What We have Learned the Last 50 Years or *Status of the Standard Model*

The Standard Model explains all known collider phenomena and almost all particle physics

**Experimental validation**
- down to $\sim 10^{-18}$ m
- up to $O(100 \text{ GeV})$

- this was beautifully verified at LEP, SLC, Tevatron and the LHC;

- the EWPO radiative corrections predicted top and Higgs masses, assuming SM and nothing else;

- With $M_H \sim 126 \text{ GeV}$, one can even extrapolate the Standard Model all the way to the Plank scale
With a well-founded theoretical model, precision measurements can be turned into discoveries - and precision measurements can guide the development of new models.

There are several missing items in the SM:

- non-baryonic dark matter
- neutrino mass
- baryon asymmetry (absence of anti-matter)
- accelerated expansion of the Universe

The clear need for long-term planning in our research field.

Theory prediction: 1964
Higgs Discovery: 2012
Beyond Standard Model Physics: Solutions

For (most of) proposed solutions:
- new particles should appear at TeV scale \( \Rightarrow \) territory of the LHC

We are embarking on an entirely new “lucky era” in fundamental physics \( \Rightarrow \) No lack of compelling questions!

**Supersymmetry**
- New particles at \( \approx \) TeV scale, light Higgs
- Unification of forces
- Higgs mass stabilized
- No new interactions

**Extra Dimensions**
- New dimensions introduced
- \( m_{\text{Gravity}} \approx m_{\text{elw}} \) \( \Rightarrow \) Hierarchy problem solved
- New particles at \( \approx \) TeV scale

**Technicolor**
- New (strong) interactions produce EWSB
- Extensions of the SM gauge group:
  - Little Higgs
  - GUTs
  - …
New Energy Frontier - Large Hadron Collider (LHC)

ATLAS / CMS: Energy Frontier
LHCb: Flavour Physics and CP-violation
ALICE: Heavy Ion Physics

The Large Hadron Collider at CERN is the largest most complex machine in the world, possibly the universe. By smashing particles together at enormous energies, it recreates the conditions of the Big Bang. The recent discovery of what looks like the “Higgs particle” is a triumph of human endeavour and international collaboration. It will change our perception of the world and has the potential to offer insights into a complete theory of everything. — Stephen Hawking

LHC will guide the way ➔ the only H, (top, Z, W...) factory for a decade(s) to come
PARTICLE PHYSICS LANDSCAPE AT CERN

**High Energy Frontier**

- **LHC**
  - Hadronic Matter
  - deconfinement
  - non-perturbative QCD
  - hadron structure
- **Low Energy**
  - heavy flavours / rare decays
  - neutrino oscillations
  - anti-matter
- **Non-accelerator**
  - dark matter
  - astroparticles
- **Multidisciplinary**
  - climate, medicine

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

**Physics Beyond Colliders Group**

Group set up in 2016: explore opportunities offered by CERN acc. complex / other scientific infrastr.

**Some Highlights in 2018:**

- Upgrades of the HIE/ISOLDE and AD/ELENA facilities were completed;
- AWAKE, demonstrated for the first time electron acceleration from plasma wakefields induced by a proton beam;
- The world’s largest liquid-argon neutrino detector, the single-phase proto-DUNE, at the CERN Neutrino Platform, reconstructed tracks from incident test-beam particles.

**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)

Report submitted to the ESPP
LHC Accelerator Complex: Glorious Run 2

- **LHC peak luminosity:** \(~2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) (2 x nominal): thanks mainly to brightness of beams from injectors and \(\beta^* \leq 30 \text{ cm}\)
- **Fraction of time in physics:** \(~50\%\)
- **Integrated luminosity in 2018:**
  - \(~66 \text{ fb}^{-1}\) ATLAS, CMS (goal was 60 fb-1)
  - \(~2.5 \text{ fb}^{-1}\) LHCb (goal was 2 fb-1)
  - \(~27 \text{ pb}^{-1}\) ALICE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2018</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (TeV)</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>2556</td>
<td>2808</td>
</tr>
<tr>
<td>Max. stored energy per beam (MJ)</td>
<td>312</td>
<td>362</td>
</tr>
<tr>
<td>(\beta^*[\text{cm}])</td>
<td>30 (\rightarrow) 25</td>
<td>55</td>
</tr>
<tr>
<td>p/bunch (typical value) (\times10^{11})</td>
<td>1.1</td>
<td>1.15</td>
</tr>
<tr>
<td>Typical normalized emittance ((\mu\text{m}))</td>
<td>(~1.8)</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity (10^{34}\text{ cm}^{-2}\text{s}^{-1})</td>
<td>2.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

ATLA/CMS pp: Every year a new record

\(\bar{s} = 7-8 \text{ TeV}\)

\[29 \text{ fb}^{-1}\]

Total Run 1 + 2:
- ATLAS, CMS: \(~189 \text{ fb}^{-1}\) (goal - 150)
- LHCb: \(~10 \text{ fb}^{-1}\)

Run 1
Run 2
\(\sqrt{s} = 13 \text{ TeV}\)

\[160 \text{ fb}^{-1}\]
Run 2 is over, ... welcome to LS 2 Preparation for Run 3 and HL-LHC

<table>
<thead>
<tr>
<th>LHC</th>
<th>We are here</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>Run 2</td>
</tr>
<tr>
<td>LS1</td>
<td>7 TeV</td>
</tr>
<tr>
<td>LS2</td>
<td>13 TeV</td>
</tr>
<tr>
<td>EYETS</td>
<td>2 x nom. luminosity</td>
</tr>
<tr>
<td>cryoRFnP4</td>
<td>ATLAS - CMS upgrade phase 1</td>
</tr>
<tr>
<td>P7.11 T dip. coll. Civil Eng. P1-P5</td>
<td>ALICE - LHCb upgrade</td>
</tr>
<tr>
<td>LS3</td>
<td>14 TeV</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>5 to 7 x nominal luminosity</td>
</tr>
</tbody>
</table>

- Despite original MSGC discharge problems, MPGDs have been chosen for many LHC upgrades.
- Successful accomplishment of LHC Upgrades will help to disseminate MPGD technologies even wider.

LS2 overview: ATLAS
- New "Small" Wheels

LS2 Overview: LHCb
- New FastBoard PCI express New Front-end electronics
- Replace Calorimeter and front-end electronics
- RICH, TPC, RHIC, detectors Hybrid Electronics

LS2 overview: CMS
- New On/Off-line computing farm (O2)
- New Trigger Detectors (FIT)
- New RICH, TPC, RHIC, detectors Hybrid Electronics

Beam-pipe (all chambers except)
- Cylindrical central barrel + Al inserts
- Al outer with shallower core
- Lower activities helps with ALARA, phase 2 Tracker compatible

Forward systems
- New T2 hadron (TOTEN, INL) with CTPPS, RP det & moving sys upgrade

Magnet System (defines critical path)
- New 4T axial field (TOTEN, INL) with new magnet
- New magnet in inner ring of T2 (TOTEN, INL) with new magnet
- New magnet in outer ring of T2 (TOTEN, INL) with new magnet

Magnet System (defines critical path)
- New 4T axial field (TOTEN, INL) with new magnet
- New magnet in inner ring of T2 (TOTEN, INL) with new magnet
- New magnet in outer ring of T2 (TOTEN, INL) with new magnet

Triggers/DAQ
- DAQ 2 --> DAQ 3, IE/IE x 4 faster
- Blueprint update

Barrel HCAL (last Phase-II upgrade)
- Replace rod damaged HPD by SiPM- depth segmentation

MAGNET (stays cold) & Yoke
- Cylindrical superconducting yoke
- New opening system (telescopic yokes)
- New cryostat Yoke (Passive services)

3D CAD model of ATLAS Barrel Inner-Outer modules
- TOAD upgrade
- Calorimeter Electrodes
- New "Small" Wheels
- New On/Off-line computing farm (O2)
- New Trigger Detectors (FIT)
From Discovery to Precision: **THE Higgs or A Higgs**

Measurements of Higgs properties with increasing precision are a formidable tool to look for new-physics manifestations → experimental precision approaching theory precision even before using full Run 2 statistics.

**Higgs is so simple and so unnatural** → a "malicious choice"
Energy Frontier vs Flavour Physics Experiments: Complementary Approaches

Direct searches at the Energy Frontier (ATLAS, CMS) probe the scale of New Physics Scale ($\Lambda$)

Limited by available CM energy

Flavour physics (LHCb, Belle II, also ATLAS/CMS) probe NP scale ($10^2$–$10^5$ TeV) indirectly, through loop effects

Limited by the size of flavor violation $\delta$ and the available statistics/precision
Lepton Flavour Universality: Intriguing Anomalies

**LFU tests in** $b \rightarrow c \nu \tau$ transitions

**BSM: Two-Higgs-Doublet Model Type II**

\[
R_{D^*} = \frac{BR(B^0 \rightarrow D\tau\bar{\nu})}{BR(B^0 \rightarrow D\mu\bar{\nu})}
\]

- **Recent Belle’s and LHCb’s results significantly improve the precision, but don’t really yield a clearer picture...**
- **With the beginning of Belle II data taking, and LHCb upgraded detector starting data taking in 2021, we can expect the flavour anomalies to soon be understood.**

**LFU test in** $b \rightarrow s l^+ l^-$ transitions

theoretically very clean $\rightarrow$ non-LFU sign of NP

**Non-LFU Hints** $\rightarrow$ Motivation to pursue leptoquark searches, e.g. 2nd/3rd generations

**Caveat:** uncertainties in predictions are matter of theory debate
The CKM Unitarity Triangle and New Physics

NP Flavor Problem:

- Most TeV-scales new physics contain new sources of CP and flavor violation
- The observed baryon asymmetry of the Universe requires CPV beyond the SM (neither necessarily in flavor changing processes, nor necessarily in quark sector)

Tremendous success of the CKM paradigm:

Crucial for improving sensitivity to BSM \( \rightarrow \) compare tree vs. loop measurements \( \rightarrow \) e.g. \( \gamma \) and \( |V_{ub}| \) (statistics limited with any currently imagined dataset/experiment)

Need experimental precision and theoretical cleanliness to increase NP sensitivity

\[
\begin{align*}
\text{(LHCb upgrade)} & \sim (\text{Belle II data set}) & \sim 50 \\
\text{(LHCb 1 fb}^{-1}) & \sim (\text{Belle data set}) & \sim (1999 \text{ CLEO data set})
\end{align*}
\]

Today:

O(10%) NP contributions to most loop processes (FCNC) are compatible with the current data

arXiv: 1704.02938

50 ab\(^{-1}\) BELLE & 50 fb\(^{-1}\) LHCb
Direct Searches for the BSM Physics

NO EVIDENCE ...

- Yet hierarchy problem remains
- Universe could be fine-tuned
- Or we need a new paradigm → widening the horizon “which SUSY” (e.g. CMSSM, PMSSM,)

- New particles may have complex signatures (SUSY hiding in some unexplored corner ?)

→ Room for discovery with sophisticated analyses / at future upgrades, colliders
Four Main Results from LHC Up-to-Now:

1. We have consolidated the Standard Model (wealth of measurements at 8 / 14 TeV, including flavor physics, rare $B_s \rightarrow \mu\mu$ decay, very sensitive to New Physics) → it works BEAUTIFULLY …

2. We have completed the Standard Model: Discovery of the messenger of the BEH field → the Higgs boson discovery

3. We found interesting properties of the hot dense matter

4. We have no evidence of new physics (YET), beyond the Standard Model – it may remain valid up to very high energies → No argument yet for a particular energy scale beyond the SM

Is this the End … What’s Next?
Put the Higgs Boson Under a Magnifying Glass

**Higgs boson is the only fundamental scalar particle ever discovered:**

- Is the Higgs elementary particle or composite?
- Is there a single Higgs or more than one Higgs?
- Additional sources of CP violation in the Higgs sector?
- Is BSM physics connected to the Higgs sector (Higgs Portal) → exotic Higgs decays?
- How does the Higgs relate to neutrino masses?
- Does the Higgs couple to Dark Matter?
- How is the Higgs mass protected from physics at high scales (“Naturalness problem”)
  → Is $m_H$ stabilized by $\sim$TeV scale new physics or is it fine-tuned?
What’s Next? - “Road Beyond the Standard Model”

At the Energy Frontier: through synergy of:
- hadron - hadron colliders
- lepton - hadron colliders
- lepton - lepton colliders

Ambitious Scope
- High Costs
- Long R&D Times
- Global Projects (Politics!)

Proton-proton collisions

<table>
<thead>
<tr>
<th>Proton is compound object</th>
<th>e⁺/e⁻ are point-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial state not known event-by-event</td>
<td>Initial state well defined (√s / polarization)</td>
</tr>
<tr>
<td>Limits achievable precision</td>
<td>High-precision measurements</td>
</tr>
</tbody>
</table>

High-Energy Circular Colliders feasible

High rates of QCD backgrounds
- Complex triggering schemes
- High levels of radiation

Clean experimental environment
- Trigger-less readout
- Low radiation levels

High cross-sections for colored-states

Superior sensitivity for electro-weak states
Future Circular Collider (FCC)

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

- variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV!)
- building stepwise at each stage on existing accelerator complex and technical infrastructure

CERN is seeking for its post-LHC future via a new collider

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

- variety of collisions (ee, pp, PbPb, eh) → impressive breadth of programme, 6++ experiments
- exploiting synergies by combining complementary physics reach and information of different colliders → maximise indirect and direct discovery potential for new physics
- starting with technologically ready machine (FCC-ee); developing in parallel best technology (e.g. HTS magnets) for highest pp energy (100++ TeV!)
- building stepwise at each stage on existing accelerator complex and technical infrastructure

Purely technical schedule
assuming green light to preparation work in 2020
A 70 years programme

<table>
<thead>
<tr>
<th></th>
<th>√s</th>
<th>L/IP (cm⁻²s⁻¹)</th>
<th>Int. L/IP(ab⁻¹)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺e⁻</td>
<td>Z</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee</td>
<td>90 GeV</td>
<td>230 x10³⁴</td>
<td>75 ab⁻¹</td>
<td>2 experiments</td>
</tr>
<tr>
<td>160</td>
<td>W</td>
<td>28</td>
<td>5</td>
<td>Total ~ 15 years of operation</td>
</tr>
<tr>
<td>240</td>
<td>H</td>
<td>8.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>~365</td>
<td>top</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>100 TeV</td>
<td>5 x 10³⁴</td>
<td>2.5 ab⁻¹</td>
<td>2+2 experiments</td>
</tr>
<tr>
<td>FCC-hh</td>
<td></td>
<td>30</td>
<td>15</td>
<td>Total ~ 25 years of operation</td>
</tr>
<tr>
<td>PbPb</td>
<td>√s_{NN} = 39 TeV</td>
<td>3 x 10²⁹</td>
<td>100 nb⁻¹/µB</td>
<td></td>
</tr>
<tr>
<td>FCC-hh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e-Pb</td>
<td>√s_{eN} = 2.2 TeV</td>
<td>0.5 x10³⁴</td>
<td>1 fb⁻¹</td>
<td>60 GeV e⁻ from ERL Concurrent operation with PbPb</td>
</tr>
<tr>
<td>FCC-eh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FCC Study: 4-volume CDR released on 15 Jan. 2019
Also studied: HE-LHC: √s=27 TeV using FCC-hh 16 T magnets in LHC tunnel; L~1.6x10³⁵ → 15 ab⁻¹ for 20 years operation

F. Gianotti, 15/01/2019

Purely technical schedule
assuming green light to preparation work in 2020
A 70 years programme
**Accelerator Magnet Technologies: International Collaboration**

- **Need 16 T** (14.3 m long dipoles) to reach 50 TeV /beam
  - move from NbTi (LHC technology) to Nb$_3$Sn
  - Nb$_3$Sn international R&D programme
  - Several EU countries and US LARP & its successor

- **Magnet is key cost driver** (improve cable performance, reduce cable cost, improve fabrication of magnet, ...)

- **Training quench is still a critical issue** → can we improve training of Nb3Sn magnets?

- **How do we manage the forces and stresses in a 16T accelerator magnet?**

- **Can we improve the manufacturing processes?**

**China:** starting the development of HTS high-field magnets (may increase field to 20T) for SppC
### FCC-hh Collider Parameters & Detector Challenges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>1.27</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>Bunch intensity [10^{11}]</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Synchr. rad. power / ring [kW]</td>
<td>2400</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>4.1</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Long. emit. damping time [h]</td>
<td>0.54</td>
<td>1.8</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.45</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>Normalized emittance [μm]</td>
<td>2.2</td>
<td>2.5</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity [10^{34} cm^{-2}s^{-1}]</td>
<td>5</td>
<td>30</td>
<td>16</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>Events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>460</td>
<td>132</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.4</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>

HL-LHC and FCC-hh have similar number of interactions per BX

- **Vertex / Tracker**: neutron fluxes – first layer (2.5 cm): \(\sim 5-6 \times 10^{17} \text{ cm}^{-2}\); external part: \(\sim 5 \times 10^{15} \text{ cm}^{-2}\)

- **Barrel ECAL, Endcap ECAL/HCAL, Forward ECAL/HCAL**: LAr technology - intrinsically radiation hard (Silicon ECAL and ideas for digital ECAL with MAPS are also discussed)

- **HL-LHC Muon gas detector technology** will work for most of FCC areas \(\Rightarrow\) opportunity for MPGDs?
Future Electron-Positron Colliders: “Higgs Factory”

Linear colliders: **ILC, CLIC** (technical extendability to TeV regime)

- **International Linear Collider (ILC):**
  - Japan (Kitakami)
  - $\sqrt{s} = 250 - 500 \text{ GeV}, 1 \text{ TeV}$
  - Length: 21 km - 31 km (50 km)

- **Compact Linear Collider (CLIC):**
  - CERN
  - $\sqrt{s} = 380 \text{ GeV}, 1.5 \text{ TeV}, 3 \text{ TeV}$
  - Length: 11 km, 29 km, 50 km

General consensus: next ”big machine” should be e+e- collider to scrutinize Higgs boson characteristics

Circular colliders: **CEPC, FCC-ee**

- **Circular Electron-Positron Collider (CEPC):**
  - China
  - $\sqrt{s} = 90 - 240 \text{ GeV}$
  - Circumference: 100 km

- **Future Circular Collider (FCC-ee):**
  - CERN
  - $\sqrt{s} = 90 - 350 \text{ GeV}$
  - Circumference: ~100 km


Storage Rings or Linear Collides for Future e+e- Accelerator

- **Energy tends to be the cost driver:**
  - hadrons - high-field magnets;
  - e+e- - high-gradient RF

**Circular collider:**
- high-luminosity from Z peak to top threshold

**Linear colliders:**
- extendability to high energies and beam polarization

- $\mathcal{L} \times E_{CM}$ drives the MWatts (at least for leptons):
  - it’s all about COST per GeV | inv fb

- Where are the acceptable limits? (not the technical limits)

- High running costs may need to be shared (global project)

- R&D needed in increasing efficiencies and/or recovering the energy

---

**ILC Upgrades:**
- 2.7 x 10^34 /cm^2/s (doubling # bunches)
- 5.4 x 10^34 /cm^2/s (repetition rate 5 → 10 Hz)

**Luminosity per IP**
(FCC-ee and CepC assumes 2)

**H. Yamamoto, M. Stanitzki**
Recoil mass measurement: detecting the Higgs boson without using its decay!

This method yields absolute measurements of all $\sigma(ZH) \times BR$ and model-independent determination of the total Higgs width / cross section (e.g. invisible Higgs, $H \rightarrow cc$, modes undetectable at LHC) and Higgs couplings.

This would be a boon to entire Higgs effort, as it feeds into hadron-collider Higgs measurements to break redundancies and maximise impact → Large quantitative and qualitative improvement over the HL-LHC.
Low mass, pixelated, radiation hard vertex detectors are needed for the LHC ILC, CLIC, FCC, B-factories, …:

- Going to smaller node sizes (65nm) does not necessarily guarantee radiation hardness improvement
- The impact of “digital” is still very small in HEP, replace “quantity” of data with “quality” of data
- More exotic technologies (TSVs, wafer stacking, adv. packaging…) may become available also for low-volume, but history teaches one should bet on mainstream opportunities

**Hybrid HAPS:**

**Monolithic (CMOS-MAPS):** 25 – 50 μm

**3D-Detectors:** 25–50 μm

**3D TSV:** < 20 μm

**Integrated sensor & electronics:** Less X0, no bonding, low noise

**Lower V_{dep} (power):** Faster charge collection

**3D vertical Integration (TSV)**
Beam polarization is a powerful tool:

- Measurement of helicity-dependent electroweak couplings; determine quantum numbers of new particles
- Suppression of backgrounds / enhancement of signals;
- Control of systematic uncertainties;
- Increased sensitivity relative to unpolarized collisions;

For Higgs coupling measurements, polarization compensates for ILC’s lower than FCC-ee 250 GeV integrated luminosity (2 vs 5 ab-1) by:

1) Increased rates
2) Removing some correlations between different EFT operators

arXiv: 1903.01629
ILC vs CLIC: Superconducting vs Normal RF

ILC:
- Higher Power Efficiency (31-35 MV/m)
- Lower RF Frequency (1.3 GHz)
  → relaxed tolerances & smaller emittance dilution
- High-Q ($Q_0 = 10^{10}$):
- Larger aperture / better beam quality
- Long beam pulses (~ 1 ms or CW)
- Cryogenics

CLIC:
- Higher Gradient (70-100 MV/m)
- Higher RF Frequency (12 GHz):
  → more accuracy required
- Ordinal-Q$_0$
- Smaller aperture / better accuracy
- Short beam pulses (μs pulse)
- Water cooling

ILC250 Higgs Factory

The LC (ILC/CLIC) can be pursued for construction starting-up in about 5 years → aiming for operation by ~ 2030-2035
A World-Wide Infrastructure for Linear Colliders

Swiss FEL (CLiC-like):
- 104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)
- Length ~ 800 CLIC structures

US infrastructure @ LCLS
- 35 cryomodules
- 280 cavities
- 4 GeV (CW)

European XFEL

ILC Kitakami proposed site

KEK-ILC Lab Hub

EXFEL SRF Cavity Gradients:

Swiss FEL (CLiC-like):
- 104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)
- Length ~ 800 CLIC structures
EXFEL @ DESY: an Ultimate Integrated System Test (10%) for ILC

The currently longest super-conducting accelerator in the world

Largest deployment of SRF technology to date:
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)

Personal remark - ILC remains:
- The most advanced of all e+e- collider projects
- The less expensive option for European budget (also new money for HEP)
  → an opportunity for European expertise and high-tech industry

Acknowledging the efforts of the Tesla Technology Collaboration (TTC)
Neutrinos are Messengers of New Physics

- Flavour mixing & $\Delta m^2$ are well known - O(10%);
  - very different in quark and leptons
- Neutrino masses: what is the absolute scale and the hierarchy (normal or inverse)?
- How large is CPV phase $\delta_{\text{CP}}$?
- Is $N_v = 3$ or there are more (sterile) neutrinos?
- Is neutrino Dirac of Majorana fermion?

Do neutrino oscillations violate CP ($\delta_{\text{CP}}$)?
- Necessary condition for successful baryogenesis (matter-antimatter asymmetry of the universe)

CP violation requires genuine 3ν oscillations, distinct from 2ν limits...

- 3 mixing angles should be nonvanishing ✔
- 2 mass gaps should be nonvanishing ✔
- 1 phase should be nonvanishing

Nature has already provided us with 5 favorable conditions at terrestrial scales...

Let us hope that the 6th is also realized!
Long-Baseline Neutrino Oscillation Programme

Present / Recent:
- Europe: OPERA, ICARUS (complete)
- Japan: T2K
- US: MINOS, MINOS+ (data analysis)
  NOvA

Near Future
- Japan: T2K, T2HK, T2HKKK
- US: DUNE

- 2σ sensitivity to CP violation for favourable parameters by 2024
- Possible hierarchy determination at 3σ in 2020

→ Both (NOvA and T2K) favor maximal mixing for neutrinos and Normal hierarchy (also slight preference by IceCube)
**Finding 1 (Science):** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms: How does the mass of the nucleon arise? How does the spin of the nucleon arise? What are the emergent properties of dense systems of gluons?

**Finding 2 (Accelerator):** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient and variable center-of-mass energy.

**Finding 3:** An EIC would be an unique facility in the world, and would maintain U.S. leadership in nuclear physics.

**Finding 4:** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders, and help to maintain scientific leadership more broadly.

**Finding 5:** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

**Finding 9:** The broader impacts of building an EIC in the U.S. are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.
The European Strategy for Particle Physics

...executing the ongoing European Strategy for Particle Physics

Energy Frontier

- Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the current design, by around 2030. This upgrade programme will also provide significant opportunities for the study of flavour physics and the quark and lepton sectors.

- To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available.

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 lead 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.

- Need to present and discuss new large scale projects in an international context before making choices

- Need to present physics case(s) always taking into account latest results at existing facilities

- Need to present (additional) benefits to society from the very beginning of the project

- Need to have excellent communication and outreach accompanying all projects

Global vision for our field going beyond regional boundaries

CERN is playing a major role in this global endeavour
Towards 2020 Update of European Strategy for Particle Physics

Preparing Update of the European Strategy for Particle Physics:
- LHC and HL-LHC Exploitation
- Next Step at the Energy Frontier (FCC / ILC / CLIC) and R&D beyond
- Accelerator-based Neutrino Programme (US & Japan) via Neutrino Platform
- Rich Diversity Physics Programme Beyond Colliders

ESPP Symposium: [https://indico.cern.ch/event/808335/timetable/#all.detailed](https://indico.cern.ch/event/808335/timetable/#all.detailed)
BACK-UP SLIDES