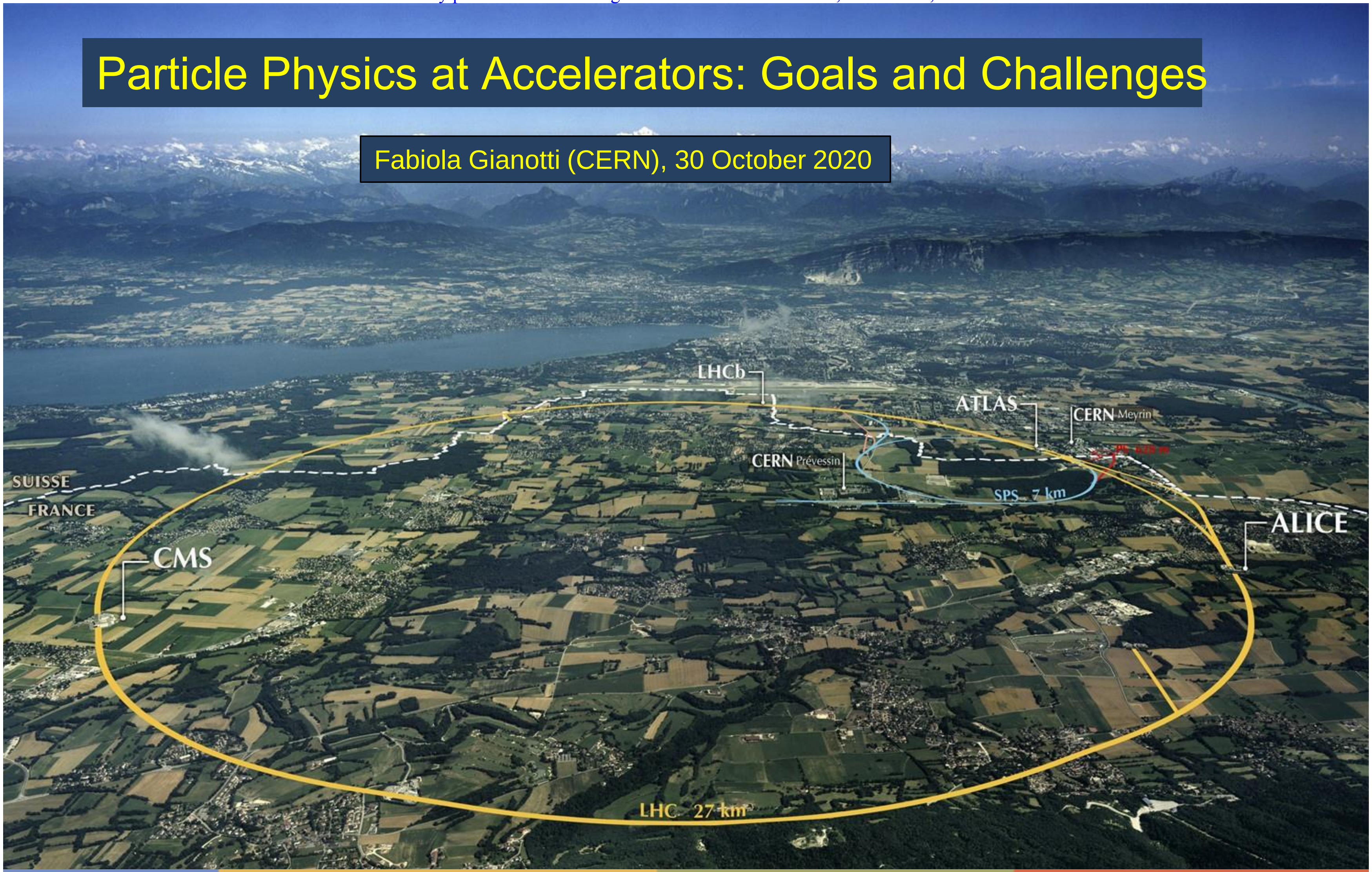
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P4 given at the virtual ASC 2020, October 30, 2020.

Particle Physics at Accelerators: Goals and Challenges

Fabiola Gianotti (CERN), 30 October 2020



ASC 2020

VIRTUAL CONFERENCE
Oct 24 – Nov 7
2020

Outline

Introduction: current understanding of particle physics

Open questions in fundamental physics (examples)

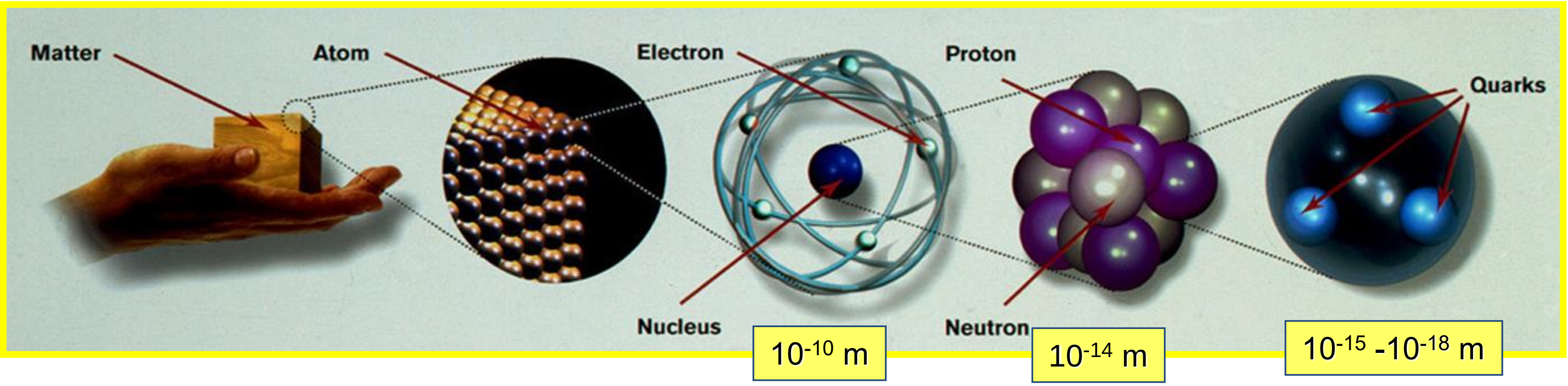
Main goals of exploration at current and future high-energy colliders

Role of superconducting high-field magnets

Conclusions

Introduction

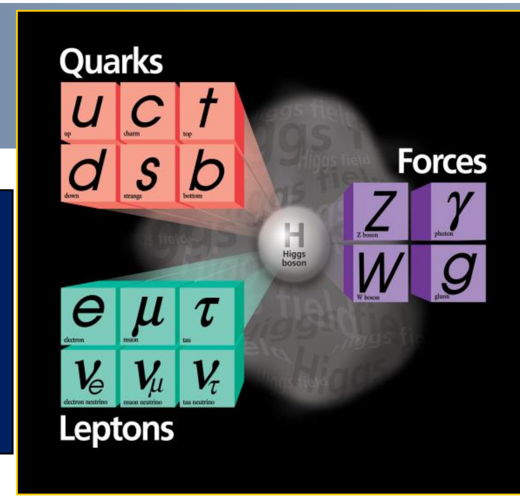
Particle physics studies the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level



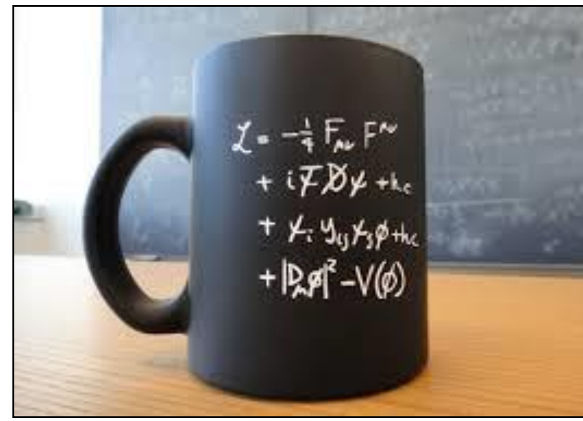
Particle physics at modern accelerators allows us to study the fundamental laws of nature on scales down to smaller than 10^{-18} m → giant "microscopes"
From > 100 years of research we have learned that nature hides most of its fundamental laws at the smallest scales → this drives us to explore the innermost structure of matter.
Get also insight into the structure and evolution of the Universe → from the very small to the very big (e.g. the Higgs boson and inflation)

Introduction

With the discovery of the Higgs boson at the Large Hadron Collider (LHC), in 2012, the Standard Model of particle physics has been completed (> 50 years of theoretical, experimental and technological efforts !).
Superconducting magnets have played a crucial role.



We have also tested the Standard Model with very high precision (wealth of measurements since early '60s, in particular at accelerators)
→ no significant deviations observed
→ it works BEAUTIFULLY (puzzling …)



Puzzling: several outstanding questions remain (raised also by very precise experimental observations) that cannot be explained within the SM
→ the SM is not a complete theory and is not the "ultimate" theory of particle physics

The outstanding questions require NEW PHYSICS beyond the SM

Main questions in today's particle physics (a non-exhaustive list ..)

Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?

What is the origin of the matter-antimatter asymmetry in the Universe ?

Why 3 families of quarks and leptons ?
Why do neutral leptons, charged leptons and quarks behave differently ?

What is the origin of neutrino masses and oscillations ?

What is the composition of dark matter (~25% of the Universe) ?

What is the cause of the Universe's accelerated expansion (today: dark energy ? primordial: inflation ?)

Why is Gravity so weak ?

Puzzling: there is NO direct evidence for new particles (yet…) from the LHC or other facilities

At which energy scale does the new physics manifest itself?

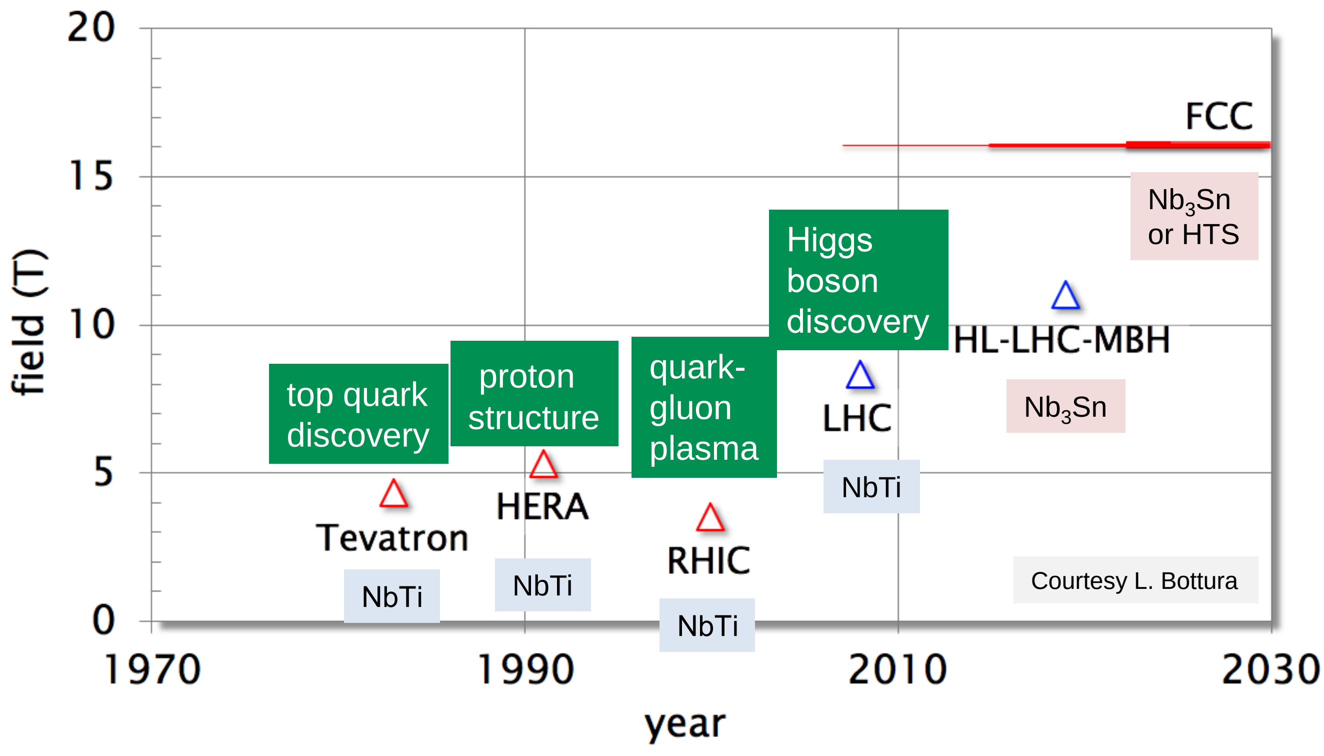
Main open questions and main approaches to address them

The outstanding questions are compelling, difficult and interrelated → can only be successfully addressed through a variety of approaches (thanks also to strong advances in accelerator and detector technologies): particle colliders, neutrino experiments, cosmic surveys, dark matter direct and indirect searches, measurements of rare processes, dedicated searches (e.g. axions, dark-sector particles)

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	x	x		x	
Neutrinos	x (ν_R)		x	x	x
Dark Matter	x			x	x
Flavour, CP, matter/antimatter	x	x	x	x	x
New particles, forces, symmetries	x	x		x	
Universe acceleration					x

Historically, high-energy accelerators (fixed-target and colliders) have been our most powerul tool for exploration and will continue to play an essential role also in the future.

Scientific milestones vs magnetic field (examples)



2 main goals of current and future colliders

Detailed studies of the Higgs boson

The Higgs boson is not just … "another particle":

- ❑ Profoundly different from all elementary particles discovered previously
- ❑ It got peculiar properties (elementary scalar); brings a different type of "force"
- ❑ Related to the most obscure sector of the Standard Model (all structural problems in the SM originates from the Higgs interactions)

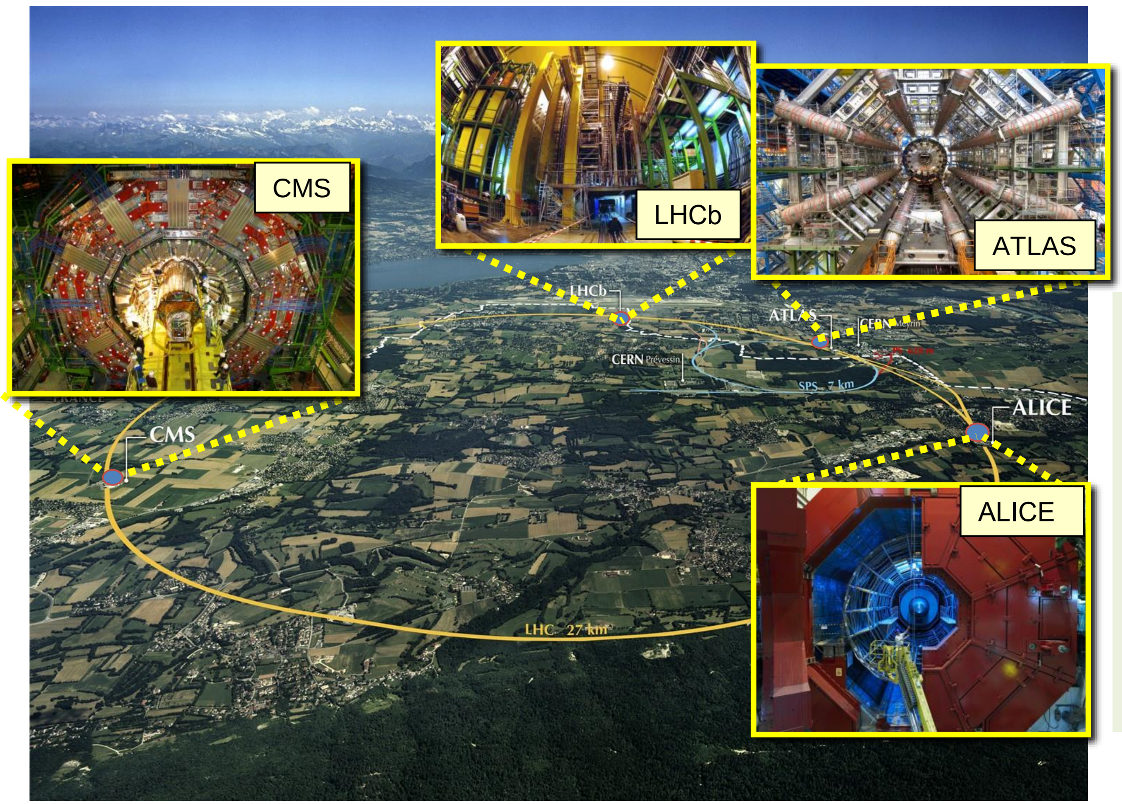
→ privileged door into physics beyond the SM → precise measurements of its properties and interactions may unveil new physics

Search for new physics at the energy frontier

To address some of the outstanding questions: dark matter, Higgs mass, fermion family problems, etc. etc.

Today: the Large Hadron Collider (LHC)

- proton-proton and heavy-ion collider 27 km ring, 100 m underground
- 1232 NbTi superconducting magnets working at 1.9 K
- operation started in 2010 → exploration of a new energy frontier (up to 14 TeV proton-proton collision energy, about x7 the Tevatron collider in the US)

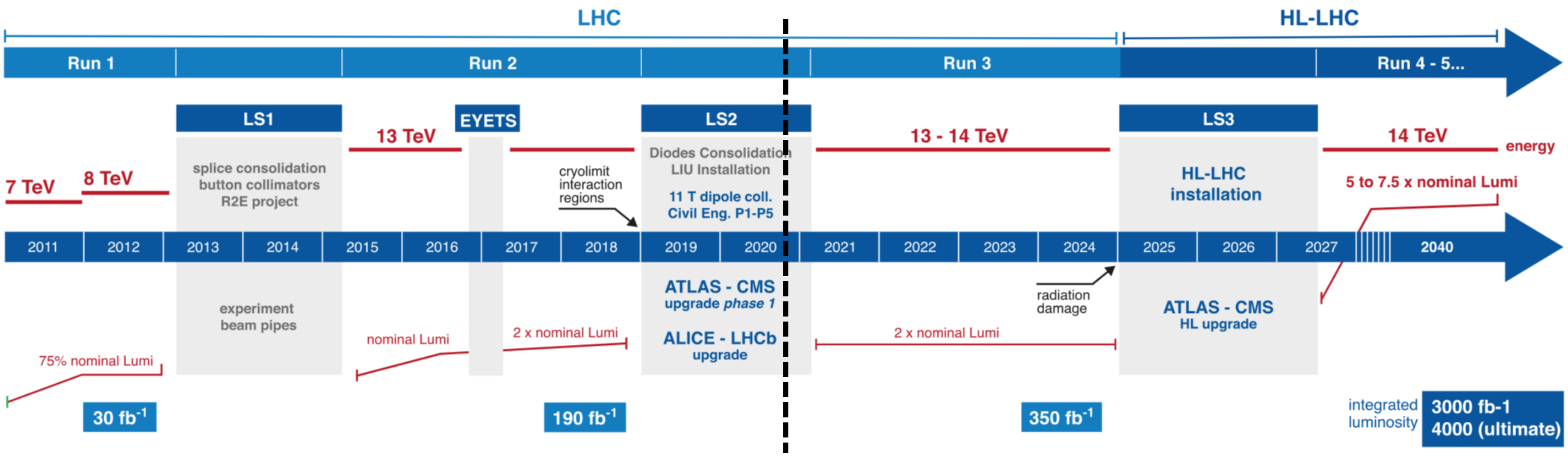


A wealth of beautiful physics results so far: discovery of the Higgs boson and of ~ 40 new (non-elementary) particles, precise measurements of SM processes, exploration of the TeV energy scale and exclusion of several scenarios for physics beyond the SM, etc.

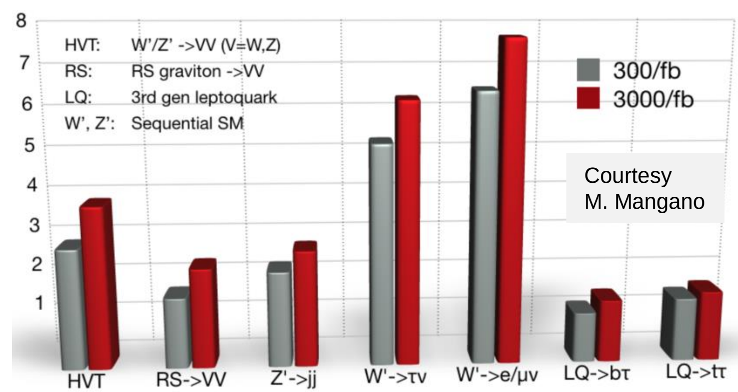
The LHC will run until 2024

Next step: High-Luminosity upgrade of LHC (HL-LHC)

~1.2 km of new technologies to provide more intense proton beams → at the end of HL-LHC (~ 2038) the experiments will have recorded ~ 10 times more data than at the end of LHC. Requires new technology dipole and quadrupole magnets (Nb_3Sn)

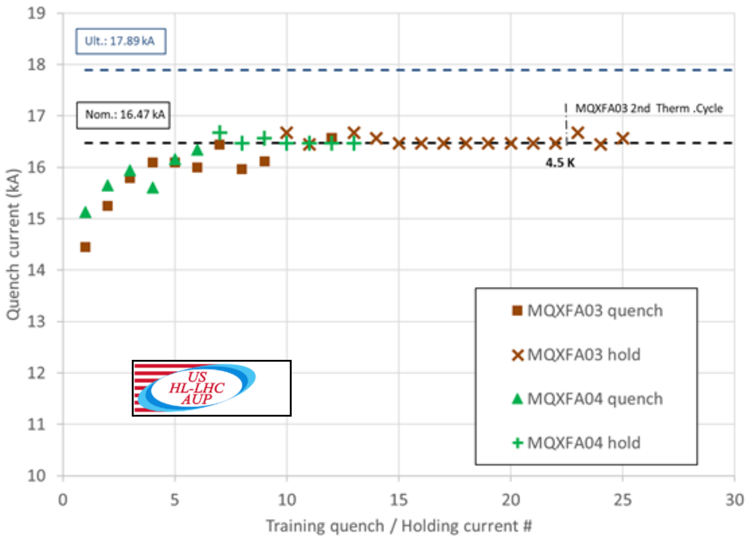


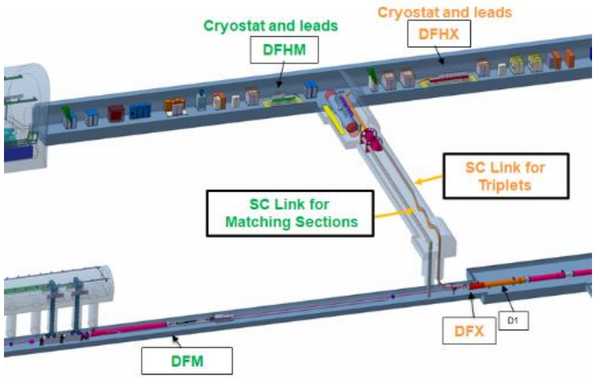
Dicovery potential for new particles in various scenarios of new physics: mass reach in TeV at **LHC** and **HL-LHC**



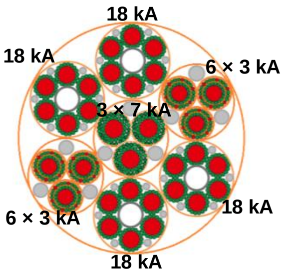
Construction of superconducting components well advanced

Two full-scale (4.2 m) 150-mm aperture Nb_3Sn quadrupoles built and successfully tested up to nominal current in the US



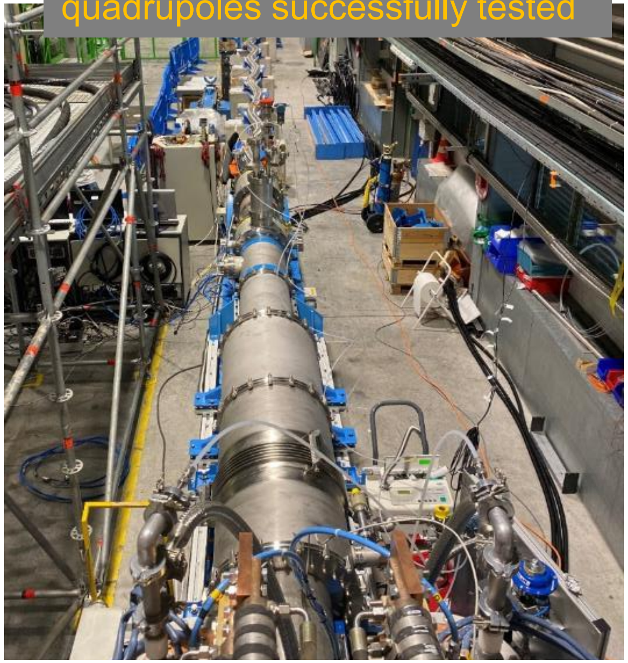


Power transmission line



MgB_2 cable:
$\Phi \sim 90$ mm
$I_{tot} > 100$ kA @ 25 K

L= 60 m demonstrator of superconducting link for quadrupoles successfully tested



Longer-term future

2020 update of the European Strategy for Particle Physics

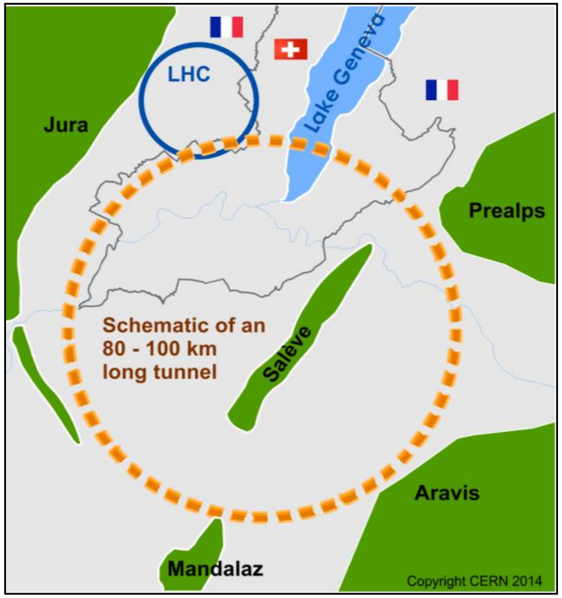
“For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”

“The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies*, in particular that for high-field superconducting magnets, including high-temperature superconductors.”*

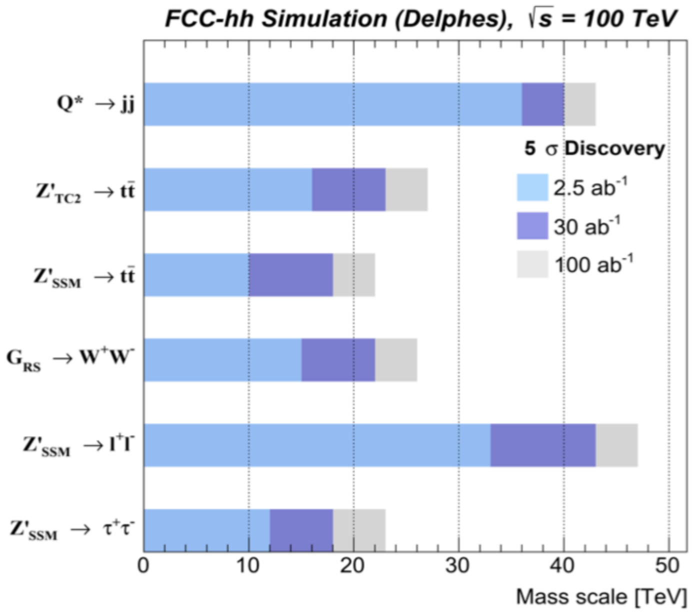
“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next strategy update.”

Future Circular Collider (FCC)

Future Circular Collider (FCC):
~ 100 km ring in Geneva area
→≥ 100 TeV collision energy requires ~ 4700 16-20 T superconducting dipole magnets



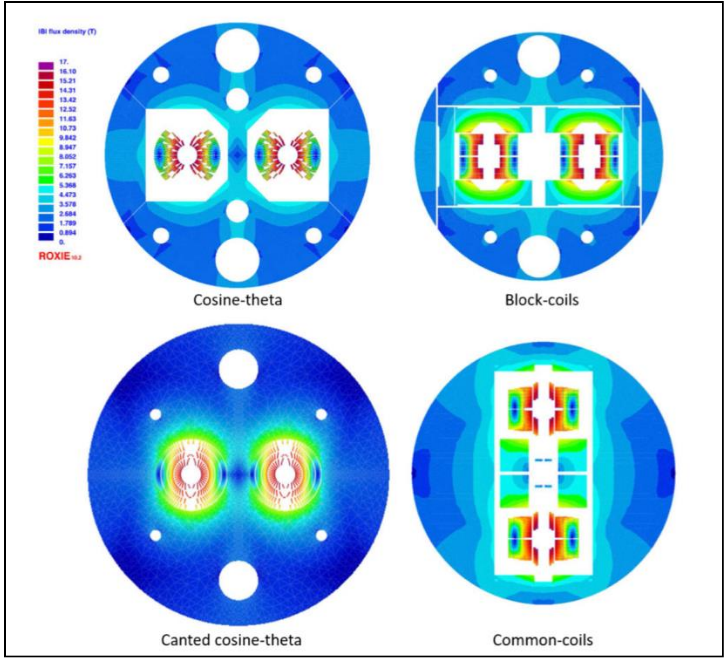
Design and feasibilty studies ongoing → if feasibilty successful, project may be appproved by the end of the decade and operation of the proton-proton collider may start by early 2060's



Dicovery potential for new particles in various scenarios of new physics: mass reach in TeV.
For comparison: the reach of HL-LHC is <10 TeV

FCC magnets: some paramters

Baseline technology	Nb_3Sn
Operating field	16 T
Operating current	11 kA
Operating temperatue	1.9 K
Number of dipoles	~4700
Coil aperture	50 mm
Magnetic length	14 m
Nb_3Sn wire	~8000 tons
Stored energy (2 apertures)	37 MJ
Current density @1.9 K	2300 A/mm^2



R&D on superconducting magnets

Feasibility study of FCC include strong R&D programme on superconducting magnets
→ key technology for particle physics: hadron colliders, muon colliders, neutrino beams, detectors, …
→ great potential for wider societal impact

Main R&D activities:

- ❑ materials: LTS (Nb_3Sn) and HTS (including iron-based)
  → goal: 16 T for LTS, at least 20 T for HTS inserts
- ❑ magnet technology: engineering, mechanical robustness, insulating materials, field quality
- ❑ production of models and prototypes to demonstrate material, design and engineering choices, industrialisation and costs
- ❑ infrastructure and test stations for tests up to ~ 20 T and 20-50 kA

Significant fresh resources invested at CERN. Strong partnership with industry and laboratories and Universities worldwide.

Goals (ambitious) for next update of the European Strategy for Particle Physics (~ 2026):

- ❑ Nb_3Sn: demonstrate technology for large-scale accelerator deployment
- ❑ HTS: demonstrate suitability for accelerator magnet applications

Conclusions (I)

These are very exciting times in particle physics

The Standard Model is complete and works very well with no significant "cracks" as yet
→ we don't understand why, as the SM is unable to address many outstanding questions

⬇

There must be new physics → BUT at which ENERGY scale???
And with which strength does it couple to the SM particles?

Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of E scales and couplings, and to properly interpret signs of new physics.

Conclusions (II)

High-energy colliders will continue to be an indispensable and irreplaceable microscope to scrutinise nature at the smallest scales, providing knowledge that cannot be obtained through any other means.

⬇

The full exploitation of the LHC, including its high-luminosity phase, and more powerful colliders will be needed in the future to advance our knowledge of fundamental physics.

No doubt that future high-E colliders are extremely challenging projects

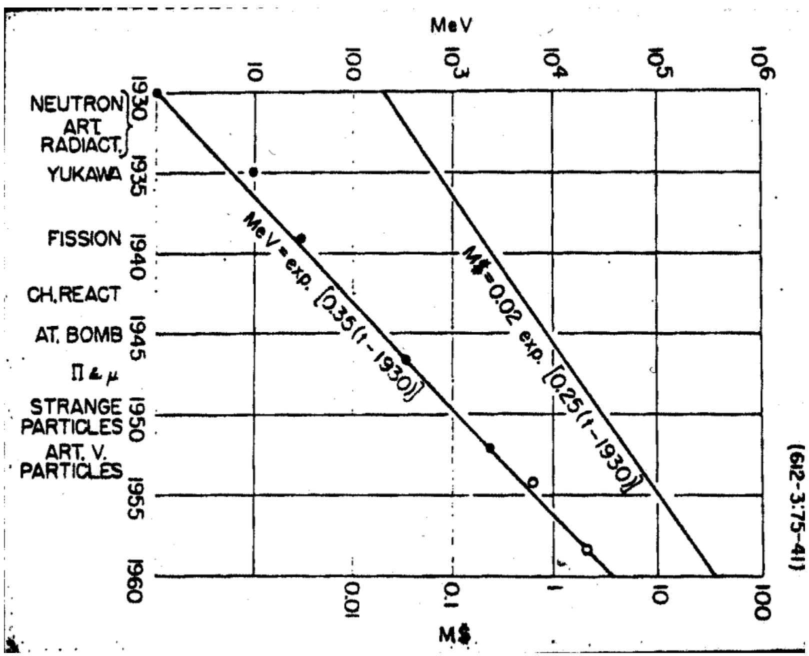
However: the correct approach as scientists is not to abandon our exploratory spirit, nor give in to financial and technical challenges. Instead, we should use our creativity to develop the **technologies** needed to make future projects financially and technically affordable.

Superconducting high-field magnets are a crucial component of this endeavour

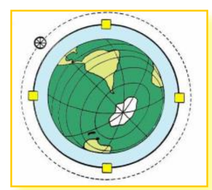
From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954

For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge.... ....certainly look for multiple production...



Fermi's extrapolation to year 1994:
2 T magnets, R=8000 km (fixed target !),
E_{beam} ~ $5x10^3$ TeV → collision energy ~ 3 TeV
Cost : 170 B$



Was that hopeless ??

We have found the solution:
we have invented colliders and **superconducting magnets** …
and built the Tevatron and the LHC