Le Futur Collisionneur du CERN FCC
l’aventure et les défis.
7 ans déjà... la découverte du boson de Higgs

Un pas de GEANT pour la Science
A collision of $4 + 4$ TeV protons (8,000,000,000,000 eV) in the ATLAS experiment at LHC produces a Higgs boson decaying into $e^+, e^-, \mu^+, \mu^-$.
Discovering (or not) the Higgs boson was the main goal of the Large Hadron Collider colliding protons of 7 + 7 TeV.

The Large Hadron Collider (LHC) was a $5'000'000'000 \text{ € (5G€)}$ construction at CERN (2000+ employees) during 15 years. LHC is in a 27km circular tunnel, built in 1983-89 (and imagined in 1976), for an electron positron collider (LEP) which ran 1989-2000 for important measurements and a big discovery (that there are only 3 families of neutrinos).
The adventure had started long before.....

Did these people know that we would be running LHC in that tunnel >60 years later?

 Did these people know that we would be running LHC in that tunnel >60 years later?

CERN 76-18
8 November 1976

ABSTRACT
This report consists of a collection of documents produced by a Study
Group on Large Electron-Positron Storage Rings (LEP). The reactions of

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, B. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

e+e- 1989-2000

62 ans

pp 2009-2038
Why was the discovery of the Higgs boson so important to particle physicists?

➔ because it represents the completion of the **Standard Model**

Is it the end?
The Standard Model

Three Generations of Matter (Fermions)

- **I**
  - Quarks: u (up), d (down)
  - Leptons: e (electron)

- **II**
  - Quarks: c (charm), s (strange)
  - Leptons: μ (muon), ν_2

- **III**
  - Quarks: t (top), b (bottom)
  - Leptons: τ (tau), ν_3

- **Bosons**
  - Z^0: 91.2 GeV
  - W^±: 80.4 GeV

- Higgs boson: 125.6 GeV

- **Masses**
  - u: 2.4 MeV
  - c: 1.27 GeV
  - t: 171.2 GeV
  - d: 4.8 MeV
  - s: 104 MeV
  - b: 4.2 GeV

- **Charge**
  - u/c/t: 2/3
  - d/s/b: 1/3

- **Spin**
  - u/c/t/d/s/b: 1/2

The Standard Model was introduced in 1997, and the Higgs boson was discovered in 2012.

Alain Blondel Futur du CERN après LHC FCC
When I started physics 46 (1973) years ago the main question was: to understand what matter was made and how it worked.

We knew matter was made of atoms (electrons and nuclei) nuclei (protons and neutrons) and there were also strange particles, muons (who ordered this?) the two neutrinos electron and muon

and there were ‘guesses’ as to how this works some of them sound pretty funny today («bootstrap», and the «Tao of Physics»)
### CONSTRUCTION of the Standard Model

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>4.8 MeV</td>
</tr>
<tr>
<td>charge</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>spin</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>name</td>
<td>up</td>
</tr>
<tr>
<td></td>
<td>$u$</td>
</tr>
<tr>
<td></td>
<td>charm</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
</tr>
<tr>
<td></td>
<td>top</td>
</tr>
<tr>
<td></td>
<td>$t$</td>
</tr>
</tbody>
</table>

#### Three Generations of Matter (Fermions)

- **I**:
  - 2.4 MeV
  - 3/2
  - 1/2
  - up
- **II**:
  - 1.27 GeV
  - 3/2
  - 1/2
  - charm
- **III**:
  - 171.2 GeV
  - 3/2
  - 1/2
  - top

#### Gauge Bosons

- **Higgs boson**: 125.6 GeV
- **Z boson**: 91.2 GeV
- **W boson**: 80.4 GeV

#### Ce qui était connu quand j’ai commencé la physique en 1973

- 1897

#### In red: at CERN

- 2012
CONSTRUCTION of the Standard Model

Three Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quark</th>
<th>Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>up</td>
<td>electron</td>
</tr>
<tr>
<td></td>
<td>down</td>
<td>μ</td>
</tr>
<tr>
<td>II</td>
<td>charm</td>
<td>τ</td>
</tr>
<tr>
<td>III</td>
<td>t</td>
<td>τ</td>
</tr>
</tbody>
</table>

- **Quarks**: u, d, s, b, c, t
- **Leptons**: e, μ, τ
- **Gauge Bosons**: Z, W^±, H

**Masses and Decades**:
- **Higgs boson**: 125.6 GeV
- **Z boson**: 91.2 GeV
- **W^± bosons**: 80.4 GeV

**Timeline**:
- 1897: Discovery of electron
- 1930-1956: Discovery of other leptons
- 1961-1970: Discovery of quarks
- 1974: Discovery of charm quark
- 2012: Discovery of Higgs boson

In red: at CERN
Depuis ~1975-80 la physique des particules est une partie intégrale de la compréhension des origines de l’Univers.
Until the middle of the XVIII\textsuperscript{th} century it was commonly assumed that the world had been created as it is, 4004 years BC.

When dinosaur bones were discovered (ca 1800) people started to realize that the world changes. Not only the living world changes (\textit{evolution of species} Lamarck, Darwin \textasciitilde1850) but the whole universe changes – it was discovered that it expands by Hubble 1929.

This discovery answered many questions, in particular why the sky is dark at night.
Extrapolating back the observed expansion of the Universe we conclude that the age of the Universe is **13.9 billion years**
We have developed a fairly good description of the evolution since the BIG BANG. This description combines the knowledge acquired on the composition of matter and the interactions between elementary particles, as well as cosmological evolution based on general relativity and astrophysics. There are however many things we do not know!
**SCALES**

**Smaller and smaller:**

<table>
<thead>
<tr>
<th>Scale</th>
<th>Measurement</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>man</td>
<td>1.8 metres</td>
<td></td>
</tr>
<tr>
<td>usual measure (vernier)</td>
<td>0.1 mm = 1/10 000 m</td>
<td>$10^{-4}$ m</td>
</tr>
<tr>
<td>microscope</td>
<td>1 micron = 1/1 000 000 m</td>
<td>$10^{-6}$ m</td>
</tr>
<tr>
<td>electronic microscope</td>
<td>1 atome = 1/10 000 000 000 m</td>
<td>$10^{-10}$ m</td>
</tr>
<tr>
<td>nuclear physics</td>
<td>1 nucleus = 1/1 000 000 000 000 m</td>
<td>$10^{-15}$ m</td>
</tr>
<tr>
<td>particle physics</td>
<td>...</td>
<td>$10^{-19}$ m</td>
</tr>
</tbody>
</table>

**More and more energetic**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy (eV)</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible light (0.6 microns)</td>
<td>2.5 electrons-volts</td>
<td></td>
</tr>
<tr>
<td>electrons in a TV tube</td>
<td>25 000 electrons-volts</td>
<td></td>
</tr>
<tr>
<td>electrons in LEP at CERN (2000)</td>
<td>100 000 000 000 electron-volts</td>
<td>= 100 GIGA eV (GeV)</td>
</tr>
<tr>
<td>protons in LHC at CERN (2016)</td>
<td>7 000 000 000 000 electron-volts</td>
<td>= 7 TERA eV (TeV)</td>
</tr>
<tr>
<td>protons in FCC</td>
<td>50-70 TeV</td>
<td></td>
</tr>
</tbody>
</table>

**Closer and closer to the origin of the UNIVERSE**

$10^{-19}$ m = 1 TeV = energy per particle = $10^{-11}$ seconds after the **BIG BANG**

1 calorie = $2.6 \times 10^{19}$ eV
Why was the discovery of the Higgs boson so important to particle physicists?

➔ because it represents the completion of the **Standard Model**

Is it the end?
Is there a future for CERN after the LHC and the discovery of the Higgs boson?
With the Higgs Boson, the Standard Model is a complete coherent and predictive theory of particles and their interactions.

Are we done?

NO!

We are certain that exist other particles and/or phenomena!
We cannot explain:

**Dark matter**

Standard Model particles constitute only 5% of the energy in the Universe

**Were is antimatter gone?**

**What makes neutrino masses?**

- Not a unique solution in the SM --
- Dirac masses (why so small?)
- Majorana masses (why not Dirac?)
- Both (the preferred scenarios, see-saw...)
- → heavy right handed neutrinos?
The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this:  

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald “for the discovery of neutrino oscillations, which shows that neutrinos have mass”
fermion masses

(large angle MSW)

$\nu_1 \cdots \nu_2 \cdots \nu_3$

d $\cdots$ s $\cdots$ b

u $\cdots$ c $\cdots$ t

e $\cdots$ $\mu$ $\cdots$ $\tau$

MeV keV eV mV NeV

$10^{12-14}$
Certainly not!

-- Dark matter
-- Baryon Asymmetry in Universe
-- Neutrino masses

are experimental proofs that there is more to understand.

We must continue our quest

HOW?

Direct observation of new particles (but not only!)

New phenomena (Neutral currents, CP violation, neutrino oscillations...)

Deviations from precise predictions

(ref. Uranus to Neptune, top and Higgs preds from LEP/SLC/Tevatron/B factories, g-2, etc...)
Il faut un programme d’exploration très vaste

-- comment se comporte exactement le boson de Higgs (e+e- + pp)

-- y a-t-il des nouvelles particules que l’on pourrait voir par leur effet indirect sur les particules connues?

mesures de précision (Z,W,\text{top}) (\ 10^{-3} \rightarrow 10^{-5} \rightarrow 10^{-6} ) e+e-

-- y a-t-il des nouvelles particules au-delà du LHC haute énergie (LHC 14 TeV \rightarrow pp 100-150 TeV)

-- ou des nouvelles particules légères intéragissant très peu? haute sensibilité (e+e-, pp)
At higher masses -- or at smaller couplings?
The Future Circular Colliders
The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the Genevois

- **Ultimate goal**: ~16 T magnets
  100 TeV pp-collider (FCC-\textit{hh})

→ defining infrastructure requirements

**First steps:**
- \(e^+e^-\) collider (FCC-\textit{ee})
  High Lumi, \(E_{CM} = 90-400\) GeV

Possible addition:
- \(p-e\) (FCC-\textit{he}) option

From European Strategy in 2013: “ambitious post-LHC accelerator project”
Study kicked-off in Geneva Feb 2014

From what we know today: the way by FCC-\textit{ee} is probably the fastest and cheapest way to 100 TeV. That combination also produces the most physics. It is the assumption in the following.

also a good start for \(\mu\)C!
Alain Blondel
Futur du CERN après LHC FCC
27.09.2019
Alain Blondel FCC CDR
presentation Outlook
The Global FCC Collaboration

- 133 Institutes
- 34 Countries
- 25 Companies

EC H2020
Present baseline position was established considering:
- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

next step: review of surface site locations and machine layout
FCC – tunnel integration in arcs

FCC-ee
FCC-hh
5.5 m inner diameter
common layouts for hh & ee

2 main IPs in A, G for both machines

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to exp
Great energy range for the heavy particles of the Standard Model.

Event statistics:

- **Z peak**
  - \(E_{\text{cm}} : 91 \text{ GeV}\)
  - \(5 \times 10^{12}\) e+e- → Z

- **WW threshold**
  - \(E_{\text{cm}} : 161 \text{ GeV}\)
  - \(10^8\) e+e- → WW

- **ZH threshold**
  - \(E_{\text{cm}} : 240 \text{ GeV}\)
  - \(10^6\) e+e- → ZH

- **tt threshold**
  - \(E_{\text{cm}} : 350 \text{ GeV}\)
  - \(10^6\) e+e- → tt

**E_{\text{cm}} errors:**

- LEP x \(10^5\)
  - 100 keV
  - 300 keV

- LEP x \(2.10^3\)
  - 2 MeV
  - Never done

- Never done
  - 5 MeV
The same caverns

Distance between detector cavern and service cavern 50 m.

FCC-ee detector

FCC-hh detector

Preliminary design of access and cable path
SRF cavity development program (examples)

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh ERL (PERLE)

Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL

CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

High strain rate technology using shockwaves in water from HV discharge. EHF investigated for half-cells and seamless Nb and Cu cavities.

† We’re saddened about the sudden death of Vincenzo Palmieri few weeks ago.

Q_c = 3 \cdot 10^{16} @ 2K

Regime of \( E_{\text{acc}} \) requirements in LHeC, PERLE, FCC-ee

31 MV/m quench limit
Low-power low-cost design for FCC-ee magnets

Twin-dipole design with $2 \times$ power saving
16 MW (at 175 GeV), with Al busbars

Twin F/D quad design with $2 \times$ power saving
25 MW (at 175 GeV), with Cu conductor

first 1 m prototype
FCC-ee arc vacuum prototyping & integration

Vacuum chamber cross section:
70 mm ID with "winglets" in the plane of the orbit (SuperKEKB-like);

- The chambers feature lumped SR absorbers with NEG-pumps placed next to them.
- Construction of chamber prototypes in coming months and integration with twin magnets.
16 T dipole design activities and options

Cos-theta
H2020
EuroCirCol
A key to New Physics

Common coils
Swiss contribution

Canted Cos-theta

INFN
CEA
CIEMAT
PSI
LBNL
FNAL

Short model magnets (1.5 m lengths) will be built from 2018 – 2022
Russian 16 T magnet program launched by BINP recently.
Additional 200 MW available for FCC at each of the three 400 kV sources.

Per-point power requirements as input for infrastructure-optimized conceptual design. (Peak FCC-ee 260 - 340 MW, total FCC-hh 550 MW)

If one power source goes down fall back to "degraded mode": FCC remains cold, vacuum preserved, controls on, RF off, no beam ("standby"). All FCC points supplied from 2 other 400 kV points, through the power transmission line.
## FCC-ee el. power consumption [MW]

<table>
<thead>
<tr>
<th>Beam energy (GeV)</th>
<th>45.6 Z</th>
<th>80 W</th>
<th>120 ZH</th>
<th>182.5 ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF (SR = 100)</td>
<td>163</td>
<td>163</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Collider cryo</td>
<td>1</td>
<td>9</td>
<td>14</td>
<td>46</td>
</tr>
<tr>
<td>Collider magnets</td>
<td>4</td>
<td>12</td>
<td>26</td>
<td>60</td>
</tr>
<tr>
<td>Booster RF &amp; cryo</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Booster magnets</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Pre injector</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Physics detector</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Data center</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cooling &amp; ventilation</td>
<td>30</td>
<td>31</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>General services</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>259</strong></td>
<td><strong>278</strong></td>
<td><strong>282</strong></td>
<td><strong>359</strong></td>
</tr>
</tbody>
</table>
FCC-ee: a sustainable accelerator

luminosity per wall plug power \([10^{34} \text{ cm}^{-2}\text{s}^{-1} / 100 \text{ MW}]\)

twin-aperture arc magnets, thin-film SRF, efficient RF power sources, top-up injection

electricity cost \(~260\) euro per Higgs boson

Zimmermann
integrated luminosity per construction cost

for the H running, with $5 \text{ ab}^{-1}$ accumulated over 3 years, the total investment cost corresponds to $10 \text{ kCHF per produced Higgs boson}$

for the Z running with $150 \text{ ab}^{-1}$ accumulated over 4 years the total capital investment cost corresponds to $10 \text{ kCHF per } 5 \times 10^6 \text{ Z bosons}$

= the number of Z bosons collected by each experiment during the entire LEP programme!

construction cost per luminosity dramatically decreased compared with LEP!
un accord a été signé entre la France et la Suisse pour l’étude du projet
FCC integrated project timeline

- Project preparation & administrative processes
- Permissions
- Funding strategy
- Funding and in-kind contribution agreements
- Geological investigations, infrastructure detailed design and tendering preparation
- Tunnel, site and technical infrastructure construction
- Superconducting wire and magnet R&D
- FCC-ee accelerator R&D and technical design
- FCC-ee detector technical design
- Set up of international experiment collaborations, detector R&D and concept development
- FCC-ee detector construction, installation, commissioning
- FCC-ee accelerator construction, installation, commissioning
- SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
- 16 T dipole magnet series production
- FCC-ee dismantling, CE & infrastructure adaptations FCC-hh
- FCC-hh accelerator R&D and technical design
- FCC-hh accelerator construction, installation, commissioning
- FCC-hh detector R&D, technical design
- FCC-hh detector construction, installation, commissioning

Update Permissions
- Funding and in-kind contribution agreements

FCC-ee detector technical design

FCC-ee accelerator R&D and technical design

FCC-ee detector construction, installation, commissioning

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator construction, installation, commissioning

FCC-hh detector construction, installation, commissioning

ESPP

work is cut out for physics and detectors

70 years seems like a long time!
Did these people know that we would be running HL-LHC in that tunnel >60 years later?

Let’s not be SHY!

e+e- 1989-2000

p p 2009-2038
les défis

1. Autorisations couts etc...
2. Le tunnel
3. La technologie d’accélérateurs
   -- e+e- : $2 \times 10^5$ fois plus de lumière que LEP!
   -- pp    aimants 16 – 24 Tesla
4. l’efficacité énergétique (300 – 500 MW)
   en particulier pour la machine à électrons
5. la technologie de détecteurs
   -- e+e- : précision!
   -- pp    : haute énergie, empilement!
6. défi théorique précision des prédictions
7. des collaborations scientifiques
   de plusieurs milliers de personnes

8. La connaissance humaine n’a pas de prix!

Alain Blondel  Futur du CERN après LHC  FCC
CONCLUSIONS

-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology. The CDR is on its way.

-- Both FCC-ee and FCC-hh have outstanding physics cases
  -- each in their own right
  -- the sequential implementation of FCC-ee, FCC-hh, FCC-eh maximises the physics reach.

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

FCC (ee) could start seamlessly at the end of HL-LHC (~2038)
A powerful program of development for 16+ T magnets will be required to reach 100 TeV.
Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
  \( m_Z, m_W, m_{\text{top}}, \sin^2 \theta_w^{\text{eff}}, R_b, \alpha_{\text{QED}} (m_z), \alpha_s (m_z, m_W, m_\tau) \), Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC \((Z \rightarrow \mu\tau, e\tau)\) in \(5 \times 10^{12}\) Z decays and \(\tau\) BR in \(2 \times 10^{11}\) \(Z \rightarrow \tau\tau\)
  + flavour physics \((10^{12} \text{bb events})\) \((B \rightarrow s\tau\tau\) etc..\)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
  such as: Right-Handed neutrinos, Dark Photons etc...

+ an enormous amount of clean, unambiguous work on QCD \((H \rightarrow gg)\) etc....

NB Not only a «Higgs Factory», «Z factory» and «top» are important for ‘discovery potential’

“First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164
FCC-hh discovery potential
Highlights

**FCC-hh is a HUGE discovery machine (if nature ...), but not only.**

FCC-hh physics is dominated by three features:

-- **Highest center of mass energy** → a big step in high mass reach!

  - ex: strongly coupled new particle up to >30 TeV
  - Excited quarks, Z’, W’, up to ~tens of TeV
  - Give the final word on natural Supersymmetry, extra Higgs etc. reach up to 5-20 TeV
  - Sensitivity to high energy phenomena in e.g. WW scattering

-- **HUGE production rates** for single and multiple production of SM bosons (H,W,Z) and quarks

  -- **Higgs precision tests** using ratios to e.g. $\gamma/\mu\mu / \tau\tau/ZZ$, $ttH/ttZ @$<% level
  -- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
  -- detection of rare decays $H \rightarrow V\gamma$ ($V=\rho,\phi,J/\psi,\gamma,Z...$)
  -- **search for invisibles** (DM searches, RH neutrinos in W decays)
  -- renewed interest for long lived (very weakly coupled) particles.
  -- rich top and HF physics program

-- **Cleaner signals for high Pt physics**

  -- allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)