National PhD Programme in Technologies for Fundamental Research in Physics and Astrophysics

LNGS, February 17th, 2025

How to discover the secrets of nature down to the smallest scales

P. Campana, INFN Frascati

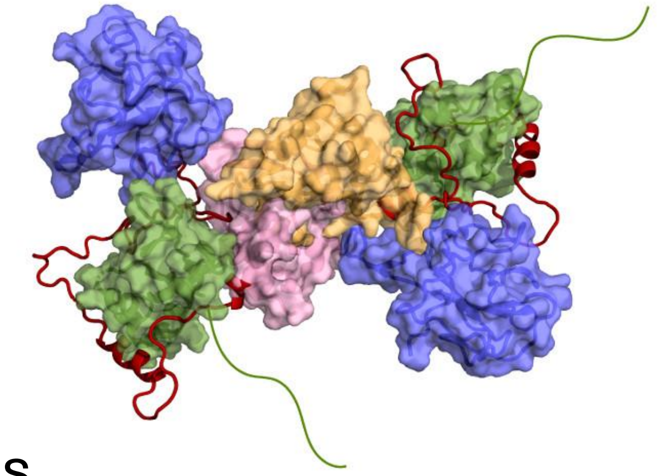
Foreword

The tools used for the study of the smallest Universe's elements, turns out, since more than 100 years, to be systematically applied to the society (health, industry, cultural heritage, environment, etc ...)

Accelerators: makers of elemental particles ($e^{-/+}$, p, n, γ, ions, etc...)
Detectors: identifiers of particle's type (m, q) and of its 6-D values (**r**, **p**)

Accelerators and detectors could not be operated without an immense amount of technologies: mech. & electro-mech., cooling & cryo, vacuum, mag. fields, diagnostics, sensing, metrology, optronics, electronics, controls, IT (online & offline), etc..., and the strong interplay among theorists, experimentalists, engineers, technicians ... and clerks, that have to buy your stuff !

A personal approach



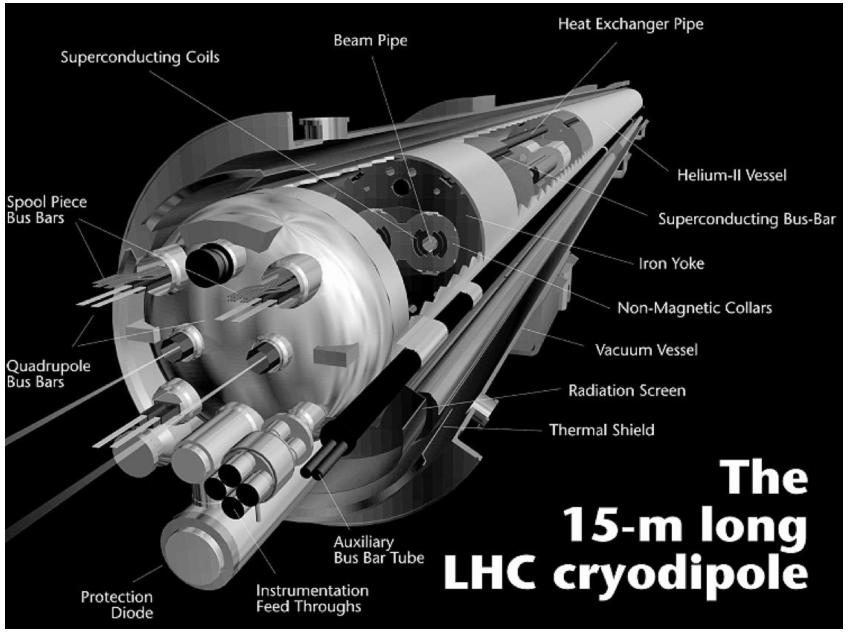
An effective way to provide an idea of the efforts to study the smallest scale and to make some examples of the "serendipity" of Particle Physics, is to discuss some examples of Large Research Infrastructures (LRIs) built for Fundamental Science from where, in part or *in toto*, a bright future in Applied Science has been originated

Often scientific journalism refer to LRIs as Big Science (sometime with disdainful meaning). Recently, economists have started to consider LRIs has an effective way of producing technological development and richness in the country/region that host LRI. Most advanced European countries host such LRI (Germany, France, UK, Sweden) and China is investing in LRI at full pace since the last 10-20 years.
More quantitative details on this will be presented at the end of the talk

LHC: protons, the particles to be "smashed"

Protons collide against protons at 7+7 TeV in 4 locations around the collider

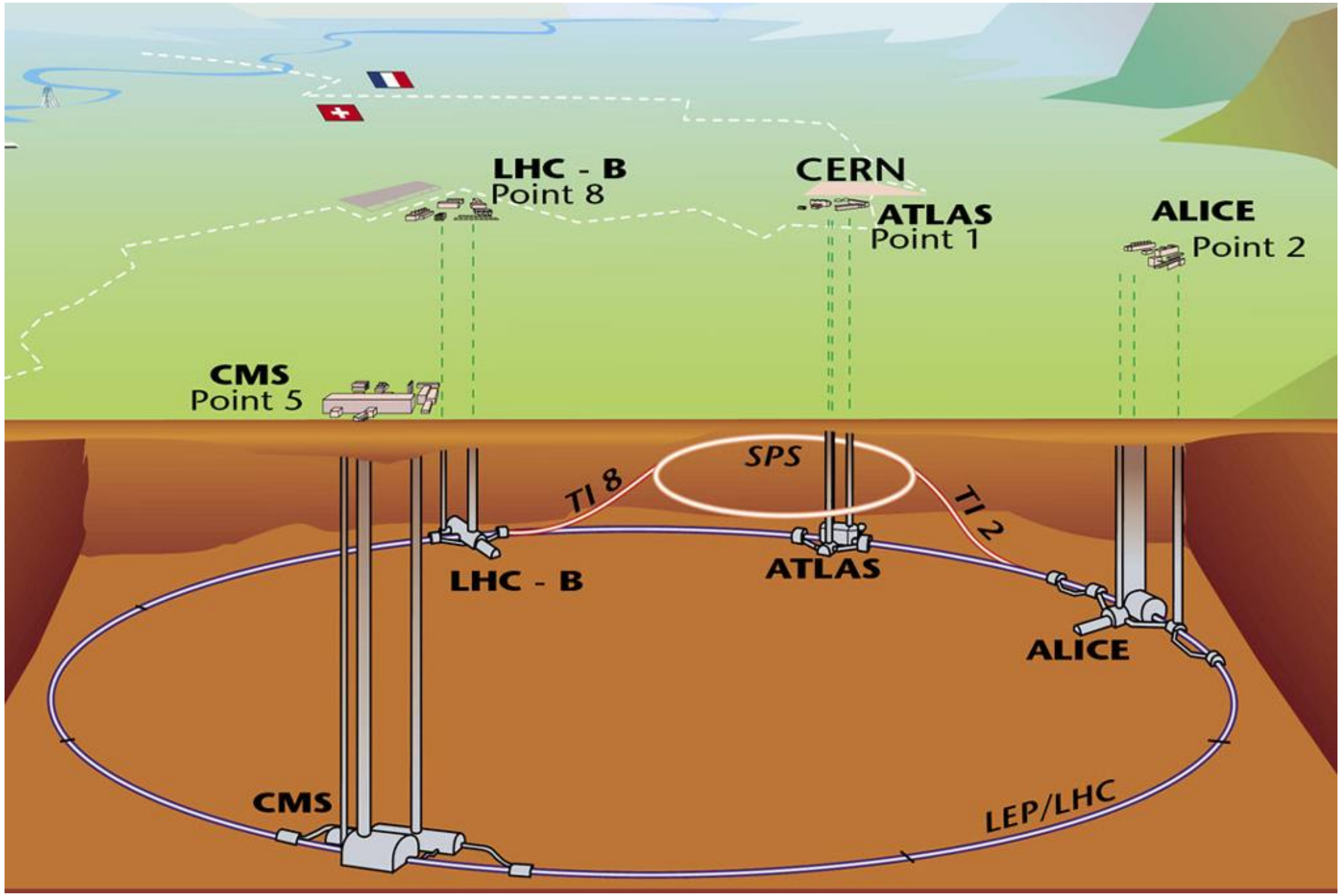
27 km tunnel length (at ~ 100 m depth)
1,200 superconducting magnetic dipoles (NbTi) at 1.9 K , providing 8 T bending field (7 TeV)
2,800 bunches with 10^{11} particles each (370 MJ)
100 km of vacuum pipes (2x27 km of beam pipes at p = 10^{-10} - 10^{-11} mbar)
~ 1 PB/day of data written by the 4 experiments

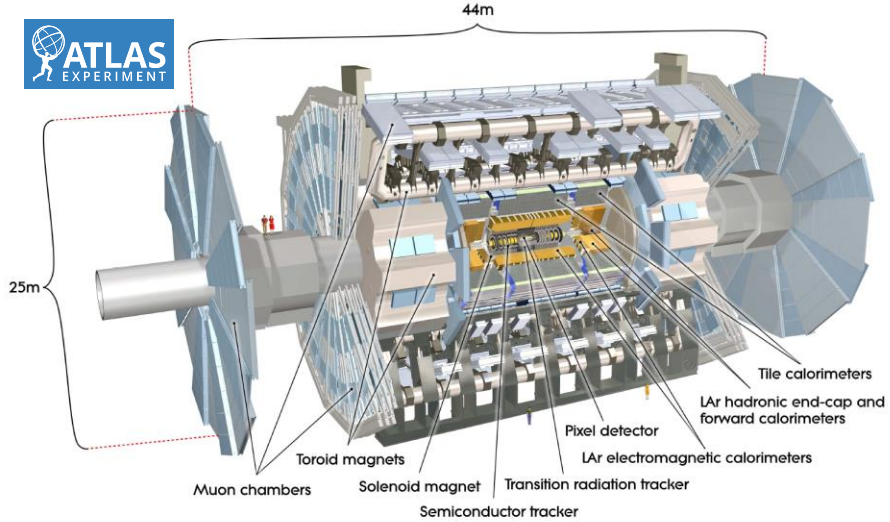


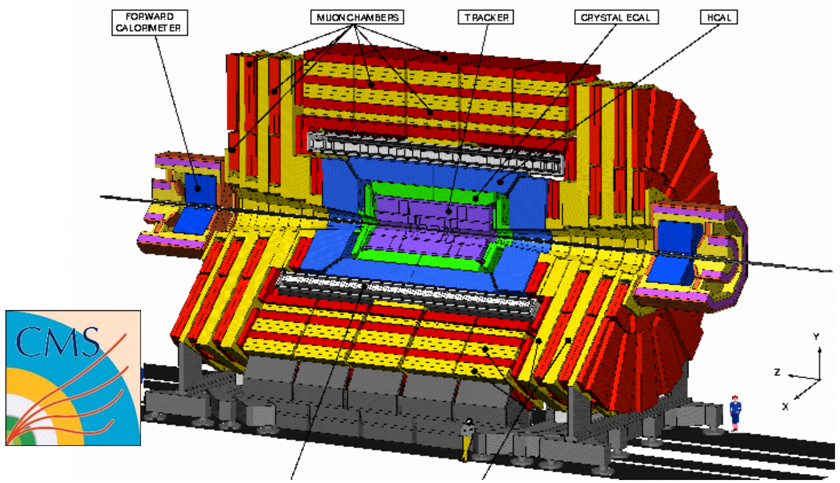
The success of the industrial production of LHC dipoles (built, 1/3 each, by companies in IT, F, D) was made possible by the R&D in NbTi magnets done since the 1980's at FERMILAB, HERA (DESY) and for SSC (US pp project terminated in 1993). More than 20 years of R&D. This is important for any development for future machines

The LHC experiments

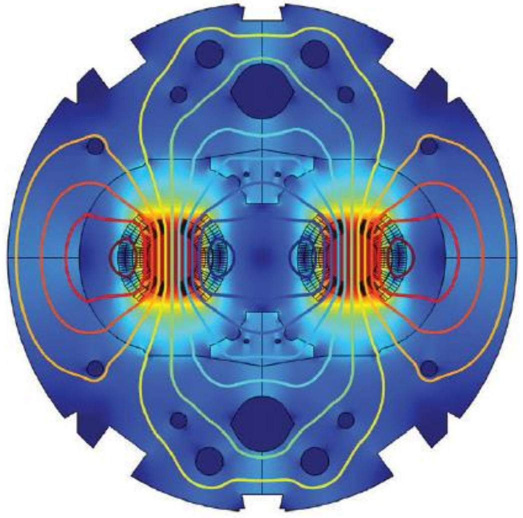
ATLAS & CMS, large dimensions, big central solenoid, general purpose experiments
LHCb, to study specifically matter/antimatter symmetry through decays of b- and c- quarks
ALICE, high density matter in ion-ion collisions (quark-gluon plasma, early times of Big Bang)





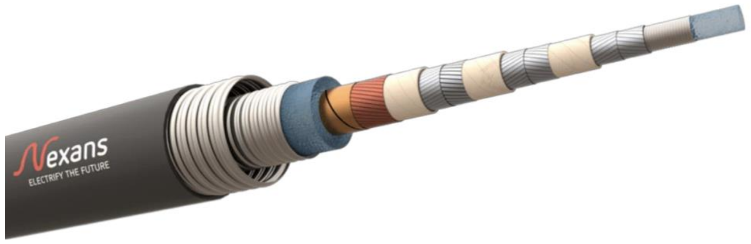


Superconducting technologies

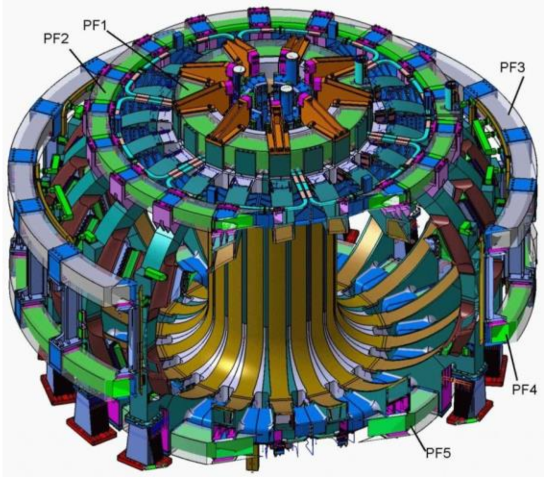


The use SC **NbTi** cables allows to reach the high magnetic fields (8-9 T) needed to bend the protons of 7 TeV in LHC tunnel, allowing ~ 11,000 A to flow through the circuit at ~ 0 resistance
Even higher currents can be reached with **Nb_3Sn** or with new a new class of **HTS** cables (High Temperature Superconductors) that can be operated at higher temperatures (~ 20-70 K), reducing complexity and power of cryogenic systems

Magnetic Resonance Imaging scanners make large use of SC cables to achieve the very high field needed (3 T commercial, with R&D up to ~ 10 T).
Nb_3Sn and HTS cables (**ReBCO**) are used for fusion toroids (e.g. ITER) to confine with high magnetic field the plasma



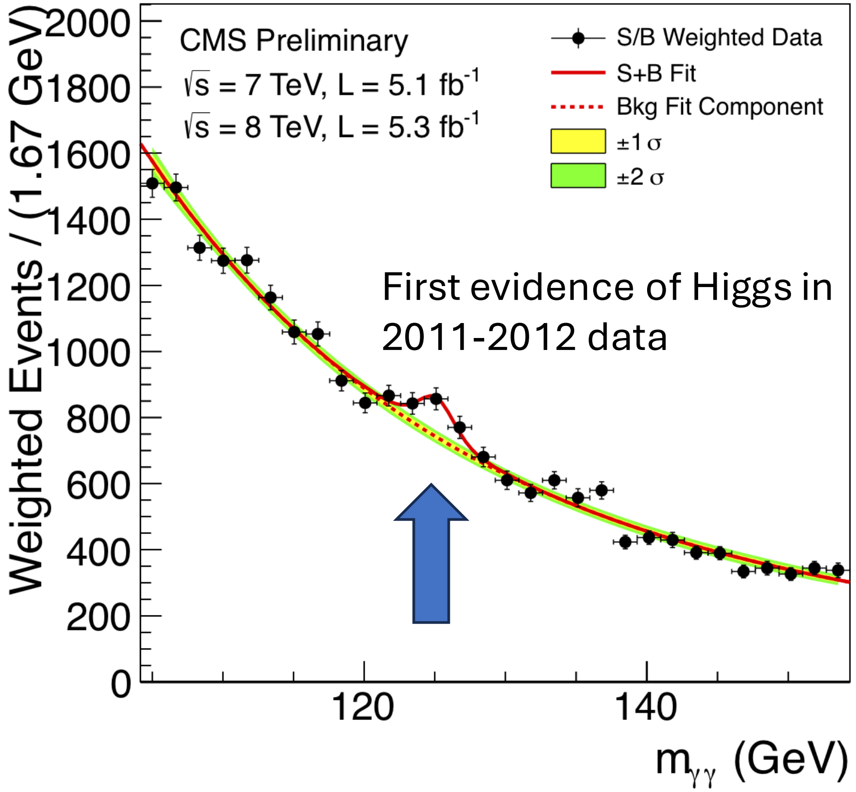
HTS cables have been suggested for high power lines at zero losses for civil and industrial use.
CERN has built a ~ 200 m long prototype, and a works are ongoing at Montparnasse Paris rail station to re-cable all electric utilities with HTS.
A INFN project (IRIS) to build a 50 kV x 40 kA line has been financed by PNRR funds

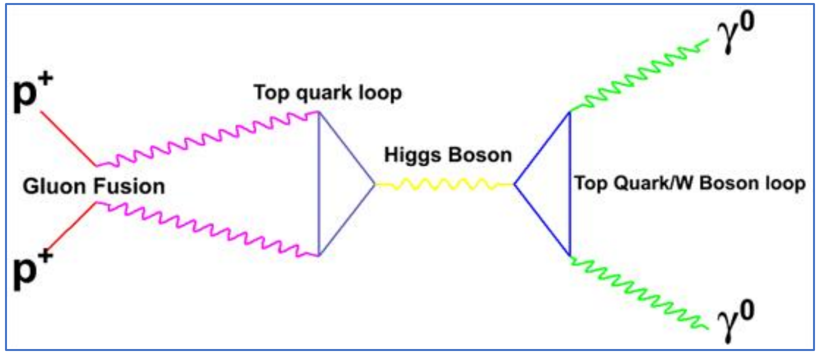


Why LHC ?

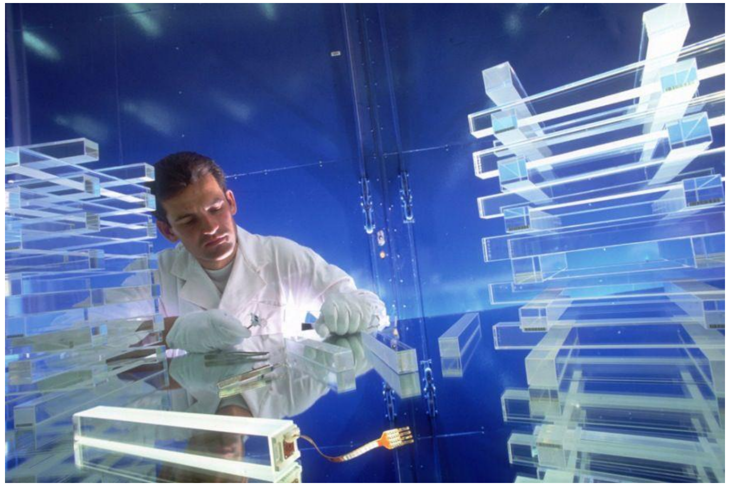
The previous large e- e+ collider at CERN
(LEP, 1989-2000, 205 GeV centre of mass energy)
was not able (lack of energy) to discovery the Higgs boson, a pillar of Standard Model of Particle Physics, sought since 1964.
Experimental hints suggested a mass slightly above 100 GeV.
LHC was built in LEP tunnel, together with 2 multi-purpose expts.

The Higgs is produced in pp collisions and expected to decay in many channels, the most promising being 2 photons. Therefore the experiments were equipped with high resolution photon detectors (in particular CMS, $PbWO_4$ crystals)

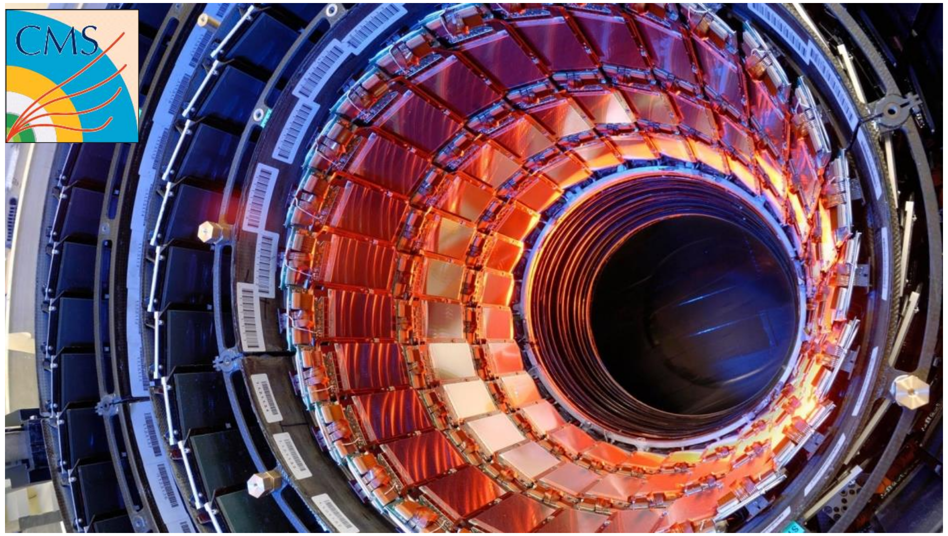




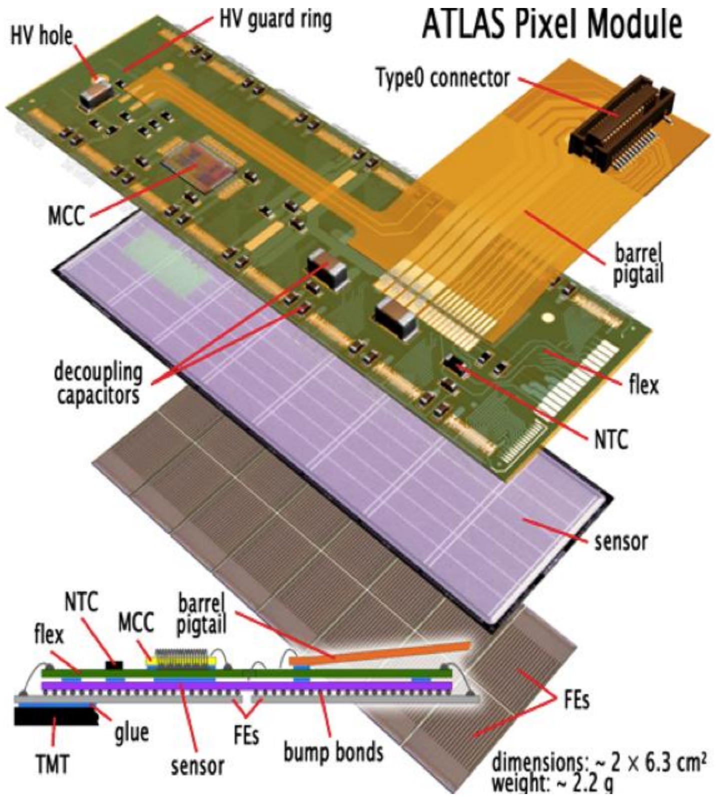
Crystals have high density (8 g/cm^3), high scintillation light yield, fast response and are read by silicon photo-diodes. Built in China and Russia, CMS mounts 80 k of them



Precise tracking devices



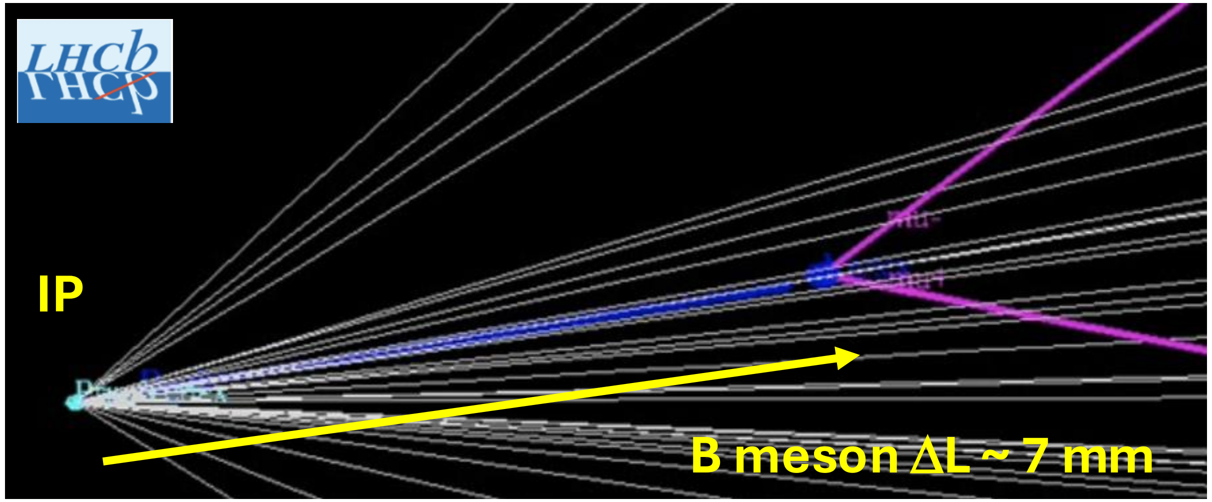
One of major challenges at LHC experiments is to identify the space points of the passage of particles in the detectors Major issues are the amount of tracks/event, the no. of superimposed events per interaction (~ 100) and sometime the extremely small lifetime of particles (e.g. B mesons decay very near to the I.P. with a decay lengths of few mm)



High level of radiation requires to have detectors still operating after fluxes of ~ few 10^{15} n/cm^2 . Surfaces to be covered at current LHC upgrades amount to ~ 20 m^2 for PIXEL detectors ($\sigma_{x,y}$ ~ few μm, 3D point, pixel size 50 μm x 400 μm) and ~ 200 m^2 SILICON strip detectors (σ ~ 20 μm, 2D point, strip size ~ 50-100 μm x few cm)

HEP physics has the state-of-the art in this technology, with applications to **Astrophysics**, **Medical Physics** and **X-ray imaging**

LHC physics goals & methods



Higgs detection:

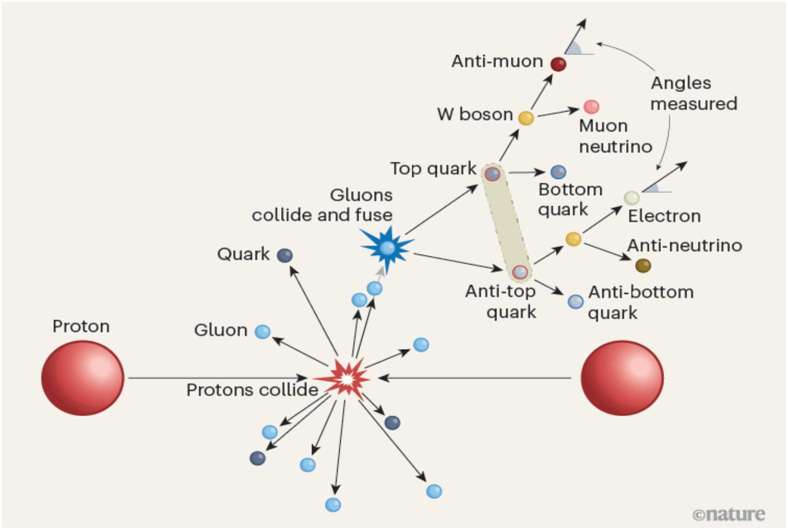
- Via calorimetry (final states with γ or **electrons**): crystals (CMS) or liquid Ar (ATLAS)
- Via final states with **muons** (tracking in solenoidal magnetic field → **P** + identification)

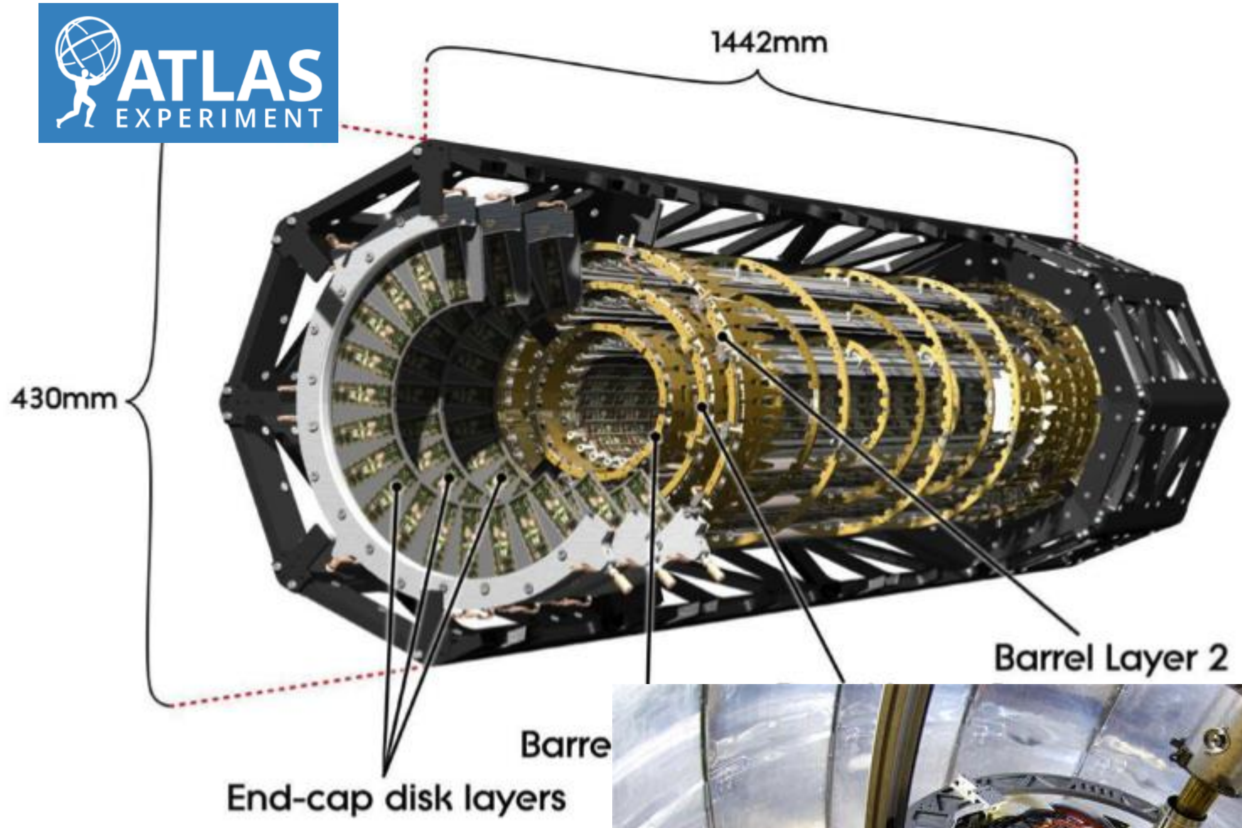
(1) New particle states: looking for mass resonances (between ~ 100 - 1,000 GeV) or looking to observables (e.g. decay rates) larger/smaller than foreseen by theory (SM): indirect searches

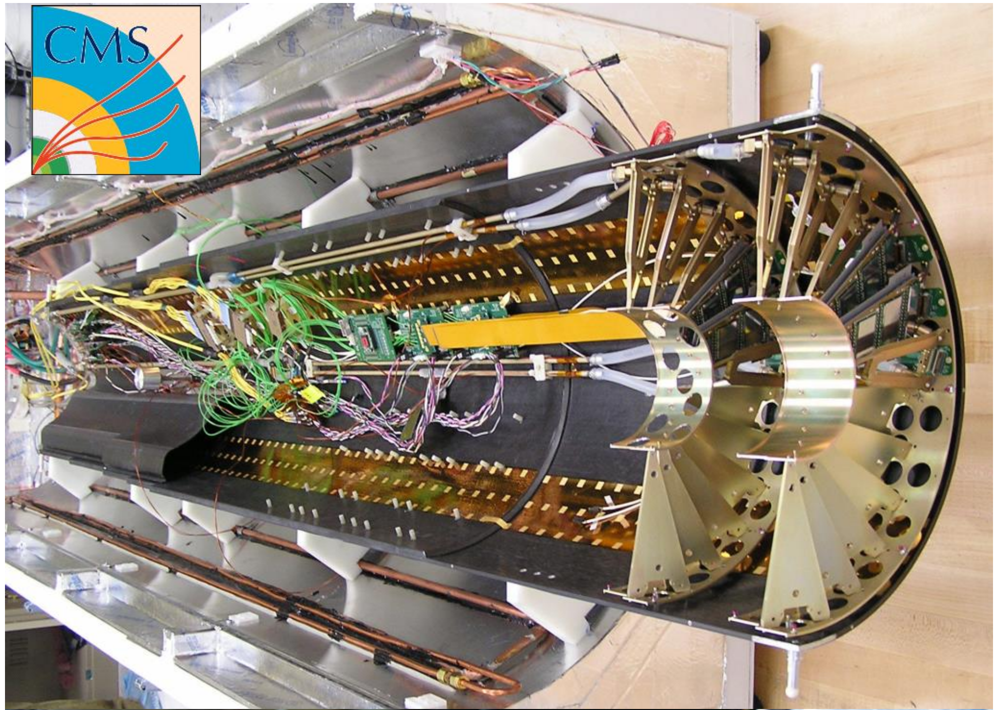
(2) Missing energy: looking for holes due to non interacting particles (maybe candidate for Dark Mass)

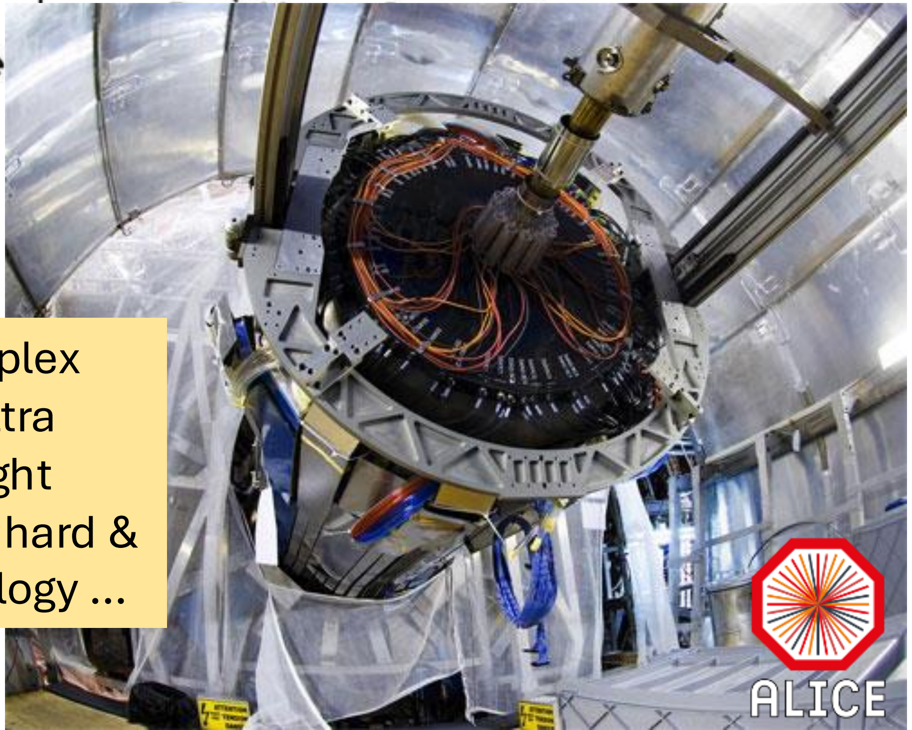
(3) Unexpected topologies/events. None of the above observed so far

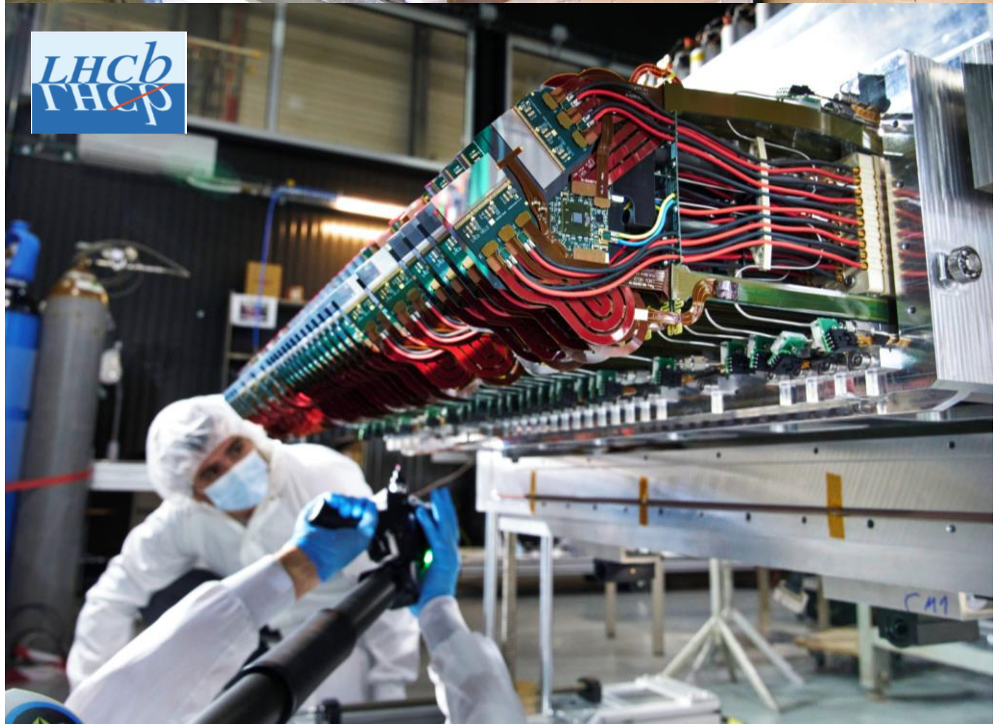
Study of heavy quarks: measuring quantum properties of charm- or beauty-based hadrons, their excited spectroscopic states (by LHCb) or top quark (the heaviest one, ~ 180 GeV), by ATLAS and CMS.
Latest result, even top quarks are produced entangled











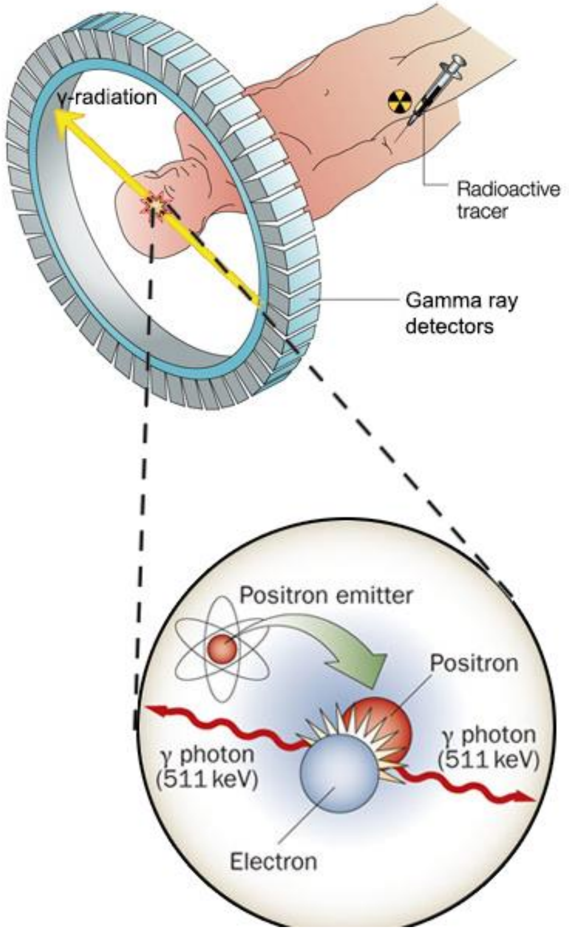
TRACKING SYSTEMS: a complex and successful mixture of ultra high technologies: C-fiber light structures, CO_2 cooling, rad hard & fast & dense readout, metrology ...

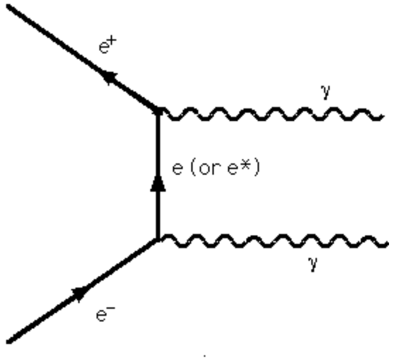
Positron Emission Tomography (PET)

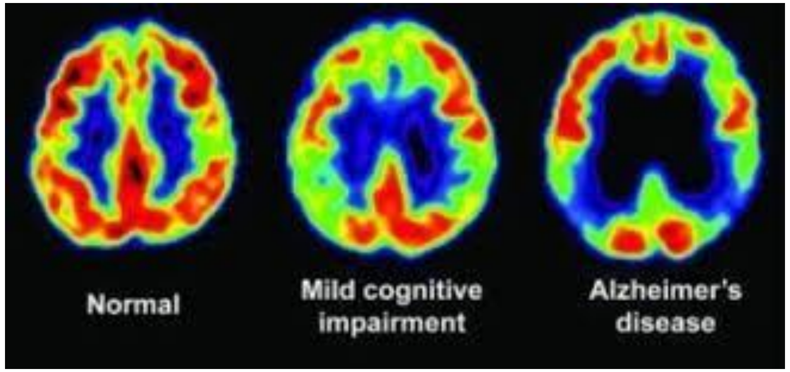
PET is a medical imaging to identify cancer at early stage or other diseases

Positrons radioemitters are injected in the patient, e.g.:
- Fluorodeoxyglucose ([^{18}F]FDG or FDG) is commonly used to detect cancer;
- [^{18}F]Sodium fluoride (Na^{18}F) is widely used for detecting bone formation;
- Oxygen-15 (^{15}O) is sometimes used to measure blood flow.

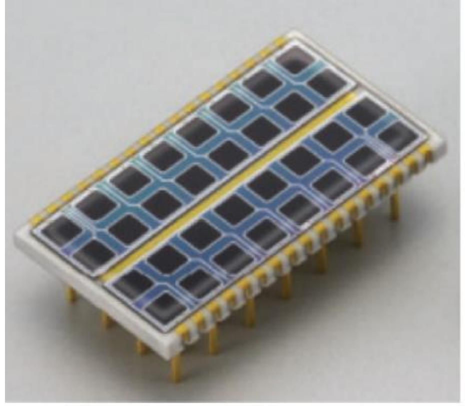
These tracers are β^+ emitters ($p \rightarrow n\, e^+ \nu$) and the positron interacts within ~ 1 mm with electrons in the tissue of interest: two photons of 511 keV are then emitted and detected by a circular array of crystals, to reconstruct the origin, and the local density, of annihilations.
PET is nowadays used in Oncology, Cardiology, Neurology, etc...
New crystals with higher performances are being used: BaF2, LYSO, etc...







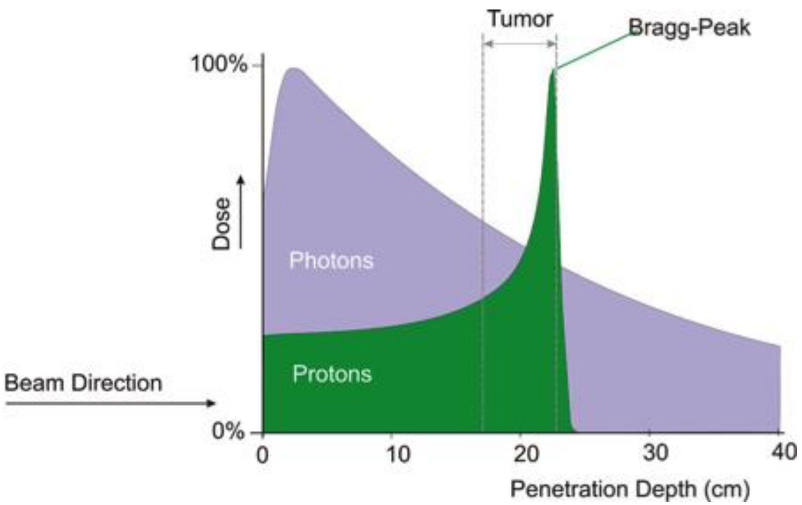
A challenging activity concerns light readout and signal processing in PET: APD and SiPM sensors, fast signal processing to reduce noise, increasing (x, y, z) resolution and decreasing doses to patient

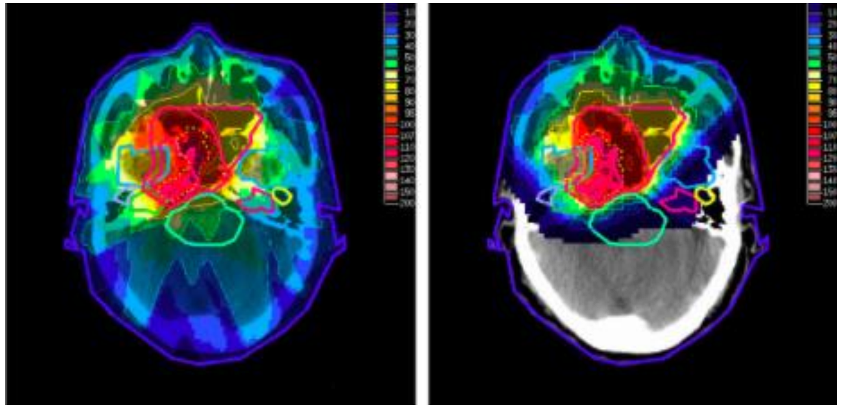


Protons and Ions not only for Fundamental Science

In most hospitals, and traditionally, cancer radiotherapies are performed with intense beams of gamma or X-rays or electrons (provided by Linacs). These machines are commercially available and easily installed in hospital bunkers.

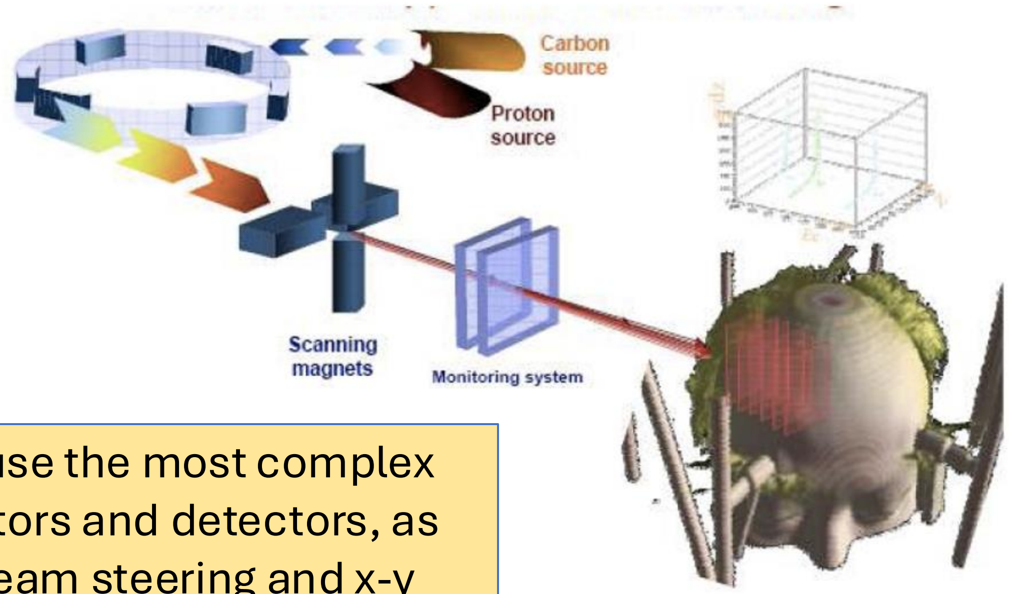
Since decades, a new method has been introduced, based on the so called **Bragg peak**, for which, use of beams with hadrons (p, ions) increases its effectivity. Protons deposit most of their ionization at the end of the track, hitting "mostly" the tumor, if their energy is correspondingly regulated, while other radiation type hits nearby organs.
The drawback is that hadron machines are more complex, expensive, and cannot stay in hospitals.
Not all cancers are suitable for treatment (typically deep ones).

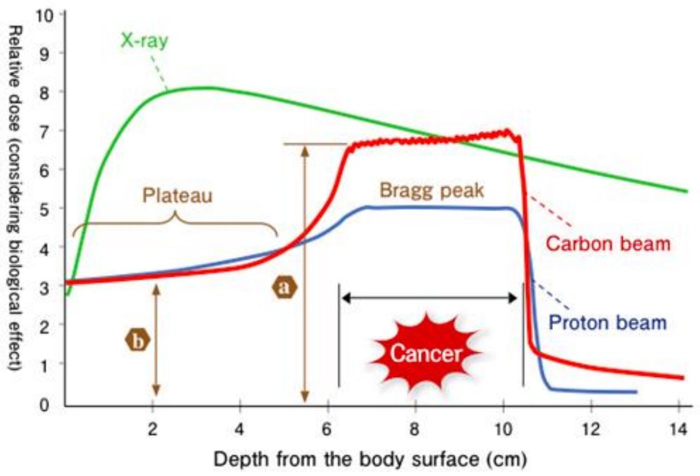




X-ray Protons

Modern technologies for hadron-based machines are basically derived from studies on proton machines for Fundamental Physics (FNAL, HERA, LHC, etc…). Some, can also provide ion beams which increases the Bragg peak effect, widening it in space.

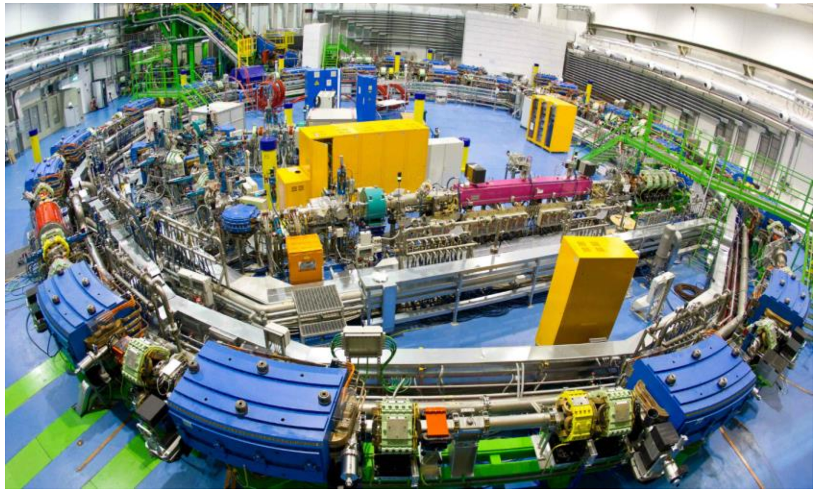




Hadron therapy makes use the most complex technologies of accelerators and detectors, as accurate high intensity beam steering and x-y coordinate tracking systems, computing technologies for beam treatment plans, sophisticated DAQ controls, HEP simulation packages. Few (4) ion centers in Europe

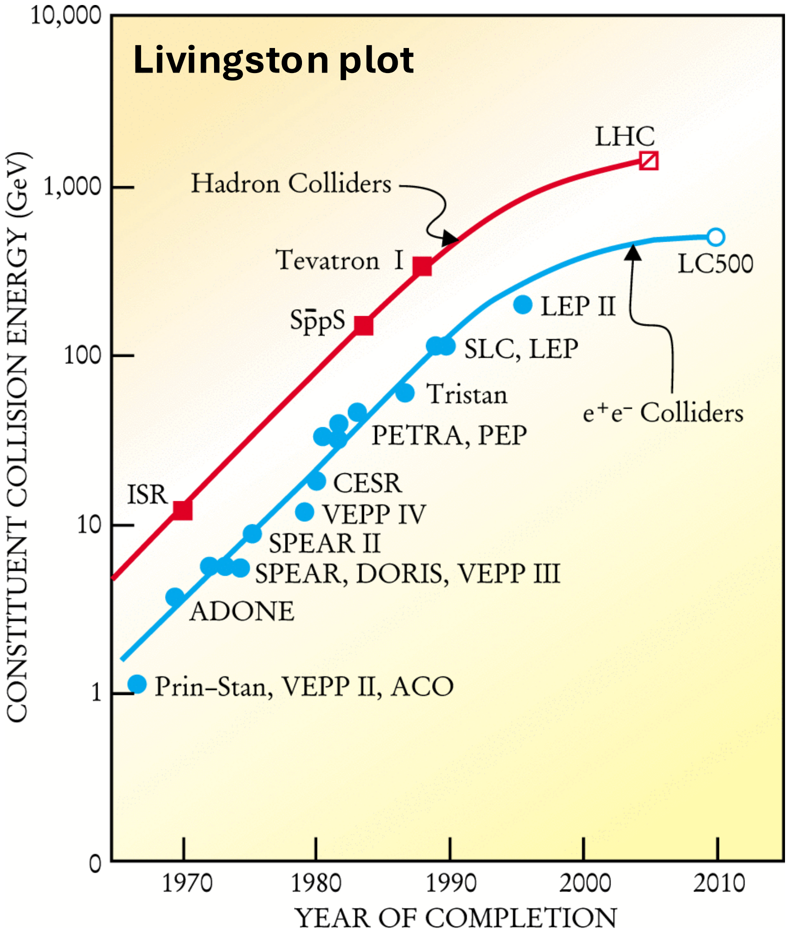
CNAO
Centro Nazionale di Adroterapia Oncologica

Complex beam delivery to patients (heavy rotating gantries). New ideas of lighter ones, based on R&D on SC and HTS cables



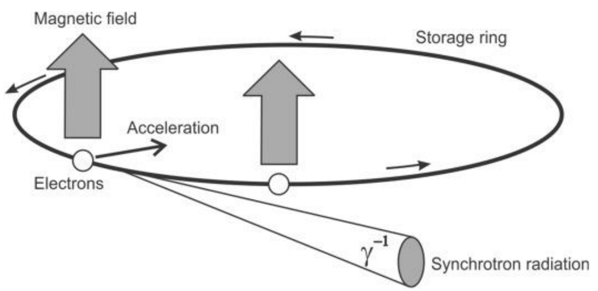
Electron-positron colliders (and e- based machines)

In 1960 Bruno Touschek at Frascati Laboratories suggest an **e+ e- colliding machine** to profit at maximum of center of mass energy (AdA, Anello di Accumulazione, 250 MeV), and in 1964 the machine was tested successfully at Orsay Lab (F). The history of colliders had started, arriving today at LHC



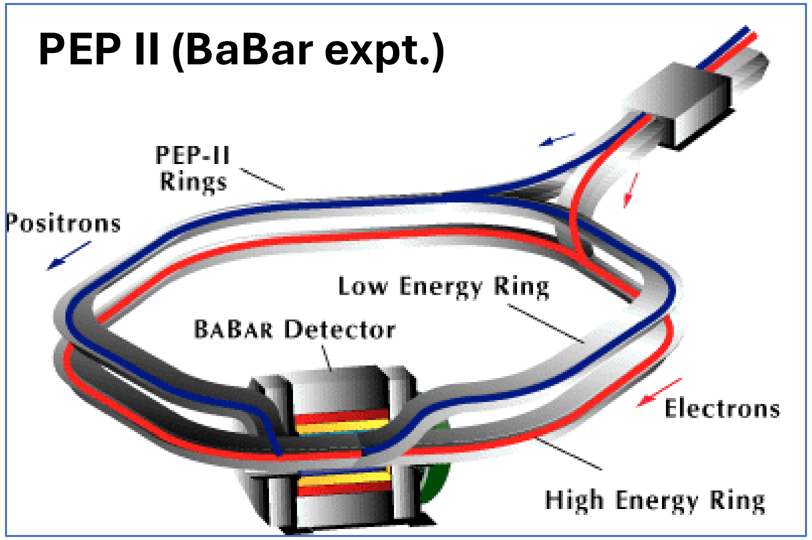
E+ e- circular colliders play a very important role in the development of HEP: up to the '80s they are discovery machines (**tau** lepton, **charm** and **beauty** quarks).
At higher energies (= mass of particles to be discovered) the synchrotron radiation limits the energies reachable.

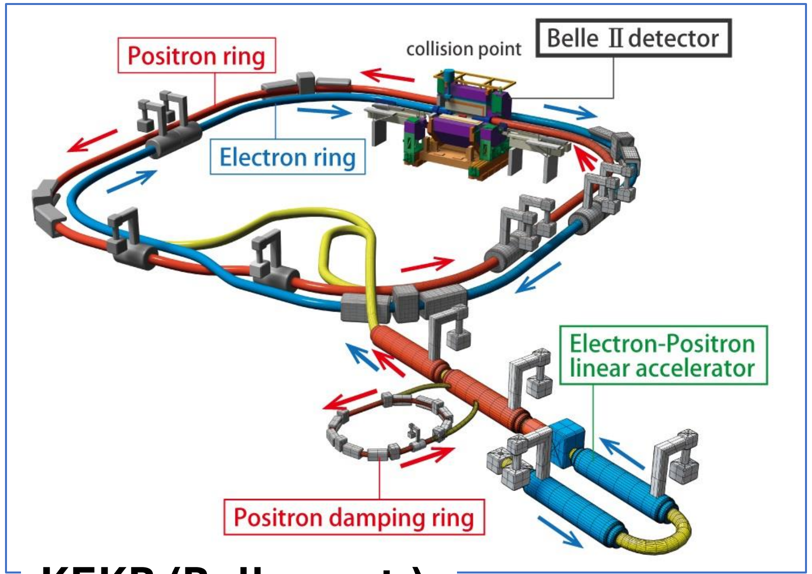
LEP has been the last high energy e+e- collider (209 GeV, slightly below the detection of **Higgs Boson,** m=125 GeV) and operated up to 2000. To reach higher energies, proton (LHC) or muon colliders must be built, as synchrotron radiation scales as ~ $1/m^2_{particle}$



The Flavor factories (2000-2020)

PEP II (BaBar expt.)





KEKB (Belle expt.)

High luminosity e+ e- circular colliders **PEP II** (SLAC), **KEKB** (Tsukuba), **DAFNE** (Frascati), built to study the problem of asymmetry in the Universe between matter and anti-matter in different initial states: **B mesons** (PEP II, KEKB) and **K meson** (DAFNE). KEKB still active.

DAFNE (KLOE expt.)

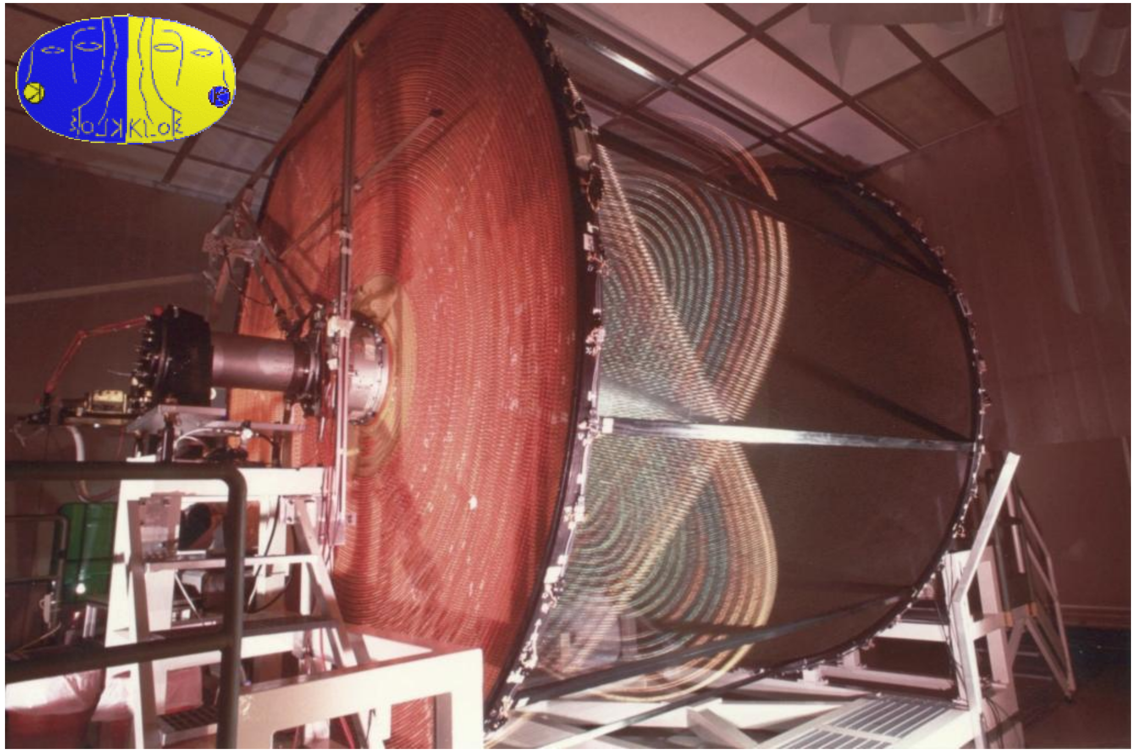
The development of high intensity colliders (x100 with respect to past machines) was possible thanks to the use of several new techniques in this field:

(1) Different beam pipes for the two colliding beams, to avoid electromagnetic interactions among them **(2)** Storage and damping system to reduce the size of beams to be injected in the machine **(3)** Special magnets, very near to the IP, to squeeze at maximum the size before beam collision.

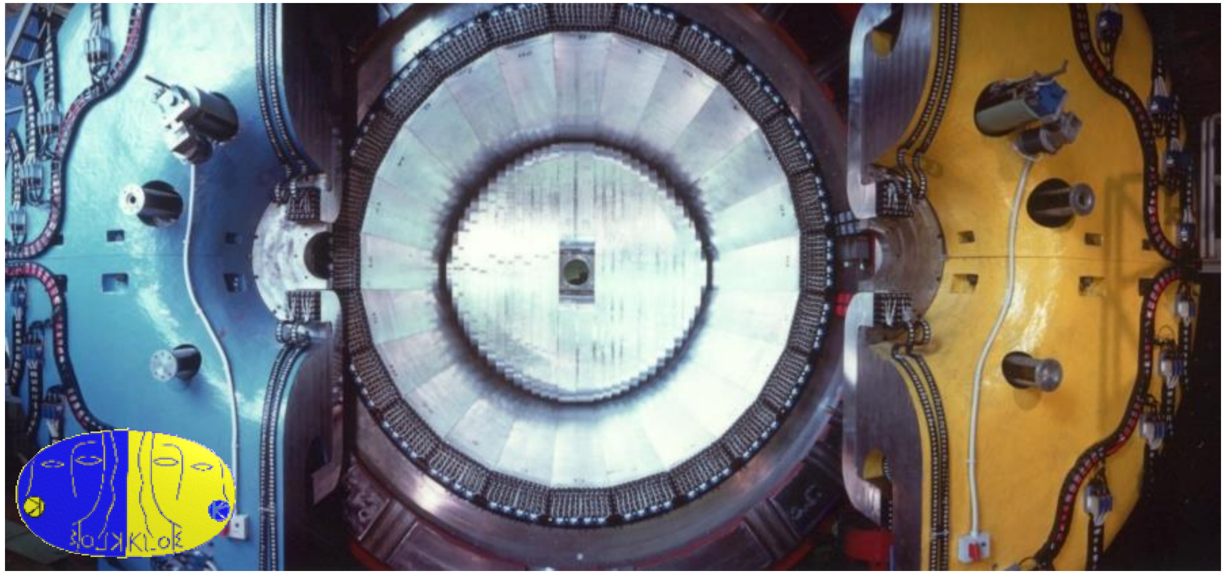
Experiments did not reported anomalies in Standard Model.

Detector systems at DAFNE-KLOE

Characteristics: charged particles of quite low energy, (e, muons, kaons), therefore extremely low material detectors needed to reduce multiple scattering, keeping high momentum resolution.
KLOE drift chamber (gas detector) in 0.6 T magnetic field with C-fiber structure and ~ 13,000 channels 4 m (D) x 3.3 m (L). Still the the largest ever built.
Momentum resolution $\sigma_{p_T}/p_T \simeq 0.4\%$



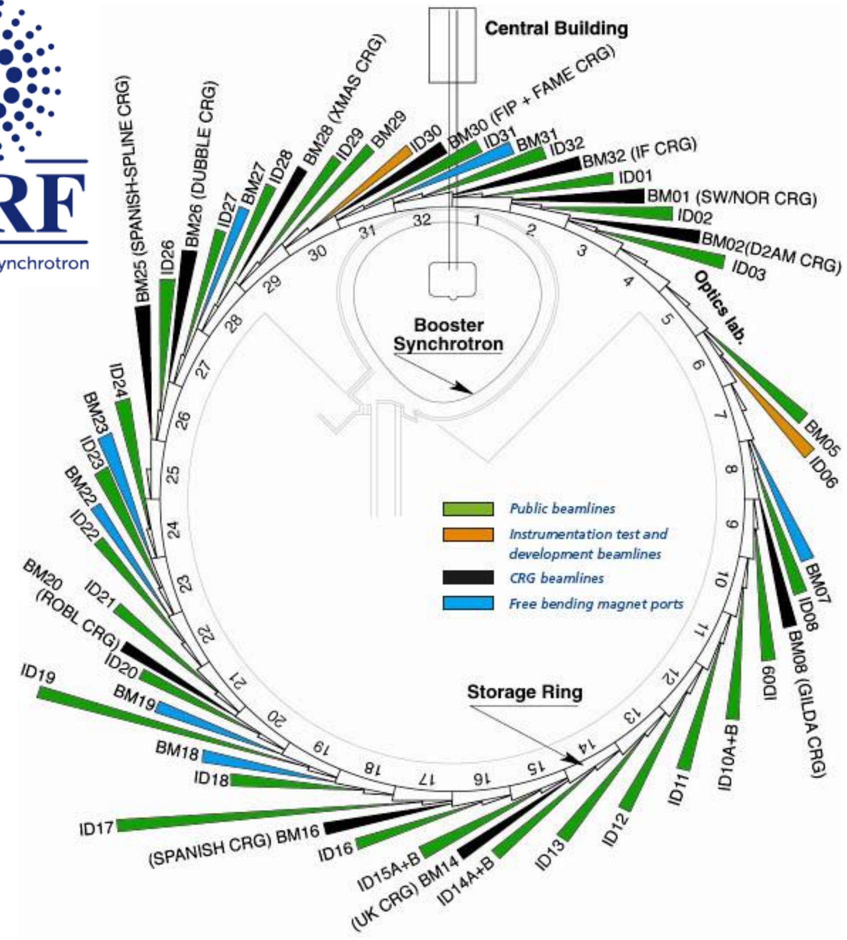
Low energy electrons and photons showering in **KLOE EM Calorimeter** made of a sampling of scintillating fibres and lead.
Excellent energy and time resolution
(6 % and 50 ps at 1 GeV)

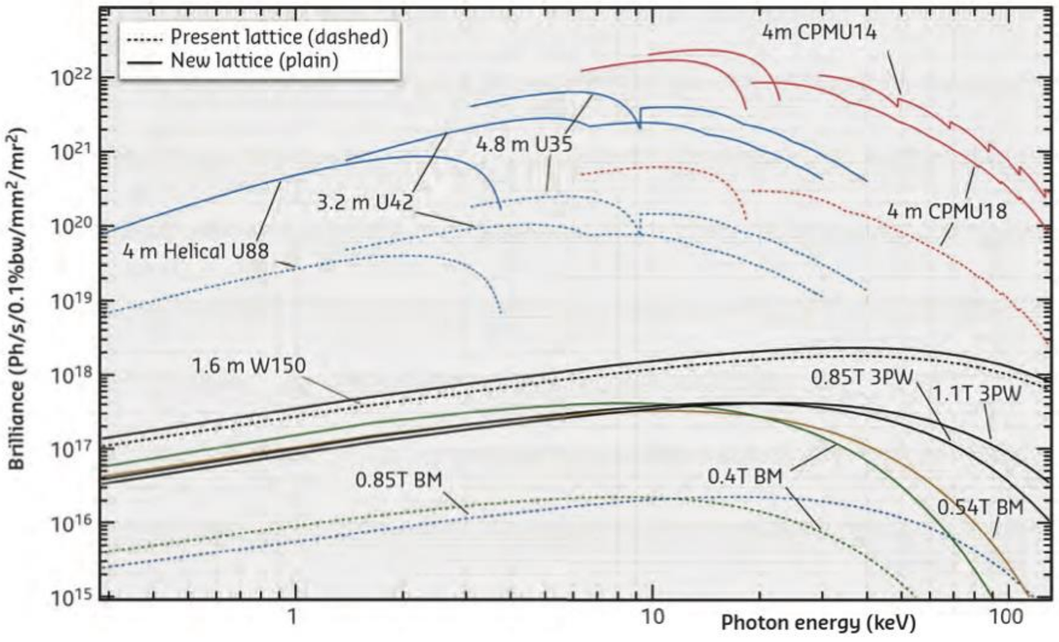


Synchrotron machines (SM)

ESRF
The European Synchrotron

Possibility to study biological systems with cell imaging, structural and functional biology, material chemistry, catalysis, new materials for photo-v. cells and batteries, electronics, and matter at extreme conditions with the **X rays emitted at synchrotron machines** (range 1 keV – 100 keV).
During COVID-19, experiments at SMs gave a decisive support to study proteins suitable for vaccines and to understand virus action

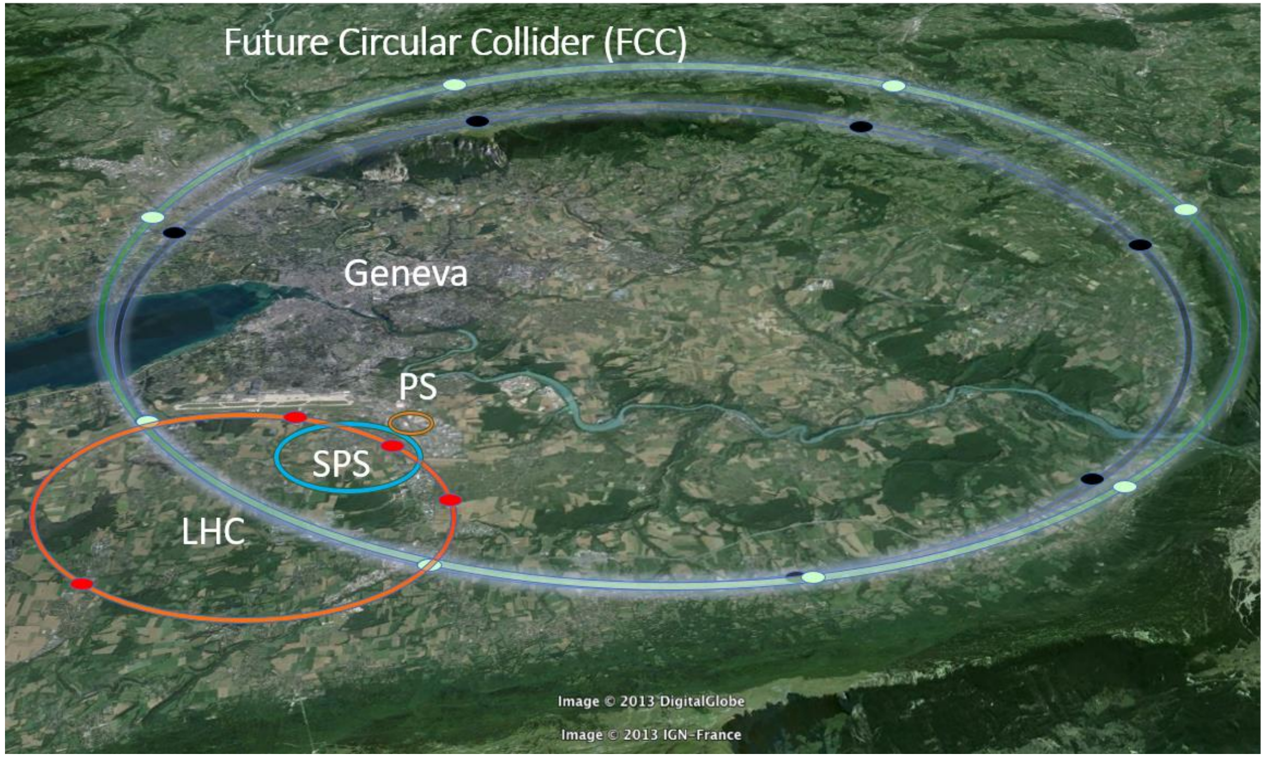




ESRF (Grenoble) is among the most advanced machines which recently underwent an upgrade from 3rd generation to 4th generation SM to increase the brilliance (= intensity) of photon beamlines, following the developments **studied for future Flavor Factories (Hybrid Multi Band Achromat)**, where dimension of e- beams which are at the limit of theoretical diffraction of the emitted radiation

What next ? (1)

Beyond HL-LHC, the community needs new tools to study further the Higgs boson and the present criticalities of the Standard Model. CERN is preparing now the 2026 European Strategy for Particle Physics, where physicists and policy makers from CERN member states will setup the next decade choices. Possible start-up of a new project (FCC) in 2028, to be operating in 2045 ?



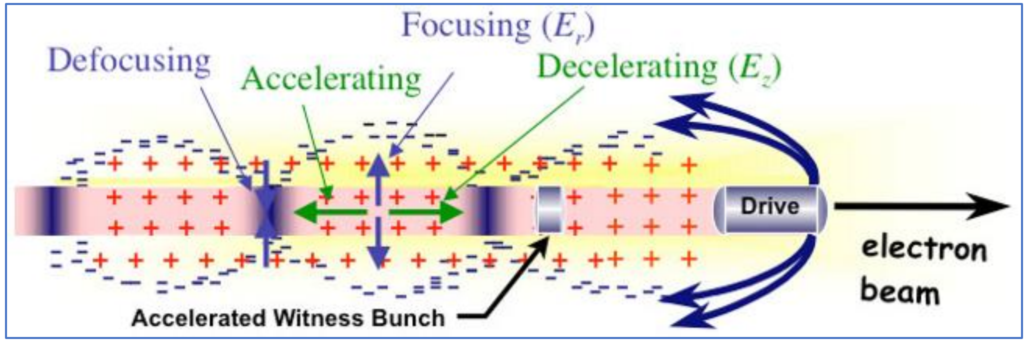
Main characteristics: ~ 90 km tunnel, two-step project. **FCC-ee** with c. m. energy up to 360 GeV (top production), and extensive production of H, Z, etc... Profound study of H couplings to catch possible deviations from SM. Estimated cost: 15 BE

FCC-hh with c. m. energy up to 90 TeV, to explore the high energy frontier, sensitivity to new states up to 10-15 TeV. Critical technology breakthrough needed: the development of high field magnets (possibly in HTS) at affordable costs (industrial production). Estimated cost, O(+10 BE)

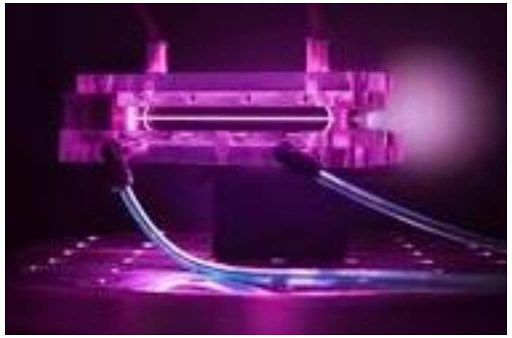
What next (2) ?

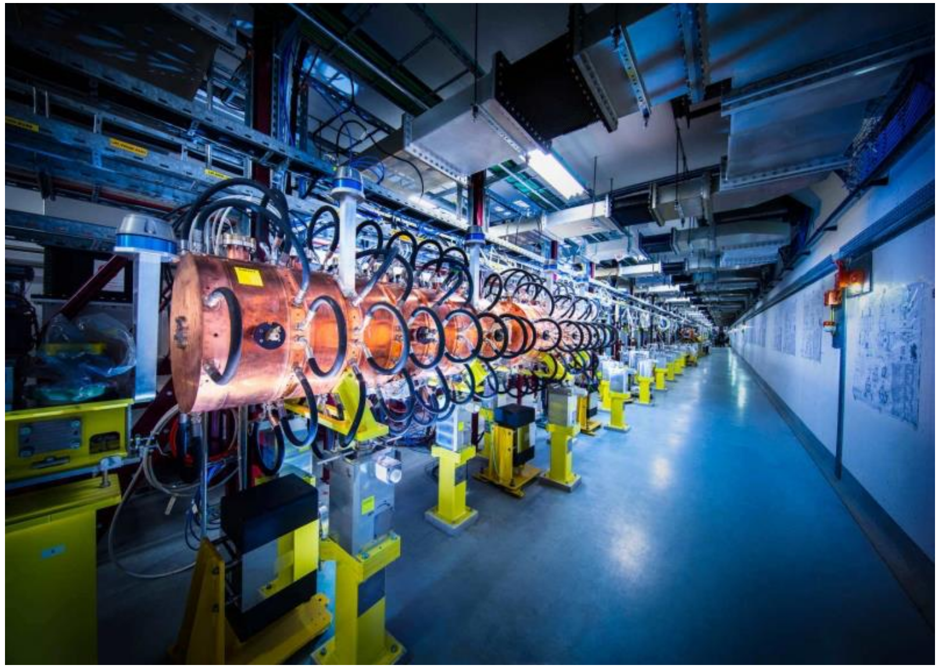
HL-LHC has brought nearly to the limit of accelerator dimensions: FCC has a footprint and a cost quite high (also in sustainability). Can we think to something much smaller ?

plasma driven acceleration



INFN is among the major leaders of this technologies, and is planning to built a large RI at LN Frascati, to study advanced technology for Plasma acceleration (EU project EuPRAXIA). The machine is expect to host users starting in 2031





Recently, teams in US, Europe and China are developing gas plasma cells where the ionized gas can provide very high fields to accelerate electrons up to 100 times the conventional systems based on RF cavities (up to 10 GV/m).
Unfortunately, so far, a similar technology for positrons is not yet available.

The INFN network of large RIs

Capable of building and running Large Flagship Programs, to participate to International Projects, given the technical infrastructures and manpower available. A strong asset for the local territory

Frascati

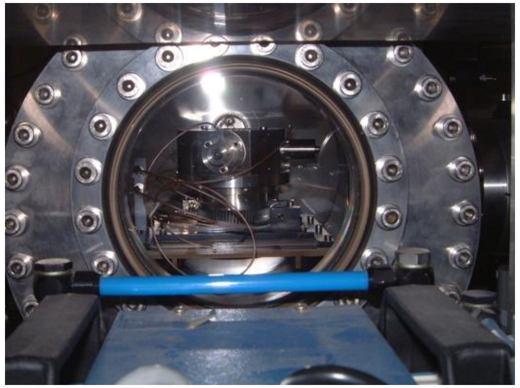
Gran Sasso

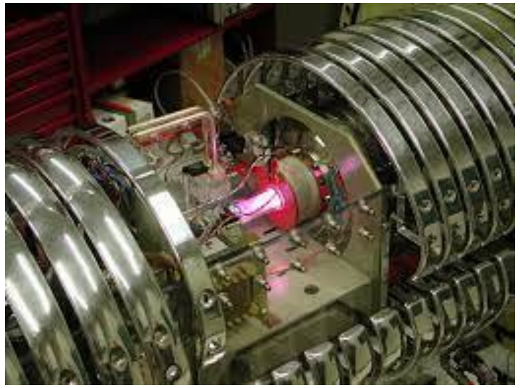
Legnaro

Catania

CNAF – Computing

Superconductivity (Milano-LASA, Genova, Salerno)





Impact of Research Infrastructures

Forecasting the socio-economic impact of the Large Hadron Collider: A cost–benefit analysis to 2025 and beyond

Massimo Florio [a], Stefano Forte [b], Emanuela Sirtori [c]

Recently, economists have started to evaluate the economical impact of Research Infrastructures, analyzing several outputs of RIs in the society, to which may be associated an economic value

KNOWLEDGE OUTPUT (S)

HUMAN CAPITAL FORMATION (H)

EXISTENCE VALUE (EXV)

TECHNOLOGICAL EXTERNALITIES (T)

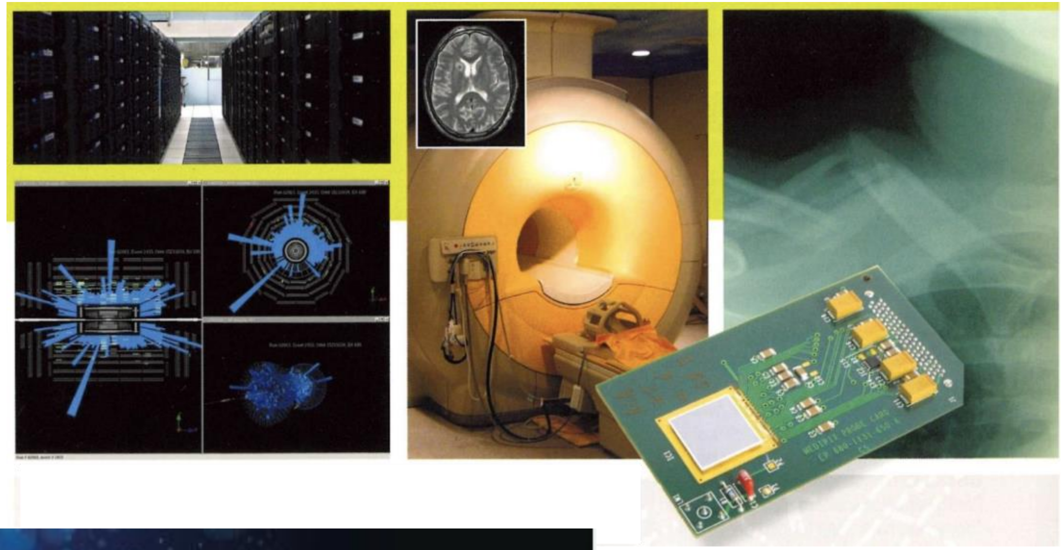
CULTURAL EFFECTS (C)

By definition, in these analyses, prospective added values coming from future exploitation of HEP discoveries (e.g., Higgs boson) are not considered.
An interesting counter-example is represented by Einstein's GW Theory (→ GPS), or by WWW

assessing its economic costs and benefits up to 2038. The Net Present Value (NPV) of the HL-LHC project is positive at the end of the observation period. The ratio between incremental benefits and incremental costs of the HL-LHC with respect to continue operating the LHC under normal consolidation (i.e. without high-luminosity upgrade) is slightly over 1.7, meaning that each Swiss Franc invested in the HL-LHC upgrade project pays back approximately 1.7 CHF in societal benefits. Simulations based on 50000 Monte Carlo

Particle Physics – it matters

99% of 35,000 operating accelerators in the world are used for industrial or medical applications, micro-electronics, pharmaceuticals, material science, national security generating a volume of 400 B$.
This is also true for detectors and associated electronics or reconstruction software.
However, the 1% used for Fundamental Science is capable to innovate the rest.



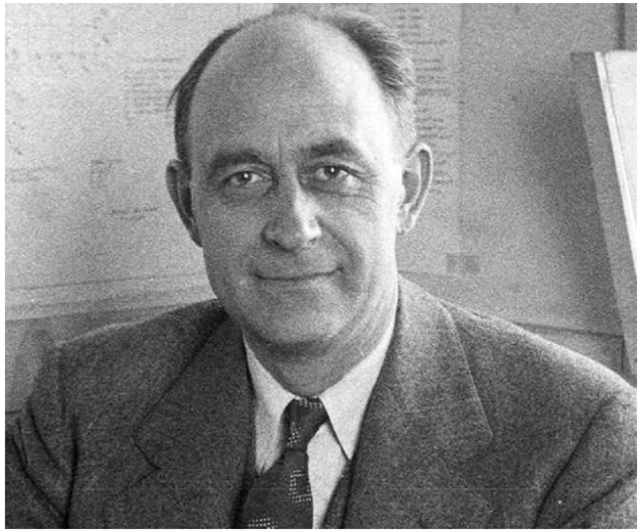
Conclusions

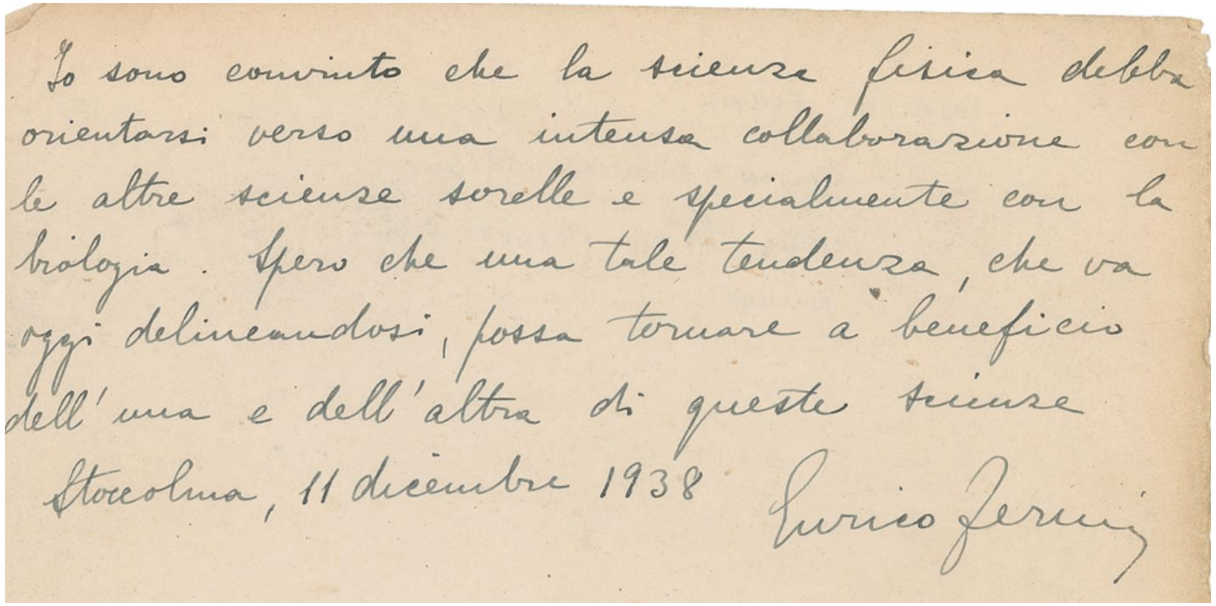
INFN is deeply involved in the realization of tools for the discovery of the fundamental elements of the microscopic world, since its foundation in 1952: accelerators, particle detectors and all the related technologies.

Large Research Infrastructures are efficient organizations in gathering the maximal know-how from several countries (and continents).

It is significant that in Draghi's report, CERN is described as a virtuous example of efficiency, in particular to promote technological leadership in Europe.

It is also evident that accelerators and detectors contribute outstandingly to various societal challenges. This added value of Fundamental Physics and of its technologies should be repeatedly highlighted, especially to motivate the young generations of scientists and technologists





Io sono convinto che la scienza fisica debba orientarsi verso una intensa collaborazione con le altre scienze sorelle e specialmente con la biologia. Spero che una tale tendenza, che va oggi delineandosi, possa tornare a beneficio dell'una e dell'altra di queste scienze

Stoccolma, 11 dicembre 1938

Enrico Fermi