The European Strategy Update: Priorities for Future Facilities

Albert De Roeck
CERN
26 November 2018
Introduction

The European Strategy for Particle Physics (ESPP) is the process by which every ~ 7 years the European particle physics community updates the priorities and strategy of the field. It also makes recommendations on related activities: education, communications and outreach, technology transfer, organisational aspects, etc.

First ESPP in 2006; first update in 2013; next update 2020.

Bottom-up process involving the community. Driven by physics*, with awareness of financial and technical feasibility.

ESPP produces the European roadmap in the worldwide context of the field. Note: particle physics requires global coordination, given the number, size and complexity of the projects → “alignment” of the European, US and Japanese roadmaps in recent years to optimise the use of resources.

The Strategy is adopted by the CERN Council. Individual (major) projects require dedicated approval: e.g. HL-LHC.

* The scientific input includes: physics results from current facilities from all over the world; physics motivations, design studies and technical feasibility of future projects; results of R&D work, etc.
Future HEP: The Three Frontiers

After the Higgs discovery

Previous Strategy Update: 2012-2014

Evaluation in all regions: Europe, Asia, the Americas

- European strategy group
- Snowmass study and IP5
- Japan strategy group
The European Strategy for Particle Physics

2006 European Strategy for Particle Physics approved by CERN Council
Contains 17 statements on scientific and organizational matters

2013 Update of the European Strategy for Particle Physics
- Open Symposium – Krakow, 10-12 Sept. 2012
- Book of Abstracts submitted to the Open Symposium

- Physics Briefing Book compiled by the Preparatory Group (200 p)


- Approved by CERN Council in a special European Strategy Session of the Council in Brussels (May 30)
Contains 17 points, labeled a – q, numbers were avoided on purpose, not to give the impression of a pure priority list.

2018-2020 Next Update
Examples of recommendations from 2013 ESPP

The success of the LHC is proof of effectiveness of the European organisational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN. Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.

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 initial design, by around 2030.  

→ HL-LHC approved by Council 2016

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 …

→ Continuation of CLIC, FCC started 2014

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

→ Neutrino Platform started 2014

CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop coordinated programmes of education and training.
2020 ESPP update: timeline and committees

2017
- Jan.2018: Call for proposals for venues for Open Symposium and Strategy Drafting Session

2018
- Feb.2018: Call for scientific input
- March.2018: For nominations of ESSG members
- June 14, 2018: Council decision on venues and dates
- Sept 27, 2018: Council launches the Strategy Update process & establishes the PPG and ESG

2019
- Dec 18, 2018: Closing submission community input
- May 13-16, 2019: Open Symposium Granada, ES
- Sept. 2019: Physics Briefing Book available

2020
- Jan 20-24, 2020: Strategy Update Drafting Session Bad Honnef, GE
- March 2020: Strategy Update submitted to Council
- May 2020: Council to approve Strategy Update

Done
- Organisation & input preparation by community

Physics results appearing after May 2019 will be taken into account in the process
2020 ESPP update: timeline and committees

- **Strategy Secretariat**
  Organizes the ESPP process
  H. Abramowicz (Chair; also chair of PPG and ESG), J. D’Hondt (ECFA Chair), K. Ellis (SPC Chair), L. Rivkin (Chair of LDG=Laboratory Directors Group)

- **Physics Preparatory Group (PPG)**
  Collects community’s input, organises Open Symposium, prepares briefing book
  Strategy Secretariat
  4 members appointed by Council on recommendation of SPC
  4 members appointed by Council on recommendation of ECFA
  1 CERN representative
  2 representatives from Asia and 2 from Americas (appointed by respective ICFA representatives)

- **European Strategy Group (ESG)**
  Drafts the final strategy document
  Strategy Secretariat, 1 representative per CERN Member State, LDG, CERN DG,
  Invited: Council President, 1 representative per Associate Member State and Observer State,
  PPG, EC representative, JINR/Dubna representative, Chairs of ApPEC, NuPECC, FALC, ESFRI

For more information see:

Focus on large facilities
The LHC Upgrade
Approved program at CERN to collect 3-4 ab^{-1} with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)
Experiments need upgrades for the HL-LHC as well
Upgrade program under way
At HL-LHC, we expect to produce $\sim 170 \text{M}$ Higgs Bosons, including $\sim 120 \text{k}$ of pair produced events.

Over 1 Million for each of the main production mechanisms, spread over many decay modes.

Enables a broad program:

- Precision $O(\text{few\%})$ measurements of couplings across different channels.
- Exploration of Higgs potential ($hh$ production).
- Sensitivity to rare decays involving new physics.
- Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays...).
Higher Energy LHC??

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV (8.3T magnet fields)
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb$_3$Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ $\sqrt{s}$~ 27 TeV)
- uses existing tunnel and infrastructure; can be built at fixed budget
- strong physics case if new physics from LHC/HL-LHC
- powerful demonstration of the FCC-hh magnet technology

F. Gianotti
FCC meeting
April 2016

HE-LHC part of the FCC study
Beyond the LHC

• Proton-proton machines at higher energy…

• Electron-positron machines for high precision…

• Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

Based on the PECFA meeting @CERN November 2018
Future Colliders

C. Grojean

Theorist view on future colliders

Hadron colliders main themes:

The study of the Higgs Boson(s)

The search for massive new physics

Precision measurements

FCC-hh: THE machine for direct search at the higher energy scale.
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the Gepveois

- **Ultimate goal**: \(\geq 16\) T magnets
- \(\geq 100\) TeV pp-collider (FCC-hh)

→ defining infrastructure requirements

Two possible first steps:

- \(\ell^+\ell^-\) collider (FCC-ee)
  High Lumi, \(E_{CM} = 90\) - 400 GeV

- **HE-LHC** 16T \(\Rightarrow\) 27 TeV
  in LEP/LHC tunnel

Possible addition:

- \(p-e\) (FCC-he) option
Now is the right time to plan for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy

FCC – design study

schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

• FCC-hh: 2043
• FCC-ee: 2039
• HE-LHC: 2040 (with HL-LHC stop LS5 /
HE-LHC:

- **Constraints:**
  - No civil engineering, same beam height as LHC
  - Magnets OD ca. 1200 m max
  - QRL (shorter than FCC) OD ca. 850 mm (all included)

- Magnet suspended during "handover" from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing + still many items to study!

If HE-LHC can work in 3.8m Ø ... it will feed-back to FCC tunnel design!
e+e- Colliders

• Circular colliders
  FCC-ee (CERN), CEPC China

• Linear Colliders
  ILC (Japan?), CLIC (CERN)
# FCC-ee collider parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
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<tr>
<td>beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
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<tr>
<td>no. bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>48</td>
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<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
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<tr>
<td>total RF voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
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<td>10.9</td>
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<td>long. damping time [turns]</td>
<td>1281</td>
<td>235</td>
<td>70</td>
<td>20</td>
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<tr>
<td>horizontal beta* [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
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<tr>
<td>vertical beta* [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
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<tr>
<td>horiz. geometric emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
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<tr>
<td>vert. geom. emittance [pm]</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>bunch length with SR / BS [mm]</td>
<td>3.5 / 12.1</td>
<td>3.0 / 6.0</td>
<td>3.3 / 5.3</td>
<td>2.0 / 2.5</td>
</tr>
<tr>
<td>luminosity per IP $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>$&gt;200$</td>
<td>$&gt;25$</td>
<td>$&gt;7$</td>
<td>$&gt;1.4$</td>
</tr>
<tr>
<td>beam lifetime rad Bhabha / BS [min]</td>
<td>68 / $&gt;200$</td>
<td>49 / $&gt;1000$</td>
<td>38 / 18</td>
<td>40 / 18</td>
</tr>
</tbody>
</table>
Event statistics:

- **Z peak**
- **WW threshold**
- **ZH threshold**
- **tt threshold**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Run duration (years)</th>
<th>Center-of-mass Energies (GeV)</th>
<th>Integrated Luminosity (ab⁻¹)</th>
<th>Event Statistics</th>
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</thead>
<tbody>
<tr>
<td>FCC-ee-Z</td>
<td>4</td>
<td>88-95</td>
<td>150</td>
<td>$3 \times 10^{12}$ visible Z decays</td>
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<tr>
<td>FCC-ee-W</td>
<td>2</td>
<td>158-162</td>
<td>12</td>
<td>$10^8$ WW events</td>
</tr>
<tr>
<td>FCC-ee-H</td>
<td>3</td>
<td>240</td>
<td>5</td>
<td>$10^6$ ZH events</td>
</tr>
<tr>
<td>FCC-ee-tt</td>
<td>5</td>
<td>345-365</td>
<td>1.5</td>
<td>$10^6$ tt events</td>
</tr>
</tbody>
</table>

Great energy range for the heavy particles of the Standard Model.
Design reports released for proposed China supercollider

The biggest particle collider in the world moves one step closer to reality. Nick Carne reports.

Iff the funding bid is successful at first round -> physics start may be in 2030
China: CEPC Project

- CEPC is Higgs Factory ($E_{\text{cms}}=240\text{GeV}$, $10^6$ Higgs)
- CEPC is Z factory ($E_{\text{cms}}\sim91\text{GeV}$), electroweak precision physics at Z pole.
  - baseline $L=1.6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, Solenoid =2T, $3\times10^{11}$ Z boson
  - $L=3.2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, Solenoid =3T, $6\times10^{11}$ Z boson
  - Assuming Z cross section with ISR correction: 32 nb
- WW threshold scan runs ($\sim160\text{GeV}$) are also expected.
  - Total luminosity $2.5 \text{ ab}^{-1}$, 14M WW events

https://indico.ihep.ac.cn/event/7389/
Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 (stat 400...) fold improved precision on many EW quantities (e.g. x 5-7 in mass)

\[ m_Z, \ m_W, \ m_{\text{top}}, \ \sin^2 \theta_W, \ R_b, \ \alpha_{\text{QED}}(m_Z), \ \alpha_s(m_Z, m_W, m_\tau), \] top quark couplings

~ Model-independent Higgs width and couplings measurements at percent-permil level.

\[ \sim 3\sigma, \ possibly \ 5 \ discovery \ of \ effect \ of \ Higgs \ self-coupling \ from \ Vertex \ corrections \]
possible investigation of Hee coupling at \( \sqrt{s} = m_H \)

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}

-- ex FCNC (Z --> \mu \tau, e\tau) in 5 \times 10^{12} Z decays and \tau BR in 2 \times 10^{11} Z \rightarrow \tau \tau

+ flavour physics (10^{12} bb events) \ (B \rightarrow s \tau \tau \text{ etc.})

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DIRECT DISCOVERY of very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc...

+ and many opportunities in -- e.g. QCD \ (H \rightarrow gg) \text{ etc.}

NB Not only a «Higgs Factory», «Z factory» and «top» are important for ‘discovery potential’

“First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164
A sample of precision observables.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Current precision</th>
<th>FCC-ee stat.</th>
<th>FCC-ee syst.</th>
<th>Dominant exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_z ) (keV)</td>
<td>( Z ) Lineshape</td>
<td>( 91187500 \pm 2100 )</td>
<td>5</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( \Gamma_z ) (MeV)</td>
<td>( Z ) Lineshape</td>
<td>( 2495200 \pm 2300 )</td>
<td>8</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( R_i \times 10^3 )</td>
<td>( Z ) Peak (( \Gamma_{\text{had}}/\Gamma_{\text{lep}} ))</td>
<td>( 20767 \pm 25 )</td>
<td>0.06</td>
<td>0.2 - 1</td>
<td>Detector acceptance</td>
</tr>
<tr>
<td>( R_b \times 10^6 )</td>
<td>( Z ) Peak (( \Gamma_{\text{bb}}/\Gamma_{\text{had}} ))</td>
<td>( 216290 \pm 660 )</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>( g \to bb )</td>
</tr>
<tr>
<td>( N_v \times 10^3 )</td>
<td>( Z ) Peak (( \sigma_{\text{had}} ))</td>
<td>( 2984 \pm 8 )</td>
<td>0.005</td>
<td>1</td>
<td>Lumi measurement</td>
</tr>
<tr>
<td>( \sin^2 \theta_w^{\text{eff}} \times 10^6 )</td>
<td>( A_{FB}^{\mu \mu} ) (peak)</td>
<td>( 231480 \pm 160 )</td>
<td>3</td>
<td>2 - 5</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( 1/\alpha_{\text{QED}}(m_Z) \times 10^3 )</td>
<td>( A_{FB}^{\mu \mu} ) (off-peak)</td>
<td>( 128952 \pm 14 )</td>
<td>4</td>
<td>&lt; 1</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( \alpha_s(m_Z) \times 10^4 )</td>
<td>( R_i )</td>
<td>( 1196 \pm 30 )</td>
<td>0.1</td>
<td>0.4 - 1.6</td>
<td>Same as ( R_i )</td>
</tr>
<tr>
<td>( m_w ) (MeV)</td>
<td>WW Threshold scan</td>
<td>( 80385 \pm 15 )</td>
<td>0.6</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( \Gamma_w ) (MeV)</td>
<td>WW Threshold scan</td>
<td>( 2085 \pm 42 )</td>
<td>1.5</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>( N_v \times 10^3 )</td>
<td>( e^+e^- \to \gamma Z, Z \to \nu \nu, \pi )</td>
<td>( 2920 \pm 50 )</td>
<td>0.8</td>
<td>small</td>
<td>?</td>
</tr>
<tr>
<td>( \alpha_s(m_w) \times 10^4 )</td>
<td>( B_i = (\Gamma_{\text{had}}/\Gamma_{\text{lep}})_w )</td>
<td>( 1170 \pm 420 )</td>
<td>2</td>
<td>small</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>( m_{\text{top}} ) (MeV)</td>
<td>Top Threshold scan</td>
<td>( 173340 \pm 760 \pm 500 )</td>
<td>17</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>( \Gamma_{\text{top}} ) (MeV)</td>
<td>Top Threshold scan</td>
<td>( ? )</td>
<td>45</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>( \lambda_{\text{top}} )</td>
<td>Top Threshold scan</td>
<td>( \mu = 1.28 \pm 0.25 )</td>
<td>0.10</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>( ttZ ) couplings</td>
<td>( \sqrt{s} = 365 ) GeV</td>
<td>( \pm 30% )</td>
<td>0.5 - 1.5%</td>
<td>&lt; 2%</td>
<td>QCD corr.</td>
</tr>
</tbody>
</table>
- Higgs tagged by a Z, Higgs mass from Z recoil

\[ m^2_H = s + m^2_Z - 2\sqrt{s}(E_+ + E_-) \]

- Total rate \( \propto g_{HZZ}^2 \)
- \( ZH \rightarrow ZZZ \) final state \( \propto g_{HZZ}^4 / \Gamma_H \)
- \( ZH \rightarrow ZXX \) final state \( \propto g_{HXX}^2 g_{HZZ}^2 / \Gamma_H \)
- Empty recoil = invisible Higgs width; Funny recoil

- Note: The HL-LHC is a great Higgs factory (10^9 Higgs events)
  - \( \sigma_{\text{observed}} \propto \sigma_{\text{prod}} (g_{H_i})^2 (g_{H_F})^2 / \Gamma_H \)
  - Difficult to extract the couplings: \( \sigma_{\text{prod}} \) is uncorrected
    - Must do physics with ratios or with additional input

- \( \rightarrow \) measure \( g_{HZZ} \) to 0.2%
- \( \rightarrow \) measure \( \Gamma_H \) to a couple %
- \( \rightarrow \) measure \( g_{HXX} \) to a few per-mil / per-cent

<table>
<thead>
<tr>
<th>Collider *</th>
<th>HL-LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab^{-1})</td>
<td>3</td>
<td>5.240</td>
</tr>
<tr>
<td>( \delta \Gamma_H / \Gamma_H ) (%)</td>
<td>50</td>
<td>2.8</td>
</tr>
<tr>
<td>( \delta g_{HZZ} / g_{HZZ} ) (%)</td>
<td>3.5</td>
<td>0.25</td>
</tr>
<tr>
<td>( \delta g_{HWW} / g_{HWW} ) (%)</td>
<td>3.5</td>
<td>1.3</td>
</tr>
<tr>
<td>( \delta g_{Hbb} / g_{Hbb} ) (%)</td>
<td>8.2</td>
<td>1.4</td>
</tr>
<tr>
<td>( \delta g_{Hee} / g_{Hee} ) (%)</td>
<td>SM</td>
<td>1.8</td>
</tr>
<tr>
<td>( \delta g_{He} / g_{He} ) (%)</td>
<td>3.9</td>
<td>1.7</td>
</tr>
<tr>
<td>( \delta g_{He} / g_{He} ) (%)</td>
<td>6.5</td>
<td>1.4</td>
</tr>
<tr>
<td>( \delta g_{He} / g_{He} ) (%)</td>
<td>5.0</td>
<td>9.6</td>
</tr>
<tr>
<td>( \delta g_{He} / g_{He} ) (%)</td>
<td>3.6</td>
<td>4.7</td>
</tr>
<tr>
<td>( \delta g_{He} / g_{He} ) (%)</td>
<td>4.2</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta_{\text{EXO}} ) (%)</td>
<td>SM</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>( \Delta_{\text{Invis}} ) (%)</td>
<td>&lt; 3.0</td>
<td>&lt; 0.3</td>
</tr>
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</table>
The International Linear Collider

Baseline design

Expected:
by fall 2018
Discussion in Science Council of Japan

by the end of Dec. 2018
Expression of Interest from Japanese government

Then a 4 years preparatory phase and 8 years construction

Electron-positron Collider

- Center-of-mass energy 250 GeV (Higgs factory)
  Extendable to higher energies (1 TeV)
- Based on superconducting RF niobium cavities
- Polarized beams
- One interaction region, two detectors
CLIC layout and power generation

Drive beam complex

Drive beam time structure - initial

140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

24 pulses - 101 A - 2.5 cm between bunches

2020–2025 Preparation Phase:
Finalisation of implementation parameters
Preparation for industrial procurement
Drive Beam Facility & other system verification
Technical Proposal of the experiment
Site authorisation

2026 Construction start
Higgs self-coupling at CLIC

Higgs self-coupling at CLIC, 3 TeV, 5 ab$^{-1}$
-80%/+80% electron polarisation, sharing 80%/20%
Main contribution from VBS, with HH $\rightarrow$ bbbb (58%)
HZZ production at 1.4 TeV, helps to resolve ambiguities

Improved analysis, includes use of angular distributions
**Trilinear Higgs self-coupling $\Delta \lambda / \lambda = -7 \%, +11 \%$ at 68 % C.L. $\Leftarrow$ new result**
assuming SM and setting the quartic HHWW coupling to the SM value.

Can interpret in concrete BSM scenarios e.g. Higgs & top-quark compositeness

**Sensitivity via EFTs**

CLIC can *discover* compositeness up to 8TeV compositeness scale (~30TeV in favourable conditions) – above what LHC can *exclude*
Hadron Colliders

• FCC-hh (CERN)
• SppC (China)
<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>
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<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>1.1</td>
<td>0.58</td>
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<tr>
<td>bunch intensity $[10^{11}]$</td>
<td>1</td>
<td>1</td>
<td>2.2</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>4.6</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>0.25</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>normalized emittance [$\mu$m]</td>
<td>2.2</td>
<td>2.5</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity $[10^{34} \text{cm}^{-2}\text{s}^{-1}]$</td>
<td>5</td>
<td>30</td>
<td>28</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>800</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.3</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
FCC goal is 16 T operating field
- Requires to use Nb$_3$Sn technology
- At 11 T used for HL-LHC
⇒ Strong synergy with HL-LHC

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

R&D on cables in test stand at CERN

Target: $J_c > 2300 \text{ A/mm}^2$ at 1.9 K and 16 T (50% above HL-LHC)

Industrial fabrication:
Target cost: 3.4 Euro/kAm

Magnet design to minimise material use and limit margins to essential level

Common coils
Cos-theta
Blocks
Canted Coil

EuroCirCol
A key to New Physics

CIEMAT, CEA, INFN

Swiss contribution via PSI

D. Tommasini at al.

D. Schulte, EPS’17

-- possible shorter term application SCSPS or HE-LHC
-- For longer timescale HTS is also studied ⇒ 20T
China: Hadron Collider

- **SppC Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, using full iron-based HTS technology
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV
  - Relatively lower luminosity for the first phase, higher for the second phase

- **Energy upgrading phase**
  - Dipole magnet field: 20 - 24T, full iron-based HTS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (e.g., adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)

- **Development of high-field superconducting magnet technology**
  - Starting to develop required HTS magnet technology; before applicable iron-based HTS wire are available, models by YBCO and LTS wires can be used for specific studies (magnet structure, coil winding, stress, quench protection method etc.)
Hadron colliders: direct exploration of the “energy frontier”

With 40/ab at $\sqrt{s}=100$ TeV expect: $\sim 10^{12}$ top, $10^{10}$ H bosons, $10^5$ m=8 TeV gluino pairs, ...

If new (heavy) physics discovered at the LHC $\rightarrow$ completion of spectrum is a “no-lose” argument for future $\sim 100$ TeV pp collider: extend discovery potential up to $m\sim 50$ TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma (100 \text{ TeV})/\sigma (14 \text{ TeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pp</td>
<td>1.25</td>
</tr>
<tr>
<td>W</td>
<td>$\sim 7$</td>
</tr>
<tr>
<td>Z</td>
<td>$\sim 7$</td>
</tr>
<tr>
<td>WW</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$\sim 30$</td>
</tr>
<tr>
<td>H</td>
<td>$\sim 15$ ($t\bar{t}H \sim 60$)</td>
</tr>
<tr>
<td>HH</td>
<td>$\sim 40$</td>
</tr>
<tr>
<td>stop ($m=1$ TeV)</td>
<td>$\sim 10^3$</td>
</tr>
</tbody>
</table>
Impact on DM bounds

Competitive with the best direct detection experiments

Higgs invisible bound

$30 \text{ ab}^{-1} (100 \text{ TeV})$

$\text{BR} (H \rightarrow \text{inv.}) < 0.0001$

Taking optimistic bound

Higgs invisible of $10^{-4}$ corresponds to $g_{\text{SM}}$ from $10^{-3}$ to $10^{-2}$
### HIGGS PHYSICS

#### Higgs couplings $g_{Hxx}$ precisions

- $hh$, $eh$ precisions assume SM or ee measurements
- FCC-hh : $H \to ZZ$ to serve as cross-normalization

<table>
<thead>
<tr>
<th>$g_{Hxx}$</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ$</td>
<td>0.22%</td>
<td>&lt; 1%</td>
<td>*</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.47%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>1.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>4.2%</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>--</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>$ttH$</td>
<td>13%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>$bb$</td>
<td>0.7%</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>0.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$cc$</td>
<td>0.7%</td>
<td></td>
<td>1.8%</td>
</tr>
<tr>
<td>$gg$</td>
<td>1.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>8.6%</td>
<td>1-2%</td>
<td></td>
</tr>
<tr>
<td>$uu,dd$</td>
<td>$H \to \rho\gamma?$</td>
<td>$H \to \rho\gamma?$</td>
<td></td>
</tr>
<tr>
<td>$ss$</td>
<td>$H \to \phi\gamma?$</td>
<td>$H \to \phi\gamma?$</td>
<td></td>
</tr>
<tr>
<td>$ee$</td>
<td>ee $\to H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$HH$</td>
<td>40%</td>
<td>~3-5%</td>
<td>20%</td>
</tr>
<tr>
<td>inv, exo</td>
<td>&lt;0.55%</td>
<td>$10^{-3}$</td>
<td>5%</td>
</tr>
</tbody>
</table>

---

*for* $ttH$, combination of $\pm4\%$ (model dependent)HL-LHC with FCC-ee will lead to $ttH$ coupling to $\pm3\%$... model independent!

*for* $g_{HHH}$ investigating now: the possibility of reaching $5\sigma$ observation at FCC-ee:

- 4 detectors
  - + recast of running scenario

---

06/07/2018
Supersymmetry

- $\tilde{\chi} \rightarrow \tilde{\chi} \tilde{\chi} \\
- $\tilde{\chi} \rightarrow Q \tilde{\chi}$
- $\tilde{\chi} \rightarrow t\tilde{\chi}$
- $\tilde{\chi} \rightarrow q\tilde{\chi}$
- $\tilde{\chi} \rightarrow g\tilde{\chi}$
- $\tilde{\chi} \rightarrow q\tilde{\chi}$

95% CL Limits
- 14 TeV, 0.3 ab$^{-1}$
- 14 TeV, 3 ab$^{-1}$
- 5 $\sigma$ Discovery
- 100 TeV, 3 ab$^{-1}$
- 100 TeV, 30 ab$^{-1}$

Mass scale [TeV]
Using a 60 Gev Electron Energy recovery linac as an electron beam (PERLE Project)

**Electron beam**
60 GeV acceleration with Recirculating Linacs

- Spreader 38m
- RF Compensation
  + Doglegs
  + Matching 96m
- Arc1,3,5 3142m

- Linac1 1008m
- RF Compensation
  + Doglegs
  + Matching 120m
- Arc2,4,6 3142m

- Recombiner 38m
  + Matching 20m
- Spreader 38m
- Linac2 1008m

- Dump
- Bypass
- IP Line 196m

**Center-of-mass energies**
- LHeC: $\sqrt{s} \sim 1.3$ TeV
- FCC-eh: $\sqrt{s} \sim 3.5$ TeV
- Up to 1 ab$^{-1}$ integrated luminosity

**Concurrent operation to pp. Power limit:** 100 MW, $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity
- LHeC/FCCeh: 1000 times HERA luminosity. It therefore extends up to $x\sim1$. 
**μ+μ- Colliders**

- Proton generated muon beams  
  MAP Scheme
- Electron generated muon collider  
  LEMMA Scheme
Muon Colliders

International R&D program

MERIT - CERN
Demonstrated principle of liquid Mercury jet target

MuCool Test Area - FNAL
Demonstrated operation of RF cavities in strong B fields

EMMA - STFC Daresbury Laboratory
Showed rapid acceleration in non-scaling FFA

MICE - RAL
Demonstrate ionization cooling principle
Increase inherent beam brightness
→ number of particles in the beam core “Amplitude”

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier
Muon Colliders

Low EMittance Muon Accelerator

Direct $\mu$ pair production: muons produced from $e^+e^-\rightarrow\mu^+\mu^-$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold ($\sqrt{s} \approx 0.212 \text{GeV}$) in asymmetric collisions (to collect $\mu^+$ and $\mu^-$). Potential of this idea, but key challenges need to be demonstrated to prove its feasibility ➔ a new proposal for machine studies and measurements.

Advantages: Low emittance possible
Reduced losses from decay
Low background
Energy spread

Disadvantages: Rate: $\sigma(e^+e^-\rightarrow\mu^+\mu^-) \approx 1 \mu$b at most

Key Challenges:
- $\sim 10^{11} \mu/$ sec from $e^+e^-\rightarrow\mu^+\mu^-$
- $10^{15} e/\text{sec}, 100 \text{ kW class target, NON}$
  destructive process in $e^+$ ring

Key R&D:

EASIER AND CHEAPER
DESIGN, IF FEASIBLE

Snowmass 2013 - M. Antonelli e P. Raimondi
Other Projects

- Electron-Ion Collider (US)
- Intensity Frontier (CERN)
- Accelerator based Neutrino Projects
US Project: Electron-Ion Collider

The Electron Ion Collider

For e-N collisions at the EIC:
- Polarized beams: e, p, d/³He
- e beam 5-10(20) GeV
- Luminosity \( L_{ep} \sim 10^{33-34} \text{ cm}^{-2} \text{sec}^{-1} \)
  - 100-1000 times HERA
- 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:
- Wide range in nuclei
- Luminosity per nucleon same as e-p
- Variable center of mass energy

World’s first
Polarized electron-proton/light ion and electron-Nucleus collider

Both designs use DOE’s significant investments in infrastructure
Excerpt from the PBC mandate: “Explore the opportunities offered by the CERN accelerator complex to address some of today’s outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world.”
(Time scale of opportunities: next 2 decades)
SHiP

Flagship programme for a comprehensive investigation of the Hidden Sector in the few GeV domain

Similar layout as NA62, with larger acceptance to reach the c / b mass range

400 GeV protons

mum active shield

Spectrometer for DM scattering + y physics

Emulsion spectrometer for DM decays

NB: NA62 plans to pave the way with short runs in beam dump mode after LS2

NA64

Hidden sector search from invisible decays with missing energy

Implemented in 2016 on e test beam

Fast analysis excluding (g-2), interpretation confirms the potential of the method

AFTER LS2:
Wish to extend the method to higher e intensity and μ / π / K / p beams

Examples of Beyond Collider Studies

IAXO - next generation Axion helioscope beyond CAST

Support from CERN for magnet design within PBC

AWAKE

CERN NEUTRINOS TO GRAN SASSO
Underground structure at CERN

R&D for electron acceleration with a plasma cell excited by proton bunches

First accelerated e seen in 2018!

Could provide ~10^15 - 30 GeV pulsed e’s/year in the post-LS3 era to an experiment located in the CNGS decay tunnel

Photon & Fermion coupling

KLEVER, TauFV

Increasing scale of underlying interactions

Increasing particle mass scale
Neutrino oscillations (e.g. $\nu_\mu \to \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos imply neutrinos have masses and mix.

Since then: great progress in understanding $\nu$ properties at various facilities all over the world.

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

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

Europe (& CERN) participate in world-wide neutrino accelerator projects such as DUNE at FNAL/US and T2K/T2HK in Japan.
Long Baseline Neutrino Facility (LBNF) at FNAL

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

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

Far site construction starts ~2017, 1$^\text{st}$ detector installed ~2022, beam from FNAL ~ 2026

FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start ~2018

ICARUS T600 (476 t) MicroBooNE (89 t) SBND (112 t)
Hyper-Kamiokande, JPARC: construction to start in 2019

0.38 $\rightarrow$ 0.75 $\rightarrow$ > 1 MW p source
$E_p = 30$ GeV $\rightarrow$ $E_{\nu} \sim 0.6$ GeV
Narrow-band $\nu$ beam
$\rightarrow$ high intensity at oscillation peak

$\sim 0.5$ Mton Water Cerenkov detector
($\sim 20 \times$ Super-K)
$\sim 1$ km underground
$\sim 2.5^0$ off-axis $\rightarrow$ narrow-band beam

Complementary to LBNE: different detector technology, shorter baseline ($\rightarrow$ less sensitive to mass hierarchy), narrow-band beam ($\rightarrow$ high statistics of $\nu$/anti-$\nu$ at oscillation peak but limited measurement of oscillation spectrum)
European Strategy Update launched
- input by December 18 2018
- Conclusion by May 2020

This is done in a worldwide context (US, China, Japan)

A lot of activity in preparing proposals at the energy and intensity frontier.

Outcome will affect all of future particle physics!