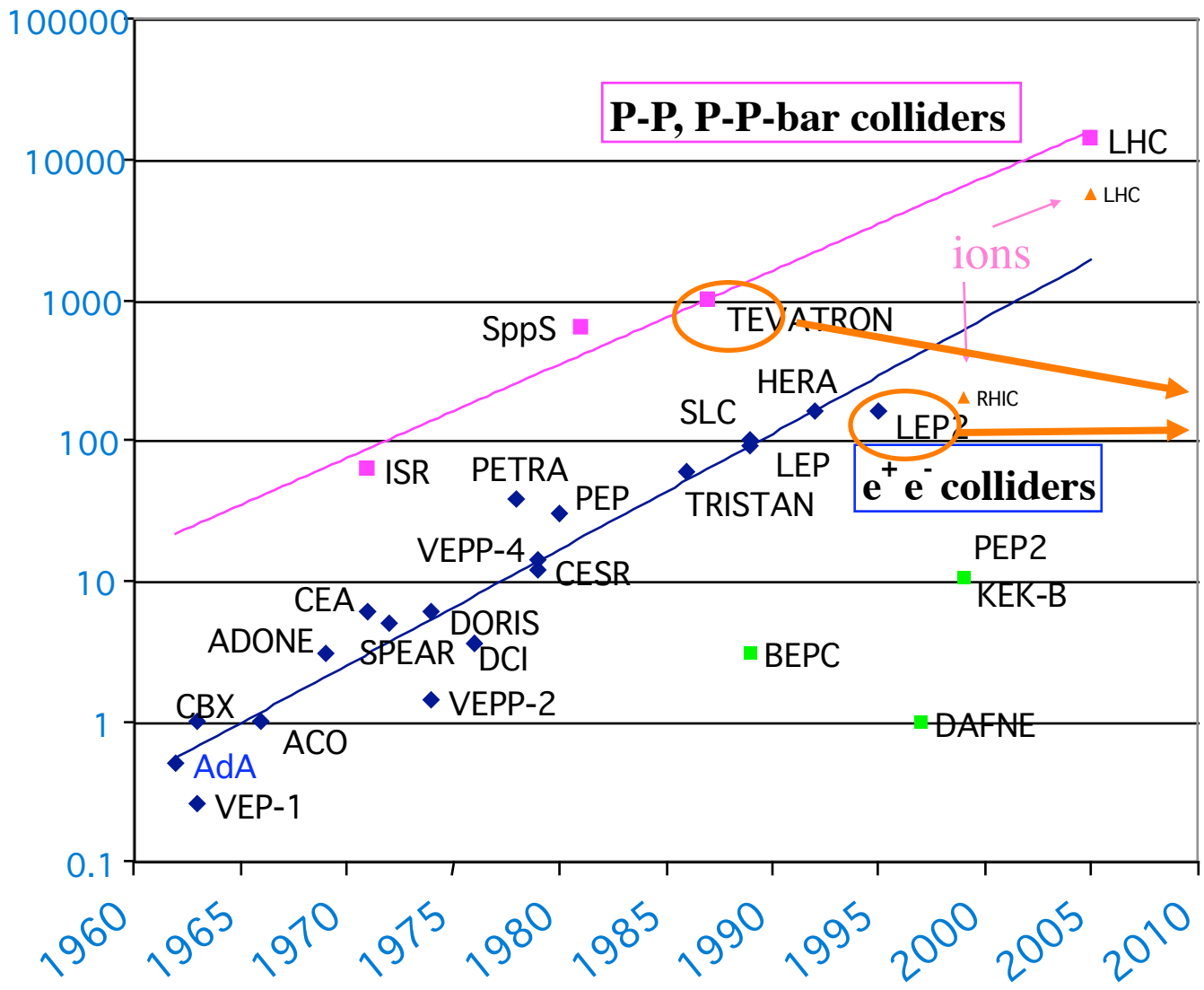
- beam-beam collisions : “train against train…” (B. Touschek)
- reach energies not possible for fixed target experiments
- Big technological problems had to be solved: intensity of beams (”nothing” against “nothing”??)), vacuum...
- First colliding e^+e^- ring: AdA, Lab. Naz. di Frascati (1962 B. Touschek and coll.)
- P-P ISR (CERN, 1971)
- P-anti P (Rubbia&VanderMeer, CERN, 1981)
- P-anti P (Tevatron, FermiLab-USA, 1987)

} same energy region, different probes

- e^+e^- (LEP, CERN, 1989)
- e^-P (HERA, Hambourg-DESY, 1993)

P-P (LHC, CERN), 2007: a new territory

Collider energies versus time



LHC planning started in between these two machines !

Preparing the way

- **1976 Richter at CERN, study of parameters of a big e+e- circular at CERN**

  Computing the optimal dimensions of an e+e- circular collider at the WW threshold, found a radius of 5-6 km, well suited to fit in the Gex plain
- CERN commissioned three study groups, starting in 1977.
- **1981** LEP project approved by CERN Council:
  - (i) conventional macchine up to 50 GeV/beam,
  - a second stage up to the WW threshold with sc radiofrequencies
  - Emilio Picasso Project Leader.

THE LEP TUNNEL

- The size of the LEP tunnel has been a delicate aspect
- Physicists had thought to make it wider than what was strictly needed, so as to be able to install later a proton machine with superconducting magnets
- The ECFA study made in Roma in 1978, chaired by A. Zichichi, had made a recommendation in this direction, nothwitstanding the resistence of those afraid that the implied cost increase would have put the very same LEP project at danger
- as a compromise, a tunnel of 4 meters diameter was accepted. This was not enough for a cryogenic system with two independent magnets (such as was designed for the SSC).
- CERN was forced to develop the more advanced design: “two-in-one”, more compact and 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 by certainly more than 20 years.

LHC two-in-one magnet in an early design (1990)

Table 3 : List of Magnets

		Magnetiic Length (m)	Number of magnets
Dipoles	B_o = 10 T	9.00	2 x 1792
Quadrupoles	G = 250 T/m	3.05	2 x 642
Tun. quads,	G = 120 T/m	0.72	2 x 400
Sextupoles	B" = 4500T/m^2	1.0	2 x 800
Orbit corr. dipoles	B_o = 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].

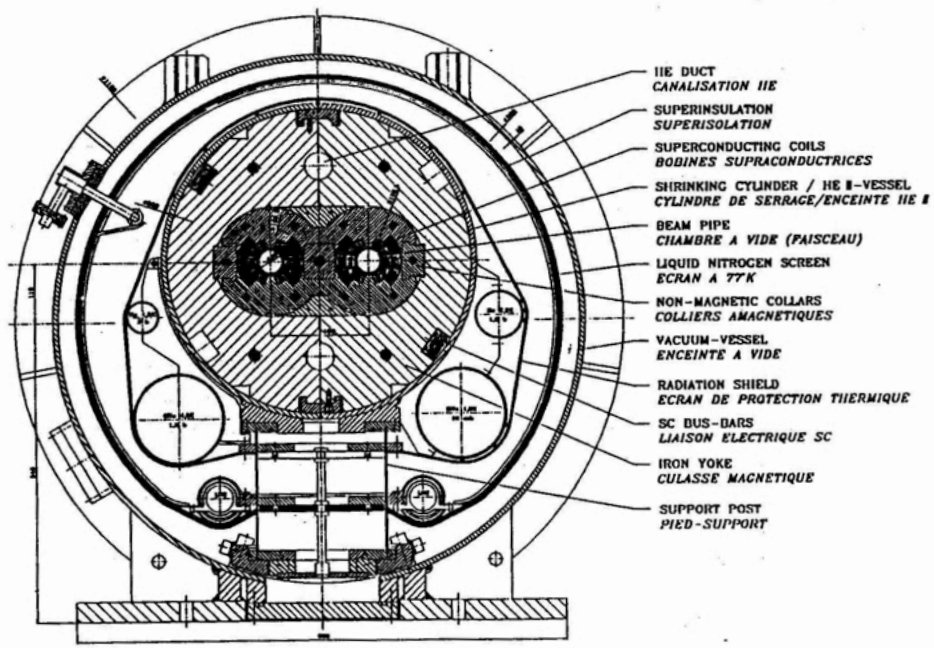


Fig. 3 : LHC dipole standard cross-section

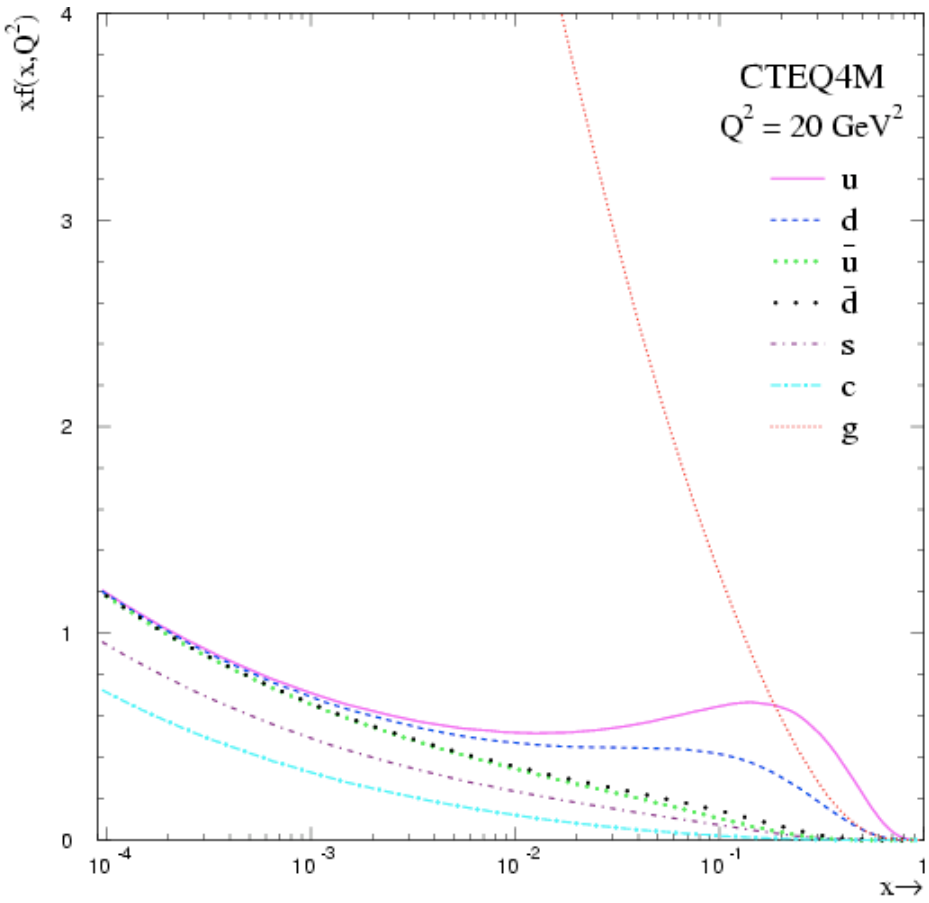
Jets and QCD evolution

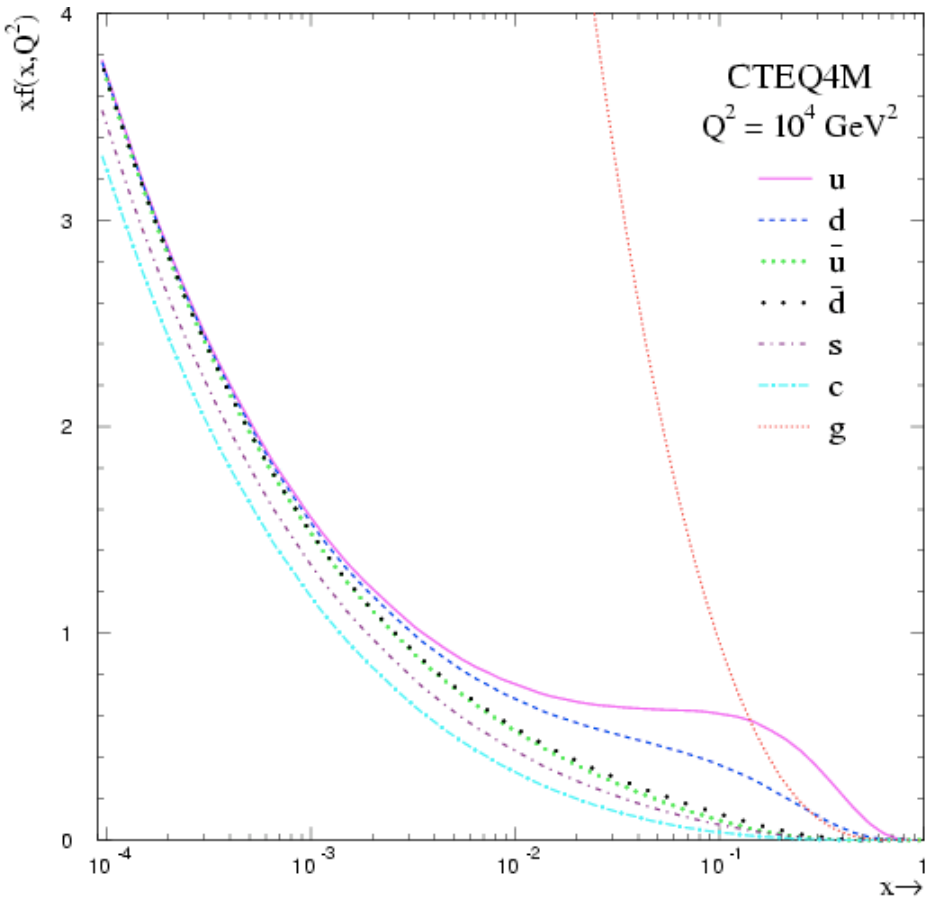
- **1982** SppbarS in operation: jets
  1983 Discovery of W&Z

  The discovery of jets (i.e. interactions of the constituents) in p-pbar has played a crucial role because it showed the possibility to study basic interactions even with hadron beams. No problem to get to high energy, compared to e+e-
- QCD evolution shows that there is no much gain in p-pbar vs. p-p collisions (gluons and sea constituents dominate). No problems with luminosity such as with pbar.
- By 1984-1985 the idea of a high energy proton collider in the LEP tunnel had gained momentum
- **July 1989 first Z0 at LEP.**

Physics at High Energy

Parton composition of High Energy protons





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): It (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 – really 14)**
- 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 2007 (+5+4=+9 years).
  - It was still considered possible to install in the tunnel together with LEP and run LEP and LHC concurrently (poosibility was kept alive until 1995-C.LL.S in Beijing mentioned that probably LEP had to be dismantled…I got protests by I. Mannelli)
  - 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.

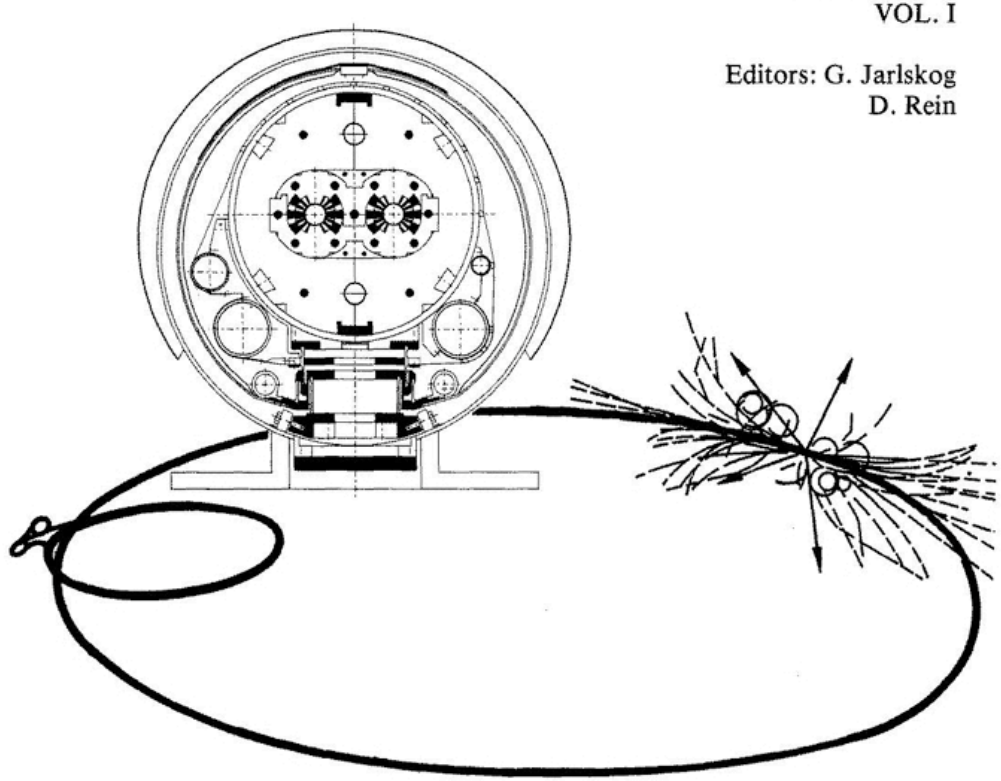
CERN 90-10
ECFA 90-133
Volume I
3 December 1990

EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

Large Hadron Collider Workshop

PROCEEDINGS
VOL. I

Editors: G. Jarlskog
D. Rein



Aachen, 4-9 October 1990

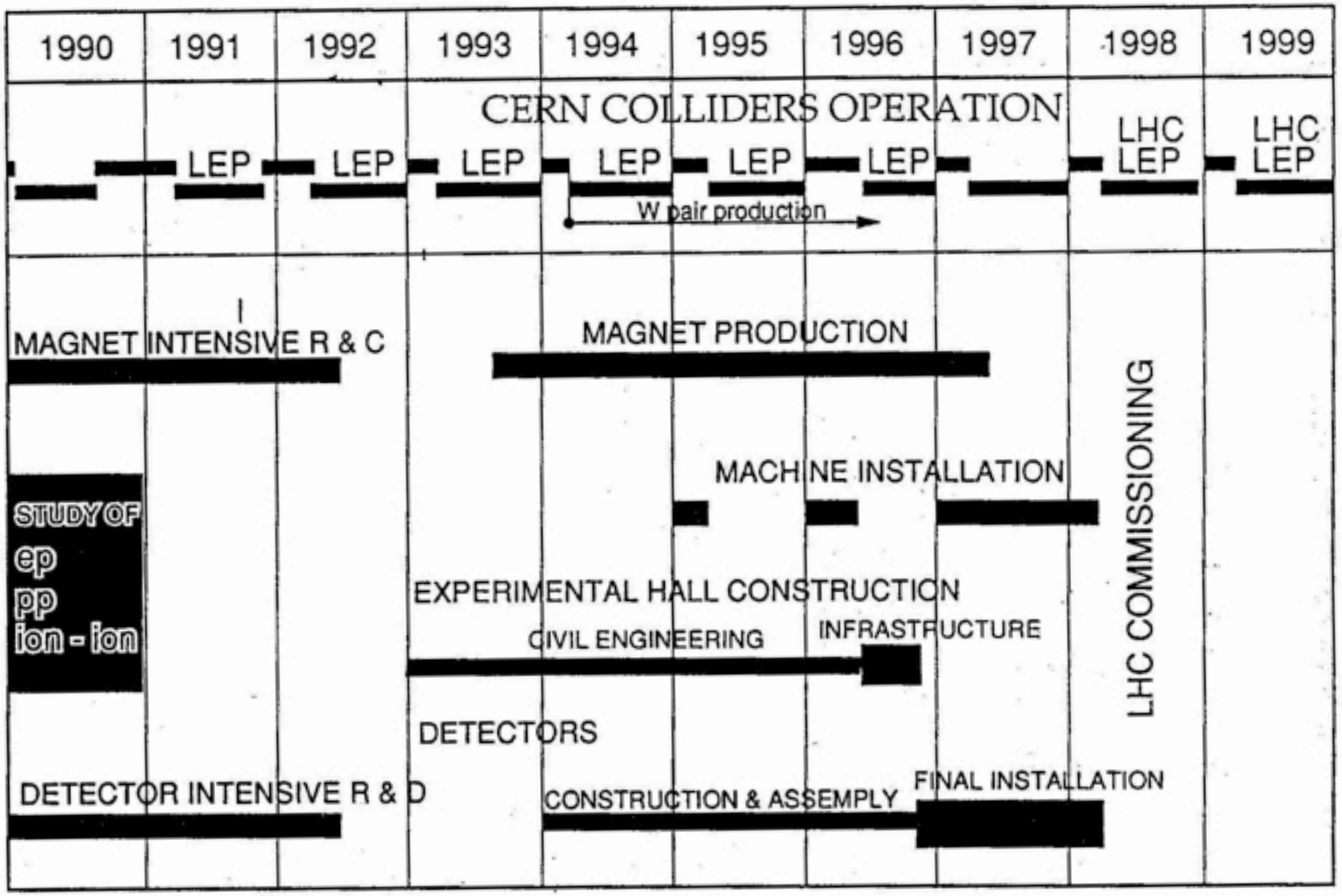


Figure 18 – Construction schedule of the LHC

Presented in Aachen, 1990

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

DIRECTOR - GENERAL

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Professor
L. Maiani
TH Division
CERN

Your reference:
Our reference: DG/CR/mcd/13651/7392

Geneva, 10th July 1992

Dear Professor Maiani,

As you know, the CERN Council has declared that the LHC will be CERN's next accelerator facility. Part of the requirements for the final approval will be a definition of the experimental programme. Preparations for this programme already started some time ago. In a very successful meeting in Evian last March, Expressions of Interest were presented. The meeting demonstrated the large interest in the physics opportunities of the LHC and the large amount of work which has already gone into the design of possible detectors.

With the SPC an experimental strategy has been outlined which foresees that first Letters of Intent should be submitted by 1st October 1992. An experimental committee, the LHCC, should evaluate these Letters of Intent, recommend to the CERN Management which collaboration should proceed with a technical proposal and monitor the development of these proposals, eventually leading to an approved programme at the time that the LHC gets its official go-ahead. It is planned that the LHCC will closely interact with the DRDC, the committee which has been instrumental in setting up a well focussed detector R & D programme, in evaluating technical aspects of the

Energy vs. Luminosity

- The first design of the LHC in the LEPtunnel have been presented in March 1984, ECFA workshop in Lausanne.
- Not competing on energy with the SSC, LHC invested in luminosity
- the ***energy-luminosity trade***:
  - since the proton energy is anyway >> parton energy, with high luminosity you can catch the rare collisions from high energy partons which are always present in the proton.
- high luminosity was a risky business:
  - betting in a machine that we knew (perhaps!) how to build with detectors that we did not know for sure how to make.
- A long R&D was necessary. Today we know!!!

The "Luminosity-Energy trade": reappears now with the SLHC !!

Indicative Physics Reach

Fabiola Gianotti: ICFA Seminar

Units are TeV (except $W_L W_L$ reach)

ILdt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	LHCx2 28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	LC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ		90σ
Z'	5	6	8	11	35	8 *	30 *
Extra-dim (δ=2)	9	12	15	25	65	5-8.5 *	30-55 *
q*	6.5	7.5	9.5	13	75	0.8	5
Λ compositeness	30	40	40	50	100	100	400

* indirect reach
(from precision measurements)

Approximate mass reach of pp machines:

$\sqrt{s}$ = 14 TeV, $L=10^{34}$ (LHC) : up to ≈ 6.5 TeV

$\sqrt{s}$ = 14 TeV, $L=10^{35}$ (SLHC) : up to ≈ 8 TeV

$\sqrt{s}$ = 28 TeV, $L=10^{34}$: up to ≈ 10 TeV

$\sqrt{s}$ = 40 TeV, $L=10^{34}$: up to ≈ 13 TeV

$\sqrt{s}$ = 200 TeV, $L=10^{34}$ (VLHC) : up to ≈ 75 TeV

The SSC drama

- The SSC (Superconducting Super Collider) was proposed in the US in the first '80s: proton-proton, very high energy, 20 TeV/beam;
- **1988** **SSC approved,** proton-proton, 20 TeV/beam, 87 km tunnel, cost 4-5 B US$.
  1989 SSC construction starts.
- **1993** SSC discontinued by the US Congress after a bitter discussion which invested all the scientific community (projected cost >10 B US$)
- the cancellation of the SSC programme made a terrible shock-wave in Europe, firing back on particle physics and CERN.
- Top discovery had a very good balancing effect (as seen from Italy)
- Luckily, on the basis of the SppbarS and LEP successes, CERN project has been approved in 1994.

The 1994 approval of LHC

Le Conseil du CERN

1) Déclare que la décision d'inclure le LHC dans le Programme de base vaut pleine approbation de la construction d'un collisionneur de 14 TeV, mais que, compte tenu des plans actuels et des recettes escomptées, cette construction devrait se faire en deux étapes.

2) Déclare que les éventuelles contributions d'Etats non-membres serviront à accélérer et améliorer le projet, et non à permettre de réduire les contributions des Etats membres.

3) Prend note avec gratitude des engagements de la France et de la Suisse de verser des contributions volontaires pour aider et accélérer la réalisation du LHC.

4) Déclare que l'indice global de variation des coûts à appliquer aux contributions des Etats membres devrait être nul dans la période de 1995 à 1997.

5) Décide que la planification devrait reposer sur l'hypothèse d'une inflation de 2% et d'une indexation des contributions des Etats membres au taux de 1% à partir de 1998.

6) Convient que l'examen complet de l'avancement du projet LHC, qui devra être effectué avant la fin de 1997, portera sur la question de savoir si le LHC doit être construit en une étape au lieu de deux.

2 stages

Role of non-MS contr.s

2% indexation + special contr.s

Indexation model

D-Sulla
15/12/94

CERN/2039(a) (REV 2)
DRAFT

DRAFT RESOLUTION
APPROVAL OF
THE LARGE HADRON COLLIDER (LHC) PROJECT

COUNCIL,

HAVING REGARD TO

the Resolution (CERN/1904) it adopted at its 93rd Session on 20 December 1991 stating that the LHC is the right machine for the advance of the subject and *for* the future of CERN;

CONSIDERING

The proposal to construct a Large Hadron Collider ***with a centre of mass energy of 14TeV*** in the LEP tunnel (CERN/SPC/679-CERN/CC/2016; CERN/SPC/677-CERN/CC/2014; CERN/SPC/677/Add.-CERN/CC/2014/Add.; CERN/CC/2030; CERN/2039; ***CERN/SPC/695-CERN/CC/2072, including the budget scenario in table 2);***

the Resolution it adopted at its 99th Session on 15 April 1994, which again endorsed the scientific case for the LHC, supported the promotion of the LHC as the central element of the long-term programme of CERN, expressed a wish that the LHC be implemented as part of the basic programme of the Laboratory, and endorsed the proposed comprehensive review of the progress of the project, to be carried out at an appropriate moment and in any case before the end of 1997 in order to define more precisely the timetable for execution of the project in the light of the foreseen funding;

Articles II, III and V of the CERN Convention;

CERN/2179 (Dec. 1996)

RESOLUTION

concerning the construction of the LH and the funding of the Organization

DECIDES

1.

that the LHC Project shall be completed in a single stage and planning shall proceed on the basis that the LHC shall be commissioned in 2005;

2.

that funding of the LHC will be preserved as foreseen when the project was approved, in the framework then agreed (CERN/2075 and the statement annexed thereto), albeit with a reduction in the Member States 'annual contributions to the Organization of 7.5%in 1997,8.5%in 1998-2000,and 9.3%in 2001 and thereafter,compared to the level foreseen in December 1994;

3.

that it will make every effort to ensure that the ordinary contributions from each Member State during the period 1997-2008 will not fall below the level implied by its above decisions;

URGES

all Member States to make every effort to pay their full ordinary annual contributions during the first quarter of each year, and to examine the possibility of making advanced payment of their ordinary annual contributions;

AND ENCOURAGES

additional contributions to enhance the vitality of the general scientific programme during the LHC construction period.

Normal sufferings...ground freezing at the CMS shaft

Status report on the LHC machine

Lyndon Evans

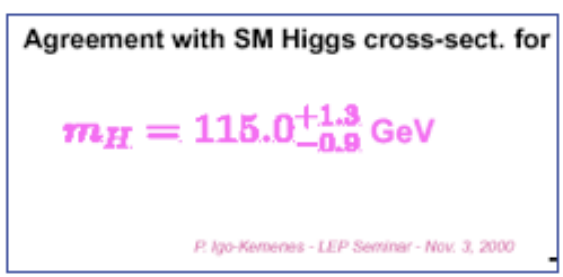
Scientific Policy Committee
CERN, Geneva,
10-11 December 2001

UX15 cavern seen from the LHC tunnel

..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.



Statistical Significance

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

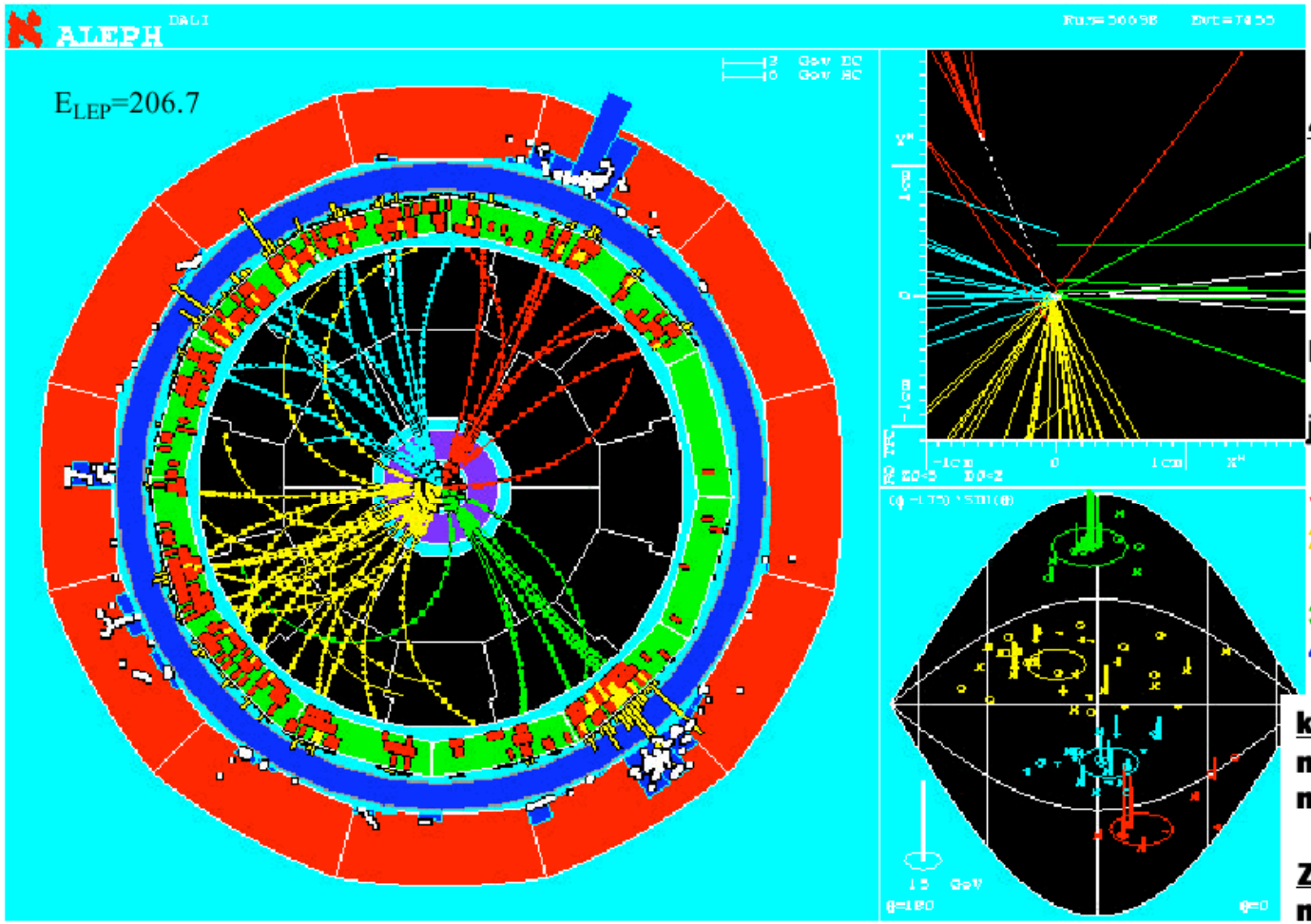
Preliminary!!

- 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

ALEPH candidate, summer 2000



4 b cand.

m_H=110 GeV
±3 GeV

NN = 0.999

jet b-tag:

	Z
1	0.99
2	0.84
	H
3	0.99
4	0.21

kin. mass fit
m_H=109.1GeV
m_Z=92.3GeV

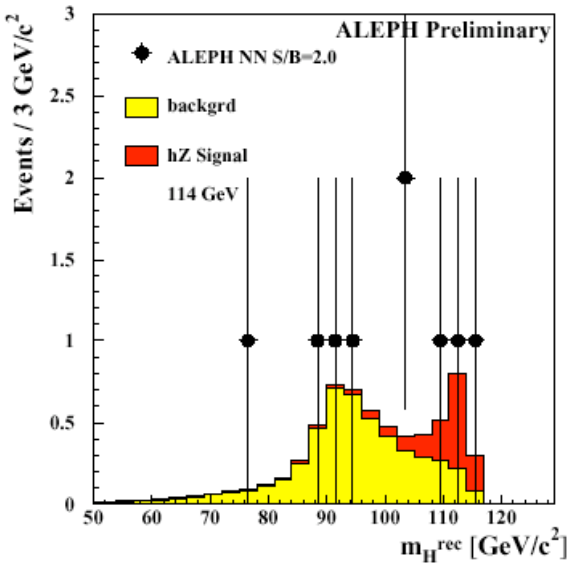
ZZ hyp.
m_Z=100 GeV
m_Z= 99 GeV

2001

Clean, startling events seen by ALEPH

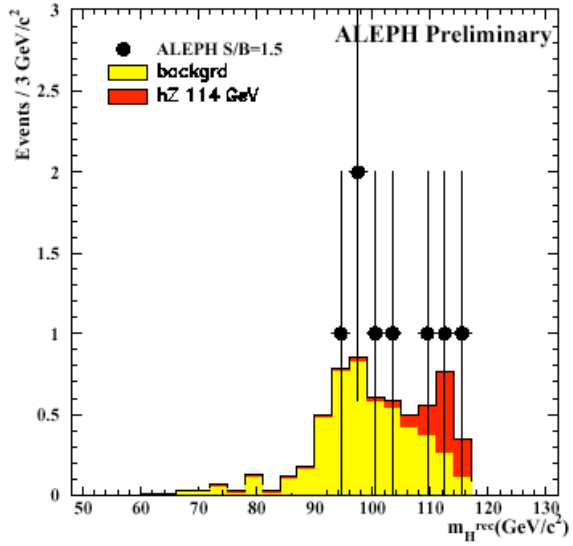
Mass Plot - Tight Cuts

NN Analysis



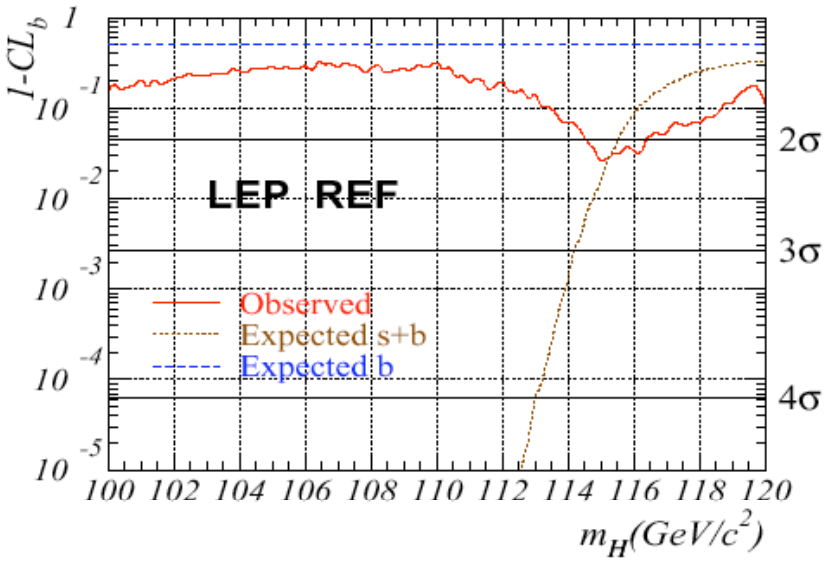
When cuts are tightened, both accept the same three four jet events with M_H >109 GeV/c^2

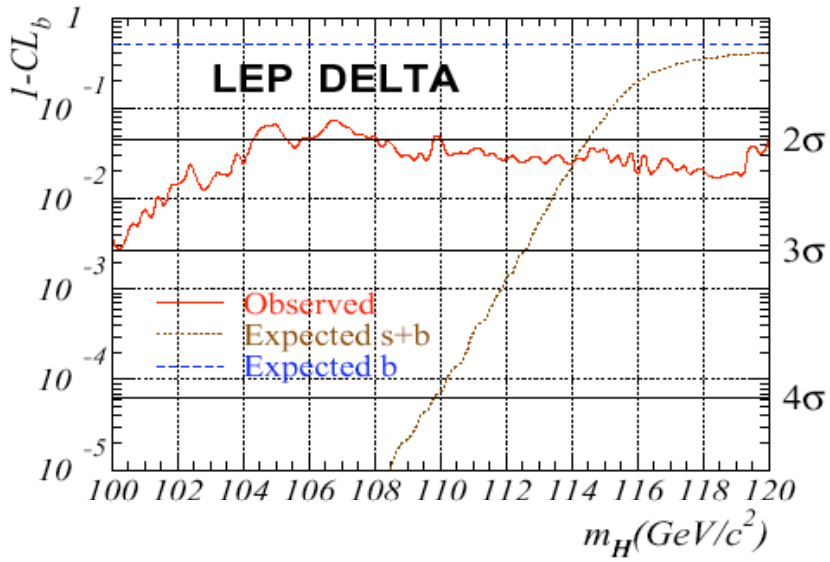
CUT Analysis

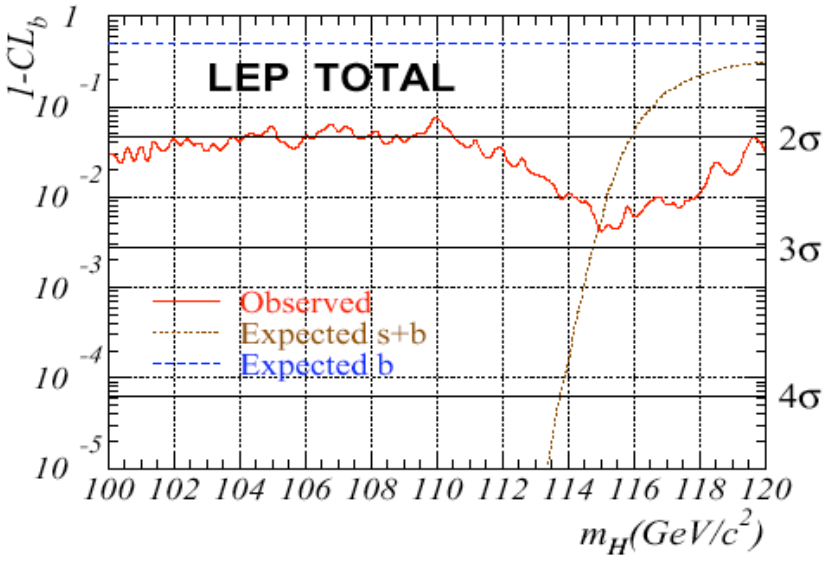


The survival of these three candidates indicates that they are indeed quite signal-like

$1 - CL_b$ ... REF, DELTA, TOTAL







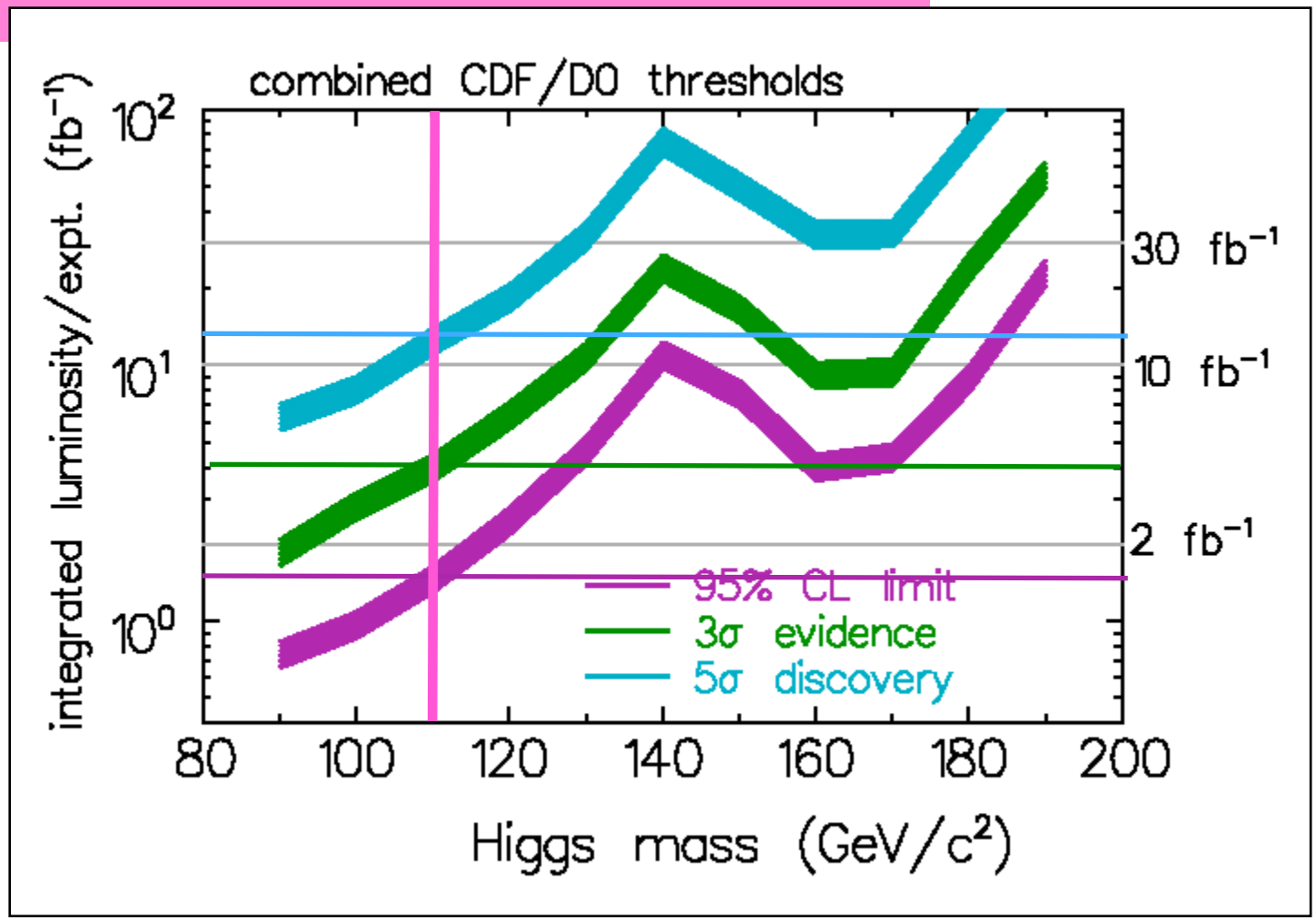
ADLO	$1 - CL_b$	
REF	2.5×10^{-2}	2.2σ
DEL	2.2×10^{-2}	2.3σ
TOT	4.2×10^{-3}	2.9σ

Brief Chronology

Institutional Committes have been consulted on LEP running in 2001

- **LEP C (Nov. 3) no consensus on a positive recommendation**
- "... the combined evidence for a Higgs near 115 GeV already to be quite significant and considers that there are sizable prospects for a major discovery to be made at LEP, but also a non-negligible risk that no definite conclusion would be reached.
- Therefore, considering only LEP and its operation costs, the committee considers that an extension in 2001 to collect 200 pb^{-1} above 208 GeV would be justified.
- However the committee also recognises that an extension could have a serious impact on the LHC and, in view of this, there was no consensus to recommend an extension. "
- **Research Board (Nov. 7) no consensus on a positive recommandation**
- **Scientific Policy Committee was consulted permanently, and reported to CC**
- **The issue arrived to the CERN Directorate on Nov. 8**:
- The Directorate considers that the risk of a major delay of LHC and the extra cost do not justify a LEP run in 2001. Therefore, the Directorate maintains that the existing programme is the best way to address this physics and unanimously does not accept the request to run LEP in year 2001.

Tevatron discovery potential



Epilogue: Committee of Council, Nov. 17

Scientific Policy Committee: majority in favour of stopping LEP

Final 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."

LEP data-taking is finished and we are moving into the LHC era.
CERN staff and LEP Collaborations have made a tremendous efforts over the time of LEP, which have led to many exceptional achievements,
notably the recent evidence for a Higgs particle at a mass of 115 GeV.

CERN-EP/2003-011
13 March 2003

Search for the Standard Model Higgs Boson at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP Working Group for Higgs Boson Searches[1]

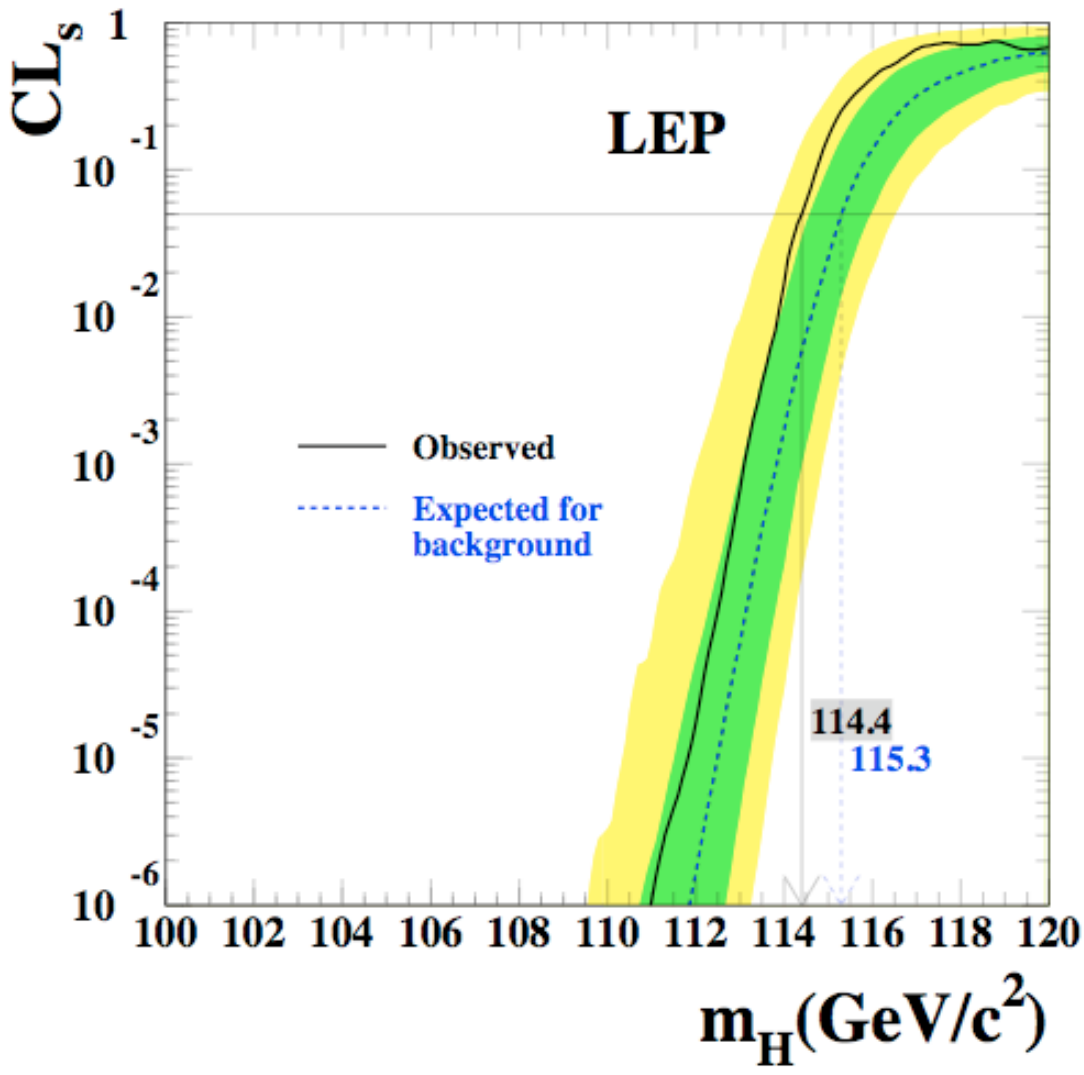


Figure 9: The ratio $CL_{s} = CL_{s+b}/CL_{b}$ for the signal plus background hypothesis. Solid line: ob-

SEARCHING FOR THE HIGGS AT LHC

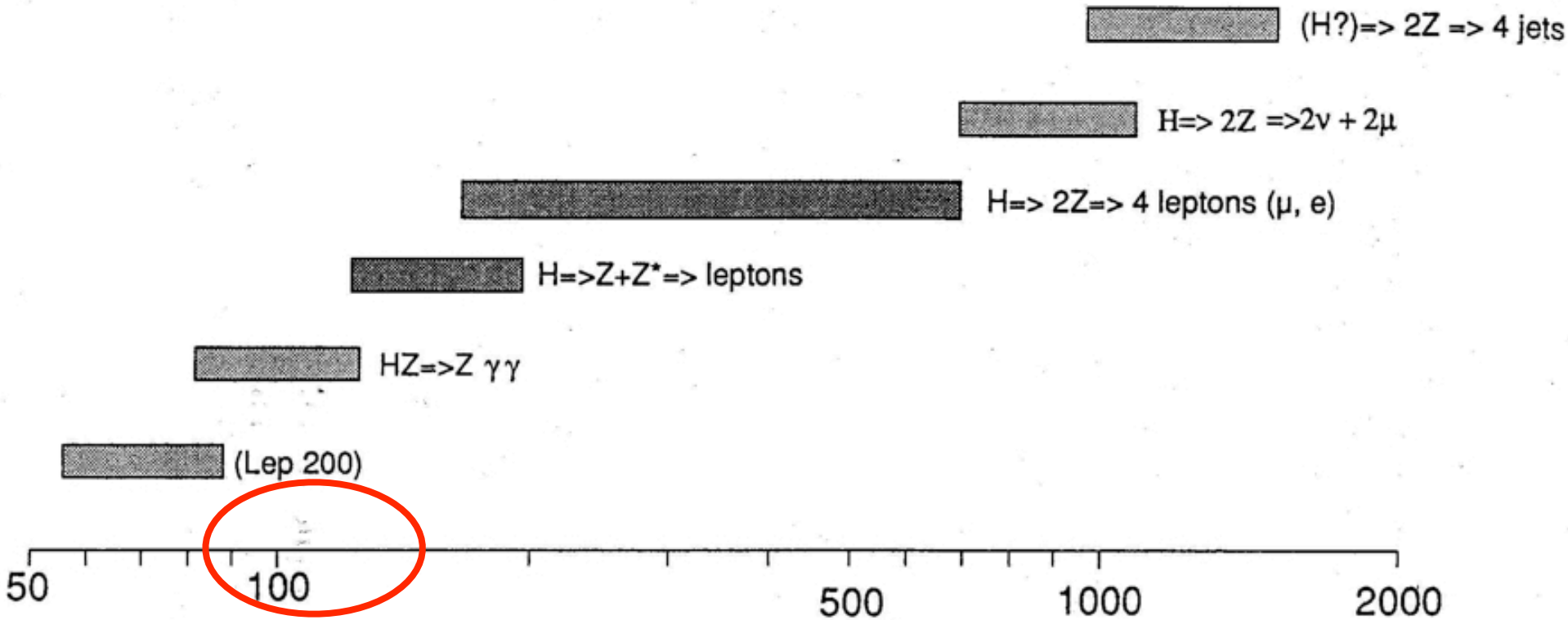
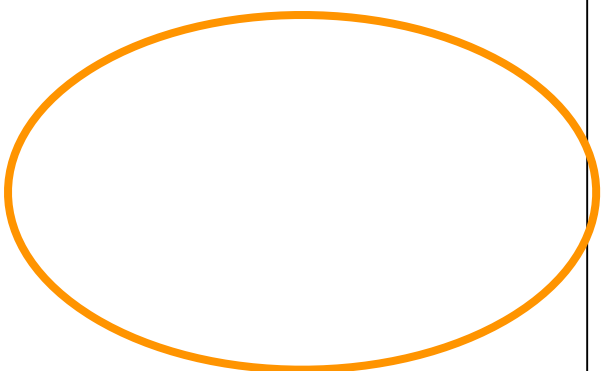


Figure 4 – The primary Higgs signatures at the LHC

the region covered by LEP 2 was larger than expected, very crucial for the LHC !!



Sept.19 talk
480
150
50
120
40
≈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

... a tough cure, a balanced package

In very rough figures:

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

An opportunity for CERN

Chinese symbol for CRISIS (危机) contains two characters

That for DANGER (危险) and

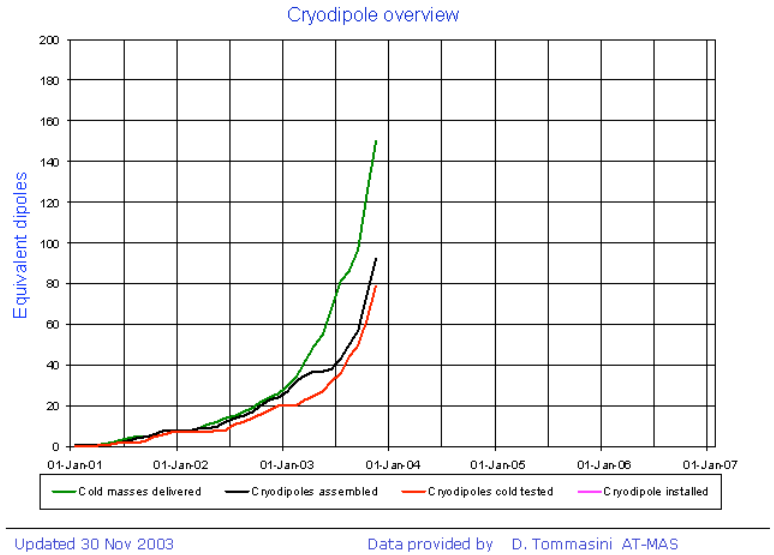
That for OPPORTUNITY (机会)

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

but also clearer opportunities coming to light

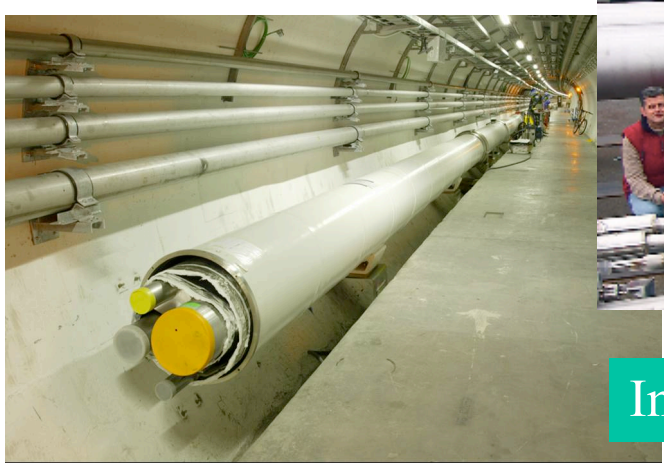
LHC Progress Dashboard

Accelerator Technology Division



LHC in progress

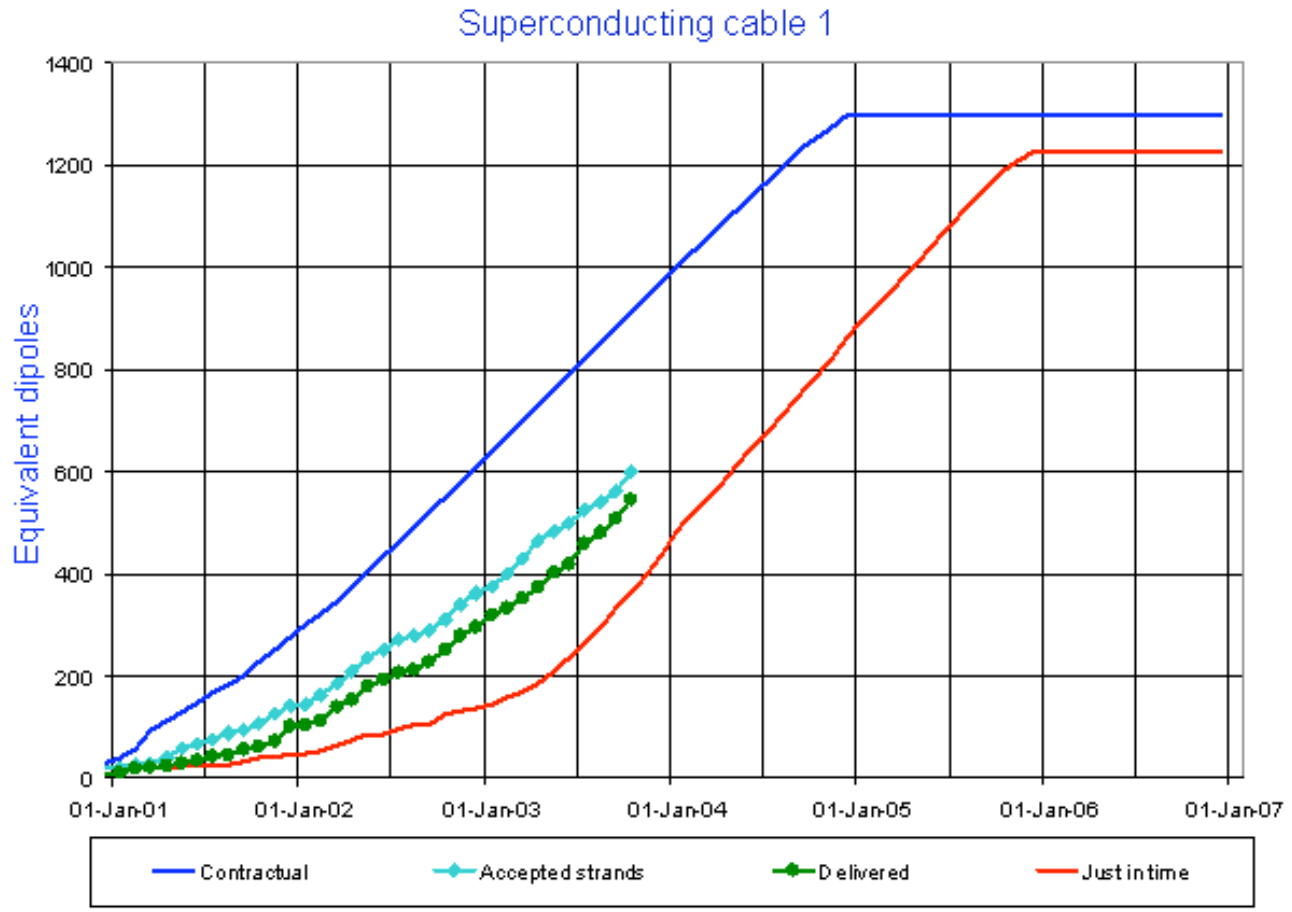
First Octant completed!



Installation of the cryo-line

LHC Progress Dashboard

Accelerator Technology Division

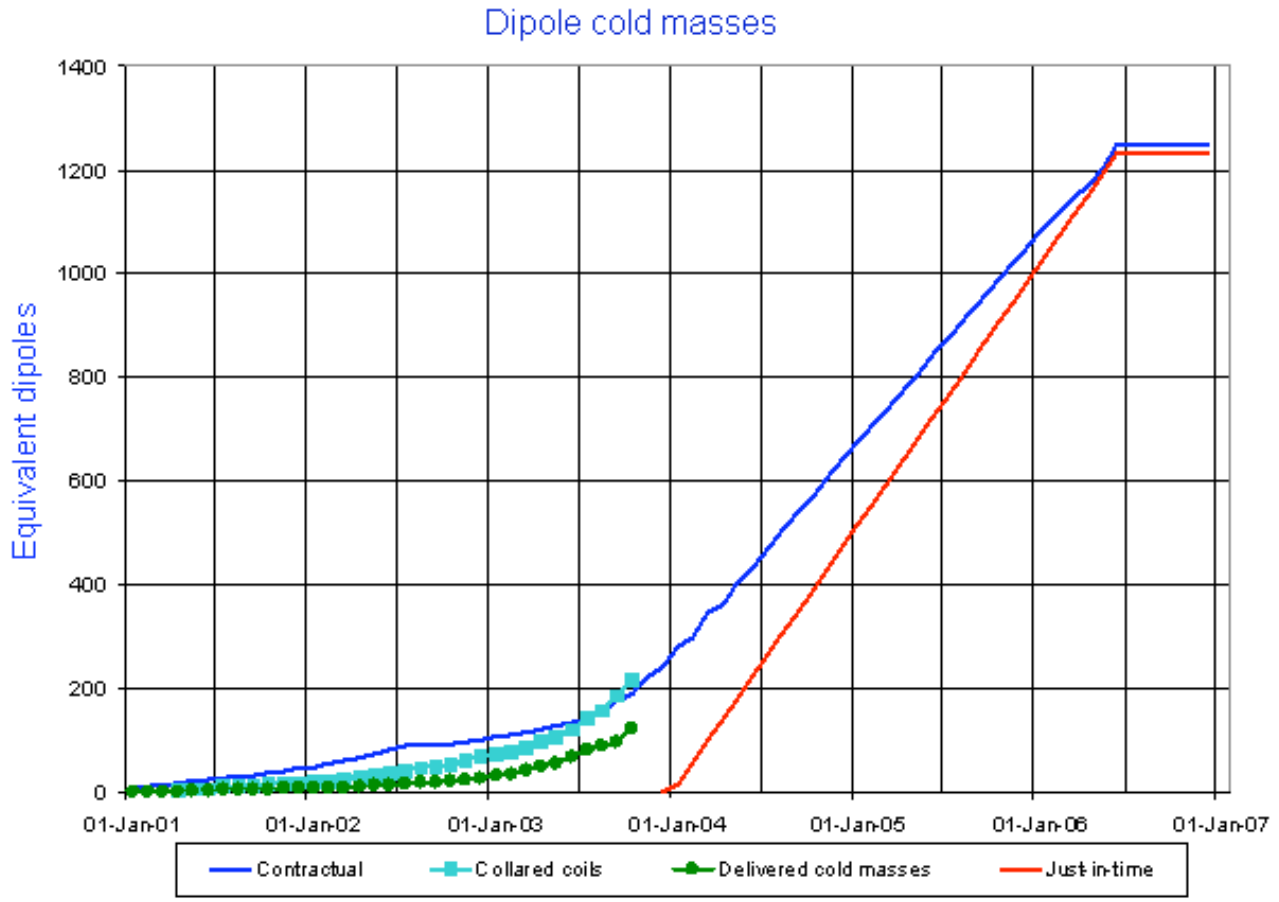


Updated 31 Oct 2003

Data provided by A. Verweij AT-MAS

LHC Progress Dashboard

Accelerator Technology Division



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Data provided by P. Lienard AT-MAS

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

- With less reservation than last year, we can confirm the LHC schedule:
  - completion of the LHC machine in the last quarter of 2006,
  - first beams injected during the spring of 2007
  - First collisions mid 2007.