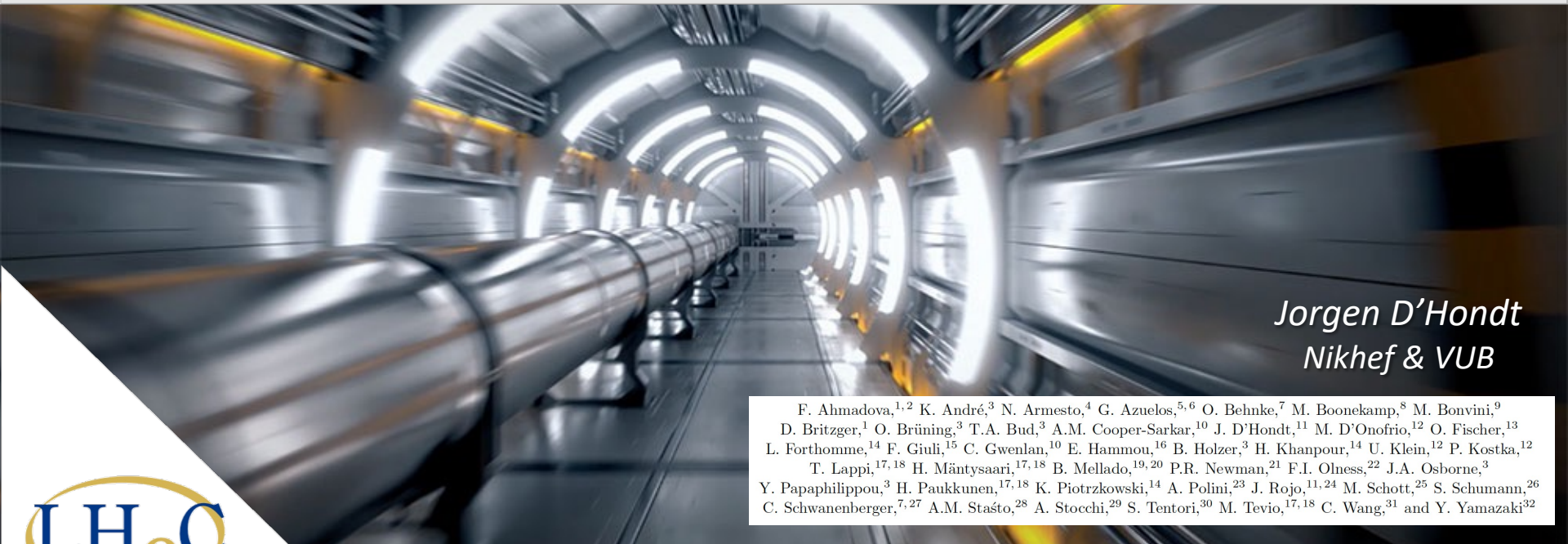


# The Large Hadron electron Collider (LHeC) *as an alternative or bridge project between major colliders at CERN*



Jorgen D'Hondt  
Nikhef & VUB

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L. Forthomme,<sup>14</sup> F. Giuliani,<sup>15</sup> C. Gwenlan,<sup>10</sup> E. Hammou,<sup>16</sup> B. Holzer,<sup>3</sup> H. Khanpour,<sup>14</sup> U. Klein,<sup>12</sup> P. Kostka,<sup>12</sup>  
T. Lappi,<sup>17,18</sup> H. Mäntysaari,<sup>17,18</sup> B. Mellado,<sup>19,20</sup> P.R. Newman,<sup>21</sup> F.I. Olness,<sup>22</sup> J.A. Osborne,<sup>3</sup>  
Y. Papaphilippou,<sup>3</sup> H. Paukkunen,<sup>17,18</sup> K. Piotrkowski,<sup>14</sup> A. Polini,<sup>23</sup> J. Rojo,<sup>11,24</sup> M. Schott,<sup>25</sup> S. Schumann,<sup>26</sup>  
C. Schwanenberger,<sup>7,27</sup> A.M. Staśto,<sup>28</sup> A. Stocchi,<sup>29</sup> S. Tentori,<sup>30</sup> M. Tevio,<sup>17,18</sup> C. Wang,<sup>31</sup> and Y. Yamazaki<sup>32</sup>



ESPP Open Symposium  
Venice-Lido, June 23-27, 2025

## Remit of the European Strategy Group (ESG)

- The aim of the Strategy update should be to develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field.**
- The ESG should take into consideration:
  - Input of the particle physics community;
  - Status of implementation of the 2020 Strategy update;
  - Accomplishments over recent years  
(Results from the LHC and other experiments and facilities worldwide, progress in the construction of the High-Luminosity LHC, outcome of the FCC Feasibility Study, recent technological developments in accelerator, detector and computing areas)
  - International landscape of the field
- The Strategy update should include the **preferred option for the next collider at CERN** and **prioritised alternative options** to be pursued if the chosen preferred plan turns out not to be feasible or competitive.
- The Strategy update should also **indicate areas of priority for exploration complementary to colliders** and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.

Karl Jakobs  
introduction slides

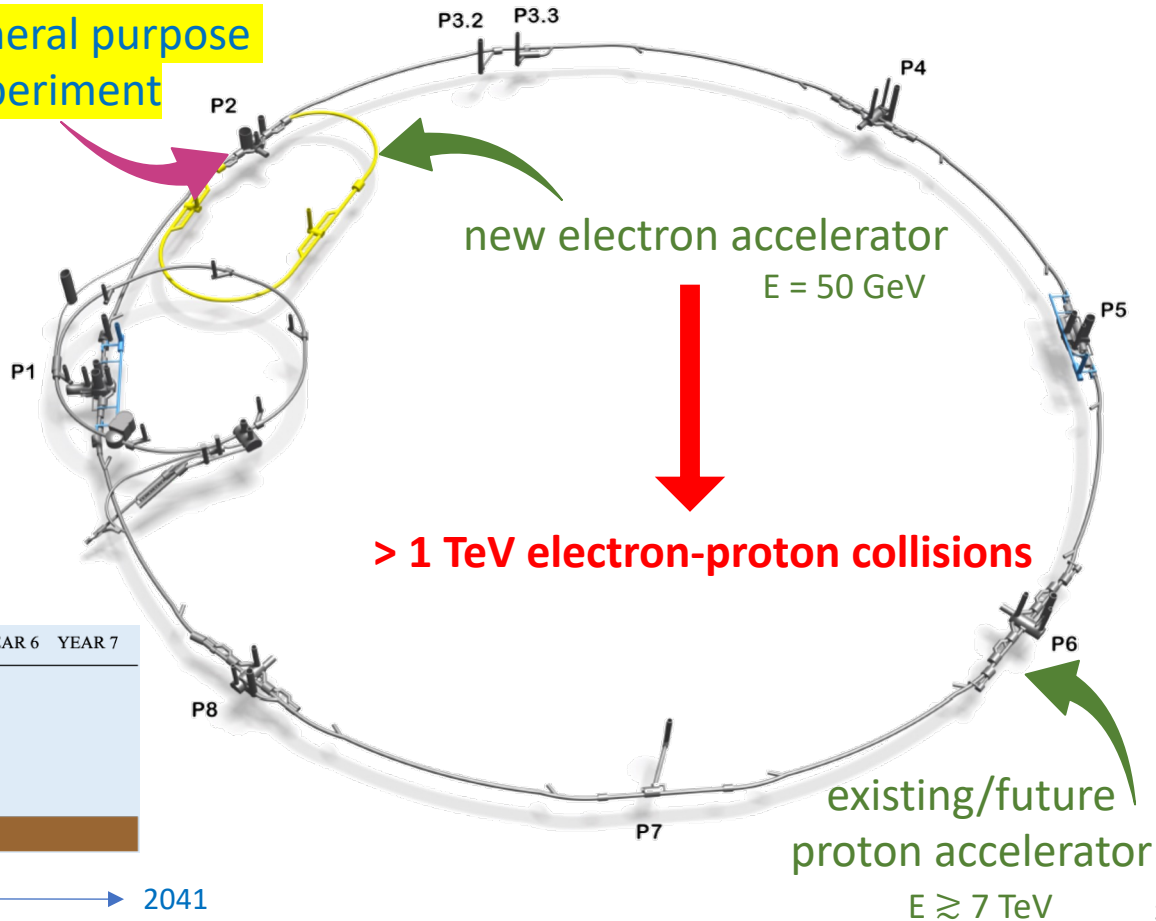
# LHeC – parameters, timeline, resources, energy consumption

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



one general purpose experiment

802.5MHz, 20MV/m in CW, 6x25mA in SRF  
ERL 3-turns, 50 GeV (1/3 of LHC circumference)  
Start operation after HL-LHC (>2041)  
Luminosity above  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$   
6 years of operation,  $1 \text{ ab}^{-1}$  (e.g. 2043-2048)  
120MW from HL-LHC + 100MW from e-beam



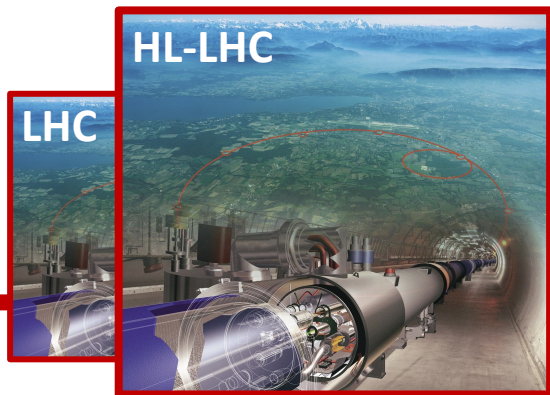
| LHeC construction planning  | YEAR 1 | YEAR 2 | YEAR 3 | YEAR 4 | YEAR 5 | YEAR 6 | YEAR 7 |
|-----------------------------|--------|--------|--------|--------|--------|--------|--------|
| Land negotiations           |        |        |        |        |        |        |        |
| Environmental Impact Study  |        |        |        |        |        |        |        |
| Building permits            |        |        |        |        |        |        |        |
| Detailed design & tendering |        |        |        |        |        |        |        |
| Construction                |        |        |        |        |        |        |        |

for example 2034 → 2041

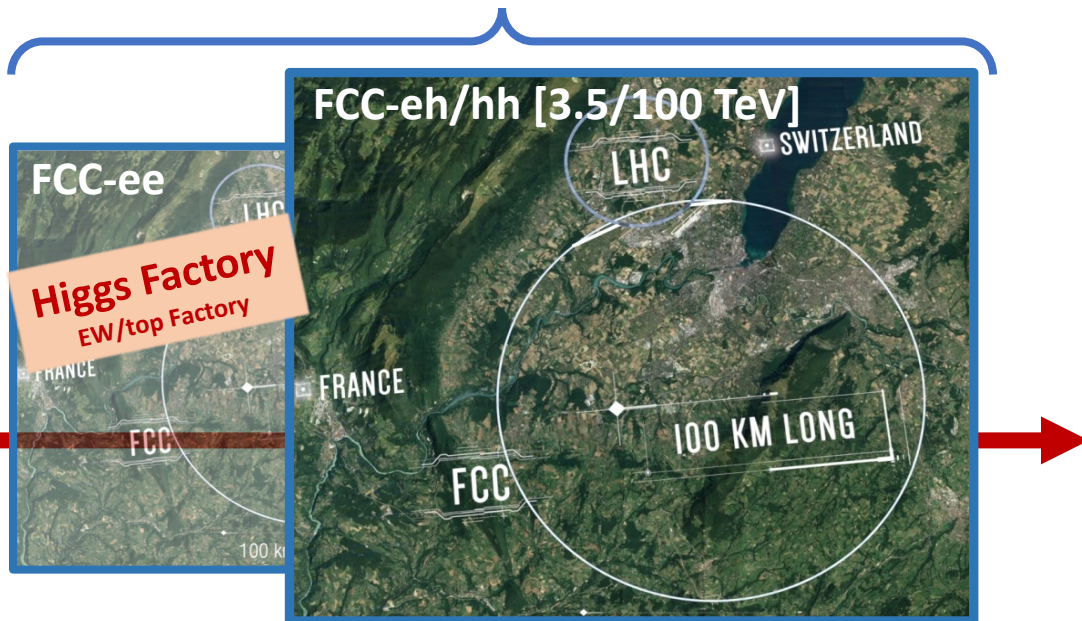


# Flagships at the energy & precision frontier

**Current flagship (27km)**  
*impressive program up to 2041*



**Future Circular Collider (FCC)**  
*big sister future ambition (90km), beyond 2048*

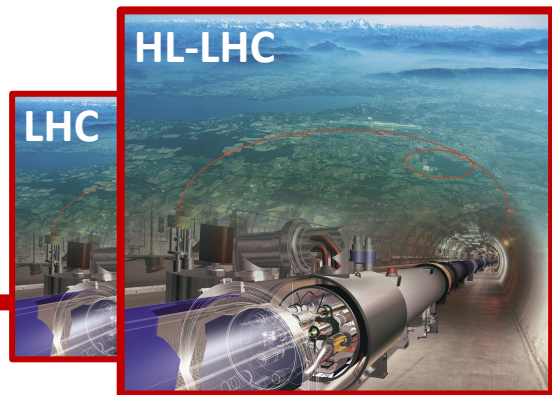




# Flagships at the energy & precision frontier

**Current flagship (27km)**  
*impressive program up to 2041*

**cost ~2 BCHF  $\oplus$  one detector**  
**operational cost similar to HL-LHC**

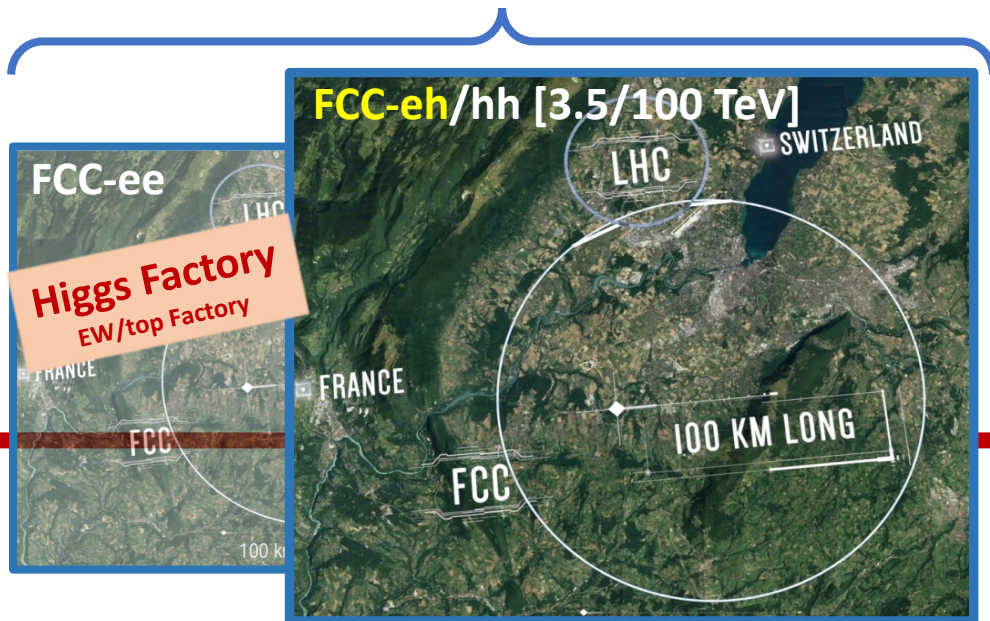


**LHeC**

**ep-option after HL-LHC: LHeC**  
**6y @ 1.2 TeV ( $1ab^{-1}$ )**

**Future Circular Collider (FCC)**

*big sister future ambition (90km), beyond 2048*



# The LHeC documents & related

## Updated CDR

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

## LHeC ESPP'26 input

<https://indico.cern.ch/event/1439855/contributions/6461616/>

## LHeC as a bridge project document (more extensive document)

<https://inspirehep.net/literature/2903314>

## PERLE as ESPP'26 input

<https://indico.cern.ch/event/1439855/contributions/6461453/>

## Other LHeC related input to ESPP'26

<https://indico.cern.ch/event/1439855/contributions/6461558/>

<https://indico.cern.ch/event/1439855/contributions/6461469/>

## Indico website

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

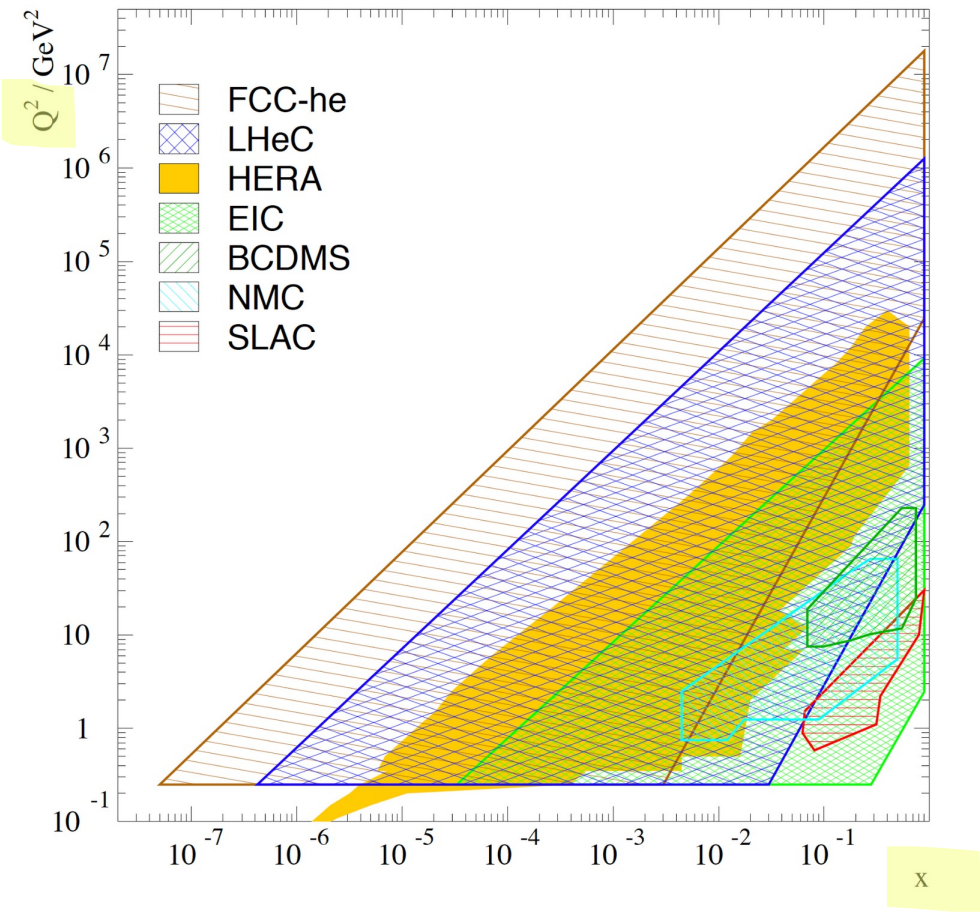
## Cost estimate

<https://cds.cern.ch/record/2652349/files/CERN-ACC-2018-0061.pdf>

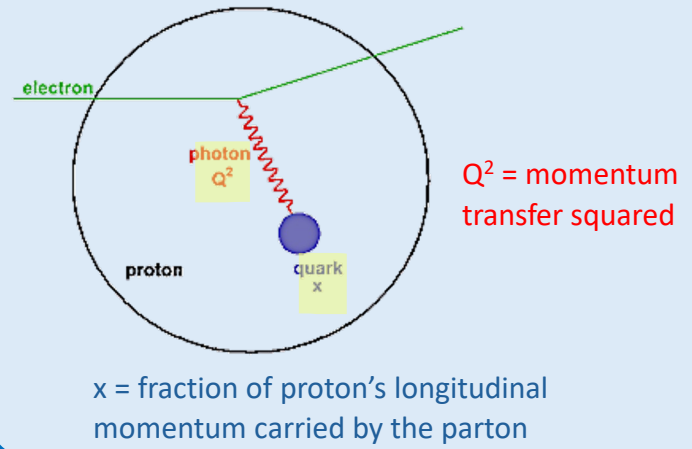
# The LHeC physics



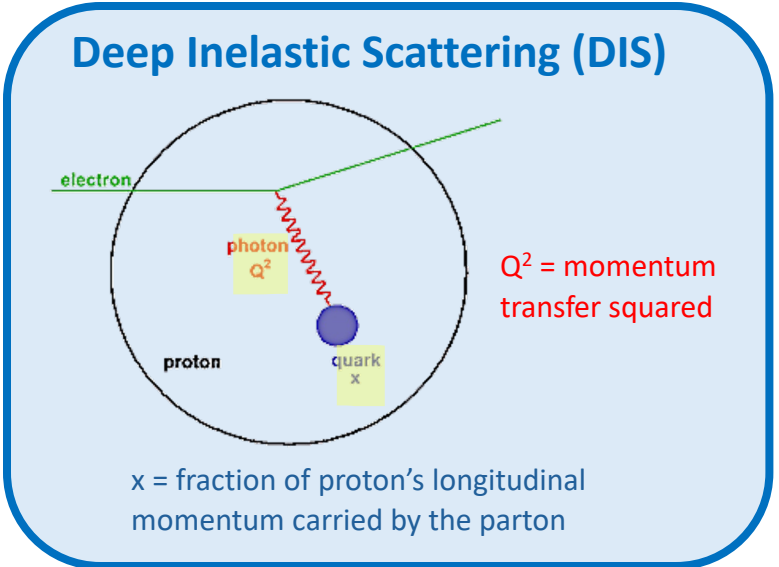
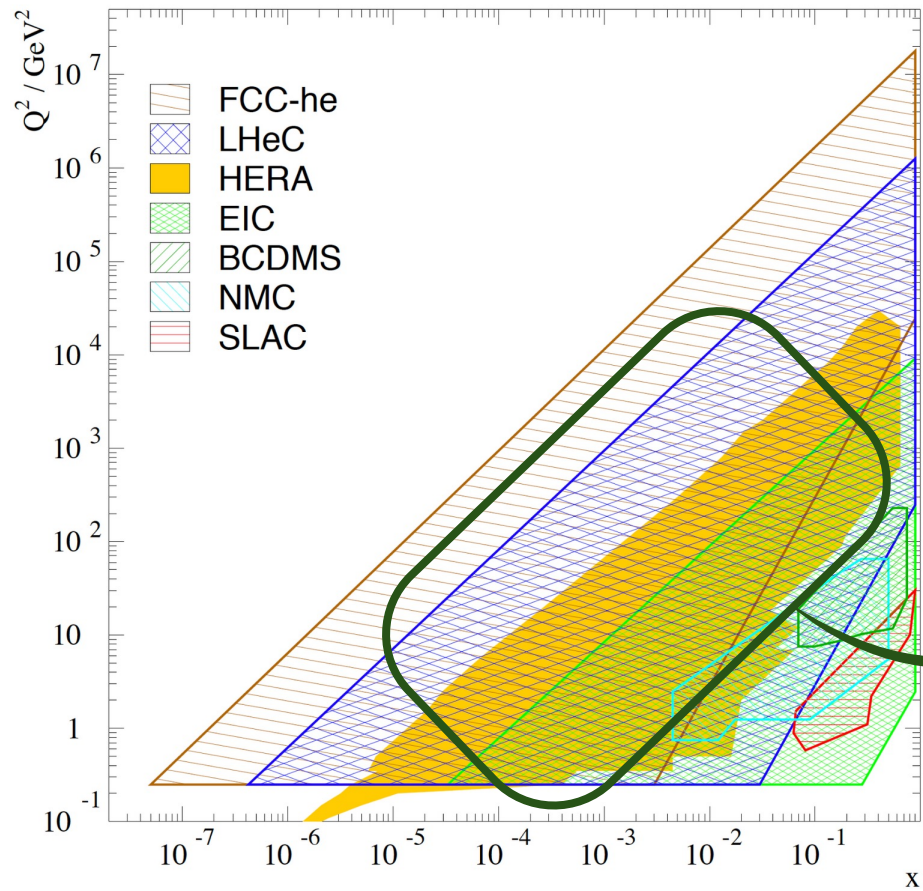
# 1.2 TeV ep collisions cover the $(Q^2, x)$ plane



## Deep Inelastic Scattering (DIS)

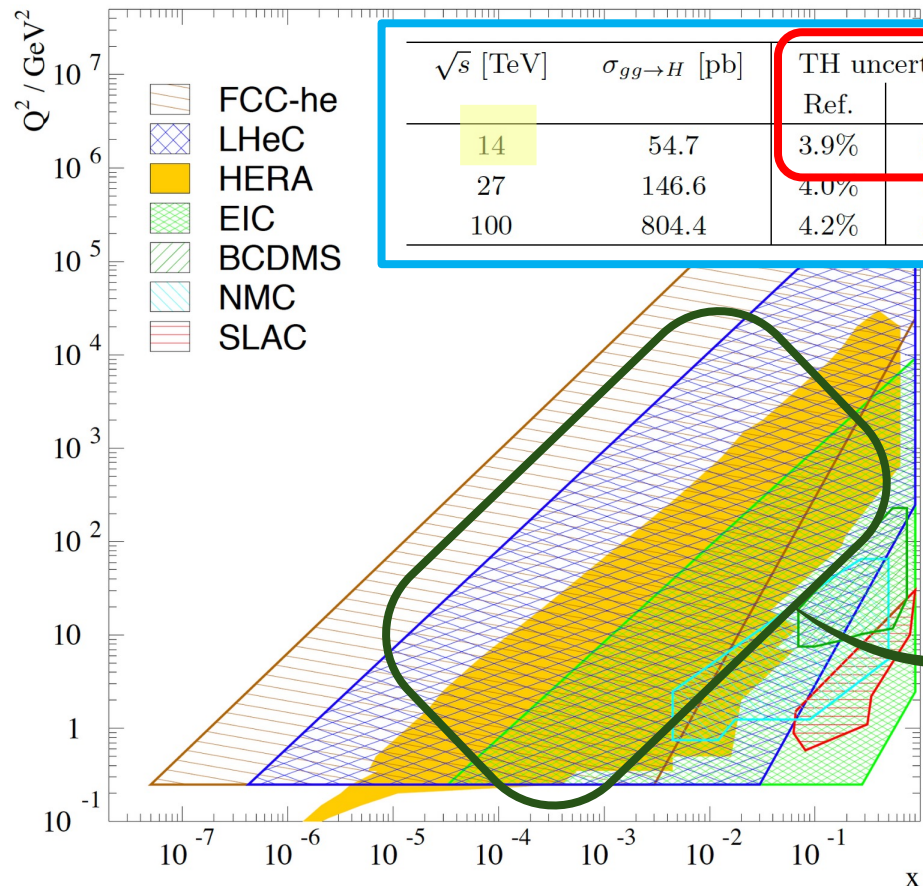


# 1.2 TeV ep collisions cover the $(Q^2, x)$ plane



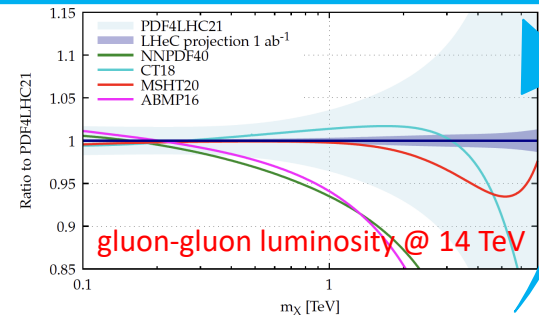
**precision QCD physics**  
 $\Delta\alpha_s \sim 0.14\%$  & running of  $\alpha_s$   
complete unfolding of PDFs covering a vast kinematic range

# 1.2 TeV ep collisions cover the $(Q^2, x)$ plane



marginalising  
PDF+ $\alpha_s$  uncertainties

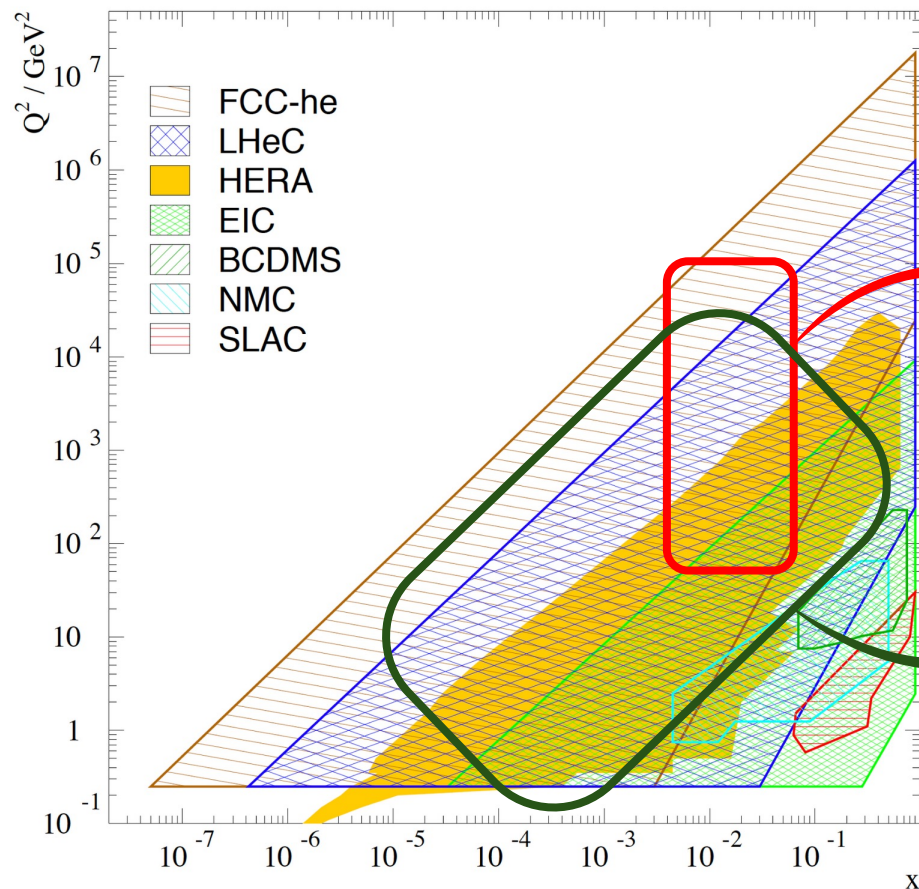
| $\sqrt{s}$ [TeV] | $\sigma_{gg \rightarrow H}$ [pb] | TH uncertainty |      | PDF+ $\alpha_s$ uncertainty |      |         | Total |      |         |
|------------------|----------------------------------|----------------|------|-----------------------------|------|---------|-------|------|---------|
|                  |                                  | Ref.           | S2   | Ref.                        | S2   | S2+LHeC | Ref.  | S2   | S2+LHeC |
| 14               | 54.7                             | 3.9%           | 2.0% | 3.2%                        | 1.6% | 0.5%    | 5.1%  | 2.6% | 2.0%    |
| 27               | 146.6                            | 4.0%           | 2.0% | 3.3%                        | 1.7% | 0.6%    | 5.2%  | 2.6% | 2.1%    |
| 100              | 804.4                            | 4.2%           | 2.1% | 3.7%                        | 1.9% | 0.7%    | 5.6%  | 2.8% | 2.2%    |



LHeC empowering  
 $gg \rightarrow H$  @ (HL)-LHC

**precision QCD physics**  
 $\Delta\alpha_s \sim 0.14\%$  & running of  $\alpha_s$   
complete unfolding of PDFs covering a vast kinematic range

## 1.2 TeV ep collisions cover the $(Q^2, x)$ plane



**at these energies and luminosities,  
interactions with all SM particles  
can be measured precisely**

### **EW, Higgs and top quark physics**

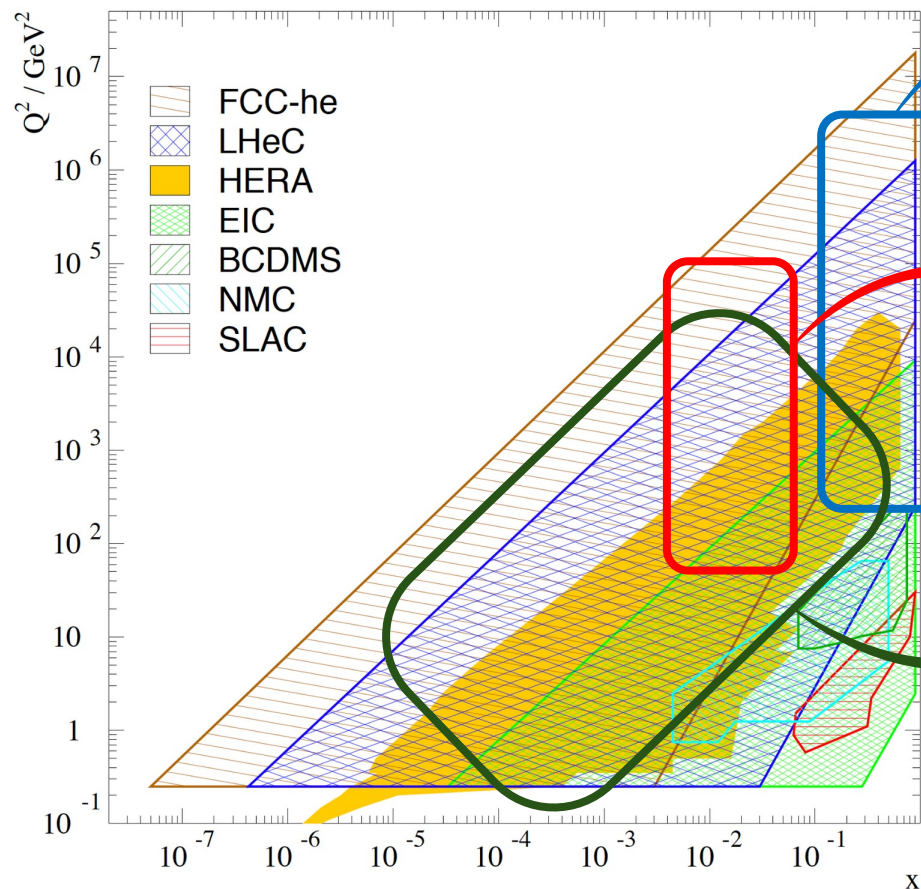
$\Delta m_W^{\text{LHC}} \sim 3 \text{ MeV}$ ,  $\Delta |V_{tb}| \sim 1\%$ , top-quark FCNC  
 $\Delta \sin^2 \theta_W^{\text{eff}} \sim 0.0002$  (full scale-dependency)  
weak neutral couplings to light quarks  $\sim 1\%$   
Higgs couplings largely improved wrt HL-LHC  
improved SMEFT fits (accuracy & degeneracy)

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## 1.2 TeV ep collisions cover the $(Q^2, x)$ plane



### direct searches for new physics

unique environment: eq only EW interactions  
e.g. heavy  $\nu$ , dark  $\gamma$ , axion-like particles

### EW, Higgs and top quark physics

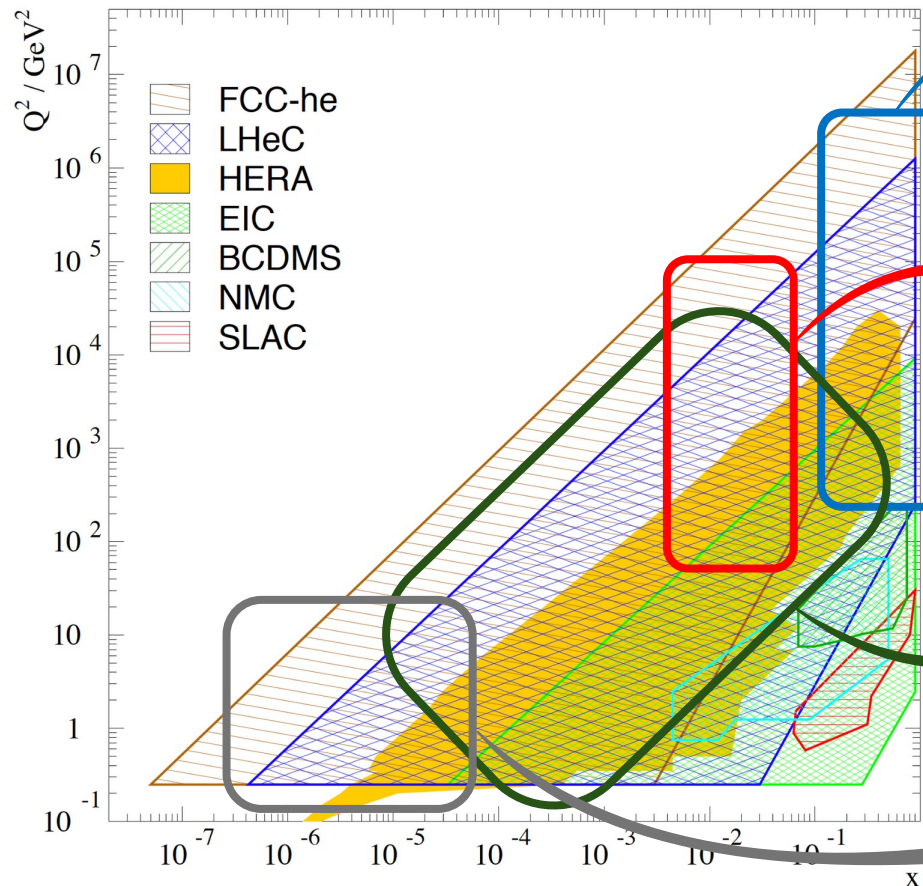
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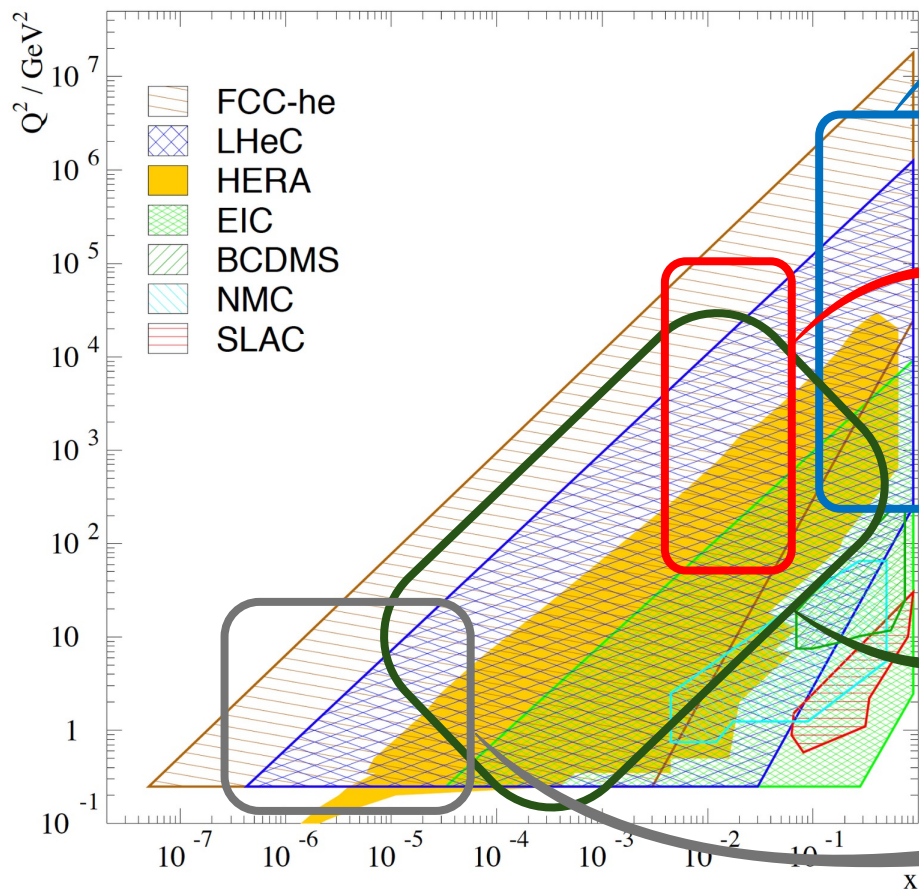
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**non-linear QCD physics**  
a new discovery frontier

## 1.2 TeV ep collisions cover the $(Q^2, x)$ plane → General Purpose Experiment



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### EW, Higgs and top quark physics

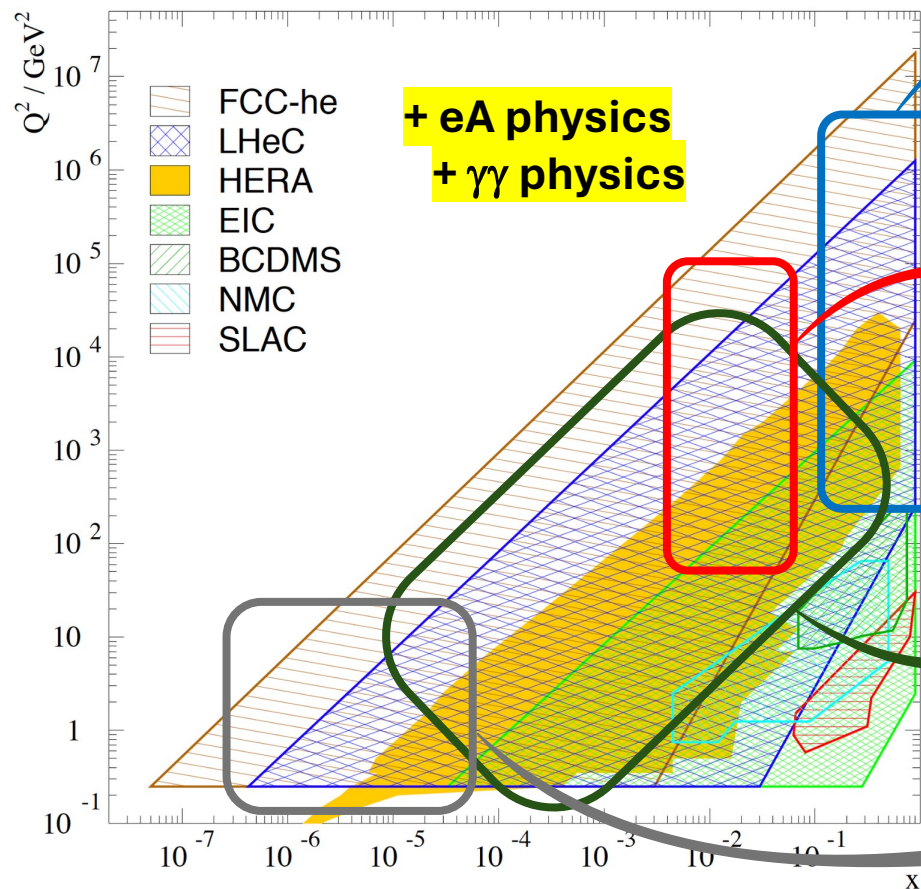
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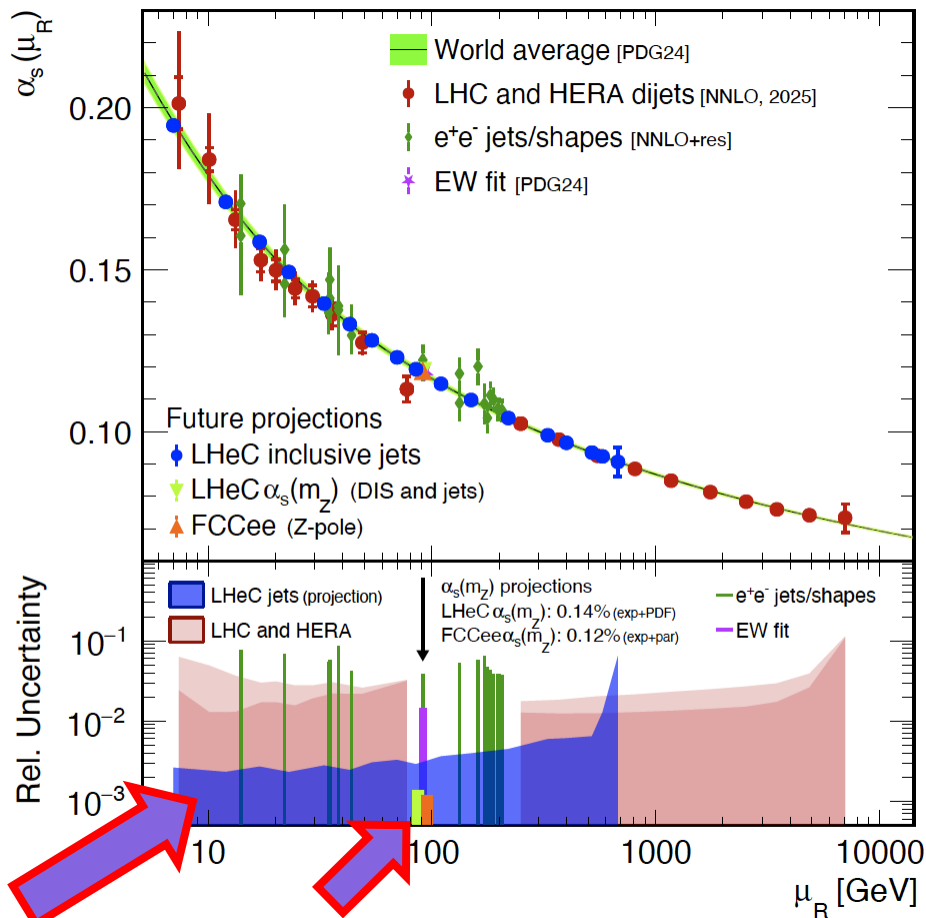
# Some physics highlights: strong coupling constant

## Measurement of a key SM parameter

- $\alpha_s$  value at  $m_Z$ : great relative accuracy of 0.14%
- $\alpha_s$  running: great accuracy over a very wide range of energy scales
- unique opportunity with the LHeC

Figure:

The lower panel displays relative uncertainties on  $\alpha_s(\mu_R)$ , where light-shaded areas show experimental plus theoretical uncertainties and dark shaded areas experimental uncertainties only.





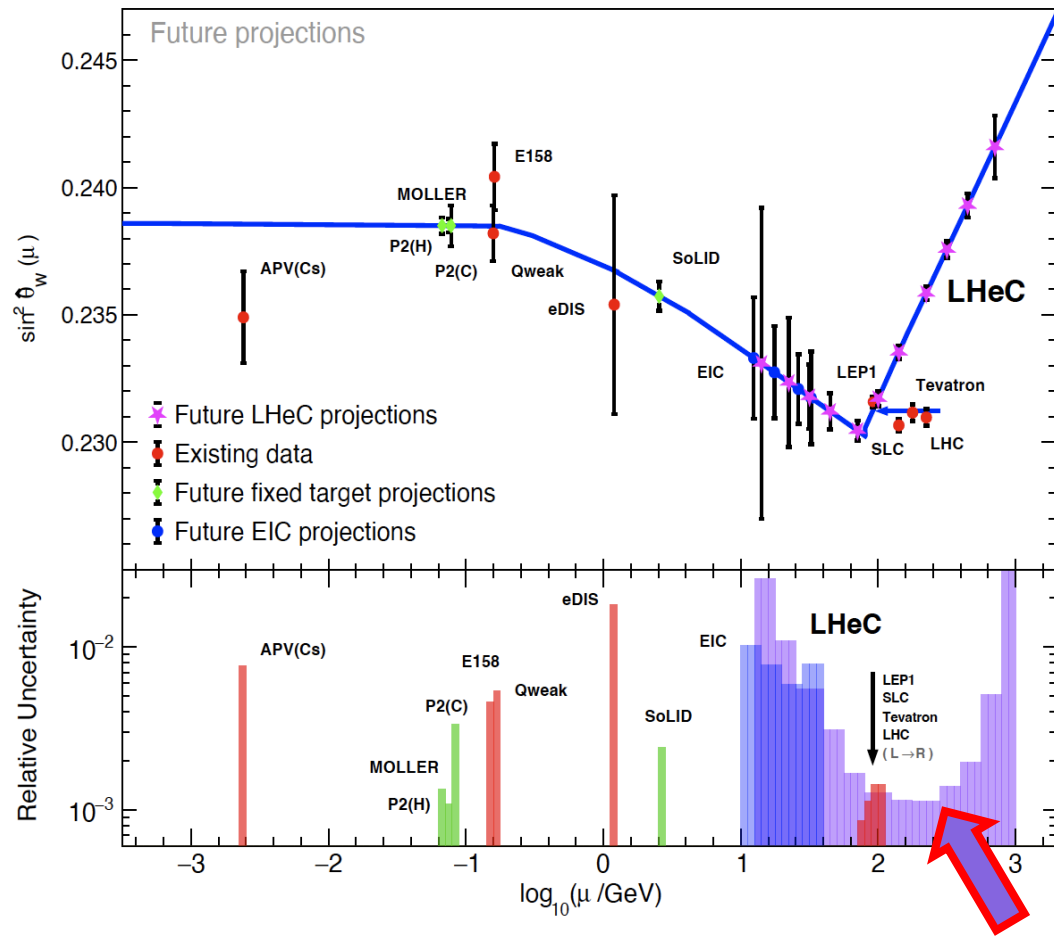
# Some physics highlights: weak mixing angle

## Measurement of a key SM parameter

- $\sin^2\theta_w$  at various scales: great accuracy over a very width range of energy scales
- first time ever
- unique opportunity with the LHeC

Figure:

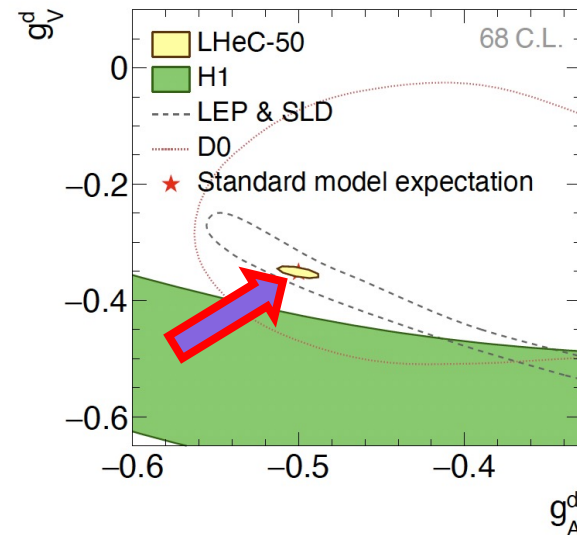
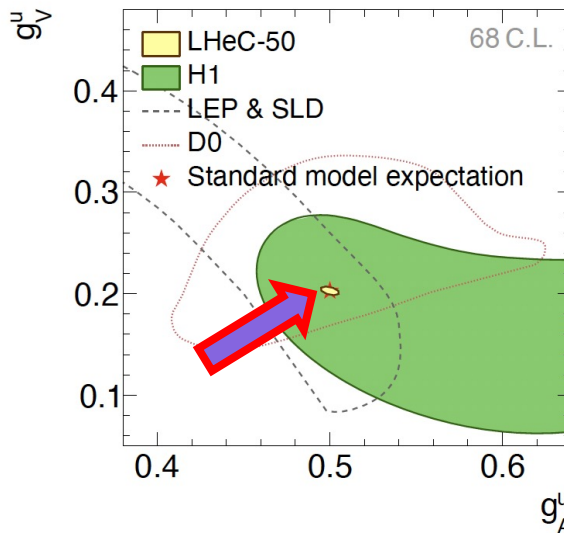
Present and future measurements of the running of the weak mixing angle in the MS scheme and prospected uncertainties as a function of the scale  $\mu$ . The red markers and red uncertainties show present measurements and their relative uncertainties, respectively, and further data points display future projections as indicated.



# Some physics highlights: more Electroweak parameters

Beyond the weak mixing angle, the Z exchange also probes weak Neutral Current couplings of light quarks (u,d) to the Z boson.

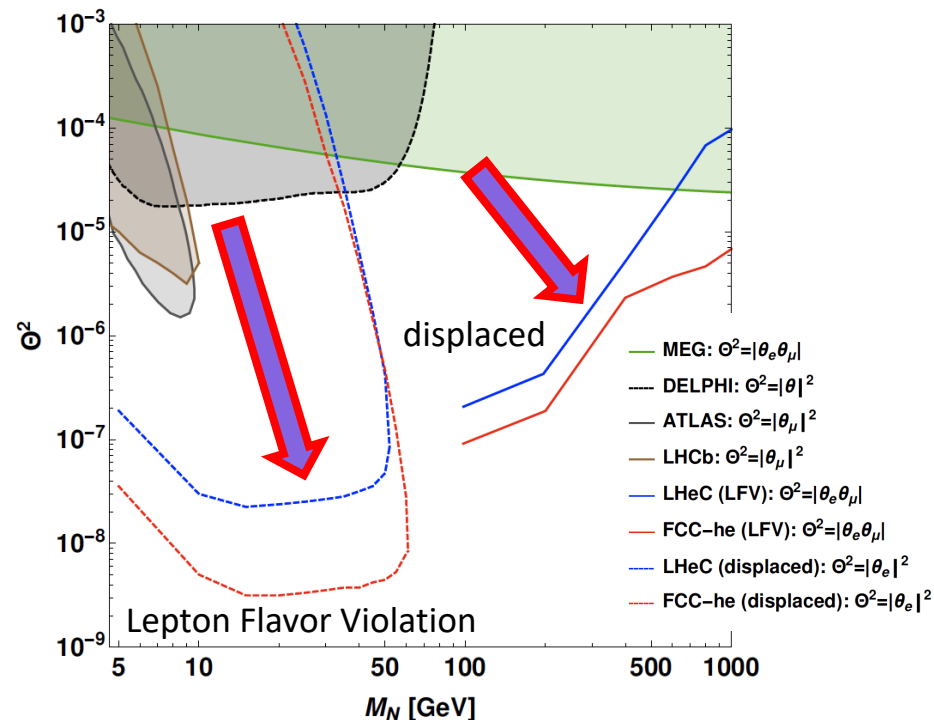
- **Vector and axial-vector couplings to light quarks:** percent level precision
- unique opportunity with the LHeC



# Some physics highlights: searches for Heavy Neutrinos

At the LHeC **Heavy Neutrinos** can be produced via charged current interactions, with cross sections dependent on the active-sterile mixing parameter  $|\theta_e|^2$ .

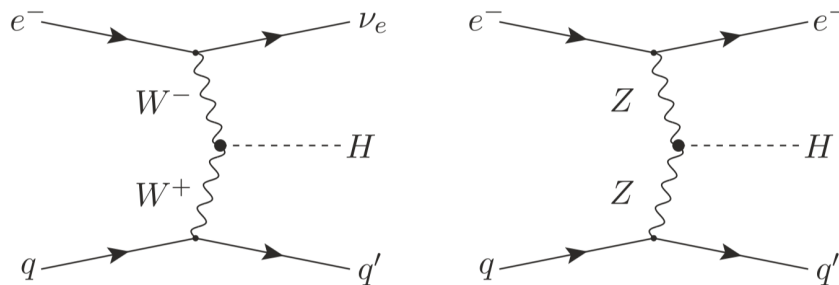
The most promising channels involve Lepton Flavor Violation (LFV) and displaced vertices for which the discovery reach is illustrated in the coupling versus mass plane in the figure, with the full and dashed lines respectively.



# Some physics highlights: Higgs physics

The LHeC is partially a **Higgs Factory** with several couplings significantly improved over HL-LHC expectations, and combines well with LEP3.

- first time ever:  
 $\kappa_c$
- greatly improved:  
 $\kappa_b, \kappa_W, \kappa_Z$
- significantly improved:  
 $\kappa_t, \kappa_\tau, \kappa_g$



200k Higgses @ LHeC



# Some physics highlights: Higgs physics

The LHeC is partially a **Higgs Factory** with several couplings significantly improved over HL-LHC expectations, and combines well with LEP3.

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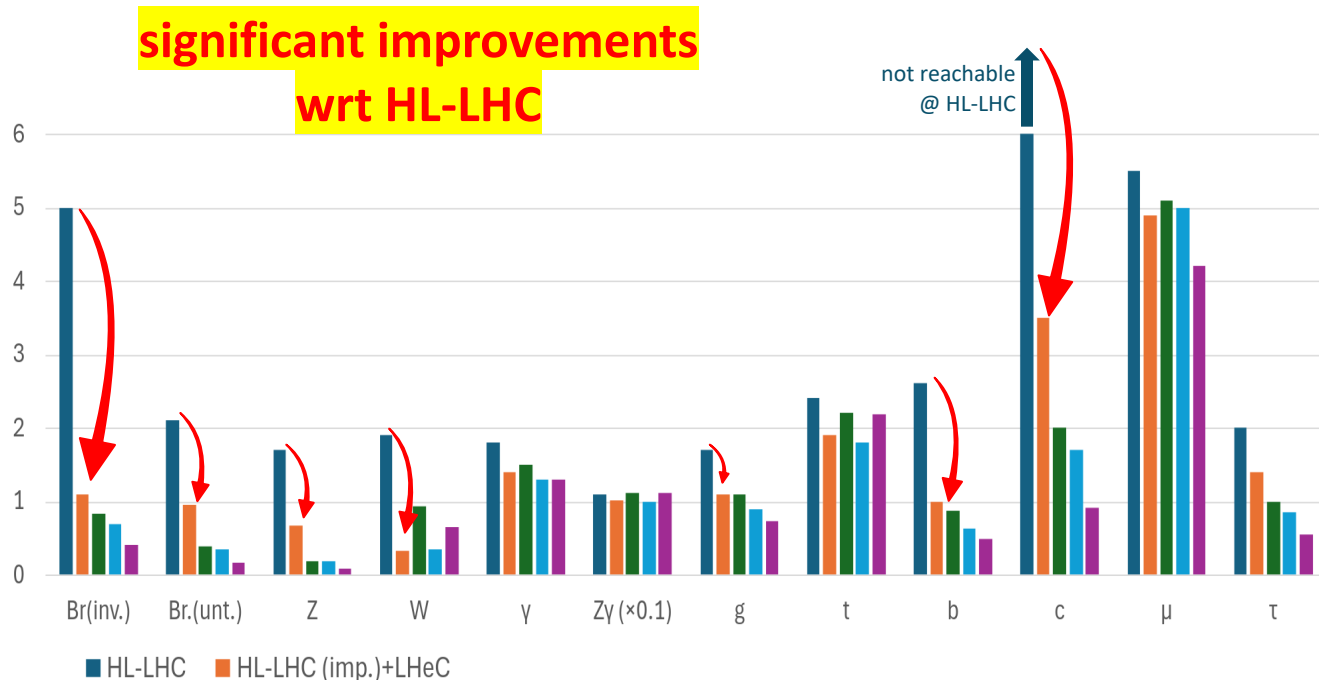


Figure:  
The relative uncertainty on the coupling modifiers obtained in the kappa-3 SMEFiT framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and  $\alpha_s$  from the LHeC), LHeC, LEP3 and FCC-ee.

for hadron-hadron and hadron-lepton: impose  $|\kappa_V| < 1$

many thanks to the SMEFiT authors (esp. Simone Tentori), 2105.00006

# Some physics highlights: Higgs physics

The LHeC is partially a **Higgs Factory** with several couplings significantly improved over HL-LHC expectations, and **combines well with LEP3**.

- first time ever:  
 $K_C$
- greatly improved:  
 $K_b, K_W, K_Z$
- significantly improved:  
 $K_t, K_\tau, K_g$

**LHeC combines well with LEP3**

wrt FCCee(240)

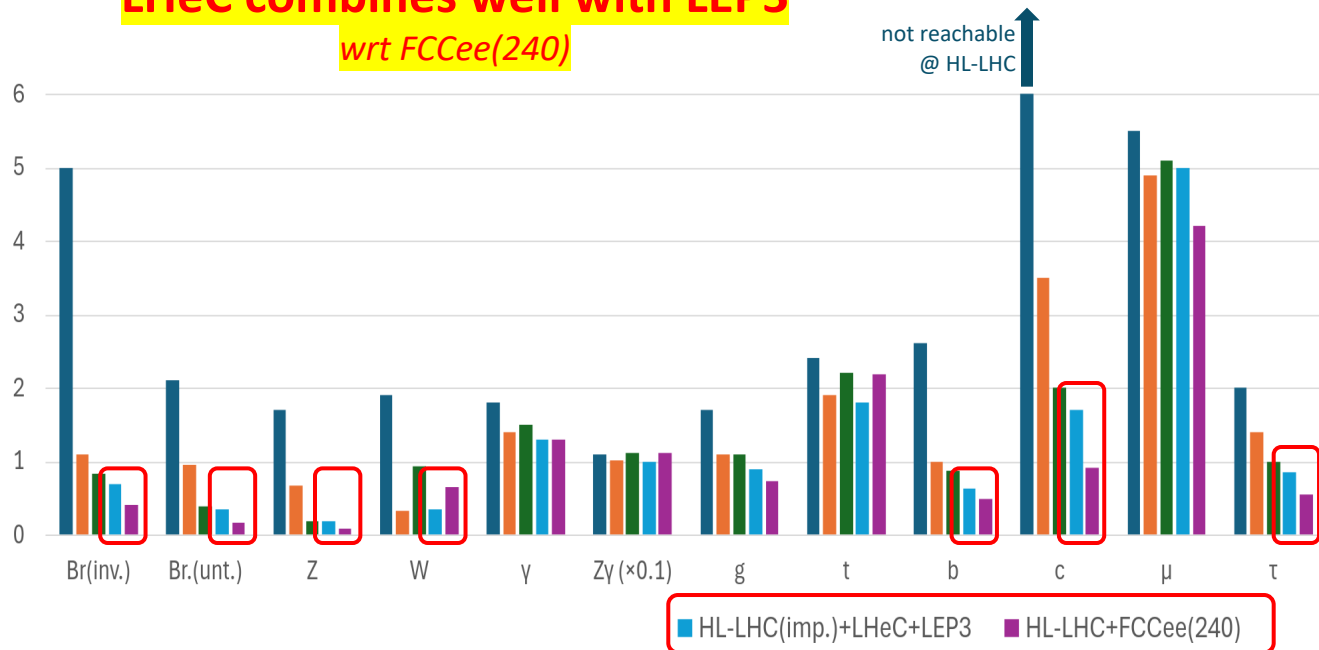


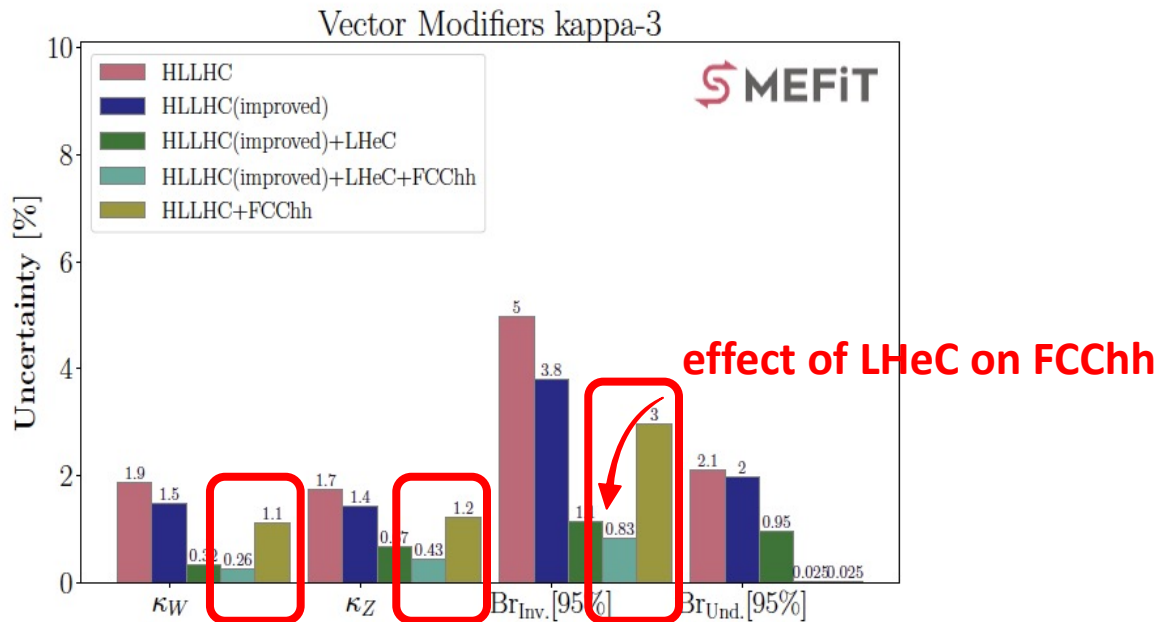
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# Some physics highlights: Higgs physics

LHeC data is essential to unlock the full potential of FCC-hh

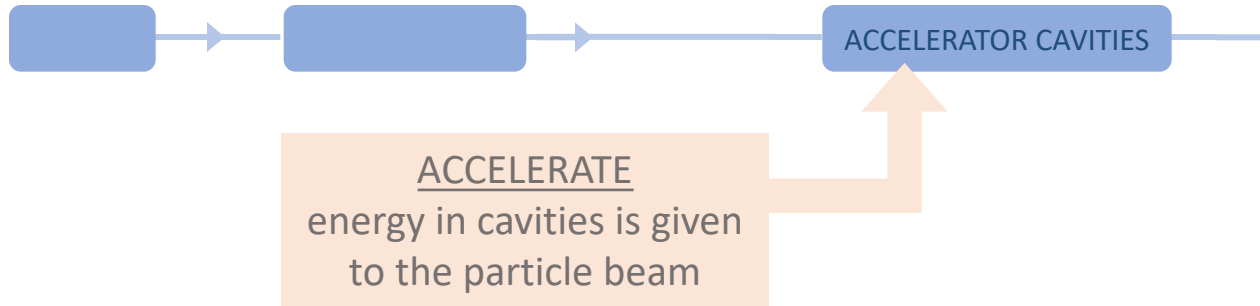
example



## Key accelerator technology for the LHeC

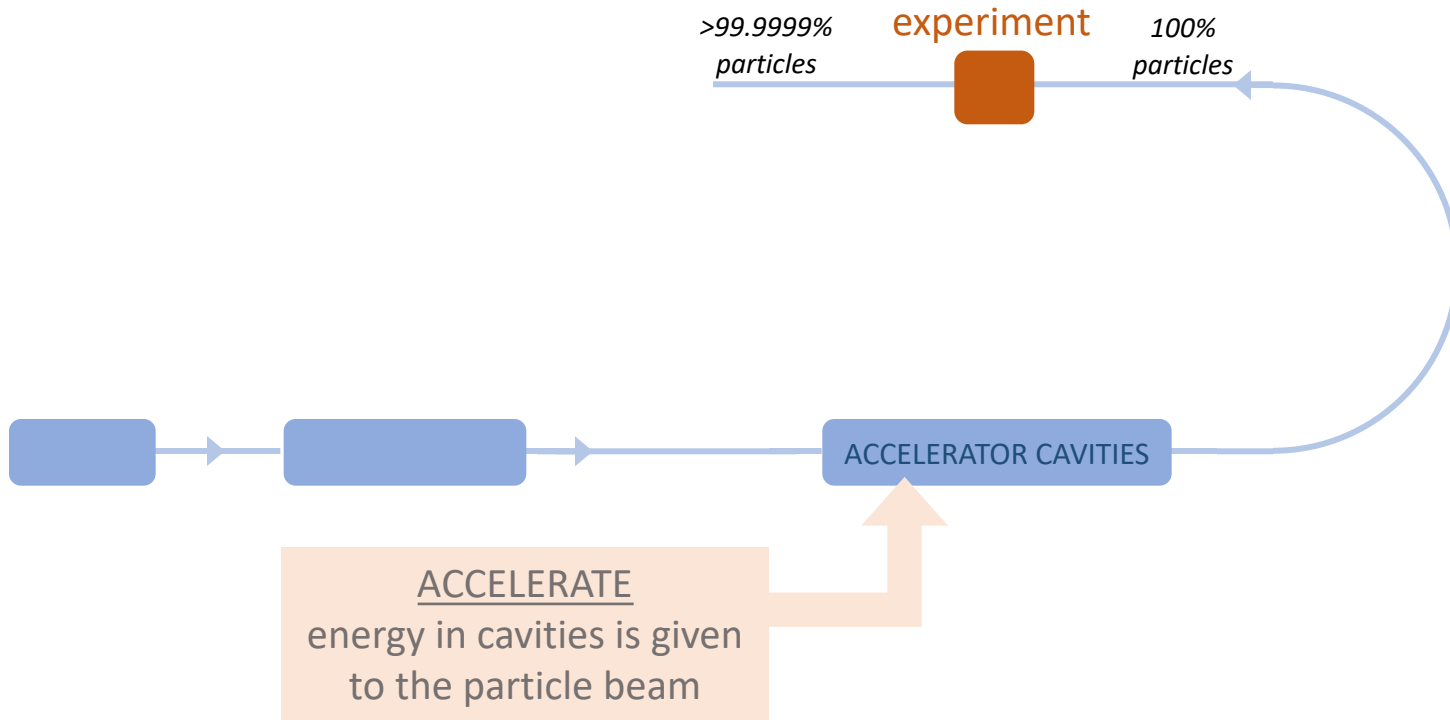
*operate a 1000 MW electron beam with only 100 MW of power  
need to use the Energy Recovery Linac technology*

# The principle of Energy Recovery

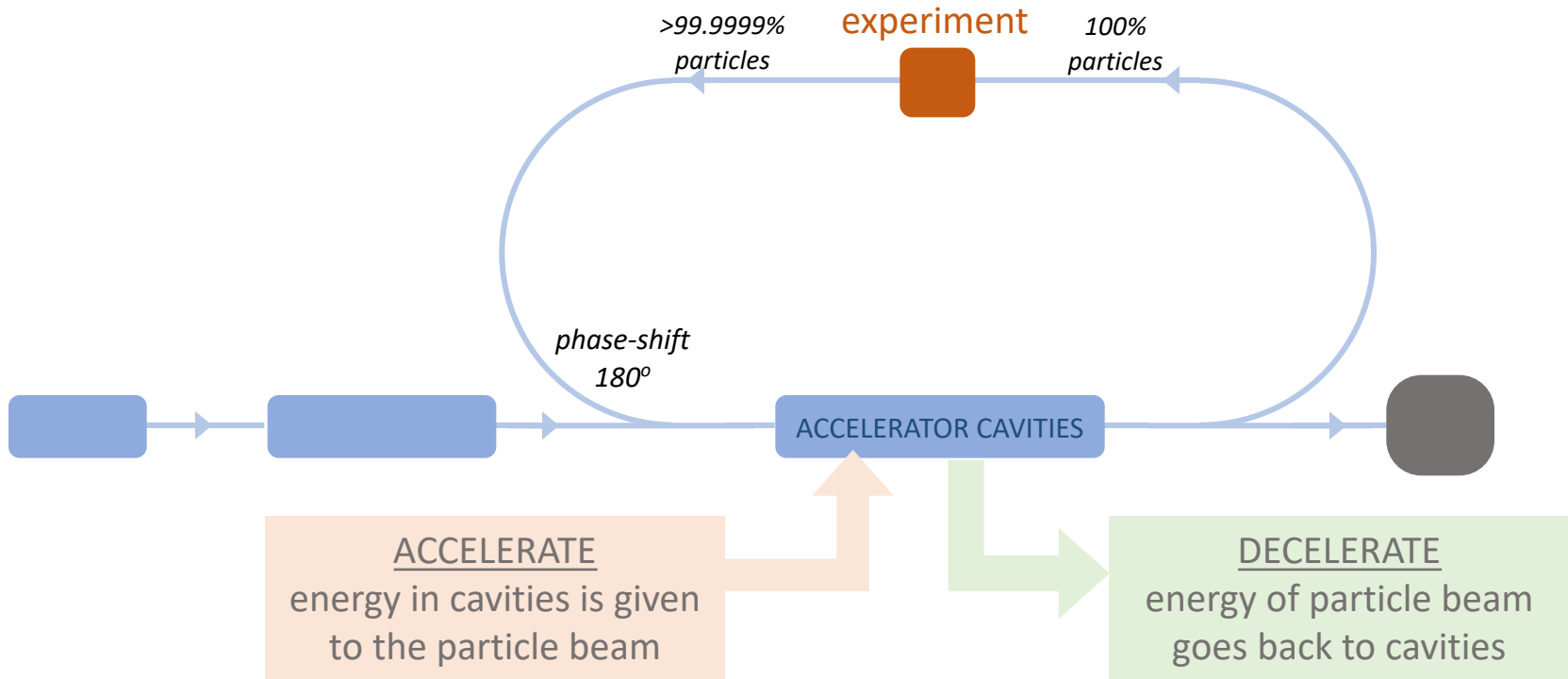




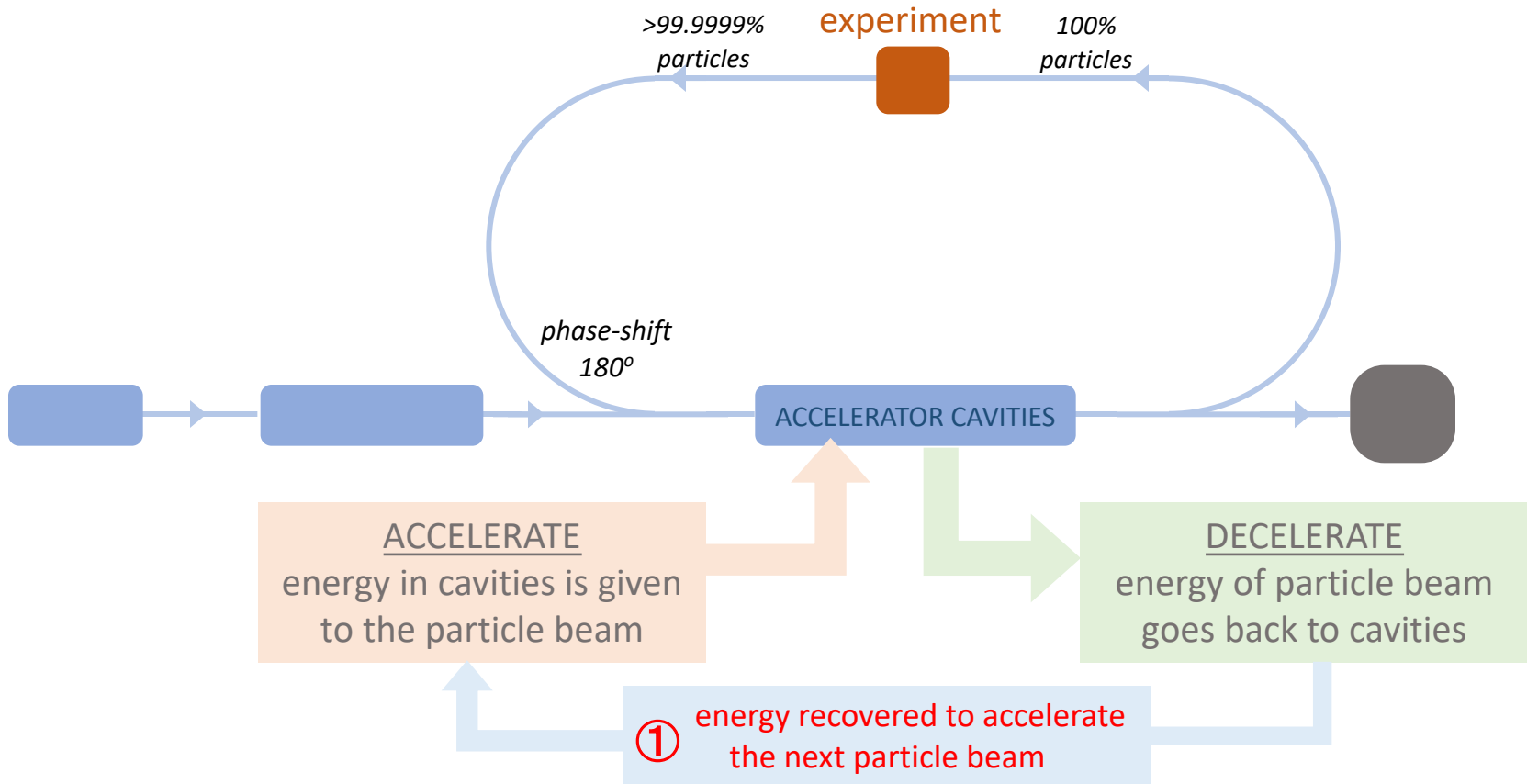
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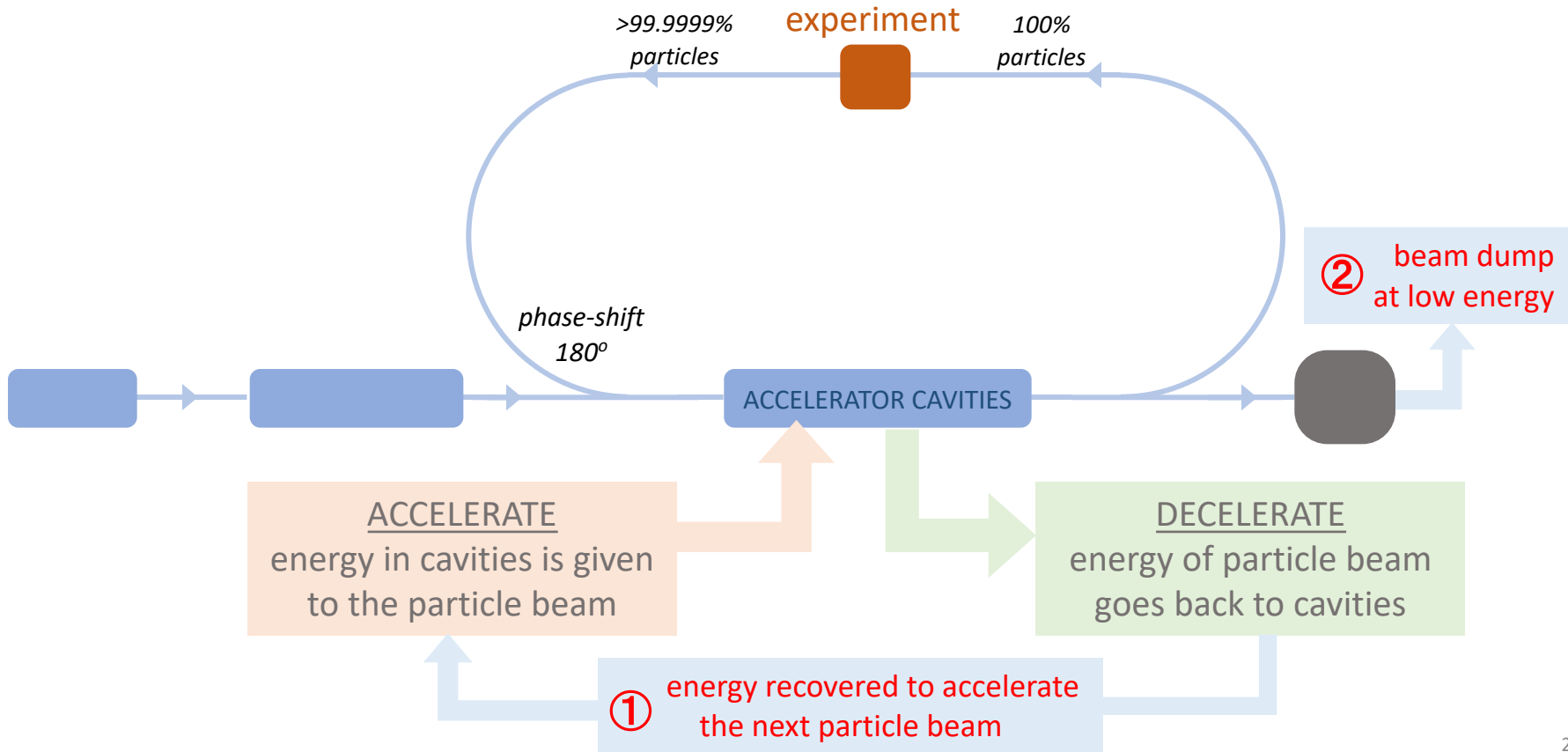
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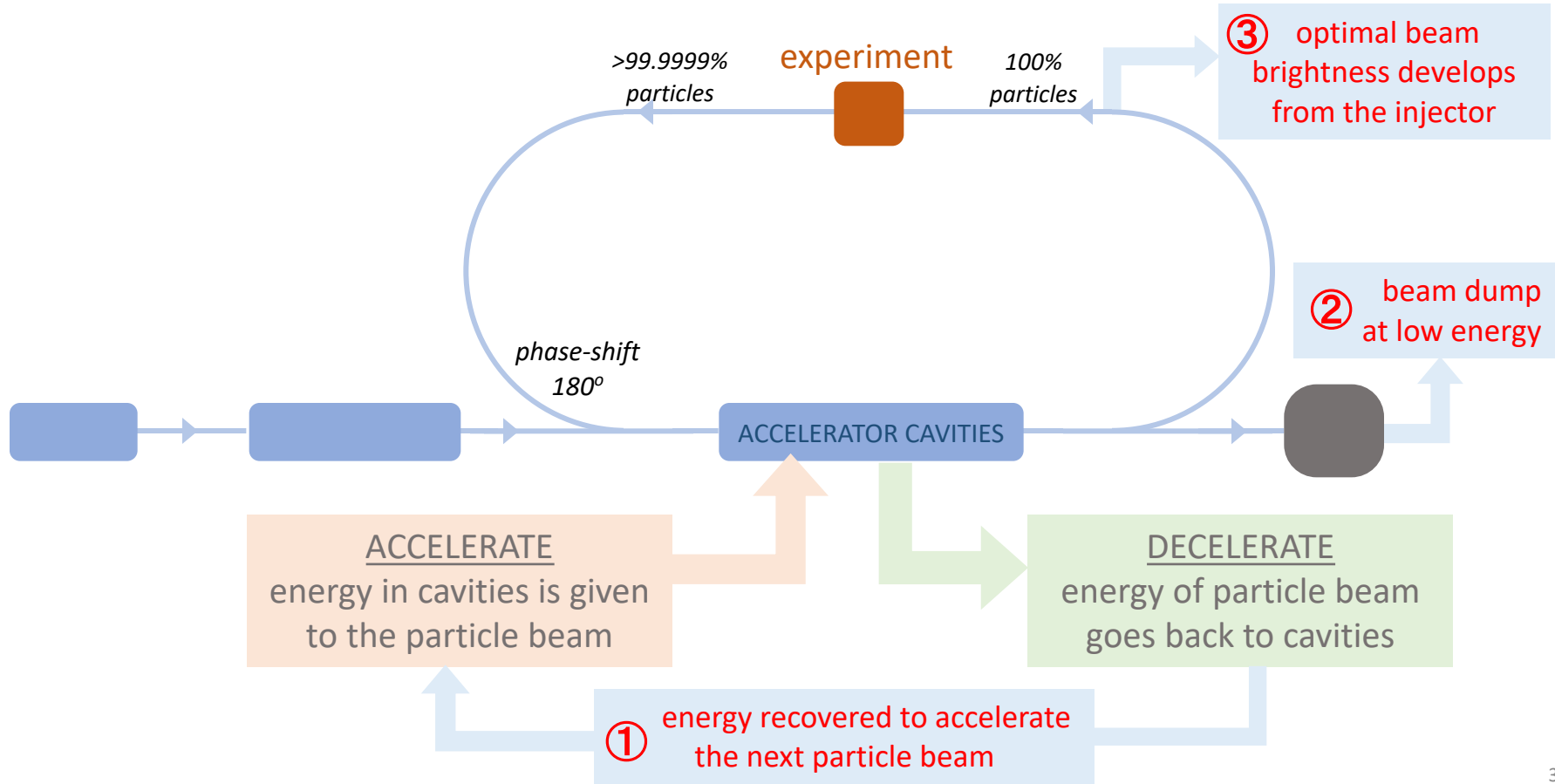
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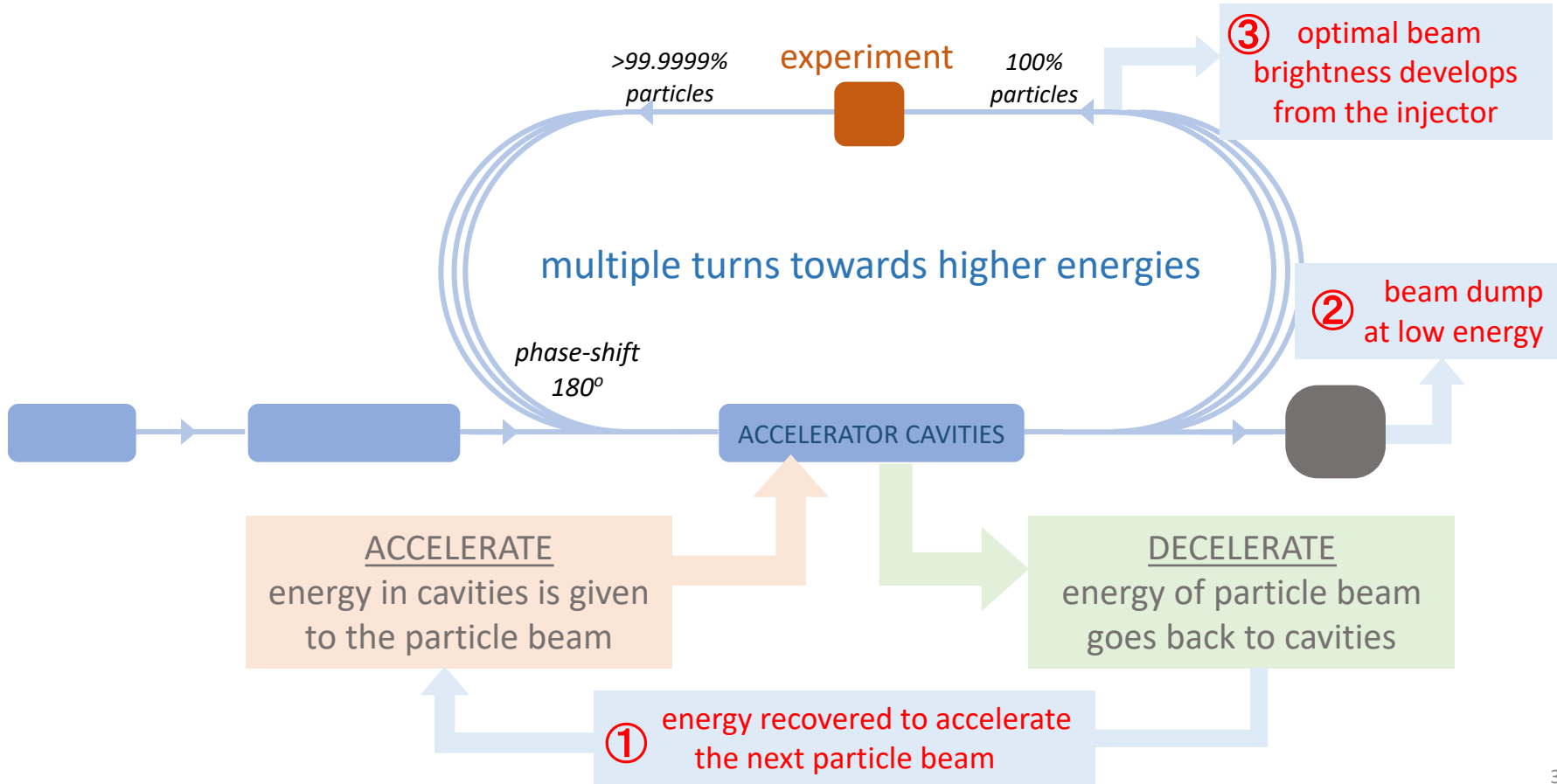
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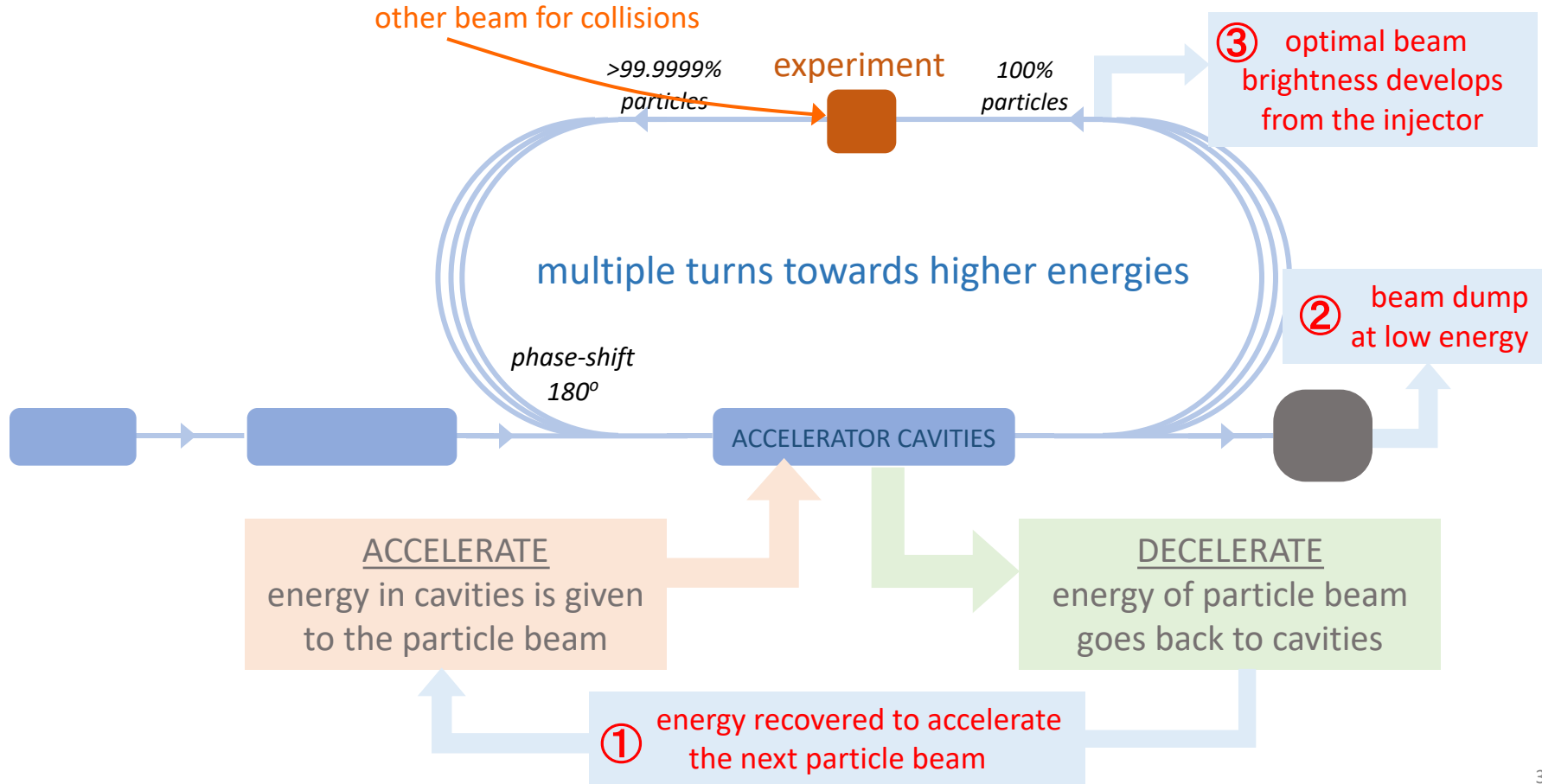


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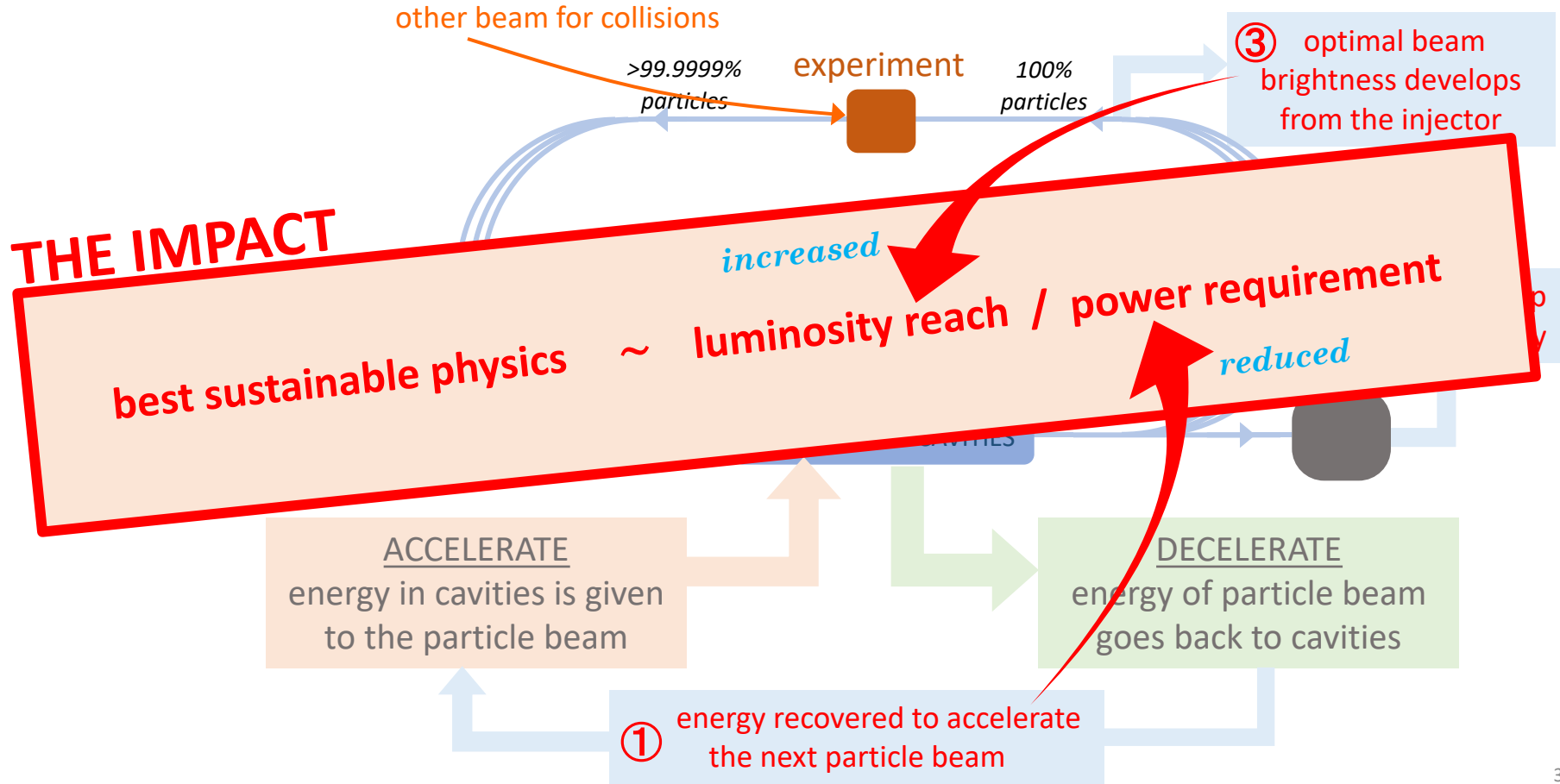


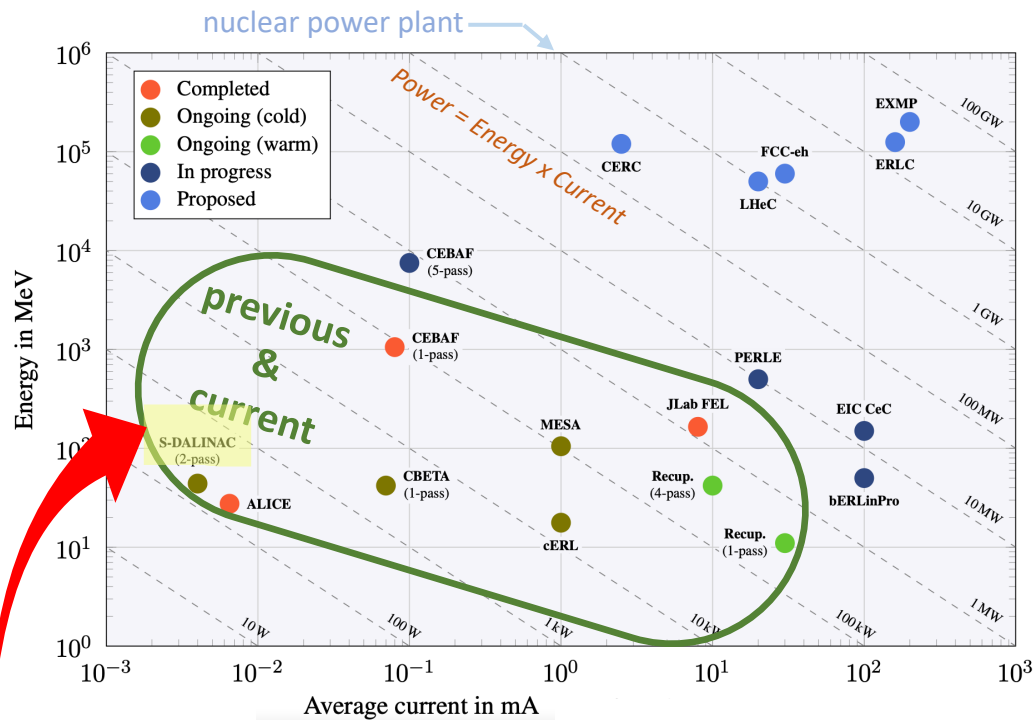


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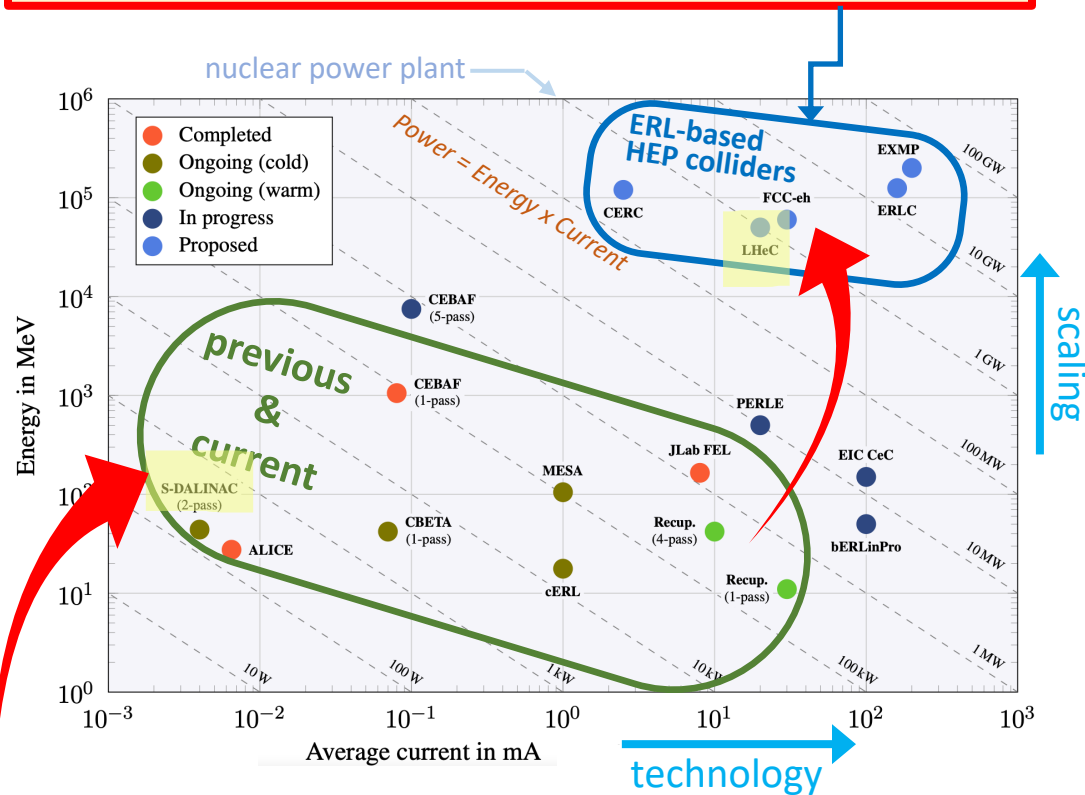


## Energy Recovery demonstrated

great achievements on all aspects  
and large research infrastructures  
based on Energy Recovery systems  
have been operated successfully

multi-turn ERL with SRF achieved, [Nature Physics](#) volume 19, pages 597–602 (2023)

**ERL to enable high-power beams that would otherwise require one or more nuclear power plants**



**Future ERL-based Colliders**

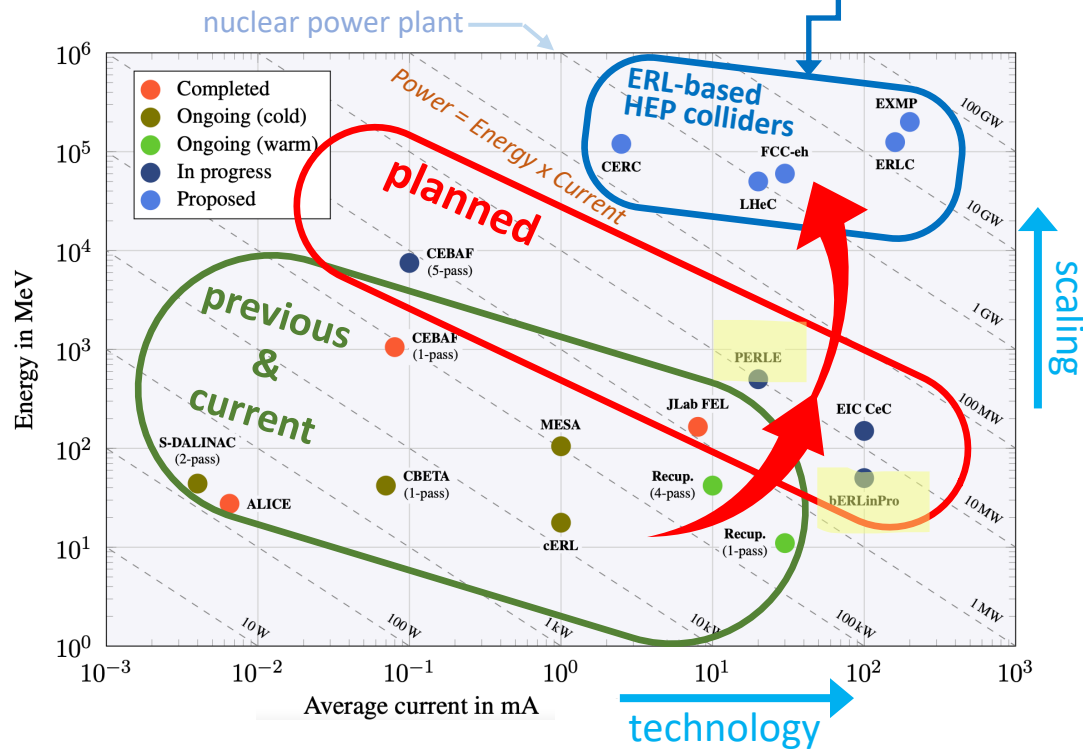
*H, HH, ep/eA, muons, ...*

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## Future ERL-based Colliders

*H, HH, ep/eA, muons, ...*

## bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

*towards high power*

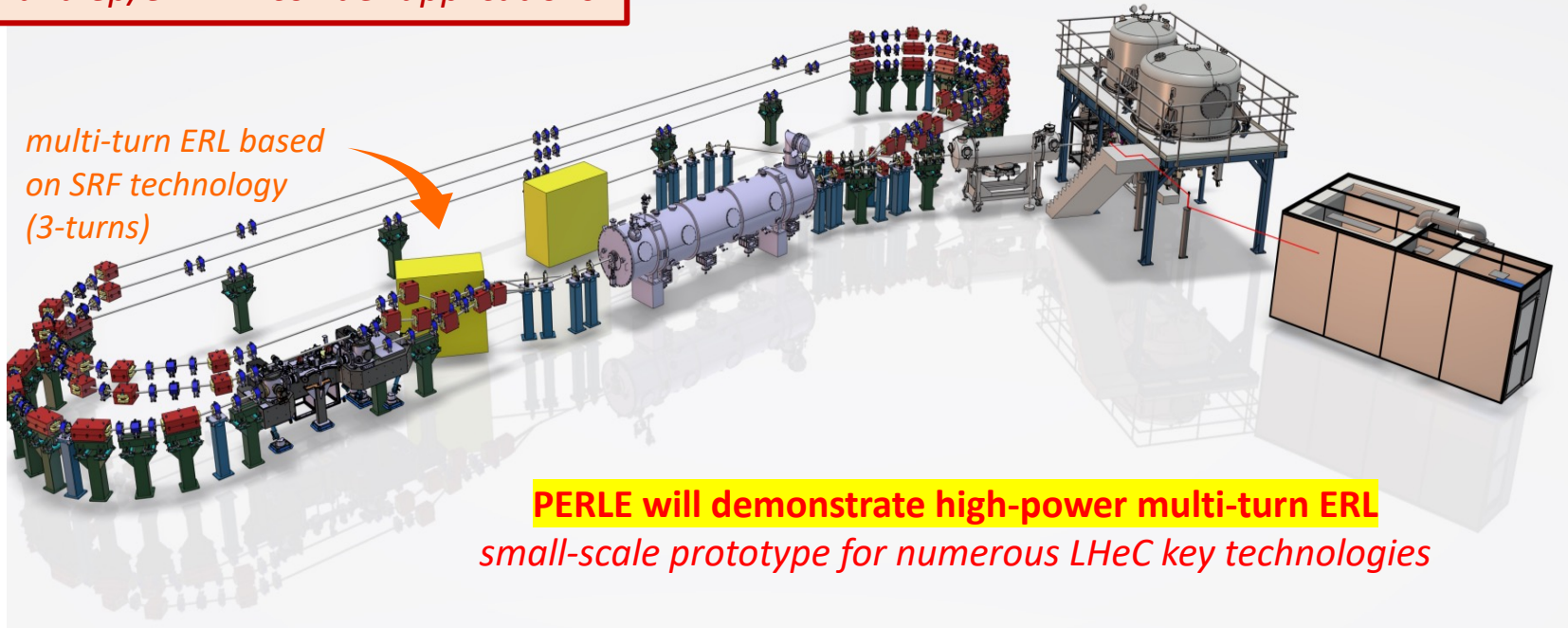
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# PERLE @ IJCLab (IN2P3) Orsay

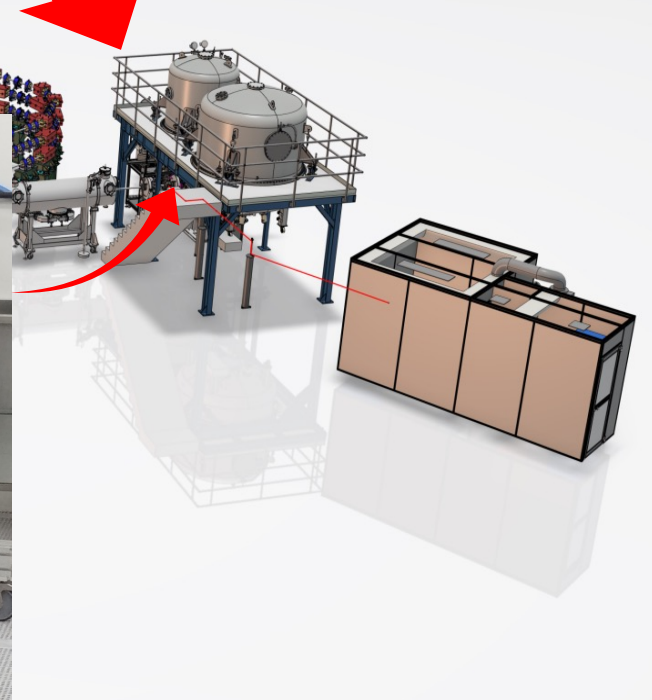
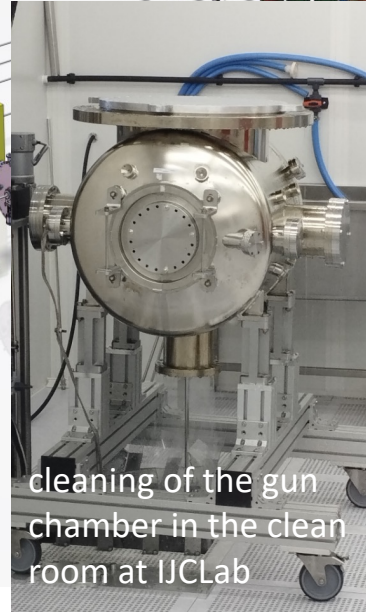
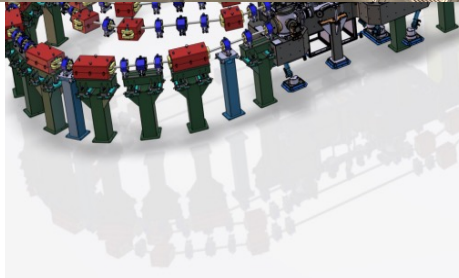
- *growing international collaboration*
- *design, build and operation this decade*
- *for  $e^+e^-$  and  $ep/eA$  HEP collider applications*

*multi-turn ERL based  
on SRF technology  
(3-turns)*



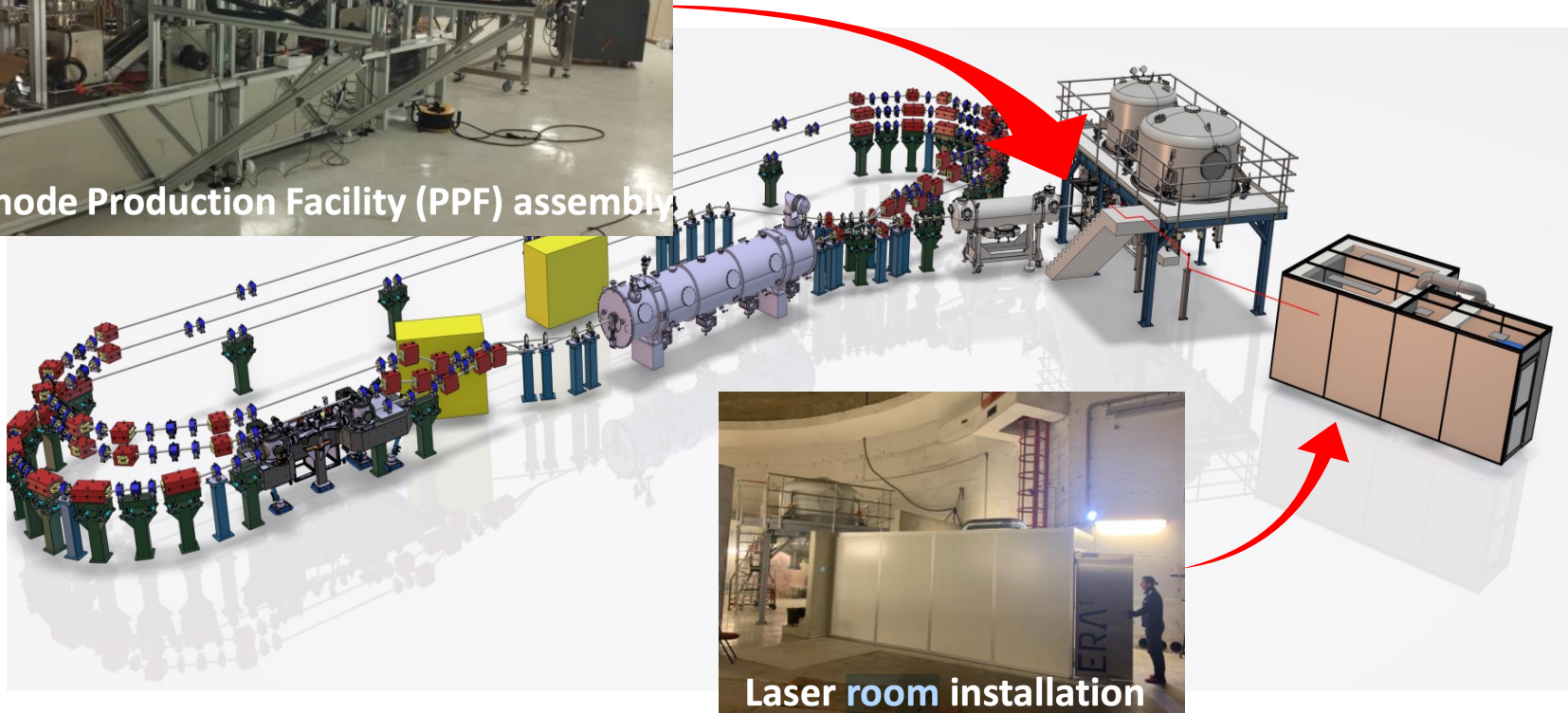
**PERLE will demonstrate high-power multi-turn ERL**  
*small-scale prototype for numerous LHeC key technologies*

# From drawings to reality with PERLE

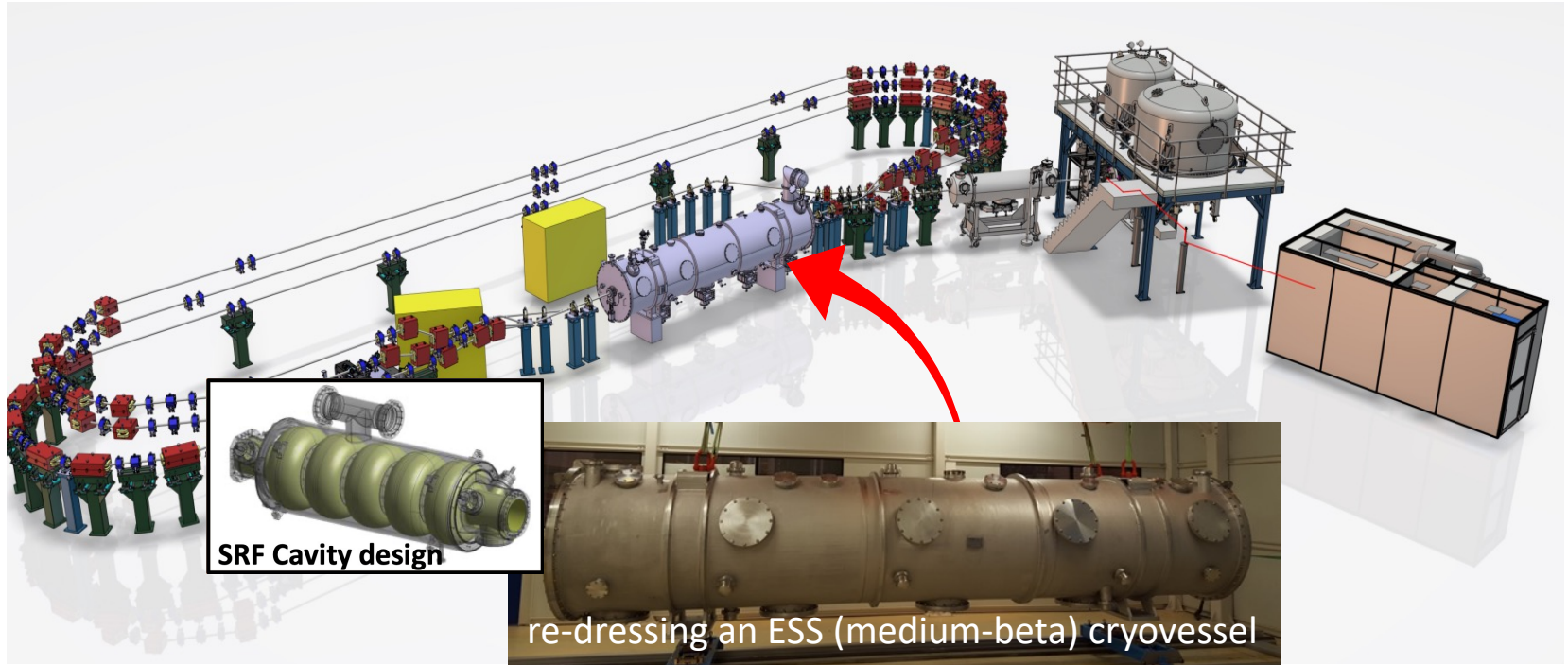




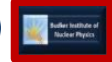
# From drawings to reality with PERLE



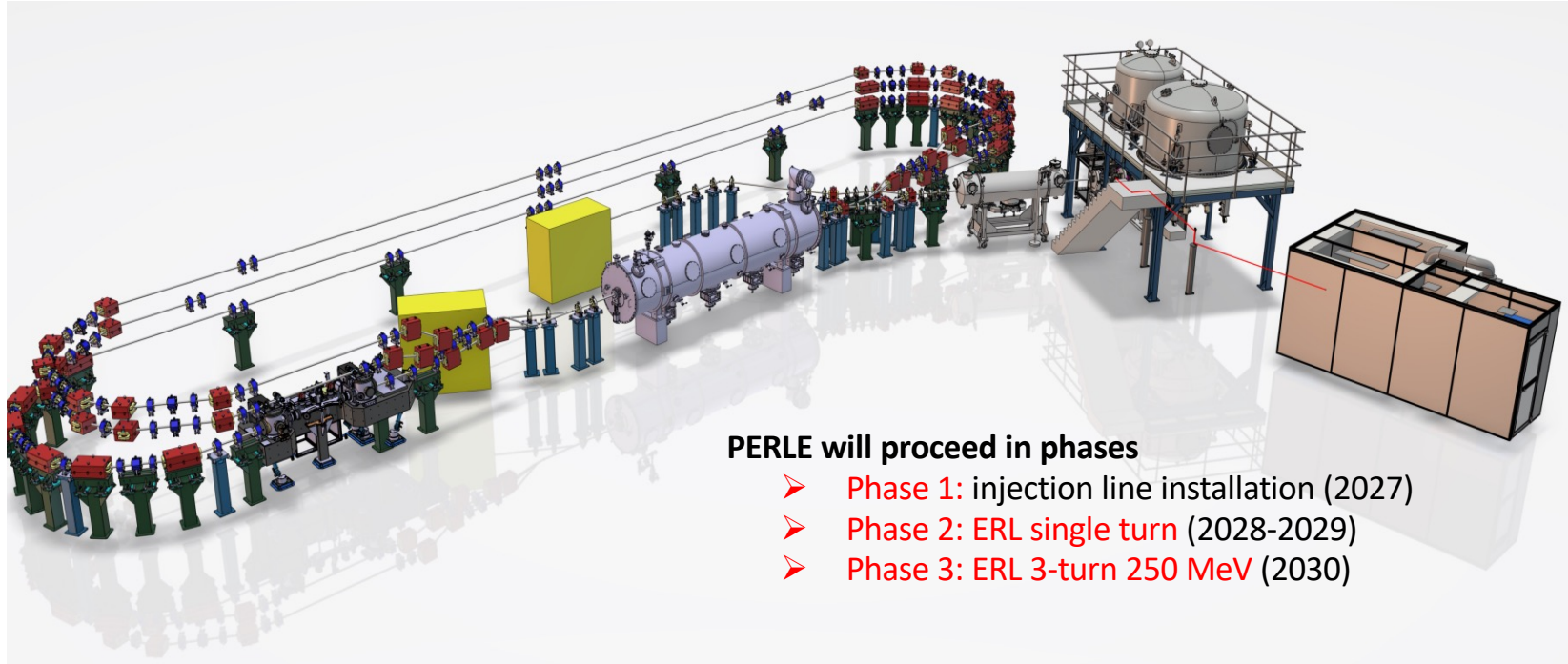
# From drawings to reality with PERLE



# From drawings to reality with PERLE



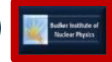
+ Contributions through iSAS of



## PERLE will proceed in phases

- Phase 1: injection line installation (2027)
- Phase 2: ERL single turn (2028-2029)
- Phase 3: ERL 3-turn 250 MeV (2030)

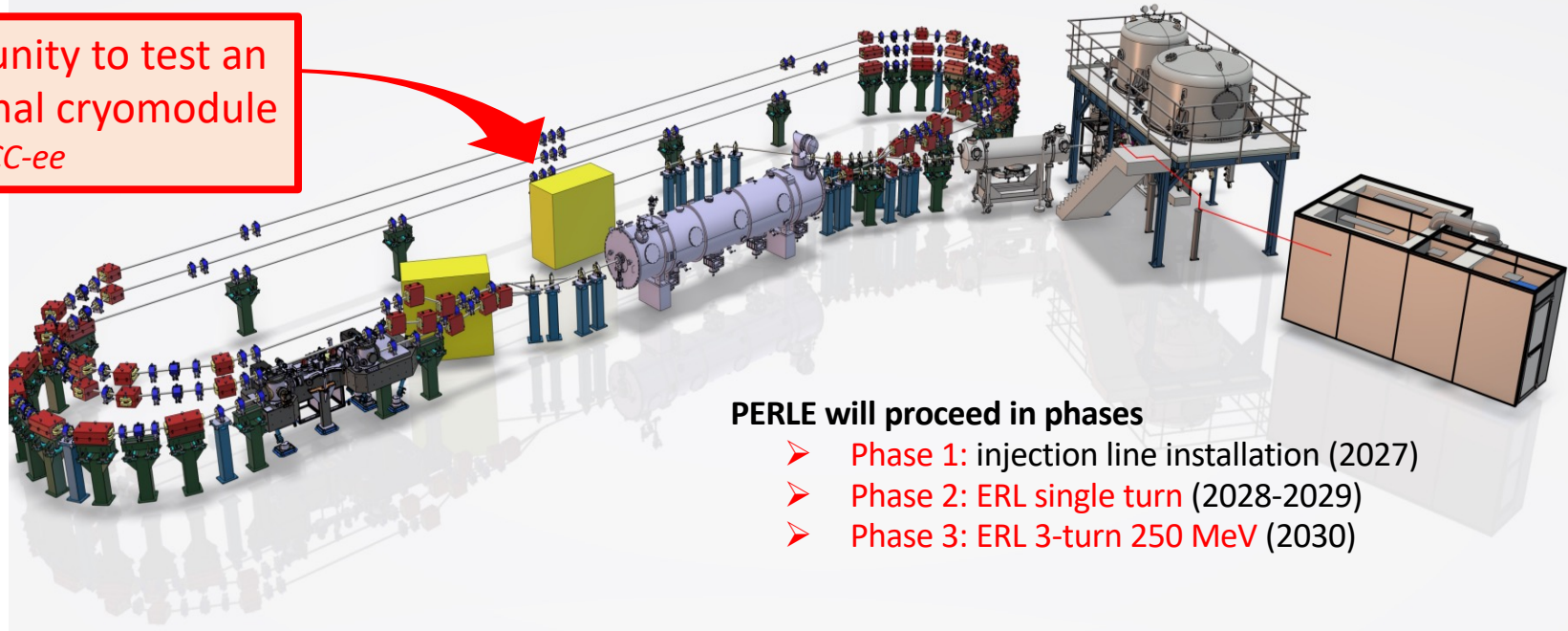
# From drawings to reality with PERLE



+ Contributions through iSAS of



opportunity to test an  
additional cryomodule  
*e.g. for FCC-ee*



**PERLE will proceed in phases**

- Phase 1: injection line installation (2027)
- Phase 2: ERL single turn (2028-2029)
- Phase 3: ERL 3-turn 250 MeV (2030)



## Accelerator R&D review – ERL part

“The readiness of ERLs for deployment in a large-scale facility (LHeC) is that with requested resources it is likely that high TRLs can be achieved for systems in time for a decision in 2034.”

| Platform                         | High Field Magnets                | High Grad Struct/Syst                                                                      | High Grad Plasma/Laser                                         | Muon Beams & Colliders | Energy Recovery Linac                                                                              |
|----------------------------------|-----------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------------------------|------------------------|----------------------------------------------------------------------------------------------------|
| R&D Scope Definition             |                                   | OK at high level,<br>Too many sub-goals,<br>many not well defined                          | “Staging” test facility is critical                            |                        | Need to be expanded to Multi-GeV issues (synchrotron radiation)                                    |
| R&D Schedule                     | Too slow                          | Many tasks behind schedule, many subtasks lack well defined schedule.                      |                                                                |                        | Resources missing.                                                                                 |
| R&D cost                         | Not using all resources available | Top level FTE and resources consistent with plan. Infrastructure needs not as well defined |                                                                |                        | Understood                                                                                         |
| Integration within the Labs (??) | Process needed to down-select     | Good communication at the WG level.                                                        | Integration of HALHF in the roadmap and the community unclear. | RF has to start        | Very good integration between participating labs and overarching to RF pillar (prime example iSAS) |
|                                  |                                   |                                                                                            |                                                                |                        |                                                                                                    |
| Overall Confidence Level         |                                   | Progress on many fronts.                                                                   |                                                                | In the long run....    | On a good road to demonstrate LHeC feasibility for a decision in 2034.                             |

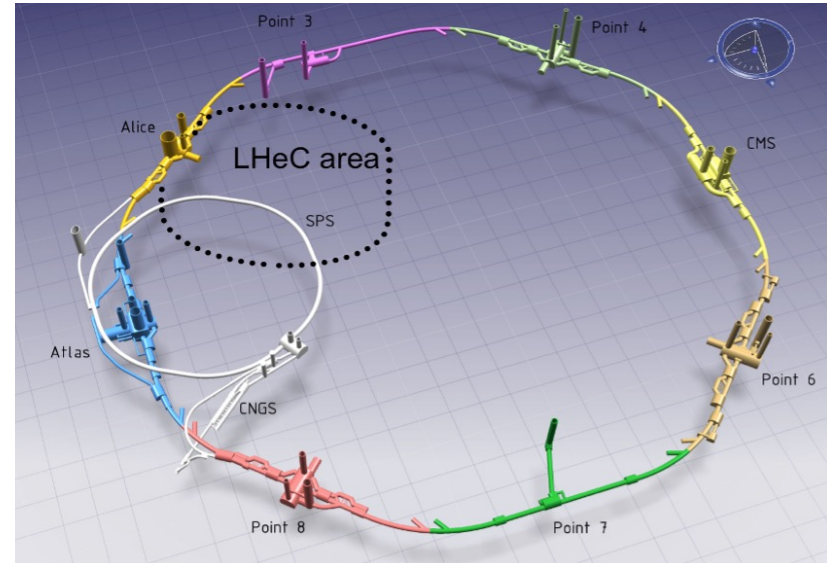
# LHeC – implementation and operational costs

## Implementation

- The new LHeC tunnel is 8.9 km
- Civil engineering works mostly during HL-LHC operations, plus one dedicated year to connect the LHeC with HL-LHC
- Optimal placement can be in function of the future Higgs factory (and potentially the Forward Physics Facility)
- Total cost of civil engineering and accelerator was estimated to be 1.6 BCHF anno 2018 (→ 2 BCHF today)
- Personpower equivalent to HL-LHC implementation (~2500 person years)

## Operation

- Power is 220 MW (including LHeC, detector and dedicated HL-LHC operation)
- 200 days of running → 1.06 TWh/year (+27MCHF per year compared to nominal HL-LHC)
- eA runs can be integrated
- Personpower for dedicated LHeC runs (1 detector, 1 proton beam, ERL) equivalent to nominal (HL-)LHC (4 detectors, 2 proton beams); ~120MCHF/y in CERN MTP (materials+people)

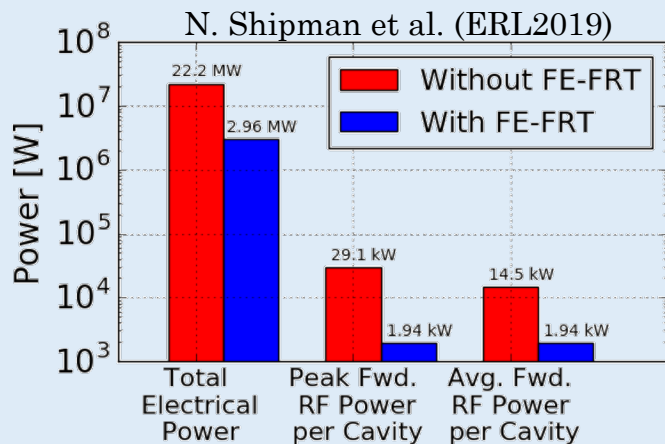


| LHeC construction planning  | YEAR 1 | YEAR 2 | YEAR 3 | YEAR 4 | YEAR 5 | YEAR 6 | YEAR 7 |
|-----------------------------|--------|--------|--------|--------|--------|--------|--------|
| Land negotiations           |        |        |        |        |        |        |        |
| Environmental Impact Study  |        |        |        |        |        |        |        |
| Building permits            |        |        |        |        |        |        |        |
| Detailed design & tendering |        |        |        |        |        |        |        |
| Construction                |        |        |        |        |        |        |        |

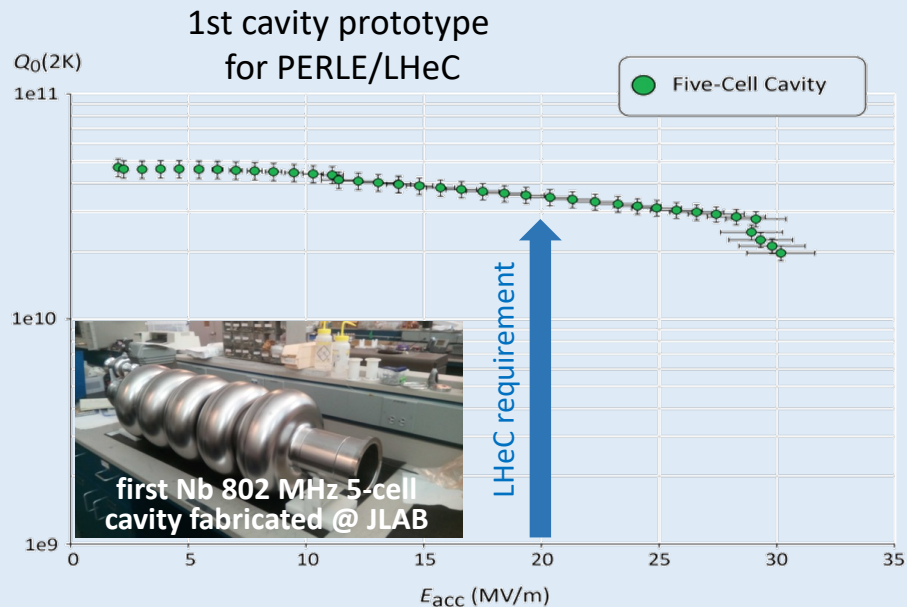
# Opportunities for improved performance



Innovate for  
Sustainable  
Accelerating  
Systems



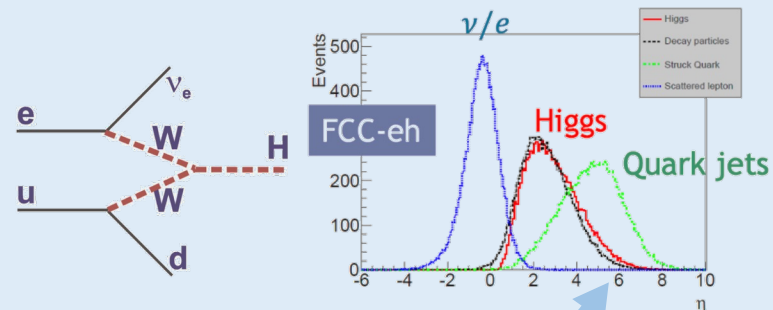
Ferro-Electric Fast Reactive Tuners for 20MW less power requirements to deal with microphonics



LHeC can be done with state-of-the-art SRF and significant room for improvements

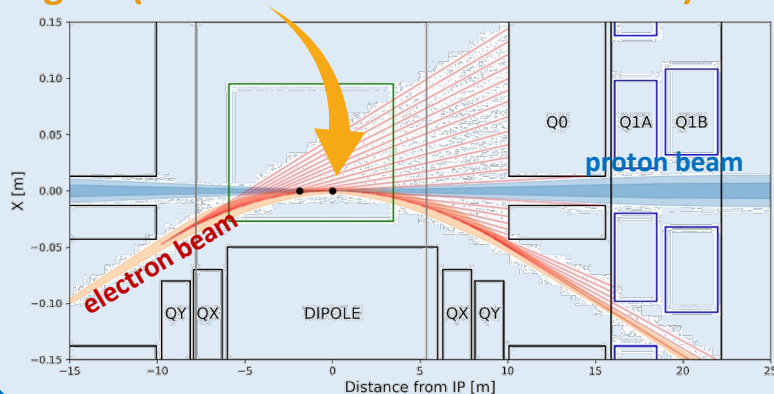


# LHeC detector



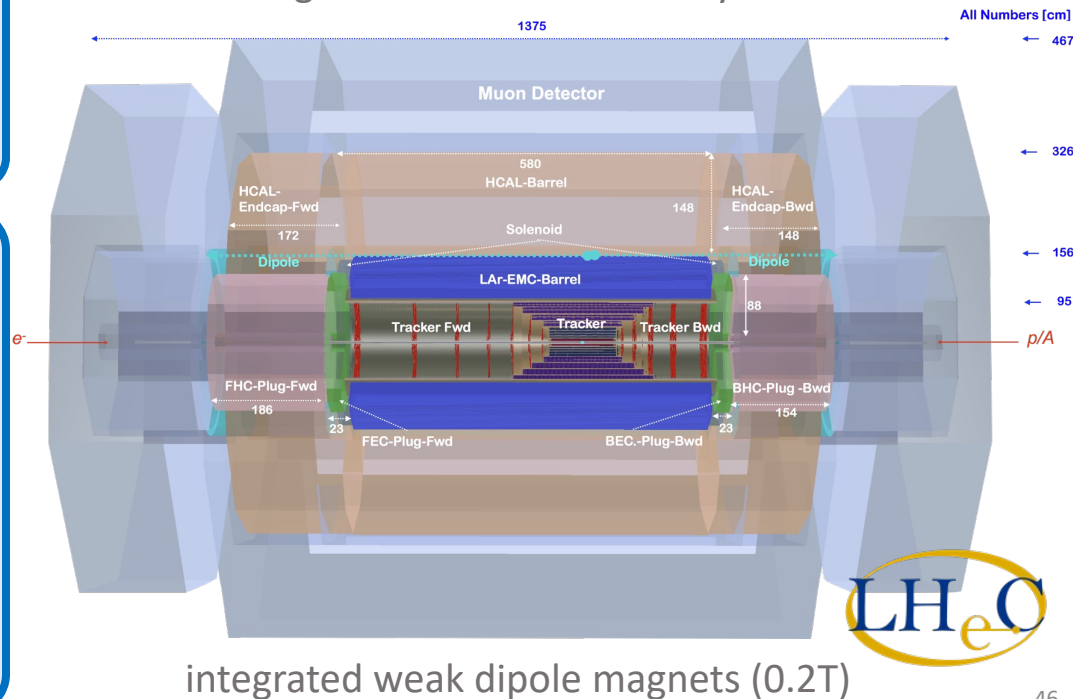
Forward jet reconstruction

Synchrotron radiation in the interaction region (reduced to a comfortable 6kW)



major features:

- 1<sup>o</sup> close to the beamline (hermiticity)
- Tracking & Vertexing
- High-resolution calorimetry



integrated weak dipole magnets (0.2T)

# LHeC detector

mostly ready to be built

Preliminary cost of 360MCHF

Central Tracker

Calorimetry (3/4 of cost)

Muon System

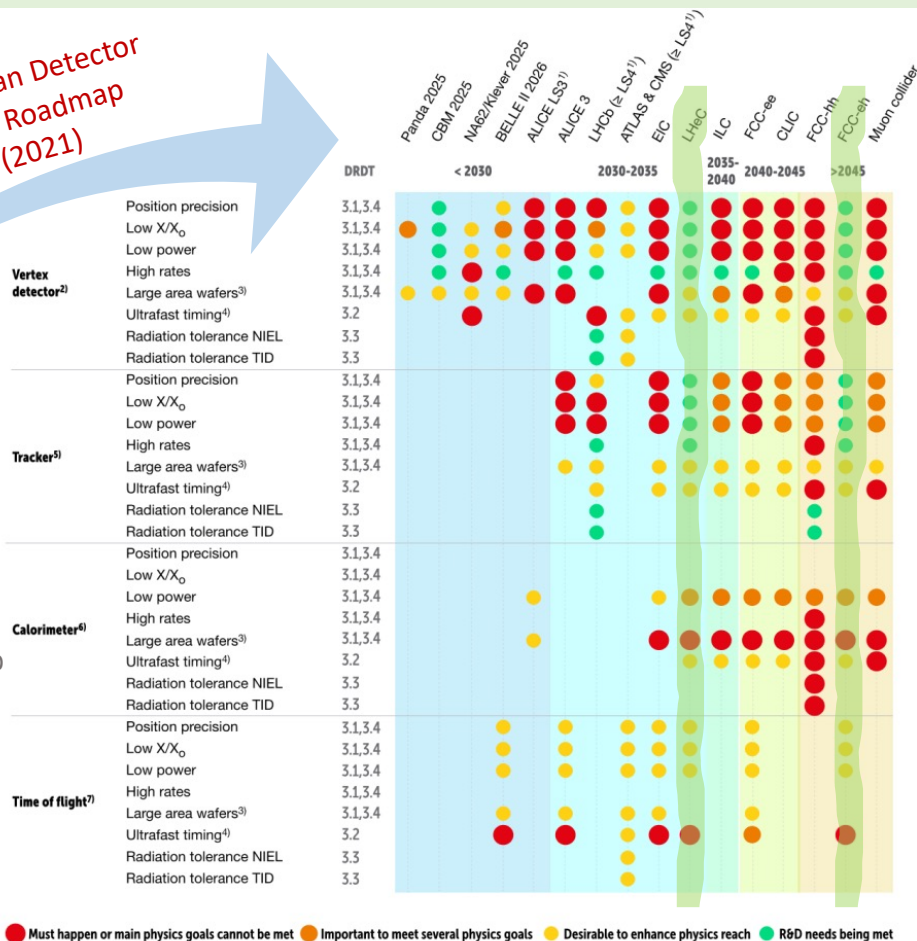
cost reductions are possible  
e.g. sampling fraction, granularity,  
reuse of LHC detectors

synergies with other projects  
stepping stones

potentially re-use LHC detectors or one detector for a  
joint DIS and Heavy-Ion program @ HL-LHC

European Detector  
R&D Roadmap  
(2021)

Detector Requirements  
e.g. Solid State Devices

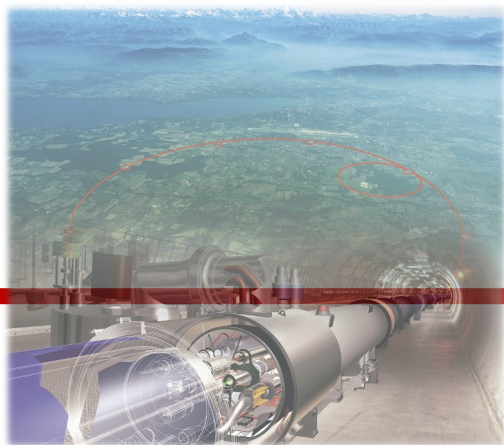


## How does the LHeC fits into the collider landscape?

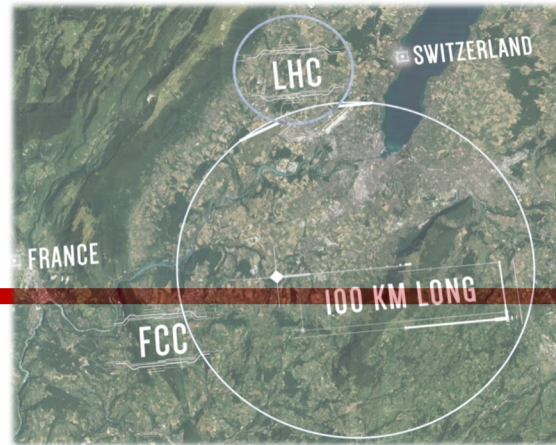
**The LHeC is a feasible and impactful alternative for the ESPP.**

**In addition, the LHeC can be a bridge between major colliders.**

# An impactful “*bridge*” between major colliders @ CERN



LHC

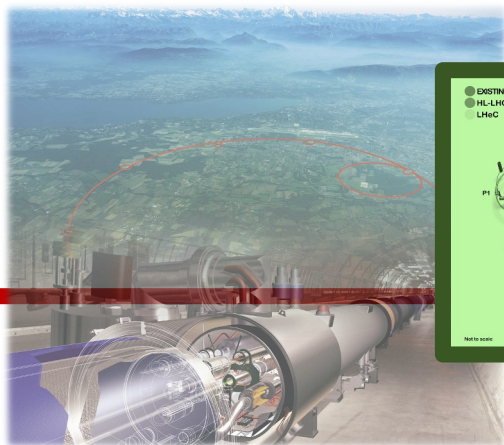


e.g. FCC (ee or hh) or LEP3

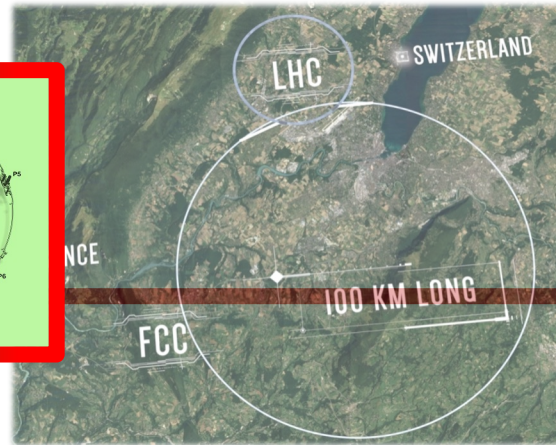
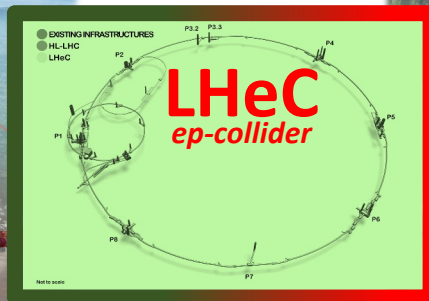
# An impactful “*bridge*” between major colliders @ CERN

*ep-option with HL-LHC: LHeC*

*e.g. 6 years ep-only@LHC >  $1 \text{ ab}^{-1}$*



LHC

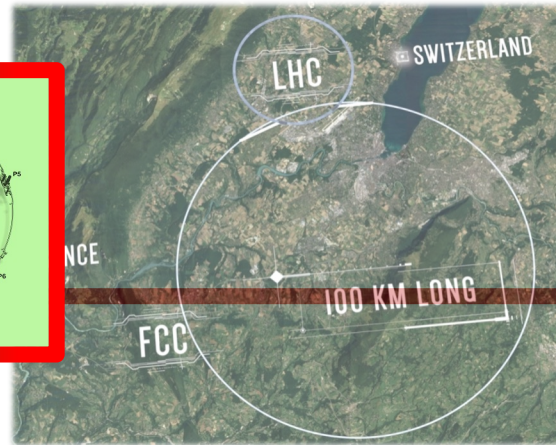
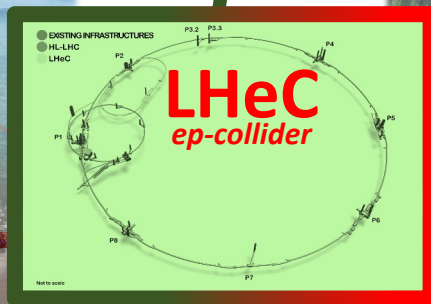
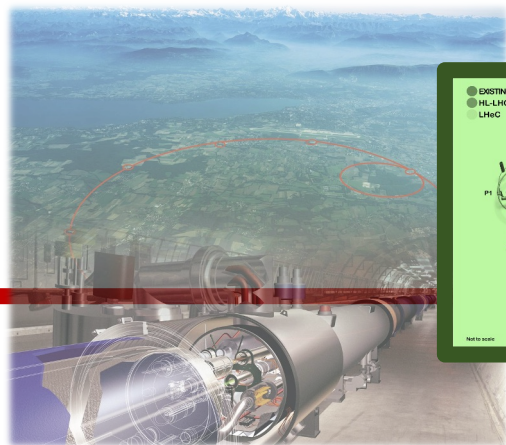


e.g. FCC (ee or hh) or LEP3



# 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

*ultimate upgrade of the LHC physics reach*

*cost-effective investment*

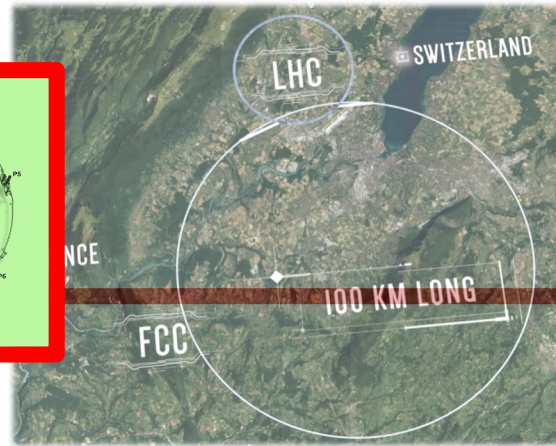
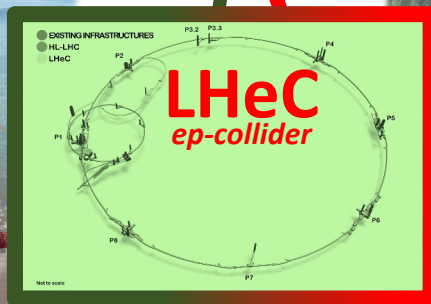
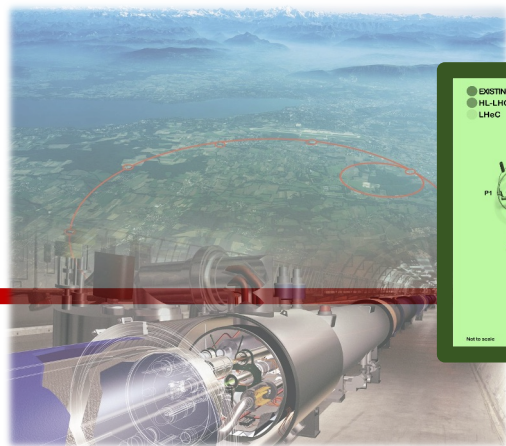
*re-use*

FCC-hh/eh

*injector*

FCC-ee/LEP3

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

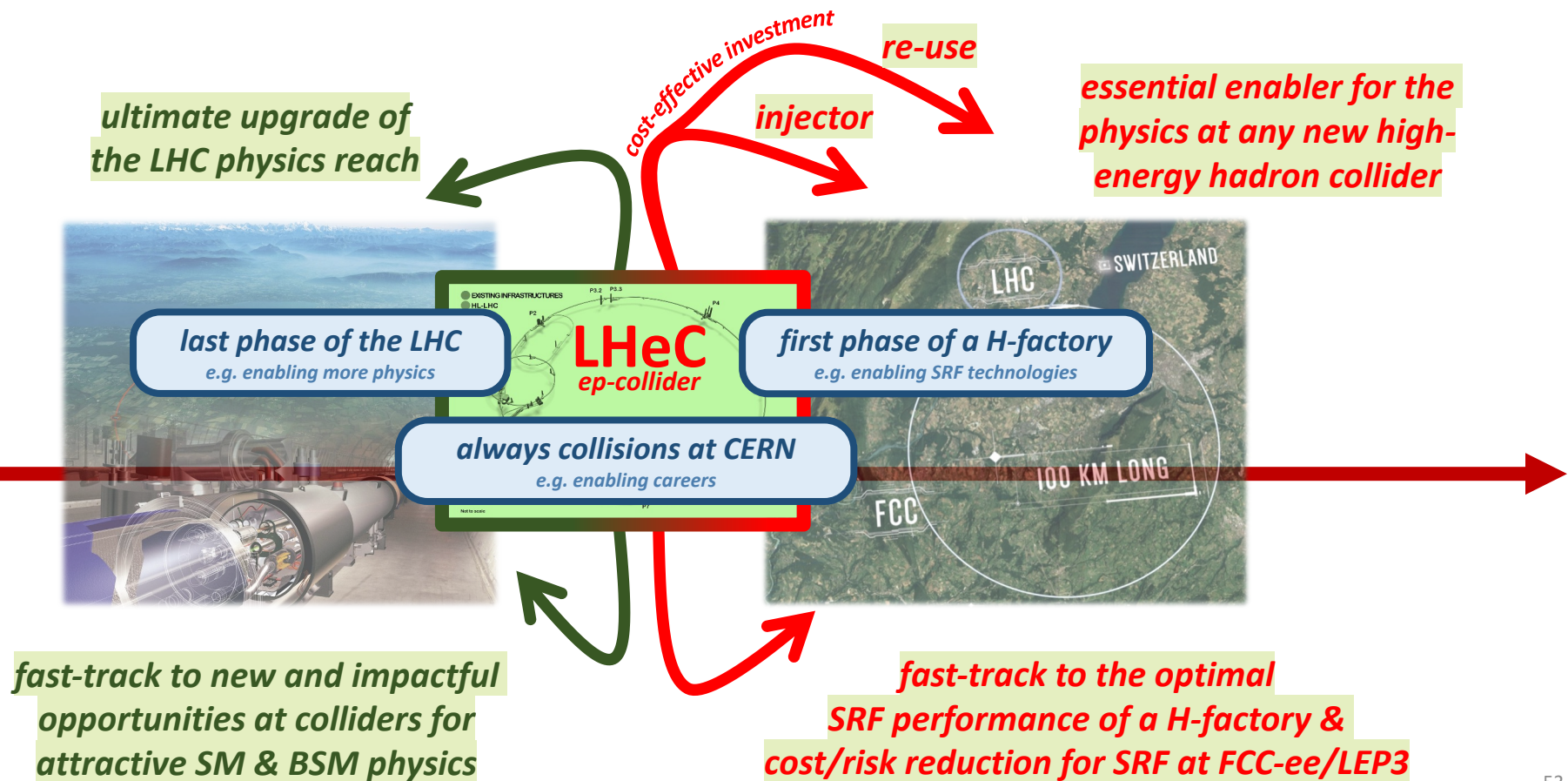


*fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics*

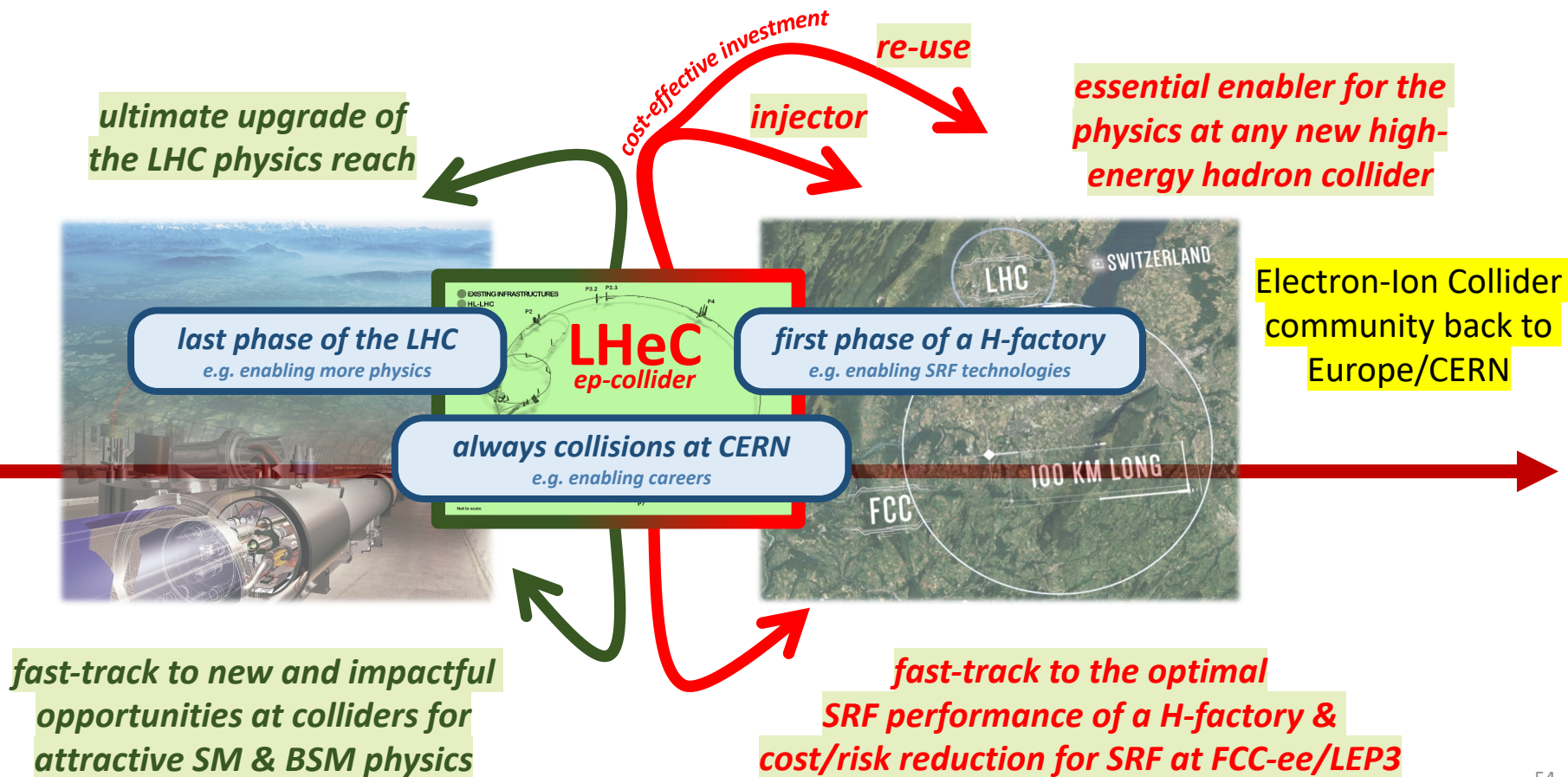
*fast-track to the optimal SRF performance of a H-factory & cost/risk reduction for SRF at FCC-ee/LEP3*

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

# An impactful “*bridge*” between major colliders @ CERN



# An impactful “*bridge*” between major colliders @ CERN



# LHeC – next steps

## ERL from the Accelerator R&D Review

- The R&D program for PERLE and bERLinPro should be implemented and financed as presented. The plan is adequate and spans up to 2032.
- For the funding of R&D that is critical for LHeC 12.5 M€ and 77 FTEy are still missing.
- Develop suitable concepts and technologies for dealing with SR power loss and induced energy spread of LHeC within the Accelerator R&D roadmap and secure funding.

## Towards a TDR for LHeC

- Further optimize the accelerator optics
- Built a mock-up for the Machine Detector Interface
- Potentially co-design the detector with ALICE3 for use also after HL-LHC
- Potentially co-develop the accelerator components for a future Higgs factory (FCC/LEP3)
- Potentially integrate novel technologies to improve performance and reduce costs/risks

# Roadmap with ERL to LHeC

demonstrated applicability of  
high-power ERL for particle physics

enables the ultimate  
upgrades of the  
LHC/FCC programs  
(*ep collisions*)

2070'sies

ERL FCC-eh



2020'sies



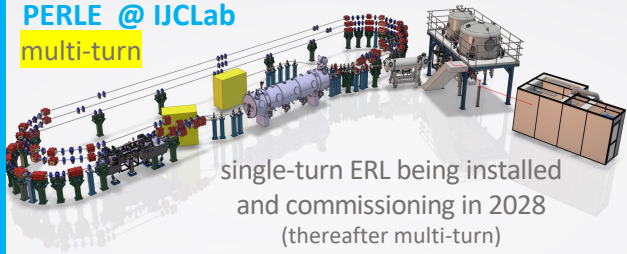
essential **energy efficient**  
technologies for SRF accelerators

bERLinPro @ HZB



beam commission from **high-brightness injector** started in 2024  
(up to 100mA in the future)

PERLE @ IJCLab  
**multi-turn**



single-turn ERL being installed  
and commissioning in 2028  
(thereafter multi-turn)

ESPP'26 → ESPP'32

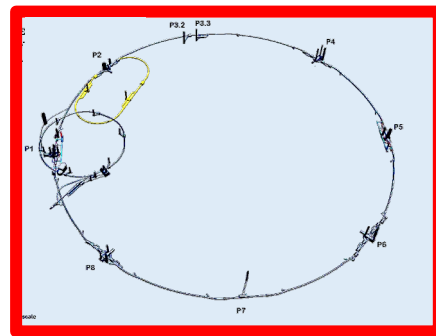
full **TDR** studies

further optimise  
schedule, costs,  
performance and  
sustainability

implementation  
7 years

DECISION ESPP'32

2040'sies



# The LHeC as an alternative or bridge between major colliders

- A high-energy, high-luminosity electron-proton collider at the LHC is an impactful alternative collider with excellent results in the Higgs, EW, top quark and QCD sectors on an interesting timeline.
- LHeC boosts the scientific return of the LHC, and is essential for any future high-energy hadron-collider program.
- To achieve the best physics for the least power, the Energy Recovery Linac technology is to be further developed to enable such an electron-proton collider.
- At least 8 national inputs formulated considerations for the LHeC, and more inputs supported developments for the ERL technology.



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

Thank you for your attention!

Jorgen.DHondt@nikhef.nl



# LHeC – additional slides

## Content

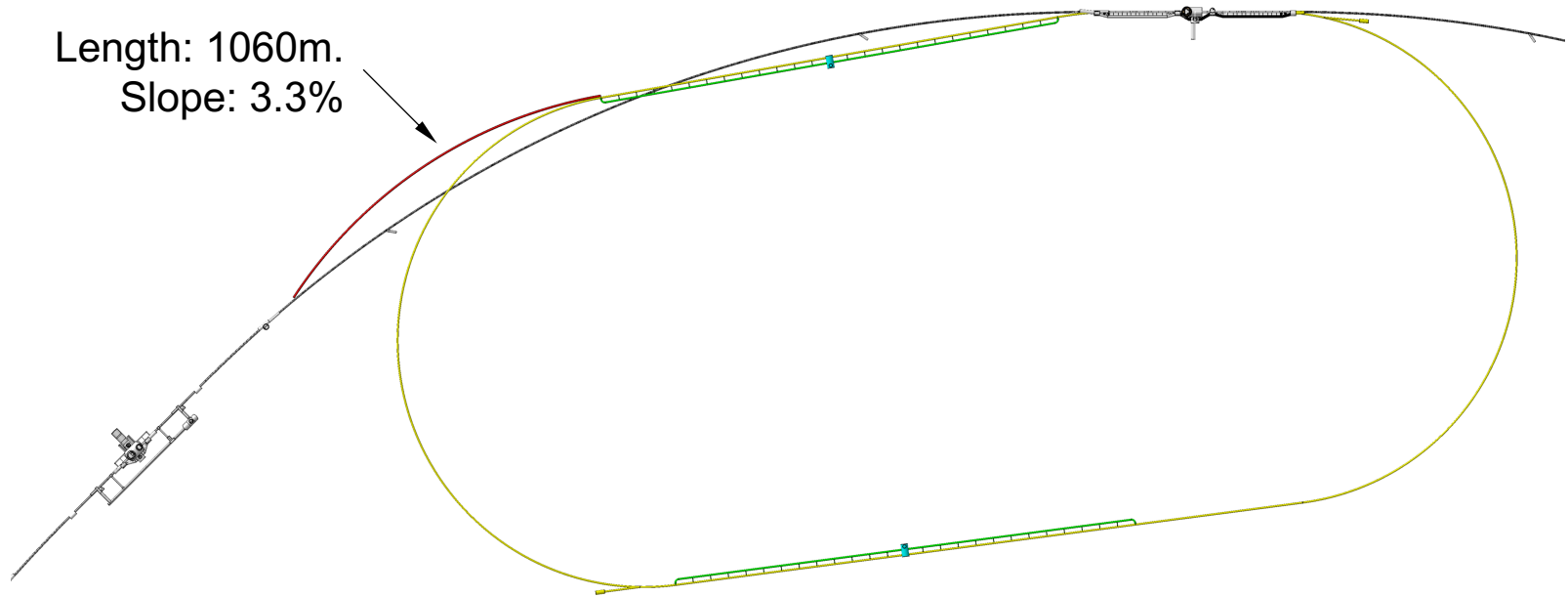
- LHeC – bridge to LEP3
- LHeC – accelerator R&D landscape
- LHeC – risks of ERL performance
- LHeC – bridge to future high-energy hadron collider
- LHeC – more physics plots (including eA)
- LHeC – ring-ring (old CDR) versus ring-linac (new CDR)

## LHeC – bridge to LEP3

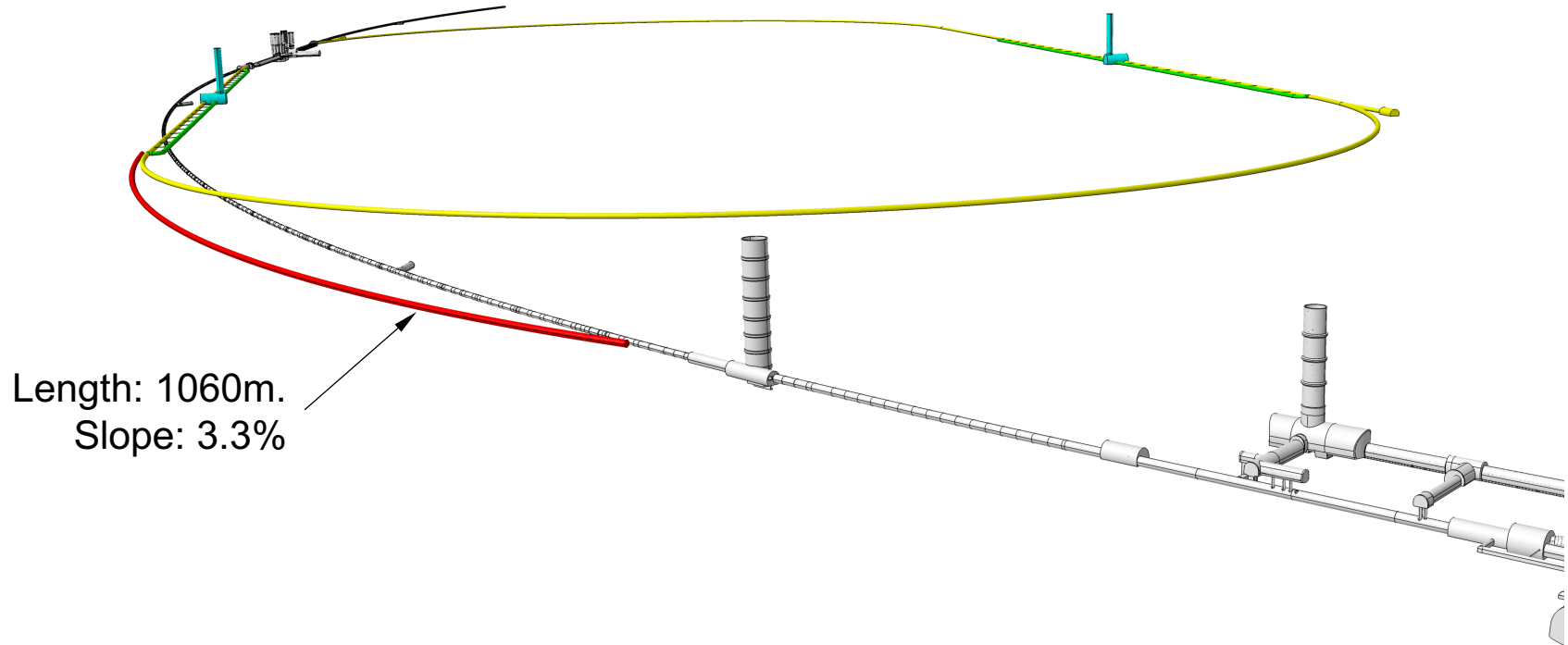
## LHeC – bridge to LEP3

- LHeC and LEP3 have a comparable number of cryomodules and thus comparable 800MHz power system and distribution lines, i.e. very similar industrial contracts and the LHeC developments can directly lead into LEP3 orders / productions.
  - clear synergies that can be exploited for common design and optimization, e.g. cryomodules, power sources, cryogenic systems, beam diagnostics, magnets
- The current LEP3 design assumes an injection energy of 10GeV which is equivalent to one of the LHeC linacs. Using both LHeC linacs could easily increase the injection energy to 20GeV, even without re-circulation.
  - one of the LHeC linacs can be the injector for LEP3
  - in re-circulation mode, the LHeC could even inject with direct top-up at the Z energy and possibility up to W production beam energies
- One could use one of the LHeC tunnel straight sections for the installation of the LEP3 booster ring RF [1km straight section → > 10GeV potential]
  - one of the LHeC linacs can be used for the LEP3 Booster ring up to W physics

## LHeC – bridge to LEP3

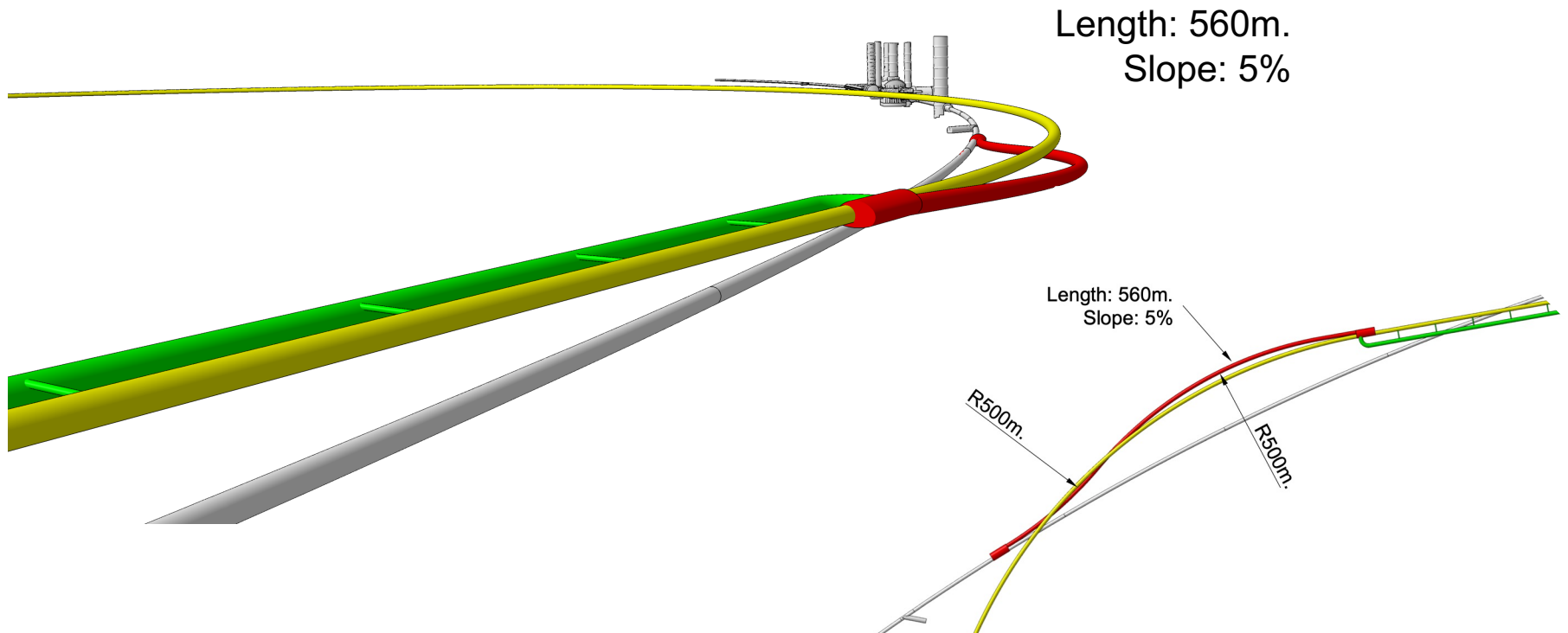


## LHeC – bridge to LEP3



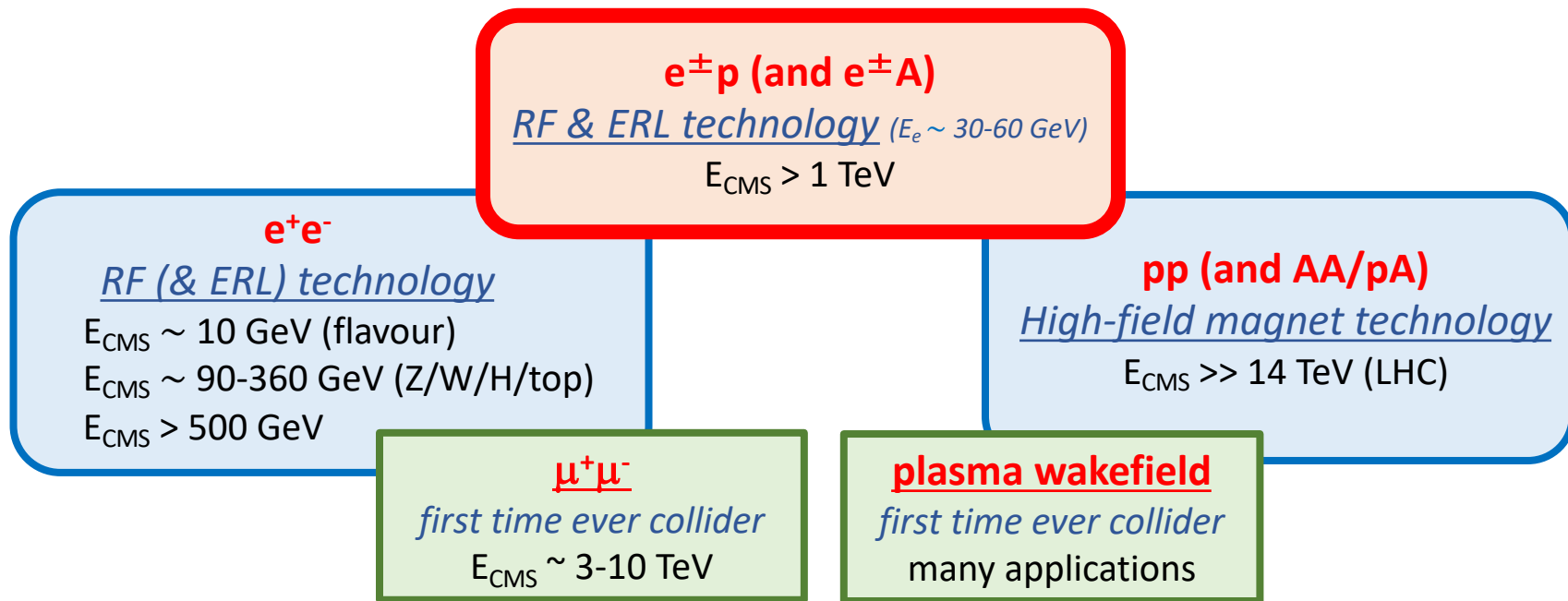


## LHeC – bridge to LEP3

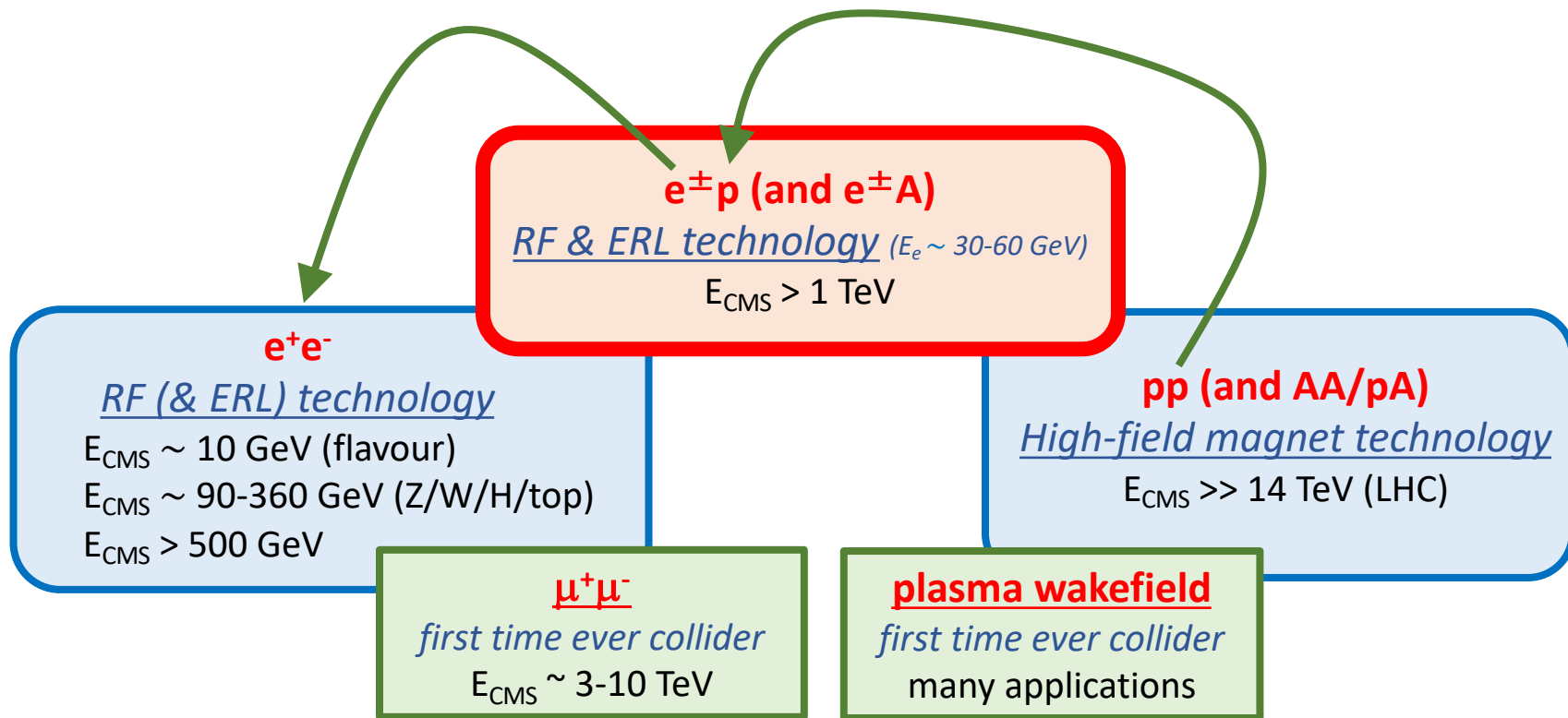


# LHeC – accelerator R&D landscape

# Accelerator R&D landscape & Colliders



# Accelerator R&D landscape & Colliders



# Accelerator R&D landscape & Colliders

**focus on the LHeC**

*high-energy & high-luminosity*

*electron-proton*



**FOCUS**

**$e^\pm p$  (and  $e^\pm A$ )**

RF & ERL technology ( $E_e \sim 30\text{-}60\text{ GeV}$ )

$E_{\text{CMS}} > 1\text{ TeV}$

**$e^+e^-$**

RF (& ERL) technology

$E_{\text{CMS}} \sim 10\text{ GeV}$  (flavour)

$E_{\text{CMS}} \sim 90\text{-}360\text{ GeV}$  (Z/W/H/top)

$E_{\text{CMS}} > 500\text{ GeV}$

**pp (and AA/pA)**

High-field magnet technology

$E_{\text{CMS}} \gg 14\text{ TeV}$  (LHC)

**$\mu^+\mu^-$**

*first time ever collider*

$E_{\text{CMS}} \sim 3\text{-}10\text{ TeV}$

**plasma wakefield**

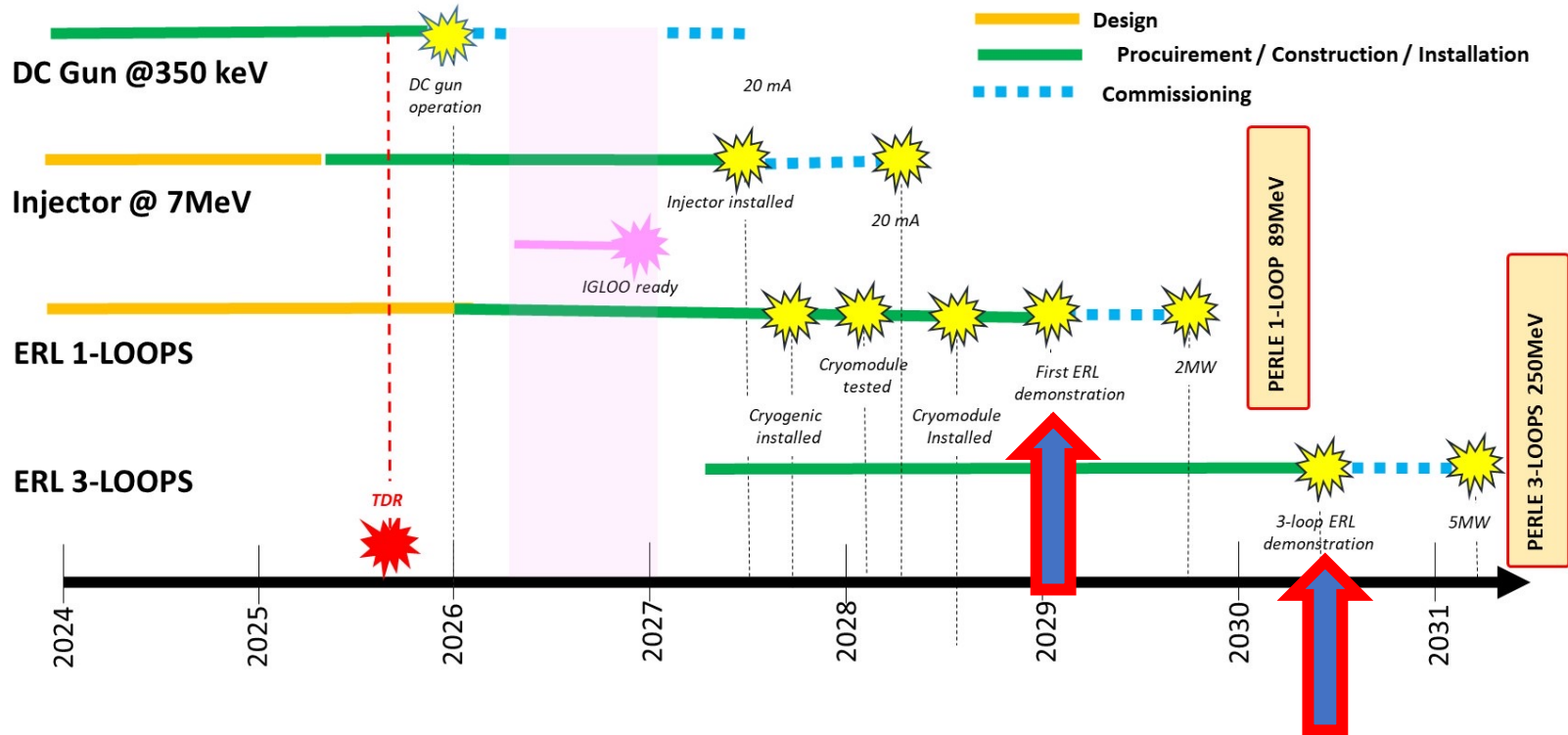
*first time ever collider*

many applications

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

# LHeC – accelerator R&D for ERL

# PERLE @ IJCLab (Orsay)





# bERLinPro @ Helmholtz Zentrum Berlin

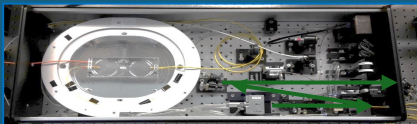
*generic accelerator R&D with several aspects as stepping stones towards HEP applications and energy efficient accelerator technologies*

**focus on a high-current & high-brightness injector**  
*first beams from the SRF gun*

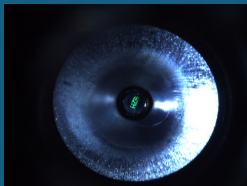


## BERLinPro: Main Project Parameters

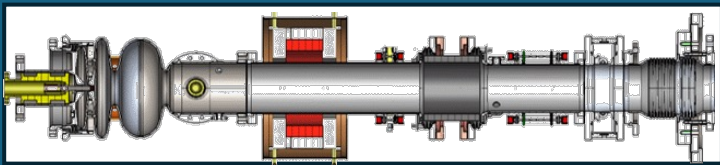
|                                       |                |
|---------------------------------------|----------------|
| Total beam energy, MeV                | 50             |
| Maximum average current, mA           | 100            |
| Bunch charge, pC                      | 77             |
| Bunch repetition rate, GHz            | 1.3            |
| Emittance (normalized), $\pi$ mm mrad | $\leq 1.0$     |
| Bunch length (rms), ps                | 2.0 or smaller |
| Maximum Losses (relative)             | $< 10^{-5}$    |



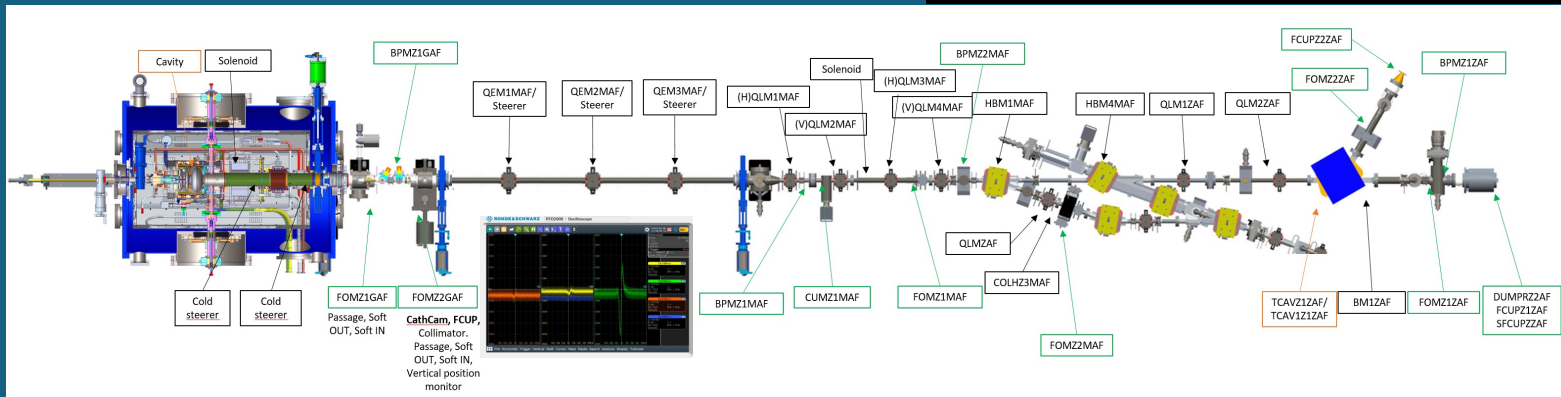
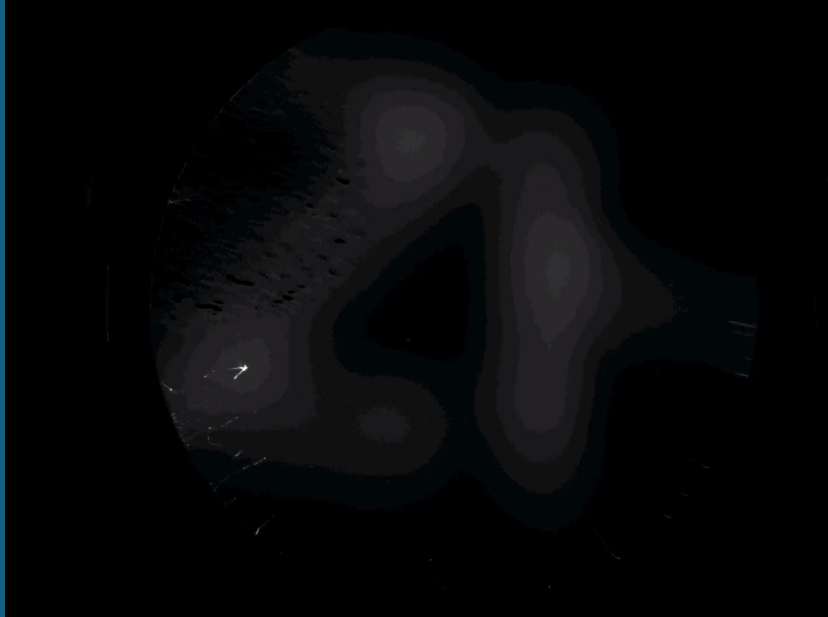
$\gamma$

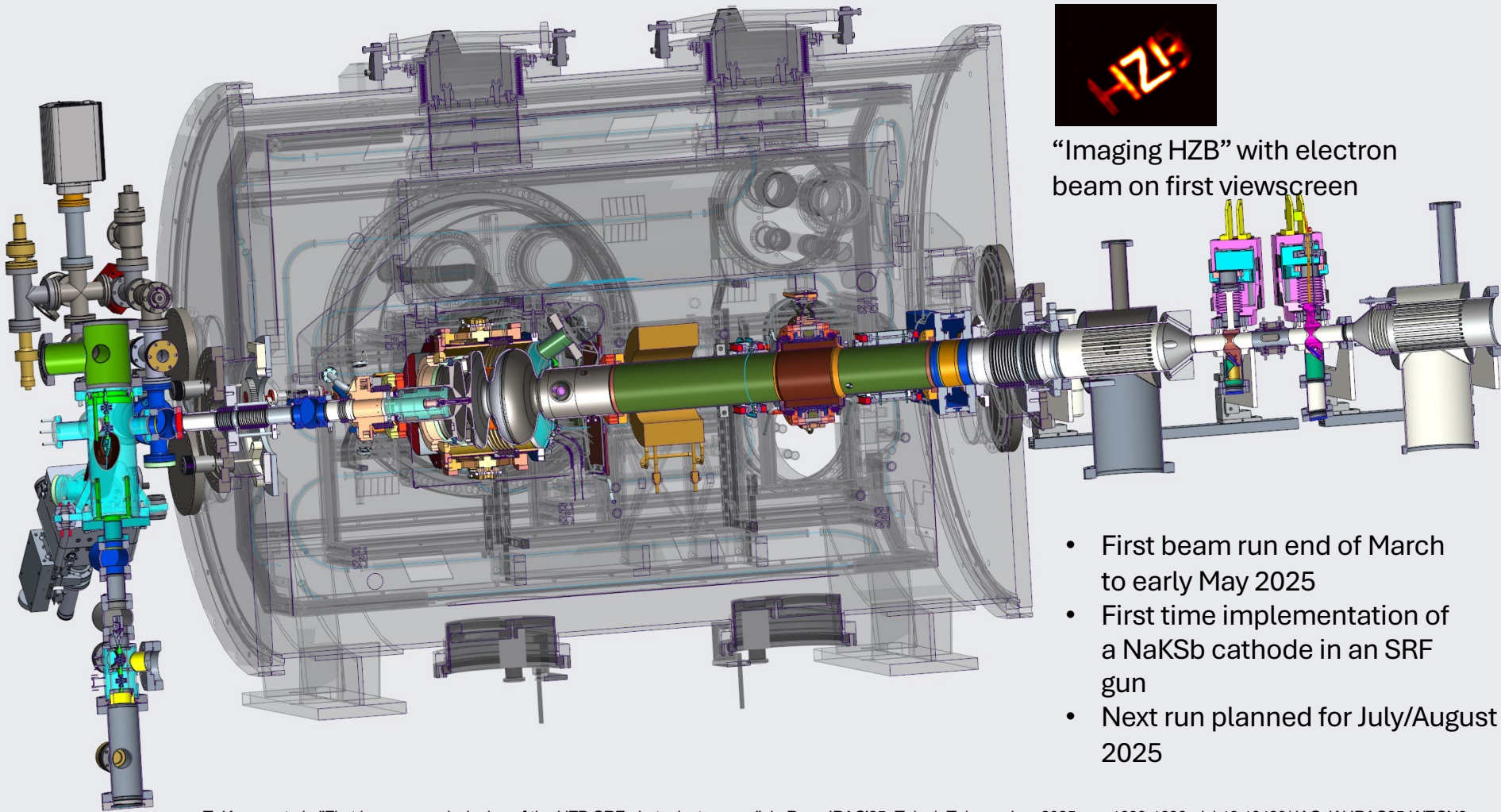


# To image HZB



$e^-$





“Imaging HZB” with electron beam on first viewscreen

- First beam run end of March to early May 2025
- First time implementation of a NaKSb cathode in an SRF gun
- Next run planned for July/August 2025

## LHeC – risks of ERL performance

# LHeC – risks of ERL performance

**Worse case scenario: LHeC has to operate in non-ERL mode and stay within 100MW**

- Physics: 10x less luminosity
  - not much impact for QCD physics, including the empowering of (HL-)LHC
  - still improvements in EW, H and top quark physics wrt to HL-LHC potential
  - still search sensitivity beyond HL-LHC potential
- Accelerator: 2x less beam current in the SRF system
  - less constraints on the SRF system
  - opportunities to deploy higher gradients, less cooling, etc.
- Synergies: even more synergies with future e+e- Higgs factories (LEP3, FCCee)
  - similar opportunities for cost reduction by reusing systems



# LHeC – physics impact of non-ERL LHeC (10x less luminosity)

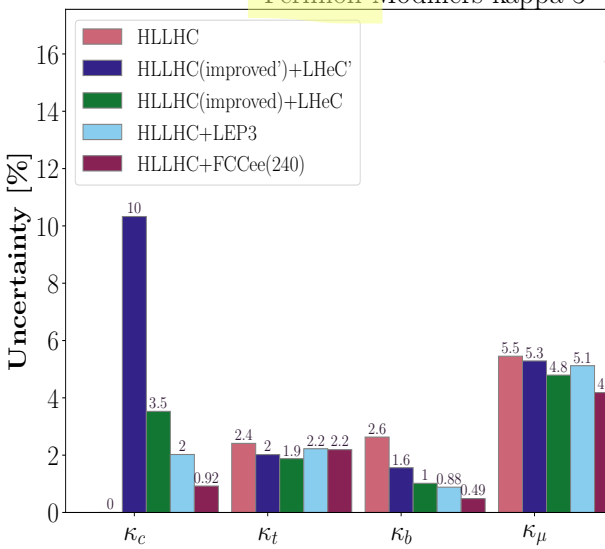
HL-LHC + LHeC' (10x less luminosity)

HL-LHC + LHeC (nominal)

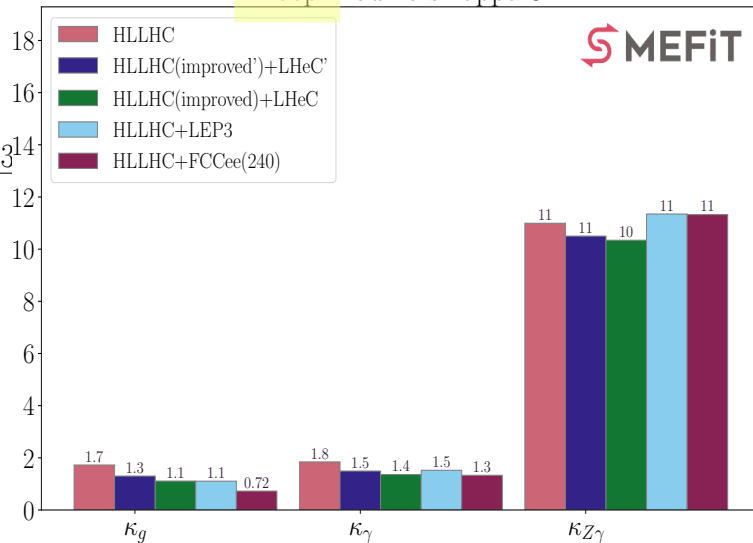
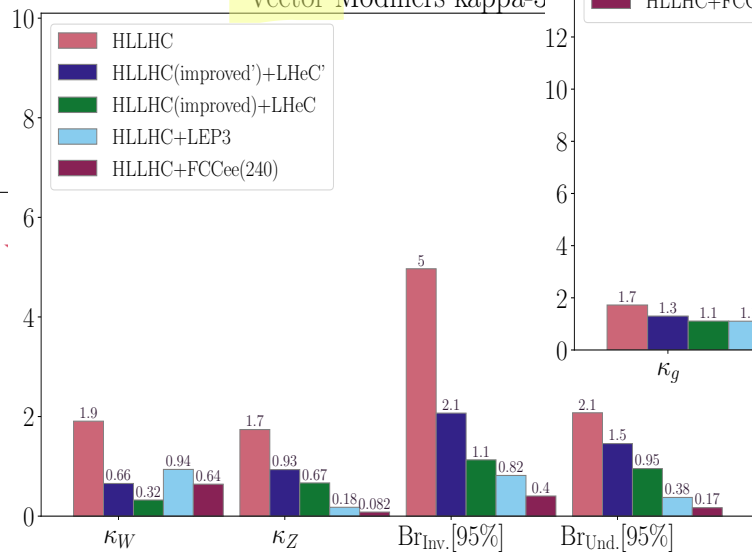
Loop Modifiers kappa-3

MEFIT

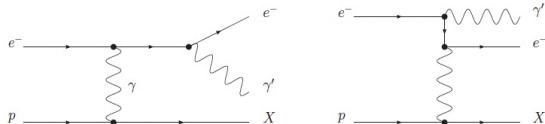
Fermion Modifiers kappa-3



Vector Modifiers kappa-3



# Dark Photons



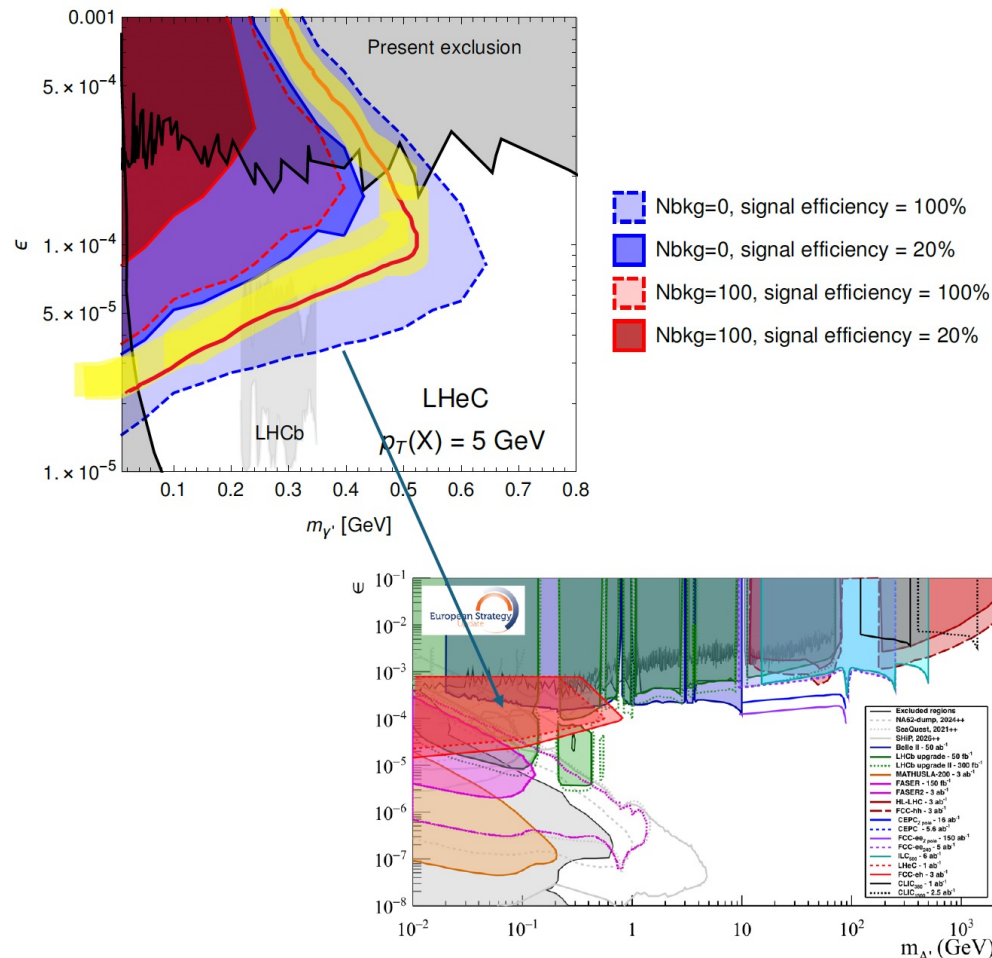
Contour for LHeC presented for 0 and 100 bkg events and for efficiency 100% and 20% (1/5)

Factor 1/10 in lumi corresponds to decrease in significance by  $\sqrt{10} \sim 3$

→ For **Nbkg=0** exclusion in between dashed and solid contours

→ **Still sensitivity!**

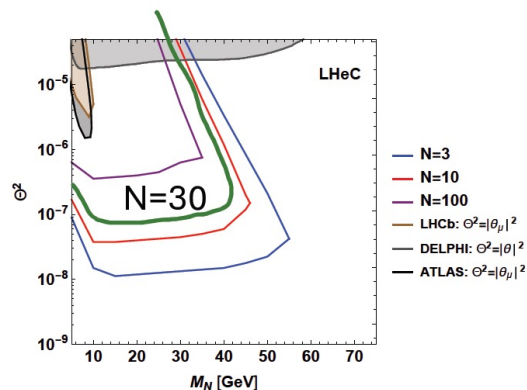
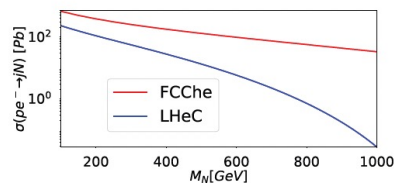
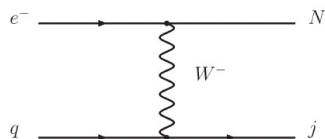
<https://doi.org/10.1103/PhysRevD.101.015020>





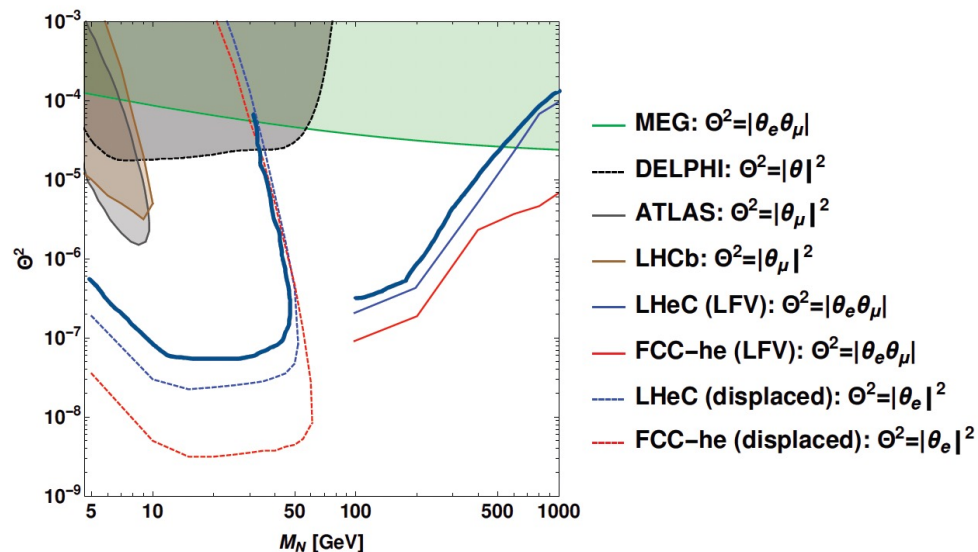
# HNLs

<https://doi.org/10.1007/JHEP03%282020%29110>

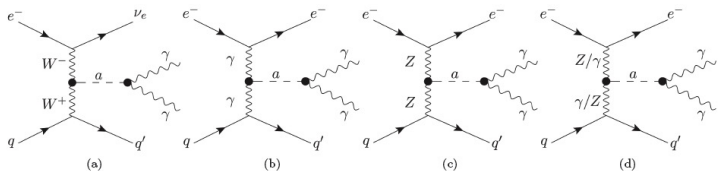


Still very good sensitivity

With 1/10 of lumi, N=3 would correspond to N=30 curve  
N=10 corresponds to N=100...



# ALPS



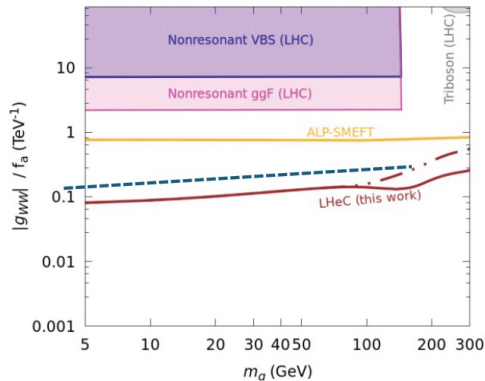
Decays only to photons

Based on  $1/\text{ab-1}$ , 95% C.L. limits

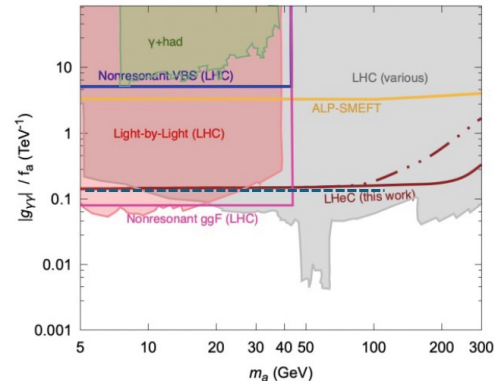
For 1/10 of the stat, dashed line are indicative

Still sensitivity complementary to HL-LHC

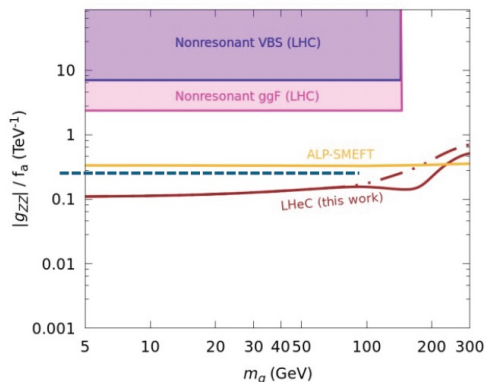
<https://arxiv.org/pdf/2307.00394>



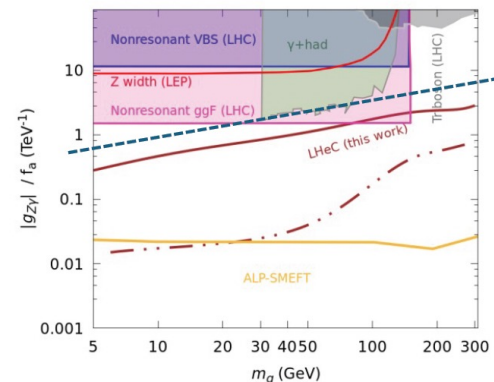
(a)



(b)

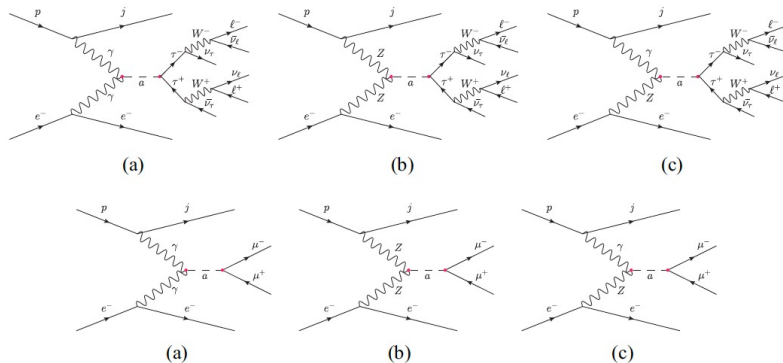


(c)



(d)

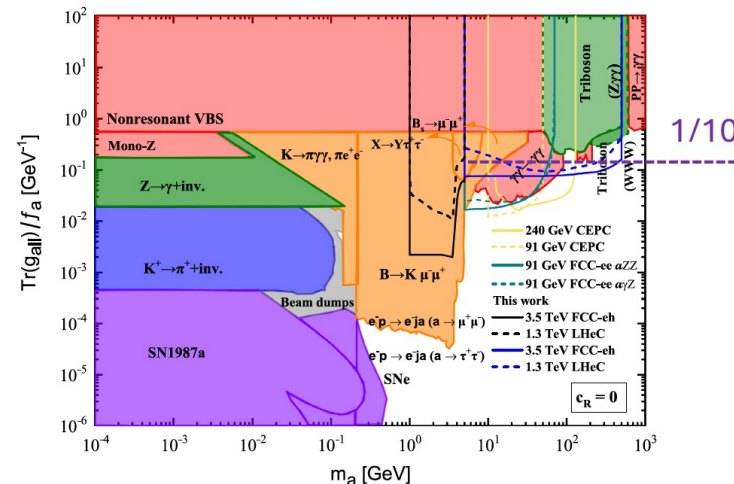
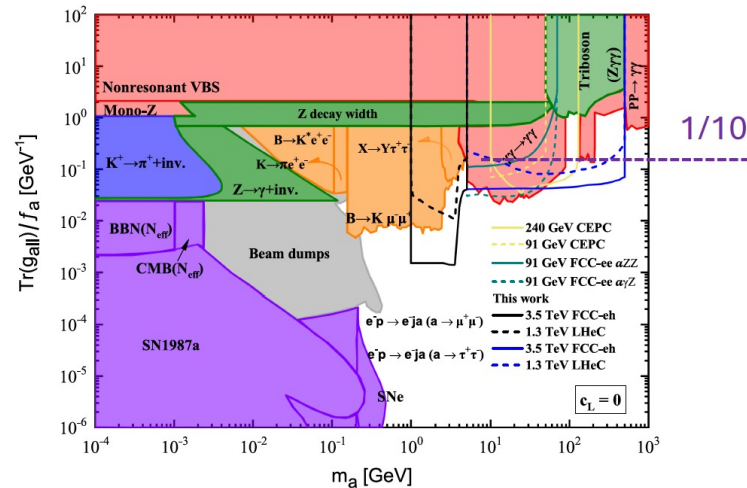
# ALPS (2)



Decays to leptons (e.g. muons and taus)

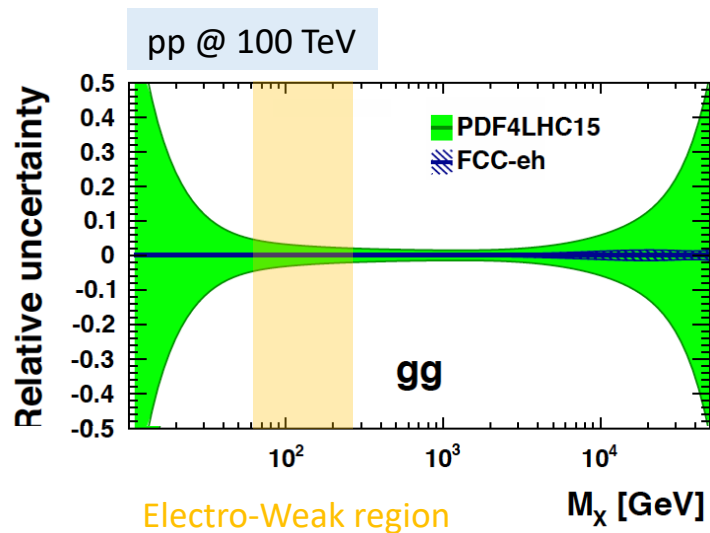
Impact of 1/10 stat of LHeC far smaller than the LHeC  
 $\rightarrow$  FCC-eh difference

CL=0 (top) and CR=0 (bottom) – cross sections varies



## LHeC – bridge to future high-energy hadron collider

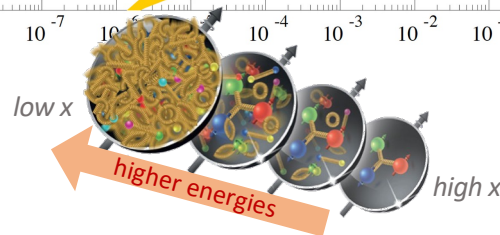
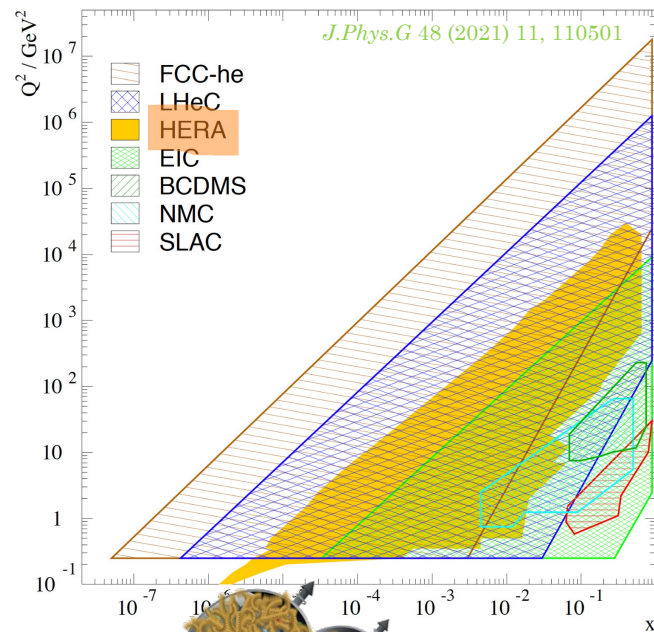
# LHeC – bridge to future high-energy hadron collider



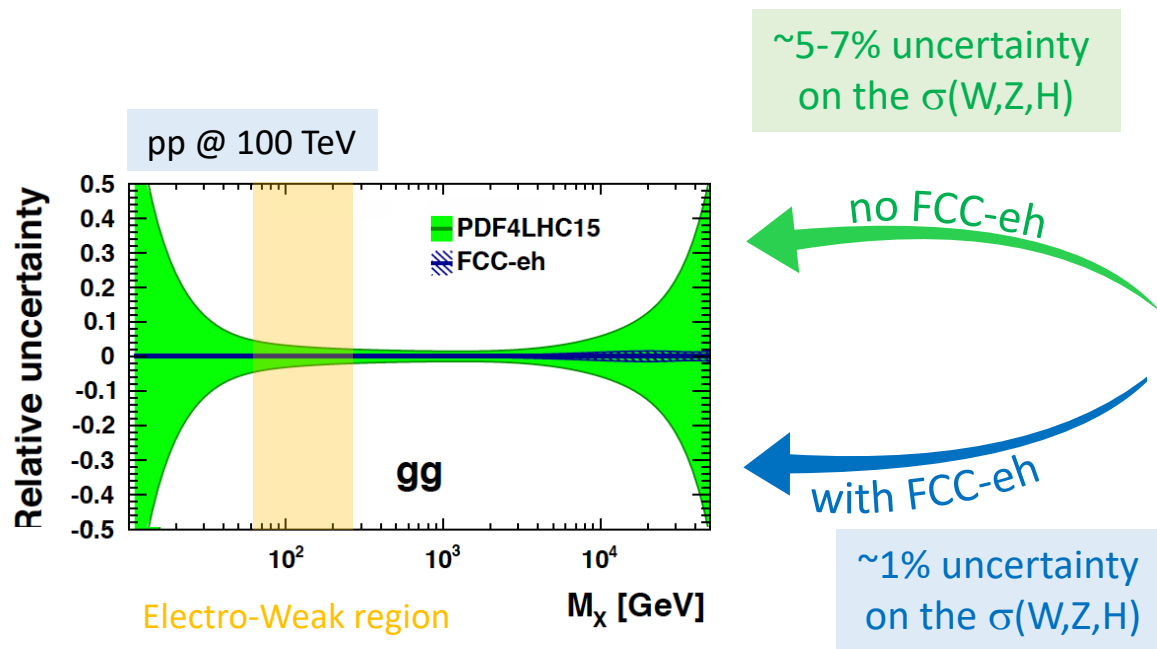
~5-7% uncertainty  
on the  $\sigma(W,Z,H)$

no FCC-eh

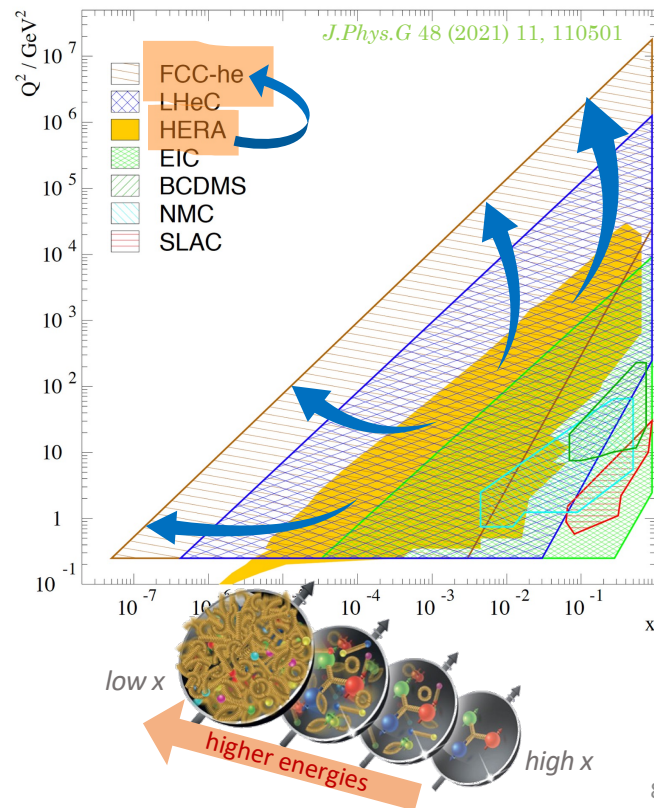
Kinematic range Parton Distribution Functions



# Empowering the FCC-hh program with the FCC-eh



Kinematic range Parton Distribution Functions



**LHeC/FCC-eh essential to unlock  
FCC-hh science potential**

# Complementarity for Higgs physics in the FCC program

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

| kappa-0-HL             | HL+FCC-ee <sub>240</sub> | HL+FCC-ee | HL+FCC-ee (4 IP) | HL+FCC-ee/hh | HL+FCC-eh/hh | HL+FCC-hh | HL+FCC-ee/eh/hh |
|------------------------|--------------------------|-----------|------------------|--------------|--------------|-----------|-----------------|
| $\kappa_W$ [%]         | 0.86                     | 0.38      | 0.23             | 0.27         | 0.17         | 0.39      | 0.14            |
| $\kappa_Z$ [%]         | 0.15                     | 0.14      | 0.094            | 0.13         | 0.27         | 0.63      | 0.12            |
| $\kappa_g$ [%]         | 1.1                      | 0.88      | 0.59             | 0.55         | 0.56         | 0.74      | 0.46            |
| $\kappa_\gamma$ [%]    | 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            |
| $\kappa_c$ [%]         | 1.5                      | 1.3       | 0.88             | 1.2          | 1.2          | —         | 0.94            |
| $\kappa_t$ [%]         | 3.1                      | 3.1       | 3.1              | 0.95         | 0.95         | 0.99      | 0.95            |
| $\kappa_b$ [%]         | 0.94                     | 0.59      | 0.44             | 0.5          | 0.52         | 0.99      | 0.41            |
| $\kappa_\mu$ [%]       | 4.                       | 3.9       | 3.3              | 0.41         | 0.45         | 0.68      | 0.41            |
| $\kappa_\tau$ [%]      | 0.9                      | 0.61      | 0.39             | 0.49         | 0.63         | 0.9       | 0.42            |
| $\Gamma_H$ [%]         | 1.6                      | 0.87      | 0.55             | 0.67         | 0.61         | 1.3       | 0.44            |

only FCC-ee@240GeV

only FCC-hh



# Complementarity for Higgs physics in the FCC program

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(expected relative precision)

| kappa-0-HL             | HL+FCC-ee <sub>240</sub> | HL+FCC-ee | HL+FCC-ee (4 IP) | HL+FCC-ee/hh | HL+FCC-eh/hh | HL+FCC-hh | HL+FCC-ee/eh/hh |
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| $\Gamma_H$ [%]         | 1.6                      | 0.87      | 0.55             | 0.67         | 0.61         | 1.3       | 0.44            |

FCC-ee prospect

FCC-hh/eh prospect

only FCC-ee@240GeV

only FCC-hh

# Complementarity for Higgs physics in the FCC program

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

| kappa-0-HL             | HL+FCC-ee <sub>240</sub> | HL+FCC-ee | HL+FCC-ee (4 IP) | HL+FCC-ee/hh | HL+FCC-eh/hh | HL+FCC-hh | HL+FCC-ee/eh/hh |
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| $\kappa_W$ [%]         | 0.86                     | 0.38      | 0.23             | 0.27         | 0.17         | 0.39      | 0.14            |
| $\kappa_Z$ [%]         | 0.15                     | 0.14      | 0.094            | 0.13         | 0.27         | 0.63      | 0.12            |
| $\kappa_g$ [%]         | 1.1                      | 0.88      | 0.59             | 0.55         | 0.56         | 0.74      | 0.46            |
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| $\kappa_{Z\gamma}$ [%] | 10.                      | 10.       | 10.              | 0.7          | 0.71         | 0.89      | 0.68            |
| $\kappa_c$ [%]         | 1.5                      | 1.3       | 0.88             | 1.2          | 1.2          | —         | 0.94            |
| $\kappa_t$ [%]         | 3.1                      | 3.1       | 3.1              | 0.95         | 0.95         | 0.99      | 0.95            |
| $\kappa_b$ [%]         | 0.94                     | 0.59      | 0.44             | 0.5          | 0.52         | 0.99      | 0.41            |
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| $\Gamma_H$ [%]         | 1.6                      | 0.87      | 0.55             | 0.67         | 0.61         | 1.3       | 0.44            |

only FCC-ee@240GeV

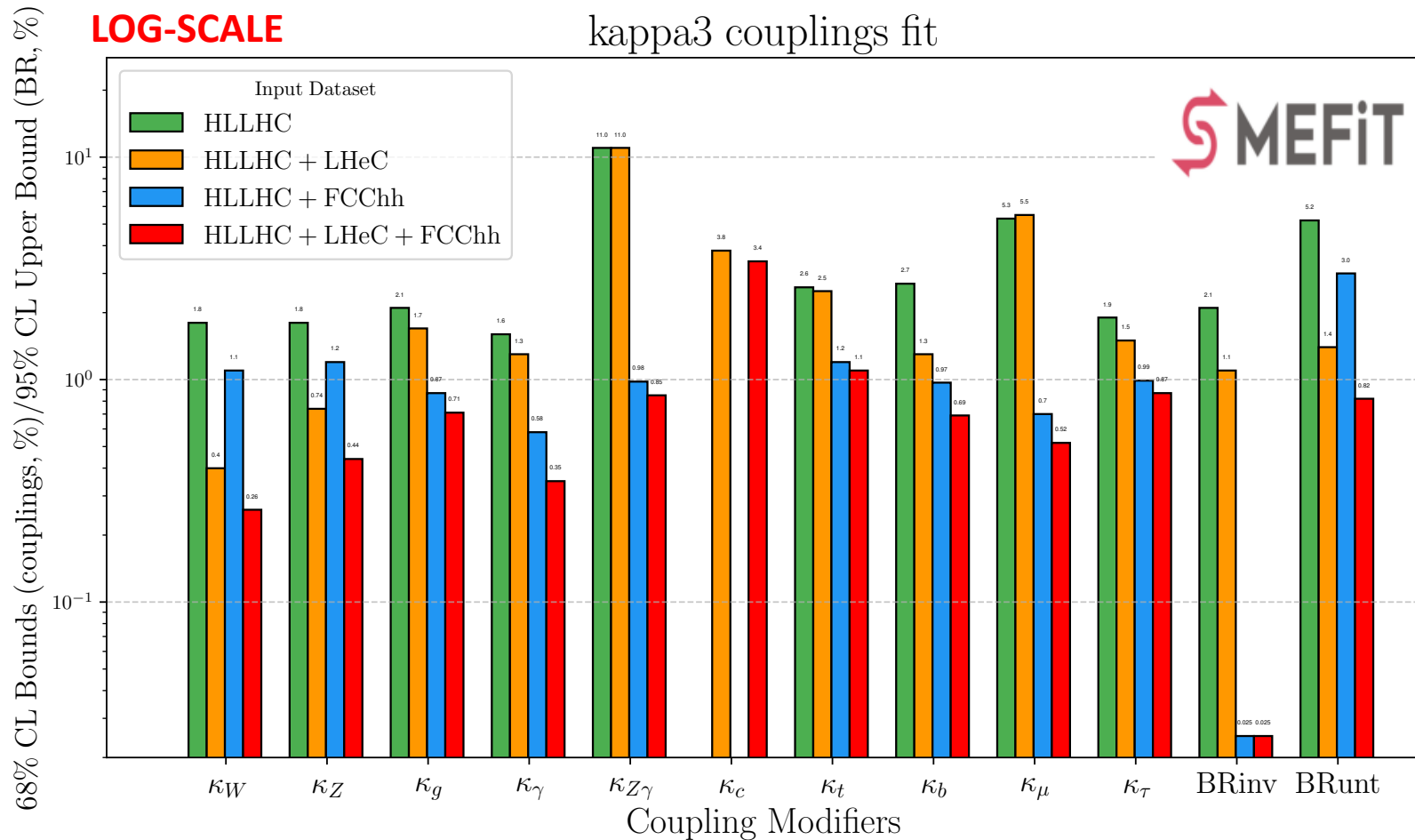
FCC-ee prospect

FCC-hh/eh prospect

only FCC-hh

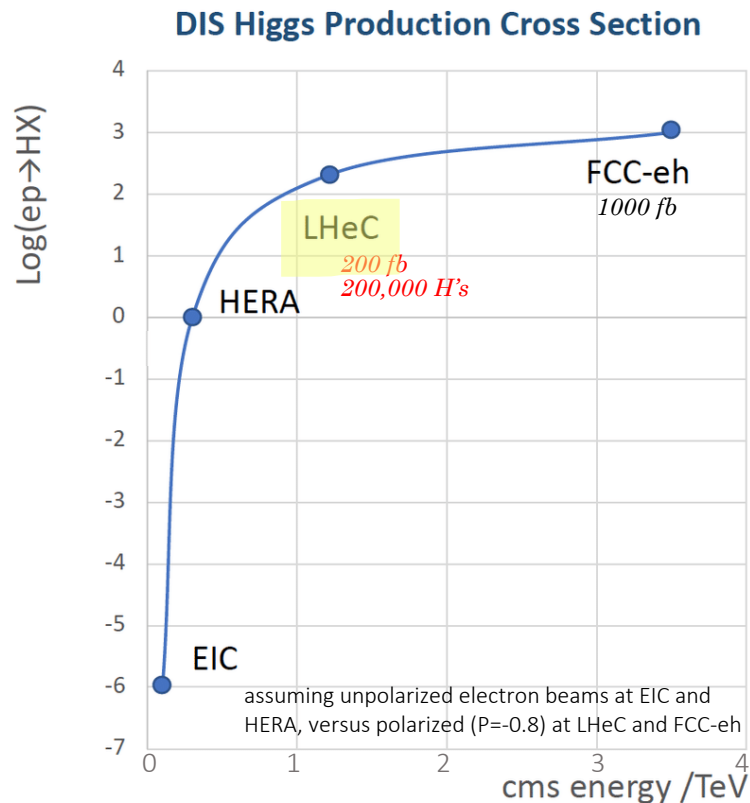
ALL COMBINED

***Ultimate Higgs Factory = {ee + eh + hh}***

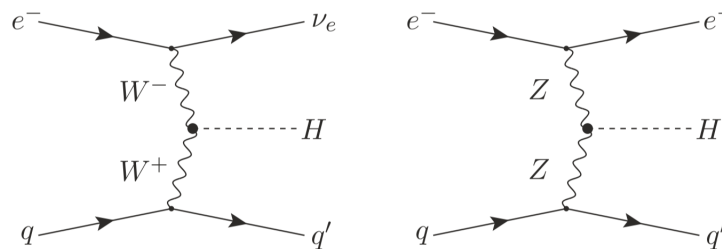


## LHeC – more physics plots

# Collision energy above the threshold for EW/Higgs/top



**The real game change between  
HERA and LHC/FCC**

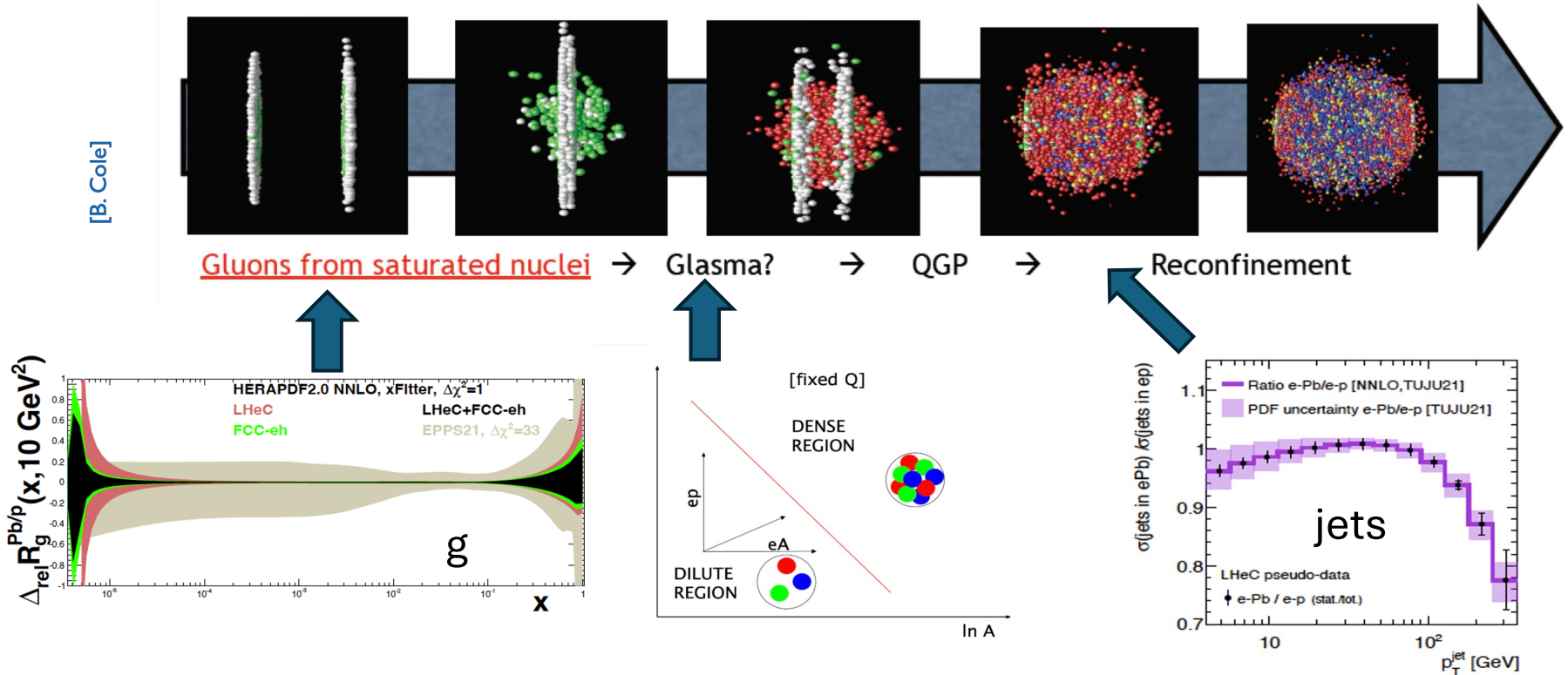


compared to proton collisions, these are reasonably  
clean Higgs events with much less backgrounds

**at these energies and luminosities, interactions  
with all SM particles can be measured precisely**

# eA at the LHeC

eA collisions at the LHeC will provide precise information on the partonic structure of nuclei and the dynamics of dense partonic systems (a new non-linear regime of QCD which requires ep and eA), relevant for all stages of HICs.

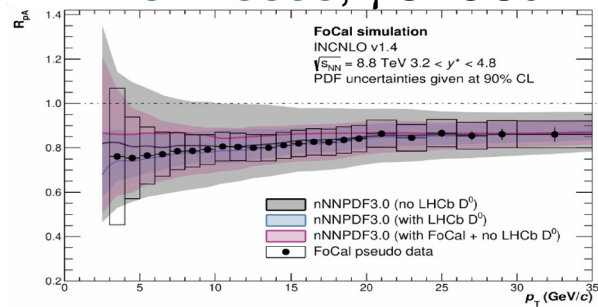


# Why DIS for PDFs?

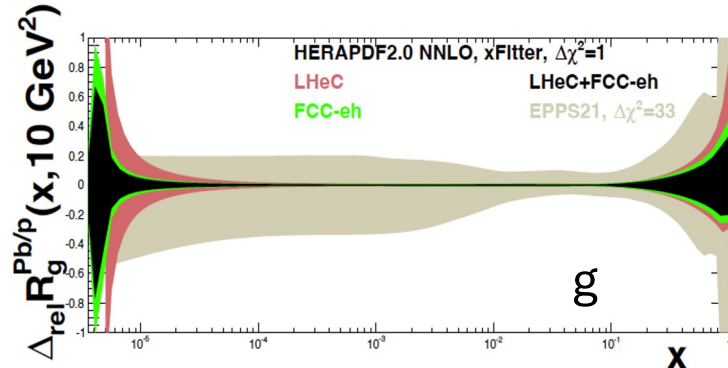
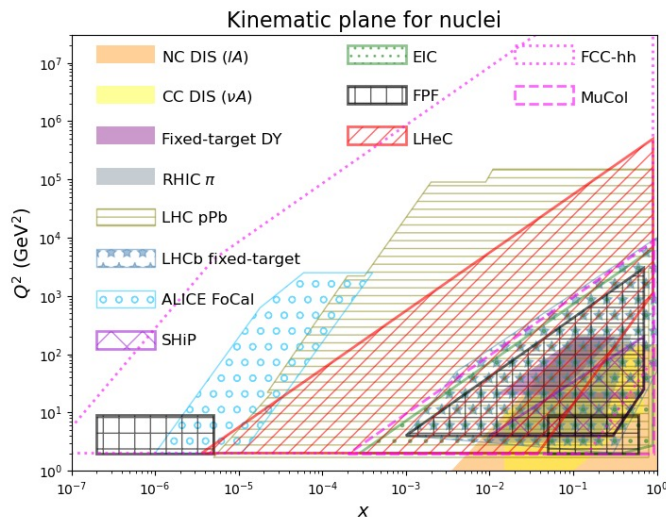
DIS is the ideal place for determining PDFs:

- Pointlike object on a composite one (hh=composite on composite): better determination of kinematic variables in the PDF, far less convoluted information than in pp.
- Much cleaner experimental environment: larger precision.
- Theory better established: factorisation proofs, evolution equations to aNNLO, etc.
- PDFs from a single experiment to get rid of inconsistencies between experiments.

2407.13058,  $\gamma$ @FoCal



- FoCal covers the same region that LHCb D-mesons, already included in EPPS21.
- LHeC determines better the gluon than available EPPS21



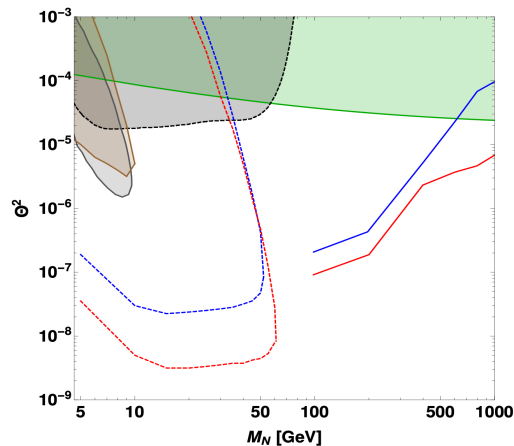


# Searching for new physics with the LHeC

*example of long-lived particles  
(benchmark models for hidden sectors)*

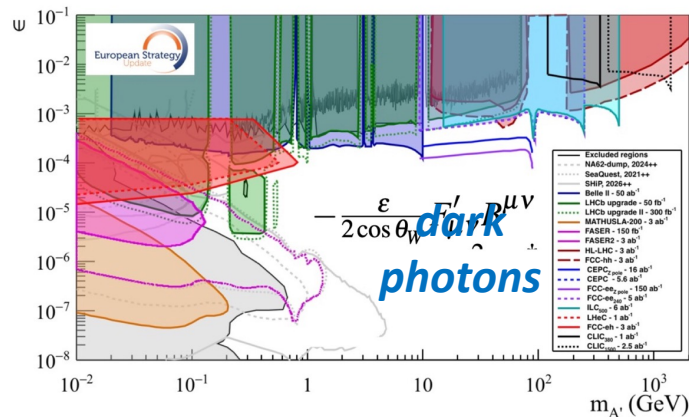
| Portal                           | Coupling                                                                                                                                               |
|----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| Vector (Dark Vector, $A_\mu$ )   | $-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$                                                                                                 |
| Scalar (Dark Higgs, $S$ )        | $(\mu S + \lambda_{HS}S^2)H^\dagger H$                                                                                                                 |
| Pseudo-scalar (Axion, $a$ )      | $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$ |
| Fermion (Sterile Neutrino, $N$ ) | $y_N LHN$                                                                                                                                              |

*compared to pp collisions the signature  
is easier to identify in ep collisions*

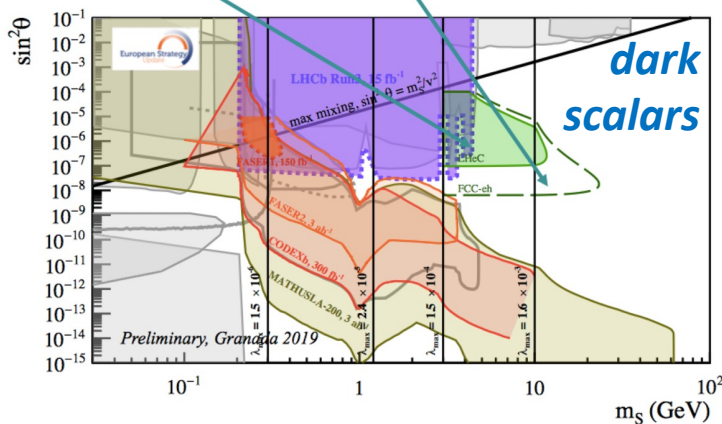


*heavy sterile neutrinos*

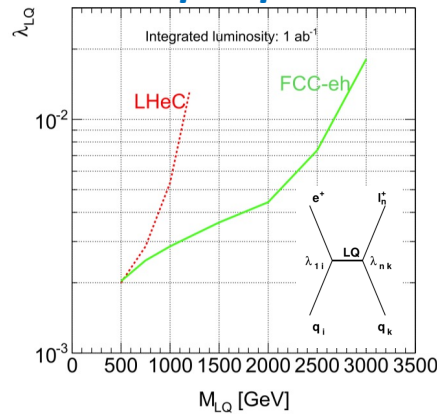
- MEG:  $\Theta^2=|\theta_e\theta_\mu|$
- DELPHI:  $\Theta^2=|\theta|^2$
- ATLAS:  $\Theta^2=|\theta_\mu|^2$
- LHCb:  $\Theta^2=|\theta_\mu|^2$
- LHeC (LFV):  $\Theta^2=|\theta_e\theta_\mu|$
- FCC-he (LFV):  $\Theta^2=|\theta_e\theta_\mu|$
- LHeC (displaced):  $\Theta^2=|\theta_e|^2$
- FCC-he (displaced):  $\Theta^2=|\theta_e|^2$



Projections for LHeC (1 ab⁻¹) and FCC-eh (3 ab⁻¹) - (fixed  $\lambda=4\times 10^{-3}$ ).



*leptoquarks*



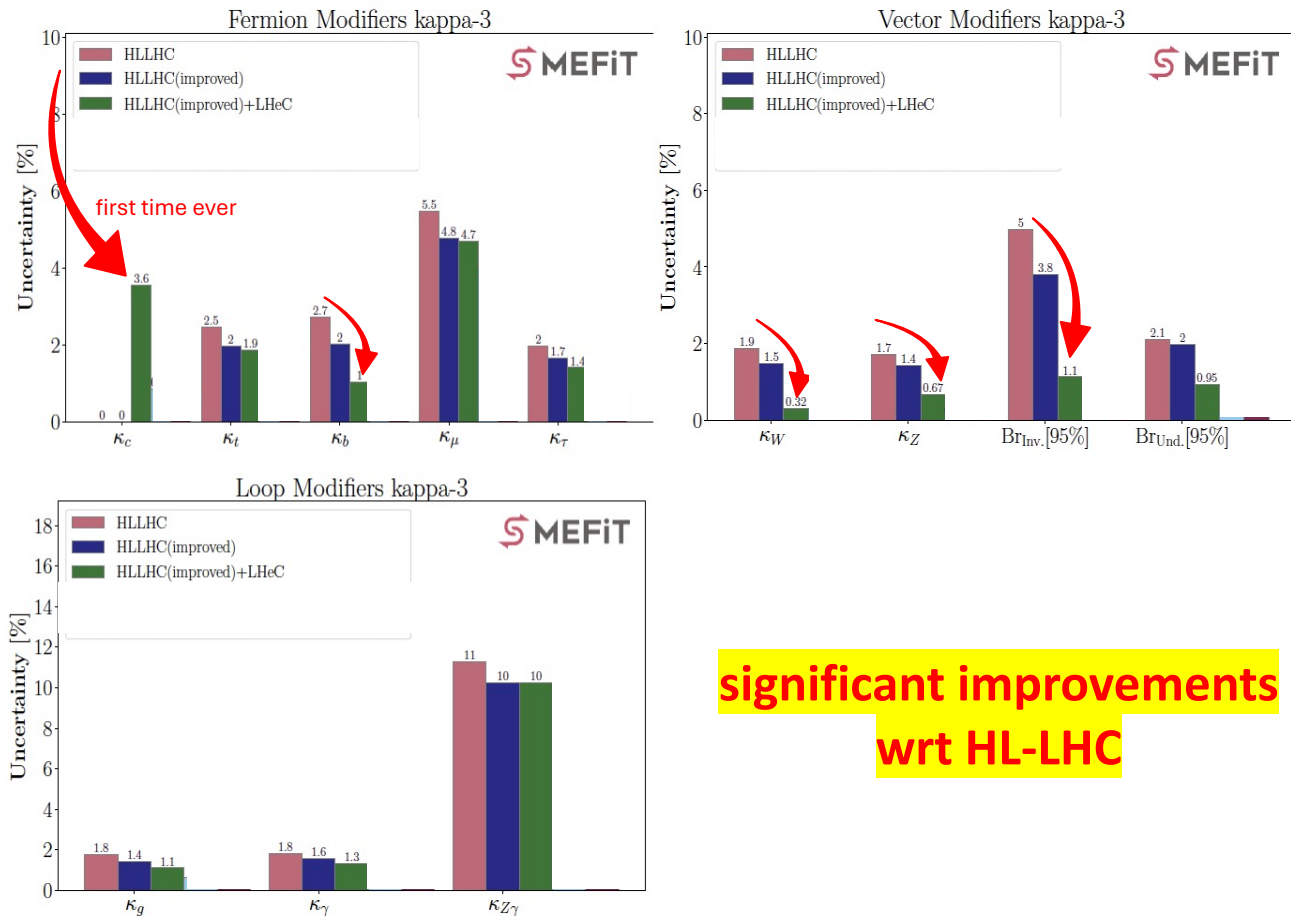
# Some physics highlights: Higgs physics

The LHeC is partially a **Higgs Factory** with several couplings **significantly improved over HL-LHC expectations**

- first time ever:  
 $\kappa_c$
- greatly improved:  
 $\kappa_b, \kappa_W, \kappa_Z$
- significantly improved:  
 $\kappa_t, \kappa_\tau, \kappa_g$

Figure:

The relative uncertainty on the fermion, vector and loop coupling modifiers obtained in the kappa-3 framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and  $\alpha_s$  from the LHeC), LHeC, and FCC-ee.



**significant improvements  
wrt HL-LHC**

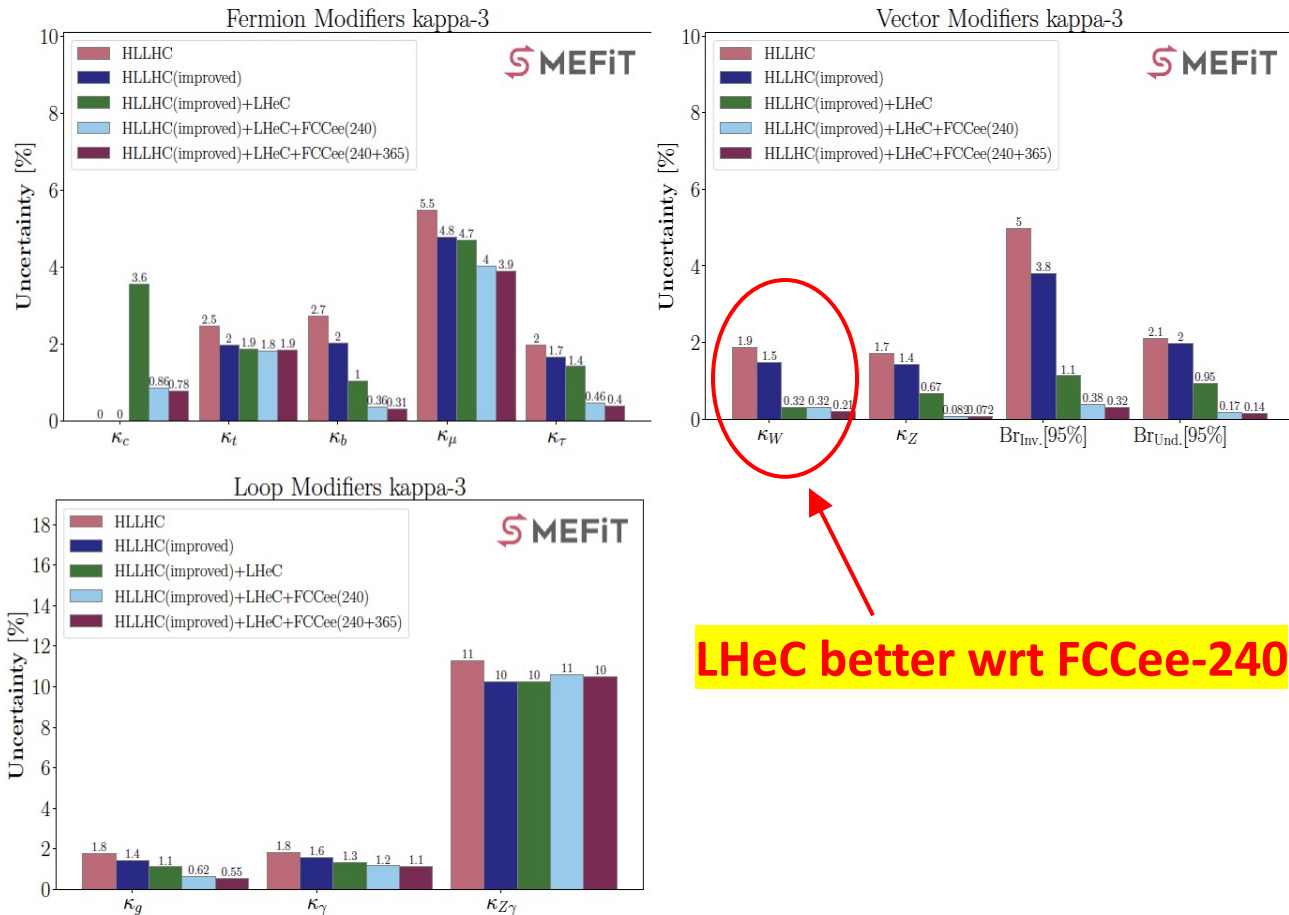
# Some physics highlights: Higgs physics

The LHeC is partially a **Higgs Factory** with several couplings significantly improved over HL-LHC expectations, and some even more accurately compared to FCC-ee at 240 GeV.

- first time ever:  
 $\kappa_c$
- greatly improved:  
 $\kappa_b, \kappa_W, \kappa_Z$
- significantly improved:  
 $\kappa_t, \kappa_\tau, \kappa_g$

Figure:

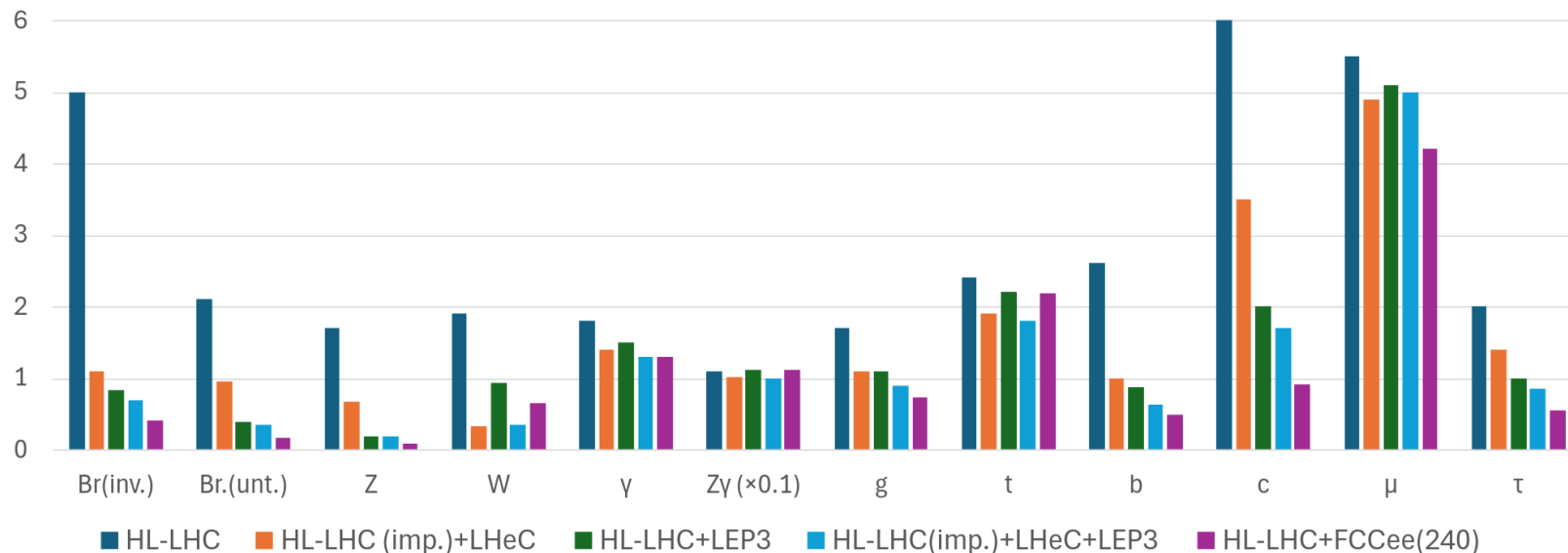
The relative uncertainty on the fermion, vector and loop coupling modifiers obtained in the kappa-3 framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and  $\alpha_s$  from the LHeC), LHeC, and FCC-ee.



# Some physics highlights: Higgs physics

**LHeC combines well with LEP3**

Higgs coupling modifiers kappa-3 in [%], @SMEFiT



# Some physics highlights: gluon distribution

LHeC will further improve the PDF determination in a much larger kinematic region and decrease the uncertainty in  $\alpha_s$  by more than a factor 2 compared to HERA+EIC

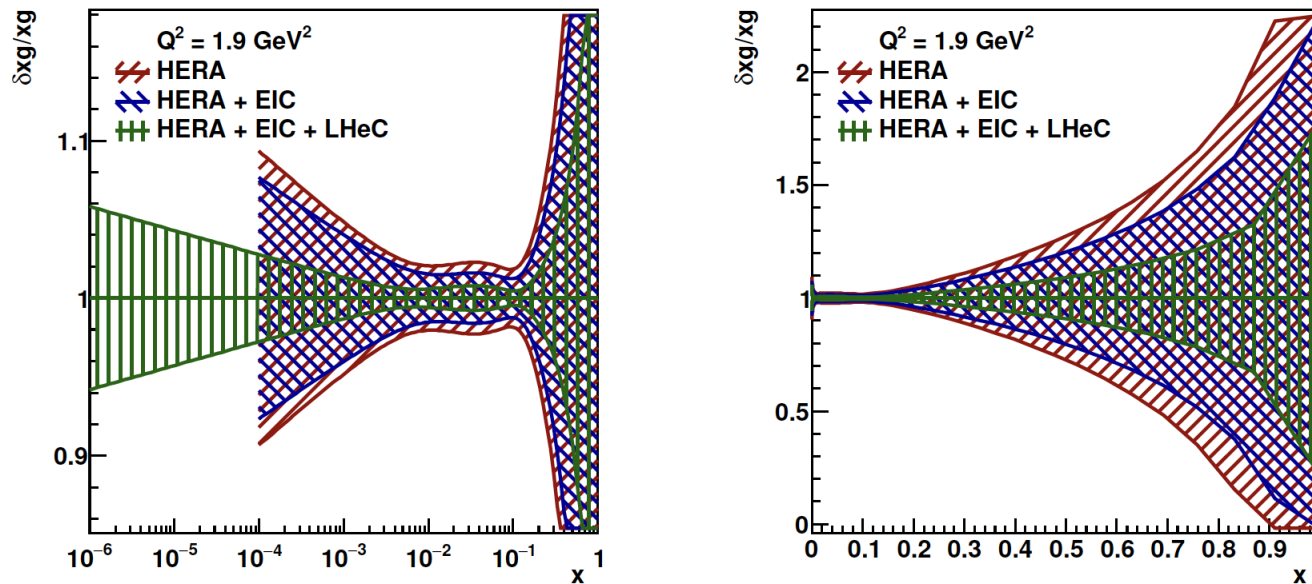
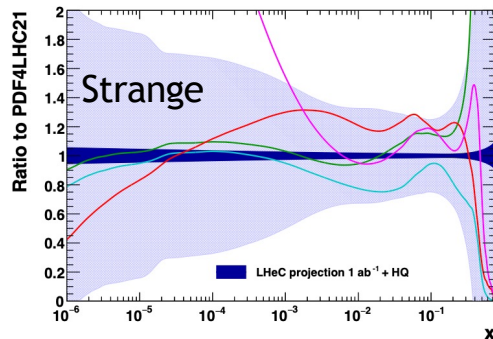
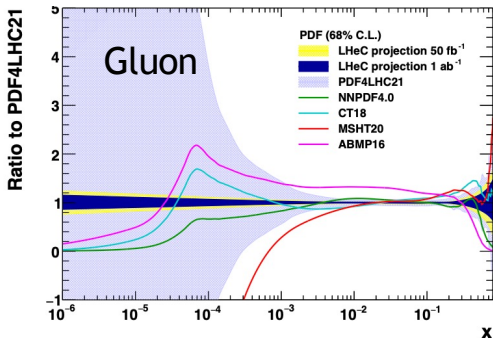
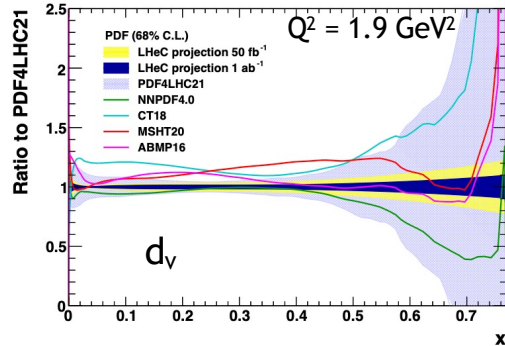


FIG. 13. Uncertainty in the determination of the gluon distribution at  $Q^2 = 1.9 \text{ GeV}^2$  in logarithmic (left) and linear (right) scale in fits to HERA data plus EIC projections plus LHeC [91].

# Proton PDF Precision



- PDF knowledge transformed over wide kinematic range, extending from  $x \sim 10^{-6}$  to  $x \rightarrow 1$

- Resolving current ambiguities

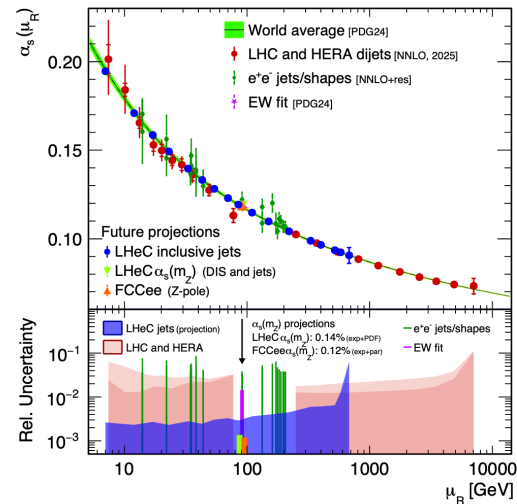
- First full and precise flavour decomposition

-  $\alpha_s$  to 0.14%, including running

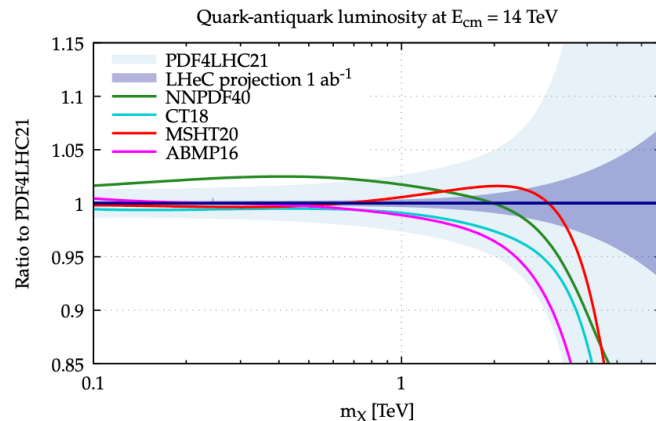
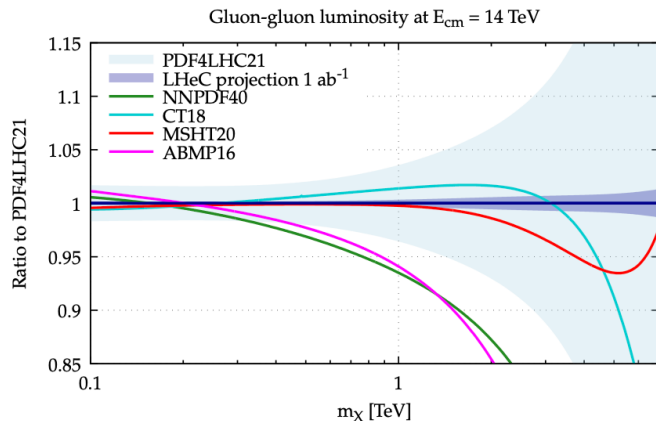
-  $M_W$  to few MeV

-  $\sin^2\theta_W$  to 0.0002 including running

- Best axial and vector Z-light quark couplings



# Enabling HL-LHC: parton lumi's revisited



- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements

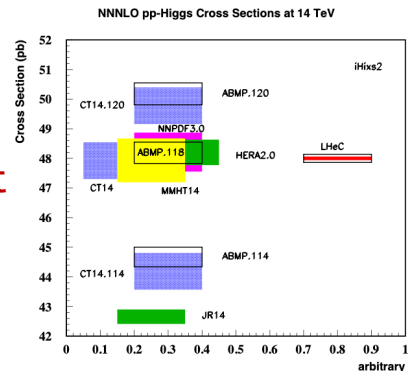
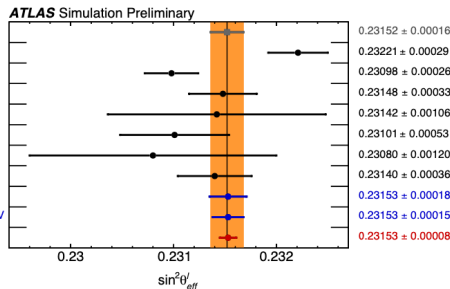
...Theory uncertainty on LHC Higgs cross section

...  $M_W$  PDF systs  $\rightarrow$  2 MeV, enabling 3 MeV measurement

...  $\sin^2\theta_W \rightarrow 0.0008$

...

LEP-1 and SLD: Z-pole average  
 LEP-1 and SLD:  $A_{\text{FB}}^0$   
 SLD:  $A_1$   
 Tevatron  
 LHCb: 7+8 TeV  
 CMS: 8 TeV  
 ATLAS: 7 TeV  
 ATLAS Preliminary: 8 TeV  
 HL-LHC ATLAS CT14: 14 TeV  
 HL-LHC ATLAS PDF4LHC15: 14 TeV  
 HL-LHC ATLAS PDFLHeC: 14 TeV





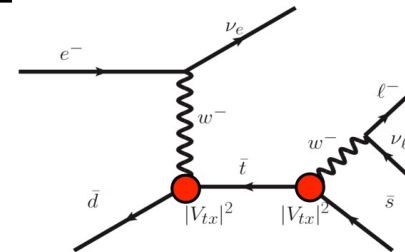
# Expected measurements of $Wtb$ couplings and $V_{tx}$

= 1 in SM

Dutta, Goyal, Kumar, Mellado,  
arXiv:1307.1688  
Kumar, Ruan, to be publ.

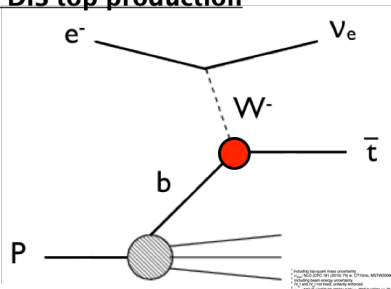
$$L = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_b \left( f_V^L P_L - f_V^R P_R \right) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} \left( f_T^L P_L - f_T^R P_R \right) t W_\mu^- + h.c.$$

| Anomalous $Wtb$ Coupling                         | $f_R^1$      | $f_L^2$      | $f_R^2$      |
|--------------------------------------------------|--------------|--------------|--------------|
| HL-LHC, 3000 fb <sup>-1</sup> ( $\mathcal{R}e$ ) | [-0.28,0.32] | [-0.17,0.19] | [-0.05,0.02] |
| HL-LHC, 3000 fb <sup>-1</sup> ( $\mathcal{I}m$ ) | [-0.30,0.32] | [-0.19,0.18] | [0.11,0.10]  |
| LHeC, 1000 fb <sup>-1</sup> ( $\mathcal{R}e$ )   | [-0.13,0.14] | [-0.05,0.04] | [-0.10,0.09] |

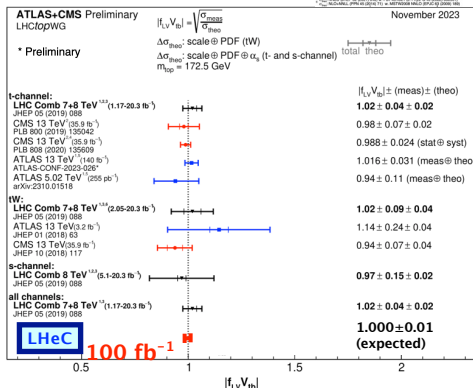
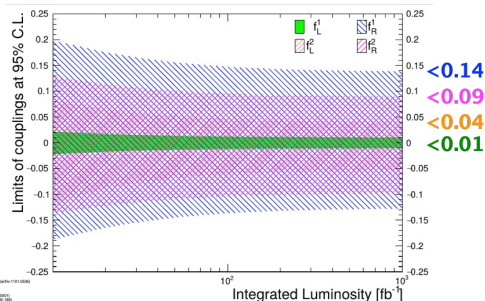


FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019) H. Sun PoS DIS 2018, 167 (2018)

## CC DIS top production

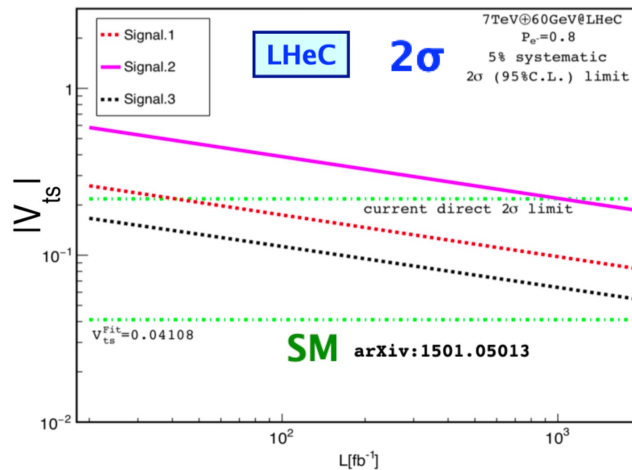


## hadronic channel:



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unprecedented  
precision < 1%



Probing SM prediction directly for the first time

arXiv:1709.07887

LHC

$|V_{ts}| < 0.052$

SM arXiv:1501.05013

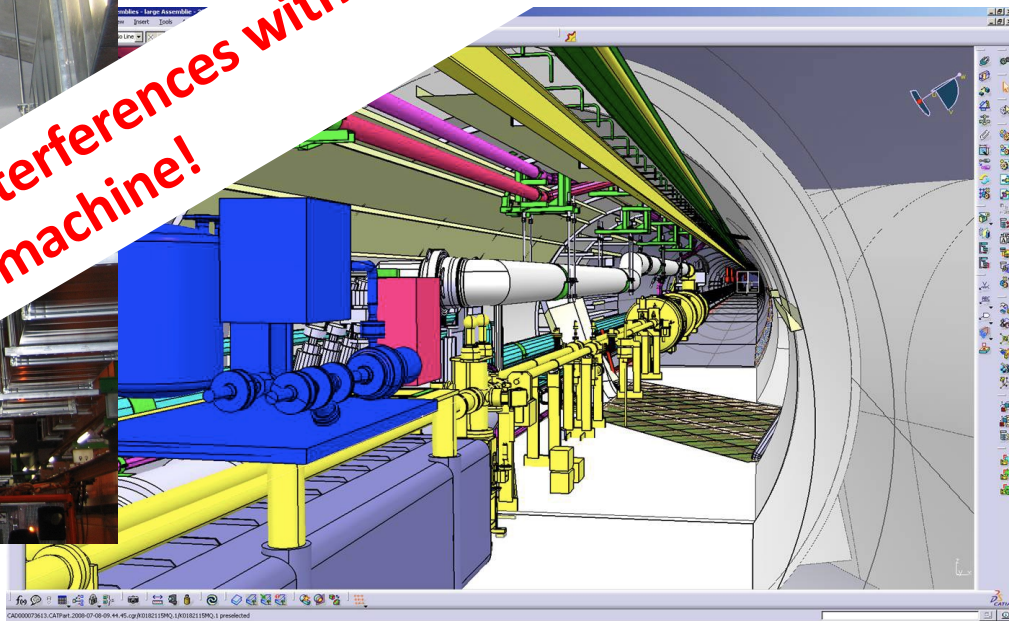
## LHeC – ring-ring versus ring-linac

 Challenge: Integration in the LHC tunnel

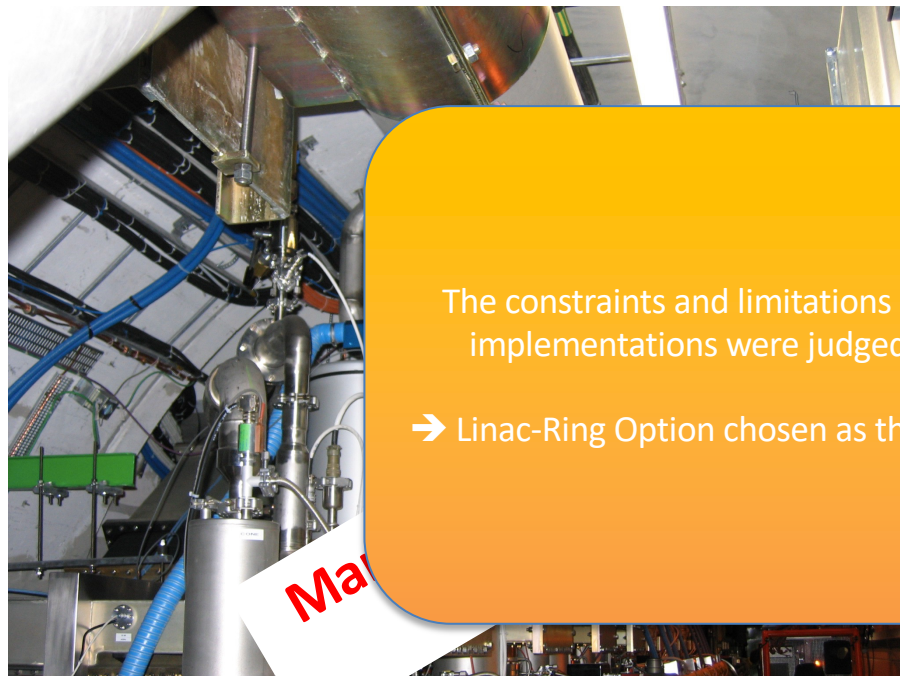


Cryo link in IR3

**Many Obstacles and interferences with existing LHC machine!**



## Challenge: Integration in the LHC tunnel



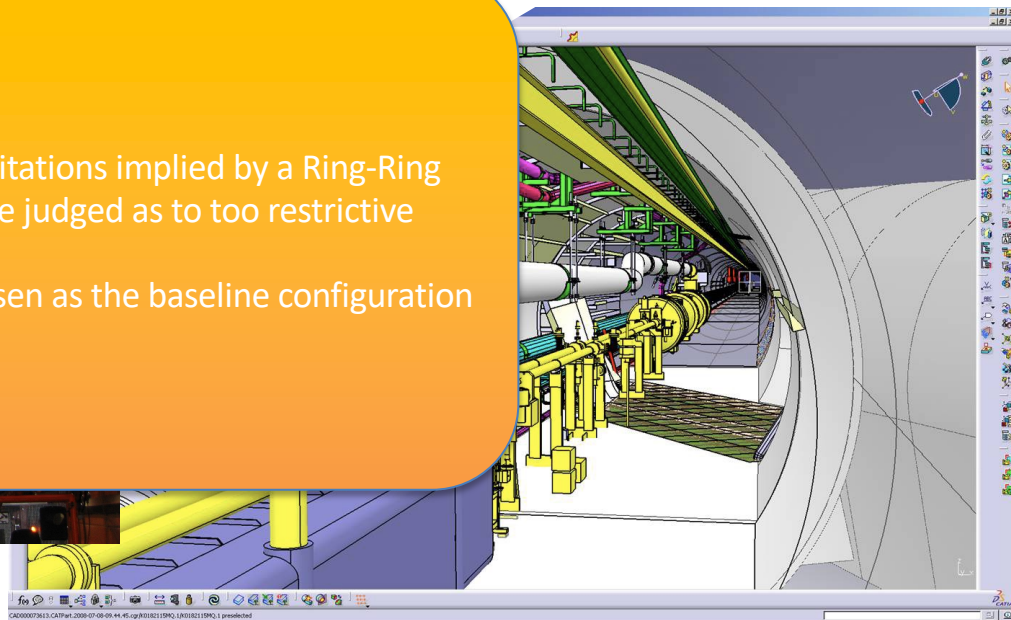
The constraints and limitations implied by a Ring-Ring implementations were judged as too restrictive

→ Linac-Ring Option chosen as the baseline configuration

Ma

Cryo link in IR3

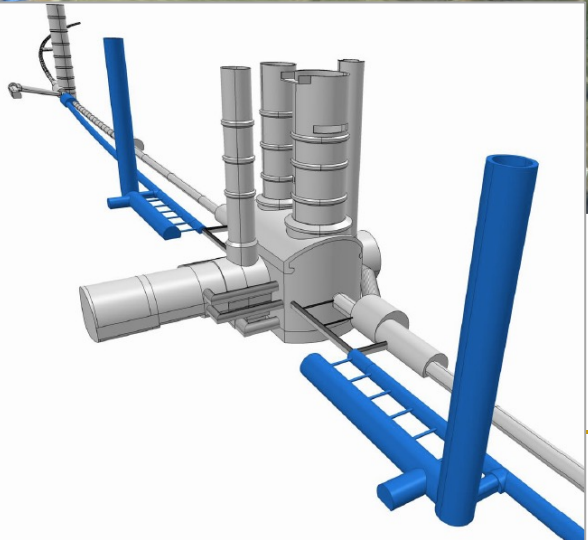
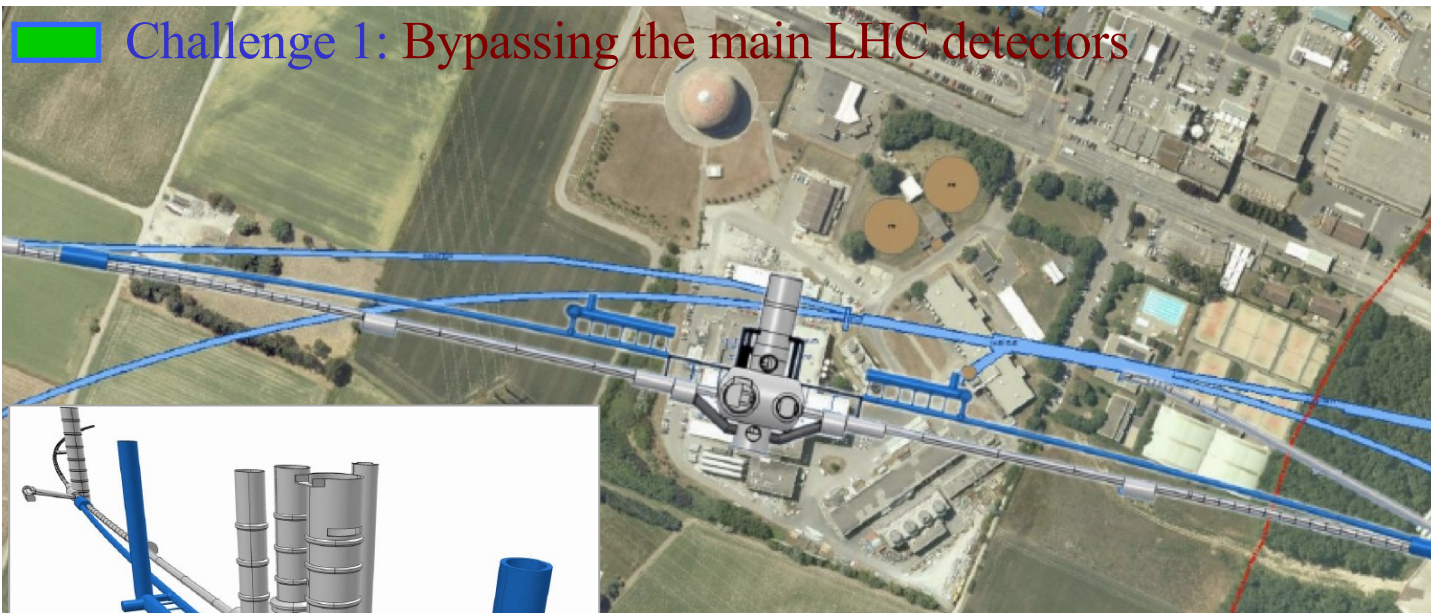
existing LHC





# CDR Choices: LHeC: Ring-Ring Option

Challenge 1: Bypassing the main LHC detectors



Without using the survey gallery the ATLAS bypass would need to be 100m away from the IP or on the inside of the tunnel!

For the CDR the bypass concepts were decided to be confined to ATLAS and CMS

ca. 1.3 km long bypass  
ca. 170m long dispersion free area for RF

Oliver Brüning, CERN