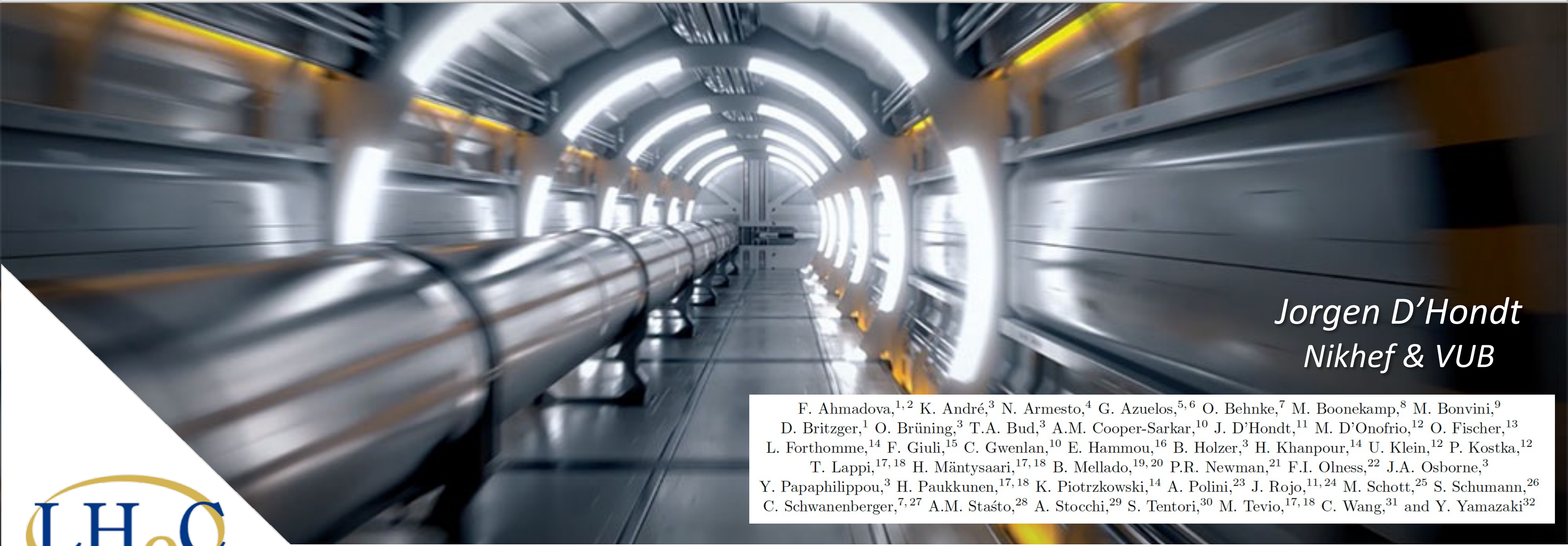
The Large Hadron electron Collider (LHeC)

as an alternative or bridge project between major colliders at CERN



Jorgen D'Hondt
Nikhef & VUB

F. Ahmadova,[1,2] K. André,[3] N. Armesto,[4] G. Azuelos,[5,6] O. Behnke,[7] M. Boonekamp,[8] M. Bonvini,[9] D. Britzger,[1] O. Brüning,[3] T.A. Bud,[3] A.M. Cooper-Sarkar,[10] J. D'Hondt,[11] M. D'Onofrio,[12] O. Fischer,[13] L. Forthomme,[14] F. Giuli,[15] C. Gwenlan,[10] E. Hammou,[16] B. Holzer,[3] H. Khanpour,[14] U. Klein,[12] P. Kostka,[12] T. Lappi,[17,18] H. Mäntysaari,[17,18] B. Mellado,[19,20] P.R. Newman,[21] F.I. Olness,[22] J.A. Osborne,[3] Y. Papaphilippou,[3] H. Paukkunen,[17,18] K. Piotrzkowski,[14] A. Polini,[23] J. Rojo,[11,24] M. Schott,[25] S. Schumann,[26] C. Schwanenberger,[7,27] A.M. Staśto,[28] A. Stocchi,[29] S. Tentori,[30] M. Tevio,[17,18] C. Wang,[31] and Y. Yamazaki[32]

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.*

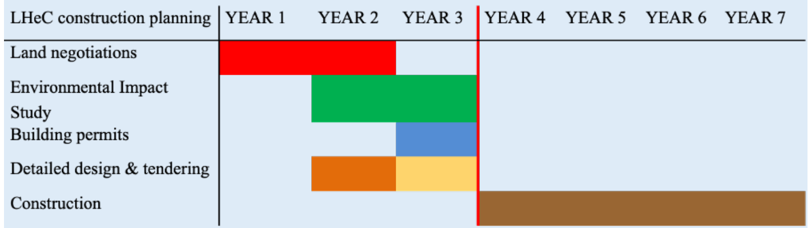
Karl Jakobs introduction slides

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

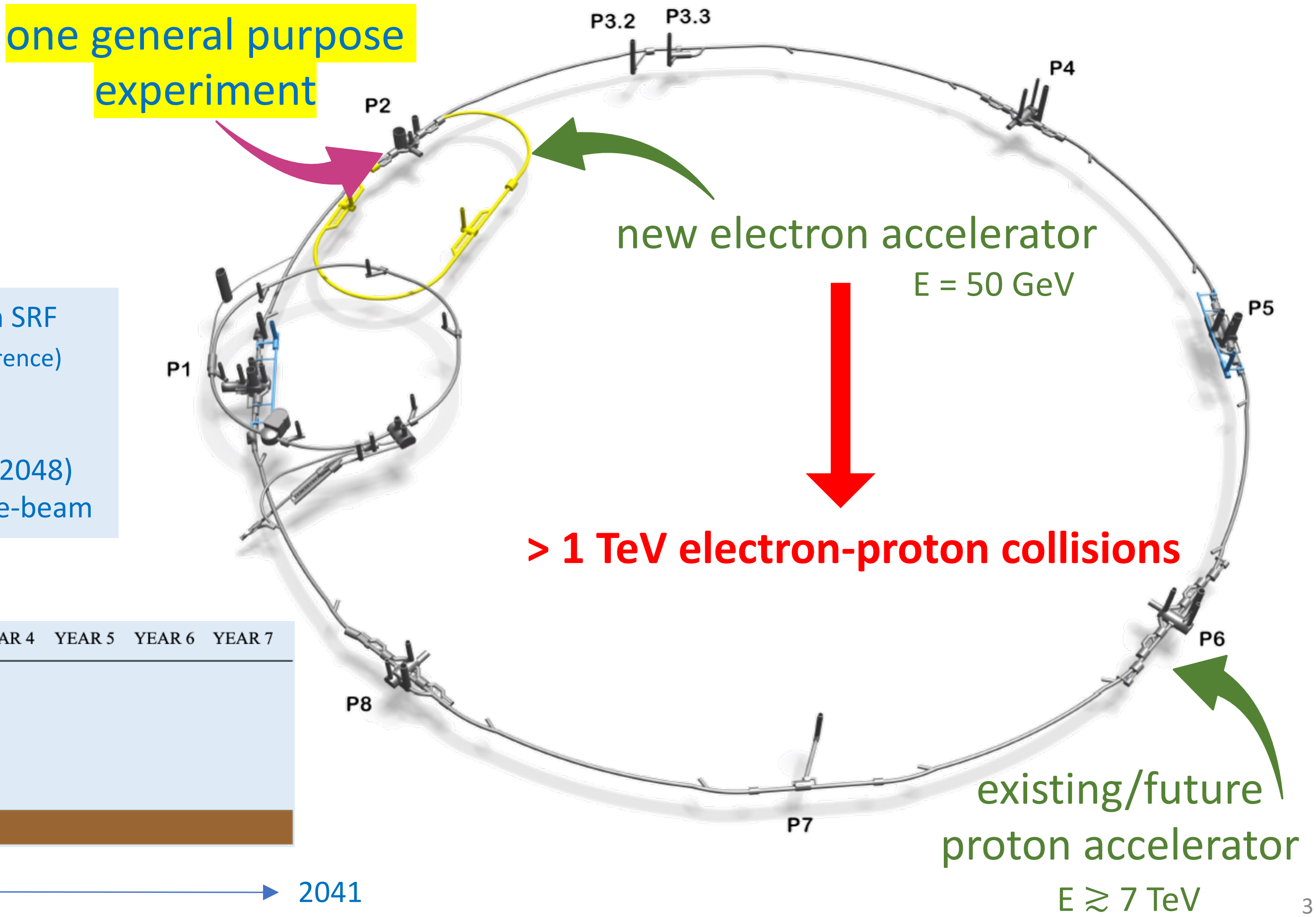
LHeC – parameters, timeline, resources, energy consumption

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

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} $cm^{-2}s^{-1}$
6 years of operation, 1 ab^{-1} (e.g. 2043-2048)
120MW from HL-LHC + 100MW from e-beam



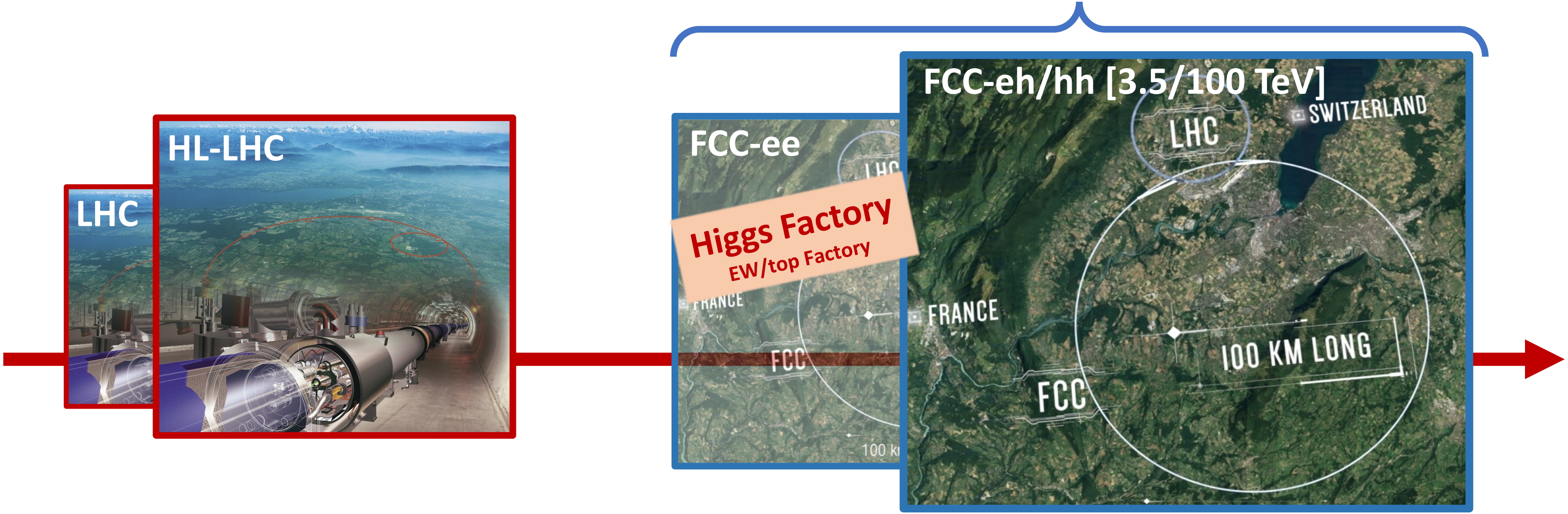
for example 2034 → 2041



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



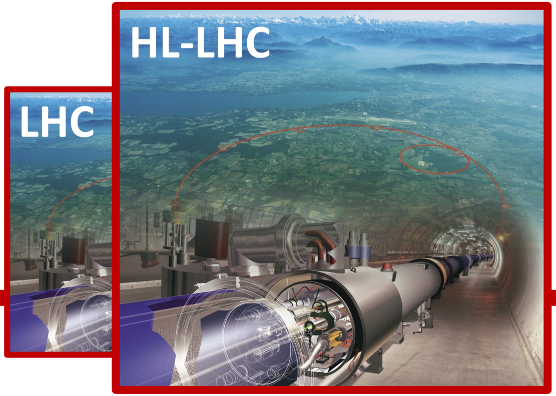
Flagships at the energy & precision frontier

Current flagship (27km)

impressive program up to 2041

cost ~2 BCHF ⊕ one detector

operational cost similar to HL-LHC

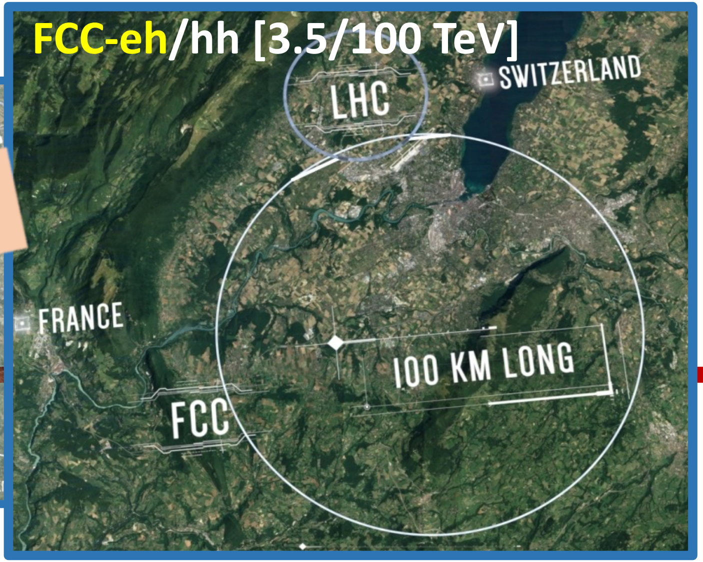


*ep-option after HL-LHC: **LHeC***

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

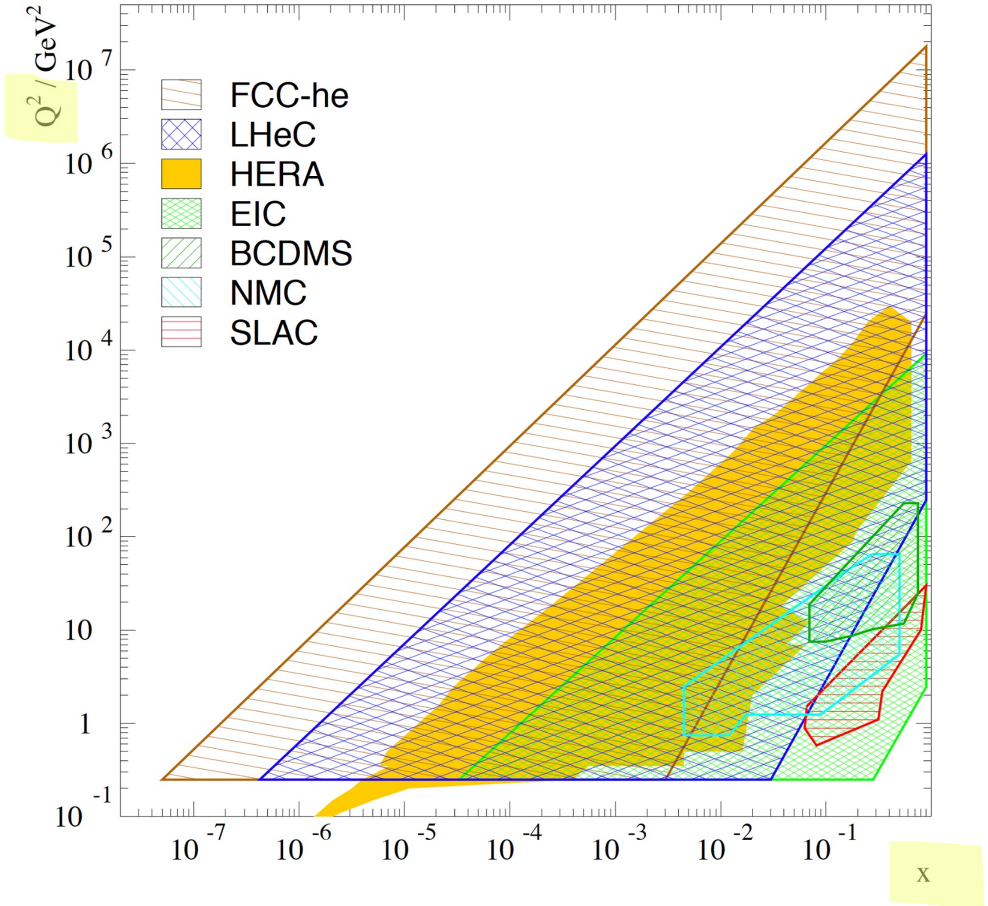
PERLE as ESPP’26 input
https://indico.cern.ch/event/1439855/contributions/6461453/

Other LHeC related input to ESPP’26
https://indico.cern.ch/event/1439855/contributions/6461558/
https://indico.cern.ch/event/1439855/contributions/6461469/

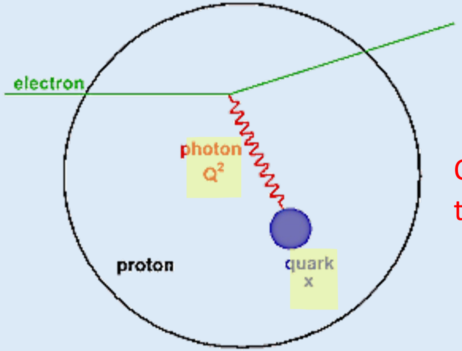
Indico website
https://indico.cern.ch/e/LHeCFCCeh

The LHeC physics

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



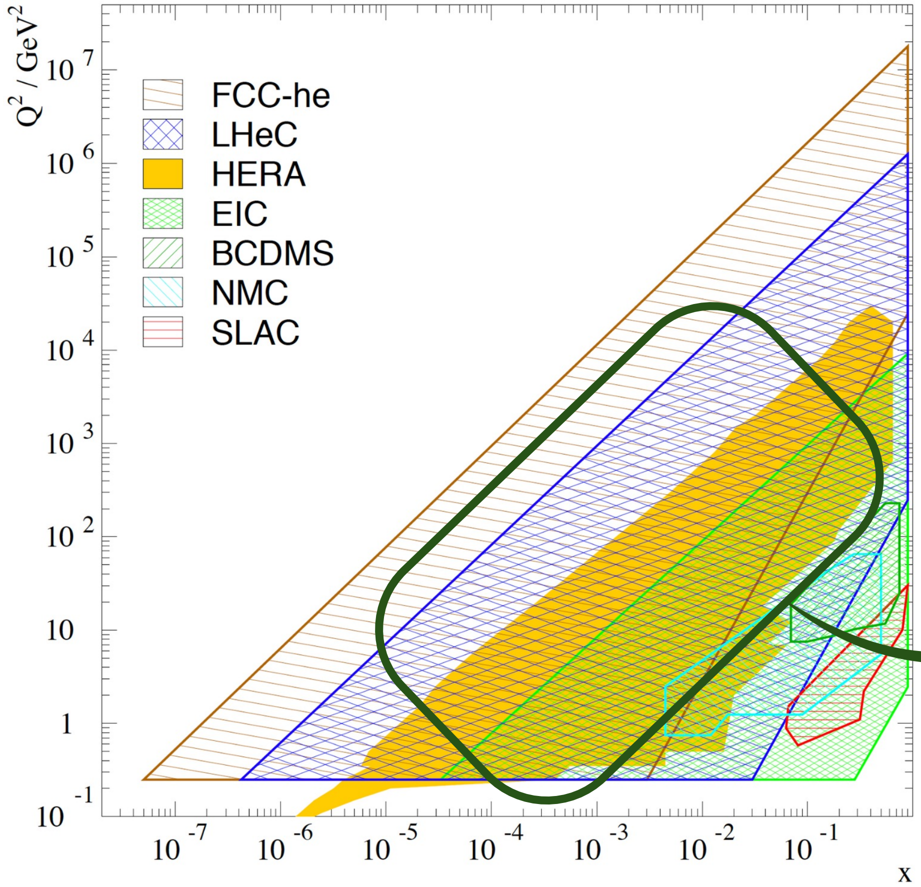
Deep Inelastic Scattering (DIS)



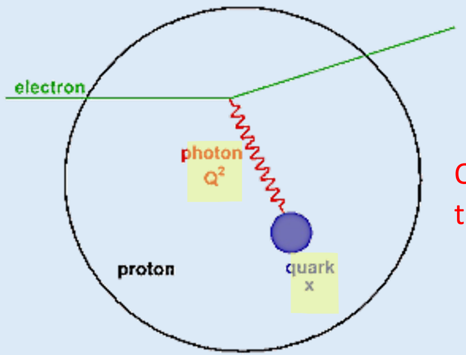
Q^2 = momentum transfer squared

x = fraction of proton's longitudinal momentum carried by the parton

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



Deep Inelastic Scattering (DIS)



Q^2 = momentum transfer squared

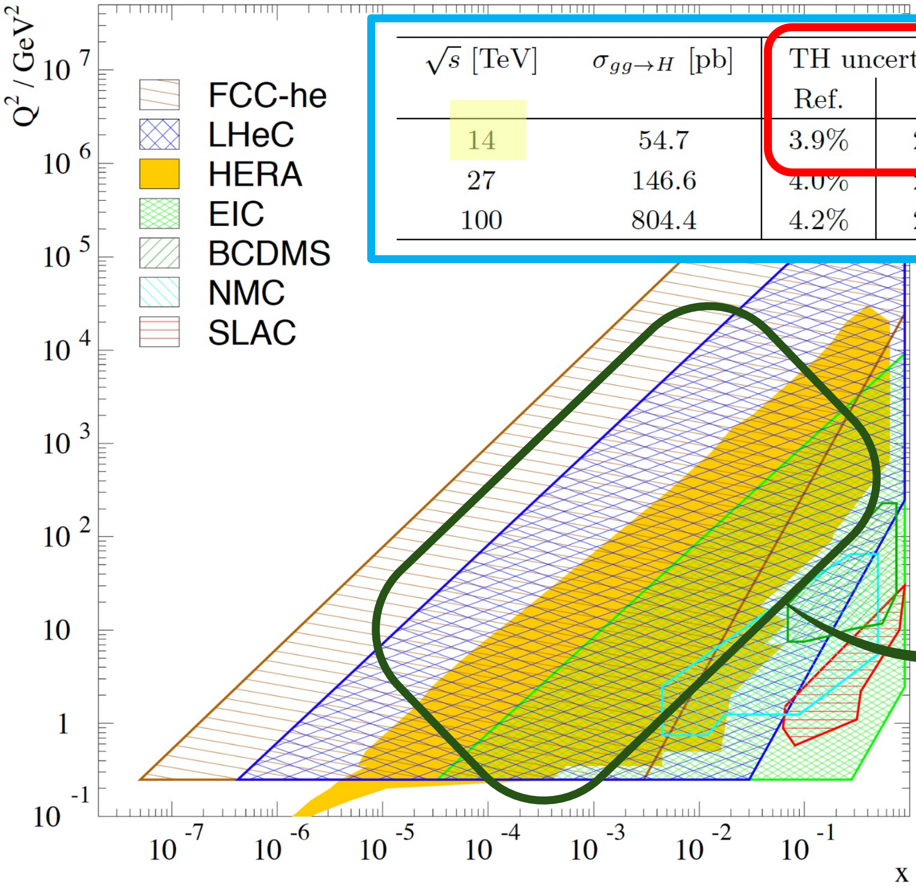
x = fraction of proton's longitudinal momentum carried by the parton

precision QCD physics

$\Delta\alpha_s \sim 0.14\%$ & running of α_s

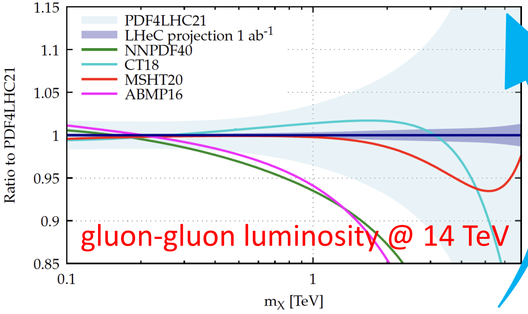
complete unfolding of PDFs covering a vast kinematic range

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



marginalising
PDF+α_s uncertainties

$\sqrt{s}$ [TeV]	$\sigma_{gg\to H}$ [pb]	TH uncertainty		PDF+α_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%



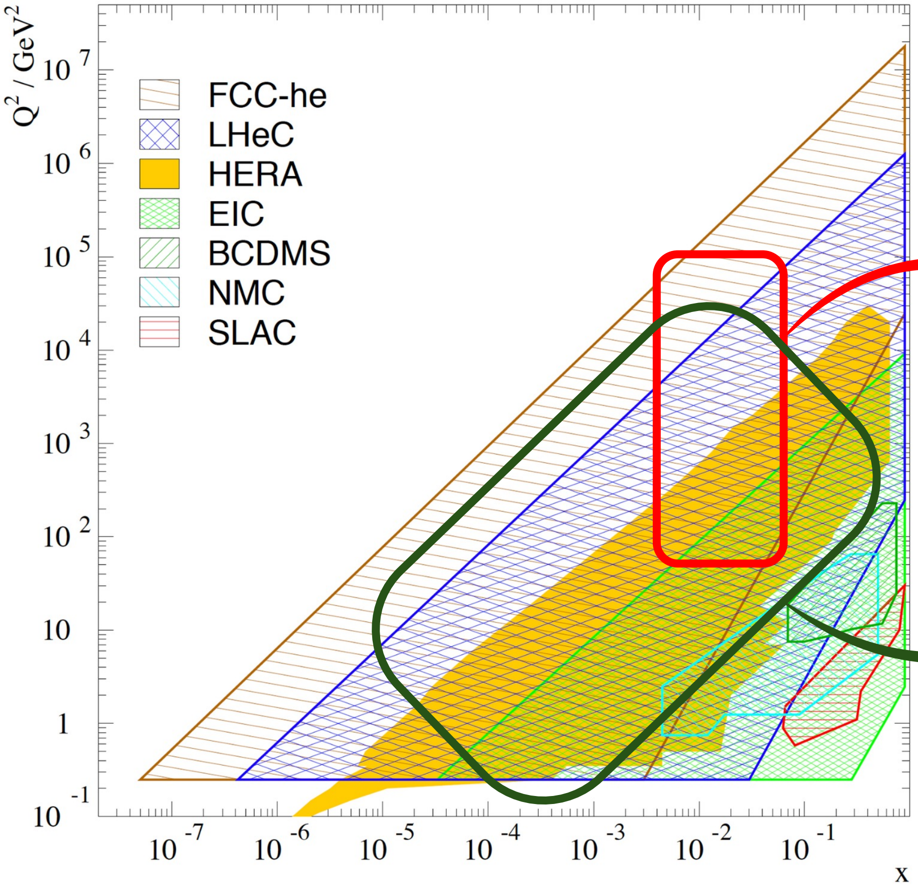
LHeC empowering gg→H @ (HL-)LHC

precision QCD physics

$\Delta\alpha_s \sim 0.14\%$ & running of α_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

Δm_W^{LHC} ~ 3 MeV, $\Delta|V_{tb}|$ ~ 1%, top-quark FCNC

$\Delta \sin^2\theta_W^{eff}$ ~ 0.0002 (full scale-dependency)

weak neutral couplings to light quarks ~ 1%

Higgs couplings largely improved wrt HL-LHC

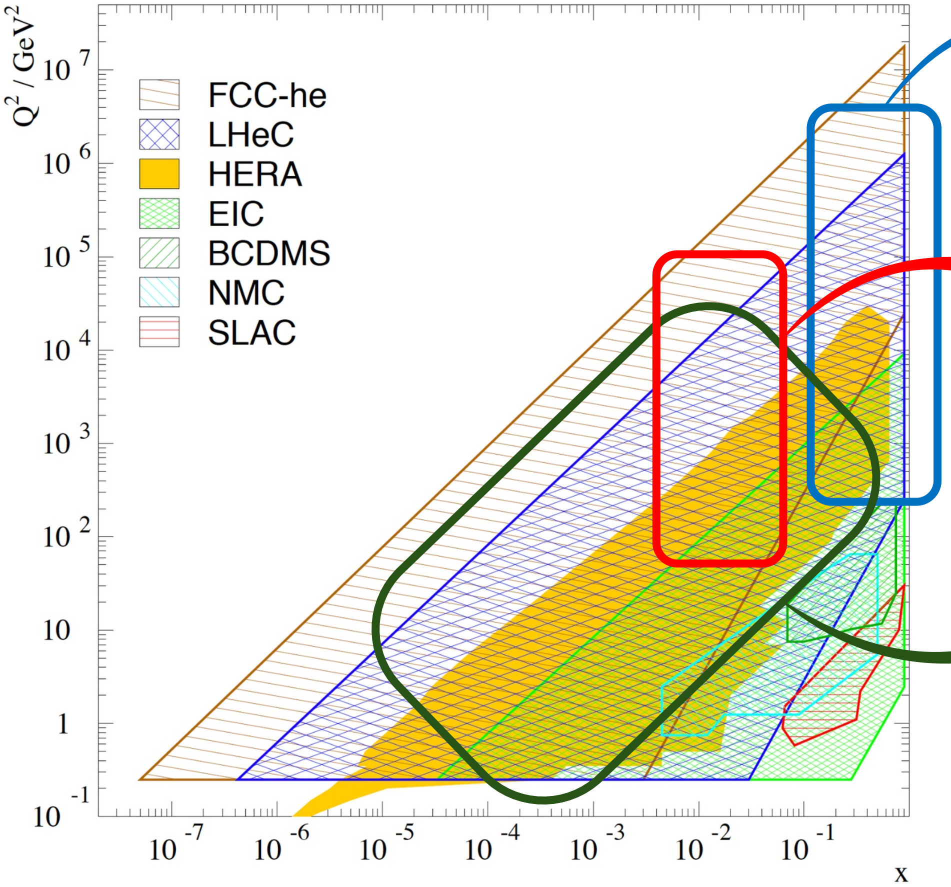
improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s$ ~ 0.14% & running of α_s

complete unfolding of PDFs covering a vast kinematic range

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 ν, dark γ, axion-like particles

EW, Higgs and top quark physics

Δm_W^{LHC} ~ 3 MeV, $\Delta|V_{tb}|$ ~ 1%, top-quark FCNC

$\Delta \sin^2\theta_W^{eff}$ ~ 0.0002 (full scale-dependency)

weak neutral couplings to light quarks ~ 1%

Higgs couplings largely improved wrt HL-LHC

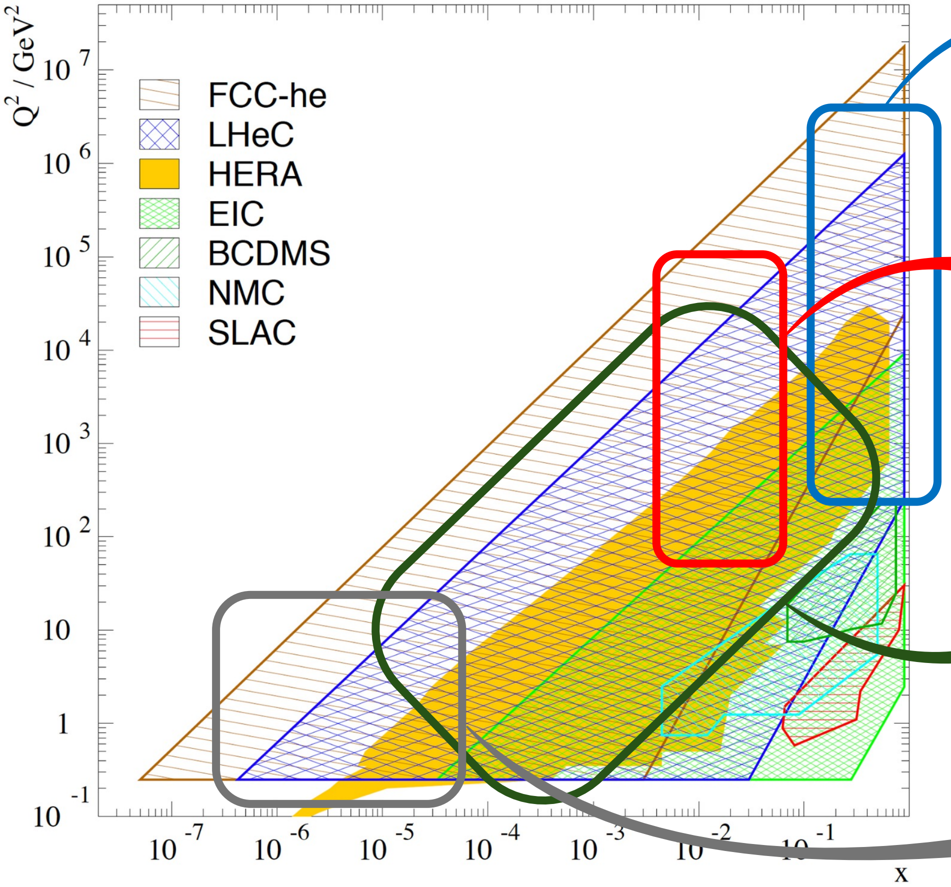
improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s$ ~ 0.14% & running of α_s

complete unfolding of PDFs covering a vast kinematic range

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 ν, dark γ, axion-like particles

EW, Higgs and top quark physics

Δm_W^{LHC} ~ 3 MeV, $\Delta|V_{tb}|$ ~ 1%, top-quark FCNC

$\Delta \sin^2\theta_W^{eff}$ ~ 0.0002 (full scale-dependency)

weak neutral couplings to light quarks ~ 1%

Higgs couplings largely improved wrt HL-LHC

improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s$ ~ 0.14% & running of α_s

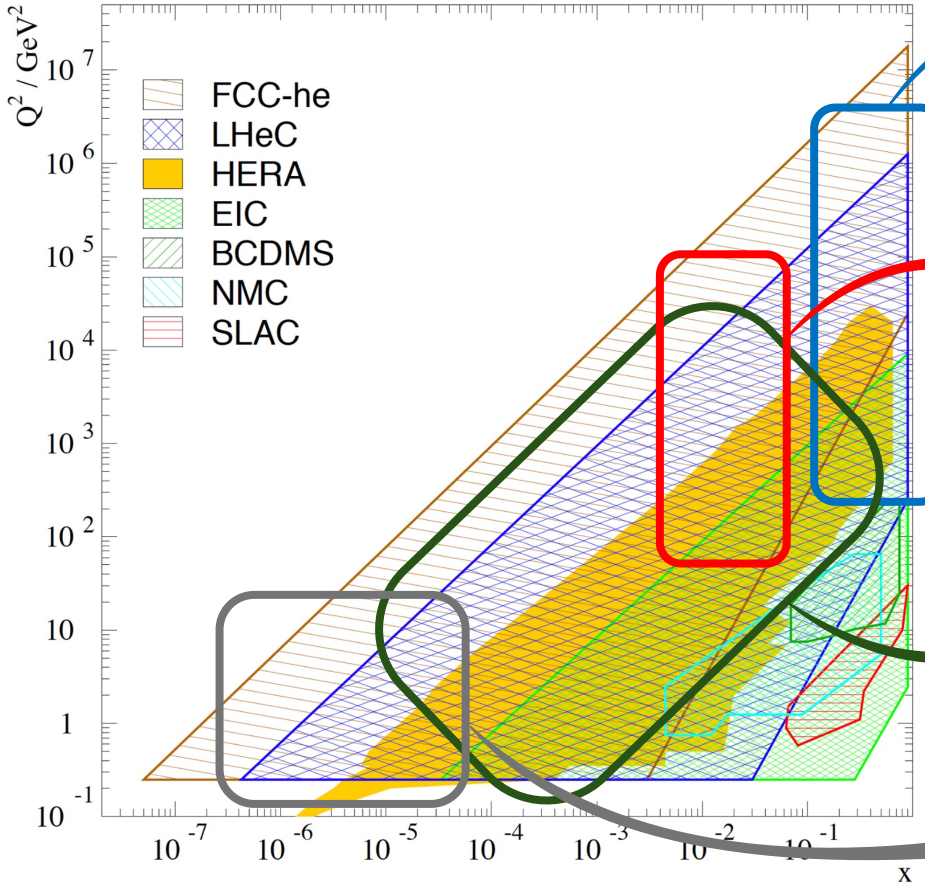
complete unfolding of PDFs covering a vast kinematic range

non-linear QCD physics

a new discovery frontier

LHeC

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



direct searches for new physics

unique environment: eq only EW interactions

e.g. heavy ν, dark γ, axion-like particles

EW, Higgs and top quark physics

Δm_W^{LHC} ~ 3 MeV, $\Delta|V_{tb}|$ ~ 1%, top-quark FCNC

$\Delta\sin^2\theta_W^{eff}$ ~ 0.0002 (full scale-dependency)

weak neutral couplings to light quarks ~ 1%

Higgs couplings largely improved wrt HL-LHC

improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s$ ~ 0.14% & running of α_s

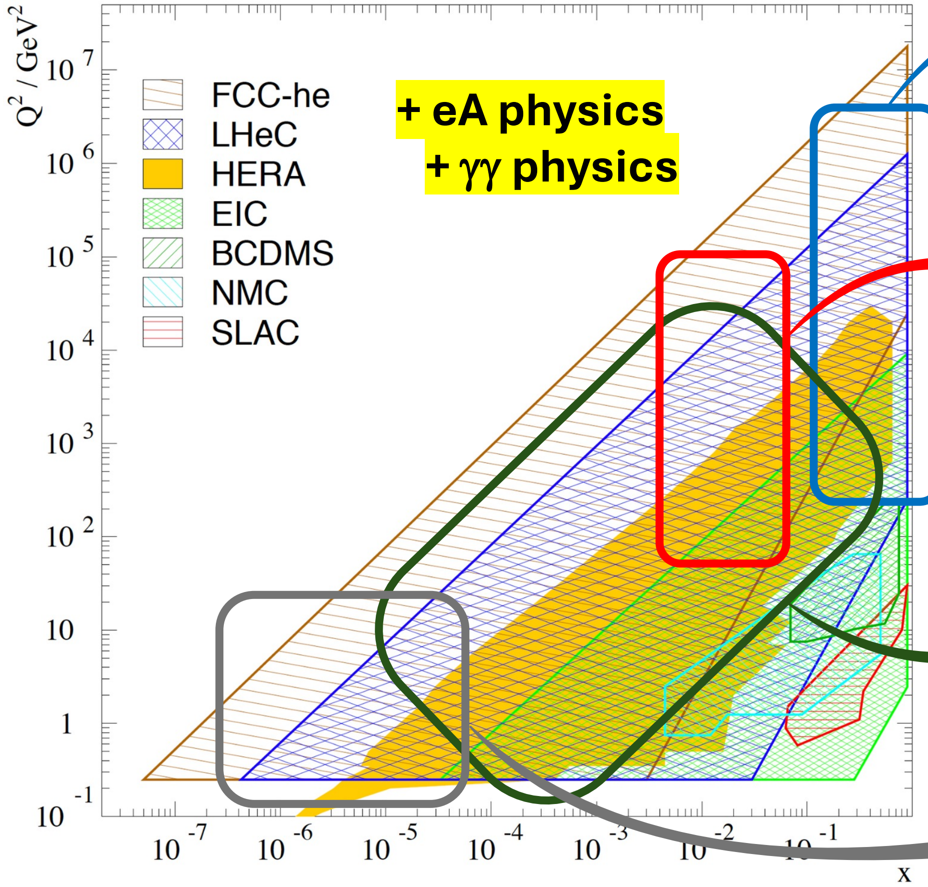
complete unfolding of PDFs covering a vast kinematic range

non-linear QCD physics

a new discovery frontier

LHeC

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



direct searches for new physics

unique environment: eq only EW interactions

e.g. heavy ν, dark γ, axion-like particles

EW, Higgs and top quark physics

$\Delta m_W^{LHC} \sim 3$ MeV, $\Delta|V_{tb}| \sim 1\%$, top-quark FCNC

$\Delta \sin^2\theta_W^{eff} \sim 0.0002$ (full scale-dependency)

weak neutral couplings to light quarks ~ 1%

Higgs couplings largely improved wrt HL-LHC

improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s \sim 0.14\%$ & running of α_s

complete unfolding of PDFs covering a vast kinematic range

non-linear QCD physics

a new discovery frontier

Some physics highlights: strong coupling constant

Measurement of a key SM parameter

- **α_s value at m_Z**: great relative accuracy of 0.14%
- **α_s running**: great accuracy over a very width range of energy scales
- unique opportunity with the LHeC

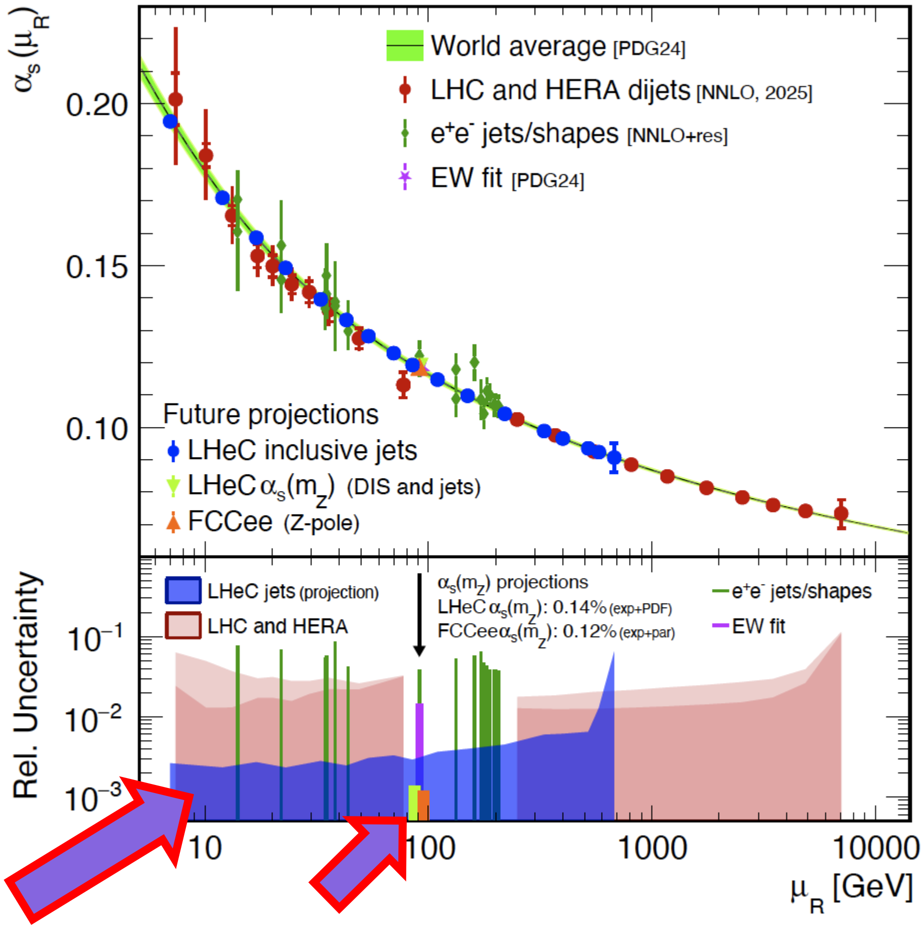


Figure:
The lower panel displays relative uncertainties on $\alpha_s(\mu_R)$, where light-shaded areas show experimental plus theoretical uncertainties and dark shaded areas experimental uncertainties only.

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

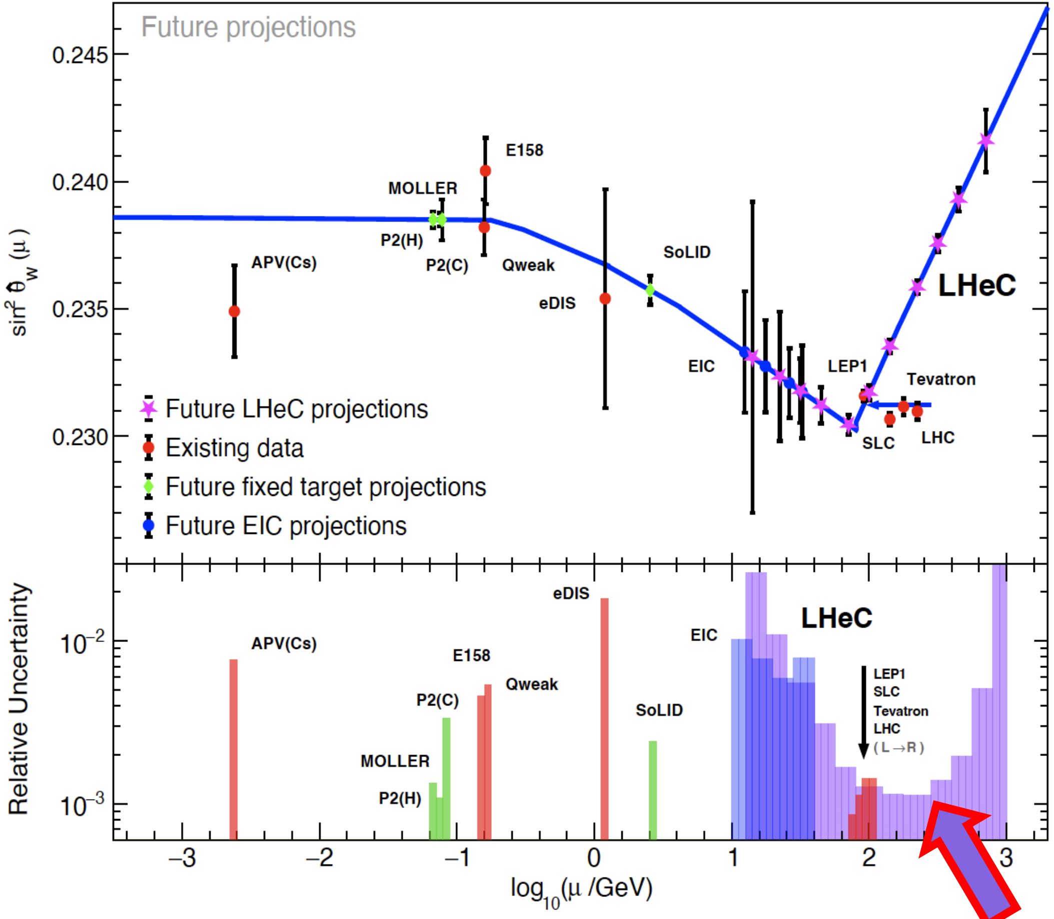
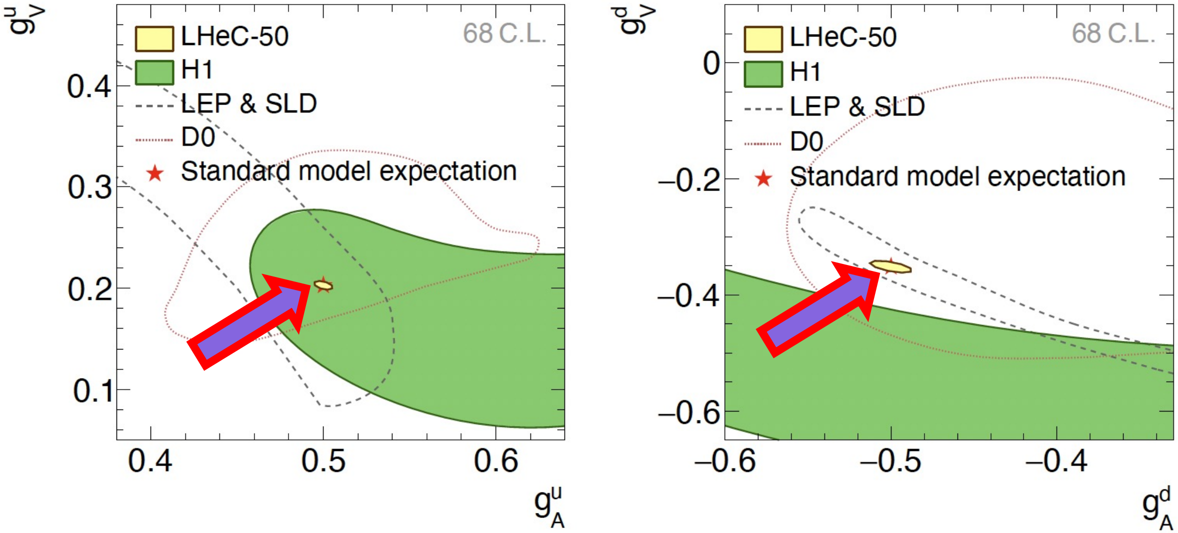


Figure:
Present and future measurements of the running of the weak mixing angle in the MS scheme and prospected uncertainties as a function of the scale μ. The red markers and red uncertainties show present measurements and their relative uncertainties, respectively, and further data points display future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

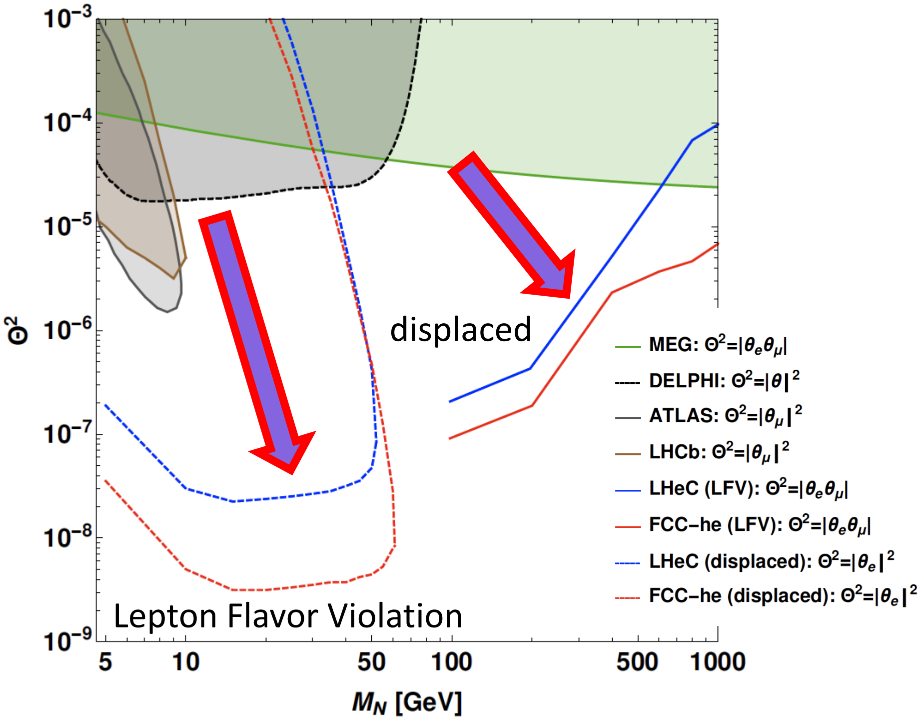
- **Vector and axial-vector couplings to light quarks**: percent level precision
- unique opportunity with the LHeC



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 $|\theta_e|^2$.

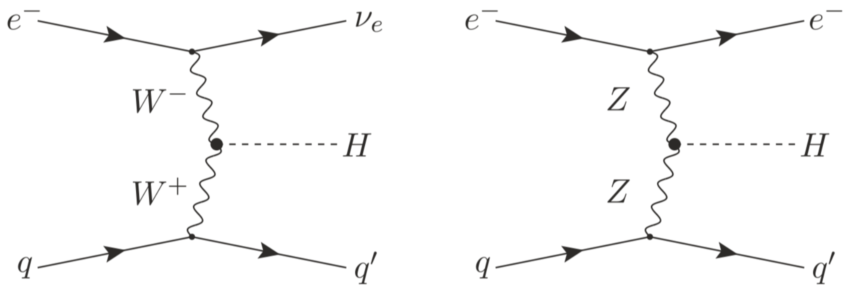
The most promising channels involve Lepton Flavor Violation (LFV) and displaced vertices for which the discovery reach is illustrated in the coupling versus mass plane in the figure, with the full and dashed lines respectively.



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:
  κ_c
- greatly improved:
  κ_b, κ_W, κ_Z
- significantly improved:
  κ_t, κ_τ, κ_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.

- first time ever: κ_c
- greatly improved: κ_b, κ_W, κ_Z
- significantly improved: κ_t, κ_τ, κ_g

significant improvements wrt HL-LHC

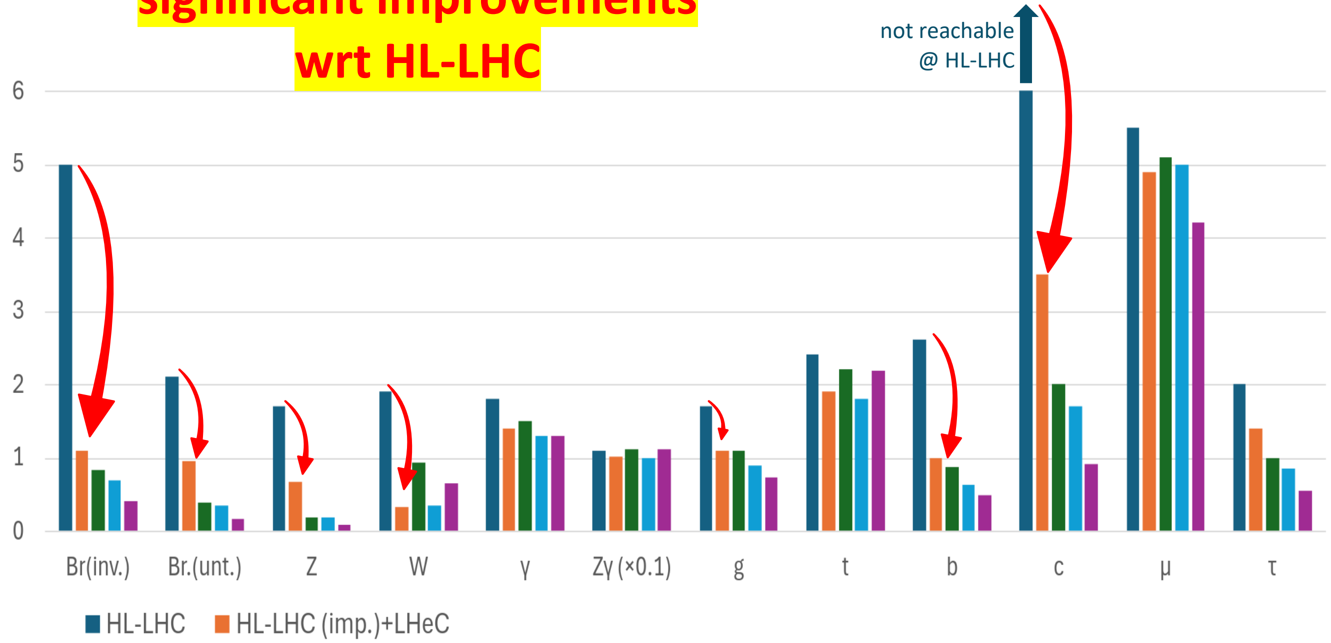


Figure:
The relative uncertainty on the coupling modifiers obtained in the kappa-3 SMEFiT framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and α_s from the LHeC), LHeC, LEP3 and FCC-ee.

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:
  κ_c
- greatly improved:
  κ_b, κ_W, κ_Z
- significantly improved:
  κ_t, κ_τ, κ_g

LHeC combines well with LEP3

wrt FCCee(240)

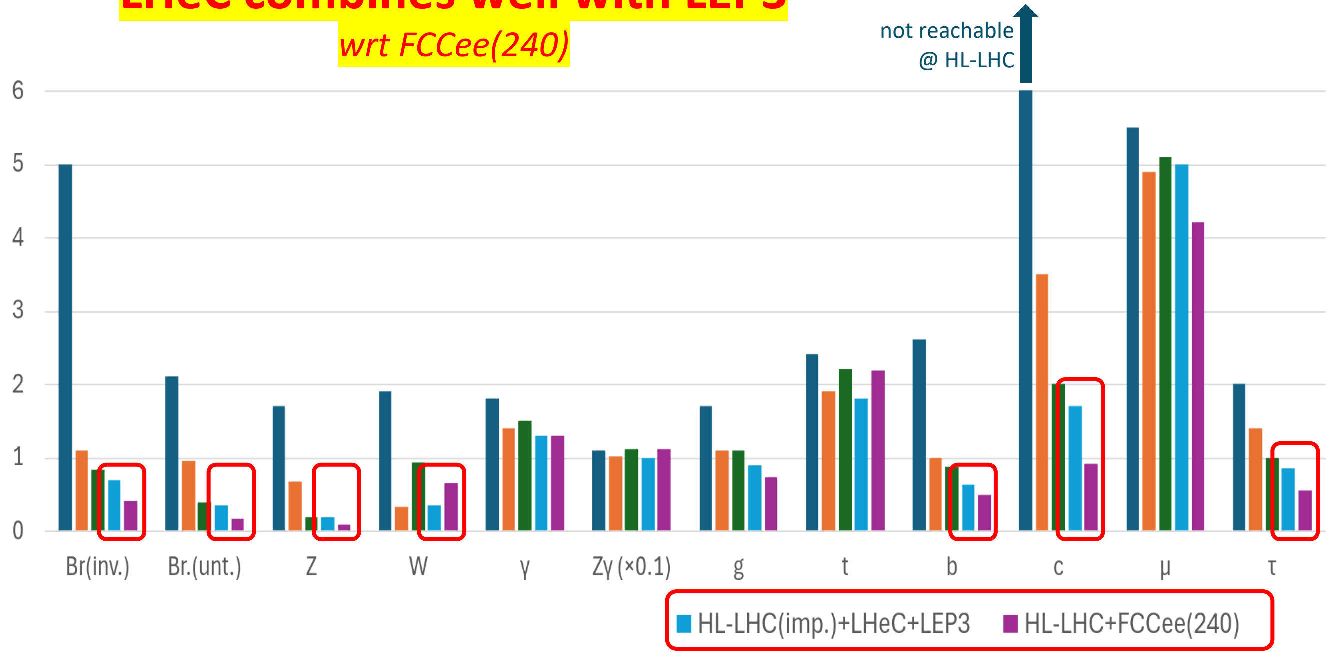


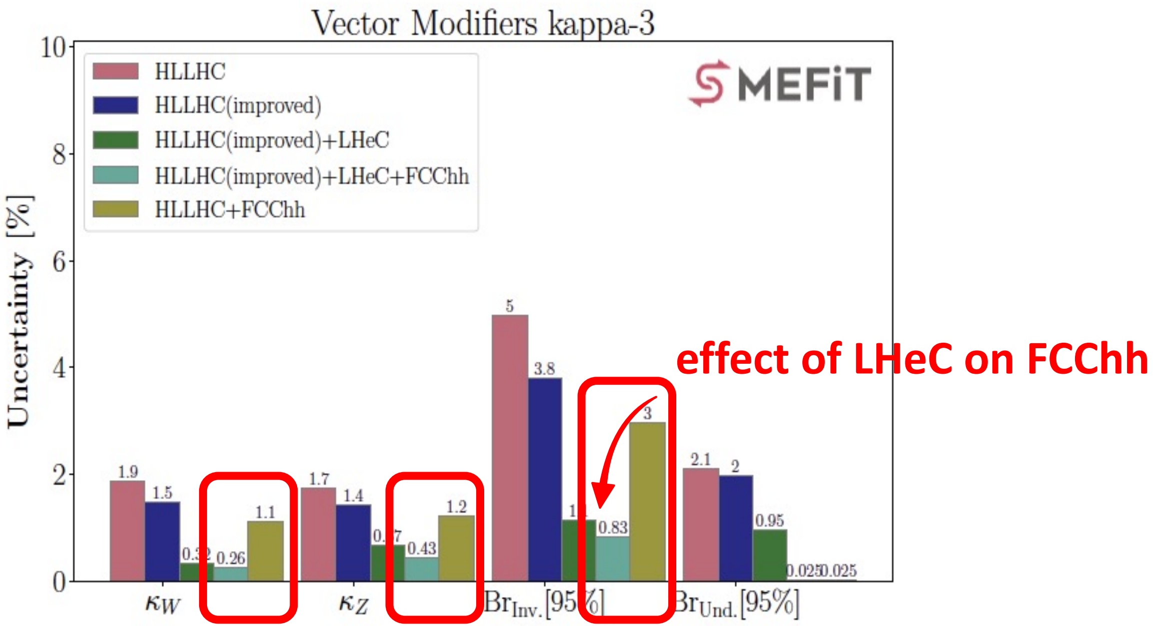
Figure:
The relative uncertainty on the coupling modifiers obtained in the kappa-3 SMEFiT framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and α_s from the LHeC), LHeC, LEP3 and FCC-ee.

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

Some physics highlights: Higgs physics

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

example



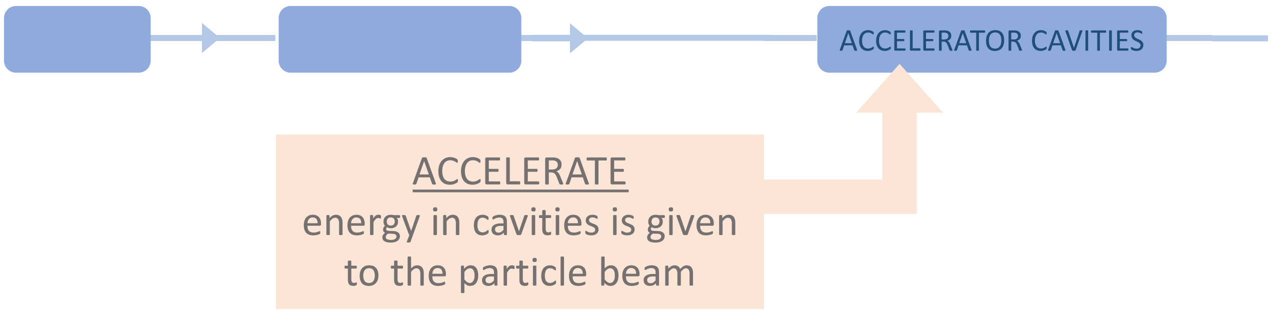
many thanks to the SMEFiT authors (esp. Simone Tentori), *2105.00006*

Key accelerator technology for the LHeC

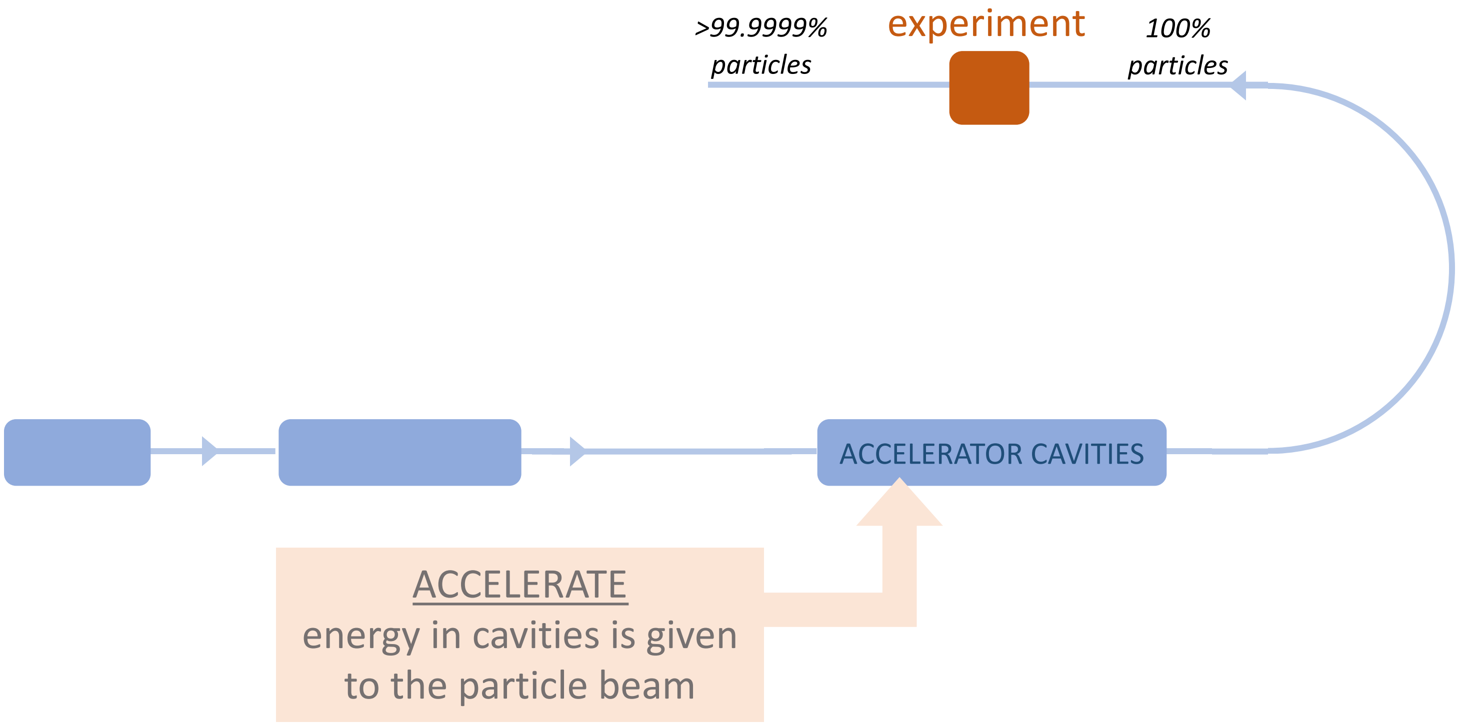
operate a 1000 MW electron beam with only 100 MW of power

need to use the Energy Recovery Linac technology

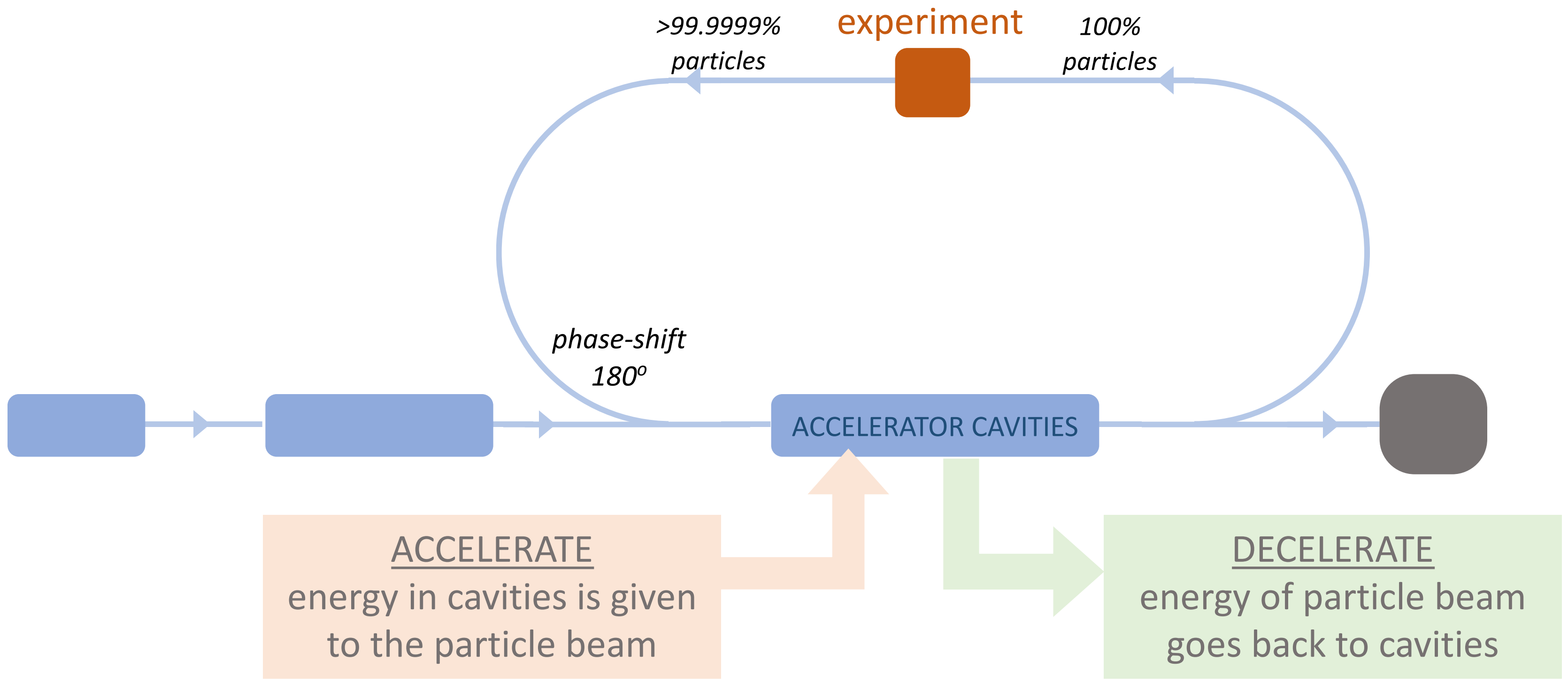
The principle of Energy Recovery



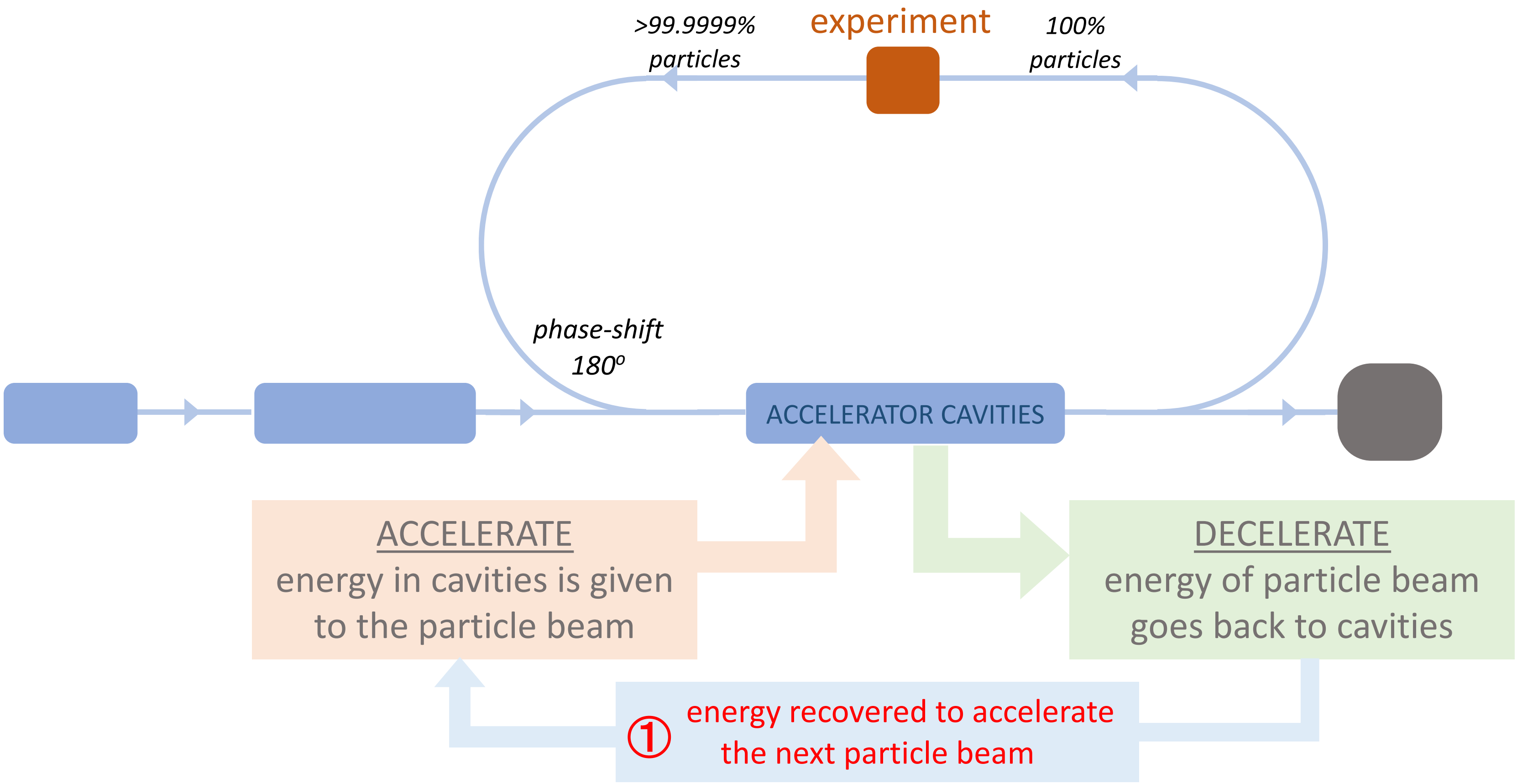
The principle of Energy Recovery



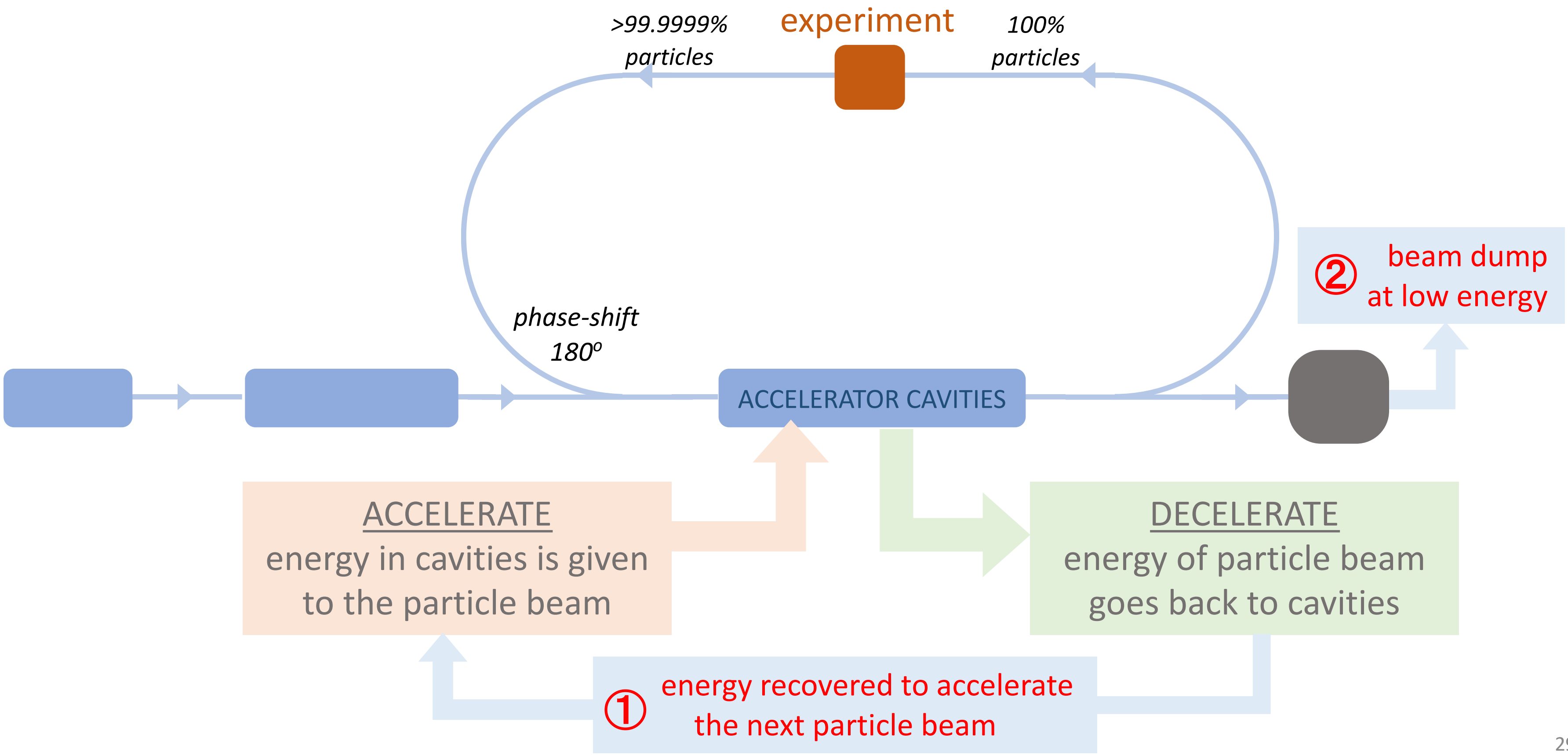
The principle of Energy Recovery



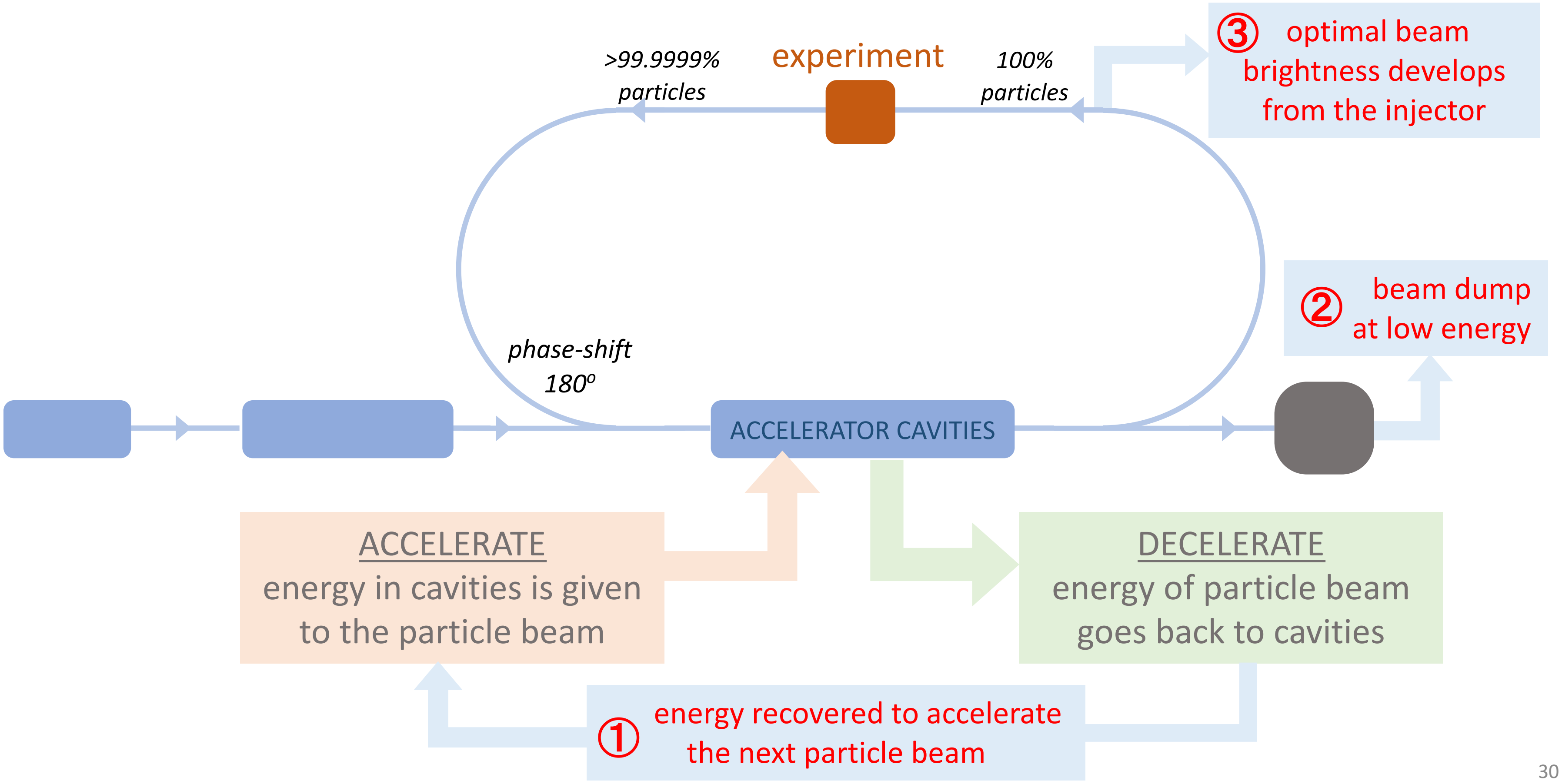
The principle of Energy Recovery



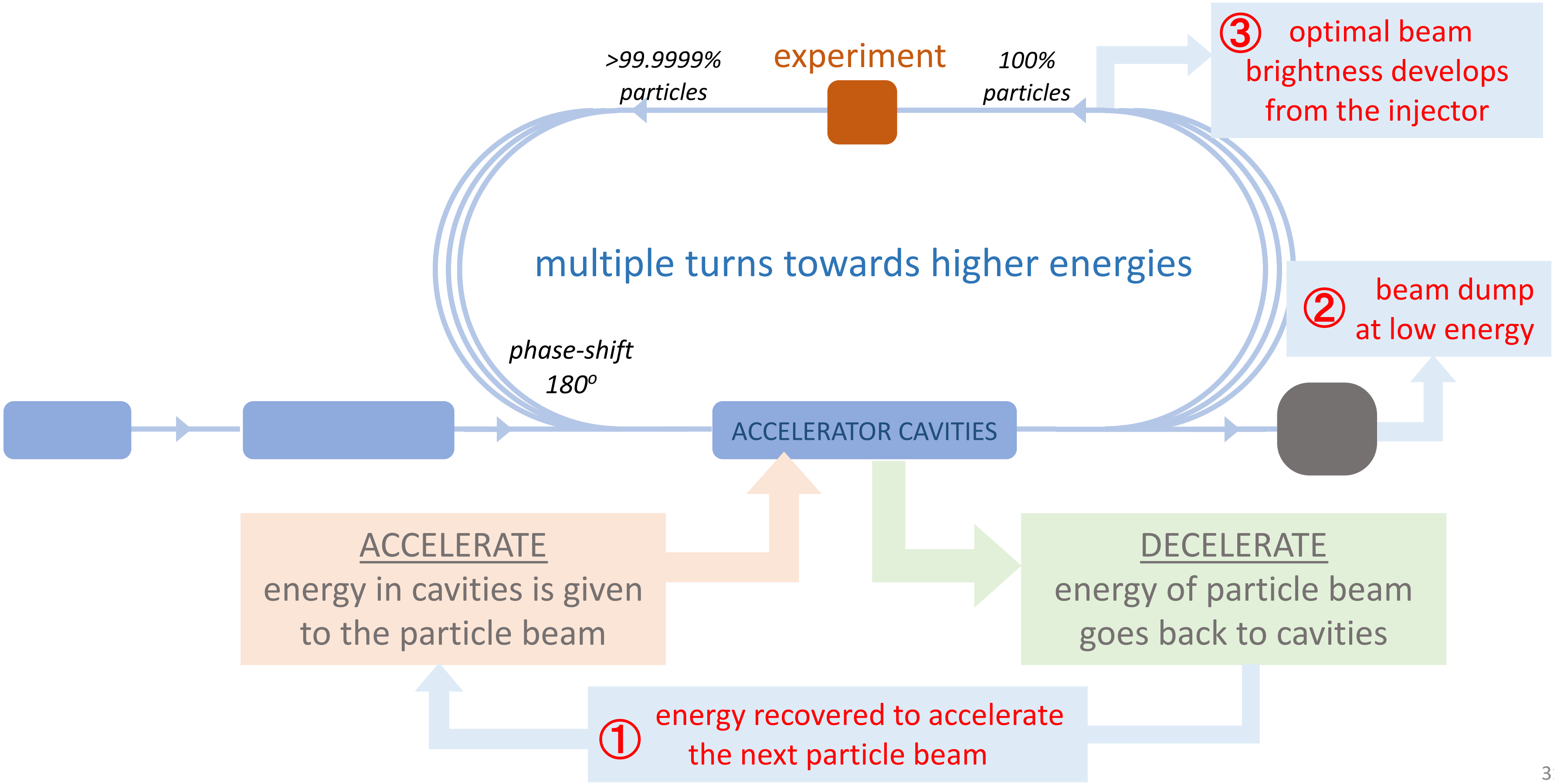
The principle of Energy Recovery



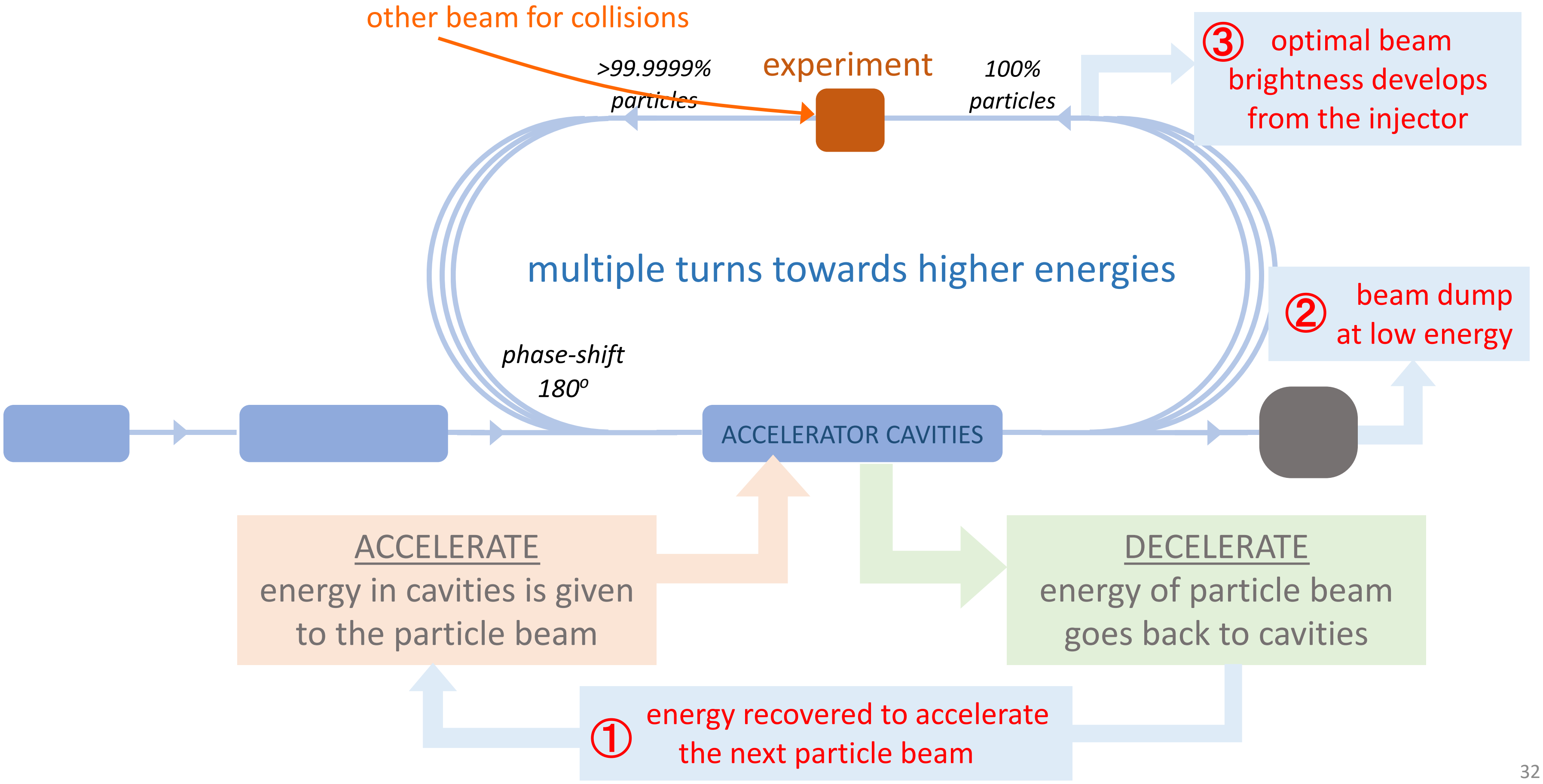
The principle of Energy Recovery



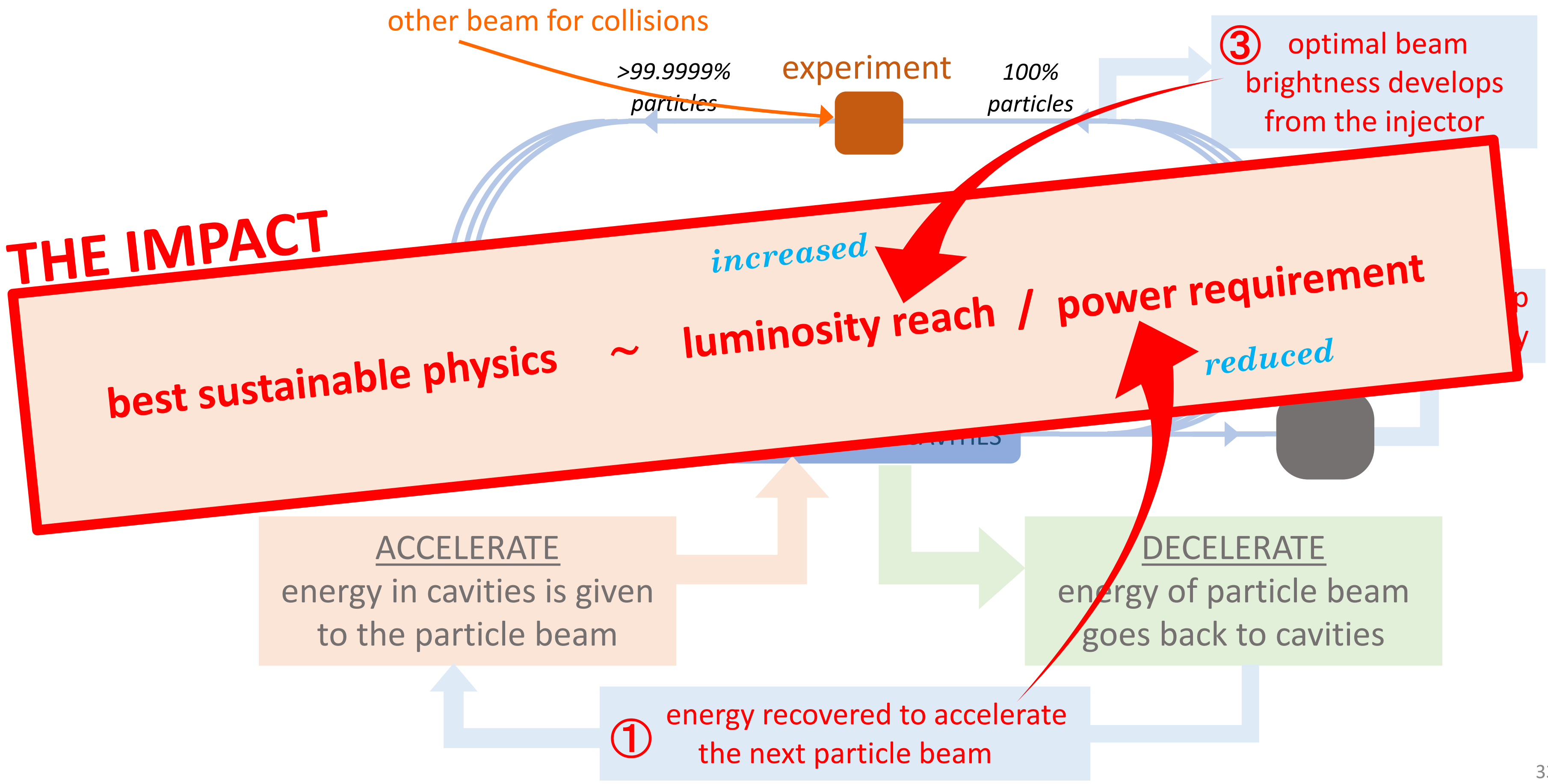
The principle of Energy Recovery

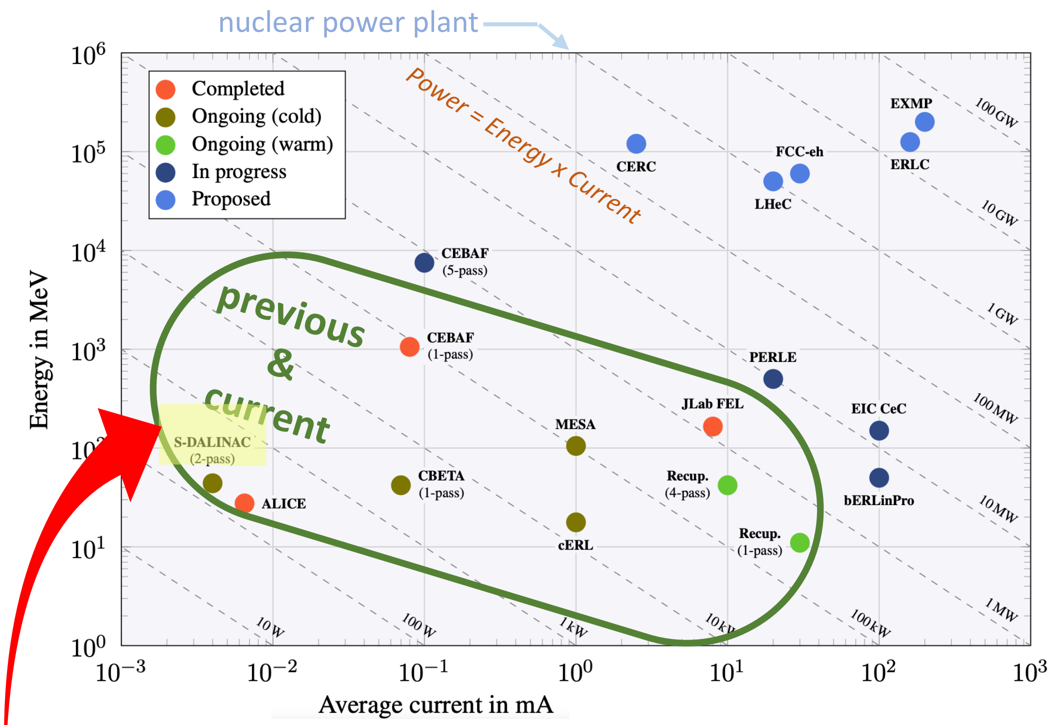


The principle of Energy Recovery



The principle of Energy Recovery





Energy Recovery demonstrated

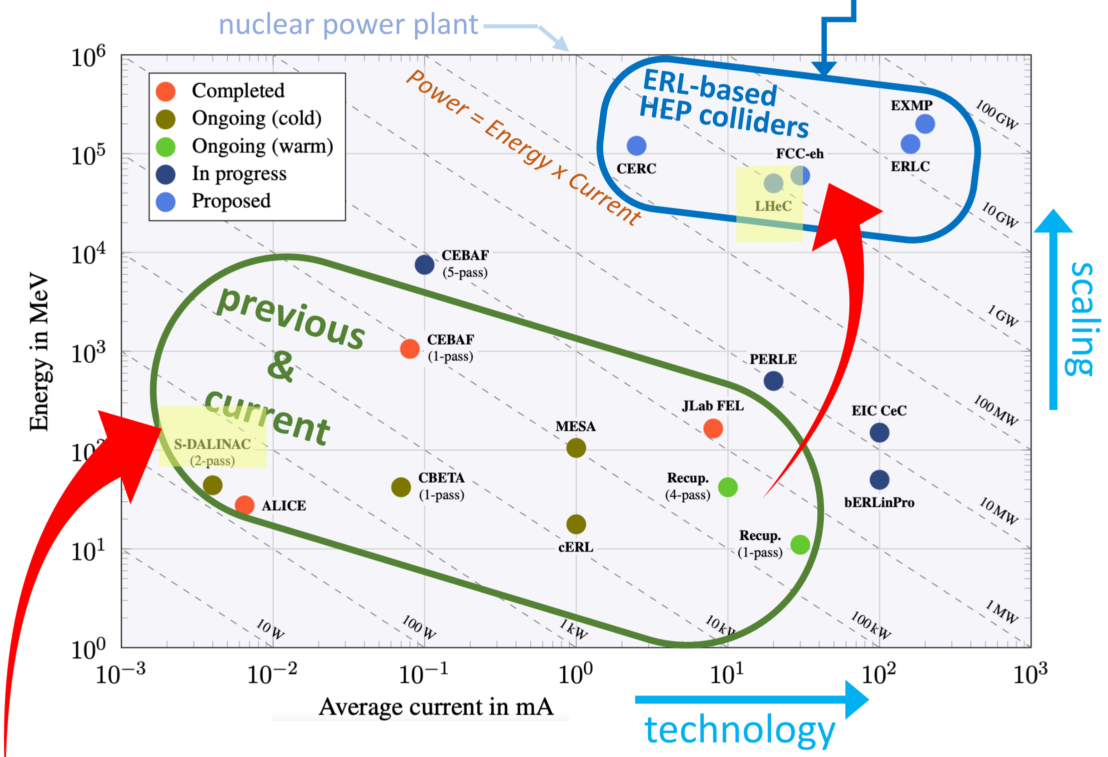
great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

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, …

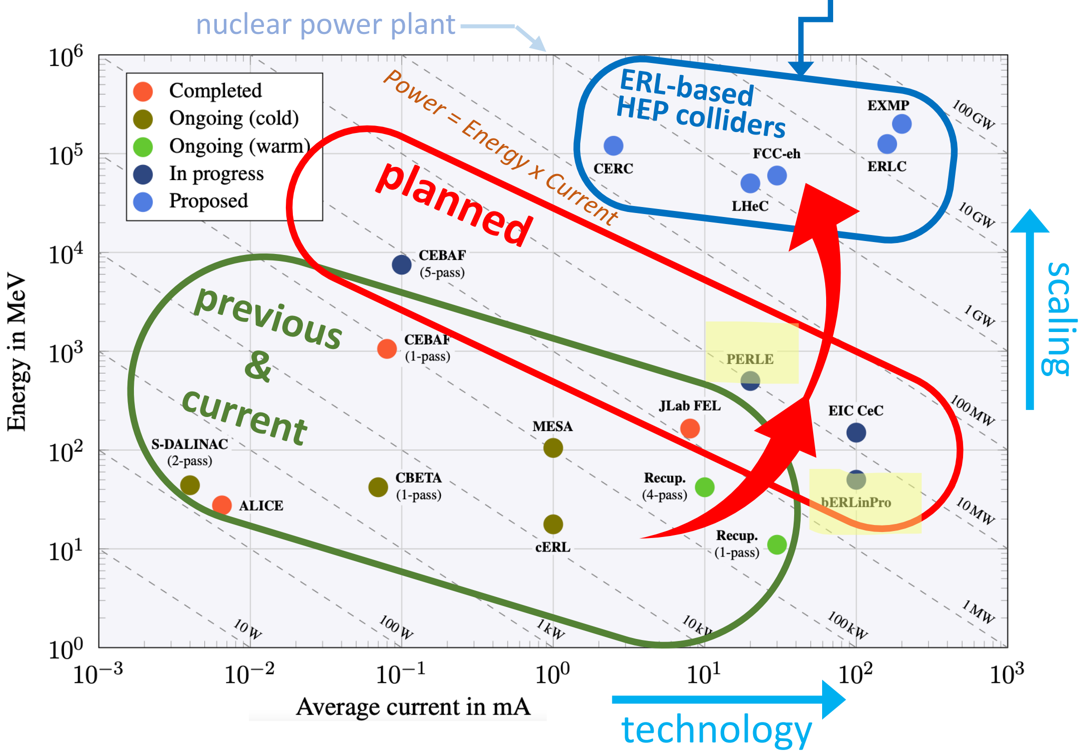


Energy Recovery demonstrated

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, …

bERLinPro & PERLE

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

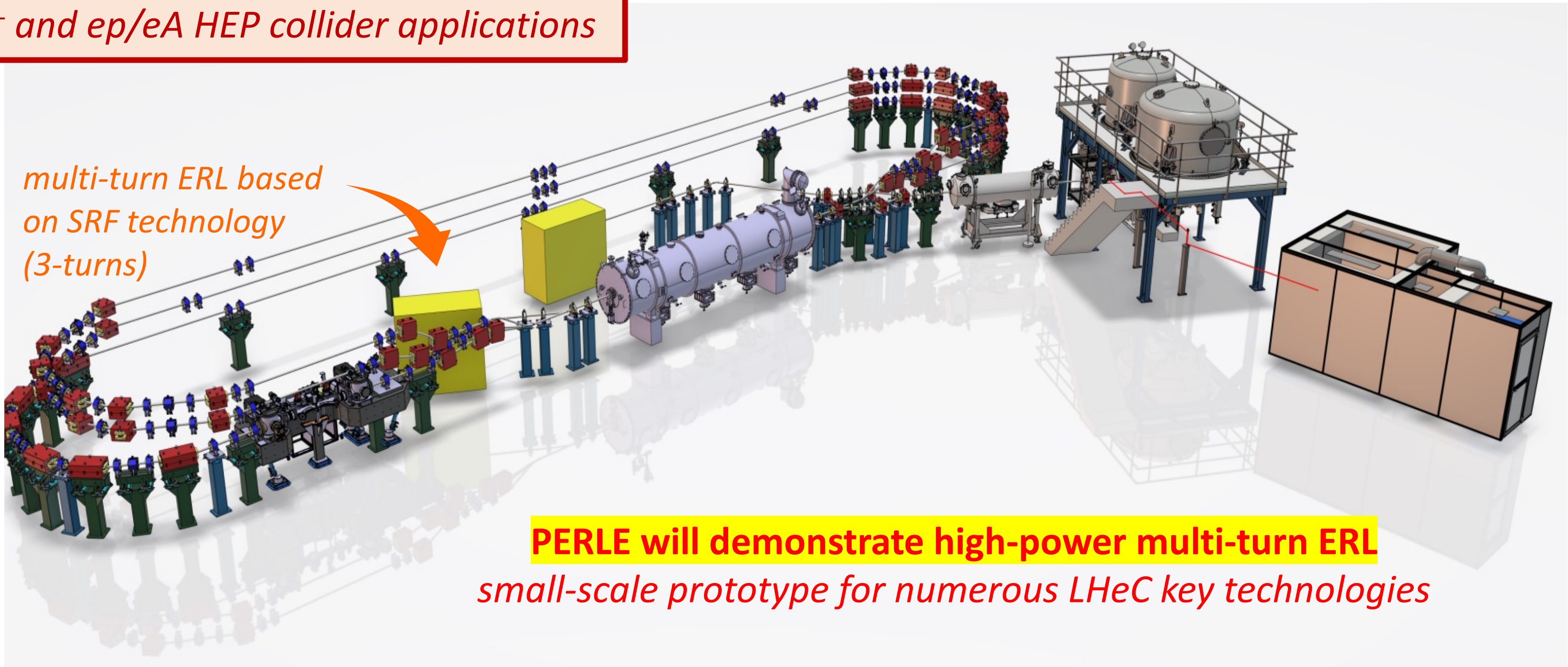
towards high power

Energy Recovery demonstrated

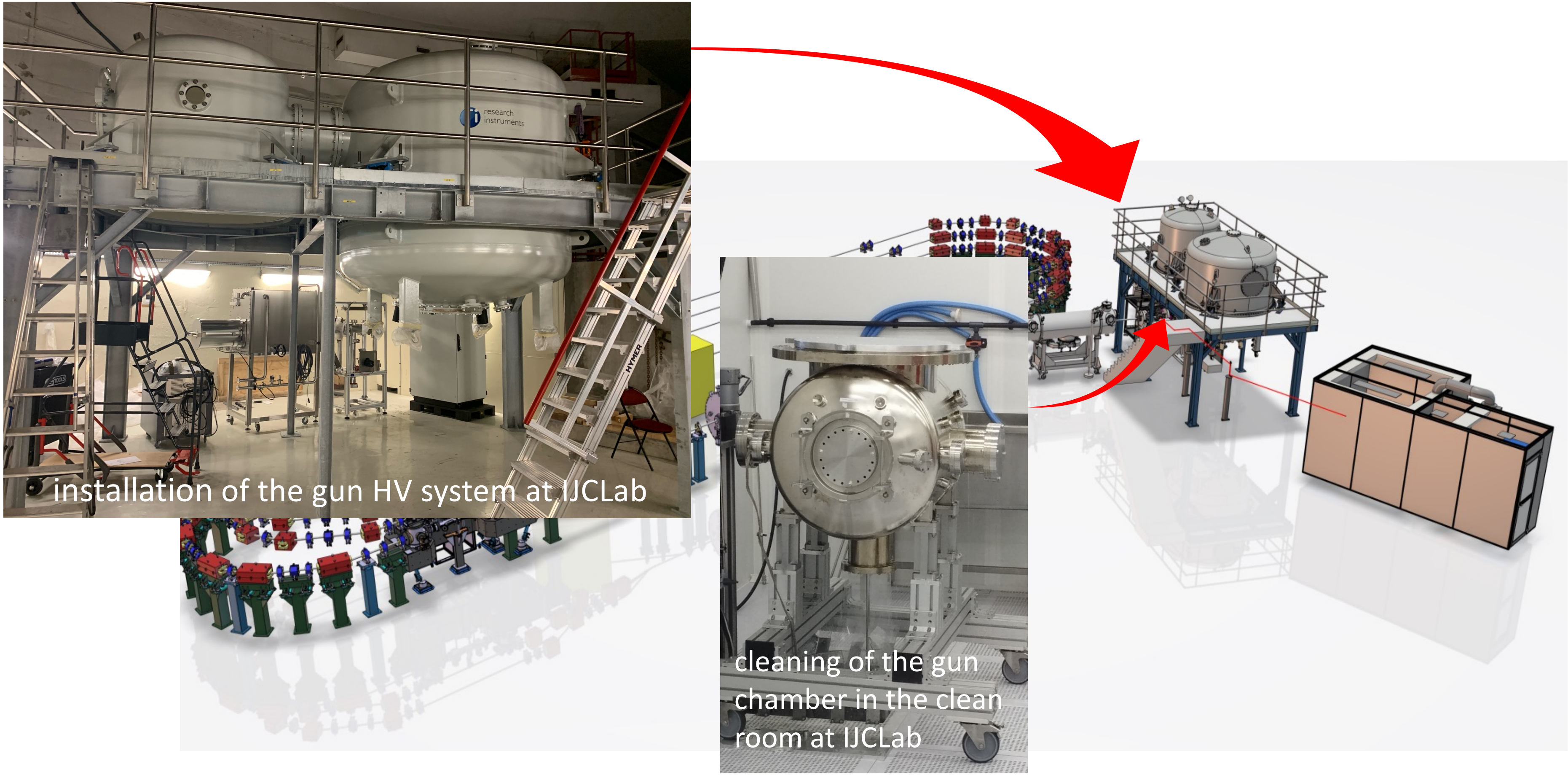
great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

PERLE @ IJCLab (IN2P3) Orsay

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



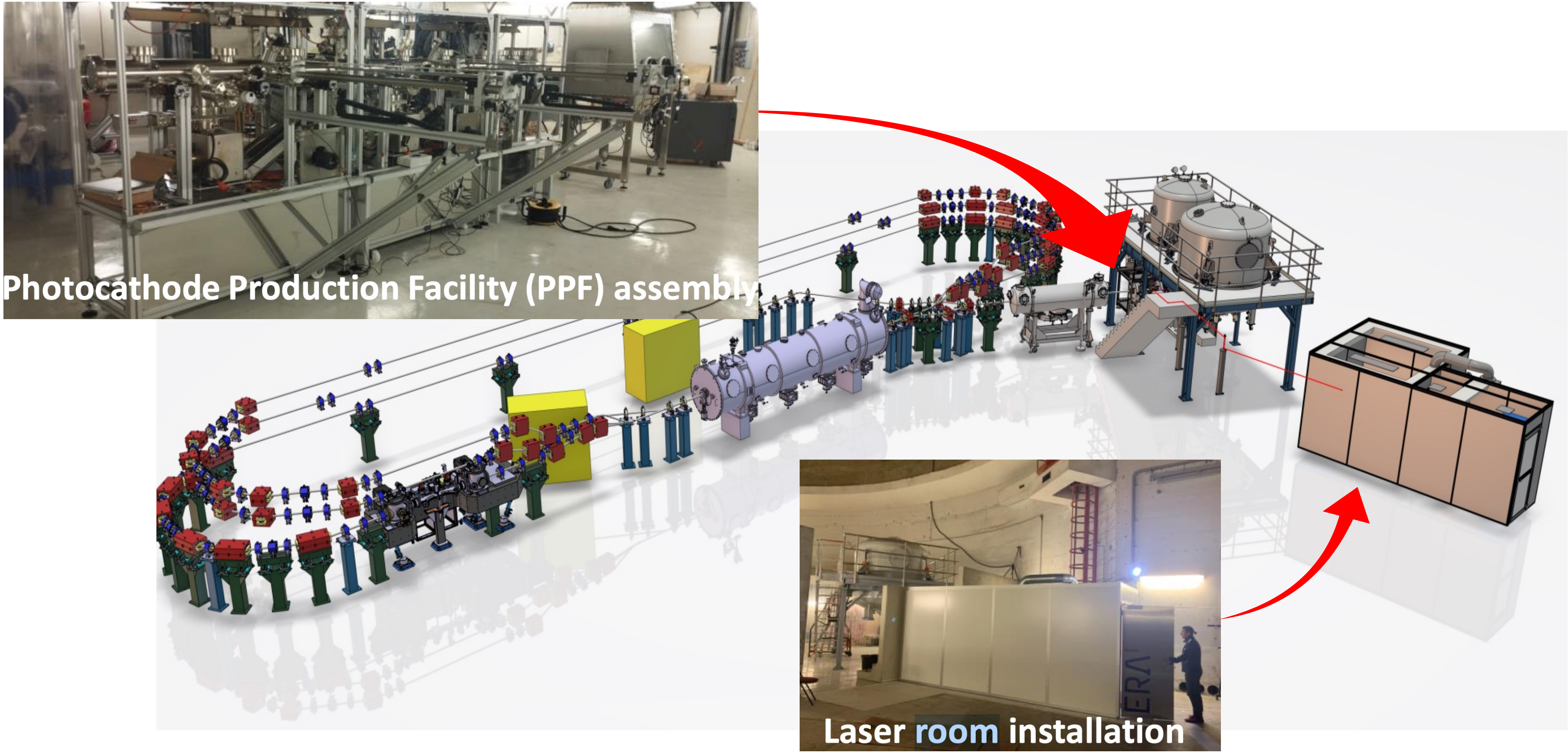
From drawings to reality with PERLE



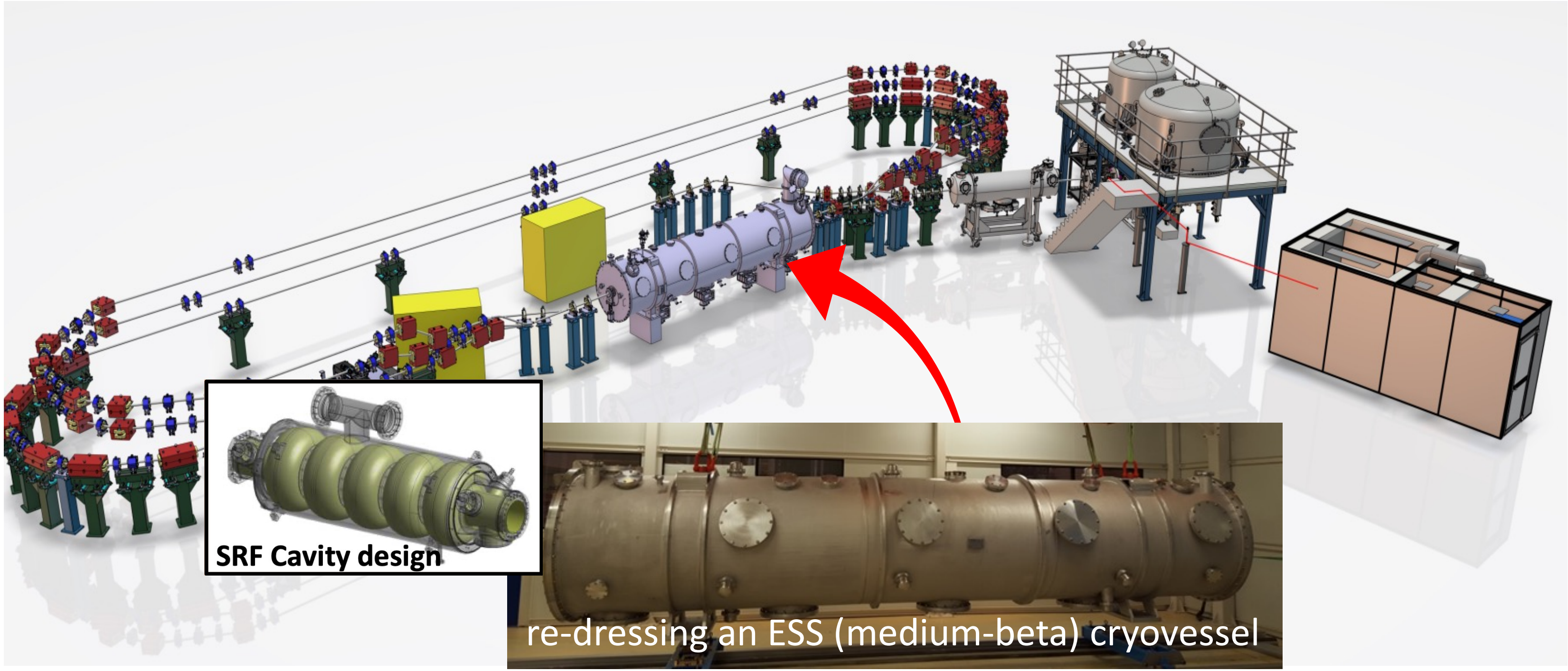
installation of the gun HV system at IJCLab

cleaning of the gun chamber in the clean room at IJCLab

From drawings to reality with PERLE

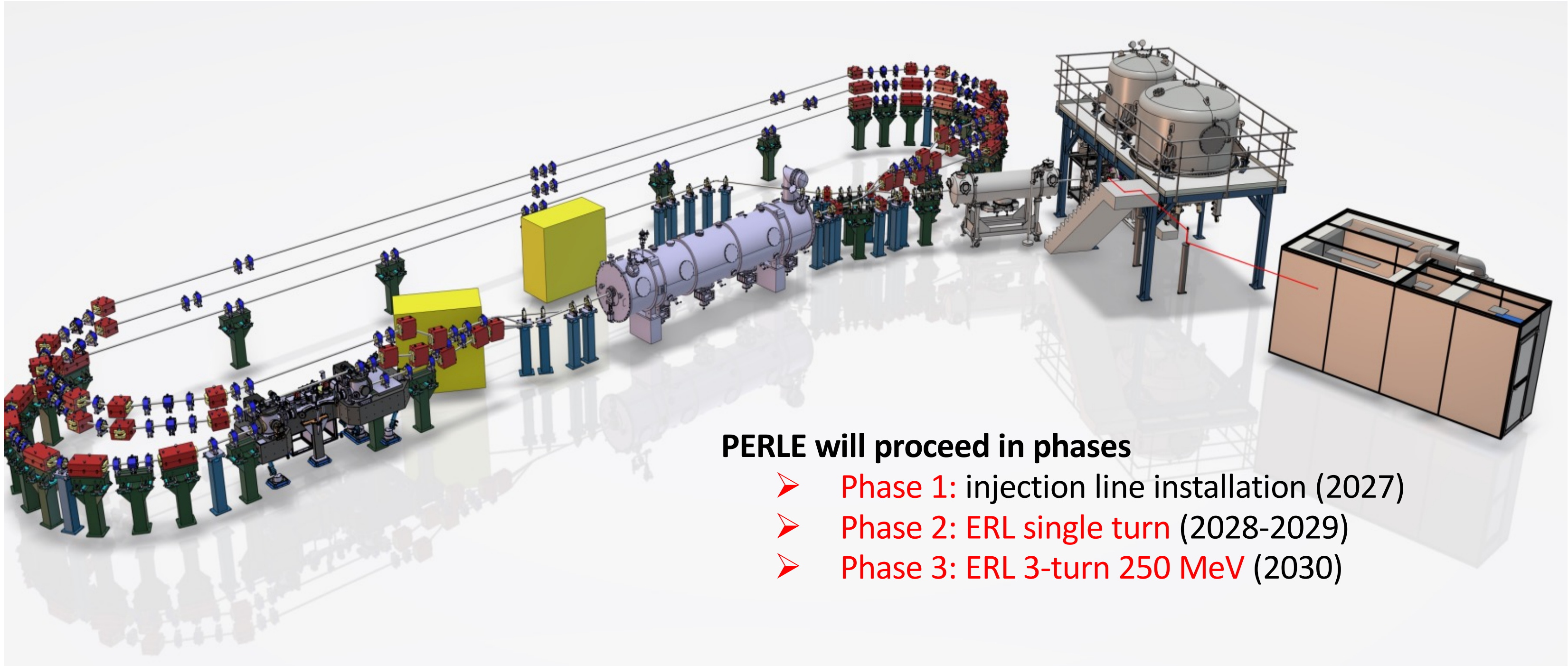


From drawings to reality with PERLE



From drawings to reality with PERLE

+ Contributions through iSAS of



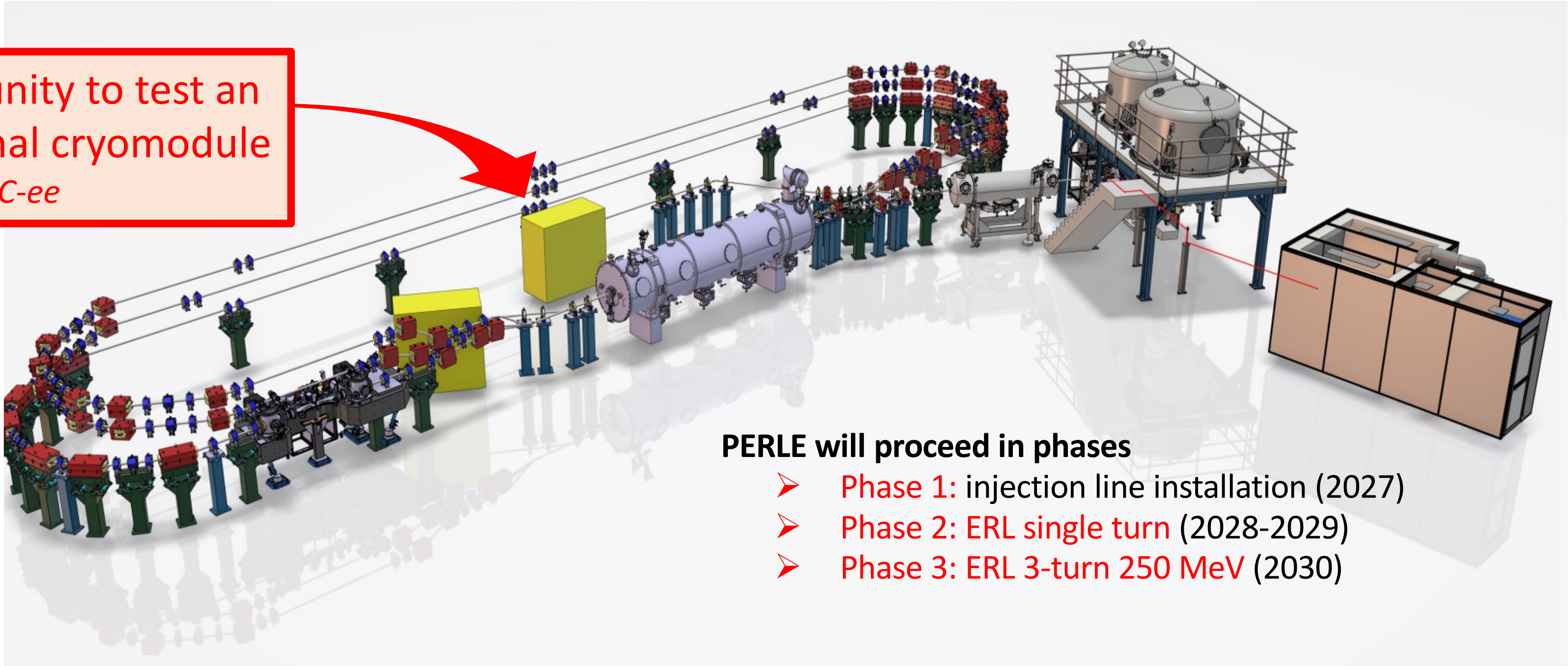
PERLE will proceed in phases

- 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

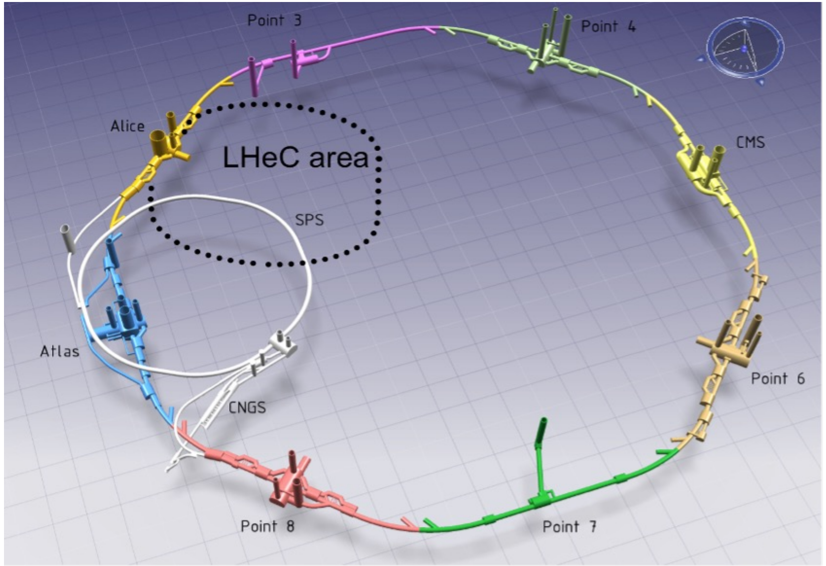
"The readiness of ERLs for deployment in a large-scale facility (LHeC) is that with requested resources it is likely that high TRLs can be achieved for systems in time for a decision in 2034."

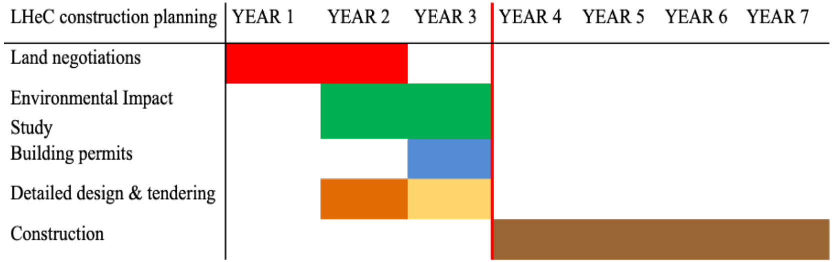
Platform	High Field Magnets	High Grad Struct/Syst	High Grad Plasma/Laser	Muon Beams & Colliders	Energy Recovery Linac
R&D Scope Definition		OK at high level, Too many sub-goals, many not well defined	"Staging" test facility is critical		Need to be expanded to Multi-GeV issues (synchrotron radiation)
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 feaslbility 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)



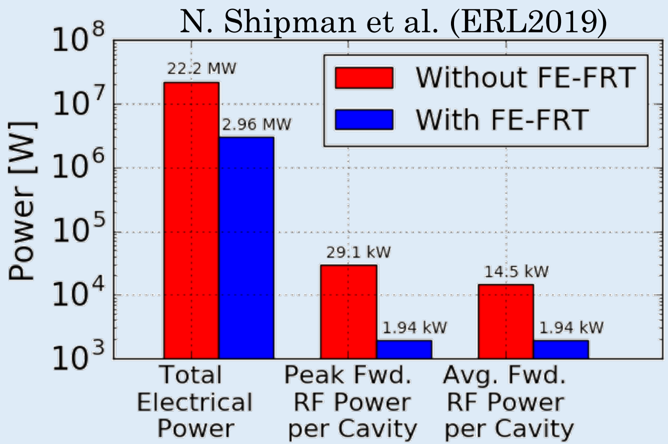


Operation

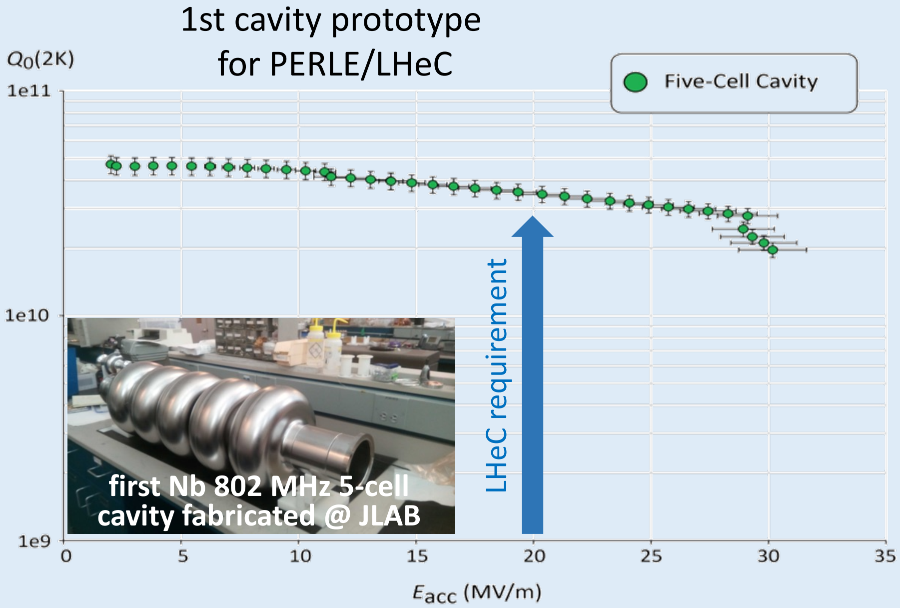
- Power is 220 MW (including LHeC, detector and dedicated HL-LHC operation)
- 200 days of running → 1.06 TWh/year (+27MCHF per year compared to nominal HL-LHC)
- eA runs can be integrated
- Personpower for dedicated LHeC runs (1 detector, 1 proton beam, ERL) equivalent to nominal (HL-)LHC (4 detectors,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

Opportunities for improved performance

Innovate for
Sustainable
Accelerating
Systems

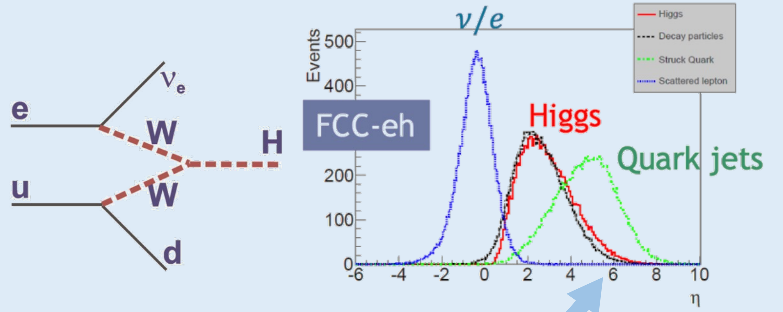


Ferro-Electric Fast Reactive Tuners for 20MW less power requirements to deal with microphonics



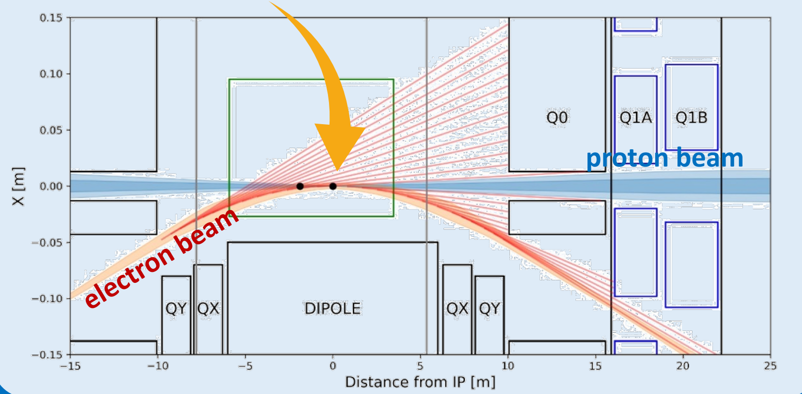
LHeC can be done with state-of-the-art SRF and significant room for improvements

LHeC detector



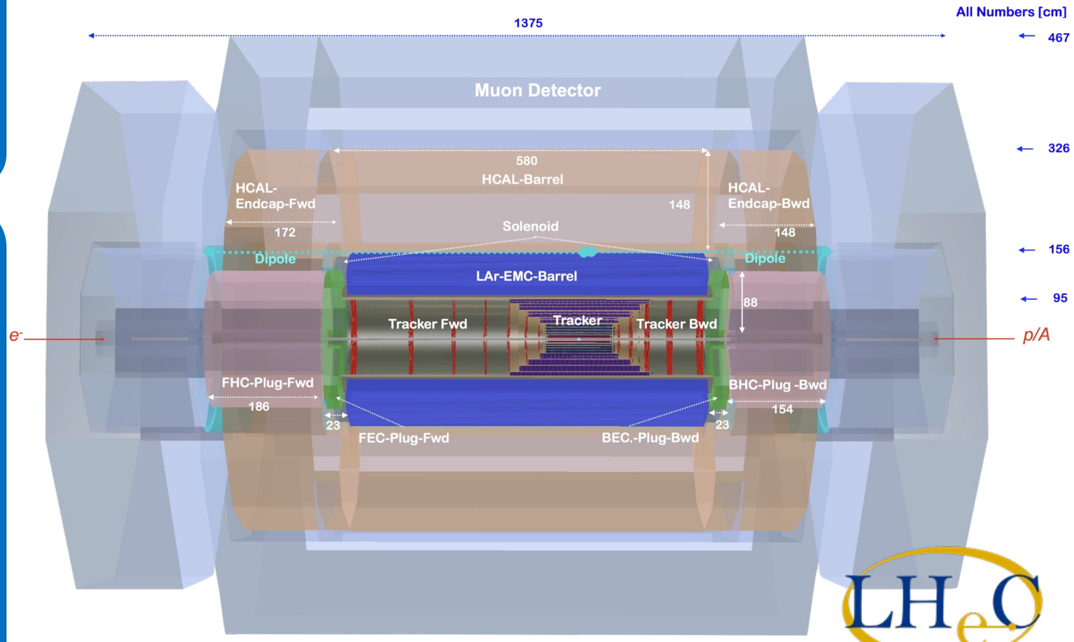
Forward jet reconstruction

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



major features:

- 1º 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

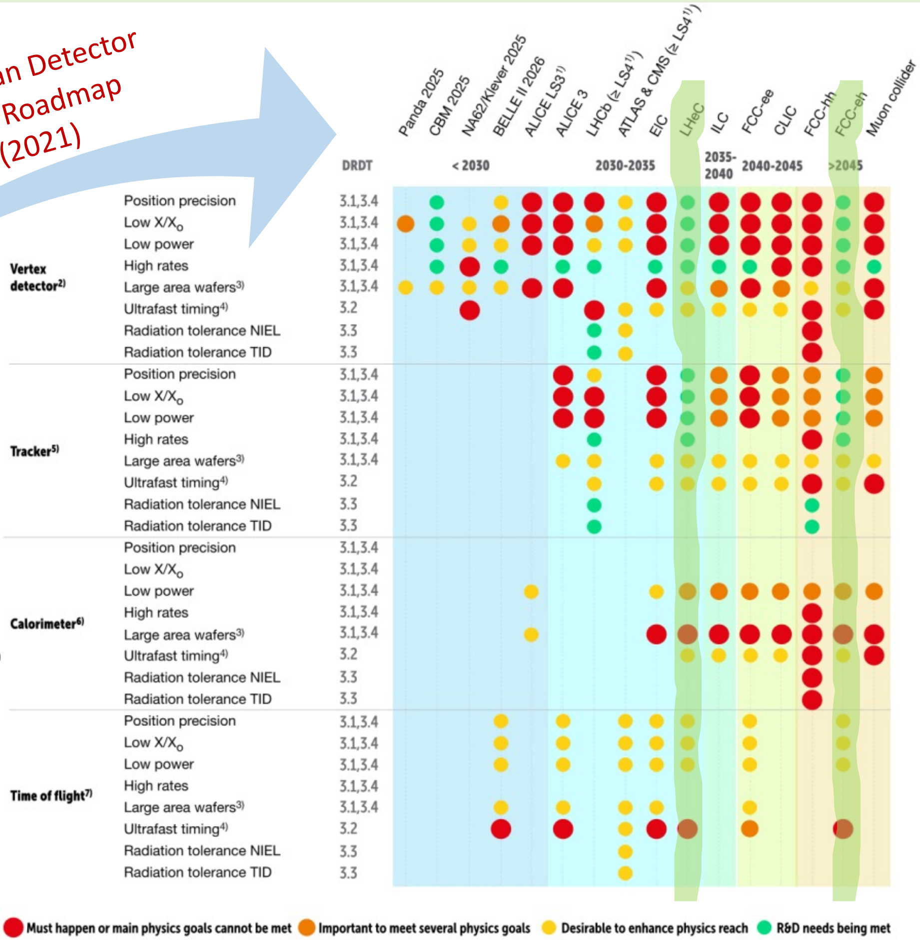
synergies with other projects
stepping stones

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

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

European Detector R&D Roadmap (2021)

Detector Requirements
e.g. Solid State Devices



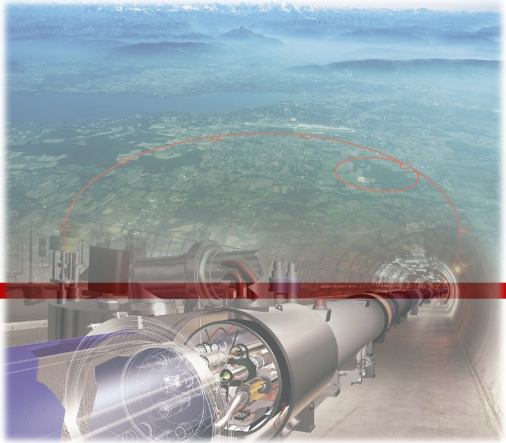
https://cds.cern.ch/record/2784893?ln=en

How does the LHeC fits into the collider landscape?

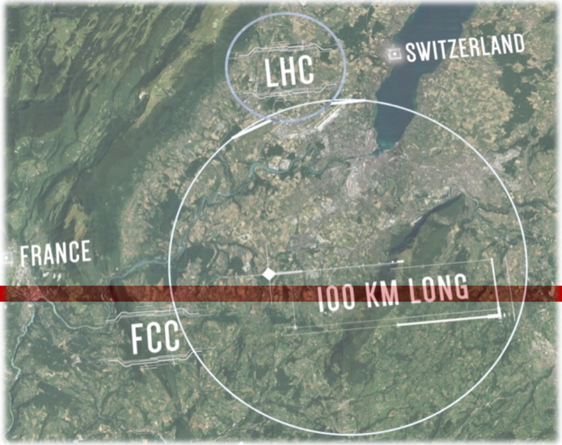
The LHeC is a feasible and impactful alternative for the ESPP.

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

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



LHC

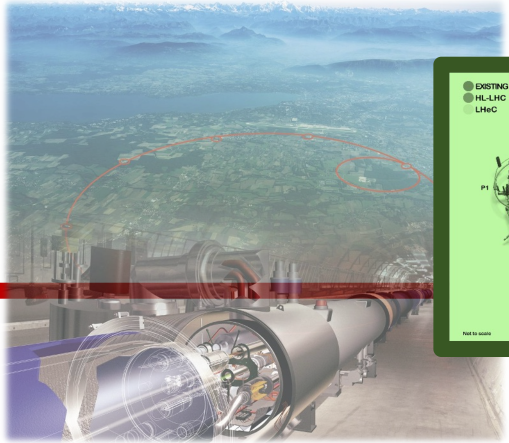


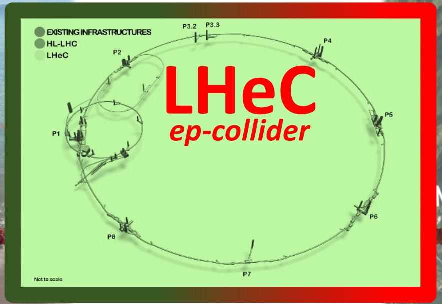
e.g. **FCC** (ee or hh) or **LEP3**

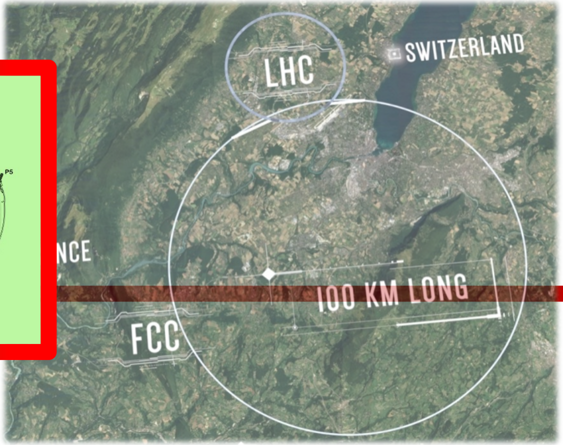
An impactful “*bridge*” between major colliders @ CERN

ep-option with HL-LHC: LHeC

e.g. 6 years ep-only@LHC > 1 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

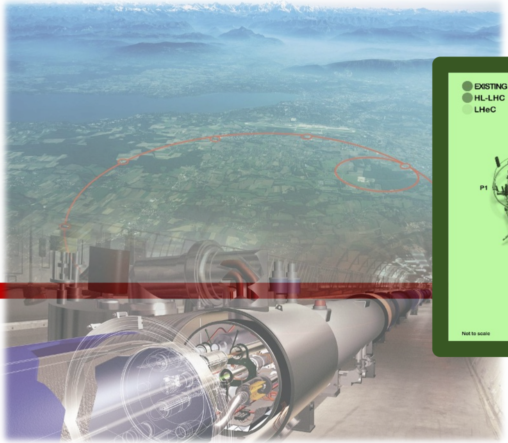
cost-effective investment

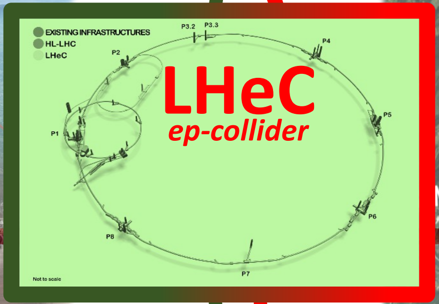
re-use
FCC-hh/eh

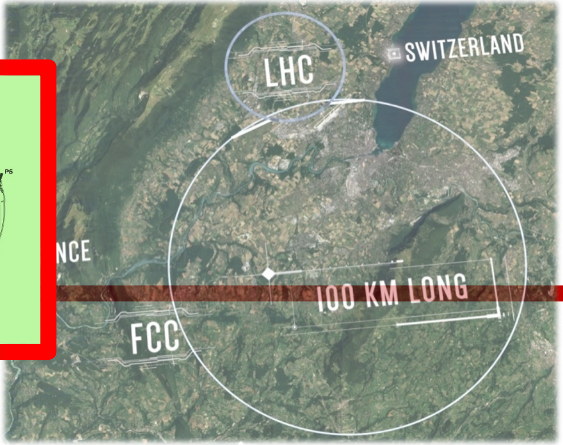
injector
FCC-ee/LEP3

ultimate upgrade of the LHC physics reach

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





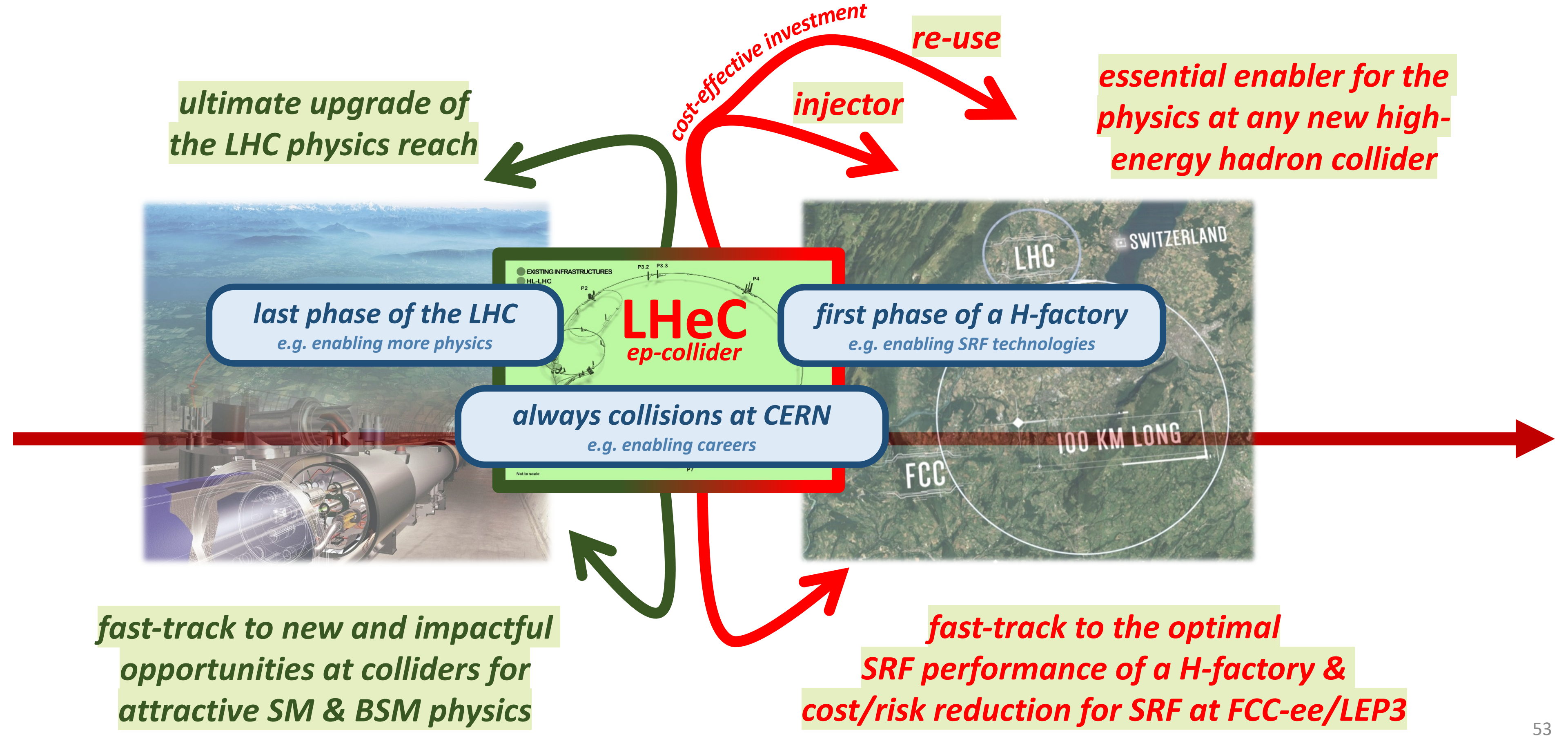


fast-track to new and impactful opportunities at colliders for attractive SM & BSM physics

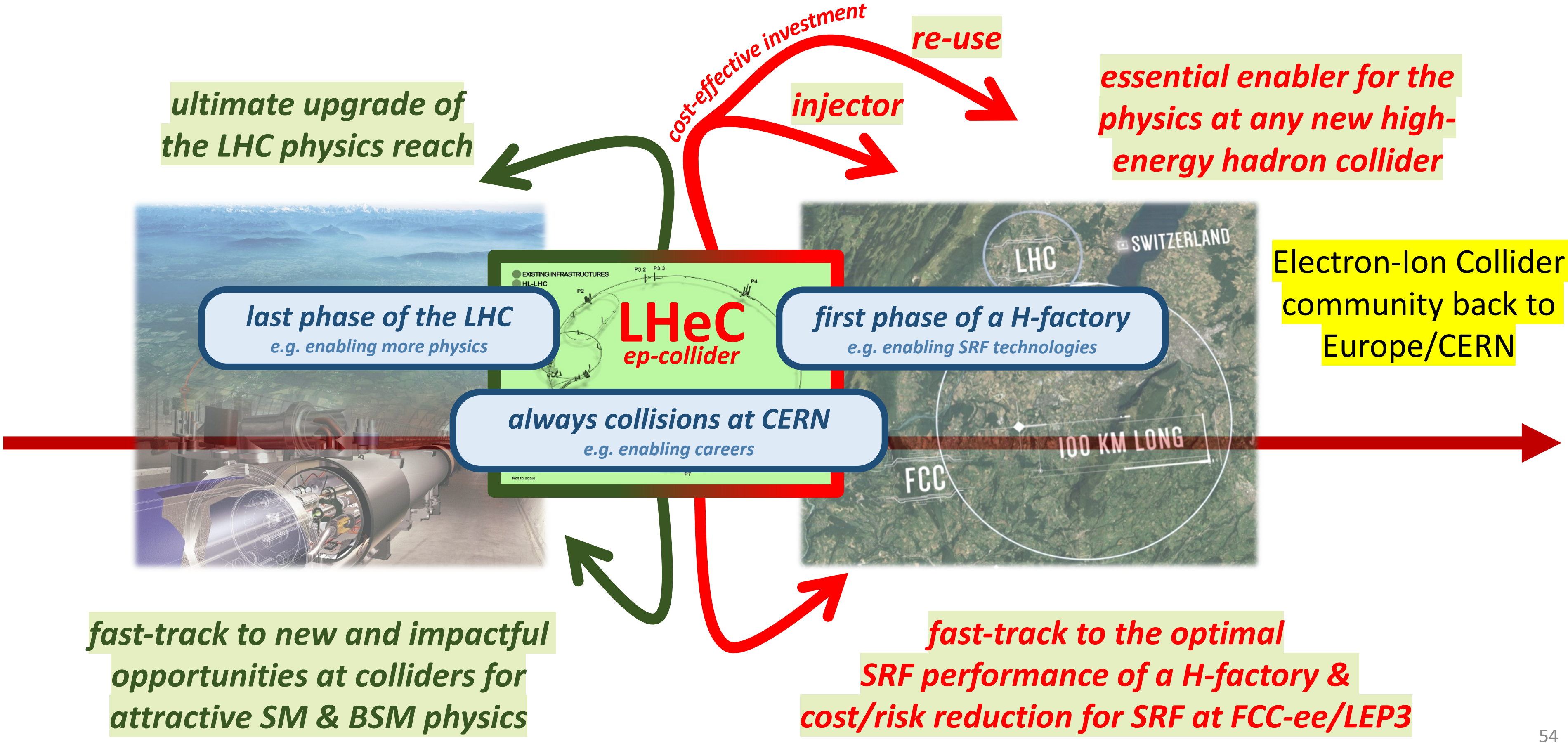
i.e. SRF@LHeC as prototype series and training for SRF@FCC-ee

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

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

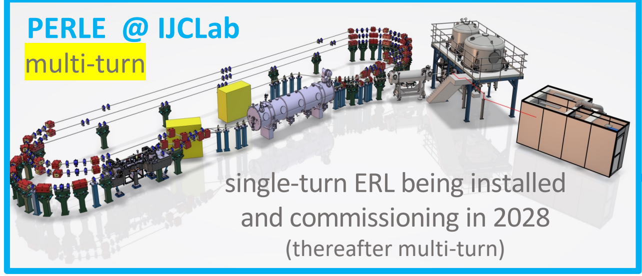
2020'ies

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

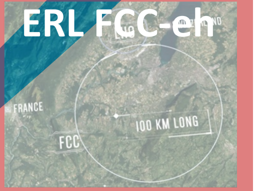
DECISION ESPP'32

implementation
7 years

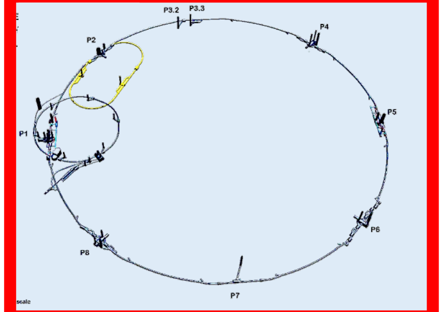
enables the ultimate upgrades of the LHC/FCC programs
(ep collisions)

2070'ies

ERL FCC-eh



2040'ies



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.

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.

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)

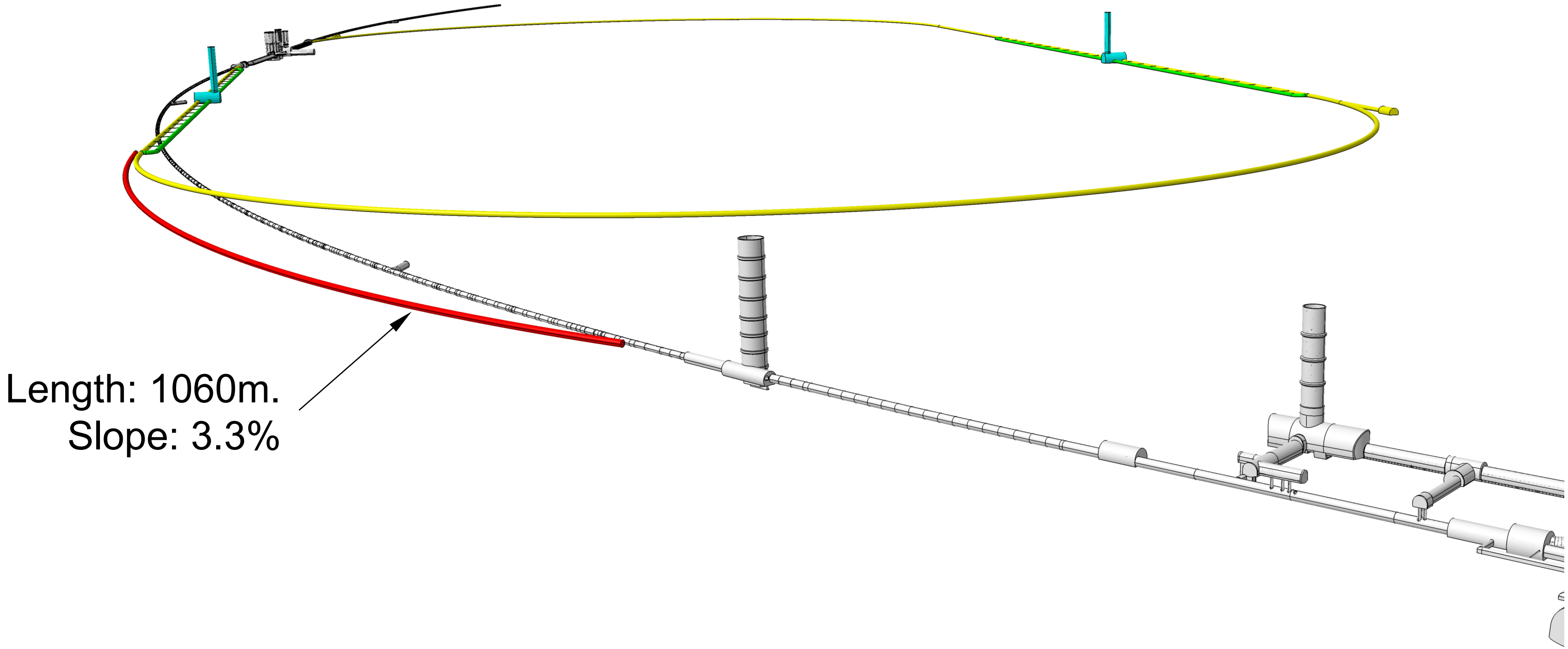
LHeC – bridge to LEP3

LHeC – bridge to LEP3

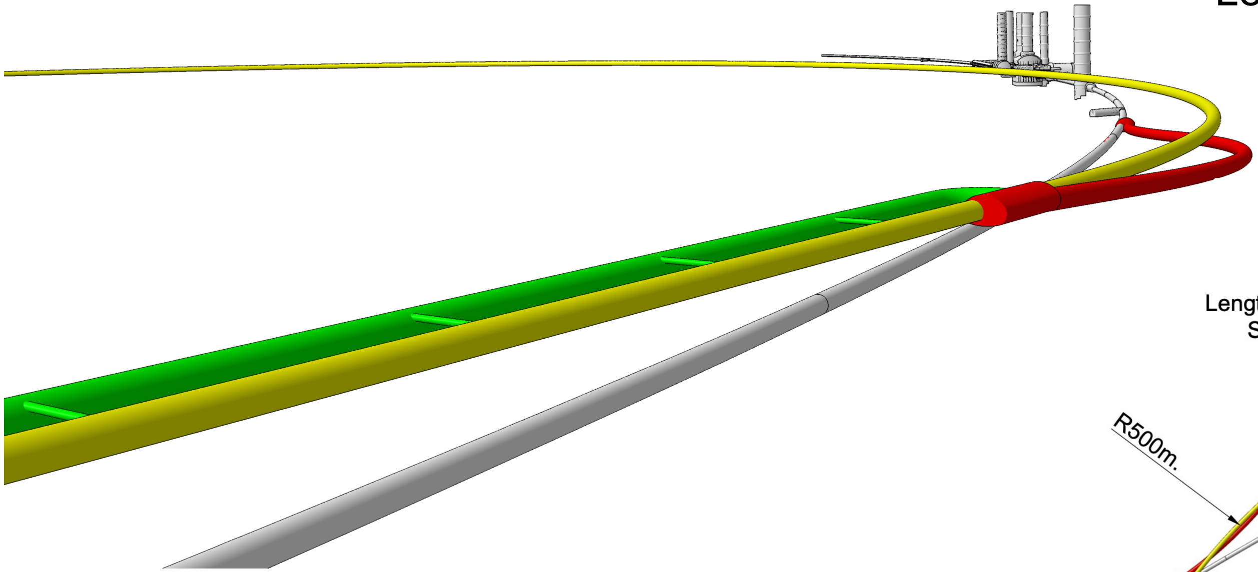
- LHeC and LEP3 have a comparable number of cryomodules and thus comparable 800MHz power system and distribution lines, i.e. very similar industrial contracts and the LHeC developments can directly lead into LEP3 orders / productions.
  - clear synergies that can be exploited for common design and optimization, 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

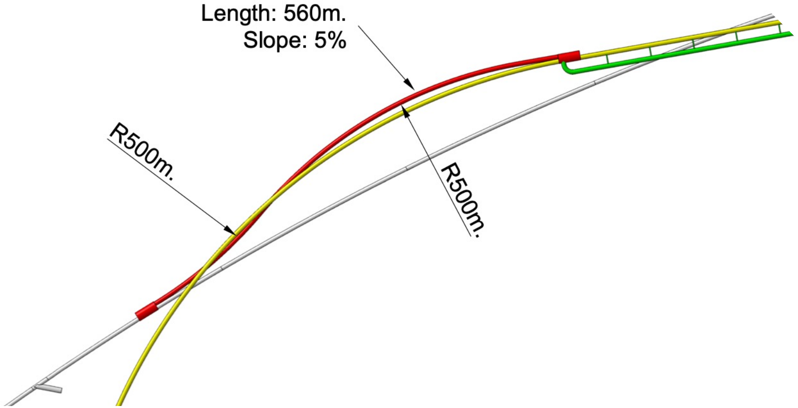
LHeC – bridge to LEP3



LHeC – bridge to LEP3



Length: 560m.
Slope: 5%



LHeC – accelerator R&D landscape

Accelerator R&D landscape & Colliders

$e^{\pm}p$ (and $e^{\pm}A$)
RF & ERL technology *($E_e \sim$ 30-60 GeV)*
E_{CMS} > 1 TeV

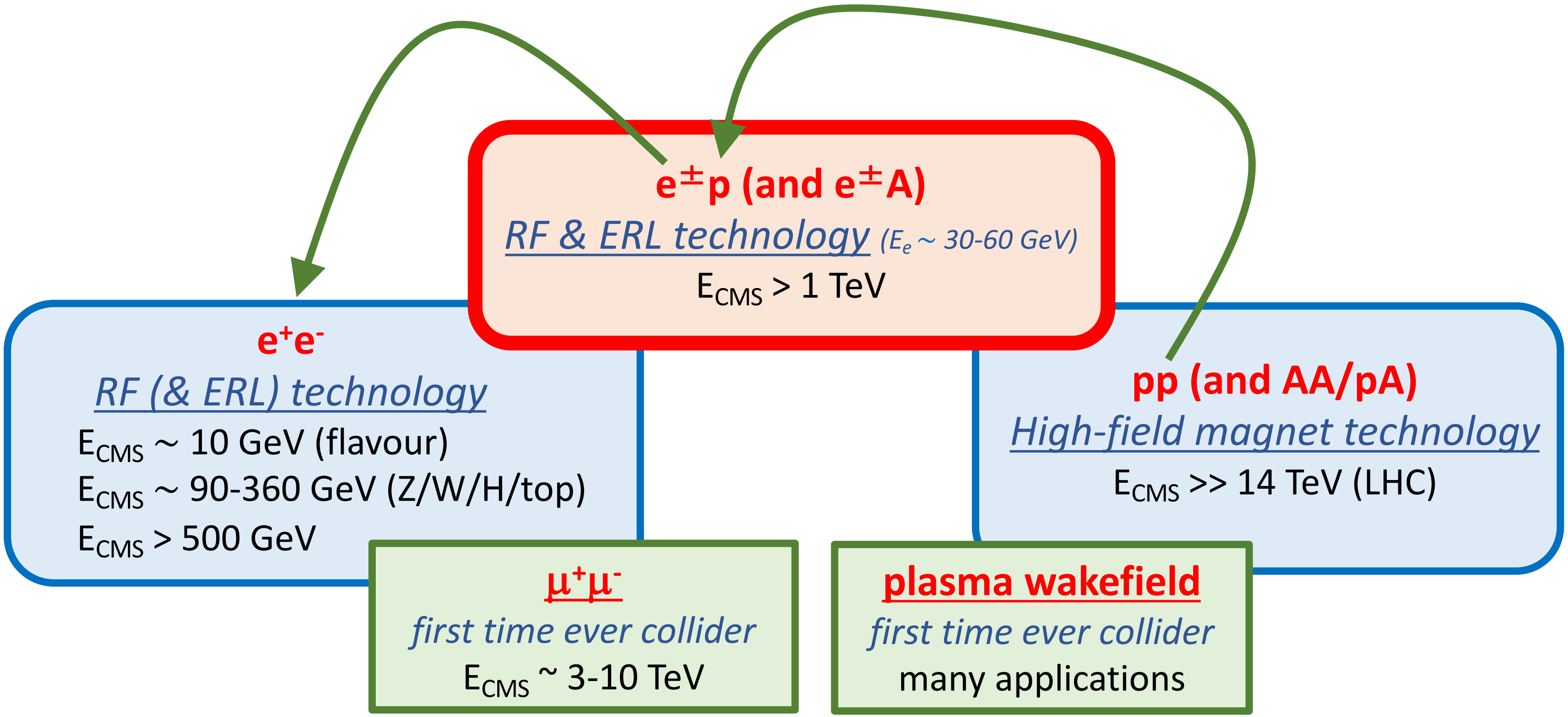
e^+e^-
RF (& ERL) technology
$E_{CMS} \sim$ 10 GeV (flavour)
$E_{CMS} \sim$ 90-360 GeV (Z/W/H/top)
E_{CMS} > 500 GeV

pp (and AA/pA)
High-field magnet technology
E_{CMS} >> 14 TeV (LHC)

$\mu^+\mu^-$
first time ever collider
E_{CMS} ~ 3-10 TeV

plasma wakefield
first time ever collider
many applications

Accelerator R&D landscape & Colliders



Accelerator R&D landscape & Colliders

focus on the LHeC

high-energy & high-luminosity electron-proton

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

FOCUS

$e^{\pm}p$ (and $e^{\pm}A$)

RF & ERL technology *(E_e ~ 30-60 GeV)*

E_{CMS} > 1 TeV

e^+e^-

RF (& ERL) technology

E_{CMS} ~ 10 GeV (flavour)

E_{CMS} ~ 90-360 GeV (Z/W/H/top)

E_{CMS} > 500 GeV

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

$\mu^+\mu^-$

first time ever collider

E_{CMS} ~ 3-10 TeV

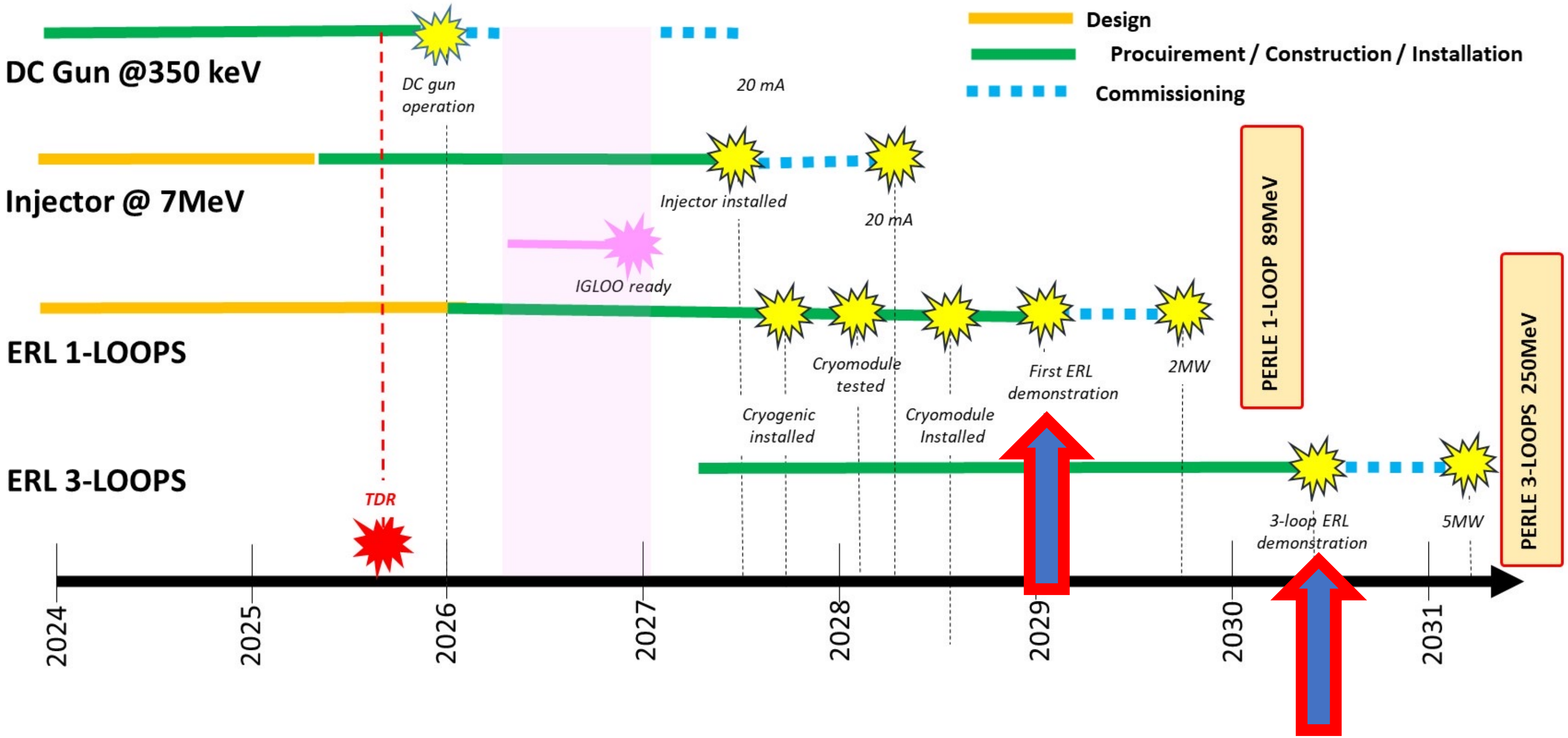
plasma wakefield

first time ever collider

many applications

LHeC – accelerator R&D for ERL

PERLE @ IJCLab (Orsay)



bERLinPro @ Helmholtz Zentrum Berlin

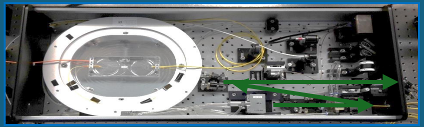
generic accelerator R&D with several aspects as stepping stones towards HEP applications and energy efficient accelerator technologies

focus on a high-current & high-brightness injector

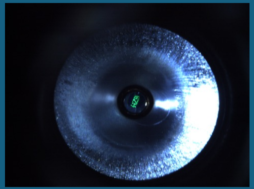
first beams from the SRF gun

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), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

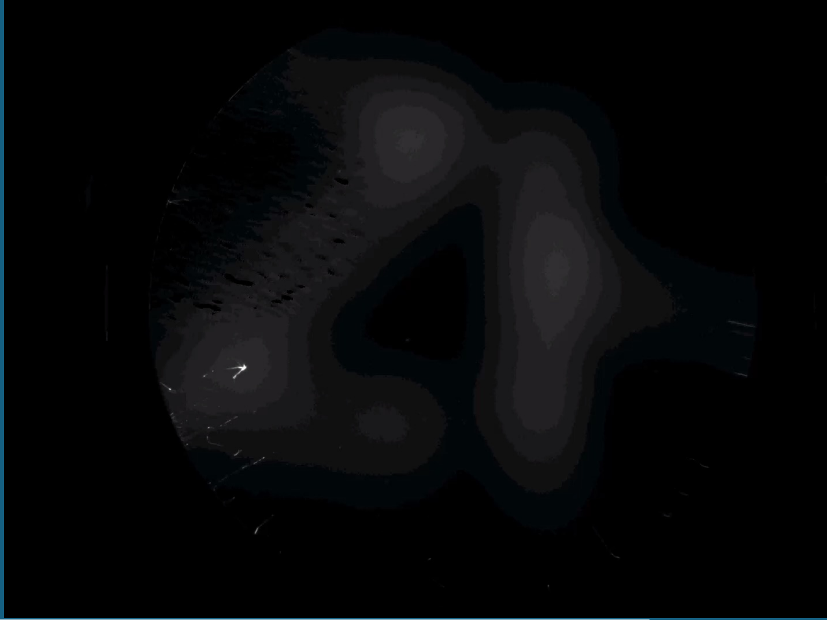
bERLinPro – Berlin Energy Recovery Linac Project

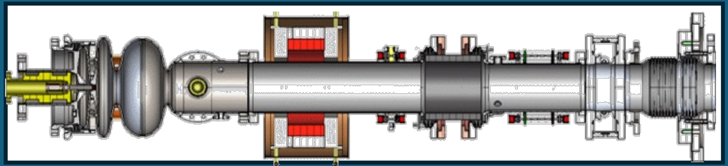


γ

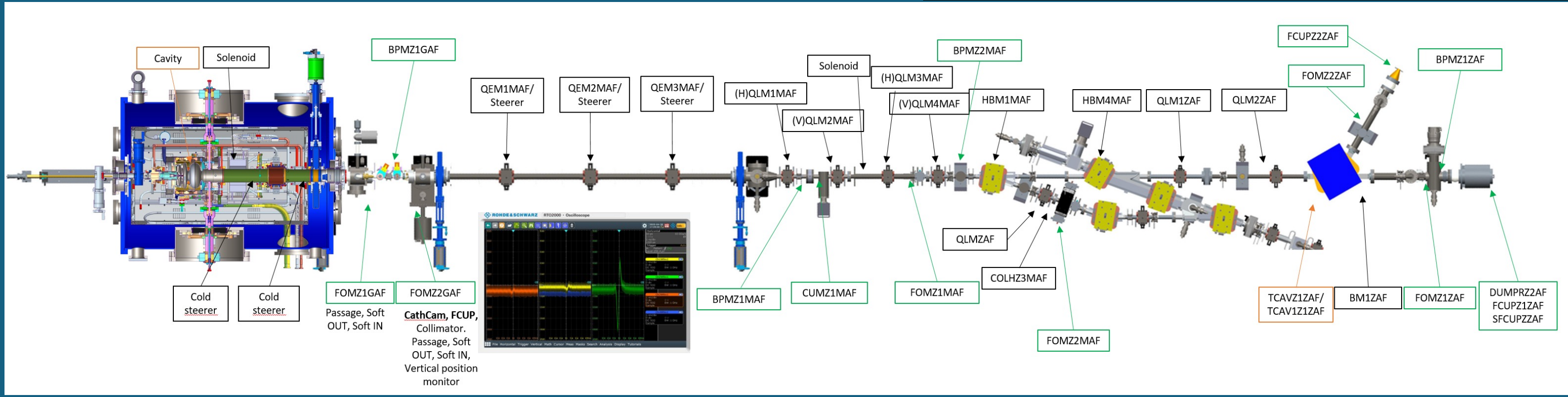


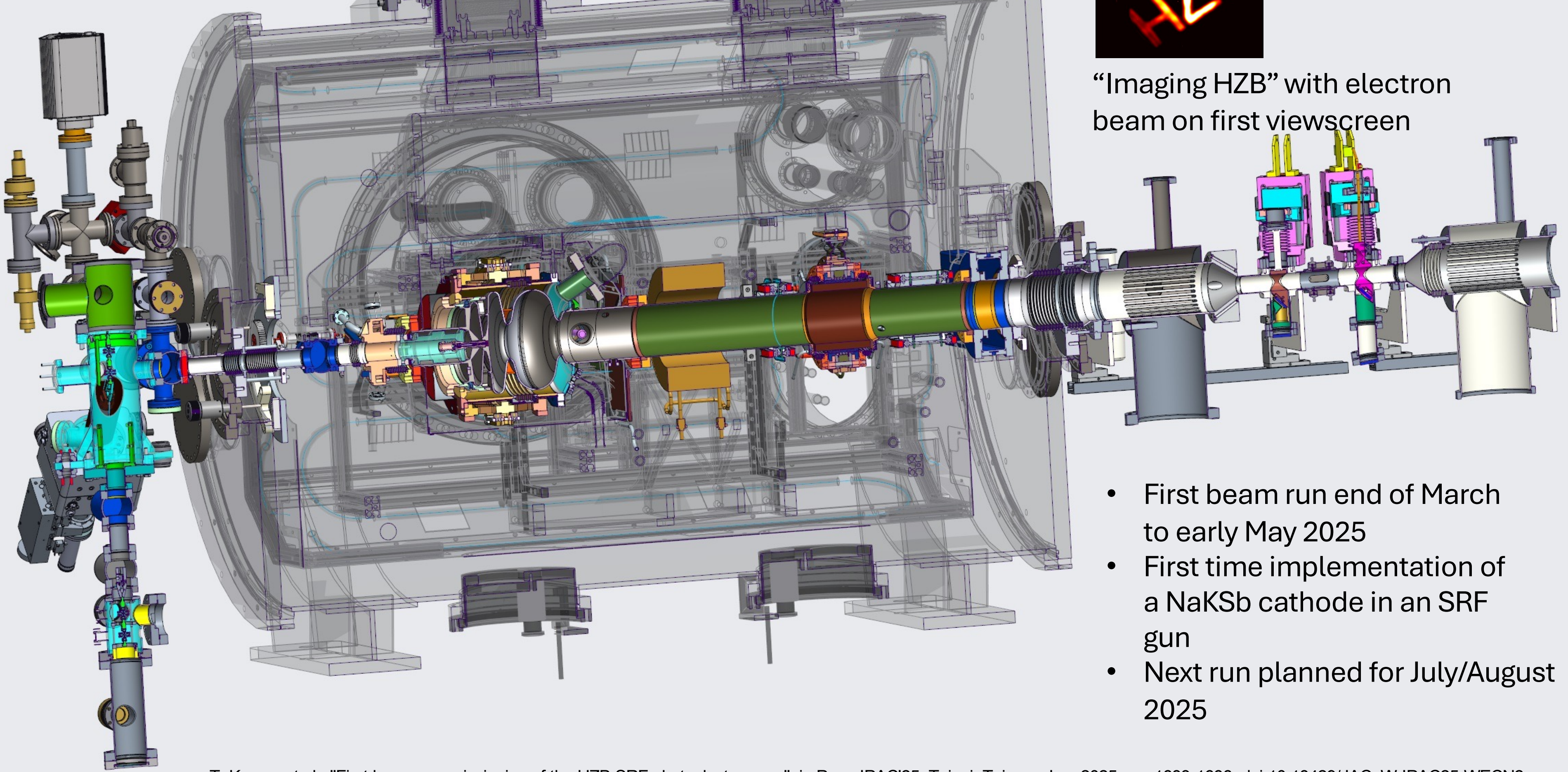
To image HZB

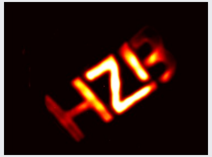




e^-







"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

T. Kamps et al., "First beam commissioning of the HZB SRF photoelectron gun", in Proc. IPAC'25, Taipei, Taiwan, Jun. 2025, pp. 1683-1686. doi:10.18429/JACoW-IPAC25-WECN2

LHeC – risks of ERL performance

LHeC – risks of ERL performance

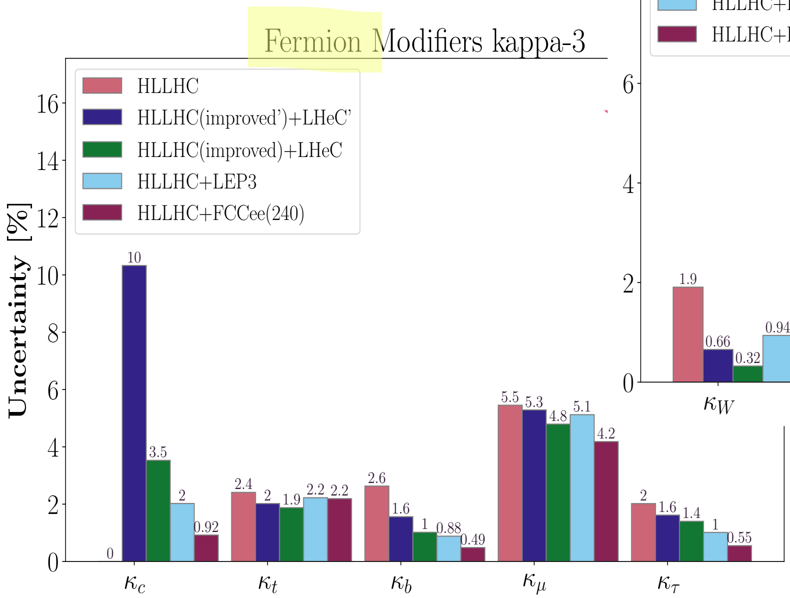
Worse case scenario: LHeC has to operate in non-ERL mode and stay within 100MW

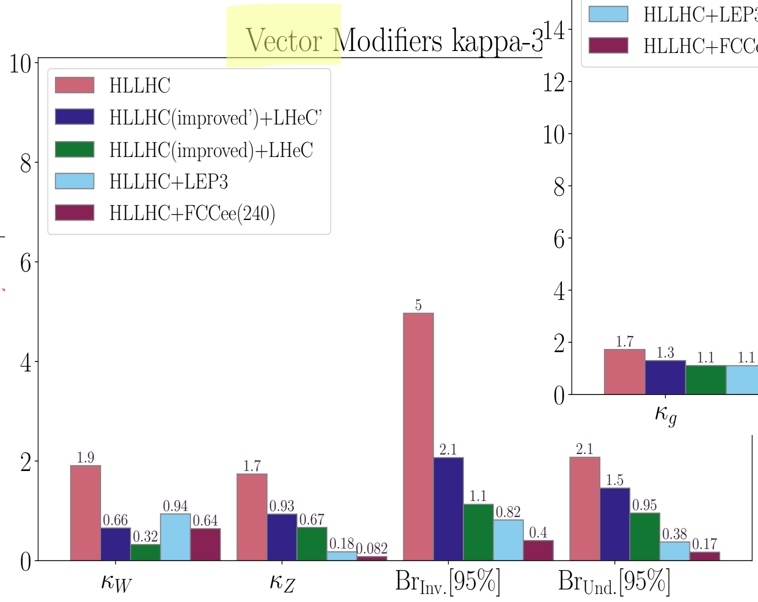
- Physics: 10x less luminosity
    - not much impact for QCD physics, including the empowering of (HL-)LHC
    - still improvements in EW, H and top quark physics wrt to HL-LHC potential
    - still search sensitivity beyond HL-LHC potential
- Accelerator: 2x less beam current in the SRF system
    - 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

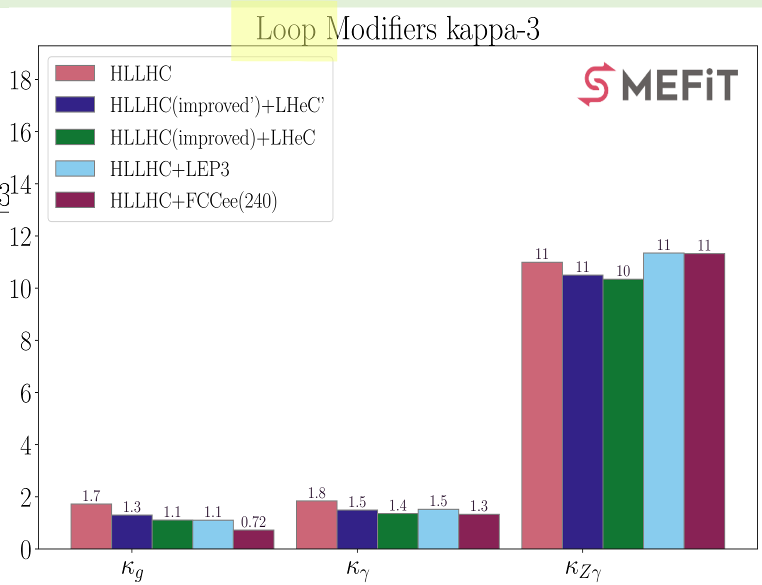
LHeC – physics impact of non-ERL LHeC (10x less luminosity)

HL-LHC + LHeC’ (10x less luminosity)

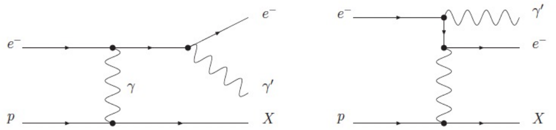
HL-LHC + LHeC (nominal)







Dark Photons

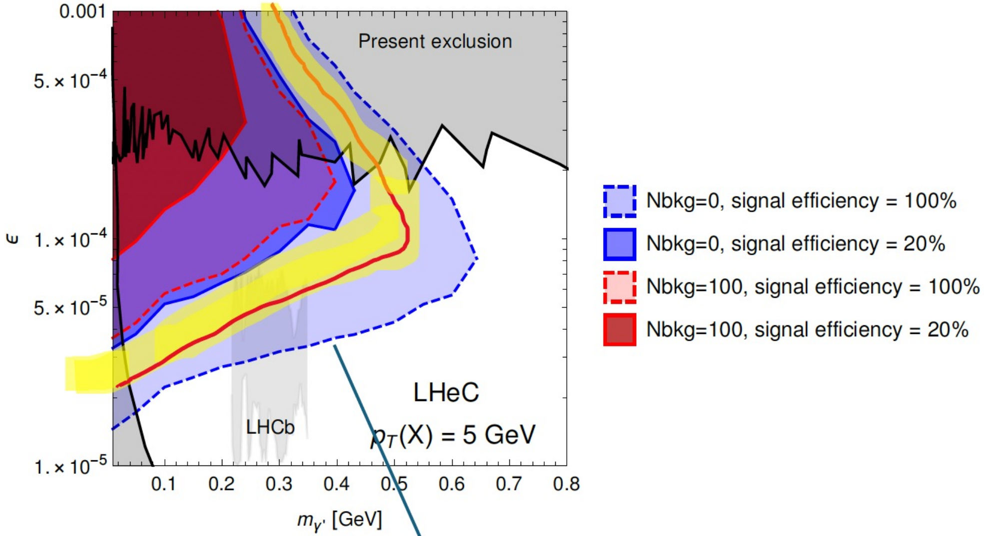


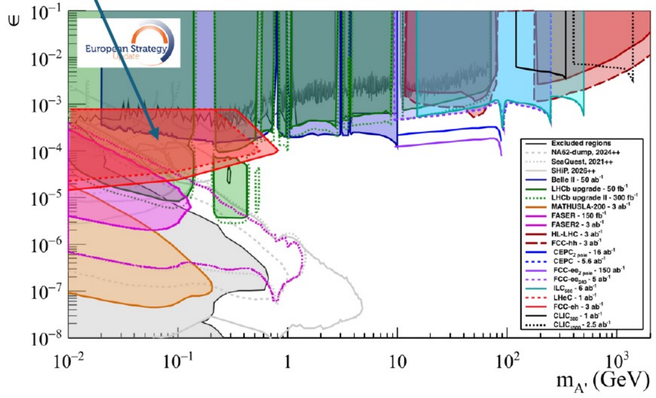
Contour for LHeC presented for 0 and 100 bkg events and for efficiency 100% and 20% (1/5)

Factor 1/10 in lumi corresponds to decrease in significance by sqrt(10)~3

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

→ Still sensitivity!

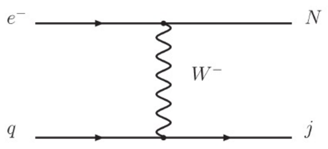


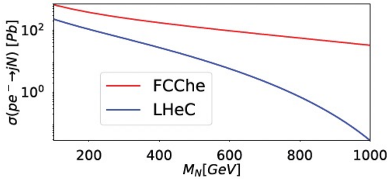


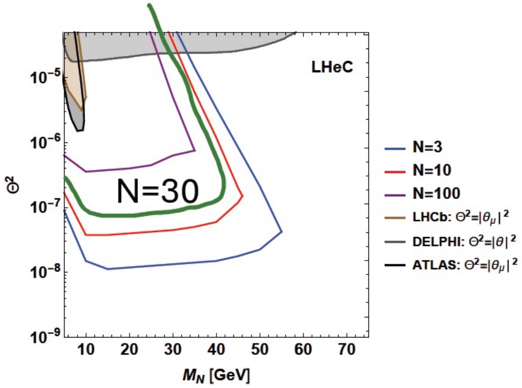
https://doi.org/10.1103/PhysRevD.101.015020

HNLs

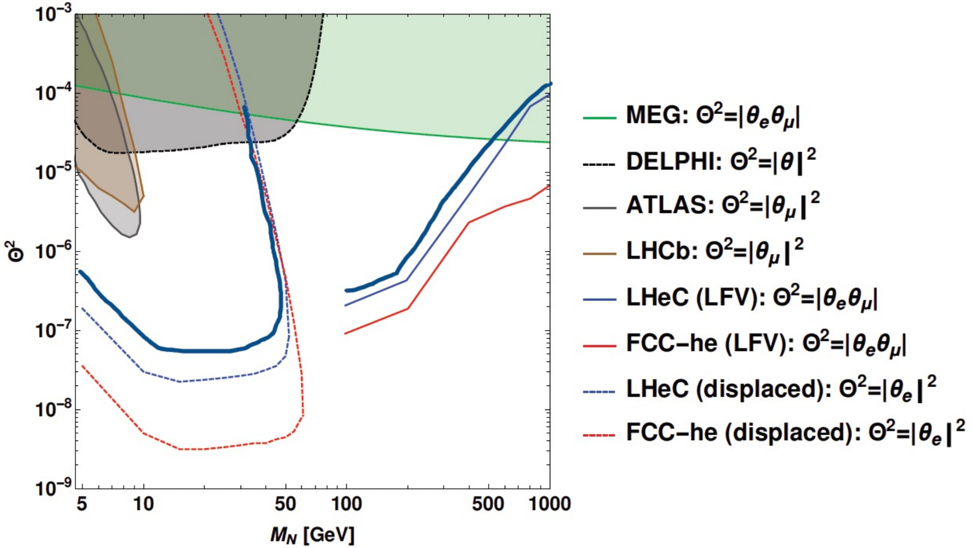
https://doi.org/10.1007/JHEP03%282020%29110





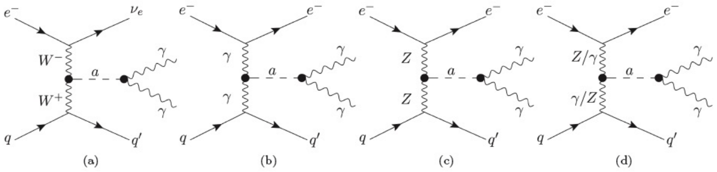


With 1/10 of lumi, N=3 would correspond to N=30 curve
N=10 corresponds to N=100...



Still very good sensitivity

ALPS



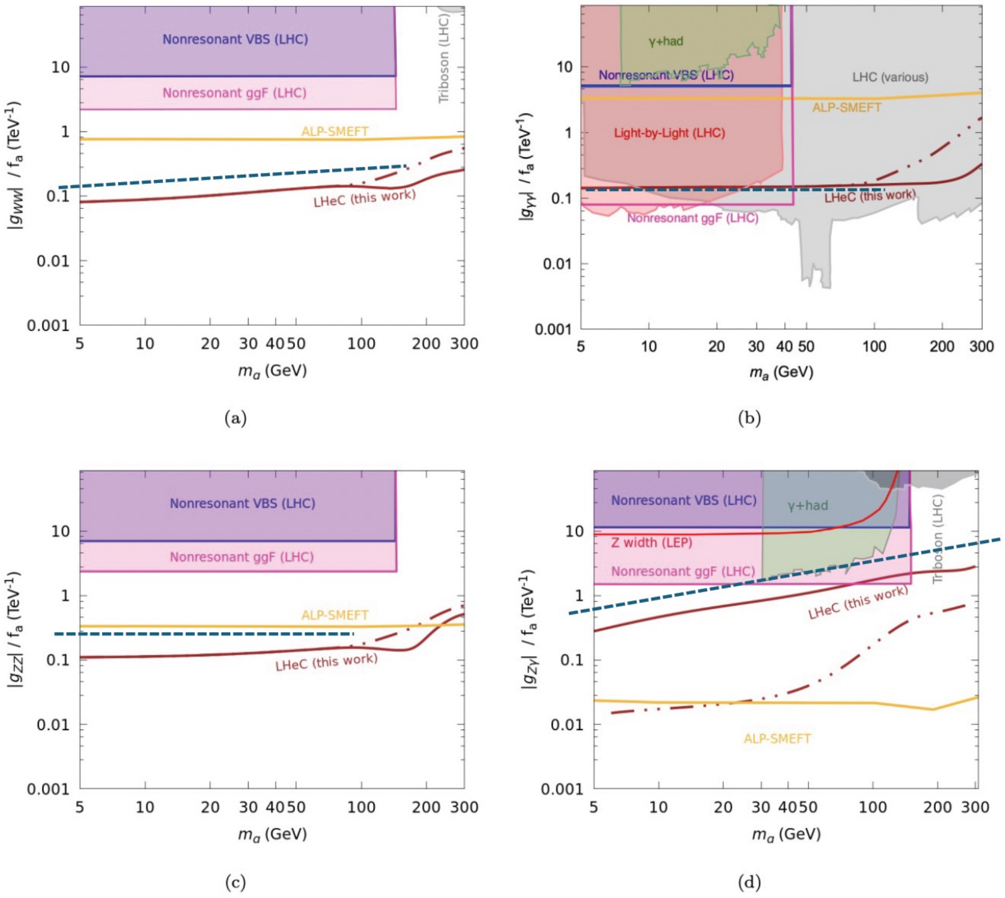
Decays only to photons

Based on 1/ab-1, 95% C.L. limits

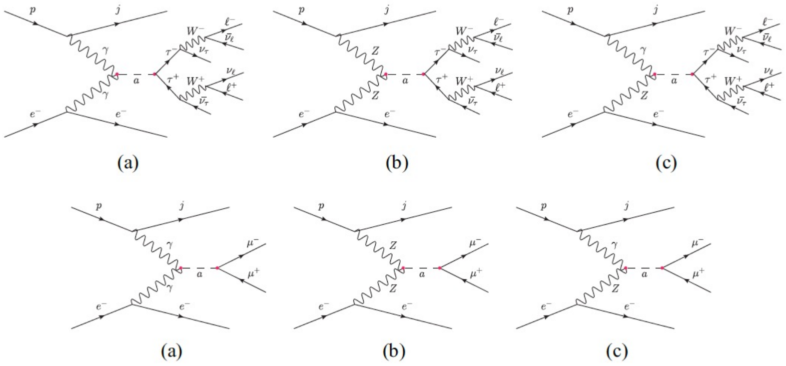
For 1/10 of the stat, dashed line are indicative

Still sensitivity complementary to HL-LHC

https://arxiv.org/pdf/2307.00394



ALPS (2)

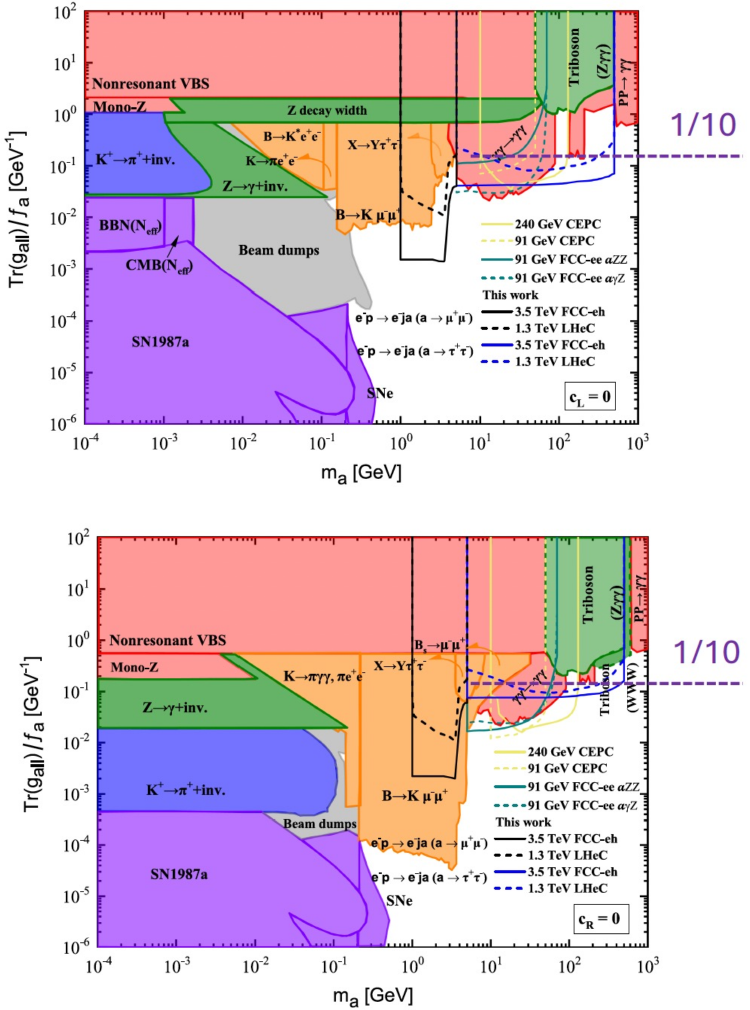


Decays to leptons (e.g. muons and taus)

Impact of 1/10 stat of LHeC far smaller than the LHeC
→ FCC-eh difference

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

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.111.075015

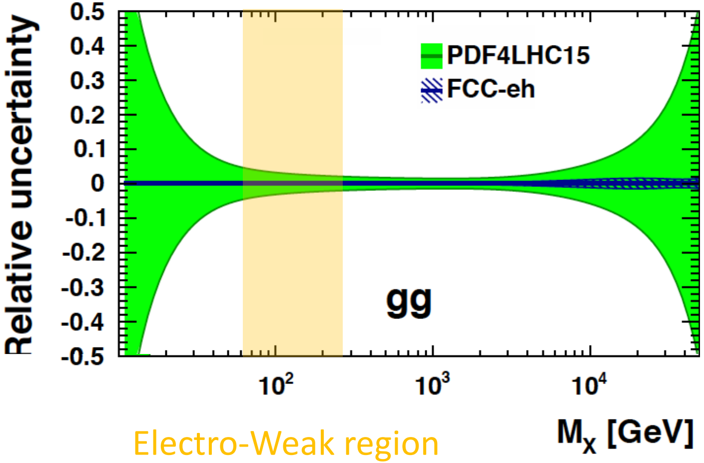


LHeC – bridge to future high-energy hadron collider

LHeC – bridge to future high-energy hadron collider

~5-7% uncertainty on the σ(W,Z,H)

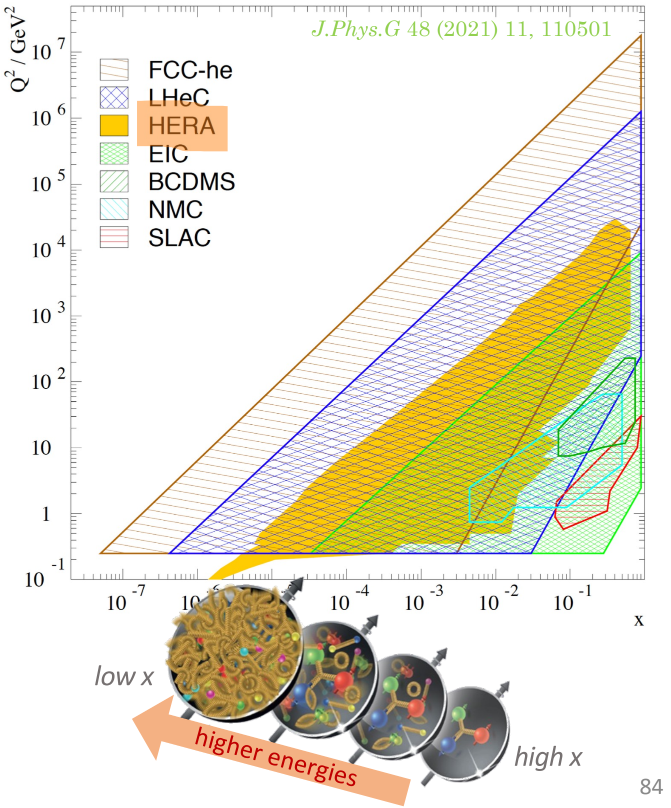
pp @ 100 TeV



Electro-Weak region

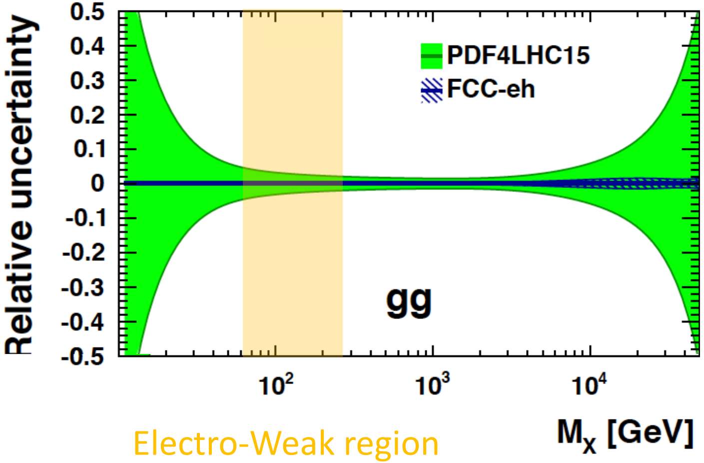
no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV



Electro-Weak region

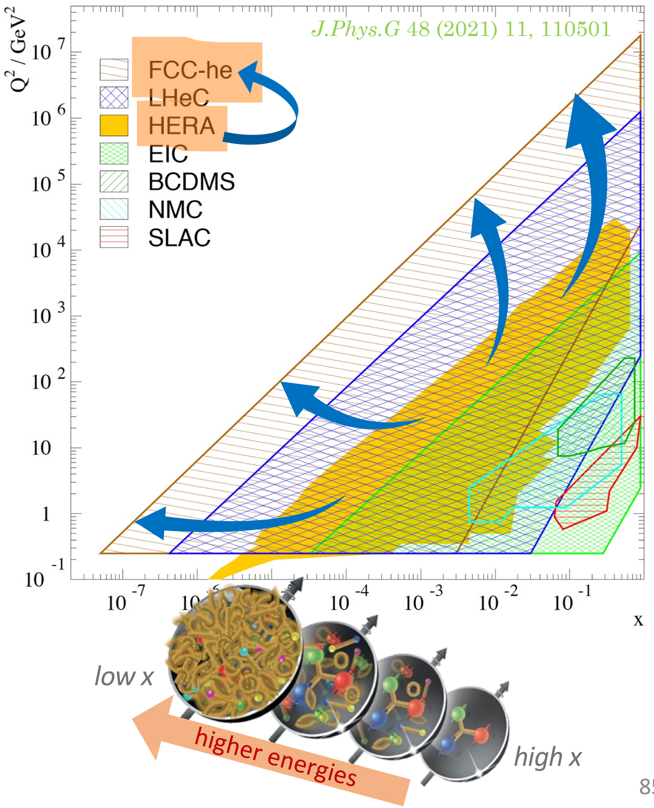
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



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

Complementarity for Higgs physics in the FCC program

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

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

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

Complementarity for Higgs physics in the FCC program

(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

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

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 κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

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

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

FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

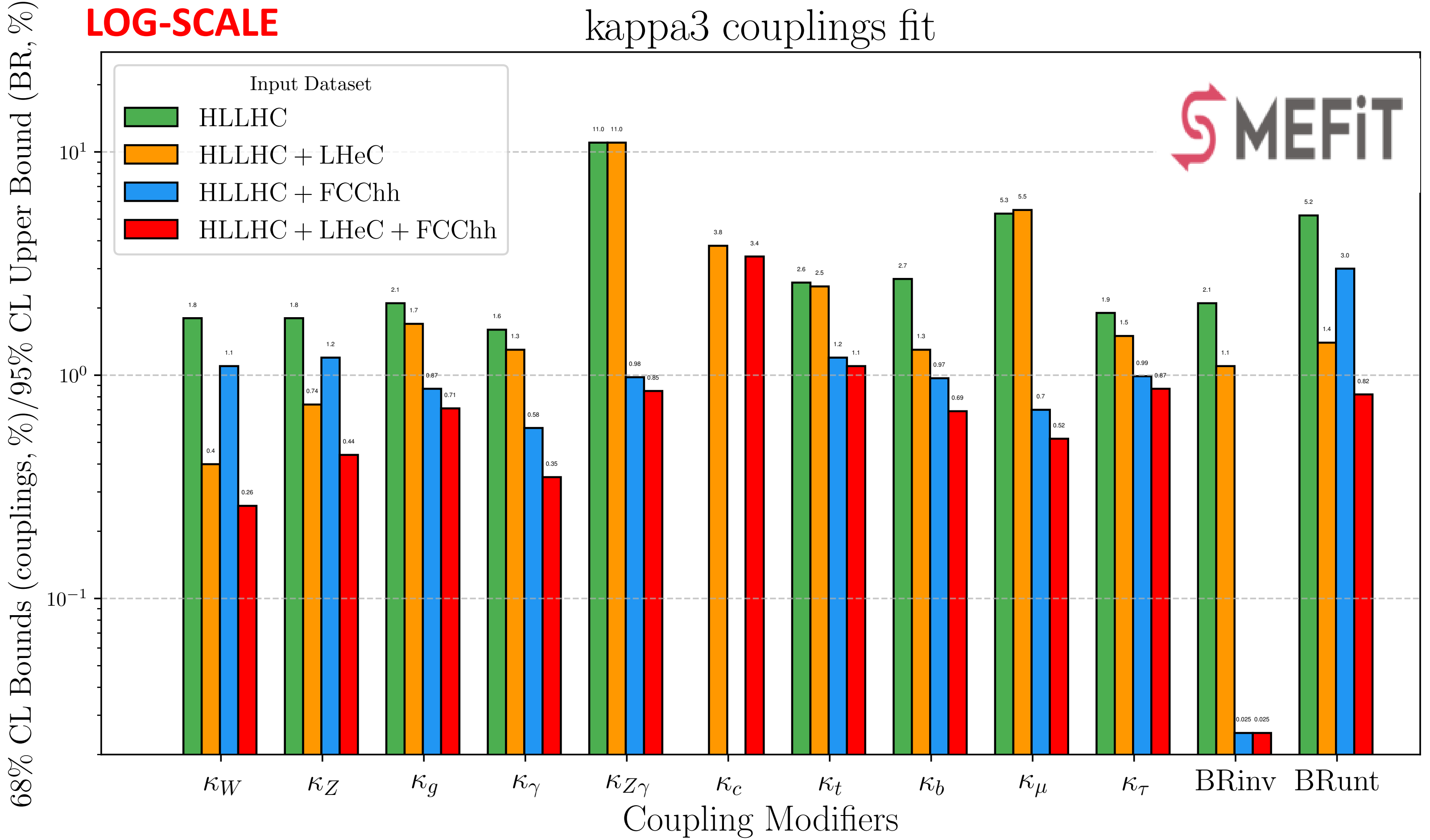
only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

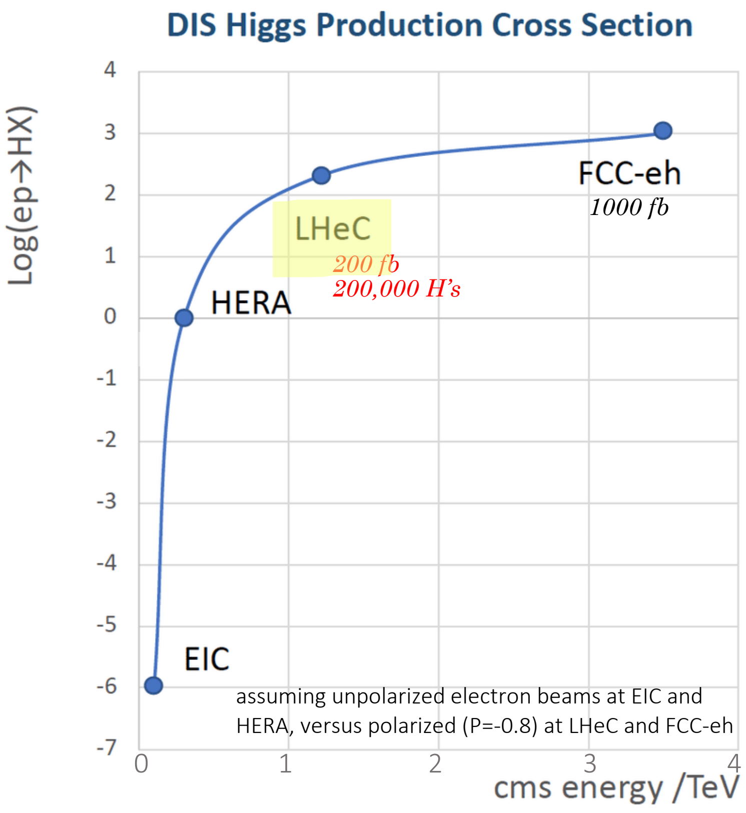
Juan Rojo et al.

LOG-SCALE

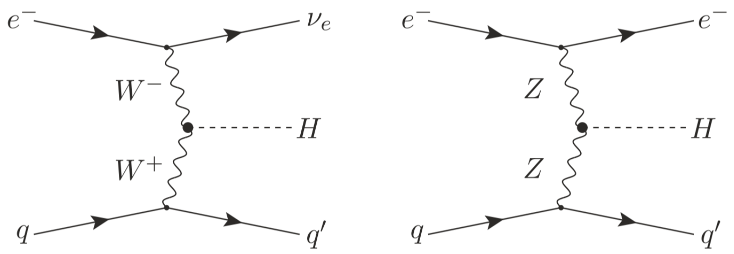


LHeC – more physics plots

Collision energy above the threshold for EW/Higgs/top



The real game change between HERA and LHC/FCC



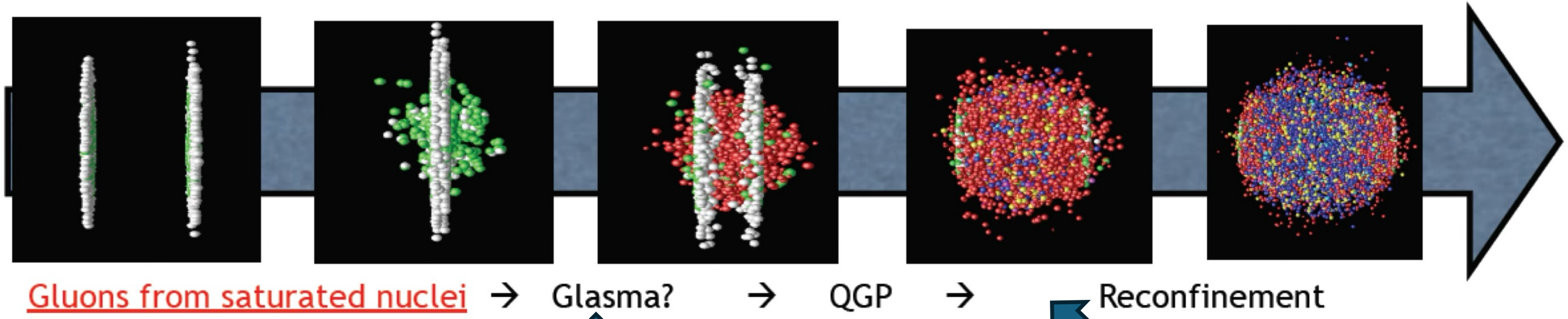
compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

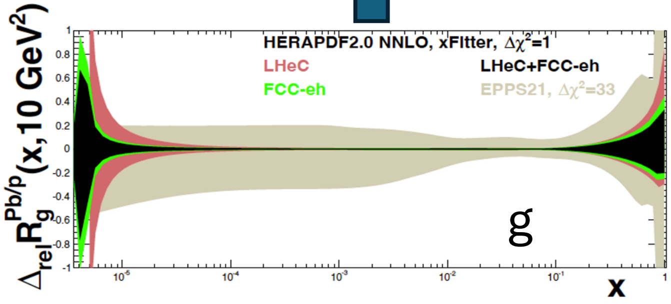
at these energies and luminosities, interactions with all SM particles can be measured precisely

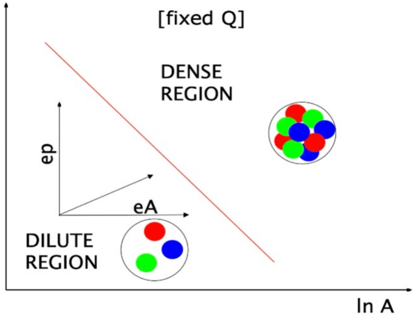
eA at the LHeC

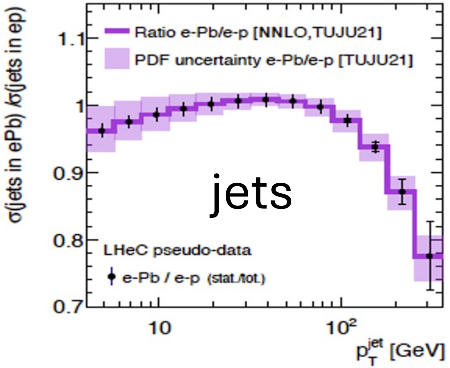
eA collisions at the LHeC will provide precise information on the partonic structure of nuclei and the dynamics of dense partonic systems (a new non-linear regime of QCD which requires ep and eA), relevant for all stages of HICs.

[B. Cole]







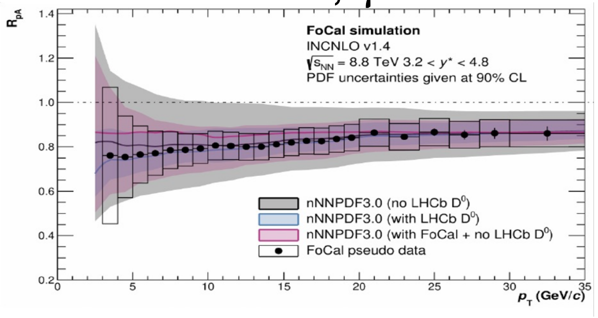


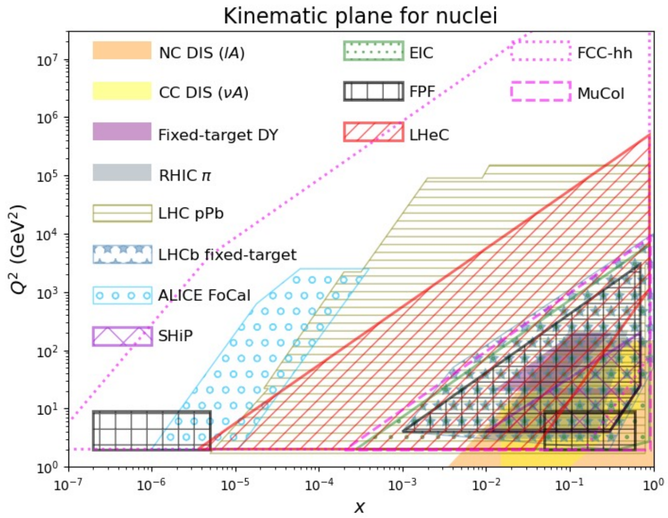
Why DIS for PDFs?

DIS is the ideal place for determining PDFs:

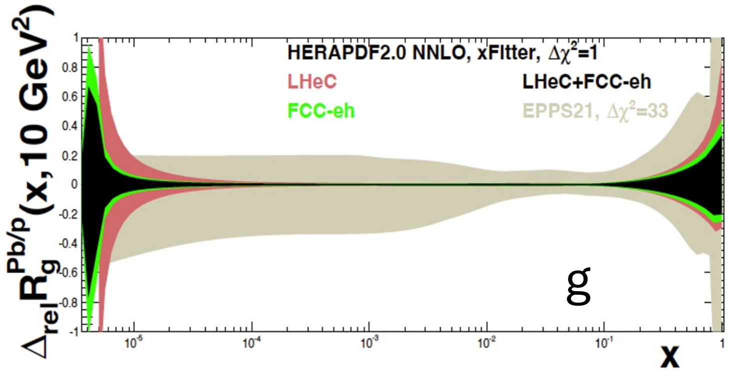
- Pointlike object on a composite one (hh=composite on composite): better determination of kinematic variables in the PDF, far less convoluted information than in pp.
- Much cleaner experimental environment: larger precision.
- Theory better established: factorisation proofs, evolution equations to aNNNLO,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

2407.13058, γ@**FoCal**





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



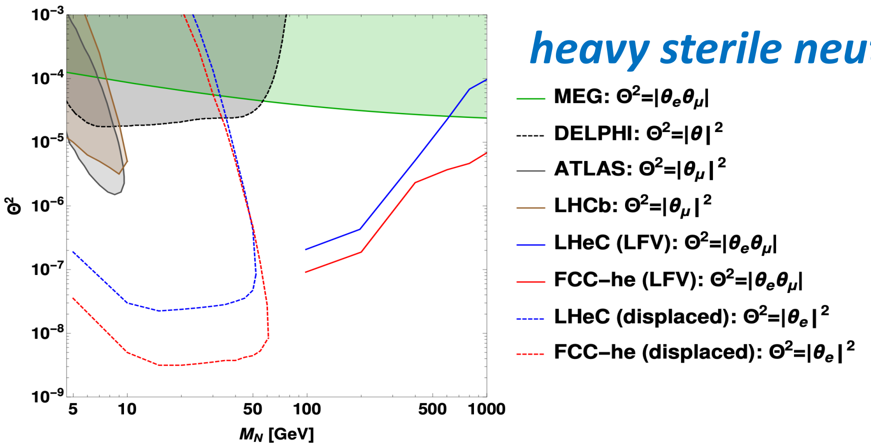
Searching for new physics with the LHeC

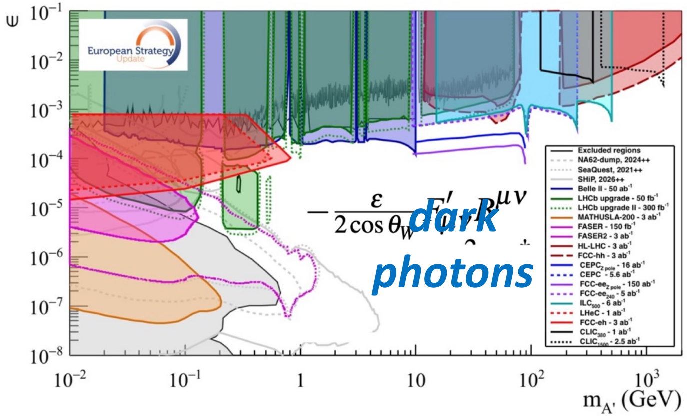
example of long-lived particles
(benchmark models for hidden sectors)

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

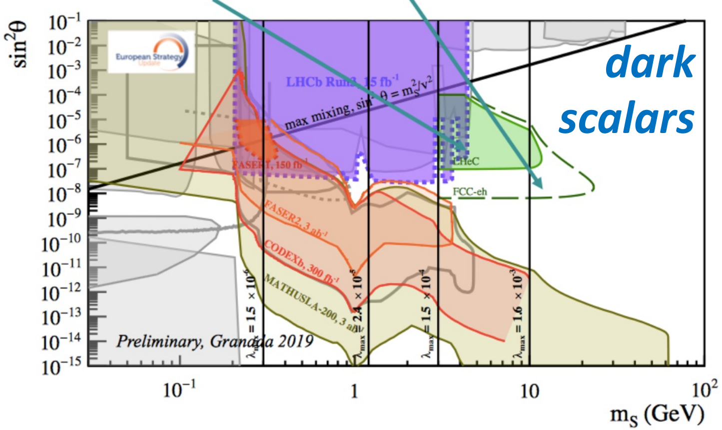
compared to pp collisions the signature is easier to identify in ep collisions

heavy sterile neutrinos

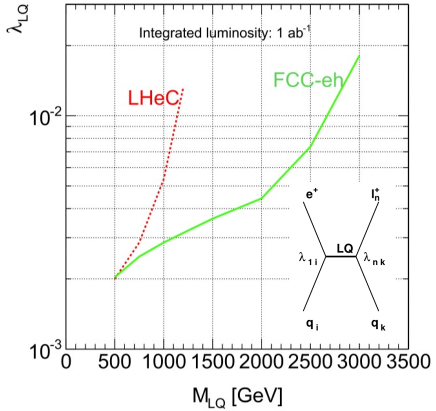




Projections for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1}) - (fixed λ=4x10^{-3}).



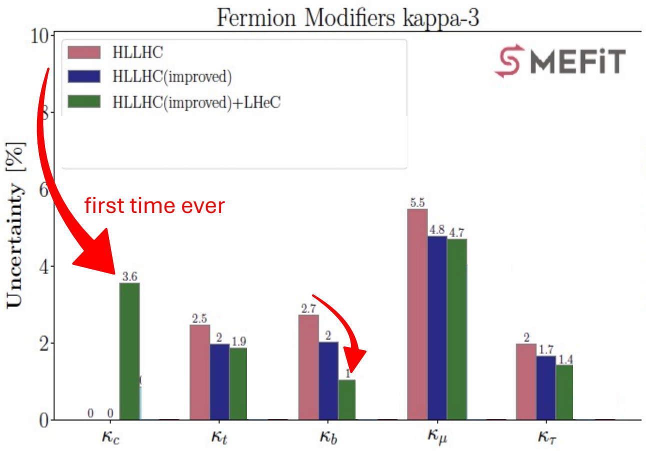
leptoquarks

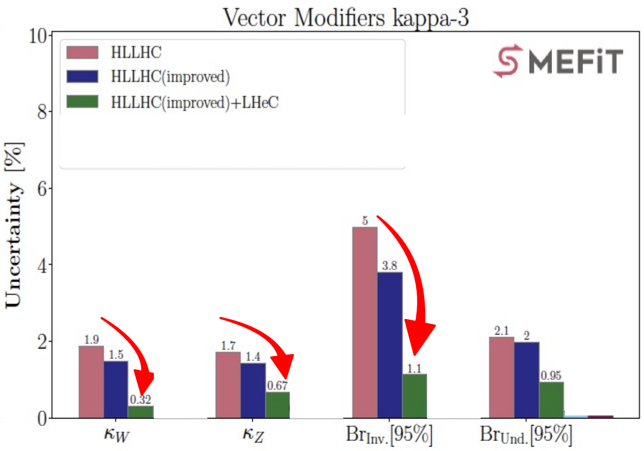


Some physics highlights: Higgs physics

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

- first time ever:
  κ_c
- greatly improved:
  κ_b, κ_W, κ_Z
- significantly improved:
  κ_t, κ_τ, κ_g





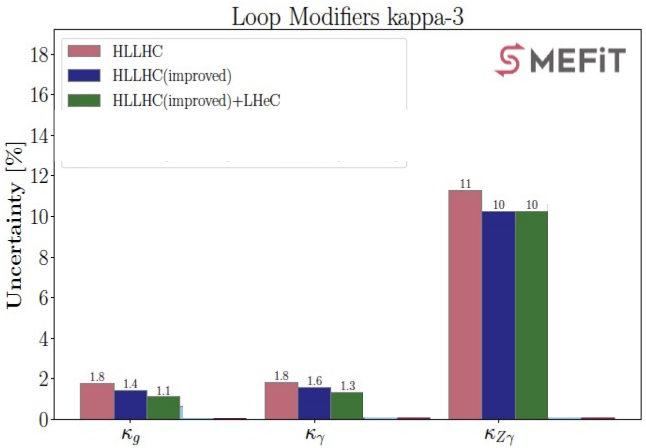


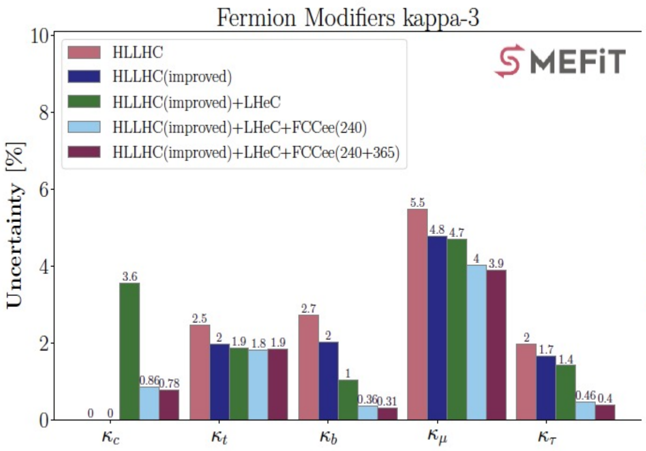
Figure:
The relative uncertainty on the fermion, vector and loop coupling modifiers obtained in the kappa-3 framework, for different combinations of the HL-LHC, HL-LHC (with improved PDFs and α_s from the LHeC), LHeC, and FCC-ee.

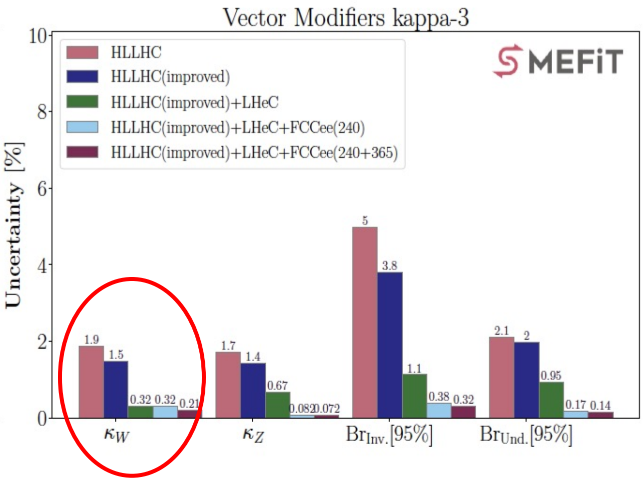
significant improvements wrt HL-LHC

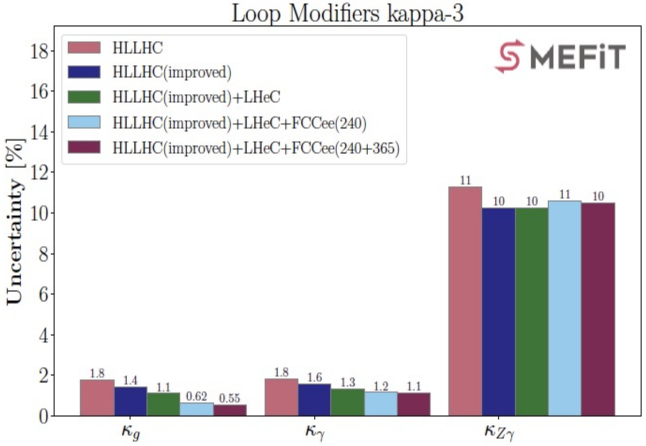
Some physics highlights: Higgs physics

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:
  κ_c
- greatly improved:
  κ_b, κ_W, κ_Z
- significantly improved:
  κ_t, κ_τ, κ_g





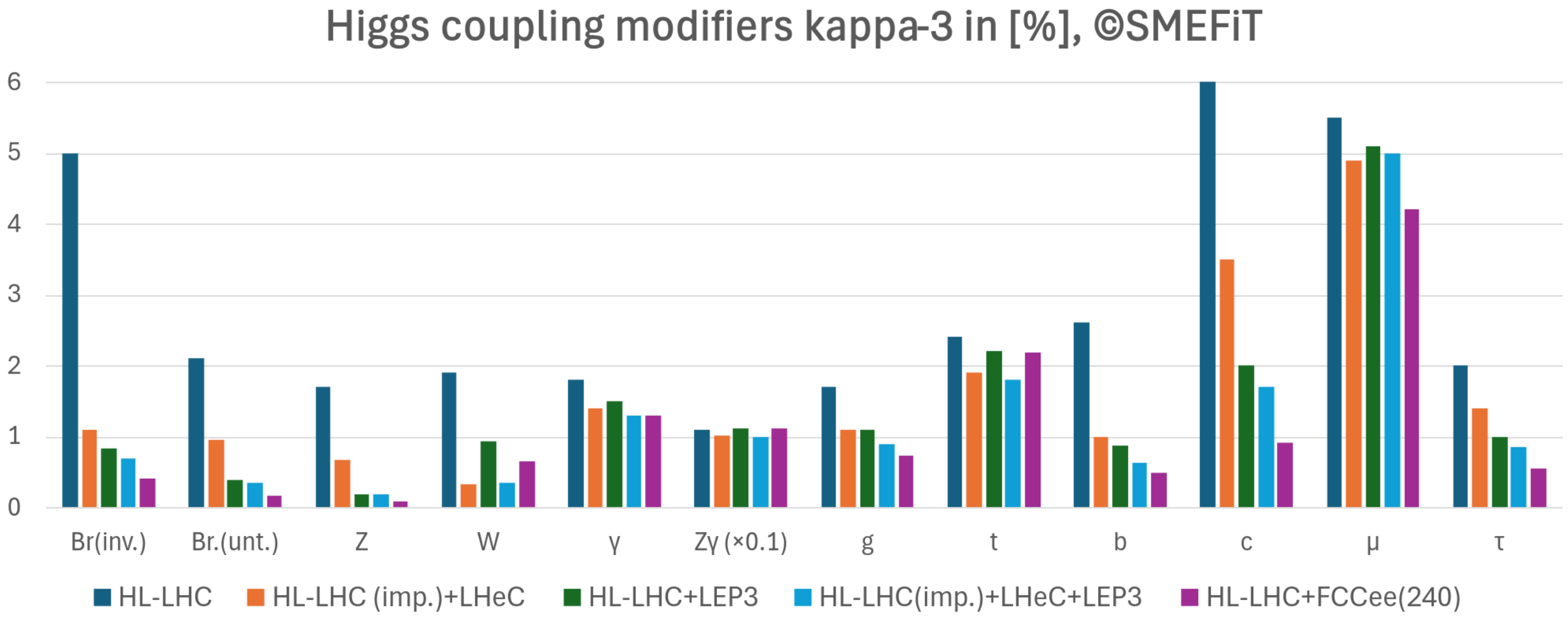


LHeC better wrt FCCee-240

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 α_s from the LHeC), LHeC, and FCC-ee.

Some physics highlights: Higgs physics

LHeC combines well with LEP3



Some physics highlights: gluon distribution

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

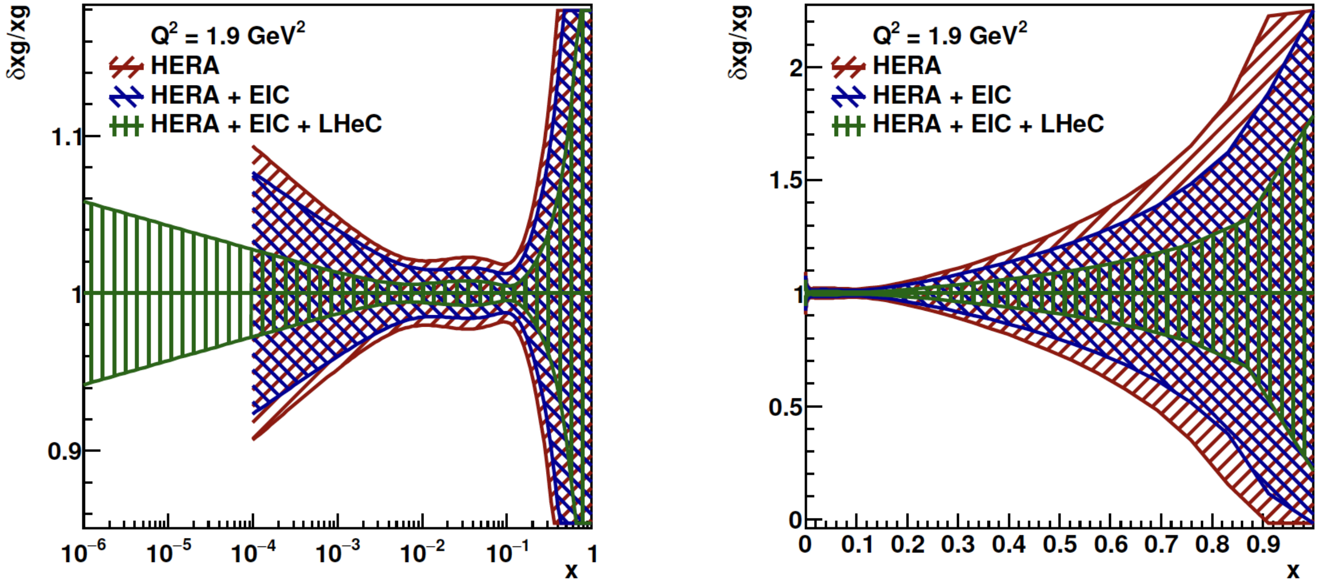
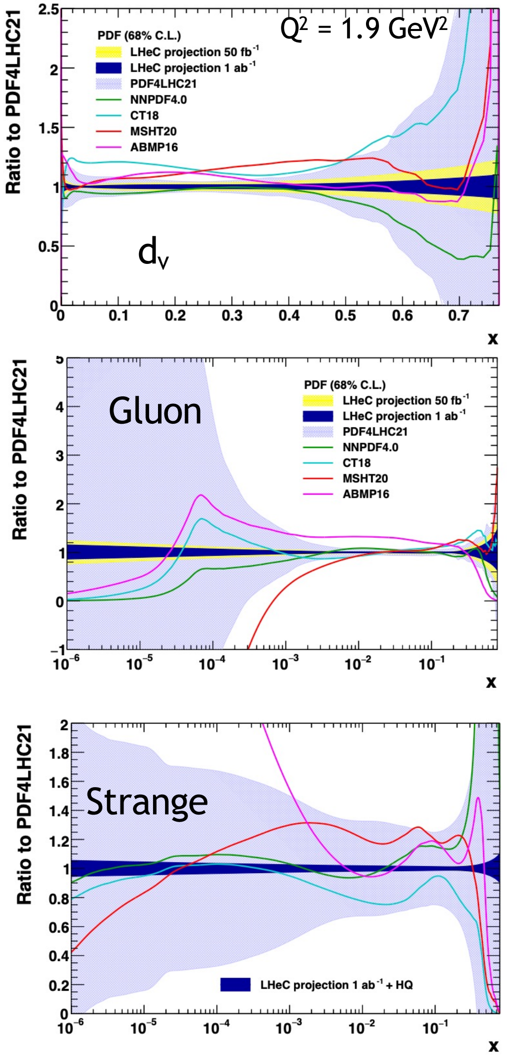


FIG. 13. Uncertainty in the determination of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$ in logarithmic (left) and linear (right) scale in fits to HERA data plus EIC projections plus LHeC [91].

Proton PDF Precision

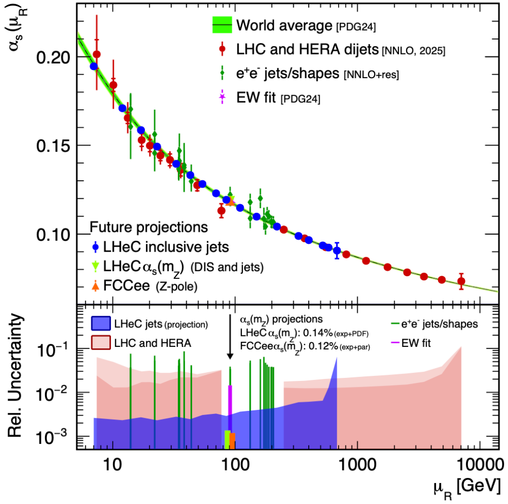


- PDF knowledge transformed over wide kinematic range, extending from x~10^{-6} to x→1

- Resolving current ambiguities

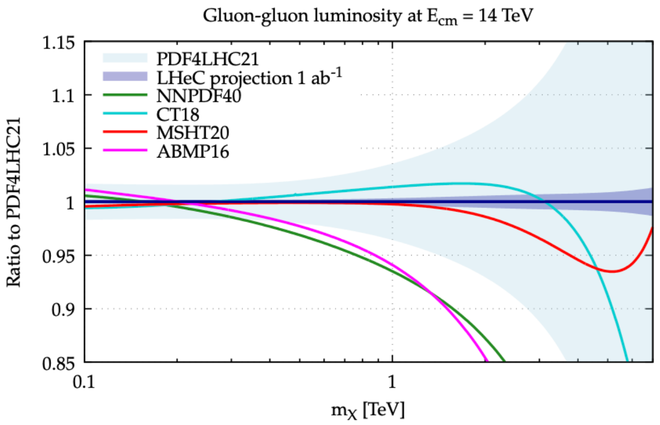
- First full and precise flavour decomposition

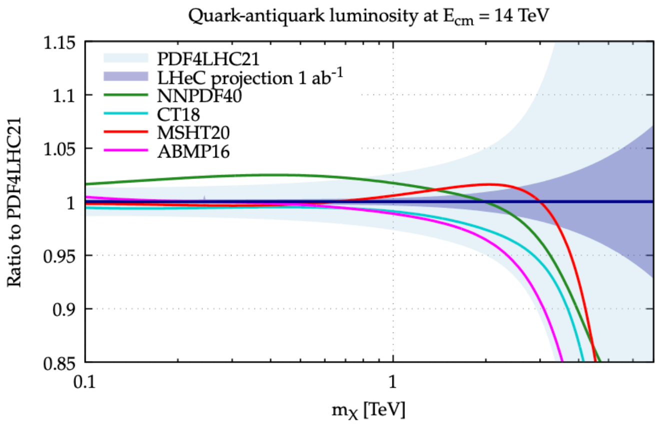
- α_s to 0.14%, including running



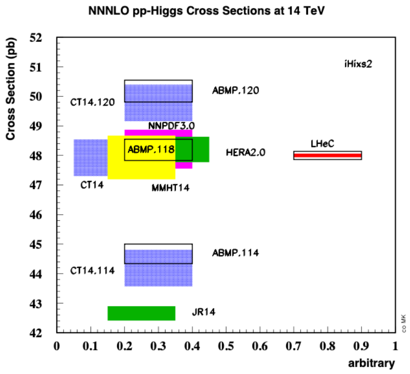
- M_W to few MeV
- $\sin^2\theta_W$ to 0.0002 including running
- Best axial and vector Z-light quark couplings

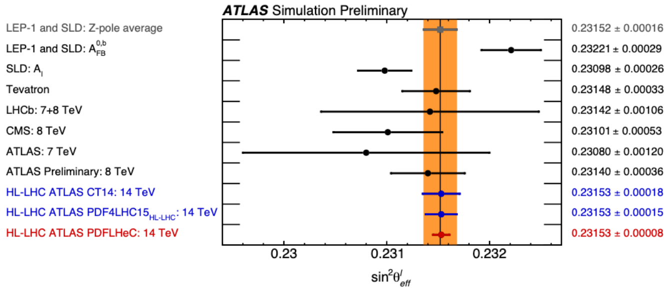
Enabling HL-LHC: parton lumi's revisited





- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements
  …Theory uncertainty on LHC Higgs cross section
  … M_W PDF systs → 2 MeV, enabling 3 MeV measurement
  … $\sin^2\theta_W$ → 0.0008
  …





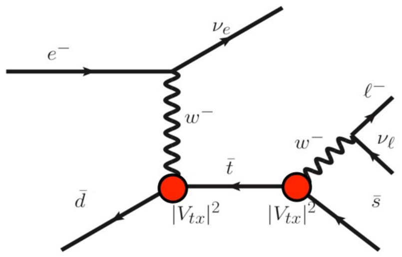
Expected measurements of Wtb couplings and V_{tx}

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

= 1 in SM

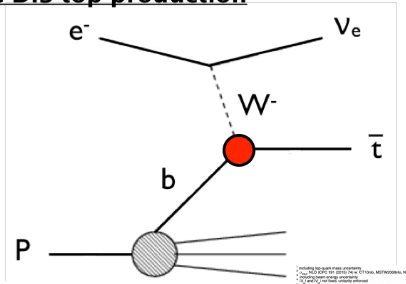
Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.

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

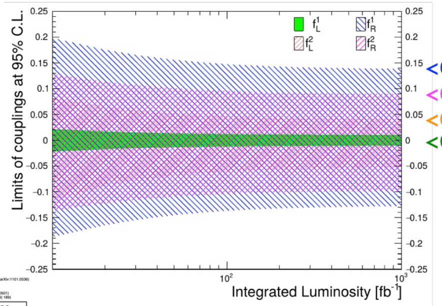


LHeC

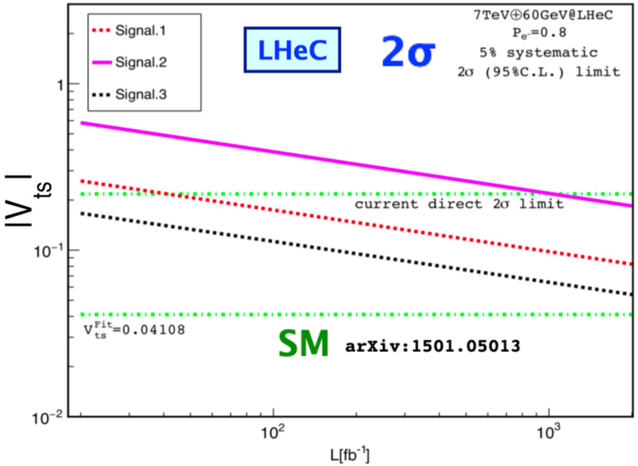
CC DIS top production



hadronic channel:



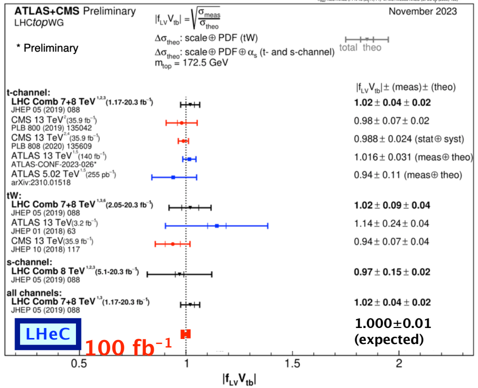
FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)   H. Sun PoS DIS 2018, 167 (2018)



arXiv:1709.07887

LHC

$|V_{ts}|<0.052$



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

Unprecedented precision < 1%

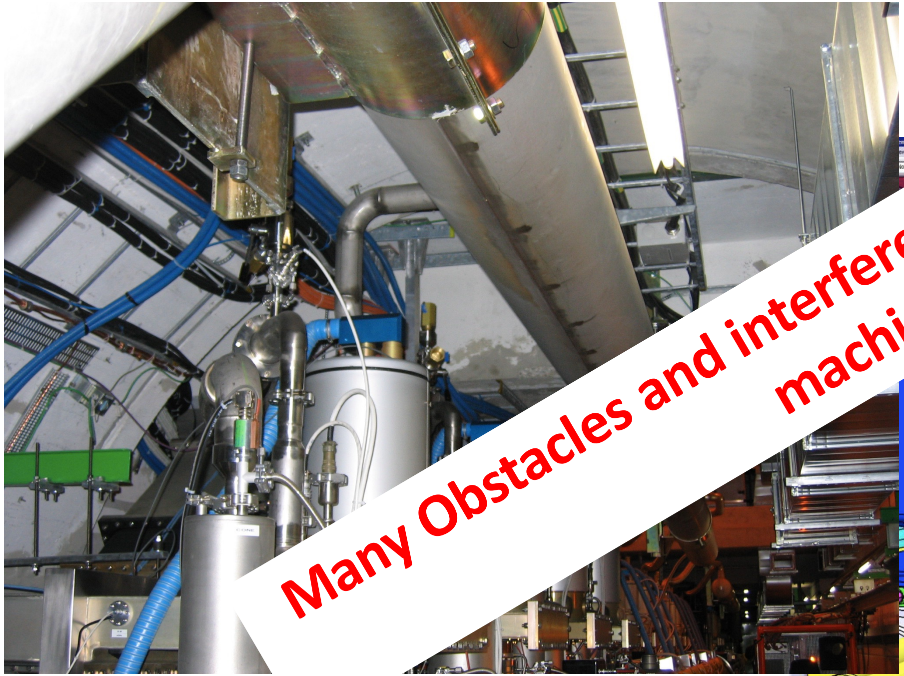
Probing SM prediction directly for the first time

LHeC – ring-ring versus ring-linac

1st Workshop @ Divonne in 2008: Ring-Ring Option

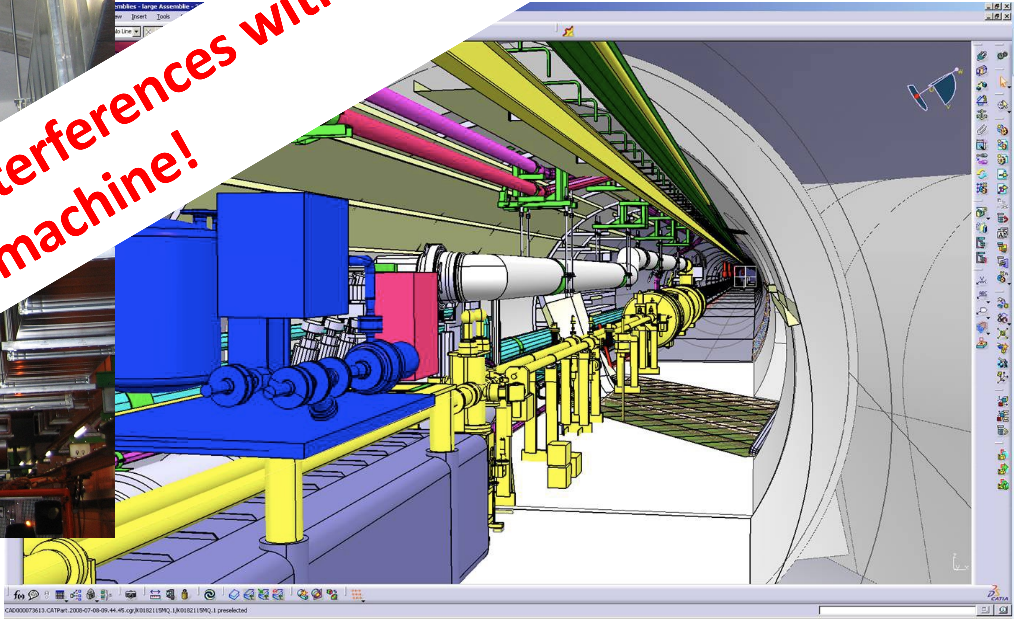
LHeC

Challenge: Integration in the LHC tunnel



Cryo link in IR3

RF In...



Many Obstacles and interferences with existing LHC machine!

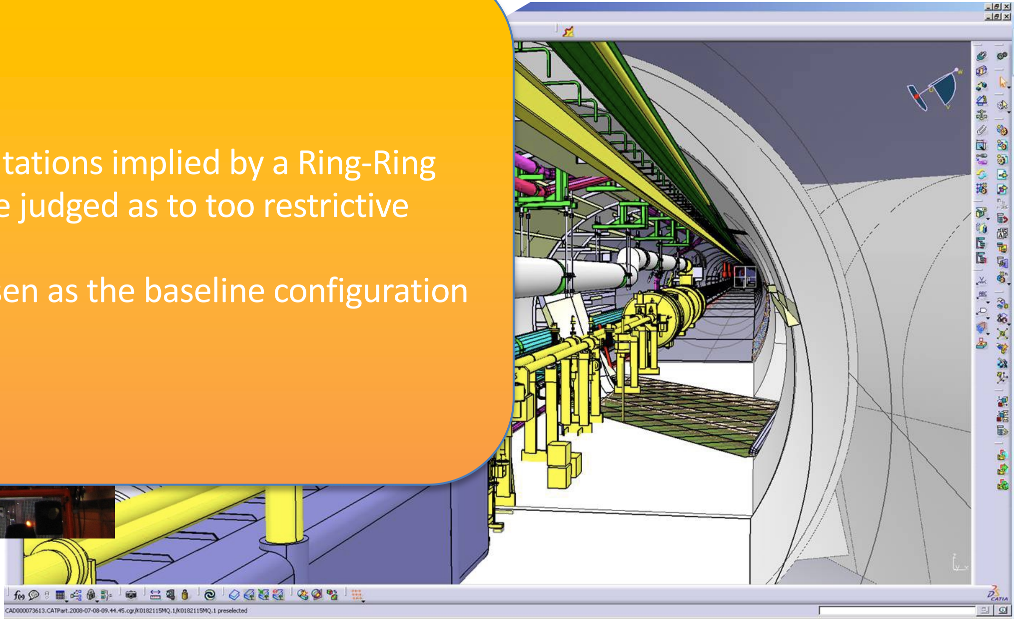
1st Workshop @ Divonne in 2008: Ring-Ring Option

Challenge: Integration in the LHC tunnel

Cryo link in IR3

RF Ins

existing LHC

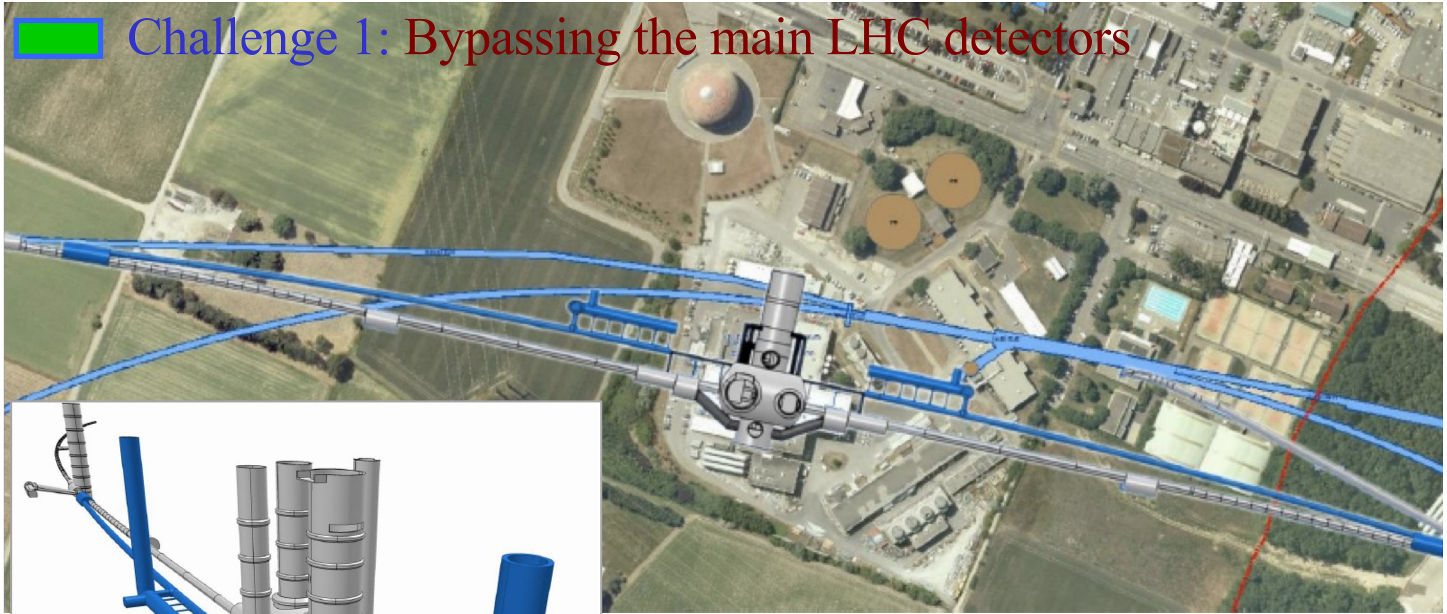


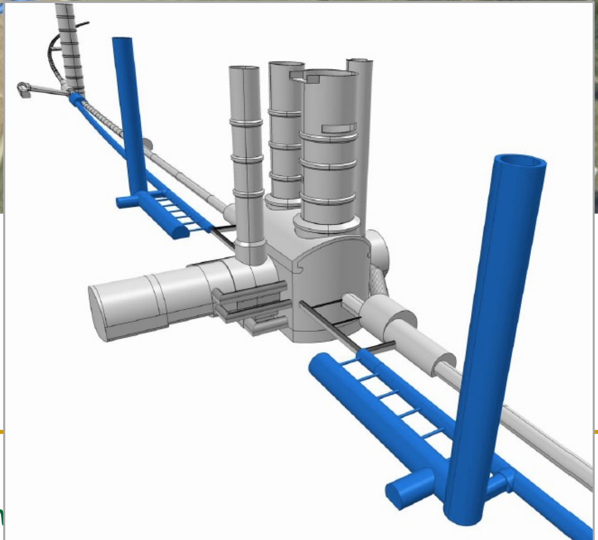
The constraints and limitations implied by a Ring-Ring implementations were judged as to too restrictive

➔ Linac-Ring Option chosen as the baseline configuration

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