Future lepton-based colliders and ERL

- Impact on the physics program and potential (J. D’Hondt for M. Klein)
- ERL-based machine developments and plans (A. Hutton)

Andrew Hutton (Jefferson Laboratory)
Max Klein (Uni. Liverpool)

LDG Workshop on Future Accelerator R&D, Frascati, 11.7.2023, for the ERL Coordination Panel
Potential impact of ERL technology

With stepping stones for innovations in technology to boost our physics reach

enables the ultimate upgrade of the LHC program

2020’ies

demonstrate multi-turn high-power ERL

2030’ies

high-power ERL demonstrated

2030’ies

ERL application electron cooling

2030-2040’ies

ERL for e^+e^- Higgs Factories

2040-2050’ies

increases the performance of the next major colliders

2070’ies

ERL FCC-eh

reuse ERL
Three kinds of lepton based colliders are studied using ERL technology:

- **electron-positron Higgs facilities**
  - CERC (FCC), arXiv:2203.07358
  - ReLiC, arXiv:2203.06476
  - ERLC (ILC), arXiv:2302.09758
  - di-Higgs, Roadmap, AH ERLWS22

- **electron-proton colliders**
  - EIC, e.g. F. Willeke EPS2021

- **muon collider**
  - EXMP, arXiv:2106.03255 & 2304.08788

High luminosity with reduced power, and focus on the exploration of the Higgs sector.
ERL technology for the EIC
Electron Ion Collider

Plot from F.Willeke: EPS2021

Optimised polarised ep luminosity vs cms energy
Peak luminosity at 105 GeV w/o cooler: $0.44 \times 10^{34}$

See also W.Fischer et al, eh luminosity optimisation, IPAC 2021
doi:10.18429/JACoW-IPAC2021-WEPAB004

Asymmetry: $A_1 \sim x$
Gluon: $\frac{\partial g_1}{\partial \ln Q^2} \sim \Delta G$

Highest possible luminosity is crucial for spin program.
ERL cooler essential for EIC
ERL-based ep/eA colliders
A paradigm shift: high-energy electron-proton collisions

existing/future proton accelerator
LHC and/or FCC

new electron accelerator
with Energy Recovery Linac technology in the design it would be a major step addressing the energy sustainability aspect
Collision energy above the threshold for EW/Higgs/Top
from mostly QCD-oriented physics to General-Purpose physics

The real game change between HERA and LHC/FCC
compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

at these energies and luminosities, interactions with all SM particles can be measured precisely
Higgs Production Cross Sections in $e^+e^-$ and ep
Higgs Production Cross Sections in $e^+e^-$ and ep

$\sigma(e^+e^- \to HX) [fb]$ vs $\sqrt{s} [GeV]$

- FCC-ee
- LHeC
- H\nuX
- He'X
- $H_{e\nu} \bar{e}$
- $He'X$
- $H_{\nuX}$

H strahlung: ZH
CC: $H_{e\nu} \bar{e}$

Higgs Production Cross Sections in $e^+e^-$ and ep

- $\sigma(e^+e^- \rightarrow HX)$ [fb]

- $2.5ab^{-1}/exp$ for FCC-ee
- $1ab^{-1}$ for LHeC

- $H_{e\overline{e}}, H_{eX}, H_{e^+e^-}, H_{e^-X}$
- $He^+e^-, H^+e^-$

- H strahlung: $ZH$
- CC: $H_{e\overline{e}}$

- $LHeC$

- $e^+e^-$
- ep

- $t\overline{t}H$
- $ZH$
- $H_{e\overline{e}}$
- $HH_{e\overline{e}}$
- $ZHH$

- $H$ width: $e^+e^-$ (ZH)
- $e^+e^- \oplus$ ep get 99% of SM decays
- ep is reasonably clean from bck & no pile-up
- FCC-eh is as precise as FCC-ee
- rare decays for FCC-hh: needs ee/ep/pp
- trilinear coupling for hh/eh & high E_\text{lab} Lumi e^+e^-

H couplings with LHC/LHeC & ILC

The HL-LHC⊕LHeC is performing very well compared to ILC250
Uncharted QCD territory
Parton Distribution Functions (PDF)

- QCD needs partonic contents to be resolved
- HL-LHC and FCC-hh are precision Higgs factories requiring accurate, N^{3}LO PDF and $\alpha_s$ input
- QCD dynamics at small x may be non-linear which would change many SM predictions for hh
- Global fits use inconsistent, hadronic data, which leads to spread of PDFs and uncertainty assumptions
- PDFs precisely determined only in high E/L DIS ep

Empowering the FCC-hh program with the FCC-eh

- Equivalent parton distribution functions
  - Higher energies
  - ~5-7% uncertainty on the $\sigma(W,Z,H)$
  - Electro-Weak region

Diagram showing parton distribution functions for different processes and energy ranges.
Empowering the FCC-hh program with the FCC-eh

- \( pp \) @ 100 TeV
- \(~5-7\%\) uncertainty on the \( \sigma(W,Z,H) \)
- \(~1\%\) uncertainty on the \( \sigma(W,Z,H) \)

Electro-Weak region

FCC-eh essential to unlock FCC-hh science potential
### Complementarity for Higgs physics in the FCC program

*(Higgs coupling strength modifier parameters $\kappa_i$ – assuming no BSM particles in Higgs boson decay)*

*(expected relative precision)*

<table>
<thead>
<tr>
<th>$\kappa_i$</th>
<th>HL+FCC-ee@240</th>
<th>HL+FCC-ee</th>
<th>HL+FCC-ee (4 IP)</th>
<th>HL+FCC-ee/hh</th>
<th>HL+FCC-eh/hh</th>
<th>HL+FCC-hh</th>
<th>HL+FCC-ee/eh/hh</th>
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<tbody>
<tr>
<td>$\kappa_W$ [%]</td>
<td>0.86</td>
<td>0.38</td>
<td>0.23</td>
<td>0.27</td>
<td>0.17</td>
<td>0.39</td>
<td>0.14</td>
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<tr>
<td>$\kappa_Z$ [%]</td>
<td>0.15</td>
<td>0.14</td>
<td>0.094</td>
<td>0.13</td>
<td>0.27</td>
<td>0.63</td>
<td>0.12</td>
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<tr>
<td>$\kappa_t$ [%]</td>
<td>1.1</td>
<td>0.88</td>
<td>0.59</td>
<td>0.55</td>
<td>0.56</td>
<td>0.74</td>
<td>0.46</td>
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<tr>
<td>$\kappa_{t\gamma}$ [%]</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>0.29</td>
<td>0.32</td>
<td>0.56</td>
<td>0.28</td>
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<tr>
<td>$\kappa_{Z\gamma}$ [%]</td>
<td>10.</td>
<td>10.</td>
<td>10.</td>
<td>0.7</td>
<td>0.71</td>
<td>0.89</td>
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<td>$\kappa_c$ [%]</td>
<td>1.5</td>
<td>1.3</td>
<td>0.88</td>
<td>1.2</td>
<td>1.2</td>
<td>–</td>
<td>0.94</td>
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<tr>
<td>$\kappa_\gamma$ [%]</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>0.95</td>
<td>0.95</td>
<td>0.99</td>
<td>0.95</td>
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<tr>
<td>$\kappa_b$ [%]</td>
<td>0.94</td>
<td>0.59</td>
<td>0.44</td>
<td>0.5</td>
<td>0.52</td>
<td>0.99</td>
<td>0.41</td>
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<td>$\kappa_\mu$ [%]</td>
<td>4.</td>
<td>3.9</td>
<td>3.3</td>
<td>0.41</td>
<td>0.45</td>
<td>0.68</td>
<td>0.41</td>
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<tr>
<td>$\kappa_\tau$ [%]</td>
<td>0.9</td>
<td>0.61</td>
<td>0.39</td>
<td>0.49</td>
<td>0.63</td>
<td>0.9</td>
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<td>$\Gamma_H$ [%]</td>
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<td>0.87</td>
<td>0.55</td>
<td>0.67</td>
<td>0.61</td>
<td>1.3</td>
<td>0.44</td>
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- **FCC-ee prospect**
- **FCC-pp/ep prospect**
- **ALL COMBINED**
- **only FCC-ee@240GeV**
- **only FCC-hh**

**Ultimate Higgs Factory = \{ee + eh + hh\}**
Future flagship at the energy & precision frontier

Current flagship (27km)
impressive programme up to ~2040

Future Circular Collider (FCC)
big sister future ambition (100km), beyond 2040
attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC
10y @ 1.2 TeV (1ab⁻¹)
ERL-based H/HH Factories
Energy Recovery applications for HEP $e^+e^-$ colliders

This plot suggests that with an ERL version of a Higgs Factory one might reach

- x10 more H’s
- or
- x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories

Full scrutiny of ERL-based proposals yet to come

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snapshot of lots of work in progress
full scrutiny of ERL-based proposals yet to come

Tri-Linear Higgs Coupling in $e^+e^-$

Kinematic limit of $e\bar{e} \rightarrow Z H H$ : $M(Z) + 2 M(H) = 341$ GeV

ZHH unpolarised cross section maximum at 500 GeV: $O(0.1) \text{ fb}$

$O(10^{34}) \text{ cm}^{-2}\text{s}^{-1} \text{ luminosity gives 1 ab}^{-1} \text{ in ten years: 100 events (A=1)}$

$O(10^{36}) \text{ cm}^{-2}\text{s}^{-1} \text{ luminosity should produce 10 000 events } \rightarrow \text{ few %}$

and $300 \text{ fb} \times 100 \text{ ab}^{-1} = 3 \times 10^7 \text{ ZH events},$

$\rightarrow$ opens rare $H$ decay channel programme in $e^+e^-$

This is a strong case for a next generation linear $ee$ collider

Gradient 20$f$ MV/m: two 25/f km linacs:

It needs: Twin cavities, $4.5K$, $\text{Nb}_3\text{Sn}$, $Q_0$ towards $10^{11}$
Remarks – impact on the physics program and potential

ERL is a novel technology, that leads to an outstanding improvement of the performance of lepton-based colliders

This basically concerns superior luminosity performances at similar or even reduced power consumption.

It regards various new options: ERL versions of FCC-ee and ILC, new ERL designs for TeV energy $e^+e^-$ colliders, high power updates of electron-proton designs for high energy (LHeC/FCC-eh) and increased luminosity (EIC) etc.

This way, ERL technology, under design worldwide and much advancing in Europe, will not only advance new sustainable accelerator techniques but directly improve the performance of forthcoming new colliders.

This, as has been illustrated with a few examples, will open new avenues for single and multiple Higgs production measurements, i.e. provide a complete and consistent view on the Higgs boson decays and verify the Higgs potential.

Further study of the principles, development of ERL technology and scrutinising the various Higgs and further physics opportunities is a task the ERL panel will pursue and invites to support and join.

Sustainability is a requirement for our future work and energy recovery the best principle answer we have at hand.

NEXT (ANDREW HUTTON): INTEGRATING ERL IN THESE FUTURE COLLIDERS
backup
Higgs Physics with ee/pp/ep/\(\mu\mu\) Colliders

**Higgs interactions**

**precision reach on effective Higgs couplings from SMEFT global fit**

**HL-LHC+FCC-ee:** Precision largely controlled by HL-LHC

**HL-LHC+FCC-ee+eh+hh:** FCC-hh brings remaining H couplings below 1%

Note also improvement in HWV from combining with FCC-eh

Jorge deBlas at FCCweek, London, June 2023, based on arXiv:2206.08326 “Global SMEFT Fit…”
High precision control of $pp \rightarrow H$ through PDFs from LHeC/FCCeh

**H couplings with LHC/LHeC & ILC**

**pp\(\rightarrow\)HX cross sections and uncertainty**

Determination of Higgs couplings in $pp/ep$ and ILC500


Parton-parton "luminosities" @ 14 TeV

<table>
<thead>
<tr>
<th>Parton-pair</th>
<th>10^2</th>
<th>10^3</th>
<th>10^4</th>
<th>Relative uncertainty</th>
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<tr>
<td>gg</td>
<td>0.8</td>
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<td>0.9</td>
<td>0.95</td>
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<td>1.2</td>
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<tr>
<td>gq</td>
<td>0.8</td>
<td>0.85</td>
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<td>0.95</td>
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<tr>
<td></td>
<td>1.05</td>
<td>1.1</td>
<td>1.15</td>
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<tr>
<td>qq</td>
<td>0.8</td>
<td>0.85</td>
<td>0.9</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td>1.1</td>
<td>1.15</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- LHeC 50 fb-1 (1st 3 yrs)
- LHeC 1ab-1 (incl.+HQ)
- (s,c,b) also included

High precision Higgs measurements in ep with LHeC (200fb) and FCC-he (1pb in CC H production)
Huge improvements vs LHC, especially for $bb$, $WW$, $ZZ$ and $cc$ results → 1% precision of LHC Higgs couplings and sub-percent for FCC-$hh$+he. 0.3% precision (strong coupling + PDFs) of $pp \rightarrow HX$ cross section, $N^3$LO

ERL-based muon collider
Higgs Physics with Muon Collider

**SM Higgs couplings in kappa framework**

Higgs Coupling Uncertainties HL-LHC, +LHeC, +125MuC, +10TeVMuC

- **HL-LHC**: 3ab⁻¹
- **LHeC**: 1ab⁻¹
- **MuC125GeV**: 5fb⁻¹
- **+10TeVMuC**: 10ab⁻¹

- LHC improvement with ep better than muC125 (apart from muon)
- 10 TeV with 10 ab⁻¹ comparable to FCC expectations

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**Tri (four) linear Higgs couplings: Potential**

\[
\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \frac{\lambda_3}{2v} m_h^2 h^3 - \frac{\lambda_4}{8v^2} m_h^2 h^4
\]

\[
\lambda_3^{SM} = \lambda_4^{SM} = 1
\]

Determine the tri-linear Higgs coupling with about 20% precision at 3 TeV (1-2ab⁻¹) raised to 4% at 10 TeV MuC (10ab⁻¹) [HHH hard]. That is comparable to FCChh expectation and A factor of two or so better than CLIC.

HH is very difficult for circular ee. Loops?? HH in HL-LHC/LHeC and FCCeh under study.

[arXiv:2303.08533 "Towards a Muon Collider"