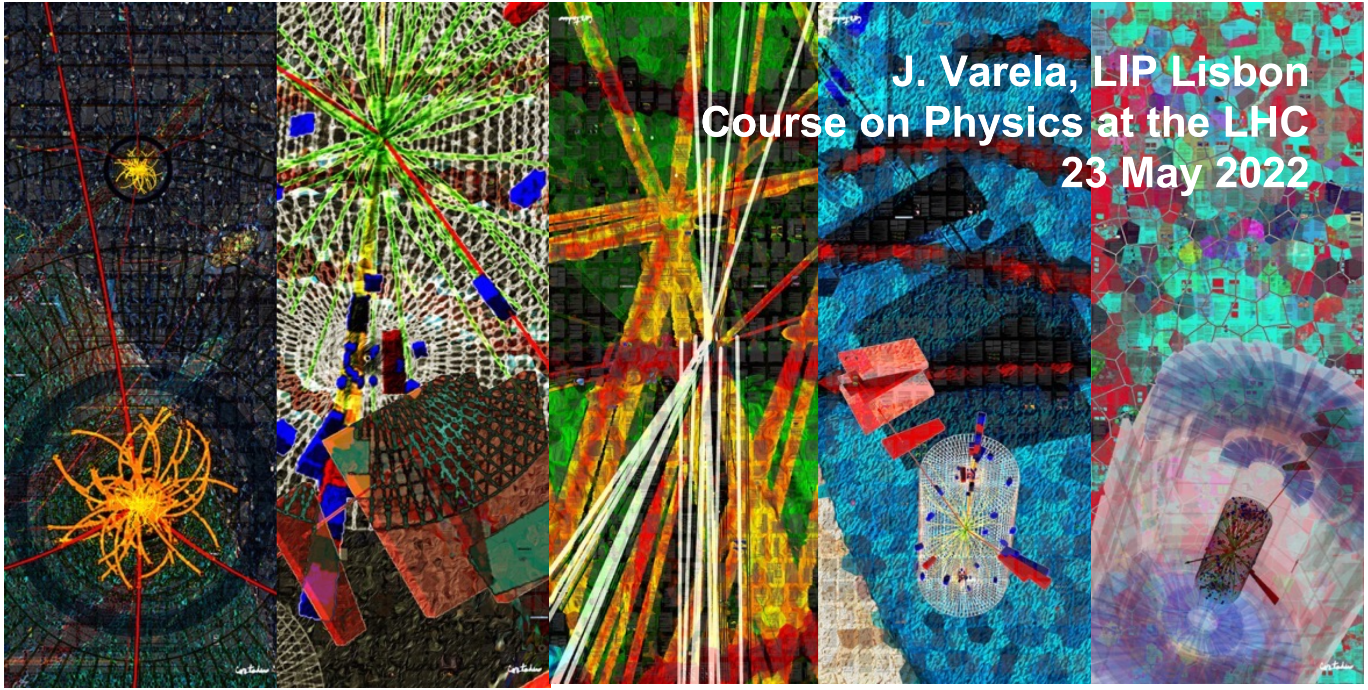
From the LHC to the future:
experimental perspective



J. Varela, LIP Lisbon
Course on Physics at the LHC
23 May 2022

Outline

- Physics motivation
- New big facilities under consideration
- Higgs factory
- The high energy frontier

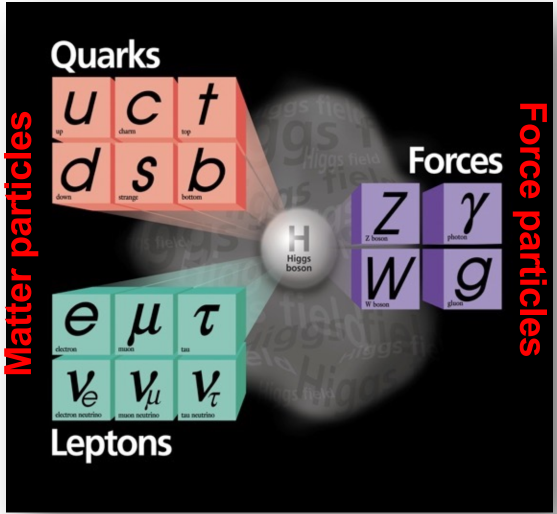
Not covered:

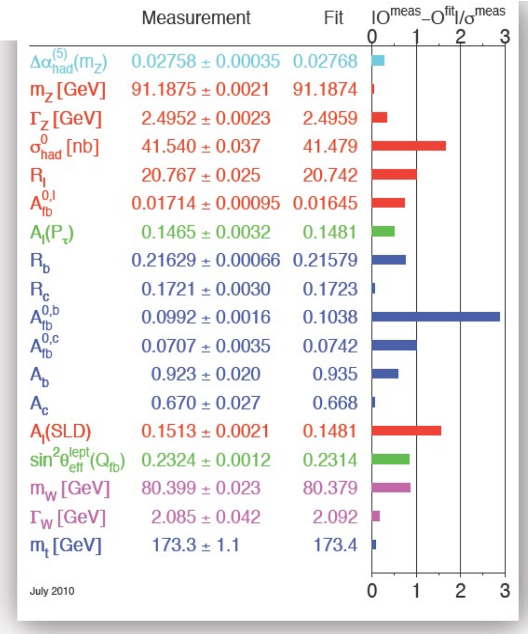
- The full exploitation of the LHC and HL-LHC potential
- The long-baseline neutrino projects in US and Japan
- Research programmes beyond colliders

The Standard Model of Particle Physics

Over the last ~100 years the Standard Model of Particle Physics was established

Confirmed experimentally at <1% level





One of the greatest achievements of the 20th Century Science

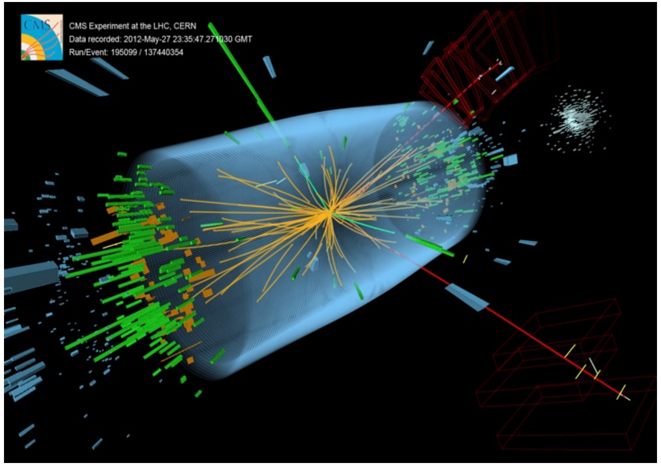
The Terascale and the LHC

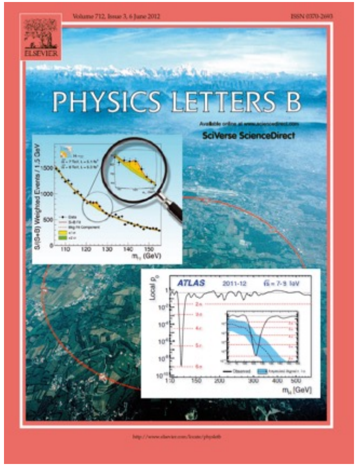
The Standard Model would fail at high energy without the Higgs boson or other 'new physics'.

It was expected that the 'new physics' would manifest at an energy around 1 TeV accessible at the LHC for the first time.

Higgs boson discovery in 2012

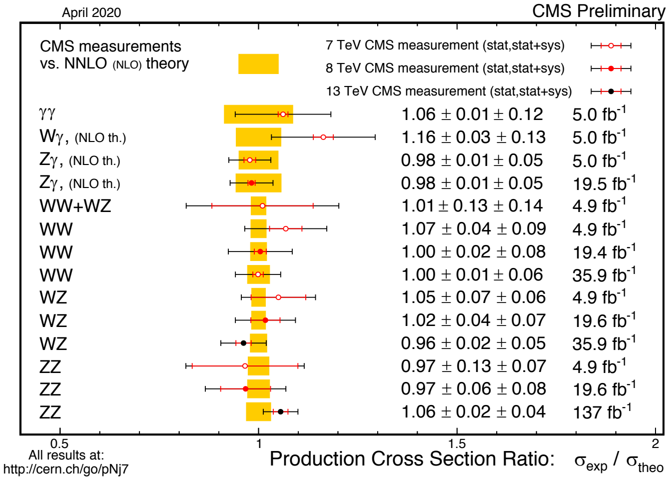
- **A major discovery in physics**
- **A new paradigm:** the space in the whole Universe is filled with the Higgs field
- The study of the nature and properties of the Higgs boson is a scientific imperative for the next decades

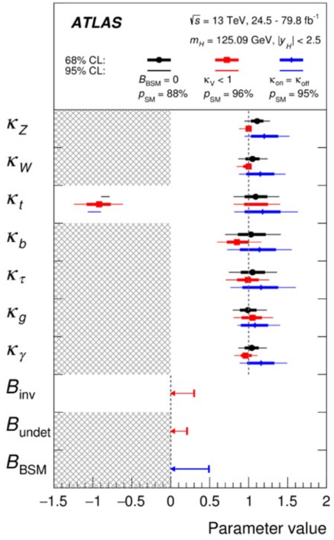




Search for new physics at LHC

- So far the measurements at LHC are compatible with the SM predictions
  - Several thousand papers have been published by the LHC collaborations
  - few discrepancies observed are not yet conclusive
- Precision of Higgs related measurements is presently ~20%



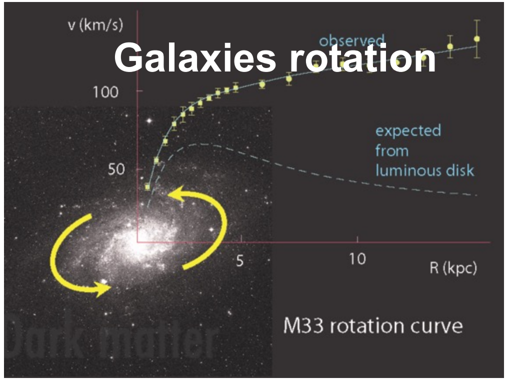


Much more data is needed to achieve 1% precision or below

Some of the major questions today

- What is the **nature of the Higgs field?**
- Why do we **observe matter and almost no antimatter** in the universe?
- Why is the **neutrino mass** so small?
- Are **quarks and leptons fundamental particles?**
- Why are there **three generations of quarks and leptons**?

The dark side of the Universe

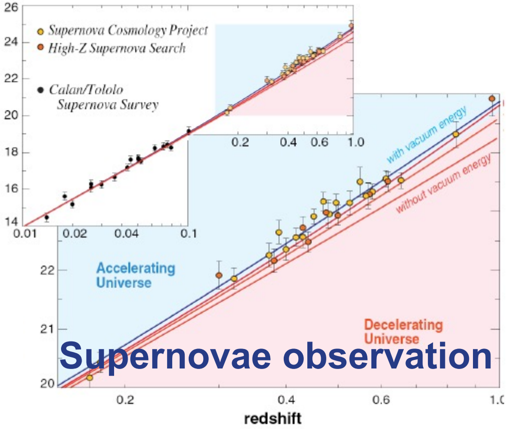


Experimental cosmology gives strong motivation for new physics:

What is Dark Matter?
What is Dark Energy?

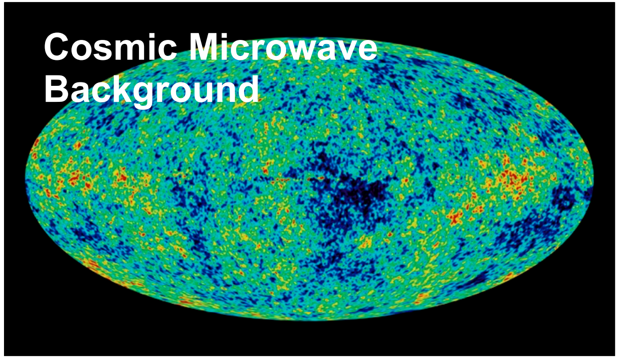
95% of the Universe is unknown

Measurements of CMB fluctuations allow precise assessment of **dark matter and energy.**



The expansion of the Universe is accelerating

Some form of **dark energy** fills the whole space creating a negative pressure



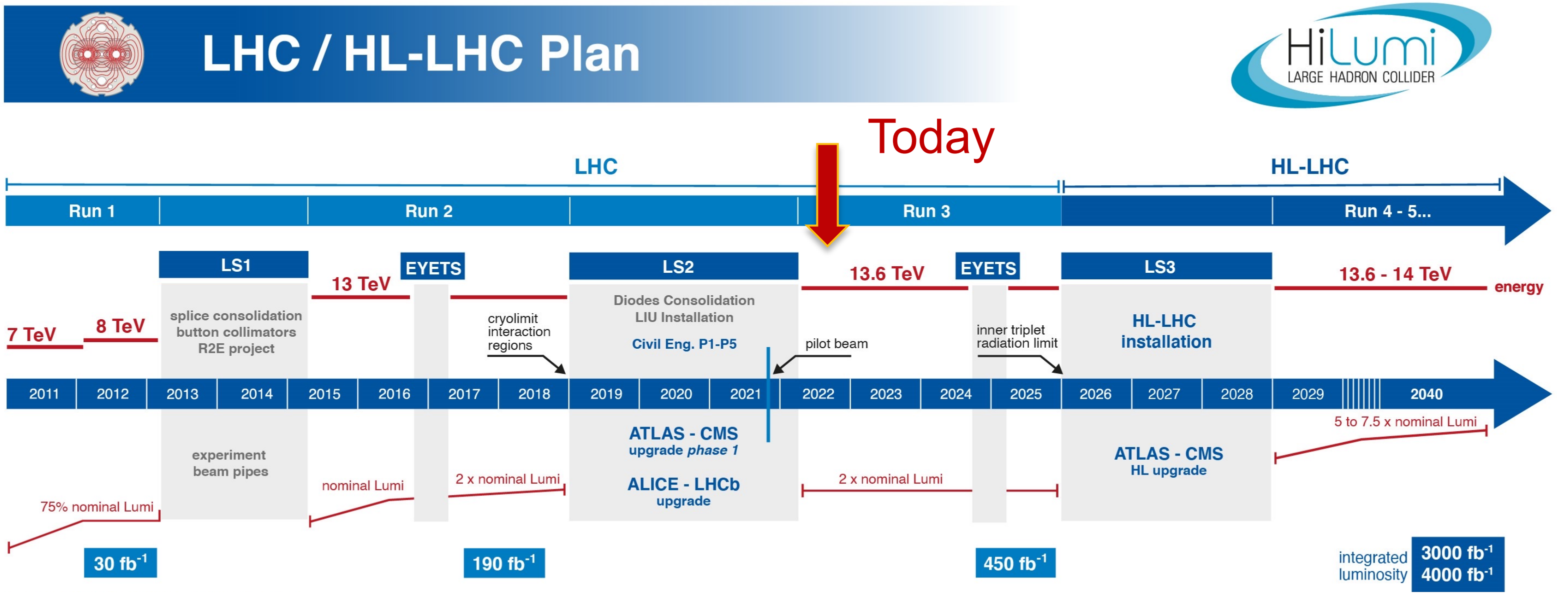
New colliders are necessary

- **New colliders are necessary to address several of the major, fundamental open questions of particle physics**
  - possible composite nature of the Higgs
  - solutions to the hierarchy problem
  - baryogenesis and the electroweak phase transition
  - the nature of dark matter
  - the origin of neutrino mass
  - the structure of possible flavor-changing neutral currents

- **Many of the open questions beyond the Standard Model are related to the Higgs scalar sector.**

The High-Luminosity LHC

HL-LHC will provide 20 times more data than available today

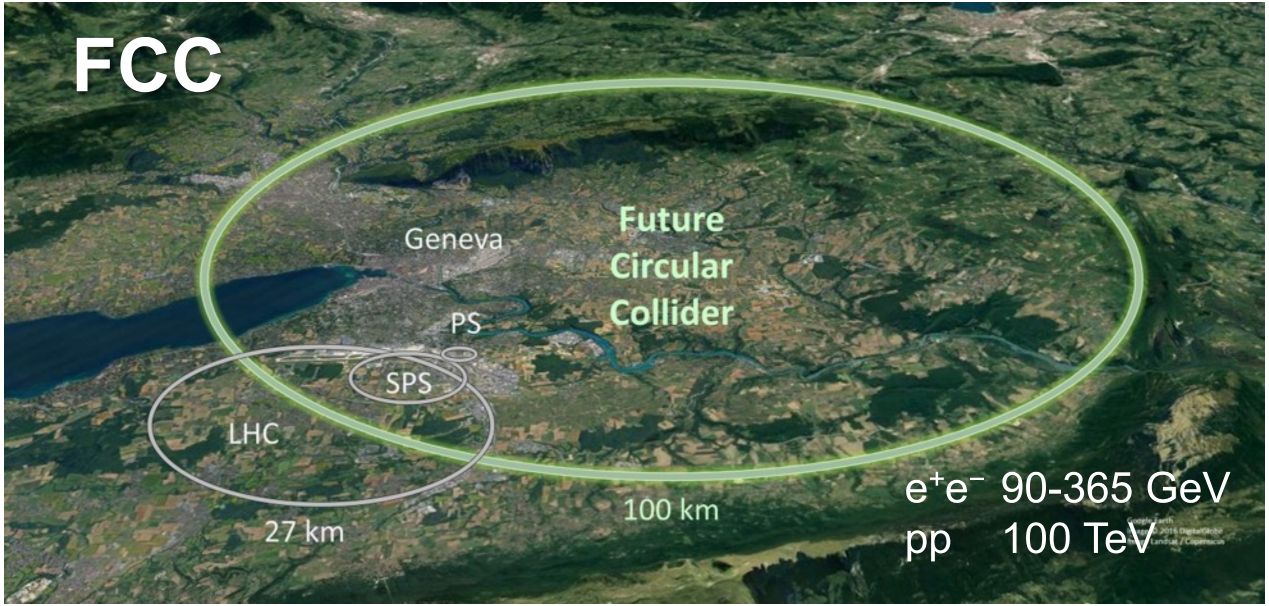


Bound to be one of the greatest endeavors of science in the 21st century

FCC: future machine at CERN

Circular collider with 100 Km circumference:

- Phase 1 (FCC-ee): electron-positron collisions at energy 90-365 GeV
- Phase 2 (FCC-hh): proton-proton collision at energy 100 TeV



Higgs factory

- There is overwhelming consensus in the HEP scientific community that an **e^+e^- collider as a Higgs factory** should be the next high-energy facility.

- Extensive studies showed that the **best option is FCC-ee** with energy from the Z peak to 365 GeV.

The Higgs boson is special

Higgs field = forces of very different nature than the other interactions

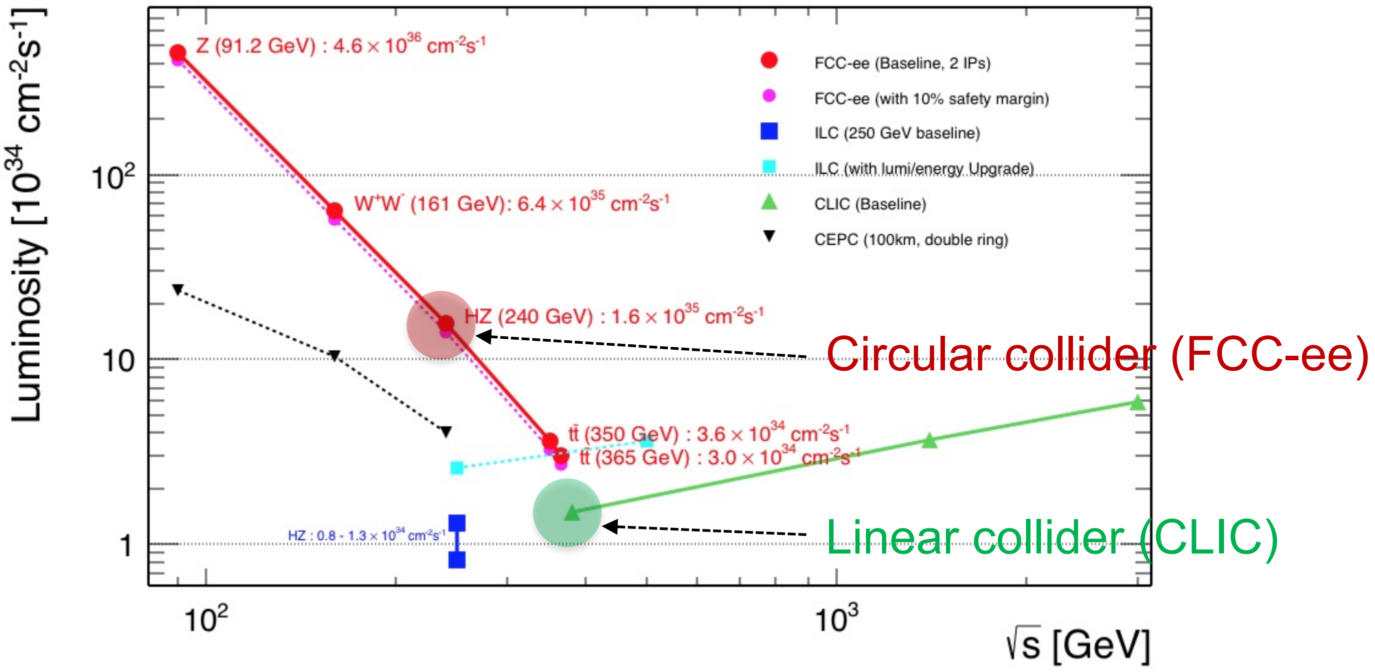
- only elementary particle with spin 0 (scalar)
- only particle (w/ defined quantum numbers) with self-interaction
- no underlying local symmetry
- no quantized charges
- deeply connected to the quantum structure of the vacuum

The precise knowledge of the **Higgs properties** is essential to our understanding of the deep structure of matter

Higgs precision program is very much needed to probe physics beyond the SM

Luminosity of e+e- machines

High luminosity is needed to achieve large Higgs statistics



Running scenario at FCC-ee

- Operation at the Z peak, at the WW threshold, **at the HZ cross-section maximum** and at the ttbar threshold

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 - 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k $WW \to H$	$10^6 t\bar{t}$ +200k HZ +50k $WW \to H$	

Higgs couplings

- Deviations from the SM Higgs boson properties are described by multiplicative coupling strength modifiers, known as the κ framework.
- Expected **precision of Higgs couplings ~1%**
- Precision of the **total Higgs width ~1.0 %**
- FCC-ee can extract the **Higgs self-coupling with a precision of ±25%**

Coupling modifier (precision in %)	HL-LHC + $CLIC_{380}$	HL-LHC + $FCC\text{-}ee_{365}$
κ_W	0.73	0.41
κ_Z	0.44	0.17
κ_g	1.5	0.90
κ_γ	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
κ_c	4.1	1.3
κ_t	3.2	3.1
κ_b	1.2	0.64
κ_μ	4.4 *	3.9
κ_τ	1.4	0.66
BR_{inv} (< %, 95% CL)	0.63	0.19
BR_{unt} (< %, 95% CL)	2.7	1.0

Feasibility of the Higgs factory

- FCC-ee requires a circular tunnel of 100 km circumference
  - Perspective of integrated programme of FCC-ee followed by FCC-hh
- The machine profits from the vast experience accumulated with previous circular e^+e^- colliders.
- Two or more detectors along the ring are possible.
- The complete FCC-ee programme will require a total investment of 11.6 BCHF.
  - The cost of the civil engineering for the FCC-ee is 5.4 BCHF.

Phase 2: FCC-hh

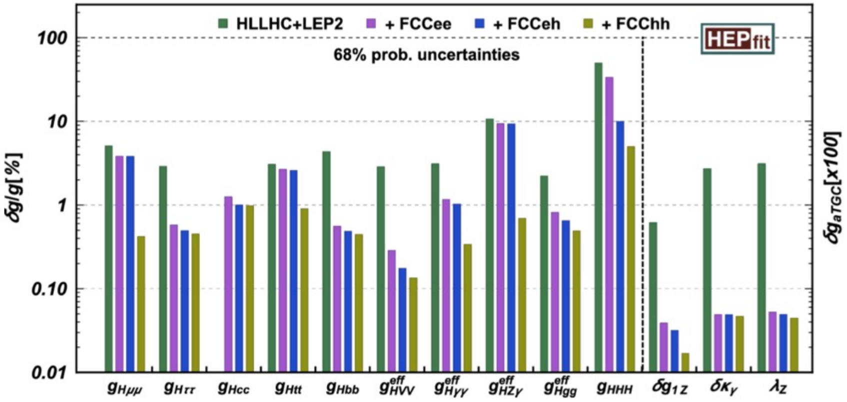
- **The 100 TeV FCC-hh will represent a major step in energy compared to LHC**
- FCC-hh programme includes ion-ion and possibly electron-hadron collisions
- Nb_3Sn superconducting magnet technology for hadron colliders still requires long development to reach **14-16 T**.
- Detailed feasibility study of FCC-hh and experiments will be carried in the next 7 years

Total Cost in BCHF:

FCC-ee [d)]	250 GeV	365 GeV	FCC-hh (100 TeV) [e)]
Total	10.5	11.6	28.6

FCC-hh physics prospects

- Possibility of **discoveries in an unchartered mass range**
  - direct production of new heavy states up to tens of TeV
- **Ultimate precision in Higgs properties**
  - huge integrated luminosity of 30 ab^{-1} (10x HL-LHC)
  - increase in production cross-section (10-60x HL-LHC)



- **Precision on the Higgs self-coupling of about 5%**
- **Access to exotic Higgs decays with tiny branching ratios**

Is it so expensive?

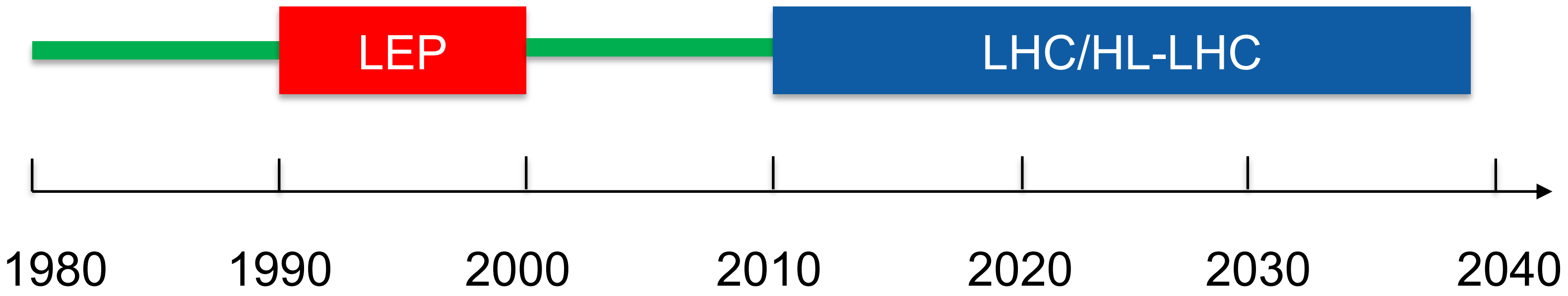
Cost of FCC	**30 Billion €**
• Construction time	30 years
• FCC cost/year	1 Billion €
• European citizens	500 Million
• FCC cost/year/citizen	2 €
FCC cost per citizen (payed in 30 years)	**60 €**

Other big projects:

• The Manhattan Project	24 Billion $
• The Space projects (1957-75)	100 Billion $
• International Space Station (over 30 years)	100 Billion €

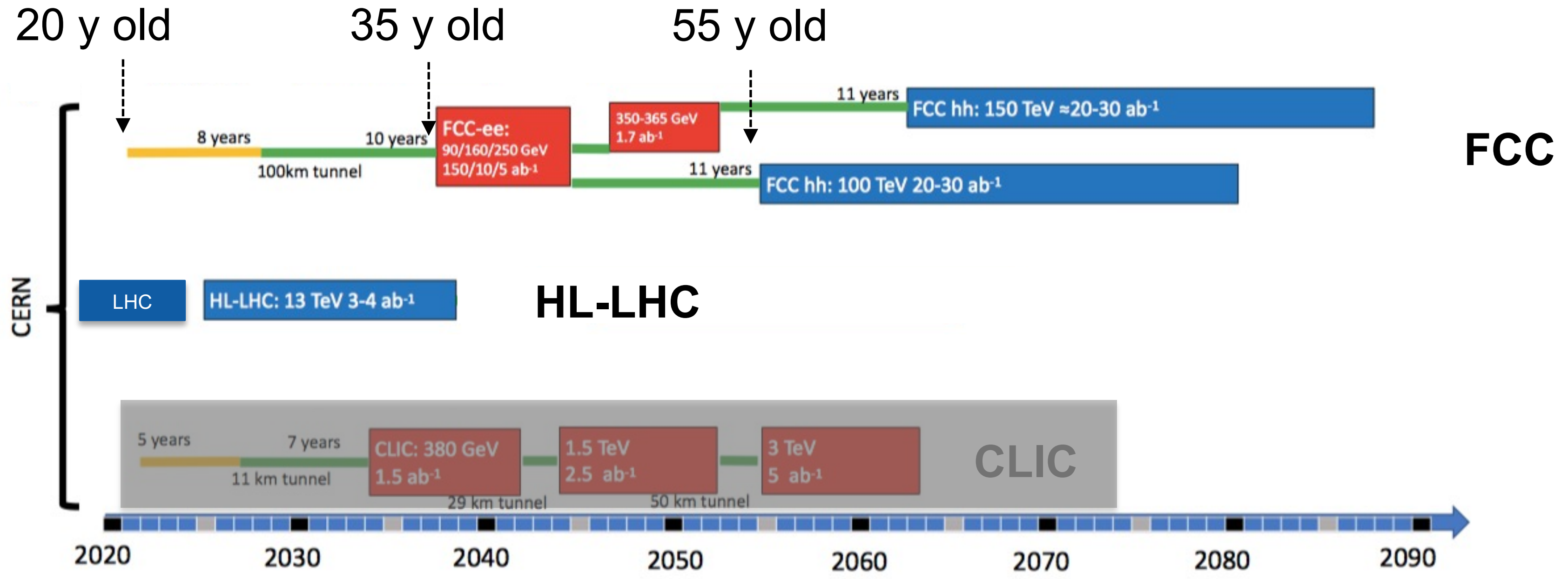
Is it so long?

- Example: the LEP-LHC programme
  - e^+e^- collider followed by a proton-proton collider in the same tunnel
  - total duration ~60 years



In the eighties, many people in the HEP community thought that it was worth to dedicate a lifetime to discover the Higgs!

The FCC scenario



Today, the HEP community think that it is worth do dedicate a lifetime to understand what hides behind the Higgs!

Thank you for your attention