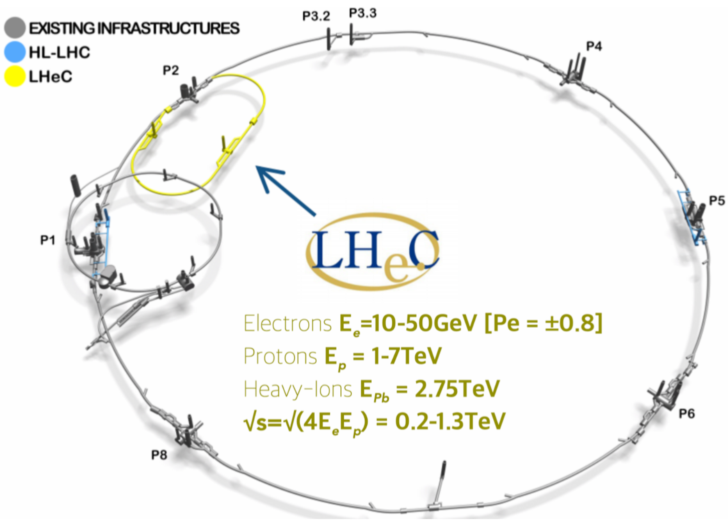
An experiment for *electron-hadron* scattering at the LHC

Krzysztof PIOTRZKOWSKI (AGH)

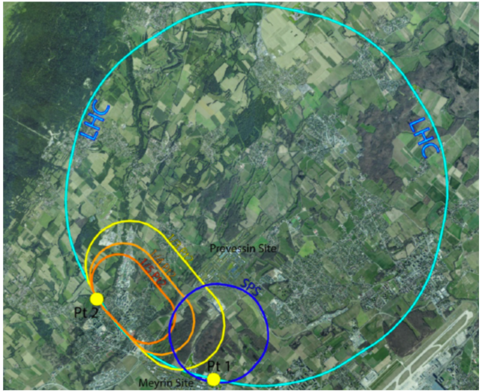


Electrons E_e=10-50GeV [Pe = ±0.8]

Protons E_p = 1-7TeV

Heavy-Ions E_{Pb} = 2.75TeV

$\sqrt{s}=\sqrt{(4E_eE_p)}$ = 0.2-1.3TeV



Before starting: A personal reflection

RAPID COMMUNICATIONS

PHYSICAL REVIEW D, VOLUME 63, 071502(R)

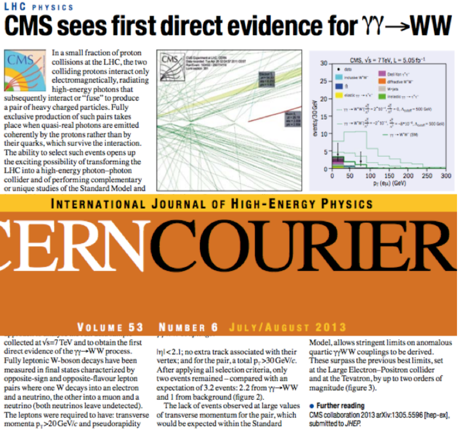
Tagging two-photon production at the CERN Large Hadron Collider

K. Piotrzkowski*
CERN, EP Division, CH–1211 Geneva 23, Switzerland
and Institute of Nuclear Physics, Kawiory 26A, PL–30055 Kraków, Poland
(Received 17 October 2000; published 6 March 2001)

Tagging two-photon interactions offers a significant extension of the CERN LHC physics program. The effective luminosity of high-energy $\gamma\gamma$ collisions reaches 1% of the proton-proton luminosity. The standard detector techniques used for measuring very forward proton scattering will allow a reliable separation of interesting two-photon interactions. Particularly exciting is the possibility of detecting exclusive Higgs boson production via the $\gamma\gamma$ fusion.

This paper was first rejected by *Physics Letters B* and *Zeit. f. Physik C*…

and by now has 136 citations on *INSPIRE*



Pomiar ekskluzywnej produkcji par bozonów W w eksperymencie CMS, seminarium IFJ, Kraków, kwiecień 2013

Lesson learned: it takes time, persistence and hard work to open new directions, but it is very much worth it!

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

TOPICAL REVIEW • OPEN ACCESS

The Large Hadron–Electron Collider at the HL-LHC

P Agostini[1], H Aksakal[2], S Alekhin[3,4], P P Allport[5], N Andari[6], K D J Andre[7,8], D Angal-
S Antusch[11], L Aperio Bella[12], L Apolinario[13] + Show full author list

Published 20 December 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd

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	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23

ERL technology resulted in a major breakthrough for the LHeC:

> 20 luminosity increase

Large Hadron electron Collider

LHeC luminosity ≈ 1000 × HERA

LHeC is **NOT** a super-HERA "only"!

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**

+

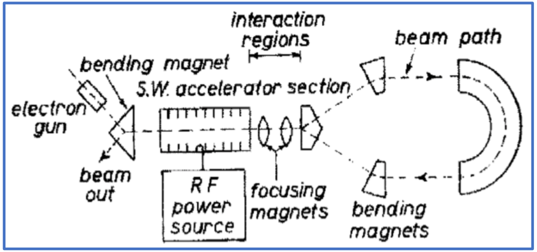
High energy *eA* collider (**very complementary** to EIC)

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

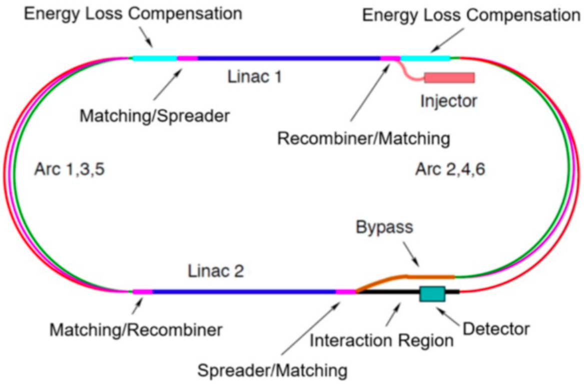
**) M. Tigner – *A Possible Apparatus for Electron Clashing-Beam Experiments*, Nuovo Cimento 10 (1965) 1228:



A quite surprising gravitational analogy: https://www.youtube.com/watch?v=6RiYXI1Tfu4

Energy Recovery Linac at the HL-LHC

ERL geometry

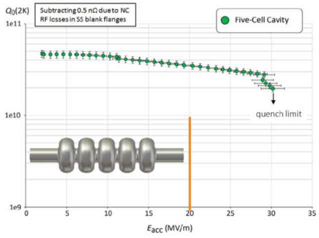


- Two SC linac accelerators
- three-pass return arcs

- 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



Achille Stocchi
IJCLab / Université Paris-Saclay, IN2P3/CNR

Future projects with ERL. The project PERLE@Orsay

- **The development of ERLs has been recognized as one of the five main pillars of accelerators R&D in support of the European Strategy for Particle Physics (ESPP).**

- The ERL Roadmap Panel, chaired by Max Klein and Andrew Hutton, has done a tremendous job with broad and active participation. **The PERLE project was recognized as one of the "essential pillars of the ERL**," with milestones to be achieved by the next ESPP in 2026.

- Two other important points :
  - Upgrade bERLinPRO toward the First ERL Facility to operate 100mA in single turn with FRT control
  - Key Technology R&D Program – next generation ERLs

ESPP R&D Accelerator RoadMap
https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf

PERLE a key ERL project : HEP and Nuclear Physics communities

ERL machines open a new Frontier for the physics of "the electromagnetic probe"

(1) At low energy e Nuclei (PERLE and Destin@Orsay) 250-500 MeV
(2) At Higher Energy e p (e A) (LHeC and/or FCC-eh) 60 GeV

You need high luminosity ⇒ High current (from 10mA up to 100mA)
You need to increase the energy (remaining compact) ⇒ Multi turns

The (1) machine (PERLE@Orsay)

- will be the **first ERL dedicated to Nuclear Physics** for studying the eN interaction with radioactive nuclei.
- It's a **necessary demonstrator for the (2) -HEP machine (LHeC / FCC-eh)-** (same technological choices & beam parameters)

The key points : high power (current x energy) and complex machine in terms of beam dynamics (multi-turns)

+ PERLE@Orsay (*not time today to discuss it)*

- is also a necessary demonstrator for other future machines and applications
- Elastic ep Scattering at PERLE (p Radius, Dark Photons, PV)
- Possibility of Nuclear Photonics (inverse Compton scattering γ's)

Achille Stocchi
IJCLab / Université Paris-Saclay, IN2P3/CNR

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

Check for updates

Regular Article - Experimental Physics

An experiment for electron-hadron scattering at the LHC

K. D. J. André[1,2], L. Aperio Bella[3], N. Armesto[4,a], S. A. Bogacz[5], D. Britzger[6], O. S. Brüning[1], M. D'Onofrio[2], E. G. Ferreiro[4], O. Fischer[2], C. Gwenlan[7], B. J. Holzer[1], M. Klein[2], U. Klein[2], F. Kocak[8], P. Kostka[2], M. Kumar[9], B. Mellado[9,10], J. G. Milhano[11,12], P. R. Newman[13], K. Piotrzkowski[14], A. Polini[15], X. Ruan[9], S. Russenschuk[1], C. Schwanenberger[3], E. Vilella-Figueras[2], Y. Yamazaki[16]

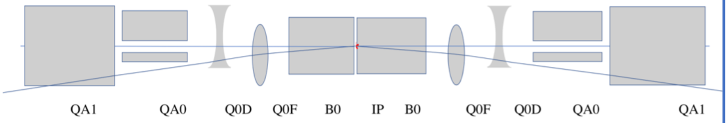


Fig. 14 Schematic view of the combined focusing and beam separation scheme

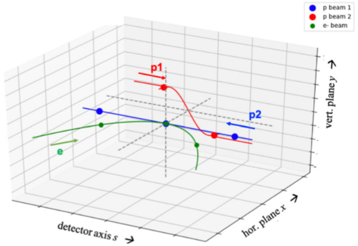


Fig. 17 Schematic view of the three beams in the interaction region. Collisions between electrons and proton beam 1 and a well separated proton beam 2

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**."

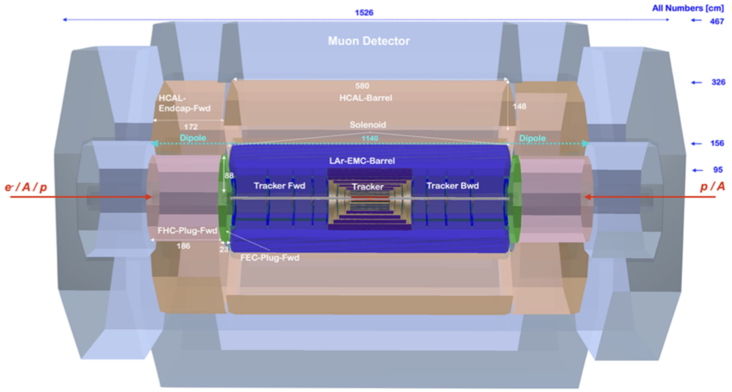
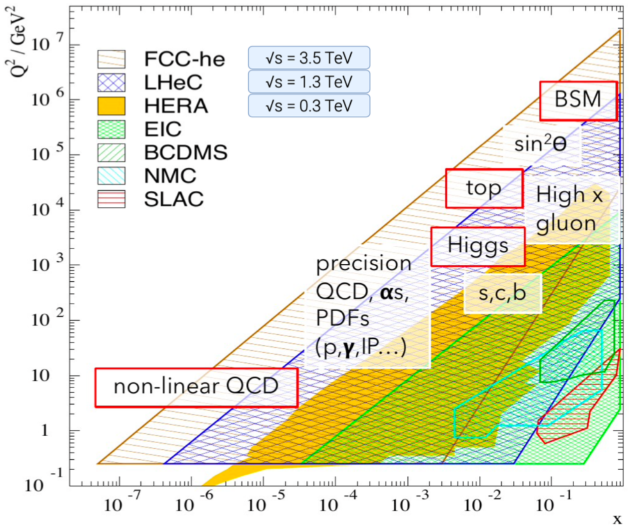


Fig. 24 Side view of a first design of the LHeC detector for both *eh* and *hh* collisions, where the detector coverage of the backward (electron) direction is extended to match that for the forward (hadron) direction.

Electron-Hadron Scattering @ LHC



LHeC

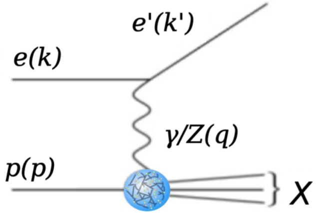
- Rich physics program at all scales
  - Higgs physics in NC and CC DIS
  - Top quark production
  - BSM physics and searches
  - Precision QCD
    Proton structure, substructure, strong coupling constant, jet physics, heavy quarks, ...
  - Electroweak physics
  - Heavy ion programme

Note: **The event pileup at the LHeC is negligible**

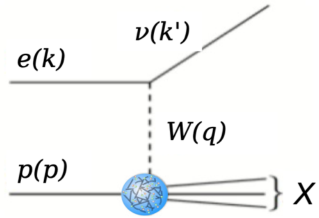
Several highlights ⇒⇒

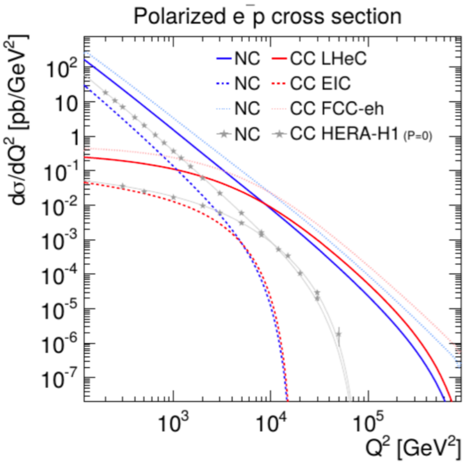
DIS @ LHeC

Neutral current scattering
$ep \to e'X$



Charged current scattering
$ep \to \nu_e X$



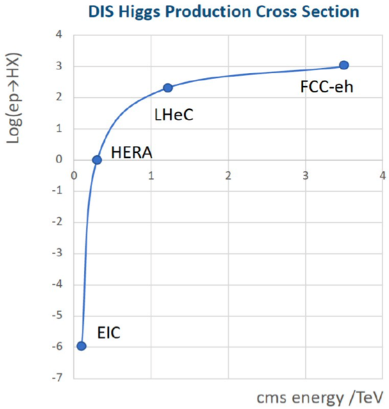


Deep-inelastic electron-proton scattering mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

LHeC as a Gauge Boson Collider

WW, ZZ and $\gamma\gamma$

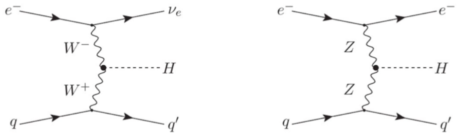
Higgs clean factory @ LHeC

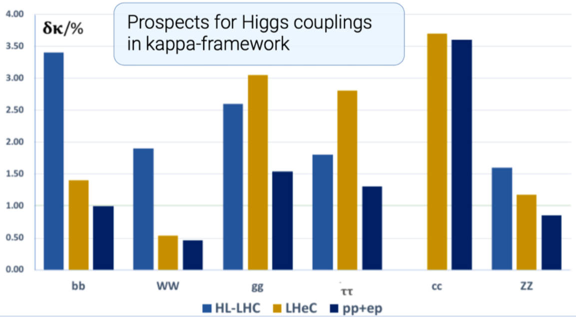


- Higgs-production cross section ~ 200pb
- Sensitivity to six decay channels

bb, WW, gg, ττ, cc, ZZ

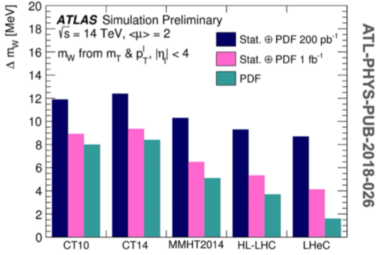
Higgs in CC and NC DIS





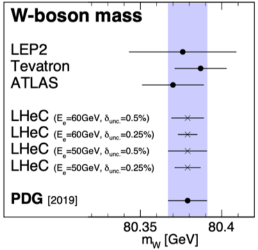
EWK measurements: W mass

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

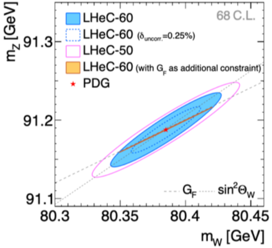


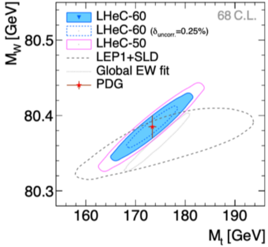
Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)
Δm_W = ±2 MeV (with improved PDF from LHeC)

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



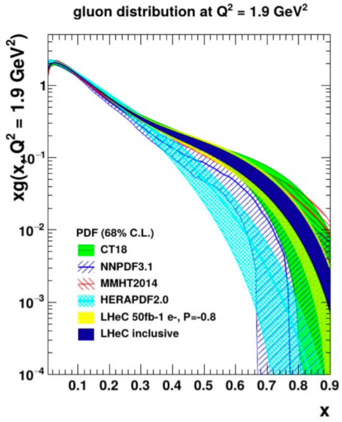
Even more relevant after recent CDF results and claimed 9 MeV precision!

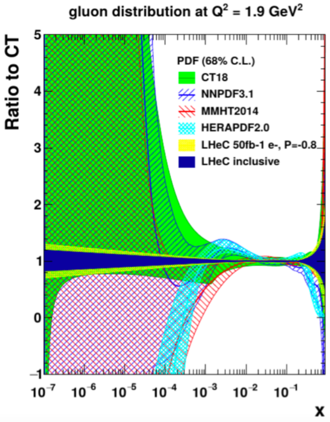


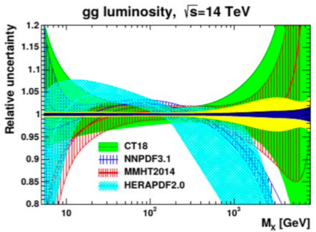


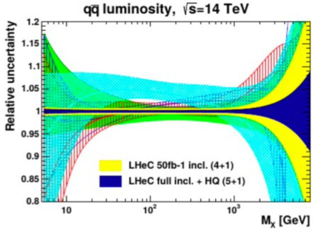
Electron-Hadron Scattering @ LHC

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

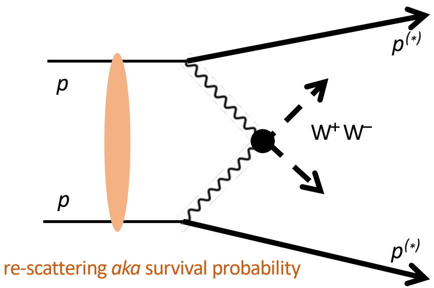




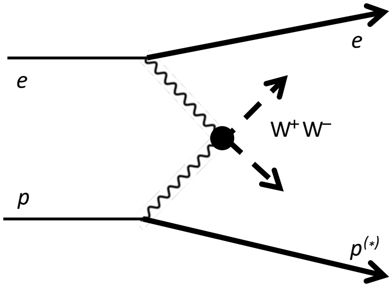




Newest aspect: HL-LHC vs. LHeC as high energy $\gamma\gamma$ colliders



vs.

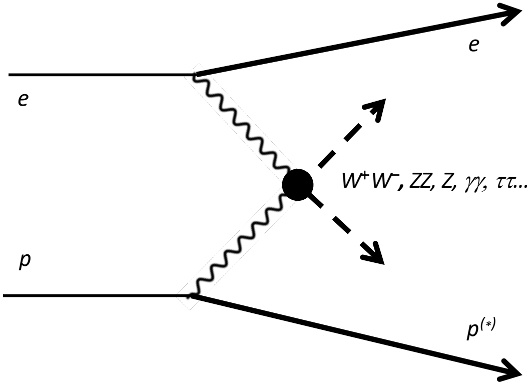


Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however at the highest W tagging is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LHeC** – it is **only 5 %** at the highest *ep* luminosity of **2.3×10^{34} cm^{-2}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



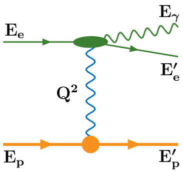
KP, Y. Yamazaki @ HEP-EPS'21 – https://arxiv.org/abs/2109.08001

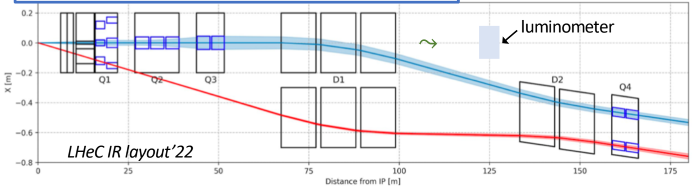
Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

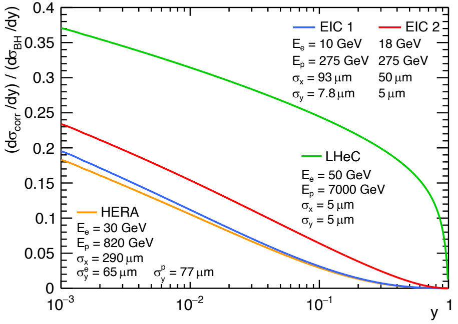
- $\gamma\gamma \to \gamma\gamma$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging $\Rightarrow$ kinematic fitting
- $\gamma\gamma \to \tau^+\tau^-$: orders of magnitude higher statistics than for *PbPb* at the HL-LHC + $\gamma\gamma$ tagging $\Rightarrow$ new decay modes
- $\gamma\gamma \to Z$: search for the anomalous single Z boson exclusive production
- $\gamma\gamma \to ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, $ZZ \to l^+l^-jj$
- $\gamma\gamma \to W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \to l\nu jj$, 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

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.







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)

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:

Event rate = Luminosity × 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

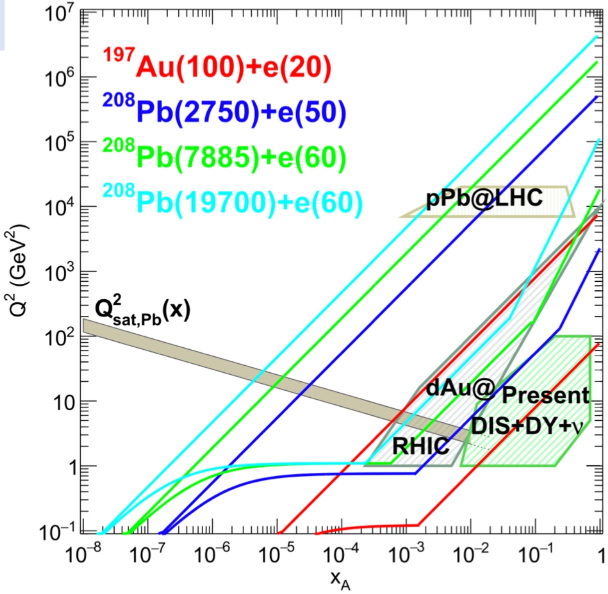
Dedicated forward instrumentation is needed to cope with such challenges – further efforts are required.

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 ⇒ 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 (⇒ 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) ⇒ strong cooling of EIC hadron beam, new designs of Next Linear Collider & electron beam injector for FCC-ee + electron beam for FCC-eh

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 ≈ half a cost of the EIC)

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 ≈ half a cost of the EIC)

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

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 ≈ half a cost of the EIC)

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

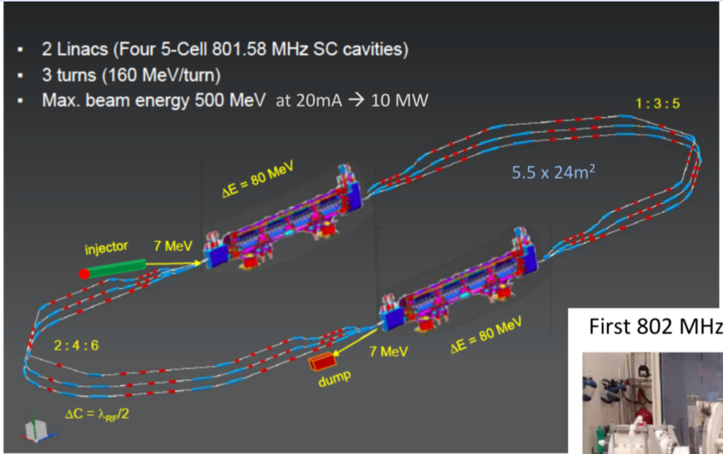
“Kick-off” workshop in October at CERN is being organized, so…

stay tuned!

Thank you for attention!

Backup slides

LHeC demonstrator: Powerful ERL for Experiments (PERLE)



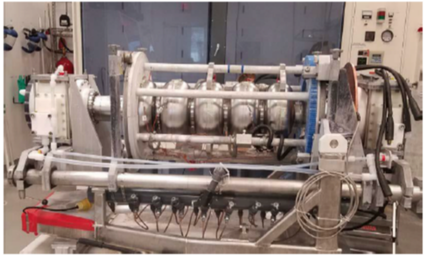
cf Walid Kaabi at Amsterdam FCC

in Orsay

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

→ CDR 1705.08783 [J. Phys G]
→ TDR in 2019

First 802 MHz cavity successfully built (Jlab)



→ ERL demonstrator
→ 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.”

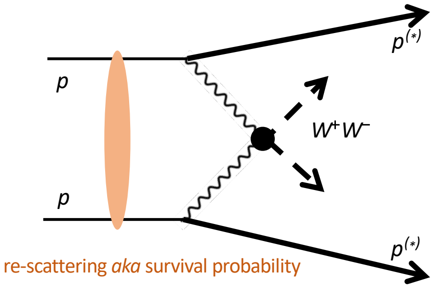
- “LHeC machine in *eA* mode will have a huge impact on physics explored in *pA* and *AA* collisions, see section 9.7, where it will provide vital input and constraints on the ‘baseline’ initial state in nuclear collisions and measurements of the impact of a cold nuclear medium on hard probes and the 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**



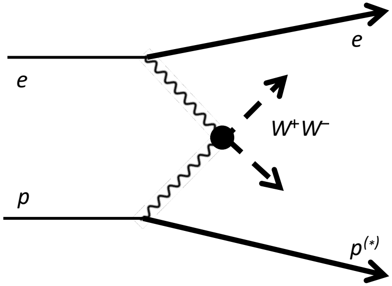
HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to 13 → 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

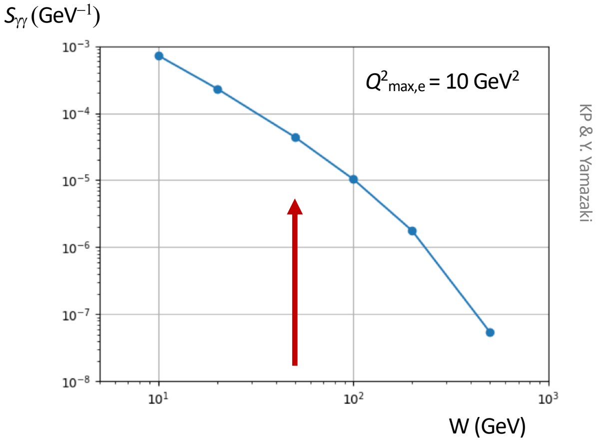


Very high LHeC luminosity is the key here ⇒ more than **1 ab^{-1}** (= 1000 fb^{-1}) is expected for *ep* collisions.

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

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

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



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