Future Colliders and Sustainability

maximum physics impact with minimal environmental impact

Jorgen D'Hondt
Vrije Universiteit Brussel

Early Career Researchers BE+NL workshop on Future Colliders
Sept 13, 2024

the past

the present

the future ?

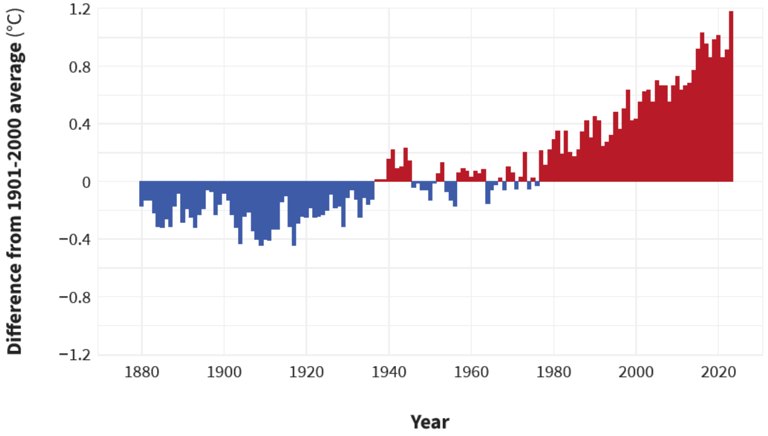
the future ?

Enormous and growing sense of awareness and urgency

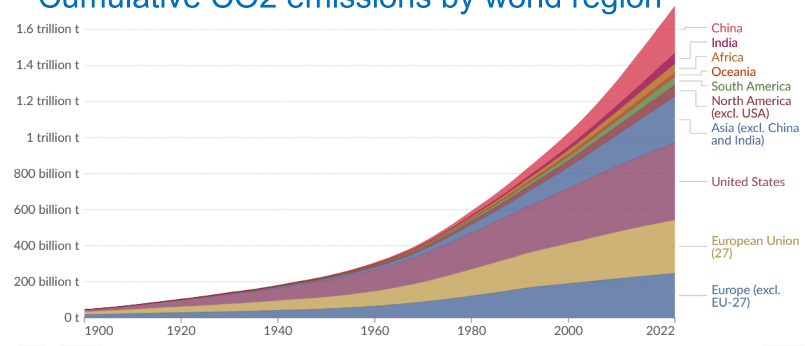
An existential threat

- Human life on earth as we know it is endangered by the unsustainable exploitation of many natural resources.
- One of the most urgent issues: CO2 from burning fossil fuels accumulates in the atmosphere. CO2 in the atmosphere is the primary determinant of the earth's average surface temperature.
- Present large HEP facilities have a significant carbon footprint - consumption of electrical energy, green house gases from detectors, heating of buildings, procurements, travel/commuting and waste.
- Present operation and future accelerator projects need justification not just in terms of scientific output vs effort (cost/resources) but also vs overall electricity consumption and carbon footprint.

Global average surface temperature

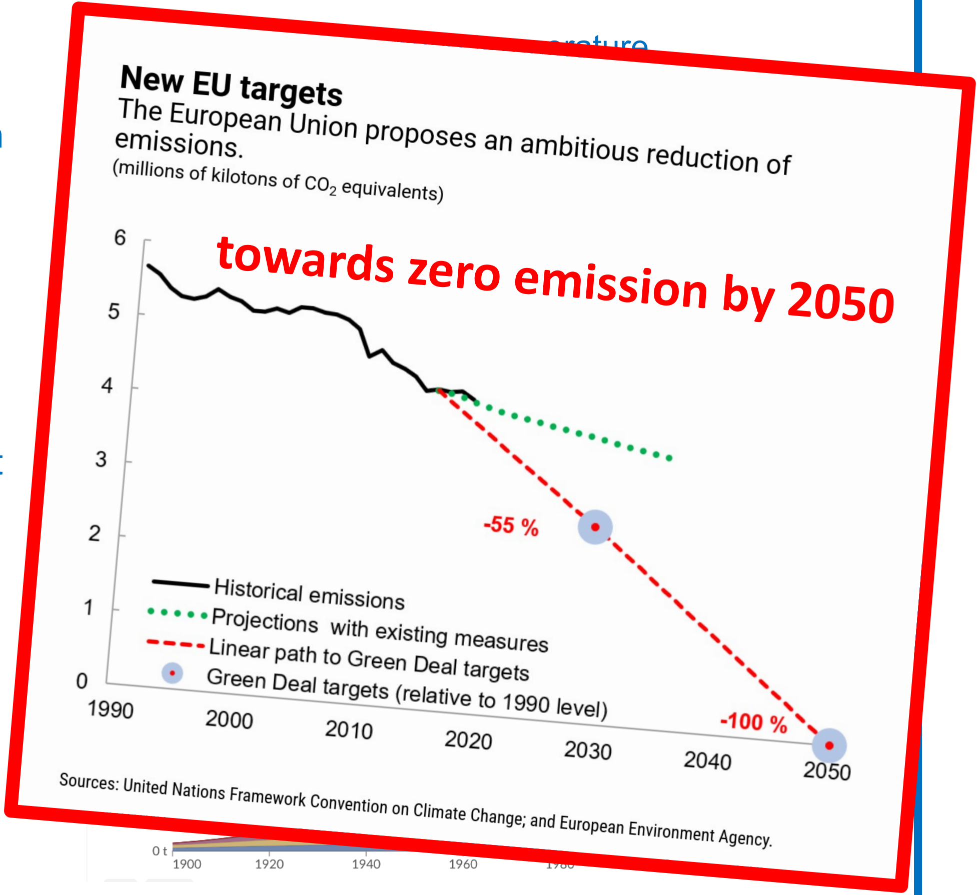


Cumulative CO2 emissions by world region



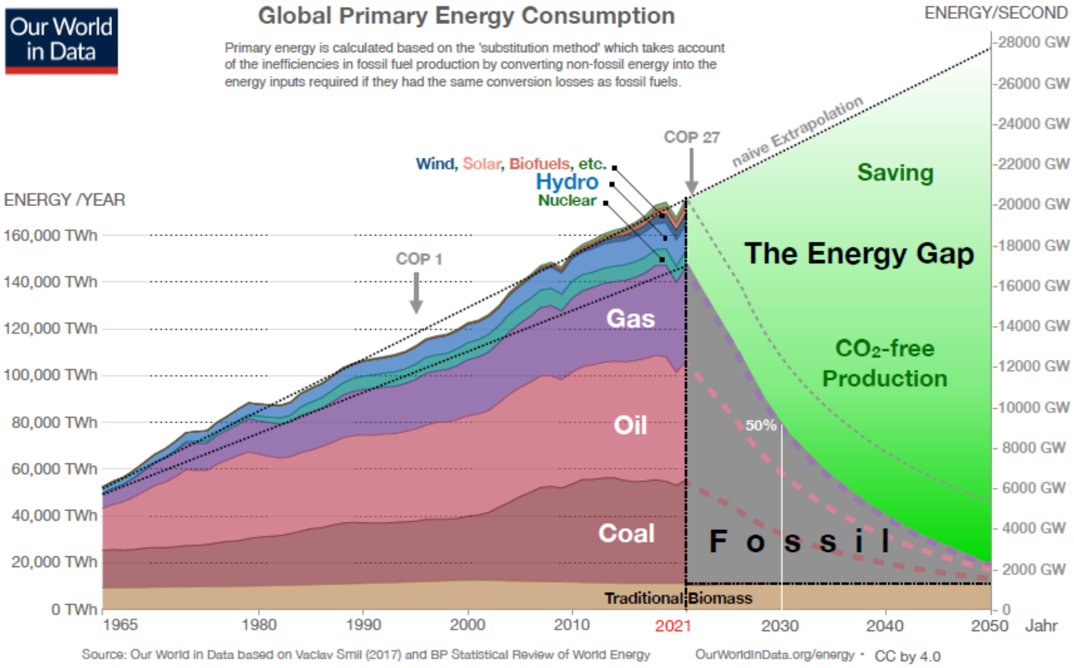
An existential threat

- Human life on earth as we know it is endangered by the unsustainable exploitation of many natural resources.
- One of the most urgent issues: CO2 from burning fossil fuels accumulates in the atmosphere. CO2 in the atmosphere is the primary determinant of the earth's average surface temperature.
- Present large HEP facilities have a significant carbon footprint - consumption of electrical energy, green house gases from detectors, heating of buildings, procurements, travel/commuting and waste.
- Present operation and future accelerator projects need justification not just in terms of scientific output vs effort (cost/resources) but also vs overall electricity consumption and carbon footprint.



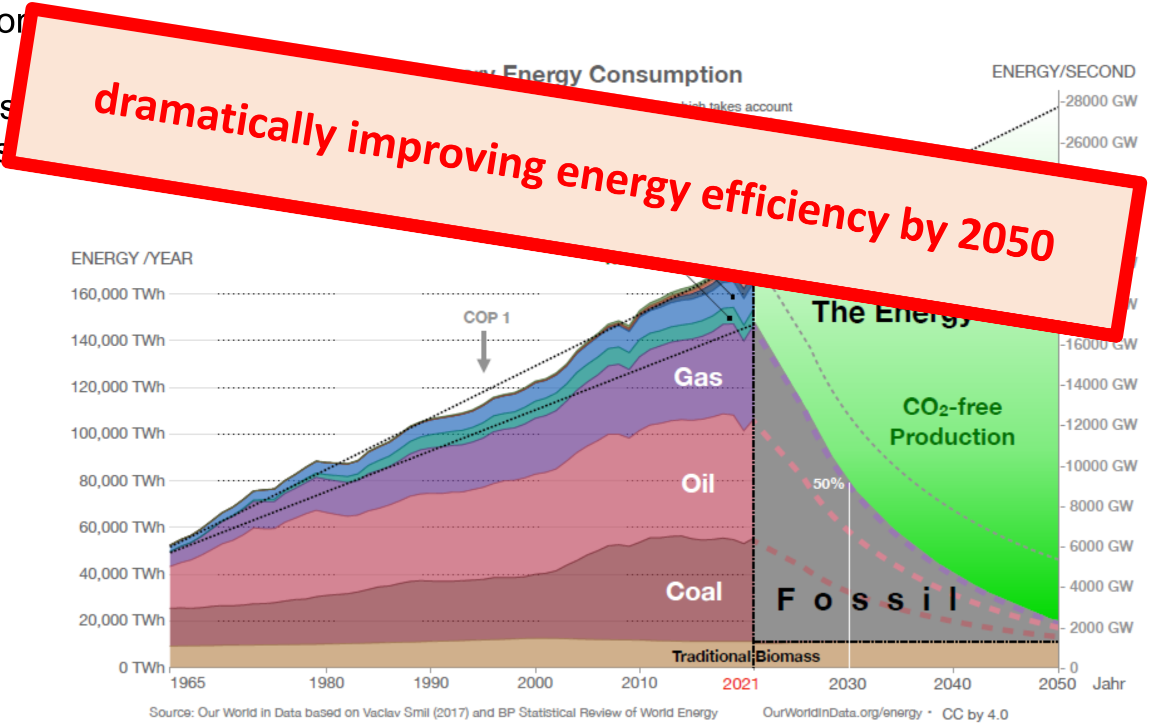
Global primary energy consumption

- Present global energy production is dominated by fossil fuels
- To reach climate change targets fossil fuel consumption requires dramatic reduction that will create an energy gap
  - Requires rapid rise of climate neutral power generation
  - Energy costs will rise
  - Requires energy savings and recuperation
- Rising costs and enhanced scrutiny will challenge HEP accelerators, experiments and data analyses centres both present and in the future



Global primary energy consumption

- Present global energy production is dominated by fossil fuels
- To reach climate change targets fossil fuel consumption requires dramatic reduction that will create an energy gap
    - Requires rapid rise of climate neutral power generation
    - Energy costs will rise
    - Requires energy savings and recuperation
- Rising costs and enhanced scrutiny will challenge HEP accelerators, experiments and data analyses centres both present and in the future



2050 might be the timescale to operate a new major collider

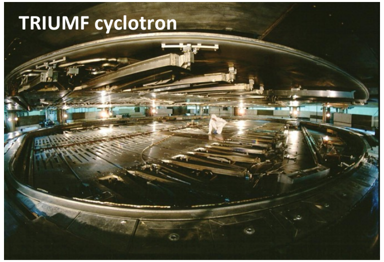
Potential future requirements for future colliders:
zero emission & drastically reduce energy footprint

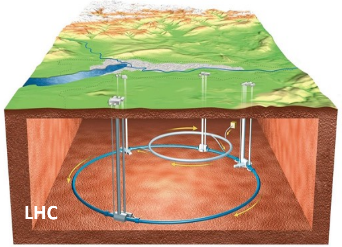
My opinion:
"If you are part of the problem, you should be part of the solution"

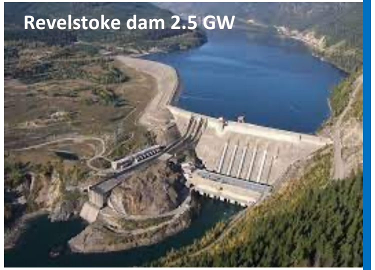
Power comparisons

Large accelerator complexes require significant electrical power

Cyclist	0.0004 MW
PET cyclotron	0.06 MW
TRIUMF 500MeV cyclotron	2.6 MW
Large Hadron Collider	120 MW
FCC-ee, @ Higgs Energy	282 MW
Nuclear Power Station	1300 MW
BC Hydro Revelstoke Dam	2500 MW
Mankind Total (all sources)	19000000 MW







The landscape of future particle physics colliders

~15-20B EUR

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

The landscape of future particle physics colliders

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

ERL technology ($E_e \sim$ 30-60 GeV)

E_{CMS} > 1 TeV

ERL: https://indico.ijclab.in2p3.fr/event/9548/

~1B EUR

~15-20B EUR

pp (and AA/pA)

High-field magnet technology

E_{CMS} >> 14 TeV (LHC)

The landscape of future particle physics colliders

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

ERL technology ($E_e \sim$ 30-60 GeV)

$E_{CMS} > 1$ TeV

ERL: https://indico.ijclab.in2p3.fr/event/9548/

~1B EUR

~7-12B EUR

e^+e^-

RF technology

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

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

$E_{CMS} > 500$ GeV

~15-20B EUR

pp (and AA/pA)

High-field magnet technology

$E_{CMS} >> 14$ TeV (LHC)

The landscape of future particle physics colliders

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

ERL technology ($E_e \sim$ 30-60 GeV)

E_{CMS} > 1 TeV

ERL: https://indico.ijclab.in2p3.fr/event/9548/

e^+e^-

RF 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 Roadmap prioritizes progress on these technologies to enable future particle accelerators in a timely, affordable and sustainable way

CERN Yellow Rep. Monogr. 1 (2022) 1-270, https://cds.cern.ch/record/2800190?ln=en

An electron-positron Higgs factory is the highest-priority next collider.

European Strategy for Particle Physics 2020

the accelerator

particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

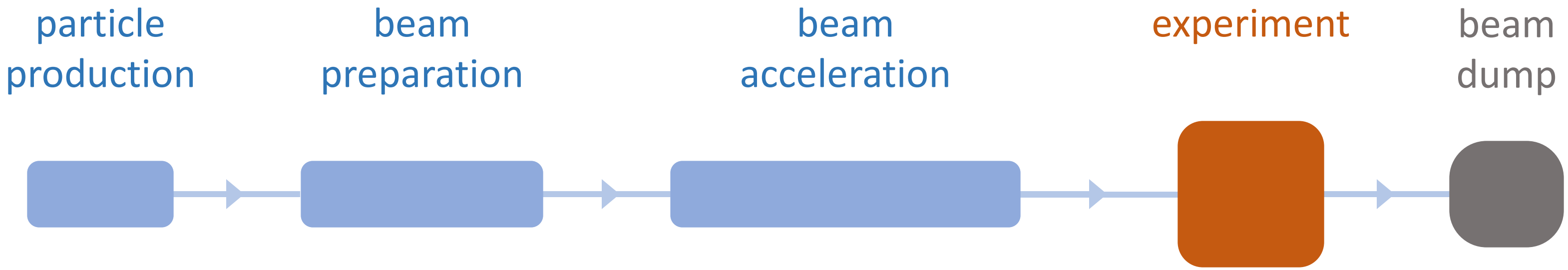
(energy x current = power)

caveat

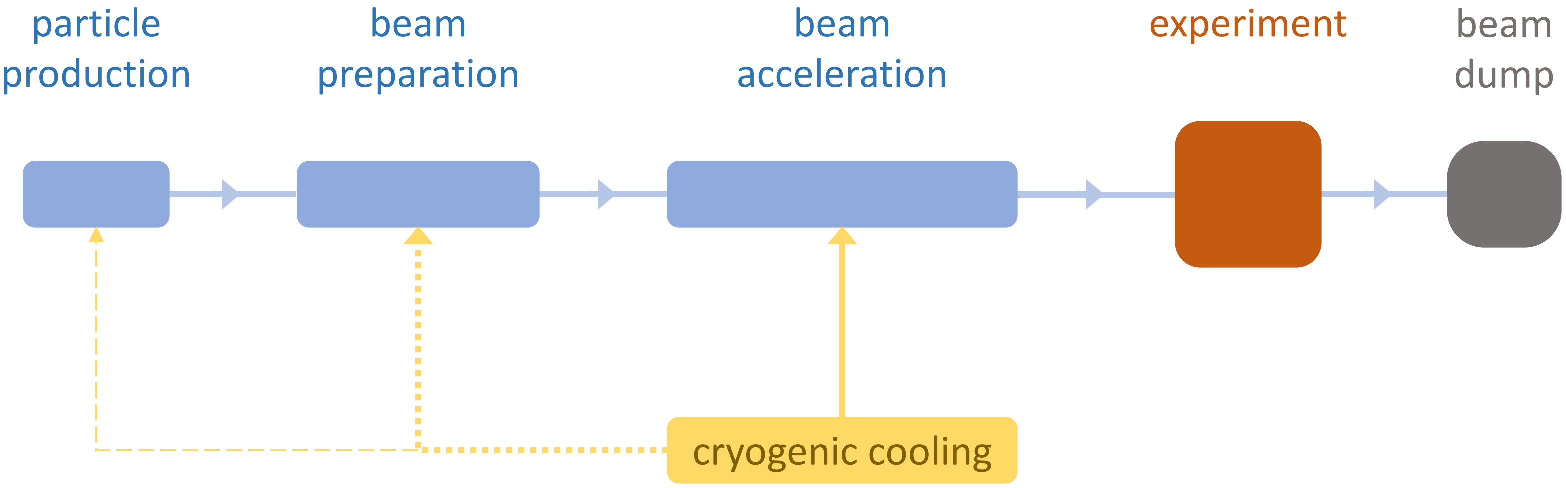
power requirements of future colliders

focus on electron/positron accelerators

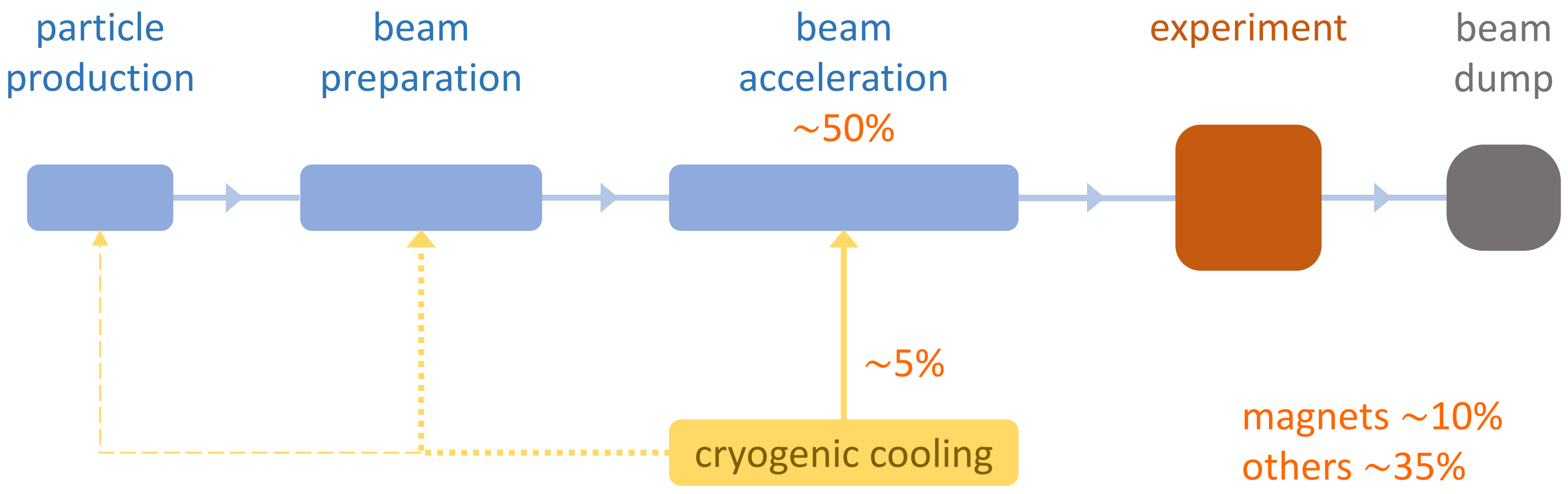
Basic structures of a particle accelerator



Basic structures of a particle accelerator



Basic structures of a particle accelerator



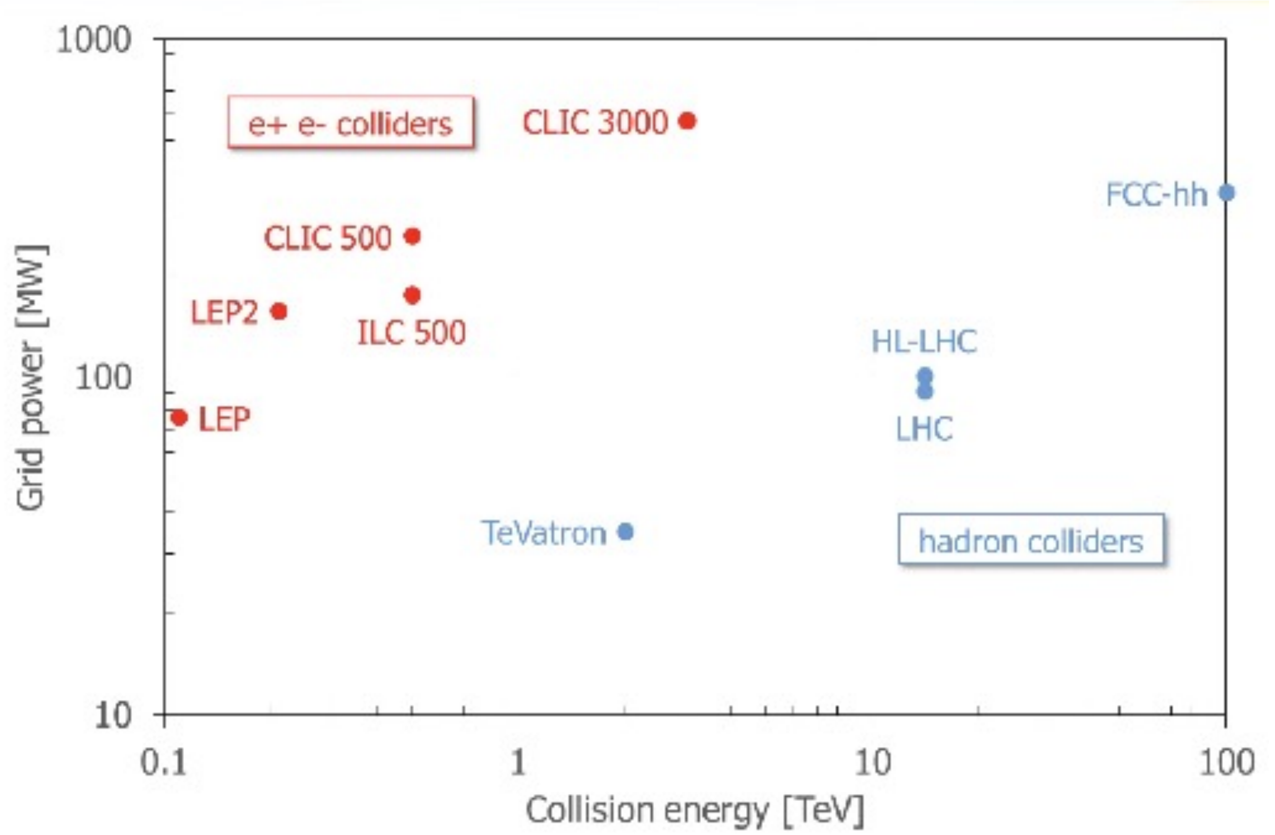
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

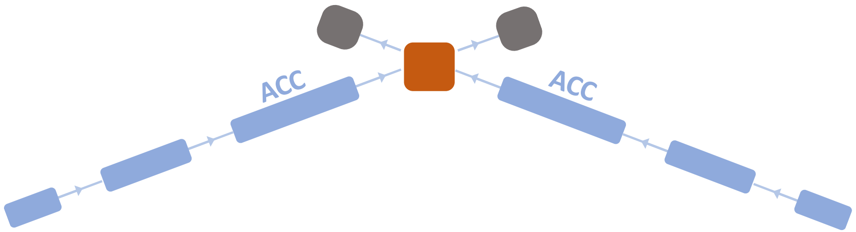
FCC CDR, Eur. Phys. J. Special Topics 228, 261–623 (2019)

All proposed future e^+e^- & pp colliders require high grid power



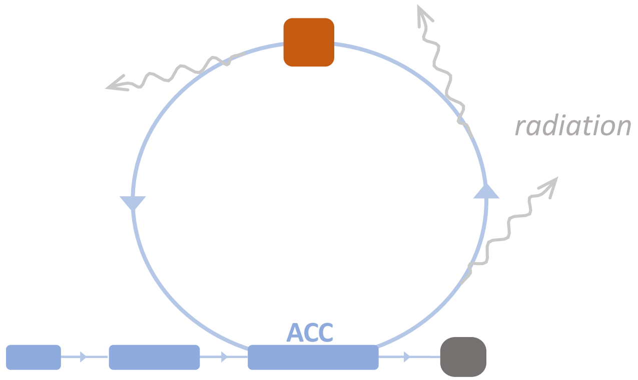
Bai, M. & Shiltsev, V. & White, Glen & Zimmermann, Frank. (2022). Ultimate Limit of Future Colliders. 10.48550/arXiv.2209.04009.

Linear colliders



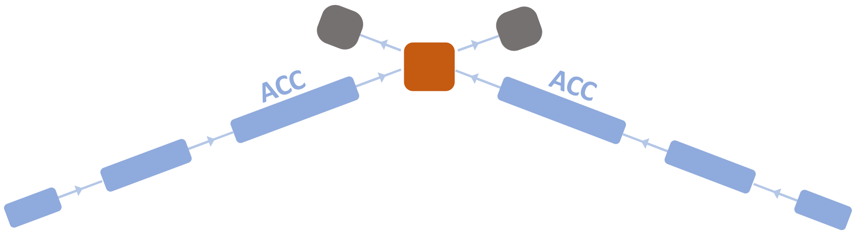
dump >99.9999% of
the beam power

Circular colliders



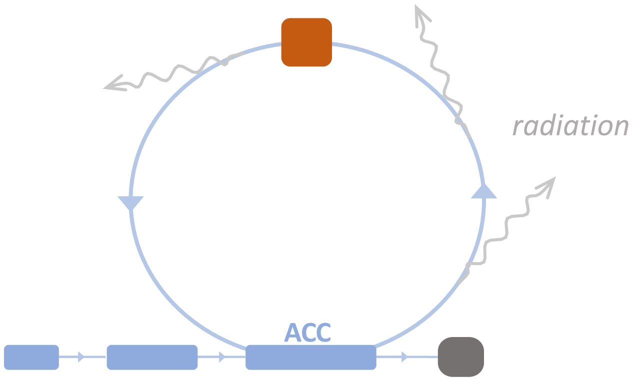
radiate away very quickly the beam power
& loose beam quality

Linear colliders



dump >99.9999% of
the beam power

Circular colliders

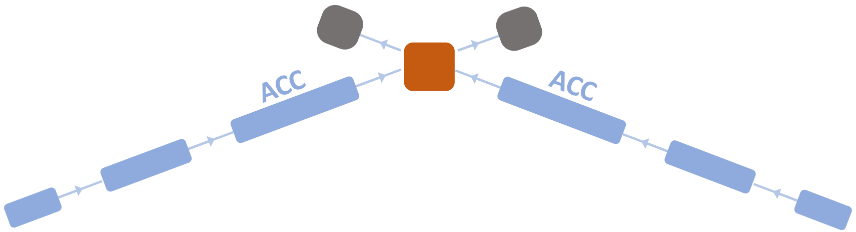


radiate away very quickly the beam power
& loose beam quality

FCC-ee@250 ≃ 300 MW

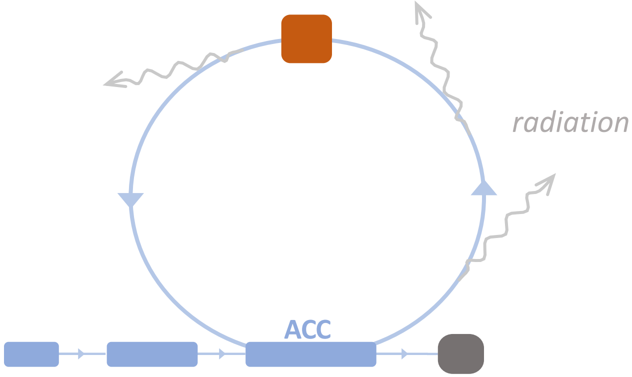
~2% of annual electricity consumption in Belgium

Linear colliders



dump >99.9999% of the beam power

Circular colliders



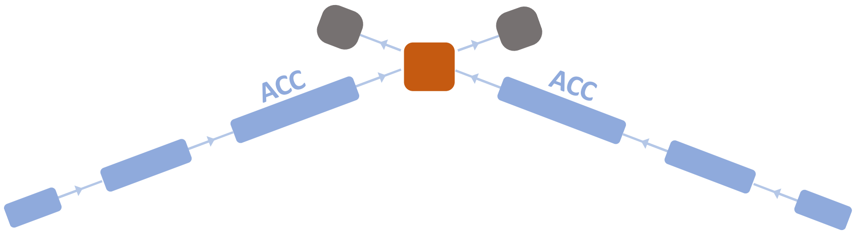
radiate away very quickly the beam power & loose beam quality

FCC-ee@250 ≃ 300 MW

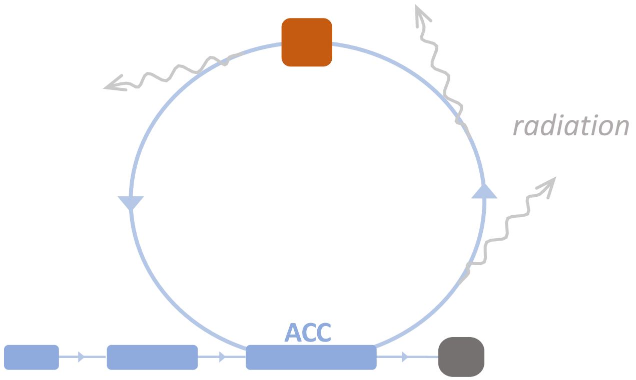
~4% of annual electricity consumption in Belgium

Energy consumption is reducing in Europe, not excluded with ½ by 2050-2060

Linear colliders



Circular colliders



dump >99.9999% of the beam power

radiate away very quickly the beam power & loose beam quality

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

about half of this is dumped or lost due to radiation

Energy consumption is reducing in Europe, not excluded with ½ by 2050-2060

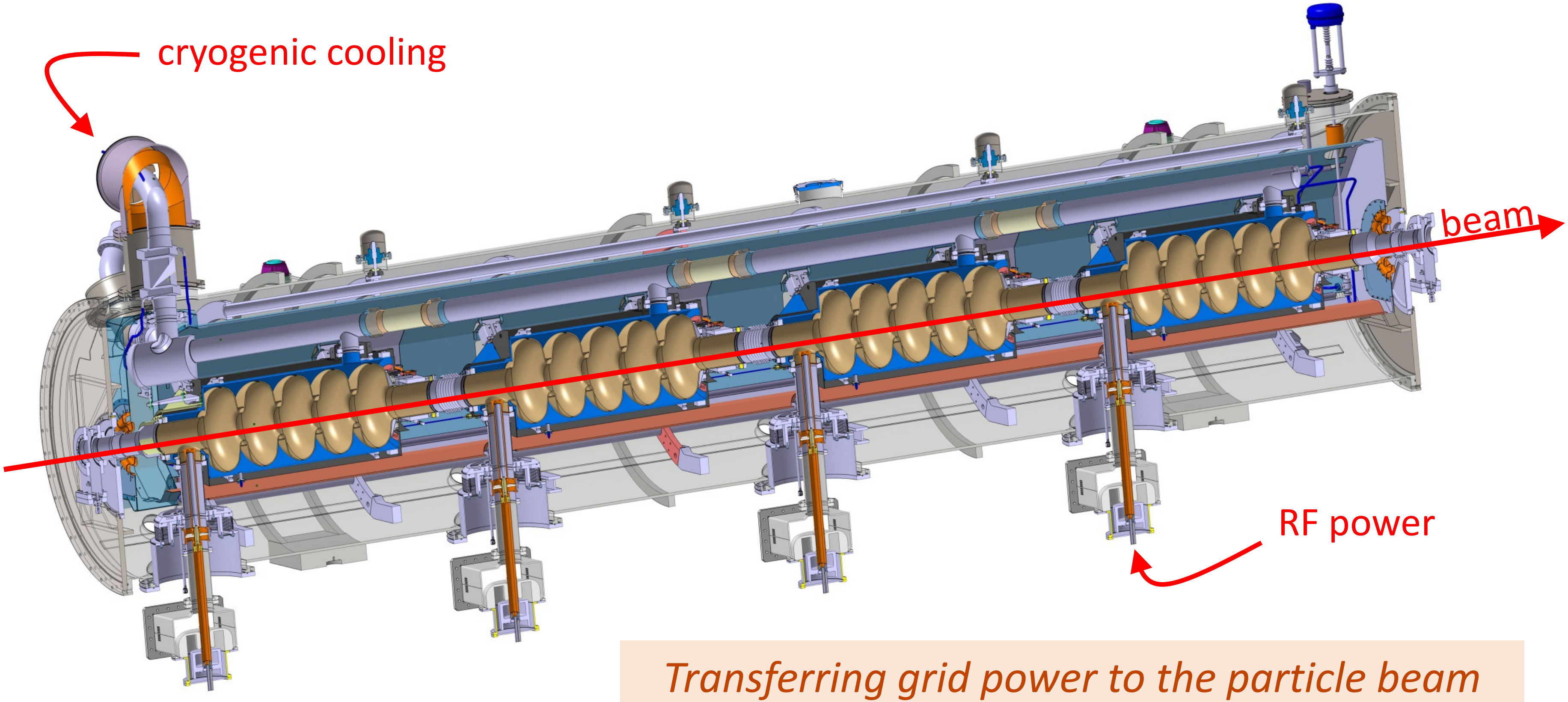
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

A detailed plan for the […] saving and re-use of energy should be part of the approval process for any major project.

European Strategy for Particle Physics 2020

Key building block for beam acceleration: the SRF cryomodule

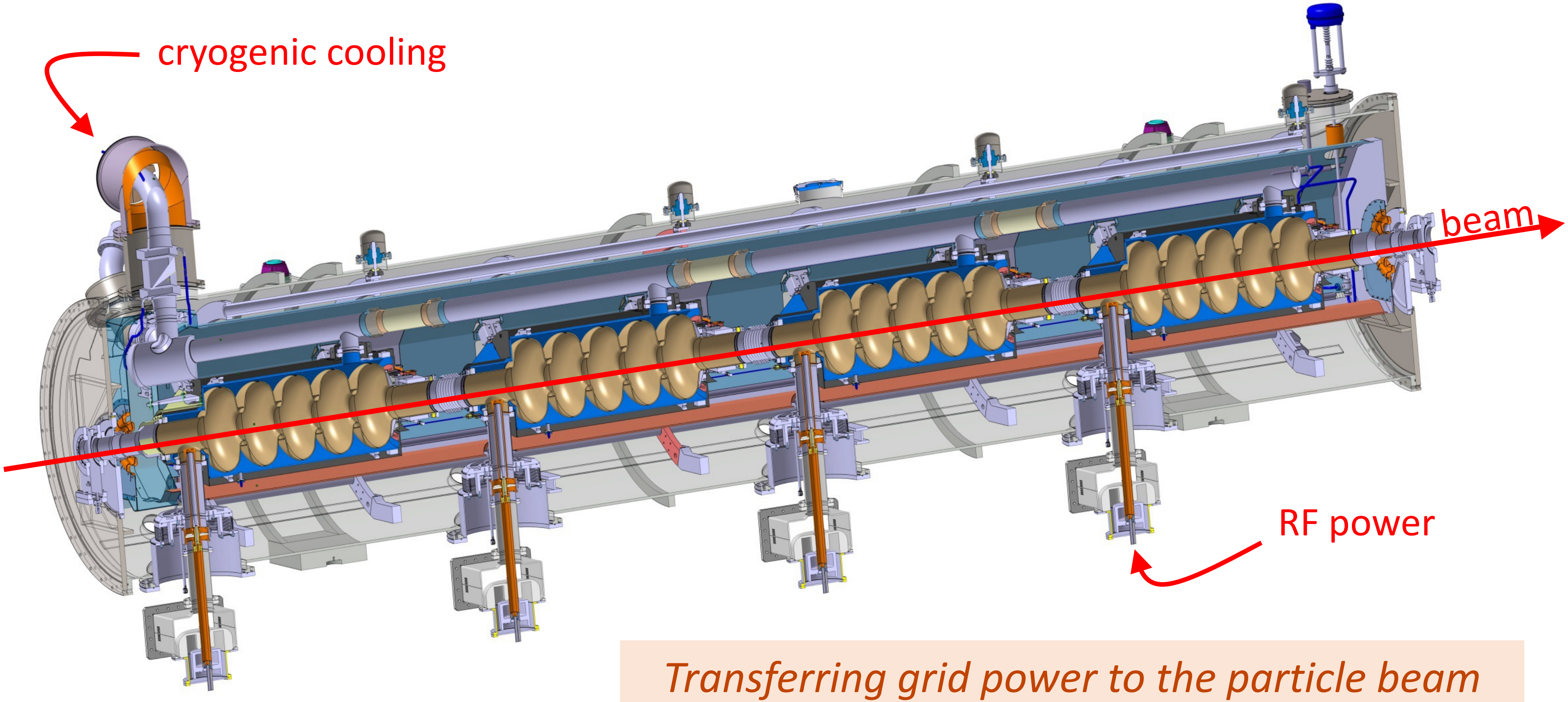
SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

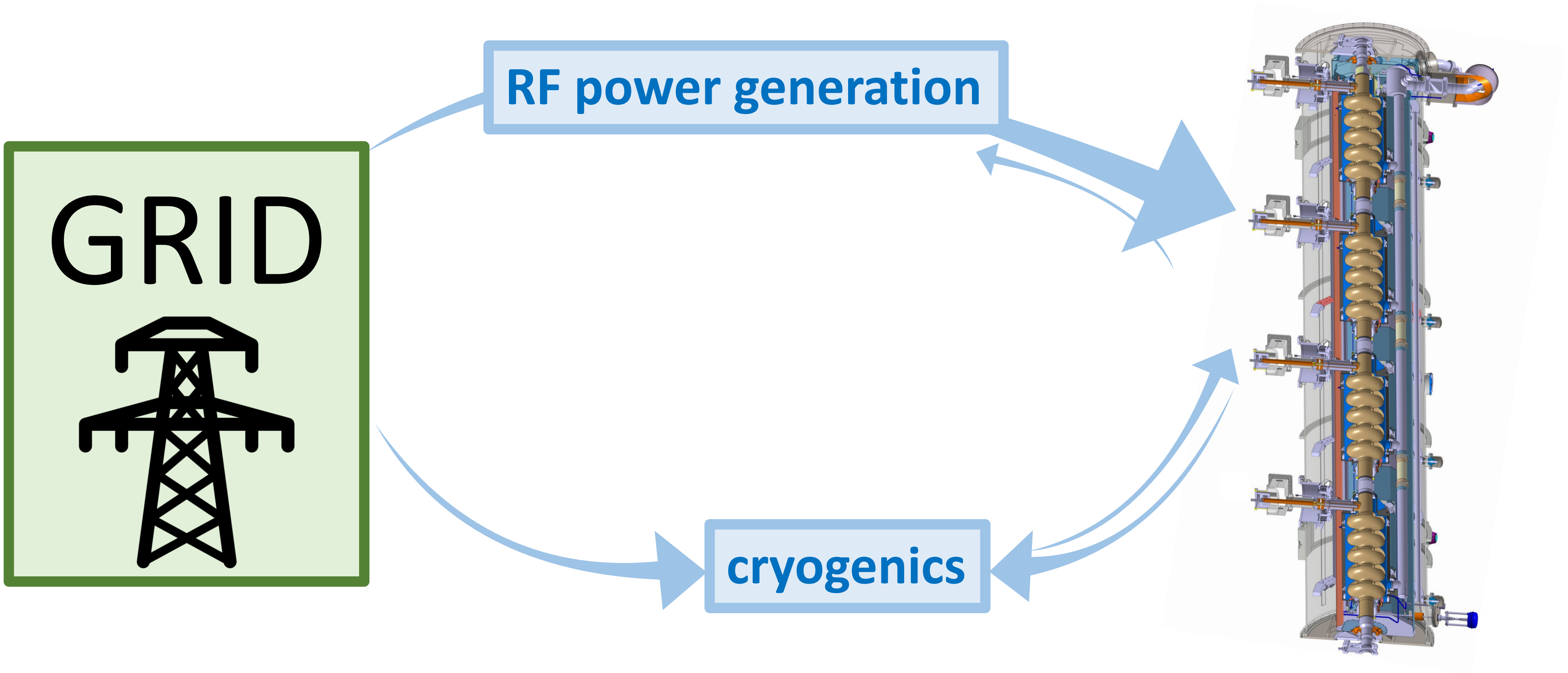
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

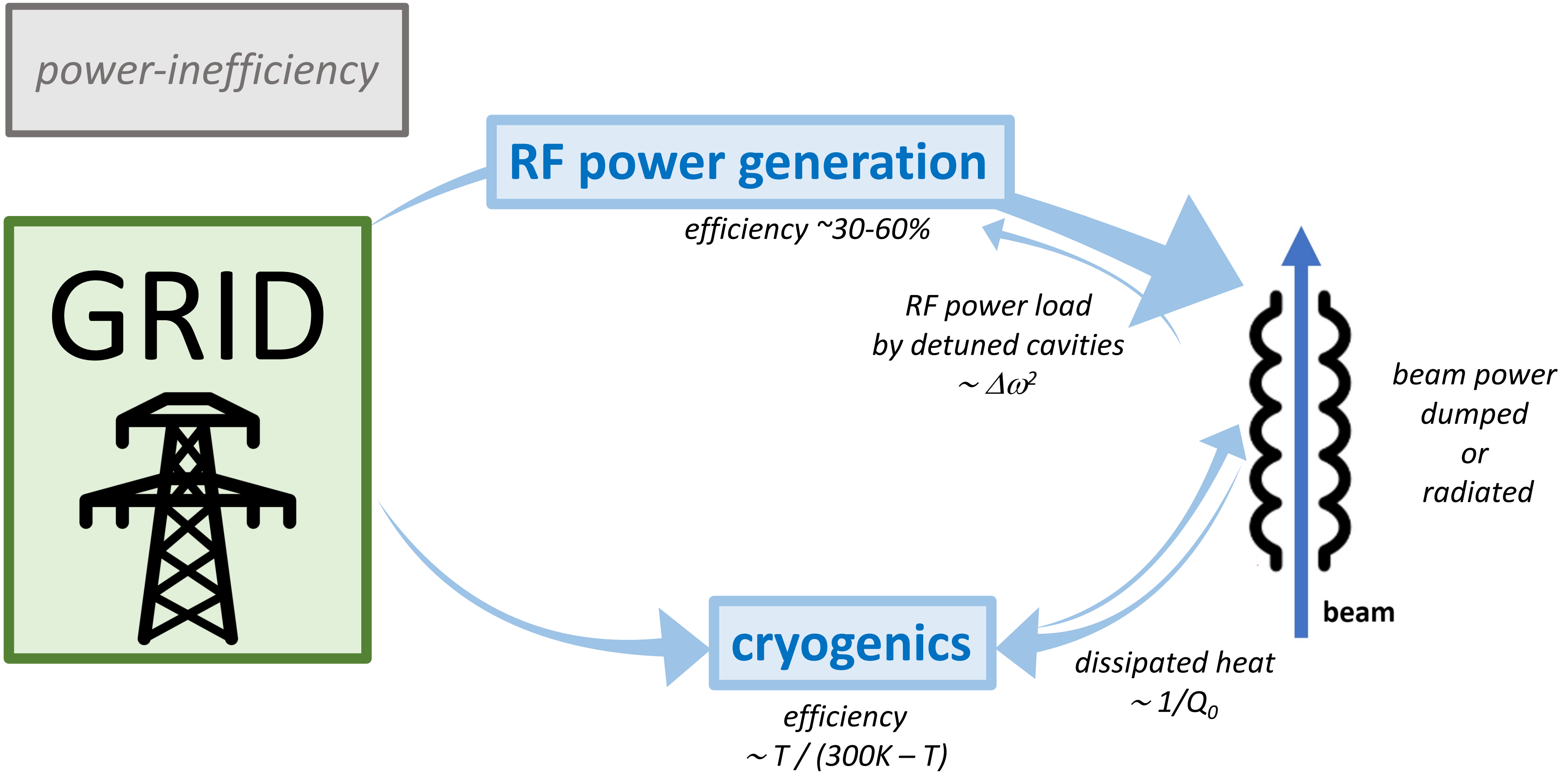


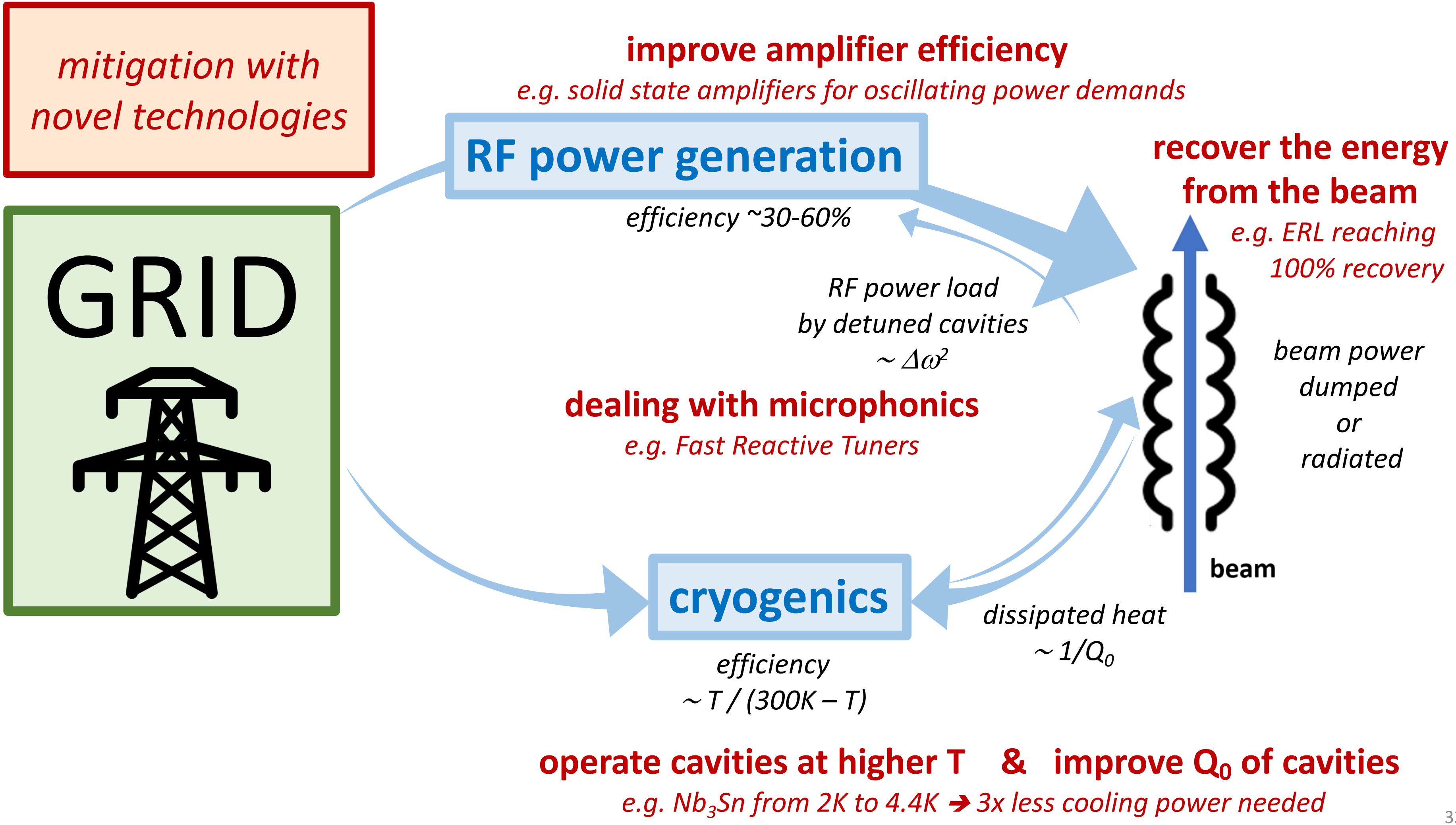
Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

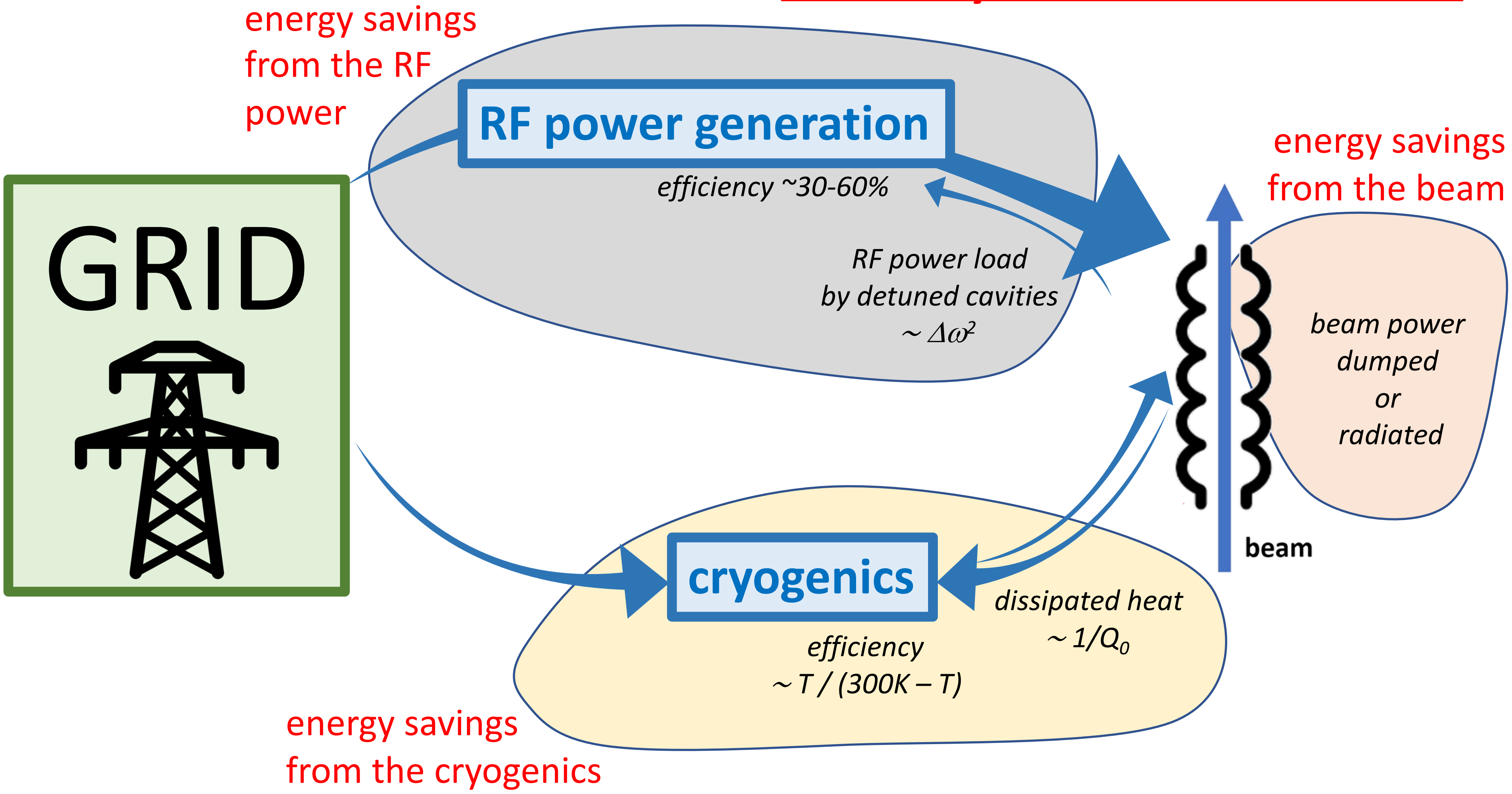


Picture adopted from M. Seidel (IPAC 2022)


power-inefficiency
RF power generation
efficiency ~30-60%
GRID
RF power load
by detuned cavities
$\sim \Delta\omega^2$
beam power
dumped
or
radiated
beam
cryogenics
efficiency
$\sim T\,/\,(300K - T)$
dissipated heat
$\sim 1/Q_0$


mitigation with novel technologies
GRID
improve amplifier efficiency
e.g. solid state amplifiers for oscillating power demands
RF power generation
efficiency ~30-60%
recover the energy from the beam
e.g. ERL reaching 100% recovery
RF power load by detuned cavities
$\sim \Delta\omega^2$
dealing with microphonics
e.g. Fast Reactive Tuners
beam power dumped or radiated
beam
cryogenics
efficiency
$\sim T / (300K - T)$
dissipated heat
$\sim 1/Q_0$
operate cavities at higher T & improve Q_0 of cavities
e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

Three key innovation directions

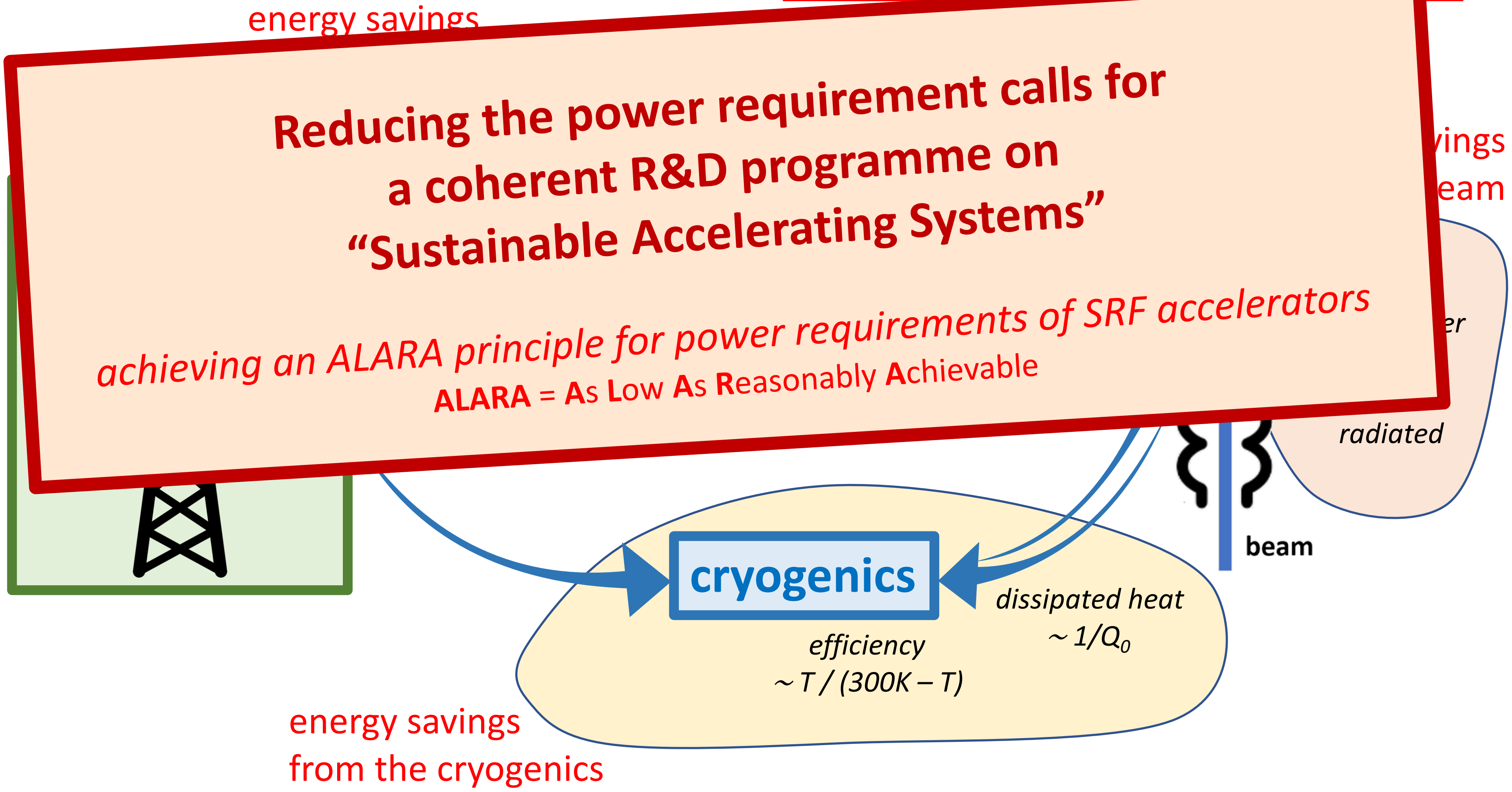


Three key innovation directions

Reducing the power requirement calls for a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

ALARA = As Low As Reasonably Achievable



Three key innovation directions

energy savings

...vings
...eam
...er

Reducing the power requirement calls for a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

ALARA = **A**s **L**ow **A**s **R**easonably **A**chievable

an example

Innovate for Sustainable Accelerating Systems (iSAS)

develop a new design of an SRF cryomodule

integrating the most impactful energy-saving technologies (incl. RF & ERL aspects)

Kick-off meeting 15-16 April 2024 @ IJCLab: https://indico.ijclab.in2p3.fr/event/10302/

https://isas.ijclab.in2p3.fr

Horizon Europe

from the cryogenics

iSAS is now an approved and ongoing Horizon Europe project

Spread over 4 years (2024-2028): ~1000 person-months of researchers and ~12.6M EUR

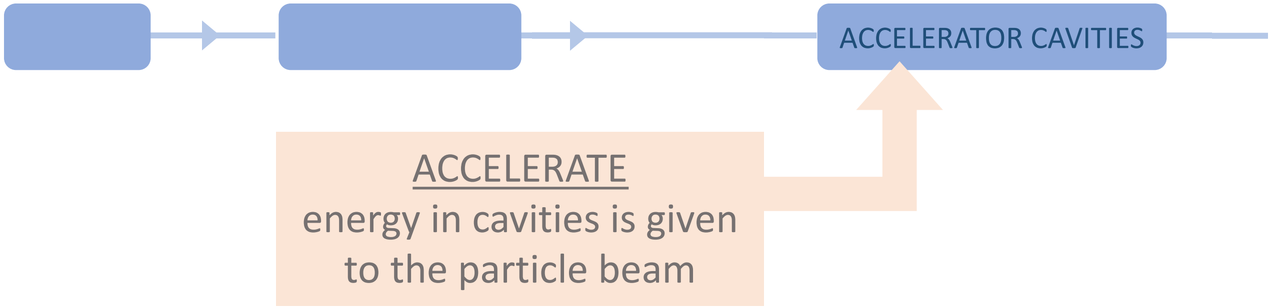
(of which 5M EUR is provided through Horizon Europe)

+ industrial companies: *ACS Accelerators and Cryogenic Systems* (France), *RI Research Instruments GmbH* (Germany), *Cryoelectra GmbH* (Germany), *TFE Thin Film equipment srl* (Italy), *Zanon Research* (Italy), *EuclidTechLab* (USA)

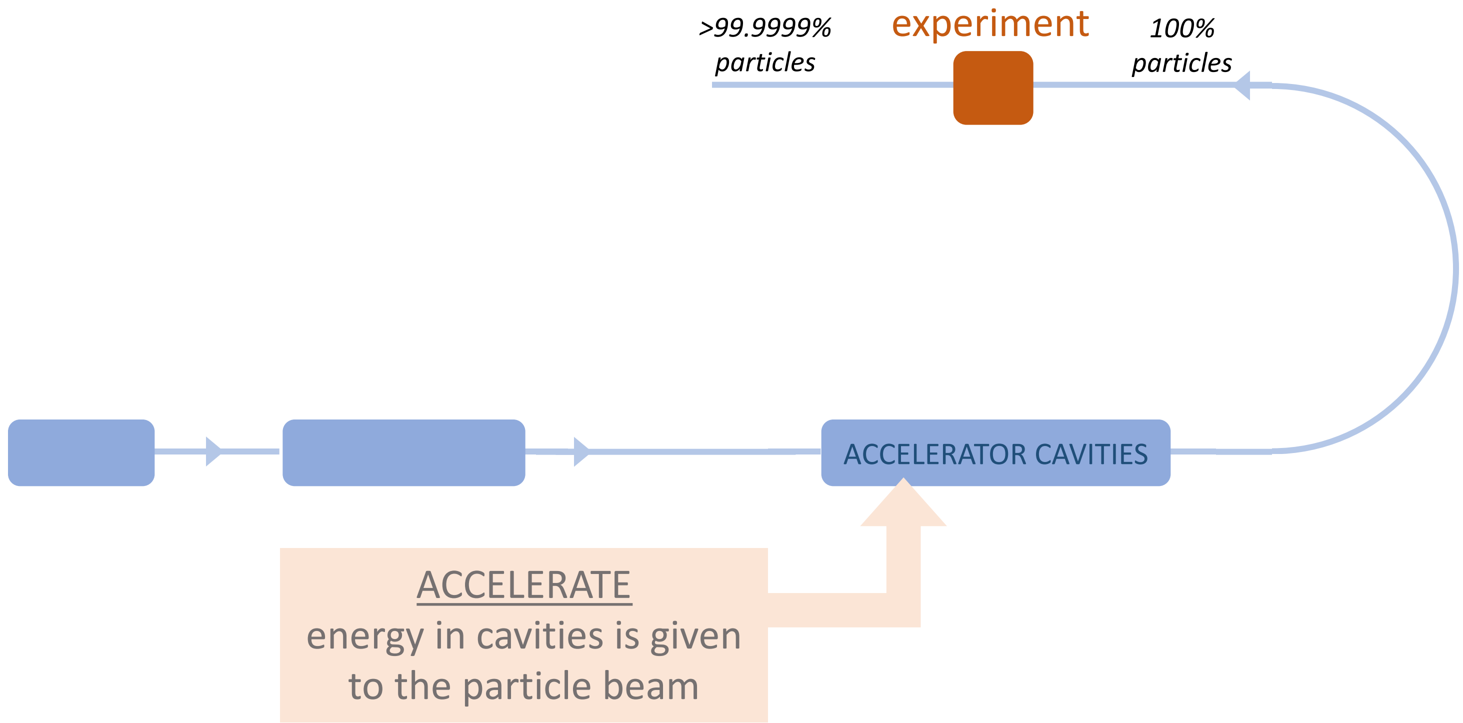
One example of an innovative technology

(which is being developed since about 50 years)

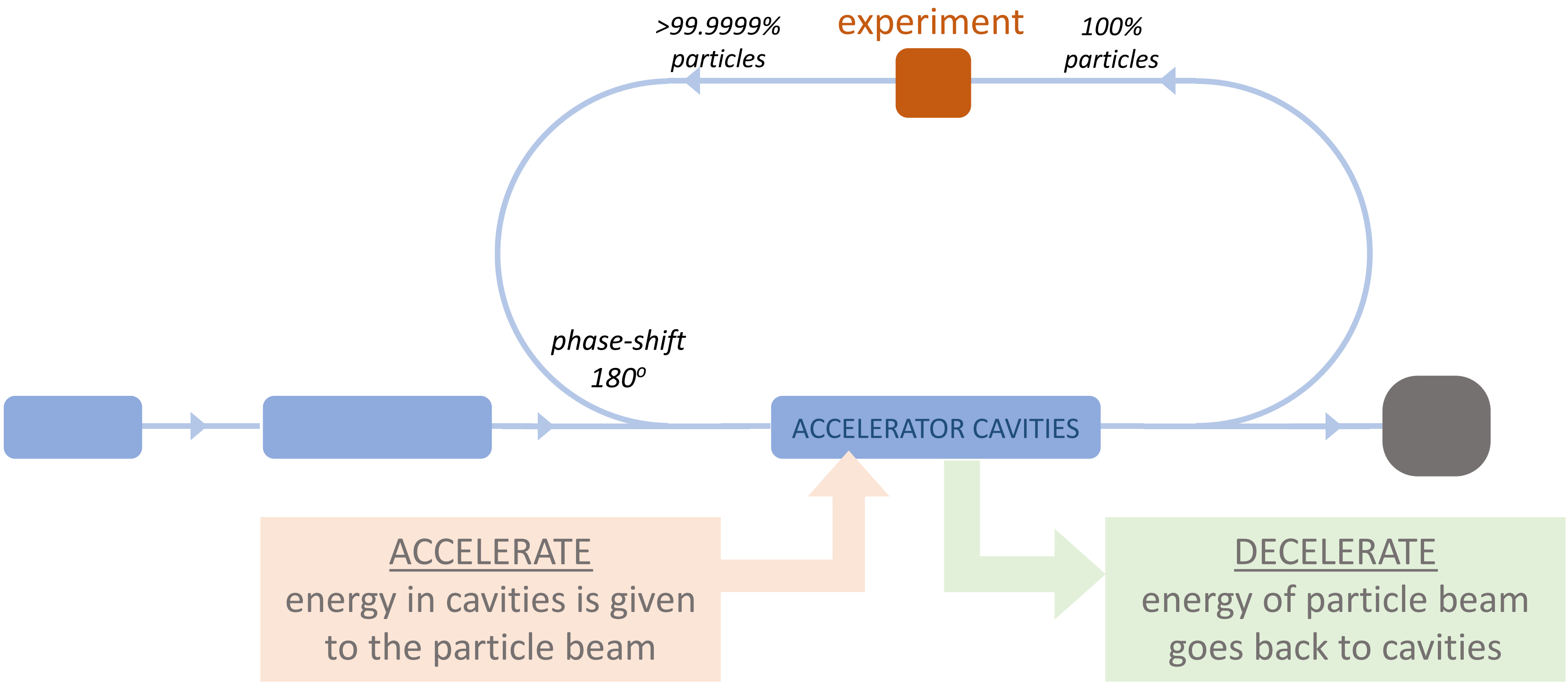
The principle of Energy Recovery



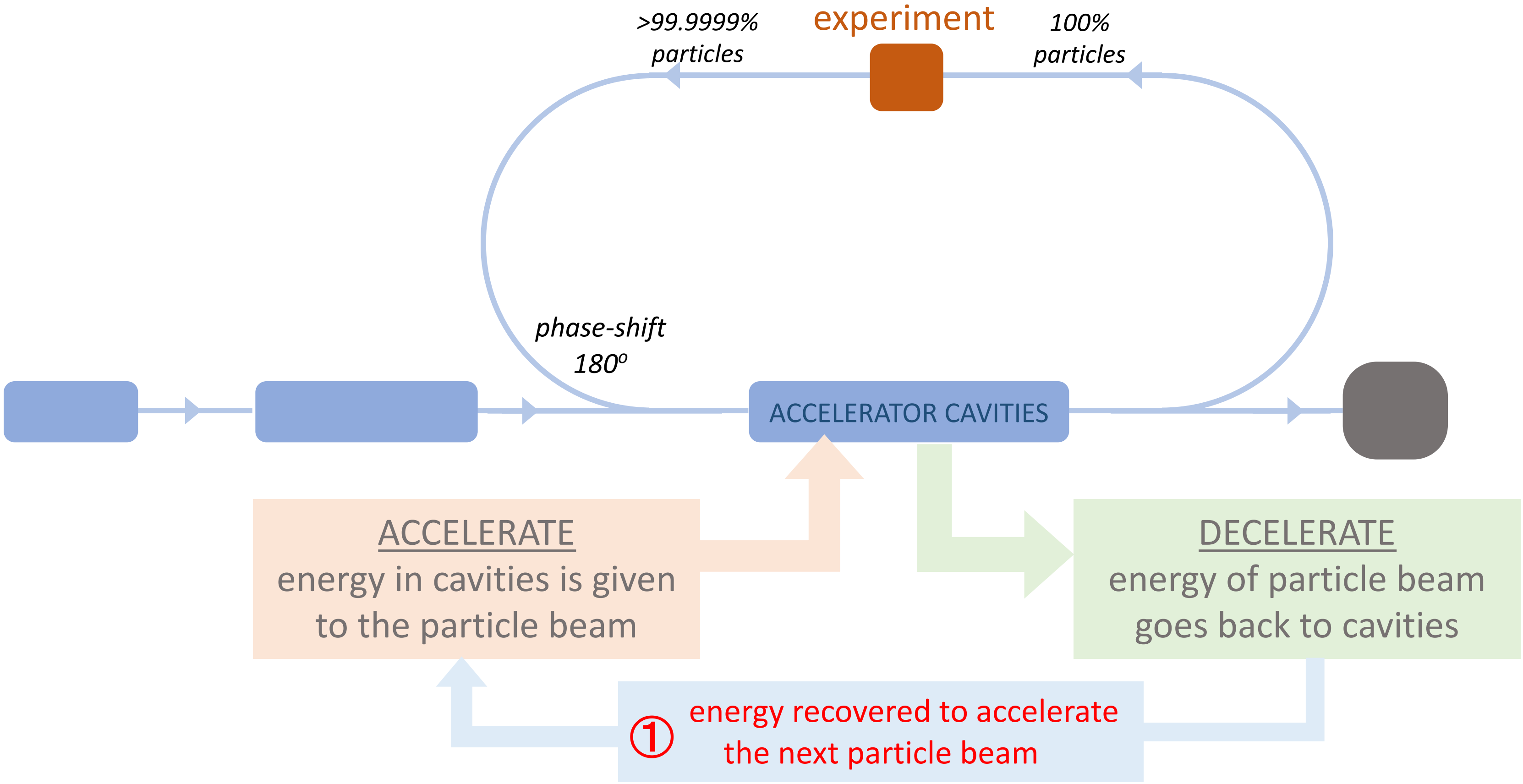
The principle of Energy Recovery



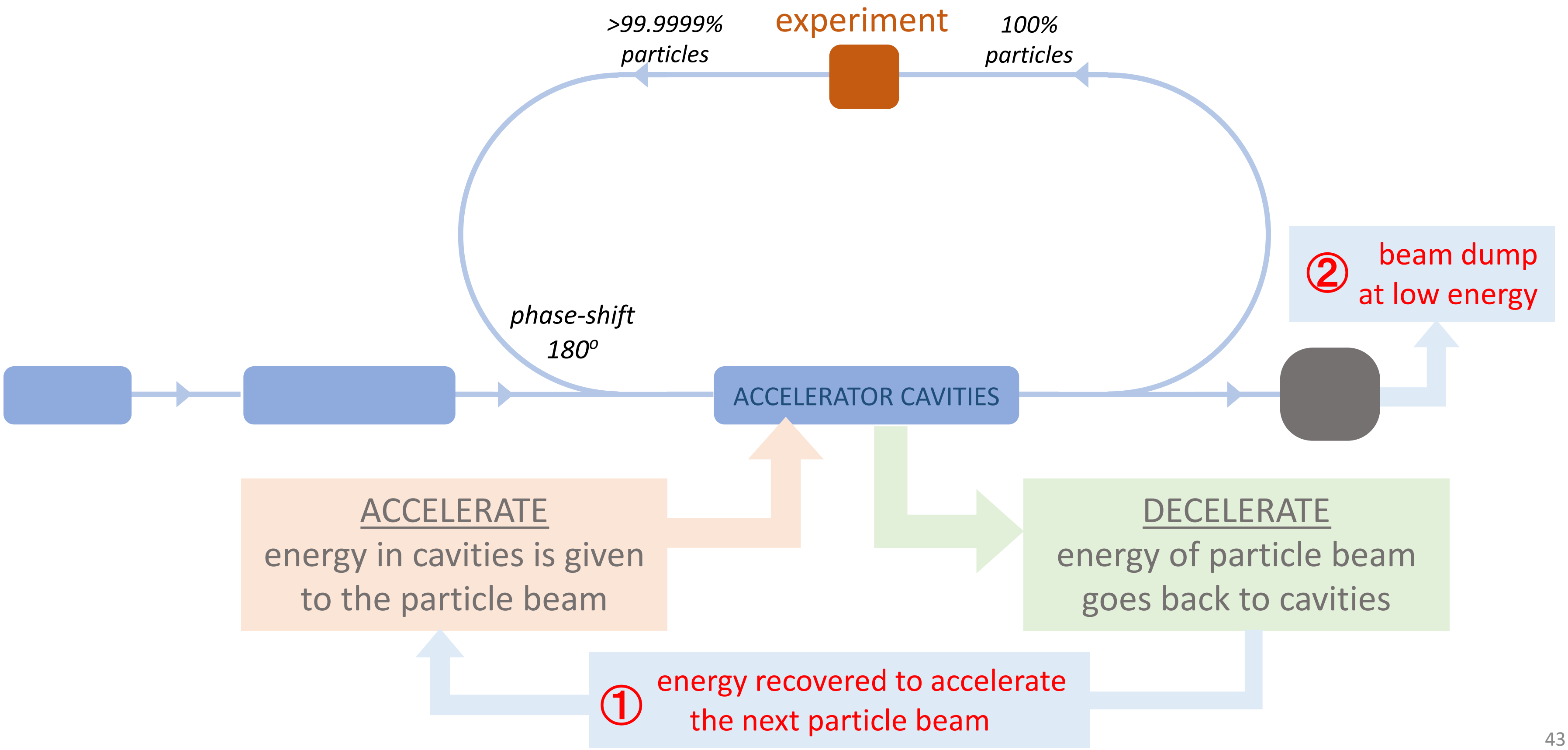
The principle of Energy Recovery



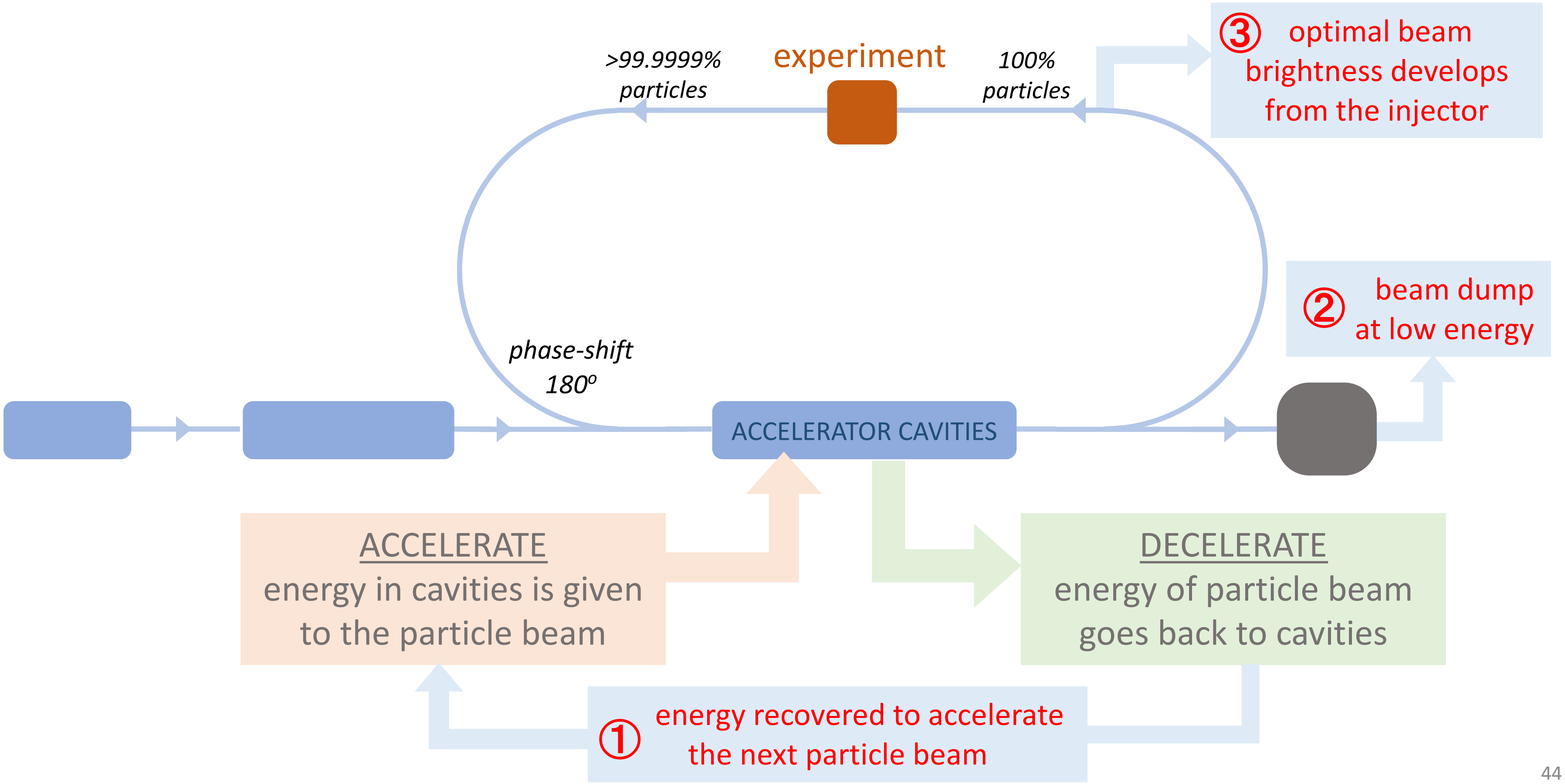
The principle of Energy Recovery



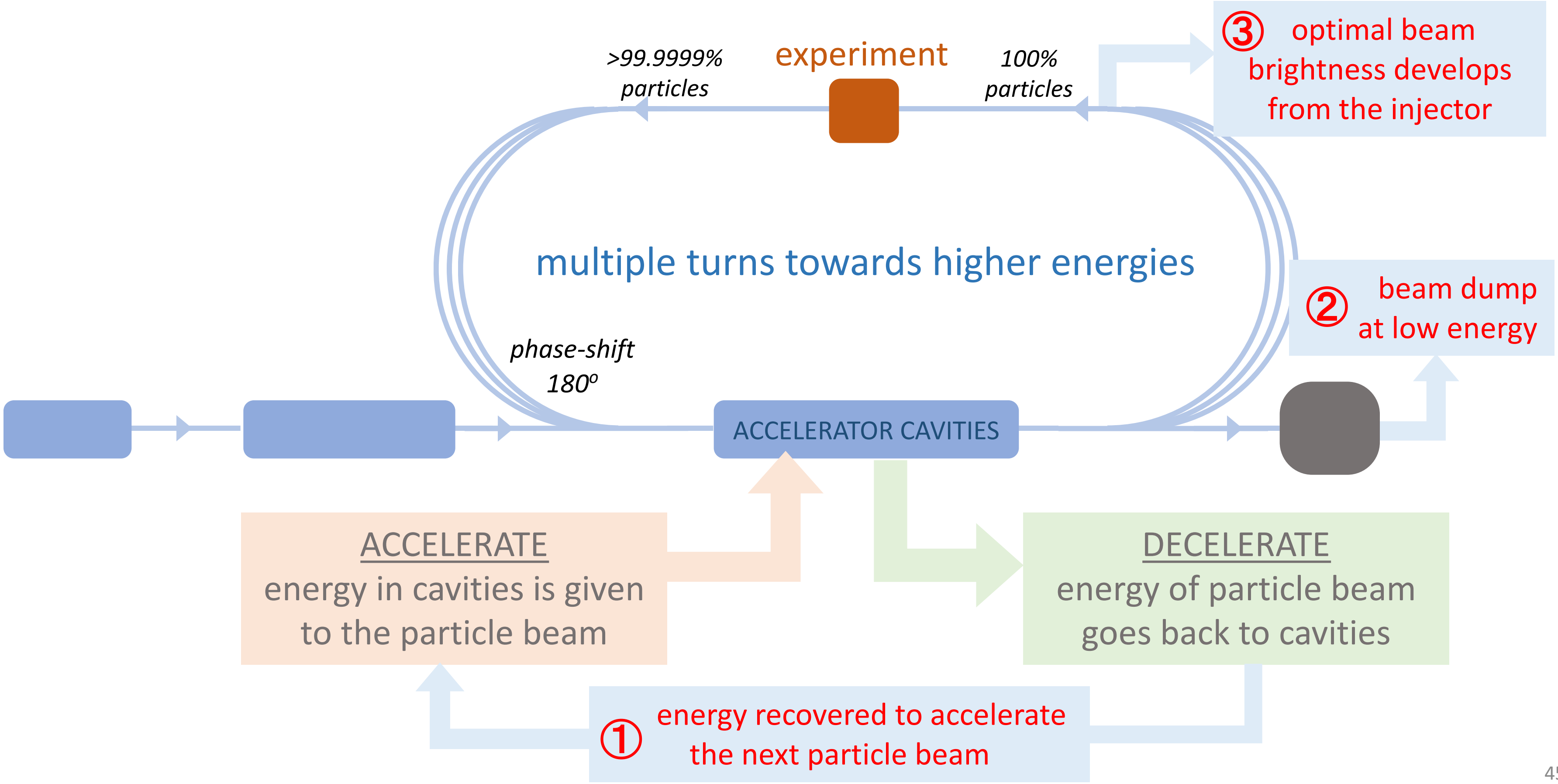
The principle of Energy Recovery



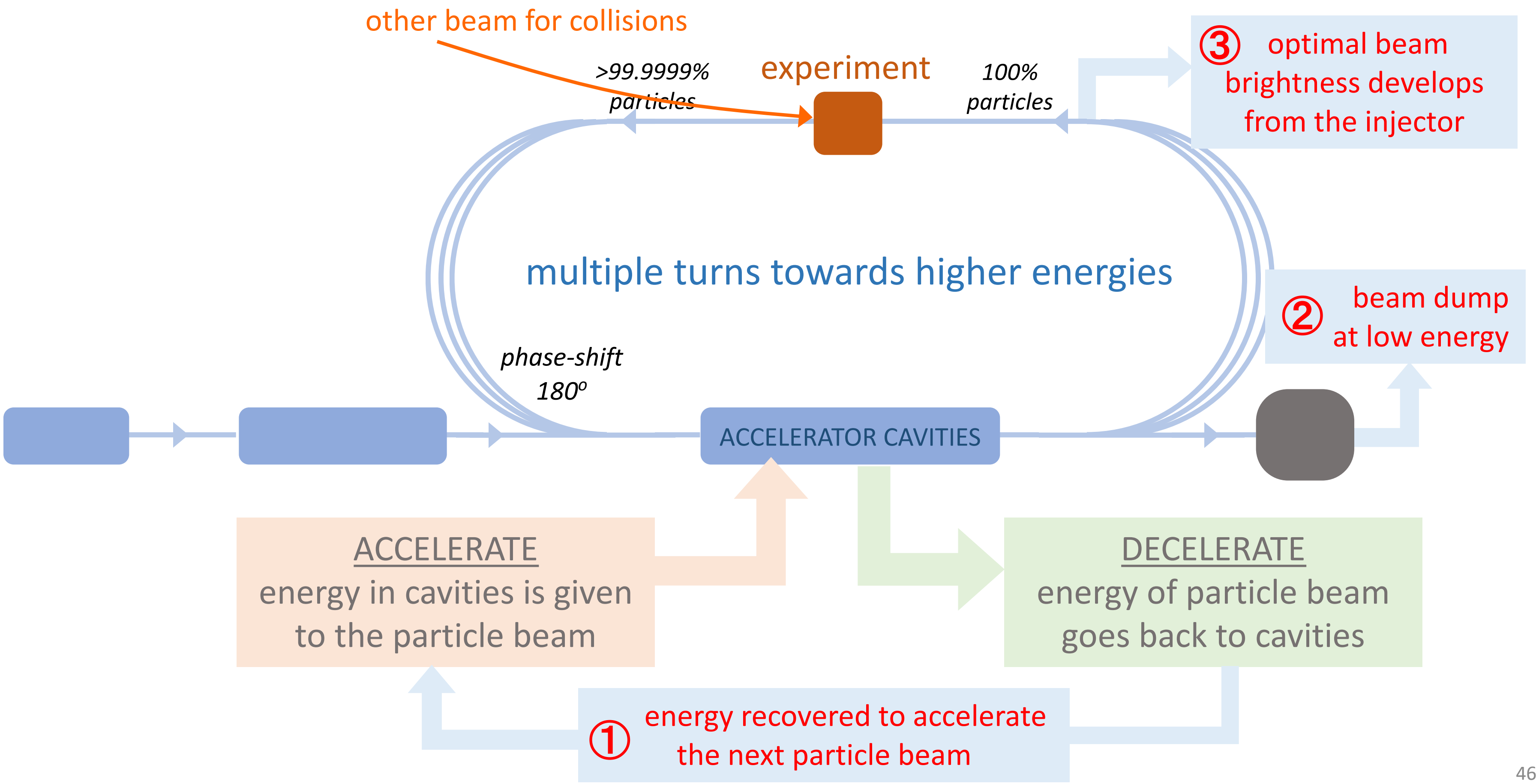
The principle of Energy Recovery



The principle of Energy Recovery



The principle of Energy Recovery



The principle of Energy Recovery

other beam for collisions

>99.9999% particles

experiment

100% particles

③ optimal beam

instead of re-circulating the beam *(and loosing brightness)***,**
the power is re-circulated *(achieving optimal brightness with the next beam)*

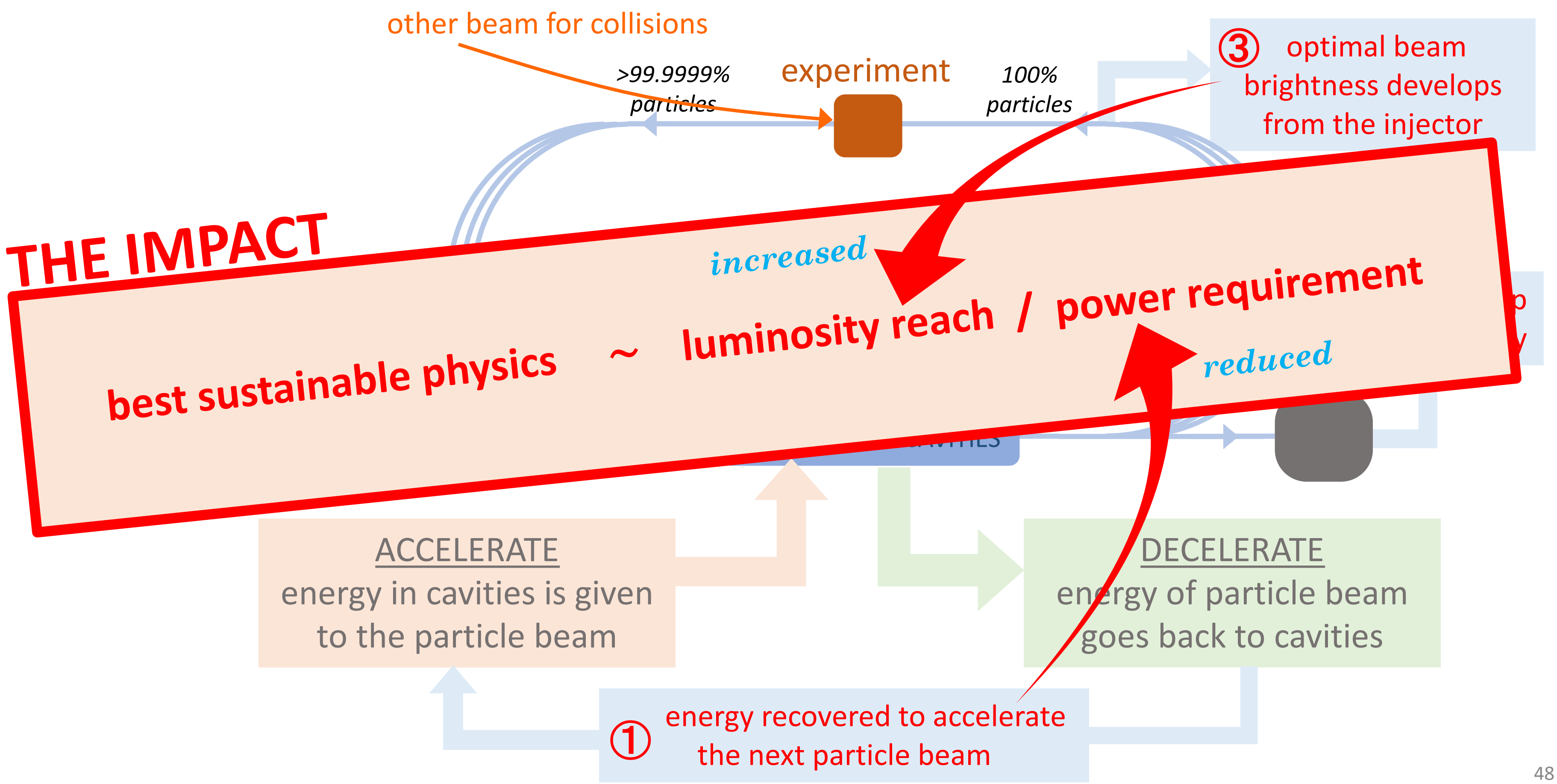
we cannot beat the physics of synchrotron radiation,
but we can adapt to recover the beam energy & to collide only the brightest beams

energy in cavities is given
to the particle beam

DECELERATE
energy of particle beam
goes back to cavities

① energy recovered to accelerate
the next particle beam

The principle of Energy Recovery

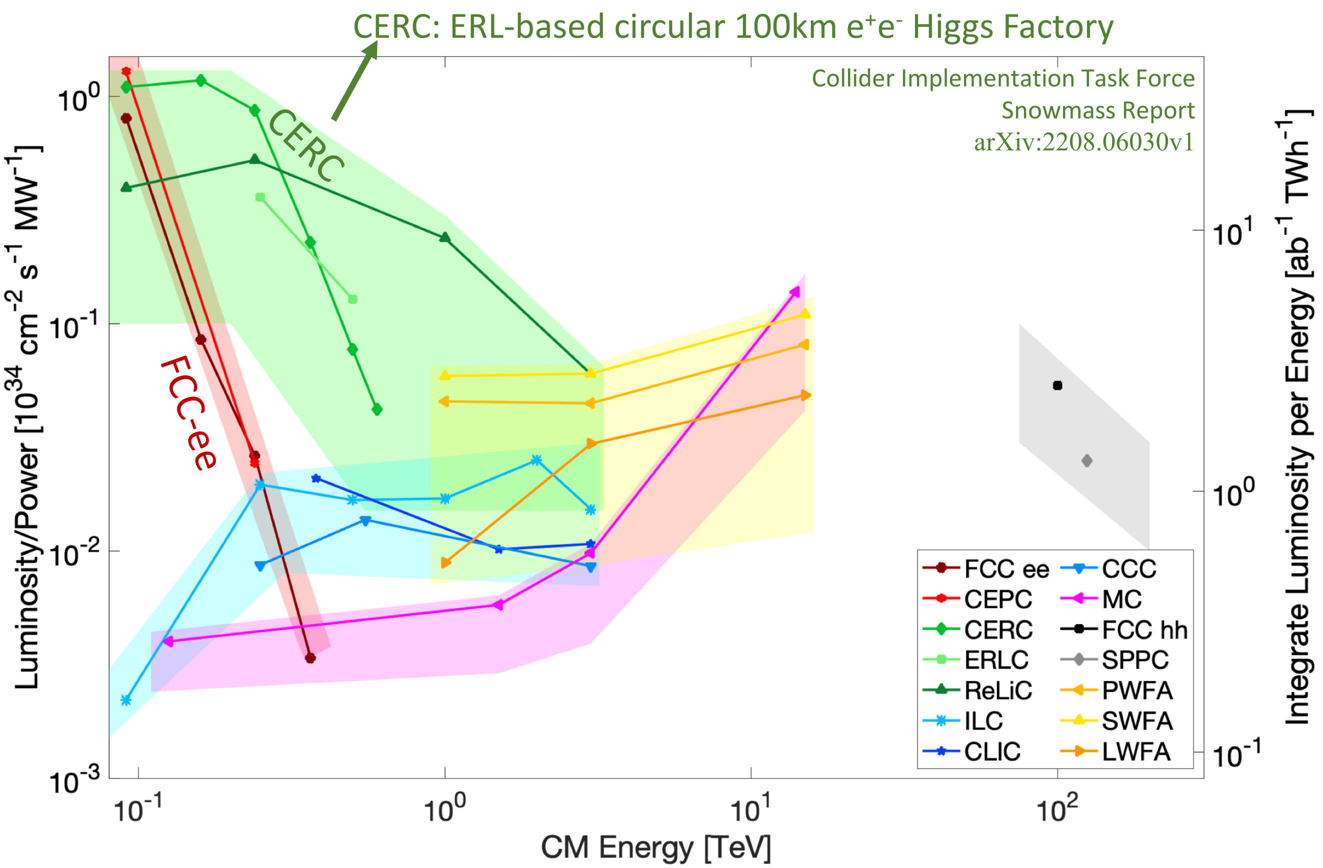


The technology of Energy Recovery Linacs as an example of innovations to address the energy consumption of future colliders

The technology of Energy Recovery Linacs as an example of innovations to address the energy consumption of future colliders

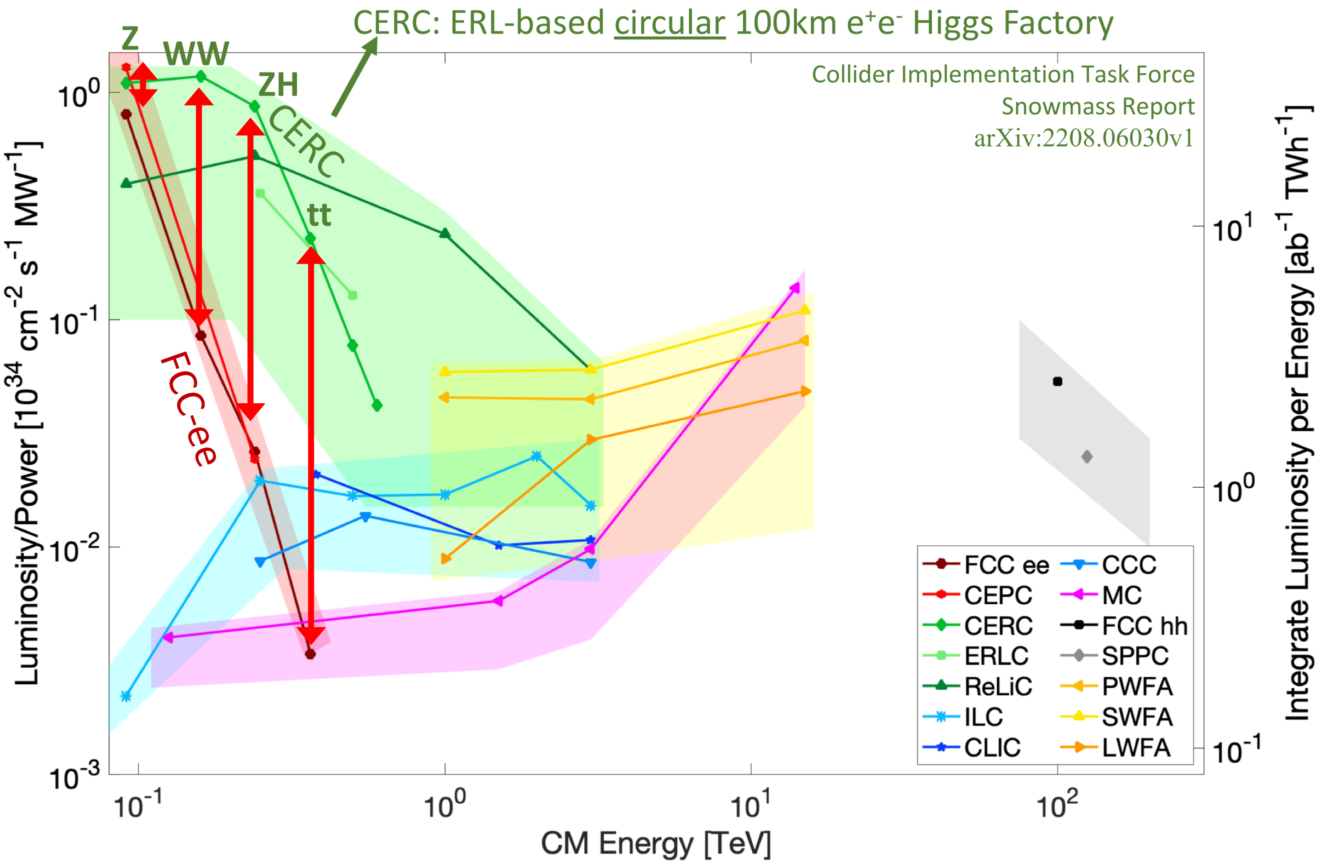
What is the potential impact?

Energy Recovery applications for HEP e^+e^- colliders



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Energy Recovery applications for HEP e^+e^- colliders



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

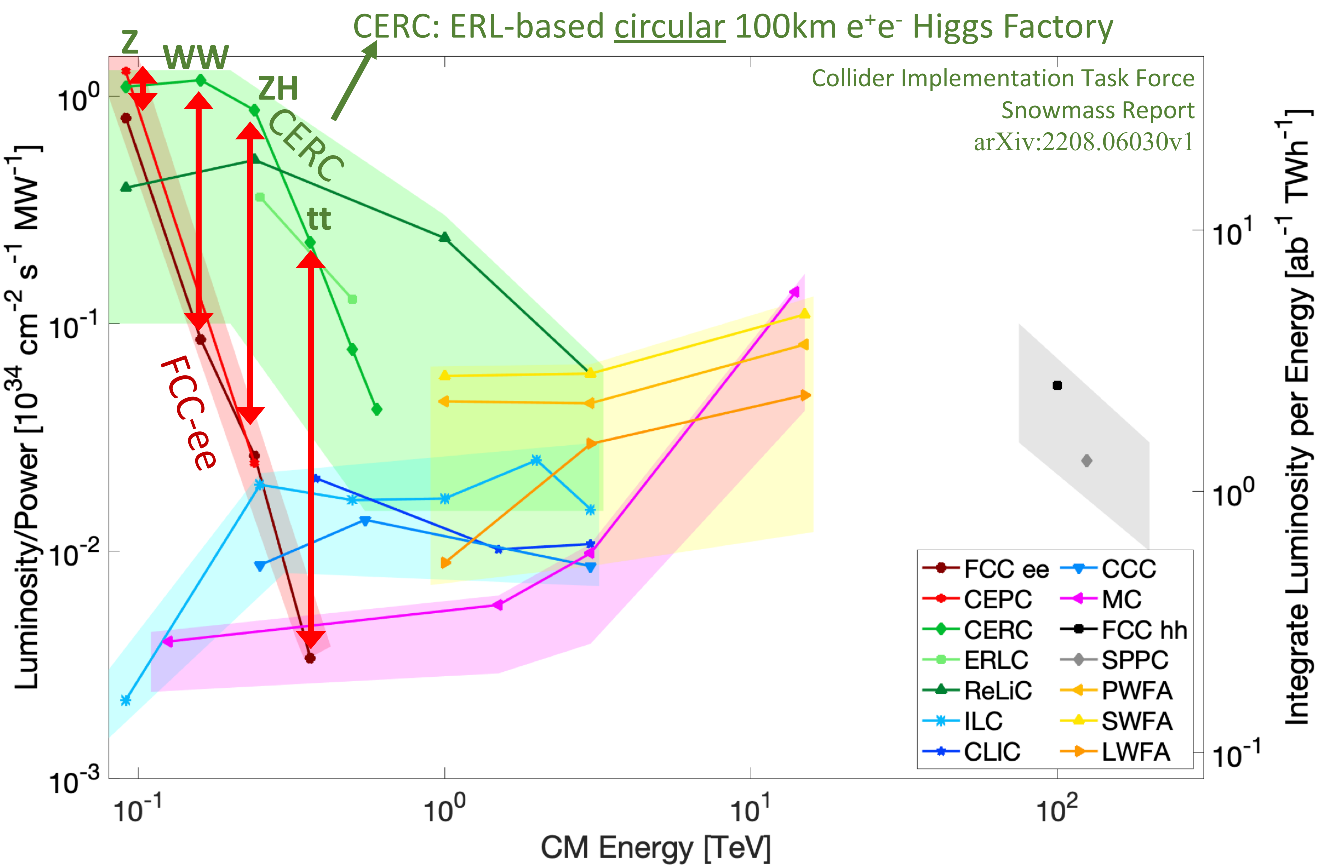
Energy Recovery applications for HEP e^+e^- colliders

This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

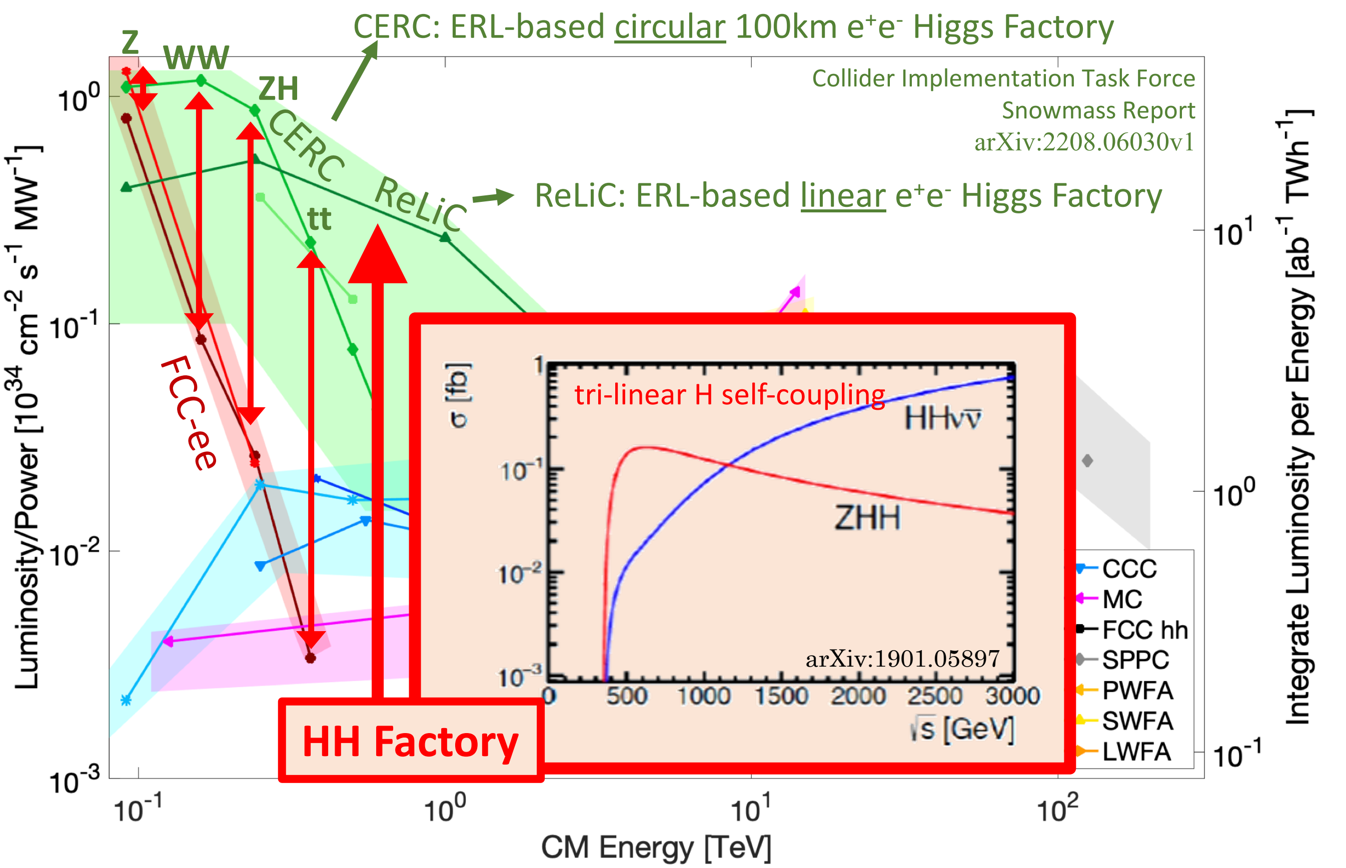
Energy Recovery applications for HEP e^+e^- colliders

This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Ref for ReLiC: arXiv:2203.06476

Energy Recovery applications for HEP e^+e^- colliders

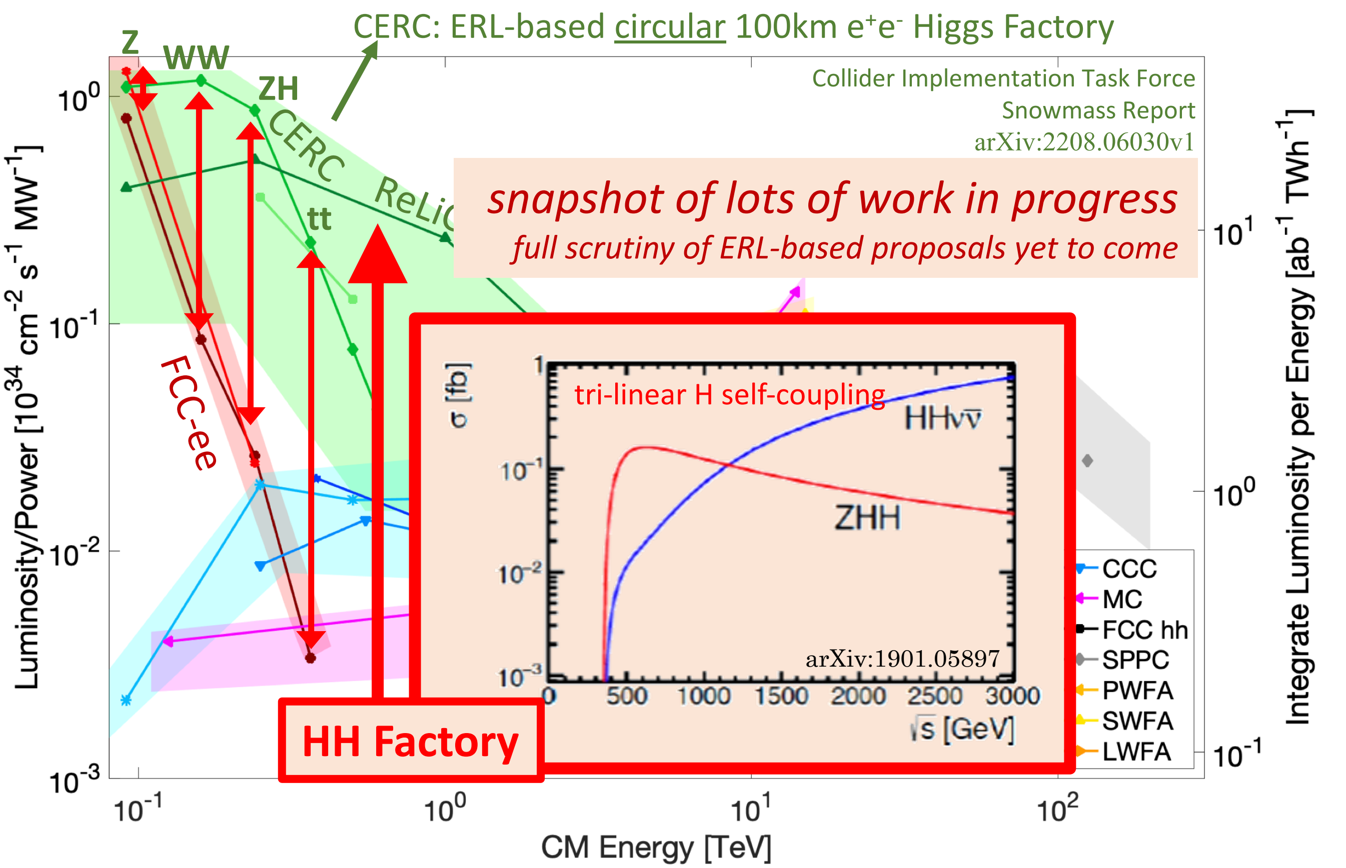
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories
(hence the large uncertainty band in the plot)



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

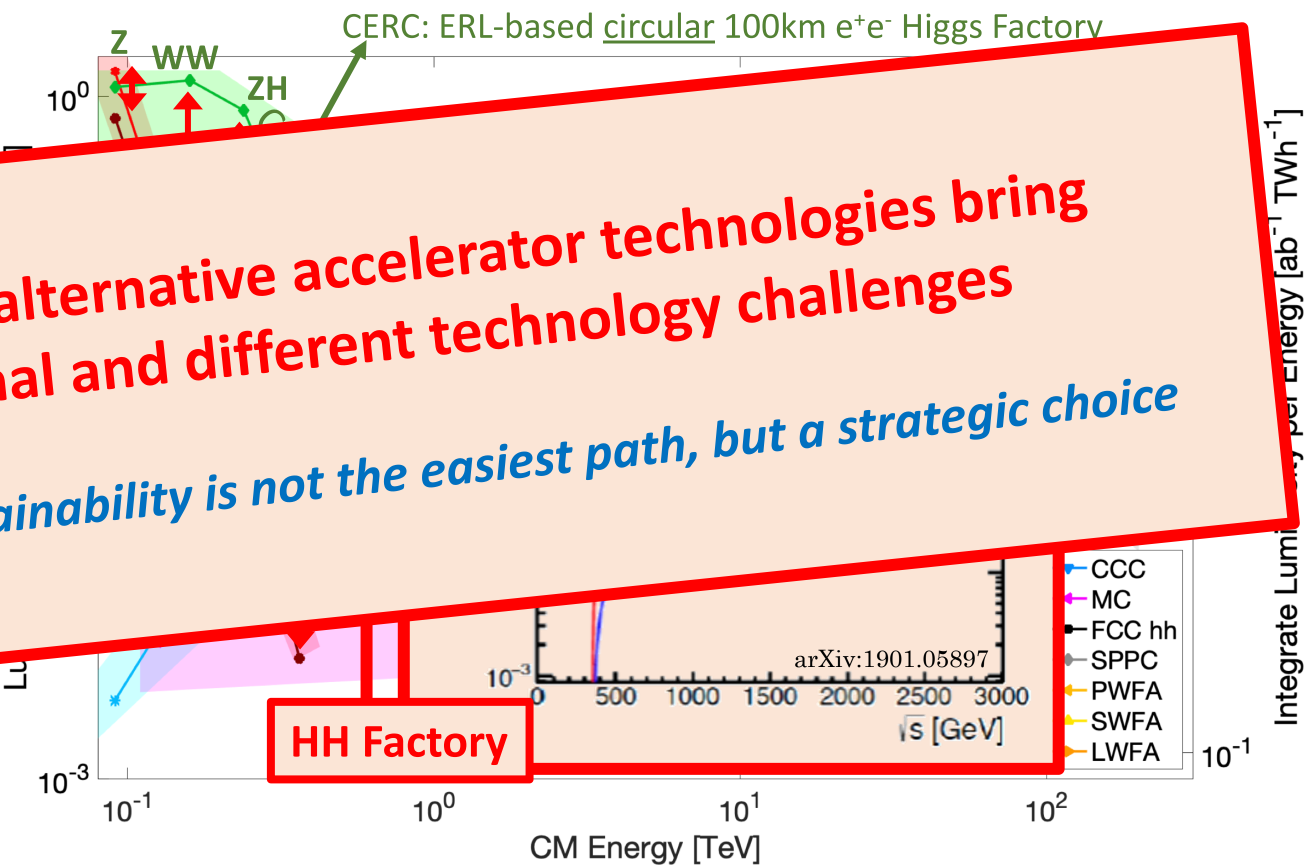
Ref for ReLiC: arXiv:2203.06476

Energy Recovery applications for HEP e^+e^- colliders

This plot suggests that with an ERL version of a Higgs Factory one might reach

x1

M...
chall... these ERL-based Higgs Factories
(hence the large uncertainty band in the plot)



In general, alternative accelerator technologies bring additional and different technology challenges

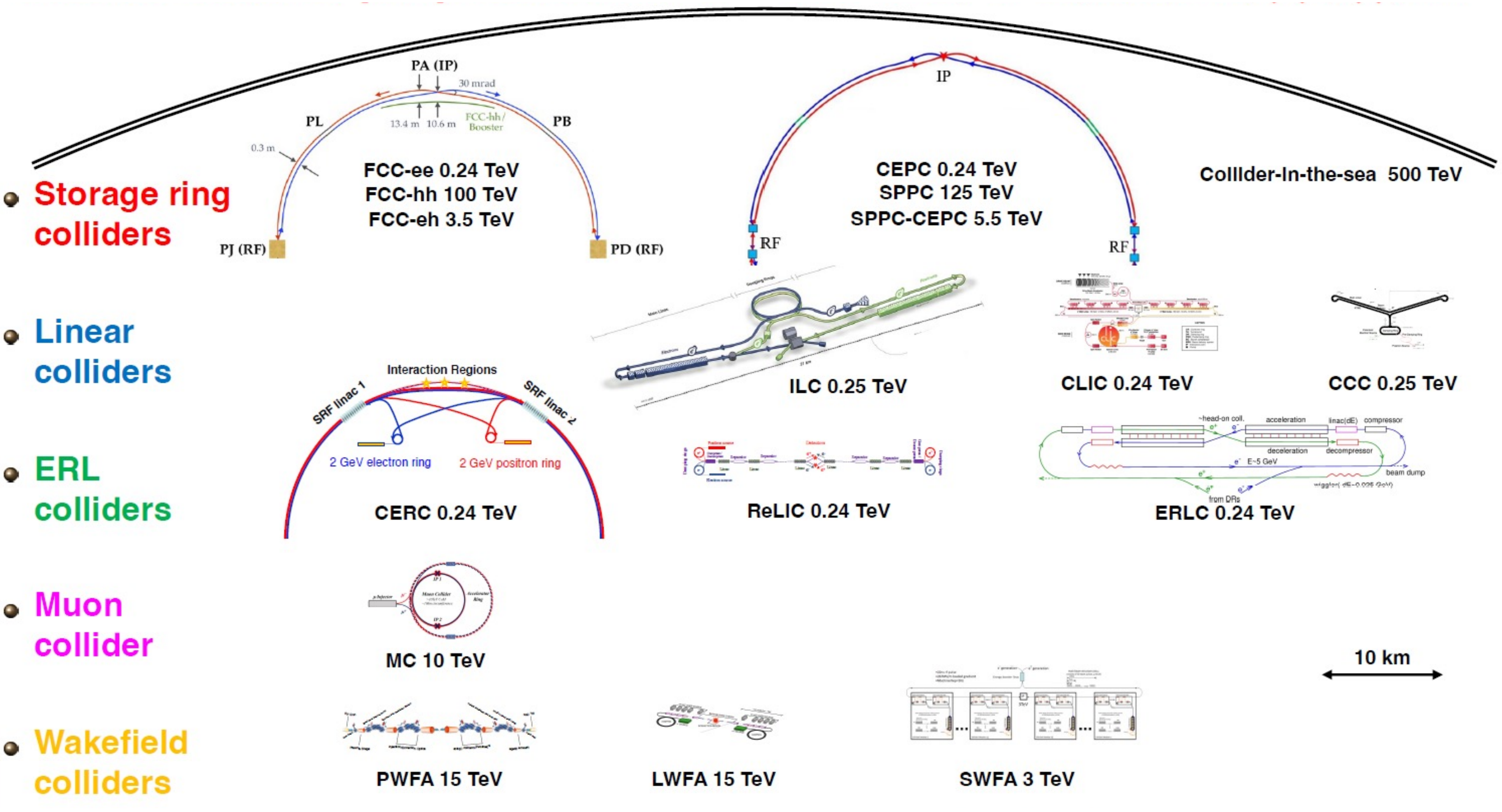
addressing sustainability is not the easiest path, but a strategic choice

Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Ref for ReLiC: arXiv:2203.06476

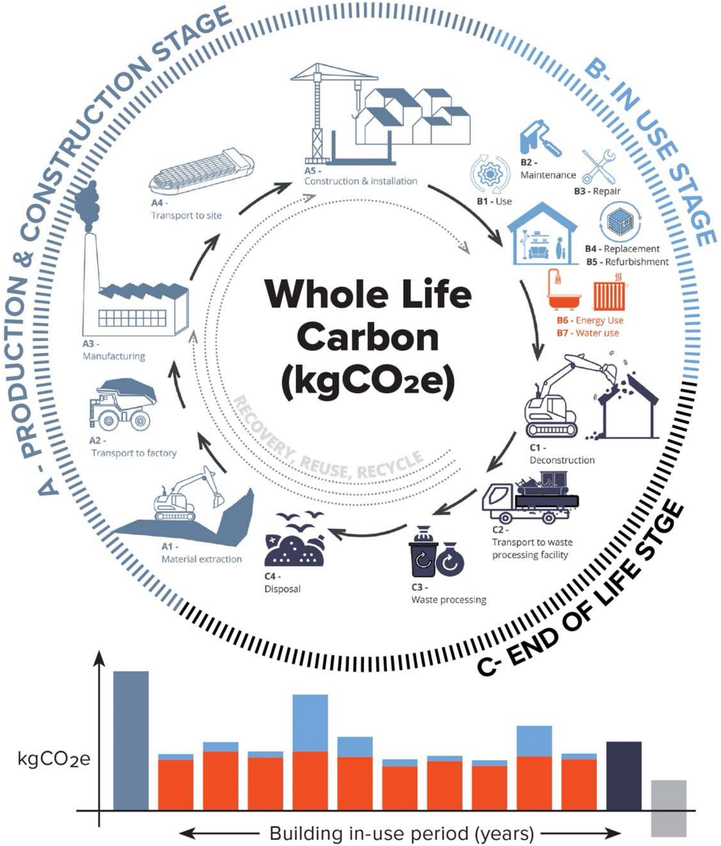
the civil engineering

Future colliders and their underground footprint



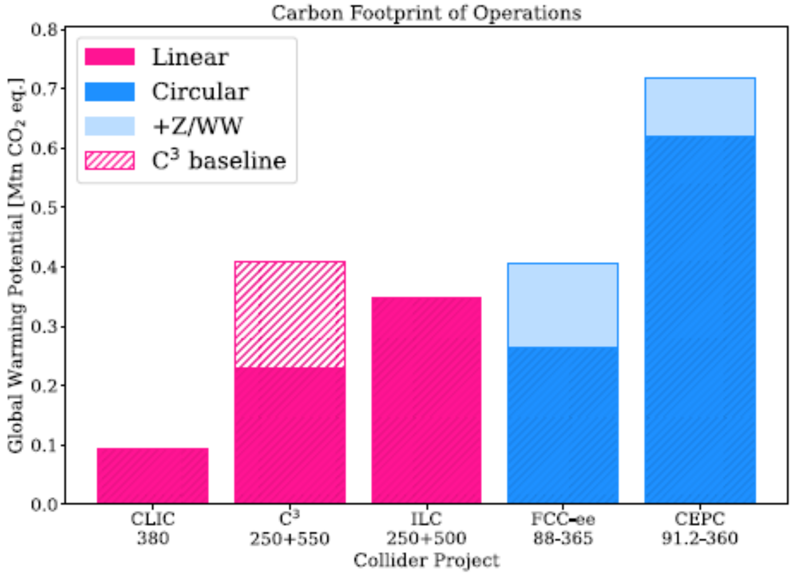
Lifecycle analysis (LCA)

- For new project proposals a full life cycle analysis methodology is being developed. The goal is to enhance scrutiny on projects beyond cost and effort.
- Such analyses estimates the total energy and carbon footprints over the full life cycle and should play an important role, maybe defining role, in selecting the next project.
- The LCA includes both the construction and operation phase with CO_2 emission and energy consumed per ton of concrete, steel, and aluminum, as well as CO_2 emission during operation and decommissioning
- Some large collider proposals (FCC, ILC, CLIC, CCC) have already prepared such lifecycle analyses. (Recent reports: Life Cycle Assessment for CLIC and ILC, July 2023; M. Breidenbach et al., PRX Energy 2, 047001; also, RUEDI, Daresbury)

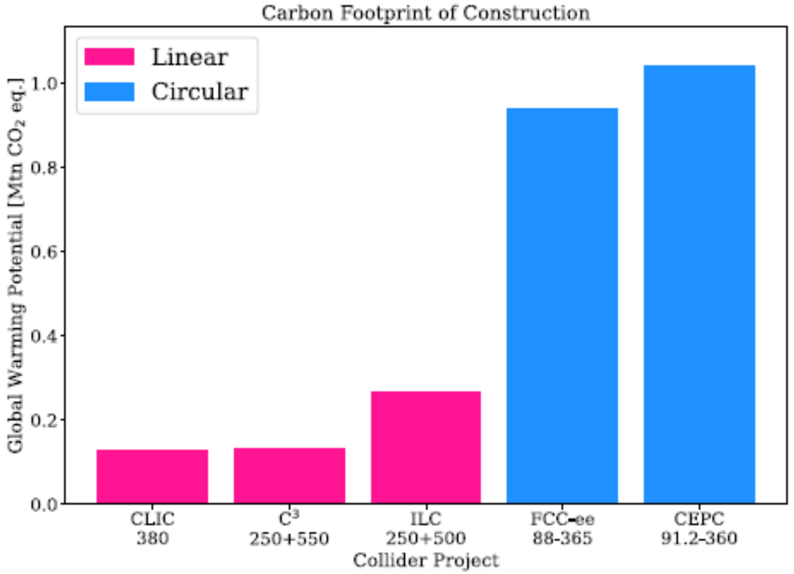


Some initial results of Lifecycle Analyses

Emissions from operations



Emissions from construction



E. Nanni, M. Breidenbachet al., PRX Energy 2, 047001 (2023)

GWP is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period of time, relative to the emission of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years.

New LDG Working Group on "*Sustainability Assessment of Future Accelerators*"

develop guidelines and key indicators to report on sustainability aspects

Ensuring broad community representation:

- *Sustainability Lab. Panels established at CERN, DESY, ESS, NIKHEF, STFC*
- *ICFA Sustainability Panel*
- *EU- Horizon Programs*
- *Future accelerator projects: FCC, ILC, CePC, CLIC/Muon, LHeC, C3*

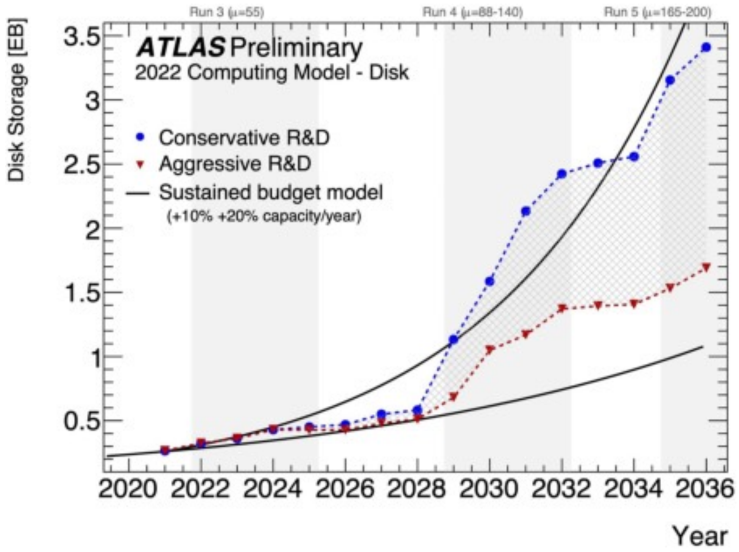
- *Invited experts on specific topics*

- Walib Kaabi - PERLE, EU-iSAS
- Mats Lindroos - ESS (deceased May 2, 2024)
- Roberto Losito - CERN Sust. Panel
- Ben Shepherd - STFC Sust. Task Force
- Andrea Klumpp - DESY Sust. Panel, EU-iFAST
- Hannah Wakeling - ISIS-II Neutron & Muon Source
- Patrick Koppenburg - NIKHEF Sust. Panel
- Johannes Gutleber - FCC
- Yuhui Li - CePC
- Benno List - ILC
- Emilio Nanni - ICFA Sust. Panel & C3
- Vladimir Shiltsev - LHeC
- Steinar Stapnes - CLIC & Muon collider
- Caterina Bloise - Co-Chair
- Maxim Titov - Co-Chair, EU-EAJADE

the computing

Some initial results of Lifecycle Analyses

- Data centers and computing contribute ~2-4% of the global GHG emissions; and this fraction is predicted to grow.
- Continuous innovations to improve power and water usage efficiency are required, together with innovations in our data & software.
- The sheer volume and complexity of data in HEP experiments is increasing and requires complex data acquisition, processing, simulation and analysis.

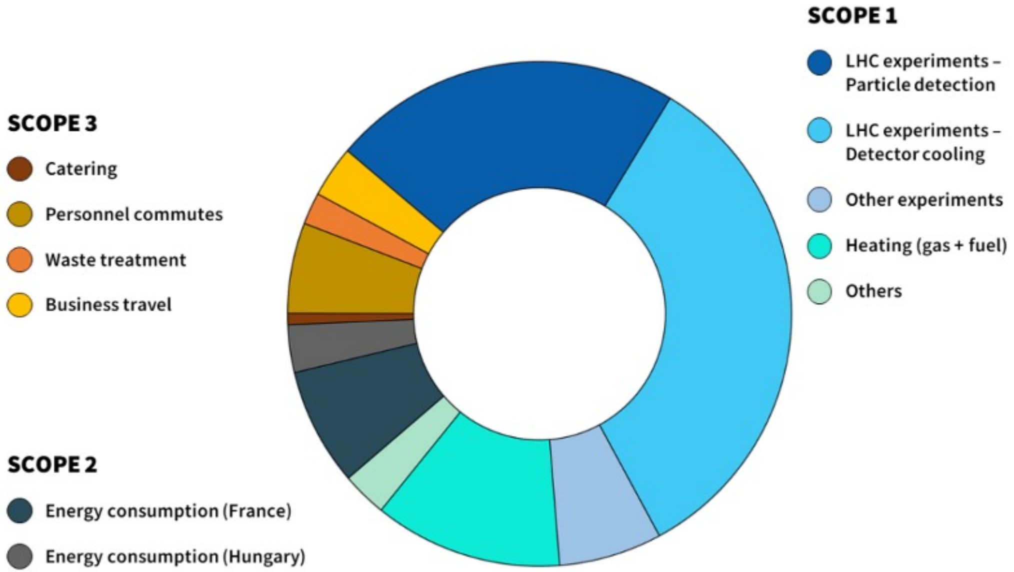


This requires enhanced R&D efforts and considerations for the environmental cost of computational infrastructure and algorithms in decision making and prioritise the development of common and reusable software solutions.

the detectors

Particle detectors and their GHG emissions

- Our particle detectors and their cooling systems use large amounts of GHGs (SF6, PFC, HFC all have high GWP values)
- Leaks in our detectors lead to GHGs escaping and in 2022 this effect was responsible for 40% of the total carbon footprint of CERN
- Europe is strongly regulating these GHG emissions



Distribution of CERN's greenhouse gas emissions in 2019

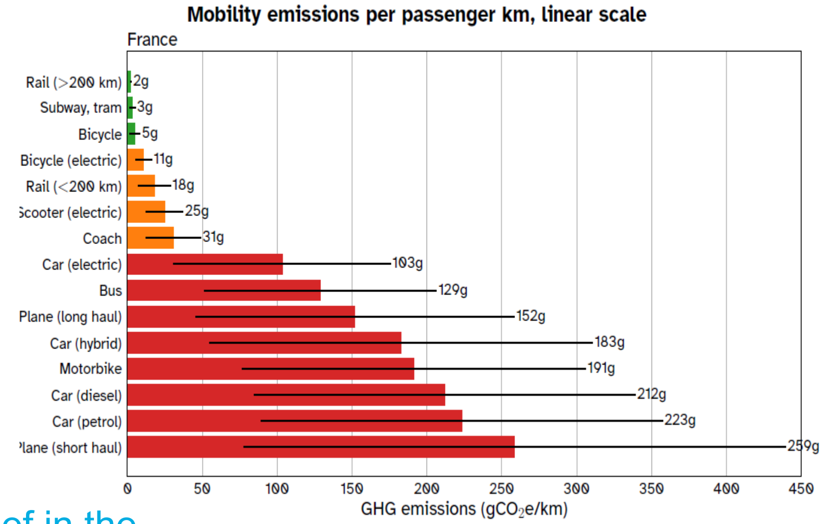
In addition to reducing the amount of GHGs used in our detectors, we must continue developing alternatives for these GHGs, i.e. environmentally friendly gas mixtures.

our travels

Travel to Collaborate

- We do travel to collaborate and must be aware of the carbon footprint

	ICHEP Melbourne 2012	ICHEP Valencia 2014	ICHEP Chicago 2016	ICHEP Seoul 2018	ICHEP Prague 2020 (virtual)
Number of participants	764	966	1,120	1,178	2,877
GHG emissions per participant [kg CO_2e]	8,432	1,902	2,699	2,648	0



The total carbon footprint of Nikhef in the Netherlands in 2019 was ~1 ktCO2e with 75% from air travel of staff.

It is a must to continue raising the awareness at the individual, research infrastructure and institution level; and potentially develop concrete targets at all levels.

More information:

- Sustainable HEP workshops: https://indico.cern.ch/event/1355767/
- Sustainability in HECAP+: https://sustainable-hecap-plus.github.io
- ESSRI workshops: https://agenda.ciemat.es/event/4431/page/474-event-description

Future Colliders and Sustainability

- Current particle physics colliders have a very large carbon and energy footprint
- Our tendency to make future colliders larger and more powerful could increase this footprint by factors, while the ambition of the society is to drastically reduce the carbon and energy footprint by 2050
- <u>With equal priority to cost and performance, the developments of future colliders must consider</u>: a Lifecycle Analysis, enhancing the R&D to develop the enabling technologies to address sustainability, energy and waste heat recovery
- We must include sustainability considerations across our community at all levels, e.g. travel, computing, detectors, procurement decisions, …

Future Colliders and Sustainability

- Current particle physics colliders have a very large carbon and energy footprint
- Our tendency to make future colliders larger and more powerful could increase this footprint by factors, while the ambition of the society is to drastically reduce the carbon and energy footprint by 2050
- With equal priority to cost and performance, the developments of future colliders must consider: a Lifecycle Analysis, enhancing the R&D to develop the enabling technologies to address sustainability, energy and waste heat recovery
- We must include sustainability considerations across our community at all levels, e.g. travel, computing, detectors, procurement decisions, …

the potential risk is so dramatic that we must foster these thoughts

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

iihe BRUXELLES BRUSSEL

fwo

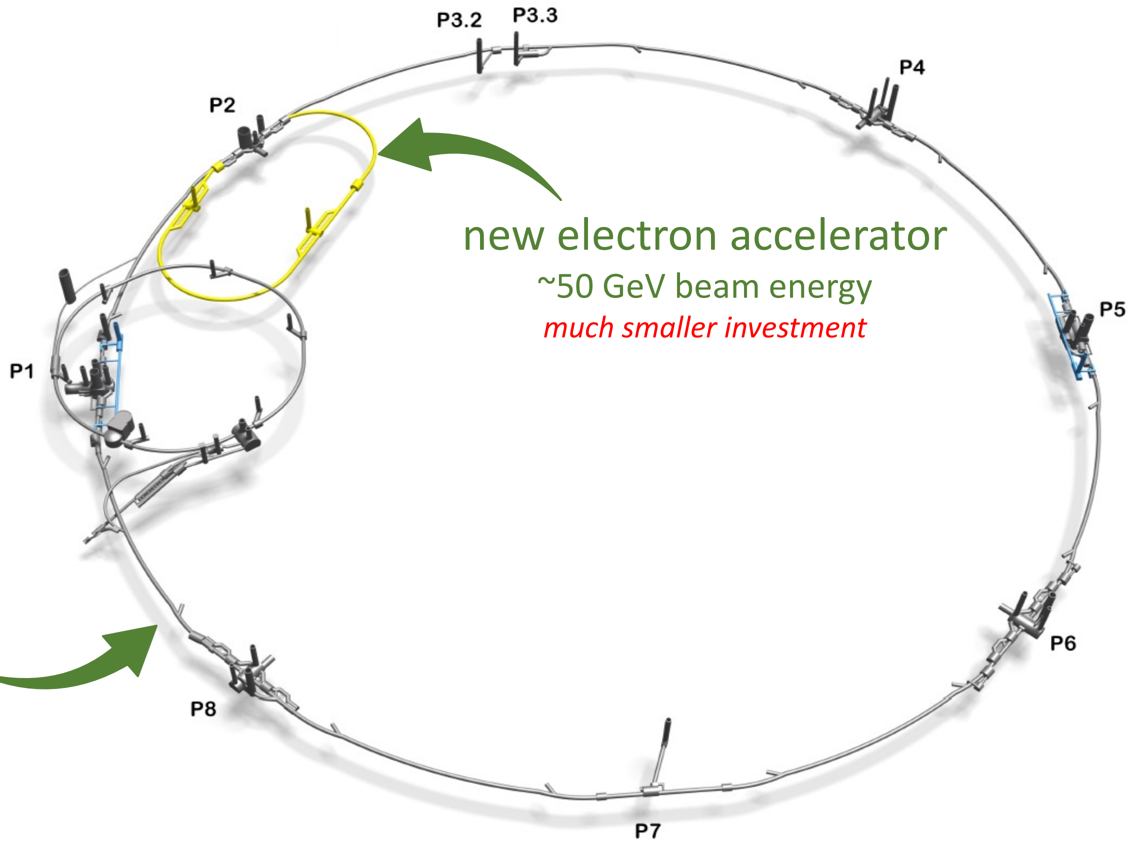
Thank you for your attention!

Jorgen.DHondt@vub.be

Not yet discussed today,
but here is the information on high-energy ep colliders
LHeC and FCC-eh @ CERN

(mostly copied from a presentation at ICHEP2024)

high-energy & high-luminosity electron-proton collisions



new electron accelerator

~50 GeV beam energy

much smaller investment

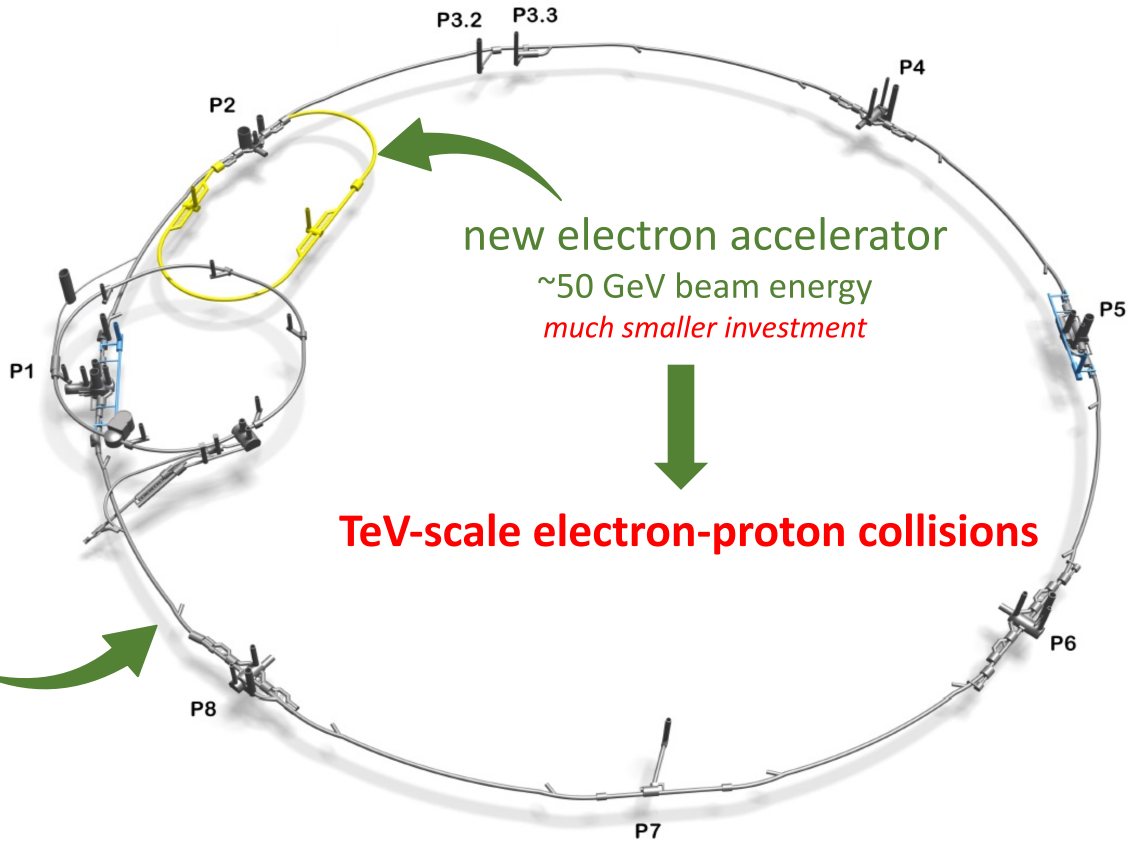
existing/future proton accelerator

LHC and/or FCC

(LHeC and/or FCC-eh)

major investment

high-energy & high-luminosity electron-proton collisions



new electron accelerator

~50 GeV beam energy

much smaller investment

TeV-scale electron-proton collisions

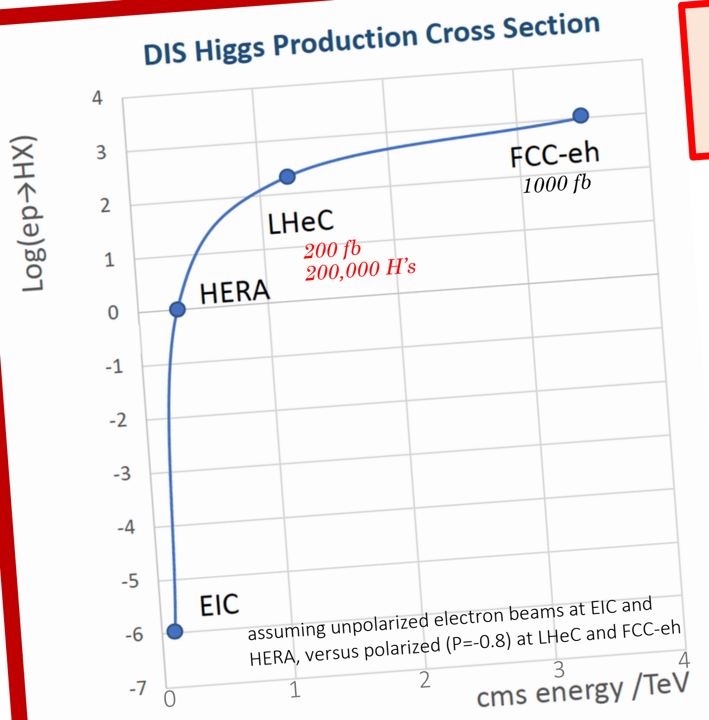
existing/future
proton accelerator

LHC and/or FCC

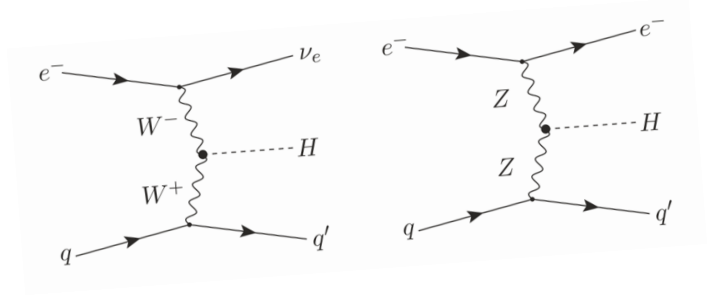
(LHeC and/or FCC-eh)

major investment

high-energy & high-luminosity electron-proton collisions

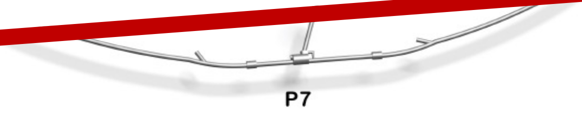


These electron-proton collisions enable a general-purpose experiment



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

major investment

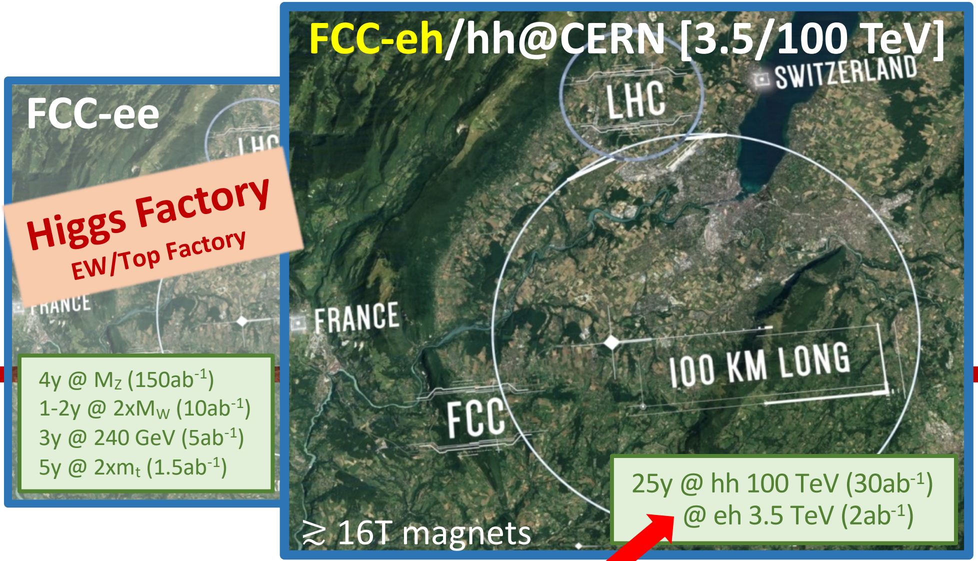


The ep/eA programs: at current & future hadron colliders

Current flagship (27km)
impressive programme up to ~2040

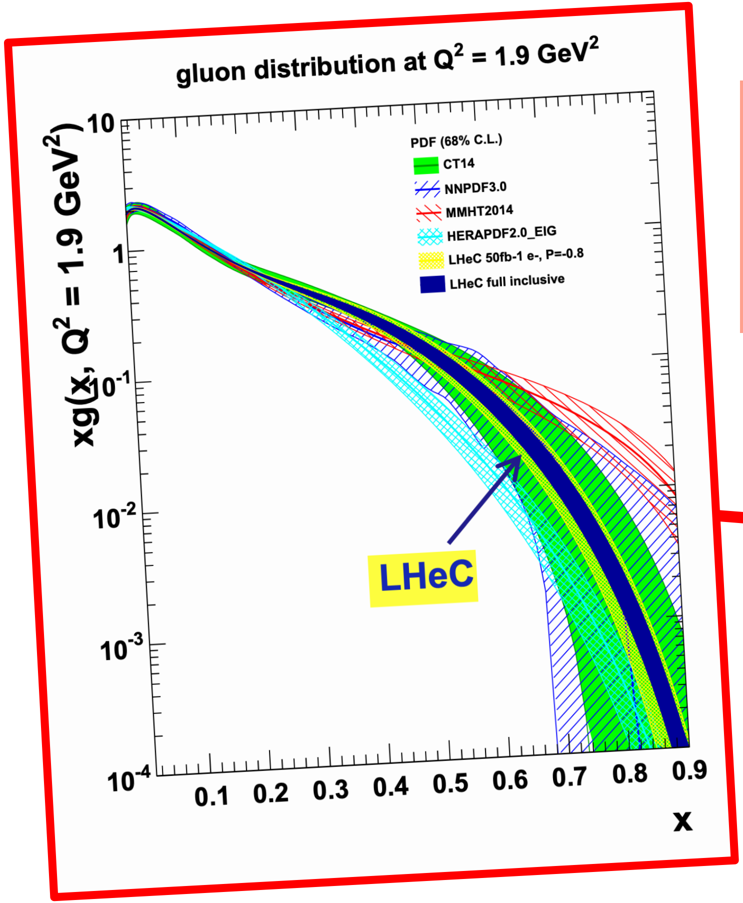
Future Circular Collider (FCC)
big sister future ambition (100km), beyond 2040
attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC
10y @ 1.2 TeV (1ab^{-1}) = Run-6 + 5y ep-only@LHC
updated CDR: J.Phys.G 48 (2021) 11, 110501
6y ep-only@LHC > 1 ab^{-1}

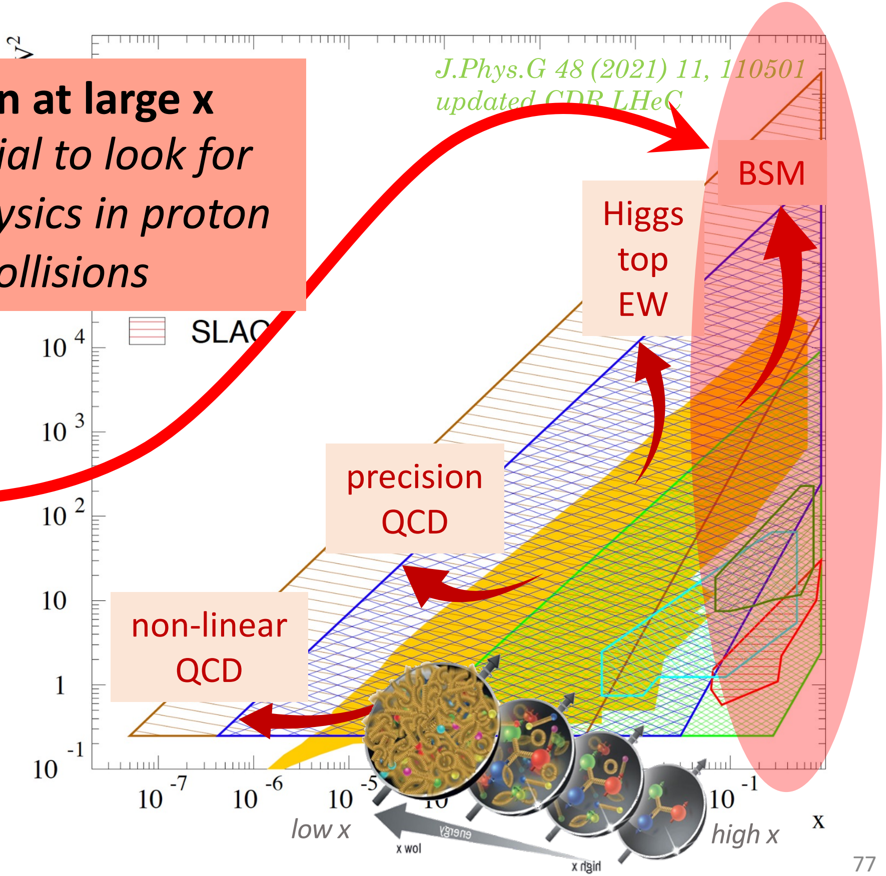


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC programme

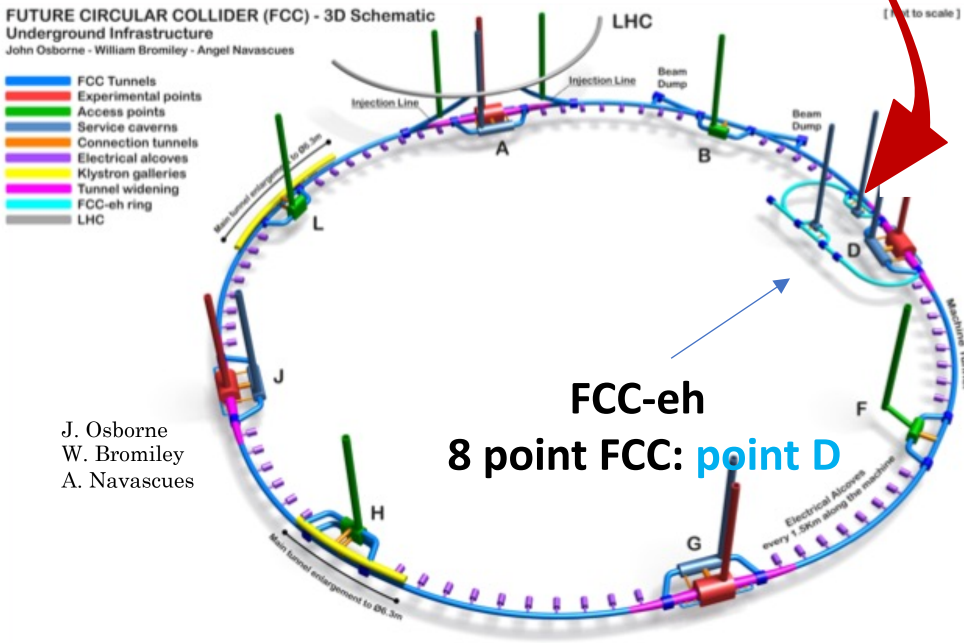


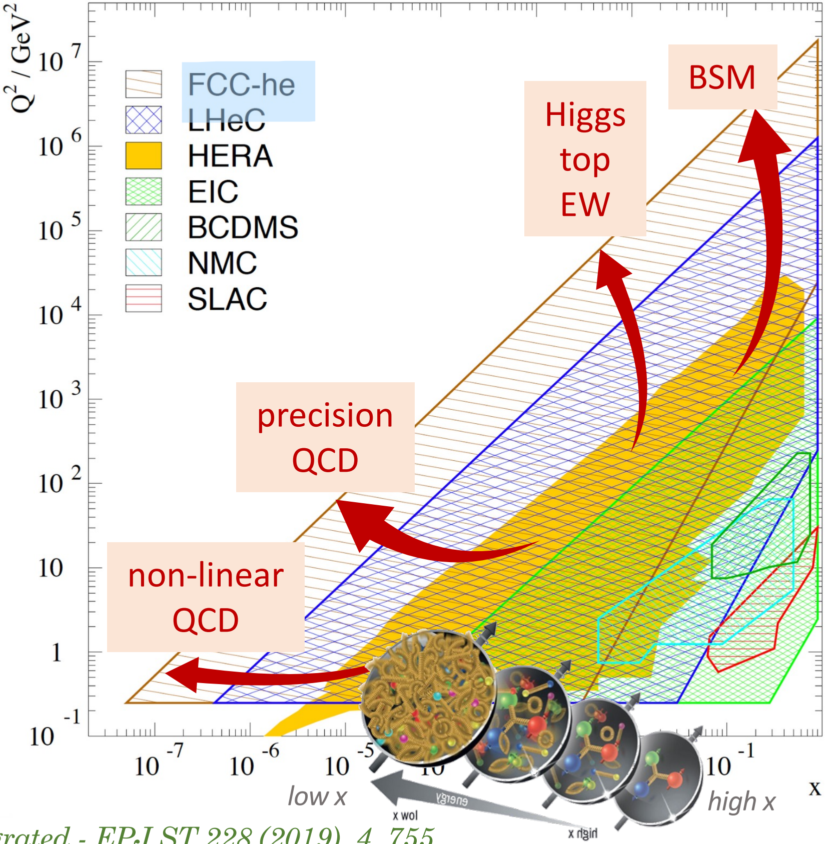
gluon at large x
essential to look for new physics in proton collisions



The FCC-eh programme

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





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

The challenge – high-power electron beam

From HERA to LHeC/FCC-eh

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

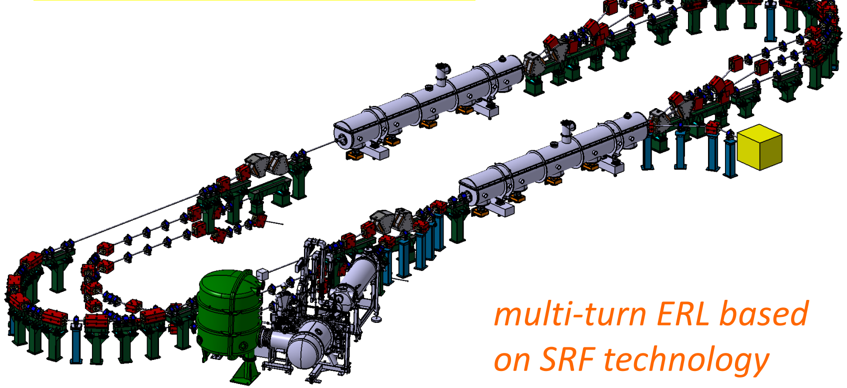
beam current × beam energy
= beam power

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

PERLE @ IJCLab (Orsay)

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

First stage: one-turn by 2028



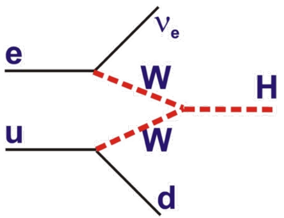
CDR: *J.Phys.G* 45 (2018) 6, 065003

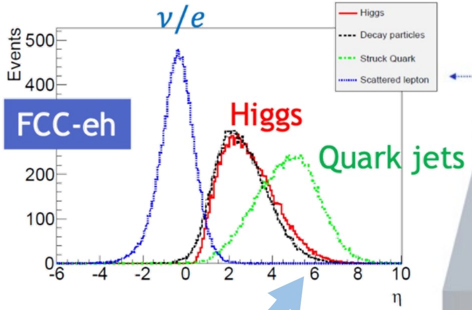
multi-turn ERL based on SRF technology
(3-turns, 500 MeV, 20 mA)

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

Make the invisible visible – Detector R&D for DIS

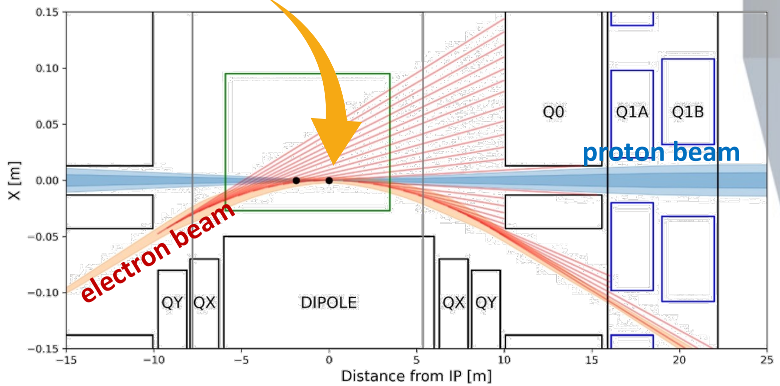
Major challenges: 1° close to the beamline (hermiticity), Tracking & Vertexing, High-resolution calorimetry

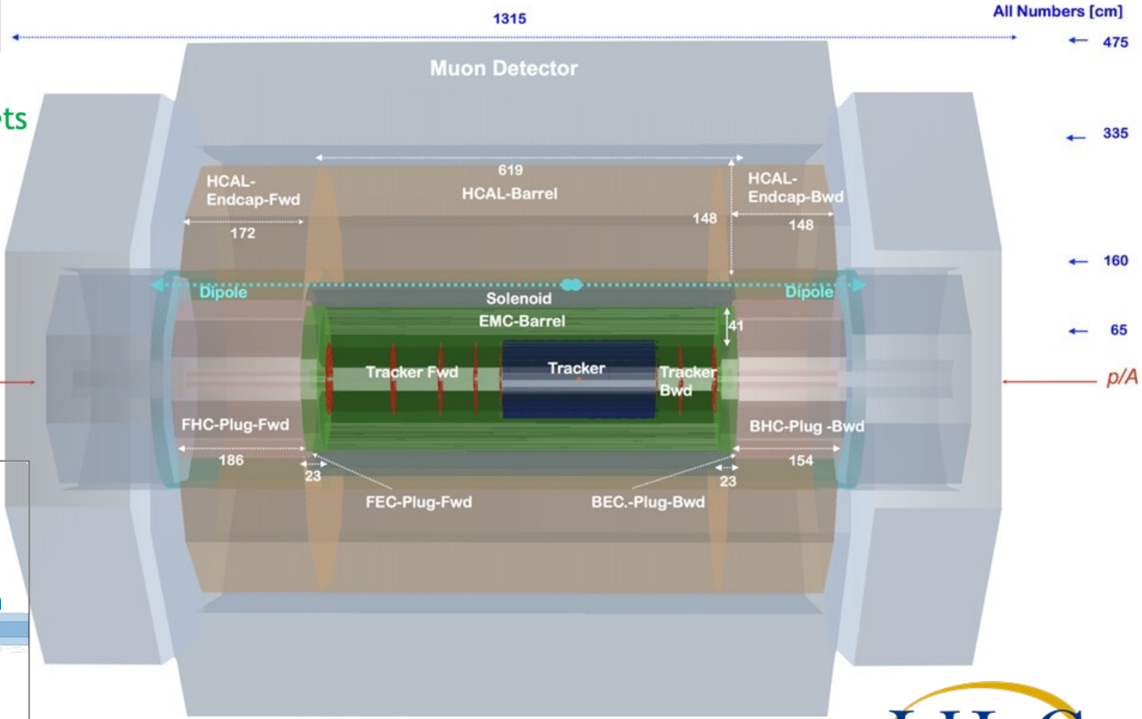




Forward jet reconstruction

Synchrotron radiation in the interaction region





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

LHeC

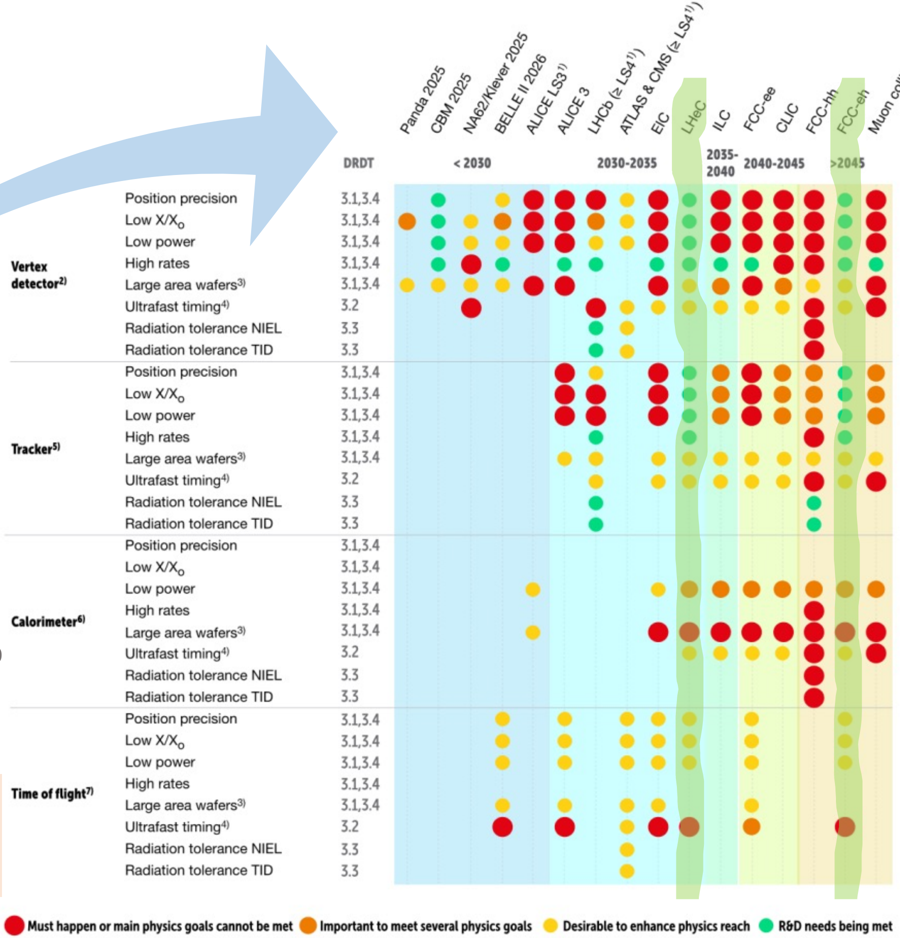
Make the invisible visible – Detector R&D for DIS

Mostly ready to be built

European Detector
R&D Roadmap
(2021)

Synergies with many other major projects, potentially as stepping stones

Detector Requirements
e.g. Solid State Devices



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

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

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

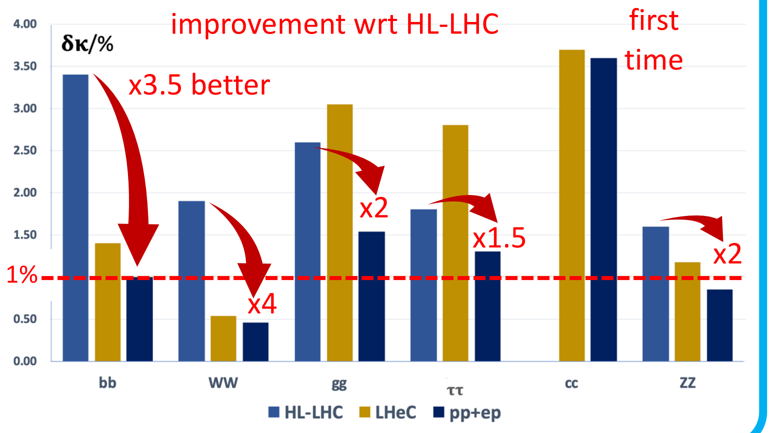
the synergistic physics impact of ep collisions

(briefly some highlights)

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

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

Higgs physics - pp+ep comb



EW physics – pp & ep

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

Top quark physics – ep only

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

DIS scattering cross sections - ep 1y

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

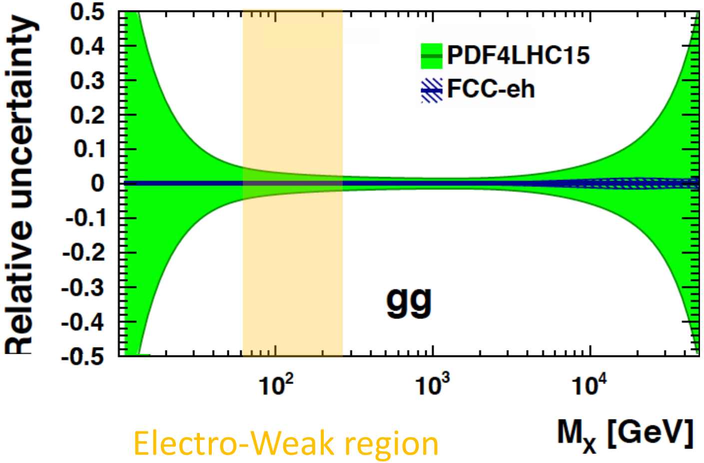
Strong interaction physics - ep 1y

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

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

Empowering the FCC-hh programme with the FCC-eh

pp @ 100 TeV

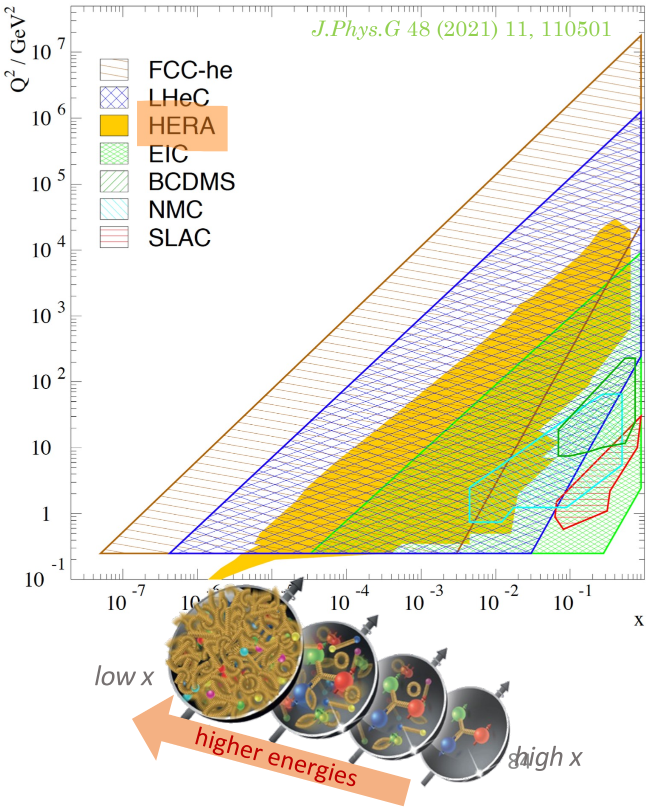


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

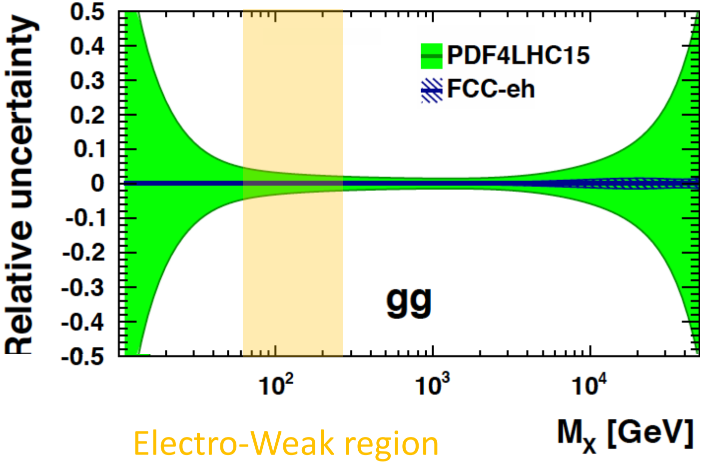
no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh programme with the FCC-eh

pp @ 100 TeV



Electro-Weak region

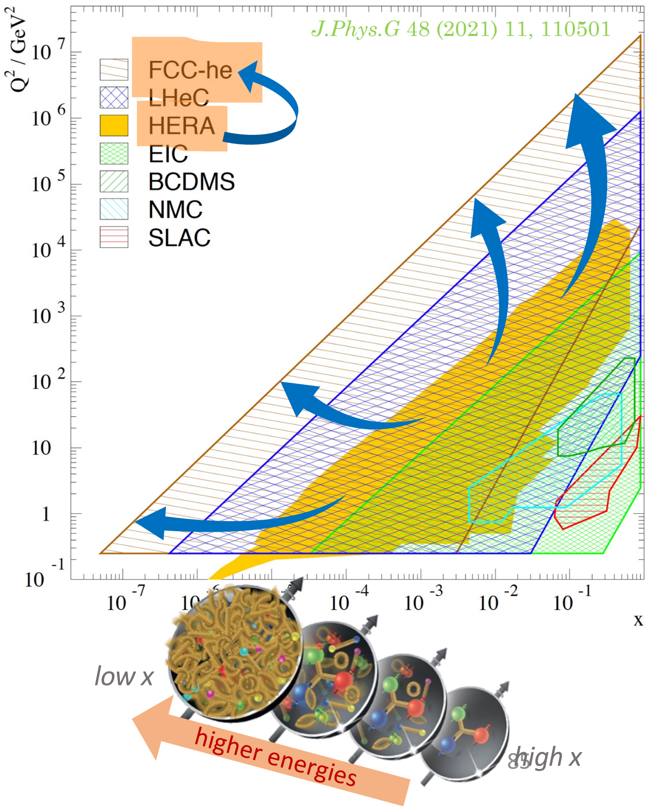
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



FCC-eh essential to unlock FCC-hh science potential

Complementarity for Higgs physics in the FCC programme

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

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

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC programme

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

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

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC programme

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

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

adding 365 GeV runs

adding FCC-eh

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC programme

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

FCC-ee versus FCC-hh/eh

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

adding 365 GeV runs

adding FCC-ep

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC programme

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

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

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC programme

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

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
[illegible]	[illegible]	[illegible]	[illegible]	0.27	0.17	0.39	0.14
κ_μ [%]	4.	3.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	[illegible]
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

What would be the combined Higgs physics reach of HL-LHC ⊕ FCC-ee/CEPC ⊕ LHeC ?

adding 365 GeV runs

adding FCC-ep

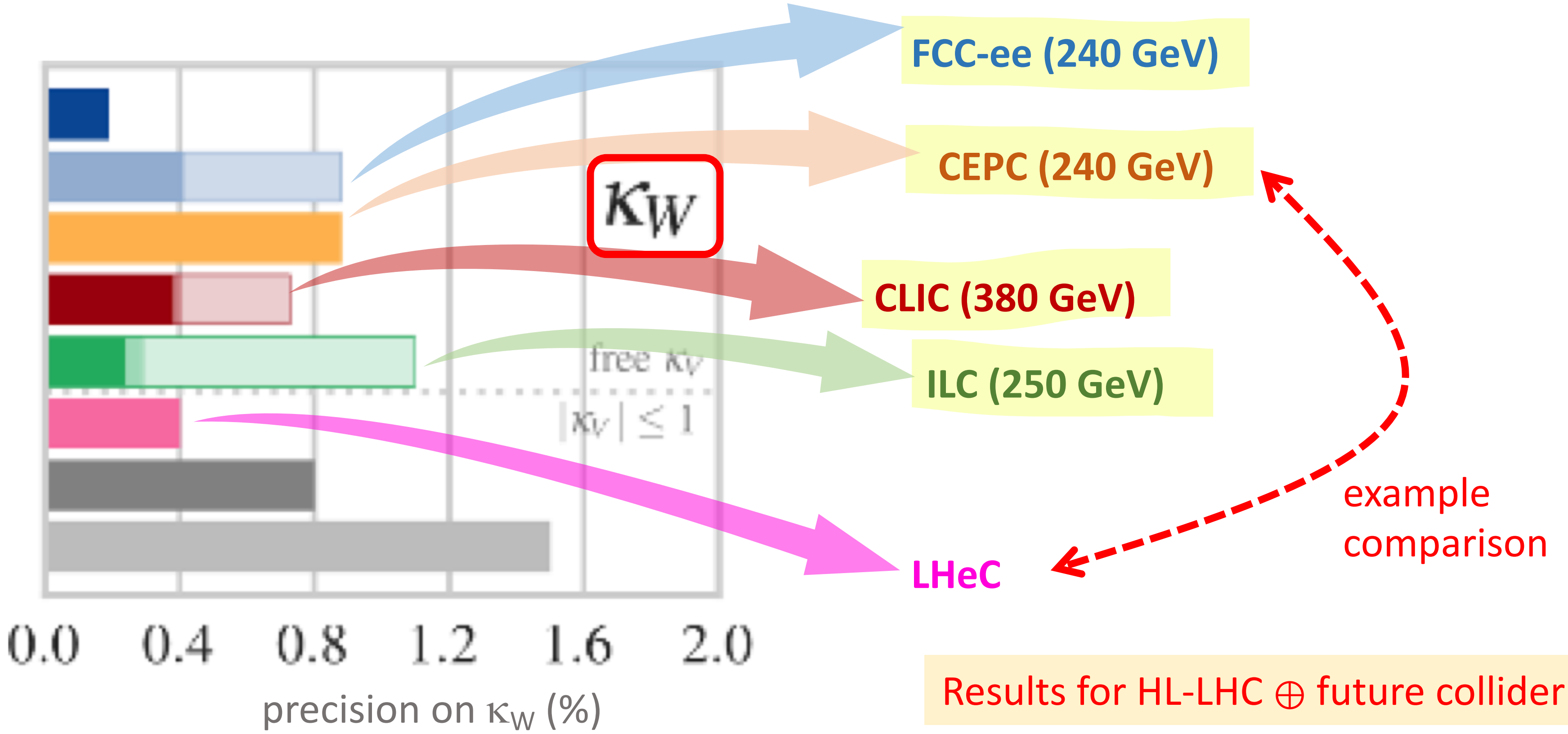
ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

Higgs physics precision: LHeC versus e^+e^- colliders



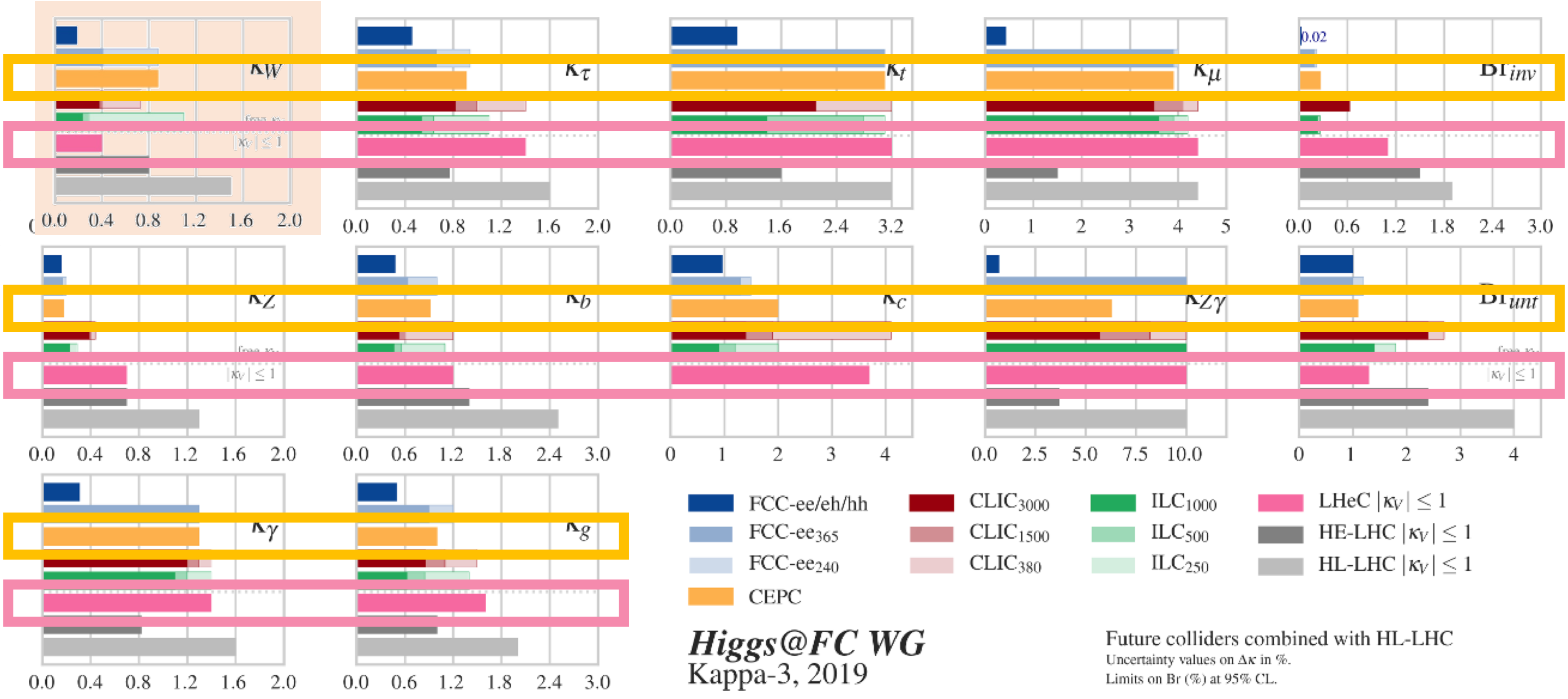
J. de Blas et al., JHEP 01 (2020) 139

Results for HL-LHC $\oplus$ future collider

LHeC: assumption is $|\kappa_V| \leq 1$ ($V = W, Z$), which is theoretically motivated as it holds in a wide class of BSM models albeit with some exceptions

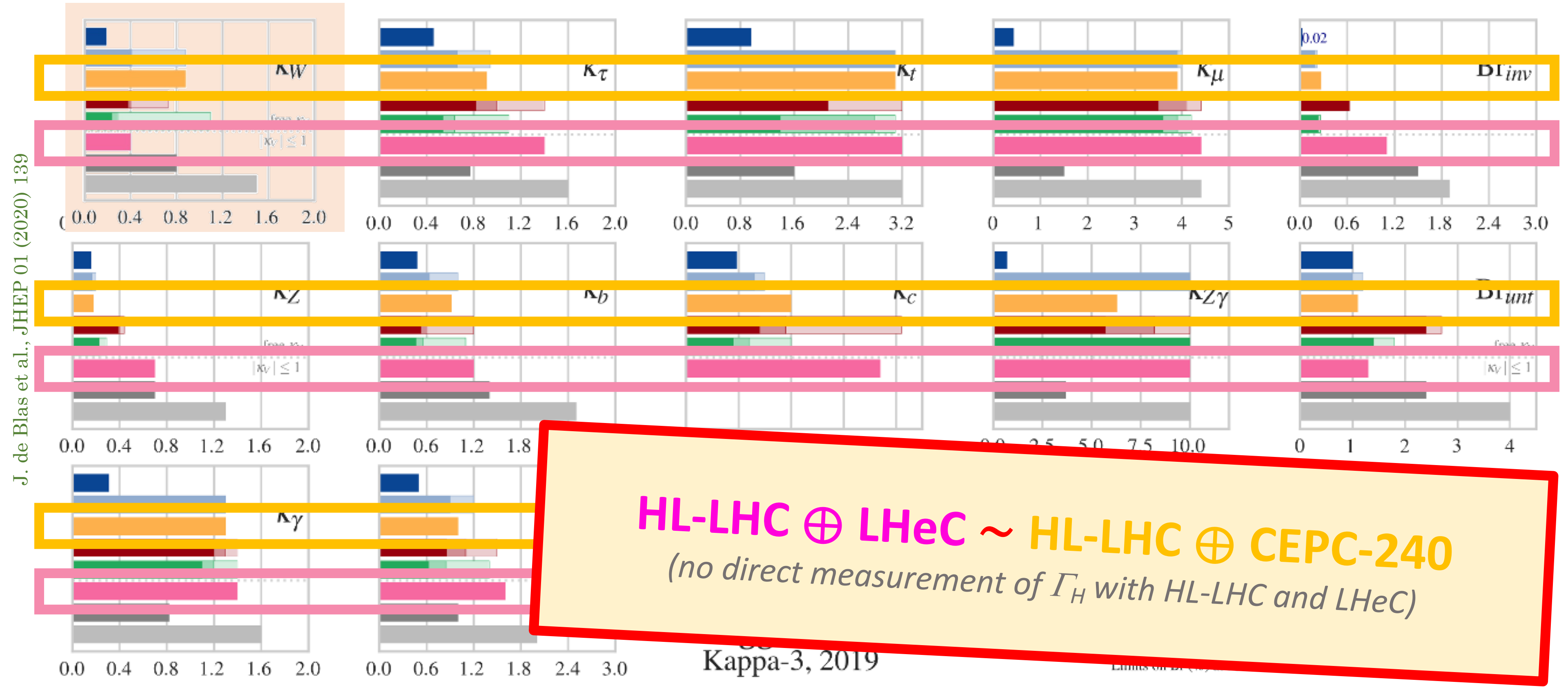
Higgs physics precision: LHeC versus CEPC

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



LHeC: assumption is $|\kappa_V| \leq 1$ (V = W, Z), which is theoretically motivated as it holds in a wide class of BSM models albeit with some exceptions

Higgs physics precision: LHeC versus CEPC

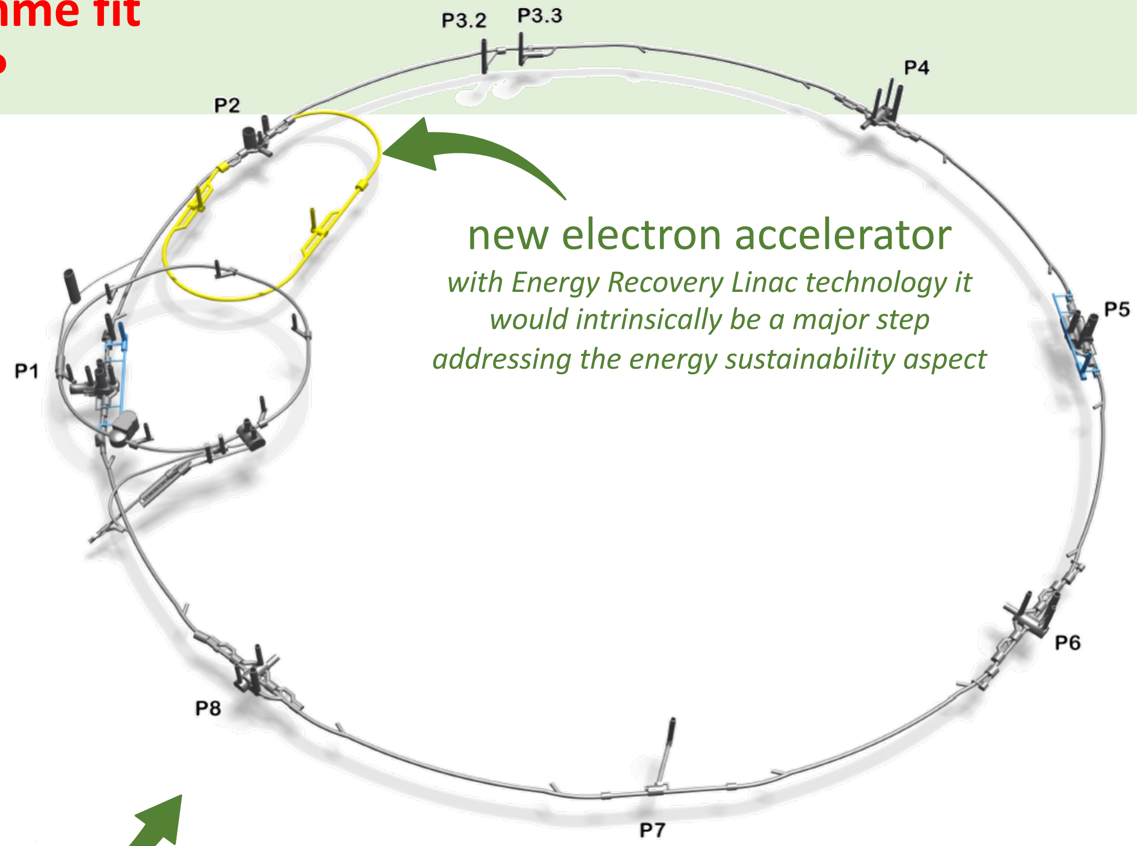


HL-LHC ⊕ LHeC ~ HL-LHC ⊕ CEPC-240

(no direct measurement of Γ_H with HL-LHC and LHeC)

LHeC: assumption is $|\kappa_V|\leq 1$ (V = W, Z), which is theoretically motivated as it holds in a wide class of BSM models albeit with some exceptions

How does the LHeC progamme fit into the collider landscape?



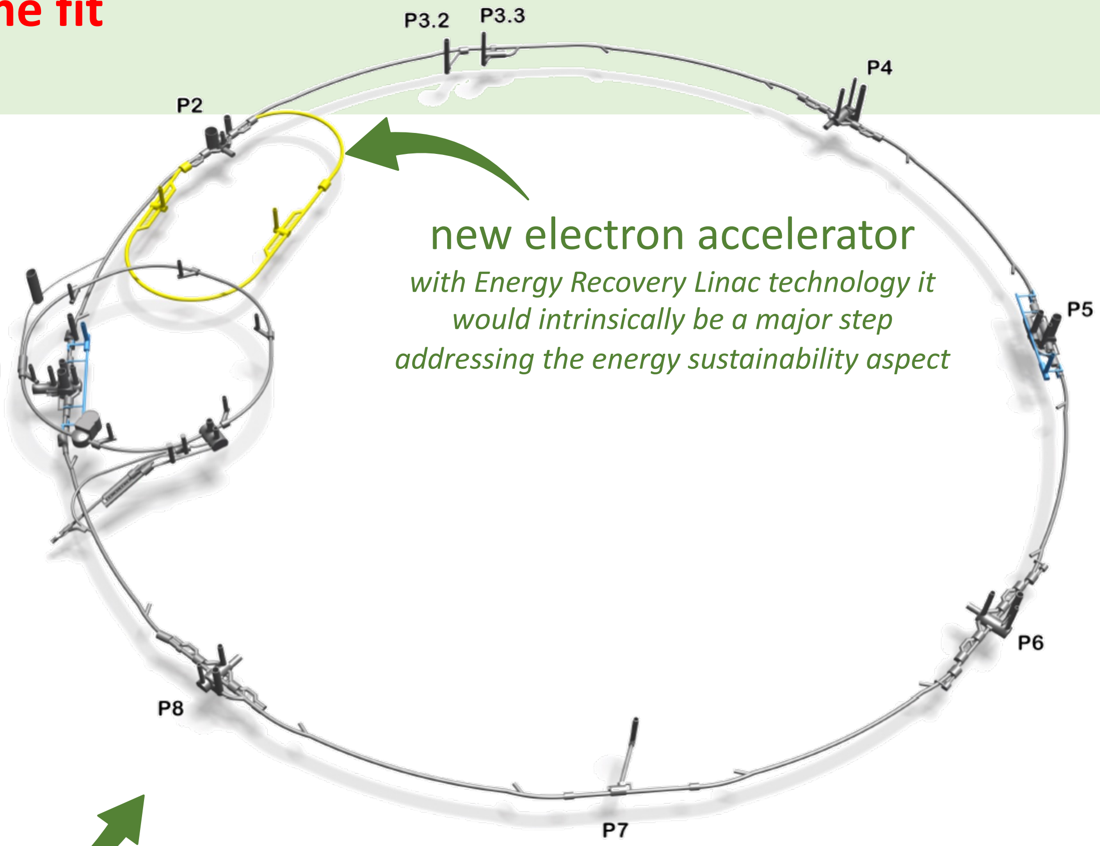
new electron accelerator

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

existing/future proton accelerator

How does the LHeC progamme fit into the collider landscape?

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



new electron accelerator

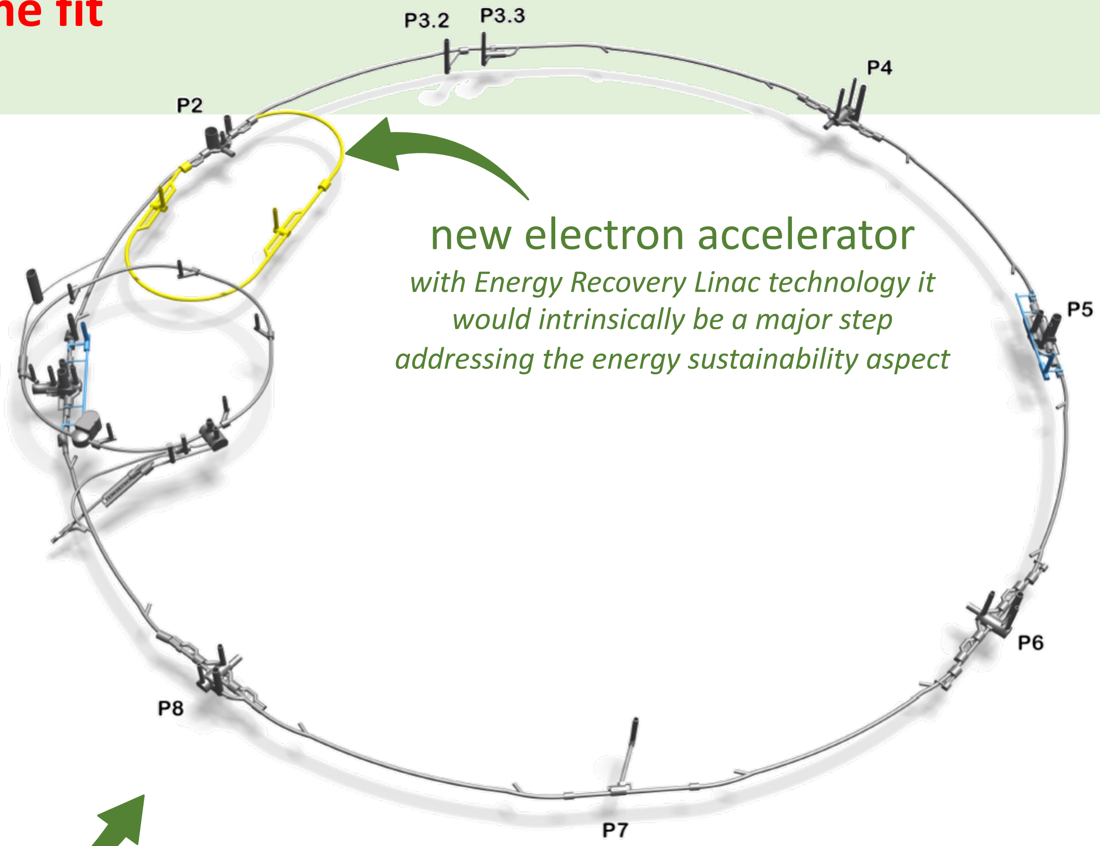
with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

existing/future proton accelerator

How does the LHeC progamme fit into the collider landscape?

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

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



new electron accelerator

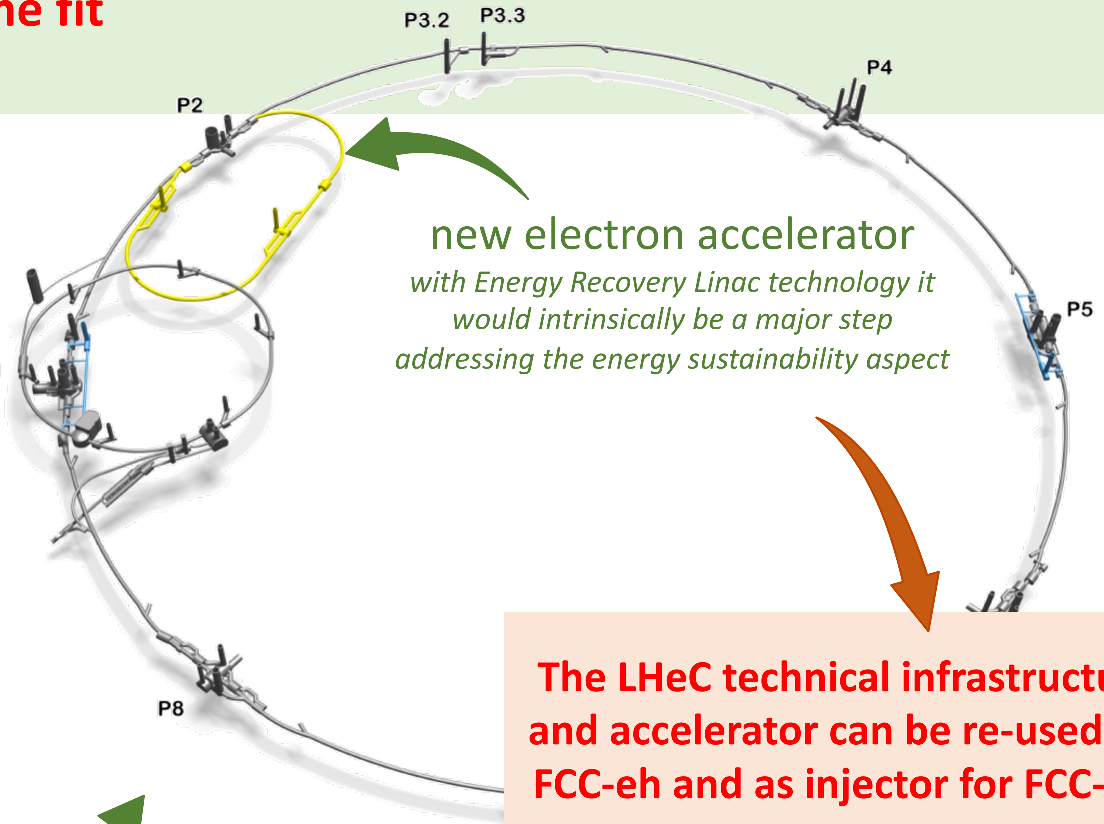
with Energy Recovery Linac technology it would intrinsically be a major step addressing the energy sustainability aspect

existing/future proton accelerator

How does the LHeC progamme fit into the collider landscape?

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

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



new electron accelerator

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

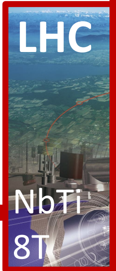
The LHeC technical infrastructure and accelerator can be re-used for FCC-eh and as injector for FCC-ee.

existing/future proton accelerator

Major current & future colliders @ CERN

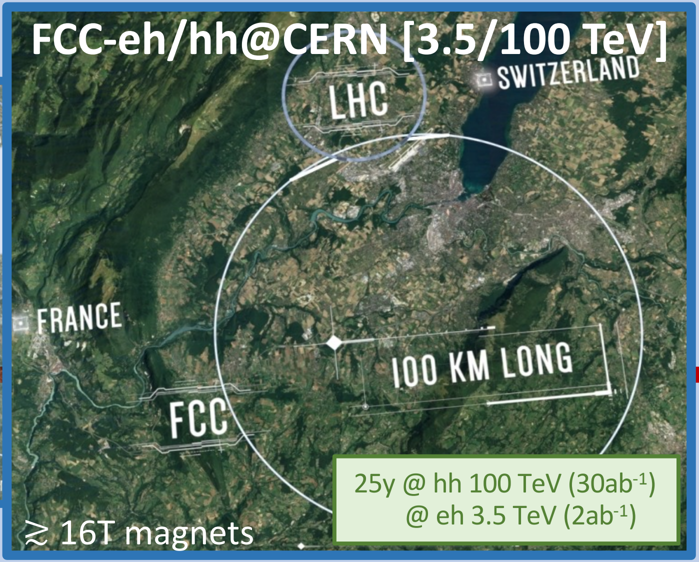
Large Hadron Collider (HL-LHC)

until early 2040'ies



Future Circular Collider (FCC)

from late 2040'ies



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

feasibility of the FCC is being investigated

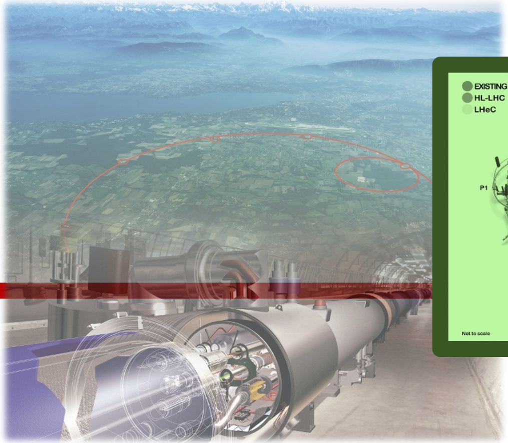
An impactful “*bridge*” between major colliders @ CERN

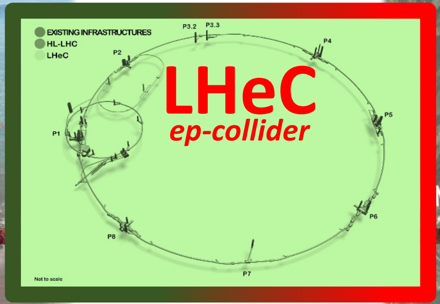
ep-option with HL-LHC: LHeC

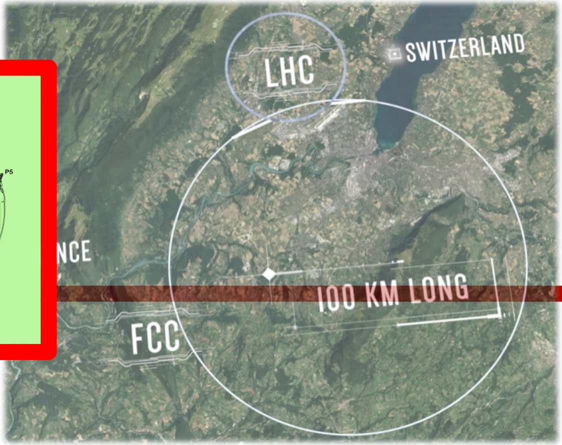
updated CDR: J.Phys.G 48 (2021) 11, 110501

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

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

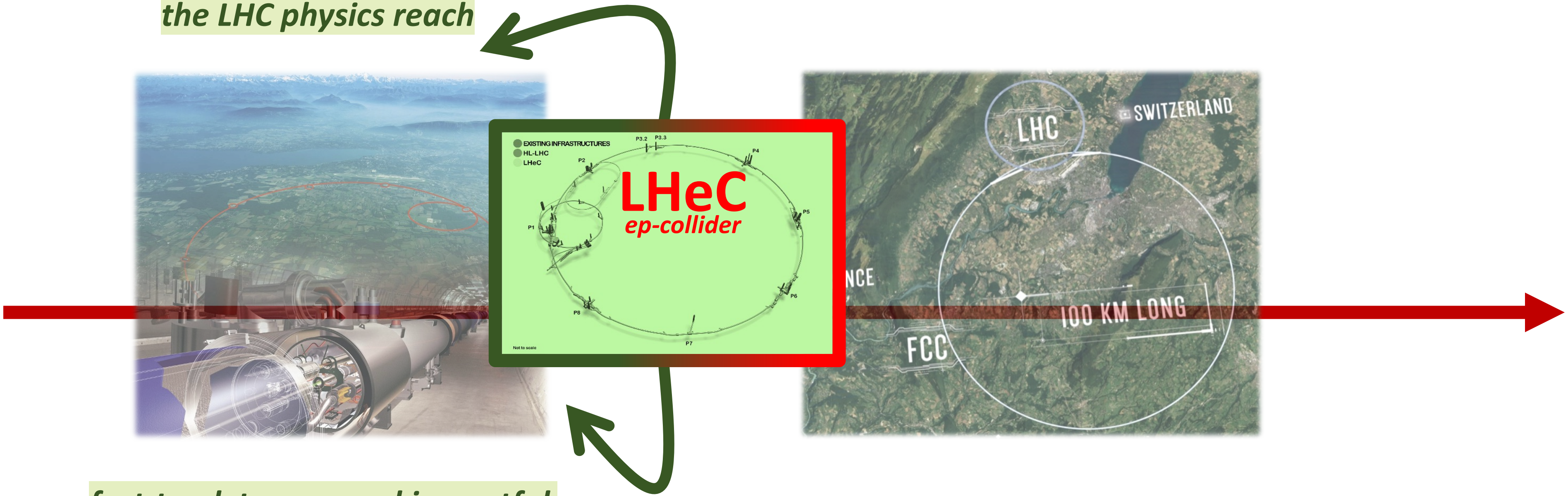






An impactful “*bridge*” between major colliders @ CERN

ultimate upgrade of the LHC physics reach



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

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

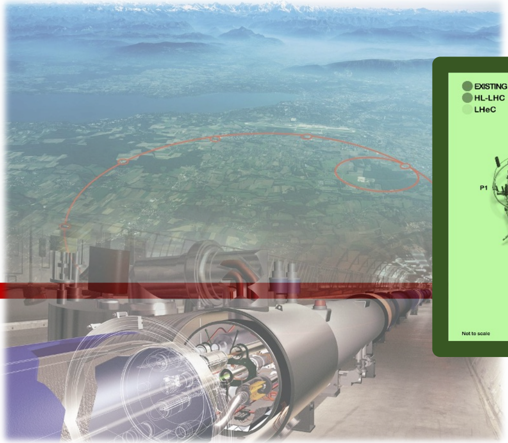
cost-effective investment

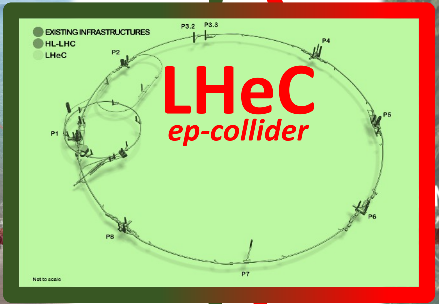
re-use

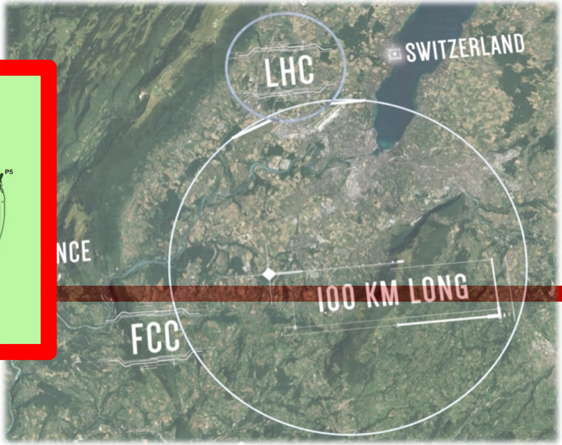
injector

ultimate upgrade of the LHC physics reach

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







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

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

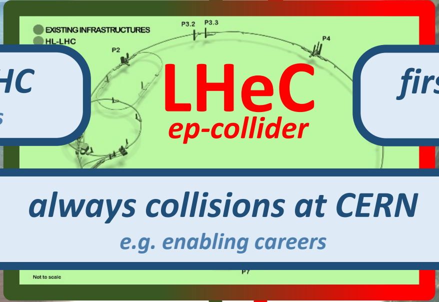
cost-effective investment

re-use

injector

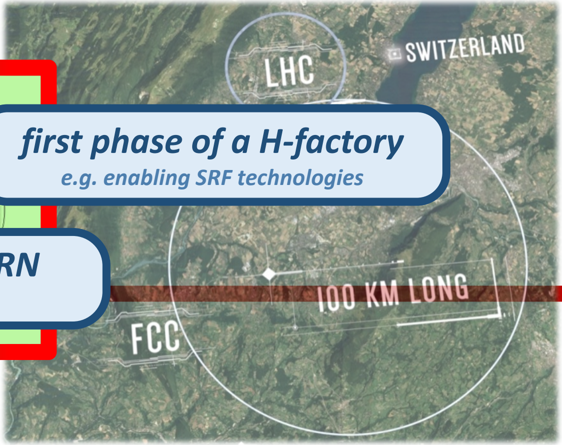
ultimate upgrade of the LHC physics reach

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



LHeC

ep-collider



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

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

always collisions at CERN
e.g. enabling careers

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

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

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

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

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

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

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

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

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

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

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

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

The ep/eA study at the LHC and FCC

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

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

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

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

iihe BRUXELLES BRUSSEL

fwo

Thank you for your attention!

Jorgen.DHondt@vub.be