CERN’s scientific programme

- Introduction
- The LHC and its upgrades
- The scientific diversity programme
- Studies for future accelerators and other projects
- Conclusions

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With the discovery of the Higgs boson, we have completed the Standard Model (> 50 years of theoretical and experimental efforts!)

However: the SM is not a complete theory of particle physics, as several outstanding questions remain (raised also by precise experimental observations) that cannot be explained within the SM.

These questions require NEW PHYSICS
Main questions in today’s particle physics (a non-exhaustive list ..)

- Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem)?
- What is the origin of the matter-antimatter asymmetry in the Universe?
- Why 3 fermion families? Why do neutral leptons, charged leptons and quarks behave differently?
- What is the origin of neutrino masses and oscillations?
- What is the composition of dark matter (~25% of the Universe)?
- What is the cause of the Universe’s accelerated expansion (today: dark energy? primordial: inflation?)
- Why is Gravity so weak?

However: there is NO direct evidence for new particles (yet…) from the LHC or other facilities

Where is New Physics sitting in terms of E-scale and couplings ???
The outstanding questions are compelling, difficult and interrelated → can only be successfully addressed through a variety of approaches (thanks also to strong advances in accelerator and detector technologies): particle colliders, neutrino experiments, cosmic surveys, dark matter direct and indirect searches, measurements of rare processes, dedicated searches (e.g. axions, dark-sector particles).

Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of $E$ scales and couplings, and to properly interpret signs of new physics → with the goal to build a coherent picture of the underlying theory.
3 main complementary ways to search for (and study) new physics at accelerators

**Direct**
- production of a given (new or known) particle
  - e.g.: Higgs production at future $e^+e^-$ linear/circular colliders at $\sqrt{s} \sim 250$ GeV through the HZ process
  - $\rightarrow$ need high $E$ and high $L$

**Indirect**
- precise measurements of known processes
  - $\rightarrow$ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
  - $\rightarrow$ sensitivities to $E$-scales $\Lambda \gg \sqrt{s}$ $\rightarrow$ need high $E$ and high $L$

**Rare processes**
- suppressed in SM $\rightarrow$ could be enhanced by New Physics
  - e.g. neutrino interactions, rare decay modes $\rightarrow$ need intense beams, ultra-sensitive (massive) detectors (“intensity frontier”)

- E.g. transitions between charged leptons of different families with Lepton-Flavour-Violation: $\mu \rightarrow e\gamma$ (MEG@PSI), $\mu \rightarrow e$ (COMET@JPARC, Mu2e@FNAL). Suppressed in SM, can occur if new physics
  - Note: flavour violation observed for $\nu$ (e.g. $\nu_\mu \rightarrow \nu_e$) and quarks (e.g. $t \rightarrow Wb$)
Full exploitation of the LHC:
- successful operation of the nominal LHC (Run 2, LS2, Run 3)
- construction and installation of LHC upgrades: LIU (LHC Injectors Upgrade) and HL-LHC
Note: expect to move to 14 TeV operation in Run 3. Currently also exploring the possibility to achieve “ultimate” energy of 15 TeV in Run4++

Scientific diversity programme serving a broad community:
- current experiments and facilities at Booster, PS, SPS and their upgrades (Antiproton Decelerator/ELENA, ISOLDE/HIE-ISOLDE, etc.)
- participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through CERN Neutrino Platform

Preparation of CERN’s future:
- vibrant accelerator R&D programme exploiting CERN’s strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- design studies for future accelerators: CLIC, FCC (includes HE-LHC)
- future opportunities of scientific diversity programme (“Physics Beyond Colliders” Study Group)

Important milestone: update of the European Strategy for Particle Physics (ESPP), to be concluded in May 2020
LHC and its upgrades

→ See also lectures by N. Pastrone
Since then: huge progress

Outstanding performance of the LHC since the beginning

- Run 1: 2010-2013: $\sqrt{s} = 7$-8 TeV, $\sim 30$ fb$^{-1}$ to ATLAS and CMS → Higgs boson discovery
- Run 2: 2015-2018: $\sqrt{s} = 13$ TeV
  - peak luminosity so far: $\sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ → x 2 higher than nominal value
  - integrated luminosity: $\sim 115$ fb$^{-1}$ ATLAS and CMS, $\sim 5$ fb$^{-1}$ LHCb, $\sim 47$ pb$^{-1}$ ALICE

$L = \frac{N^2 k_b f}{4}$

$N = \int L dt \times \sigma$

Detectors and computing also performing very well in spite of challenging conditions (pile-up up to $\sim 60$ events/x-ing, huge amount of data, etc.)
Excellent progress on Higgs boson studies

Higgs boson discovered and now well measured in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{*} \rightarrow 4l$, $H \rightarrow WW^{*} \rightarrow l\nu l\nu$ channels (small branching ratios but clean final states)

Decays and couplings to 3rd generation fermions ($H \rightarrow bb$, $H \rightarrow \tau\tau$, $Htt$ production) experimentally more difficult as affected by huge backgrounds

Couplings to 2nd generation fermions (through rare $H \rightarrow \mu\mu$ decay) will only be accessible at HL-LHC
Higgs couplings to 3rd generation fermions well established recently.

$H \rightarrow \tau\tau$

5.9 $\sigma$ (5.9 expected) 
$\mu = 1.1 \pm 0.3$

$W/Z \rightarrow$ leptons $H \rightarrow bb$

3.5 $\sigma$ (3.0 expected) 
$\mu = 0.9 \pm 0.3$

Note: very complex final state topologies, huge backgrounds $\rightarrow$ excellent detector performance, exquisite control of the backgrounds and sophisticated analysis techniques required.
Hints (so far inconclusive) for violation of lepton universality reported by BaBar, Belle and LHCb (Run 1 data, \(\sim 3 \text{ fb}^{-1}\)).

Note: couplings of leptons \((\ell = e, \mu, \tau)\) should be identical apart from (calculable) mass effects.

Deviations from SM decay rates may indicate new physics in the loop.
Heavy Ion collisions: conditions of high density and temperature of nuclear matter \(\rightarrow\) formation of a plasma of deconfined quarks and gluons (QGP). Permeated early universe \(\sim 10\ \mu s\) after Big Bang.

One of QGP manifestations is suppression of production of heavy-flavour resonances (J/\(\psi\), \(\psi(2s)\), \(\Upsilon\), etc.) due to screening by the dense medium.

\[
R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin} \rangle N(J/\psi)_{pp}}
\]

\(R_{AA}\) = quantifies departure from binary scaling
\(\rightarrow 1\) if no nuclear effects in HI collisions
\(\rightarrow \neq 1\) if medium effects
HL-LHC parameters and timeline

Nominal LHC: \( \sqrt{s} = 14 \text{ TeV}, L = 1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)  (Note: \( 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \) achieved already)
Integrated luminosity to ATLAS and CMS: 300 fb\(^{-1}\) by 2023 (end of Run 3)

HL-LHC: \( \sqrt{s} = 14 \text{ TeV}, L = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
Integrated luminosity to ATLAS and CMS: 3000 fb\(^{-1}\) by \( \sim \) 2035

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**LS2 (2019-2020):**
- LHC Injectors Upgrade (LIU)
- Civil engineering for HL-LHC equipment P1,P5
- Phase-1 upgrade of LHC experiments

**LS3 (2024-2026):**
- HL-LHC installation
- Phase-2 upgrade of ATLAS and CMS
One of most crucial challenges: new-generation superconducting magnets (Nb$_3$Sn) → fundamental milestone also for future, more powerful colliders (HE-LHC, FCC)
HL-LHC physics case

1. Precise measurements of the Higgs boson

Impact of New Physics on Higgs couplings to other particles:

\[
\Delta k/k \sim 5\%/\Lambda^2_{\text{NP}} \quad (\Lambda_{\text{NP}} \text{ in TeV})
\]

Precision ~2-5% at HL-LHC (~10% at nominal LHC)

In addition: measure H couplings to second-generation particles through rare \( H \rightarrow \mu\mu \) decay. Nominal LHC: only couplings to (heavier) third-generation particles (top-quark, b-quark, \( \tau \)-lepton) accessible

2. Discovery potential for new particles

~20-30% larger (up to \( m \sim 8 \text{ TeV} \)) than nominal LHC

3. If new particles discovered in Run 2-3:

\( \rightarrow \) HL-LHC may find more and provide first detailed exploration of the new physics with well understood machine and experiments
Scientific diversity programme
~20 projects, > 1200 physicists

**AD:** Antiproton Decelerator for antimatter studies

**CAST, OSQAR:** axions

**CLOUD:** impact of cosmic rays on aerosols and clouds → implications on climate

**COMPASS:** hadron structure and spectroscopy

**ISOLDE:** radioactive nuclei facility

**NA61/Shine:** heavy ions and neutrino targets

**NA62:** rare kaon decays

**NA63:** interaction processes in strong EM fields in crystal targets

**NA64:** search for dark photons

**Neutrino Platform:** ν detectors

**R&D:** for experiments in US, Japan

**n-TOF:** n-induced cross-sections

**UA9:** crystal collimation

Exploits unique capabilities of CERN’s accelerator complex; complementary to other efforts in the world → future opportunities being explored by “Physics Beyond Colliders” Study Group
**Scientific diversity: a compelling programme beyond the LHC**

**ISOLDE:** facility to produce radioactive nuclei:

- > 1000 isotopes of ~ 70 elements
- 12 beam lines, ~ 50 experiments/year, ~ 500 users
- nuclear physics, astrophysics, life sciences, etc.

**HIE-ISOLDE:** includes SC LINAC to accelerate nuclides to 10 MeV/nucleon → construction completed in 2018
Scientific diversity: a compelling programme beyond the LHC

**nTOF**: measurements of n-induced cross-sections (wide E-range, high flux, excellent E-resolution) → nuclear physics, astrophysics, imaging, etc.

**EAR1**: 180 m from target

**EAR2**: 18 m from target → much higher flux
Scientific diversity: a compelling programme beyond the LHC

Antiproton Decelerator: AEgIS, ALPHA, ASACUSA, ATRAP, BASE, GBAR
Precise spectroscopic and gravity measurements of antimatter using anti-p and anti-H → some of today’s most stringent limits on CPT
ELENA (additional decelerating and cooling ring) being commissioned → decelerates anti-p from 5.3 MeV to 100 KeV → x100 larger trapping efficiency by experiments
Scientific diversity: a compelling programme beyond the LHC

**NA62:** measure the rare, theoretically well known, $K^+ \rightarrow \pi^+ \nu \nu$ decay (BR $\sim 10^{-10}$ in SM) using high-intensity kaon beams → powerful test of the SM, indirect sensitivity to high-scale new physics.
Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos $\rightarrow$ imply neutrinos have masses and mix. Since then: great progress in understanding $\nu$ properties at various facilities all over the world.

Nevertheless, several open questions:
- Origin of $\nu$ masses (e.g. why so light compared to other fermions?)
- Mass hierarchy: normal ($\nu_3$ is heaviest) or inverted ($\nu_3$ is lightest)?
- Why mixing much larger than for quarks?
- CP violation (observed in quark sector): do $\nu$ and anti-$\nu$ behave in the same way?
- Are there additional (sterile) $\nu$ (hints from observed anomalies)?

Accelerator experiments can address some of above questions studying $\nu_\mu \rightarrow \nu_e$ oscillations. Need high-intensity $p$ sources (> 1 MW) and massive detectors, as $\nu$ are elusive particles and the searched-for effects tiny. Next-generation facilities planned in US and Japan.

Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. **CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.**

$\rightarrow$ see lectures by S. Pascoli
The CERN Neutrino Platform
South Dakota

DUNE experiment:
4x10 kt LAr detectors
~1.5 km underground

Long Baseline Neutrino Facility (LBNF) at FNAL

1.2 MW p beam, 60-120 GeV
Wide-band $\nu$ beam 0.5-2.5 GeV

Far site construction started 2017, beam from FNAL ~ 2026

FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start mid 2019

ICARUS T600 (476 t)
MicroBooNE (89 t)
SBND (112 t)
- supports European participation in accelerator-based neutrino projects in US and Japan
- North Area extension completed → provides charged beams and test space for neutrino detectors
- R&D to demonstrate large-scale LAr technology (cryostats, detectors, …); construction of cryostat for first DUNE module; participation in construction and test of two prototypes of DUNE detector: single and double-phase LAr TPC, ~ 6x6x6 m³, ~ 700 tons
Preparation for the future
The H boson is not just … “another particle”:
- Profoundly different from all elementary particles discovered previously
- Related to the most obscure sector of Standard Model
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

→ Its discovery opens new paths of exploration, provides a privileged door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades

- Precision measurements of couplings (as many generations as possible, loops, ...)
- Forbidden and rare decays (e.g. $H \to \tau \mu$) → flavour structure and source of fermion masses
- $H$ potential (HH production, self-couplings) → EWSB mechanism
- Exotic decays (e.g. $H \to E_T^{\text{miss}}$) → new physics?
- Other $H$ properties (width, CP, ...)
- Searches for additional $H$ bosons
- Etc.

→ See lectures by F. Maltoni
- Low backgrounds → all decay modes (hadronic, invisible, exotic) accessible
- Model-indep. coupling measurements: $\sigma(HZ)$ and $\Gamma_H$ from data
- $ttH$ and $HH$ require $\sqrt{s} \geq 500$ GeV
- High energy, huge cross-sections → optimal for (clean) rare decays and heavy final states ($ttH$, $HH$)
- Huge backgrounds → not all channels accessible; only fraction of events usable
- Model-dep. coupling measurements: $\Gamma_H$ and $\sigma(H)$ from SM
Compact Linear Collider (CLIC)

Linear $e^+e^-$ collider with $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine

→ based on normal-conducting accelerating structures and a two-beam acceleration scheme:
  power transfer from low-E high-intensity drive beam to (warm) accelerating structures of main beam

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<th>Parameter</th>
<th>Unit</th>
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<th>3 TeV</th>
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<td>Centre-of-mass energy</td>
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<td>Acceleration gradient</td>
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Physics goals:

- Direct discovery potential and precise measurements of new particles (couplings to $Z/\gamma^*$) up to $m\sim 1.5$ TeV
- Indirect sensitivity to $E$ scales $\Lambda \sim O(100)$ TeV
- Measurements of “heavy” Higgs couplings: $t\bar{t}H$ to $\sim 7\%$, $HH \sim 20\%$
Future Circular Colliders (FCC)

Conceptual design study of a ~100 km ring:

- **pp collider (FCC-hh):** ultimate goal
  \[ \sqrt{s} \sim 100 \text{ TeV}, \ L \sim 2 \times 10^{35}; \ 4 \text{ IP,} \sim 20 \text{ ab}^{-1}/\text{expt} \]

- **e^+e^- collider (FCC-ee):** possible first step
  \[ \sqrt{s} = 90-350 \text{ GeV}, \ L \sim 200-2 \times 10^{34}; \ 2 \text{ IP} \]

- **pe collider (FCC-he):** option \[ \sqrt{s} \sim 3.5 \text{ TeV}, \ L \sim 10^{34} \]

Also part of the study: HE-LHC: FCC-hh dipole technology (~16 T) in LHC tunnel \[ \rightarrow \sqrt{s} \sim 27 \text{ TeV} \]

FCC-hh: a ~100 TeV pp collider is expected to:

- explore directly the 10-50 TeV E-scale
- conclusive exploration of EWSB dynamics
- say the final word about heavy WIMP dark matter

FCC-ee: 90-350 GeV

- measure many Higgs couplings to few permill
- indirect sensitivity to E-scale up to O(100 TeV) by improving by ~20-200 times the precision of EW parameters measurements, \[ \Delta M_W < 1 \text{ MeV}, \Delta m_{\text{top}} \sim 10 \text{ MeV} \]
These are very exciting times in particle physics

The Standard Model is complete and works very well with no significant “cracks” as yet → we don’t understand why, as it is unable to address the outstanding questions

There must be new physics → BUT at which energy scale???
And with which strength does it couple to the SM particles?

Scientific diversity, and combination of complementary approaches, are crucial to directly and indirectly explore the largest range of E scales and couplings, and to properly interpret signs of new physics.
Historically, high-energy accelerators have been our most powerful tool for exploration in particle physics.

The full exploitation of the LHC, and more powerful future colliders, will be needed to advance our knowledge of fundamental physics.

No doubt that future high-E colliders are extremely challenging projects.

However: the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. Instead, we should use our creativity to develop the technologies needed to make future projects financially and technically affordable.