Future Particle Physics Colliders with Energy Recovery Linacs

an impactful accelerator technology addressing the European Strategy

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16 January 2024

MPP Munich, ~~5 December 2023~~

observable universe

$8.8\ 10^{26} m$

quarks

$< 10^{-19} m$

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

atoms

proton neutron

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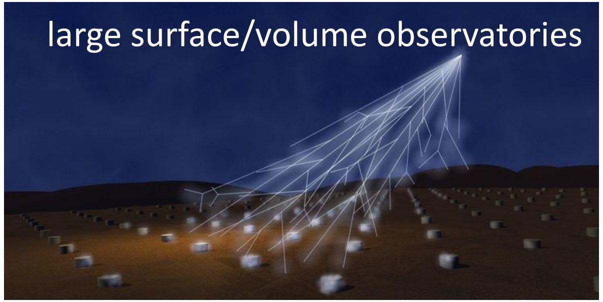

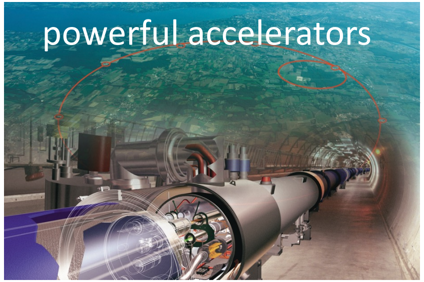

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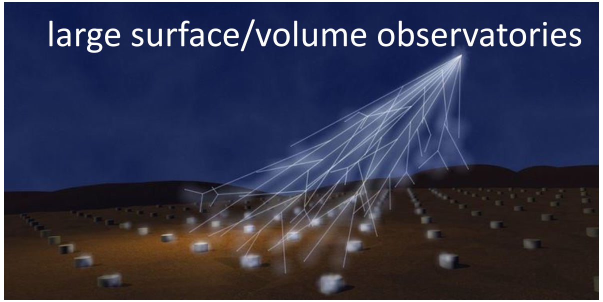
age universe
4.4 10^{18} s

observable universe
$8.8\ 10^{26}m$



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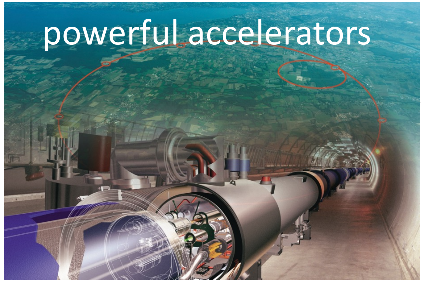

lifetime top quark
5 10^{-25} s

quarks
$< 10^{-19}m$

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

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biological cell

atoms

proton neutron

lifetime star
10^{13}-10^{16} s

duration supernova & GRB
0.1-100 s

lifetime proton
> 3 10^{41} s

lifetime kaon ($K^{\pm}$)
1.2 10^{-8} s

Develop a model to describe how objects behave in this space and time

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Basic Principles

FROM INTUITION

e.g. the locality principle:
all matter has the same set of constituents

e.g. the causality principle:

a future state depends only on the present state

e.g. the invariance principle:

space-time is homogeneous

FROM LONG-STANDING OBSERVATIONS

the wave-particle duality principle
the quantisation principle
the cosmological principle
the constant speed of light principle
the uncertainty principle
the equivalence principle

no obvious reason for these long-standing observations to be what they are…

Develop a model to describe how objects behave in this space and time

Basic Principles

Fundamental Theories

MATHEMATICAL FRAMEWORKS HOW OBJECTS BEHAVE

① ***General Relativity*** *(for gravity)*

② ***Quantum Mechanics + Special Relativity = Quantum Field Theory***
(for electromagnetic, weak and strong forces)

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Concrete Models

APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

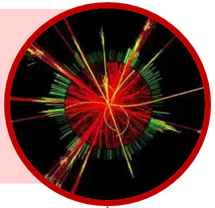
① ***General Relativity → Standard Model of Cosmology***
② ***Quantum Field Theory → Standard Model of Particle Physics***

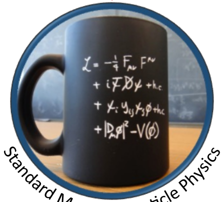
need to be valid into even the tiniest cracks of space and time and for all energies or masses of the objects… even at the extremes

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

observations how small objects behave in our laboratories





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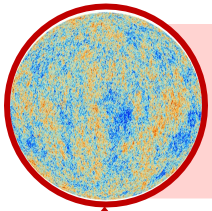
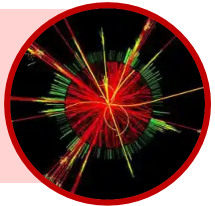


observations how large objects behave in our universe

Standard Model of Cosmology



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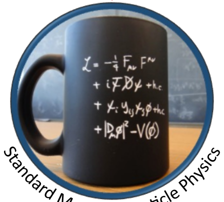

Standard Model of Particle Physics

Einstein's field equations of gravity from which the Friedmann equations are derived to model the evolution of the universe

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

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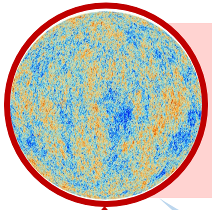
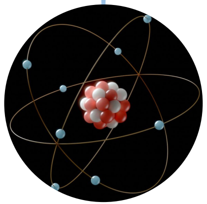
building blocks of life on the human scale



observations how large objects behave in our universe

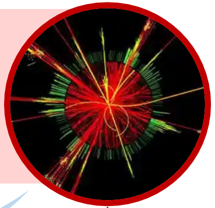
Standard Model of Cosmology

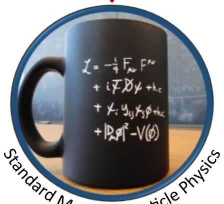
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





Standard Model of Particle Physics

A century of scientific revolutions

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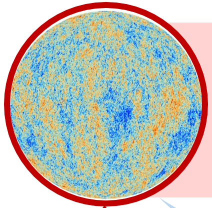

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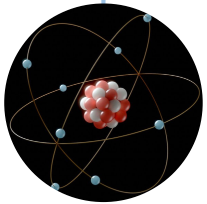

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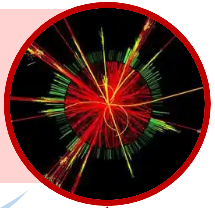
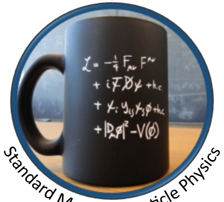
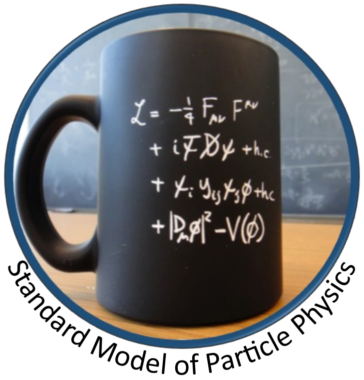




Standard Model of Particle Physics

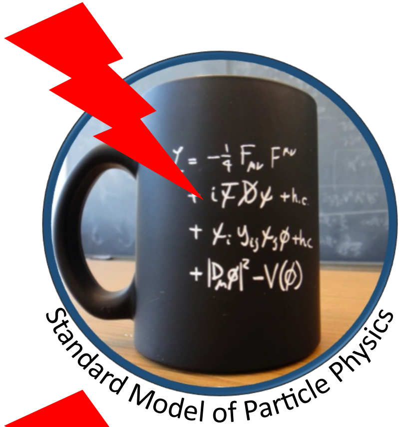
The quest for understanding physics

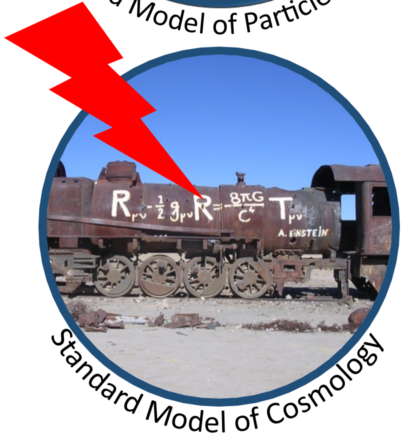


"Problems and Mysteries"

e.g. Abundance of dark matter?
Abundance of matter over antimatter?
What is the origin and engine for high-energy cosmic particles?
Dark energy for an accelerated expansion of the universe?
What caused (and stopped) inflation in the early universe?
Scale of things (why do the numbers miraculously match)?
Pattern of particle masses and mixings?
Dynamics of Electro-Weak symmetry breaking?
How do quarks and gluons give rise to properties of nuclei?…

The quest for understanding physics





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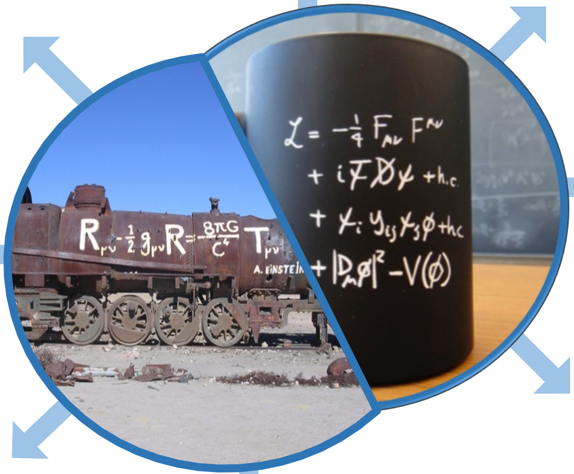
Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

higher energy interactions
in the lab

earlier universe

rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

IMPACT OF (FUTURE) COLLIDERS

higher energy interactions
in the lab

indirectly
earlier universe

rarer processes

higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

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

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~1B EUR

~7-12B EUR

e^+e^-

RF technology

E_{CMS} ~ 10 GeV (flavour)

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

E_{CMS} > 500 GeV

~15-20B EUR

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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

The landscape of future particle physics colliders

This talk will focus on the Energy Recovery Linac technology to improve the performance of these colliders

FOCUS

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

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

E_{CMS} > 1 TeV

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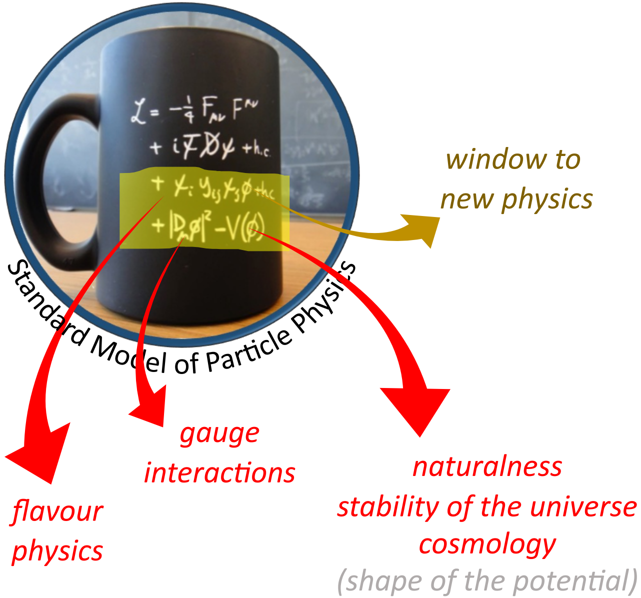
An electron-positron Higgs factory is the highest-priority next collider.

European Strategy for Particle Physics 2020

The Higgs field fills the vacuum as a scalar field

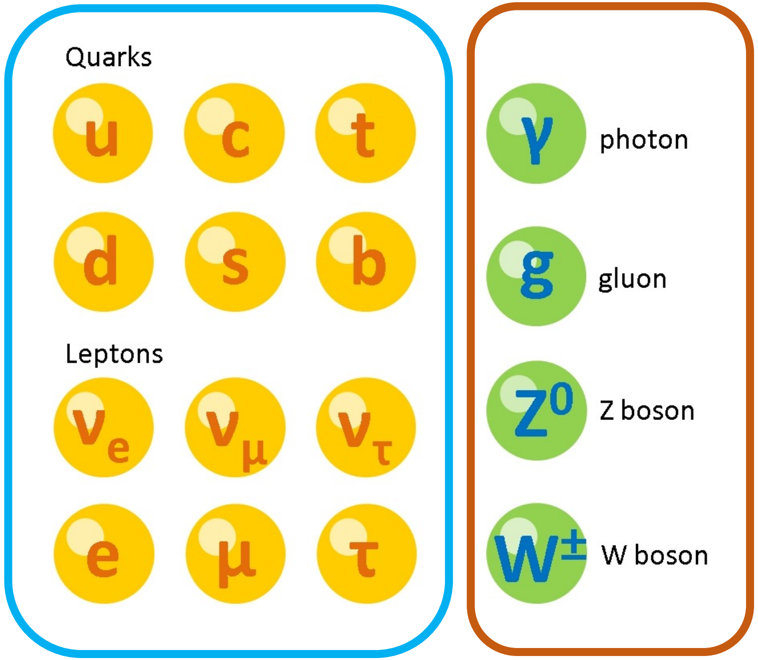


The particle fields in this vacuum feel an interaction with the H field and the particle acquires a mass.
(≠ Newton, not slowing down by inertia)

The scalar H field is home to the scalar H boson which is deeply intertwined with the vacuum structure throughout space-time and its mass is wildly sensitive to quantum fluctuations emerging from new physics phenomena at higher energies.

Essentially all problems of the Standard Model are related to the dynamics and couplings of the scalar field, and we do not know very much about them.

Higgs couplings



building blocks of matter
(fermions *f*)

forces between them
(bosons *V*)

Theory prediction

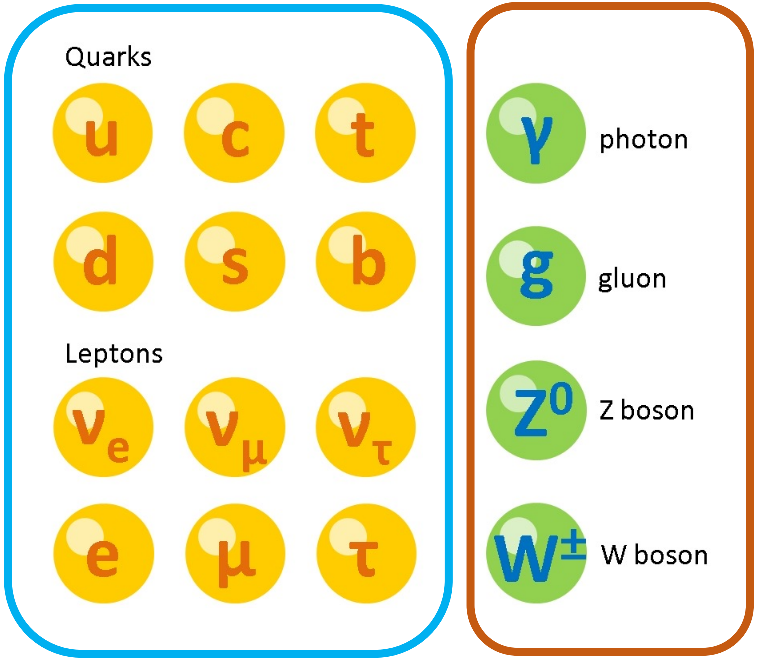
The particle mass depends on the coupling strength with the H field

$$y_f \propto m_f$$

$$g_V^2 \propto m_V^2$$

be aware, only the relation is predicted, and both sides of the relation are to be measured

Higgs couplings



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$\boxed{y_f \propto m_f}$ → **impact**

$g_V^2 \propto m_V^2$

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Higgs couplings

Quarks

Leptons

building block
(fermio

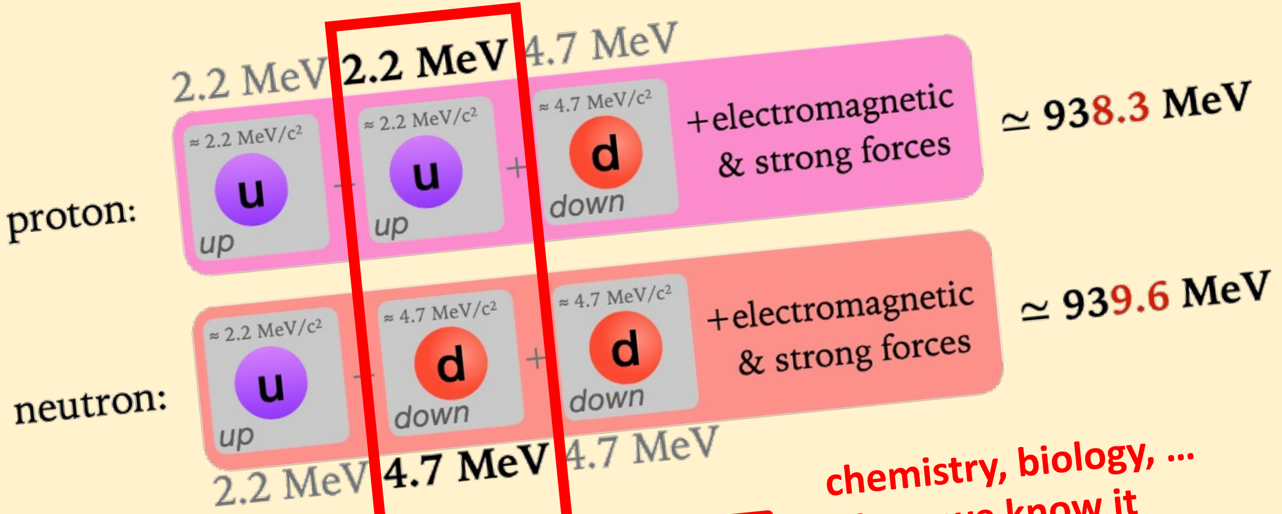
n the
field

mpact

is
the
d

Why do hydrogen atoms exist?

Because the proton is stable!

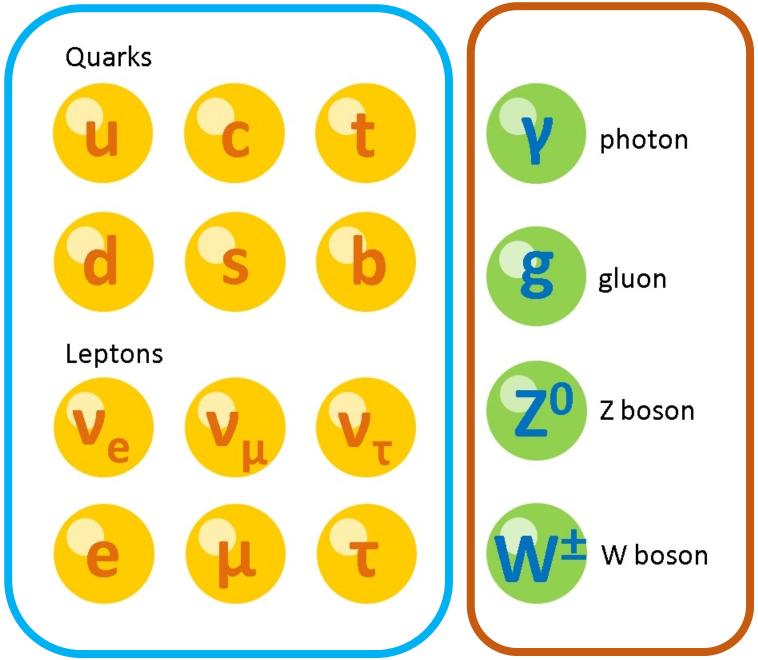


hypothesis: because $y_u < y_d$

chemistry, biology, …
life as we know it
depends on this hypothesis

adapted from G. Salam

Higgs couplings



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Theory prediction

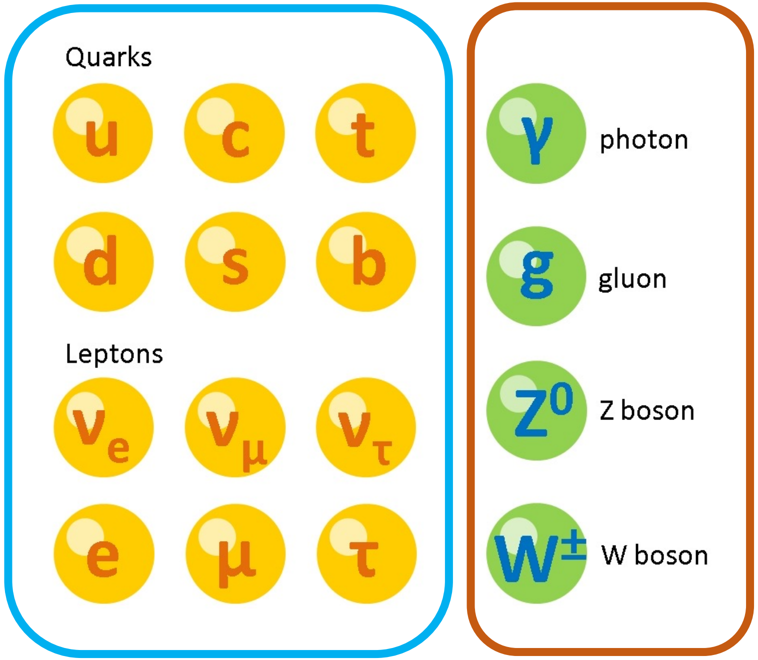
The particle mass depends on the coupling strength with the H field

$$\boxed{y_f \propto m_f} \Rightarrow \textbf{impact}$$

$$g_V^2 \propto m_V^2$$

Is it so beautifully simple, or does the interaction include a more complex structure beyond the standard model?

Higgs couplings



building blocks of matter
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forces between them
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Theory prediction

The particle mass depends on the coupling strength with the H field

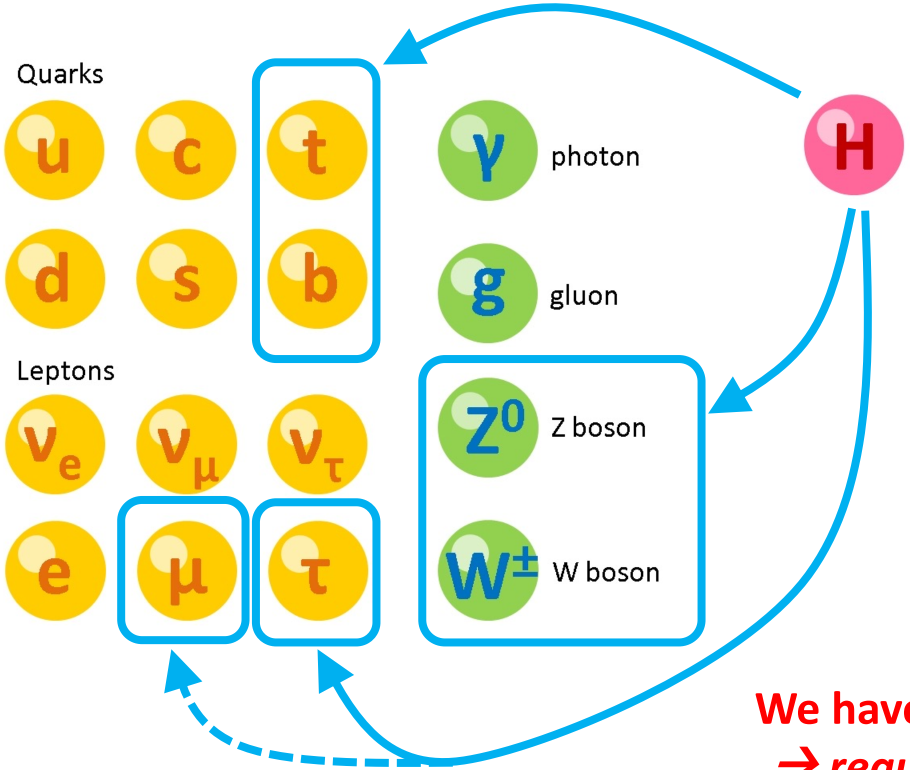
$$y_f \propto \kappa_f m_f \oplus \text{others}$$

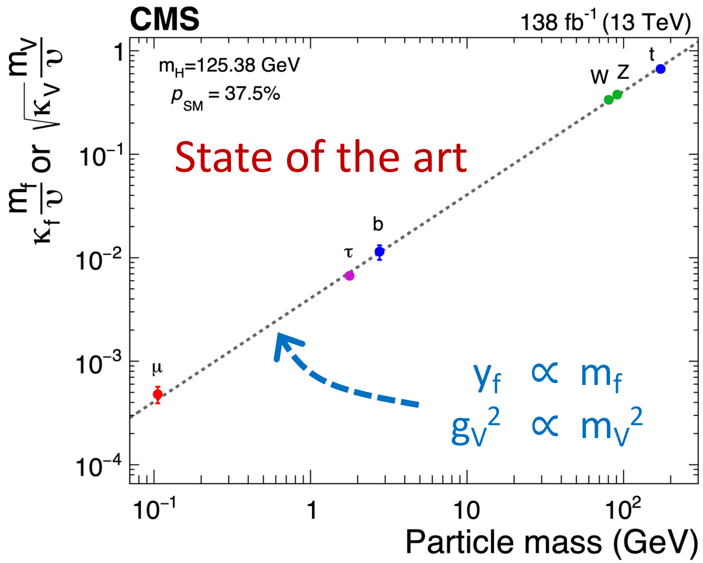
$$g_V^2 \propto \kappa_V m_V^2 \oplus \text{others}$$

simple coupling modifiers

involving new particles and/or new interactions

Higgs couplings





We have only seen a first glimpse of the H sector

→ *require more observations & more precision*

Future flagship at the energy & precision frontier

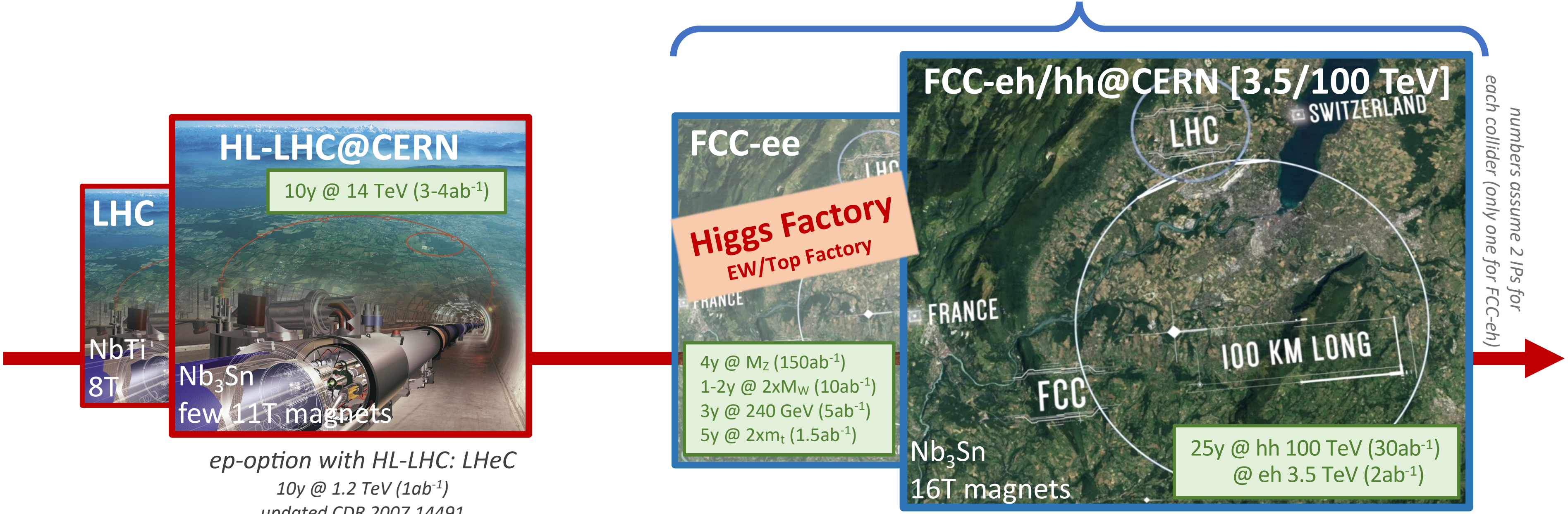
Current flagship (27km)

impressive programme up to 2042

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2048

attractive combination of precision & energy frontier



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

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

by around 2026, verify if it is feasible to plan for success
(techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider

Breakthroughs with more precise observations

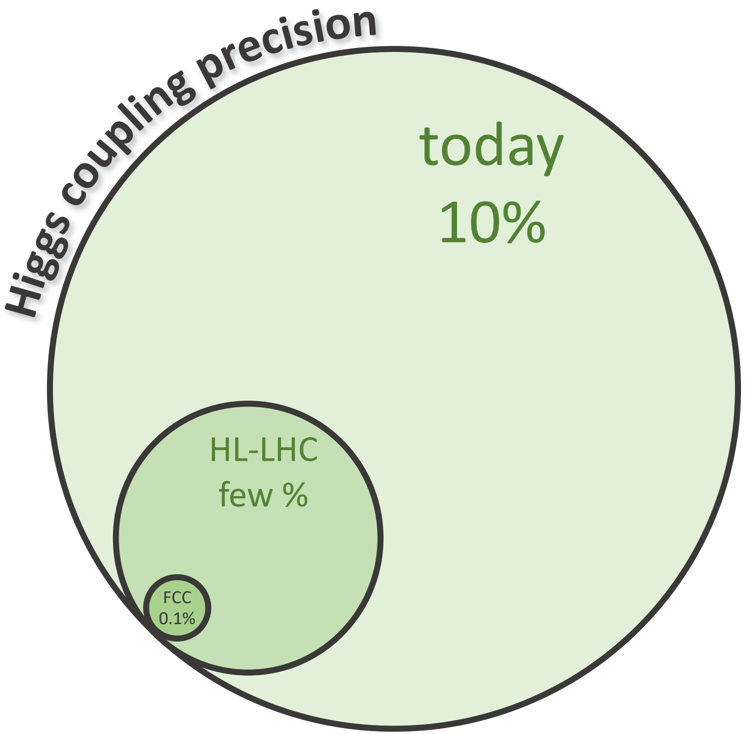
e.g., a more precise analysis of measured UV light reaching Earth revealed the ozone hole

e.g., with improved interferometers gravitational waves were finally directly observed

e.g., more precise measurements of the nature of the CMB unlocked early universe cosmology

Unless dramatic new insights appear, we might have to built a Higgs Factory to ever be able to answer our open fundamental questions.

i.e. finding our ozone hole, our missing link, the true nature of fundamental interactions, …



Surely, future collider programmes go beyond only precision Higgs physics

Breakthroughs with more precise observations

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e.g., with improved i

Numerous arguments for building new colliders dedicated to produce copiously Higgs bosons in order to map precisely its interactions with other particles and itself.

U ... peal,
w ... built a Higgs Factory
to ever be able to answer our open fundamental questions.

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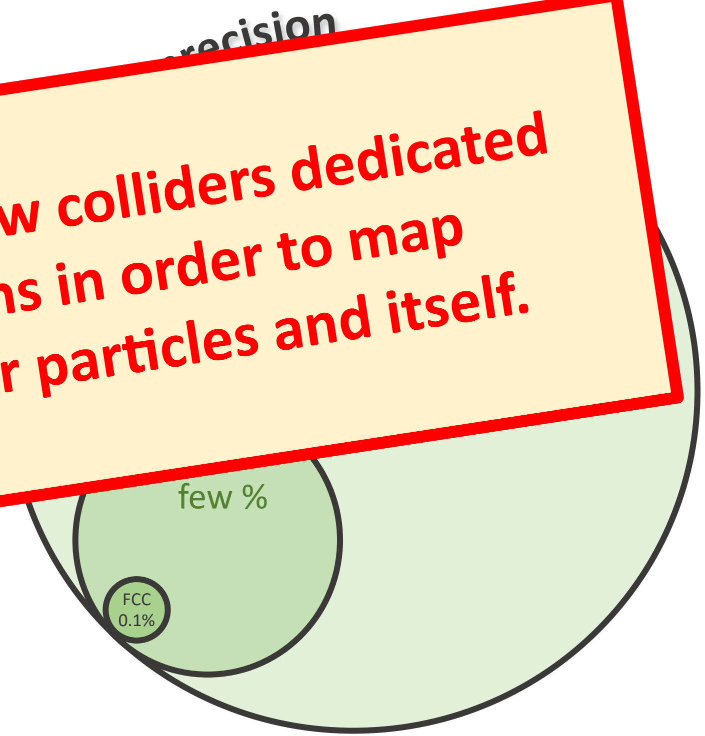

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particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

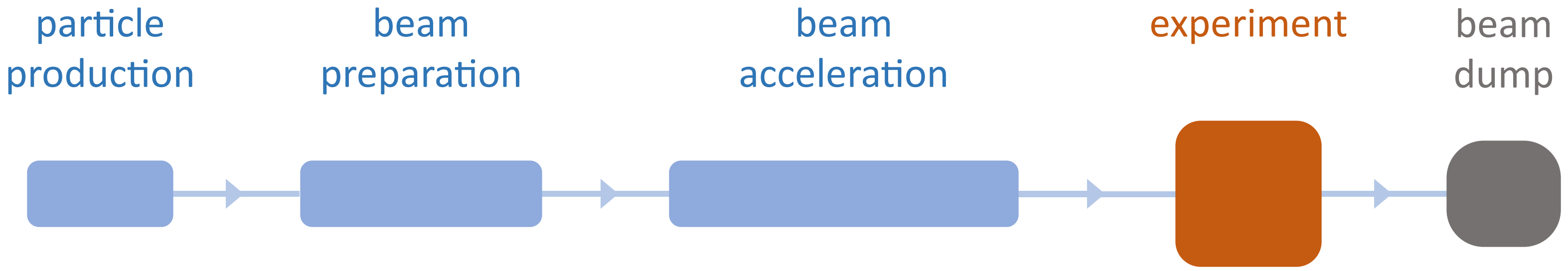
(energy x current = power)

caveat

power requirements of future colliders

focus on electron/positron accelerators

Basic structures of a particle accelerator



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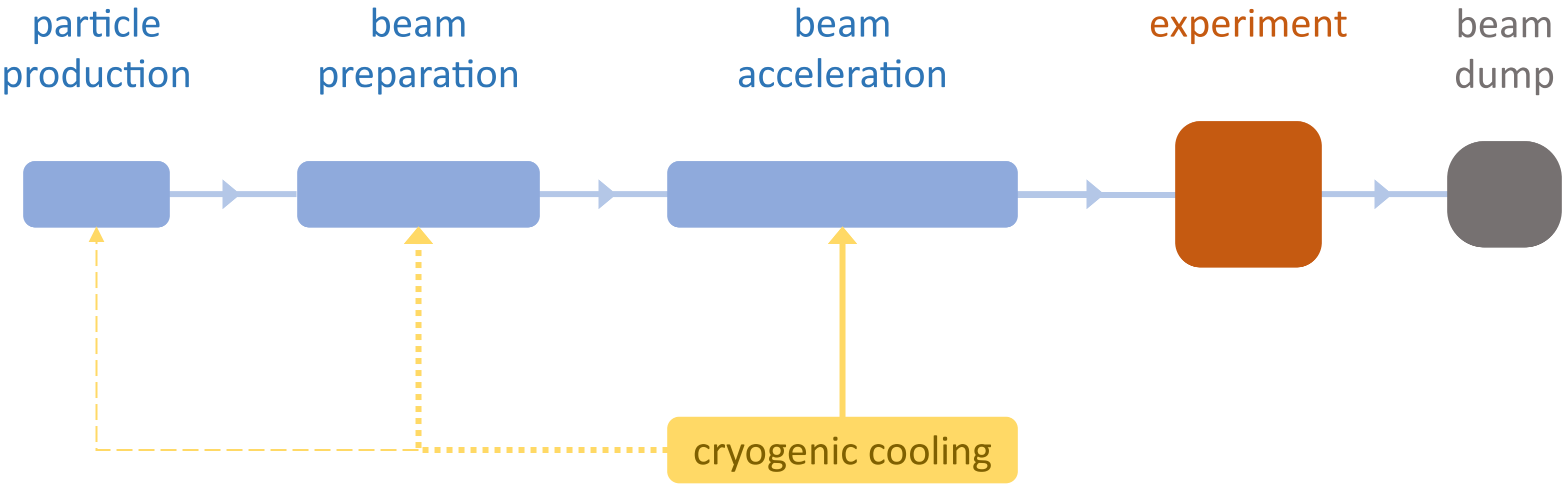

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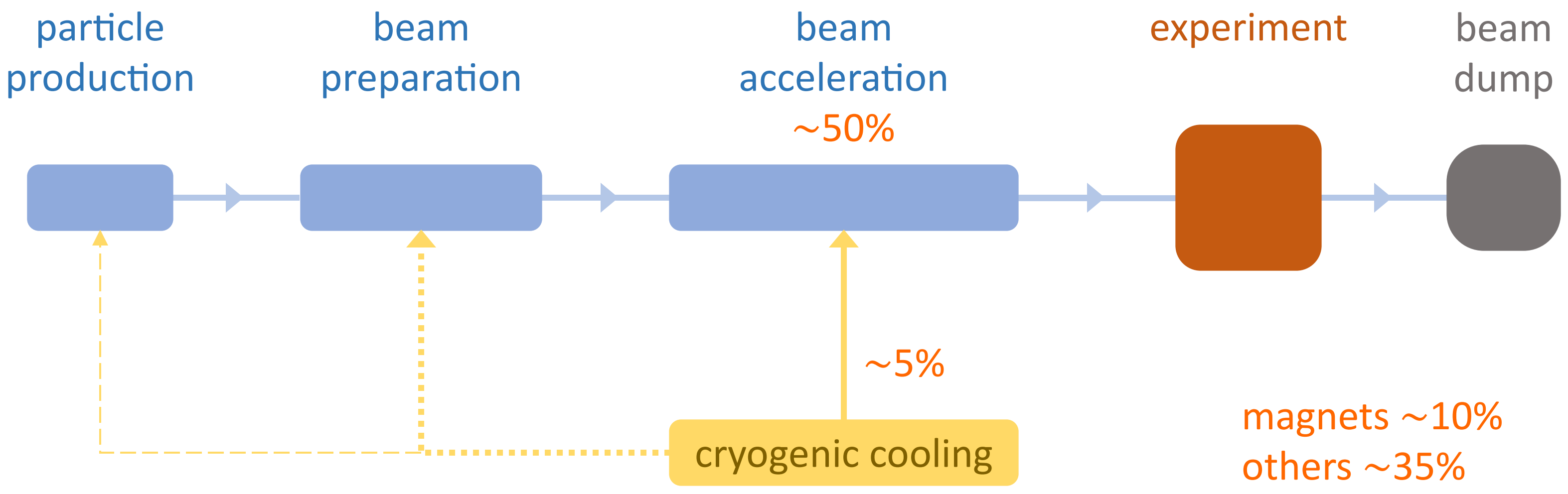


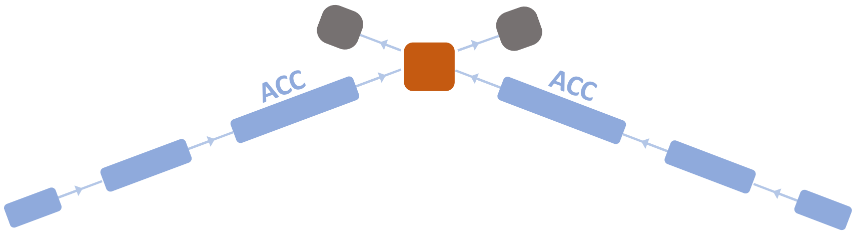
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

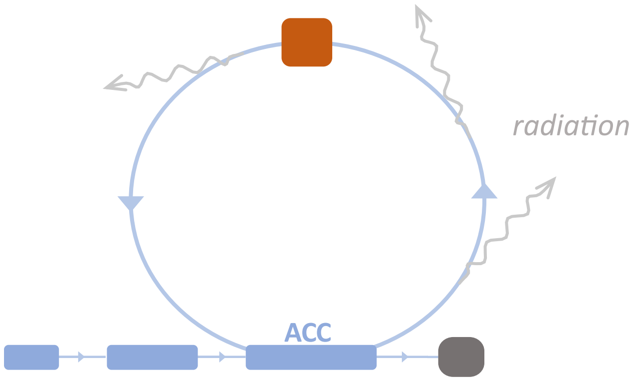
FCC CDR, Eur. Phys. J. Special Topics 228, 261–623 (2019)

Linear colliders



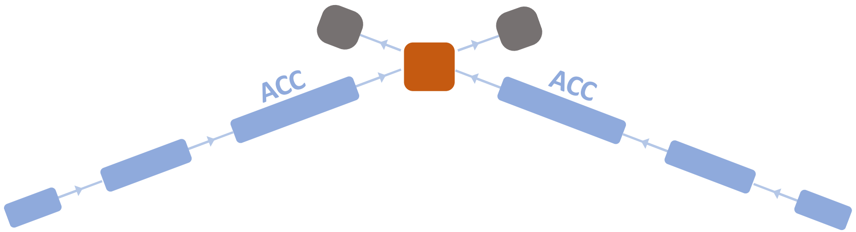
dump >99.9999% of
the beam power

Circular colliders



radiate away very quickly the beam power
& loose beam quality

Linear colliders



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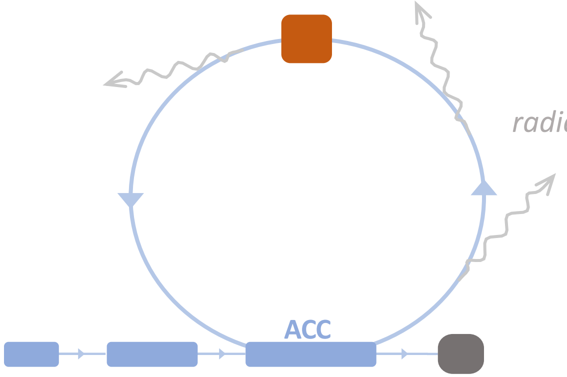
Circular colliders

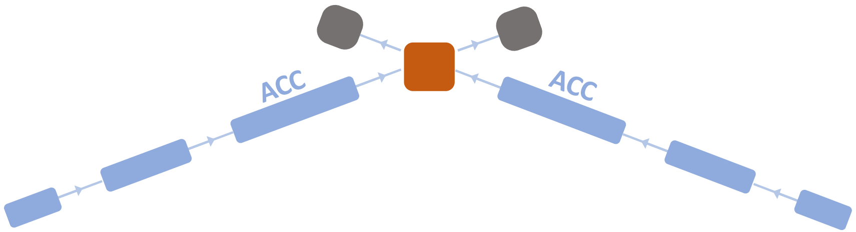


radiate away very quickly the beam power & loose beam quality

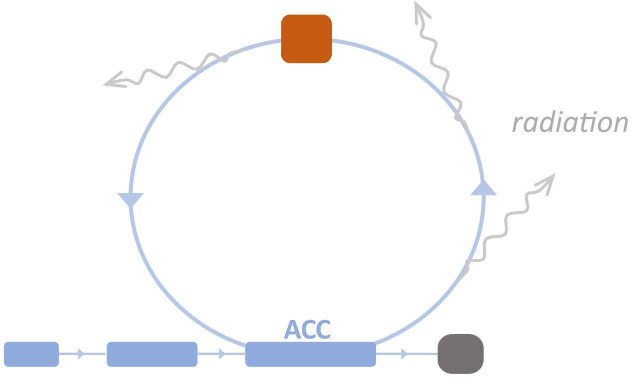
FCC-ee@250 ≃ 300 MW

~2% of annual electricity consumption in Belgium

Linear colliders



Circular colliders



dump >99.9999% of the beam power

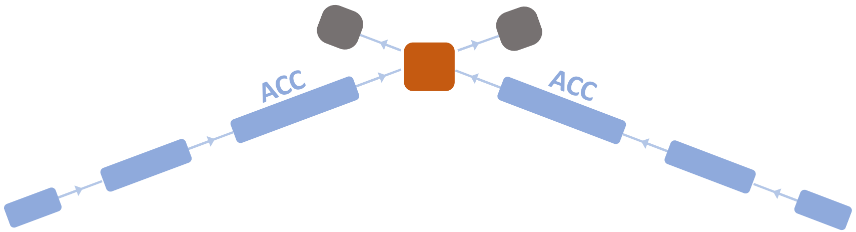
radiate away very quickly the beam power & loose beam quality

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

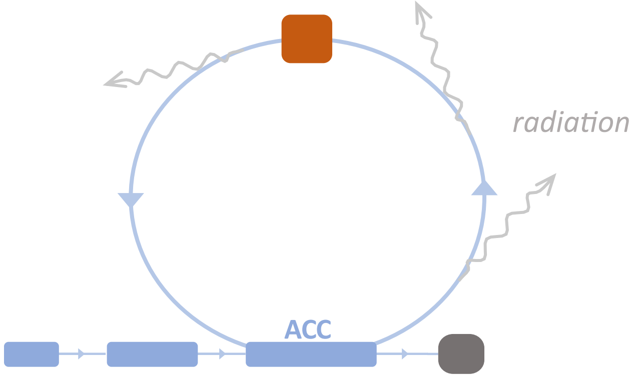
Energy consumption is reducing in Europe, not excluded with ½ by 2050-2060

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

about half of this is dumped or lost due to radiation

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

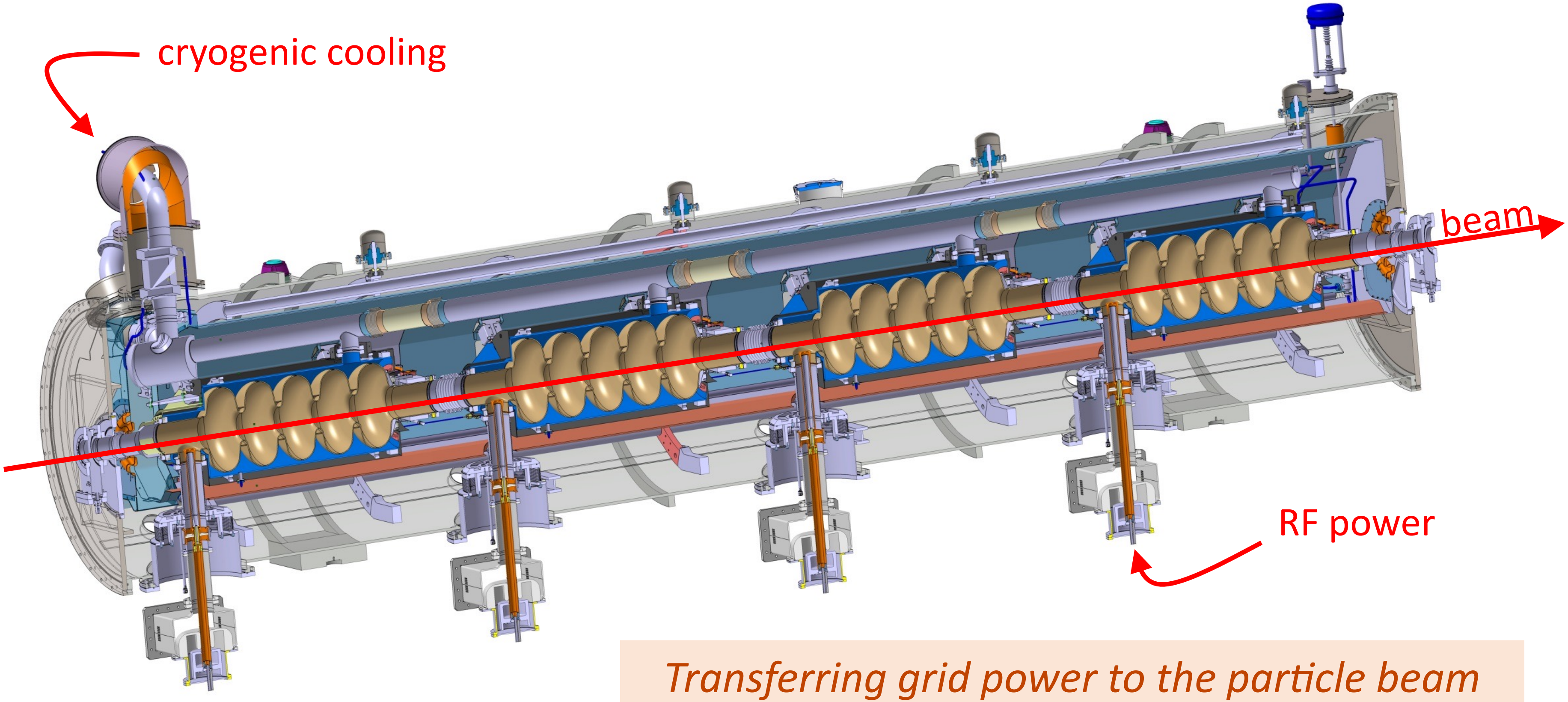
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

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

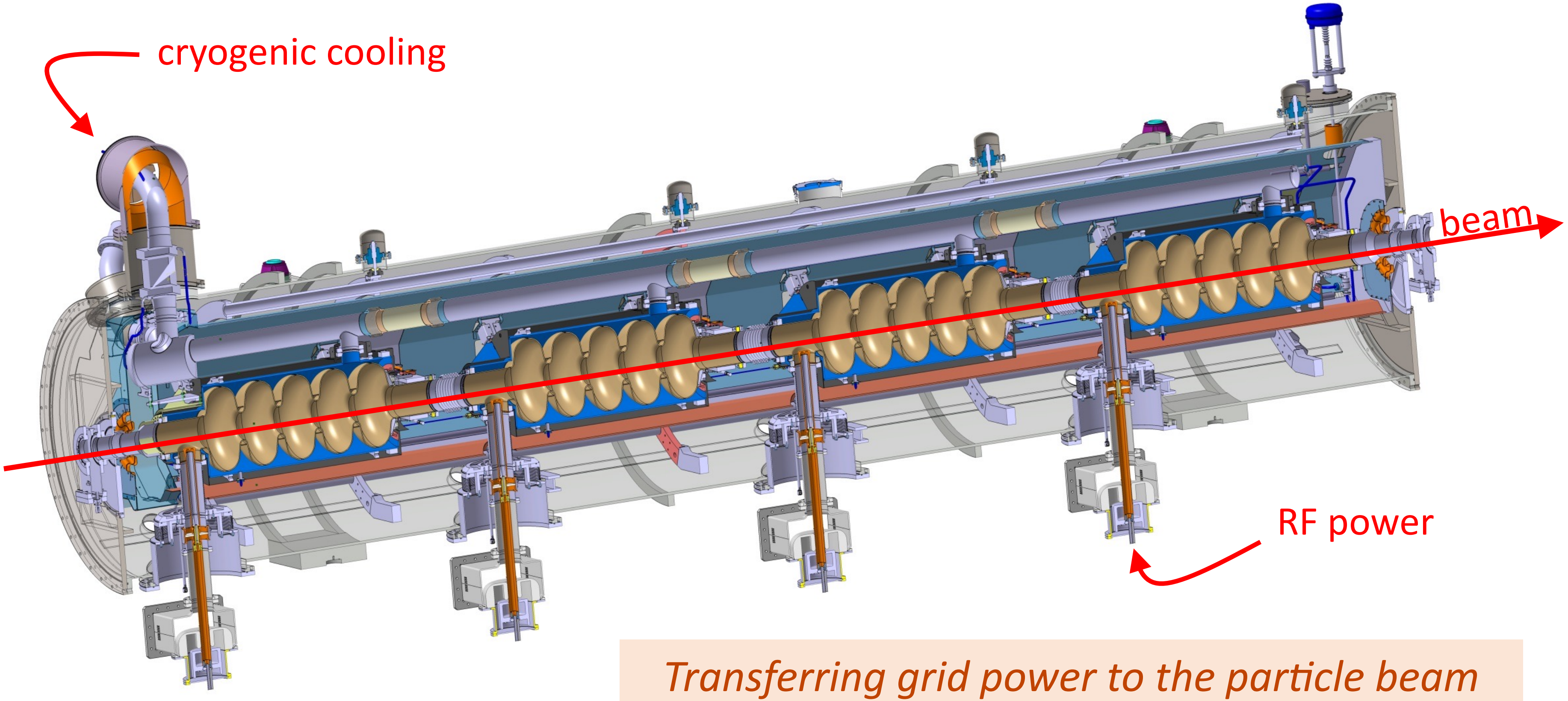
SRF: Superconducting Radio Frequency



Transferring grid power to the particle beam

Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

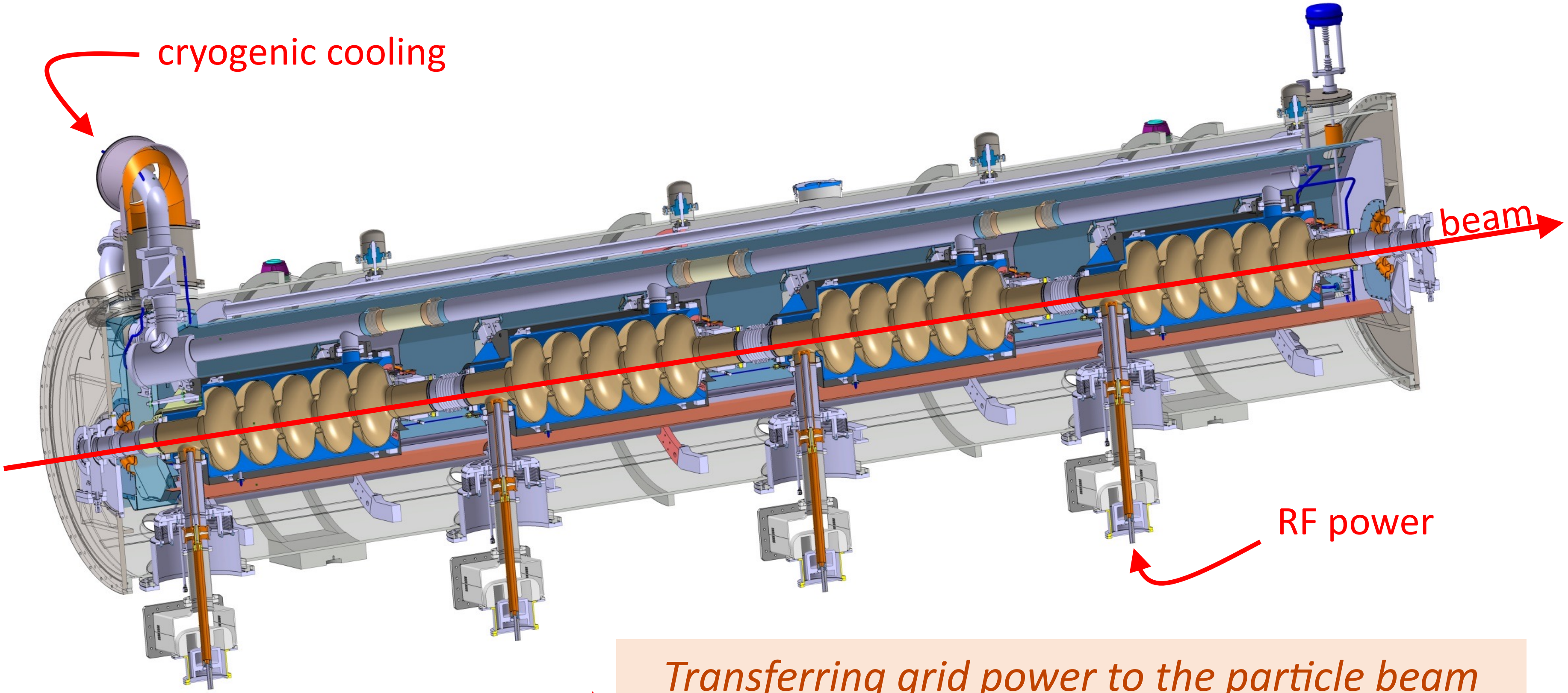


Transferring grid power to the particle beam

EVERY NEW BEAM REQUIRES NEW RF POWER

Key building block for beam acceleration: the SRF cryomodule

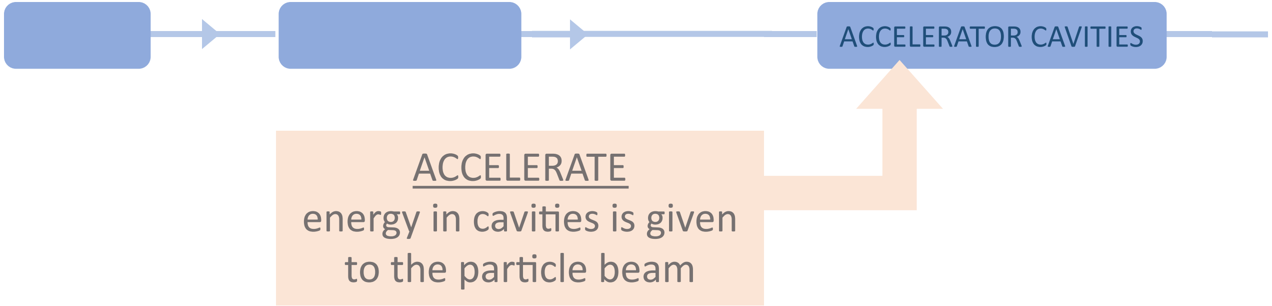
SRF: Superconducting Radio Frequency



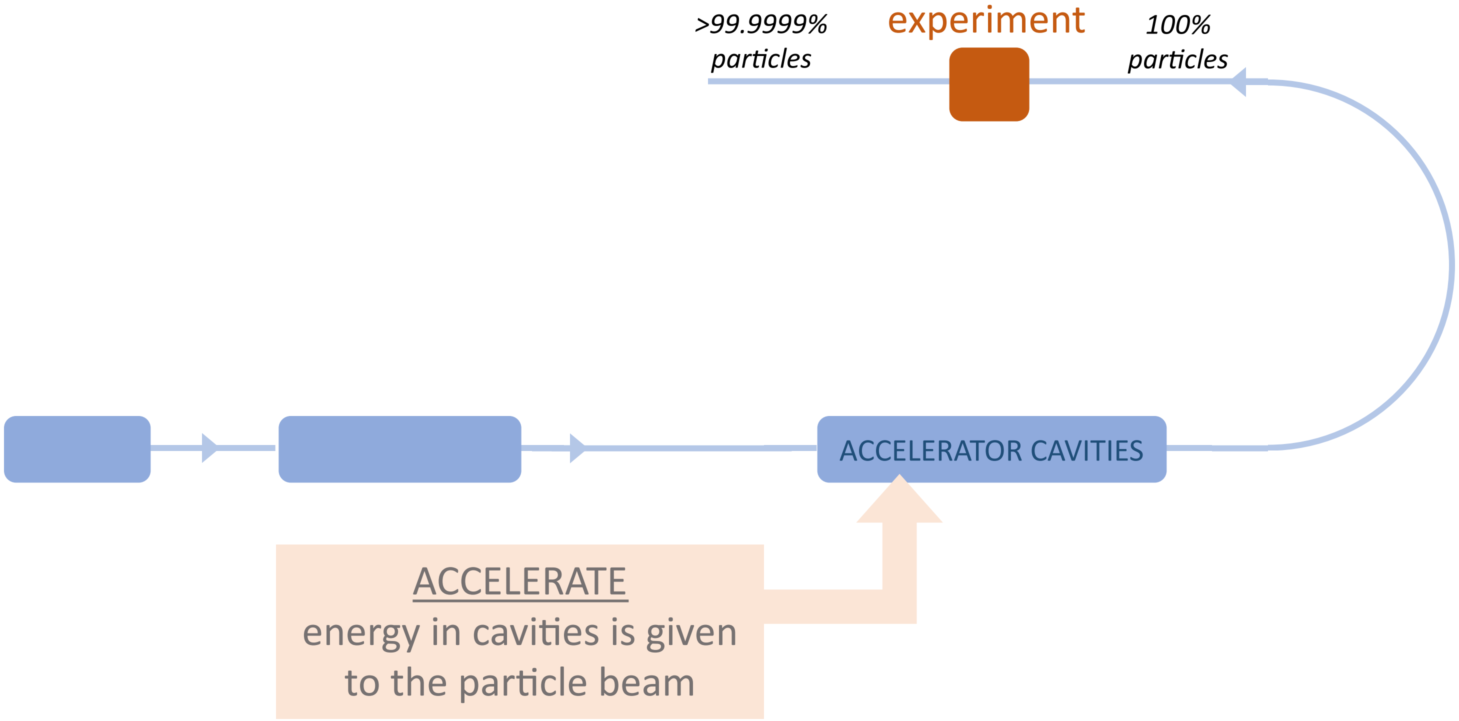
Transferring grid power to the particle beam

ENERGY RECOVERY → ***RECOVER THE ENERGY FROM THE USED BEAM***

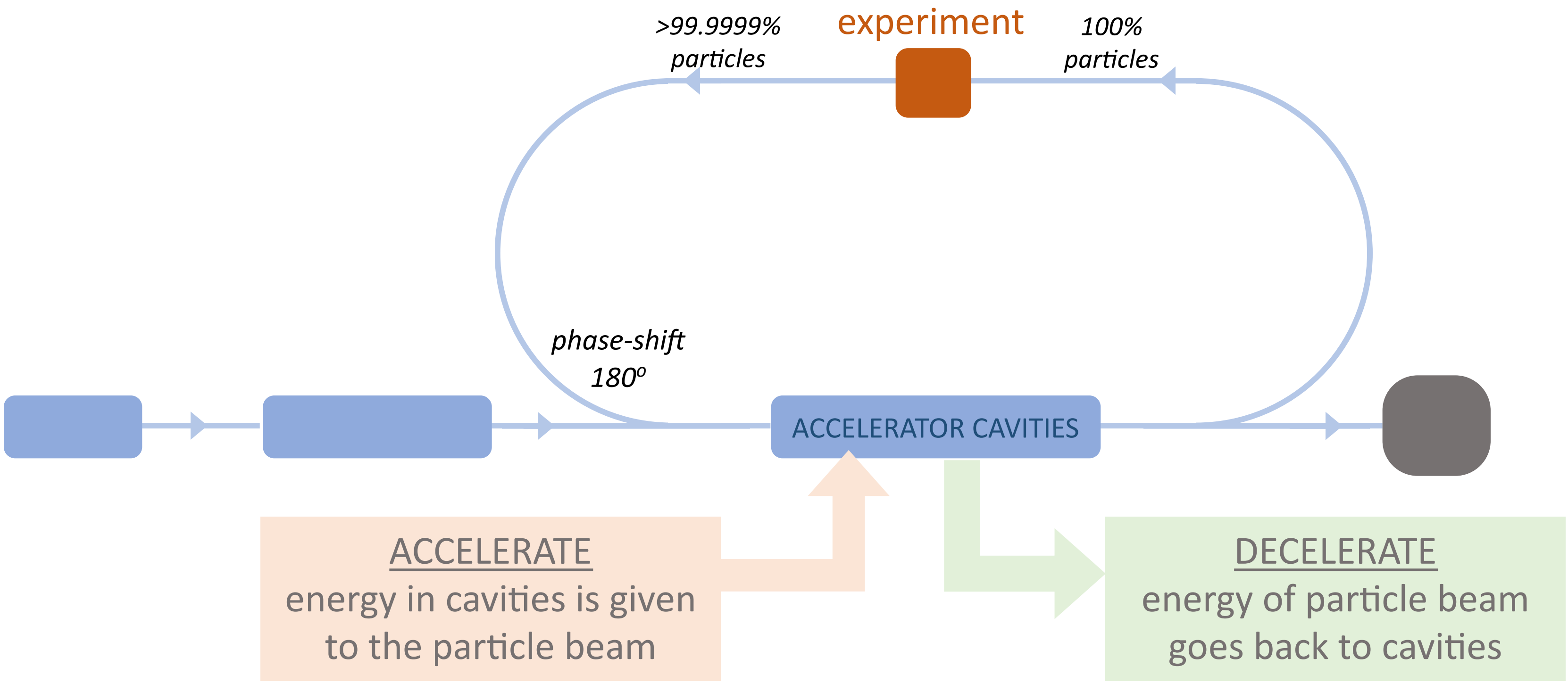
The principle of Energy Recovery



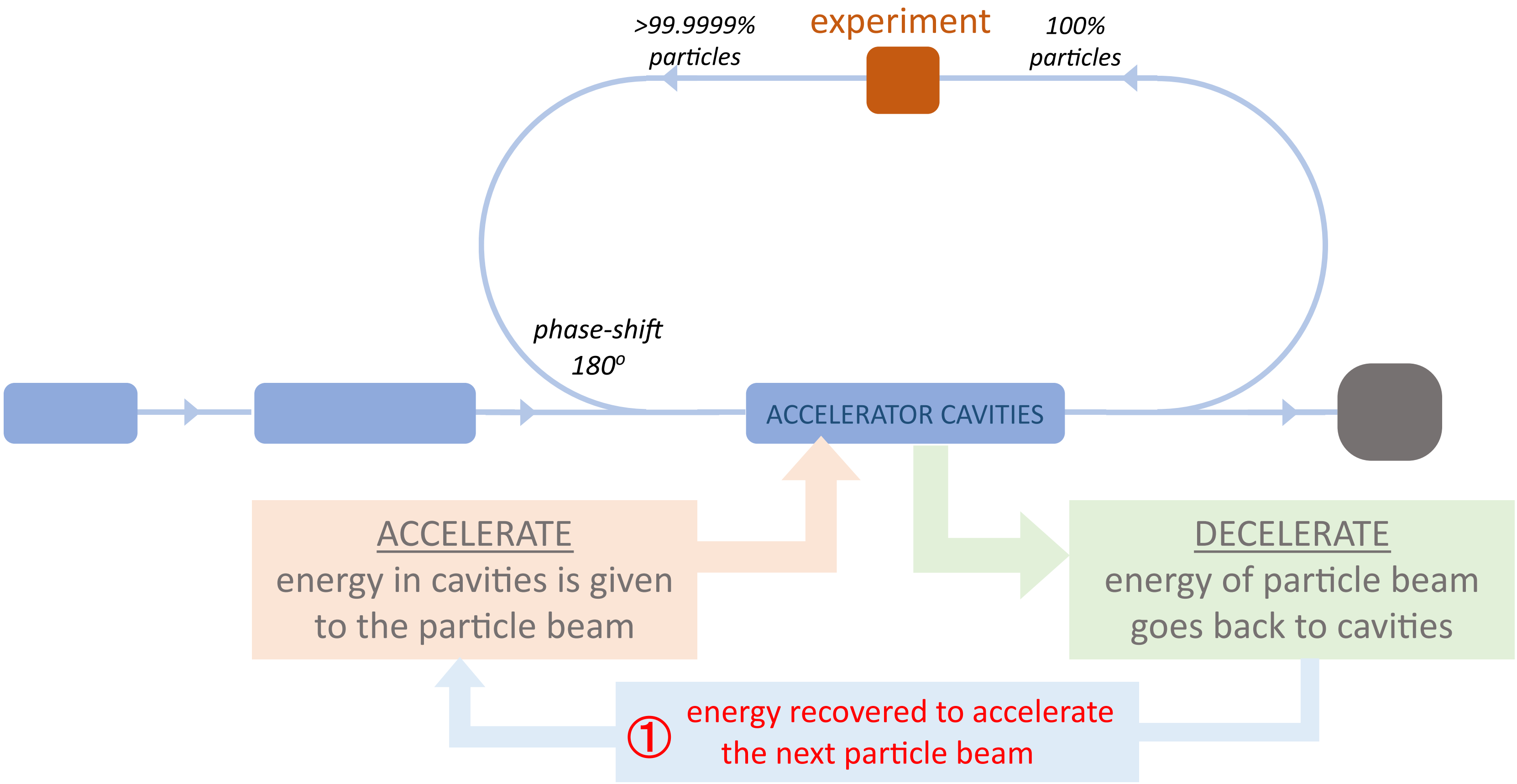
The principle of Energy Recovery



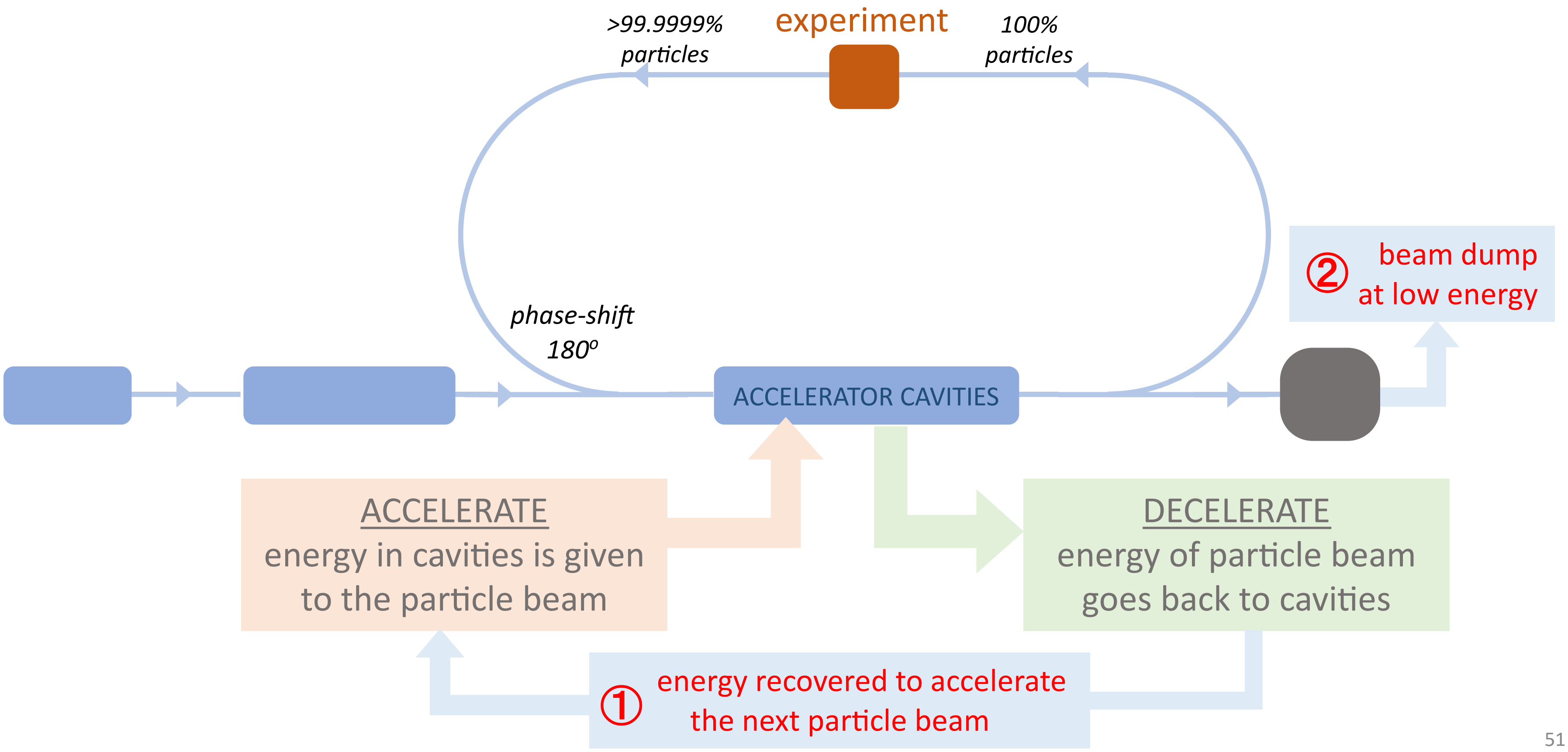
The principle of Energy Recovery



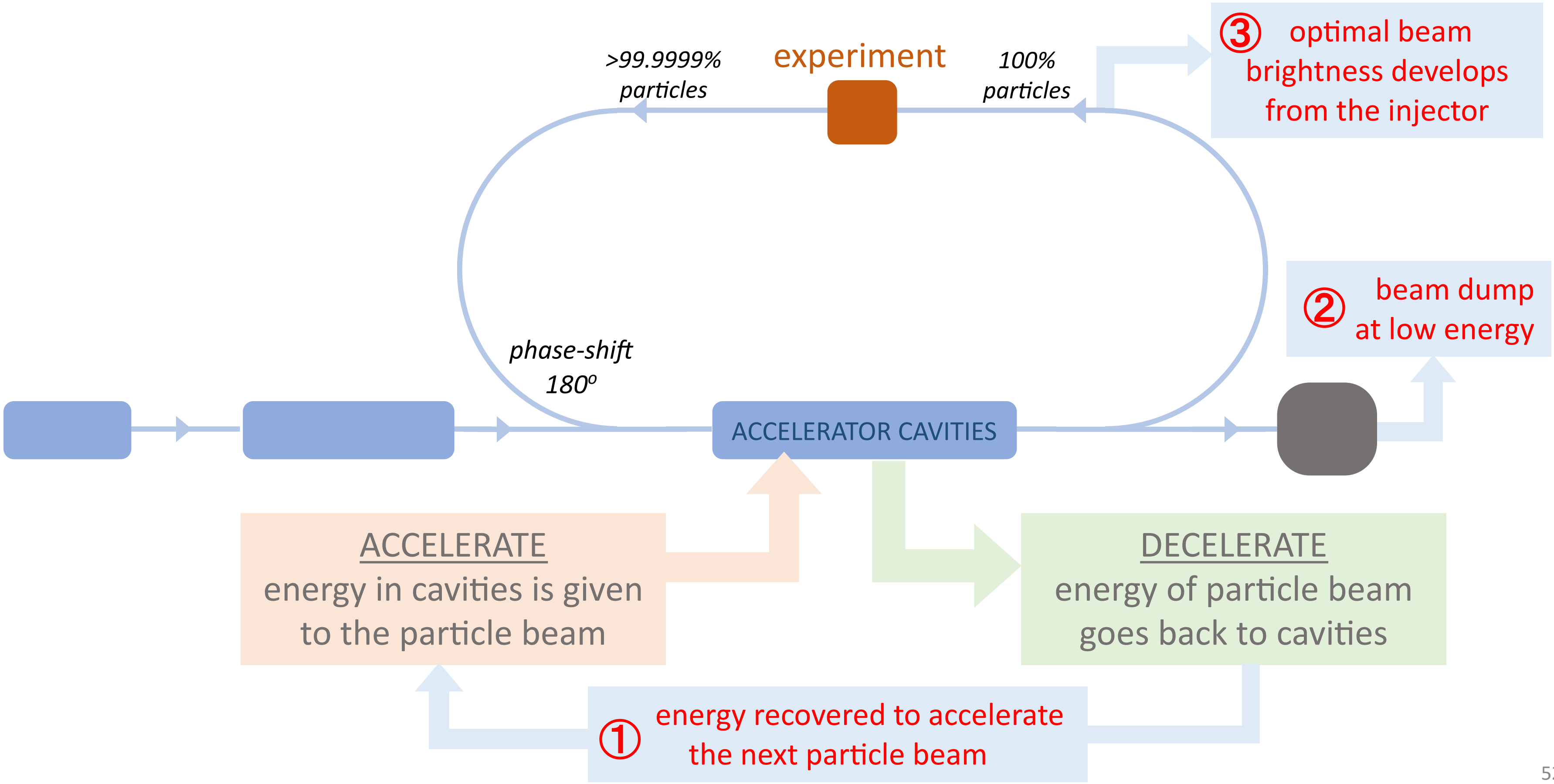
The principle of Energy Recovery



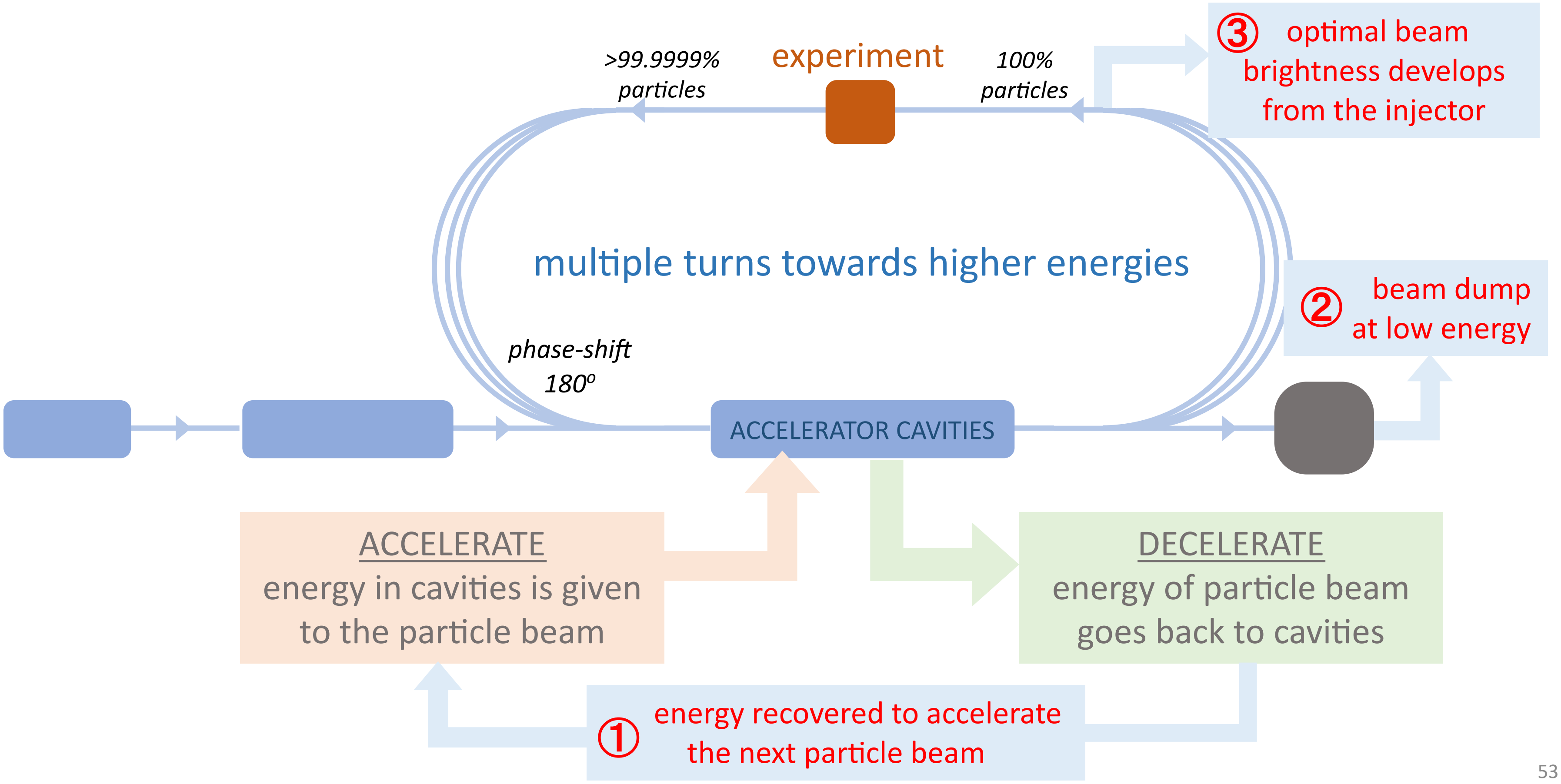
The principle of Energy Recovery



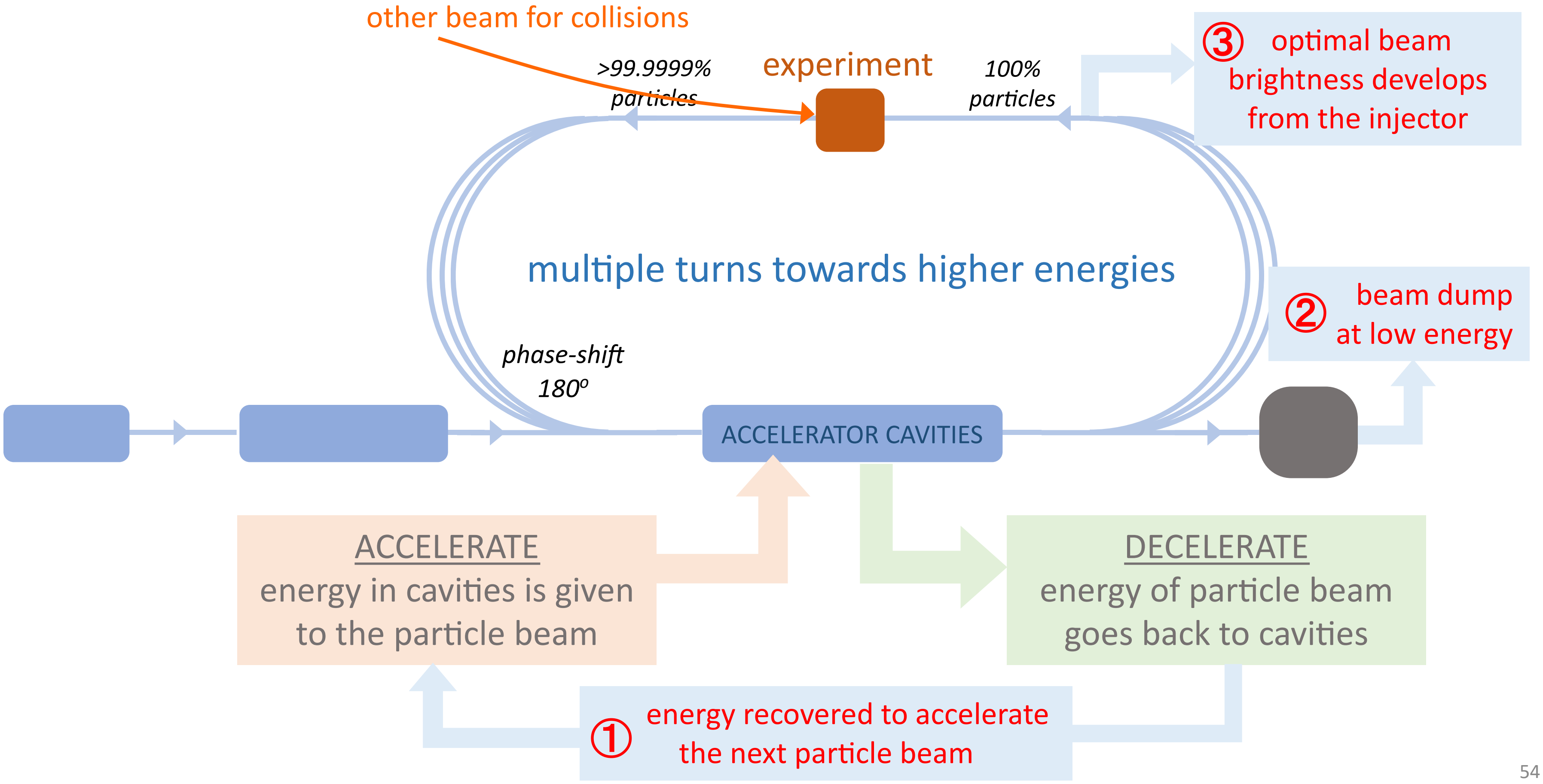
The principle of Energy Recovery



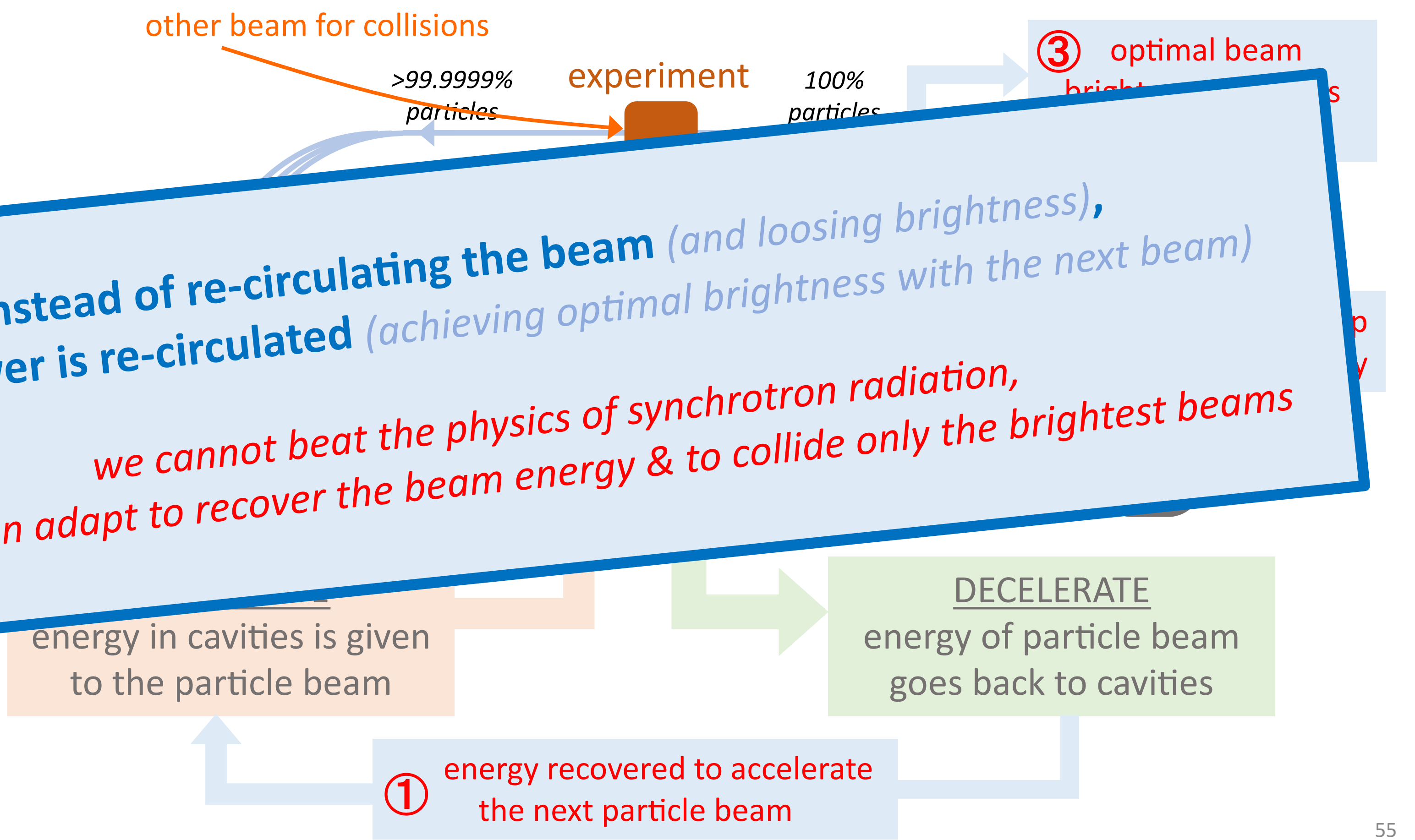
The principle of Energy Recovery



The principle of Energy Recovery



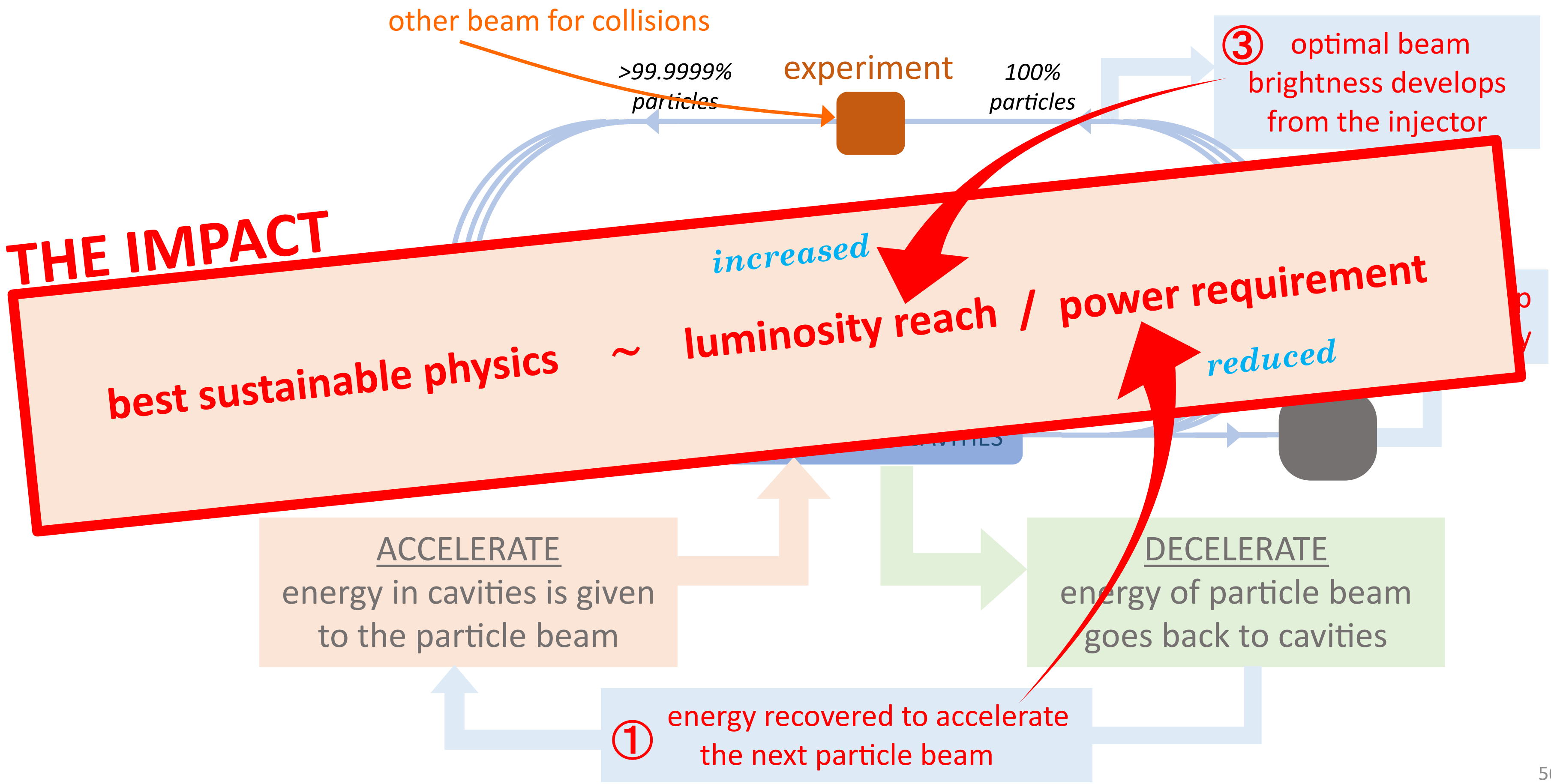
The principle of Energy Recovery



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

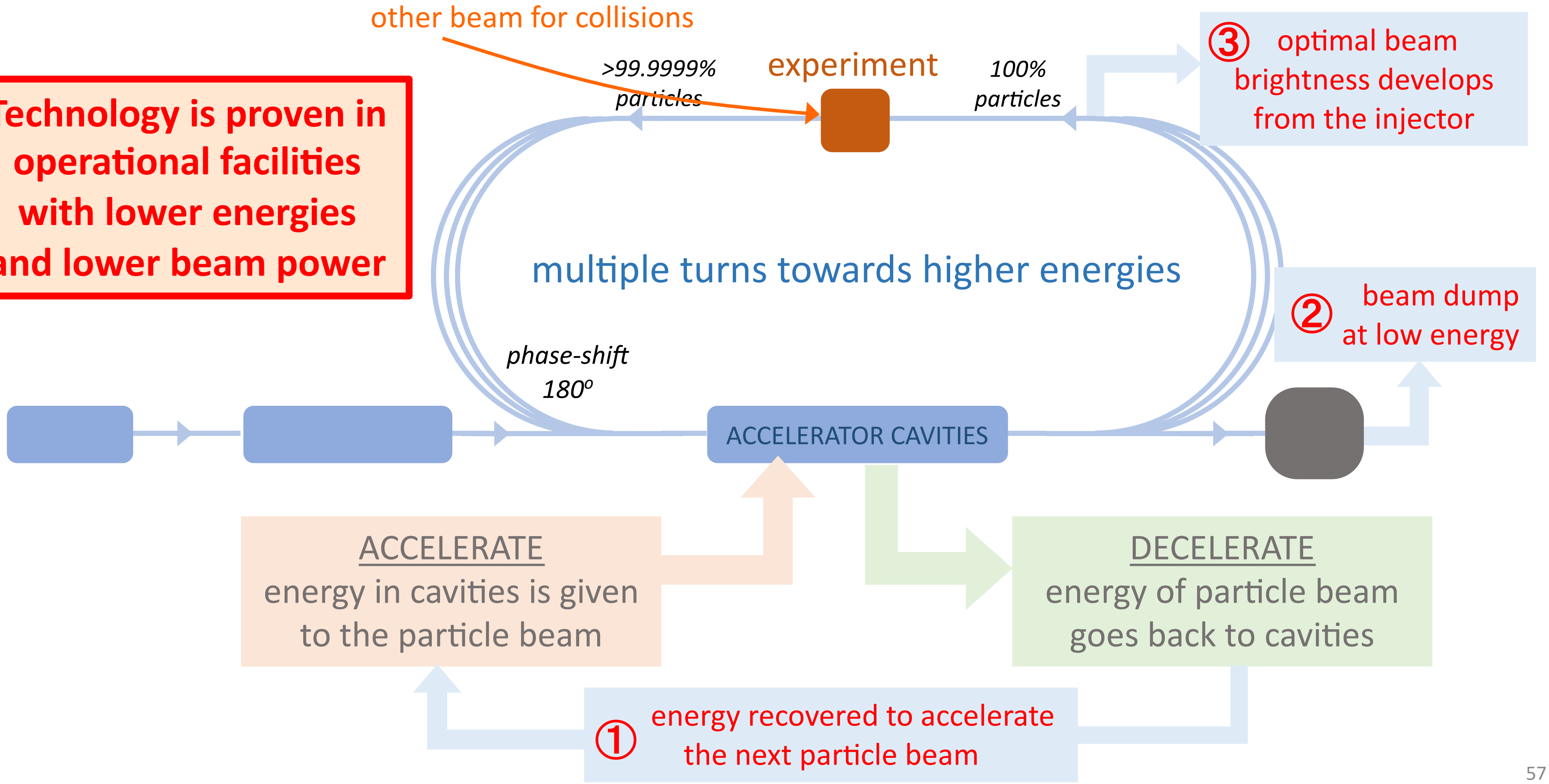
we cannot beat the physics of synchrotron radiation,
but we can adapt to recover the beam energy & to collide only the brightest beams

The principle of Energy Recovery



The principle of Energy Recovery

Technology is proven in operational facilities with lower energies and lower beam power



Ongoing & Upcoming facilities with ERL systems

worldwide several facilities are operational or are emerging

ongoing

s-DALINAC *TU Darmstadt. Germany*

two pass operation demonstrated

ongoing

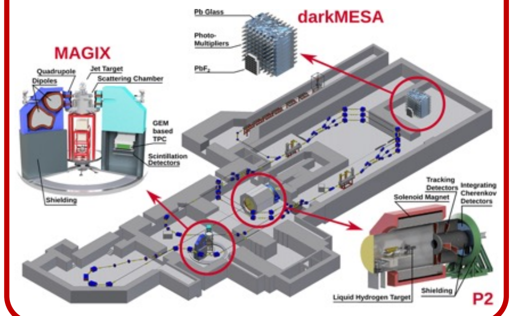
CBETA *Cornell University, USA*

highest number of passes achieved in SRF ERL

in progress

MESA *U Mainz, Germany*

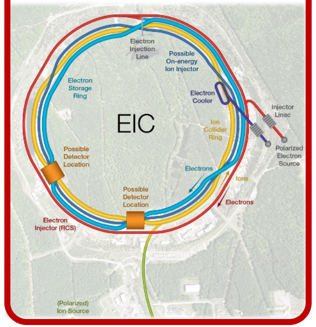
complete ERL facility for particle and nuclear physics



in progress

EIC Cooler *BNL, USA*

electron cooling with ERL



cERL *KEK, Japan*

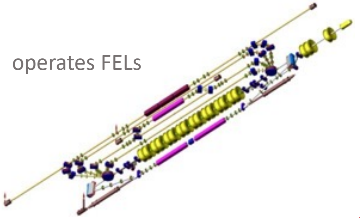
highest gun voltage (500 keV)

ongoing

Recuperator *BINP, Russia*

highest current (10 mA)

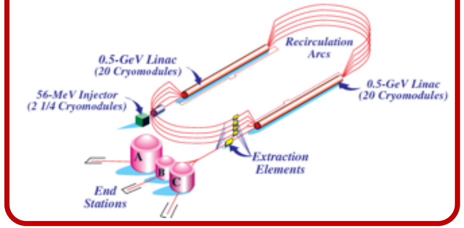
operates FELs



ongoing

CEBAF 5-pass *JLab, USA*

highest energy & highest number of passes

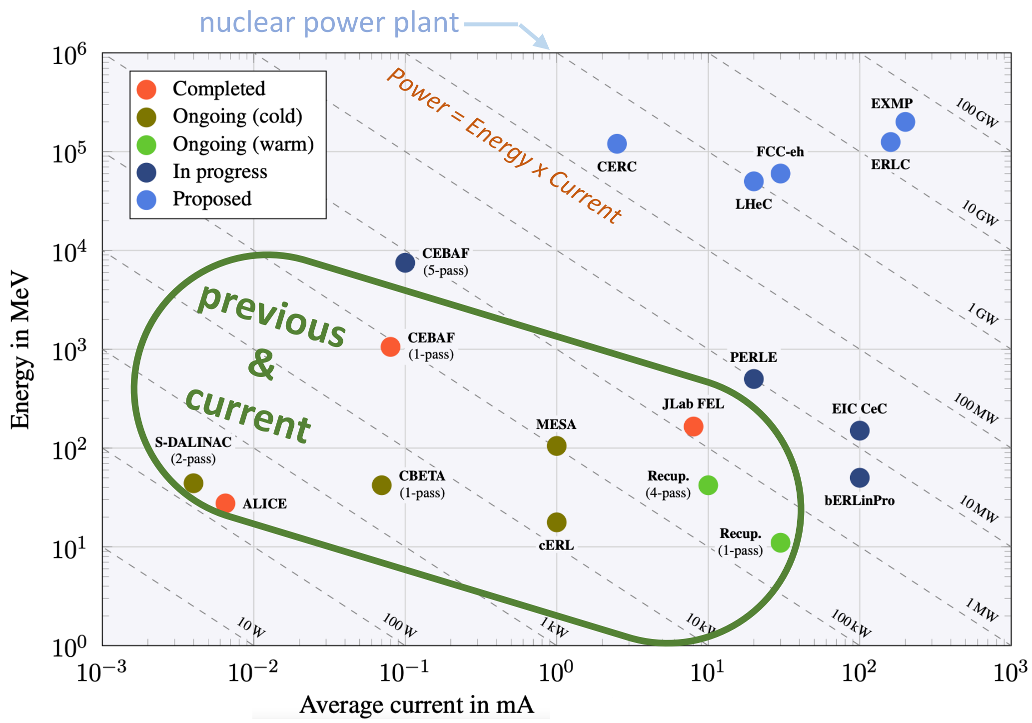


in progress

Upcoming: bERLinPro & PERLE

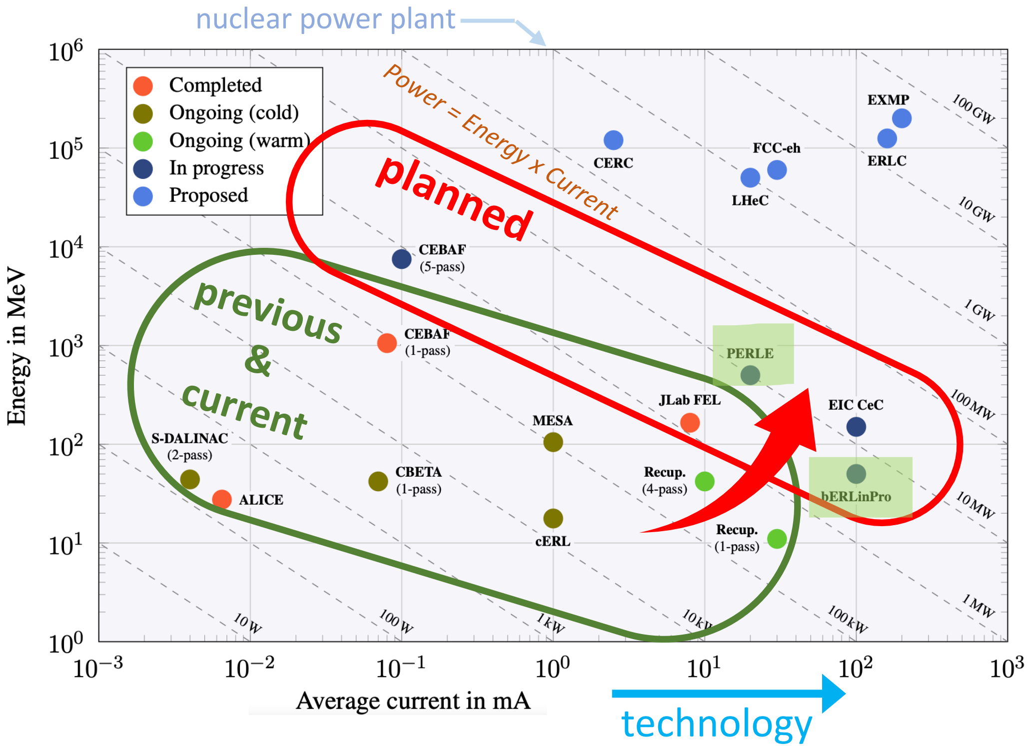
More facilities in design

- **DIANA (STFC, UK)**
- **DICE (Darmstadt, Germany)**
- **BriXSino (Milano, Italy)**



Energy Recovery demonstrated

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



bERLinPro & PERLE

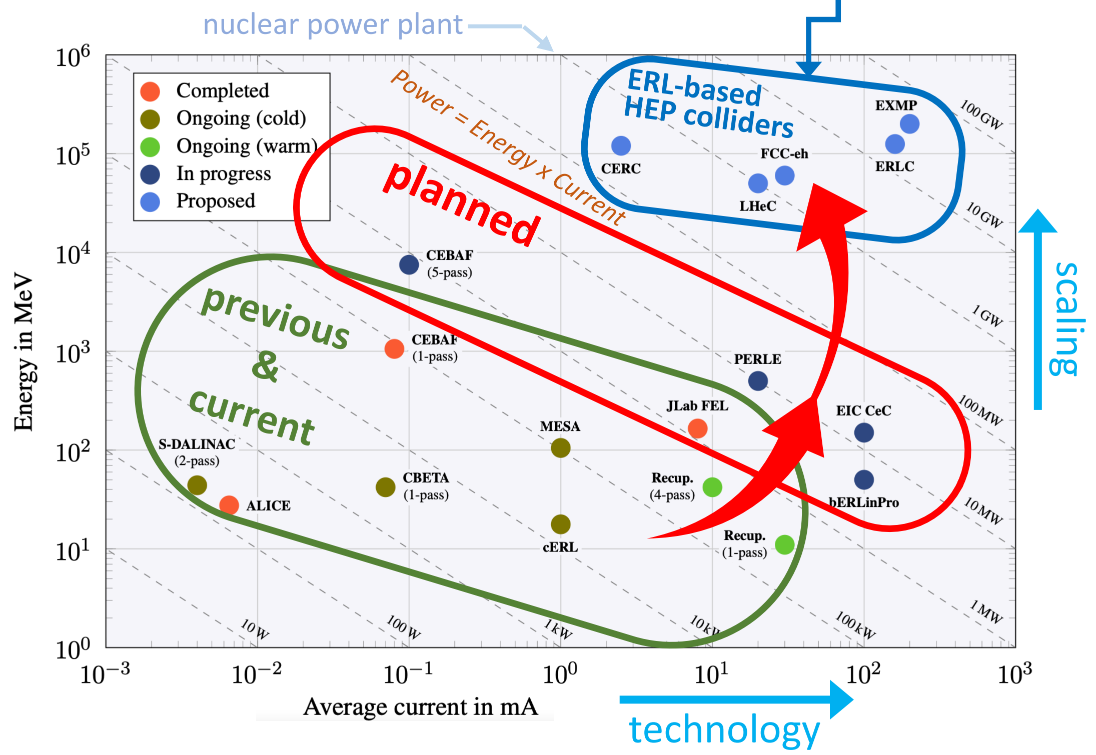
essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high power

Energy Recovery demonstrated

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

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

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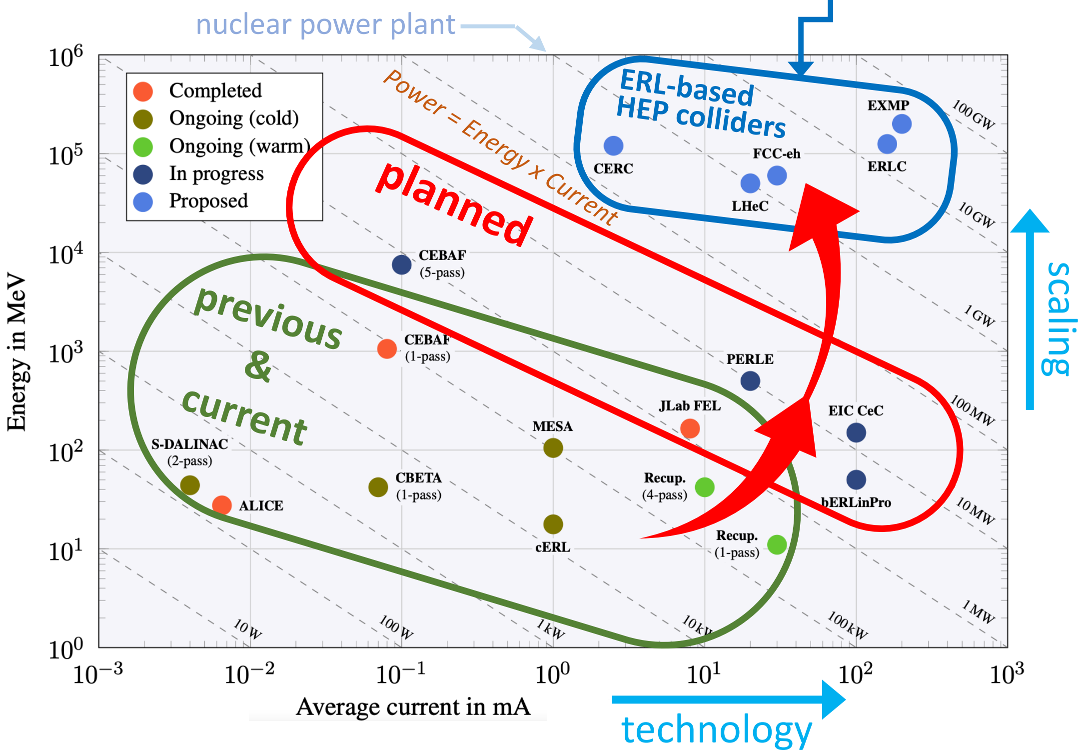


Future ERL-based Colliders

H, HH, ep/eA, muons, …

R&D Roadmap

bERLinPro & PERLE

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

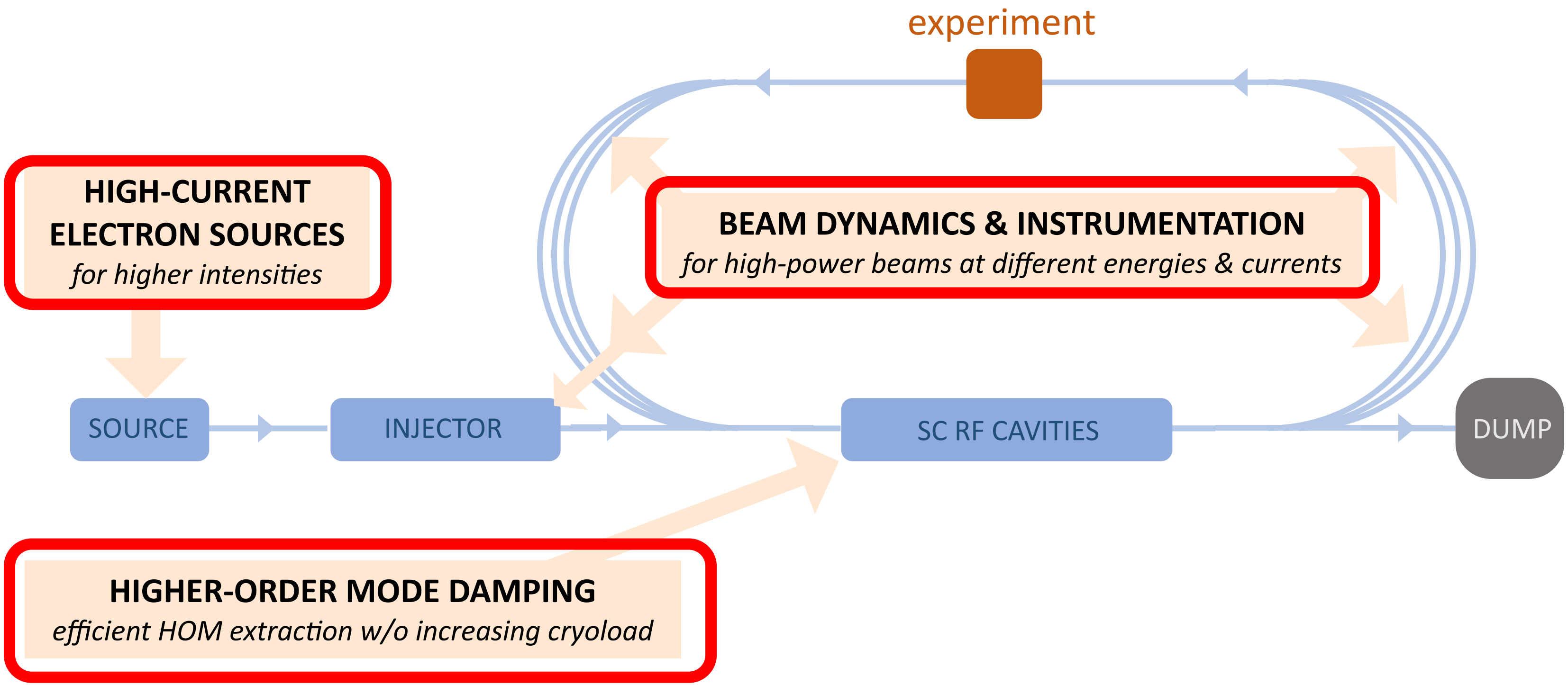
towards high power

Energy Recovery demonstrated

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

Energy Recovery Linacs (ERL): reaching higher luminosities with less power requirements

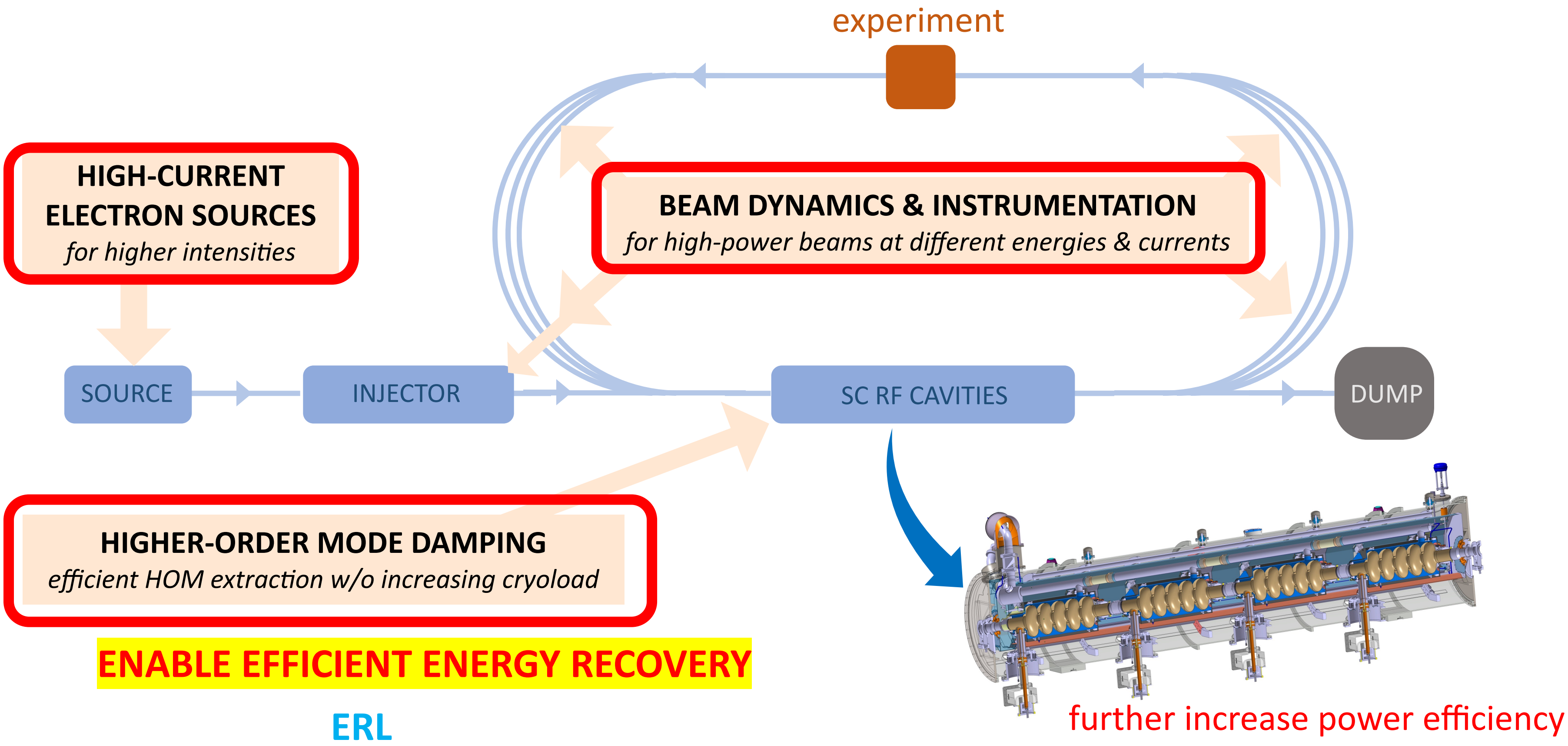
Sustainable Accelerating Systems



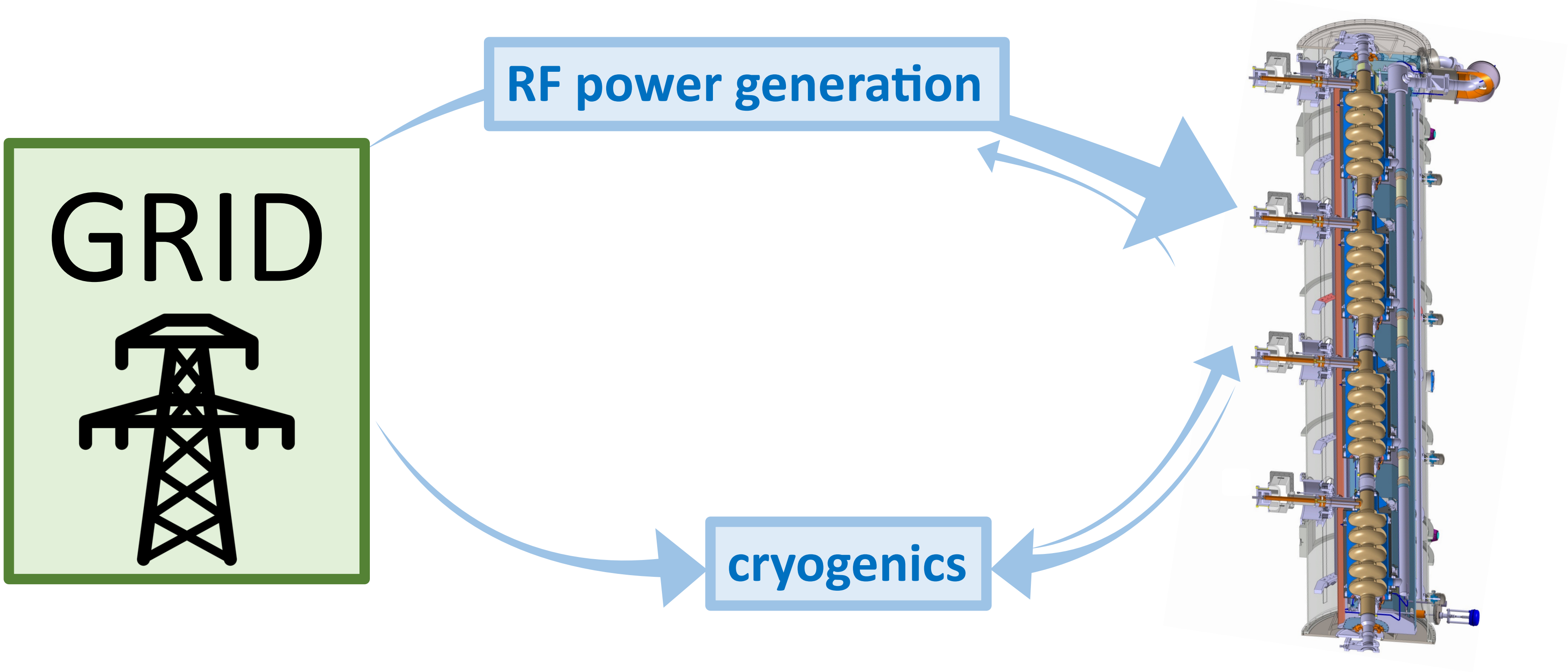
ENABLE EFFICIENT ENERGY RECOVERY

ERL

Sustainable Accelerating Systems

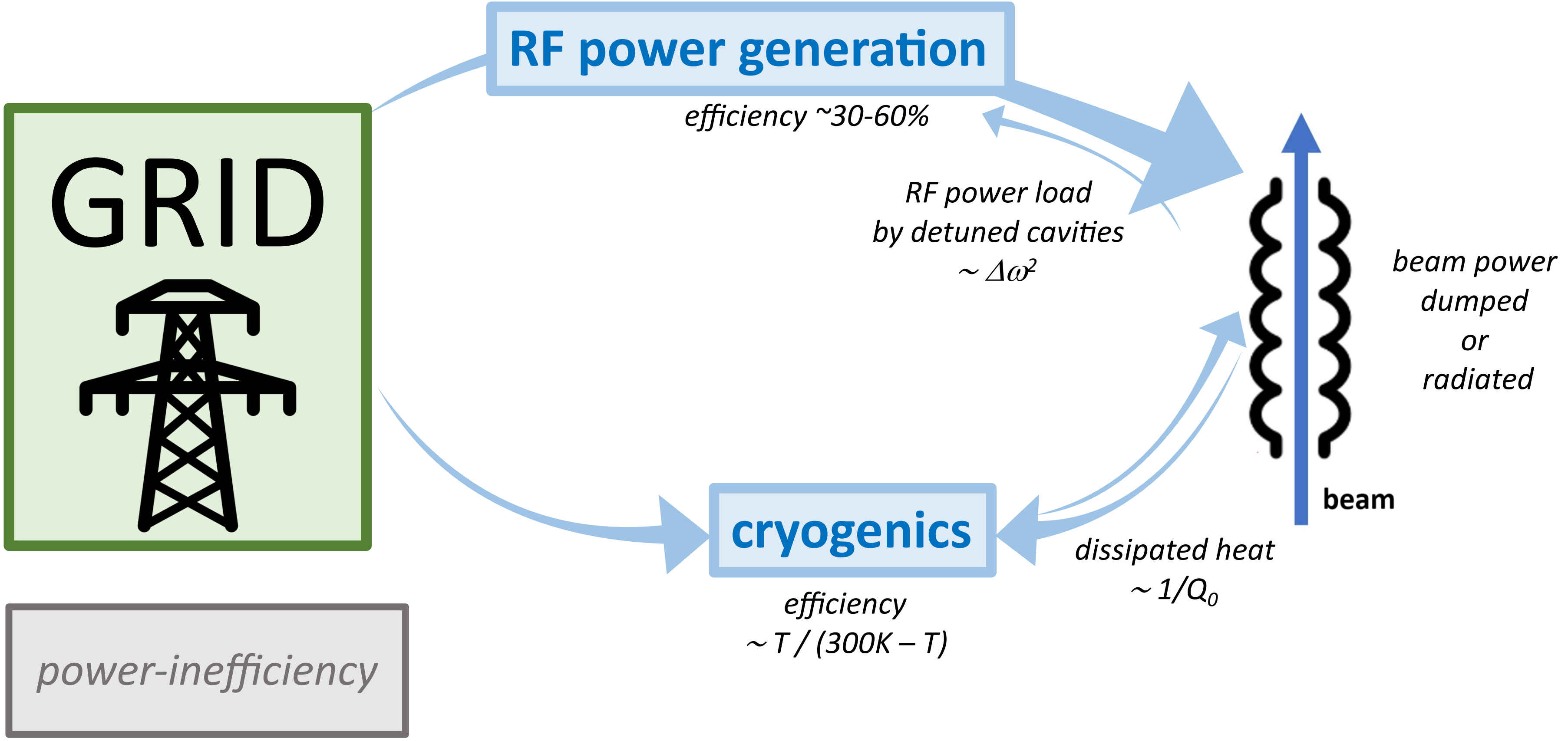


From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam

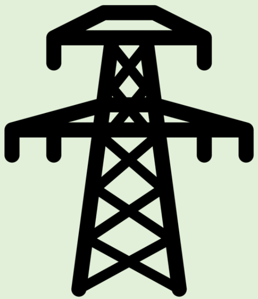


From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

GRID

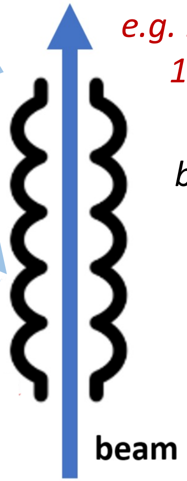


RF power generation

efficiency ~30-60%

recover the energy from the beam

e.g. ERL reaching 100% recovery



beam power dumped or radiated

RF power load by detuned cavities $\sim \Delta\omega^2$

dealing with microphonics

e.g. Fast Reactive Tuners

cryogenics

efficiency $\sim T\,/\,(300K - T)$

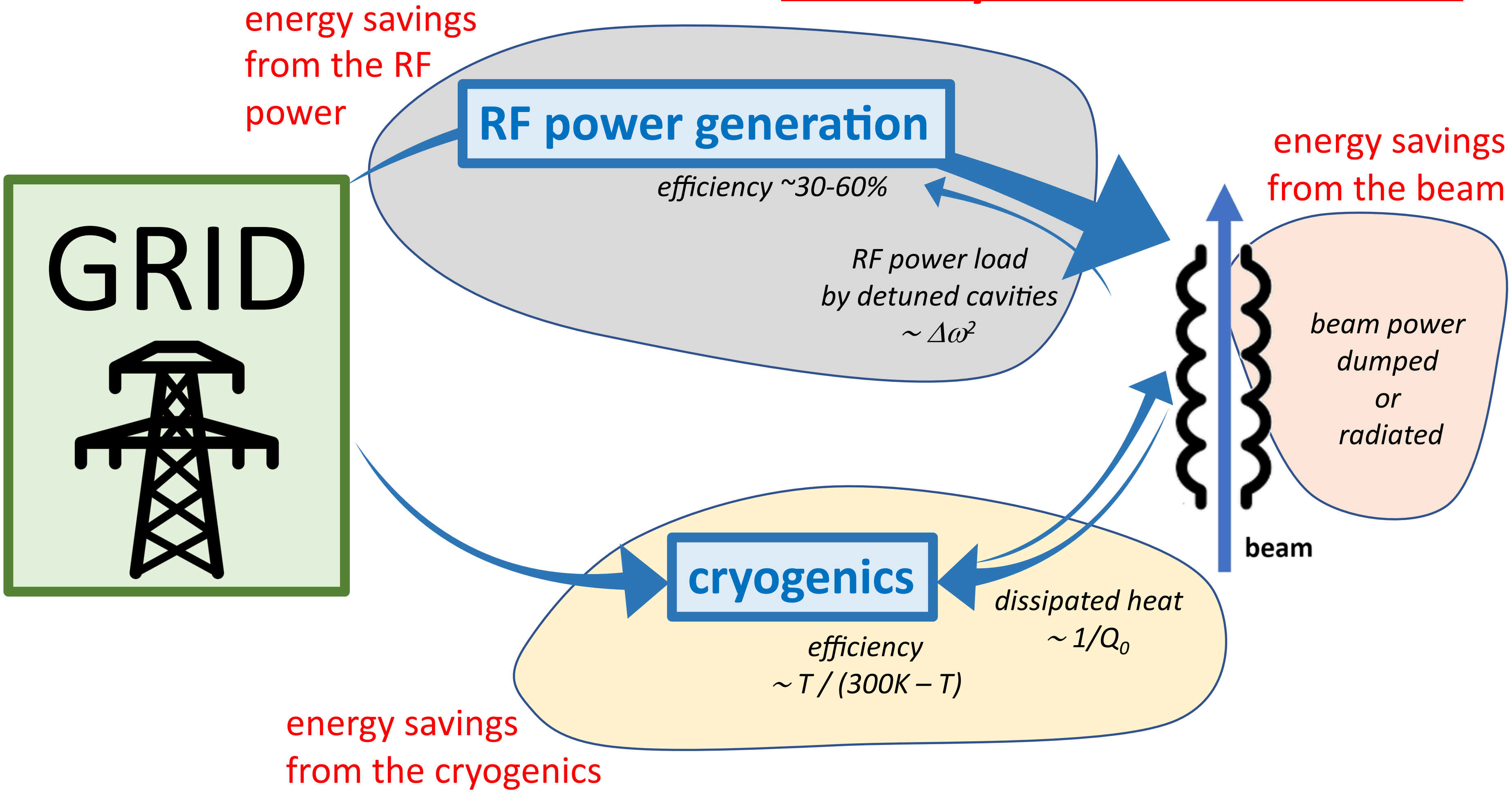
dissipated heat $\sim 1/Q_0$

mitigation with novel technologies

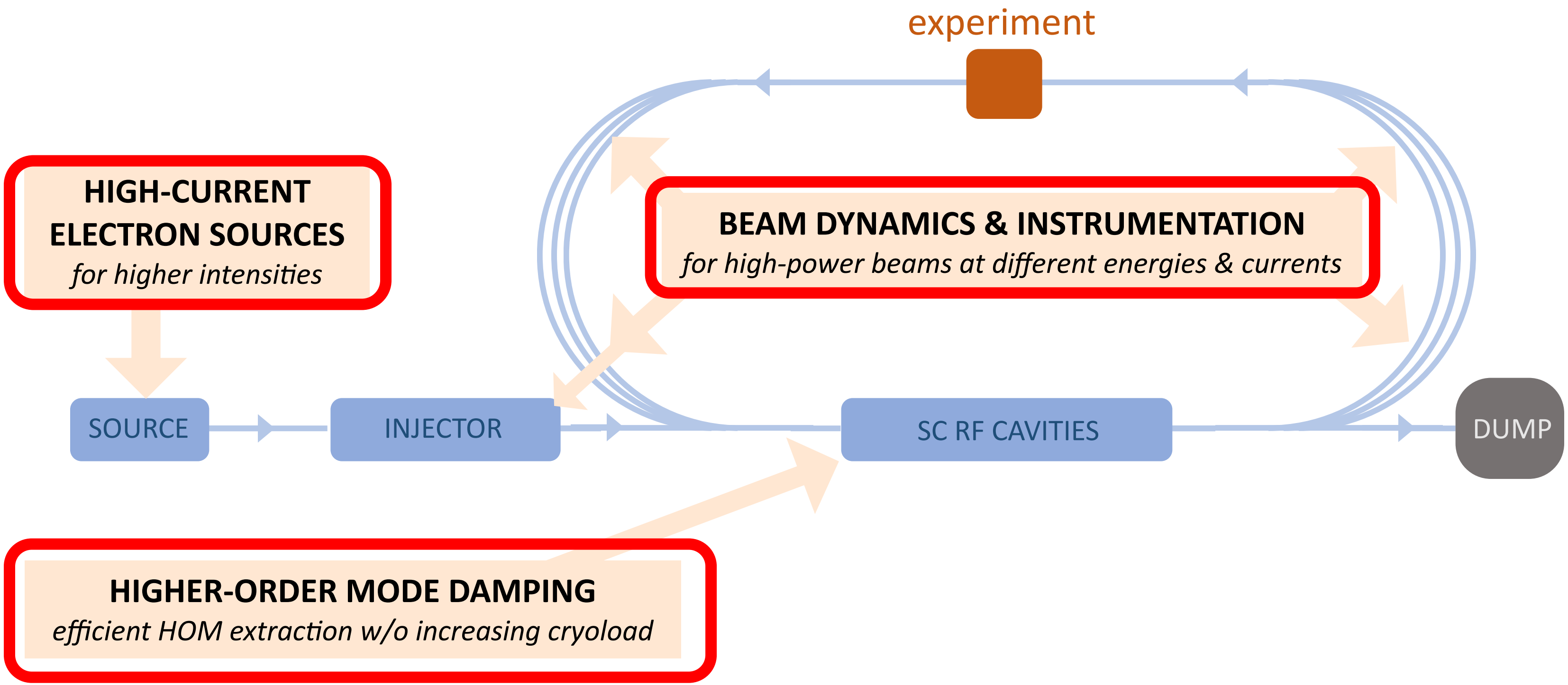
operate cavities at higher T & improve Q_0 of cavities

e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

Three key innovation directions



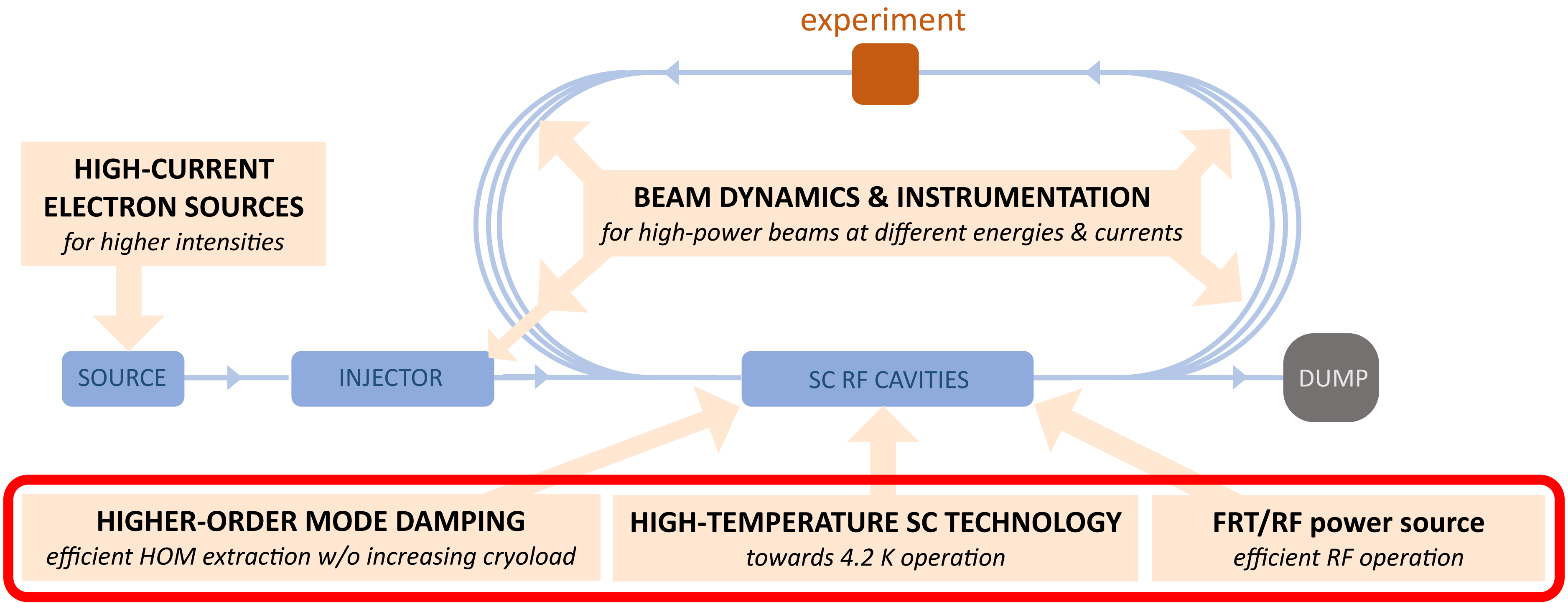
Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY

ERL

Sustainable Accelerating Systems



ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

ERL **RF**

Sustainable Accelerating Syste[...]

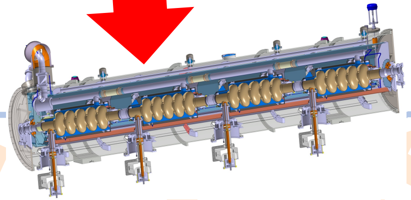
Innovate for Sustainable Accelerating Systems (iSAS)

https://indico.ijclab.in2p3.fr/event/9521/

develop a new design of an SRF cryomodule

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

for high-power beam[...] different energies & currents

SOURCE → INJECTOR →  → DUMP

HIGHER-ORDER MODE DAMPING *efficient HOM extraction w/o increasing cryoload*	**HIGH-TEMPERATURE SC TECHNOLOGY** *towards 4.2 K operation*	**FRT/RF power source** *efficient RF operation*

ENABLE EFFICIENT ENERGY RECOVERY & FURTHER REDUCE POWER REQUIREMENTS

ERL **RF**

iSAS is now an approved Horizon Europe project

Grant Agreement has been signed in Nov 2023 – project starts on March 1, 2024

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

(of which 5M EUR was requested to Horizon Europe)

DESY.

INFN

UKRI UK Research and Innovation

HZB Helmholtz Zentrum Berlin

ess EUROPEAN SPALLATION SOURCE

Lancaster University

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

cea

VUB VRIJE UNIVERSITEIT BRUSSEL

cnrs

IJCLab Irène Joliot-Curie

CERN

+ 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)

Three key innovation directions

energy savings
from the RF

Innovate for Sustainable Accelerating Systems (iSAS)

https://indico.ijclab.in2p3.fr/event/9521/

ambition: significantly reduce the energy footprint of SRF accelerators

achieving an ALARA principle for power requirements of SRF accelerators

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

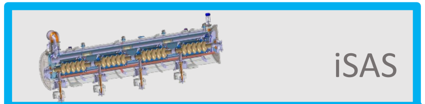
dissipated heat
$\sim 1/Q_0$

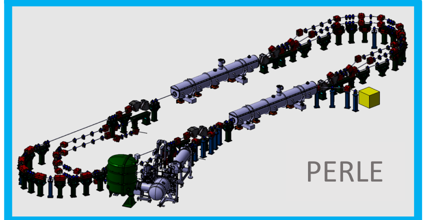
efficiency
$\sim T\,/\,(300K - T)$

energy savings
from the cryogenics

High-power ERL technology timeline

2020'ies





high-power ERL demonstrated

Upcoming facilities for Energy Recovery Linac R&D

bERLinPro @ Helmholtz Zentrum Berlin

generic accelerator R&D with several aspects as stepping stones towards HEP applications

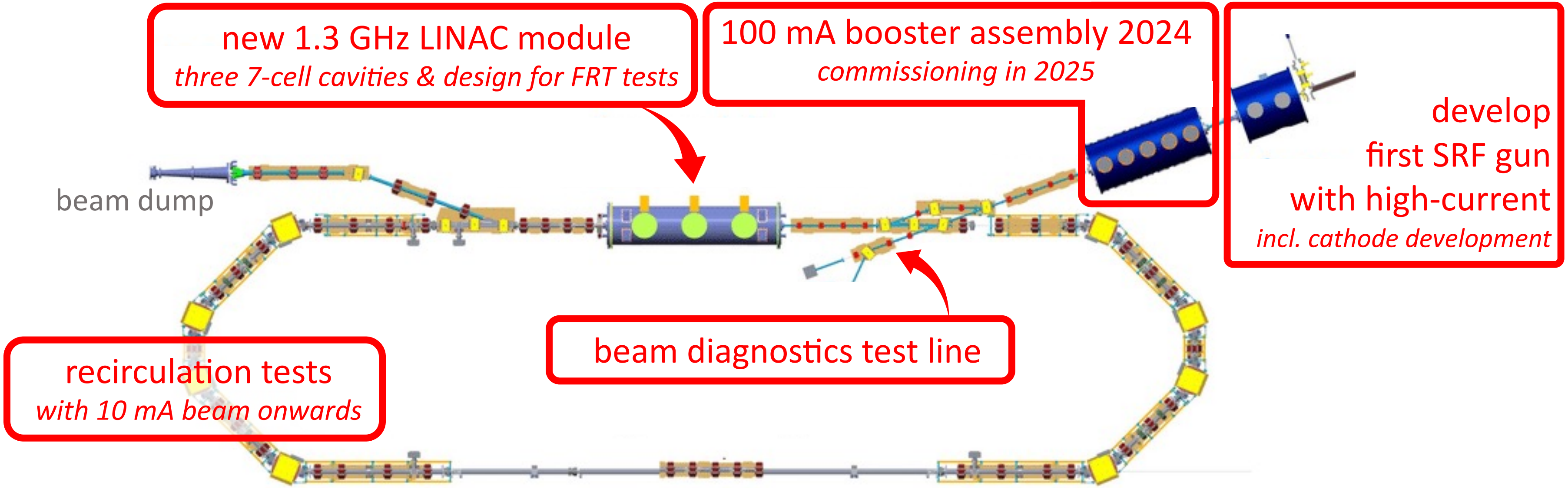
BERLinPro: Main Project Parameters	
Total beam energy, MeV	50
Maximum average current, mA	100
Bunch charge, pC	77
Bunch repetition rate, GHz	1.3
Emittance (normalized), π mm mrad	≤ 1.0
Bunch length (rms), ps	2.0 or smaller
Maximum Losses (relative)	$< 10^{-5}$

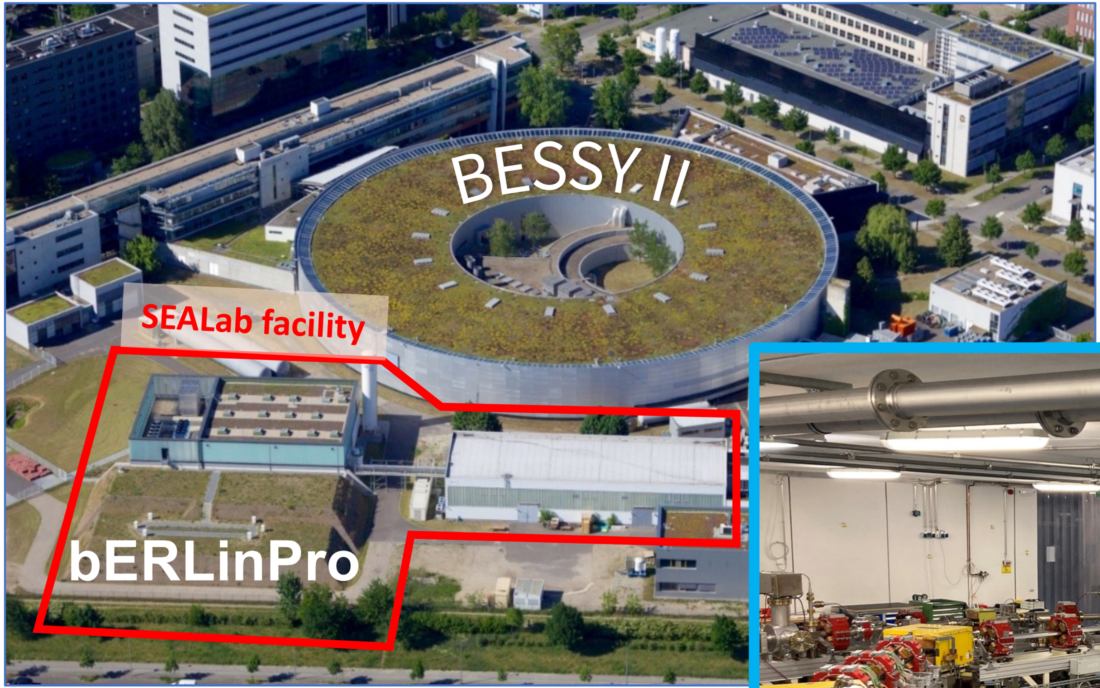
bERLinPro – Berlin Energy Recovery Linac Project

Upcoming facilities for Energy Recovery Linac R&D

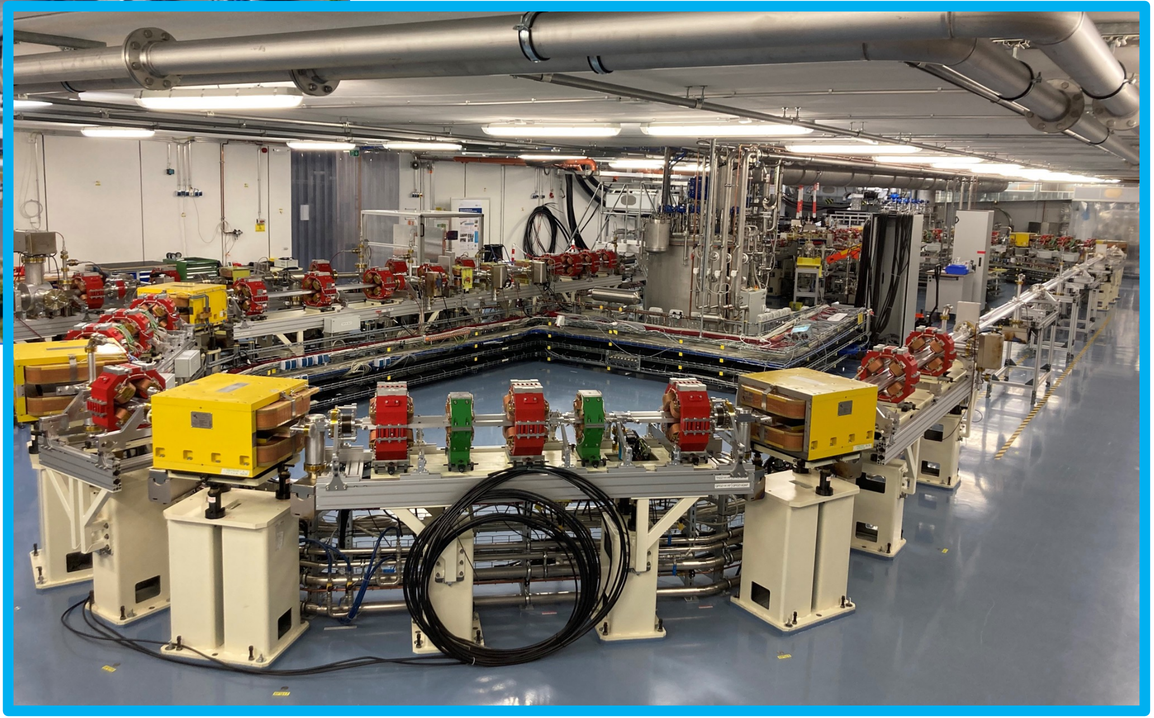
bERLinPro @ Helmholtz Zentrum Berlin
addressing HEP related challenges

bERLinPro ready for operation at 10 mA
contingent on additional budgets upgrades to 100 mA and ERL at 50 MeV can be planned to be operational by 2028





First beam of bERLinPro@SEALab to be expected in 2024



- focus on commissioning injector with SRF gun + diagnostic line
  (map out the reachable parameter space)
- installation of the Booster module
- recirculation, when LINAC funding is secured

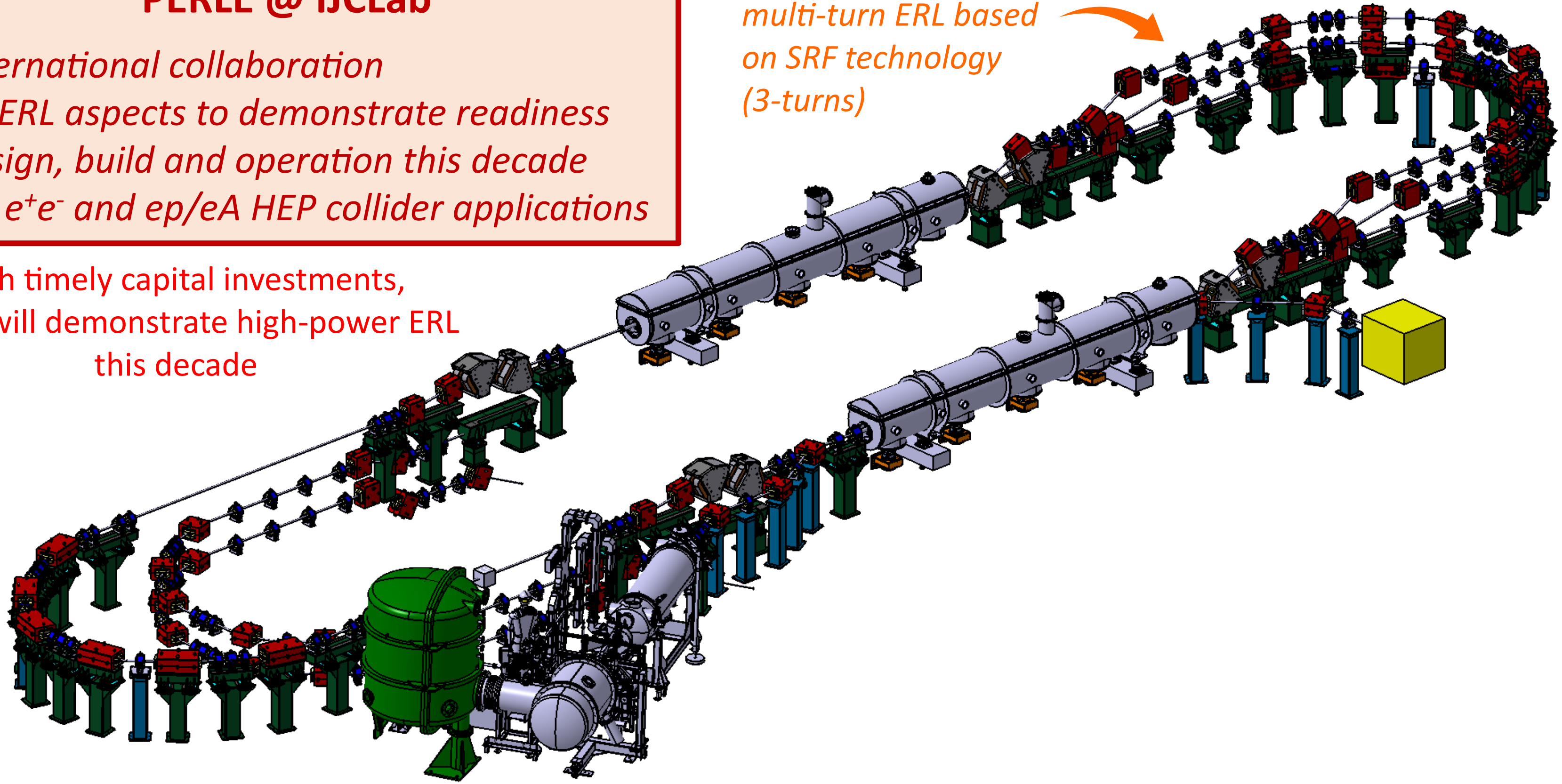
Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

- *international collaboration*
- *all ERL aspects to demonstrate readiness*
- *design, build and operation this decade*
- *for e^+e^- and ep/eA HEP collider applications*

With timely capital investments,
PERLE will demonstrate high-power ERL
this decade

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



PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

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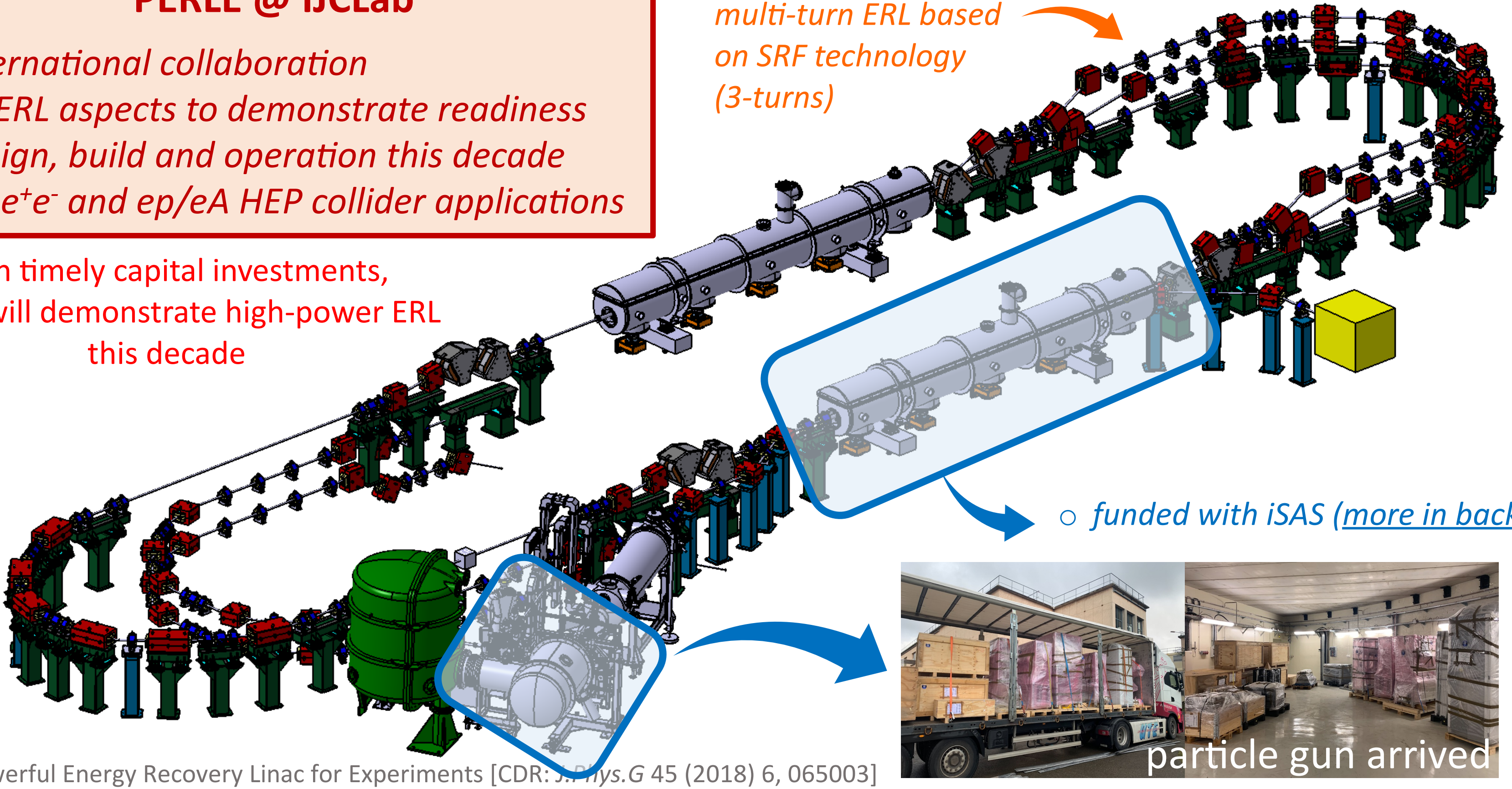

- *funded with iSAS (more in back-up)*

PERLE – Powerful Energy Recovery Linac for Experiments [CDR: J.Phys.G 45 (2018) 6, 065003]

Upcoming facilities for Energy Recovery Linac R&D

PERLE @ IJCLab

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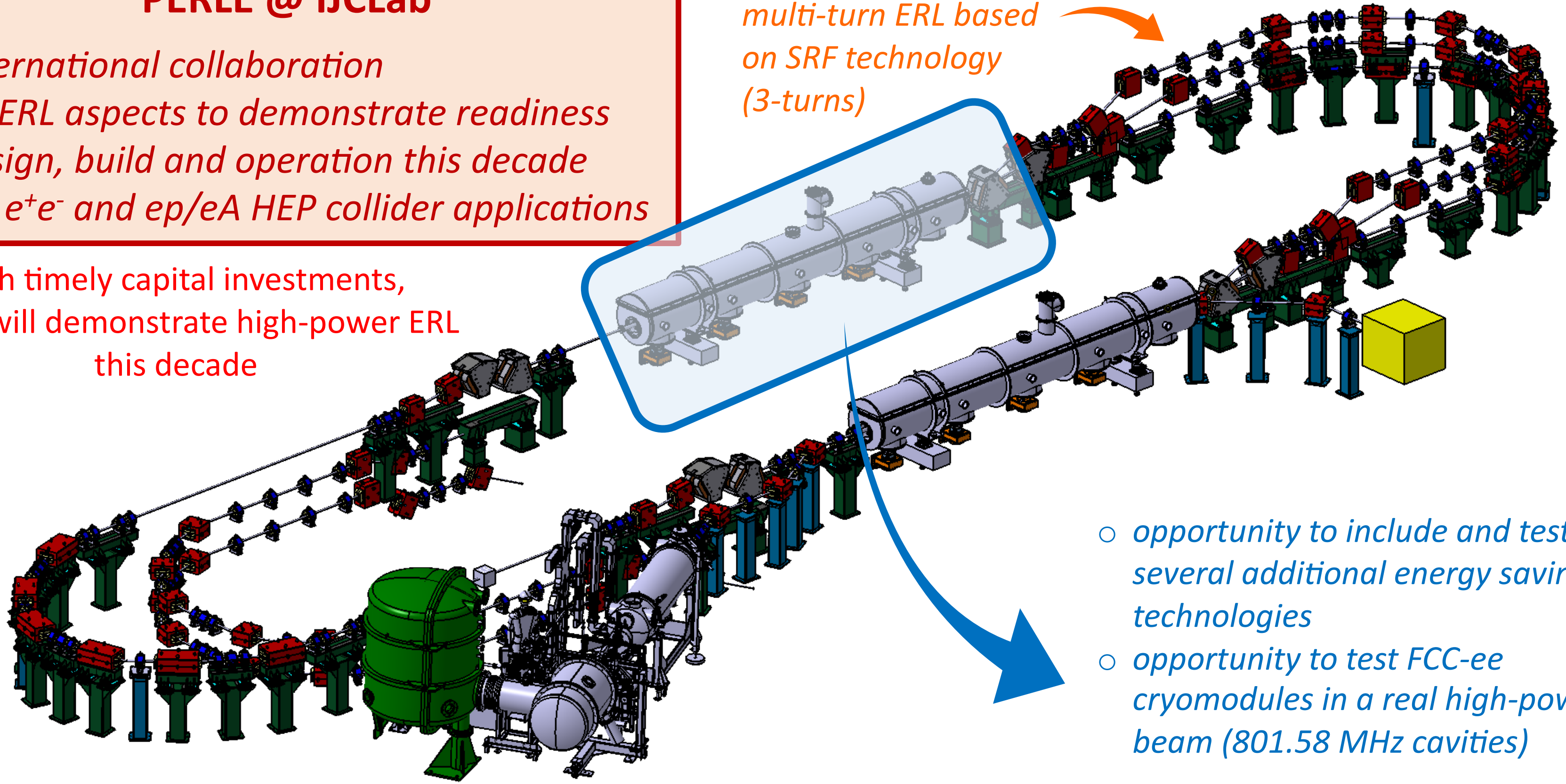


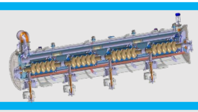
- *opportunity to include and test several additional energy saving technologies*
- *opportunity to test FCC-ee cryomodules in a real high-power beam (801.58 MHz cavities)*

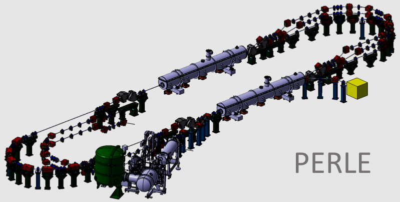
PERLE – Powerful Energy Recovery Linac for Experiments [CDR: *J.Phys.G* 45 (2018) 6, 065003]

Potential impact of ERL technology

demonstrate multi-turn high-power ERL

2020'ies





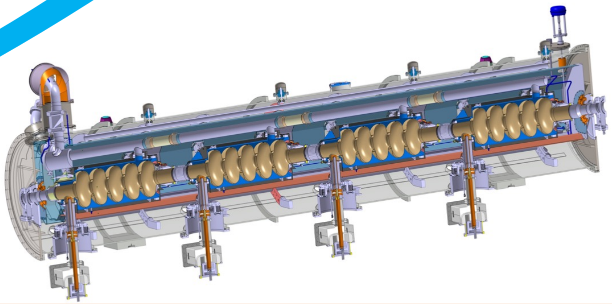
high-power ERL demonstrated

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

high-power ERL demonstrated

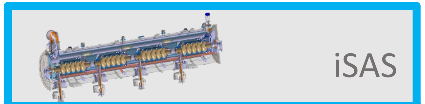


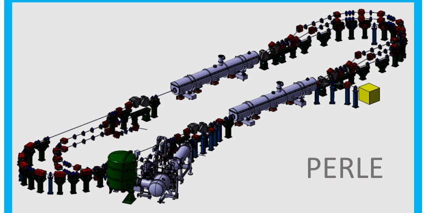
***iSAS**: new design including various energy-saving and energy-recovery technologies*

Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

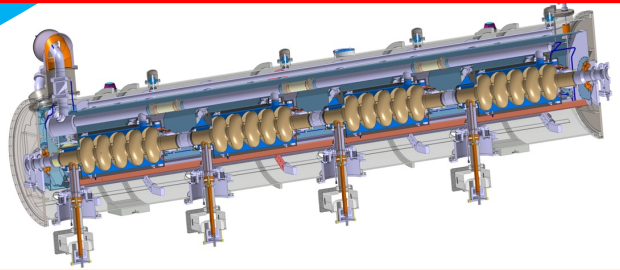
2020'ies





high-power ERL
demonstrated

Beyond the iSAS timescale and resources:
build and test this new cryomodule
(applications, e.g. FCC, LHeC, XFEL, ESS, …)



iSAS: *new design including various energy-saving and energy-recovery technologies*

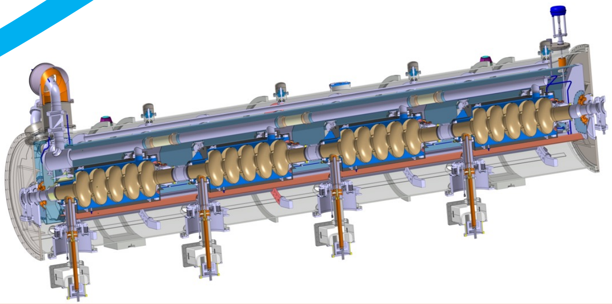
Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

2020'ies

high-power ERL
demonstrated

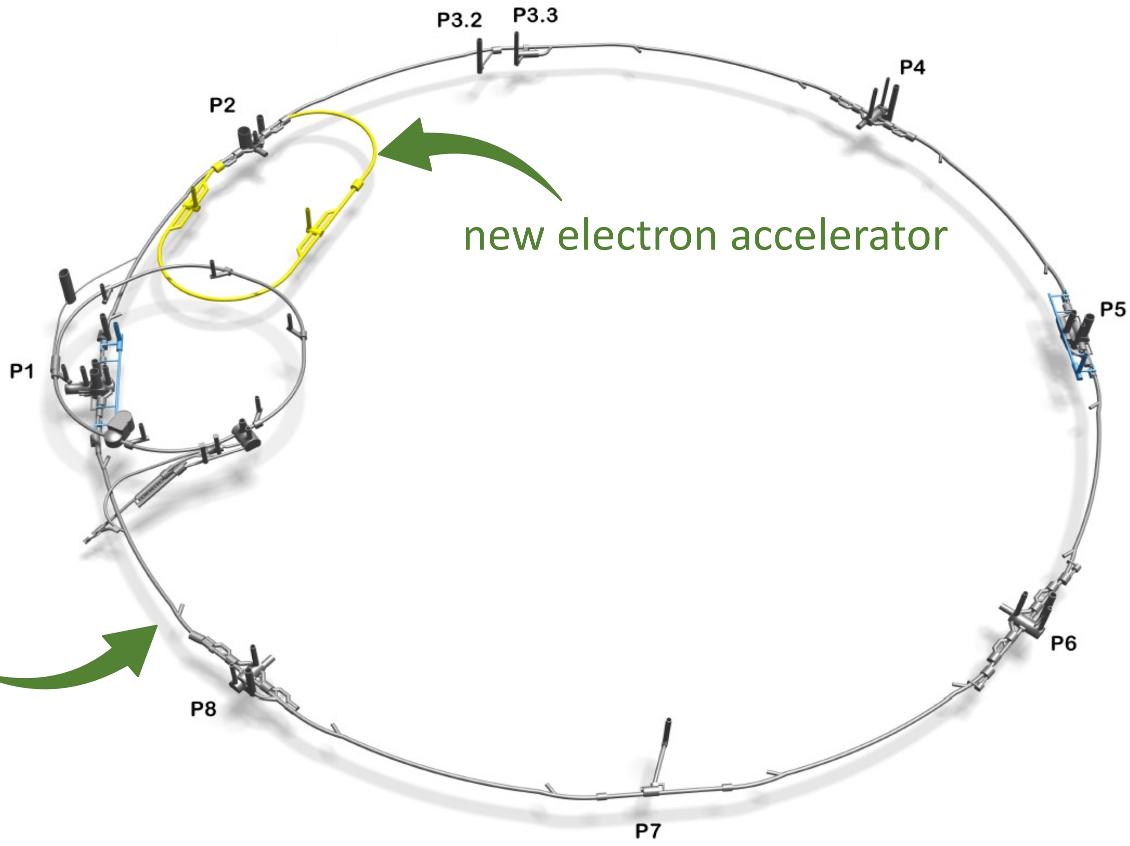
ERL ready for high-energy and high-luminosity colliders



***iSAS**: new design including various energy-saving and energy-recovery technologies*

ERL-based ep/eA colliders at CERN

high-energy & high-luminosity electron-proton collisions



new electron accelerator

existing/future
proton accelerator
LHC and/or FCC
(LHeC and/or FCC-eh)

The challenge

High-intensity electron beam

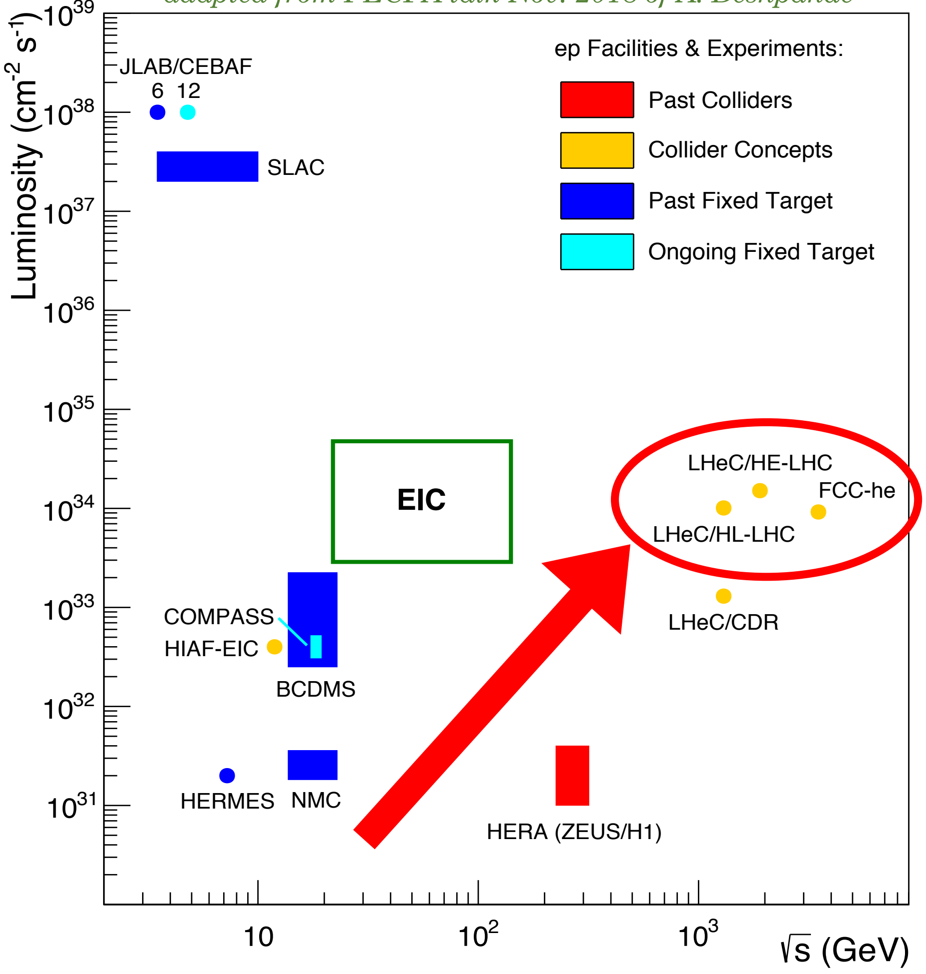
From HERA@DESY to LHeC@CERN

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

beam current × beam energy
= beam power

LHeC ~ 1 GW beam power
equivalent to the power delivered by a nuclear power plant

adapted from PECFA talk Nov. 2018 of A. Deshpande



The challenge

High-intensity electron beam

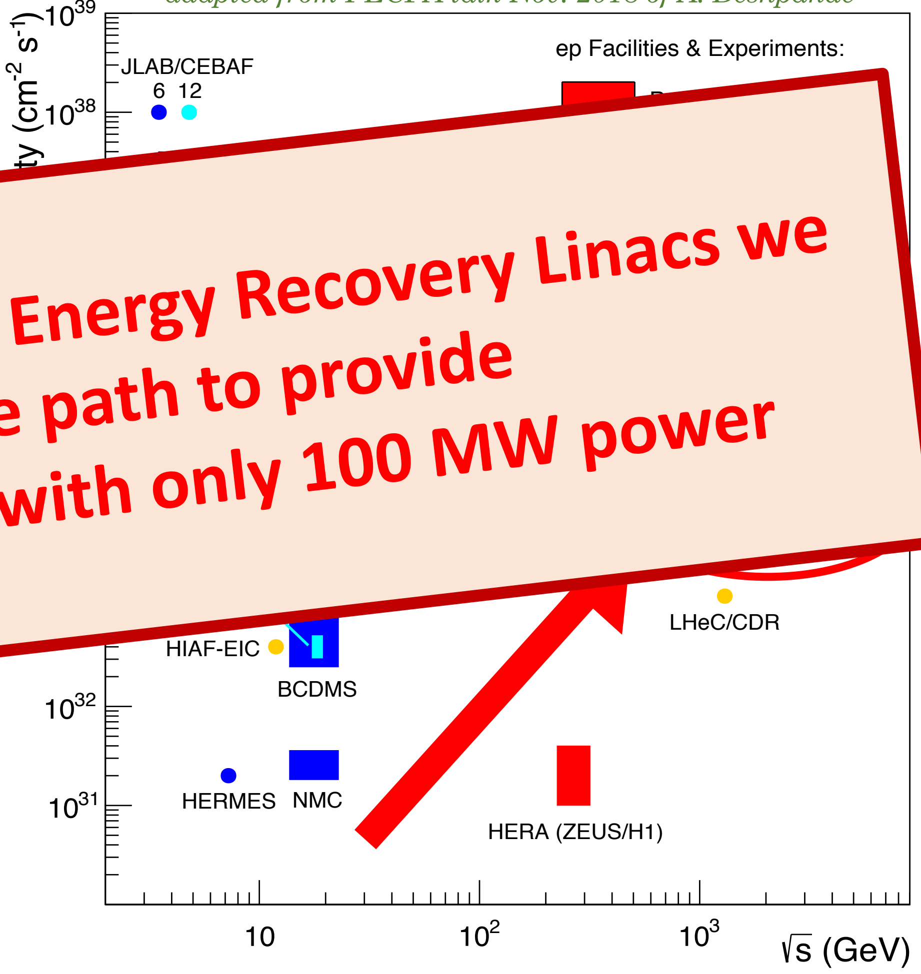
From HERA

With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 100 MW power

LHeC ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant

adapted from PECFA talk Nov. 2018 of A. Deshpande



Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

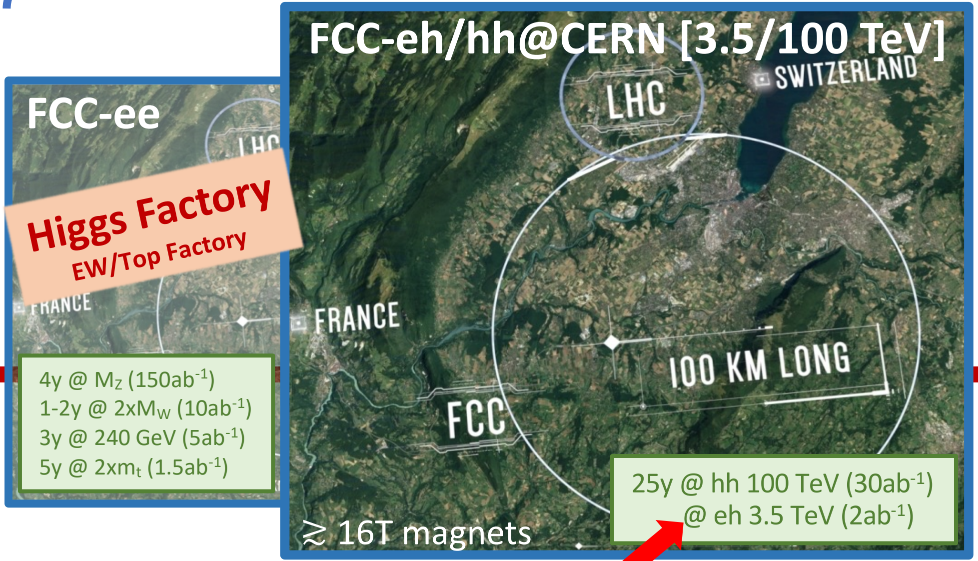
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

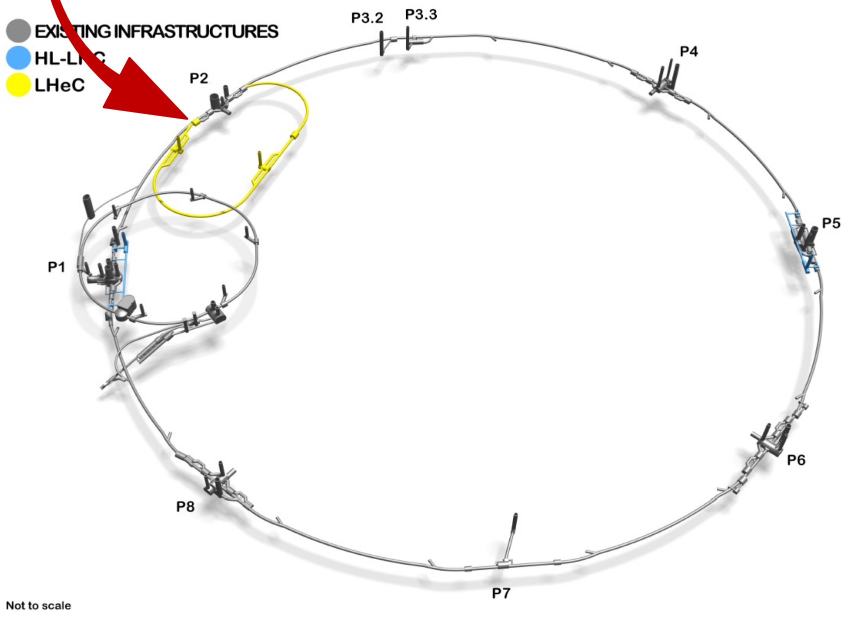
updated CDR: J.Phys.G 48 (2021) 11, 110501

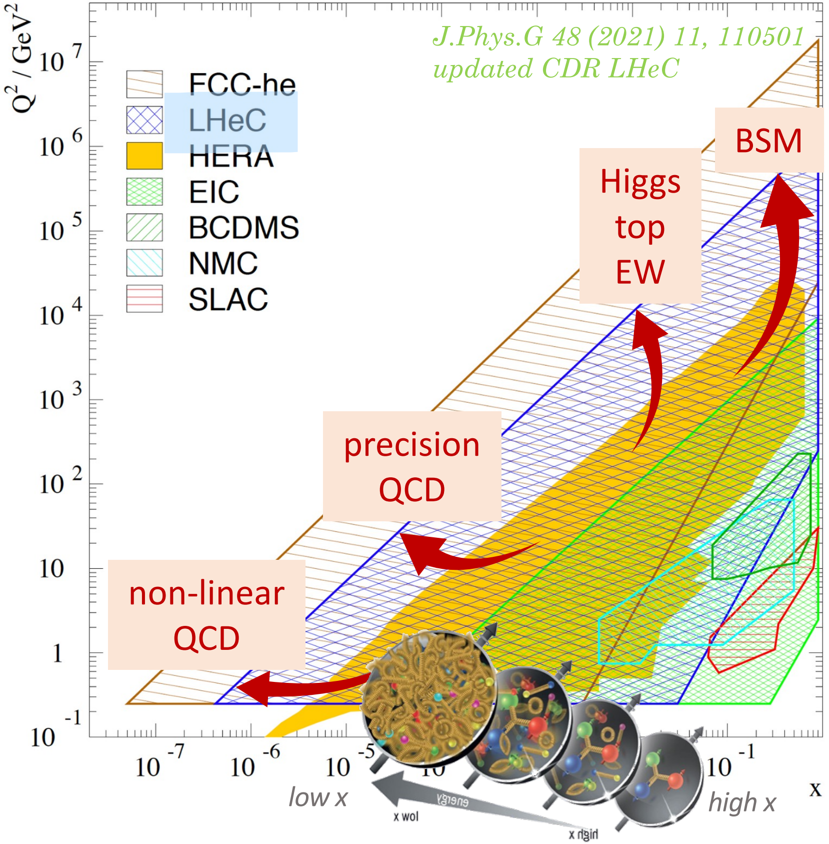


numbers assume 2 IPs for each collider (only one for FCC-eh)

The LHeC program

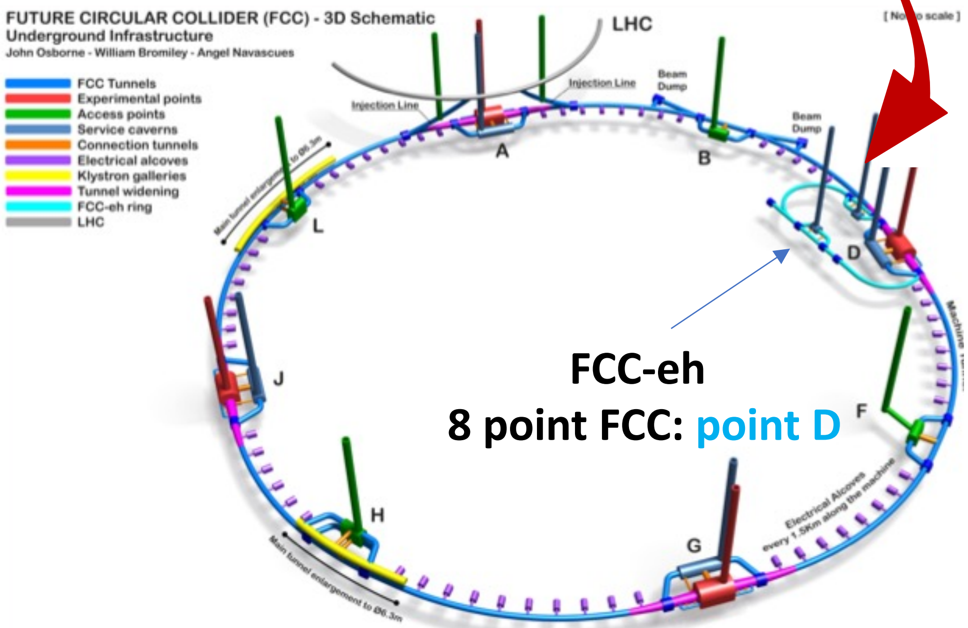
LHeC (>50 GeV ERL electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



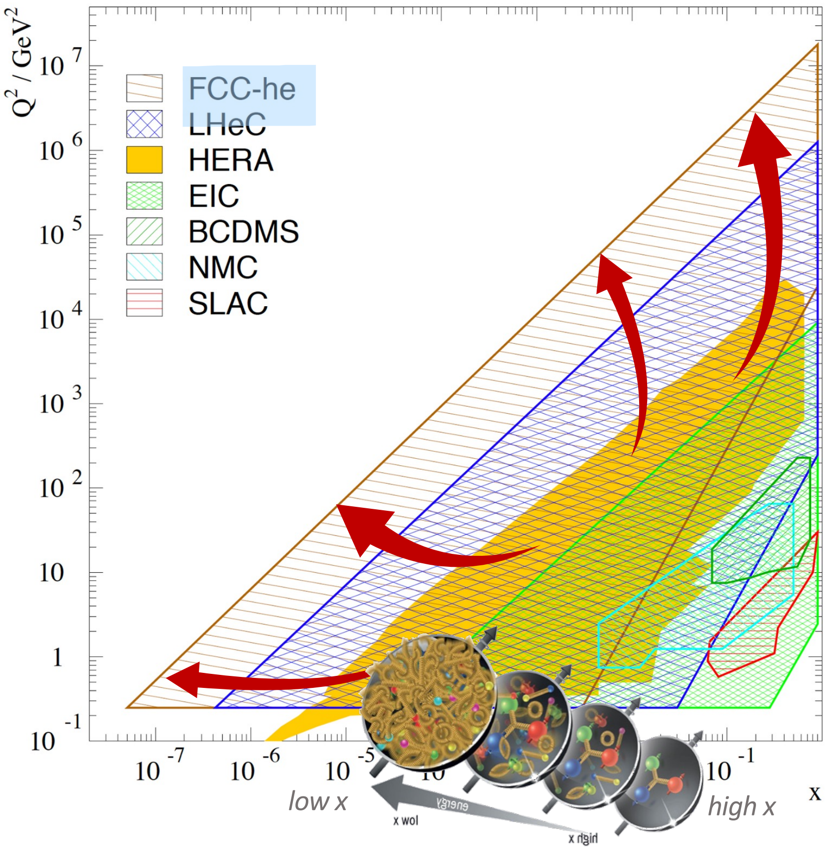


The FCC-eh program

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

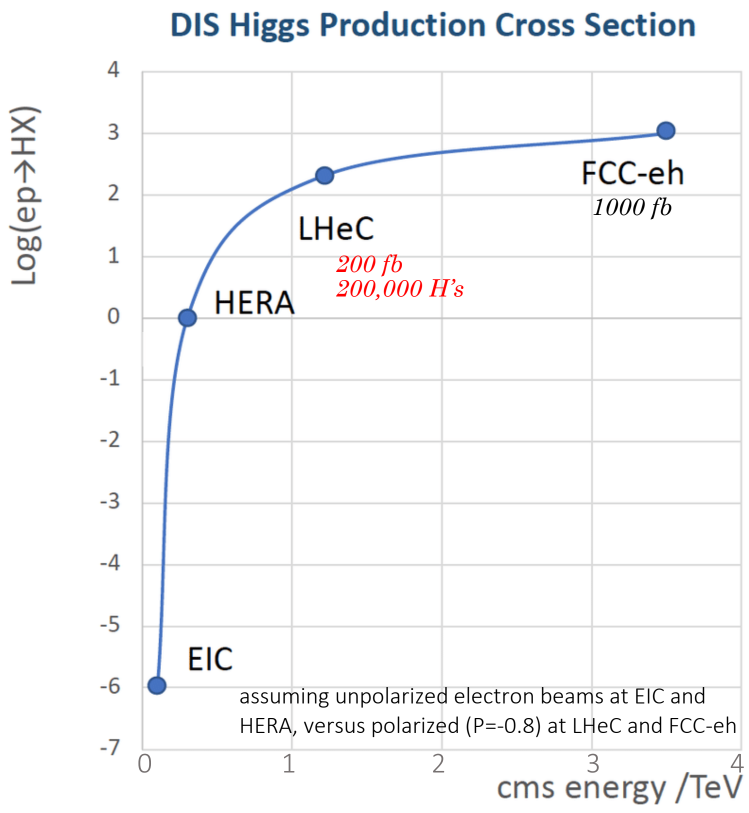


J. Osborne, W. Bromiley, A. Navascues

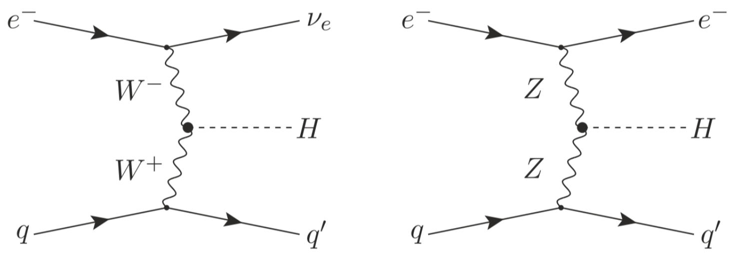


the physics impact

Collision energy above the threshold for EW/Higgs/Top



The real game change between HERA and LHC/FCC

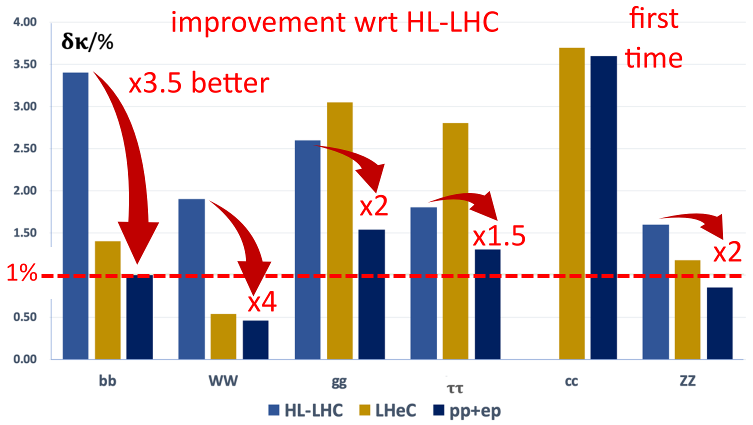


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

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

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

Higgs physics



EW physics

- Δm_W down to 2 MeV (today at ~10 MeV)
- $\Delta\sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics

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

DIS scattering cross sections

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

Strong interaction physics

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

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

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

Higgs physics

The LHeC is a general-purpose experiment

i.e. H/EW/top/QCD/search factory

EW/Higgs/top: improvement from LHC → HL-LHC similar to HL-LHC → LHeC

Open Kick-Off meeting on Oct 31, 14:00-16:00 (ZOOM-only): https://indico.cern.ch/event/1335332/

DIS scattering cross sections

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

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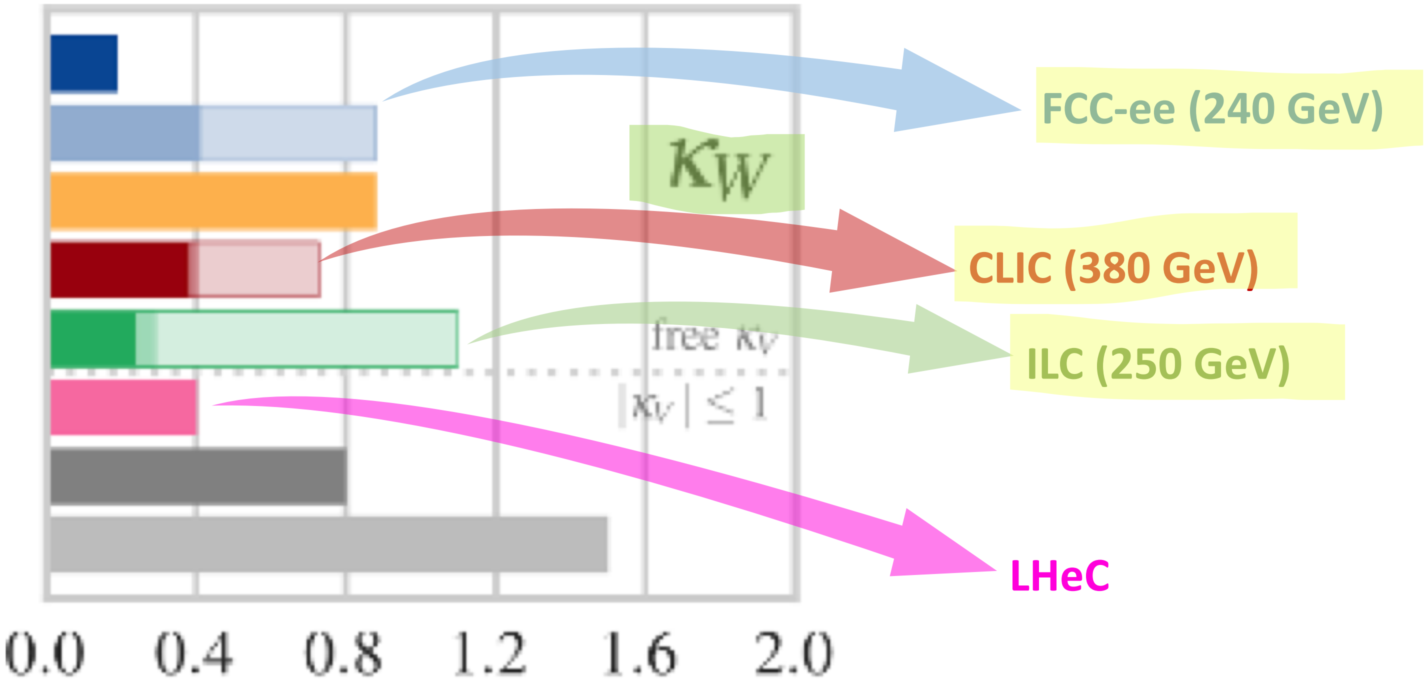
Higgs physics precision: LHeC versus e^+e^- colliders

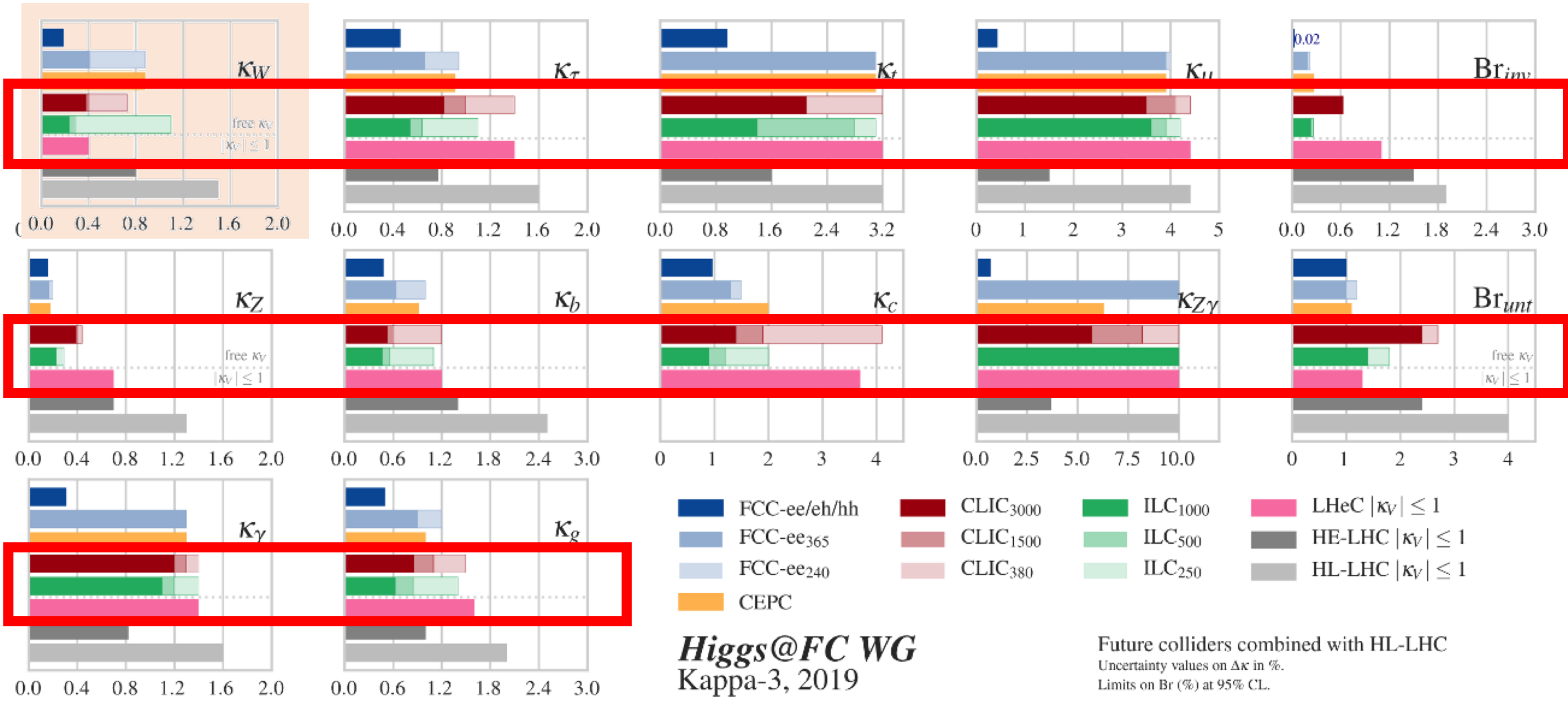
J. de Blas et al., JHEP 01 (2020) 139



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 e^+e^- colliders

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



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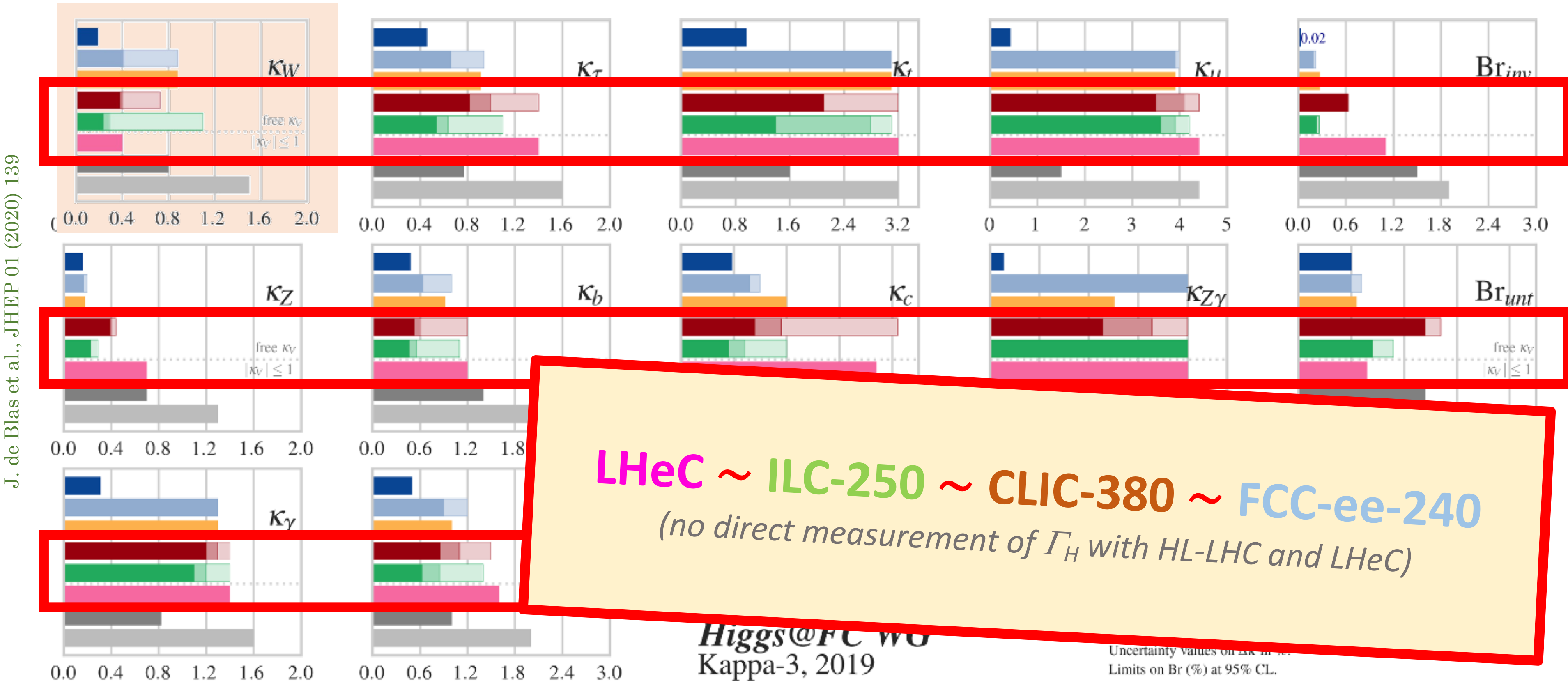
Higgs physics precision: LHeC versus e$^+$e$^-$ colliders



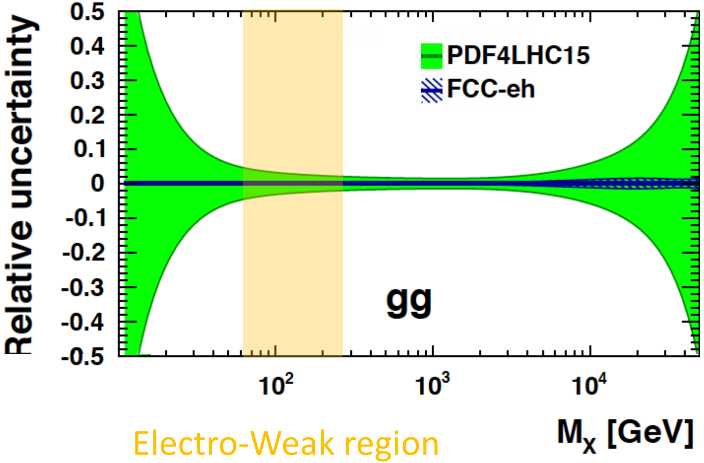
LHeC ~ ILC-250 ~ CLIC-380 ~ FCC-ee-240

(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

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

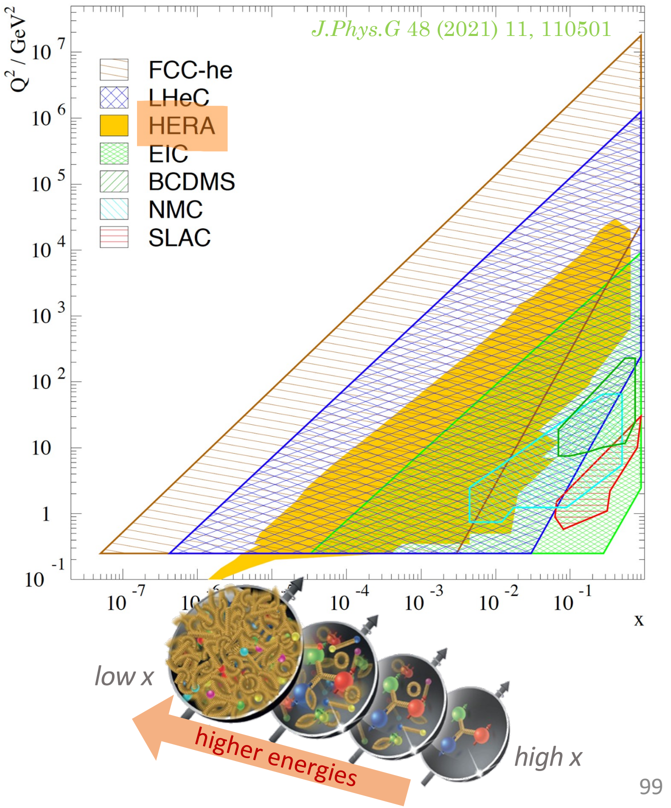


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

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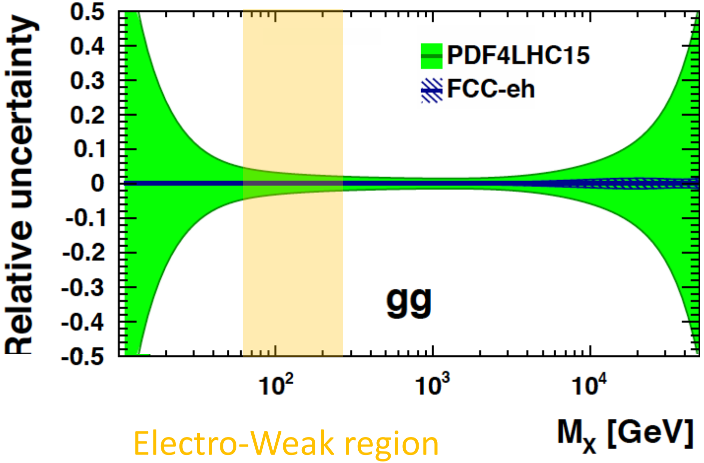


Electro-Weak region

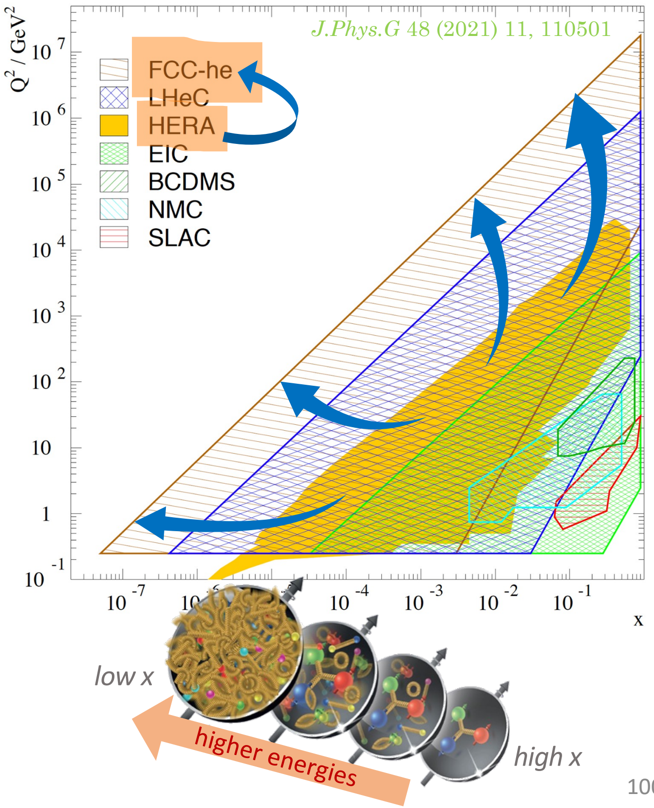
~5-7% uncertainty on the σ(W,Z,H)

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 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

only FCC-ee@240GeV

only FCC-hh

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

Complementarity for Higgs physics in the FCC program

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

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FCC-ee prospect

FCC-hh/eh prospect

only FCC-ee@240GeV

only FCC-hh

Complementarity for Higgs physics in the FCC program

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

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FCC-ee prospect

FCC-hh/eh prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

Complementarity for Higgs physics in the FCC program

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
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kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	[illegible]			
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only FCC-ee@240GeV

FCC-ee prospect

FCC-hh/eh prospect

only FCC-hh

ALL COMBINED

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

Explore the physics opportunity of a joint ep/eA/pp/pA/AA/(ee) program at the LHC and/or the FCC

Ultimate Higgs Factory = {ee + eh + hh}

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

More information:
https://indico.cern.ch/event/1335332/

2023 | WS | 2024 | WS | 2025 | TWS | *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

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

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 programme

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

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

- typically 2-3 conveners per theme
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

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

More information:
https://indico.cern.ch/event/1335332/

2023 | WS | 2024 | WS | 2025 | WS

proton and nuclear st…

Mandate: "CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics. The study is to further develop the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with emphasis on FCC."

…pp/eA/pA/AA physics

…community with regular ep/eA Newsletters

- everybody is welcome to join

d… LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

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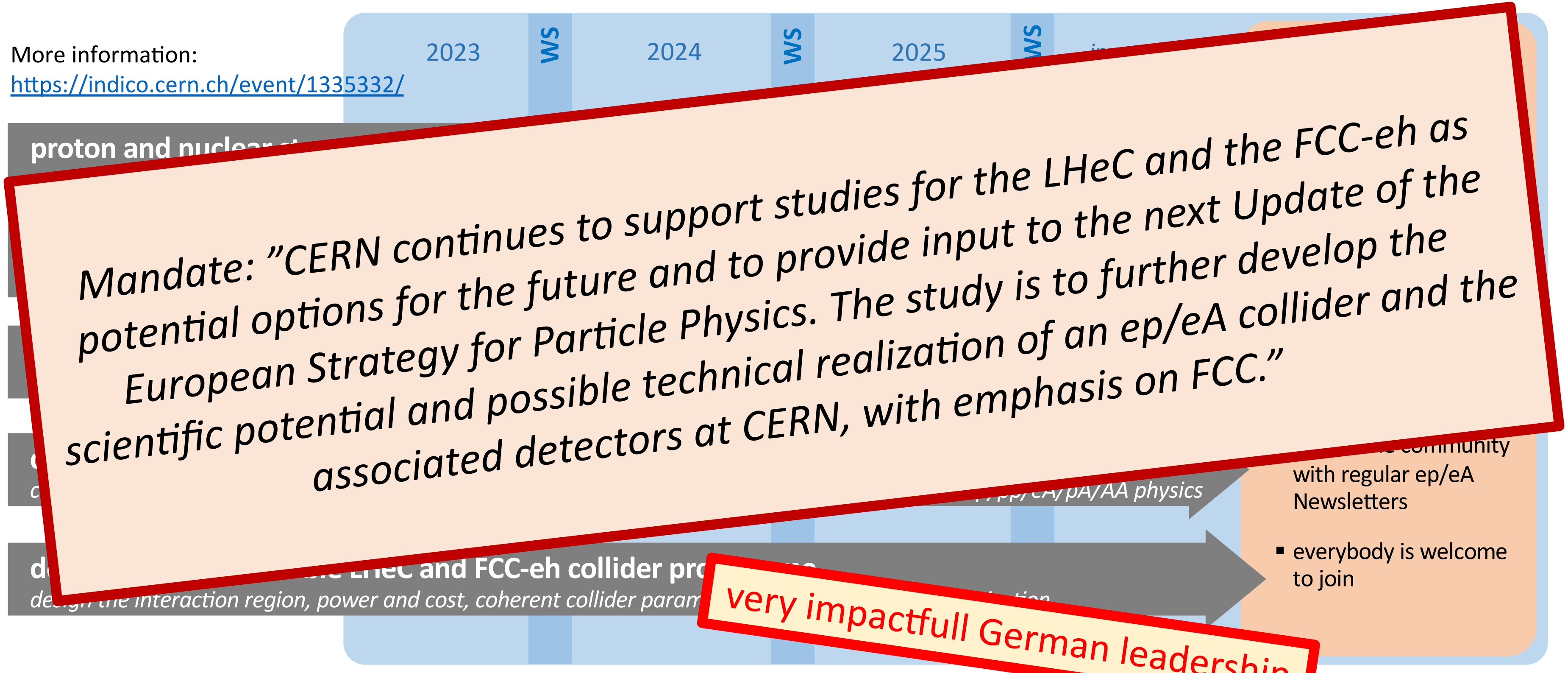

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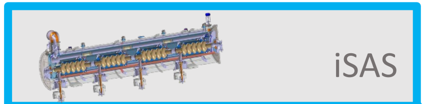
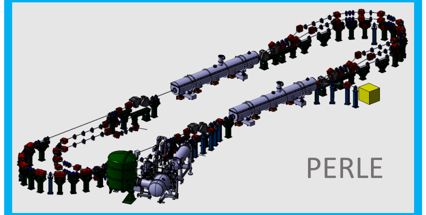
Potential impact of ERL technology

demonstrate
multi-turn high-power ERL

enables the ultimate upgrade of the LHC program

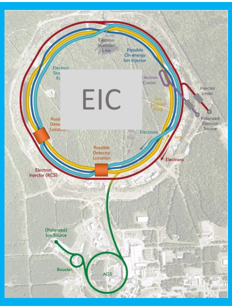
2020'ies





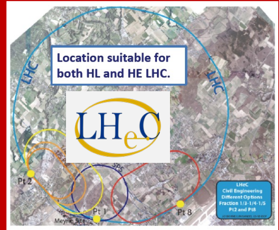
high-power ERL demonstrated

2030'ies



ERL application electron cooling

2030-2040'ies

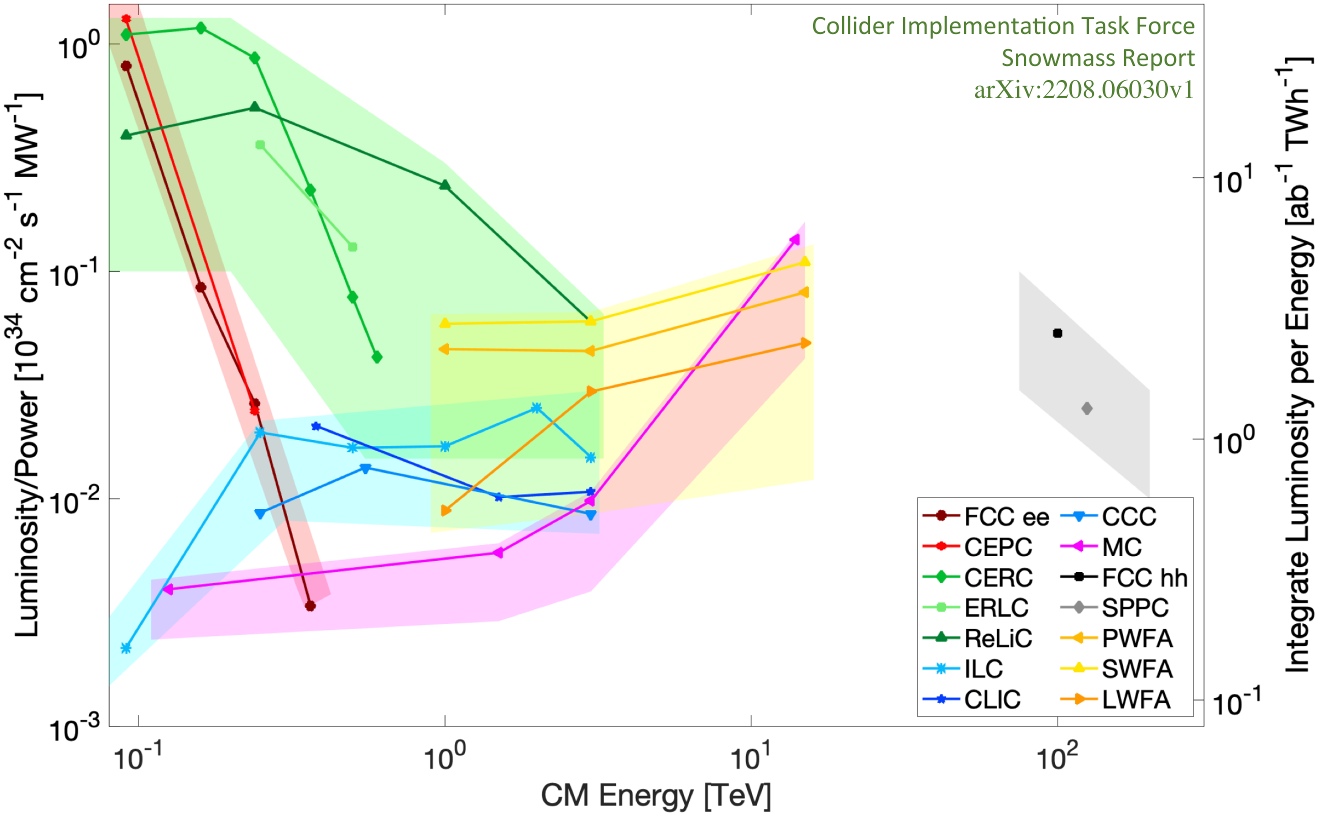


1 ERL beam

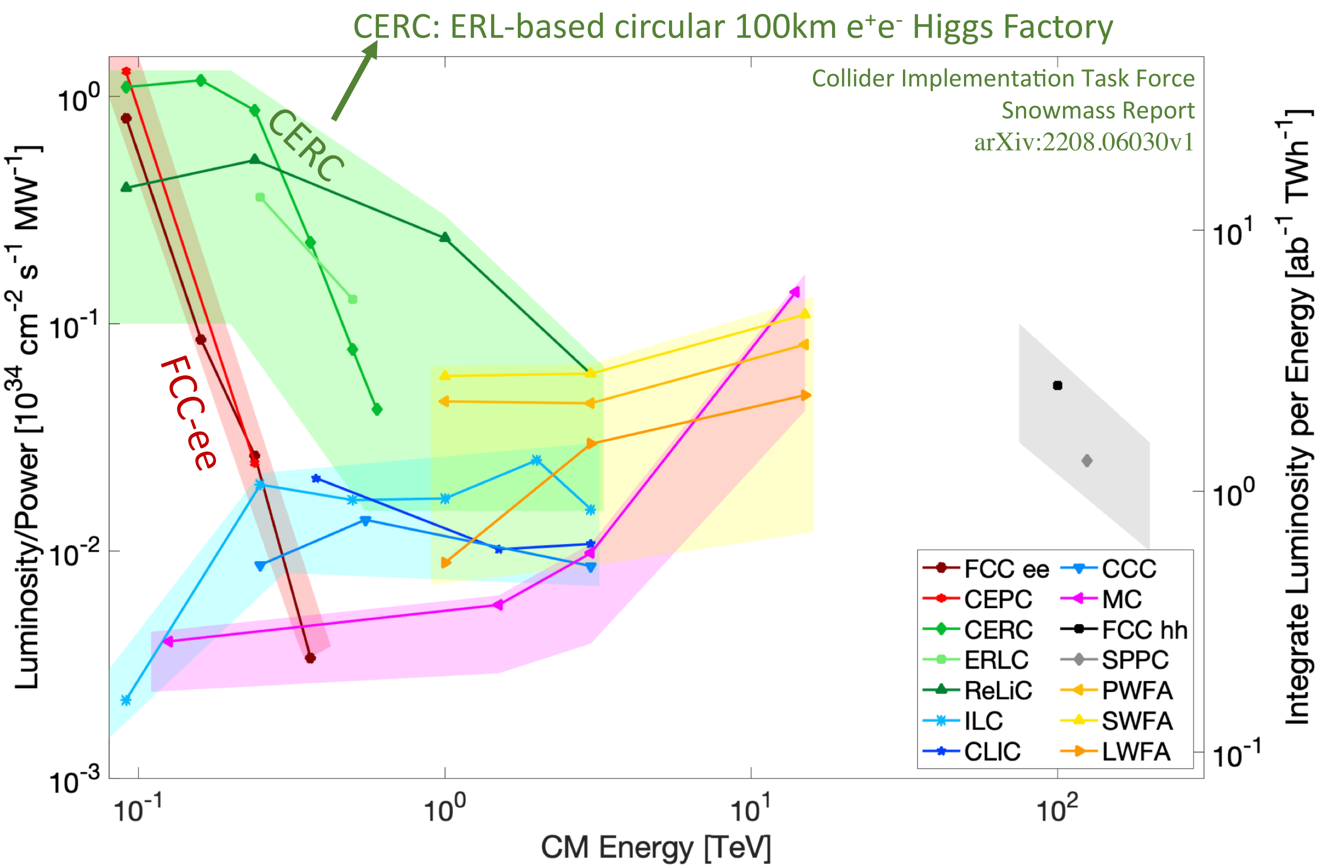
high-power ERL
e^- beam in collision
(ep/eA @ LHC program)

ERL-based H/HH Factories

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

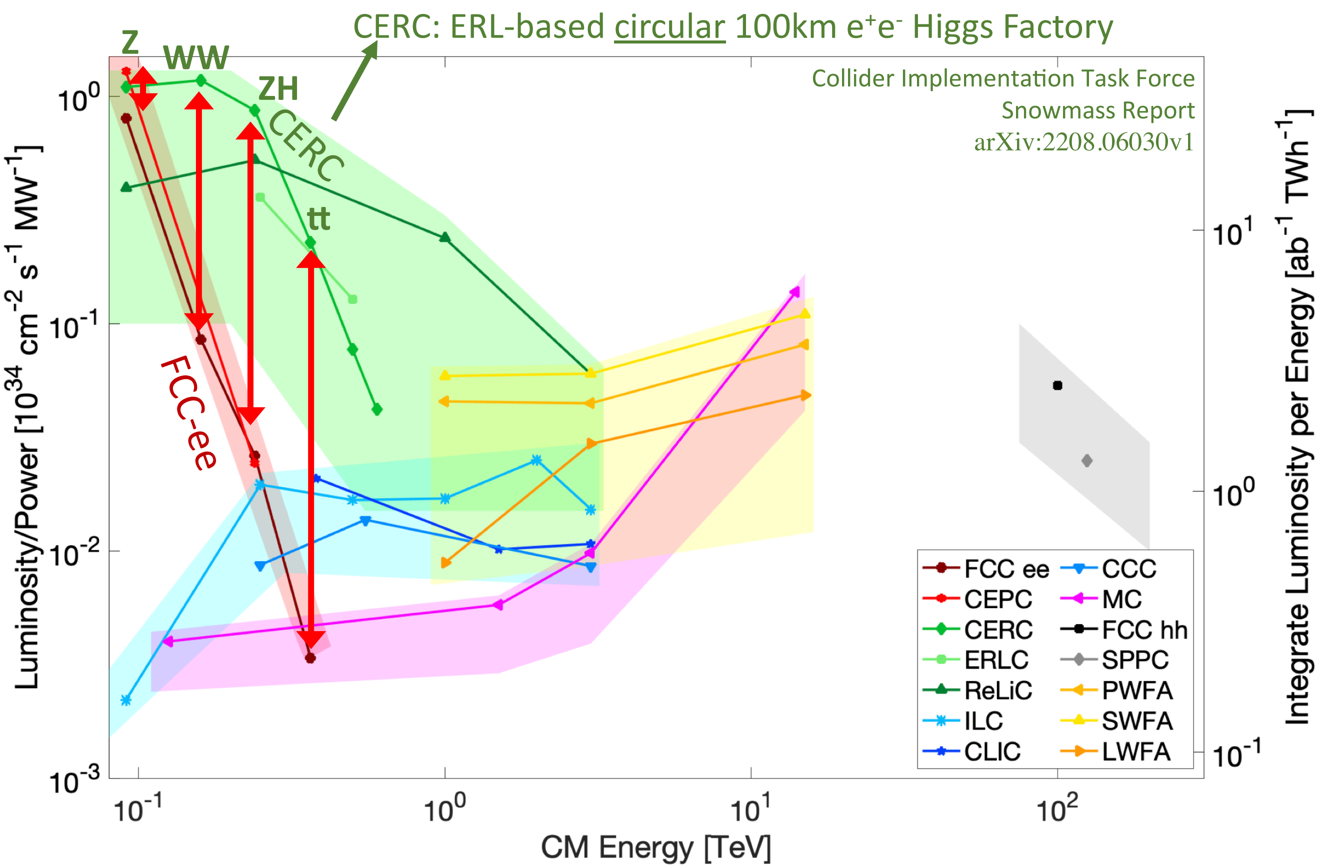


Energy Recovery applications for HEP e^+e^- colliders



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

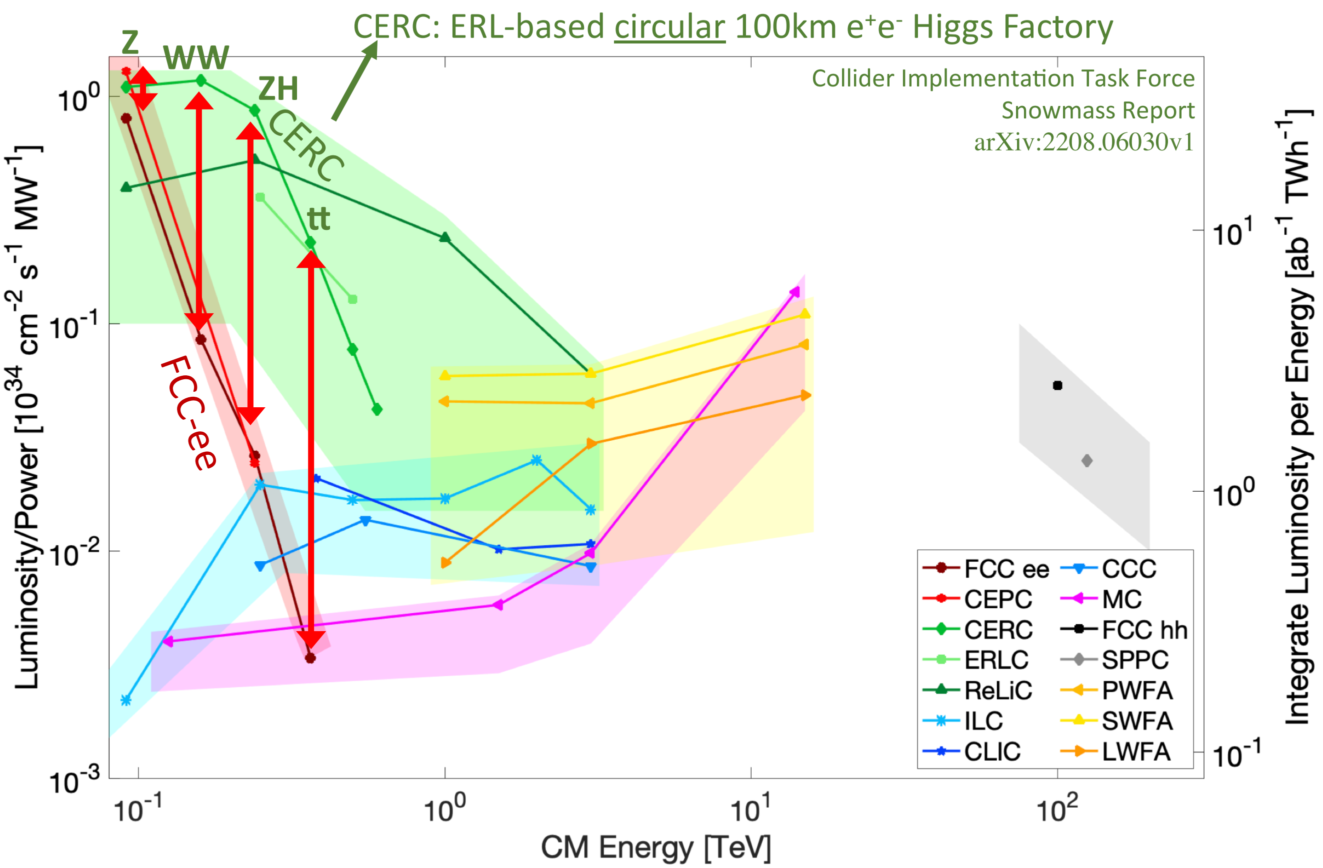
Energy Recovery applications for HEP e^+e^- colliders

This plot suggests 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

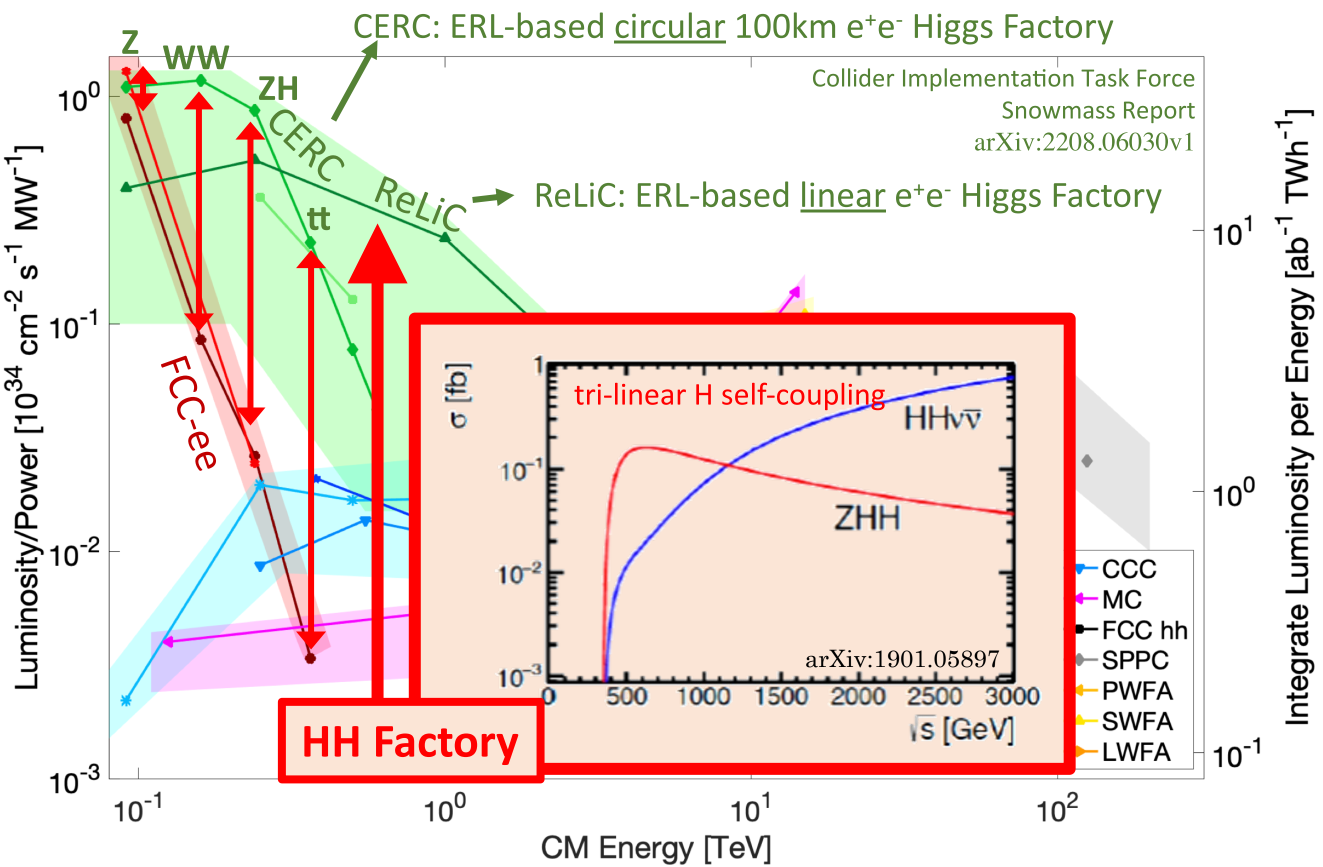
Energy Recovery applications for HEP e^+e^- colliders

This plot suggests 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

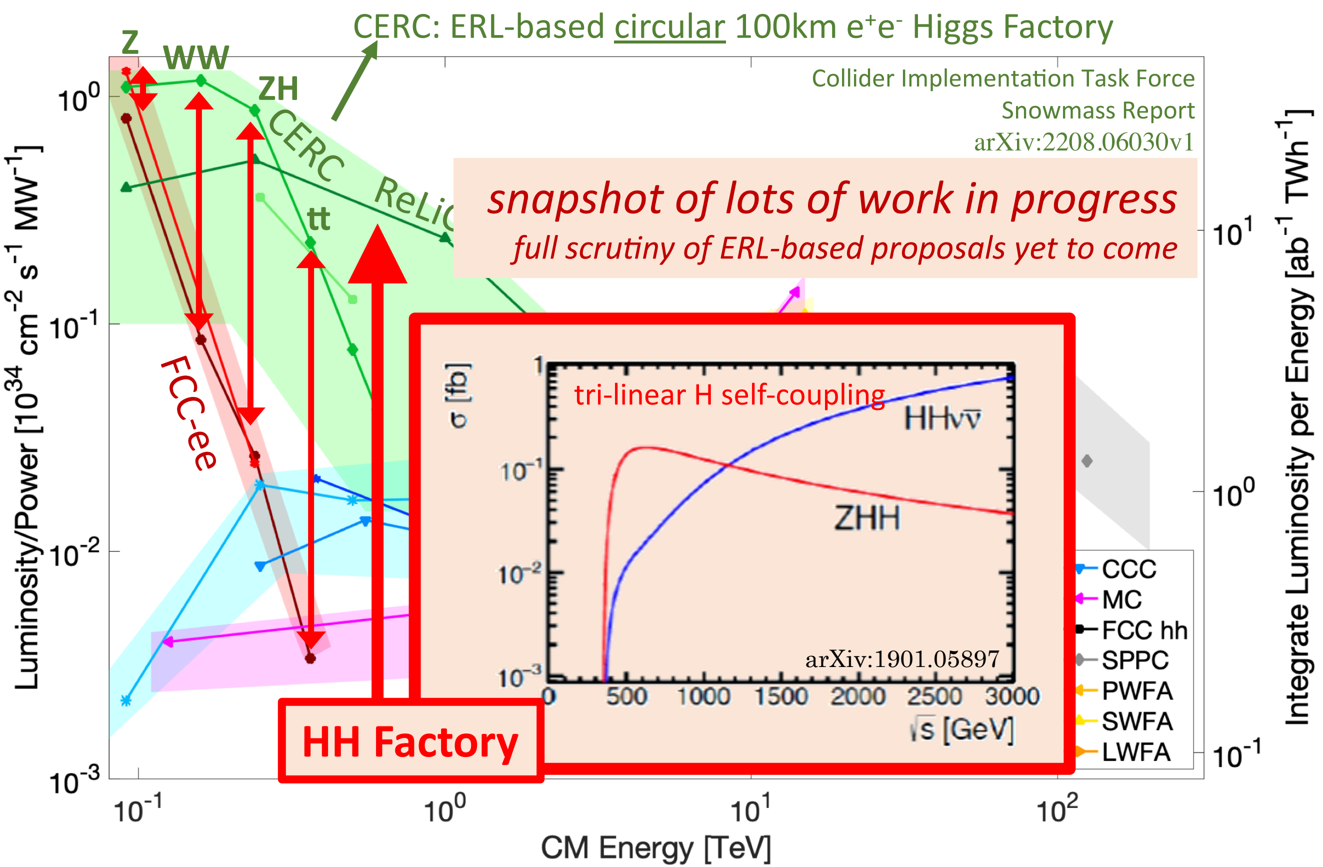
This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

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

Th
a
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x10

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challe
these E
(hence the ... uncertainty band in the plot)

Can we dream to have an ERL-based Higgs Factory in the LHC tunnel?

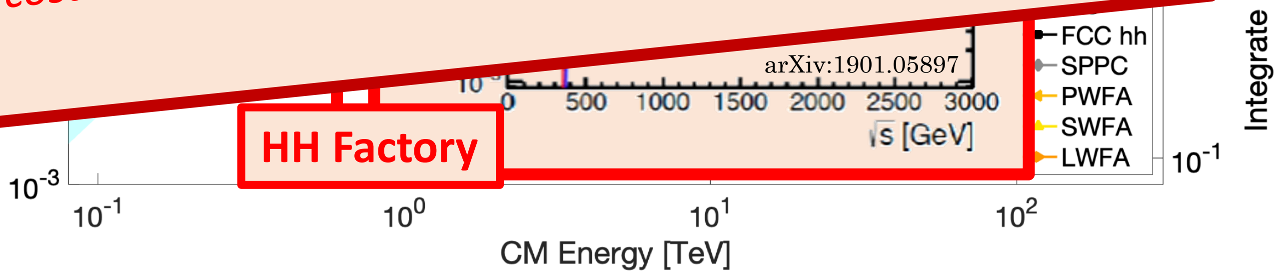
Power of Synchrotron Radiation ~ 1/R

R : radius of circular collider

Synchrotron Radiation in 27km versus 100km e^+e^- collider ~ x4

LHC ERL-based Higgs Factory *versus* non-ERL FCC-ee

same electricity cost and same number of Higgses without new tunnels



Energy Recovery applications for HEP

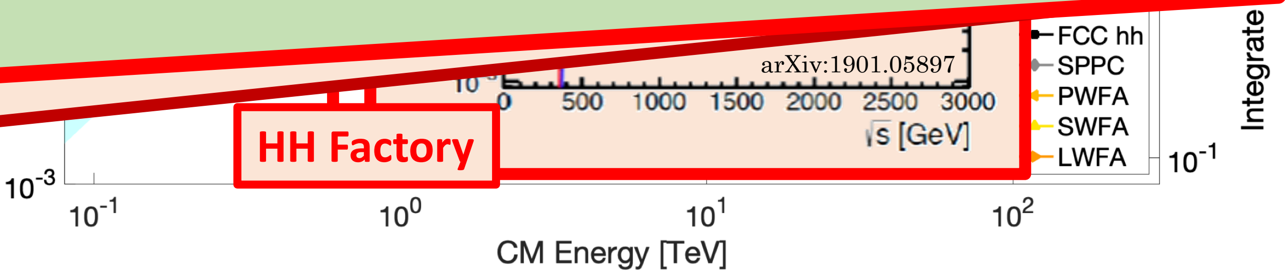
...the LHC tunnel?

Th

Through beam dynamics studies develop a self-consistent set of operating parameters with associated achievable luminosity and power requirements.

Reduce uncertainties on performance indicators
&
Develop confidence for the feasibility of ERL-based H/HH factories

cl
these E
(hence the ... ertainty band in the plot)



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

Ref for ReLiC: arXiv:2203.06476

Potential impact of ERL technology

With stepping stones for innovations in technology
to boost our physics reach

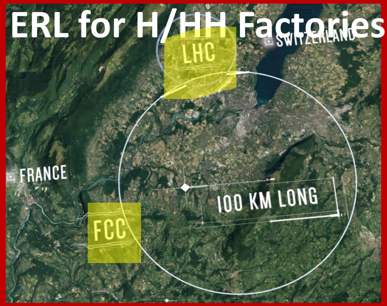
demonstrate
multi-turn high-power ERL

enables the ultimate
upgrade of the
LHC program

2070'ies

reuse ERL

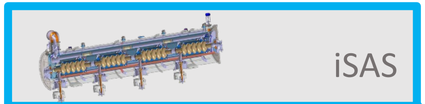
2040-2050'ies

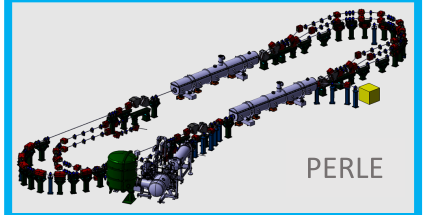


2 ERL beams

high-power ERL for
e^+e^- Higgs Factories
(Z/W/H/top/HH program)

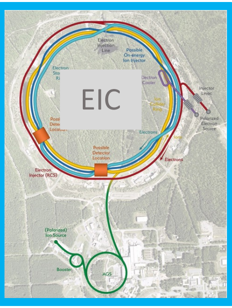
2020'ies





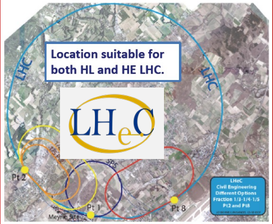
high-power ERL
demonstrated

2030'ies



ERL application
electron cooling

2030-2040'ies



1 ERL beam

high-power ERL
e^- beam in collision
(ep/eA @ LHC program)

increases the performance of
the next major colliders

Potential impact of ERL technology

With stepping stones for innovations in techn...
to boost our physics reach

enables ...

demonstrat...

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

European Strategy for Particle Physics 2020

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation

...creases the performance of the next major colliders

...pplication
electron cooling

Potential impact of ERL technology

With stepping stones for innovations in tech
to boost our physics reach

enables

demonstrat

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

European Strategy for Particle Physics 2020

An ERL-route towards an e^+e^- Higgs Factory

potentially enabling additional (ep/eA) and more (e^+e^-) physics
with less impact on the environment and less power requirements
with a timely and affordable realisation
requires additional support to complete the R&D program (e.g. PERLE, bERLinPro, iSAS)
requires enhanced interest and resources for design efforts of ERL-based colliders

Not without challenges!

increases the performance of
the next major colliders

electron cooling

Future Particle Physics Colliders with Energy Recovery Linacs

- ERL is an enabling technology for our most prominent future ep/eA and e^+e^- colliders, delivering breakthrough performances on an interesting timeline
- The engine of our curiosity-driven exploration with particle physics is society's appreciation for the portfolio of technological innovations and knowledge transfer that we continue to realize: ERL technology delivers on this front
- To achieve the best physics for the least power, with iSAS we connect leading European institutions and industry to expedite the development of various sustainable technologies that are essential to realize the ambition expressed in the European Strategy for Particle Physics

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

The potential impact of ERL is so appealing that we must foster this R&D path

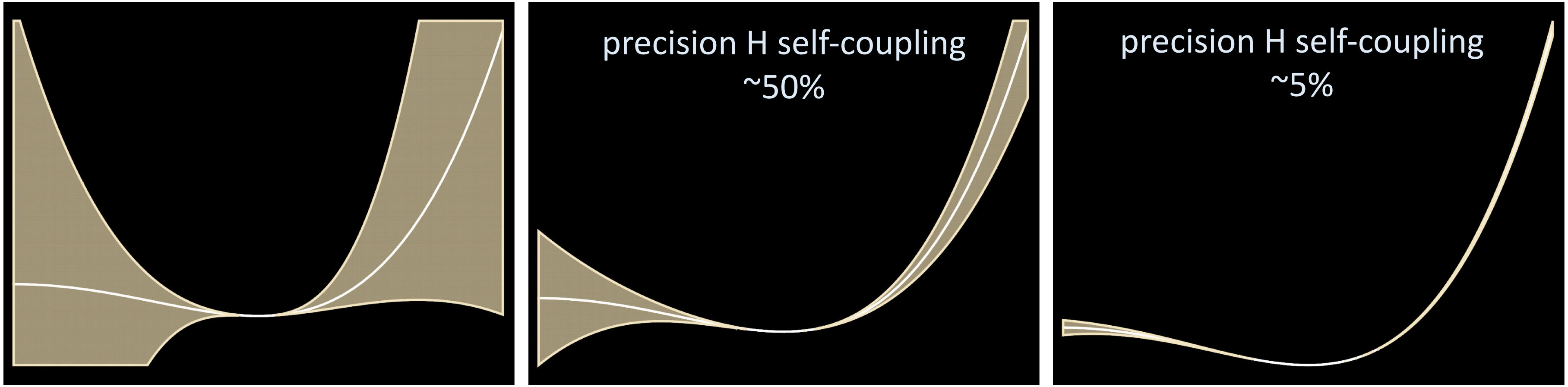
HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be

Ultimate Higgs Factory = {ee + eh + hh}

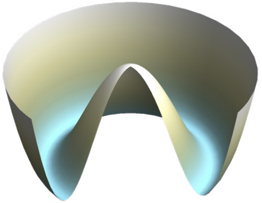
NOW | HL-LHC | FCC

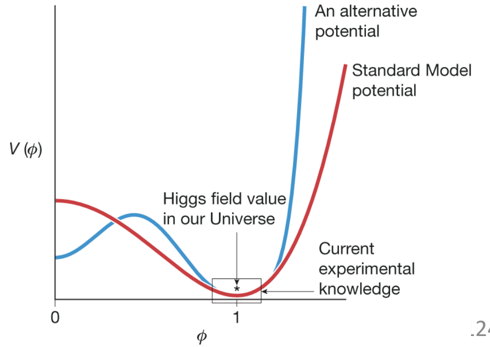


Adapted from Nathanial Craig

Is the H-field indeed represented by the standard model H-potential?

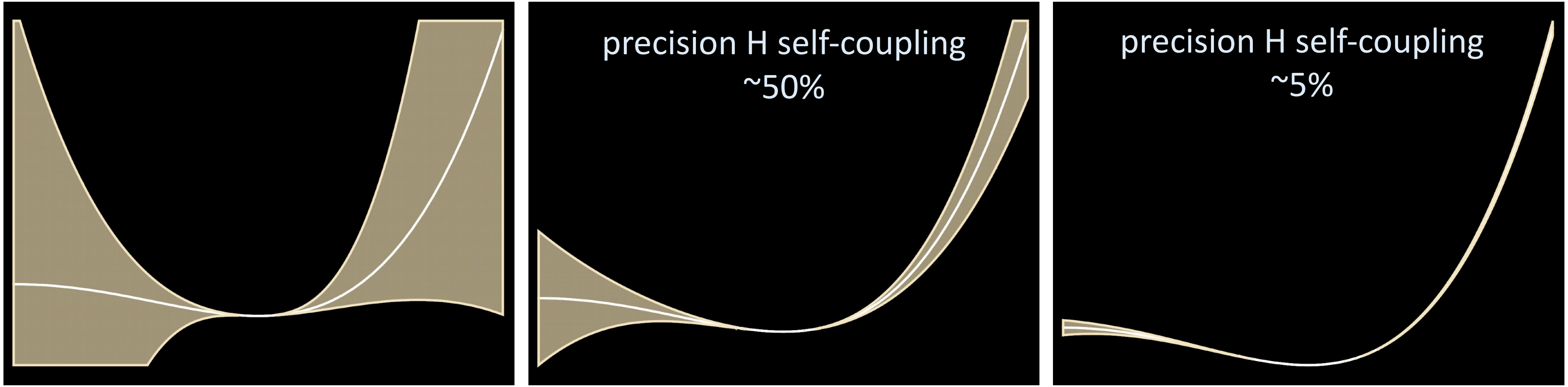
$$V_{\mathrm{higgs}} = -\underbrace{\frac{1}{2}m^2}_{m_H}|\varphi|^2 + \underbrace{\frac{\lambda}{4}}_{\textit{H self-coupling}}|\varphi|^4$$





Ultimate Higgs Factory = {ee + eh + hh}

NOW HL-LHC FCC



Adapted from Nathanial Craig

Is the H-field indeed represented by the standard model H-potential?

Was the electro-weak symmetry broken (from $\phi=0$ to $\phi\neq0$) via a smooth transition or via a tunneling effect where two vacuum states emerge together with potentially lots of new physics?