Future – Path to Very High Energies: Hadron/e+e-/Muon Colliders

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CERN Council Open Symposium on the Update of European Strategy for Particle Physics
13-16 May 2019 - Granada, Spain
Accelerator Science and Technology: major advances since the 2013 European Strategy

• Impressive technology progress (see Akira’s talk):
  – 11 T Nb₃Sn magnets for HL-LHC
  – 17 GeV of SRF European X-FEL and \( N_2 \) doping for \( Q_0 > 10^{10} \)

• Expanded frontiers of beams:
  – Absolute* luminosity record \( 2.1 \times 10^{34} \) at the LHC (* repeat KEK-B ’2009)
  – Record 760 kW \( p^+ \) beam power on neutrino target at Fermilab
  – Super-KEKB built and being commissioned

• Beam physics breakthroughs:
  – Ionization cooling of muons demonstration MICE at RAL
  – \( e^- \)-lens compensation of \( pp \) head-on beam-beam effects in RHIC
  – Record beam-beam parameter 0.25 in VEPP2000 \( e^-e^+ \) “round beams”
  – Bunched beam electron cooling in RHIC
  – Plasma acceleration records 2/4/9 GeV in AWAKE/BELLA/FACET
  – 40 nm beam focus attained at the ATF2 (ILC facility)
I WILL ATTEMPT TO OVERVIEW

1. Higgs factory implementation options: accelerator physics and technology challenges, readiness, cost and power

2. Path towards the highest energies: how to achieve the ultimate energy and performance, R&D required

3. Promises, challenges and expectations of new acceleration techniques
Higgs Factories

- $e^+e^-$ linear
  - ILC
  - CLIC

- $e^+e^-$ circular
  - FCC-ee
  - CePC

- $\mu^+\mu^-$ circular
  - $\mu$-HF

Requirement: high luminosity $O(10^{34})$ at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine:
- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost “1 LHC Unit” *

* as a project, i.e. w/o existing tunnel and injectors
International Linear Collider

Key facts:

- 20 km, including 5 km of Final Focus
- SRF 1.3 GHz, 31.5 MV/m, 2 K
- 130 MW site power @ 250 GeV c.m.e.
- Cost estimate 700 B JPY*

* ±25% err, includes labor cost
Compact Linear Collider

Key facts:
11 km main linac @ 380 GeV c.m.e.
NC RF 72 MV/m, two-beam scheme
168 MW site power (~9MW beams)
Cost est. 5.9 BCHF ± 25%
Challenges of Linear Colliders Higgs Factories

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} \quad N n_b f_r \quad \frac{1}{\sigma_y} \quad \sim 10^{34} \]

- **Luminosity Spectrum** (Physics)
  - \( \delta E/E \sim 1.5\% \) in ILC
  - Grows with \( E \): 40\% of CLIC lumi 1\% off \( \sqrt{s} \)

- **Beam Current** (RF power limited, beam stability)
  - Challenging \( e^+ \) production (two schemes)
  - CLIC high-current drive beam bunched at 12 GHz (klystrons + 1.4 BCHF)

- **Beam Quality** (Many systems)
  - Record small DR emittances
  - 0.1 \( \mu m \) BPMs
  - IP beam sizes
    - ILC 8nm/500nm
    - CLIC 3nm/150nm
Recent progress: Linear Colliders

- **Accelerating gradients** demonstrated with beams:
  - ILC 31.5 MeV/m – FNAL’17, KEK’19
  - CLIC ~100 MeV/m – CLEX@CERN

- **Beam focusing**
  - 40 nm V beam size ATF2@KEK’16
Linear Colliders $e^+e^-$ Higgs Factories

**Advantages:**
- Based on mature technology ([Normal Conducting RF, SRF](#))
- Mature designs: ILC TDR, CLIC CDR and test facilities
- Polarization ([ILC: 80%-30%; CLIC 80% - 0%](#))
- Expandable to higher energies ([ILC to 0.5 and 1 TeV; CLIC to 3 TeV](#))
- Well-organized international collaboration (LCC) → “we’re ready”
- Wall plug power ~130-170 MW (i.e. <= LHC)

**Pay attention to:**
- Cost more than LHC ~(1-1.5) LHC
- LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
  - e.g. factor of 4 for ILC: $x2 \ N_{\text{bunches}}$ and $5 \ Hz \rightarrow 10 \ Hz$
- Limited LC experience ([SLC](#)), two-beam scheme ([CLIC](#)) is novel, klystron option as backup
- Wall plug power may grow >LHC for $lumi / E$ upgrades
Circular $e^+e^-$ Higgs Factories

Key facts:

100 km tunnel, three rings ($e^-$, $e^+$, booster)
SRF power to beams 100 MW (60 MW in CepC)
Total site power <300MW (tbd)
Cost est. FCCee 10.5 BCHF (+1.1BCHF for tt)
("< 6BCHF" cited in the CepC CDR)

FCC-ee CDR (2018)
Challenges of e+e- Ring HF’s

- **Power limited regime.** Synchrotron radiation power from both beams limited to \(100 \text{ MW}\) \((P/\eta=\text{total cite power})\) → current \(I\) is set by power

\[
I = \frac{e\rho}{2C\gamma E^4} P_T, 
\]

- **Luminosity** determined by bend radius \(\rho\), beam-beam parameter \(\xi_y\), beta function at the IP \(\beta_y^*\) and power

\[
\mathcal{L} \gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)} \left[ \rho \frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z) \right]
\]

- \(\xi_y = 0.13\) new beam-beam instability; while synchrotron radiation \(\Delta E_{\text{turn}}/E \sim 0.1-5\%\) per turn \(Z\) to 360 GeV, the beam-strahlung is at IPs only and spreads \(\Delta E/E \sim 0.1-0.2\%\), but tails upto \(10\times\) that \(\pm 2.5\%\) determine 18 min beam lifetime \(\sim 18\ \text{min}\) → need large acceptance optics \(\beta_y^* = 0.8-1.6\ \text{mm}\), crab-waist scheme and full energy booster
$e^+e^-$ Higgs Factories: Circular vs Linear

![Graph showing luminosity vs SQRT(s) for different Higgs processes and experiments.](image-url)
### e+e- Ring Higgs Factories

**Advantages:**
- Based on mature technology (SRF) and rich experience → lower risk
- High(er) luminosity and ratio luminosity/cost; upto 4 IPs, EW factories
- 100 km tunnel can be reused for a pp collider in the future
- Transverse polarization ($\tau \sim 18$ min at $tt$) for $E$ calibration $O(100\text{keV})$
- CDRs addressed key design points, mb ready for ca 2039 start
- Very strong and broad *Global FCC Collaboration*

### Strategic R&D ahead:

- **High efficient RF sources:**
  - Klystron 400/800 MHz $\eta$ from 65% to >85%
- **High efficiency SRF cavities:**
  - 10-20 MV/m and high $Q_0$; Nb-on-Cu, Nb$_3$Sn
- **Crab-waist collision scheme:**
  - *Super KEK-B* nanobeams experience will help
- **Energy Storage and Release R&D:**
  - Magnet energy re-use > 20,000 cycles
- **Efficient Use of Excavated Materials:**
  - 10 million cu.m. out of 100 km tunnel
**μ+μ- Higgs Factory**

### Key facts:

- 1/100 luminosity requirements (large cross-section in \(s\)-channel)
- Half the energy: \(2 \times 63 \text{ GeV} \rightarrow \mu+\mu- \rightarrow H_0\)
- Small footprint (<10 km) and low cost
- Small(est) energy spread: ~3 MeV
- Total site power: ~200MW (tbd)

### Additional Details:

- Energy in the center of mass: \(E_{cm} = 126 \text{ GeV}\)
- Compact distance: \(C = 300\text{m}\)

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JINST Special Issue *(MUON)*
Recent progress: $\mu^+\mu^-$ Colliders

- **Ionization cooling of muons:**
  - Demonstrated in MICE @ RAL
  - 4D emittance change $O(10\%)$

- **NC RF 50 MV/m in 3 T field**
  - Developed and tested at Fermilab

- **Rapid cycling HTS magnets**
  - Record 12 T/s – built and tested at FNAL

- **First RF acceleration of muons**
  - J-PARC MUSE RFQ 90 KeV

- **US MAP Collaboration $\rightarrow$ Int’l**

- **Low emittance (no cool) concept**
  - 45 GeV $e^+e^- \rightarrow \mu^+\mu^-$ : CERN fixed target
Future Energy Frontier Colliders

• All proposals are focused on:
  – (Affordable) Cost and (High) Luminosity

• Usually:
  – Scale of civil construction grows with Energy
  – Cost of accelerator components grows with Energy
  – Requirement site power grows with Energy

• So, the total cost grows with ENERGY
  – Thankfully, not linearly, more like \( \text{cost} \sim \beta E^\kappa \), \( \kappa \approx \frac{1}{2}...\frac{2}{3} \)
    • Take ILC as an example: 0.25 \( \rightarrow \) 0.5 \( \rightarrow \) 1 TeV \( 0.69 : 1 : 1.67 \)
  – Still, huge challenge for energies \( E \) some \( \times 10 \) of LHC
  – Choice of technology (\( \beta \)) and prior investments are critical
let’s consider

Limits of Linear $e^+e^-$ Colliders

• Both ILC and CLIC offer staged approach to ultimate $E$

• The limits are set by:
  - Cost
  - Electric power required
  - Total length
  - (complication of) Beamstrahlung

<table>
<thead>
<tr>
<th>System</th>
<th>Energy (TeV)</th>
<th>Cost (B$)</th>
<th>±25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC TDR</td>
<td>1</td>
<td>17</td>
<td>25%</td>
</tr>
<tr>
<td>CLIC CDR</td>
<td>3</td>
<td>18.3</td>
<td>25%</td>
</tr>
</tbody>
</table>
Beamstrahlung rms energy spread:

$$\delta_{BS} \propto \left( \frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

→ Luminosity:

$$L \propto P_{beam} \sqrt{\frac{\delta}{\gamma \varepsilon_y}} \ H_D$$

Luminosity Dilution by Beamstrahlung

Total Facility Site Power Required

Total Facility Length

CERN

LHC
Circular $pp$ Colliders

**Key facts:**

- **HE-LHC / FCC-hh**
  - Large tunnel: 27 / 100 / 100 km
  - SC magnets: 16 / 16 / 12 T
  - High Lumi / pileup: $O(10^{35}) / O(500)$
  - Site power (MW): 200 / 500? / ?
  - Cost (BCHF): 7.2 / 17.1 / ?

- **SppC**
  - 75 TeV

* follow up after e+e- Higgs factories
Strategic R&D Ahead:

- **High field dipoles:**
  - Nb3Sn 16 T / iron-based 12 T, wire
  - (see also Akira’s talk)

- **Intercept of synchr radiation:**
  - 5 MW FCC-hh / 1 MW CepC

- **Collimation:**
  - x7 LHC circulating beam power

- **Optimal injector:**
  - 1.3TeV scSPS, 3.3 TeV in LHC/FCC

- **Overall machine design:**
  - IRs, pileup, vacuum, etc
  - Power and cost reduction

*All that might take 12-18 years*
Unique opportunities:

- ion-ion collisions
- ep/ei collisions
- ~60 GeV e- Energy Recovery Linac

Key facts: LHeC / FCC-eh

6-9 km tunnel

Energy
- LHeC \( \sqrt{s} = 1.3 \text{ TeV} \)
- FCC-eh \( \sqrt{s} = 3.5 \text{ TeV} \)

SRF 800 MHz CW

Luminosity \( O(10^{34}) \)

Site power ~100 MW

Cost ~1.3-1.6 BCHF *

Key R&D: PERLE @ Orsay
High Energy $\mu^{+}\mu^{-}$ Colliders

**Advantages:**
- $\mu$’s do not radiate / no beamstrahlung $\rightarrow$ acceleration in rings $\rightarrow$ low cost & great power efficiency
- $\sim x7$ energy reach vs $pp$

Offer “moderately conservative - moderately innovative” path to cost affordable energy frontier colliders:
- US MAP feasibility studies were very successful $\rightarrow$ MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

**Key to success:**
- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA $e^{+}$-$45$ GeV + $e^{-}$ at rest $\rightarrow$$\mu^{+}$-$\mu^{-}$, design study of acceleration, detector background and neutrino radiation

\[ M_{\text{NewPhysics}} = \sqrt{s}/2 \]

\[ \mu\mu \ @ \ 14 \ \text{TeV} \]
\[ pp \ @ \ 100 \ \text{TeV} \]
Finding **Common Denominators** * – Three Factors

* to be further discussed in the Symposium’s accelerator sessions

- **F1 “Technology Readiness”**:
  - **Green**: TDR
  - **Yellow**: CDR
  - **Red**: R&D

- **F2 “Energy Efficiency”**:
  - **Green**: 100-200 MW
  - **Yellow**: 200-400 MW
  - **Red**: > 400 MW

- **F3 “Cost”**:
  - **Green**: < LHC
  - **Yellow**: 1-2 x LHC
  - **Red**: > 2x LHC
<table>
<thead>
<tr>
<th>Higgs Factories</th>
<th>Readiness</th>
<th>Power-Eff.</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee Linear 250 GeV</td>
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<tr>
<td>ee Rings 240 GeV/ττ</td>
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<tr>
<td>μμ Collider 125 GeV</td>
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<tr>
<td>Highest Energy</td>
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<td></td>
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<tr>
<td>ee Linear 1-3 TeV</td>
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<td>pp Rings HE-LHC</td>
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<tr>
<td>FCC-hh/SppC</td>
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<tr>
<td>μμ Coll. 3-14 TeV</td>
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</tbody>
</table>
7-10 YEARS FROM NOW
WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

• **ILC:**
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)

• **CLIC:**
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning

• **CepC:**
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)

• **FCC-ee:**
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039

• **HE-LHC:**
  - **R&D and prepar’ns** 2020-2035
  - Construction 2036-2042

• **FCC-hh (w/o FCC-ee stage):**
  - **16T magnet prototype** 2027
  - Construction 2029-2043

• **μ⁺-μ Collider:**
  - **CDR completed** 2027, cost known
  - Test facility constructed 2024-27
  - Tests and TDR 2028-2035
ALTERNATIVE ACCELERATION TECHNIQUES
promise, status and challenges
**Plasma Wakefield Accelerators**

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{GeV}{m} \right] \cdot \sqrt{n_0 \left[ 10^{18} \text{ cm}^{-3} \right]} \]

**Key facts:**

Three ways to excite plasma (drivers)

- **laser** \( dE \sim 4.3 \text{ GeV} \) \( (10^{18} \text{ cm}^{-3} \) 9cm)  
- **e- bunch** \( dE \sim 9 \text{ GeV} \) \( (~10^{17} \text{ cm}^{-3} \) 1.3m)  
- **p+ bunch** \( dE \sim 2 \text{ GeV} \) \( (~10^{15} \text{ cm}^{-3} \) 10m)  

Impressive proof-of-principle demos

In principle, feasible for **e+e- collisions**

Collider cost and power will greatly depend on the **driver technology**:

- lasers, super-beams of electrons or protons
Plasma Colliders:

Key Issues to Study:
- acceleration of positrons
- Staging efficiency
- emittance control vs scatter
- beamstrahlung
- HP lasers / HP operation
- power efficiency

Plenty of interest and opportunities:
- Collaborations: EuPRAXIA, ALEGRO study, ATHENA
- Facilities: PWASC, ELBE/HZDR, AWAKE, CILEX, CLARA and SCAPA, EuPRAXIA @ SPARC_LAB at INFN-LNF, Lund, JuSPARC at FZJ and FLASHFor-ward and SINBAD at DESY; also in Japan (ImPACT), China (SECUF) and in the US (FACET-II, BELLA)
- Proposals of plasma $e^-$ injectors:
  - 100 MeV to IOTA (FNAL)
  - 700 MeV to PETRA-IV booster (DESY)

* the first four can be addressed by using $\mu$’s in $10^{22}$ cm$^{-3}$ crystals – up to 1 PeV
Summary:

- **Remarkable progress of the projects/proposals/technologies:**
  - esp. ILC, CLIC, FCC-ee, -hh, CepC, μ-Colinders, plasma, …
  - allow in-depth evaluation of readiness, power and costs

- **Higgs Factories Implementation:**
  - several feasible options on the table
  - the choice might define high-energy future collider choice

- **Highest Energy Future Colliders:**
  - demand very high AC power & cost; some options to save
  - each machine has a set of key R&D items for next 7-10 yrs
  - core acceleration technology R&D – SC magnets, SRF and plasma – are of general importance and help all - $pp/ee/\mu\mu$

- **We also expect to gain valuable experience from the machines to be built and operated over the next decade**
  - (see next slide)
<table>
<thead>
<tr>
<th>Facility</th>
<th>Country</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperKEKB</td>
<td>Japan</td>
<td>7+4 Gev $e^+e^-$, 8e35 nano-beams scheme</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>CERN</td>
<td>x5 LHC luminosity Nb$_3$Sn magnets, crab cavities</td>
</tr>
<tr>
<td>NICA</td>
<td>Russia</td>
<td>ii/pp 11-27 GeV electron and stochastic cooling</td>
</tr>
<tr>
<td>PIP-II</td>
<td>USA</td>
<td>SRF linac to double # $\nu$'s CW SRF, &gt;1 MW targetry</td>
</tr>
<tr>
<td>ESS</td>
<td>Sweden</td>
<td>5 MW pulsed SRF SRF, cryo, targetry</td>
</tr>
<tr>
<td>LCLS-II-HE</td>
<td>USA</td>
<td>8 GeV CW SRF efficient SRF, cryo</td>
</tr>
<tr>
<td>SuperC-Tau</td>
<td>Russia</td>
<td>2-6 GeV $e^+e^-$ crab waist scheme</td>
</tr>
<tr>
<td>EIC</td>
<td>USA</td>
<td>20-140 GeV $ep/ei$ polarization, cool’g</td>
</tr>
</tbody>
</table>
greatly appreciate input from:

M.Benedikt (CERN), P.Bhat (FNAL), M.Benedikt (CERN), C.Biscari (ALBA), A.Blondel (CERN), J.Brau (UO), O.Bruning(CERN), A.Canepa (FNAL), W.Chou (IHEP, China), M.Klein (CERN), J.P.Delahaye (CERN), D.Denisov (BNL), V.Dolgashev (SLAC), E.Gschwendtner (CERN), A.Grasselino (FNAL), W.Leemans (DESY), E.Levichev (BINP), B.List (DESY), H.Montgomery (JLab), P.Muggli (MPG), D.Neuffer (FNAL), H.Padamsee (Cornell), M.Palmer (BNL), N.Pastrone (INFN), Q.Qin (IHEP), T.Raubenheimer (SLAC), L.Rivkin (EPFL/PSI), A.Romanenko (FNAL), M.Ross (SLAC), D.Schulte (CERN), A.Seryi (Jlab), T.Sen (FNAL), F.Willeke (BNL), V.Yakovlev, A.Yamamoto (KEK), F.Zimmermann (CERN), A.Zlobin (FNAL)
Thank You for Your Attention!

* In depth discussions in the parallel sessions:
  – LHC HL HE
  – FCC
  – Linear Colliders
  – Higgs Factories
  – Muon Colliders
  – Present plasma
  – Future plasma
  – Neutrino beams
  – Beyond colliders
  – Energy efficiency
BACK UP SLIDES
Cost of the LHC

How much does it cost?

The cost for the machine alone is about 4.6 billion CHF (about 3 billion Euro). The total project cost breaks down roughly as follows:

<table>
<thead>
<tr>
<th>Construction costs (BCHF)</th>
<th>Personnel</th>
<th>Materials</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Machine and areas</td>
<td>0.92</td>
<td>3.68</td>
<td>4.60</td>
</tr>
<tr>
<td>CERN share to Detectors</td>
<td>0.78</td>
<td>0.31</td>
<td>1.09</td>
</tr>
<tr>
<td>LHC injector upgrade</td>
<td>0.09</td>
<td>0.07</td>
<td>0.16</td>
</tr>
<tr>
<td>LHC computing (CERN share)</td>
<td>0.09</td>
<td>0.09</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.88</strong></td>
<td><strong>4.15</strong></td>
<td><strong>6.03</strong></td>
</tr>
</tbody>
</table>

*) (including 0.43 BCHF of in-kind contributions)

The total cost for the LHC, detectors and computing is as follows:

<table>
<thead>
<tr>
<th></th>
<th>Material costs (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC machine and areas*</td>
<td>3756</td>
</tr>
<tr>
<td>CERN share to detectors</td>
<td>493</td>
</tr>
<tr>
<td>and detector areas **</td>
<td></td>
</tr>
<tr>
<td>LHC computing (CERN</td>
<td>83</td>
</tr>
<tr>
<td>share)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4332</strong></td>
</tr>
</tbody>
</table>

*) This includes: Machine R & D and injectors, tests and pre-operation.

**) Contains infrastructure costs (such as caverns and facilities). The total cost of all LHC detectors is about 1500 MCHF.