The Future Circular Collider (FCC)

Presentation to the European School Brussels III

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FCC hh ee he

EuroCirCol A key to New Physics

EASITrain

ARIES

E-JADE

http://cern.ch/fcc

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18 February 2021

photo: J. Wenninger

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- The physics landscape
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Research

- Here at CERN we mainly do fundamental research
- Applied research is directed towards the body: it helps us live better
- Fundamental research is directed towards our soul: it frees us from the shackles of ignorance
- Both make us dream!
- (actually, both are very important for Mankind. Fundamental science helps us move levels with paradigm shifts)

What is Physics?

- Physics tries to understand the nature of reality
- We have really gone a long way, especially during the 20th century, but there are still miles to go
- 20th century physics pivots around the Theory of Relativity and Quantum Mechanics, both established during the first part of the century
- Regarding the nature of matter, particle physics, the theory that explains how things work was unimaginatively called “the Standard Model”
- The Standard Model has been an extremely successful collective effort of many people and is the best description of nature to date.

SM success stories


Peter Higgs, lecturer, Edinburgh, circa 1964


Peter Higgs, Nobel laureate, CERN, 2014

A theory developed by a 35-year-old physicist in 1964 proved correct in 2012 with the discovery of the Higgs particle, 48 years later.

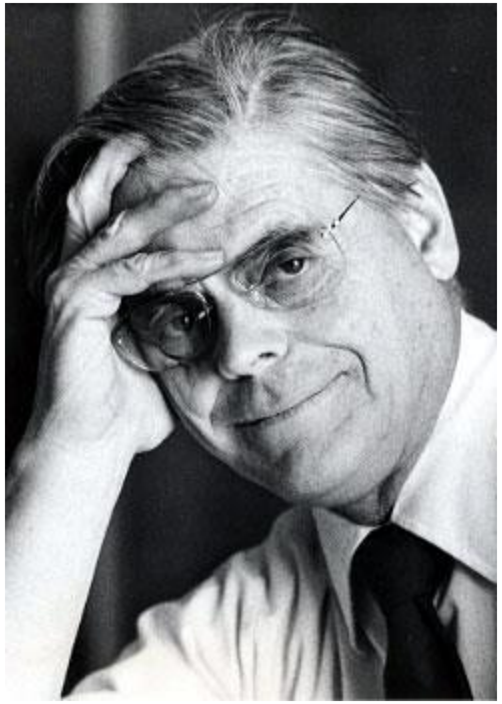
Discovery machine: LHC, a 27-km accelerator.
“Big Science”

This, I believe, is the epitome of 20th century science: perseverance, solid foundations, progress

Why do we do it?

«… We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard…» J.F. Kennedy, US president, 1962, in his famous speech about the Apollo program

Why do we do it?(2)



Robert R Wilson

"during the 1969 congressional hearings concerning a proposed multimillion-dollar particle accelerator facility to be built in Batavia, Illinois (Fermilab), its first director Robert R. Wilson, was asked: "Is there anything connected with the hopes of this accelerator that in any way involves the security of the country?" His reply was: "It has nothing to do directly with defending our country except to make it worth defending"

Is history repeating itself...?

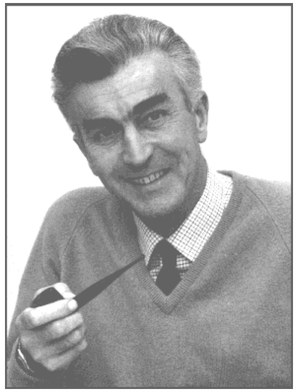
When **Lady Margaret Thatcher** visited CERN in 1982, she asked the then CERN Director-General **Herwig Schopper** ***how big would the next tunnel after LEP be.***

Margaret Thatcher, British PM 1979-90

Herwig Schopper
CERN DG 1981-88
built LEP

Dr. Schopper's answer was ***there would be no bigger tunnel at CERN***.

Lady Thatcher replied that she had obtained ***exactly the same answer from Sir John Adams when the SPS was built 10 years earlier***, and therefore she did not believe him.



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

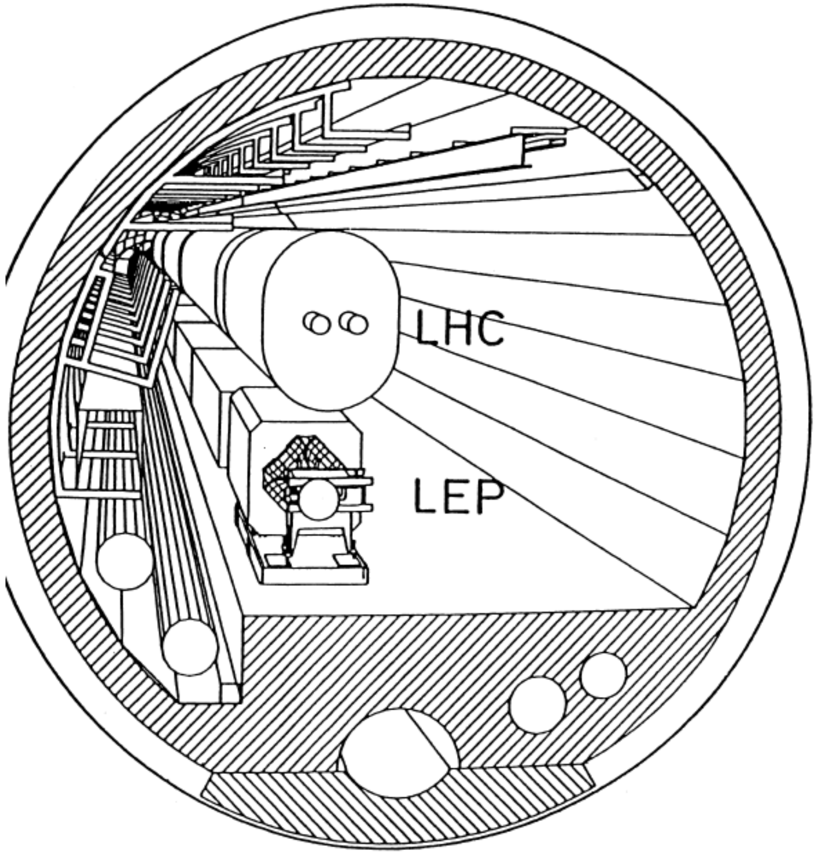
Was lady Thatcher right?

Herwig Schopper, private communication, 2013; courtesy F. Zimmermann

The scale of projects: the LHC

- 1982 : first studies about the LHC
- The LHC will be in operation most probably until 2038…
- 50+ years, two generations of physicists…

The next project will also extend for fifty years… it is very difficult for us to imagine life on earth in the 2070ies… …colonization of Mars would have started and we will all be going aroud in self-driving cars…



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

The view of a theoretical physicist

Nima Arkani-Hamed

In my view, the scientific questions at stake in our field today are the most difficult + profound ones we have faced since the 1930's

The scale of our vision and ambition — both theoretically + experimentally — must be commensurate with the ... tasks at hand

Clearly, how to proceed will depend on first LHC13 results.

But in every scenario I can imagine, we will need the 100 TeV pp machine

* Circular e^+e^- machine Higgs Factory plays very important, complementary role

Looking for $\frac{h^\dagger h\,(h\,Q\,b^c)}{\Lambda^2}$, $\frac{(h^\dagger D h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

The physics case – the experimentalist's point of view

Fabiola Gianotti

- "Regardless of the (outcome of the LHC), [...] the directions for future high-Energy colliders are clear:
  - highest precision → to probe E scales potentially up to O(1OO) TeV and smallest couplings (e+e- collider)
  - highest energy → to explore directly new territories and get crucial information to interpret results from indirect probes (pp collider)"
- This calls for an approach similar to the LEP-LHC approach: a new tunnel than can host a variety of circular colliders (pp, ee, ep, …)

The physics landscape

- The Standard Model is a fantastic 20th century collective accomplishment
- Completed in 2011 (Higgs discovery)
- Self-consistent theory, valid to arbitrary scales
- Yet, cannot explain all observations (dark matter, baryon asymmetry, neutrino sector questions) – especially the first two have become a major embarrassment – more than half a century-old problems still persist today
- All attempts to finding new high mass states have up to now failed.
- Theory provides no guidance

What do we do?

- We certainly do not give up
- Pursue all avenues:
  - Smaller couplings
  - Higher masses
  - Indirect effects (= precision)
- Need an array of small, clever experiments and one large infrastructure project. Largest project to date is the LHC, a 27 km circular proton collider
- FCC is in the latter category. It cannot do everything, but it can do a lot incredibly well.

Direct and indirect discoveries

To measure the size of a rock that fell into a pond one can do two things:

- Capture an image of the rock just before it impacts the water. Or
- Infer the size of the rock by measuring the ripples it produces and knowing the nature of water that propagates them

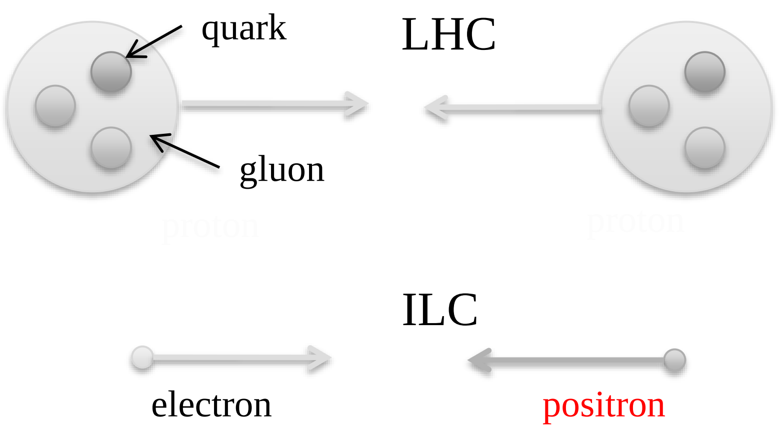
Both methods are perfectly valid but reply on different assumptions. Typically, seeing the rock feels more direct with less room for error. But if you know what you are doing, the indirect method has many advantages: you can be far away from the impact point and still able to make a good measurement.

Difference between proton and electron colliders

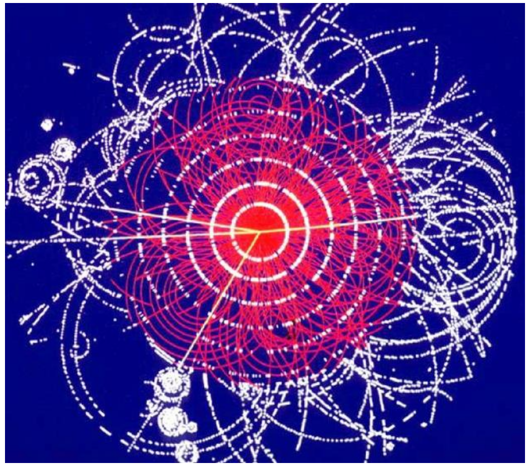
- e^+e^- colliders provide a clean environment, but cannot go to very high energies ➔ ideal for indirect discoveries
- pp colliders are more dirty (protons are not fundamental particles) but can reach higher energies ➔ good for direct discoveries
- FCC-ee: 90 to 350GeV but FCC-hh 100 (or even 140) TeV
- For a proton machine the most important parameter is energy, whereas for an electron machine is luminosity (which is proportional to the number of collisions produced)

Protons vs electrons

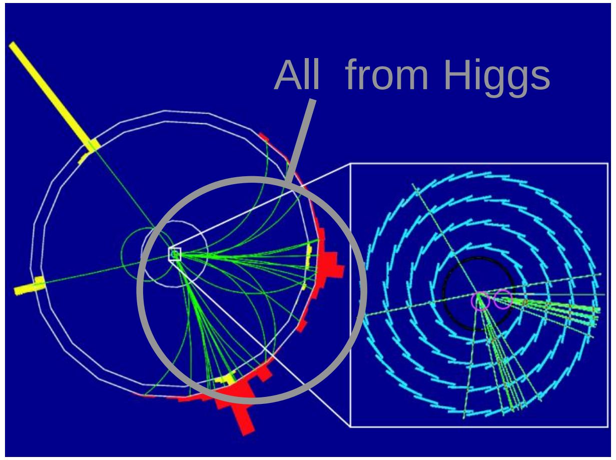
- Protons are not fundamental particles. They are made up from O(10) smaller fundamental particles (quarks and gluons)
- Electron collisions are both technically and theoretically purer (electrons are fundamental particles)



Proton accelerator



Electron accelerator



protons – electrons : 0 - 1

Maximum energy

- Electrons emit photons when they follow a circular orbit. This lost energy increases as the fourth power of the energy of the electrons

$$E_{loss}[GeV] = 8.85 \times 10^{-5} \frac{E^4}{r_{bend}}$$

- This makes it unfeasible to build very high energy circular electron accelerators (while linear electron accelerators have other disadvantages).

protons – electrons : 1 - 1

Linear vs circular colliders

- An electron in a circular orbit radiates (looses energy which becomes heat). Twice the energy -> 16 times more radiated power. Electrons pass by the interaction region millions of times.
- The limit of circular colliders is therefore how much energy one can put back in the system, but for high energies they become inefficient
- Linear colliders do not have these issues but the electrons after every acceleration are lost and are only used once. Linear colliders are very inefficient, but can go to high energies

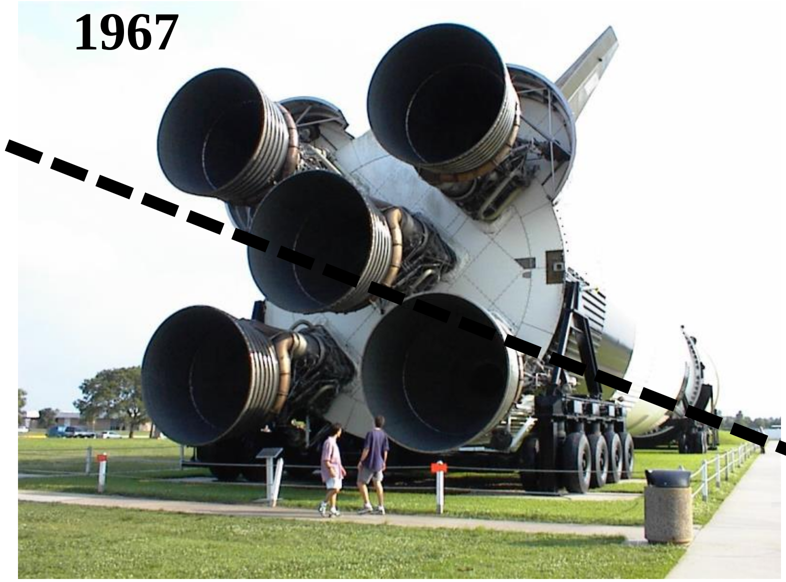
FCC in a nutshell

- **Think big**
- Sacrifice energy reach (at the first stage) for precision (=high luminosity)
  - This choice was dictated by the following:
    - The mass of the Higgs is low
    - LHC has put limits on most exotic particles at 1TeV or beyond. – a 1TeV collider is not needed today!
- Give a fantastic upgrade option – a hadron collider with ~10 times the energy of the LHC (repeat the successful LEP-LHC paradigm: e^+e^- collider followed by a proton collider in the same tunnel)

Immediate (and legitimate) question:

- Surely you are not proposing another synchrotron in the 21st century? Isn't this a bit old-fashioned?
- Answer:
- Sometimes making something bigger is the winning recipe
- Example:
- (we did not need to invent warp drive to go to the moon – a bigger rocket was sufficient)

In history, many times progress is made by incrementally improving a known concept, simply making it bigger (and better)



Challenges for FCC (and similar projects)

Challenge Nº 1

- For all major accelerators being designed today, there is no “guarantee of discovery”.
- This is something new in our field. When the LHC was approved it was guaranteed to solve the problem of the Higgs particle. It would either discover it, or the Higgs theory would have been proven wrong.
- This lack of guaranteed discovery makes it difficult to secure funding – a sensationalist approach worked well when talking to governments in the past
- Maybe the argument of "prestige" will play a role (Europe vs. Asia)

Challenge N^{o}. 2: the lack of challenge

- It is regrettable that the most efficient machine for the future is based on Fifties technology, only bigger.
- Scaling up rather than being more clever has helped in the past.
- Of course on closer inspection the FCC has very few things in common with the synchrotron by Edwin McMillan in 1945 (University of California). It is also not simply a bigger LEP, CERN’s flagship project of the nineties.
- It is a state-of-the-art synchrotron which pushes the technology envelope to the limit
- Given what we know about Nature today, it is the most efficient machine for the same cost by large factors, in some cases larger than 10, from machines of innovative and new technologies like the ILC and CLIC.

The circular e^+e^- collider approach

- e^+e^- colliders cannot compete with linear colliders in terms of energy. But they can compensate in terms of luminosity
- It turns out that the luminosity of a collider is directly proportional to its circumference

For the high luminosities aimed at, the beam lifetimes due to natural physics processes (mainly radiative Bhabha scattering) are of the order of a few minutes – the accelerator is 'burning' the beams up very efficiently

A "top-up" scheme (*a la* B factories) is a must

- Booster ring the same size as main ring, tops up the main ring every ~O(10s)
- Main ring does not ramp up or down

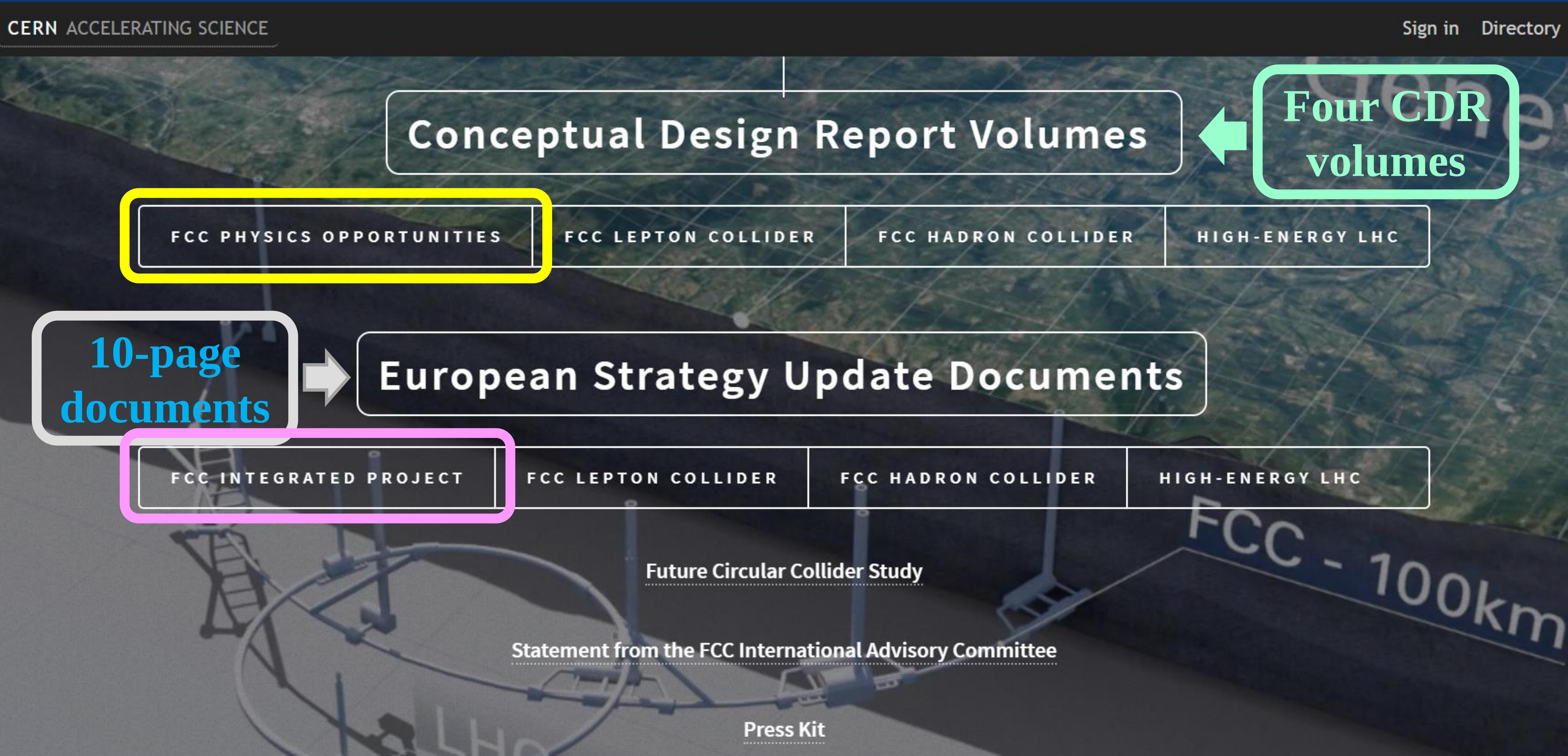
Brief history of FCC

- December 2011 (the day after the announcement of the Higgs signal): first paper by Blondel and Zimmermann
- Early pioneers:

A. Blondel F. Zimmermann M. Koratzinos J. Ellis P. Janot R. Aleksan

- 2013: CERN launches the FCC study. Project leader M. Benedikt
- Kick-off meeting: University of Geneva, Feb. 2014
- CDR released Jan 2019

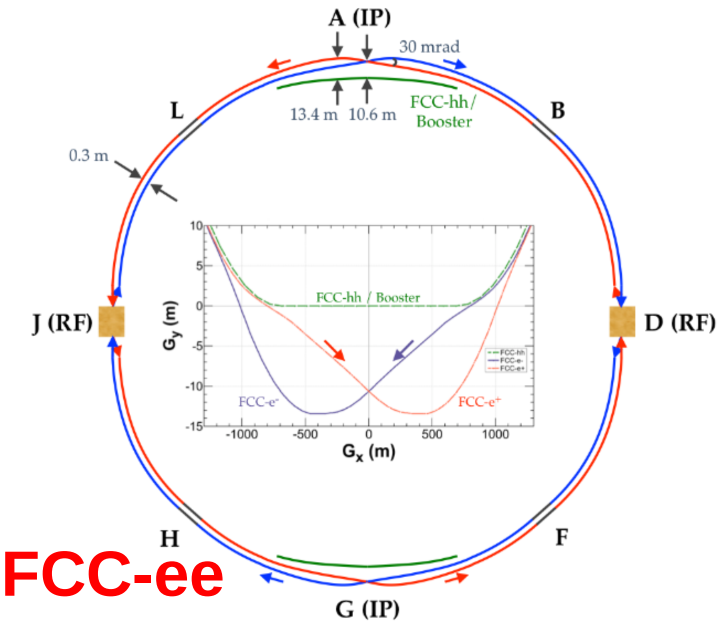
FCC study: CDR released on 15 January 2019



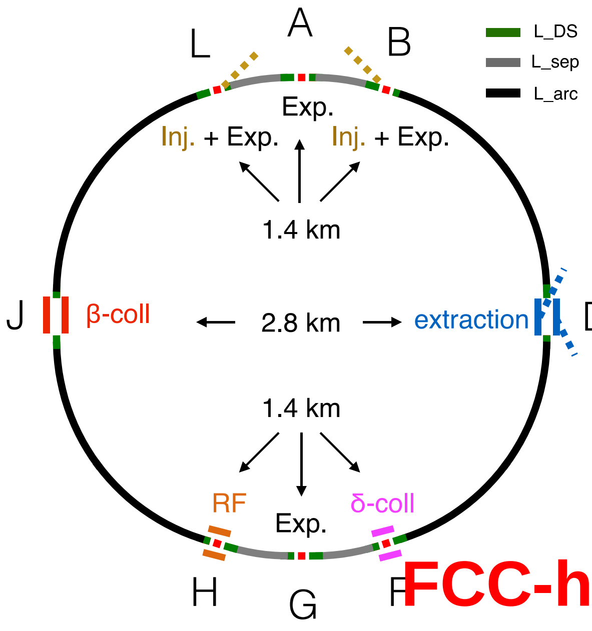
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

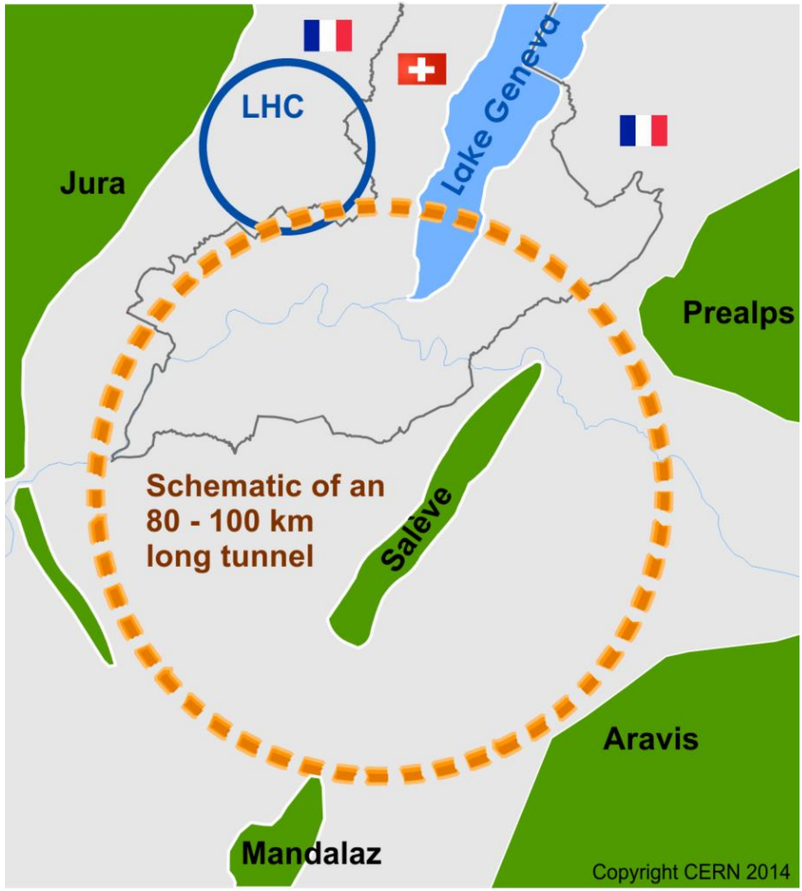
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC



FCC-ee



FCC-hh



The FCC-ee accelerator – interesting facts

The FCC-ee accelerator is not simply a bigger LEP! It is a modern synchrotron that pushes the design envelope to the maximum.

- The luminosity is so high that the beams burn up very quickly (beam lifetime 12 minutes at the ZH). Mandatory to use a full-size booster – the injector is the same size as the main ring and injects at top energy)
- Full LEP physics dataset every 2 minutes!
- Beam energy will be known to (much) better than 100keV, whereas the (gravitational) effect of the moon passing overhead gives an energy change of 100MeV, one thousand times bigger.
- The performance quoted in the CDR is not a paper exercise, it is fully backed by simulations, leading to stringent requirements: Colliding bunches must have the same charge to within 10%
- Emittance blow up in the region $\pm$2m from the IPs is equal to the emittance of the rest of the 100 kilometers – the area around the IP is very tricky and complex

Luminosity

- The number of events in a collider is given by

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

Where:
L = Luminosity
σ = cross section

so

$$N = \int L[cm^{-2}] \cdot \sigma[cm^{2}]$$

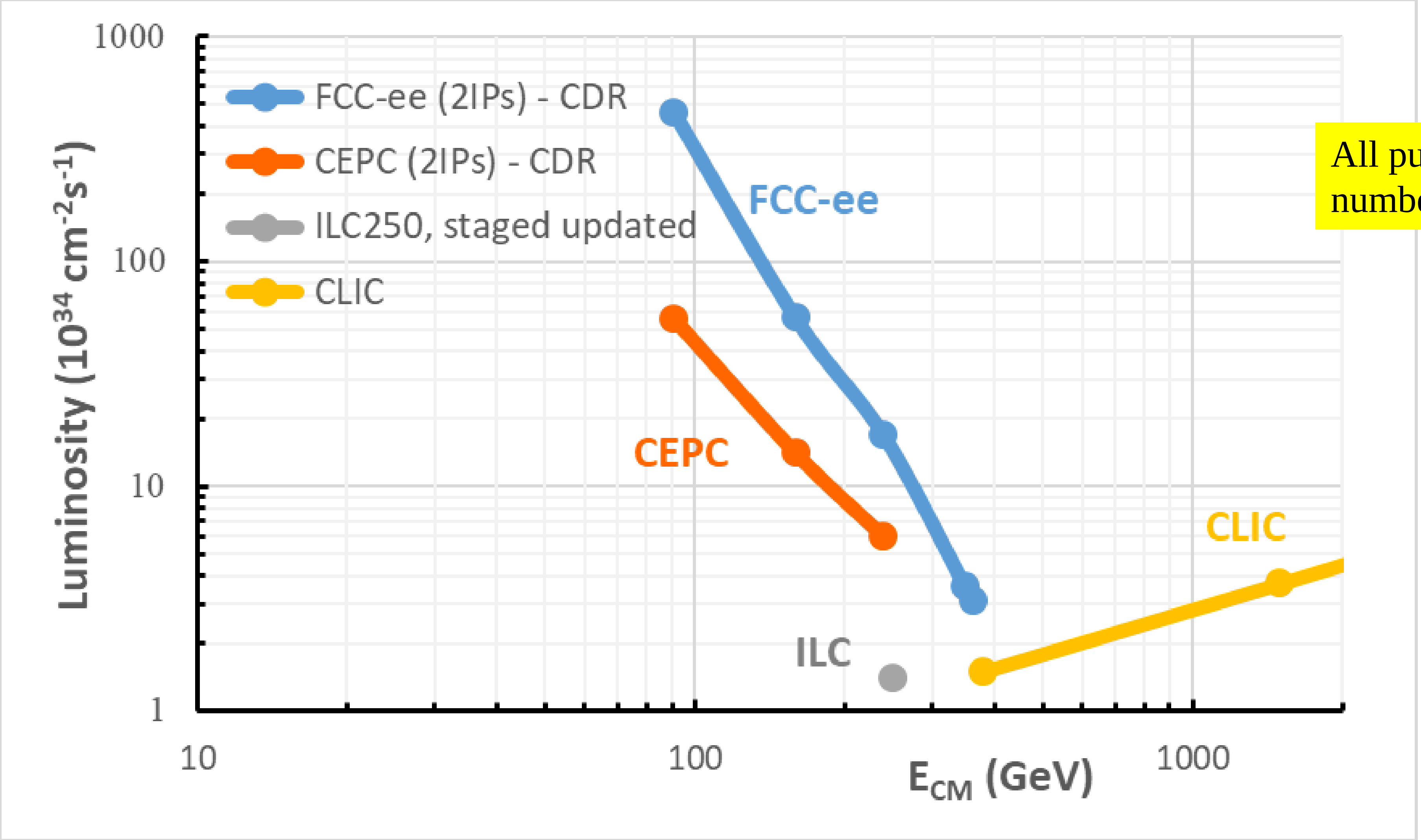
And luminosity can be defined as

$$L = \frac{N^{2} \cdot f \cdot n_{b}}{4\pi \cdot \sigma_{x} \cdot \sigma_{y}}$$

where:
N = number of particles per bunch
f = revolution frequency
n_b = number of bunches per beam
σ_x , σ_y = size of the beam at the interaction point

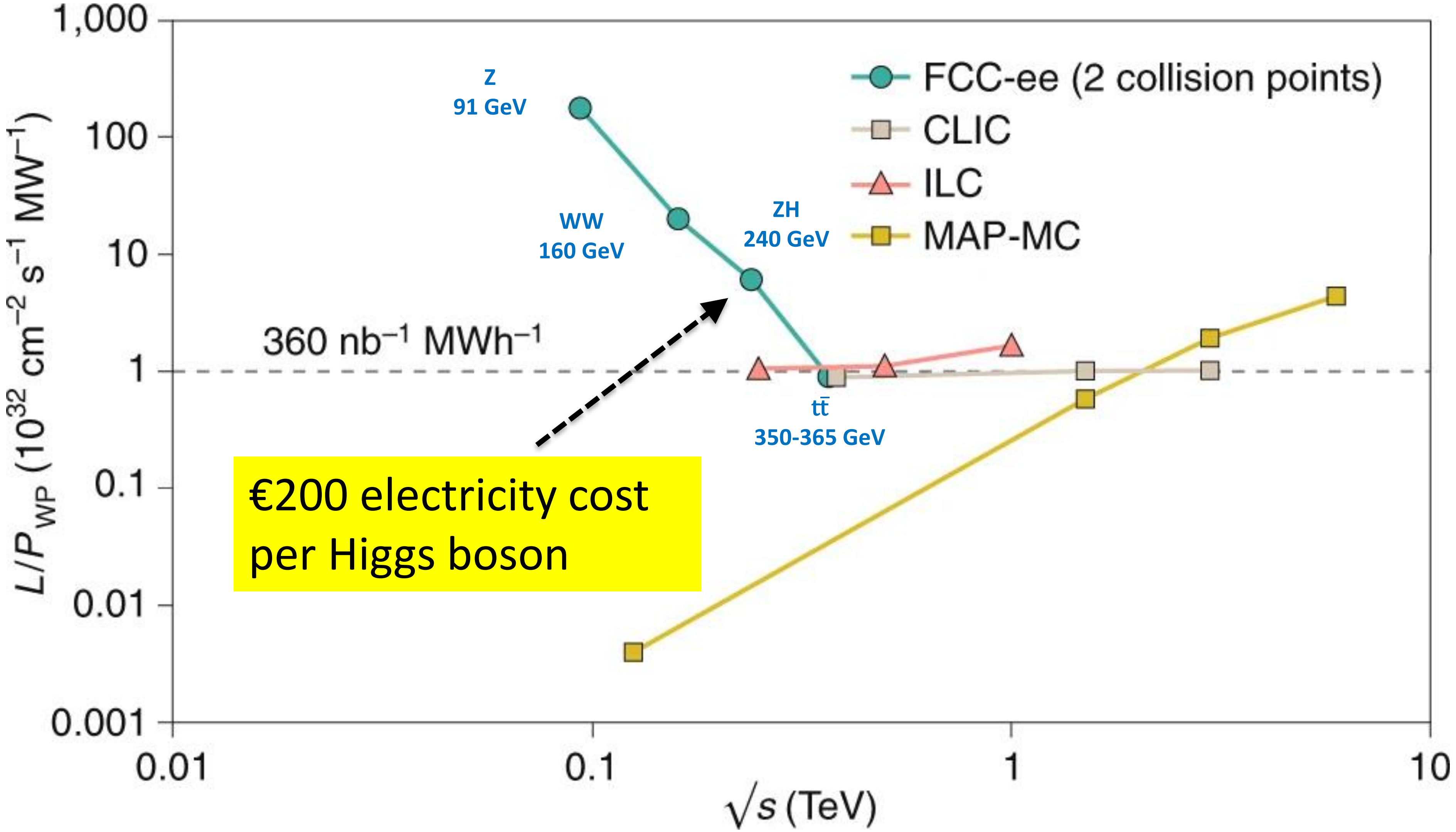
An accelerator always tries to maximize luminosity

Lepton collider luminosities - published



All published numbers

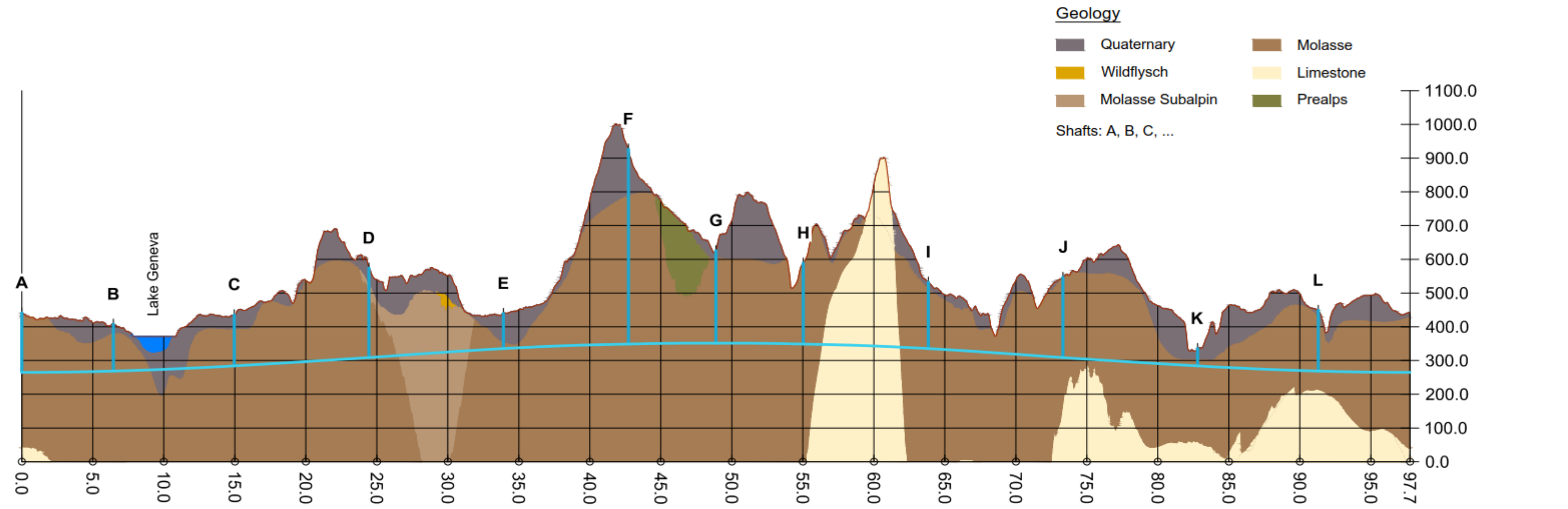
FCC-ee: efficient Higgs/electroweak factory

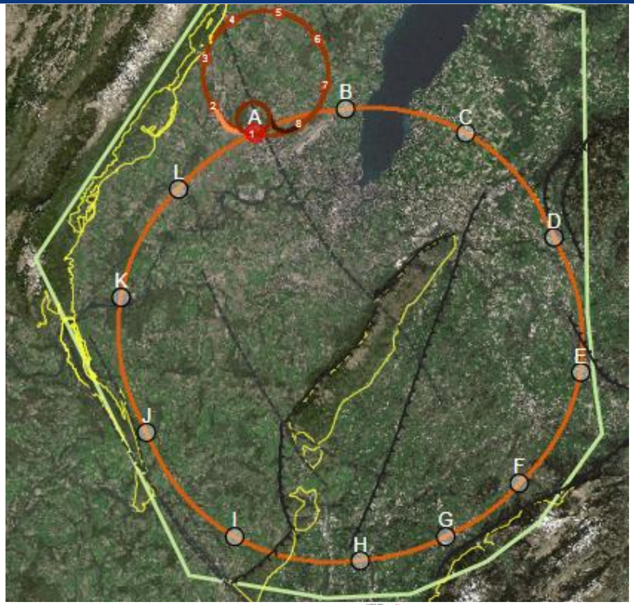


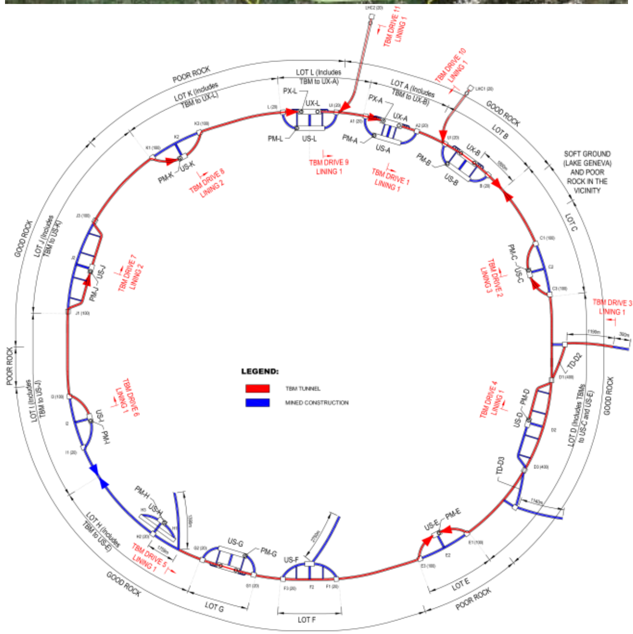
Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders.

M. Benedikt, A. Blondel, P. Janot, et al., **Nat. Phys. 16**, 402-407 (2020), and
European Strategy for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

FCC implementation - footprint baseline



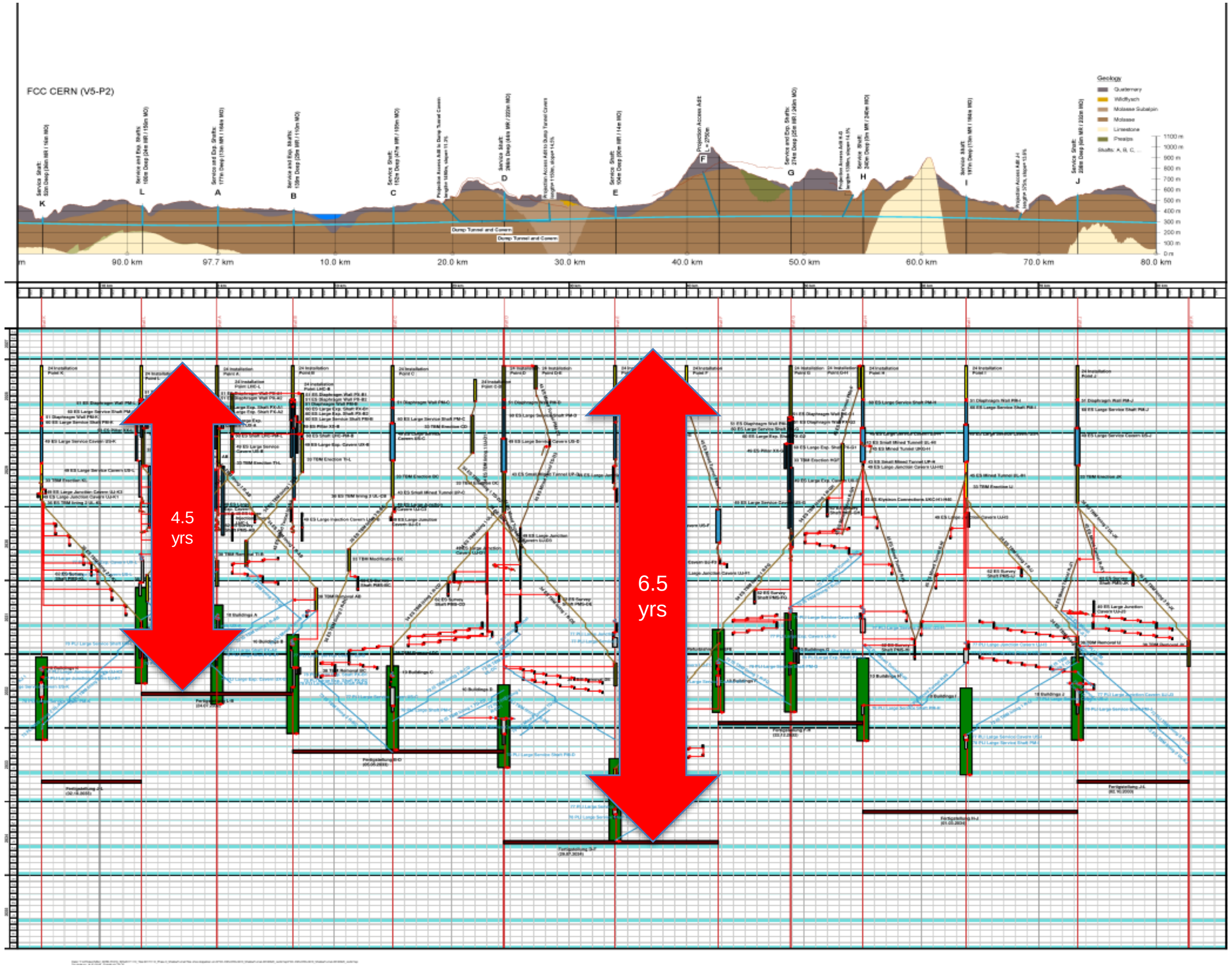


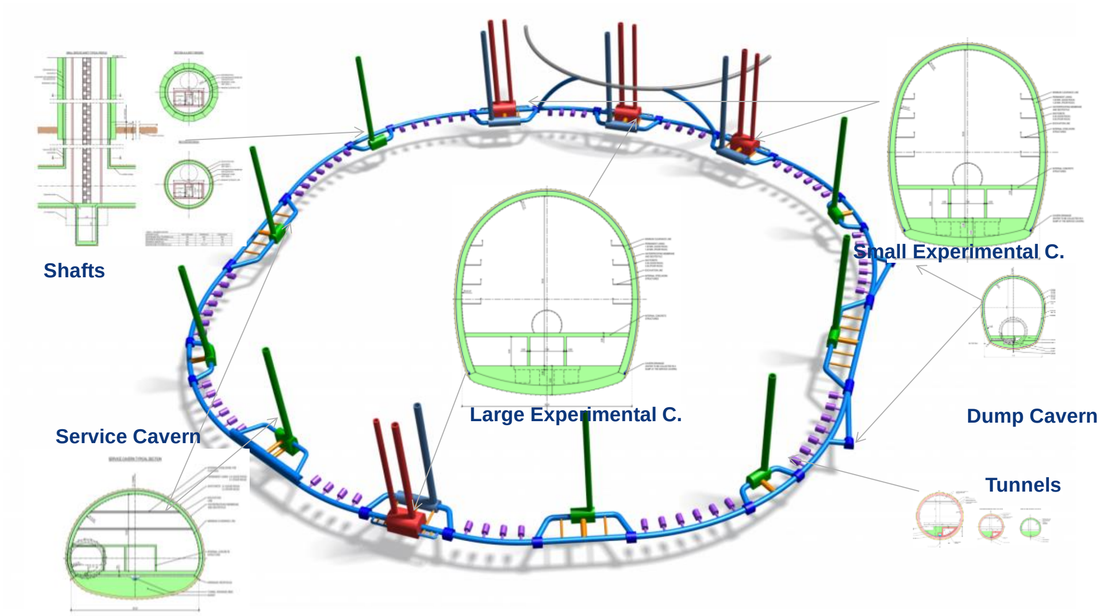


- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

- **More than 75% tunnel in France, 8 (9) / 12 access points in France.**
- **next step: review of surface site locations and machine layout**

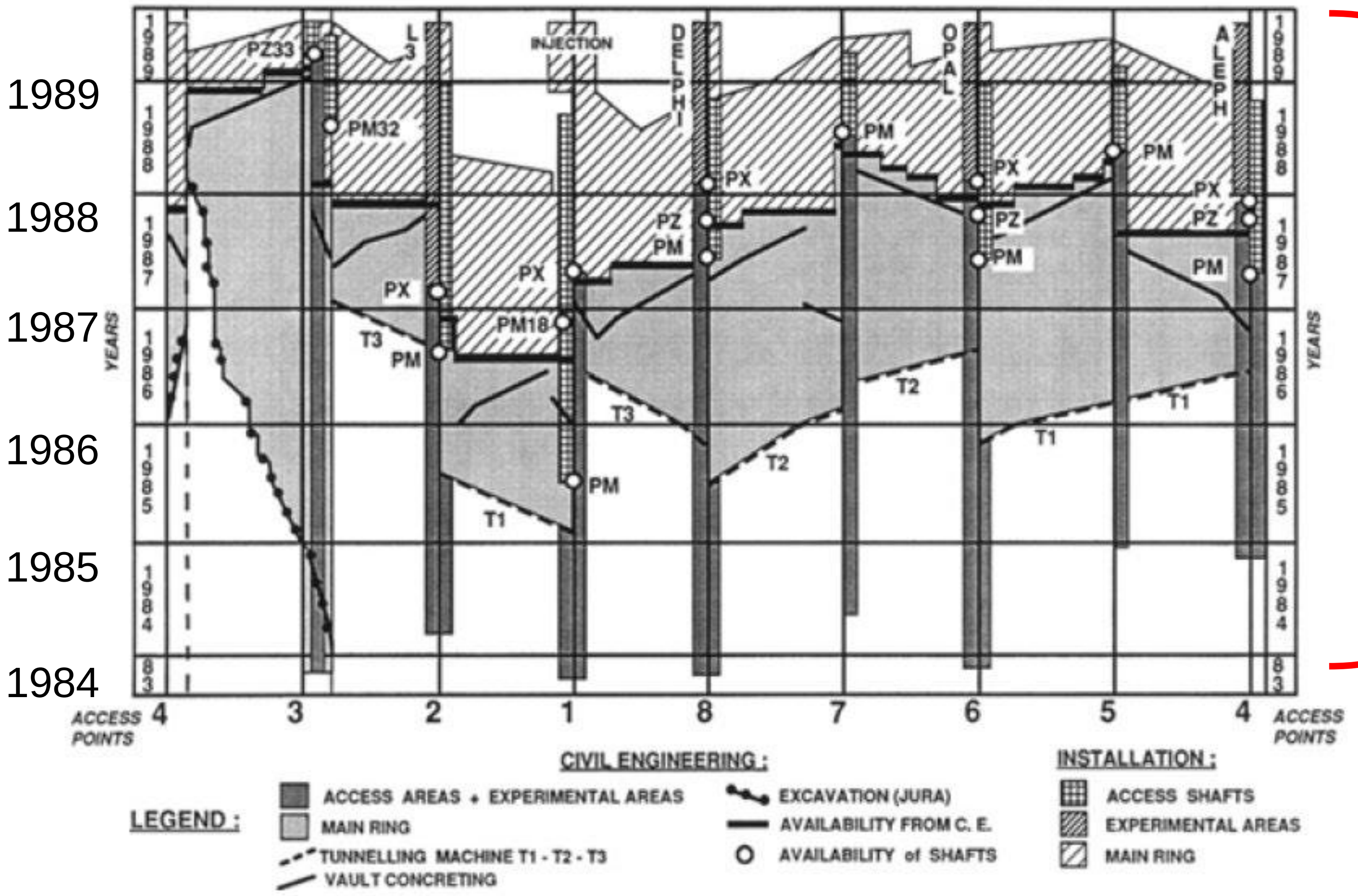
Civil Engineering studies





- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

recall the construction of LEP



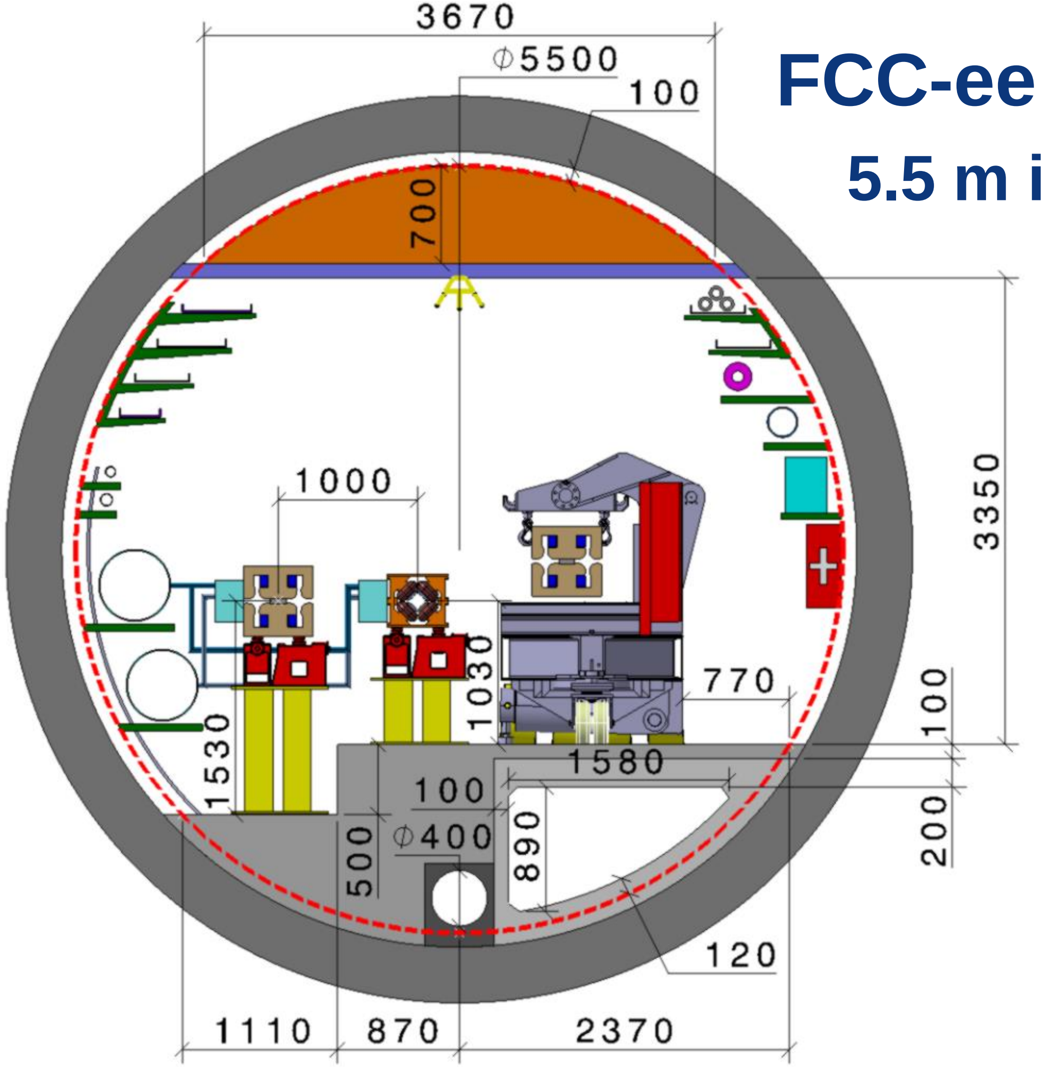
<6 years from zero to physics

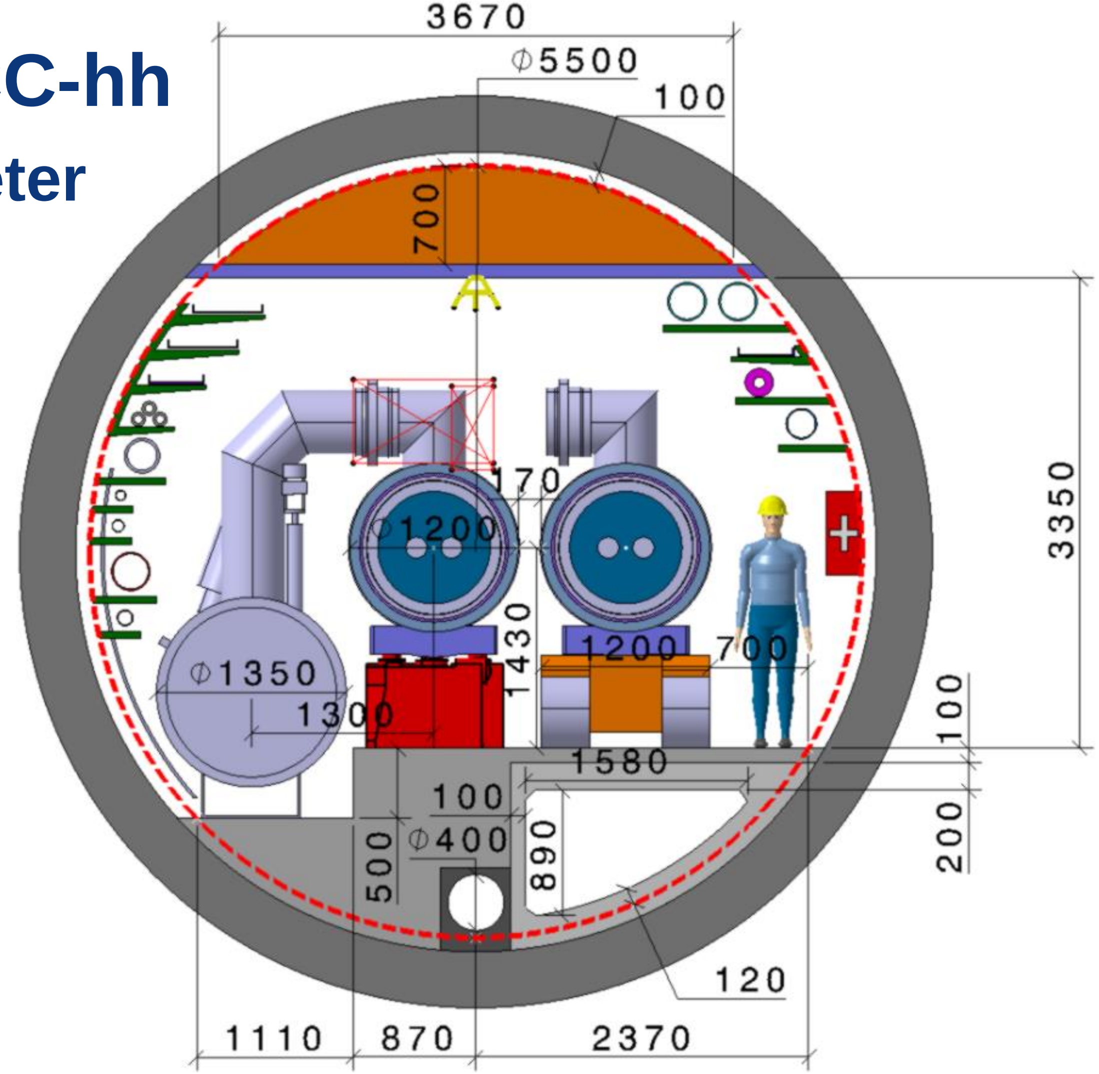
E. Picasso
H. Schopper

FCC-tunnel integration in arcs

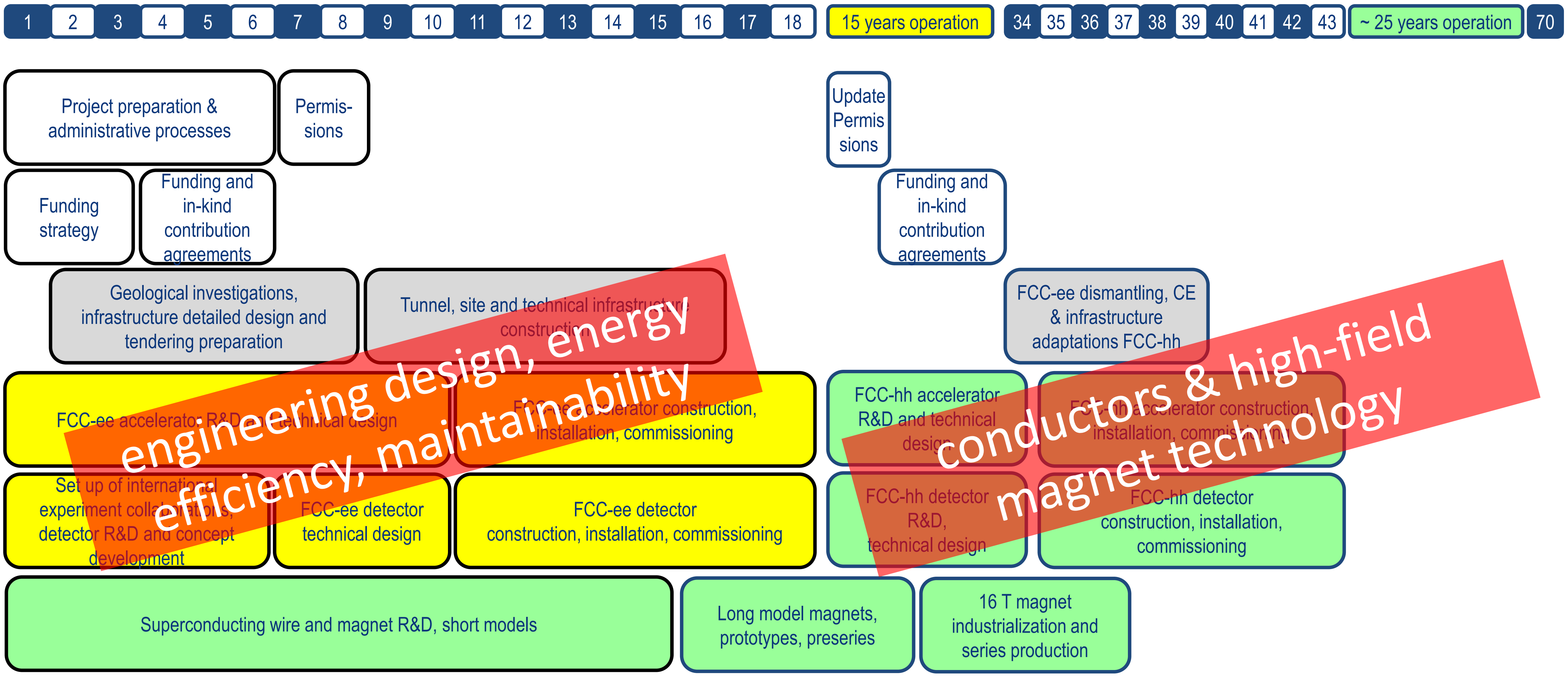
FCC-ee FCC-hh

5.5 m inner diameter





FCC integral project technical schedule



Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

139 Institutes

30 Companies

34 Countries

EC H2020

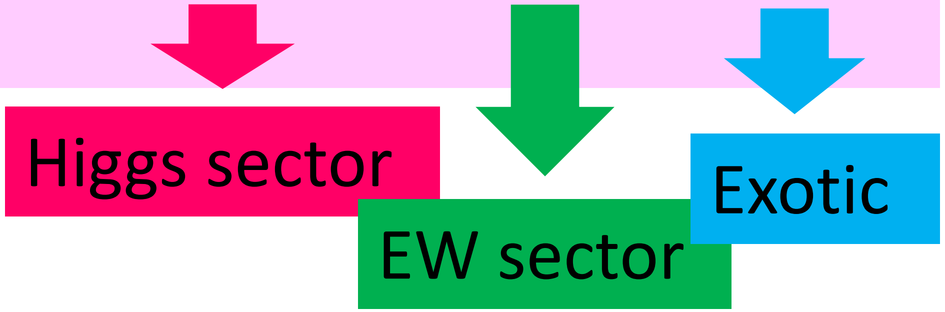
M. Koratzinos

Physics goals of FCC

- We start with (FCC-ee)
  - Higgs couplings
  - EW measurements
  - Rare decays
  - Rare processes
- We continue with (FCC-hh)
  - Direct mass reach
  - Measurements that still have insufficient precision with FCC-ee (for instance Higgs self-coupling)

Philosophy of FCC-ee:

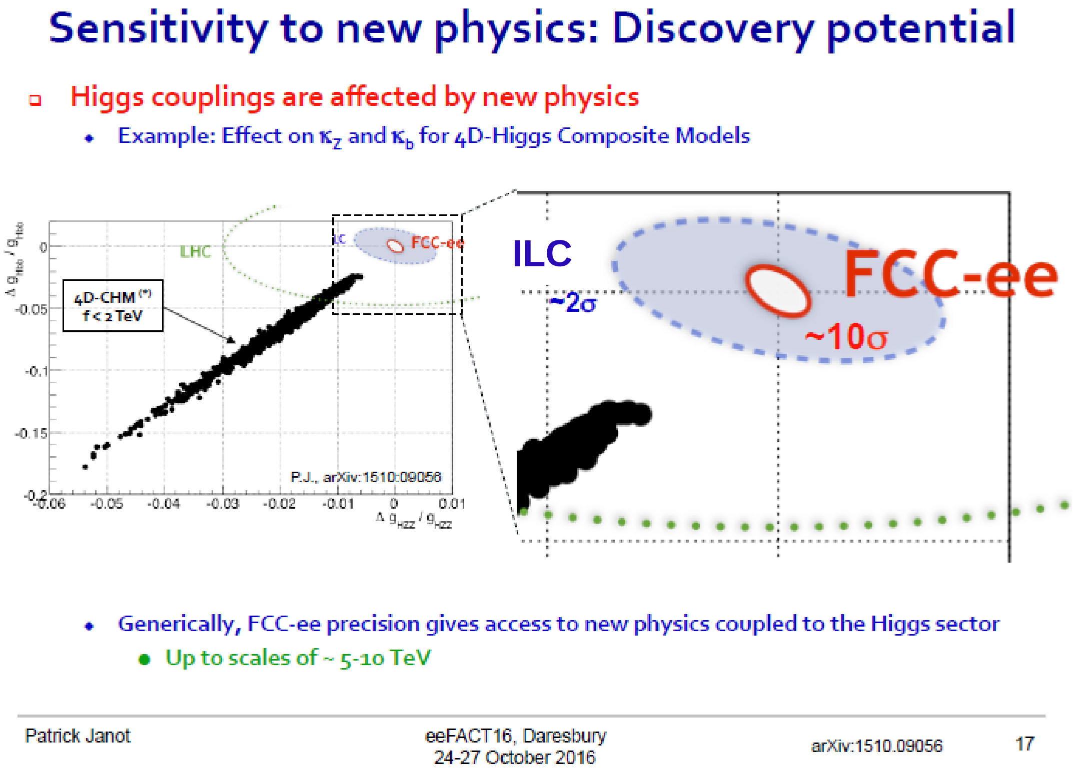
- No theory guidance, no discoveries, no easy way forward. Therefore:
- Our approach: measure, measure, measure



A note on precision

- The strategy behind all (e^+e^-) future colliders is to measure as many parameters which are sensitive to new physics as possible
- HOWEVER: we need to have a measuring power which is better than the expected signal! For example: Higgs couplings: most extensions to the standard model predict deviations from the standard model of the order of 1%. It is imperative, therefore, to build a machine that can probe these quantities to order ~0.1%

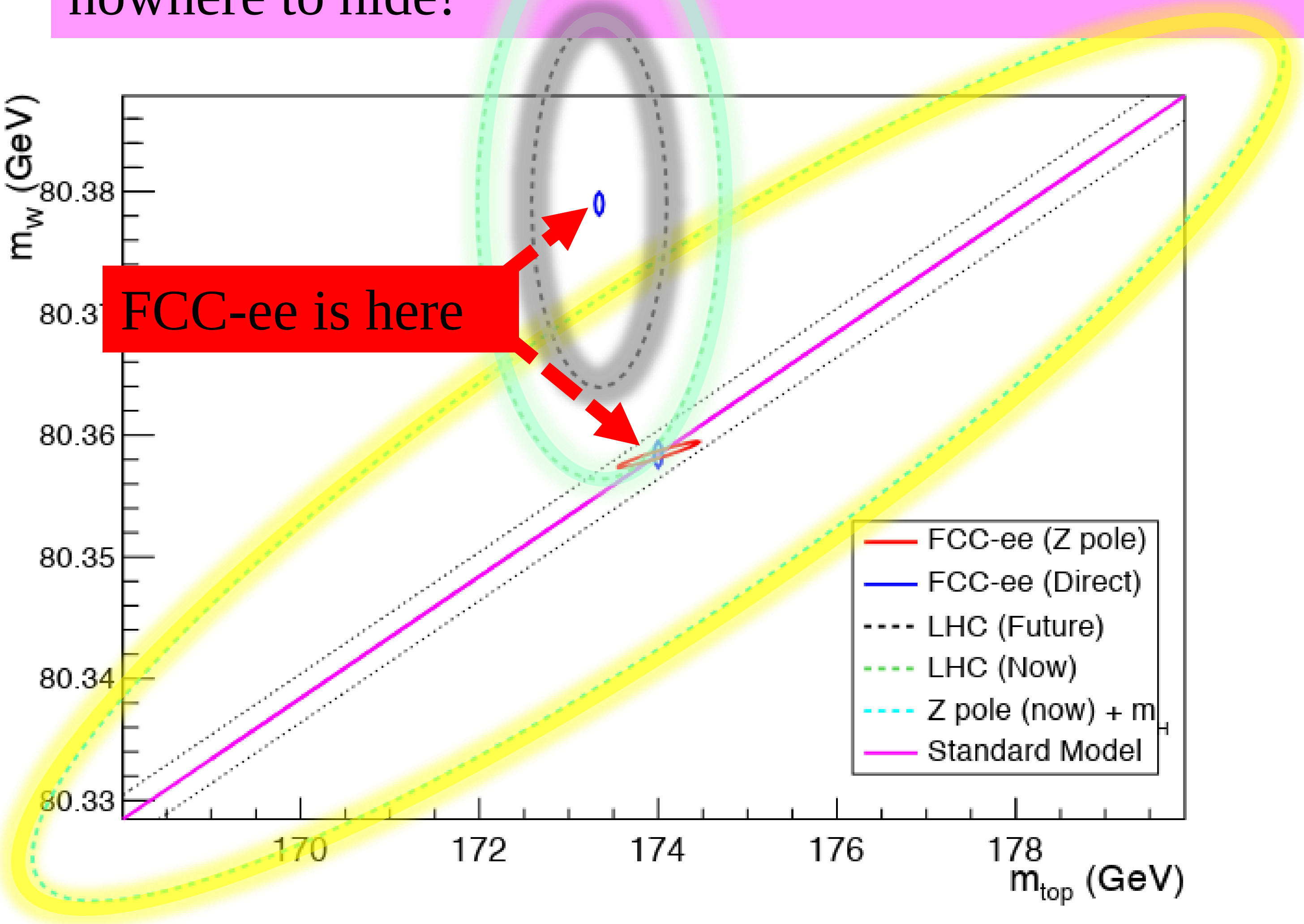
Composite Higgs models with a new physics scale limited to 2TeV



The LHC cannot distinguish between models, even if it could measure a deviation

Combination of all EW measurements

With m_{top}, m_H and m_W known, the standard model has nowhere to hide!



Effect of BSM physics is to modify EW observables through quantum effects (cf top & H @ LEP)

LEP + M_H @LHC

LHC (now)

LHC (future)

Standard model

FCC-ee direct FCC-ee Z-pole

A note on attainable precision

Example: the W mass

Prediction:

before FCC | After FCC

$$m_W = 80.3593 \pm \boxed{0.0001} (m_{top}) \pm \boxed{0.0001} (m_Z) \pm \boxed{0.0003} (\alpha_{QED})$$
$$\pm \boxed{0.0002} (\alpha_S) \quad \pm \boxed{0.0000} (m_H) \pm 0.0040 \, (\text{theo.})$$

direct measurement:

$$m_W = 80.385 \pm \boxed{0.0005}$$

If only one ingredient is missing, the sensitivity to new physics may entirely vanish

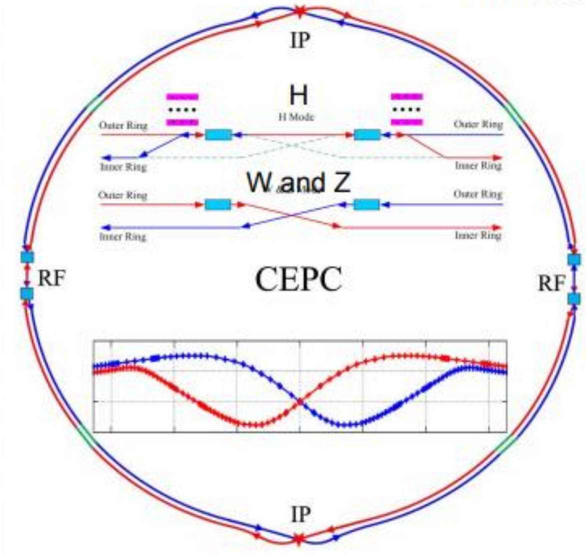
Essential to reduce theory error: necessitates calculation up to 3-4 loops. Effort has already started. 2 loop calculations finished – 3 loops started. There is good hope that the theory error can be reduced so that it does not dominate the calculations

Our “sister” project, the CEPC

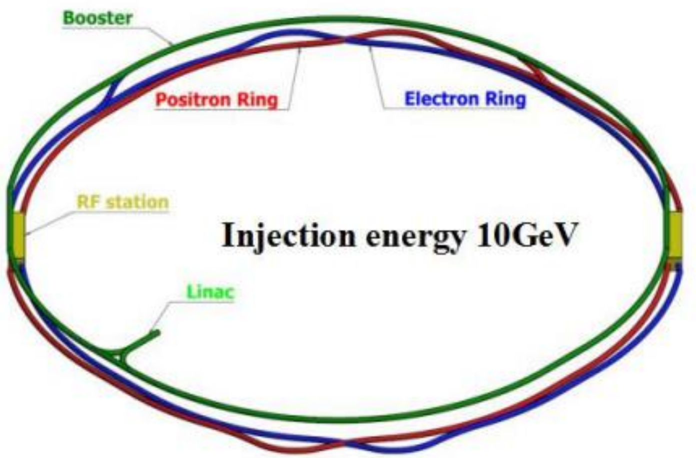
100 kms circumference, e+e- followed by pp, near-identical design, somewhere in China in the 30ies if approved

CEPC CDR Baseline Layout

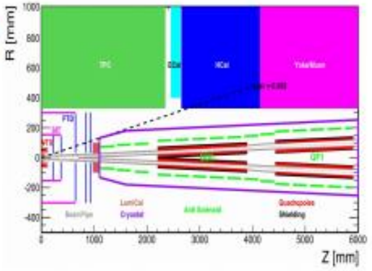
CEPC as a Higgs Factory： H, W, Z, followed by a SppC ~100TeV

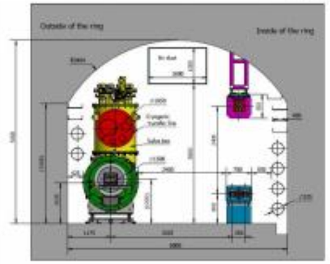


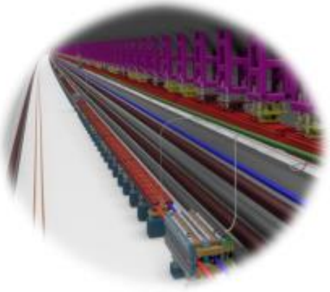
CEPC collider ring (100km)

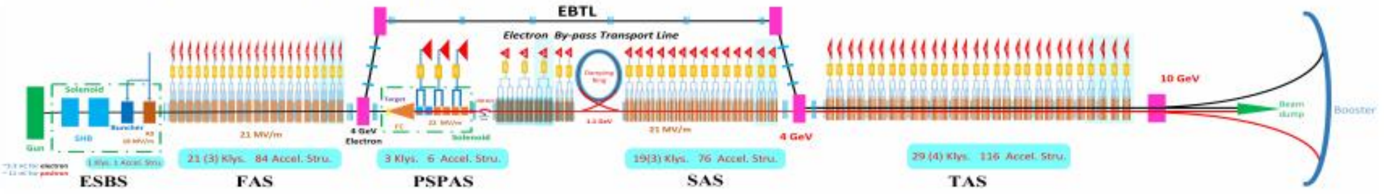


CEPC booster ring (100km)







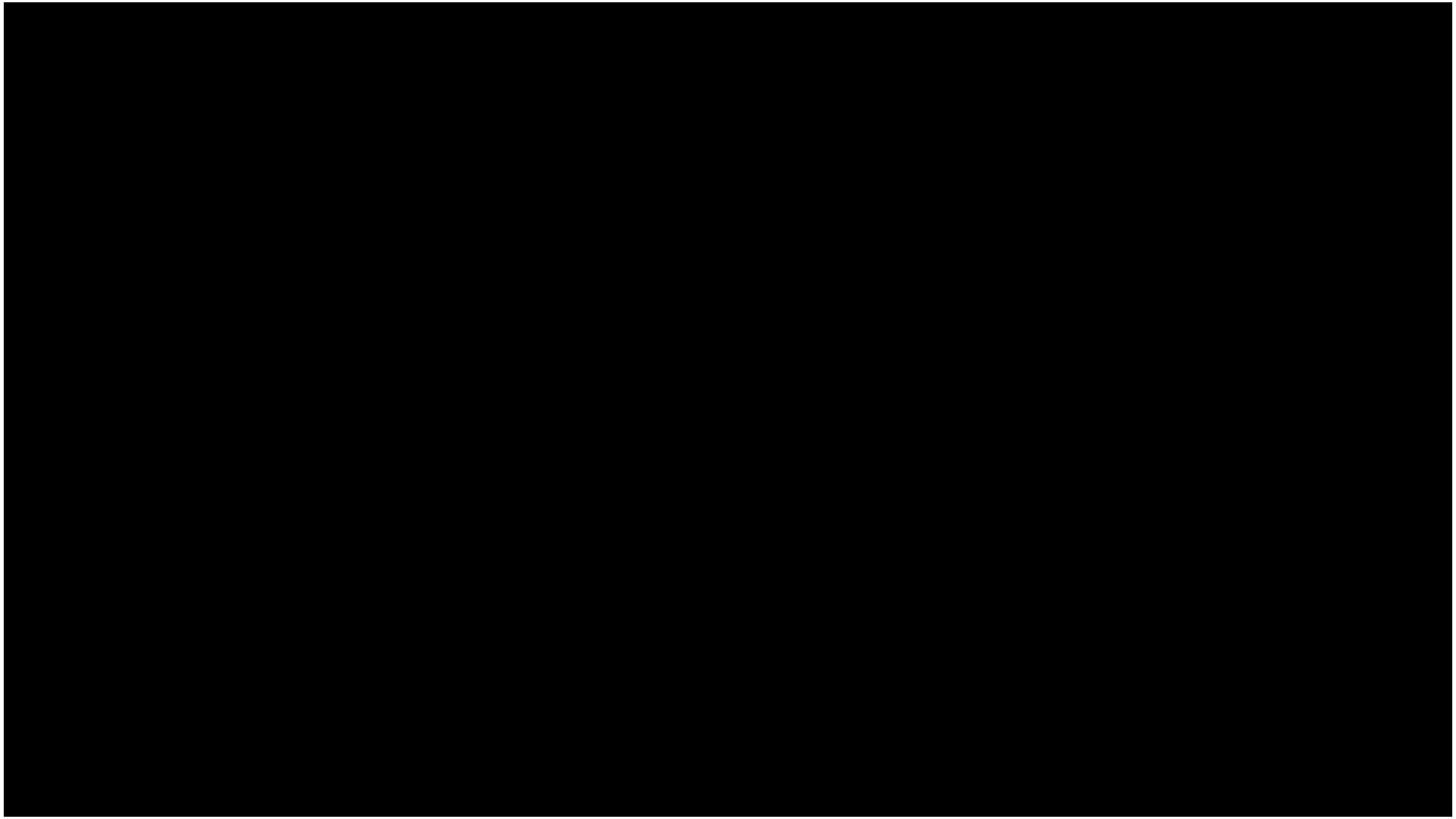


CEPC Linac injector (1.2km, 10GeV)

Summary

- The FCC is a great prospect for CERN and the world. It is a state-of-the-art accelerator in a 100 kilometre tunnel, 3.5 times larger than the LHC
- The tunnel can house an e+e- accelerator that will perform measurements with unprecedented precision followed by a proton accelerator with ~10 times more energy than the LHC
- If approved, it will shape the physics landscape for the next 50 years

FCC video clip



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