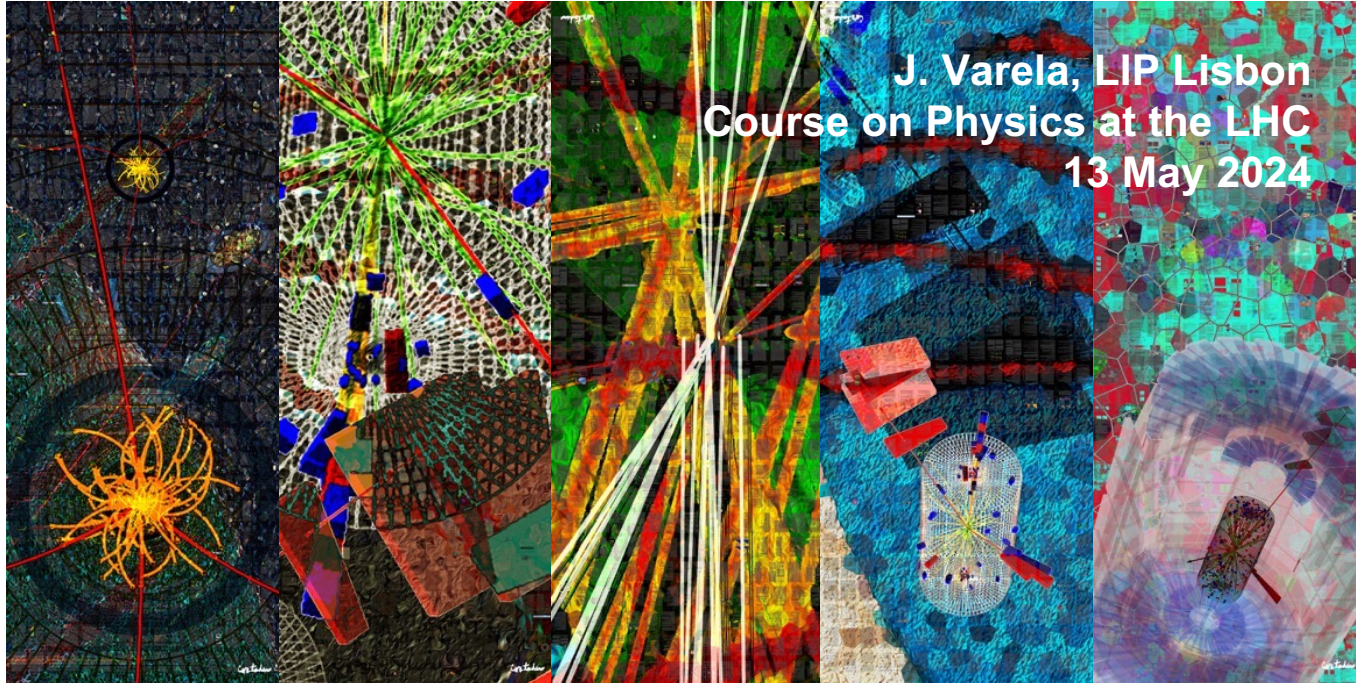


# Future endeavors in Particle Physics



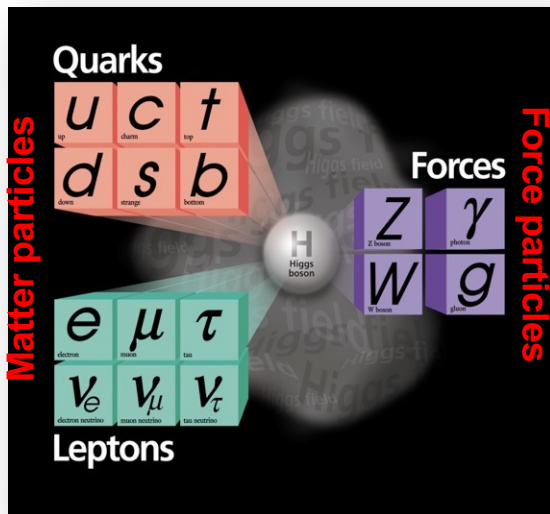
- Physics motivation
- New big facilities under consideration
- Higgs factory
- The high energy frontier

## Not covered:

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

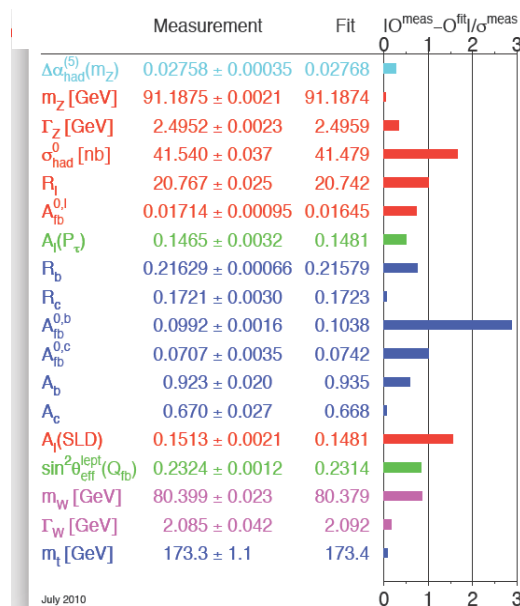
# The Standard Model of Particle Physics

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



One of the greatest achievements of the 20<sup>th</sup> Century Science

Confirmed experimentally at <1% level



# The Terascale and the LHC

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

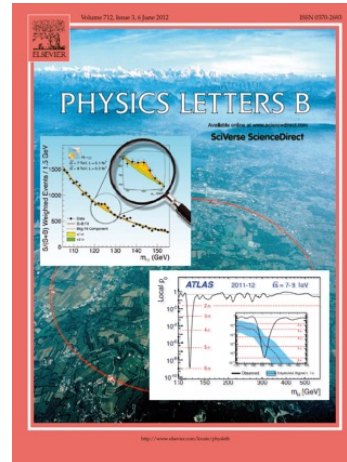
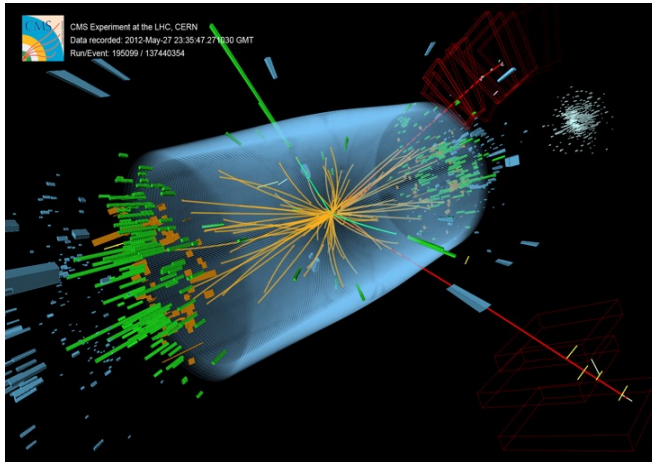
It was expected that the 'new physics' would manifest at an energy around 1 TeV accessible at the LHC for the first time.





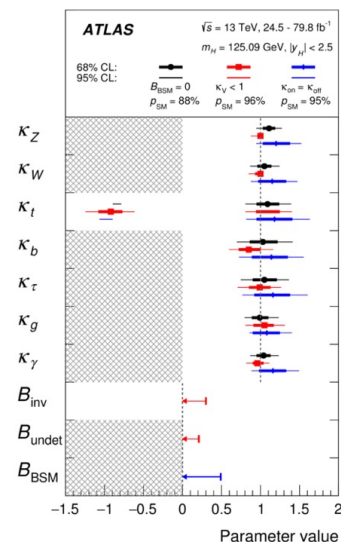
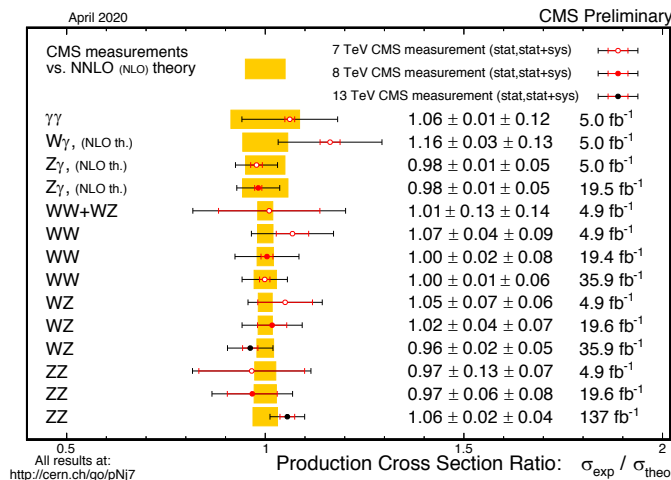
# Higgs boson discovery in 2012

- **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  $\sim 20\%$



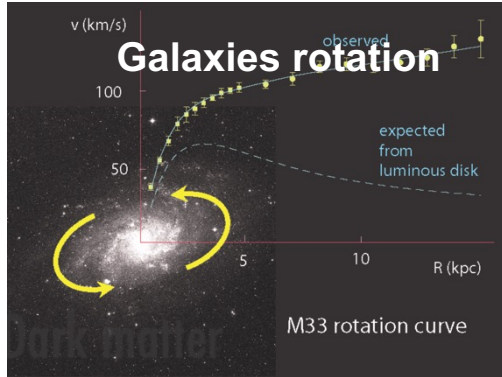
**Much more data is needed to achieve 1% precision or below**

# Some of the major questions today

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- 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**?

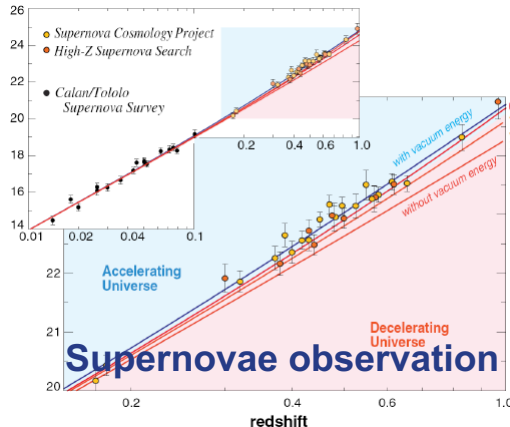
# The dark side of the Universe



Experimental cosmology gives strong motivation for new physics:

**What is Dark Matter?**  
**What is Dark Energy?**

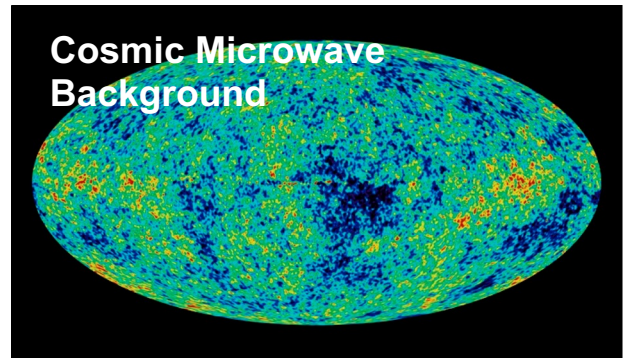
**95% of the Universe is unknown**



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**.





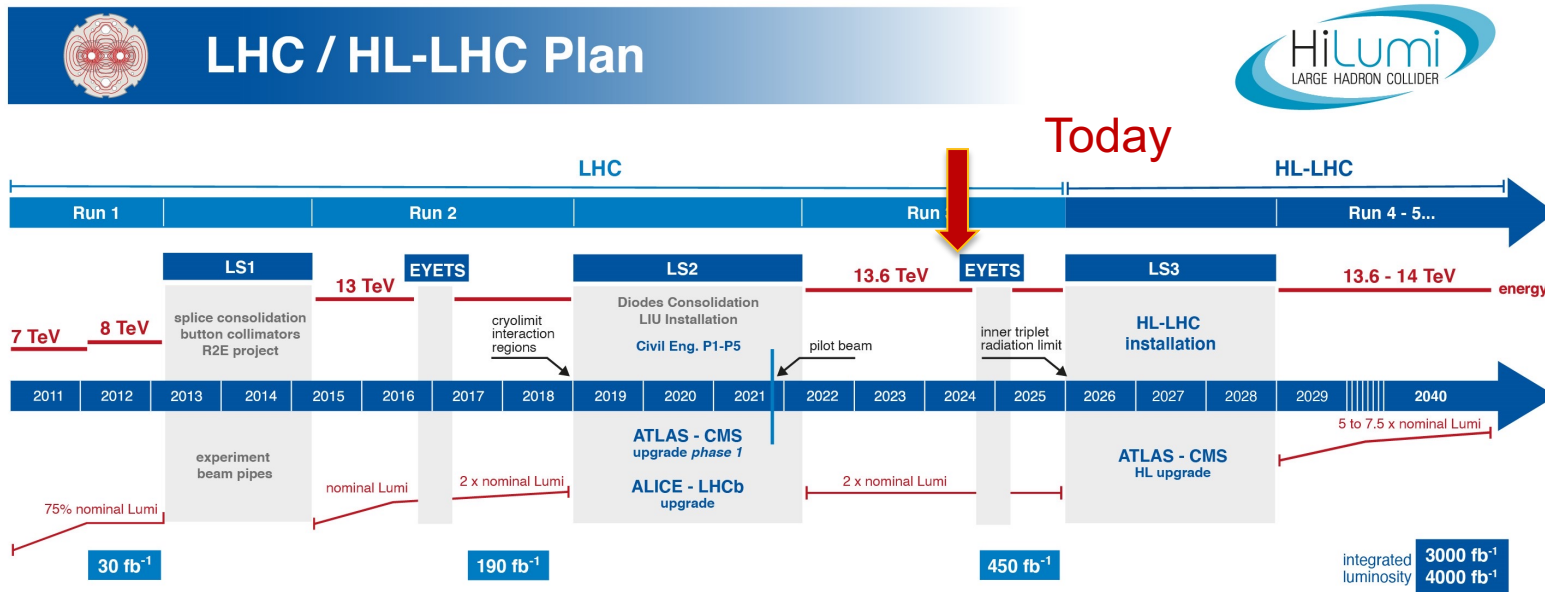
# New colliders are necessary

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- **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 10 times more data than LHC**

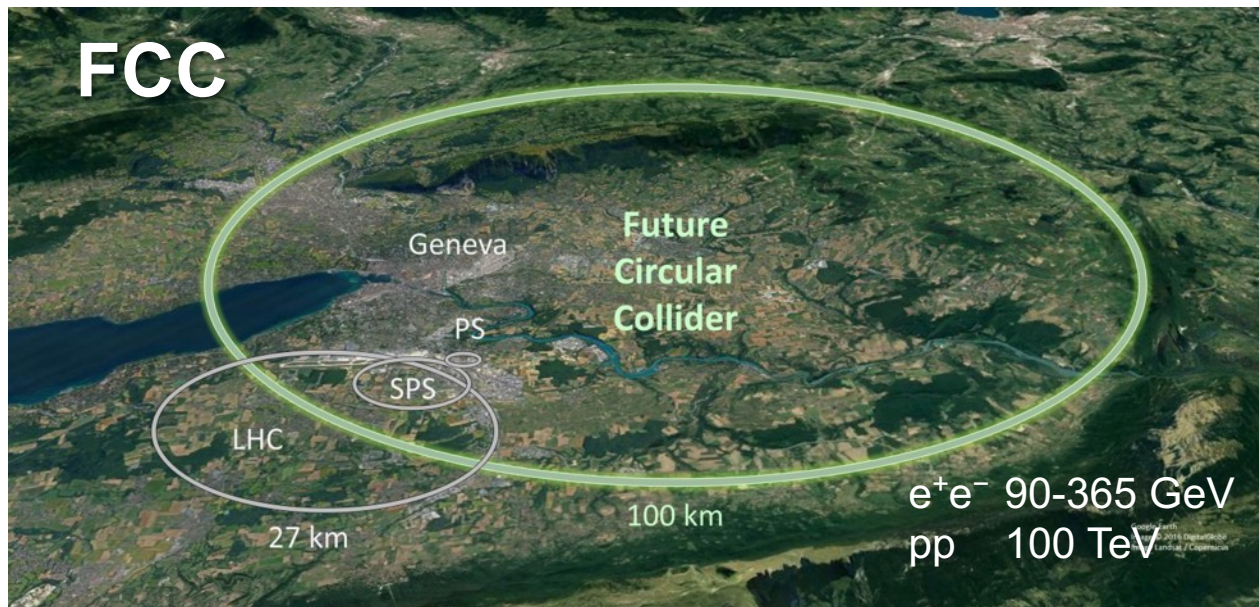


**Bound to be one of the greatest endeavors of science in the 21<sup>st</sup> century**

# 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



- 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

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

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

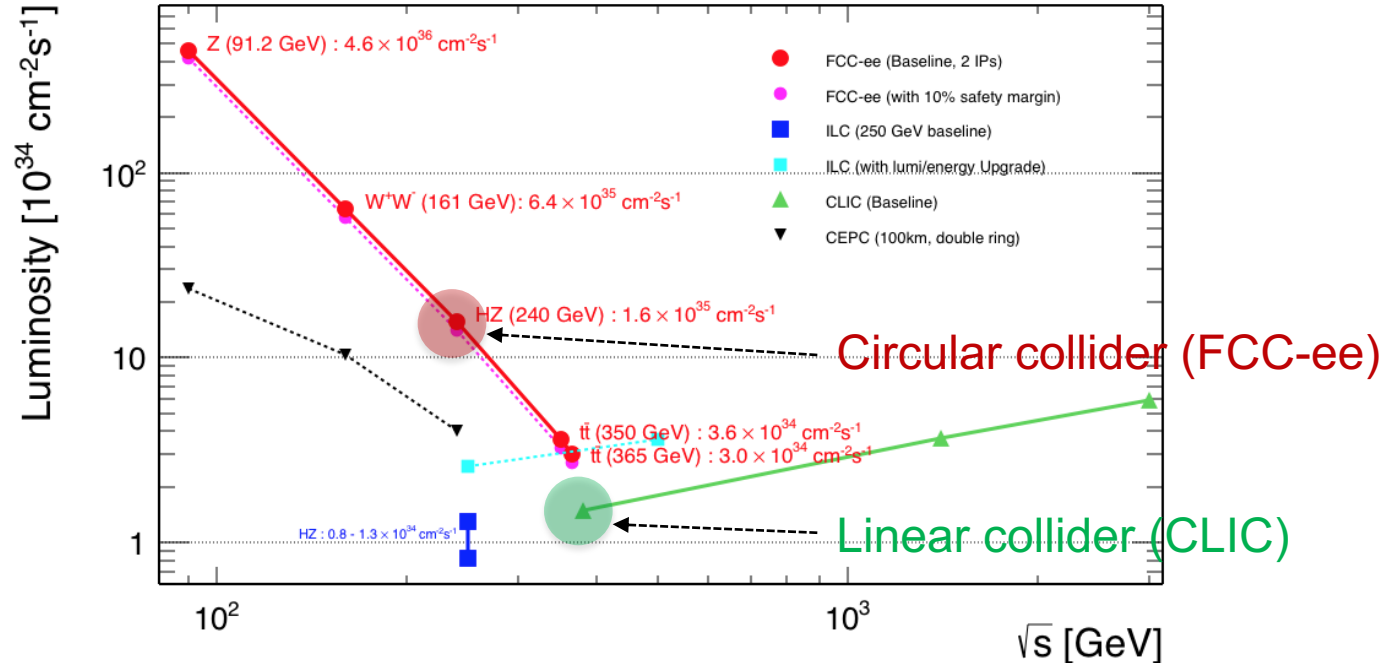
The precise knowledge of the **Higgs properties** is essential to our understanding of the deep structure of matter

**Higgs precision program is needed  
to probe physics beyond the SM**



# Luminosity of e<sup>+</sup>e<sup>-</sup> 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 ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )	115	230	28	8.5	0.95	1.55
Lumi/year ( $\text{ab}^{-1}$ , 2 IP)	24	48	6	1.7	0.2	0.34
Physics goal ( $\text{ab}^{-1}$ )	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	$5 \times 10^{12} Z$		$10^8 WW$	$10^6 HZ$ + 25k $WW \rightarrow H$	$10^6 t\bar{t}$ +200k $HZ$ +50k $WW \rightarrow H$	

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

Coupling modifier (precision in %)	HL-LHC +	
	CLIC <sub>380</sub>	FCC-ee <sub>365</sub>
$\kappa_W$	0.73	0.41
$\kappa_Z$	0.44	0.17
$\kappa_g$	1.5	0.90
$\kappa_\gamma$	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
$\kappa_c$	4.1	1.3
$\kappa_t$	3.2	3.1
$\kappa_b$	1.2	0.64
$\kappa_\mu$	4.4 *	3.9
$\kappa_\tau$	1.4	0.66
BR <sub>inv</sub> (< %, 95% CL)	0.63	0.19
BR <sub>unt</sub> (< %, 95% CL)	2.7	1.0

# Feasibility of the Higgs factory

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- 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.

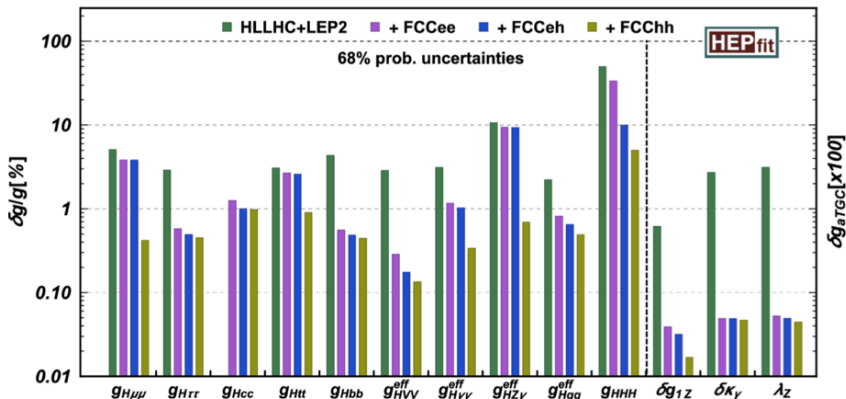
- **The 100 TeV FCC-hh will represent a major step in energy compared to LHC**
- FCC-hh programme includes ion-ion and possibly electron-hadron collisions
- Nb<sub>3</sub>Sn superconducting magnet technology for hadron colliders still requires long development to reach **14-16 T**.
- Detailed feasibility study of FCC-hh and experiments is being carried

Total Cost in BCHF:

FCC-ee <sup>d)</sup>	250 GeV	365 GeV	FCC-hh (100 TeV) <sup>e)</sup>
Total	10.5	11.6	28.6



- Possibility of **discoveries in an uncharted mass range**
  - direct production of new heavy states up to tens of TeV
- **Ultimate precision in Higgs properties**
  - huge integrated luminosity of  $30 \text{ ab}^{-1}$  (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

- Construction time
- FCC cost/year
- European citizens
- FCC cost/year/citizen

30 Billion €

30 years

1 Billion €

500 Million

2 €

**FCC cost per citizen (payed in 30 years)**

**60 €**

## Other big projects:

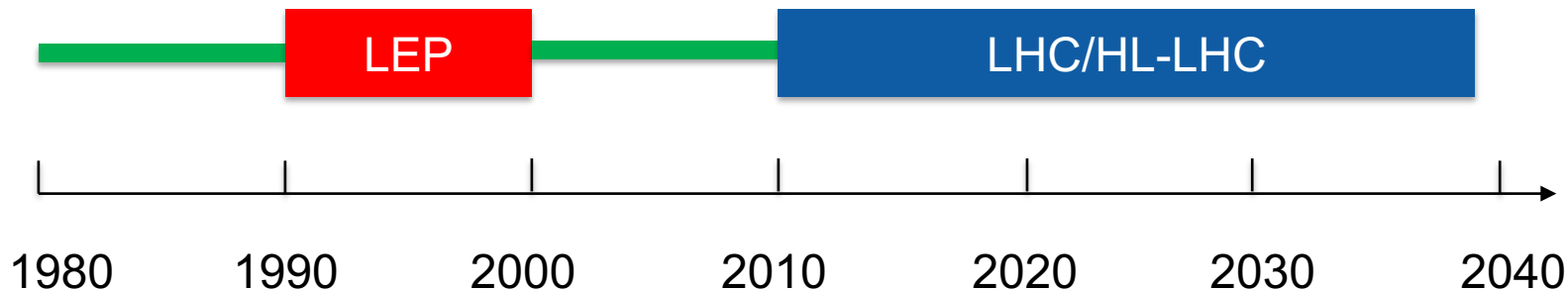
- The Manhattan Project
- The Space projects (1957-75)
- International Space Station (over 30 years)

24 Billion \$

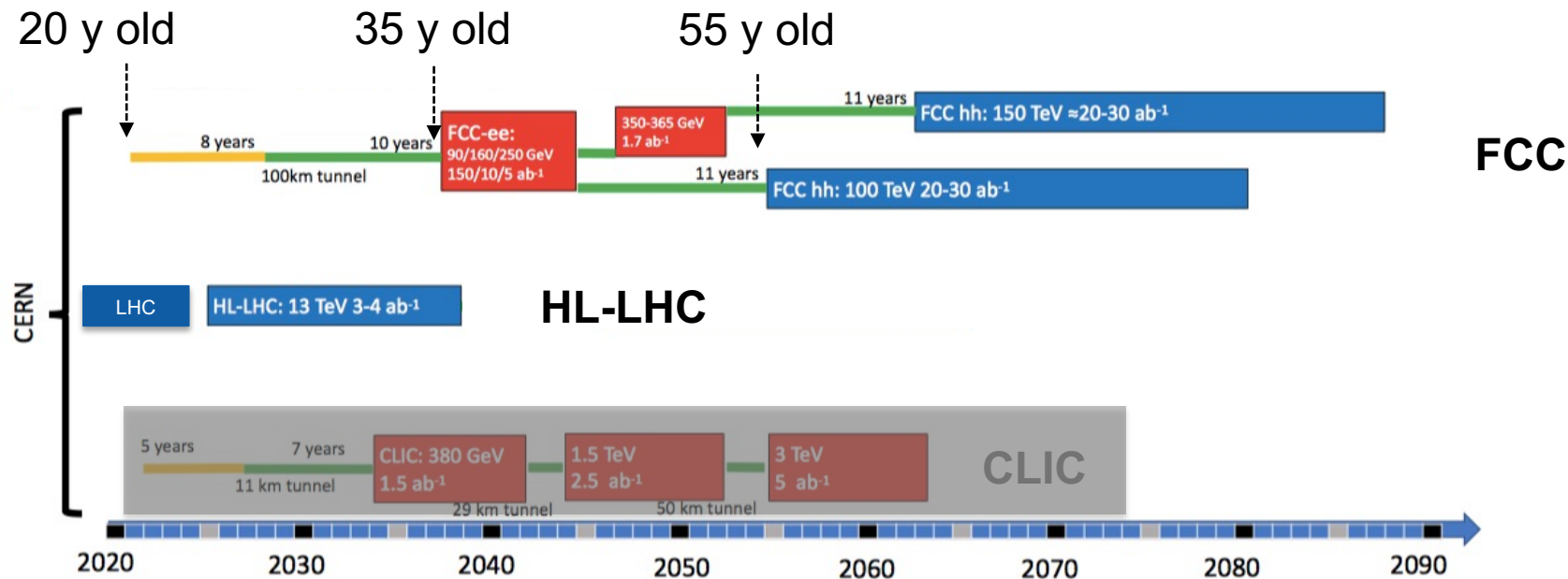
100 Billion \$

100 Billion €

- 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 the effort to discover the Higgs**



**Today, the HEP community thinks that it is worth the effort to understand what hides behind the Higgs**

**Thank you for your attention**