Status and Plans for the CERN accelerator Complex

P. Collier, CERN
Outline

- A Short history of LHC Run 2
- The Approved Programme: Prospects for Run 3 and beyond
  - The LHC Injector Upgrade Project
  - The HL-LHC upgrade project
  - The Diversity Physics Programme at CERN
- The European Strategy Update and Directions towards the Future
  - Energy Frontier Studies at CERN
  - Science Diversity Options (PBC Study)
  - Constraints & Timelines
- Summary & Conclusions
Run 2: p-p operation

- Important milestones were set by the LHC during Run 2:
  - Demonstrated reliable operation with 6.5 TeV beams
  - Exploited 25 ns bunch spacing to operate with >2500 bunches
  - Reached design luminosity $L_{\text{IP1/5}} = 10^{34}$ cm$^{-2}$s$^{-1}$ … and doubled it!
  - Delivered 6.7 fb$^{-1}$ to LHCb and 33 pb$^{-1}$ to ALICE
Operational efficiency

- In spite of their complexity **key systems are very reliable**
- **Robust machine configuration**
- Efficient and optimized **operational procedures and tools**
- **Specialist teams** ready to intervene on short notice in case of problem

Efficiency very high in spite of the complexity of the machine and the very high stored beam energy (> 300MJ per beam)

2018 data
Squeezing more luminosity

• The machine was **beautifully designed and built extremely well**
  → no major bad surprises, most systems performing even better than expected!
• Very good **control and reproducibility** of the beams thanks to excellent performance of magnets, power converters, RF, collimation
• **Beam dynamics well under control**
  o Complex and involved combination of orbit, optics, aperture, collimation, stability, coupling, non-linearities, noise, beam-beam, RF settings, feedbacks

→ **Exploited to push the luminosity**
• Stronger focusing at the interaction points: **β* down to 30 cm** (design was 55 cm)
• Use of **high-brightness beams** from the injectors (BCMS)
• Operational use of **luminosity levelling** (separation, crossing angle and β* - down to 25 cm!)
Peak luminosity in Run 2

- Machine and beam configuration progressively pushed over Run 2
- Deployment of several optimizations and innovations (testing HL-LHC concepts)

<table>
<thead>
<tr>
<th>Injected beam type</th>
<th>N bunches (prod. scheme)</th>
<th>β* (at start fill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 ns (std.)</td>
<td>2200</td>
<td>80 cm</td>
</tr>
<tr>
<td>25 ns (high brightness)</td>
<td>2556</td>
<td>40 cm</td>
</tr>
<tr>
<td>8b+4e</td>
<td>1900</td>
<td>30 cm</td>
</tr>
<tr>
<td>25 ns (high bright.)</td>
<td>2556</td>
<td></td>
</tr>
</tbody>
</table>

- ATS optics
- RF full detuning
- Crossing Angle leveling (CAL)
- Continuous CAL
- β* levelling

Peak Luminosity [cm^-2 s^-1]

5/8/2019 CERN Status & plans
Outline

- A Short history of LHC Run 2
- The Approved Programme: Prospects for Run 3 and beyond
  - The LHC Injector Upgrade Project
  - The HL-LHC upgrade project
  - The Diversity Physics Programme at CERN
- The European Strategy Update and Directions towards the Future
  - Energy Frontier Studies at CERN
  - Science Diversity Options (PBC Study)
  - Constraints & Timelines
- Summary & Conclusions
Long Shutdown 2 (now):
• Maintenance and consolidations works (entire complex)
• Deployment of LHC injectors upgrade
• Preparation for HL-LHC upgrade
LHC injectors upgrade (LIU project)

The goal is to double the present beam intensity while keeping the same beam size (HL-LHC design).

Major upgrade works taking place in LS2:

- The LHC injector complex is by itself one of the largest accelerator facilities in the world.

**PSB**
- **157 m**
- **2.0 GeV**

**Linac4**
- **160 MeV**
- Construction **completed in 2017**
- **Higher energy 160 MeV**
- **Acceleration of H-ions** (charge exchange injection to the PSB)
- **Extensively tested in 2017-2018**
- **Connection to the rest of the chain during LS2**

- **H- charge exchange injection** at 160 MeV → improved beam brightness (weaker space charge forces)
- **Energy:** 1.4 GeV → 2 GeV
  - New main power supply
  - New RF systems
LHC injectors upgrade (LIU project)

PS upgrade
- **Injection at 2 GeV** → improved beam brightness (weaker space charge)
- **RF upgrades** to increase beam intensity

A New Injector Chain to be commissioned in 2020!

SPS
- **Main RF system upgrade** (new solid state power plants – 2 x 1.6 MW)
- **Impedance mitigation** to improve beam stability
- More robust **beam dump and protection devices**
### Technical limitation on the Instantaneous Luminosity:
1. **Collider** (cryolimit in the triplet region) at $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ twice the nominal design luminosity
2. **Experiments** (pile up in the detectors). Designed for peak of 40 they are actually dealing with 60!

### Technical limitation on Integrated Luminosity:
1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)
2. **Experiments** (radiation damage in the Inner Tracker)

---

**LHC / HL-LHC Plan**

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>13 TeV</td>
<td>13 - 14 TeV</td>
</tr>
<tr>
<td>8 TeV</td>
<td>8 TeV</td>
<td>8 TeV</td>
</tr>
<tr>
<td>2011</td>
<td>2012</td>
<td>2011</td>
</tr>
<tr>
<td>2013</td>
<td>2014</td>
<td>2015</td>
</tr>
<tr>
<td>2015</td>
<td>2016</td>
<td>2017</td>
</tr>
<tr>
<td>2018</td>
<td>2019</td>
<td>2020</td>
</tr>
<tr>
<td>2021</td>
<td>2022</td>
<td>2023</td>
</tr>
</tbody>
</table>

**LS1**
- splice consolidation button collimators
- R2E project
- experiment beam pipes
- nominal luminosity $0.75 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 50 ns spacing high pile up ~40

**LS2**
- Diodes Consolidation
- LIU Installation
- P7 11 T dip. coll.
- Civil Eng. P1-P5
- nominal luminosity $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- 25 ns spacing pile up ~60
- levelled at $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ 25 ns bunch spacing pile up ~60 continuous

**Run 2**
- **13 TeV**
- **EYETS**
- **ATLASS - CMS upgrade phase 1**
- **ALICE - LHCb upgrade**
- **2 x nom. luminosity**
- **2 x nominal luminosity**

---

**75% nominal luminosity**

---

**CERN Status & plans**
Outlook to LHC Run 3 (2021-2023)

LIU forecast for beam intensity ramp up for HL: can be used in LHC Run3

<table>
<thead>
<tr>
<th></th>
<th>2021</th>
<th>2022</th>
<th>2023*</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td># bunches</td>
<td>Up to 2748 (BCMS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon_n$ [\mu m]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3 $\rightarrow$ 1.55</td>
<td>Intensity Ramp Up</td>
</tr>
<tr>
<td>$N_b$ [$10^{11}$ p]</td>
<td>0 $\rightarrow$ 1.4</td>
<td>1.4 $\rightarrow$ 1.8</td>
<td>1.8 $\rightarrow$ 2.1</td>
<td>Max bunch population at the end of each year</td>
</tr>
</tbody>
</table>

Approaching cryogenic limitations: Different heat load by sector emerged in Run2 and must be understood

Pushing the present LHC using HL-LHC studies and early installation of HiLumi equipment in LS2… Levelling, low-Z collimators and dispersion suppressor collimation

LIU forecast for beam intensity ramp up for HL: can be used in LHC Run3

Swapping the vertical crossing polarity

$\Gamma$ = 1.35

9.7 kW/arc (195 W/hc)

Heat load contributions

Pure BCMS

$\text{EY} = 1.35$

9.7 kW/arc (195 W/hc)

r=30% decrease $\Rightarrow$ 40% increase in integrated luminosity

$L_{int}$ 160 fb$^{-1}$ can be reached in Run3 with margins
Goal of HL-LHC

Enable the LHC to deliver $\sim 250 \text{ fb}^{-1}/\text{year}$ in ATLAS and CMS reaching $3000 \text{ fb}^{-1}$ by $\sim 2037$ (leveling at a pile-up of 140 events/crossing)

**Strategy:**

- **Complete redesign of regions next to ATLAS and CMS,** in order to:
  - Achieve smaller beam size and crossing angle at the experiments
  - Withstand radiation from the increased luminosity debris
- **Profit from the increased beam intensity** provided by the injector upgrades
- **Upgrade key LHC systems** to cope with the increased intensity and luminosity (collimation, cryogenics, injection and dump systems)

→ Requires **development of new technologies** (magnets, crab cavities, sc. links)

→ Relying on large international collaborations

→ Needs **significant new underground and surface infrastructure**

**Ultimate** performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{\text{peak ult}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and **Ultimate Integrated** $L_{\text{int ult}} \sim 4000 \text{ fb}^{-1}$

LHC should not be the limit, should Physics require more...
Rebuilding ~1.2km of LHC (the most complicated bit!)

But also touches very many other systems around the machine

- New IR-quads Nb$_3$Sn (inner triplets)
- New 11 T Nb$_3$Sn (short) dipoles
- Other NbTi magnets in the IR
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
...
Half way

• Now deep into the construction phase …
• Some installations already during LS2 as well as civil engineering works
• Main installation work during a 30 month stop (LS3): 2024-2026
The Diversity Programme at CERN

Isolde/HIE-Isolde

Installation Completed and operational in 2018 at slightly reduced energy.
Cavity repair during LS2 to allow full energy (10MeV/u)

CERN-MEDICIS
First medical isotopes produced

Antiproton Decelerator (AD)
Construction and initial commissioning of ELENA complete to provide antiprotons at 100keV kinetic
Connection to the existing experimental area during LS2

Will allow a substantial increase in the availability of trapped antiprotons (x10 – x100) and serve several experiments simultaneously
The Diversity Programme at CERN (Approved Upgrades)

**AWAKE**

Proof-of-Principle Accelerator R&D to study Proton Driven Plasma Wakefield acceleration

- Demonstrate seeded self-modulation in a the proton bunch and successfully accelerated a witness electron bunch – 200MV/m
- Programme funded to accelerate further and preserve electron beam quality

**North Area Consolidation**

Infrastructure dates from the 1970’s enhancement of beamlines and infrastructure planned during LS3 (and beyond)

- Over 6km of beam lines!
- T4 wobbling
- T2 wobbling

... but also in view of new requests coming out of the Physics Beyond Collider study
Outline

- A Short history of LHC Run 2
- The Approved Programme: Prospects for Run 3 and beyond
  - The LHC Injector Upgrade Project
  - The HL-LHC upgrade project
  - The Diversity Physics Programme at CERN
- The European Strategy Update and Directions towards the Future
  - Energy Frontier Studies at CERN
  - Science Diversity Options (PBC Study)
  - Constraints & Timelines
- Summary & Conclusions
The European Strategy for Particle Physics Update

Very successful Granada Symposium
Lots of input …
Lively discussions!
Some areas of consensus seem to be emerging
Next milestone will be the publication of the Physics briefing book.

Clearly deliberations are continuing … so any opinions expressed are my own !!
Consensus seems to be emerging that the next machine should be capable of exploring the Higgs - an $e^+e^-$ Higgs-Factory ...

Much less consensus on what shape it should be !!
CLIC: multi-TeV e⁺e⁻ Linear Collider

100 MV/m accelerating gradient needed for a compact (~50 km) machine at 3 TeV based on room temperature, 12 GHz accelerating structures and a two-beam acceleration scheme providing short (244 ns) high-power RF pulses.

### Table: CLIC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>vs</td>
<td>GeV</td>
<td>380</td>
<td>1500</td>
<td>3000</td>
</tr>
<tr>
<td>Tunnel length</td>
<td>km</td>
<td>11</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>Gradient</td>
<td>MV/m</td>
<td>72</td>
<td>72/100</td>
<td>72/100</td>
</tr>
<tr>
<td>Pulse length</td>
<td>ns</td>
<td>244</td>
<td>244</td>
<td>244</td>
</tr>
<tr>
<td>Luminosity (above 99% of vs)</td>
<td>10³⁴ cm⁻²s⁻¹</td>
<td>1.5</td>
<td>3.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bunches per train</td>
<td></td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Particles/bunch</td>
<td></td>
<td>10⁹</td>
<td>5.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Beam size at IP (σ⊥/σₐ)</td>
<td>nm</td>
<td>2.9/149</td>
<td>1.5/60</td>
<td>1/40</td>
</tr>
<tr>
<td>Annual energy consumption</td>
<td>TWh</td>
<td>0.8</td>
<td>1.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Construction cost</td>
<td>BCH</td>
<td>5.9</td>
<td>+5.1</td>
<td>+7.3</td>
</tr>
</tbody>
</table>

Since 2012 CDR:
- 100 MV/m accelerating structures with target low breakdown rate (< 3x10⁻⁷/m/pulse)
- Two-beam acceleration scheme demonstrated (CTF3)
- ~nm vertical emittance achieved by light sources
- R&D on alignment and vibration stabilization systems
- Reduction of energy consumption (high-efficiency klystrons)
- Cost reduction – optimization continuing
- Project Implementation Plan published

Profiting from synergies with FEL and light-sources
CLIC: multi-TeV e⁺e⁻ Linear Collider

Technically, construction could start in ~2026 (TDR in 2025) → first collisions at √s=380 GeV in ~2035 → 25-30 years of physics exploitation

Physics reach:
- Measurements of Higgs couplings, including ttH (to ~3%) and HH (~ 10%) from direct production
- Direct discovery potential and precise measurements of new particles up to the kinematic limit
- Indirect sensitivity to E scales up to Λ ~ 100 TeV; different √s probe E-dependent operators of new physics

CERN is currently consuming ~1.2TWh/y (~90% in accelerators)
## FCC: Future Circular Collider(s)

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s}$</th>
<th>$L/IP$ (cm$^{-2}$ s$^{-1}$)</th>
<th>Int. $L/IP$ (ab$^{-1}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$ FCC-ee</td>
<td>~90 GeV ZW</td>
<td>230 x $10^{34}$</td>
<td>75 ab$^{-1}$</td>
<td>2 experiments</td>
</tr>
<tr>
<td></td>
<td>160 WW</td>
<td>28</td>
<td>5</td>
<td>Total ~ 15 years of operation</td>
</tr>
<tr>
<td></td>
<td>240 H</td>
<td>8.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>~365 top</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>pp FCC-hh</td>
<td>100 TeV</td>
<td>5 x $10^{34}$</td>
<td>2.5 ab$^{-1}$</td>
<td>2+2 experiments</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>Total ~ 25 years of operation</td>
</tr>
<tr>
<td>PbPb FCC-hh</td>
<td>$\sqrt{s_{NN}} = 39$ TeV</td>
<td>$3 \times 10^{29}$</td>
<td>$100$ nb$^{-1}$/run</td>
<td>1 run = 1 month operation</td>
</tr>
<tr>
<td>ep Fcc-eh</td>
<td>3.5 TeV</td>
<td>$1.5 \times 10^{34}$</td>
<td>2 ab$^{-1}$</td>
<td>$60$ GeV e- from ERL Concurrent operation with pp for ~ 20 years</td>
</tr>
<tr>
<td>e-Pb Fcc-eh</td>
<td>$\sqrt{s_{eN}} = 2.2$ TeV</td>
<td>$0.5 \times 10^{34}$</td>
<td>1 fb$^{-1}$</td>
<td>$60$ GeV e- from ERL Concurrent operation with PbPb</td>
</tr>
</tbody>
</table>

Sequential implementation, FCC-ee followed by FCC-hh, would enable:

- Variety of collisions (ee, pp, PbPb, eh) $\rightarrow$ impressive breadth of programme, 6++ experiments
- Exploiting synergies by combining complementary physics reach and information of different colliders $\rightarrow$ maximise indirect and direct discovery potential for new physics
- Starting with technologically ready machine (FCC-ee); developing in parallel best magnet technology for highest pp energy (100++ TeV!)
- Building stepwise at each stage on existing accelerator complex and technical infrastructure

Additional request after Granada:

Develop an option for an initial FCC-hh using NbTi magnets $\rightarrow$ 37.5 TeV with 6T dipoles.
**FCC Integrated Project Technical Schedule**

1. **Project preparation & administrative processes**
   - Permissions

2. **Geological investigations, infrastructure detailed design and tendering preparation**
   - Tunnel, site and technical infrastructure construction

3. **FCC-ee accelerator R&D and technical design**
   - FCC-ee accelerator construction, installation, commissioning

4. **Detector R&D and concept development**
   - FCC-ee detector technical design, collaborations
   - FCC-ee detector construction, installation, commissioning

5. **Superconducting wire and high-field magnet R&D**
   - SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
   - 16 T dipole magnet series production

6. **FCC-hh accelerator construction, installation, commissioning**

7. **FCC-hh detector R&D, technical design**
   - FCC-hh detector construction, installation, commissioning

8. **FCC-ee dismantling, CE & infrastructure adaptations FCC-hh**

<table>
<thead>
<tr>
<th>Cost-estimate /BCHF</th>
<th>AC-Power /MW</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>5.5</td>
<td>100km tunnel and surface infrastructure</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>5</td>
<td>260-350 +1.1BCHF for the Top stage (365GeV)</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>17</td>
<td>580</td>
</tr>
</tbody>
</table>

**FCC project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.**

5/8/2019
Future of the CERN Scientific Diversity Programme

Pretty Impressive response with lots of ideas for new experiments – most based around the present CERN infrastructure. No time to mention these all proposals in any detail … Just a little on some facilities

All submitted as input to the EPPSU

Projects should exploit the uniqueness of CERN accelerator complex and infrastructure.

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, bending crystals) in ALICE and LHCb

Rare decays and precise measurements
KLEVER ($K^0 \rightarrow \pi^0\nu\bar{\nu}$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP ($\eta$ decays)
MUonE (hadronic vacuum polarization for $(g-2)_\mu$)
Proton EDM

Hidden sector with “beam dump”
NA64++ ($e,\mu$)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Other facilities:
$\gamma$-factory from Partially Stripped Ions; nuSTORM

Non-accelerator projects
Exploit CERN’s technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)
Many Dark Sector proposals are in the SPS North Area

- BDF -> SHiP, TauFV
  400 GeV protons
  $4 \times 10^{19}$ pot/year

- EHN1 Neutrino Platform

- T2, T4, T6 targets

- T10 target

- ECN3

- EHN2

- K12

- M2

- NA64++ (electrons)
  H4: 100 GeV
  up to $5 \times 10^{12}$ pot/year

- KLEVER
  - K12: 400 GeV protons
  - up to $1 \times 10^{19}$ pot/year

- NA62
  - dump mode

- M2: 100 – 160 GeV
  up to $1 \times 10^{13}$ mot/year

- Material Cost ~160MCHF

- The future Hidden Sector Campus?
eSPS & LDMX

- ~70 m long X-band based linac (CLIC technology) in the old West Area accelerates e- to 3.5 GeV
- SPS filled in 1 to 2 s via TT60
- Acceleration to 16 GeV in the SPS
- Slow resonant extraction in ~10 s
- Beam delivered via the existing TT10 line to the Meyrin site
- A new, short beamline would branch from TT10 to the experimental hall (LDMX)

Motivation

- Staged deployment of X-band – return on the significant investment
- Possible deployment of FCC-ee RF cavities and high-efficiency power generation
- Strong case made for accelerator based R&D and other studies at the linac R&D facility
- Physics case - unique LDM search reach
- Material Cost ~80 MCHF
Important milestone reached with the successful acceleration and storage of partially stripped ions in LHC ($\text{Pb}^{81+}$)

Proof of principle experiment with full configuration foreseen in the SPS after LS2

Physics potential and performance reach to be assessed once all ingredients are better understood
nu-Storm

Well developed proposal for possible siting at FNAL circa 2013

Siting at CERN – Exploratory study:
- Via existing SPS fast extraction into a new 600m transfer line
- Graphite target, magnetic horn
- Target complex based on previous CENF design
- Containment & transport of pion beam studied
- Far Detector (2000m) at LHC Point 2
- New design for the decay ring
  - SC Combined function magnets in arcs
  - Central energy 1 – 6 GeV/c
  - Momentum acceptance up to ±16%

Scientific objectives:
1. %-level ($\nu_eN$) cross sections
   - Double differential
2. Sterile neutrino search
   - Beyond Fermilab SBN

Preliminary cost estimate (without far detector)
160 MCHF
## Experiment Readiness and Cost

<table>
<thead>
<tr>
<th>Detector Maturity</th>
<th>Cost</th>
<th>Earliest Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Ready</td>
<td>A: &lt;10 MCHF</td>
<td></td>
</tr>
<tr>
<td>B: Under Design</td>
<td>B: 10-50 MCHF</td>
<td></td>
</tr>
<tr>
<td>C: Needs R&amp;D</td>
<td>C: &gt;50 MCHF</td>
<td></td>
</tr>
</tbody>
</table>

### SPS Machine
- **NA61++**: QGP Charm
  - Beam Required: B
  - Detector Maturity: B
  - Cost: A
  - Earliest Operation: Run3
- **COMPASS+**: $R_p$ QCD
  - Beam Required: A
  - Detector Maturity: A
  - Cost: A
  - Earliest Operation: Run3
- **NA62++**: dark sector
  - Beam Required: B
  - Detector Maturity: A
  - Cost: A
  - Earliest Operation: Run3
- **NA64++**: dark photon
  - Beam Required: A
  - Detector Maturity: A
  - Cost: A
  - Earliest Operation: Run3
- **MUonE**: $H_{V} (g-2)_\mu$
  - Beam Required: A
  - Detector Maturity: A
  - Cost: A
  - Earliest Operation: Run3
- **COMPASS++**: QCD
  - Beam Required: B
  - Detector Maturity: A
  - Cost: B
  - Earliest Operation: Run4
- **DIRAC++**: Chiral QCD
  - Beam Required: C
  - Detector Maturity: B
  - Cost: B
  - Earliest Operation: Run4
- **KLEVER**: $K^0 \rightarrow \pi^0 \bar{\pi}^0$
  - Beam Required: B
  - Detector Maturity: C
  - Cost: B
  - Earliest Operation: Run4
- **SHiP**: dark sector &... photon
  - Beam Required: C
  - Detector Maturity: B
  - Cost: C
  - Earliest Operation: Run4
- **eSPS**: dark photon
  - Beam Required: C
  - Detector Maturity: B
  - Cost: C
  - Earliest Operation: Run4
- **nuStorm**: ...
  - Beam Required: C
  - Detector Maturity: C
  - Cost: C
  - Earliest Operation: Run4
- **TauFV**: $\rightarrow 3\pi$
  - Beam Required: C
  - Detector Maturity: C
  - Cost: C
  - Earliest Operation: Run5

### LHC Machine
- **LHC-FT++**: Spin/MM/EDM
  - Beam Required: A
  - Detector Maturity: C
  - Cost: A
  - Earliest Operation: Run3
- **FASTER**: Long lived Particles
  - Beam Required: A
  - Detector Maturity: A
  - Cost: A
  - Earliest Operation: Run3
- **MATHUSLA**: Long lived Particles
  - Beam Required: A
  - Detector Maturity: C
  - Cost: B
  - Earliest Operation: Run4

### Novel
- **AWAKE++**: dark photon
  - Beam Required: C
  - Detector Maturity: B
  - Cost: B
  - Earliest Operation: Run4
- **Factory**: High rate
  - Beam Required: C
  - Detector Maturity: C
  - Cost: A
  - Earliest Operation: Run5
- **EDM ring**: p EDM
  - Beam Required: C
  - Detector Maturity: C
  - Cost: C
  - Earliest Operation: Run5

### PS Machine
- **REDTOP**: decays
  - Beam Required: B
  - Detector Maturity: C
  - Cost: B
  - Earliest Operation: Run4

### Tentative long term schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>LHC</th>
<th>Injectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td></td>
<td>Run3</td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td>Run4</td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td>Run5</td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2028</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2032</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2034</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clearly not everything can be done!
Will need guidance from the EPPSU as well as careful scrutiny of resources availability at CERN
Constraints and Timelines

Whatever Path is decided (straight, or circular)

The next 5 years will have to be spent:
- Continue preparations including detailed site design and administrative actions with the Host State Authorities
- Continue high-priority R&D and Prototyping activities – including Energy Efficiency
- Advancing towards a full TDR – preparing for approval
- Defining the funding model for the necessary resources
- Establishing the project as a world-wide facility

However:
- Both energy frontier projects require an initial preparation phase of 6-8 years
- If we can concentrate on one project, only relatively modest additional resources will be required during the next 5 years

CERN is hoping for a clear recommendation on which route to take
Summary

CERN is presently in the construction phase of a major upgrade to the LHC and Experiments with a view to collecting 10x the data originally foreseen (~3ab⁻¹)

The present Long Shutdown (2019/2020) is being used to upgrade the LHC injector chain as well as undertake the major civil engineering works for HL-LHC

At the same time the diversity physics programme is being enhanced with new facilities and experiments coming on line

For the future CERN has prepared 2 detailed studies for a future energy frontier machine. Both would initially be e⁺e⁻ Higgs-factories, followed by either a hadron collider (100TeV), or a lepton collider (3TeV) the choice should be made based on the physics potential and hopefully consensus will be reached via the EPPSU

In parallel, we have solicited suggestions for new diversity physics experiments and facilities with a very rich and varied set being proposed. Not all can be realized!

CERN has ambitious plans for the future which will help set the direction of the field for decades to come