High-energy & high-luminosity electron-proton collisions

the ep/eA@CERN Study for the LHeC and FCC-eh

https://indico.cern.ch/e/LHeCFCCeh

Jorgen D'Hondt
Vrije Universiteit Brussel

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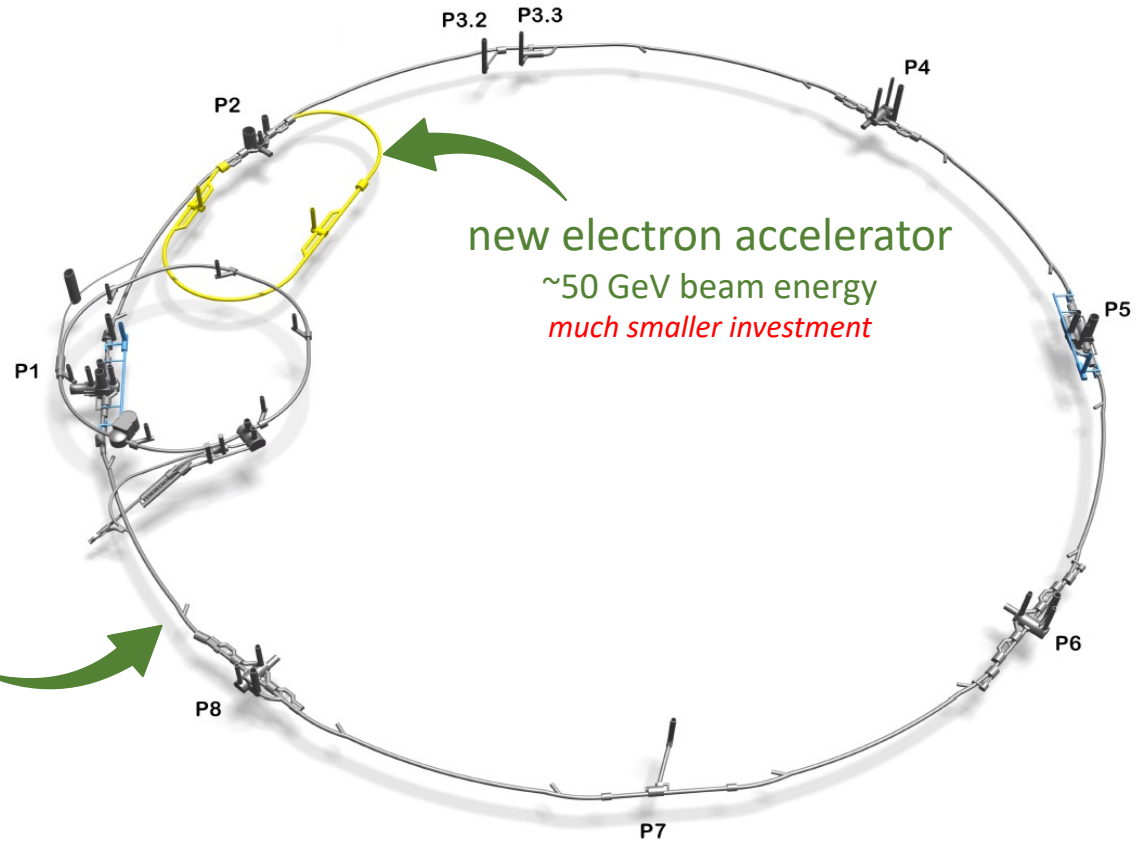
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

ICHEP 2024, Prague, July 2024

high-energy & high-luminosity electron-proton collisions



new electron accelerator

~50 GeV beam energy

much smaller investment

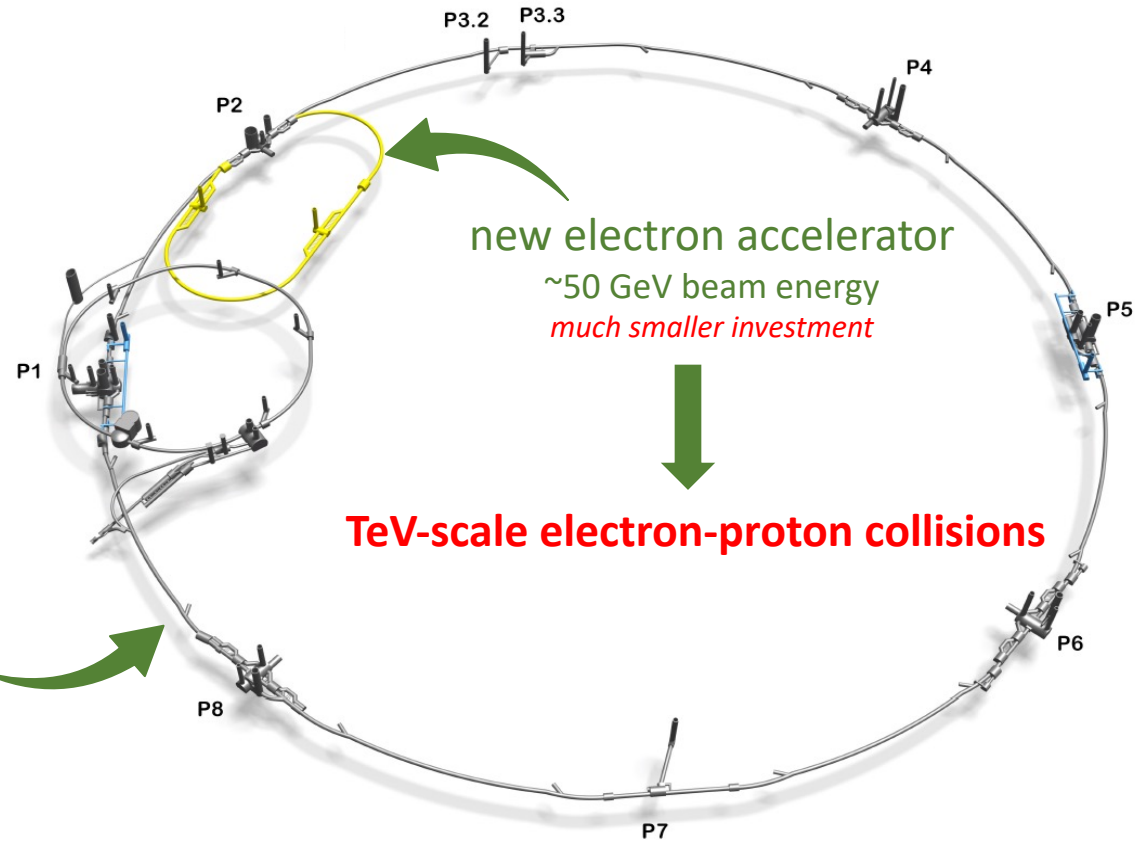
existing/future proton accelerator

LHC and/or FCC

(LHeC and/or FCC-eh)

major investment

high-energy & high-luminosity electron-proton collisions



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~50 GeV beam energy

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TeV-scale electron-proton collisions

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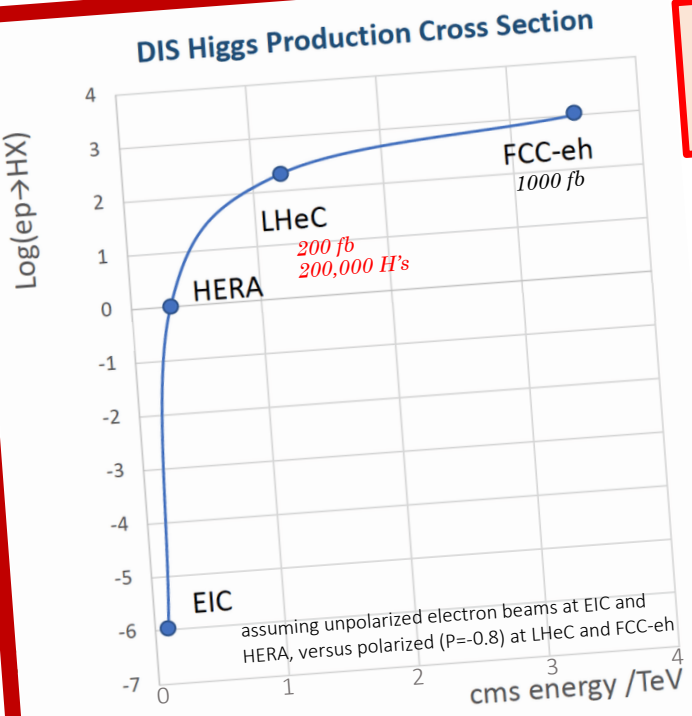
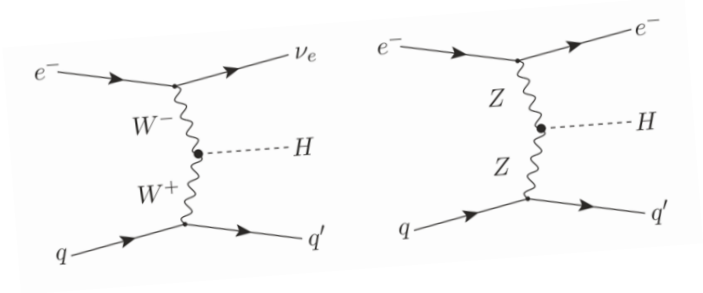


These electron-proton collisions enable a general-purpose experiment



compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

major investment

P7

The ep/eA programs: at current & future hadron colliders

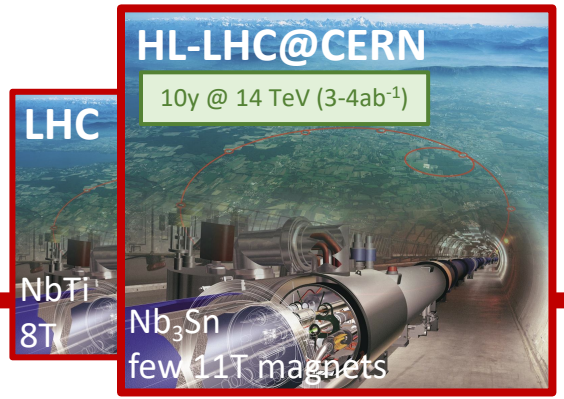
Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

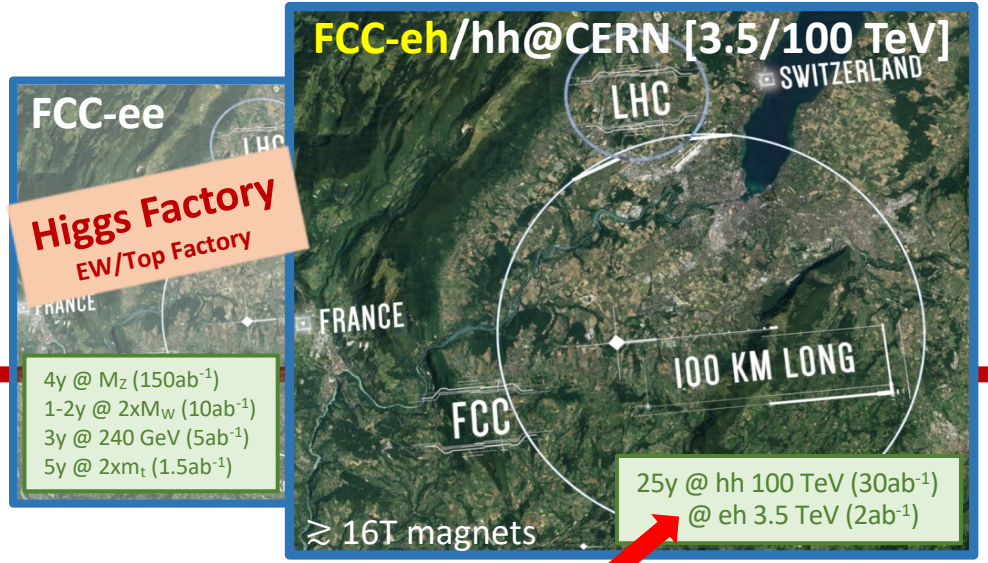


ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1}) = Run-6 + 5y ep-only@LHC

updated CDR: J.Phys.G 48 (2021) 11, 110501

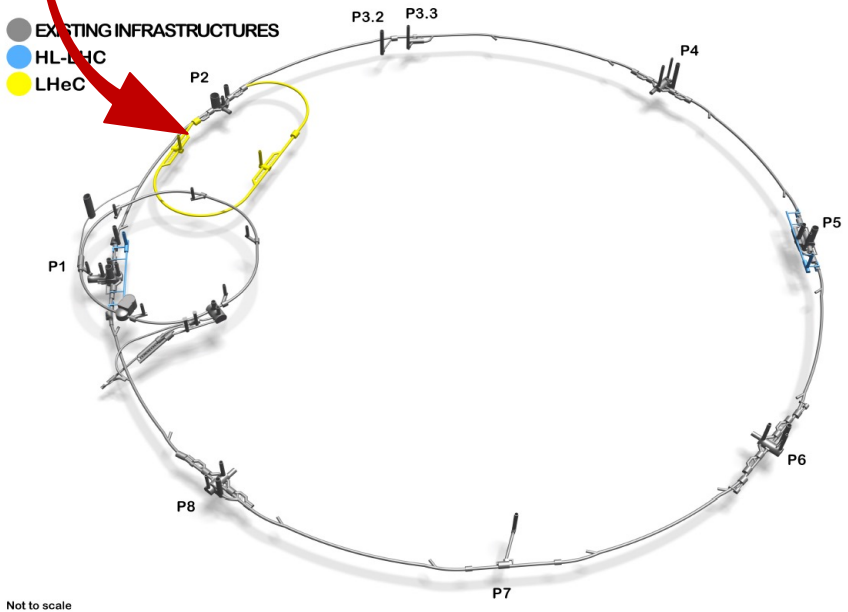
6y ep-only@LHC > 1 ab^{-1}

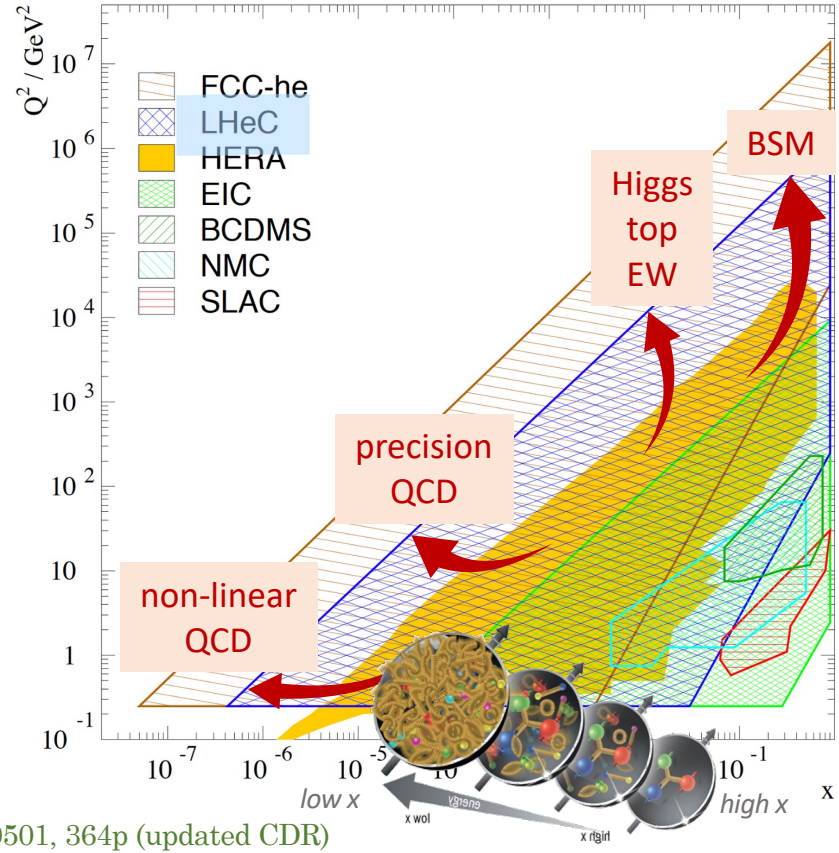


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC programme

LHeC (50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)





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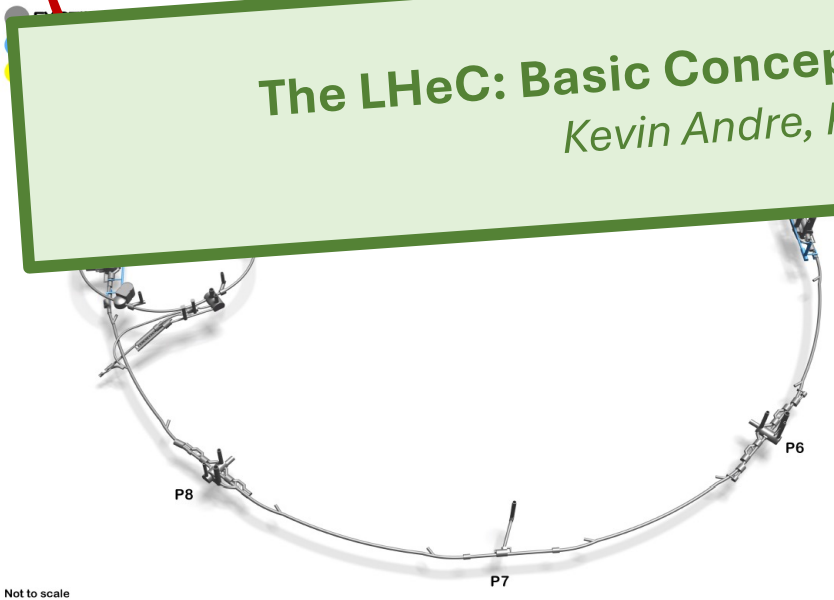
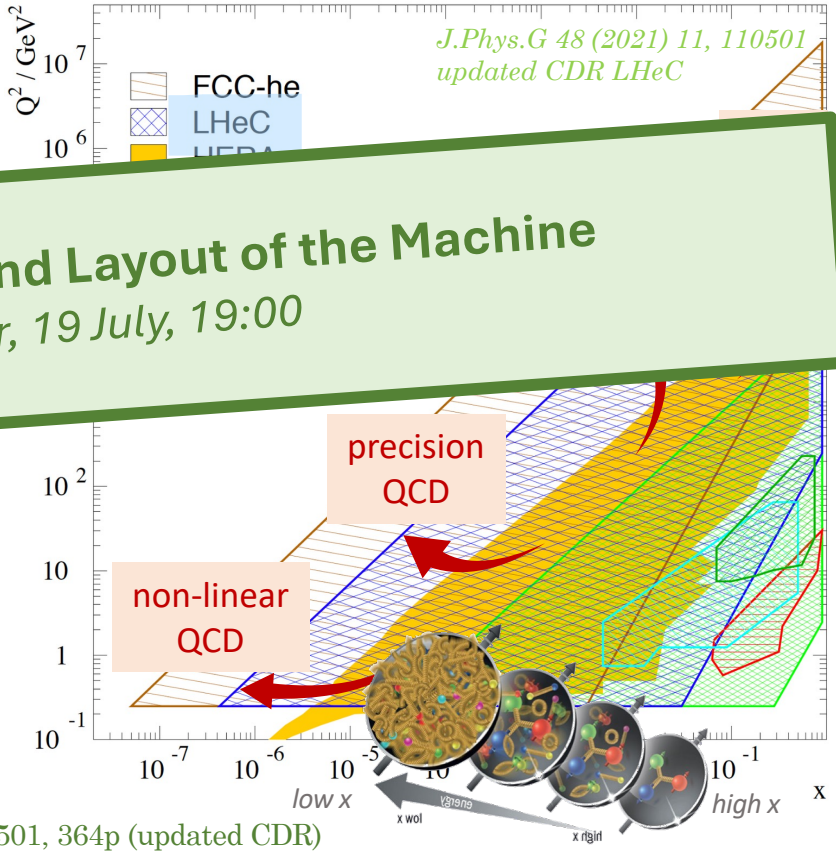
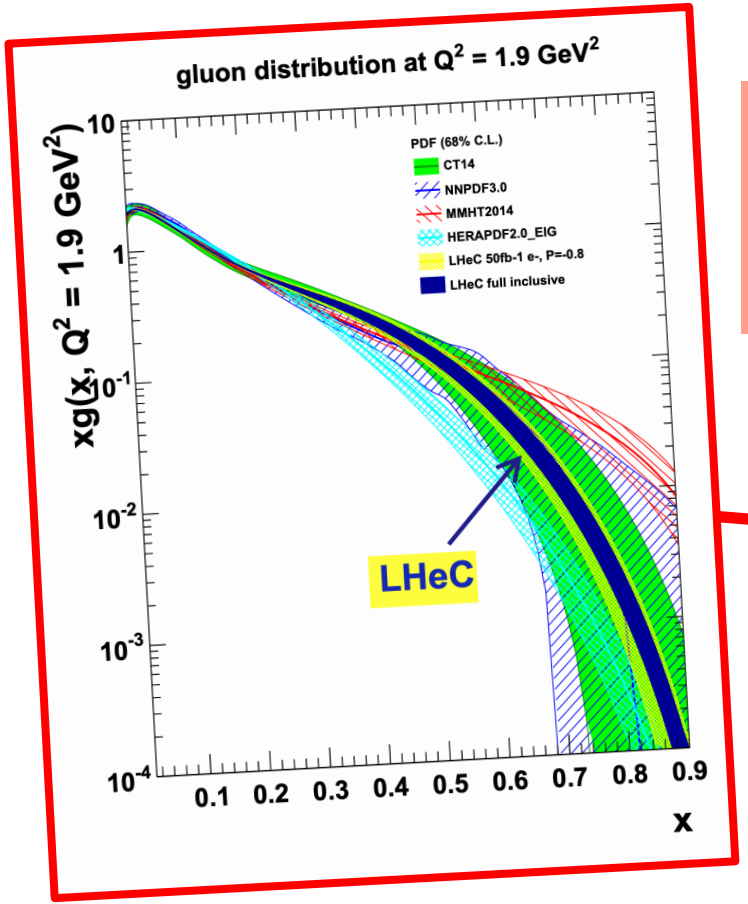
The LHeC: Basic Concepts and Layout of the Machine
Kevin Andre, Poster, 19 July, 19:00



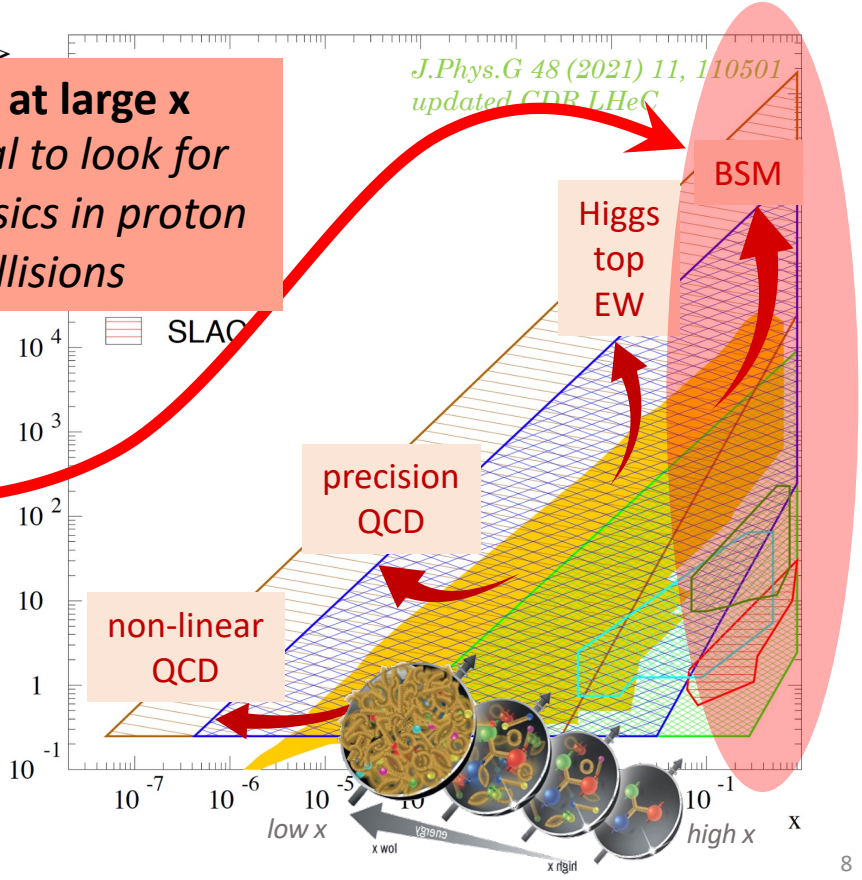


The Large Hadron-Electron Collider at the HL-LHC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

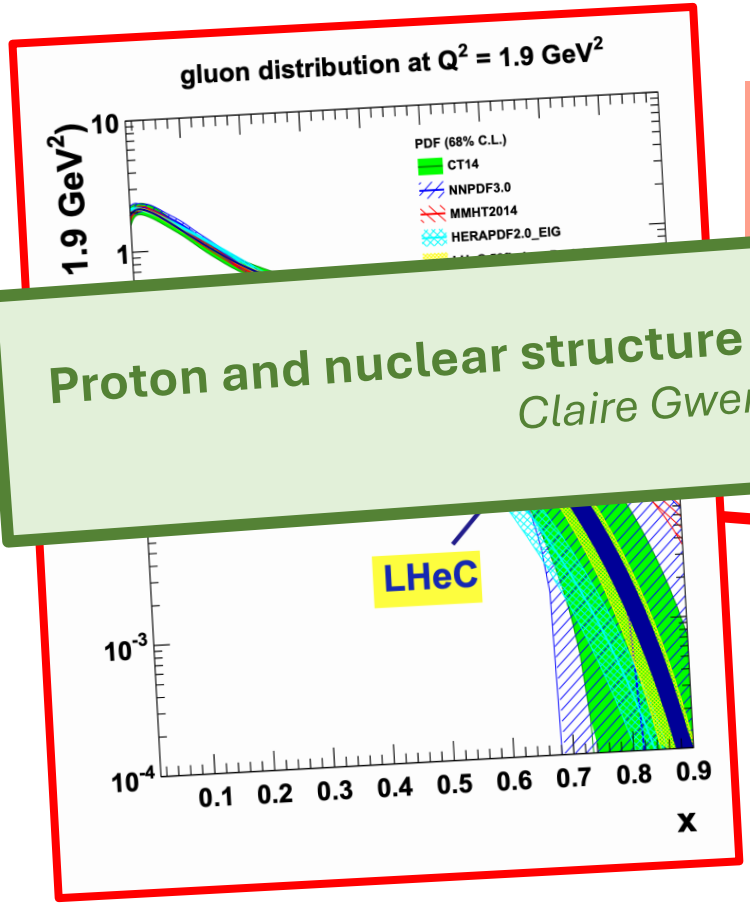
The LHeC programme



gluon at large x
essential to look for new physics in proton collisions



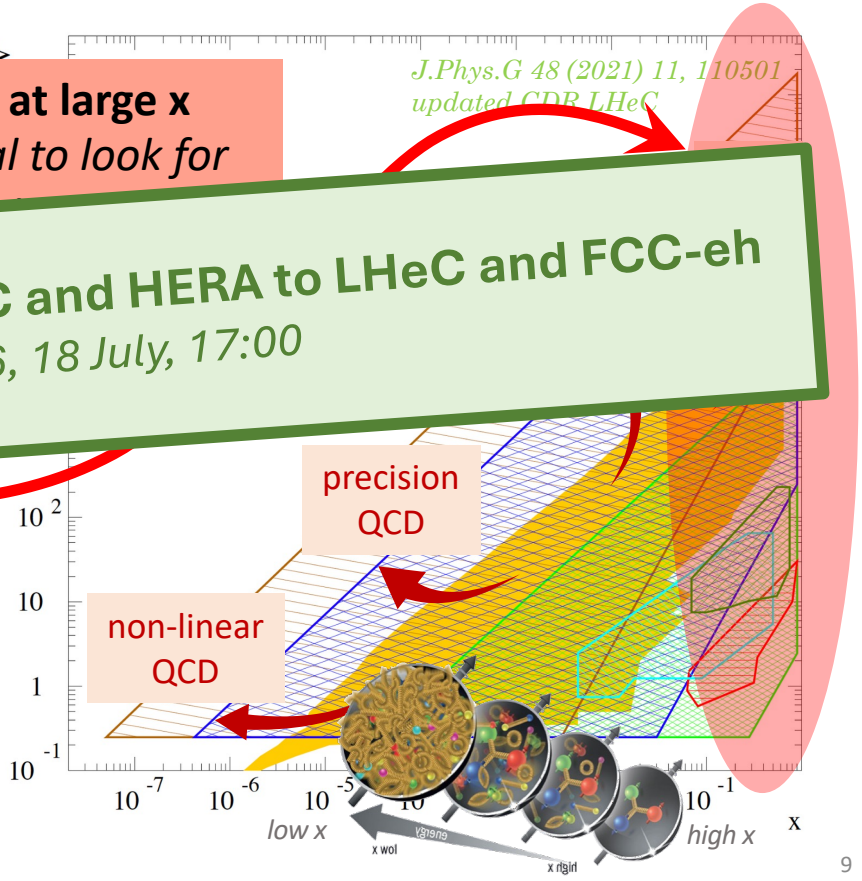
The LHeC programme



gluon at large x
essential to look for

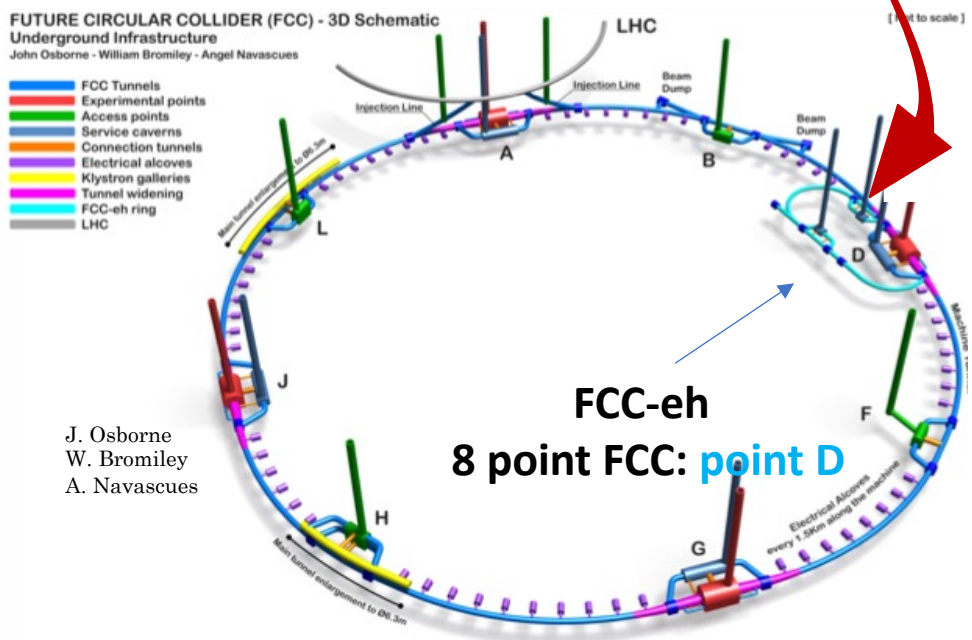
Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
Claire Gwenlan, WG6, 18 July, 17:00

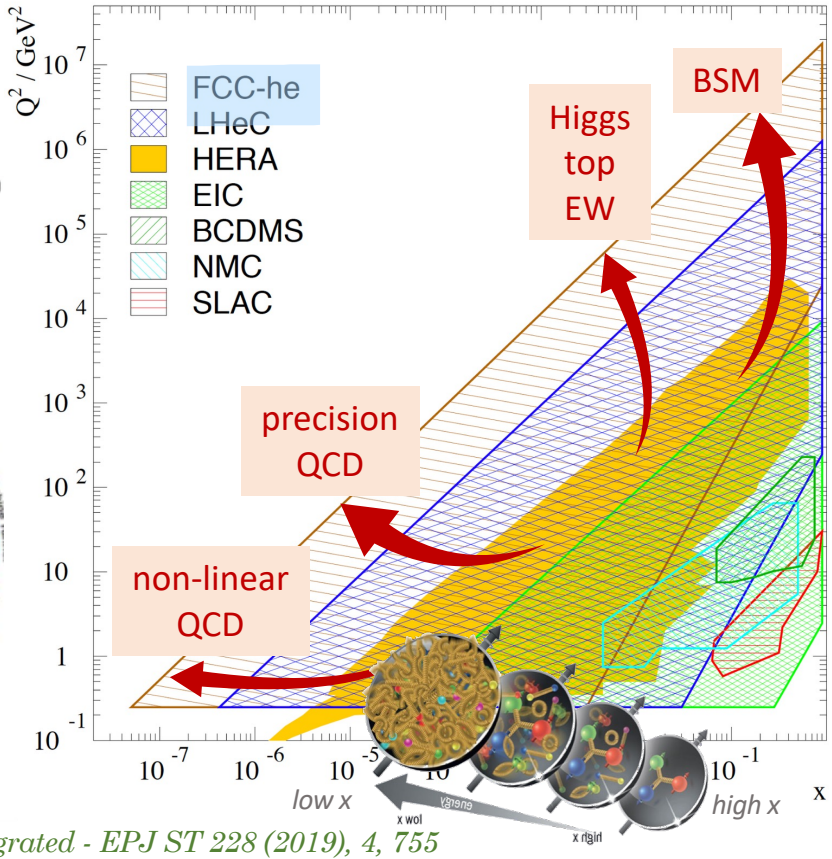
J.Phys.G 48 (2021) 11, 110501
updated CDR LHeC



The FCC-eh programme

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh





FCC CDR, vols 1 and 3: Physics – EPJ C79 (2019), 6, 474 & FCC with eh integrated - EPJ ST 228 (2019), 4, 755

The challenge – high-power electron beam

From HERA to LHeC/FCC-eh

3 orders in magnitude in luminosity
1 order in magnitude in energy

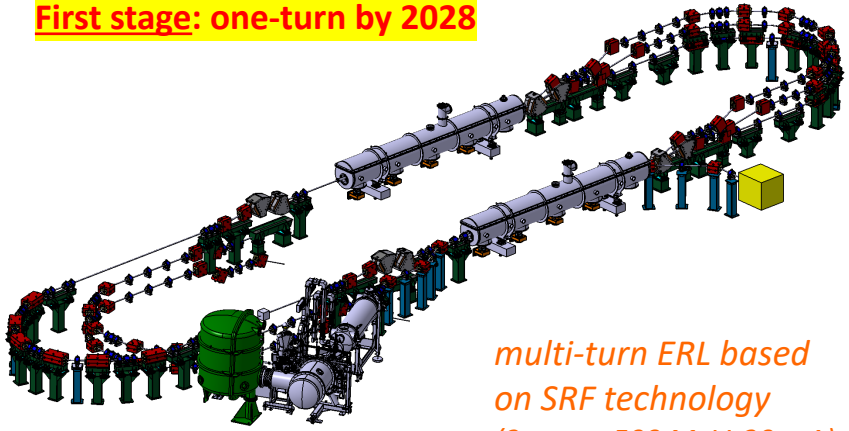
beam current × beam energy
= beam power

LHeC/FCC-eh ~ 1 GW beam power
equivalent to the power delivered by a nuclear power plant

PERLE @ IJCLab (Orsay)

being constructed to demonstrate all ERL aspects for LHeC/FCC-eh

First stage: one-turn by 2028



multi-turn ERL based on SRF technology (3-turns, 500 MeV, 20 mA)

CDR: *J.Phys.G* 45 (2018) 6, 065003

The planned R&D on Energy Recovery Linacs will enable to provide a 1 GW electron beam with only 100 MW power

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3 orders in magnitude in luminosity
1 order in magnitude in energy

PERLE @ IJCLab (Orsay)

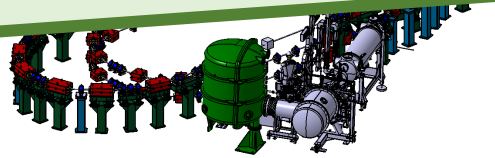
being constructed to demonstrate all ERL aspects for LHeC/FCC-eh

PERLE and bERLinPro, two key accelerator projects as pathfinders for future ERL based HEP colliders

Walid Kaabi, WG11, 18 July, 10:00

1 GW beam power

equivalent to the power delivered by a nuclear power plant



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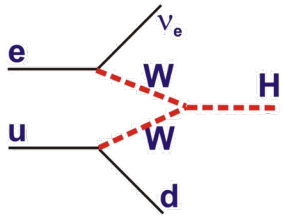
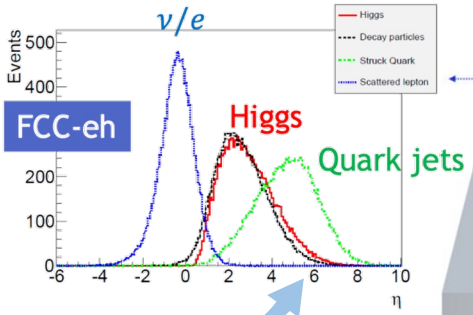
The planned R&D on Energy Recovery Linacs will enable to provide a 1 GW electron beam with only 100 MW power

Make the invisible visible – Detector R&D for DIS

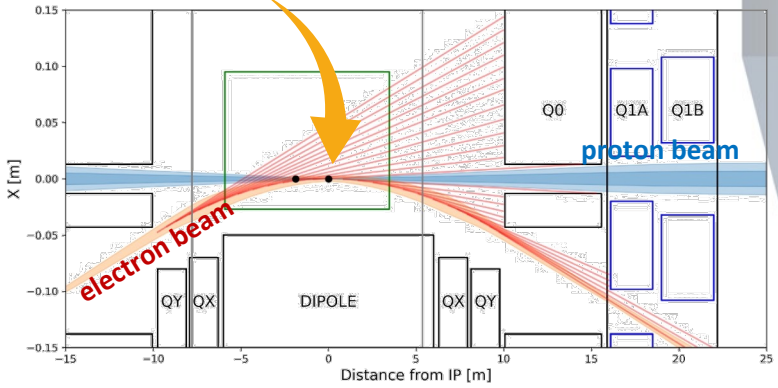
Major challenges: 1° close to the beamline (hermiticity), Tracking & Vertexing, High-resolution calorimetry

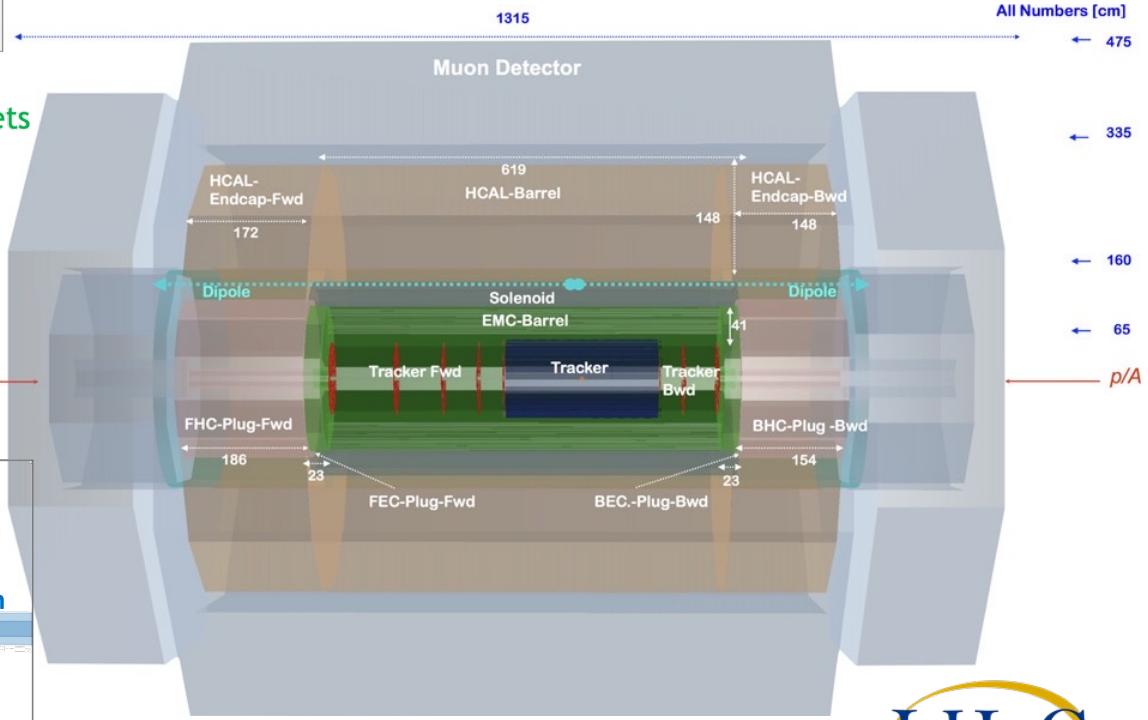




Forward jet reconstruction

Synchrotron radiation in the interaction region





Machine Detector Interface workshop (19-24 Sept): https://indico.cern.ch/event/1423983/

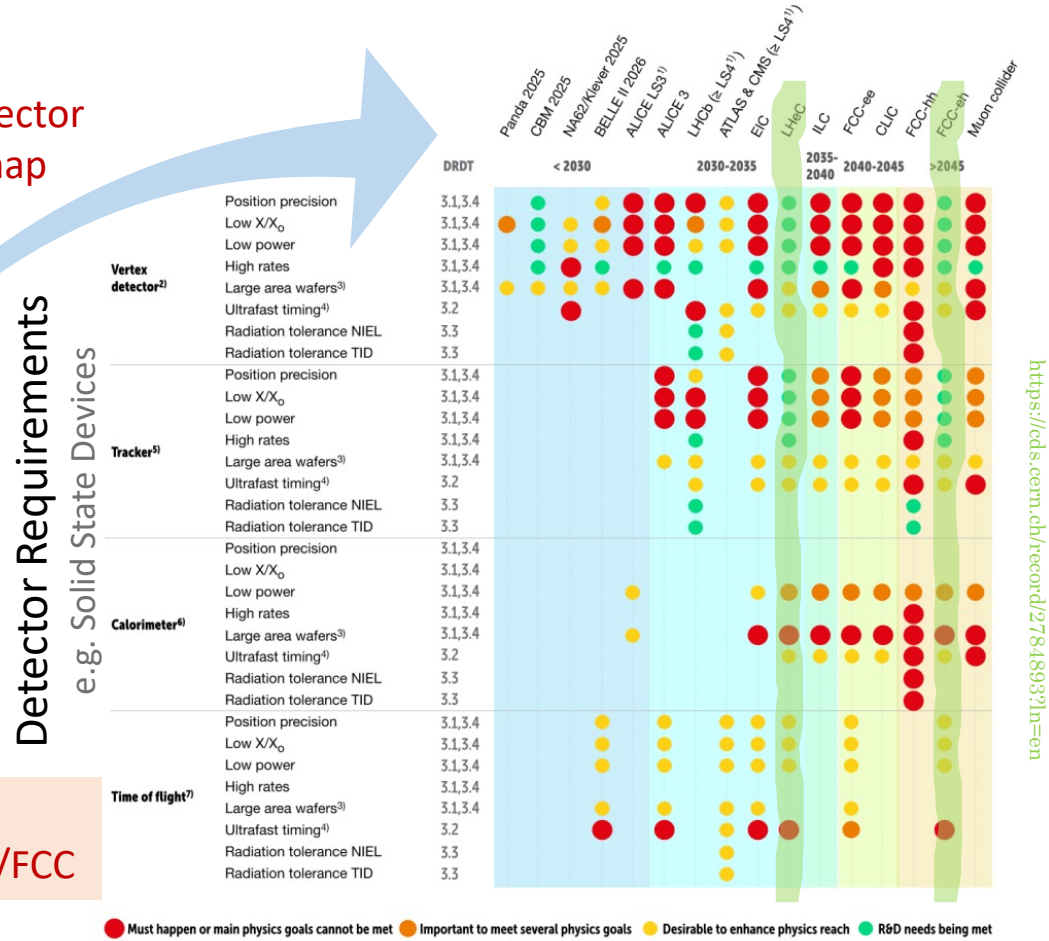
Make the invisible visible – Detector R&D for DIS

Mostly ready to be built

European Detector R&D Roadmap (2021)

Synergies with many other major projects, potentially as stepping stones

Potentially one detector for a joint DIS and Heavy-Ion program @ HL-LHC/FCC



https://cds.cern.ch/record/2784893?ln=en

Eur.Phys.J.C 82 (2022) 1, 40

Make the invisible visible – Detector R&D for DIS

Mostly ready to be built

European Detector
R&D Roadmap
(2021)

A detector for future DIS at the energy frontier

Laurent Forthomme, WG13, 18 July, 15:21

Sy
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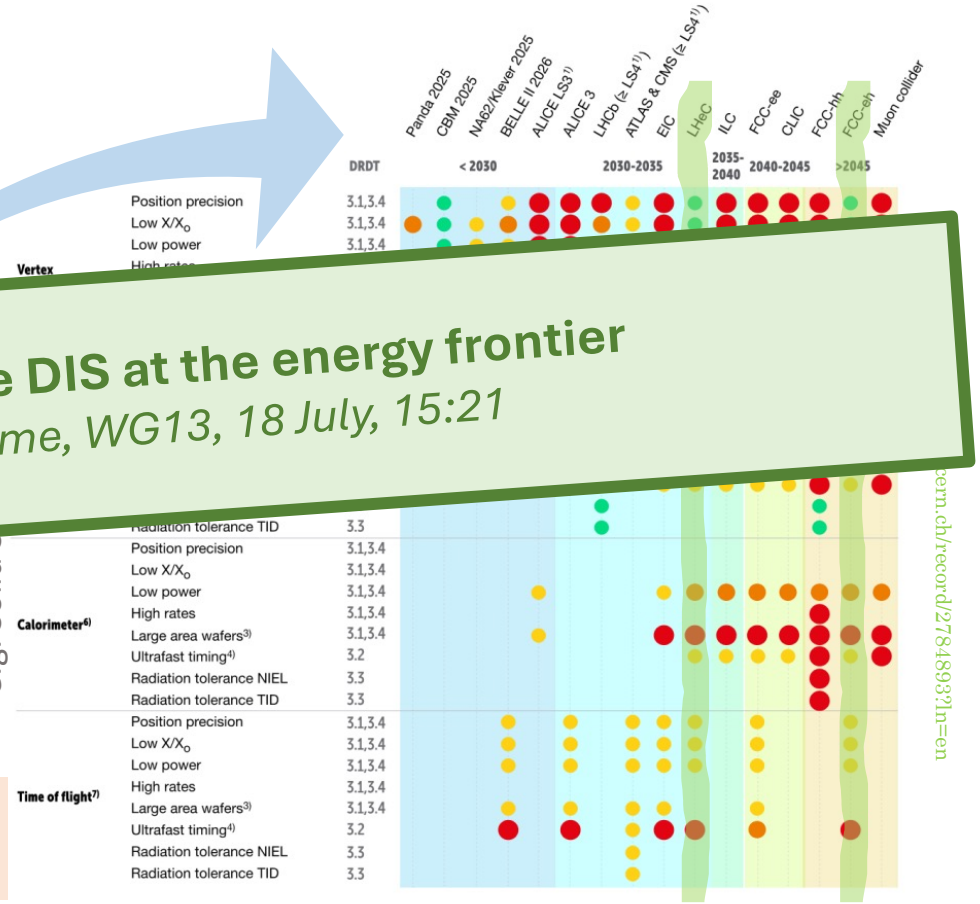
stepping stones

Detector R
e.g. Solid S



Potentially one detector for a
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Eur.Phys.J.C 82 (2022) 1, 40

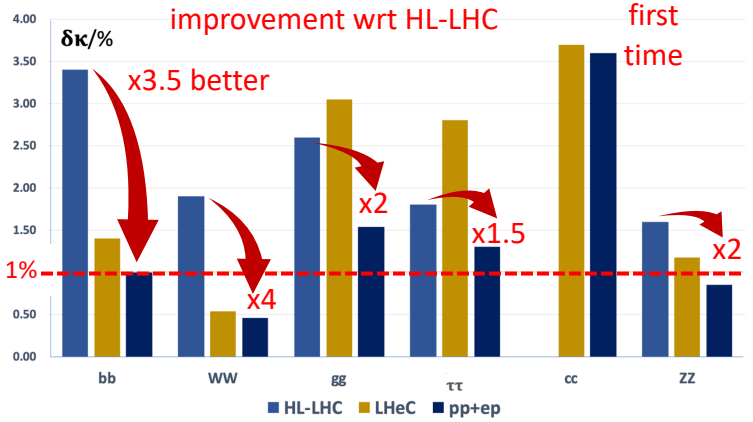
the synergistic physics impact of ep collisions

(briefly some highlights)

Some physics highlights of the LHeC (ep/eA@LHC)

on several fronts comparable improvements between LHC → HL-LHC as for HL-LHC → LHeC

Higgs physics - pp+ep comb



EW physics – pp & ep

- Δm_W to 2 MeV (today at ~10 MeV) **pp with ep input**
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP + scale dep) **ep only**

Top quark physics – ep only

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

DIS scattering cross sections - ep 1y

- complete unfolding of PDFs extended in (Q^2,x) by orders of magnitude

Strong interaction physics - ep 1y

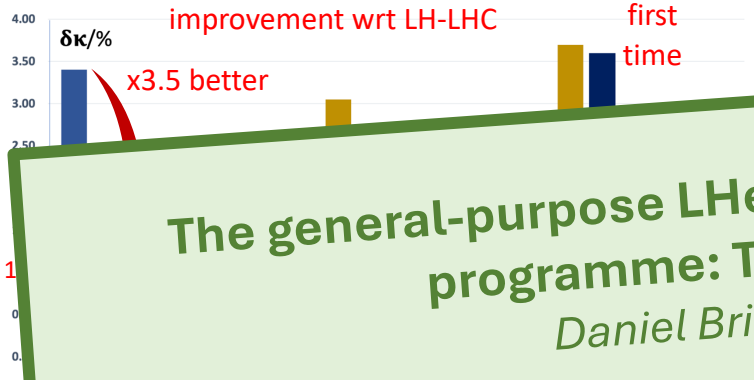
- α_s precision of 0.2%
- low-x: a new discovery frontier

The Large Hadron-Electron Collider at the HL-LHC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

Some physics highlights of the LHeC (ep/eA@LHC)

on several fronts comparable improvements between LHC → HL-LHC as for HL-LHC → LHeC

Higgs physics - pp+ep comb



EW physics – pp & ep

- Δm_W to 2 MeV (today at ~10 M
- top quark FCNC and γ, W, Z couplings

The general-purpose LHeC and FCC-eh high-energy precision programme: Top and EW measurements

Daniel Britzger, WG4, 20 July, 18:12

DIS scattering cross sections - ep 1y

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Strong interaction physics - ep 1y

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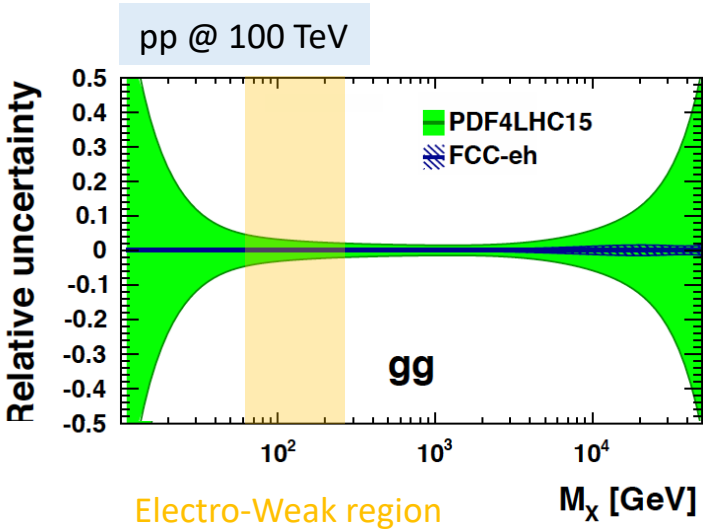
The Large Hadron-Electron Collider at the HL-HC, J. Phys. G 48 (2021) 110501, 364p (updated CDR)

Empowering the FCC-hh programme with the FCC-eh

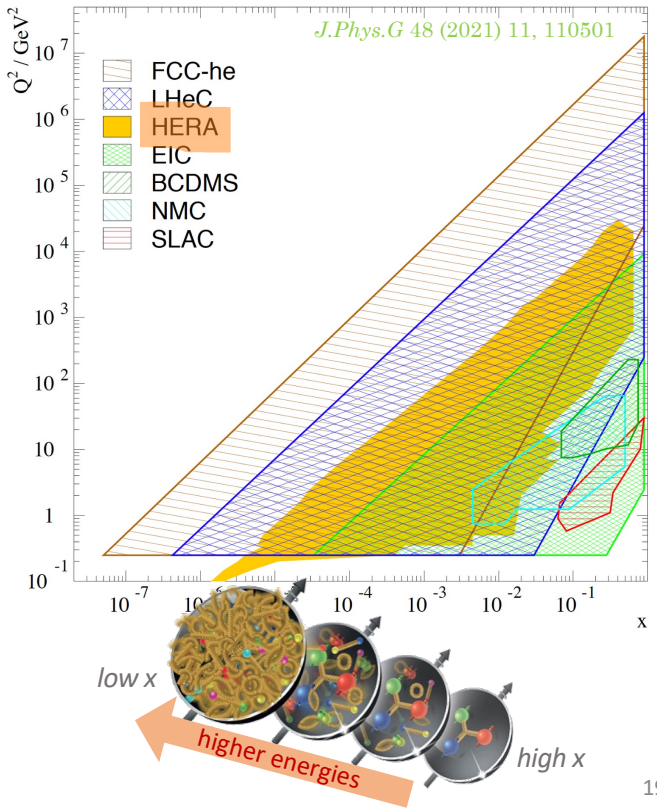


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

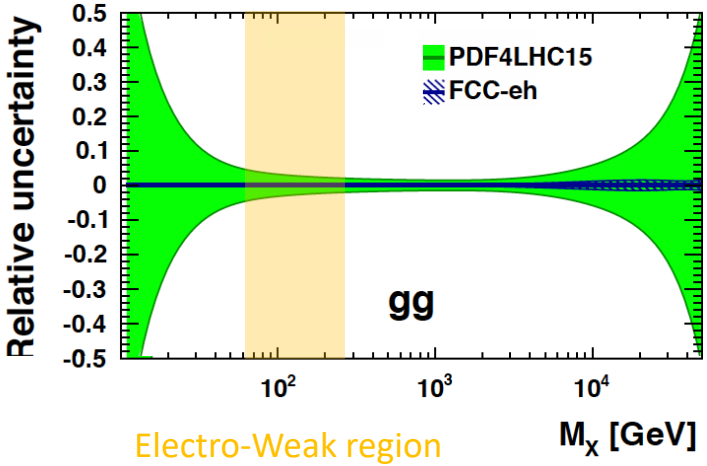
no FCC-*eh*

Kinematic range Parton Distribution Functions



Empowering the FCC-hh programme with the FCC-eh

pp @ 100 TeV



Electro-Weak region

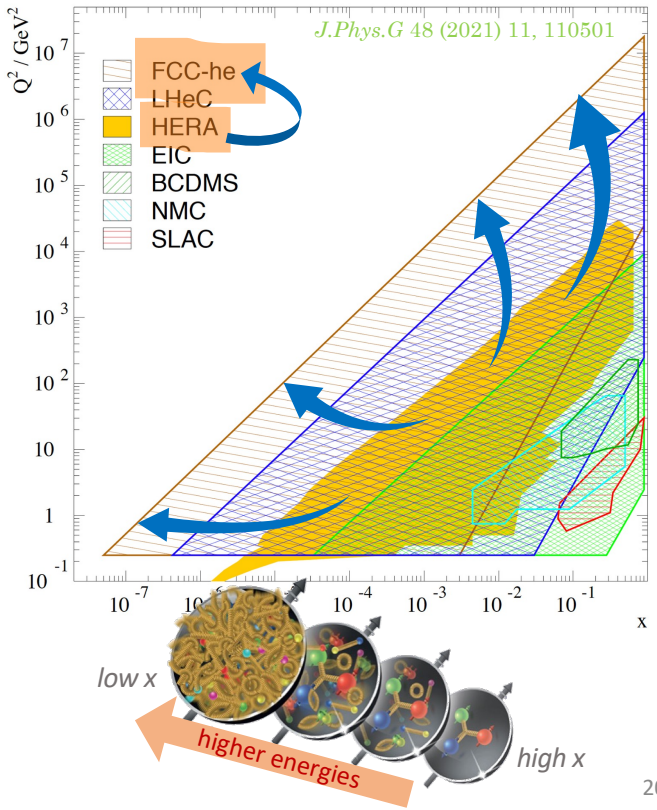
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



FCC-eh essential to unlock FCC-hh science potential

Complementarity for Higgs physics in the FCC programme

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

only FCC-hh

[J. de Blas et al., JHEP 01 (2020) 139]

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adding 365 GeV runs

adding FCC-eh

only FCC-ee@240GeV

only FCC-hh

[J. de Blas et al., JHEP 01 (2020) 139]

Complementarity for Higgs physics in the FCC programme

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FCC-ee versus FCC-hh/eh

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κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

adding 365 GeV runs

adding FCC-ep

only FCC-ee@240GeV

only FCC-hh

[J. de Blas et al., JHEP 01 (2020) 139]

Complementarity for Higgs physics in the FCC programme

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
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What would be the combined Higgs physics reach of HL-LHC ⊕ FCC-ee/CEPC ⊕ LHeC ?

adding 365 GeV runs

adding FCC-ep

only FCC-ee@240GeV

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ALL COMBINED

[J. de Blas et al., JHEP 01 (2020) 139]

Complementarity for Higgs physics in the FCC programme

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

Higgs precision physics in electron–proton scattering at CERN
Uta Klein, WG1, 18 July, 18:10

	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)				
κ_μ[%]	4.	3.9					
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ALL COMBINED

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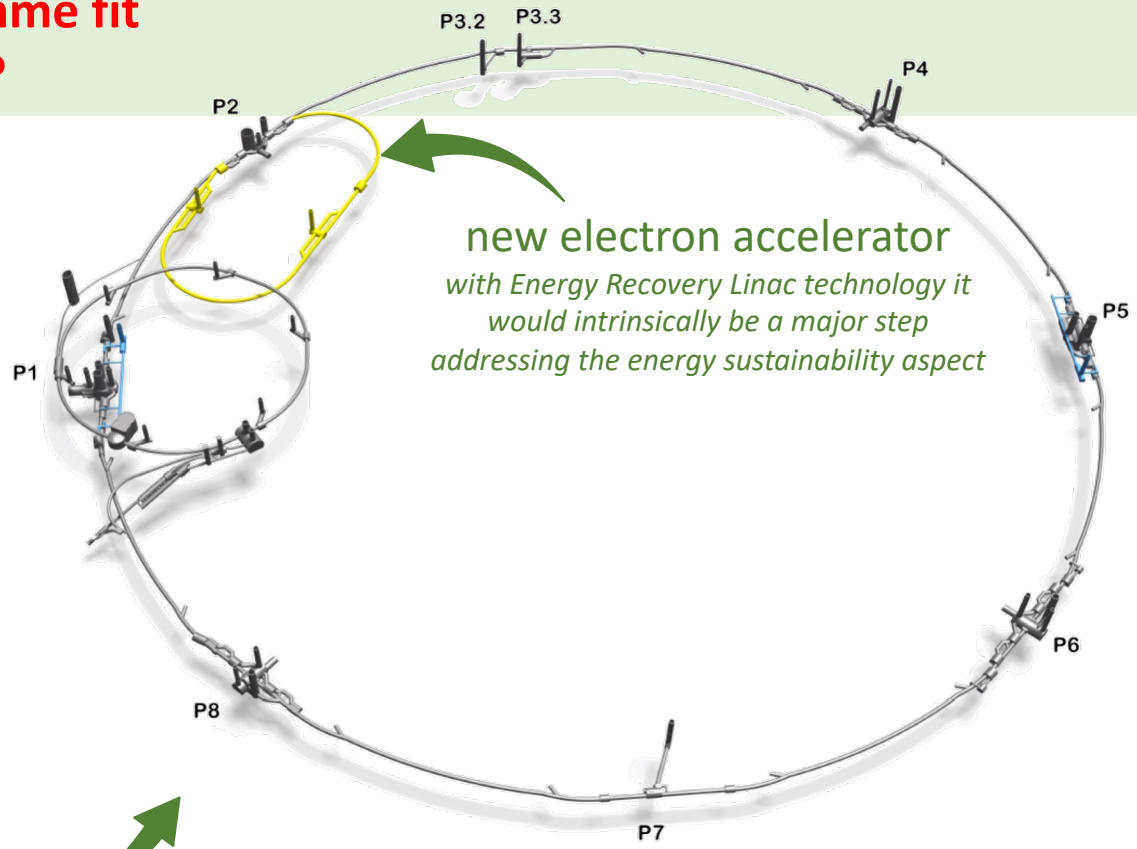
[J. de Blas et al., JHEP 01 (2020) 139]

How does the LHeC progamme fit into the collider landscape?



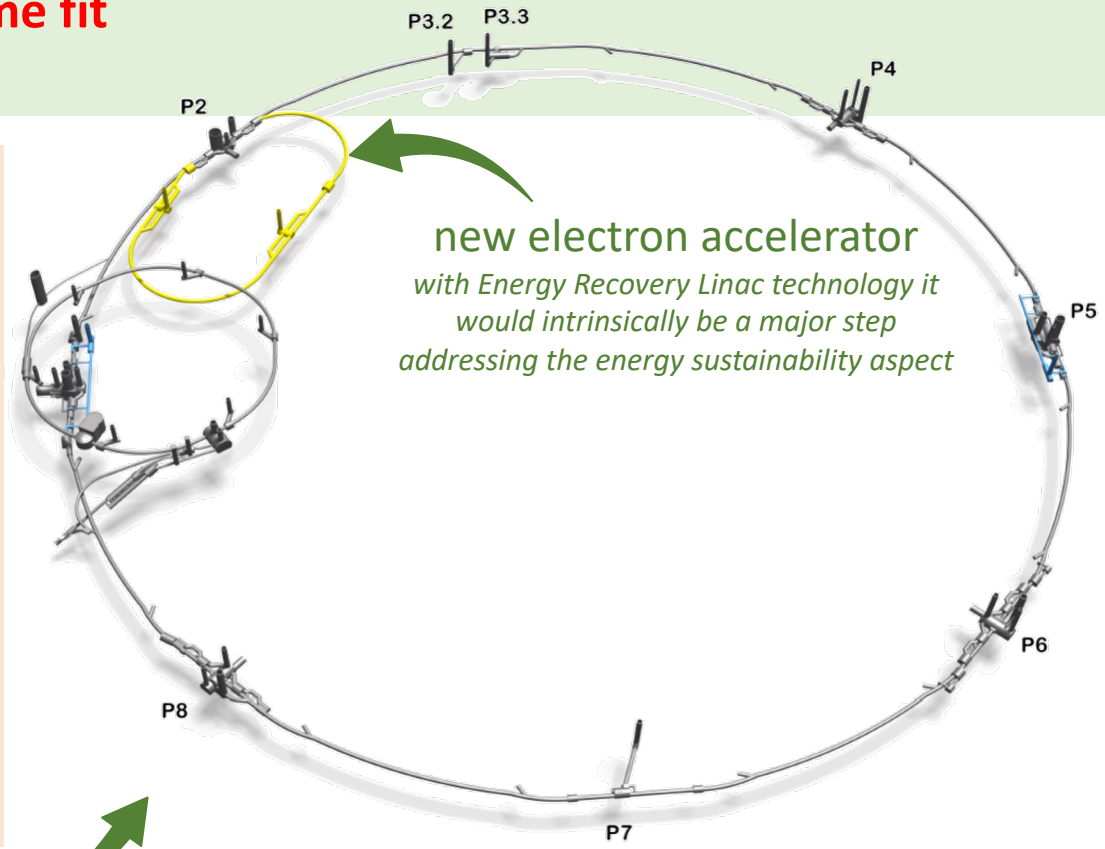
new electron accelerator

with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

existing/future proton accelerator

How does the LHeC progamme fit into the collider landscape?

The LHeC (and/or FCC-eh) is not "*the*" major new collider for CERN, but enables an ultimate upgrade of the existing LHC (and/or future FCC) programme.



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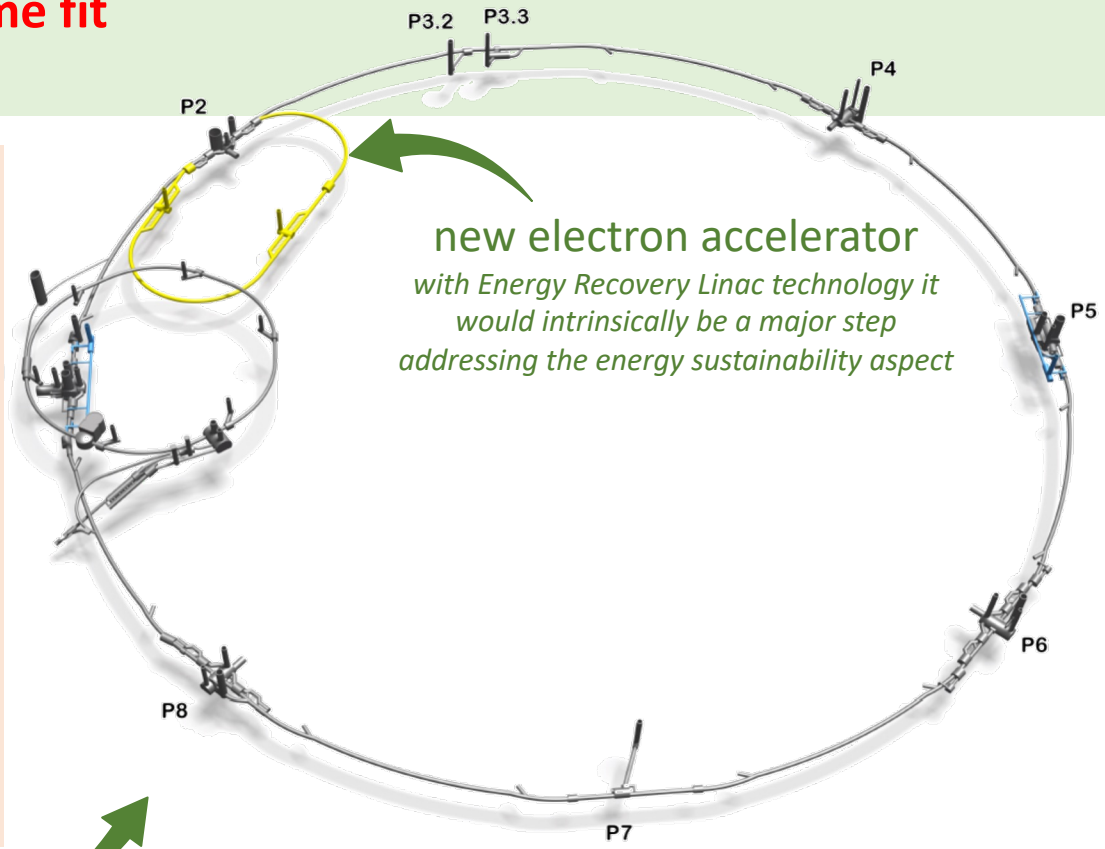
The LHeC (and/or FCC-eh) is not *"the"* major new collider for CERN, but enables an ultimate upgrade of the existing LHC (and/or future FCC) programme.

However, the LHeC is the first affordable collider at CERN that can significantly go beyond the HL-LHC physics reach and complete its physics programme in the 2040'ies.



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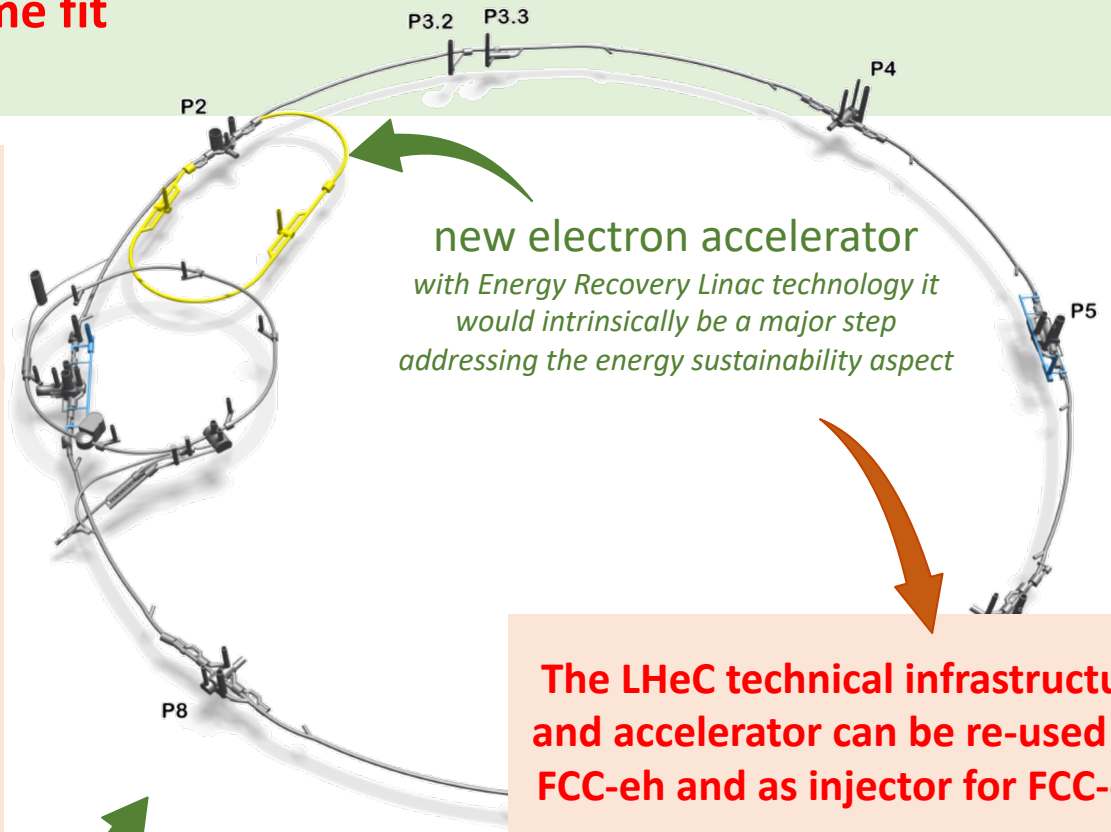

new electron accelerator

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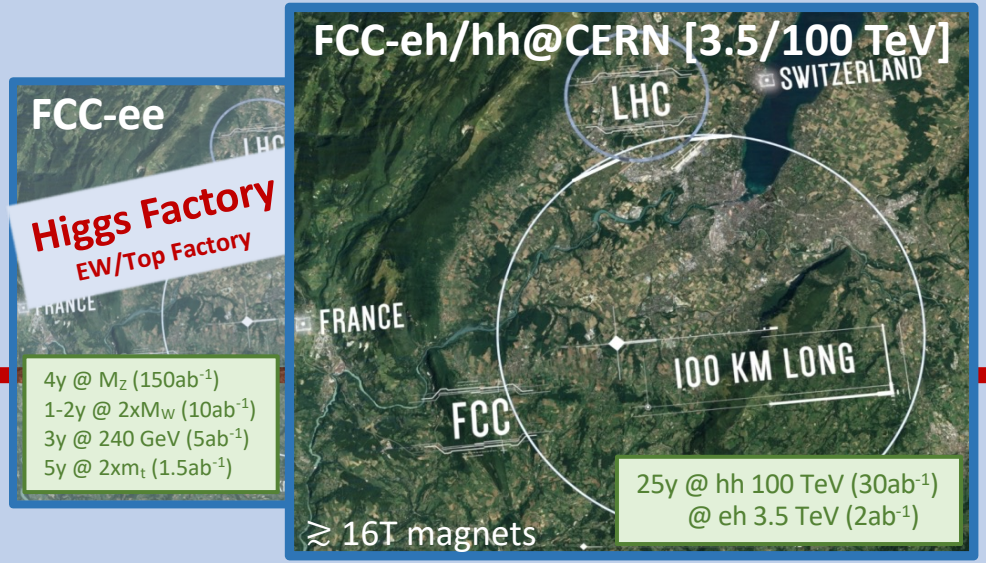
The LHeC technical infrastructure and accelerator can be re-used for FCC-eh and as injector for FCC-ee.

existing/future proton accelerator

Major current & future colliders @ CERN

Large Hadron Collider (HL-LHC)
until early 2040'ies

Future Circular Collider (FCC)
from late 2040'ies



numbers assume 2 IPs for each collider (only one for FCC-eh)

feasibility of the FCC is being investigated

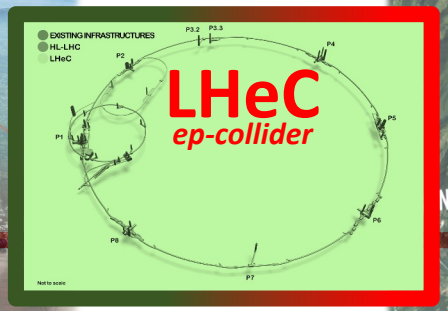
An impactful "*bridge*" between major colliders @ CERN

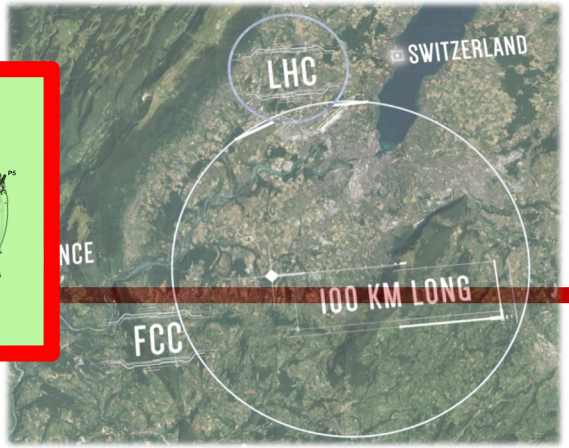
ep-option with HL-LHC: LHeC

updated CDR: J.Phys.G 48 (2021) 11, 110501

10y @ 1.2 TeV (1ab^{-1}) = Run-6 + 5y ep-only@LHC

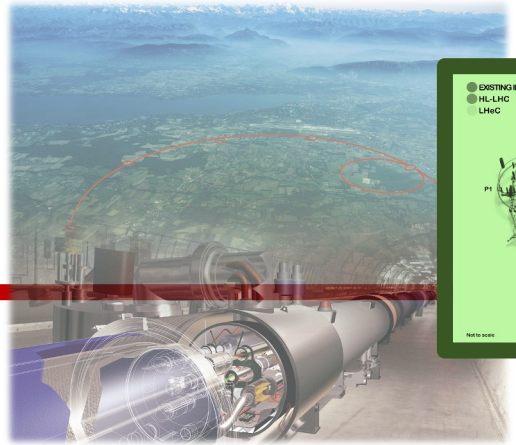
6y ep-only@LHC > 1 ab^{-1}

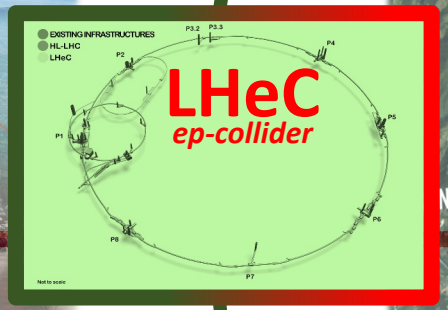


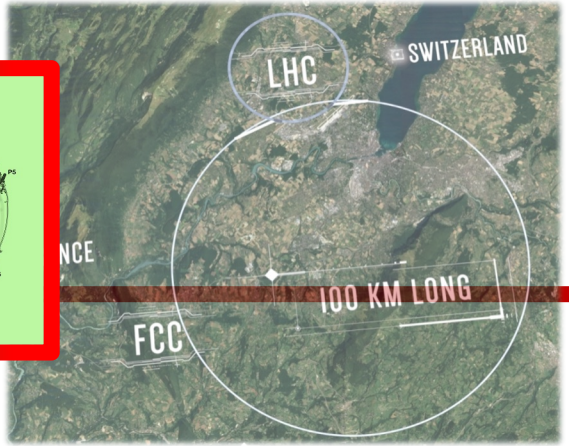


An impactful "*bridge*" between major colliders @ CERN

ultimate upgrade of the LHC physics reach







fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

An impactful "*bridge*" between major colliders @ CERN

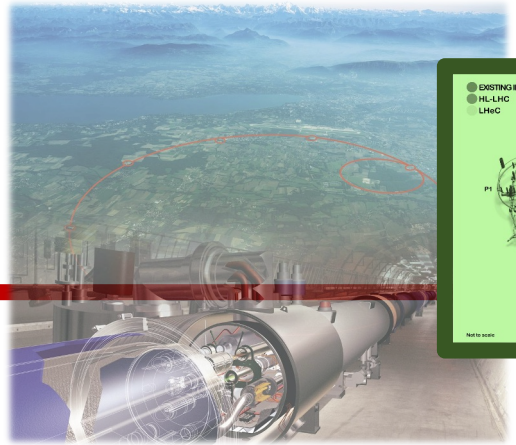
cost-effective investment

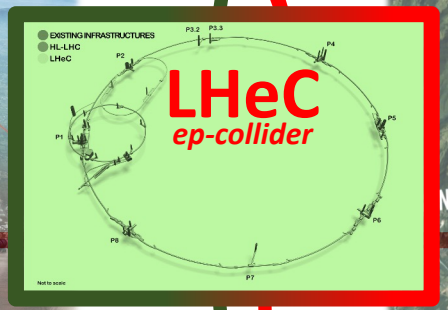
re-use

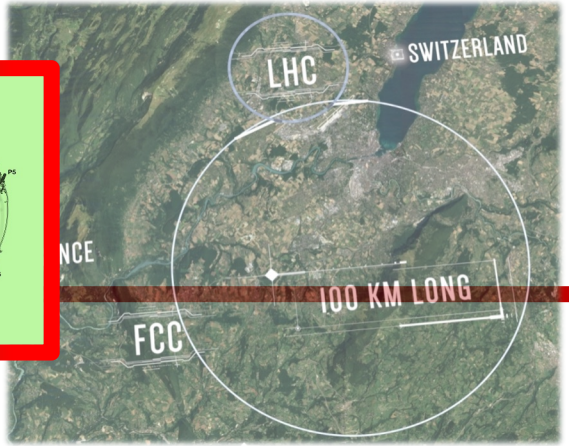
injector

ultimate upgrade of the LHC physics reach

essential enabler for the physics at any new high-energy hadron collider







i.e. SRF@LHeC as prototype series and training for SRF@FCC-ee

fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee

An impactful "*bridge*" between major colliders @ CERN

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ultimate upgrade of the LHC physics reach

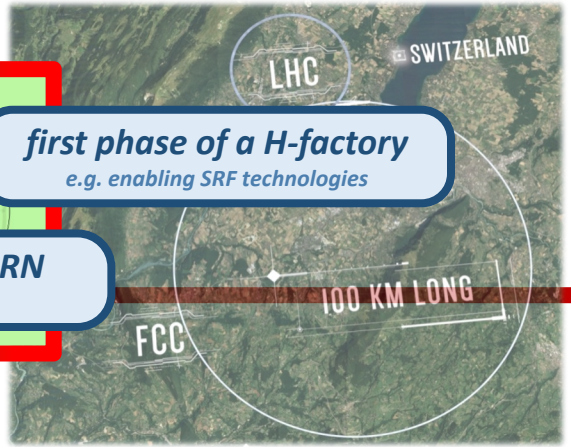
essential enabler for the physics at any new high-energy hadron collider

LHeC
ep-collider

last phase of the LHC
e.g. enabling more physics

first phase of a H-factory
e.g. enabling SRF technologies

always collisions at CERN
e.g. enabling careers



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The ep/eA study at the LHC and FCC

- The ESPP emphasizes the importance of studying the Higgs boson sector with improved precision and diversifying our search for new physics phenomena.
- Guided by these strategic objectives, we study how high-energy, high-luminosity ep/eA physics can empower pp/pA/AA physics at the LHC and FCC.
- There is important synergistic impact on topics such as proton structure, EW/H/top physics, Hidden Sector searches and Detector R&D.

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The LHeC project emerges as an impactful bridge between present and future major colliders at CERN

a White Paper will be developed for the ESPP input, with a workshop planned for 28-29 November 2024

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Thank you for your attention!

Jorgen.DHondt@vub.be

The ep/eA study at the LHC and FCC – new impactful goals for the community

More information:
https://indico.cern.ch/e/LHeCFCCeh

2023 | WS | 2024 | WS | 2025 *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces
Nestor Armesto, Claire Gwenlan, Paul Newman

general-purpose high-energy physics program: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions
Monica D'Onofrio, Uta Klein, Christian Schwanenberger

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics program
Maarten Boonekamp, Daniel Britzger, Christian Schwanenberger

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics
Paul Newman, Yuji Yamazaki

developing a sustainable LHeC and FCC-eh collider program
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …
Oliver Bruning, Yannis Papaphilippou

- five thematic physics and technology working groups
- annual ep/eA workshops (**WS**)

Subscribe to mailing lists via https://e-groups.cern.ch/ : use the search option, and search for "lhec-fcceh-all" or "ep-eA-WG" in all e-groups