Progress with the European Strategy Update presented @ Higgs couplings 2019, Oxford

R. Keith Ellis
IPPP, Durham

- European Strategy for Particle Physics Update
- Proposed future colliders
- The importance of Higgs Physics
- Assessing the reach in Higgs Physics of future machines.
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. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

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

Europe looks forward to a [ILC] proposal from Japan to discuss a possible participation.

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.
Last strategy process led to initiation of CERN/European activity in neutrino physics

Prototype cryostats for liquid Argon detectors at CERN
Status of ILC

- **MEXT view of the ILC project**: (From LCB and ICFA Meetings, Tokyo, 7 March 2019)
  - Following the opinion of the SCJ, MEXT has not yet reached declaration for hosting the ILC in Japan. The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain understanding and support from domestic academic community.
  - MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

- September update on SCJ Master Plan:
  - ILC passed first selection, along with 60 other projects invited to a hearing (~ 30% of initial applicants).
  - SCJ will release Master Plan by the end of January 2020 (expect ~ 20 projects in final list).

- Hoping to get some useful indication for the ESPP update, a LCB meeting provisionally scheduled in Tokyo on 20 December 2019 to hear about progress from MEXT and Diet members promoting ILC.
European Strategy 2013 (Other scientific activities essential to the particle physics programme)

- Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.

- Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.

- Detector R&D programmes should be supported strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.

- In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community’s capability for unique projects in this field.

- The CERN Laboratory should maintain its capability to perform unique experiments. CERN should continue to work with NuPECC on topics of mutual interest.
European Strategy 2013 (organisational issues)

- CERN should be the framework within which to organise a global particle physics accelerator project in Europe, and should also be the leading European partner in global particle physics accelerator projects elsewhere. Possible additional contributions to such projects from CERN’s Member and Associate Member States in Europe should be coordinated with CERN.

- CERN and the particle physics community should strengthen their relations with the European Commission in order to participate further in the development of the European Research Area.
Strategy Timeline for 2020 update

- **2017**
  - Jan 2018: Call for proposals for venues for Open Symposium and Strategy Drafting Session
  - Febr 2018: Call for scientific input
  - March 2018: Call for nominations of PPG & ESG members
  - June 14, 2018: Council decision on venues and dates

- **2018**
  - Sept 27, 2018: Council launches the Strategy Update process & establish 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, DE
  - March 2020: Strategy Update submitted to Council
  - May 2020: Council to approve Strategy Update

ESG, about 80 people, UK representatives, Thomson & Butterworth

Briefing book, 1/10/2019 CDS (CERN-ESU-004)

Budapest
Briefing book and strategy update concern a much broader spectrum of activities than just future colliders.
Preparing CERN’s future

I think it would be good for CERN if the 2020 Strategy update recommended:

- the direction for a future collider at CERN: linear or circular
  - so that its technical and financial feasibility can be assessed by next Strategy update in ~2026 → pre-requisite for project approval by the Council

- a compelling scientific diversity programme at the injectors, complementary to high-E colliders for physics reach and size/type of projects (→ attract a diverse community). Based on input from Physics Beyond Colliders (PBC) study group.

- a vigorous and transformational accelerator R&D programme at CERN and other European laboratories and institutions: high-field magnets (including High-Temperature Superconductors), high-efficiency klystrons, high-gradient accelerating structures, plasma wakefield, feasibility of muon colliders, etc.
Proposed future colliders
To make the discussion more concrete we can imagine 5 scenarios, which can be pursued in Europe.

We are working in a global context, but we should take the lead and decide what is best for Europe.

Hope to make decisions which are robust, whatever happens elsewhere.

Machine parameters and integrated luminosities defined for CERN machines, 1810.13022
## Comparisons

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<th>Project</th>
<th>Type</th>
<th>Energy[TeV]</th>
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Notes: 1 ILCU=1 US$(2012)  
C.f. Schulte Granada
Luminosity at lepton colliders

FCC-ee (Baseline), Zimmerman, Ottawa
ILC (Staging), 1711.00568
ILC (Baseline), 1306.6328
Muon collider, 1502.01647
CLIC (Baseline), 1608.07537
CEPC (Baseline), IHEP–CEPC–DR–2015–01
Lepton colliders

- Luminosity per Megawatt, wall plug power
Higgs at $e^+e^-$ collider: generalities

- WW fusion production ten times smaller at 250 than 500.
- $\sim$40% increase in ZH cross section with polarization($-0.8,+0.3$)
- In terms of precision Higgs parameters polarization is like a factor of $\sim$2 in integrated luminosity.
A limiting factor for setting the schedule for high energy hh machines is the time scale for magnet development.

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*Note: LHC experience: NbTi, 10 T R&D started in 1980’s and 8.3 T Production started in late 1990’s, after ~ 15 years*

A. Yamamoto, 190513b/updated:190628a

Yamamoto, Granada
## Timeline (from T₀)

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Possible timeline of future colliders

Possible scenarios of future colliders

CERN
- HL-LHC: 13 TeV 3-4 ab\(^{-1}\)
- LHCEC: 1.2 TeV 0.25-1 ab\(^{-1}\)
- FCC-eh: 3.5 TeV 2 ab\(^{-1}\)

Japan
- CepC: 90/160/240 GeV 16/2.6/5.6 ab\(^{-1}\)
- SppC aim similar to FCC-hh
- FCC-hh: 150 TeV \(\approx\) 20-30 ab\(^{-1}\)

China
- 100km tunnel
- 8 years to 10 years
- FCC-ee: 90/160/250 GeV 150/10/5 ab\(^{-1}\)
- FCC hh: 100 TeV 20-30 ab\(^{-1}\)

ILC: 250 GeV 2 ab\(^{-1}\)
- 20km tunnel
- 4 years
- 9 years

500 GeV 4 ab\(^{-1}\)
- 31km tunnel
- 9 years

1 TeV \(\approx\) 4-5.4 ab\(^{-1}\)
- 40 km tunnel
- 11 years

350-365 GeV 1.7 ab\(^{-1}\)
- Construction/Transformation
- 11 years

FCC-hh: 150 TeV \(\approx\) 20-30 ab\(^{-1}\)

2020 2030 2040 2050 2060 2070 2080 2090
In January 1954, Enrico Fermi made a presentation in New York, on the occasion of Fermi stepping down as president of the APS, and being replaced by Bethe. The title of the presentation was **What can we learn from High-Energy Accelerators?** The following are quotations from Fermi’s notes.

- Fermi starts off by “Congratulate Society on Loosing(sic) mediocre President and getting eccellent(sic) one.”
- “But to solve the mysteries, higher energy data are needed.”
- “For these reasons clamoring for higher and higher energies..”
- “Preliminary design...8000 km, 20,000 gauss” (2 Tesla)
- “Energy of 5x10^6 GeV, cost $170 Billion” ($\sqrt{s}=3$TeV !)
- “What we can learn impossible to guess. .main element surprise. .some things look for, but see others”

- Human ingenuity allowed us to reach higher field and energies
Higgs Physics = Guaranteed deliverable of future machine.
Known (in part) facets of Higgs Physics

- Fundamental? spin-0 particle;
- Coupling to heavy bosons confirms role in generation of $W$ & $Z$ mass;
- Coupling to charged third generation fermions $t$, $b$, $\tau$ confirms new Yukawa-type interaction;
- Many couplings known at the 10% level;
Yukawa couplings of the Higgs boson

- Moving on from the results of the third generation of 2018.
- There is already information that coupling to $\mu$ and $e$ is less than coupling to $\tau$;
- Charm coupling less than the coupling to the top;
- Not yet demonstrated that coupling to charm less than coupling to bottom.

Open questions

- Is $h$ the only scalar degree of freedom?
- Is $h$ elementary?
- What keeps $m_h^2 << m_{\text{planck}}^2$?
- Was the electroweak phase transition first order?
- Did CP violating $h$ interactions generate the baryon asymmetry?
- Are there light SM-singlet degrees of freedom (in particular, related to Dark Matter)?
- What is the solution of the flavor puzzle(s)?

Heinemann and Nir 1905.00382
Higgs Boson studies at future particle colliders

J. de Blas$^{1,2}$, M. Capella$^3$, J. D'Hondt$^4$, R. K. Ellis$^5$, C. Grojean$^{6,7}$, B. Heinemann$^{6,3}$, F. Maltoni$^{8,10}$, A. Nisati$^{11,12}$, E. Petit$^{12}$, R. Rattazzi$^{13}$, and W. Verkerke$^{14}$

Contents
1 Introduction ................................................. 2
2 Methodology ............................................. 5
3 The Higgs boson couplings to fermions and vector bosons ....... 6
3.1 The kappa framework ................................... 7
3.2 Results from the kappa-framework studies and comparison ... 9
3.3 Effective field theory description of Higgs boson couplings ... 12
3.4 Results from the EFT framework studies .................... 17
3.5 Impact of Standard Model theory uncertainties in Higgs calculations ........................................ 24
4 The Higgs boson self-coupling ................................ 31
5 Rare Higgs boson decays .................................. 34
6 Sensitivity to Higgs CP .................................... 37
7 The Higgs boson mass and full width ......................... 39
8 Future studies of the Higgs sector, post-European Strategy ... 41
8.1 Higgs prospects at the muon collider ...................... 41
8.2 Higgs physics at multi-TeV electron-positron colliders ...... 42
8.3 What and Why: Higgs prospect studies beyond this report ... 42
9 Summary .................................................. 45

ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

- Comparison using a single methodology (using the submitted inputs) of the potential of various future machines.
Start from the basis of HL-LHC

❖ Progress from 2013 to 2019
❖ 2% optimistic in 2013, achievable in 2019.
❖ Dominance of theoretical errors.
- $\kappa$ has the advantage that it is simple;
- the effects of polarization are undervalued in this approach;
- Would give indications of deviations from the SM, but not necessarily diagnostic information to interpret deviation;
- In this kappa framework HL-LHC projections are included and the untagged and invisible branching ratios are constrained by the measurements.
First-stage $e^+e^-$ machines all show large improvement in $\kappa_z$, $\kappa_c$, $\text{Br}_{\text{inv}}$.

The rare, statistically dominated decays, $Z\gamma$ and the top couplings are improved over HL-LHC only by FCC-hh.

**Improvement wrt HL-LHC**

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</tr>
<tr>
<td>$\text{Br}_{\text{inv}}$</td>
<td>1.7</td>
<td>1.3</td>
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<tr>
<td>$\text{Br}_{\text{inv}}$ *</td>
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<td>1.7</td>
<td>2.2</td>
<td>2.9</td>
<td>2.9</td>
<td>1.5</td>
<td>1.7</td>
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<tr>
<td>$\text{Br}_{\text{inv}}$ **</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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</tr>
</tbody>
</table>

(*) $|\kappa_\nu| \leq 1$ applied for hadron colliders  
(**) Not requiring $|\kappa_\nu| \leq 1$  
(+) Not measured in HLLHC
Improvement wrt HL-LHC in SMEFT

- First-stage $e^+e^-$ machines all show improvement, especially (i.e. more than a factor of 10) for $g_{HZZ}$, $g_{HWW}$, $g_{Hbb}$, $g_{Hcc}$.

<table>
<thead>
<tr>
<th>HE-LHC</th>
<th>ILC-250</th>
<th>ILC-500</th>
<th>CLIC-380</th>
<th>CLIC-1000</th>
<th>CLIC-3000</th>
<th>FCCee</th>
<th>FCCee/eh/hh</th>
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<tr>
<td>$g_{HZZ}^{\text{eff}}$</td>
<td>1.7</td>
<td>1.3</td>
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<tr>
<td>$g_{HWW}^{\text{eff}}$</td>
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<td>7.8</td>
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<td>2.8</td>
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<tr>
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<td>1.6</td>
<td>1.1</td>
<td>2.4</td>
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<tr>
<td>$g_{Hbb}^{\text{eff}}$</td>
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<td>$\ast$</td>
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<tr>
<td>$g_{Hg8}^{\text{eff}}$</td>
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<td>1.5</td>
<td>6.7</td>
<td>$\geq 10$</td>
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<tr>
<td>$g_{Hg8}^{\text{eff}}$</td>
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<td>1.4</td>
<td>4.1</td>
<td>5.8</td>
<td>6.8</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
<td>$g_{Hg8}^{\text{eff}}$</td>
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<td>1.9</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>1.3</td>
<td>1.6</td>
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<tr>
<td>$\delta g_{1Z}[\times 10^2]$</td>
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<td>1.5</td>
<td>6.9</td>
<td>$\geq 10$</td>
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<tr>
<td>$\delta K_T[\times 10^2]$</td>
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<td>$\geq 10$</td>
<td>$\geq 10$</td>
<td>$\geq 10$</td>
<td>$\geq 10$</td>
</tr>
</tbody>
</table>

SMEFT ND (not measured at HL-LHC)
We consider SMEFT fit scenarios in the Higgs basis.

To assess the deviations from the SM in a basis-independent way we define effective couplings

\[ g_{HX}^{\text{eff}} = \frac{\Gamma(H \to X)}{\Gamma^{\text{SM}}(H \to X)} \]
Measuring the Higgs potential

- First order phase transition at finite temperature can give a framework for baryogenesis

- Sensitivity to Higgs trilinear coupling in
  - double Higgs production
  - one-loop effects in single Higgs production

In SM potential fixed in terms of $m_H$ and $\nu$:

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2 v^2}$
Sensitivity to $\lambda$ via single-H and di-H production

- **Di-Higgs**
  - HL-LHC ~50%
  - Improved by HE-LHC (20%), LE-FCC (15%), ILC$_{500}$ (25%)
  - Precisely by CLIC$_{3000}$ (9%), FCC(hh) (5%)
  - Robust w.r.t. other operators

- **Single Higgs**
  - Global analysis FCCee$_{365}$ and ILC$_{500}$ sensitive to ~35% when combined with LHC.
  - ~21% if FCC-ee has 4 detectors
Conclusions

- First stage $e^+e^-$ Higgs factories have a similar reach, albeit with different time scales, and differing potential at other energies.

- Projected uncertainties at first stage $e^+e^-$ Higgs factories are in many cases a significant improvement on HL-LHC, $e^+e^-$ adds information about the $Br_{\text{invisible}}$, (semi-direct measurement of Higgs width);

- Higgs physics is the central concern of HL-LHC and beyond; this community (experiment and theory).