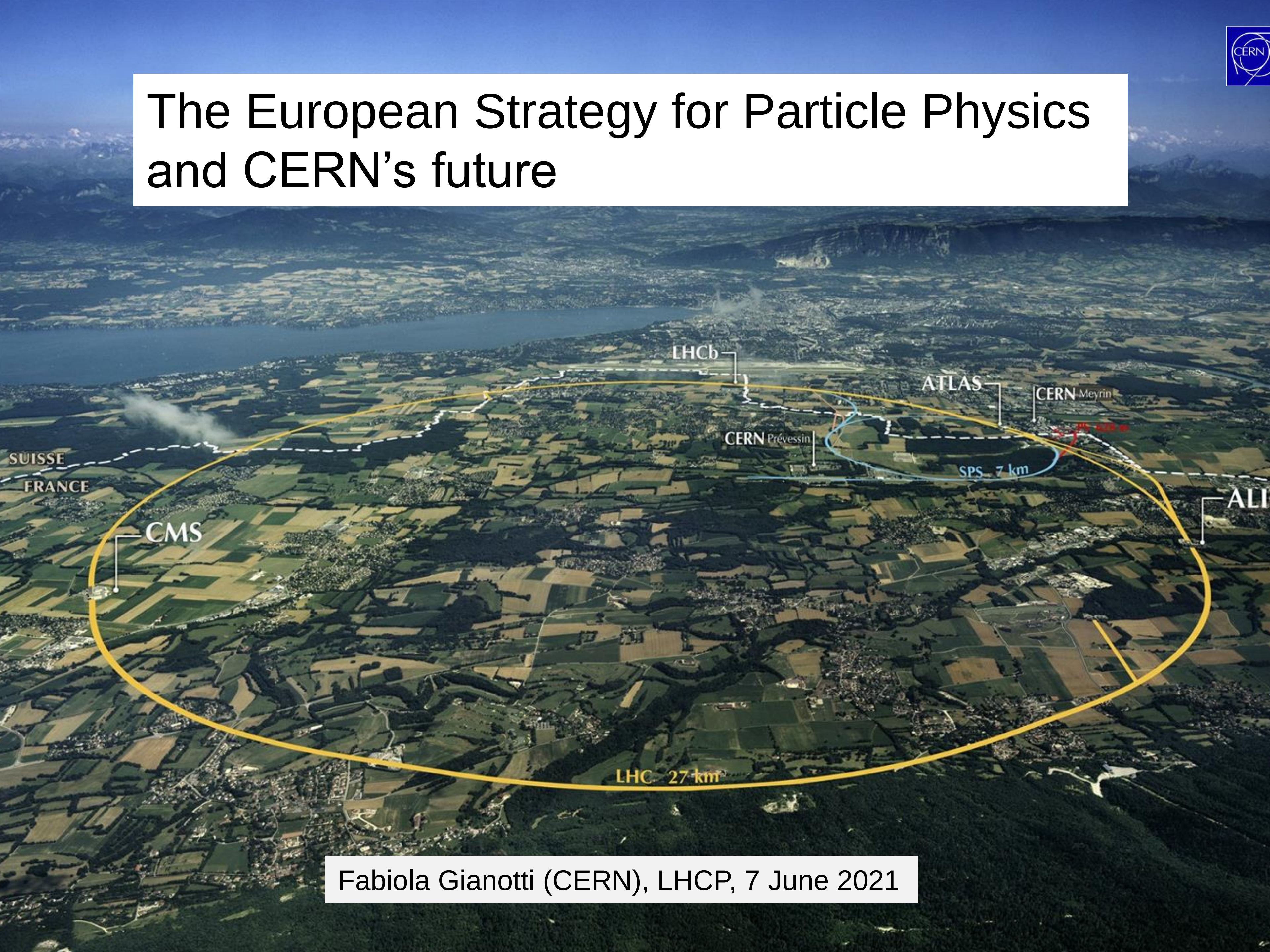
The European Strategy for Particle Physics and CERN's future



Fabiola Gianotti (CERN), LHCP, 7 June 2021

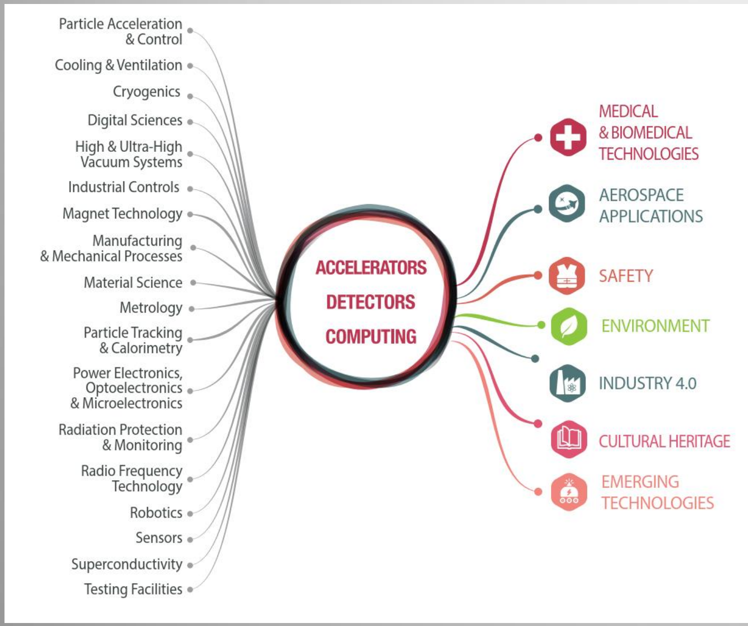
Outline

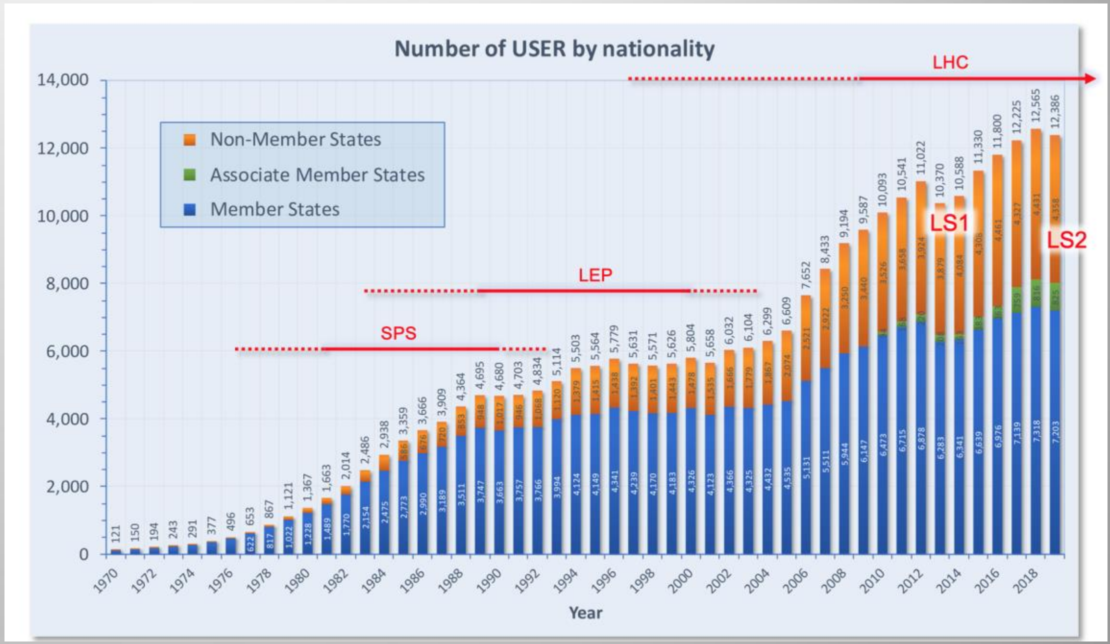
- Initial remarks
- The ESPP 2020 scientific roadmap
- Other recommendations of the ESPP
- Conclusions

Initial remarks

(on the future of CERN and the field)

CERN leading role in particle physics, its innovative wide-ranging technologies, and its large community (~17000 people) come primarily from its “flagship project”: **LHC**





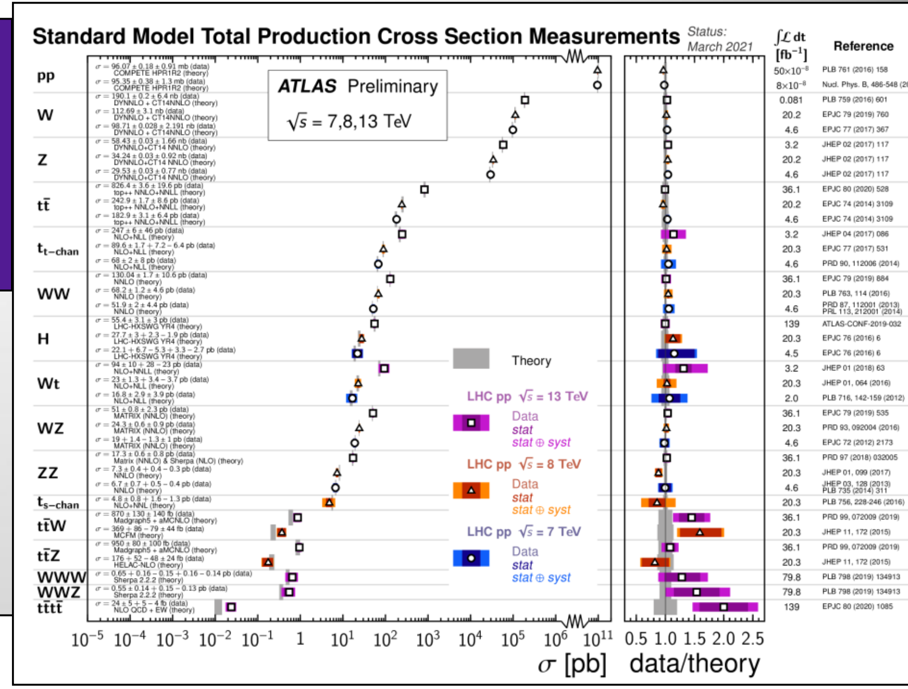
This leading role, technological innovation capability and large community will NOT survive without a flagship project, strongly motivated by physics, following the LHC within a short time (<10 years).

→ A first-stage future collider running in the mid 2040’s is crucial to retain and expand CERN’s community and expertise → crucial for long-term survival of CERN and the field

Standard Model:

- ❑ particle spectrum experimentally completed
- ❑ very precise and extensive tests of predictions
  → no significant deviations (but difficult to accommodate non-zero neutrino masses)

"The excessive success of the SM", Guido Altarelli



The outstanding questions

Why is the Higgs boson so light (naturalness/hierarchy problem)?

What is the origin of the universe matter-antimatter asymmetry?

Why 3 fermion families ? 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?

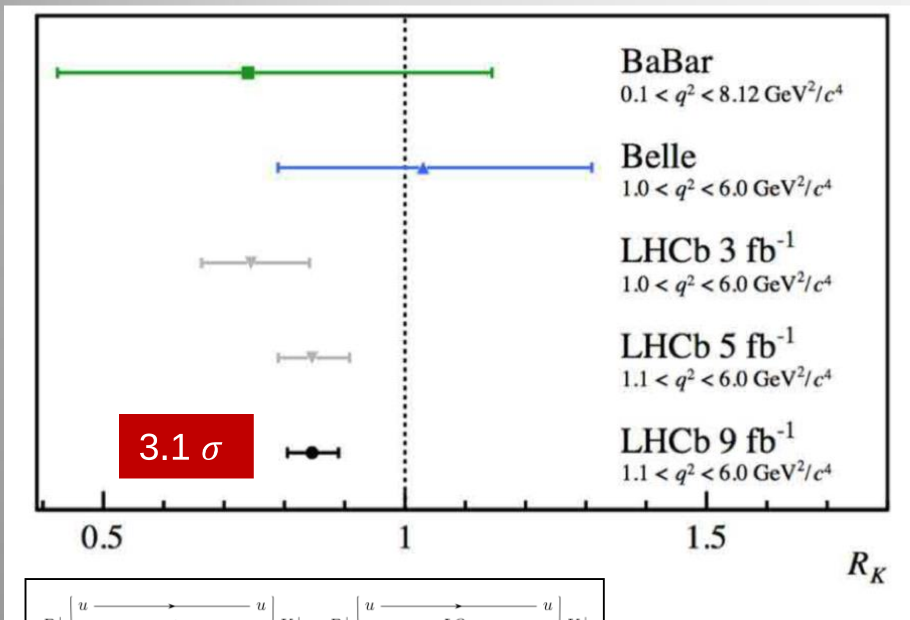
What is the cause of the Universe's accelerated expansion ?

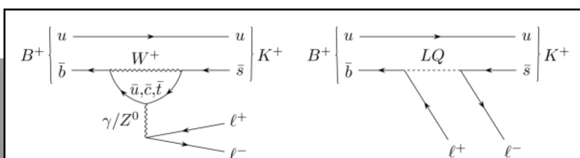
Why is Gravity so weak ?   Etc.

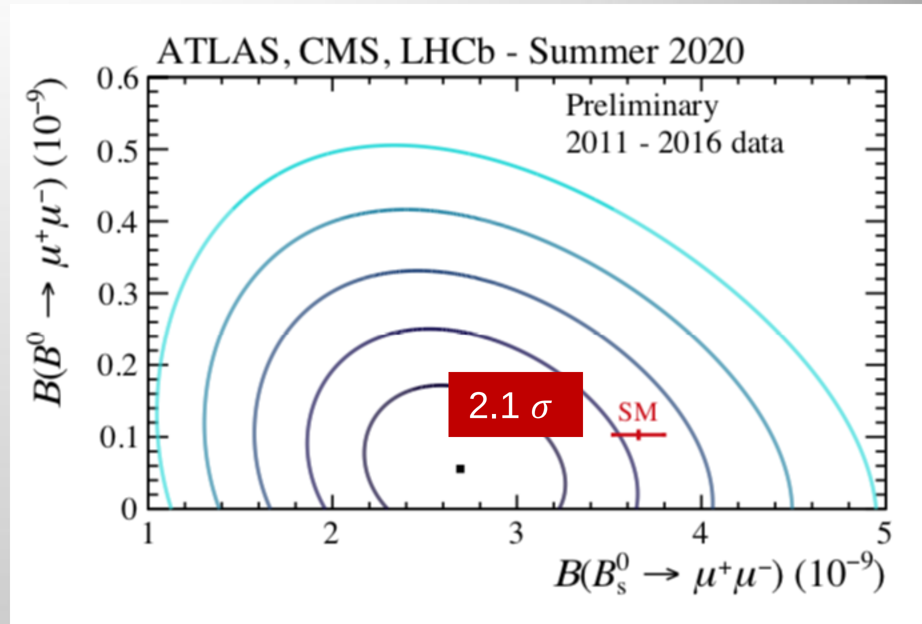
New physics required but no clear indication of the E-scale

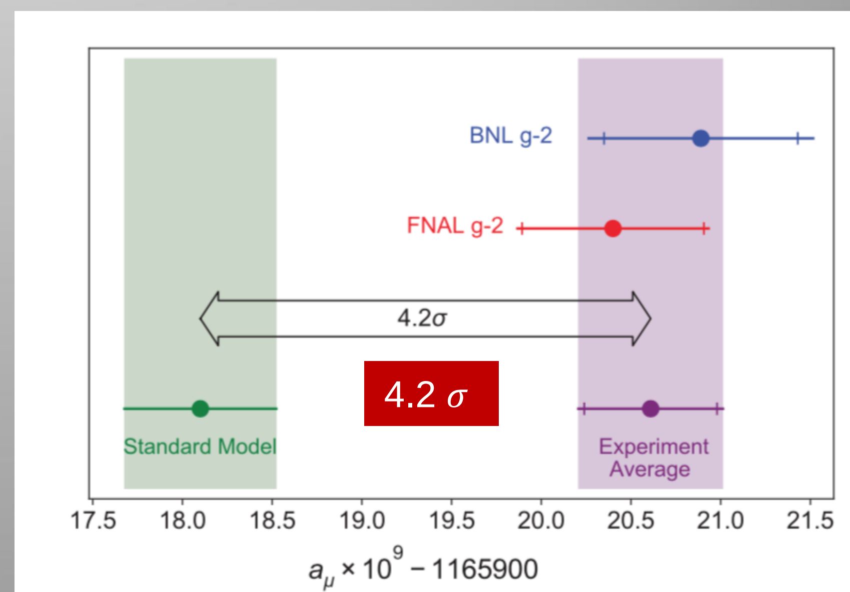
Recent muon anomalies, **IF** confirmed, may indicate (a close) scale of new physics
(and drive a paradigm shift in particle physics)

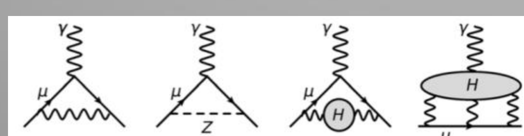
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$











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), etc.

	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 have been one of the best tools for exploration

1) Scientific diversity, and combination of complementary approaches, are crucial to explore directly and indirectly the largest range of E scales and couplings, and to properly interpret signs of new physics → with the goal to build a coherent picture of the underlying theory

2) Global coordination and optimisation of the particle physics programme is necessary to maximise the opportunities of the field, given so many exciting physics questions and the cost and complexity of the projects.

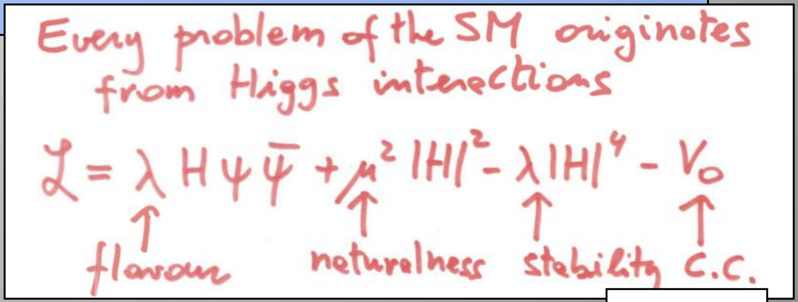
Main lines of research at current and future colliders

- Detailed studies of the Higgs boson (only possible at colliders) → a "guaranteed deliverable"
- Searches for new physics: directly through observation of new particles and indirectly through precise measurements revealing deviations from SM expectations

H is not just … "another particle":

- Profoundly different from all elementary particles discovered previously
- It got almost no properties; carries a different type of "force"
- Related to the most obscure sector of SM
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

→ It provides a unique door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades



G. Giudice

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- Precision measurements of couplings (as many generations as possible, loops, …)
- Forbidden and rare decays (e.g. H→ τμ) → flavour structure and source of fermion masses
- H potential (HH production, self-couplings) → EWSB mechanism
- Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- Other H properties (width, CP, …)
- Searches for additional H bosons, etc.

The ESPP scientific roadmap

The 2020 update of the Strategy provides a realistic and prudent approach to visionary and ambitious scientific objectives.
It lays the foundations for a bright future for particle physics in Europe, within the global context of the field.

Full exploitation of the physics potential of LHC and high-luminosity LHC (including HI, flavour, …)
→ CERN's highest priority in the short/medium term (→ see M. Lamont's talk)

Highest-priority next collider: e^+e^- Higgs factory
→ continued development of FCC-ee and CLIC technologies; support to ILC

Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc.
→ see next slide

Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
→ see next slide

Support to long-baseline neutrino projects in US and Japan, in particular successful implementation of DUNE at LBNF
→ continued/expanded support to Neutrino Platform

Support to high-impact scientific diversity programme complementary to high-E colliders
→ increased support to Physics Beyond Colliders

Support to R&D on detector, SW and computing, as crucial tools for the field
→ R&D for future detectors initiative; new Quantum Technology Initiative

Support to theory as an essential driver for particle physics
→ increased synergies with neighbouring fields

Remarks

ESPP gives the preferred direction for future collider(s) at CERN: FCC

However, prudently:

- ❑ feasibility study first
- ❑ intensified accelerator R&D for FCC and to prepare alternatives if FCC not pursued

No consensus in European community on which type of Higgs factory (linear or circular)

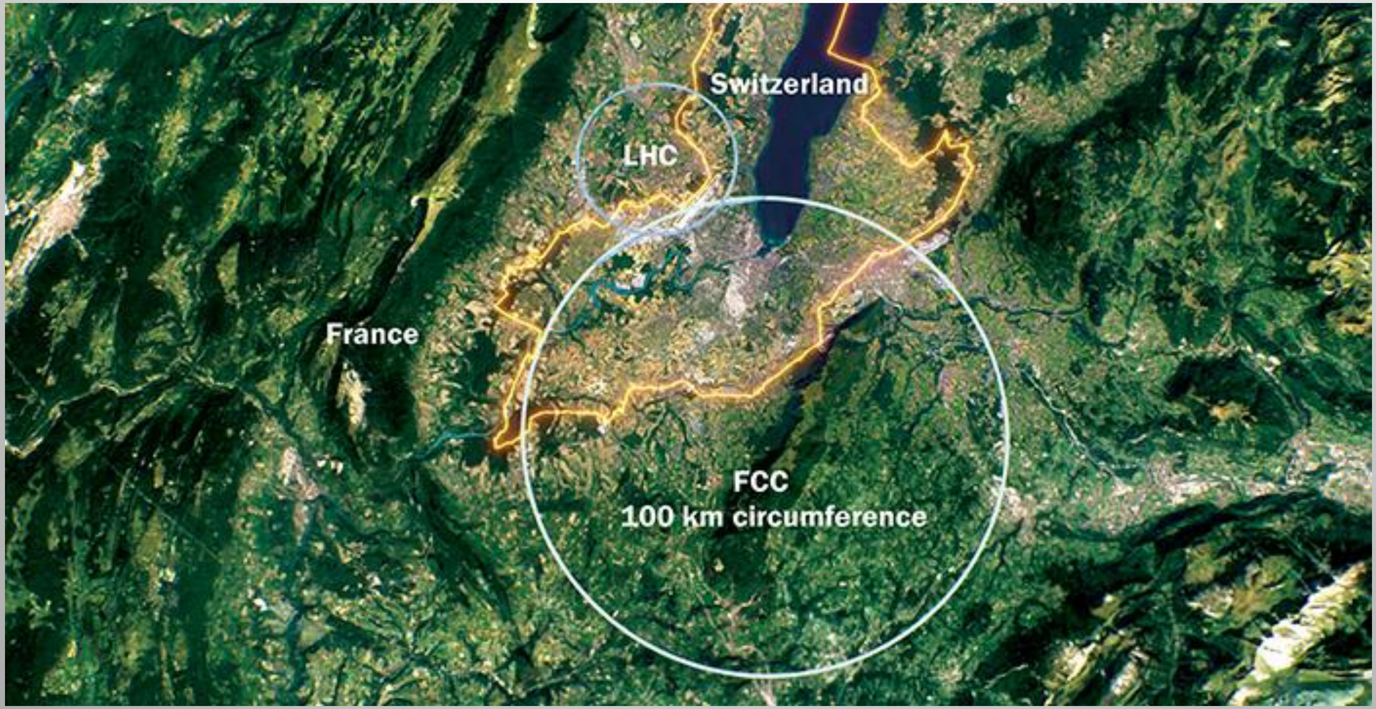
ILC:

- ❑ compatible with ESPP if timely (otherwise conflict of resources with next collider at CERN)
- ❑ are ILC and FCC-ee complementary enough in terms of physics? No consensus.

Chinese colliders (CepC, SppC): “direct competition” with FCC

Desired timeline for a future collider at CERN: recommendation by next ESPP ~ 2026
→ approval by CERN’s Council by end of the decade → start of construction early- 2030’s
→ start of operation mid 2040’s.
Realistic for FCC-ee and CLIC, difficult for FCC-hh (magnet technology, cost)

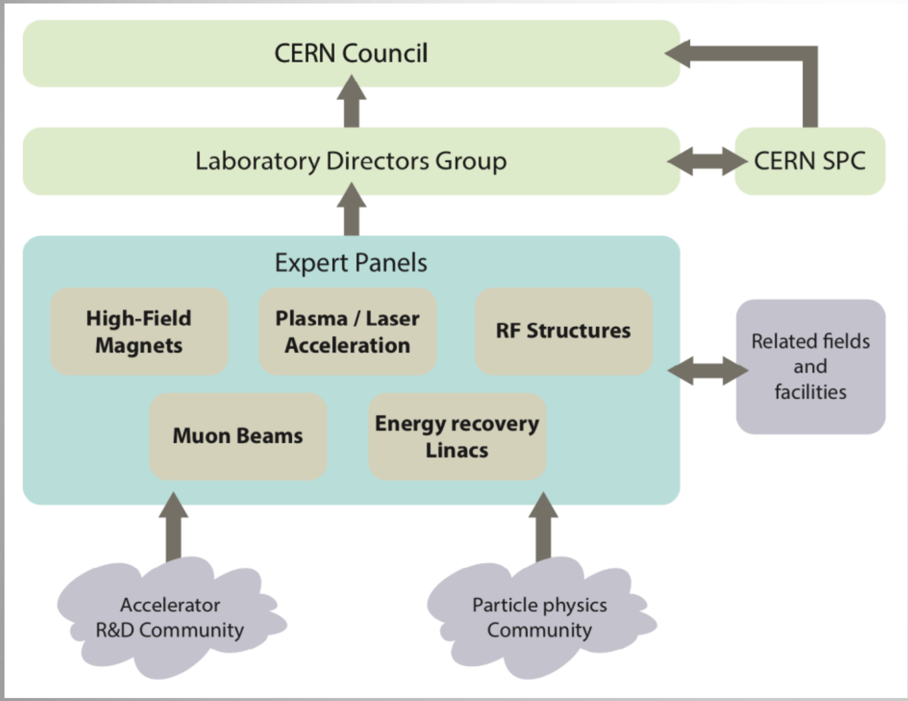
FCC Feasibility Study (2021-2025)

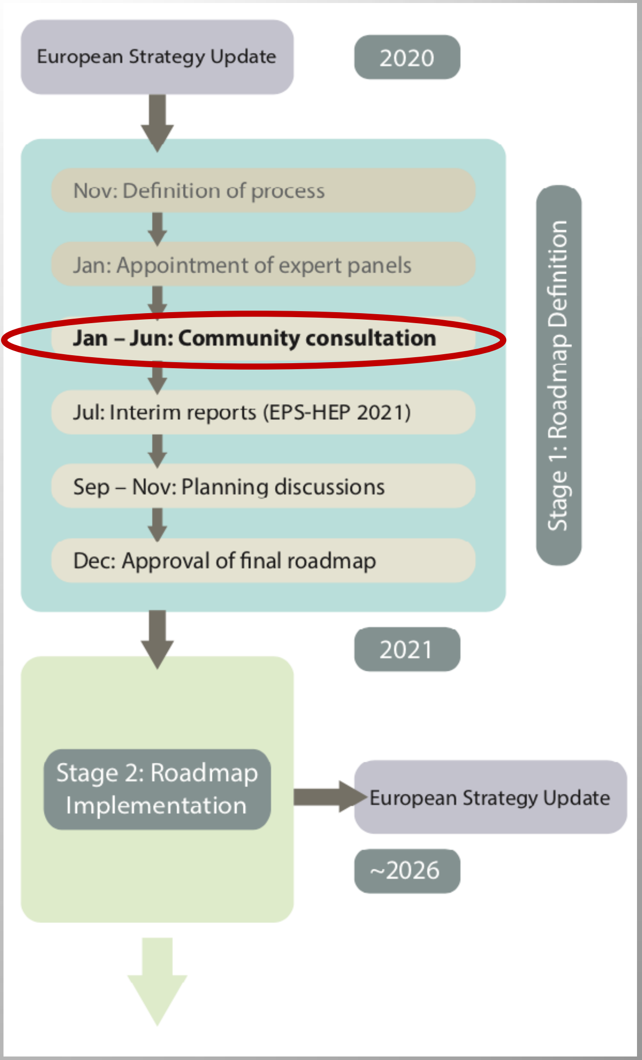


- ❑ Tunnel: assess geological, technical, administrative, environmental feasibility → aim is to demonstrate there is no show-stopper for ~ 100 km ring in Geneva region
- ❑ Technologies: superconducting high-field magnets and RF accelerating structures; high-efficiency power production; energy savings and other sustainable technologies
- ❑ Funding: development of funding model for first-stage machine (FCC-ee and the tunnel, total ~ 10 BCHF) and identification of substantial resources from outside CERN’s budget
- ❑ “Consensus building”: gathering scientific, political, societal support → communication campaign targeting scientists, governmental and other authorities, industry, general public

→ Release Feasibility Study Report by end 2025

Accelerator R&D roadmap





From 2020 ESPP:

"Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry"

"The particle physics community should ramp up its efforts focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors."

"The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy revovery linacs."

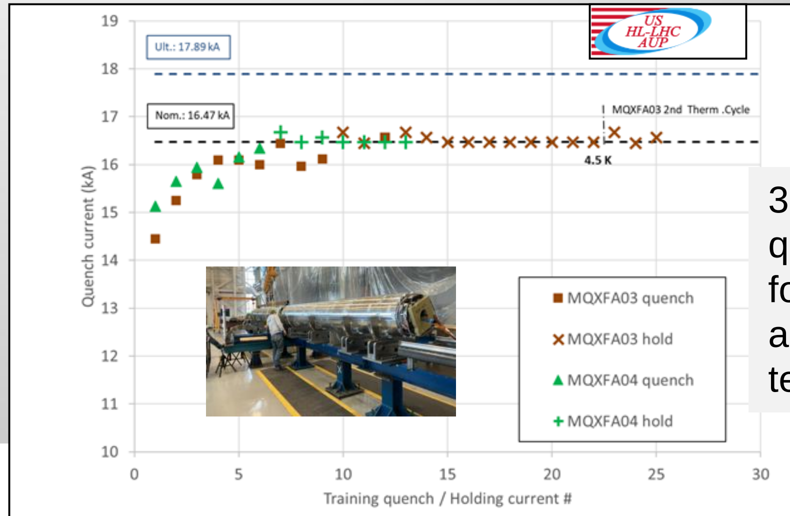
"A roadmap should prioritise the technology, taking into account synergies with international partners and other communities … Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes."

High-field superconducting magnets: a step-wise approach

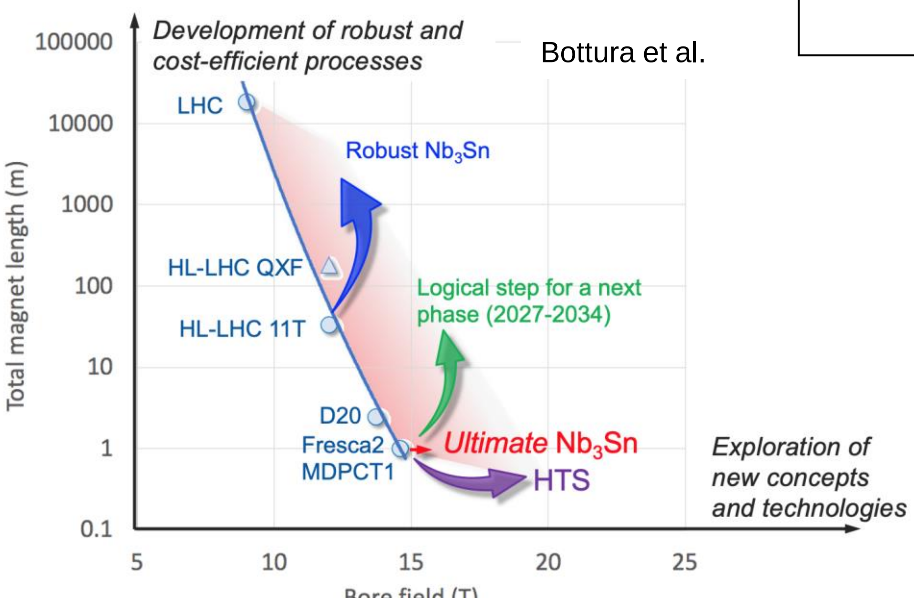
R&D on high-field superconducting magnets strengthened significantly at CERN, following ESPP recommendation: key technology for future accelerators (hadron colliders, muon colliders, neutrino beams, etc.) and detectors, with great potential for wider societal applications.

LHC 8.3 T NbTi dipoles

HL-LHC 11-12 T Nb_3Sn dipoles and quadrupoles



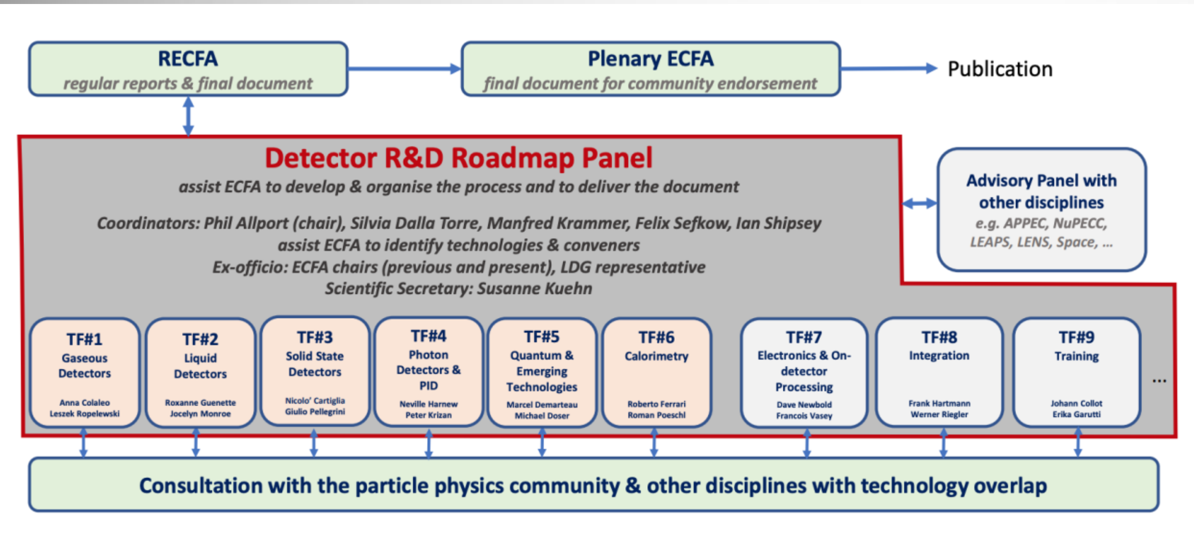
3 full-scale Nb_3Sn quadrupoles for HL-LHC built and successfully tested in the US.



Bottura et al.

16-20 T magnets for FCC

Detector R&D roadmap



From 2020 ESPP:

"The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures."

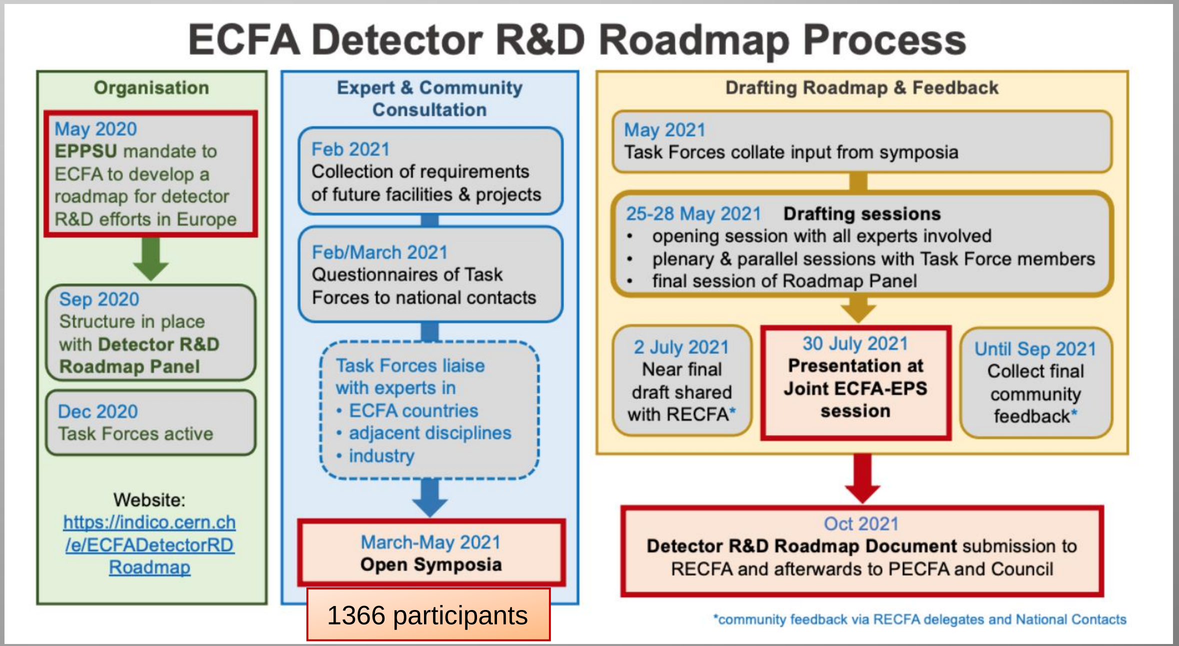
"The community must maintain a strong focus on instrumentation."

"Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities."

CERN: "R&D for future detectors" strategic initiative established in 2018

"The community should define a global detector R&D roadmap."

"The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term."



Other recommendations of the ESPP

Not only science ... the ESPP provides an integrated vision for modern, sustainable science:

- environmental responsibility and proactive development of sustainable technologies
- technology transfer to society as an inherent goal of our projects (not just as a by-product)
- close connections with other branches of science and with industry for synergetic R&D
- knowledge, technology and education accessible to all
- training and career prospects of the future generations
- public engagement

Synergies with astroparticle and nuclear physics
→ e.g. Joint ECFA, NuPECC and ApPEC workshops (JENAS); sharing of technologies; theory

Open science
→ recent open data policy from LHC experiments

Sustainability and environment
→ next slide

Careers of the young people
→ New CERN graduate programme being developed; several initiatives by experiments, ECFA and CERN

Knowledge transfer to society
→ being pursued at CERN with special focus on health, environment, computing

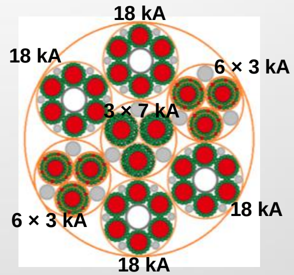
Public engagement, education and communications
→ Science Gateway at CERN and other initiatives

Sustainability and environment at CERN (examples)

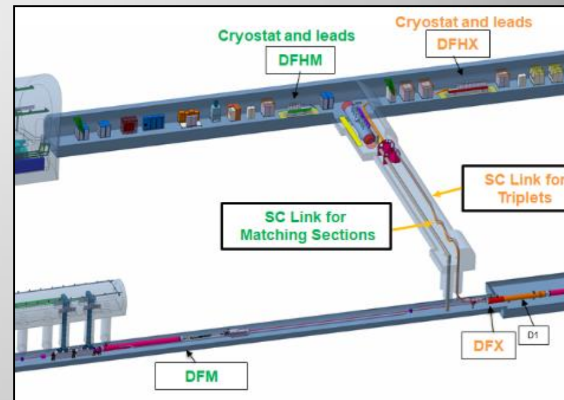
CERN's first public Environment Report released in 2020, and on 24 June we will launch CERN's Year of Environmental Awareness

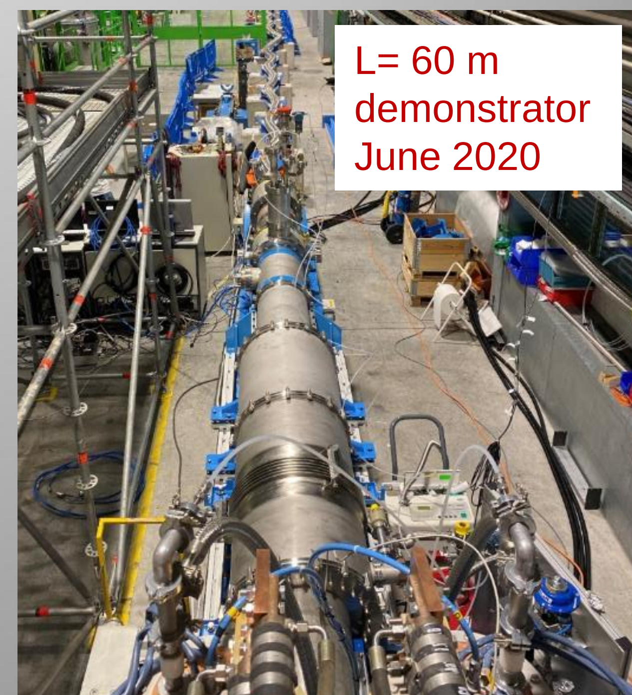
Sets ambitious objectives, e.g. reduce ~ 30% reduction of GHG emissions by 2024

High-current transmission lines for HL-LHC



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





L= 60 m demonstrator June 2020

Energy savings and re-use

Heat from LHC cooling towers at Point 8 to heat a nearby housing (8000 people)

Heat from new Computing Centre to heat Prévessin buildings

Conclusions

These are very exciting times in particle physics

The Standard Model is complete and works very well with no significant “cracks” (as yet).
But what about the outstanding questions?

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What is the scale of new physics and how (weakly) does it couple to the SM?

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

Historically, high-energy accelerators have been our most powerful tool for exploration in particle physics and will continue to play a major role in the future, complementary to other approaches

The full exploitation of the LHC, and more powerful future colliders, will be needed 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, but rather to use our creativity to develop the technologies needed to make future projects financially and technically affordable.

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

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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....[illegible]y.....certainly look for multiple
production...
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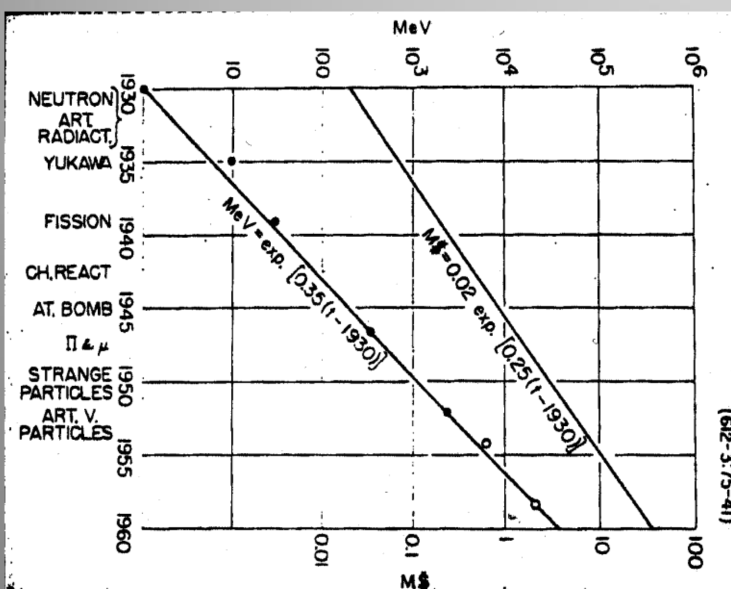

Fermi's extrapolation to year 1994:
E_{beam} ~ 5x10^3 TeV, 2T magnets → R=8000 km
Note: fixed target accelerator → √s ~ 3 TeV
Cost : 170 B$

Was that hopeless ??

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