Particle Accelerators and Five Decades of Colliders

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Subject Matter

- Rutherford
- Five Decades of High Energy Colliders
  - Components
  - CERN Intersecting Storage Rings (ISR)
  - SppbarS and TeVatron
  - LEP and SLC
  - LHC and SSC
- Societal Applications of particle physics technologies
- The Future Circular Collider (FCC)

Rutherford

- Lord Rutherford was the “god-father” of accelerators.
- In his inaugural presidential address to the Royal Society in London in 1928, he said “I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances”.
- This was the start of a long quest for the production of high energy beams of particles in a very controlled way.
- Particle accelerators and detectors of today are among the most complicated and expensive scientific instruments ever built by mankind and they exploit every aspect of today’s cutting edge technologies.

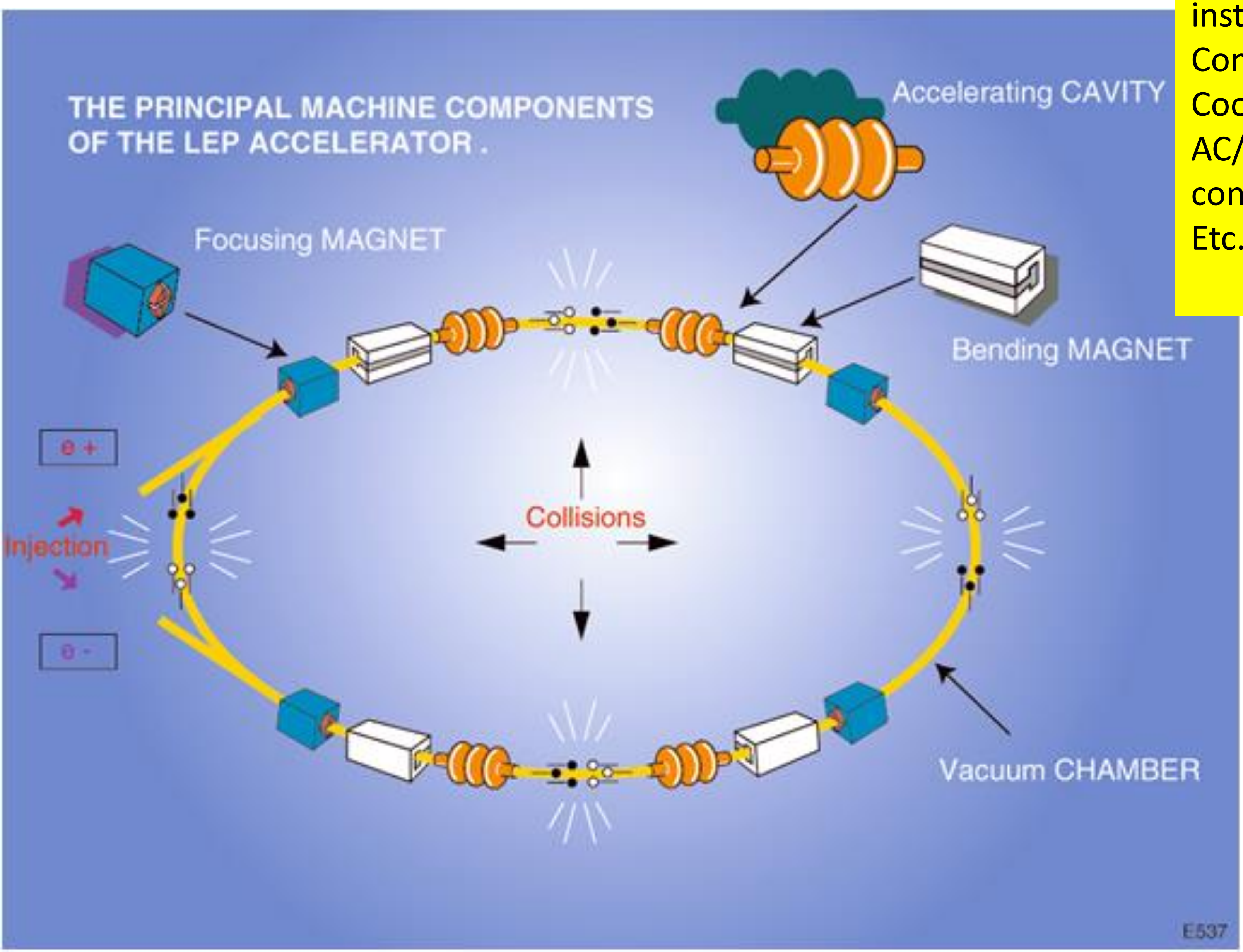
Types, Locations and Energies (1959-present)

	Location		Energy, GeV
Proton synchrotrons			
CERN PS	Geneva		28
BNL AGS	Brookhaven, Long Island		32
KEK	Tsukuba, Tokyo		12
Serpukhov	USSR		76
SPS	CERN, Geneva		450
Fermilab Tevatron II	Batavia, Illinois		1000
Electron accelerators			
SLAC linac	Stanford, California		25–50
DESY synchrotron	Hamburg		7
Colliding-beam machines			
PETRA	DESY, Hamburg	e^+e^-	$22 + 22$
PEP	Stanford	e^+e^-	$18 + 18$
CESR	Cornell, NY	e^+e^-	$8 + 8$
TRISTAN	Tsukuba	e^+e^-	$30 + 30$
SLC	Stanford	e^+e^-	$50 + 50$
LEP I	CERN	e^+e^-	$50 + 50$
LEP II	CERN	e^+e^-	$100 + 100$
$Sp\bar{p}S$	CERN	$p\bar{p}$	$310 + 310$
Tevatron I	Fermilab	$p\bar{p}$	$1000 + 1000$
HERA	Hamburg	ep	$30e + 820p$
LHC (2005)[a]	CERN	pp	$7000 + 7000$

All are synchrotrons except the two red boxes

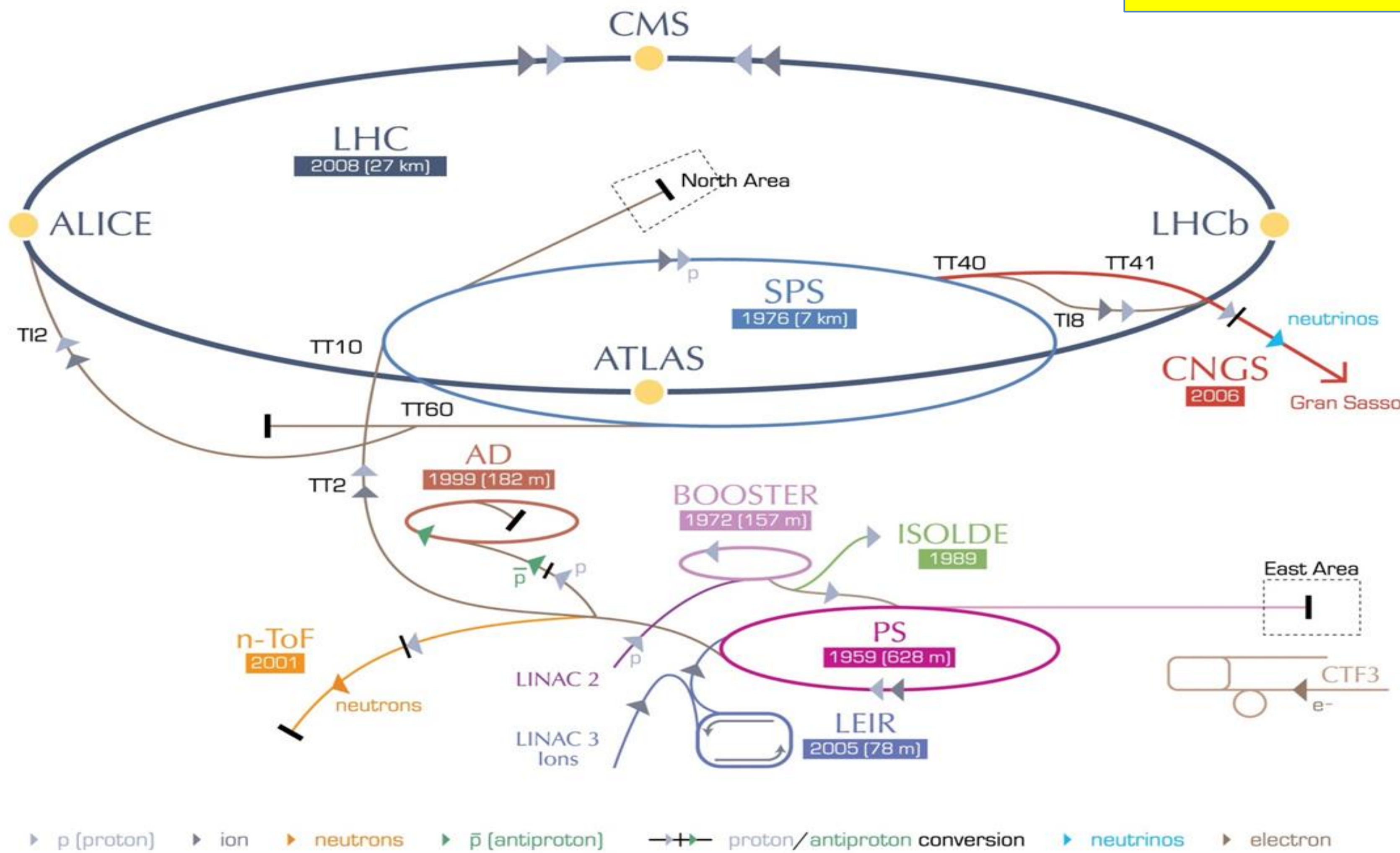
Principal Components of a Synchrotron Co

Beam diagnostics and instrumentation,
Computer control,
Cooling,
AC/DC Power converters,
Etc…..



CERN's accelerator complex

2 Linacs, 9 synchrotrons



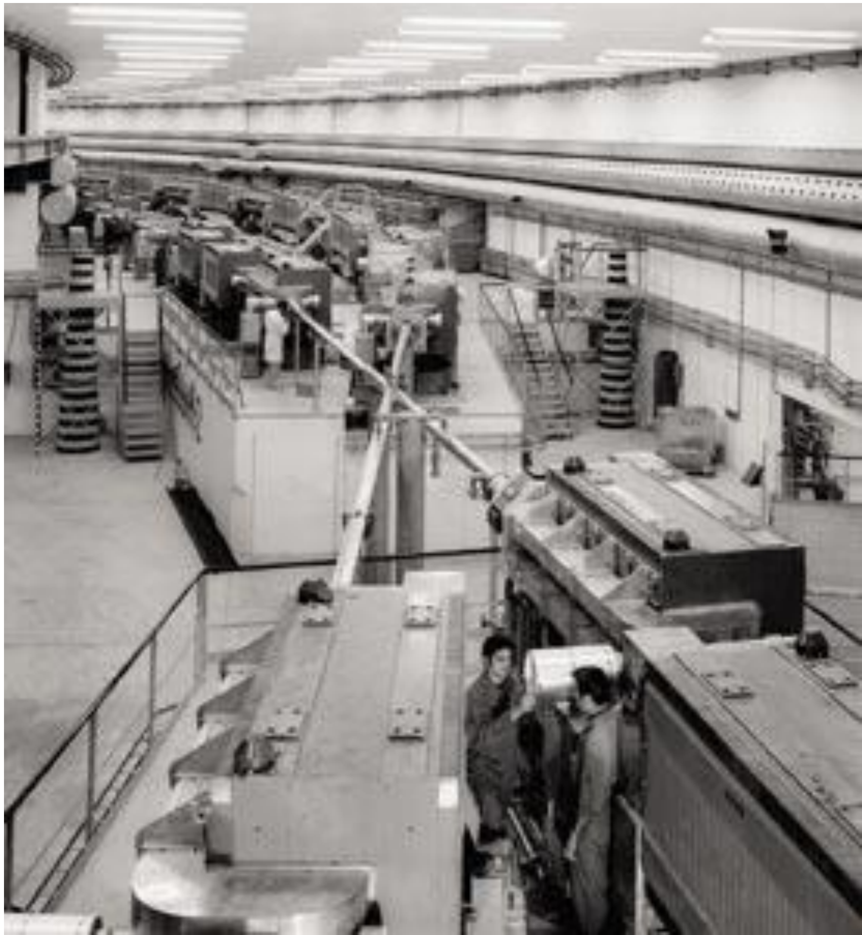
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

The Path to Higher Energy Colliders for Fundamental Research

The CERN Intersecting Storage Rings (ISR 1971-1984) The first hadron Collider

The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970's. One can see the "massive" rings and two of the intersection points.



What is the Legacy of ISR?

How to design detectors for collider

Schottky, stochastic cooling (ppbar in SPS)

Collimation and background control

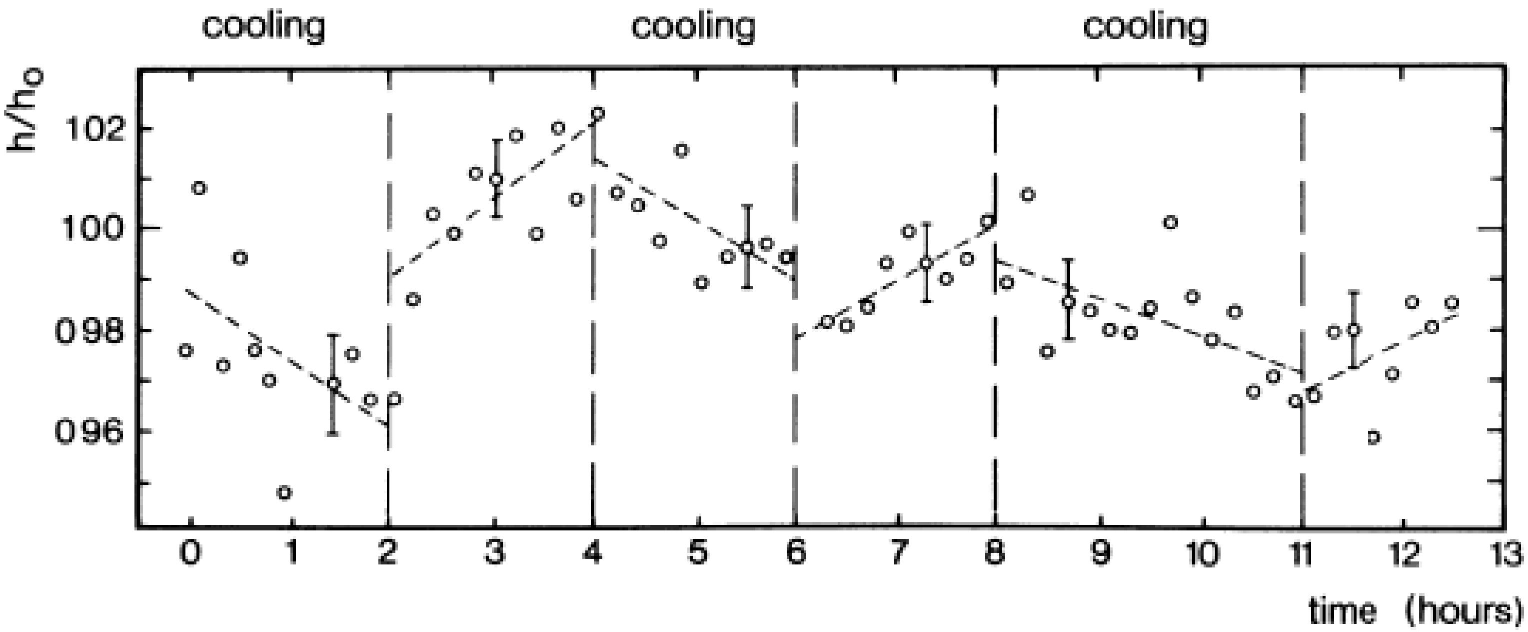
Luminosity calibration by Van der Meer scans; still used in LHC

Impedance control and transverse instabilities

SppbarS and Tevatron

In 1976 Carlo Rubbia, Peter McIntyre and David Cline proposed to convert a high energy proton accelerator into a proton-antiproton collider. At the time there were two possibilities: one was already running at Fermilab and one was under construction at CERN (SPS)

Stochastic Cooling at ISR (1974)



P. Bramham, G. Carron, H. G. Hereward, K. Hübner, W. Schnell and L. Thorndahl, Stochastic cooling of a stored proton beam, NIM 125 (1975), pp. 201.

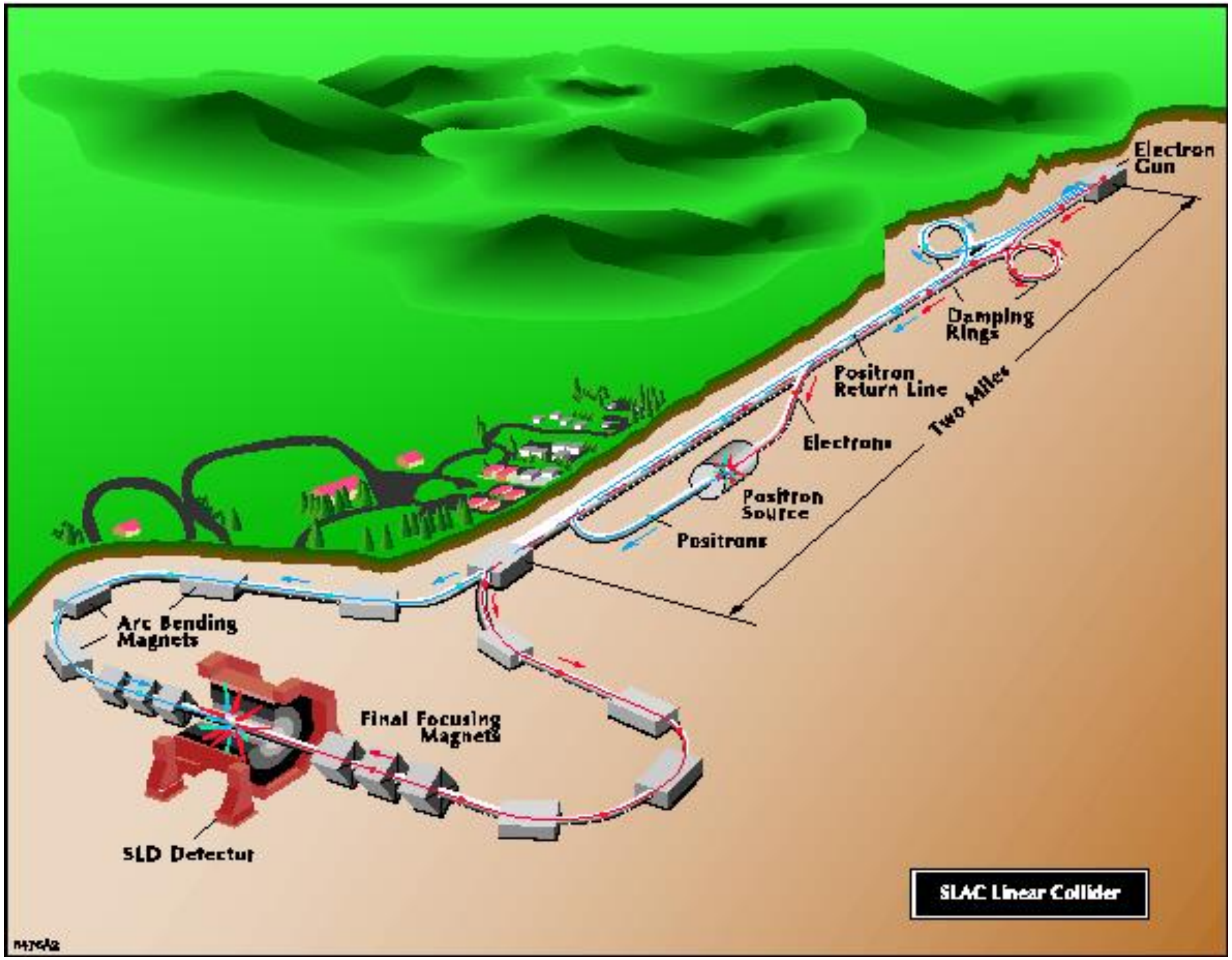
Fig 8 Observation of stochastic cooling in the ISR through measurements of the effective beam height (h/h_0), as a function of time, decreasing when cooling is applied and increasing when not applied The cooling equipment, installed in only one ring, detects and corrects statistical fluctuations of average beam position Luminosity is inversely proportional to the effective beam height

Simon van der Meer and Carlo Rubbia celebrate their Nobel Prize in 1984 with a toast at CERN.

…

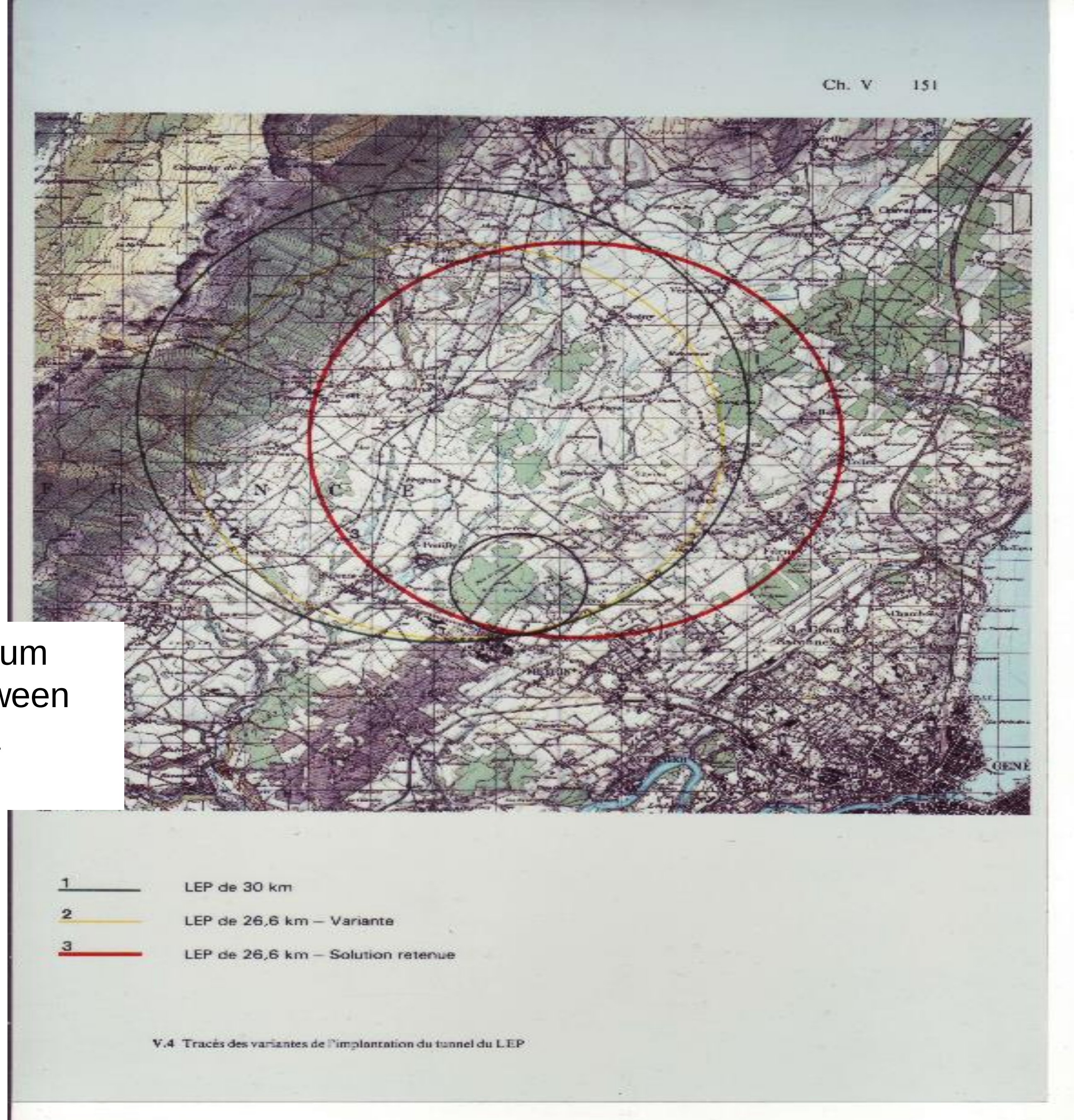
LEP
and SLC

Stanford Linear Collider (SLC)



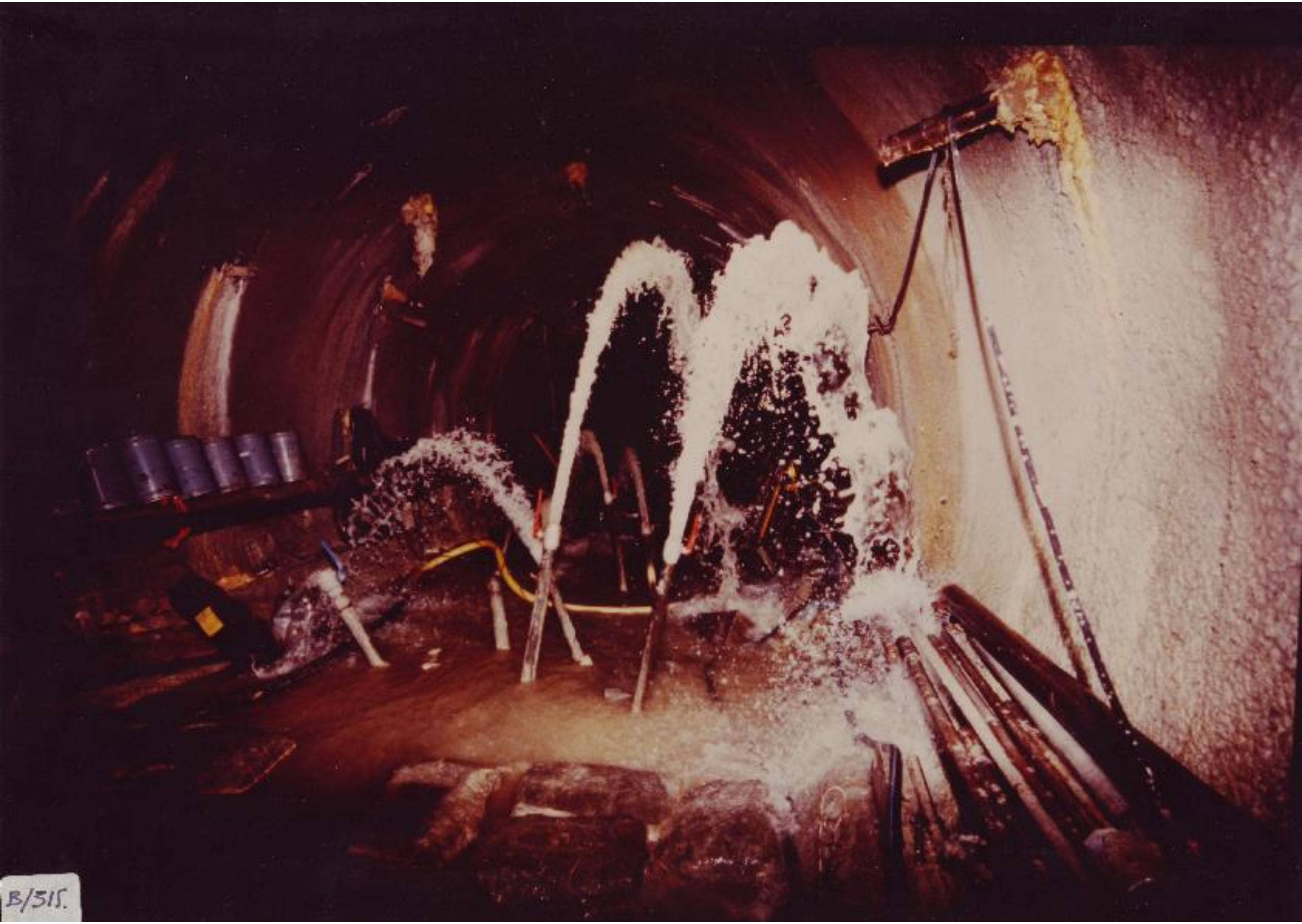
The Three Variants for the LEP/LHC Tunnel

22km was optimum for LEP but LHC was already being considered



Chosen Variant gave Maximum Circumference possible between Geneva Airport and the Jura Mountains

27km circumference underground tunnel (cross-section diameter 4m)
(was built in 1985)


B/315.

Short History with Beam @ LEP

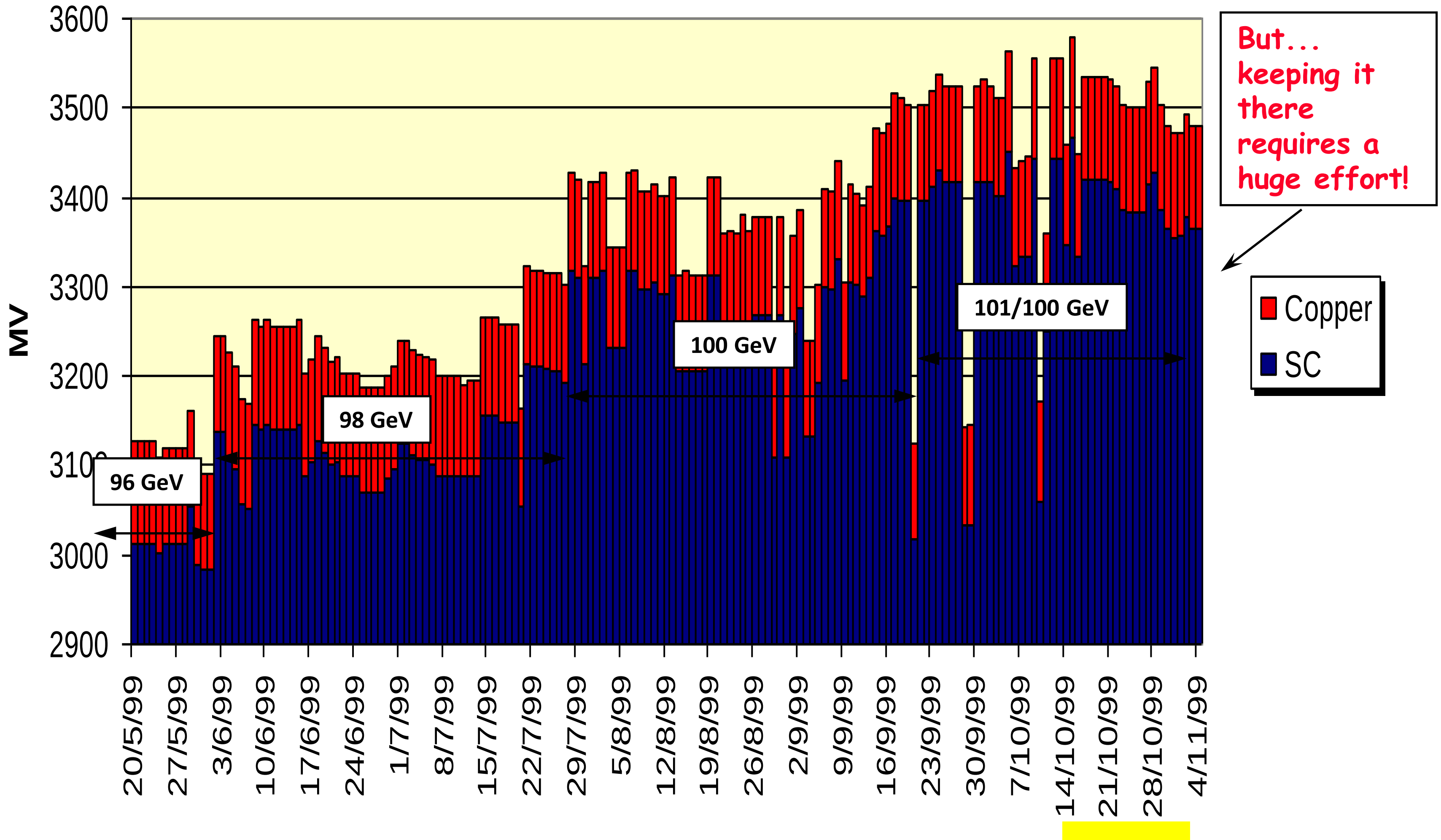
- 1988: July 12: Octant test
- 1989:
  - July 14, First turn (15 minutes ahead of schedule!)
  - August 13, First Collisions
  - Aug13--Aug 18: Physics pilot run
  - Aug 21--Sept 11: Machine Studies
  - Sept 20-- Nov 5 Physics

Exciting period, But usually not very productive

- 1990--1994: Z physics
- 1995: Z + 65 & 70 GeV
- 1996: 80.5--86 GeV
- 1997: 91--92 GeV
- 1998: 94.5 GeV
- 1999: 96--102 GeV
- 2000: 102--104.4 GeV

LEP Energy Upgrade:
Gradual addition of 288 superconducting cavities during annual shutdowns

Increasing the Acceleration Voltage/turn



1999

LEP Amusing Stories

- Tidal Forces
- Lake Geneva water level
- TGV
- Beer bottles
- Electrocuted deers
- Sextupole mis-wiring
- .....

Tidal Forces, Lake Geneva water level, TGV: Affecting Beam Energy

Beer bottles, Electrocuted deers, Sextupole mis-wiring: Affecting Operational Efficiency

The Higgs' Boson

To be discovered at
LEP (events seen at 114 GeV in 2000)
or LHC or Tevatron?

Year 2000: Run LEP2 in 2001 or STOP?

LEP vs LHC (old vs new)

- running LEP would delay LHC by 0, 1, 1.5, 2 (?) years
- the competition with Tevatron
- manpower transfers needed from LEP to LHC
- “materials“ budget considerations (+electrical power etc)

The first and only Civil war in CERN

no consensus in CERN committees

DG made the decision to stop LEP

What is the Legacy of LEP?

The physics data (luminosity, energy, energy calibration).

LEP is the reference for any future e^+e^- ring collider design.

<u>Legacy to Future Colliders</u>

Avoid mountains for the tunnel!!! (FCC)

Running large accelerators (shutdown planning, cold checkouts…)

Real-time feedback on beam parameters (orbit, tune, instabilities..)

Running large Superconducting and cryo systems

…….

Following the decision to close LEP

LMC Mission February 14, 2001

Use the experience and expertise gained in LEP to prepare beam commissioning and operation of the LHC

- Evaluate and maximise the performance of the injectors,
- Evaluate experience with other relevant machines,
- Prepare a detailed scenario for initial commissioning,
- Specify special software requirements for commissioning and operation.
- Plan MD experiments for the LHC and its injectors

LHC Machine Committee (LMC1 February 14, 2001)

BAILEY Roger, CLAUDET Serge, CORNELIS Karl, EVANS Lyn, FAUGERAS Paul, FERNQVIST Gunnar, JEANNERET Jean-Bernard, KOUTCHOUK Jean-Pierre, LAMONT Mike, LINNECAR Trevor, MERTENS Volker, MYERS Steve (Chair), POOLE John, PROUDLOCK Paul, ROY Ghislain, RUGGIERO Francesco, SABAN Roberto, SASSOWSKY Manfred, SCANDALE Walter, SCHMICKLER Hermann, SCHMIDT Rudiger, TSESMELIS Emmanuel, WENNINGER Jorg

http://lhc.web.cern.ch/lhc/lcc/lcc.htm

A Tale of Two Cities (Colliders)

LHC
Largest hadron collider
EVER built

SSC
Largest hadron collider
NEVER built

(April 1983)

LEP Note 440

11.4.1983

First Document to evaluate a Hadron Collider in the «LEP» Tunnel

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the [illegible] es where very large $p\bar{p}$ and pp colliders are actively be [illegible] at the moment. Indeed, a first look at the basic perform [illegible] ions of possible $p\bar{p}$ or pp rings in the LEP tunnel seems ove [illegible] r far off in the future a possible start of such a p-LEP pr [illegible] t be in time. What we shall discuss is, in fact, rather [illegible] such a discussion has, to the best of our knowledge, not bee [illegible] so far.

We shall [illegible] any detailed design questions but shall give basic equat [illegible] ke a few plausible assumptions for the purpose of illustr [illegible] us, we shall assume throughout that the maximum energy pe [illegible] TeV (corresponding to a little over 9 T bending field in very [illegible] superconducting magnets) and that injection is at 0.4 TeV. The [illegible] circumference is, of course that of LEP, namely 26,659 m. It should [illegible] e clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

REPORT OF THE DOE REVIEW COMMITTEE on the CONCEPTUAL DESIGN of the SUPERCONDUCTING SUPER COLLIDER

S. Myers Chair of Accelerator Physics Sub-Panel

May 1986

DOE Review Executive Summary May 1986

The DRC concludes that the design set forth in the CDR is technically feasible and properly scoped to meet the requirements of the U.S. high energy physics program in the period from the mid-1990s to well into the next century. The design of the SSC is based to a large extent on previous experience with storage rings and synchrotrons (particularly the Tevatron which uses superconducting magnets). While, in many aspects, the SSC requires extension of this experience, there is no question that a facility with the SSC specifications is feasible.

…higher confidence in meeting performance goals would be obtained by further studies of magnet aperture requirements.

capable of major discoveries. Nevertheless, in our judgment even higher confidence in meeting performance goals would be obtained by further studies of magnet aperture requirements. This work is an important part of the continuing development of the SSC design.

The SSC CDR has documented the estimated cost for constructing an SSC facility at $3.01 billion in FY 1986 dollars, which includes $529 million in contingency. Not included in this estimate are costs for further R&D on accelerator components, for site acquisition, for the

Accelerator Physics Sub-Panel (1986)

At present the basic techniques employed to study the effects of magnetic field quality have not been developed to the extent required to conclude that the magnet designs for the SSC are conservative……..one must hold open the possibility that the field qualities have to be improved…….and for the dipole magnets an increase in aperture may be required…

CDR are adequate, until a substantial fraction of that work is finished, one must hold open the possibility that the field qualities will have to be improved. The cost consequences for the interaction region quadrupoles were mentioned above, and for the dipole magnets an increase in aperture may be required. The maximum possible cost of such a change is estimated to be $160 million. The aperture studies are of high priority, and the Accelerator Physics Subcommittee strongly urges vigorous pursuit of them. This remaining aperture question is one of improving the certainty of meeting the design goals.

DOE Review Committee SSCD SSC, September 1990

Collider Accelerator Physics sub Panel: Chair S. Myers

…Comparing the SCDR with the CDR of 1986…

- Injection energy has been doubled to 2 TeV
- Dipole magnet aperture increased from 40 to 50 mm
- New 90 deg lattice and shorter cell length

- The dipole magnet aperture has been increased from 40 mm to 50 mm.
- A new lattice with 90 degrees betatron phase advance and shorter cell length has been adopted.
- The correction system is now based on lumped elements.
- The cycle periods of the SSC and HEB have been substantially increased.

The present scenario assumes a 40-mm-bore quadrupole magnet and a 50-mm-bore dipole magnet. For consistency, consideration should be given to increasing the quadrupole aperture to 50 mm in order to get a more efficient use of space and a smooth vacuum chamber.

DOE Review Committee SSCD SSC, September 1990

Collider Accelerator Physics sub-Panel: Chair S. Myers

5.1 Collider Accelerator Physics

The design of the SSC is based on previous experience with storage rings ... synchrotrons. Its most striking feature, its physical size, does not invalid... accelerator principles used for its design. Comparing the SCDR ... highlights the following substantial changes:

- The injection energy of the SSC ... eV.
- The dipole magn... ...sed from 40 mm to 50 mm.
- A ... betatron phase advance and shorter cell length has ...
- ...orrection system is now based on lumped elements.
- The cycle periods of the SSC and HEB hav... ...sed.

The present s... ...-mm-bore quadrupole magnet and a 50-mm-bore

...Consi... ...hould be given to increasing the q... ...e aperture to 50 mm. To get more efficient use of space and a smooth vacuum chamber

The SSC was cancelled by Congress in 1993

This opened the door for LHC approval (1994)

LHC: Short History

Approval 1994

Construction 1995-2008 (L. Evans)

First Beam plus accident 2008

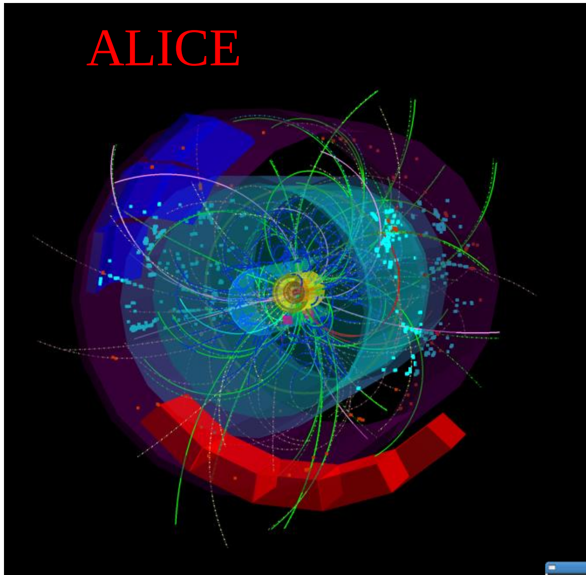
Repair 2009

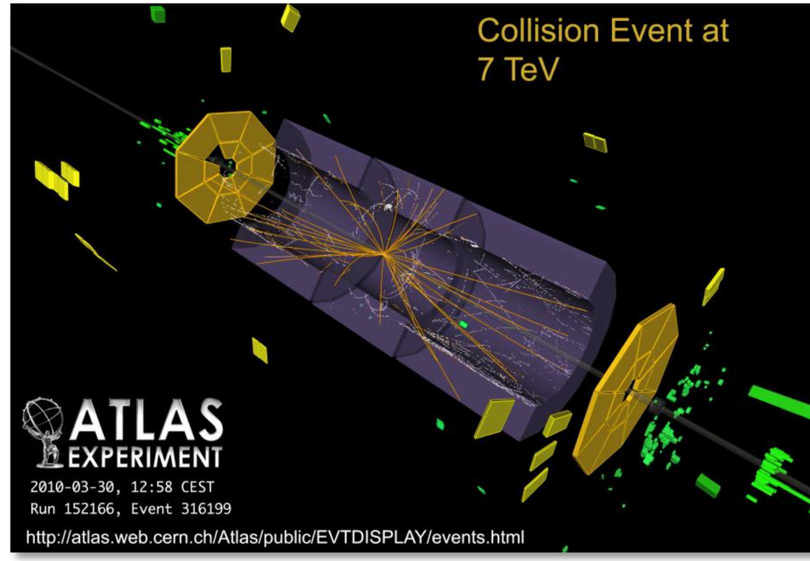
Operation 2010-present (initially at 7 TeV, then at 8TeV and then after LS1 repair 13 TeV)

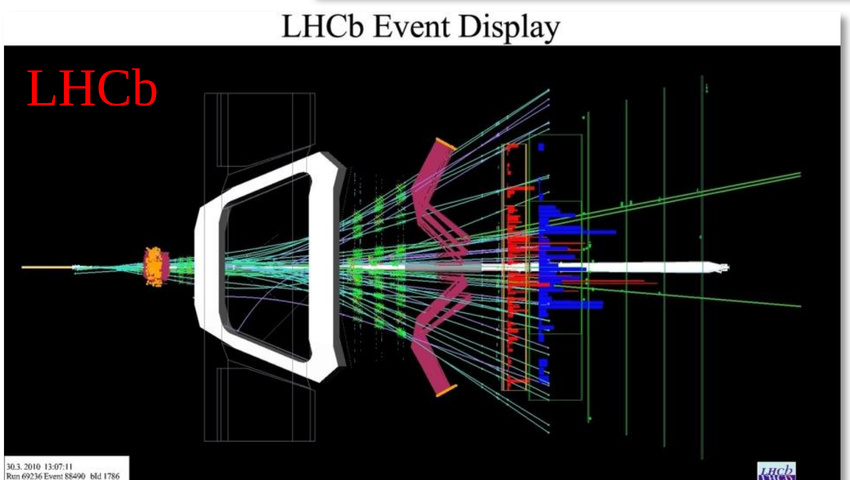
27km circumference underground tunnel (cross-section diameter 4m)
(was built for LEP collider in 1985)

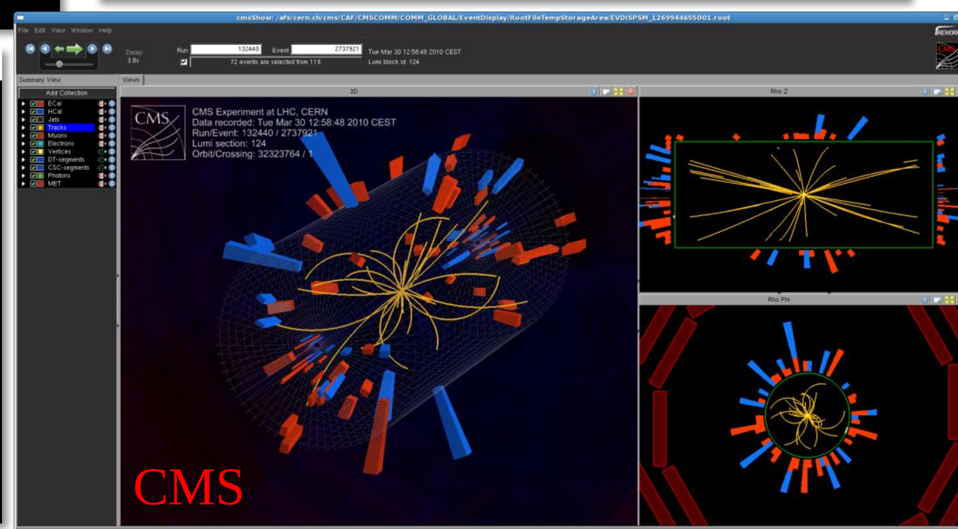
LHC Operation Since 2008
(Brief summary)
THE ACCIDENT, REPAIR, RESTART, AND OPERATION

LHC: First collisions at 7 TeV on 30 March 2010

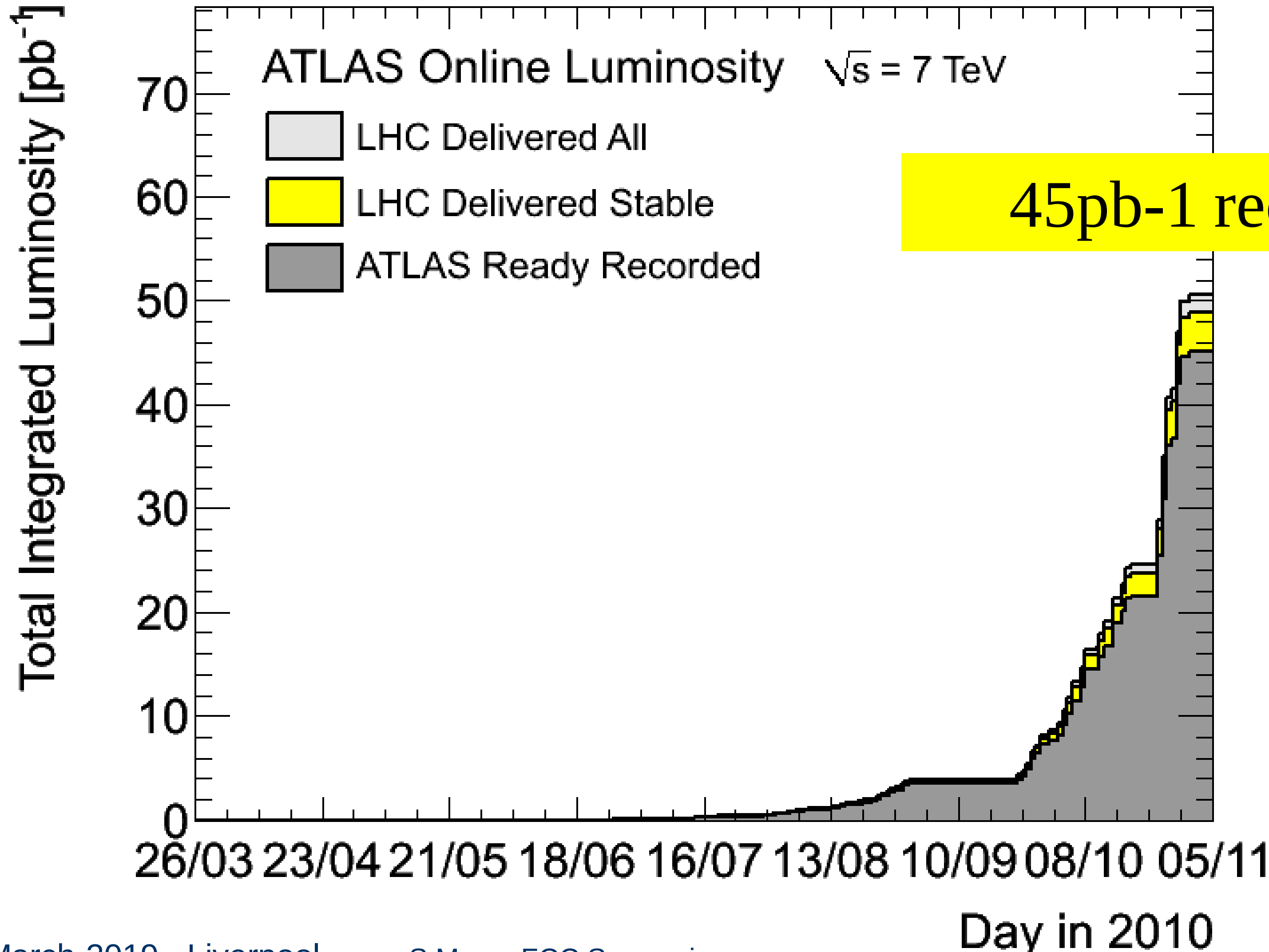






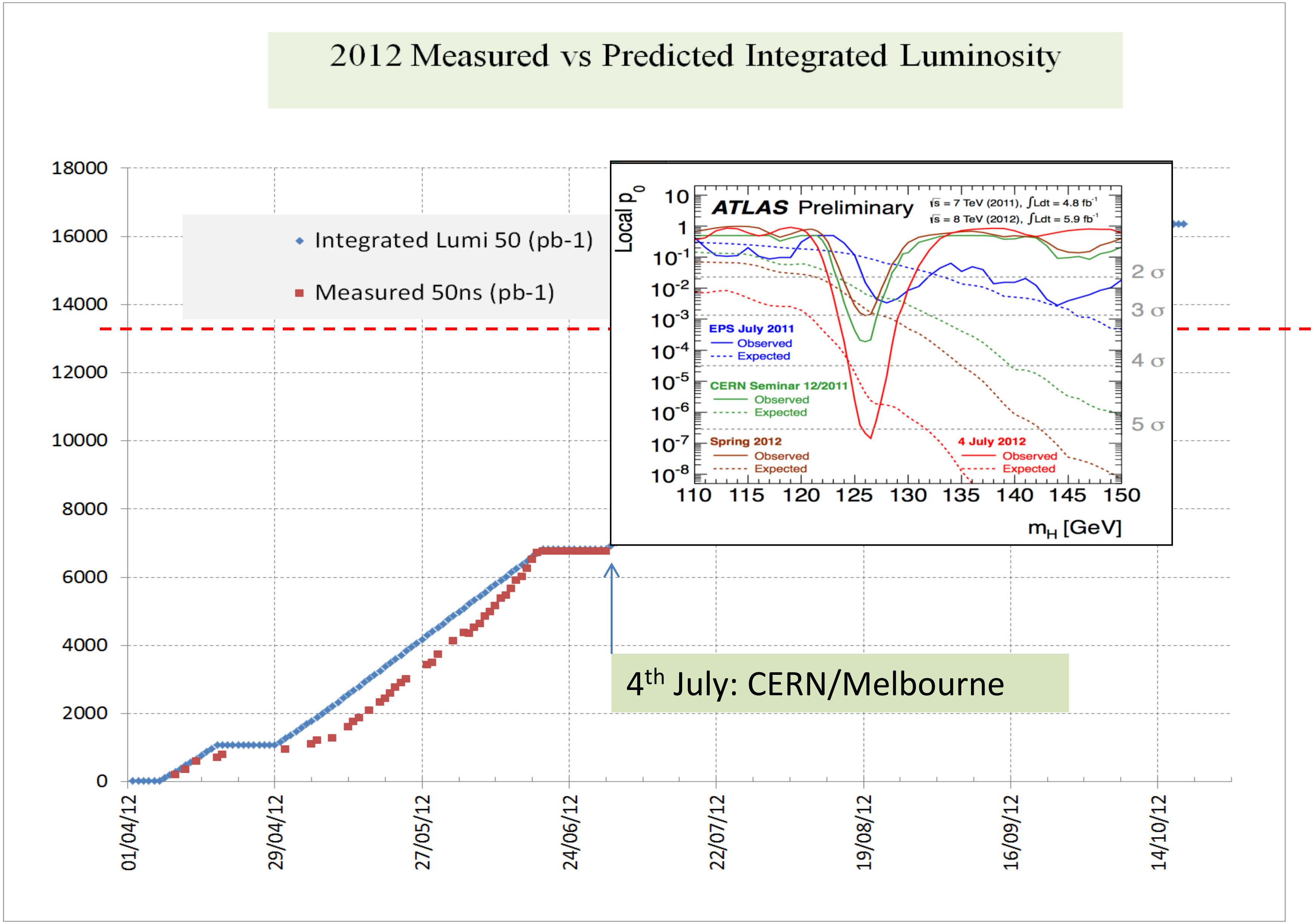


Integrated Luminosity in 2010

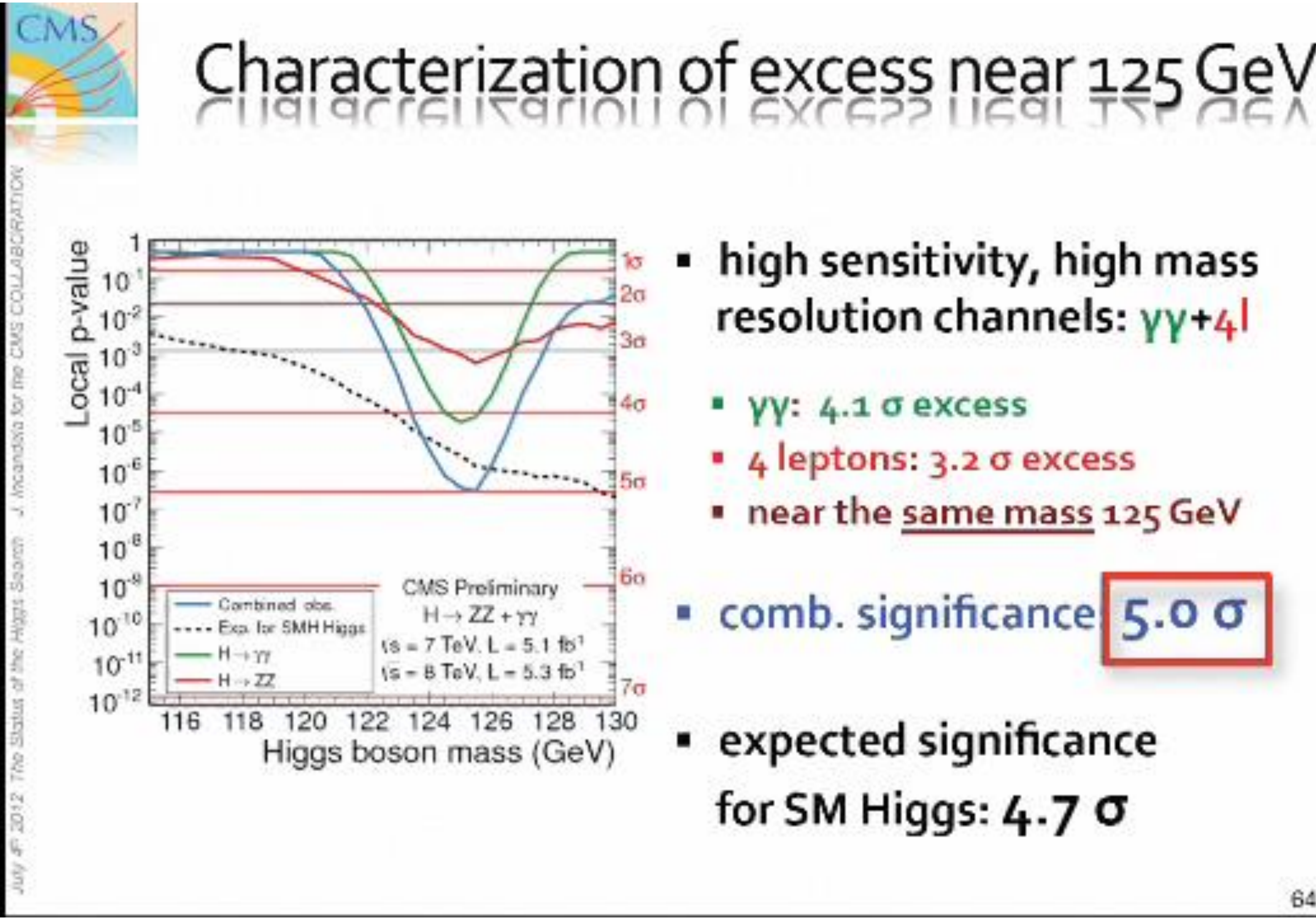


45pb-1 recorded

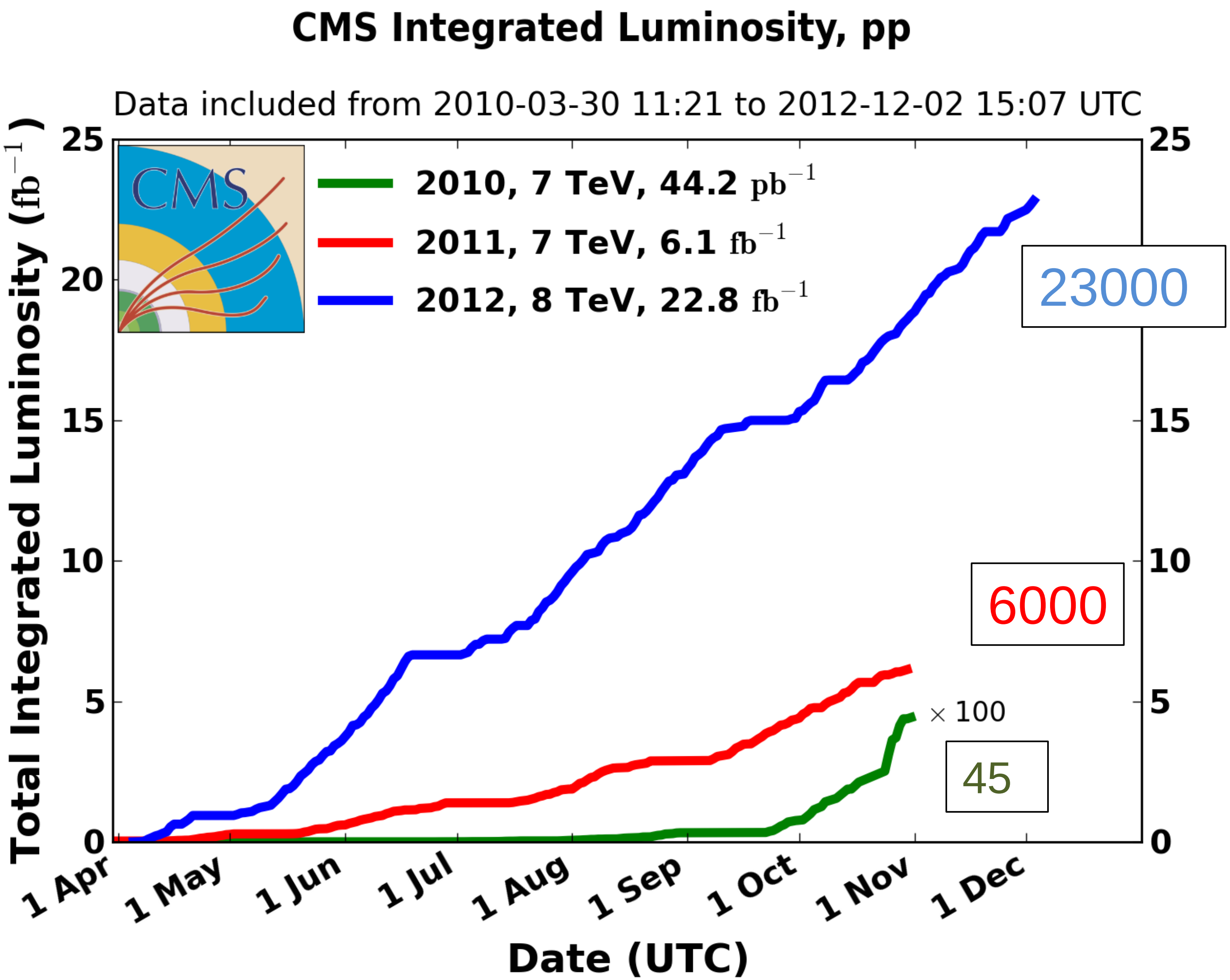
With Respect to estimates



Seminar on Discovery of Higgs' Boson



2010 → 2012



CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-02 15:07 UTC
CMS
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 22.8 fb⁻¹
23000
6000
× 100
45
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
0
5
10
15
20
25

Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"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".*

Accelerator APPLICATIONS

Summary Table of the Applications of Particle Accelerators (from APAE)

Area	Application	Beam	Accelerator	Beam energy/MeV	Beam current/mA	Number
Medical	Cancer therapy	e	linac	4-20	10^{-2}	>14000
		p	cyclotron, synchrotron	250	10^{-6}	60
		C	synchrotron	4800	10^{-7}	10
	Radioisotope production	p	cyclotron	8-100	1	1600
Industrial	Ion implantation	B, As, P	electrostatic	< 1	2	>11000
	Ion beam analysis	p, He	electrostatic	<5	10^{-4}	300
	Material processing	e	electrostatic, linac, Rhodatron	≤10	150	7500
	Sterilisation	e	electrostatic, linac, Rhodatron	≤10	10	3000
Security	X-ray screening of cargo	e	linac	4-10	?	100?
	Hydrodynamic testing	e	linear induction	10-20	1000	5
Synchrotron light sources	Biology, medicine, materials science	e	synchrotron, linac	500-10000		70
Neutron scattering	Materials science	p	cyclotron, synchrotron, linac	600-1000	2	4
Energy – fusion	Neutral ion beam heating	d	electrostatic	1	50	10
	Heavy ion inertial fusion	Pb, Cs	Induction linac	8	1000	Under development
	Materials studies	d	linac	40	125	Under development
Energy – fission	Waste burner	p	linac	600-1000	10	Under development
	Thorium fuel amplifier	p	linac	600-1000	10	Under development
Energy – bio-fuel	Bio-fuel production	e	electrostatic	5	10	Under development
Environmental	Water treatment	e	electrostatic	5	10	5
	Flue gas treatment	e	electrostatic	0.7	50	Under development

Summary Table of Operating Particle Therapy Centres in Europe (from APAE)

Note:
C indicates cyclotron
S indicates synchrotron

Table 3.1: Operating proton therapy centres in Europe (Adapted from PTCOG data, 14 May 2016). Three centres (HIT, Marburg and CNAO) also offer carbon-ion therapy. Centres offering scanned beams are indicated.

Czech Republic	PTC Czech s.r.o, Prague	C 230 (scan)	3 gantries, 1 horizontal	2012
France	CAL, Nice	C165	1 horizontal	1991
France	CPO, Orsay	S 250	1 gantry, 2 horizontal	1991
Germany	HZB, Berlin	C 250	1 horizontal	1998
Germany	RPTC, Munich	C 250 (scan)	4 gantries, 1 horizontal.	2009
Germany	HIT, Heidelberg	S 250 (scan)	2 horizontal, 1 gantry	2009, 2012
Germany	WPE, Essen	C 230 (scan)	4 gantries, 1 horizontal	2013
Germany	PTC, Uniklinikum Dresden	C 230 (scan)	1 gantry	2014
Germany	MIT, Marburg	S 250 (scan)	3 horizontal, 1 45 degrees	2015
Italy	INFN-LNS, Catania	C 60	1 horizontal	2002
Italy	CNAO, Pavia	S 250	3 horizontal, 1 vertical	2011
Italy	APSS, Trento	C 230 (scan)	2 gantries, 1 horizontal	2014
Poland	IFJ PAN, Krakow	C 60	1 horizontal	2011
Russia	ITEP, Moscow	S 250	1 horizontal	1969
Russia	St. Petersburg	S 1000	1 horizontal	1975
Russia	JINR 2, Dubna	C 200	1 horizontal	1999
Sweden	The Skandion Clinic,Uppsala	C 230 (scan)	2 gantries	2015
Switzerland	CPT, PSI, Villigen	C 250 (scan)	2 gantries, 1 horizontal.	1984, 1996, 2013
United Kingdom	Clatterbridge	C 62	1 horizontal.	1989

Table 3.2: Particle therapy centres under construction in Europe (adapted from PTCOG data, 14 March 2017).

Denmark	DCPT, Aarhus	p	C250	2018
France	ARCADE, Caen	p	C230	2017
Netherlands	HollandPTC, Delft	p	C250	2017
Netherlands	UMC Groningen PTC, Groningen	p	C230	2017
Russia	PMHPTC, Protvino	p	S250	2017?
Russia	FMBA Dimitrovgrad	P	C230	2018
Slovak Republic	CMHPTC, Ruzomberok	p	S250	2017?
UK	The Christie Proton Therapy Centre, Manchester	p	C250	2018
UK	PTC, UCLH, London	p	C250	2019
UK	Proton Partners/Rutherford, Newport	p	C230	2018

Summary Table of Particle Therapy Centres under construction in Europe (from APAE)

Technological Spin-Offs of Particle Physics

Accelerator apps: http://www.symmetrymagazine.org/category/accelerator-apps

- The World Wide Web
- Synchrotron Light Sources
- Cryogenics and Superconductivity
  - MRI scanners (also phenomenon of magnetic resonance)
  - Sc cables for transfer of electrical power (under development)
- Accelerators for radio-isotope production
  - Isotopes for medical R&D, tools for medical imaging (e.g. PET scans) and therapy
- Accelerators for Cancer Therapy
- Accelerators for
  - Food sterilization (electron beams), diaper production, mining ore analysis,
  - Rapid cancer diagnosis
- Detectors for Medical imaging

QuestionsQuestioning Fundamental Research

Q: Why spend millions of $, Euros, CHF, on studying obscure thing which have no uses?

Q: What possible use or application could there be for say, dark matter, neutrinos, or the Higgs boson?

A: We never know what is going to be useful until we study and understand it.

Fundamental Research Drives Disruptive Innovation

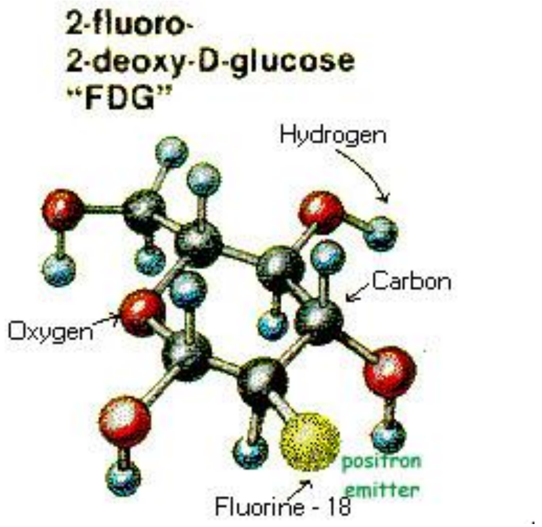
(However the path from discovery to application is, in most cases, totally unpredictable)

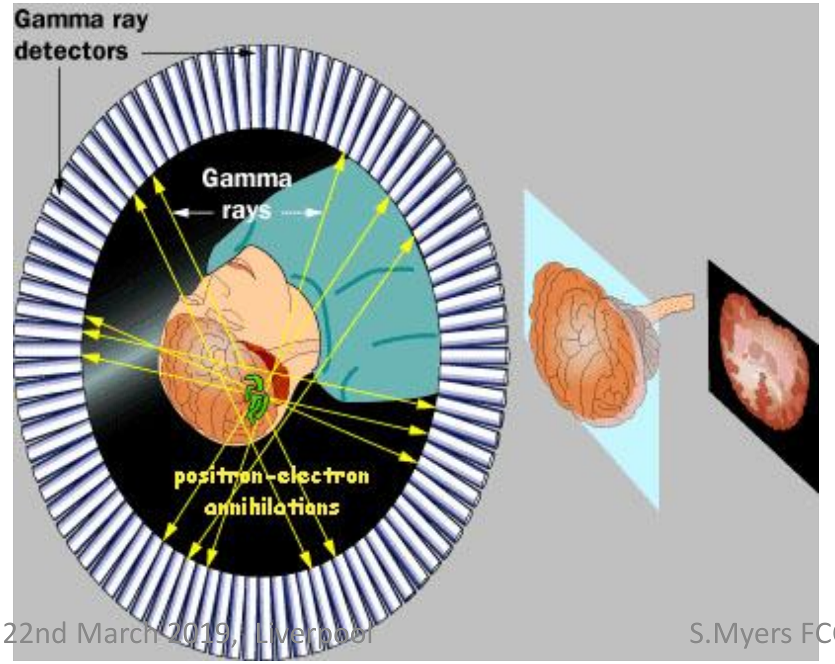
Antimatter application: Positron Emission Tomography

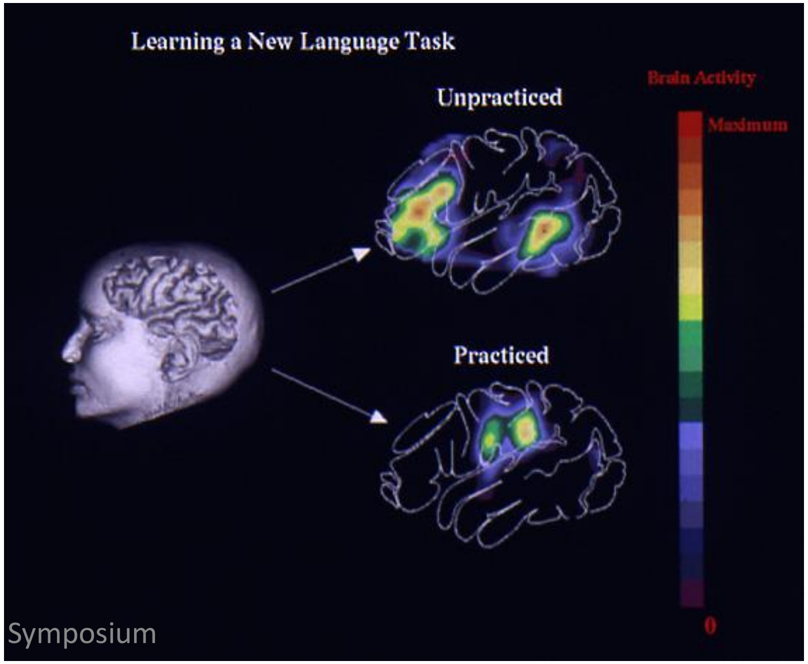
PET Scans

$^{18}F \rightarrow ^{18}O + e^{+} + \text{neutrino}$

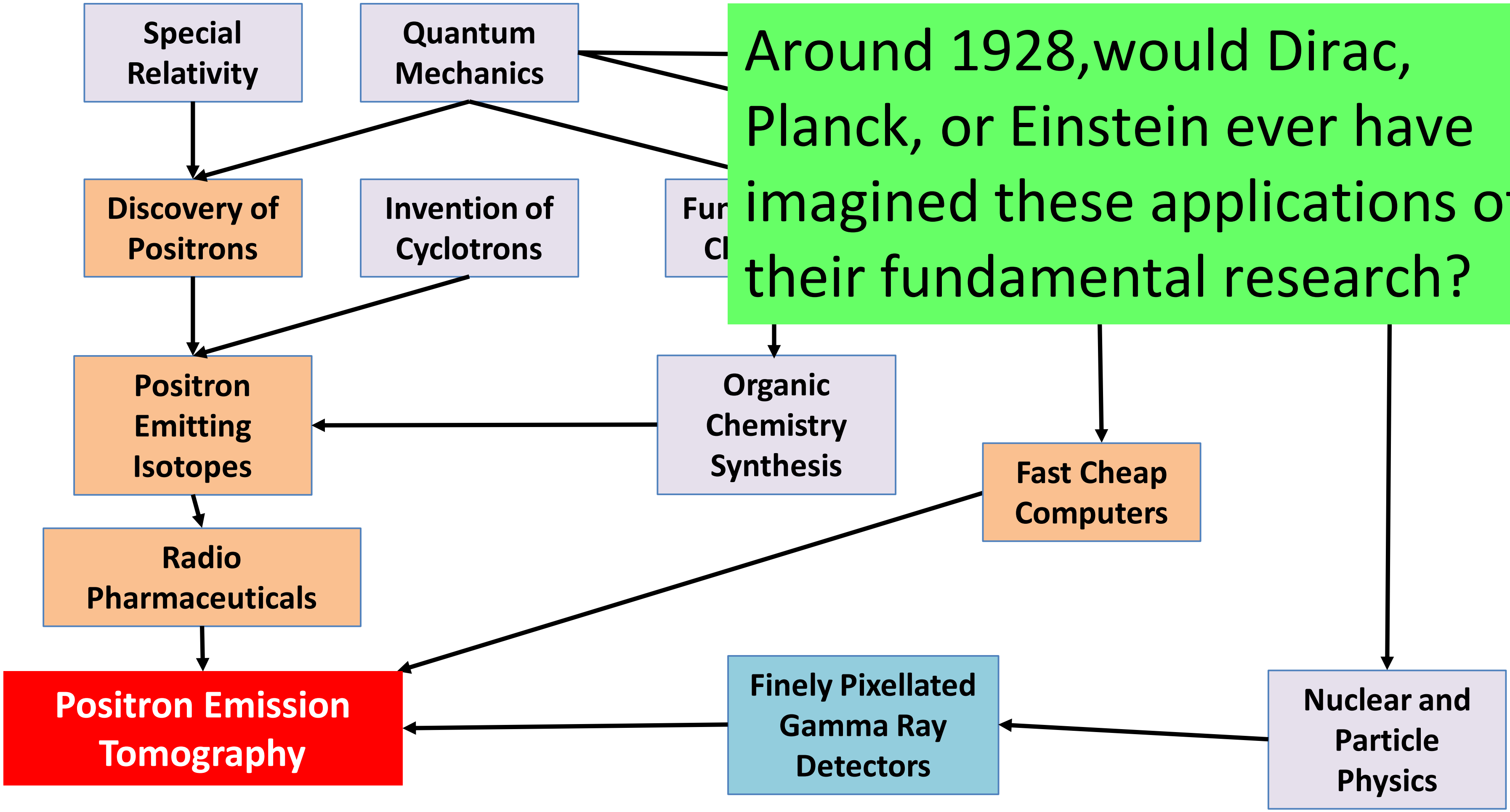
$e^{+} + e^{-} \rightarrow 2 \text{ photons}$







Positron Emission Tomography: the perfect storm of applications



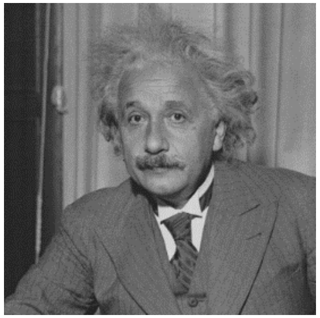
Around 1928,would Dirac, Planck, or Einstein ever have imagined these applications of their fundamental research?

The great scientists themselves did not foresee the applications

E. Rutherford

When questioned by a journalist about the splitting of the atom, Rutherford said
"The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from transformation of these atoms is talking moonshine."

The great scientists themselves did not foresee the applications



A. Einstein

Relativity

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!

J.C.
Maxwell

Electro-magnetism

Telephones use electromagnetic waves to communicate

Last Topic FCC

Accelerator Sector Proposals (13) to the European Strategy Group in 2012

Document	Accelerator Science and Technology	Physics at High Energy Frontier	Physics of Neutrinos
120814_01: HL-LHC	X	X	
120814_02: LIU	X		
120814_03:HE-LHC	X	X	
120814_04: LHeC	X		
120814_05: LEP3	X		
120814_06: CLIC	X	X	
120814_07: Neutrinos	X		X
120814_08: EURISOL	X		
120814_09: Generic Accelerator RD	X		
120814_10: Test Beams	X		
120814_11: Medical Applications	X		
120814_12: Heavy Ions LHC-HI	X	X	
120814_13: 80 Km Tunnel	X		

1st August 2012

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

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High Energy LHC
Document prepared for the European HEP strategy update

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The farthest energy frontier

HE-LHC in the LHC tunnel has many advantages, however inevitably this scheme has two main drawbacks:

1) The use of a narrow tunnel will make integration of larger magnets a difficult exercise.
2) The beam energy reach is necessarily limited, between 13 and 16.4 TeV/beam.

The use of a larger new circular tunnel will remove radically these two limitations. Preliminary studies recently launched at CERN indicate that there are two possible positions for an 80 km circumference tunnel, see Fig. 10, around the CERN site. Such an option is at a very early stage of study, however costing of such a tunnel may be envisaged in the 4 BCHF range.

Figure 10. Two possible l… …udy, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

Super High Energy LHC + LEP3 + SLHeC = FCC

In cas… …a new optimization space to explore is open. At this stage we can only en… …g possibilities of collision energy as a function of the dipole field:

1) …TeV c.o.m. with 8.3 T (present LHC dipoles)
2) 80 TeV c.o.m. with 16 T (high field based on Nb_3Sn)
3) 100 TeV c.o.m with 20 T (very high field based on HTS)

Actually in a new tunnel, with a cross section larger than the present LEP/LHC tunnel (3.8 m in diameter) a dipole could be larger than the one sketched in Fig.8, therefore in principle 20 T dipole field is not anymore a hard limit. However, considerations about technical complexity and cost indicate that would be extremely difficult, if not unrealistic, substantially increase the field above 20 tesla.

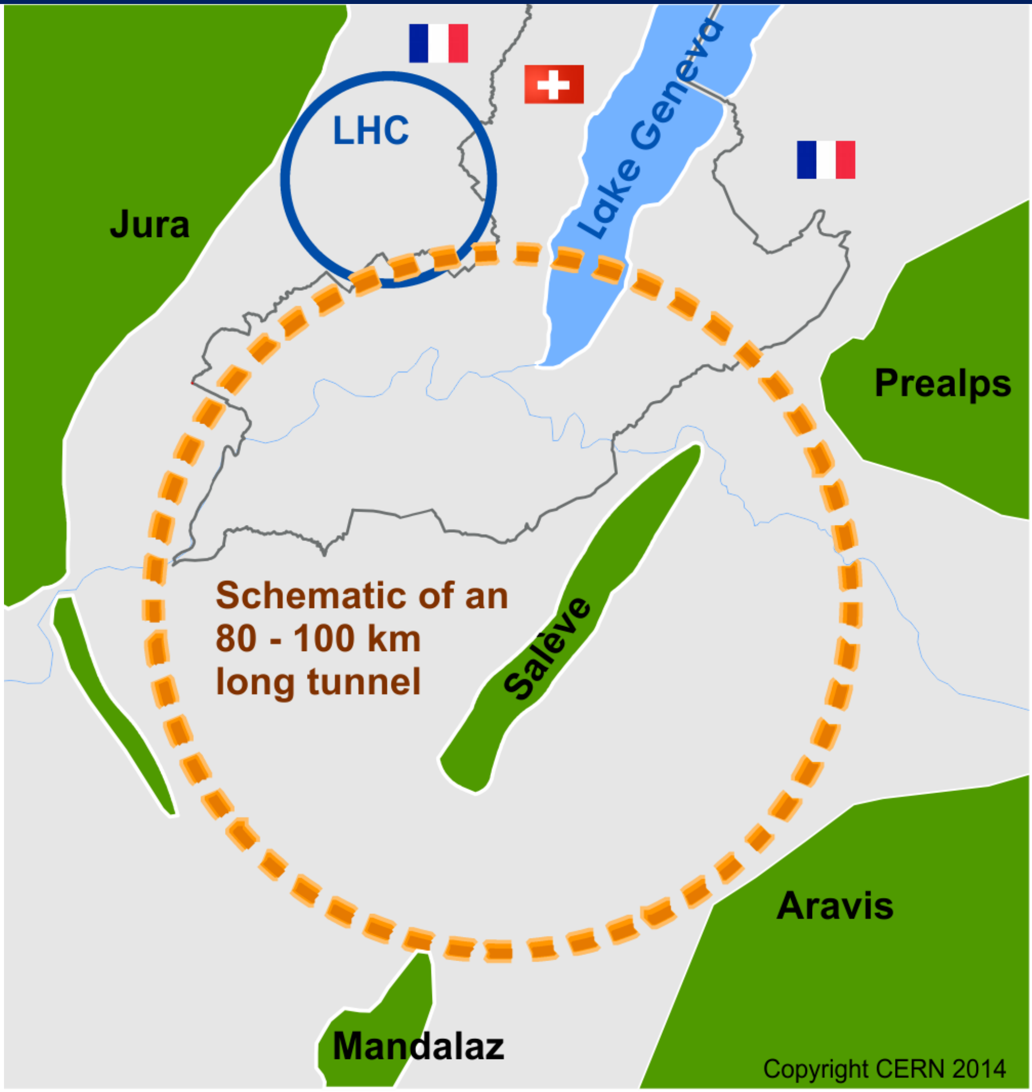
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

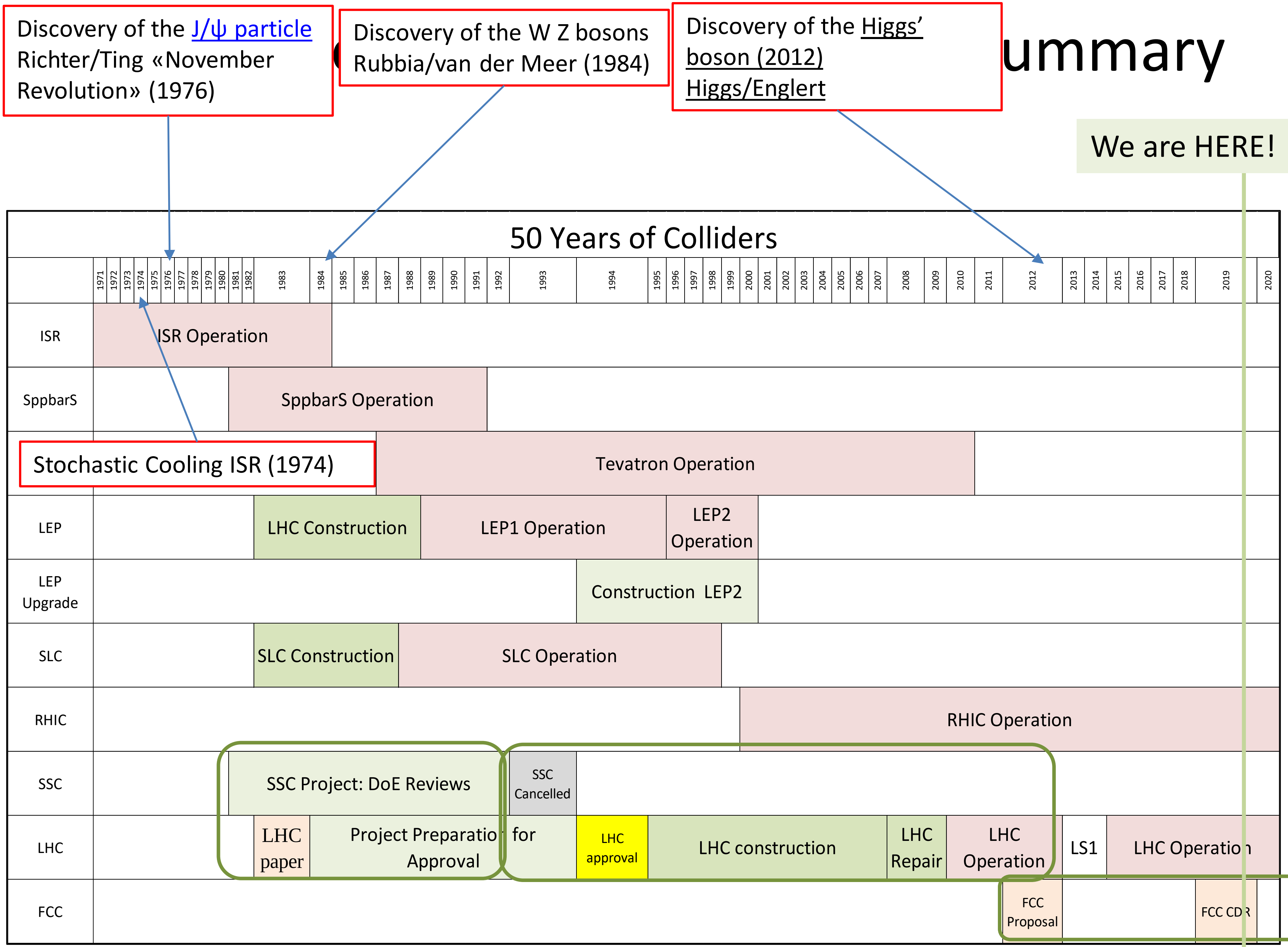
- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



The LHC Life cycle

- 1983: Preliminary Performance Estimates for the LHC.
- 1984: Kick off meeting to discuss ideas for an accelerator t… e protons at very high energy
- 1994: Decision to construct the LHC
- 2008 First beam and then the acciden…
- 2009 Repair
- 19 November 2009: … eam operation
- 2010,2011 S… performance of the LHC, detectors, and the GRID
- Ju… overy of a Higgs' boson
- … 2035: The LHC physics programme to be finished ?
- BUT in 2012, proposal of a study of a Super LHC (100TeV collision energy with a 100km tunnel in the Geneva area).
- 2019 FCC CDR and proposal to ESG

A >100 Years Adventure


ummary
Discovery of the J/ψ particle
Richter/Ting «November Revolution» (1976)
Discovery of the W Z bosons
Rubbia/van der Meer (1984)
Discovery of the Higgs' boson (2012)
Higgs/Englert
We are HERE!
50 Years of Colliders
1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
ISR
ISR Operation
SppbarS
SppbarS Operation
Stochastic Cooling ISR (1974)
Tevatron Operation
LEP
LHC Construction
LEP1 Operation
LEP2 Operation
LEP Upgrade
Construction LEP2
SLC
SLC Construction
SLC Operation
RHIC
RHIC Operation
SSC
SSC Project: DoE Reviews
SSC Cancelled
LHC
LHC paper
Project Preparation for Approval
LHC approval
LHC construction
LHC Repair
LHC Operation
LS1
LHC Operation
FCC
FCC Proposal
FCC CDR

Thank you for your attention