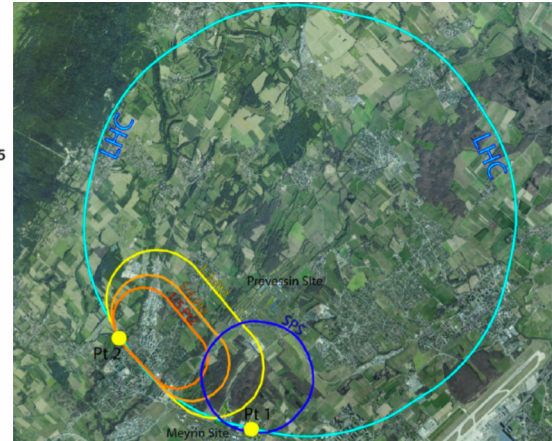
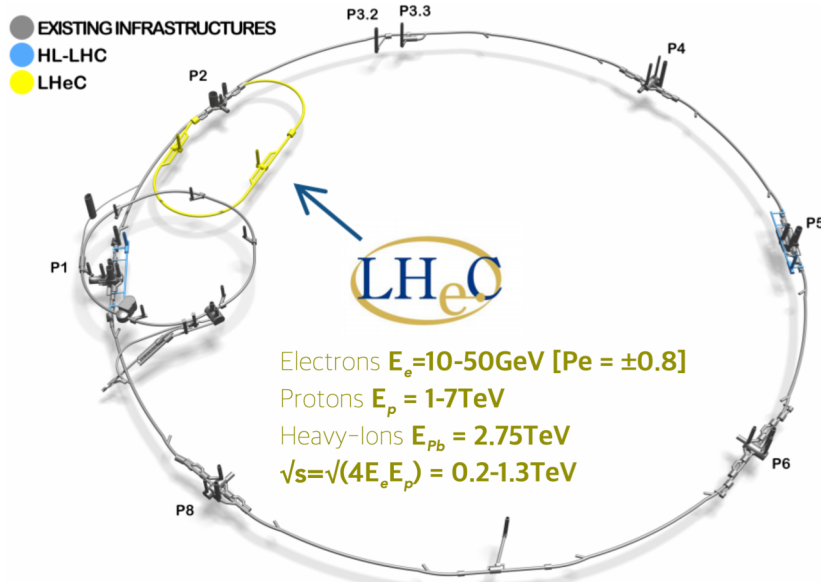


An experiment for *electron-hadron* scattering at the LHC

Krzysztof PIOTRKOWSKI



Electron-Hadron collisions at TeV scales: State-of-the-art

TOPICAL REVIEW • OPEN ACCESS

The Large Hadron–Electron Collider at the HL-LHC

P Agostini¹, H Aksakal², S Alekhin^{3,4}, P P Allport⁵, N Andari⁶, K D J Andre^{7,8}, D Angal
S Antusch¹¹, L Aperio Bella¹², L Apolinario¹³ + [Show full author list](#)

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[Journal of Physics G: Nuclear and Particle Physics](#), [Volume 48](#), [Number 11](#)

Reminder:

LHeC CDR in 2012 – proposing **concurrent** *ep* collisions at > 1 TeV at the LHC

New LHeC proposal in 2020 (337 authors from 156 institutions)

Includes discussion of *FCC-eh* physics (1.2 → 3.5 TeV)

Eur. Phys. J. C (2019) 79:474

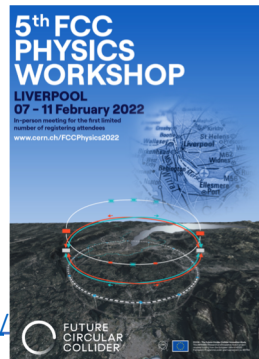
<https://doi.org/10.1140/epjc/s10052-019-6904-3>

Review

- 1.1 Physics scenarios after the LHC and the open questions
- 1.2 The role of FCC-ee
- 1.3 The role of FCC-hh
- 1.4 The role of FCC-eh

FCC Physics Opportunities

<https://indico.cern.ch/event/1066234/>



Large Hadron *electron* Collider

Energy Recovery Linac technology, or the on-going revolution in high energy electron acceleration techniques

Machine Parameters and Operation - ep

arXiv:2007.14401

Parameter	Unit	LHeC			
		CDR	Run 5	Run 6	Dedicated
E_e	GeV	60	30	50	50
N_p	10^{11}	1.7	2.2	2.2	2.2
ϵ_p	μm	3.7	2.5	2.5	2.5
I_e	mA	6.4	15	20	50
N_e	10^9	1	2.3	3.1	7.8
β^*	cm	10	10	7	7
Luminosity	$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	1	5	9	23

ERL technology resulted in a major breakthrough for the LHeC:

> 20 luminosity increase

Large Hadron *electron* Collider

LHeC is **NOT** a super-HERA “only”!

LHeC luminosity $\approx 1000 \times$ HERA

LHeC is not just *ep* **DIS super-collider** – it is much more:

New **very powerful lab** for electroweak & Higgs physics

+

Provides sensitivity to **new BSM signatures**

+

High energy eA collider (**very complementary** to EIC)

Energy Recovery Linac (green) technology

“Energy Recovery is at the threshold of becoming a key means for the advancement of accelerators. **Recycling the kinetic energy of a used beam for accelerating a newly injected beam**, i.e. **reducing the power consumption***, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago**. The potential of this technique may be compared with the finest innovations of accelerator technology such as by Widerøe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare, and their impact is only approximately predictable. **The fundamental principles of Energy-recovery linacs (ERLs) have now been successfully demonstrated across the globe.** There can no longer be any doubt that an ERL can be built and achieve its goals.”

-- European Strategy for Particle Physics – Accelerator R&D Roadmap (CERN Yellow Report)

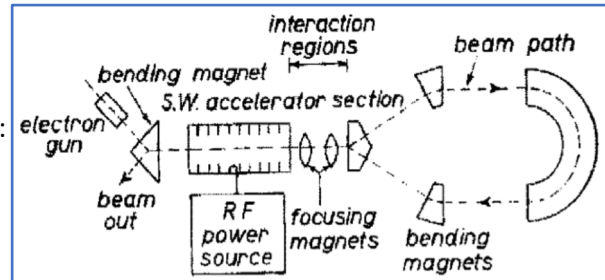
<https://arxiv.org/abs/2201.07895>

*) Even by an order of magnitude

**) M. Tigner – *A Possible Apparatus for Electron Clashing-Beam Experiments*, Nuovo Cimento 10 (1965) 1228:

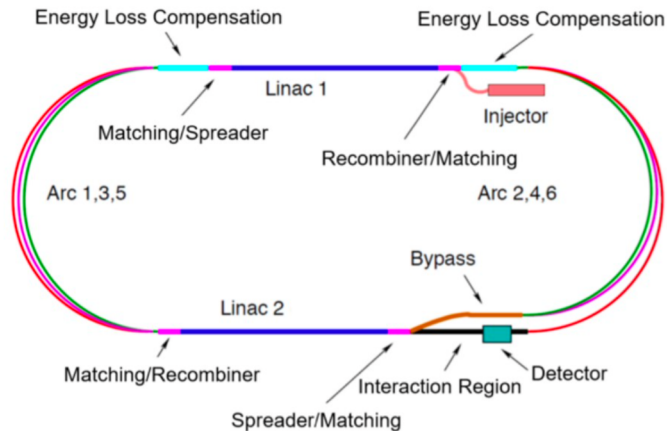
A quite surprising gravitational analogy:

<https://www.youtube.com/watch?v=6RiYXI1Tfu4>



Energy Recovery Linac at the HL-LHC

ERL geometry

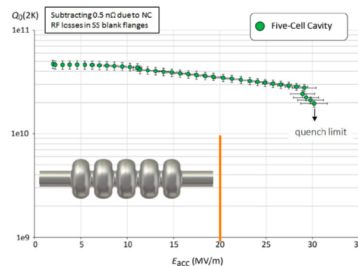


- Two SC linac accelerators
- three-pass return arcs

ERL main parameters

Parameter	Unit	Value
Beam energy	GeV	50
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
trans. norm. emittance	μm	30
RF frequency	MHz	801.58
Acceleration gradient	MV/m	20.06
Total length	m	6665

Q-parameter of 5-cell prototype



Experiment for eh (and hh too!) scattering @ IP2

Eur. Phys. J. C (2022) 82:40
<https://doi.org/10.1140/epjc/s10052-021-09967-z>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

An experiment for electron-hadron scattering at the LHC

K. D. J. André^{1,2}, L. Aperio Bella³, N. Armesto^{4,a}, S. A. Bogacz⁵, D. Britzger⁶, O. S. Brüning¹, M. D’Onofrio², E. G. Ferreira⁴, O. Fischer², C. Gwenlan⁷, B. J. Holzer¹, M. Klein², U. Klein², F. Kocak⁸, P. Kostka², M. Kumar⁹, B. Mellado^{9,10}, J. G. Milhano^{11,12}, P. R. Newman¹³, K. Piotrkowski¹⁴, A. Polini¹⁵, X. Ruan⁹, S. Russenschuk¹, C. Schwanenberger³, E. Vilella-Figueras², Y. Yamazaki¹⁶

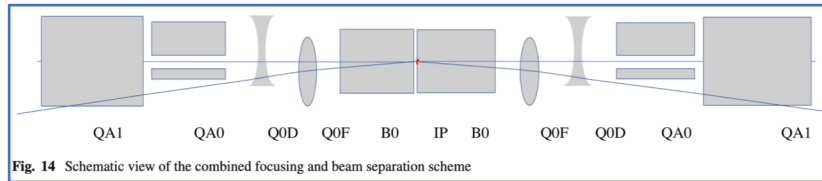


Fig. 14 Schematic view of the combined focusing and beam separation scheme

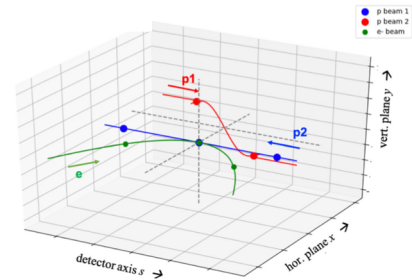


Fig. 17 Schematic view of the three beams in the interaction region. Collisions between electrons and proton beam 1 and a well separated proton beam 2

Experiment for electron-hadron scattering @ IP2

- The detector is required to have a magnet system consisting of **a central solenoid along with a dipole system** to steer the electron beam allowing for head-on *eh* collisions at the interaction point;
- The non-interacting proton/ion beam has to bypass the *ep* interaction yet to be guided through the same beam pipe housing the interacting electron and proton/ion beams;
- The shape of the beam pipe has to allow for the electron beam generated synchrotron fan to leave the interaction region unaffected and with minimal back-scattering;
- Good vertex resolution implies a small radius and thin beam pipe optimised in view of synchrotron radiation and background effects;
- The tracking and calorimetry in the forward and backward directions are set up to take into account the extreme asymmetry of the DIS production kinematics, see [1], with multi-TeV energies emitted in the forward, proton beam direction while the electromagnetic and hadron energies emitted backwards are limited by the electron beam energy.
- Very forward and backward detectors have to be set up to access diffractive produced events and to tag photo-production processes besides measuring the luminosity with high precision in Bether–Heitler scattering, respectively.

<https://link.springer.com/article/10.1140/epjc/s10052-021-09967-z>

Experiment for *eh* and *hh* scattering @ IP2

“As described above in Sect. 4.6, the **new accelerator optics** is able to provide collisions for *eh* and *hh* configurations in the same interaction point. As a consequence and if confirmed by further study, IP2 could indeed house one, common multi-purpose detector serving for all of these, mostly related physics programs, of *ep*, *pp*, *eA*, *pA* and *AA* interactions, with high precision and large acceptance, and the **unique advantage for cross-calibration of performance and physics.**“

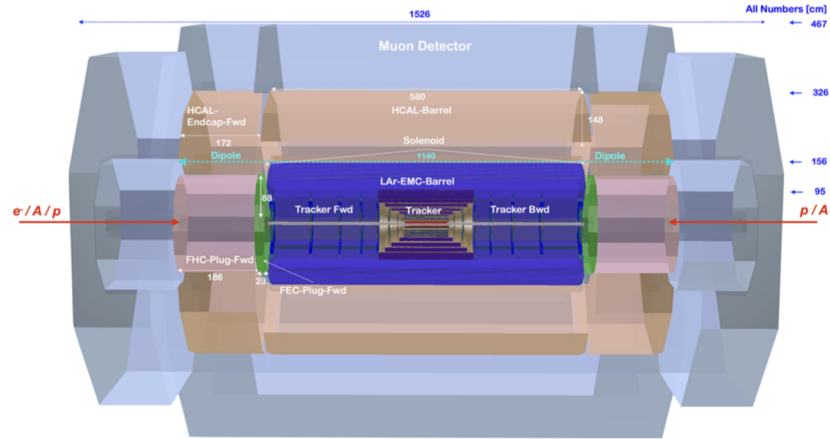
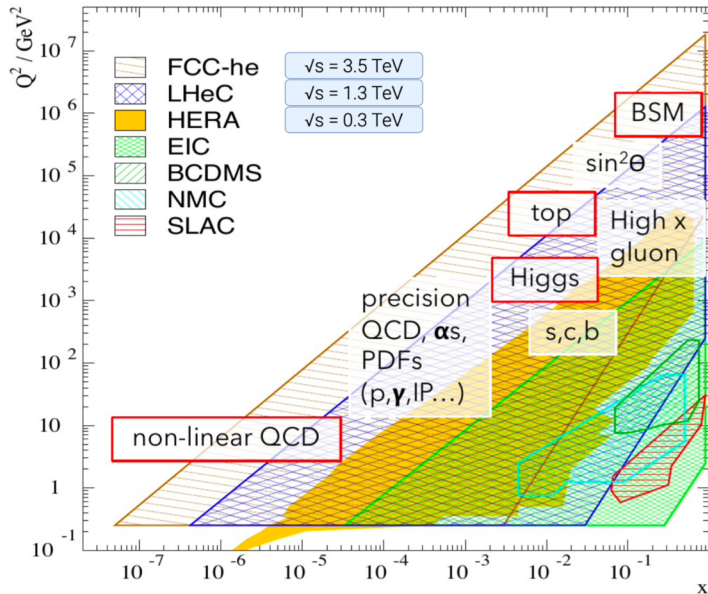


Fig. 24 Side view of a first design of the LHeC detector for both *eh* and *hh* collisions, where the detector coverage of the backward (electron) direction is extended to match that for the forward (hadron) direction.

Electron-Hadron Scattering @ LHC



LHeC

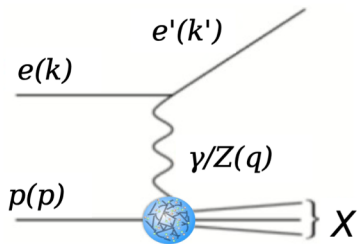
- Rich physics program at all scales
 - Higgs physics in NC and CC DIS
 - Top quark production
 - BSM physics and searches
 - Precision QCD
Proton structure, substructure, strong coupling constant, jet physics, heavy quarks, ...
 - Electroweak physics
 - Heavy ion programme

Note: The event pileup at the LHeC is negligible

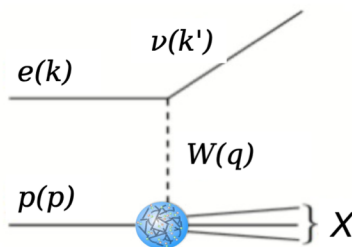
Several highlights $\Rightarrow \Rightarrow$

DIS @ LHeC

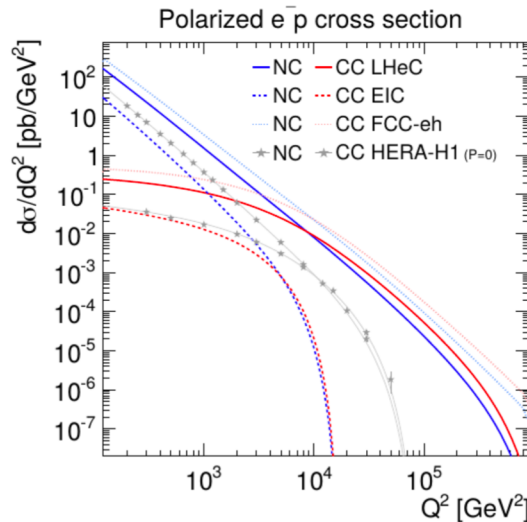
Neutral current scattering
 $ep \rightarrow e'X$



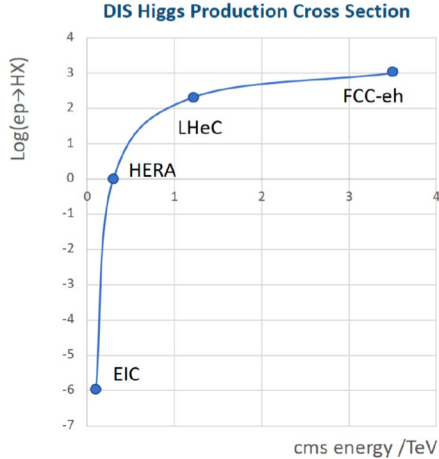
Charged current scattering
 $ep \rightarrow \nu_e X$



Deep-inelastic electron-proton scattering mediated in spacelike regime, by γ , γZ , Z or W -boson exchange

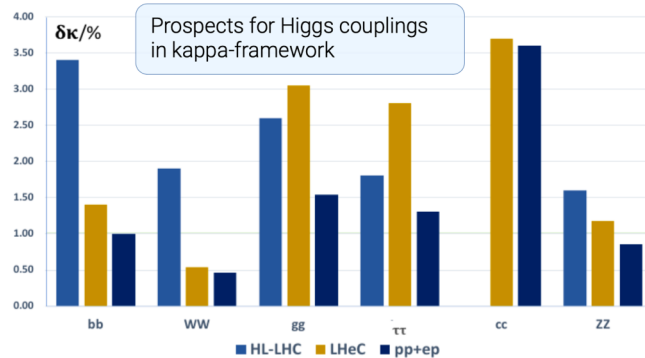
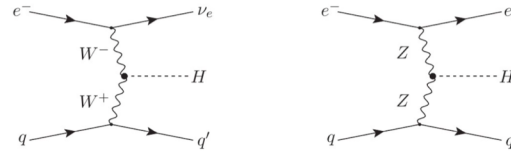


Higgs (clean) factory @ LHeC

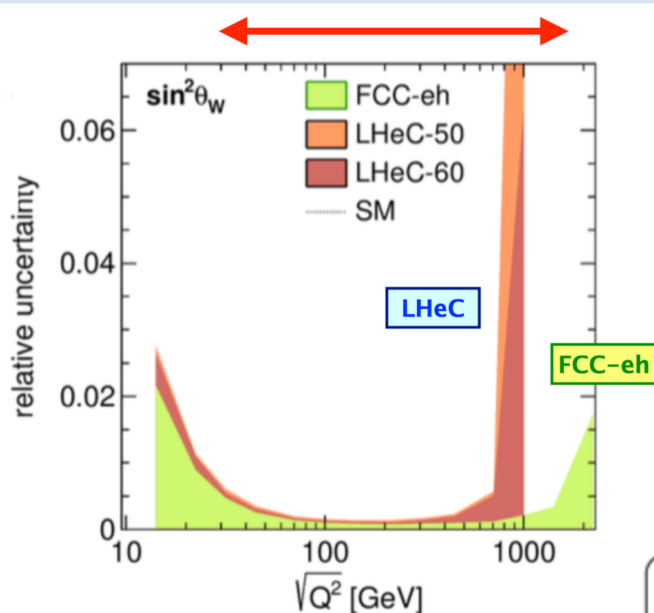


- Higgs-production cross section $\sim 200\text{pb}$
- Sensitivity to six decay channels
 $bb, WW, gg, \tau\tau, cc, ZZ$

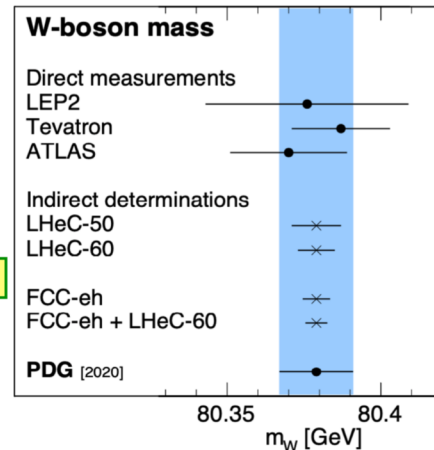
Higgs in CC and NC DIS



EWK precision tests @ LHeC



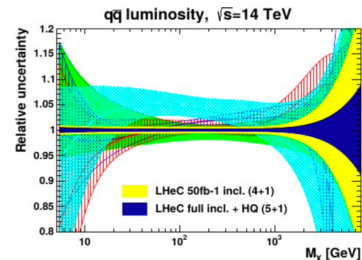
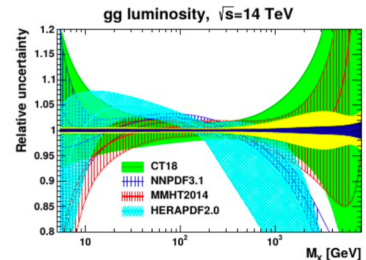
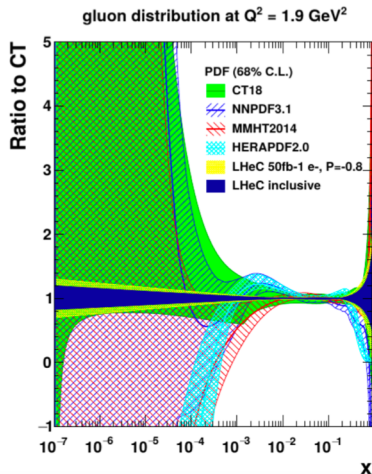
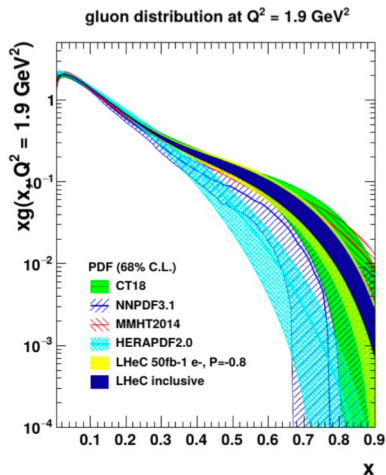
on-shell definition $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$



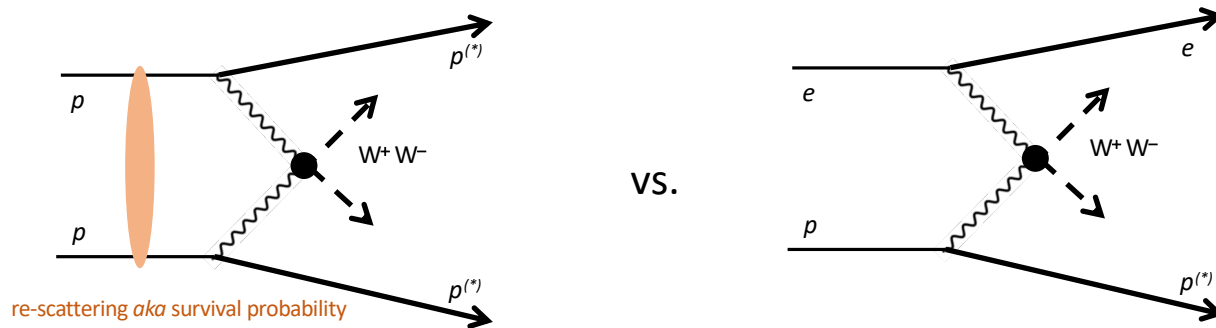
$\Delta m_W = \pm 4.5 \text{ MeV}$

Electron-Hadron Scattering @ LHeC

- Parton distribution functions (PDFs) of the proton with unprecedented precision
- Full determination of all flavors



Newest aspect: HL-LHC vs. LHeC as high energy $\gamma\gamma$ colliders

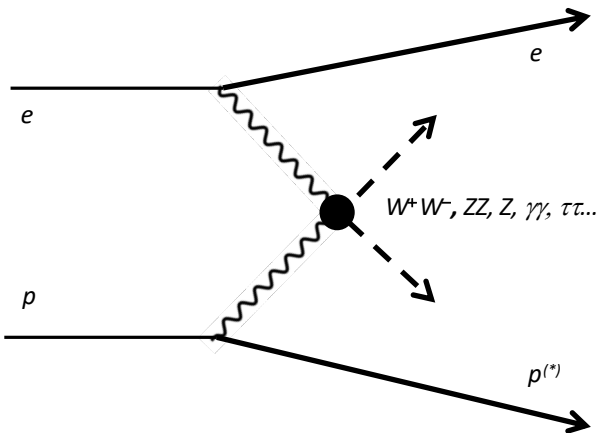


Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest W tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LHeC** – it is **only 5 %** at the highest ep luminosity of $2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

This is not only allowing to **use calorimetry for the selection** of exclusive production, but will also significantly **increase** detection efficiency, including $\gamma\gamma$ tagging, and **suppress** backgrounds!

LHeC as a unique, generic high energy $\gamma\gamma$ collider



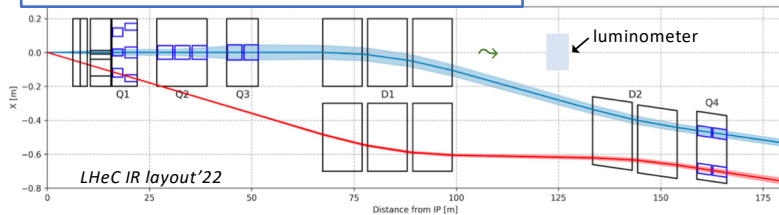
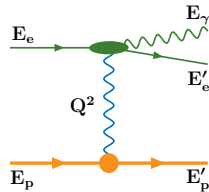
Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

- $\gamma\gamma \rightarrow \gamma\gamma$: orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging \Rightarrow kinematic fitting
- $\gamma\gamma \rightarrow \tau^+\tau^-$: orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging \Rightarrow new decay modes
- $\gamma\gamma \rightarrow Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \rightarrow ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, $ZZ \rightarrow l^+l^-jj$
- $\gamma\gamma \rightarrow W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \rightarrow l\nu jj$, will allow for a use of Optimal Observable methods (even with single $\gamma\gamma$ tagging) for probing aQGCs; yet high statistics (\approx as at the HL-LHC) is expected for fully leptonic W^+W^- decays + tagging

KP, Y. Yamazaki @ HEP-EPS'21 – <https://arxiv.org/abs/2109.08001>

ep (& eA) luminosity

To get precise pdf/parton luminosities one needs to measure ep luminosity with high precision, at $\lesssim 1\%$. As was shown at HERA, ep bremsstrahlung is an excellent candidate for such a task.

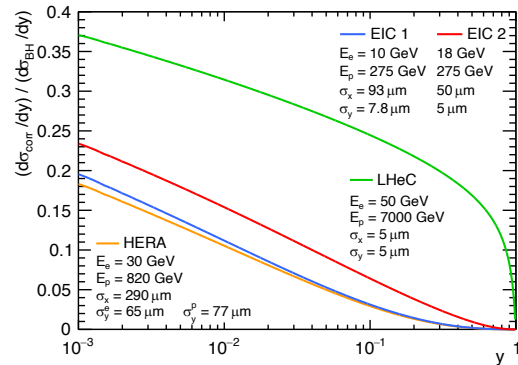


However, rates of high energy bremsstrahlung will be extremely high at FCC-eh, well in excess of 1 GHz, and in addition strong **Beam-Size Effect** will take place – *effective* bremsstrahlung *suppression* at high energies due to small lateral beam-sizes of **both** colliding beams:

$$\text{Event rate} = \text{Luminosity} \times \text{cross section}$$

where colliding particles are represented by PLANE waves – but this **assumption breaks down** if the lateral beam sizes are comparable to relevant impact parameter of a process. Its understanding can be deeply tested by measuring the bremsstrahlung spectrum while displacing a hadron beam:

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.L051901>



At LHeC bremsstrahlung spectrum, where $y = E_\gamma/E_e$, will be strongly distorted over **entire** range of photon energies!

(see KP, M. Przybycien @ HEP-EPS'21)

Dedicated forward instrumentation is needed to cope with such challenges – further efforts are required.

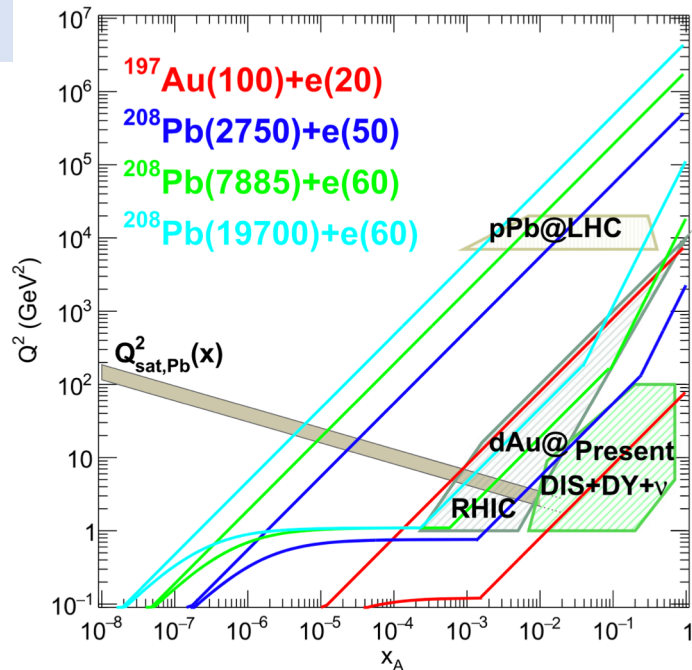
See, for example:

<https://iopscience.iop.org/article/10.1088/1748-0221/16/09/P09023>

eA scattering at LHeC

Unprecedented access to (x, Q^2) kinematic plane (in eA):

- coverage extended with respect to EIC by up to **2 orders of magnitude**
- DIS with nuclei down to $x=10^{-6}$ in **perturbative** regime \Rightarrow saturation scale (non-linearities) in fully perturbative regime



LHeC: Summary

LHeC will complete the HL-LHC science in a very profound & relevant way – in **QCD**, HF, top, **Higgs** & Electroweak sectors

LHeC offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions and will open a new era in the *eA* studies

NEW detector and beamline designs have been developed for IP2, accommodating both *eh* and *hh* collisions (\Rightarrow LHeC project “includes” ALICE 3)

LHeC has been driving the developments of the **green** ERL technology for high-energy colliders (very appropriate response to demands of our time) \Rightarrow strong cooling of EIC hadron beam, new designs of Next Linear Collider & electron beam injector for FCCee + electron beam for FCCeh

LHeC: (Personal) Outlook

Doing the best science at the LHC is our obligation – the LHeC will open a vast new field of research and significantly strengthen the hadron-hadron research (at \approx half a cost of the EIC)

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Decisive developments in accelerator/detector/physics case must be performed **before the next iteration** (in 2027?) of European Strategy for Particle Physics

LHeC: (Personal) Outlook

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In 2036 the LHeC should replace that last UK aerial ropeway as a prime example of a state-of-the-art energy recovery, green project

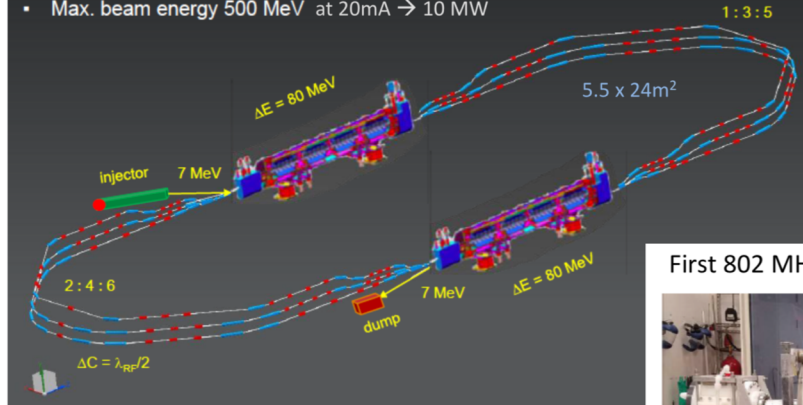
Stay tuned!

Thank you for attention!

Backup slides

LHeC demonstrator: Powerful ERL for Experiments (PERLE)

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA \rightarrow 10 MW



cf Walid Kaabi at Amsterdam FCC

in Orsay

- BINP
- CERN
- Daresbury/Liverpool
- Jlab
- Orsay

\rightarrow CDR 1705.08783
[J. Phys G]
 \rightarrow TDR in 2019

First 802 MHz cavity successfully built (Jlab)



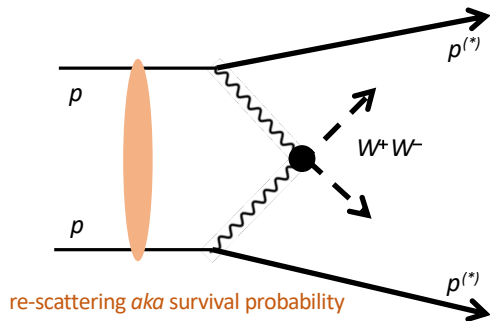
\rightarrow ERL demonstrator
 \rightarrow O(10 MeV) physics

Nuclear particle physics with electron-ion scattering at the LHeC

- “The LHeC will be able to test and establish or exclude the phenomenon of parton saturation at low x in protons and nuclei. [...] The LHeC will be a unique machine with which to address both of their variations, such that the saturation concepts can be precisely tested.”
- “LHeC machine in eA mode will have a huge impact on physics explored in pA and AA collisions, see section 9.7, where it will provide vital input and constraints on the ‘baseline’ initial state in nuclear collisions and measurements of the impact of a cold nuclear medium on hard probes and the effects of hadronisation. It will also explore the effect of the initial-state correlations on the final-state observables, which are relevant in order to understand collectivity in small systems explored in pp or pA collisions.”
- “The measurements of diffraction of protons and nuclei as well as the inclusive structure functions in the nuclear case will allow us to explore the very important relation between nuclear shadowing and diffraction [...]
- Similarly to the proton case, DVCS and exclusive vector-meson production will provide unique insight into 3D nuclear structure.”

<https://iopscience.iop.org/article/10.1088/1361-6471/abf3ba>

HL-LHC as a high energy $\gamma\gamma$ collider: challenges & limitations



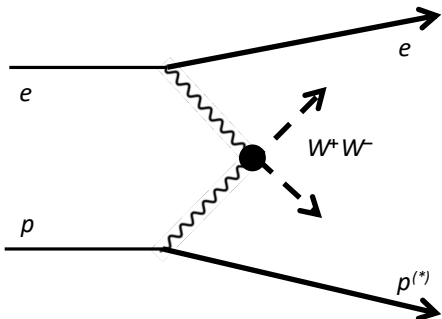
HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to 13 \rightarrow 14 TeV increase)
- PU yet 4 times higher (≈ 140) than for Run 2 – but new tracking **with** ps resolution timing should cope well with it
- Very high event pileup will make tagging with forward protons even more tricky – **ps resolution timing detectors** will help – however, the problem of overall efficiency loss still persists

Major limitations for the high luminosity pp case of a $\gamma\gamma$ collider:

- **Only** tracks can be used for the selection of (quasi-)exclusive production
- **Only** exclusive charged dilepton states could be successfully measured so far (after 10-year efforts)
- And, the **re-scattering suppression** is large and uncertain, especially at very large W

LHeC as a high energy $\gamma\gamma$ collider



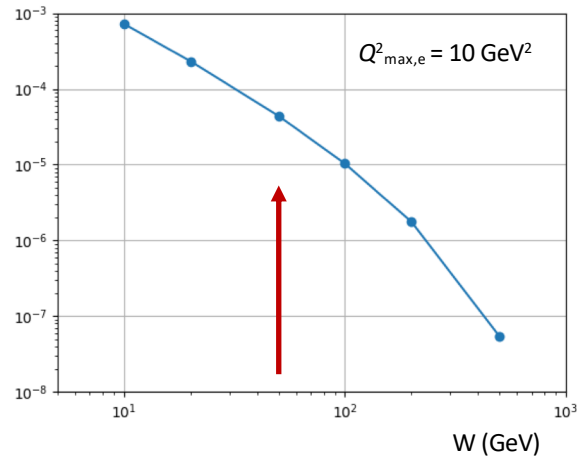
Very high LHeC luminosity is the key here \Rightarrow more than **1 ab⁻¹** (= 1000 fb⁻¹) is expected for ep collisions.

Electrons will have “only” 50 GeV, but **higher** photon flux, as approximately:

$$S_{\gamma\gamma} \propto \ln(Q_{\max,e}^2/Q_{\min,e}^2) \ln(Q_{\max,p}^2/Q_{\min,p}^2)$$

where $Q_{\min}^2 \propto m^2$, and $Q_{\max,e}$ can be very high

$S_{\gamma\gamma}$ (GeV⁻¹)



KP & Y. Yamazaki

For $W < 50$ GeV the *fully* exclusive $\gamma\gamma$ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!