Experimental synergies between DIS and the LHC (and beyond)

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HUGE THANKS to Max Klein, Uta Klein, Nestor Armesto, Daniel Britzger, Oliver Brüning, Achille Stocchi, Oliver Fischer, Claire Gwenlan, Paul Newman, Christian Schwanenberger and many others!

DIS, Santiago de Compostela
6/5/2022
Introduction

- The LHC experiments are delivering excellent results and have an outstanding programme of searches and precision measurements which will last for many years.

- The Run 3 is just starting, with exciting opportunities offered by the upgrade of the accelerator, leading to an increased centre-of-mass energy (13.6 TeV), renewed detectors and novel triggers.
Introduction

- The LHC experiments are delivering excellent results and have an outstanding programme of searches and precision measurements which will last for many years.

- The Run 3 is just starting, with exciting opportunities offered by the upgrade of the accelerator, leading to an increased centre-of-mass energy (13.6 TeV), renewed detectors and novel triggers.

- The HL-LHC, to be hopefully started at the end of this decade for 10 years of operations, will maximise the experiments potential, giving us the opportunity to tackle objectives of fundamental importance, such as: get the first direct constraints on the Higgs trilinear self-coupling and its natural width, measure SM and Higgs parameters with unprecedented precision, search for new physics increasing the present reach in mass and coupling by at least 20-50%, confirm (or not) the intriguing LHCb results in the flavour sector, push boundaries of nuclear physics etc...

- Can we do more?

Certainly, YES!
The European Strategy and Snowmass/P5

- A huge combined effort of the theory and experimental particle physics communities during the last 5 years led to several proposals for new collider (and non-collider) projects at CERN and elsewhere

  - Beyond HL-LHC, an electron-positron Higgs and electroweak factory is certainly considered as the next big priority, followed by a future high-energy hadron collider with 100 TeV c.o.m. energy
  
  - R&D efforts should be focused on advanced accelerator technologies (high-field magnets, plasma wakefield acceleration, bright muon beams, energy recovery linacs)

- Using the LHC complex beyond the 4 main experiments also opens huge possibilities (e.g. Physics Beyond Collider experiments)

- What else?

Use the proton beams of the LHC for DIS, and associate ep with any pp high-energy future collider!
DIS and pp colliders: an historical synergy

The idea of an e-p collider at CERN, the LHeC, was proposed in 2005 and developed since then: http://cern.ch/LHeC

Basic idea is not new: physics at the Fermi scale was developed thanks to the synergy of LEP/SLC, HERA and the Tevatron

The future Particle Physics at colliders

Tevatron/HERA/LEP (Fermiscale)

HL-LHC/LHeC (Terascale)

FCC-hh/FCC-eh (Terascale)

e^+e^- CepC, ILC
FCC-ee, CLIC, C^3

... μ^+μ^-

M. Klein
The LHeC as e-p and e-Ion collider and its update – the FCCeh

- Unique opportunity to take lepton-hadron physics to the TeV centre-of-mass scale at high Lumi

LHeC e-p: $E_e=60$ (*) GeV, $E_p=7$ TeV $\sqrt{s} = 1.3$ TeV
→ For FCC-eh: 50 TeV protons, $\sqrt{s} = 3.5$ TeV

LHeC e-Ion: $E_e=60$ (*) GeV, $E_{ion}=2.76$ TeV
→ For FCC-eh: increase up to ~20 TeV

(*) OR 50 GeV

Concurrent ep + pp (eA + AA) operations

LHeC (FCC-eh): operation 2035+ (2050+)
Integrated luminosity: ~ 1-2 ab$^{-1}$
Figure 2: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2, three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60$ GeV), 1/4 (the size of the SPS, $E_e = 56$ GeV) and 1/5 (most inner track, $E_e = 52$ GeV). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100km ring of the FCC. Present considerations suggest that Point L may be preferred as the position of the ERL, while two GPDs would be located at A and G.
LHeC: from the CDR in 2012 to today!

An enormous amount of studies has been carried out on LHeC physics and technologies needed

- Conceptual Design Report 2012: 5 years of studies commissioned by CERN, ECFA and NuPECC
  - At the time, about 200 participants, 69 institutes

- Most recent - CDR updated:
  300+ pages document, ~300 authors among experimentalists and theorists, + documents submitted for the European Strategy of PP 2020 and Snowmass 2021

ECFA newsletter No. 5, August 2020

Similar studies have been developed for the FCC and several papers published in the past few years


Definitely at an advanced stage!
Possible scenarios of future colliders

Schedule shifted by few years now due to various delays

- e+e- US options (C3, HELENA) and mu+mu- collider not included
Outline: where synergies are

The \( eh \) programmes of LHC and FCC are designed to operate synchronously with \( hh \) → the biggest synergy one may have, and the best way to exploit the expensive hadron beams we (will) have...

Physics complementarity

- PDFs, strong coupling constant, low-\( x \) measurements
- \( W \) mass, top mass, on other precision measurements in EWK and Top sectors
- Higgs measurements with additional sensitivity
- Searches for new physics, including prompt and long-lived new scalars from Higgs, SUSY particles, heavy neutrinos, dark photons and axions
- High-energy and high-density measurements of heavy ion collisions

Synergies in technology

- ERL technology and its potential e.g. for FCC-ee to reach highest energy
- Tracking and calorimeters technologies and the common aspects to \( ee \) and \( pp \)
- Possibility to have a \textit{dual} detector (and an interaction region) suitable for hh and eh collisions, serving ALICE and LHeC at the same time (\textit{Eur. Phys. J. C (2022) 82:40})

Note: dedicated talks on most of these points in WG6
Strong interactions: PDF

- A precision physics era at the HL-LHC will be maximally precise if it was accompanied by the LHeC PDF programme
- Complete unfolding of parton contents in unprecedented kinematic range: u,d,s,c,b,t, xg

PDFs at the HL-LHC (Q = 10 GeV)

Crucial for HL-LHC:
- Extension of high mass search range
- Non-linear low x parton evolution; saturation?
- high precision electro-weak, Higgs measurements (e.g. remove essential party of QCD uncertainties of gg → H)

Range relevant for new heavy particles and where new physics can be!
alpha_s and Higgs cross section

- Strong coupling constant could be measured to the permille accuracy (incl. + jets analysis)

\[
\Delta \alpha_s(M_Z) \text{(incl. DIS)} = \pm 0.00022 \text{(exp+PDF)}
\]

\[
\Delta \alpha_s(M_Z) \text{(incl. DIS & jets)} = \pm 0.00018 \text{(exp+PDF)}
\]

- Improvement in the calculation of pp→HX calculated at N^3LO in pQCD thanks to PDF

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_H$ [pb]</th>
<th>$\Delta \sigma_{\text{scales}}$</th>
<th>$\Delta \sigma_{\text{PDF+}\alpha_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon-fusion</td>
<td>54.7</td>
<td>5.4%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Vector-boson-fusion</td>
<td>4.3</td>
<td>2.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$pp \rightarrow WH$</td>
<td>1.5</td>
<td>0.5%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$pp \rightarrow ZH$</td>
<td>1.0</td>
<td>3.5%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}H$</td>
<td>0.6</td>
<td>7.5%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

Cross sections of Higgs production N^3LO for existing PDF sets (left side) and for the LHeC PDFs (right side)

See also talk by Daniel Britzger on 4/5
[where even more up to date studies are shown]
Strong interactions: eA and nuclear structure

- Extraction of Pb-only PDFs by fitting NC+CC pseudodata, using xFitter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LHeC (HL-LHC)</th>
<th>eA at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{p_b}$ [GeV]</td>
<td></td>
<td>0.574</td>
<td>1.03</td>
<td>4.1</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\sqrt{s_{eN}}$ electron-nucleon [TeV]</td>
<td></td>
<td>0.8</td>
<td>1.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Large improvements at all $x$

Fit to a single nucleus possible

Extension of fixed target range by $10^{3-4}$

de-confinement, saturation

nPDFs independent of p PDFs
EWK measurements: W mass

- **@ HL-LHC W mass** precision measurement uses dedicated dataset at low $<\mu>$
  - exploit the extended leptonic coverage
  - LHeC will provide additional precision through PDF

\[ \Delta m_W = \pm 6 \text{ MeV} \] (with reduced PDF unc from HL LHC)
\[ \Delta m_W = \pm 2 \text{ MeV} \] (with improved PDF from LHeC)

- $M_W$ and $M_Z$ (as well as $m_{\text{Top}}$) will be measurable at unprecedented precision independently at the LHeC

Even more relevant after recent CDF results and claimed 9 MeV precision!
EWK measurements: $\sin^2\theta_{\text{eff}}$

LHeC will contribute to $\sin^2\theta_{\text{eff}}$ precision measurements directly and indirectly

- **Direct** measurements using higher-order loop corrections

$$\sin^2 \theta_{W}^{\text{eff,\ell}}(\mu^2) = \kappa_{NC,\ell}(\mu^2)\sin^2 \theta_W$$

- Scale dependence of $\sin^2\theta_{\text{eff}}$ not negligible
  - simultaneous fits made with PDFs

- **Indirect**: improving precision of HL-LHC studies
  - Use F-B Asymmetry measurements

Precisions $\rightarrow 1 \cdot 10^{-5}$ if PDF uncertainties are improved with LHeC

![Graph showing values of $\sin^2\theta_{\text{eff}}$ for different LHeC energies and comparing with world average.](image)
Higgs physics at ep

**Production of Higgs boson via Vector-Boson-Scattering**

A large dataset of Higgs events for precision measurements!

### Charged Currents

- **DIS Higgs Production Cross Section**

### Neutral Currents

- **Log(σ_{HH})**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LHeC</th>
<th>HE-LHeC</th>
<th>FCC-eh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$</td>
<td>TeV</td>
<td>7</td>
<td>13.5</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>$\sqrt{s}$</td>
<td>TeV</td>
<td>1.30</td>
<td>1.77</td>
<td>2.2</td>
<td>3.46</td>
</tr>
<tr>
<td>$\sigma_{CC}$ $(P = -0.8)$</td>
<td>fb</td>
<td>197</td>
<td>372</td>
<td>516</td>
<td>1038</td>
</tr>
<tr>
<td>$\sigma_{NC}$ $(P = -0.8)$</td>
<td>fb</td>
<td>24</td>
<td>48</td>
<td>70</td>
<td>149</td>
</tr>
<tr>
<td>$\sigma_{CC}$ $(P = 0)$</td>
<td>fb</td>
<td>110</td>
<td>206</td>
<td>289</td>
<td>577</td>
</tr>
<tr>
<td>$\sigma_{NC}$ $(P = 0)$</td>
<td>fb</td>
<td>20</td>
<td>41</td>
<td>64</td>
<td>127</td>
</tr>
<tr>
<td>HH in CC</td>
<td>fb</td>
<td>0.02</td>
<td>0.07</td>
<td>0.13</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**Total cross section (m_H=125 GeV)**

- **1000 fb**
- **Higgs σ in CC**

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Prospects for Higgs in ep

Prospects for signal strength measurements of Higgs decays

\[ \delta \mu / \mu [\%] \]

![Graph showing signal strength constraints to 0.8% (bb) and 7.4% (cc)]

**LHeC:** 1ab⁻¹, 7 TeV \( E_p \)
**HE LHeC:** 2ab⁻¹, 13 TeV \( E_p \)
**FCC-eh:** 2ab⁻¹, 50 TeV \( E_p \)

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Kappa factor framework

- $\kappa_i$: coupling strength modified parameters
- powerful method to parameterise possible deviations from SM couplings

From the ES Briefing Book: uncertainties on $\kappa_i$

Note: good potential for improving on Higgs invisible with HL+LHeC but more refined analyses needed

$\text{Br}(h \to \text{invisible}) = 6\%$ at $2\sigma$ level

Electron-jet invariant mass

Higgs@FC WG

Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\delta \kappa / \kappa$. Limits on $\text{Br}(%)$ at $95\%$ CL.
Combinations of LHeC + HL-LHC

Determination of SM Higgs couplings jointly from pp + ep

The combined ep+pp at LHC reaches below 1% for dominant channels

LHeC adds charm decays.

Overall, adding electrons makes the LHC a Higgs precision facility.

The cross section depends strongly on the CMS energy as is shown. The production section being smaller but still measurable. The production
Searches for new physics

- ep collider is ideal to study common features of electrons and quarks with
  - EW / VBF production, LQ, forward objects, long-lived particles
- BSM programme at e-p aims to
  - Explore new and/or challenging scenarios
  - Characterize hints for new physics if some excess or deviations from the SM are found at pp colliders
- Differences and complementarities with pp colliders
  - Some promising aspects:
    - small background due to absence of QCD interaction between \( e \) and \( p \)
    - very low pileup
  - Some difficult aspects:
    - low production rate for NP processes due to small \( s \)


8 Searches for Physics Beyond the Standard Model
8.1 Introduction
8.2 Extensions of the SM Higgs Sector
  8.2.1 Modifications of the Top-Higgs interaction
  8.2.2 Charged scalars
  8.2.3 Neutral scalars
  8.2.4 Modifications of Higgs self-couplings
  8.2.5 Exotic Higgs boson decays
8.3 Searches for supersymmetry
  8.3.1 Search for the SUSY Electroweak Sector: prompt signatures
  8.3.2 Search for the SUSY Electroweak Sector: long-lived particles
  8.3.3 R-parity violating signatures
8.4 Feebly Interacting Particles
  8.4.1 Searches for heavy neutrinos
  8.4.2 Fermion triplets in type III seesaw
  8.4.3 Dark photons
  8.4.4 Axion-like particles
8.5 Anomalous Gauge Couplings
  8.5.1 Radiation Amplitude Zero
8.6 Theories with heavy resonances and contact interaction
  8.6.1 Leptoquarks
  8.6.2 \( Z' \) mediated charged lepton flavour violation
  8.6.3 Vector-like quarks
  8.6.4 Excited fermions \((u', e', \nu')\)
  8.6.5 Colour octet leptons
  8.6.6 Quark substructure and Contact interactions

Only a few specific examples given here

Complementary to Oliver Fischer talk on 3/5
Hidden, dark sectors at e-p

- New physics models predicting long-lived particles gained lot of attention in the past few years
  
  - Hidden, dark sector
  - populated by feebly interacting particles
  - Might be difficult in certain regions at hh
    
    - Large backgrounds and high pileup
    - detector dimensions and geometrical acceptance
      
      - [e.g. short-distances are hard to cover for hh]

- At LHeC and FCC-eh, one can reconstruct displaced vertices and as such be sensitive to non-promptly decaying, light new particles

<table>
<thead>
<tr>
<th>Portal</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector (Dark Vector, $A_{\mu}$)</td>
<td>$- \frac{1}{2} \cos \theta_W f_{\mu \nu} B_{\mu \nu}$</td>
</tr>
<tr>
<td>Scalar (Dark Higgs, $S$)</td>
<td>$(\mu S + \lambda_{HS} S^2) H \dagger H$</td>
</tr>
<tr>
<td>Pseudo-scalar (Axion, $a$)</td>
<td>$\frac{a}{f_a} F_{\mu \nu} F^\mu \nu$, $\frac{a}{f_a} G_{i, \mu \nu} \tilde{G}^{i \mu \nu}$, $\frac{a}{f_a}$ $\bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>Fermion (Sterile Neutrino, $N$)</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>

benchmark value is $r_{\text{min}} = 40\mu$m (~ 5 nominal detector resolutions); $p_T$ threshold for reconstruction of a single charged particle is chosen as 100 MeV
Complementarity of e-p: new scalars

- Interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by the scalar mixing angle.
- The contours are for 3 events and consider displacements larger than 50 μm to be free of background.

\[(\mu S + \lambda_{HS} S^2) H^\dagger H\]

Covering important regions between pp and ee / low-energy experiments
Complementarity of e-p: Dark photons

- have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter \( \varepsilon \).

\[
\frac{\varepsilon}{2\cos \theta_W} F_{\mu \nu} B^\mu V
\]

Covering important regions between pp and ee / low-energy experiments

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Sterile neutrinos

Similarly to the case of the Higgs exotics decays, sterile neutrinos

\[ y_N LHN \]

active-sterile neutrino mixing with the electron flavour \( \rightarrow |0e|2 \)

production channel: \( W_t^{(q)} \)

production channel: \( W_t^{(\gamma)} \)

Sensitivity of the LFV lepton-trijet searches (at 95 % C.L.) and DV one

Different analyses depending on \( m(N) \) and \( m(W) \) relations
Synergy in technology
Aim is to accumulate up to 500/fb - 1/ab in few years of operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>50.0</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>20.0</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td></td>
<td>1188</td>
</tr>
<tr>
<td>Bunch population</td>
<td>(\times 10^{10})</td>
<td>0.3</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>nC</td>
<td>0.50</td>
</tr>
<tr>
<td>Normalised emittance at IP</td>
<td>mm.mrad</td>
<td>30.0</td>
</tr>
<tr>
<td>Betatron function at IP</td>
<td>cm</td>
<td>10.0</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>cm</td>
<td>0.06</td>
</tr>
<tr>
<td>Installed RF voltage</td>
<td>GV</td>
<td>17.2*</td>
</tr>
<tr>
<td>Beam-beam disruption</td>
<td>cm².s⁻¹</td>
<td>14.3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>cm⁻².s⁻¹</td>
<td>(6.5 \times 10^{33})</td>
</tr>
</tbody>
</table>

cost: \(O(1)\) BCHF
Scope of FCC-eh Structures

Small Experimental Caverns
- 30 m x 35 m x 66m

Junction Caverns
- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m

Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

Shafts:
- 2 x Service shafts: 9 m dia. x 175 m depth

Service Caverns
- 25 m x 15 m x 50 m

Aim is to accumulate up to 3/ab in 10+ yrs of operations
The electron beam: the Energy Recovery Linac

Electron E depends on the linac!

- ERL: 20mA $I_e$
- Allow inst lumi $10^{-34}$ cm$^{-2}$ s$^{-1}$ and integrated lumi in e·p up to $O(1)$ ab$^{-1}$
- $U(ep) = 1/n U(LHC)$, with $n=3$ (for CDR) → now more $n=4$
  This gains 20-30% cost but $E < 60$ GeV

Higgs, BSM, top, low x physics → all require $E > 50$ GeV

Frequency set to 802 MHz, commensurate with LHC and 401/802 at CERN+FCC, beam-beam stability

Front-to-end simulations including synchrotron radiation and beam-beam interaction at the IP have shown an excellent transmission and energy recovery efficiency.

See also K.D.J André talk, 5/5
Test facility: PERLE

- Low energy ERL facility in Orsay
- Collaboration involving CERN, Jefferson Laboratory, STFC-Daresbury, University of Liverpool, BINP-Novosibirsk and the Irene Curie Lab at Orsay.
- Major parameters taken from LHeC:
  - 3-turn configuration, source
  - 802MHz frequency
  - cavity-cryomodule technology
- Suitable facility for the development of LHeC ERL technology and the accumulation of operating experience prior to and later in parallel with it
- It has its own physics programme and industrial applications

See talk by Achille Stocchi on 5/5

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### Phase I operation by 2025

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

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### Table 9.1: Summary of main PERLE beam parameters.

<table>
<thead>
<tr>
<th>Target parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>MeV</td>
<td>7</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>MeV</td>
<td>500</td>
</tr>
<tr>
<td>Norm. emittance $\gamma \epsilon_{x,y}$</td>
<td>mm-mrad</td>
<td>6</td>
</tr>
<tr>
<td>Average beam current</td>
<td>mA</td>
<td>20</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>pC</td>
<td>500</td>
</tr>
<tr>
<td>Bunch length</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>25</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>801.6</td>
</tr>
<tr>
<td>Duty factor</td>
<td>CW</td>
<td></td>
</tr>
</tbody>
</table>

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Footprint: 24 x 5.5 x 0.8 m³
ERL Applications

Very diverse and interesting applications of the ERL technology, well beyond the sole DIS - pp synergy! A few examples from ERL R&D Roadmap symposia and related documents:

- [industry & physics] An ERL-FEL based on a 40 GeV LHeC electron beam would generate a record laser with a peak brilliance similar to the European XFEL but an average brilliance exceeding that of the XFEL by orders of magnitude.

- [industry] It would bring technological advancement in industrial process of producing semiconductor chips.

- [high-energy physics] Two recent concepts have been published for ERL variants of the FCC-ee and ILC.

Green FCC-ee: ERL-based collider

ILC as an ERLC

Two parallel superconducting linacs


Synergies in technology: the LHeC Detector

R=4.6 m [6.2 FCCeh]
L=13.6 m [FCCeh:19.3 about CMS size]

FCC-eh Detector


- Asymmetric, reflecting the beam energy asymmetry
- Can be built based on established technologies from ATLAS and CMS
- Must be highly hermetic
- Must have fine segmentation and good resolution for EM calo
- Must have good tracking capabilities (e.g. for b-tagging) also in forward region
A synergy example: the tracking detector

6 hits for $|\eta| < 3.6$, 2 hits for $-4.3 < \eta < 4.8$

outer radius $\sim 80$ cm
number of layers: 10
Solenoid B field: 3 T

Must minimise the material impact at high $\eta$

Relatively small radiation level $\rightarrow$ can employ CMOS-based technology for the inner silicon tracker. E.g.: Depleted Monolithic Active Pixel Sensors (DMAPS), also in study for ATLAS, LHCb, mu3e and other HEP experiments
Joint eh-hh operations: the ultimate synergy

- Two basic operation modes have to be established:
  - hh collisions in IP1 (ATLAS), 2, 5 (CMS) and 8 (LHCb)
  - eh collisions in IP 2 and hh collisions 1, 5 and 8

The two proton beams must be housed in the same quadrupole aperture
The detector could be adapted to be symmetric, suitable for both eh and hh collisions

Could combine the ALICE and LHeC experiments at point 2 of the HL-LHC:

- e-h detector design for the LHeC
- e-h & h-h detector design for the LHeC

See also K.D.J André talk, 5/5
Conclusions

- An electron-proton facility represents a seminal opportunity to develop and explore QCD, to study high precision Higgs and electroweak physics and to substantially extend the range and prospects for accessing BSM physics, on its own and in combination of pp with ep.

- Physics complementarities and technology development offer full synergies from many perspectives → **DIS can sustain HL-LHC and bridge to CERN’s long-term future**

- LHeC leads to novel accelerator studies:
  - Energy Recovery Linacs are a green power facility nowadays very interesting
  - An international collaboration is in place to realise the first multi-turn 10 MW ERL facility, PERLE at Orsay, with its main parameters set by the LHeC and producing the first encouraging results

- The possibility to make eh/hh and eA/AA/pA concurrent even at IP2 opens even further opportunities for the Heavy Ion community, with unique discovery potential on nuclear structure, dynamics and QGP physics

Overall, the LHeC would keep accelerator and detector developments up to date while preparing for colliders that cost O(10)BSF, and paves the way to the **FCC complex** in its full hh-eh capacity

**DIS at CERN with hh is a concrete, huge opportunity that should not be missed**
Back up
Parton luminosities and alpha_S

Impact on the gg, gq, qqbar and qq parton luminosities, e.g. just using 50/fb of data (first phase of LHeC):
- at low mass the LHeC places the dominant constraint
- at intermediate masses the LHeC and HL-LHC constraints are comparable in size (HL-LHC stringer for gg and gq)

Strong coupling to permille accuracy (incl + jets):

\[ \Delta \alpha_s(M_Z) \text{(incl. DIS)} = \pm 0.00022_{\text{(exp+PDF)}} \]
\[ \Delta \alpha_s(M_Z) \text{(incl. DIS & jets)} = \pm 0.00018_{\text{(exp+PDF)}} \]
Impact of LHeC on pp: Higgs cross section

- Calculation of all production modes improved by PDF
- Even clearer for pp→HX calculated at N^3LO in pQCD

Cross sections of Higgs production calculated to NLO using the iHix program for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side)

Increasing impact of resummation on the cross section with increasing energy → main effect comes through the modification of the extraction of parton densities and their extrapolation.
Top physics: e.g. Flavour Changing Neutral Current

- Dominated by single top production
  - ~ 1.9 pb - e.g. Vtb vertex studies
  - In addition, photoproduction of top-pairs

- Can do precision measurements and measurements of rare processes: FCNC

- Excellent complementarities with ee and pp colliders
  - Shown: HL-LHC and ILC 250 GeV
Higgs to bbar and cobar

- Higgs to bb or cc signal, -0.8 polarization considered
- Detector level analysis with realistic tagger
  - Efficiency 60-75% for b-tagged jets
  - ~ 10% efficiency for charm jets [conservative]

Can effectively separate bb and cc final states
### International Advisory Committee

Mandate by CERN (2014+17) to define “...Direction for ep/A both at LHC+FCC”

- Sergio Bertolucci (CERN/Bologna)
- Nichola Bianchi (Frascati)
- Frederick Bordry (CERN)
- Stan Brodsky (SLAC)
- Hesheng Chen (IHEP Beijing)
- Eckhard Elsen (CERN)
- Stefano Forte (Milano)
- Andrew Hutton (Jefferson Lab)
- Young-Kee Kim (Chicago)
- Victor A Matveev (JINR Dubna)
- Shin-Ichi Kurokawa (Tsukuba)
- Leandro Nisati (Rome)
- Leonid Rivkin (Lausanne)
- **Herwig Schopper (CERN) - Chair**
- Juergen Schukraft (CERN)
- Achille Stocchi (LAL Orsay)
- John Womersley (ESS)

### Coordination Group

- **Accelerator+Detector+Physics**
  - Gianluigi Arduini
  - Nestor Armesto
  - Oliver Brüning - Co-Chair
  - Andrea Gaddi
  - Erk Jensen
  - Walid Kaabi
  - Max Klein - Co-Chair
  - Peter Kostka
  - Bruce Mellado
  - Paul Newman
  - Daniel Schulte
  - Frank Zimmermann

5(12) are members of the FCC coordination team

- OB+MK: co-coordinate FCCeh

### Working Groups

- **PDFs, QCD**
  - Fred Olness, Claire Gwenlan
- **Higgs**
  - Uta Klein, Masahiro Kuze
- **BSM**
  - Georges Azuelos, Monica D’Onofrio
  - Oliver Fischer
- **Top**
  - Olaf Behnke, Christian Schwanenberger
- **eA Physics**
  - Nestor Armesto
  - Paul Newman, Anna Stasto
- **Detector**
  - Alessandro Polini
  - Peter Kostka

prev. Guido Altarelli.

Monica D’Onofrio, DIS2022, Santiago de Compostela 6/5/22
Recent ERL achievements

F Marhauser et al.
Jlab, CERN

First 5 cell Niobium Cavity, 802 MHz
High $Q_0$, high stability

Demonstration of energy recovery in new cBETA facility at Cornell, with BNL

G Hoffstaetter et al 19.6.2019
Project staging strategy:

The PERLE configuration entails the possibility to construct PERLE in stages. We propose in the following two main phases to attend the final configuration.

**Phase 1:** Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)
- To allow a rather rapid realisation of a 250 MeV machine.
- To test with beam the various SRF components.
- To prove the multi-turn ERL operation.
- To gain essential operation experience.

**Phase 2:** Realisation of PERLE at its design parameters as a 10MW machine:
- Upgrade of the e-gun
- Installation of the 2nd Spreader and recombinar
- Installation of the second cryomodule in the second straight.
Costs

Costs are partially driven by the ERL size

High Electron Energy beams achievable with longer linacs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>1/3 LHC</th>
<th>1/4 LHC</th>
<th>1/5 LHC</th>
<th>1/6 LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>m</td>
<td>9000</td>
<td>6750</td>
<td>5332</td>
<td>4500</td>
</tr>
<tr>
<td>Arc radius</td>
<td>m \cdot 2\pi</td>
<td>1058</td>
<td>737</td>
<td>536</td>
<td>427</td>
</tr>
<tr>
<td>Linac length</td>
<td>m \cdot 2</td>
<td>1025</td>
<td>909</td>
<td>829</td>
<td>758</td>
</tr>
<tr>
<td>Spreader and recombiner length</td>
<td>m \cdot 4</td>
<td>76</td>
<td>76</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>Electron energy</td>
<td>GeV</td>
<td>61.1</td>
<td>54.2</td>
<td>49.1</td>
<td>45.2</td>
</tr>
</tbody>
</table>

Figure 2.1: Cost estimate for the civil engineering work for the tunnel, rf galleries and shafts for the LHeC at 1/5 of the LHC circumference (left), at 1/3 (middle) and the FCC-eh (right). The unit costs and percentages are consistent with FCC and CLIC unit prices. The estimate is considered reliable to 30%. The cost estimates include: Site investigations: 2%, Preliminary design, tender documents and project changes: 12% and the Contractors profit: 3%. Surface site work is not included, which for LHeC exists with IP2.
Target two kind of EWK mass spectra:

"Classic" compressed spectrum

→ "decoupled-slepton scenario"

Slepton mass

Large gap

Chargino ~ Neutralino1 masses

Mass difference ~ 1-2 GeV

\[ p e^- \rightarrow j e^- \tilde{\chi} \tilde{\chi} \quad (\tilde{\chi} = \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^\pm_1) \]

VBF production

\[ p e^- \rightarrow j \tilde{\chi} e_L, \quad j \tilde{\chi} \tilde{\nu} \rightarrow j e^- \tilde{\chi} \tilde{\chi} \]

(Note: as sleptons are heavier than charginos and neutralinos, they do not play a role in the pp cross sections)

Benchmarks slepton mass

SUSY EWK production
Compressed slepton scenarios: results

- Evaluate significance with stat and syst uncertainties
  \[ \sigma_{\text{stat}} = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s].} \]
  \[ \sigma_{\text{stat+syst}} = \left[ 2\left((N_s + N_b)\ln\left(\frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2}\right) - \frac{N_b^2}{\sigma_b^2}\ln\left[1 + \frac{\sigma_b^2N_s}{N_b(N_b + \sigma_b^2)}\right]\right]^{1/2}. \]

- Of course, systematic uncertainties play a crucial role (0-5% here)

- Comparisons with HL-LHC:
  - Not straightforward because of differences in models but similar mass range

<table>
<thead>
<tr>
<th>LHeC [1 ab(^{-1})]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0} ) [GeV]</td>
<td>250</td>
<td>( j e^- \nu \nu )</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} ) [GeV]</td>
<td>285</td>
<td>( j e^- \ell \nu )</td>
</tr>
<tr>
<td>initial</td>
<td>1231</td>
<td>( 2.80 \times 10^5 )</td>
</tr>
<tr>
<td>Pre-selection</td>
<td>453</td>
<td>( 2.01 \times 10^6 )</td>
</tr>
<tr>
<td>BDT &gt; 0.172</td>
<td>49</td>
<td>( 6.60 \times 10^4 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 1.66 \times 10^5 )</td>
</tr>
<tr>
<td>( \sigma_{\text{stat+syst}} )</td>
<td>1.0</td>
<td>278</td>
</tr>
</tbody>
</table>

![Graph showing significance as a function of slepton mass](image)

![Graph showing discovery and exclusion limits](image)
SUSY EWK production: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the $M_1, M_2, \mu$ (bino, wino, higgsino) values and hierarchy
- EWK phenomenology broadly driven by the LSP and Next-LSP nature
- Examples of classifications (cf: arXiv: 1309.5966)

Used as benchmarks:
- **Bino LSP, wino-bino cross sections**
  1. $\text{Mass}(\chi^+_1) = \text{Mass} (\chi^0_2)$
  2. $\chi^+_1 \chi^-_1$ and $\chi^\pm_1 \chi^0_2$ processes
- **Higgsino-LSP, higgsino-like cross sections**
  1. Small mass splitting $\chi^0_1, \chi^+_1, \chi^0_2$
  2. Consider triplets for cross sections
  3. Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^\pm_1 \chi^0_2 + \chi^+_1 \chi^-_1 + \chi^\pm_1 \chi^0_1)$$

[depending on masses!]

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Monica D’Onofrio, DIS2022, Santiago de Compostela

6/5/22
What if the $m(\text{chargino}) \sim m(\text{neutralino}1)$?

- The decay of chargino is **NOT prompt** → long-lived particles (LLP)!

**Simplest models at FCC-he:** four-body process and tiny cross section

- Charginos (Wino or Higgsino)
- Sleptons decaying via
  - gravitational interaction
  - R-parity violation

SUSY Searches for disappearing tracks: LLCP with $c\tau > \sim 10^{-4}$

Cross section enhanced with "co-production"

- Chargino (Wino) with selectron
- Selectrons with neutralino

In this case, only the scenario with heavy (decoupled) sleptons is considered (most conservative)
Comparisons with other facilities

- Thermal Higgsino/Wino dark matter mass
- Comparisons computed for the European strategy

- FCC-eh not directly competitive with FCC-hh but still reasonable reach
- In all cases FCC-eh sensitivity to short decay lengths, possibly much less than a single micron, improves with respect to what the FCC-hh can accomplish with disappearing track searches
Results for disappearing track analysis

- contours of $N_{1+LLP}$ and $N_{2\ LLP}$

- green region: 2σ sensitivity estimate in the presence of $\tau$ backgrounds
- black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

Sensitive to very short lifetimes exceeds that of hh colliders
Results for disappearing track analysis @ FCC

- contours of $N_{1+LLP}$ and $N_{2\; LLP}$

Green region: $2\sigma$ sensitivity estimate in the presence of $\tau$ backgrounds
Black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic) and the FCC-hh

Sensitive to very short lifetimes exceeds that of $hh$ colliders
Compressed slepton scenarios: results

Evaluate significance with statistical and systematic uncertainties

$$\sigma_{\text{stat}} = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s]}.$$  

$$\sigma_{\text{stat+syst}} = \left[2\left((N_s + N_b) \ln \frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2 N_s}{N_b(N_b + \sigma_b^2)}\right]\right)^{1/2}\right].$$

Of course, systematic uncertainties play a crucial role, as in monojet searches at pp

Here we consider 0-5%

Projections for HL-LHC consider 1-3%

<table>
<thead>
<tr>
<th>FCC-eh [1 ab$^{-1}$]</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}$ [GeV]</td>
<td>400</td>
<td>$j e^- \nu \nu$</td>
</tr>
<tr>
<td>$m_{\tilde{\ell}}$ [GeV]</td>
<td>435</td>
<td>$j e^- \ell \nu$</td>
</tr>
<tr>
<td>initial</td>
<td>4564</td>
<td>$1.08 \times 10^6 ; 7.96 \times 10^5$</td>
</tr>
<tr>
<td>Pre-selection</td>
<td>3000</td>
<td>$3.87 \times 10^5 ; 5.71 \times 10^5$</td>
</tr>
<tr>
<td>BDT $&gt; 0.262$</td>
<td>149</td>
<td>600</td>
</tr>
<tr>
<td>$\sigma_{\text{stat+syst}}$</td>
<td>3.3</td>
<td>86</td>
</tr>
</tbody>
</table>

![Graph showing significance as a function of mass](image-url)
Compressed slepton scenarios: the analysis

- **Final state:** 1 e- + 1 j + MET
- **Analysis at detector-level** using a simple Boost Decision Tree.
- **Backgrounds:** all processes with one or two neutrinos (to also take into account mis-identified leptons): \( p e^- \rightarrow j e^- \nu \nu \), \( p e^- \rightarrow j e^- \ell \nu \)

- **Pre-selections:**
  - At least one jet with \( p_T > 20 \text{ GeV} \), \( |\eta| \leq 6.0 \);
  - Exactly one electron with \( p_T > 10 \text{ GeV} \), \(-5.0 < \eta < 5.2 \);
  - No b-jet with \( p_T > 20 \text{ GeV} \);
  - No muon or tau with \( p_T > 10 \text{ GeV} \);
  - Missing transverse momentum \( E^{\text{miss}}_T > 50 \text{ GeV} \)
- **Use BDT with simple kinematic variables and angular correlations as input**
Long-lived EWKinos: disappearing tracks

- long lived charginos are typically significantly boosted along the proton beam direction, which increases their lifetime in the laboratory frame.

\[ b_{\text{com}} \approx \frac{1}{2} \sqrt{E_e/E_p} \approx 5.5 \]

3-4 hits only in the inner-most tracker \( \text{à missing} \) (disappearing track) (or a “kink” if the harder daughter \( d1 \) is charged)
**Analysis strategy**

- One or two charginos are produced at the PV, which is identified by the triggering jet (A).
- A chargino decaying to a single charged particle (B)
- If the impact parameter with respect to the PV is greater than a given $r_{\text{min}}$ we can tag this track as originating from an LLP decay

- heavily relies on backgrounds due to pile-up being either absent or controllable.
  - benchmark value is $r_{\text{min}} = 40 \mu\text{m} (~ 5$ nominal detector resolutions$)$; $p_T$ threshold for reconstruction of a single charged particle is chosen as 100 MeV
  - Assume 100% efficiency
- Estimate probability of detecting 1 or 2 LLP

**Backgrounds:**
- Taus: proper lifetime of $\sim 0.1\text{mm}$ and beta-decay into the same range of final states as the charginos.
- suppressed considerably with simple kinematic cuts as it is central in eta
- rejection of $10^{-4}(10^{-5})$ for 1(2)$\tau$
Combined hh | eh interaction region

From K.D.J André talk, 5/5

Accelerator considerations to combine the ALICE and LHeC experiments at point 2 of the HL-LHC:

- Flexible interaction region optics and lattice to provide e-h and h-h.
- h-h operation: standard HL-LHC optics.
- e-h operation: the compact electron final focus system is embedded in the HL-LHC proton lattice.
- A beam separation scheme guides the electron beam after the collision point back to the ERL return arc.

Standard HL-LHC, $L^* = 23$ m, $\beta^* = 15$ cm, $\theta = 590$ μrad

HL-LHC with LHeC, $L^* = 15$ m, $\beta^* = 10$ cm, $\theta = 7$ mrad

Courtesy from Massimo Giovannozzi (2019)
Combined \textit{hh|eh} interaction region

\textbf{From K.D.J André talk, 5/5}

- Based on HL-LHC optics and lattice design, the \textit{two} proton beams must be housed in the same quadrupole aperture unlike the past LHeC proton interaction design.
- Horizontal separation at the IP and vertical crossing angle to avoid parasitic interactions.
- The second proton beam should have a \textit{flexible optics design}:
  - a \textit{relaxed optics design, during eh operation}, as it acts as a spectator beam with an “injection like optics”,
  - a \textit{collision optics design, during hh operation}, to realise the HL-LHC luminosity
- Tradeoff between quadrupole aperture and achievable beam size at the IP for both \textit{eh} and \textit{hh} configurations.

LHC proton beam trajectories from the IP to the matching quadrupole Q4

Relaxed (left) and collision optics (right) in a quadrupole aperture