Experimental Particle Physics - Future Perspectives

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Two centennial events

Research Programme 2017

Kaiser-Wilhelm-Institut für Physik

General Relativity

Nobel Prize Gravitational Waves 2017
Today

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years
Rotational Curves of Galaxies

- Outer rim of galaxies is seen to rotate faster than expected from Newtonian mechanics

- There is more mass than is seen interacting

Dark Matter
...executing the ongoing European Strategy for Particle Physics
LHC as #1 tool...
Example of Dark Matter Search at the LHC
Goal of LHC – Identify the Physics beyond the Standard Model

- Explore an energy regime that has not been chartered before
  - have entered 13 TeV regime in production mode
  - 14 TeV after Long Shutdown 2 and possibly 15 TeV (study group)

- Look for small deviations (small couplings) from the Standard Model
  - Precision measurements of (rare) processes
  - Higgs particle as a portal

Luminosity need in both cases

- Direct search
- Indirect search
H → fermions

Using
\( \tau_h \tau_h \)
\( e \tau_h \)
\( \mu \tau_h \)
\( e \mu \)

\( H \rightarrow \tau \tau \)

4.9 \( \sigma \) from run 2

\( H \rightarrow b \bar{b} \)

3.5 \( \sigma \)
Search for dark photons

- Hypothesis: Dark sector not directly interacting with SM fields
- Coupling through kinetic term with mixing $\varepsilon$
- Dark photons $A'$ couple with strength $10^{-6} < \varepsilon < 10^{-2}$ and would open a portal for searches
- LHCb searches (online) in $\mu\mu$ mode
LHC schedule

Substantial upgrades for ALICE and LHCb; preparatory upgrades for ATLAS and CMS including civil construction

end of original LHC

HL-LHC
High Luminosity Phase of LHC
HL-LHC schedule

Nominal LHC: $\sqrt{s} = 14$ TeV, $L = 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$

Integrated luminosity ATLAS and CMS 300 fb$^{-1}$ by 2023 (end of Run 3)

HL-LHC: $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (levelled)

Integrated luminosity ATLAS and CMS 3000 fb$^{-1}$ by ~2035

LS2 (2019-2020):
- LHC Injectors Upgrade (LIU)
- Civil engineering for HL-LHC equipment P1, P5
- First 11 T dipoles P7; cryogenics in P4
- Phase-1 upgrade of LHC experiments

LS3 (2024-2026):
- HL-LHC installation
- Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)
A few physics example for HL-LHC

• measurement of Higgs couplings
  • deviations may be at the few %-level
  • access to second generation couplings $H \rightarrow \mu \mu$

• 20-30% larger discovery potential (8 TeV)
  • precision measurements

If new particles discovered in Run 2-3:

Æ HL-LHC may find more and provide first detailed exploration of the new physics with well understood machine and experiments

Precise measurements of the Higgs boson

E.g. $H$ couplings (interaction strengths) to other particles with precision $2-5\%$ ($10\%$ at nominal LHC)

New Physics can alter these couplings by $< 5\%$

Æ highest experimental precision needed to detect it

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)

Discovery potential for new particles ~20-30% larger (up to $m \sim 8$ TeV) than nominal LHC
SM Physics Menu on the LHC and HL-LHC Running Schedule

Credits: A. David @ GRC 2017

HL-LHC: >5E34 cm$^{-2}$s$^{-1}$
>300 fb$^{-1}$/year, pile-up >140

- Beware: 20 years extrapolation
- Nature may choose to serve surprises
Phase II Detector upgrades

- replace radiation-damaged components
- enable detectors to withstand the rates at phase I performance
ATLAS ITk strips TDR (Phase II Upgrade)

- Settled on 5 pixel + 4 strips system
- Only the strips are evaluated in TDR – although status of pixel mentioned
- The pixel TDR will follow at the end of 2017
- Large document (>500 pages)
Highest energy hadron colliders

From European Strategy of Particle Physics
CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.
Future Circular Collider FCC

- Study for a 100 km ring providing collisions at 100 TeV cm
- employs injector chain of CERN
High-field magnets

• Key to high energies
  • FCC and
  • HE-LHC = use of high field magnets in existing LHC ring

• Technology
  • Nb$_3$Sn allows $\sim$16 T magnets that need to be developed (size, cost, industry…)
    • HL-LHC magnets provide a $\sim$1.2 km test of the technology (11 T magnets)
  • an insert of HTS may increase field to 20 T (requires considerable research)
International Collaboration on Magnet Development

- **Nb$_3$Sn magnets:** international R&D programme
- several European countries and US LARP programme and its successor

**Diagram:**
- World record field 13.8 T
- VLHC 10 T Dipole
- LARP 200 T/m TQ quadrupole
- LHC 11 T Dipole

**Graph:**
- Field progress in accelerator magnets
- Tesla vs. Year
- Nb$_3$Sn, Nb-Ti, Tevatron, SPS, Main Ring, RHIC, LHC, HI-LHC

**Timeline:**
- 1999-2015
- LHC upgrades R&D

**Magnet Development:**
- HFDC (R&W) 40 mm 10 T dipole
- HFDA 43.5 mm 10 T dipole
- HFDM-LM Dipole mirror
- TQC 90 mm 200 T/m quadrupole
- TOM-LDM Quadrupole mirror
- MBHSP 60 mm 11 T dipole
- MBHSM Dipole mirror
- MBHDP 60 mm 11 T dipole

**Text:**
- 1.2KM of LHC modified
FCC Conceptual Design Report by end 2018

- **pp-Collider (FCC-hh)** – sets the boundary conditions
  - 100 km ring, \( \sqrt{s}=100 \text{ TeV}, L \approx 2 \times 10^{35} \)
  - HE-LHC is included (~28 TeV)
- **\( \text{e}^+\text{e}^-\)-Collider** as a possible first step
  - \( \sqrt{s}= 90 - 350 \text{ GeV}, \ L \approx 1.3 \times 10^{34} \) at high E
- **eh-Collider** as an option
  - \( \sqrt{s}=3.5 \text{ TeV}, L \approx 10^{34} \)
Highest energy with lepton colliders
Compact Linear Collider CLIC

- e^+e^- collider 1-3 TeV
- currently only option for the TeV region
- 380 GeV study has been completed both for 2-beam and klystrons approach; now explore 250 GeV
- decisive input to next update of European Strategy for Particle Physics

- CDR 2013
- CTF3 has provided key results
  - experimental programme ended 2016
- ready for a demonstrator
Beyond current technologies
AWAKE – proton driven plasma wakefield acceleration

- Single stage acceleration to high energy
  - plasma allows few GeV/m acceleration
  - exhaust the 20 kJ energy per bunch at the SPS and transfer the energy to the witness bunch
- Idea: generate the field where and when you need it
  - CLIC analogy with metallic structures
• Charge fluctuations in the bunch (or external laser pulse) starts to seed a plasma at the characteristic wavelength

• self-modulates the charge density of the proton bunch

• electrons injected into the plasma would then be accelerated
AWAKE Set-up

- Installation at former proton beam line for neutrinos to Gran Sasso
- Experimental area for plasma cell and electron injector
Observation of Transverse Blow-up of beam

- Considerable transverse blow-up of beam
- only possible in the presence of large electrical fields

Clearly see the transverse blow-up of the proton beam. Only possible with very strong electric fields!!
AWAKE: First observation of self-modulation

**Optical Transition Radiation Diagnostic**

- No Plasma
- Plasma

**Average of 45 FFTs**

- Lineout
- Band Projection
- Outside of Band

Fourier transform -> see modulation frequency

SPC, CERN
AWAKE Overview

• Understand the physics of self-modulation instability

• Probe the accelerating wakefields with externally injected electrons
AWAKE: Run II

Goals:
• stable acceleration of bunch of electrons with high gradients over long distances
• ‘good’ electron bunch emittance at plasma exit

Require:
• Compressed proton beam in SPS
• Short electron bunch with higher energy for loading wakefield
• Density step in plasma for freezing modulation
• Alternative plasma cell developments

<table>
<thead>
<tr>
<th>Preliminary Run 2 electron beam parameters</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Acc. gradient</td>
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<tr>
<td>Energy gain</td>
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<tr>
<td>Injection energy</td>
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<td>Bunch length, rms</td>
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<td>Peak current</td>
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<td>Bunch charge</td>
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<tr>
<td>Final energy spread, rms</td>
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<tr>
<td>Final emittance</td>
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</table>
From European Strategy of Particle Physics

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

Europe looks forward to a proposal from Japan to discuss a possible participation.
International Linear Collider ILC

- $e^+e^- \text{ collider } \sqrt{s} = 0.5 \text{ TeV (upgradeable to 1 TeV)}$

- precision Higgs and Top programme and beyond

- Ministry MEXT continues to evaluate the implications of hosting ILC in Japan w.r.t. cost, manpower (skills)

- Project is mature (TDR 2012)
- hosting evaluated by Japanese government
- expect (some) statement by the end of 2018
Japanese developments since release of TDR

ILC Advisory Panel

- Setup by MEXT in May 2014
- Activities in the first year (May 2014-June 2015)
  - Elementary particle and nuclear physics WG, TDR-validation WG
  - 1st Nomura Research Institute survey (Spin-off and research trend)
  - Summary of the ILC advisory panel’s discussions to date
- Activities in the second year (June 2015-July 2016)
  - Human resource securing and developing WG
  - Report on measures to secure and develop human resources for the ILC
  - 2nd Nomura Research Institute survey (technology issues)
- Activities in the third year (July 2016-July 2017)
  - Management and organizational structure WG, 3rd survey on large international projects
  - Report on ILC management and organizational structure (English translation being prepared)
- The Panel activity will continue.

MEXT-DOE discussion group

1st meeting in May 2016 in Washington, A meeting in August 2016 during ICHEP 2016
2nd meeting in October 2016, decided to start US-Japan cooperative R&Ds for ILC cost reduction.
Discussion group meetings will continue.
ILC – Technical Developments

• Recent Proposal to start with 250 GeV cm
  • Higgs precision studies complementing LHC
  • contrast with HL-LHC results and theory assumptions
  • Upgrade option needs to be preserved to tackle top threshold
• TDR cost of ~8 bn ILCU* can be reduced by ~40% for 250 GeV machine
  • Japanese hosting discussion reinvigorated

* 1 ILCU = 1 $US in 2012
ILC Project Phases

2017 – 2018 Pre - preparation phase

• The ongoing activities with relevance to the ILC in Europe are reviewed.

2019 – 2022: Preparation phase

• This period needs to be initiated by a positive statement from the Japanese government about hosting the ILC, followed by a European strategy update that ranks European participation in the ILC as a high-priority item. The preparation phase focuses on preparation for construction and agreement on the definition of deliverables and their allocation to regions.

2023 and beyond: Construction phase

• The construction phase will start after the ILC laboratory has been established and intergovernmental agreements are in place. At the current stage, only the existing capabilities of the European groups relevant for this phase can be described.
Pre-preparation phase – current focus areas (2017-2018)

Focused R&D on some key areas (cost, power, technically critical)
Pre-preparation phase – European XFEL and ESS

- Expertise across all essential parts of ILC
- Facilities set up in Europe
- Industrial capacity in Europe
- E-XFEL: ~7% of a 250 GeV ILC (~100 modules)

- ESS cryo-module production next
- Expertise/facilities being maintained and developed
ATF2: International collaboration with many European groups:

- Final focus studies (crucial for LC luminosities)
- Extensively used for Ph.D training

Many obvious common areas for ILC/CLIC, beyond RF technologies:

- Common WGs on Beam-dynamics, Sources, MDI, DRs, RTML, BDS (yearly LC workshops built around these WGs/topics – all with CLIC co-conveners)
- Cost and power studies and comparison

Pre-preparation phase – Common studies w/CLIC, ATF2 KEK

<table>
<thead>
<tr>
<th>Goal</th>
<th>CERN</th>
<th>France LAL</th>
<th>France LAPP</th>
<th>Germany DESY</th>
<th>Spain IFIC</th>
<th>UK Oxford</th>
<th>RHUL</th>
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<td>Stabilisation/Feedback</td>
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Pre-preparation summary:

Europe has played – and continues to play – a central role in development of the ILC project.

Large European projects are being implemented where the ILC/SCRF technology is being put to use and is being validated.

European Industry is well prepared to construct parts for ILC.
The construction phase will start after the ILC laboratory has been established and inter-governmental agreements are in place. At the current stage, only the existing capabilities of the European groups relevant for this phase can be described.

As mentioned above, the detailed contributions will have to be defined during the preparation phase and formalized by inter-governmental agreements. Some contributions from Europe are imperative for the project - most prominently superconducting RF modules.

So premature to plan in detail, however some comments can be made:

• Focus on technical items for ILC (not CE and infrastructure)
• E-XFEL ~7% of a 250 GeV ILC – and more than 10% of the cryo-modules needed
• Detector construction expected to follow LHC detector model
• Spending significantly above the levels mentioned on previous page only by ~2025-26
Preparation Phase 2019-22: Key activities

This period needs to be initiated by a positive statement from the Japanese government about hosting the ILC, followed by a European strategy update that ranks European participation in the ILC as a high-priority item. The preparation phase focuses on preparation for construction and agreement on the definition of deliverables and their allocation to regions.

- The European groups will concentrate on preparation for their deliverables, including European industry.
- Europe and European scientists, as part of an international project team, will also participate in the overall finalization of the design, while in parallel contributing to the work of setting up the overall structure and governance of the ILC project and of the associated laboratory.

<table>
<thead>
<tr>
<th>Key activities in Europe</th>
<th>More details</th>
</tr>
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<tbody>
<tr>
<td>SCRF activities</td>
<td>Cavity fabrication and preparation, Power Couplers, Automation of assembly, E-XEL -&gt; ILC</td>
</tr>
<tr>
<td>High efficiency klystron R&amp;D</td>
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<tr>
<td>Cryogenics system</td>
<td>LHC system similar in size to ILC</td>
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<tr>
<td>Accelerator Domain Issues</td>
<td>Positron source, Damping Rings, Beam Delivery Systems, Low emittance beam transport, Beam dumps, Positron source</td>
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<tr>
<td>Detector and Physics</td>
<td>Design optimization, MDI, Technical prototypes, TDR, physics studies</td>
</tr>
<tr>
<td>Documentation system</td>
<td>Experience from E-FEL</td>
</tr>
<tr>
<td>“Regional” Design office</td>
<td>Naturally at CERN, linking to other European National Labs</td>
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</tbody>
</table>
From European Strategy of Particle Physics

*Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*
Neutrinos at CERN

• Long tradition

  • detection of neutral currents at Gargamelle in 1973
  • CDHS and CHARM…

• More recently

  • CNGS

  • sending neutrinos from CERN to Gran Sasso
CNGS 2006 - 2012

- CERN ν-beam to Gran Sasso

Integrated Protons on target:
Total: $18.24 \times 10^{19}$ p.o.t.

1.8x$10^{20}$ p.o.t.
OPERA

• 5 $\nu_\tau$ were detected in emulsion detector

• Detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations

The OPERA Detector

- 31 Walls (each containing 3328 bricks)
- SM1: 31 walls (brick walls+TT)
- SM2: 1 spectrometer

In total there are 206336 bricks
~ 1.8 kton
ICARUS at Gran Sasso

- LArTPC
  - search for $\nu_\mu \rightarrow \nu_e$ oscillations and LSND effect
    - $P_{\nu_\mu \rightarrow \nu_e} \leq 5.4 \times 10^{-3}$ @ 90% CL
  - search for $\nu_\mu \rightarrow \nu_\tau$ oscillations
Neutrino Physics at CERN in the LHC era

• with the ESPP of 2012…
  …decision to end CNGS in 2012

• Establishment of a Neutrino Platform at CERN
  • as a springboard for European Physicists to engage in accelerator based neutrino physics in the US and in Japan
  • Detector development (initial emphasis on Lar TPC)
  • Extension of EHN1 hall

Charged particles from SPS available
Fast entry into Short Baseline Programme at Fermilab

• ICARUS
  • ended data taking at LNGS
  • pioneered LarTPC technology
  • space at LNGS had to be cleared
ICARUS overhaul at CERN (WA104 - NP01)

- Detector upgrade
  - more PMTs
  - new cathode, inner cabling
  - new electronics
- Scintillator layer (cosmic tagger)
- New cryostat and cryogenic plant
- Reassembly of the 2 T300 modules inside cryostats and shipment to Fermilab
Sterile neutrino search

\[ 4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 \theta_{24} \sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e} \]
Short baseline programme at Fermilab

• To resolve experimental inconsistencies in the measured $\nu$-spectrum

• SBND (near detector)

• MicroBooNE (operating)

• MiniBooNE

• refurbished ICARUS arrived at Fermilab
ICARUS Trip

CERN → Burns Harbor → Fermilab
ICARUS arrival at Fermilab

- Novel cryostat technology for ICARUS
  - based on GTT technology well established for vessels carrying liquid gases
  - much more demanding on stability

![Route Planning Table]

- Route Planning
  - Dep. CERN: 12 June 2017
  - Arr. Basel (CH): 14 June 2017
  - Dep. Basel (CH): 15 or 16 June 2017
  - Barge: 21 June 2017
  - Arr. Antwerp (NL): earliest/latest on 23/30 June 2017
  - Dep. Antwerp (NL): approx. 23-24 days after departure from Antwerp
  - Ship: approx. 2 days after dep. from Burns Arbor
  - Trunk: FERMILAB
J-PARC at Neutrino Platform

- 3% precision $\text{H}_2\text{O}/\text{C}_n\text{H}_n$ cross-section ratio
- Study of $\nu_\mu$ energy reconstruction
- Wide angle $\theta$ coverage
- Complementary to ND280
Long baseline neutrino programmes

- Fermilab is constructing a long baseline neutrino facility (LBNF), a wide band neutrino beam to the DUNE experiment (40 kt LArTPC) in South Dakota

- Tokyo is considering Hyper-K (water Cherenkov detector) at Kamioka

- Goals: neutrino-oscillation parameters, mass hierarchy and CP-violation, …
CP violation

- Both Noνa and T2K see slight preference for CP violation in neutrino sector
  - angle around 270°
  - good prospects for large mass detectors

\[ \theta_{13} \text{ from reactor exp.} \]

\[ CP - \text{conservation excluded @90\% CL} \]

\[ \sin^2 \theta_{13} = -2.978 \pm 0.467 (90\% CL) \]

\[ \sin^2 \theta_{23} \]

\[ T2K: \text{From J Parc to Super-K (295 km)} \]

\[ NOvA: \text{Exclude maximal mixing at 2.6\sigma} \]

\[ T2K: \text{consistent with maximal mixing} \]

Constraints:
- Global reactor constraint of \( \sin^2 2\theta_{13} = 0.086 \pm 0.05 \)
- Solar neutrino oscillation parameters to PDG
- \( \sin^2 \theta_{23} \) and with NOvA Q\( \mu \) disappearance results

Global best fit:
- Normal Hierarchy, \( \delta_{CP} = 1.49\pi \)
- \( \sin^2 \theta_{23} = 0.4 \)

- IH, \( \delta_{CP} \sim \pi/2 \) is rejected (3σ) for lower octant
- Both octants and MHs are allowed at 1σ, best fit IH - NH: \( \Delta \chi^2 = 0.47 \)

\[ NOvA: \text{From Fermilab to Minnesota (810 km)} \]
LAr Technology

- LarTPC large scale active detectors
  - few mm precision
  - good energy resolution
Neutrino Platform at CERN

To develop experimental techniques, e.g. protoDUNE
- single phase LArTPC
- double phase LArTPC
Preparing the protoDUNE cryostat structures at CERN

preparing the cryostat inner structures

active volume 6x6x6 m³

at the neutrino platform
LBNF / DUNE - far detector

- Sanford Lab Reliability FY16 – 18 (~30M$)
  - Ross shaft rehab; Hoist motor rebuild…

- Pre-Exc Construction FY17 – 18 (~15M$)
  - Rock disposal systems
  - Ross headframe upgrade, more…

- Excavation & Surface Construction FY19 – 22 (~300M$)

- Cryostats/Cryogenic Systems FY20 – 25 (In kind)
International DUNE Project
Towards 2020 Update of European Strategy for Particle Physics

- LHC and HL-LHC exploitation (√)
- Prepare for the next step at the energy frontier
- Rich diversity programme…
LHC and its injector chain used for physics

- LHC
  - ongoing Run 2 @ 13 TeV
- Injectors supporting
  - Fixed target programme
  - ISOLDE (isotopes)
  - n-ToF
  - AD-programme

\[ \text{75\% of all p} \]
Physics Beyond Collider Study

- Kickoff meeting held in September 2016
  Follow-up in November 2017
- Study of fixed target programme

...even with LHC beams

SMOG
PBC Study cont’d: Beam Dump Facility (BDF)

Joint operation of North Area and BDF
PBC Study cont’d: Proton EDM

Study of an all-electrostatic storage ring

Design sensitivity: $4 \times 10^{-29}$ e-cm

Requires:
- electrostatic deflector 8MV/m
- magnetic shielding
- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW

Sensitivity of $10^{-29}$ e-cm corresponds to 100 TeV for new physics scale
Possible realisation at CERN in ISR building

Polarized protons with $p = 0.7$ GeV/c, $v/c = 0.6$
Summary

- Experimental Programme of LHC extremely rich; long range experimental programme guarantees physics return
  - by exploring the highest energies
  - by searching for violations of the SM in (highly sensitive) rare decays
- Preparing Update of the European Strategy for Particle Physics
  - LHC and HL-LHC
  - Energy Frontier (FCC / CLIC) and R&D beyond
  - Accelerator based neutrino programme (US & Japan) via neutrino platform
  - Vibrant physics programme Beyond Colliders

2018 (end): reports on Physics
2019: community discussion with input from other regions