From the LHC to the future

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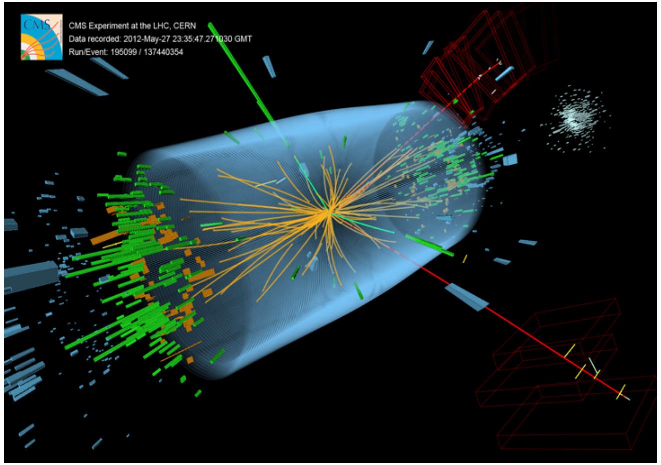
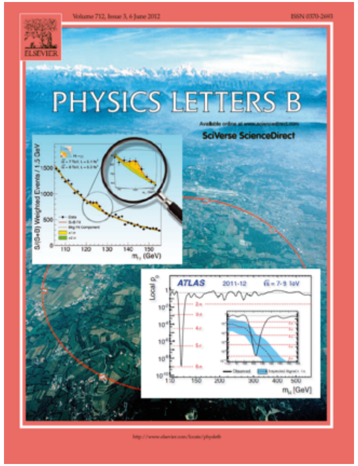
Higgs boson discovery in 2012

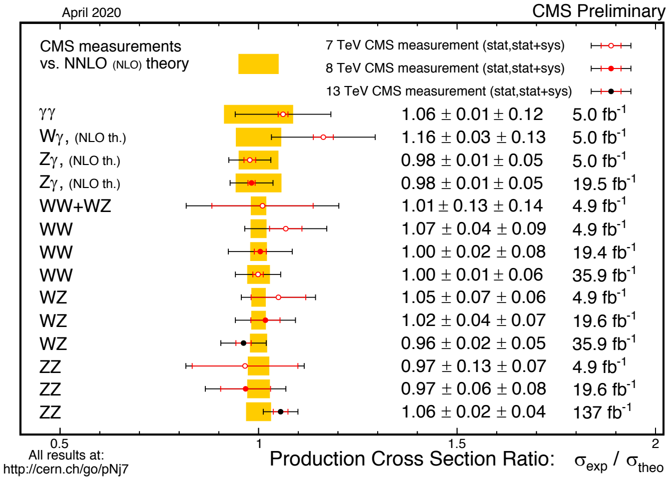
- **A major discovery in physics**
- **A new paradigm:** the space in the whole Universe is filled with the Higgs field
- **The study of the nature and properties of the Higgs boson is a scientific imperative for the next decades**

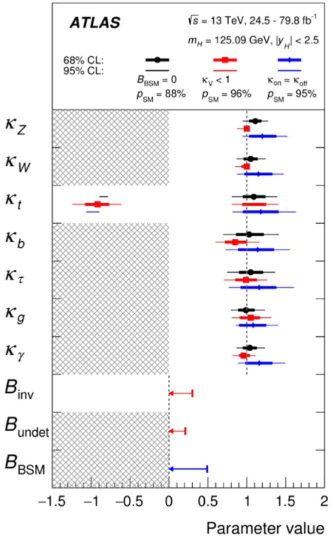




Search for new physics at LHC

- So far the measurements at LHC are compatible with the SM predictions
  - about ~2500 papers have been published by the LHC collaborations
  - few discrepancies observed are not yet conclusive
- Precision of Higgs related measurements is presently ~20%



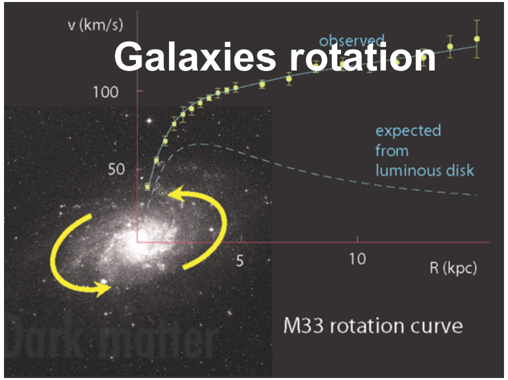


Much more data is needed to achieve 1% precision or below

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**?

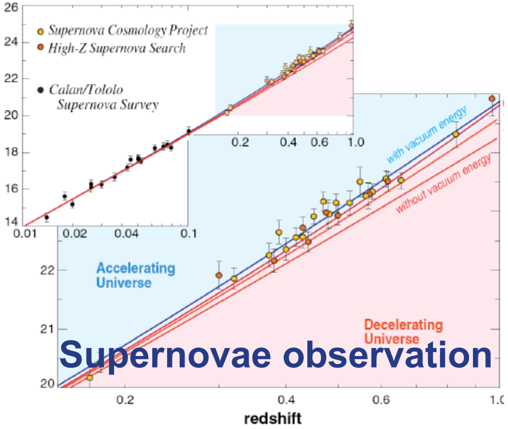
The dark side of the Universe



Experimental cosmology gives strong motivation for new physics:

What is Dark Matter?
What is Dark Energy?

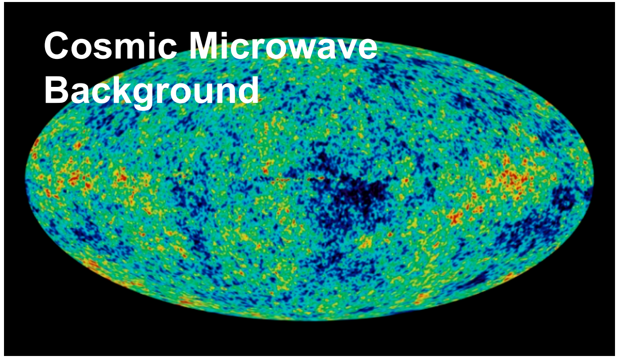
95% of the Universe is unknown



The expansion of the Universe is accelerating

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

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



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 Higgs boson is special

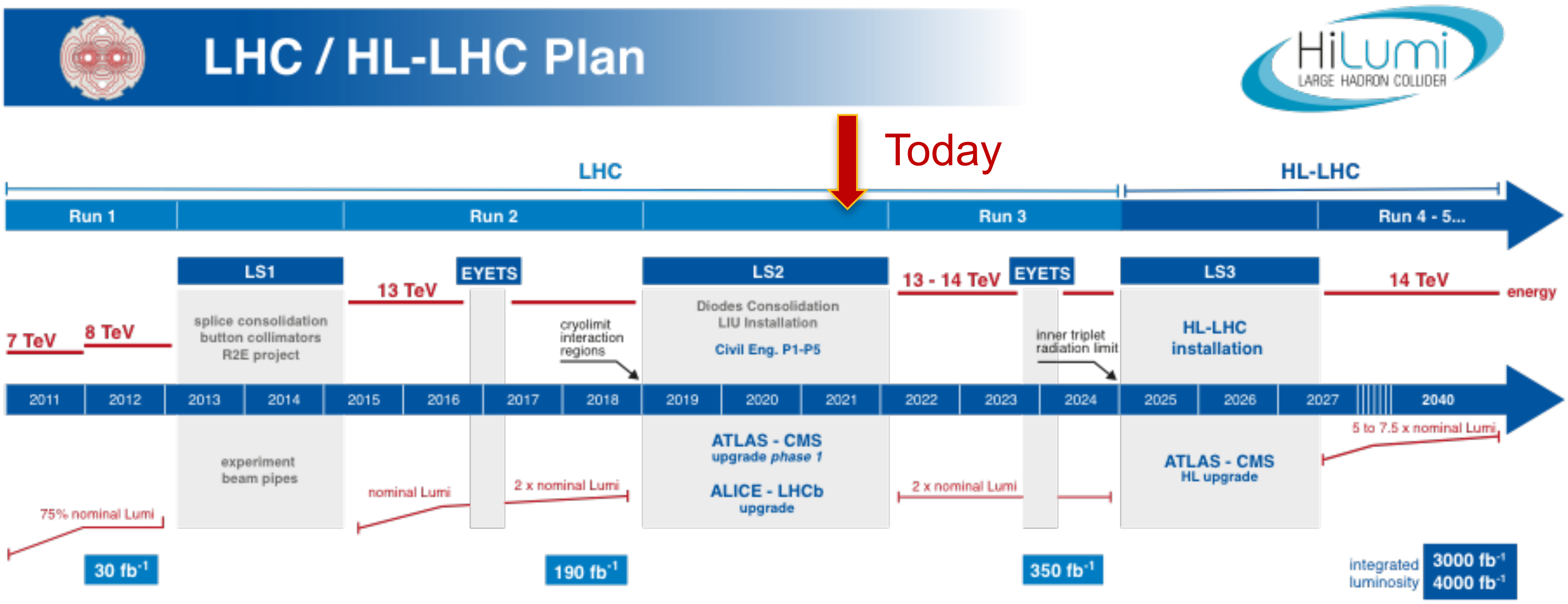
Higgs field = forces of very different nature than the other interactions

- 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

The High-Luminosity LHC

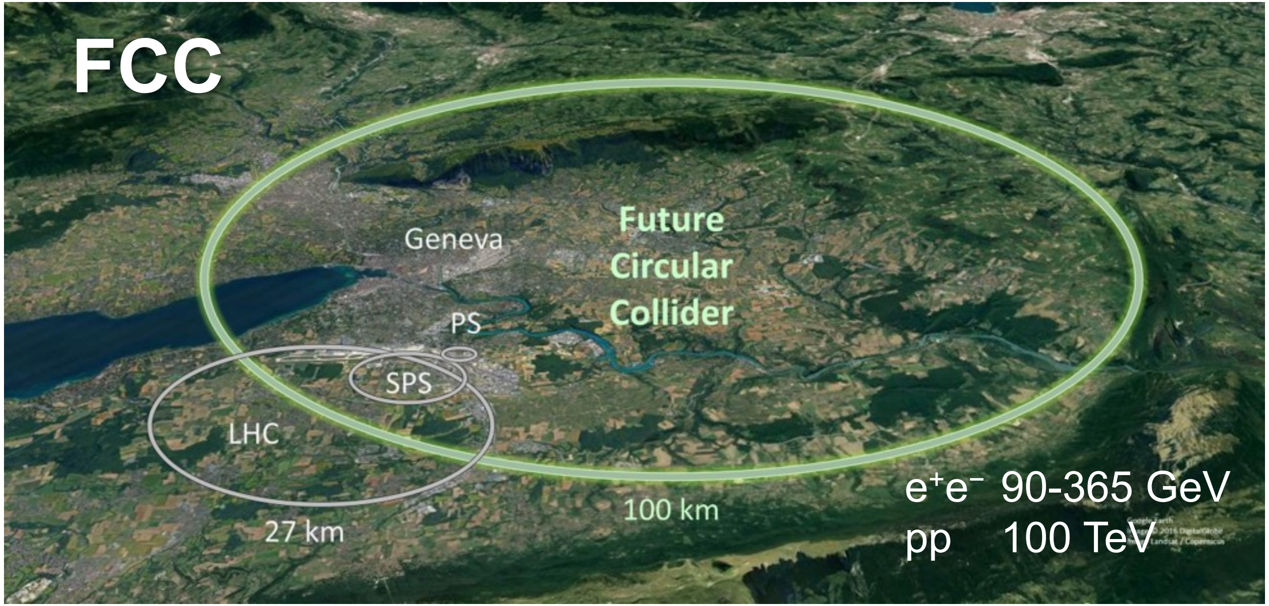


HL-LHC will provide 20 times more data than available today

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



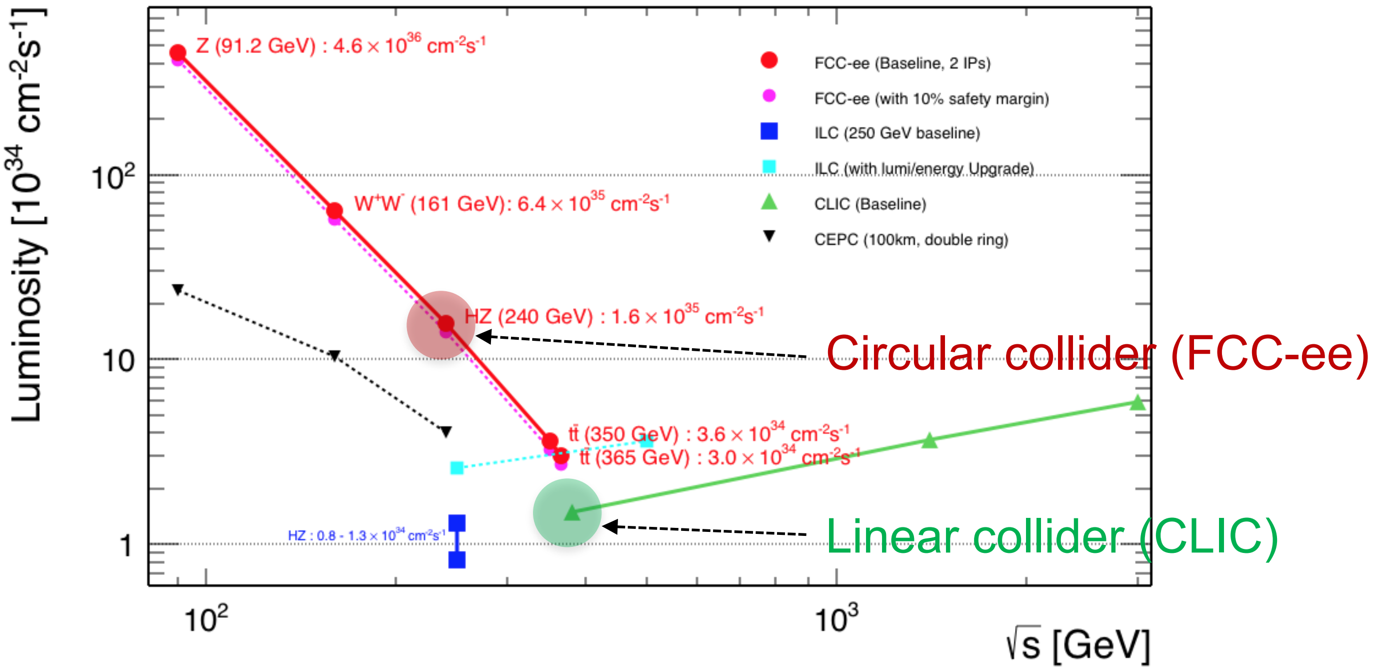
Higgs factory

- There is consensus in the HEP scientific community that a **e^+e^- collider as a Higgs factory** should be the next machine.

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

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	$\mathrm{t\bar{t}}$	
$\sqrt{s}$ (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 $WW \to H$	

One million Higgs bosons !

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%**

- FCC-ee can extract the **Higgs self-coupling with a precision of ±25%**

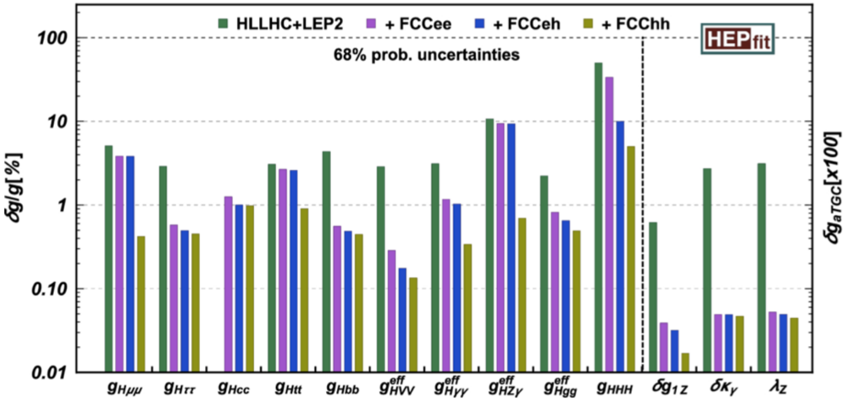
Coupling modifier (precision in %)	HL-LHC + CLIC$_{380}$	HL-LHC + FCC-ee$_{365}$
κ_W	0.73	0.41
κ_Z	0.44	0.17
κ_g	1.5	0.90
κ_γ	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
κ_c	4.1	1.3
κ_t	3.2	3.1
κ_b	1.2	0.64
κ_μ	4.4 *	3.9
κ_τ	1.4	0.66
BR_{inv} (< %, 95% CL)	0.63	0.19
BR_{unt} (< %, 95% CL)	2.7	1.0

Phase 2: FCC-hh

- **The 100 TeV FCC-hh will represent a major step in energy compared to LHC**
- 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 until 2027.

FCC-hh physics prospects

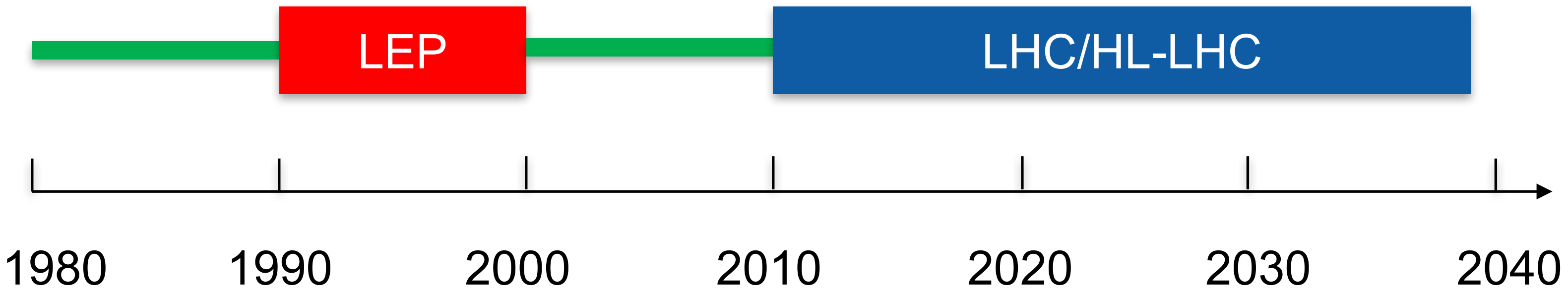
- Possibility of **discoveries in an unchartered mass range**
  - direct production of new heavy states up to tens of TeV
- **Ultimate precision in Higgs properties**
  - huge integrated luminosity of 30 ab^{-1} (10x HL-LHC)
  - increase in production cross-section (10-60x HL-LHC)



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

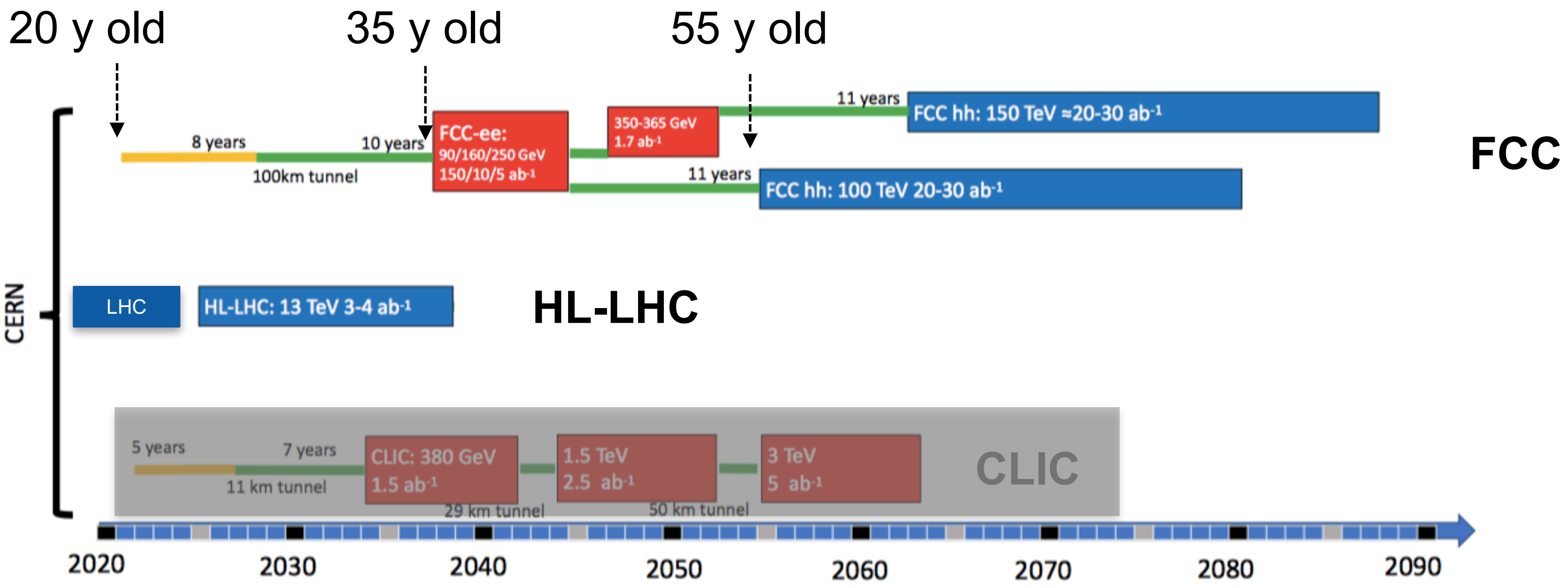
Past example

- 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, many people think that it is worth do dedicate a lifetime to understand what hides behind the Higgs!

Thank you for your attention