Building the future together

Open questions in fundamental physics and our main future facilities to address them

Jorgen D'Hondt
Vrije Universiteit Brussel

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iihe BRUXELLES BRUSSEL
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE
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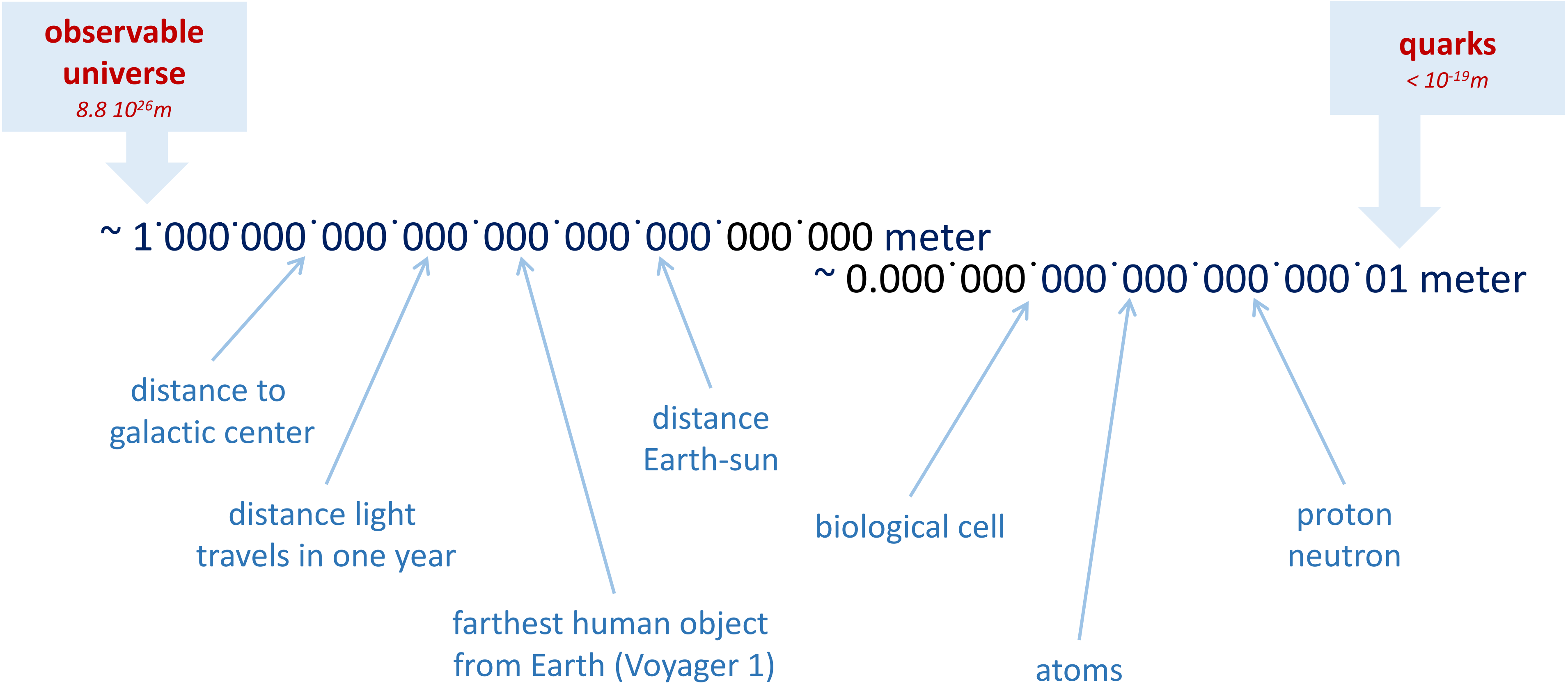
KIT, 9 February 2023


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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8.8 10^{26}m

visible with our own eyes

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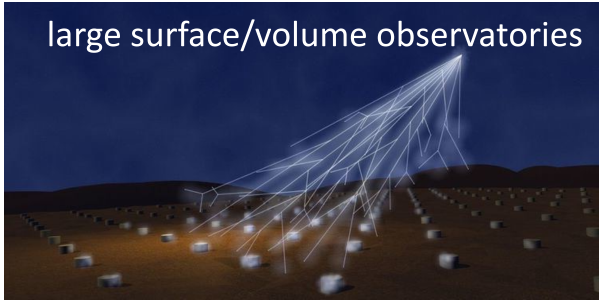

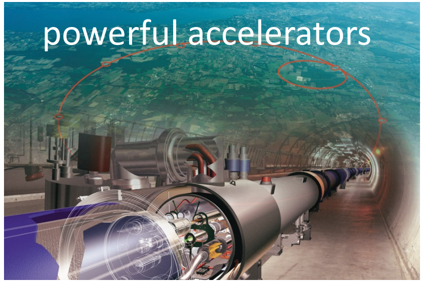

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distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

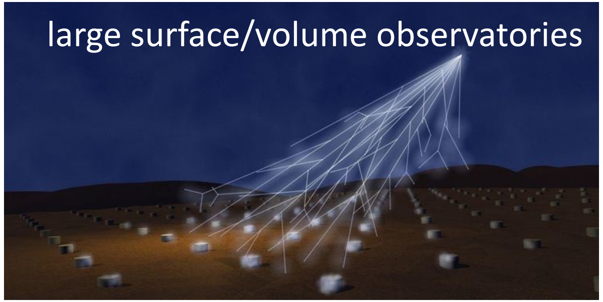
biological cell

atoms

proton neutron

age universe
$4.4\ 10^{18}$ s

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



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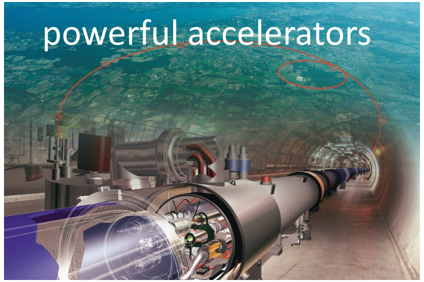

lifetime top quark
$5\ 10^{-25}$ s

quarks
< 10^{-19}m

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distance to galactic center

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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

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

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

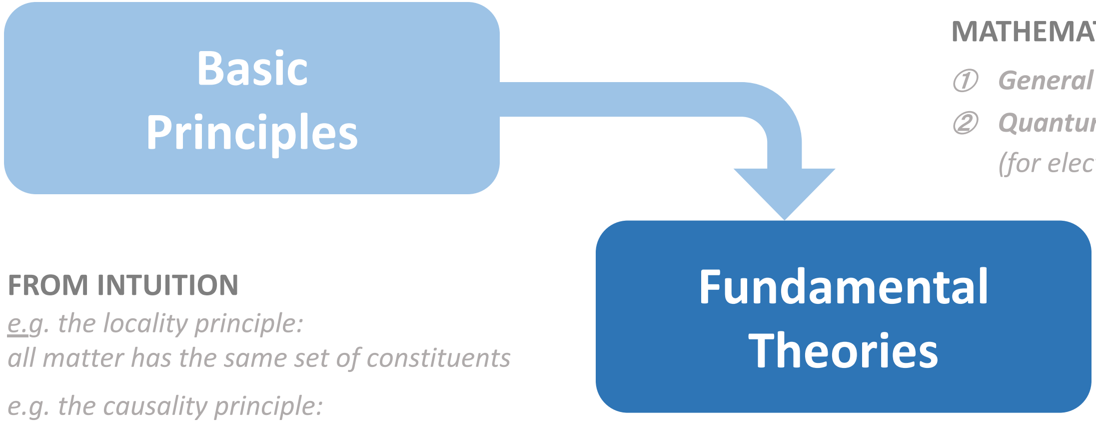
e.g. the invariance principle:
space-time is homogeneous

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



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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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)

Concrete Models

APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

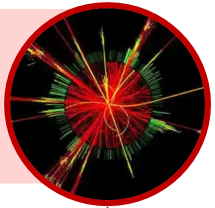
① ***General Relativity → Standard Model of Cosmology***
② ***Quantum Field Theory → Standard Model of Particle Physics***

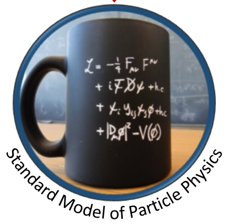
need to be valid into even the tiniest cracks of space and time
and for all energies or masses of the objects… even at the extremes

~ 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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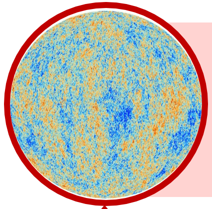
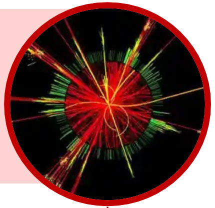
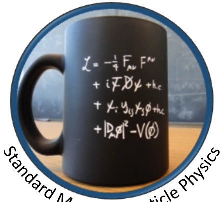


observations how large objects behave in our universe

Standard Model of Cosmology

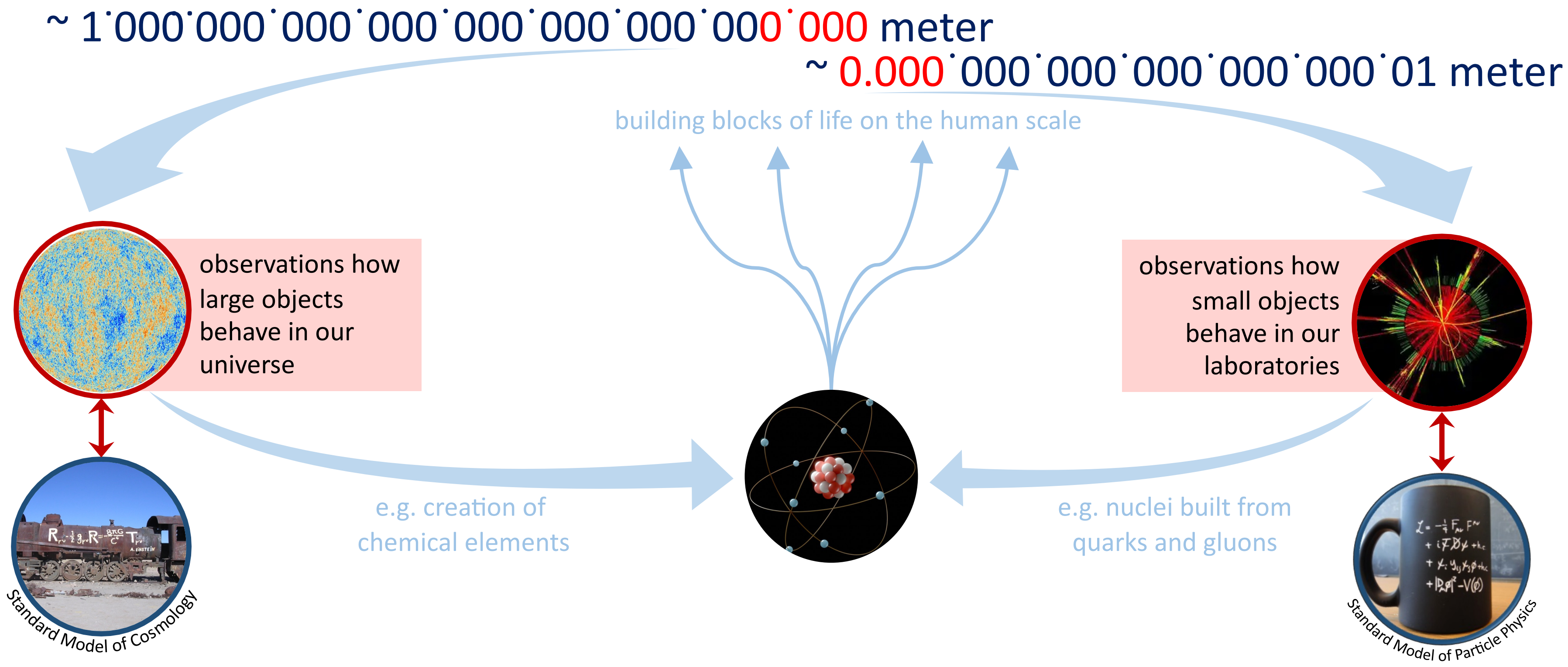


observations how small objects behave in our laboratories



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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building blocks of life on the human scale
observations how large objects behave in our universe
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

A century of scientific revolutions

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

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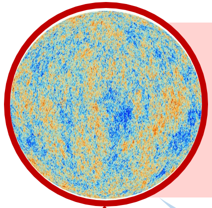
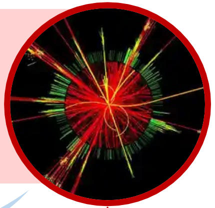
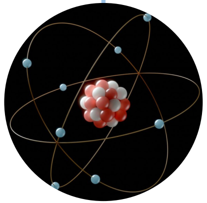


observations how large objects behave in our universe



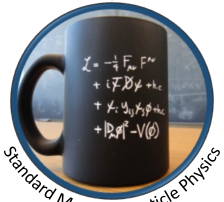
observations how small objects behave in our laboratories

Standard Model of Cosmology



e.g. creation of chemical elements

e.g. nuclei built from quarks and gluons



Standard Model of Particle Physics

communication
satellites
GPS

A century of scientific revolutions

World Wide Web
touchscreens

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

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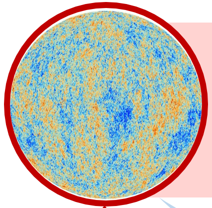
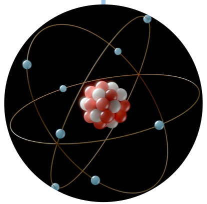
building blocks of life on the human scale



observations how large objects behave in our universe

Standard Model of Cosmology

production of particles and radiation
nuclear diagnosis and medicine



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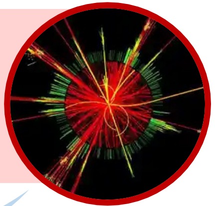
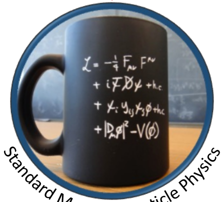


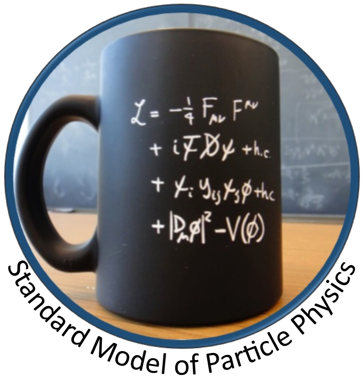


Standard Model of Particle Physics

“Scientific curiosity which ends up in your pocket”

Rolf Heuer (previous Director General of CERN)

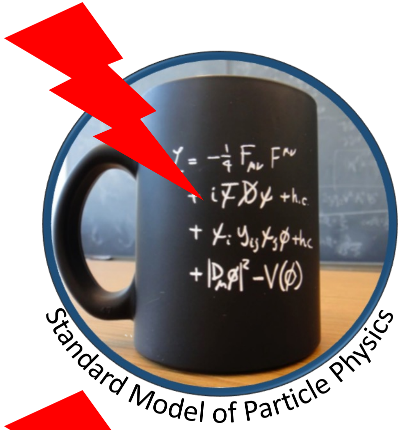
The quest for understanding physics

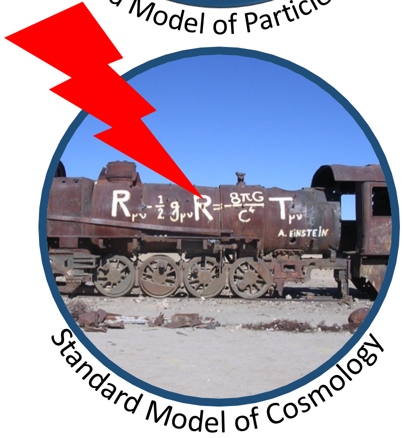


"Problems and Mysteries"

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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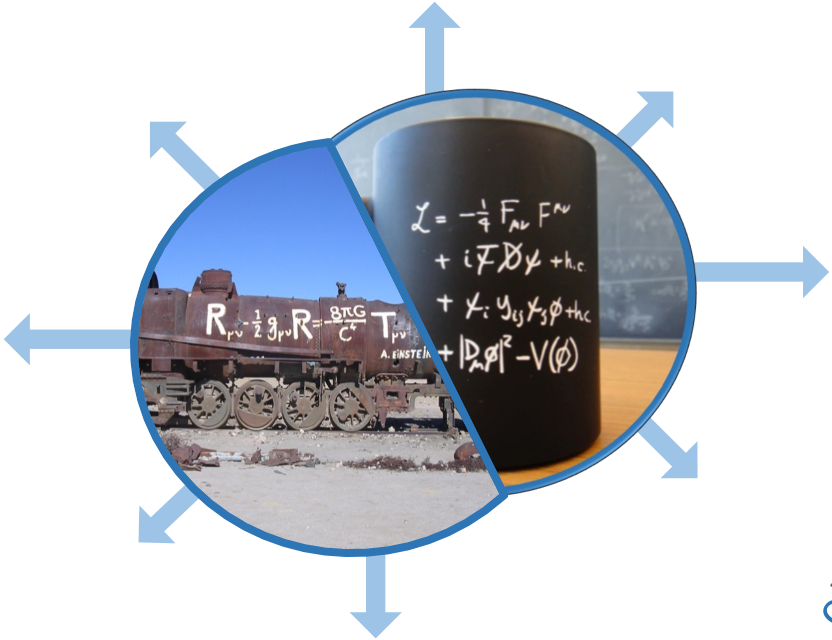
Pattern of particle masses and mixings?
Dynamics of Electro-Weak symmetry breaking?
How do quarks and gluons give rise to properties of nuclei?...

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

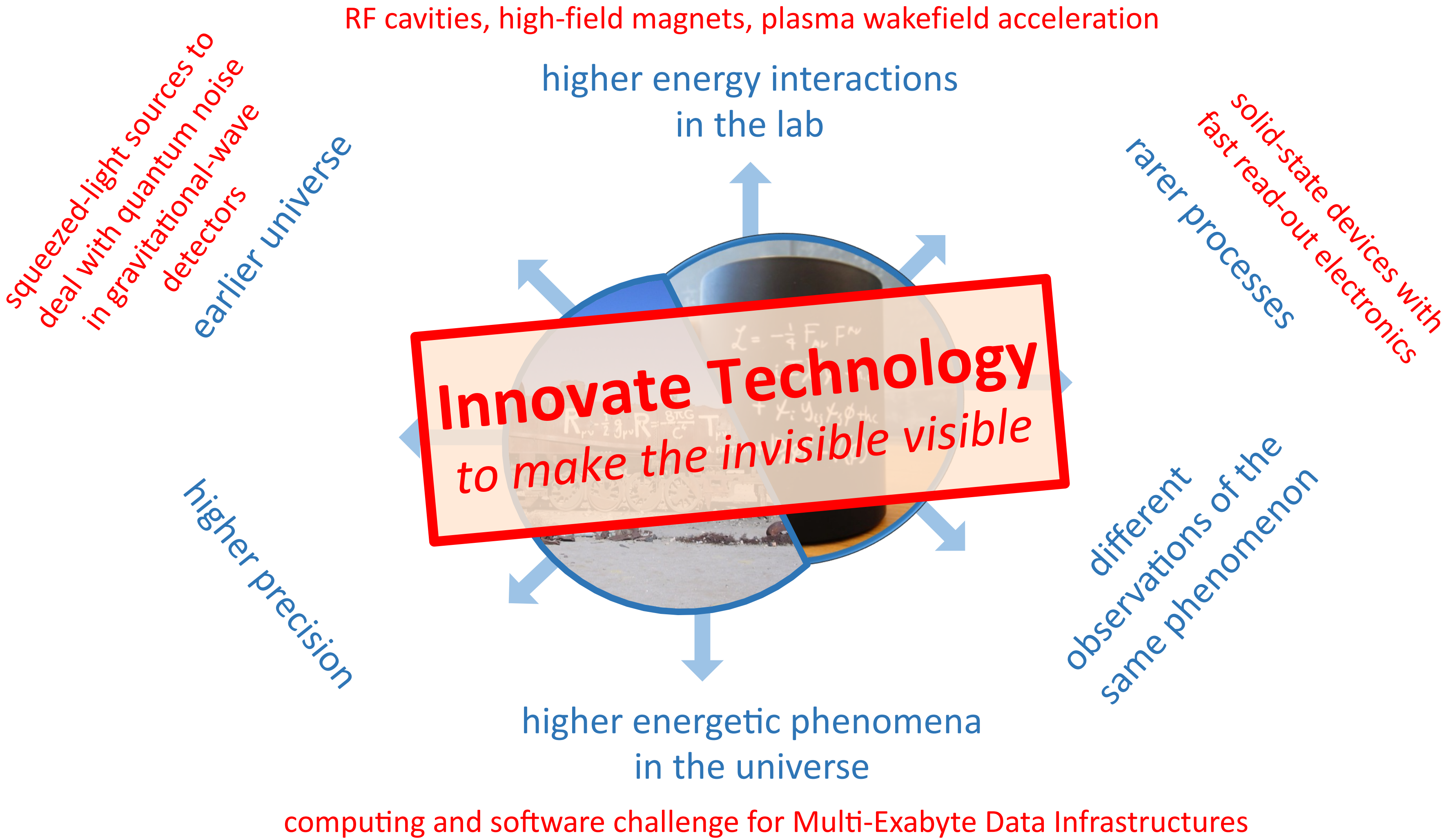
rarer processes



higher precision

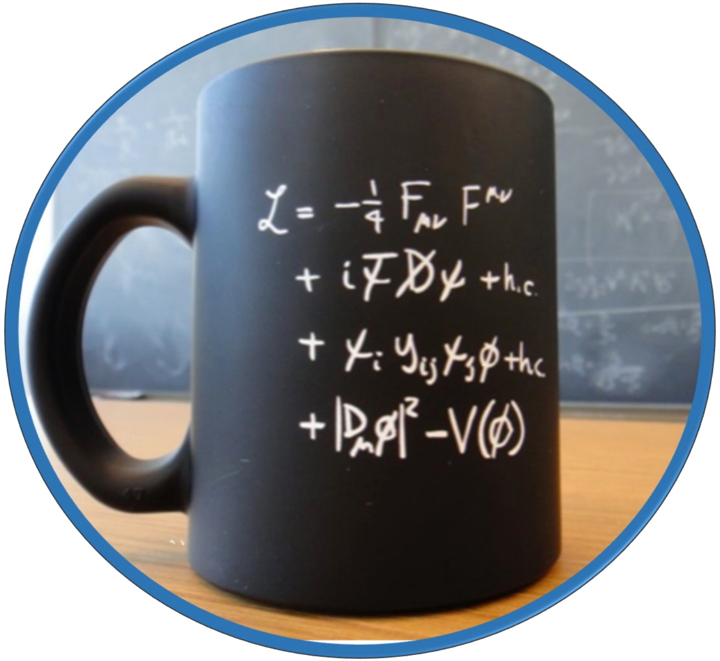
different
observations of the
same phenomenon

higher energetic phenomena
in the universe


RF cavities, high-field magnets, plasma wakefield acceleration
higher energy interactions in the lab
squeezed-light sources to deal with quantum noise in gravitational-wave detectors
earlier universe
solid-state devices with fast read-out electronics
rarer processes
Innovate Technology
to make the invisible visible
higher precision
different observations of the same phenomenon
higher energetic phenomena in the universe
computing and software challenge for Multi-Exabyte Data Infrastructures

Extending our models with new phenomena

(assuming our basic principles and theoretical frameworks hold)



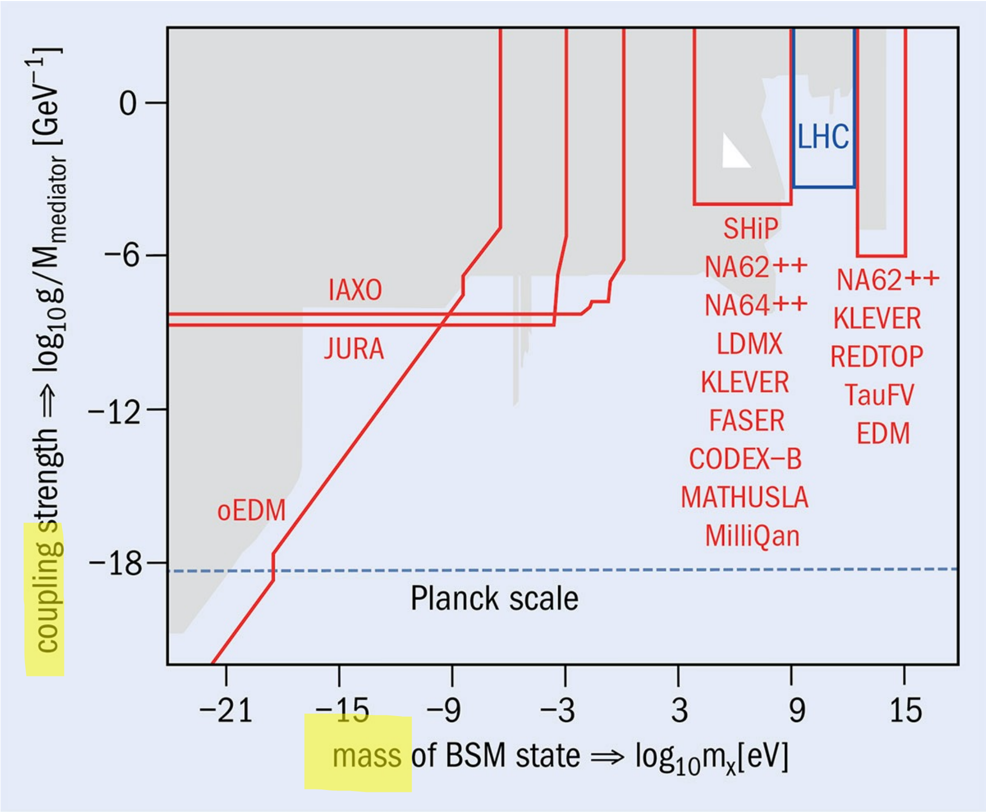
connection

(coupling strength)

Extending our models with new phenomena

(assuming our basic principles and theoretical frameworks hold)

Requires a coherent portfolio of complementary experiments to cover the whole parameter space where new physics can be hiding



Most recent European Strategies

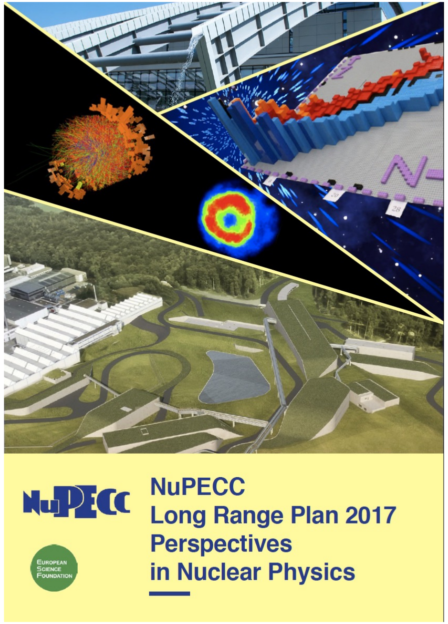
the large …

weblink

2017-2026 European
Astroparticle Physics Strategy

… the connection …

weblink



Long Range Plan 2017
Perspectives in Nuclear Physics

… the small

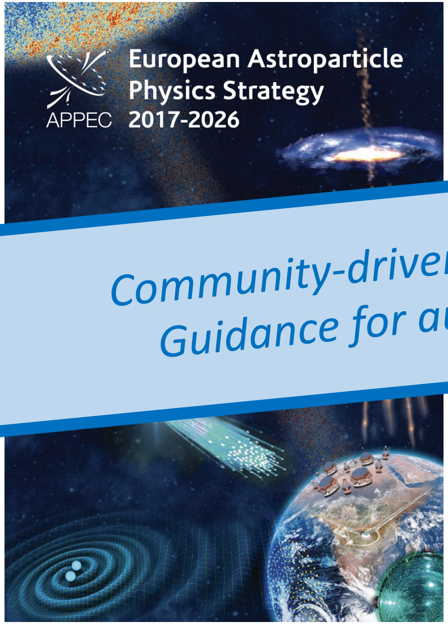
weblink

2020 Update of the European
Particle Physics Strategy

Most recent European Strategies

the large … … the connection … … the small

weblink



weblink

weblink

Community-driven strategies reflecting our ambition to address open questions.
Guidance for authorities to develop resource-loaded research programmes.

2017-2026 European Astroparticle Physics Strategy

Long Range Plan 2017 Perspectives in Nuclear Physics

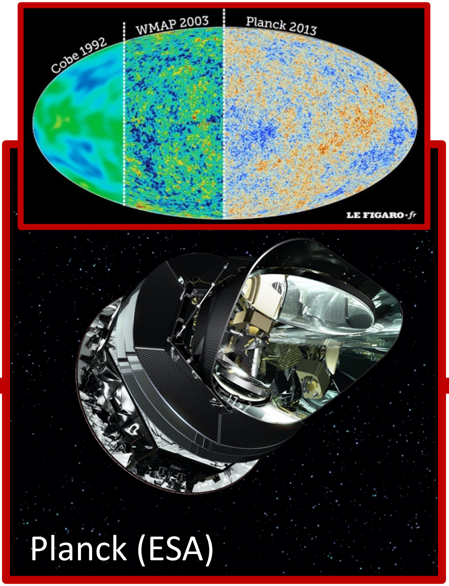
2020 Update of the European Particle Physics Strategy

our eyes on the sky

The cosmic frontier: Cosmic Microwave Background precision physics

Previous flagship

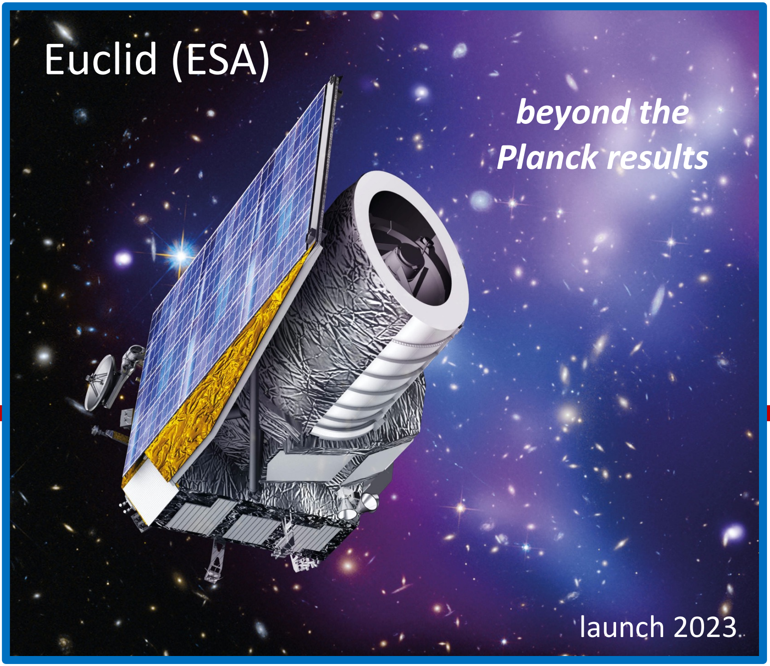
impressive science



completed

Next generation "Dark Universe" flagship

>30 M spectroscopic redshifts with 0.001 accuracy up to z~2
to measure the acceleration of the universe

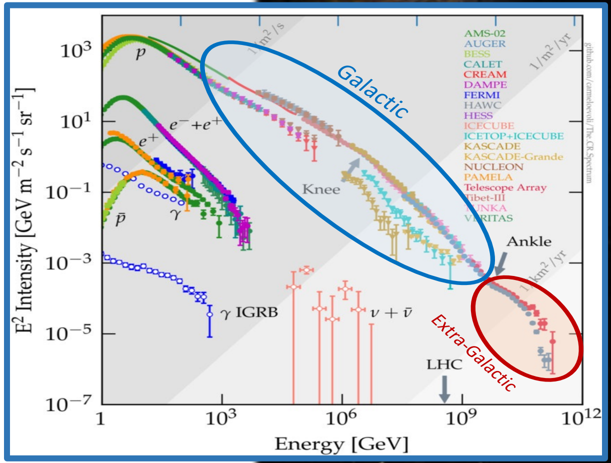


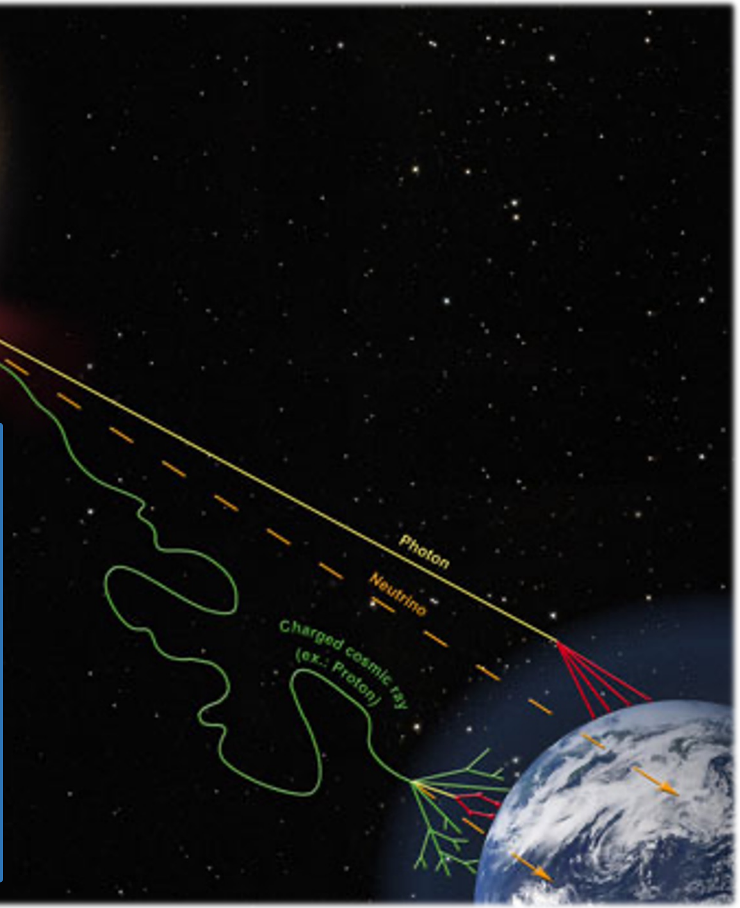
Properties of dark energy, dark matter and gravity

ESA: European Space Agency

A variety of very high-energy particles from our universe

cosmic particles





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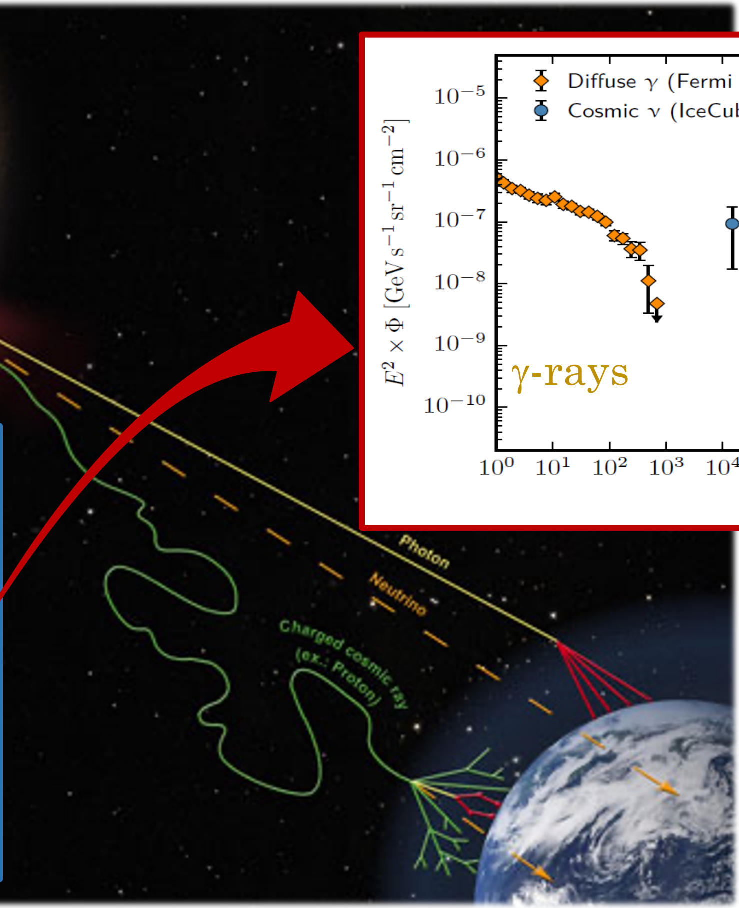
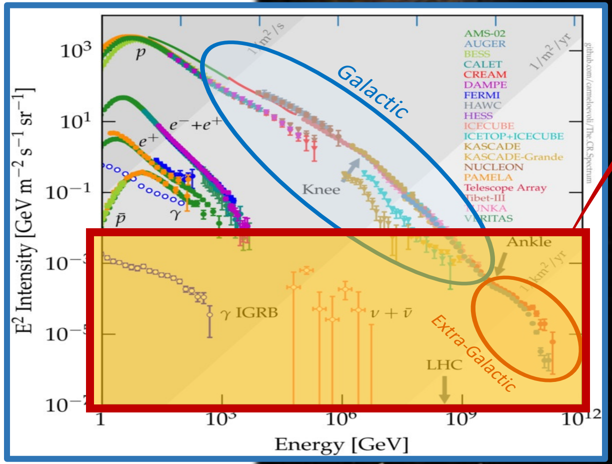
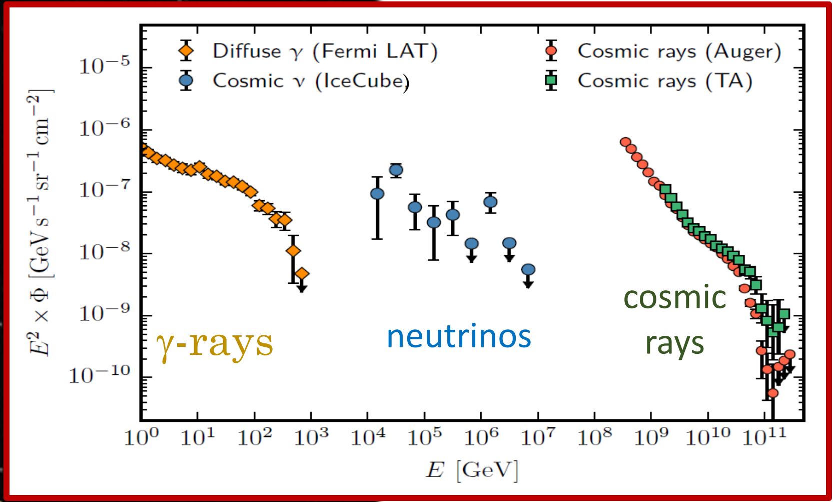




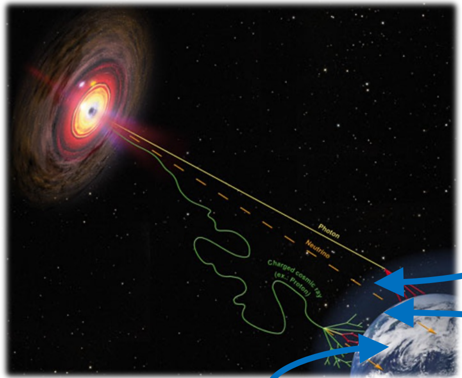


Similar cosmic energy density:
would they have a common origin?

into the global Multi-Messenger Realm for Astronomy to discover the sources

Major Cosmic Particle Facilities in Europe

advance our major participation outside Europe: Pierre Auger Observatory, IceCube(-Gen2), …



observatory in orbit

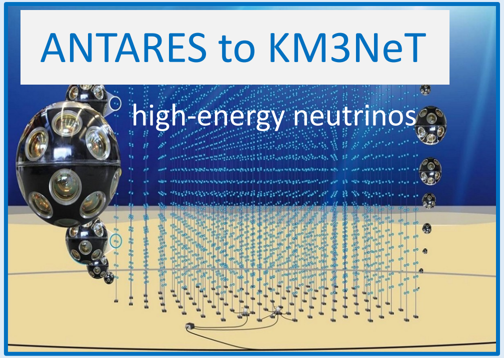
AMS-2

anti-matter in cosmic rays

assembled at CERN

data taking

observatory below surface



ANTARES to KM3NeT

high-energy neutrinos

construction, partially operational

BAIKAL-GVD

high-energy neutrinos

construction, partially operational

observatory on the surface

H.E.S.S./MAGIC/VERITAS to CTA

high-energy gamma-rays

construction, start observations >2023

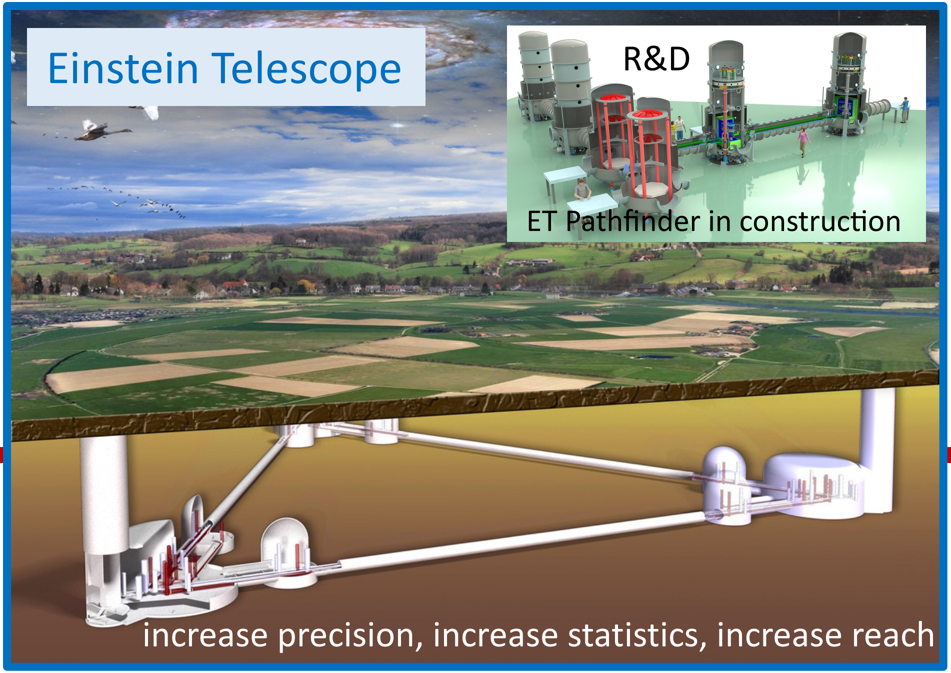
Gravitational Wave Facilities in Europe

Current flagships

Advanced & Plus upgrades up to 2035

3rd generation interferometer, beyond 2035

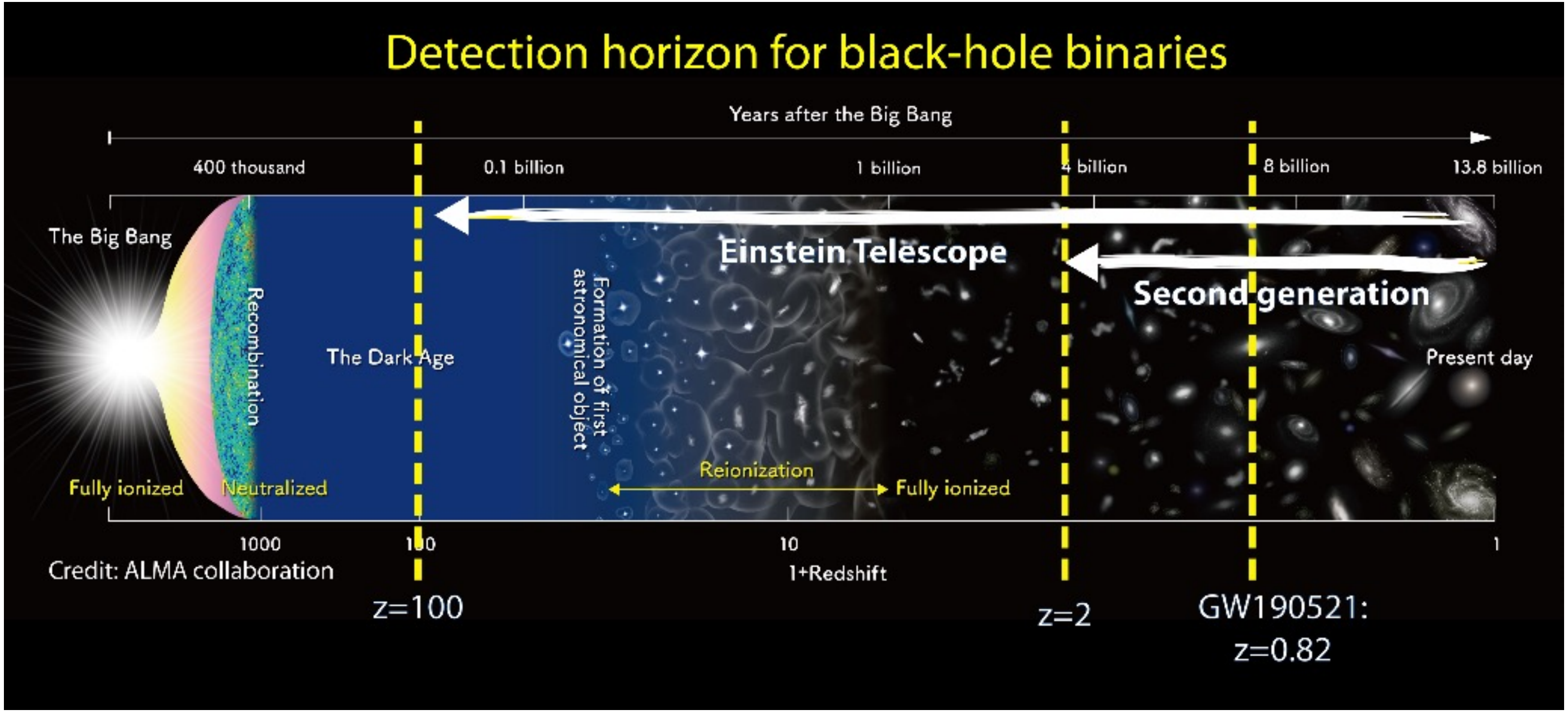
underground – triangle (10km arms) – cryogenic



on the ESFRI Roadmap (EU) (European Strategy Forum on Research Infrastructures)

complementary: LISA (ESA) to be launched around 2037

Gravitational Wave with the Einstein Telescope



Will our basic principles and theoretical frameworks hold throughout the cosmic history?

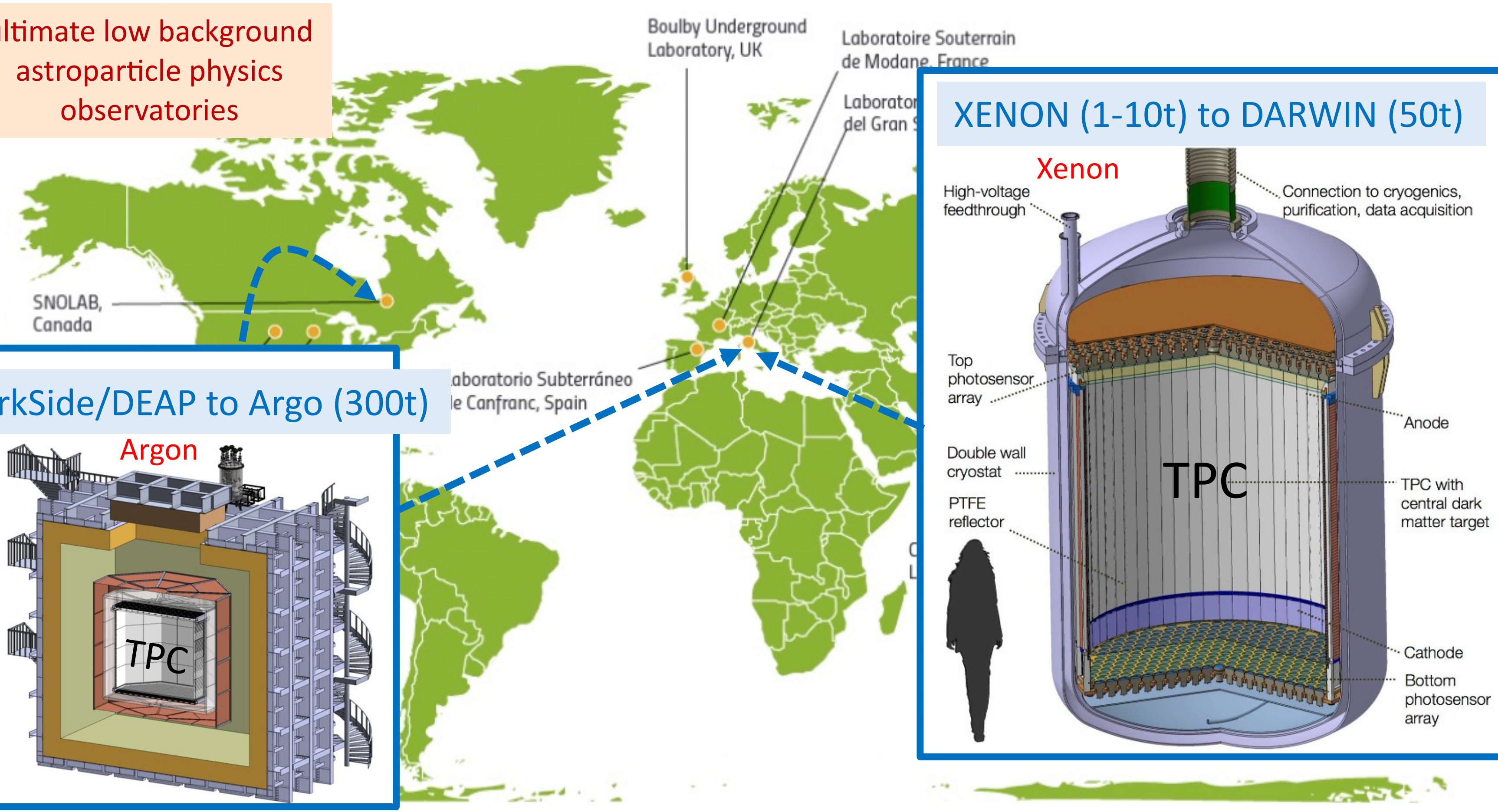
our eyes on the invisible

Major underground Facilities – shielding the visible

image courtesy of Susana Cebrián, "Science goes underground"

Major underground Facilities in Europe – Dark Matter

ultimate low background astroparticle physics observatories



DarkSide/DEAP to Argo (300t)

proposal

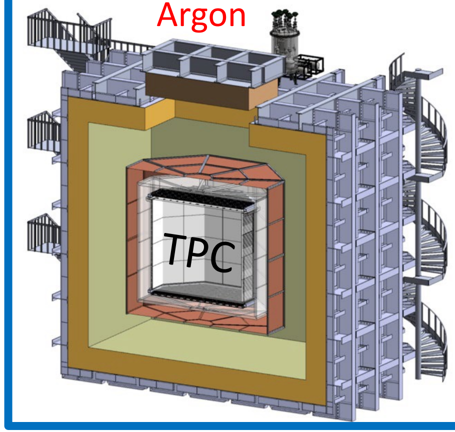
XENON (1-10t) to DARWIN (50t)

proposal towards CDR (beyond 2027)

Major underground Facilities in Europe – Dark Matter

ultimate low background astroparticle physics observatories

DarkSide/DEAP to Argo (300t)



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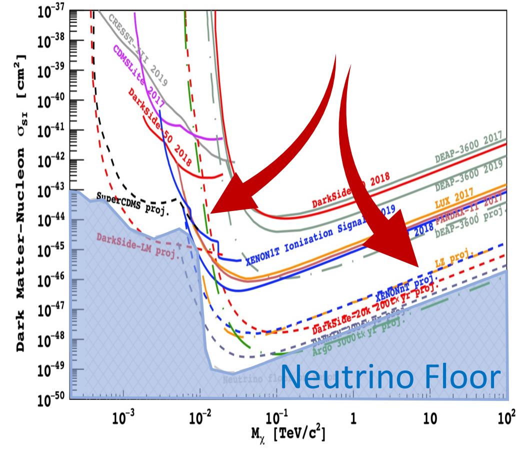
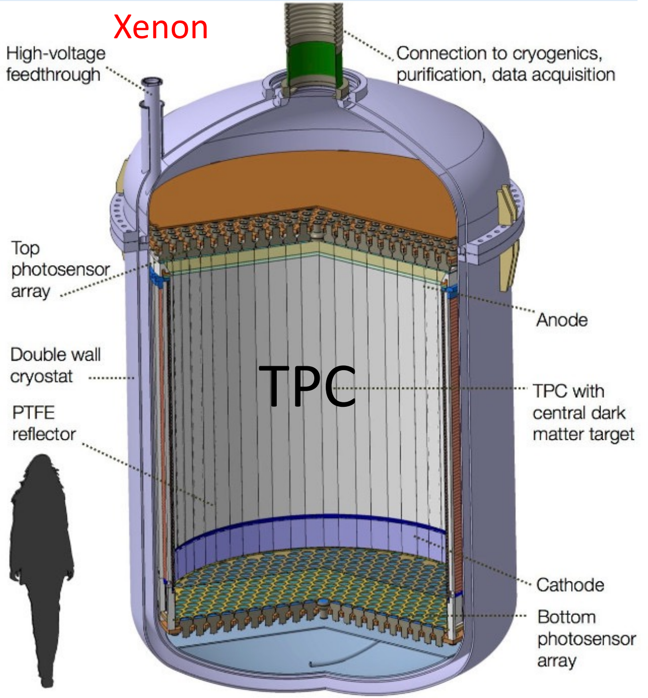


reaching the "neutrino floor"

where the neutrino backgrounds dominate

XENON (1-10t) to DARWIN (50t)

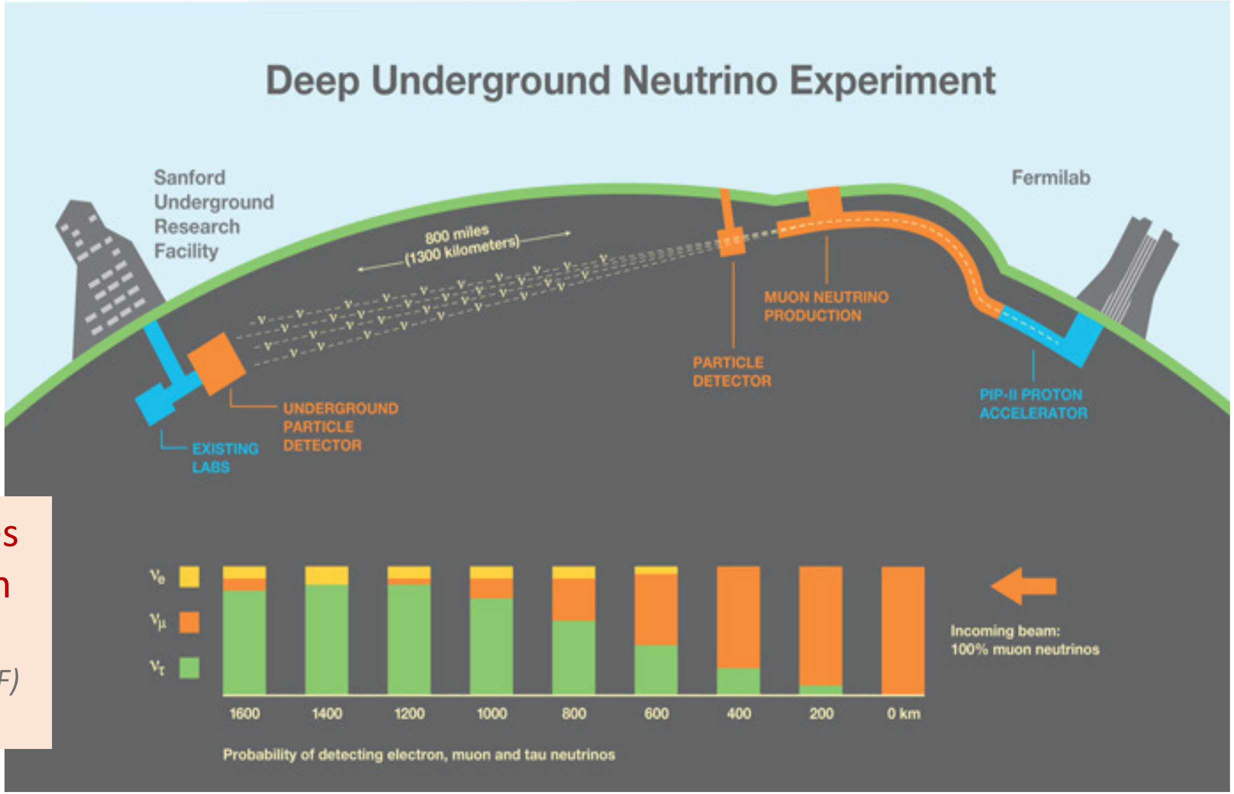


proposal towards CDR (beyond 2027)

Neutrino sector extends the Standard Model

Because neutrinos oscillate, they have mass… but how to extend the Standard Model?

- *Is a neutrino its own anti-particle?*
- *Is there CP violation in the leptonic sector?*
- *What is the absolute mass scale?*
- *How does the neutrino mass spectrum look like?*



Measure the oscillation probabilities of neutrinos and antineutrinos with ultimate precision

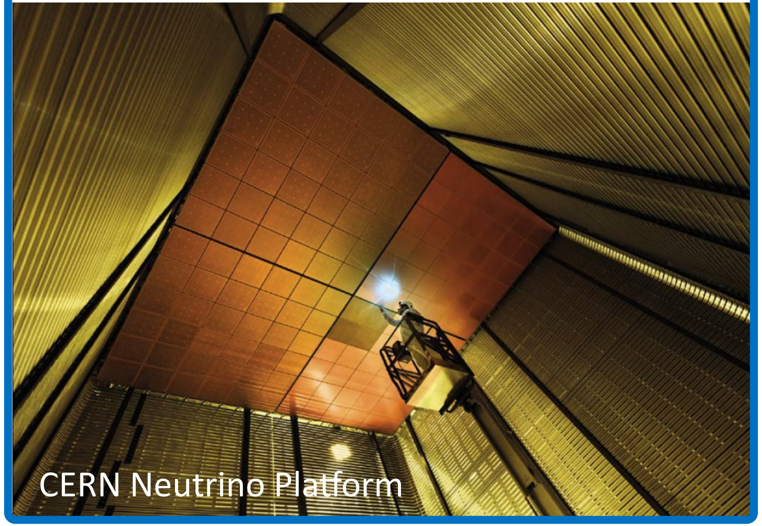
e.g. at the Long-Baseline Neutrino Facility (LBNF) with the DUNE experiment

Neutrino beams in Japan and in the US

CERN's Neutrino Platform in LBNF & DUNE (US), and in T2K (Japan)

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC



BabyMIND @ T2K (near detector)

Prototype for Magnetised Iron Neutrino Detector

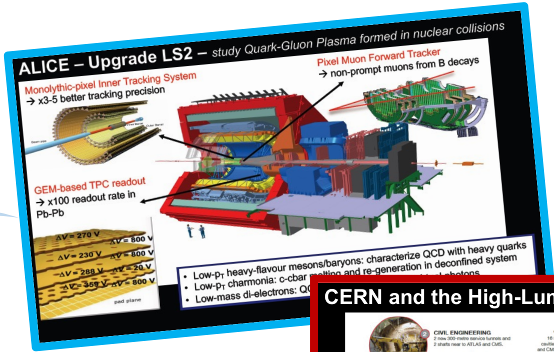
Within the next decade, we will know much more how to develop the neutrino sector to extend the Standard Model

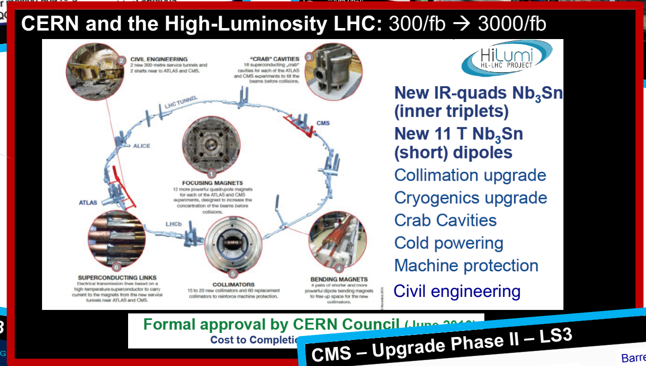
our eyes on direct discoveries

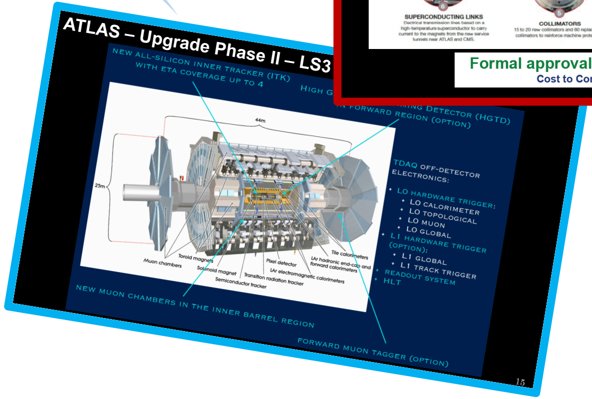
Today's Flagship: from LHC to HL-LHC

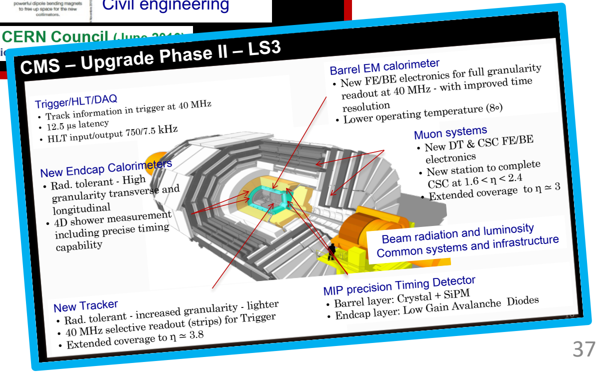
Current flagship (27km)

impressive programme up to 2040









continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

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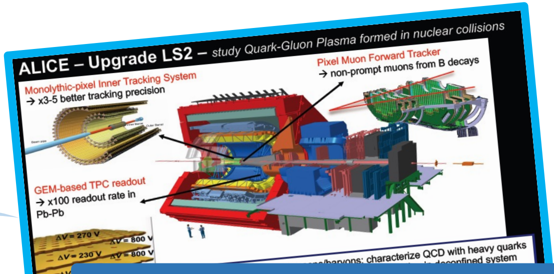
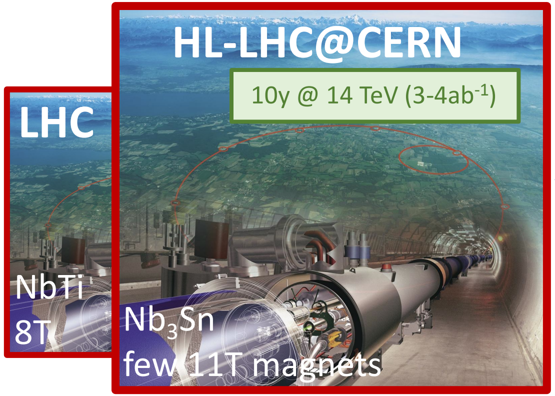


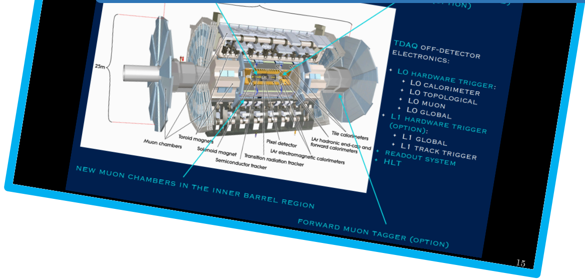


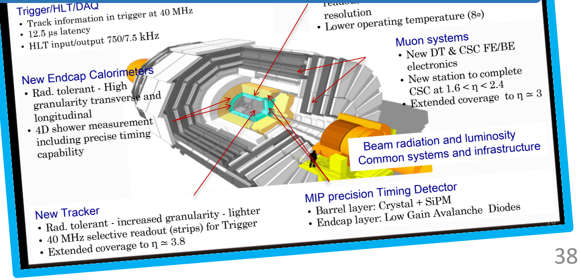
Talented researchers make the difference

In 2013, the expected precision on the top quark to Higgs coupling reachable with the HL-LHC programme was estimated 7-10%

In 2019, with innovated experimental and theoretical techniques this improved to 4% ... the HL-LHC is yet to start

continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers



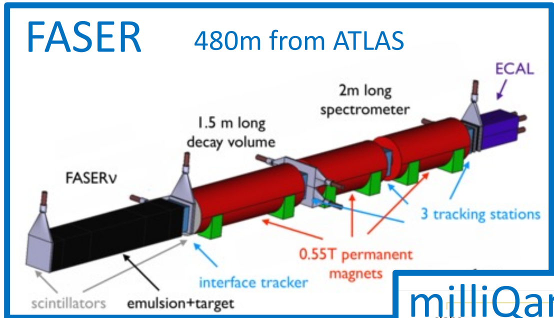


(HL-)LHC as a catalyser for dedicated experiments

Current flagship (27km)

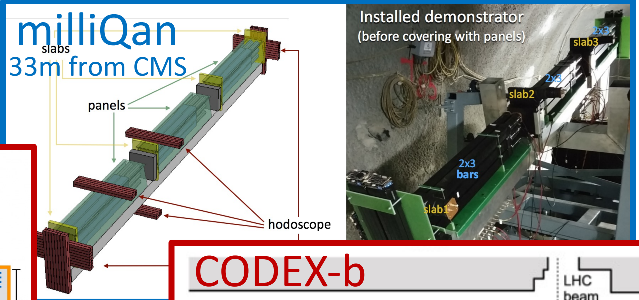
impressive programme up to 2040

Additional opportunities with high-energy proton collisions

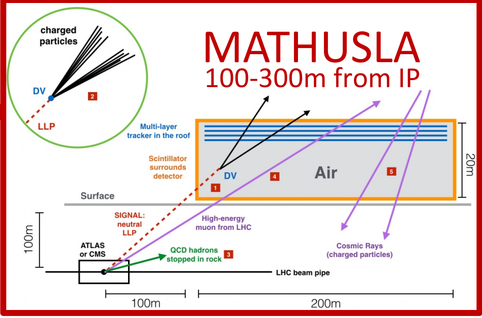


being installed

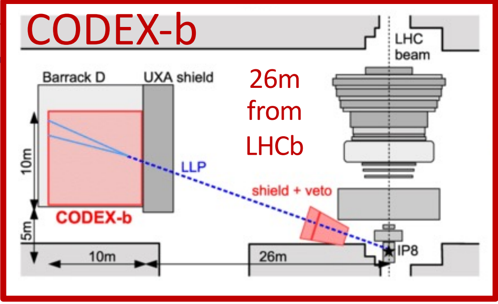
Long Lived Particles
Light & weakly coupling particles
Milli-charged particles
Magnetic Monopoles (MoEDAL)



being demonstrated



proposal



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(HL-)LHC as a catalyser for dedicated experiments

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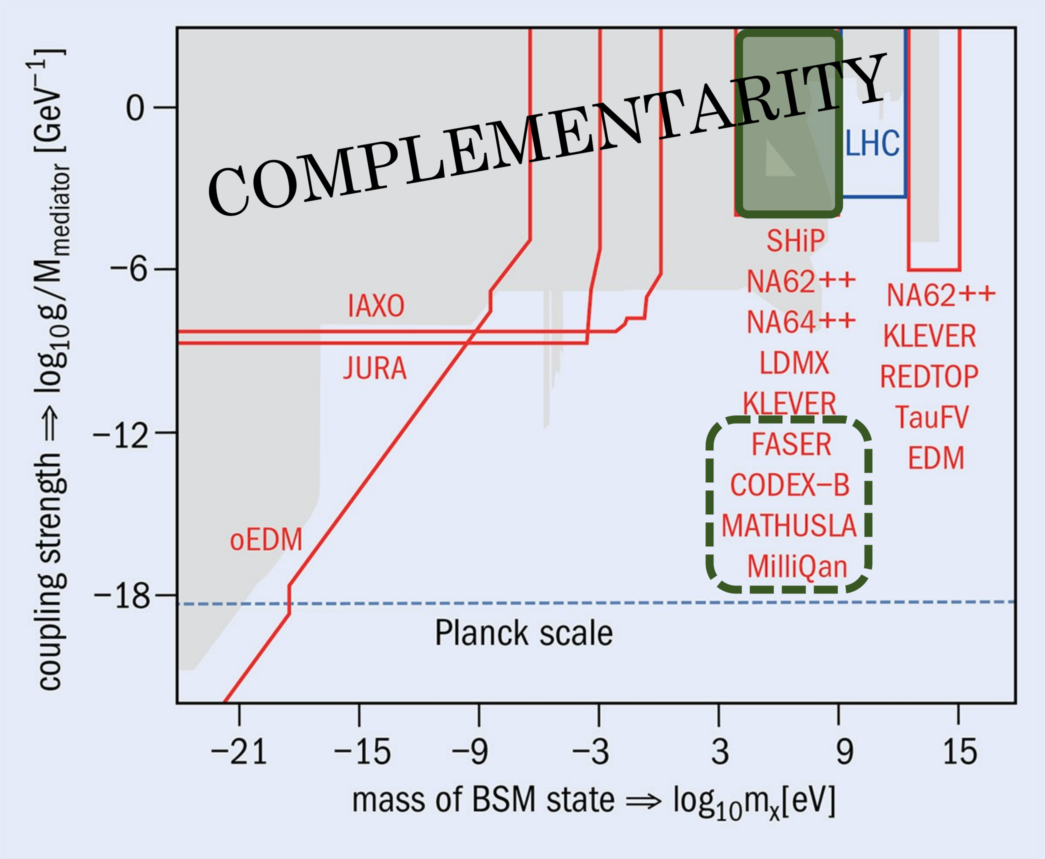
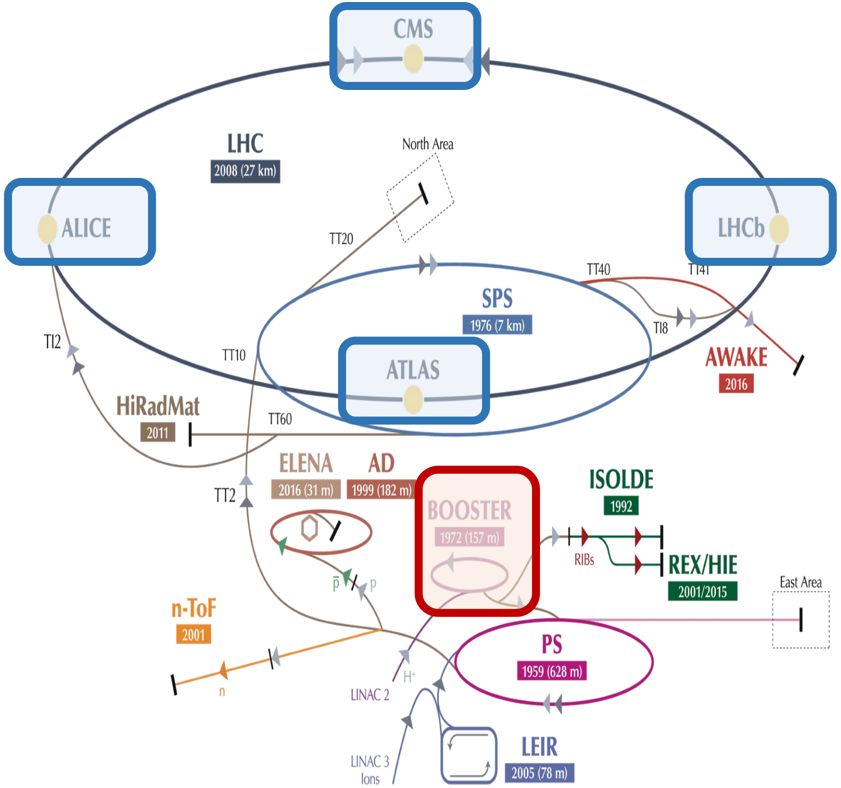
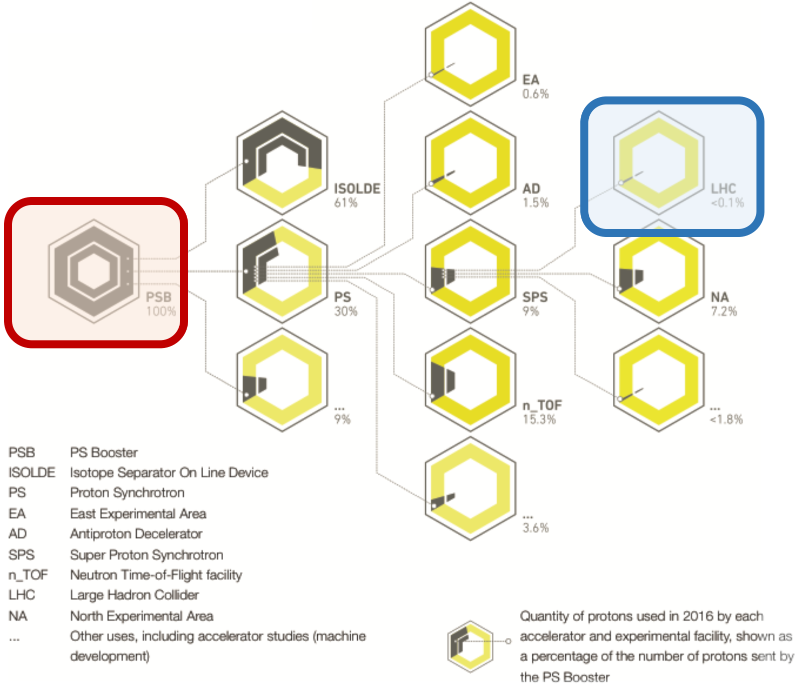


a high-energy proton collider is a catalyser for a unique portfolio of complementary research

While running the (HL-)LHC: Accelerated Beams at CERN

The CERN accelerator complex and the LHC – protons from Booster only <0.1% to LHC





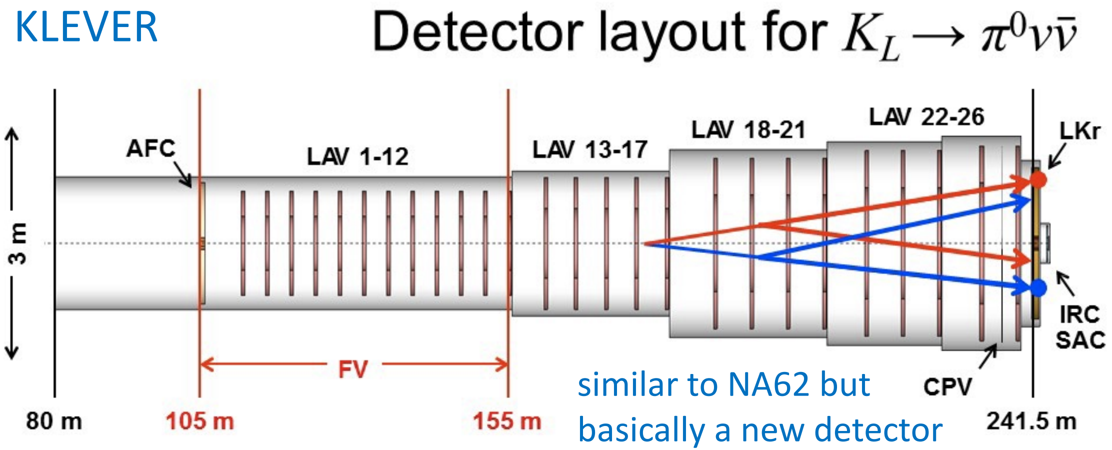
Kaon physics from NA62 to KLEVER @ SPS-CERN

During LHC era

running

During HL-LHC era

KLEVER



similar to NA62 but basically a new detector

proposal

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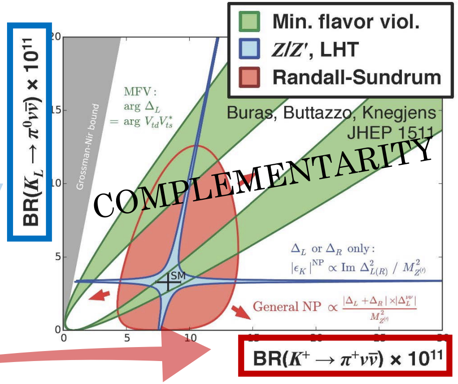
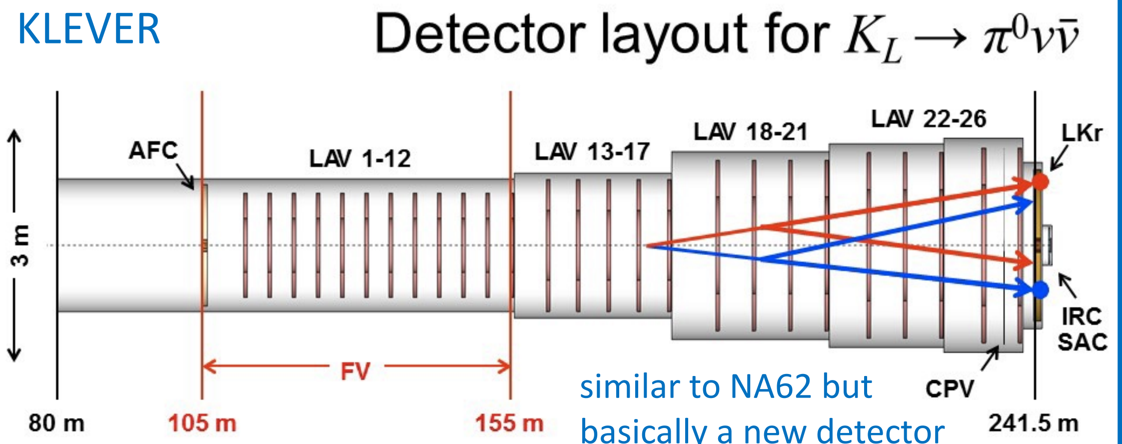


During LHC era

running

During HL-LHC era

KLEVER



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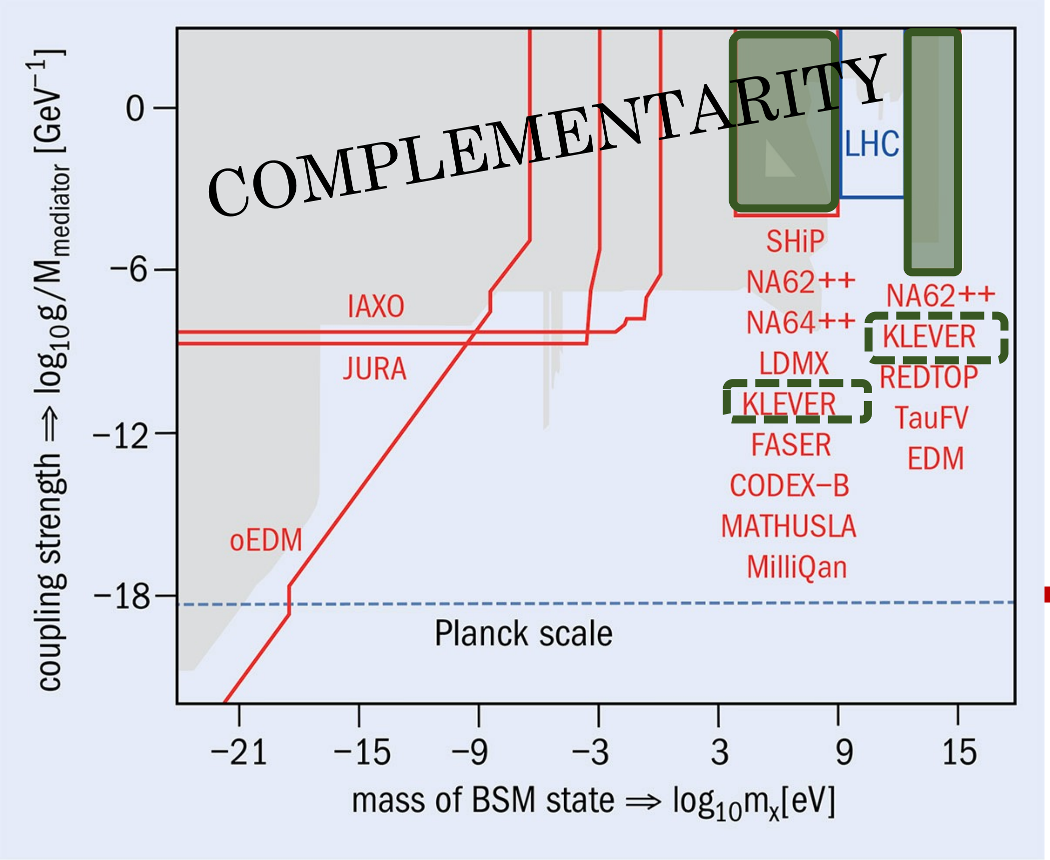
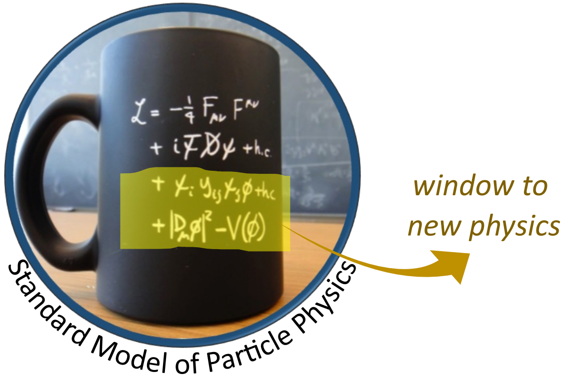


Future high-energy particle colliders

Essentially all problems of the Standard Model are related to the Higgs sector, hence the argument to built new colliders dedicated to produce copiously Higgs bosons in order to map precisely its interactions with other particles.

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



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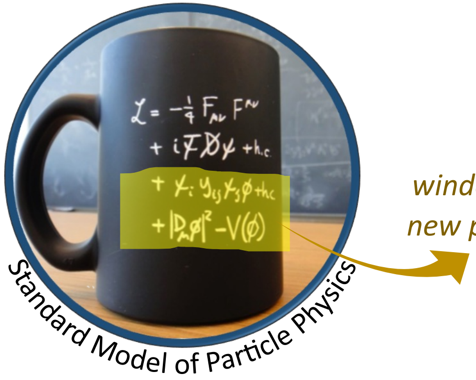
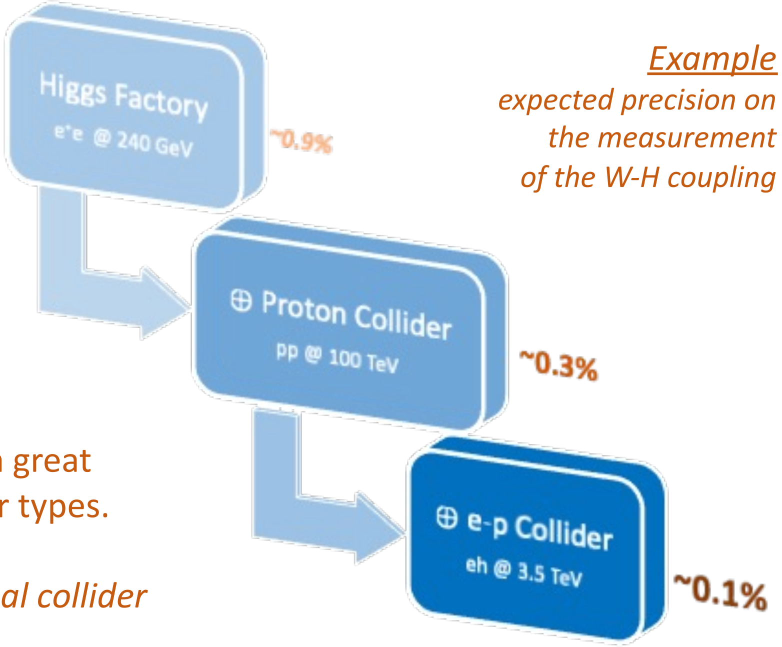


window to new physics



<u>Example</u>

expected precision on the measurement of the W-H coupling

In the search for answers to open questions, we discovered a great complementarity among the science reach of different collider types.

the combined precision is much better than that of each individual collider

We need a coherent program allowing for a variety of future colliders

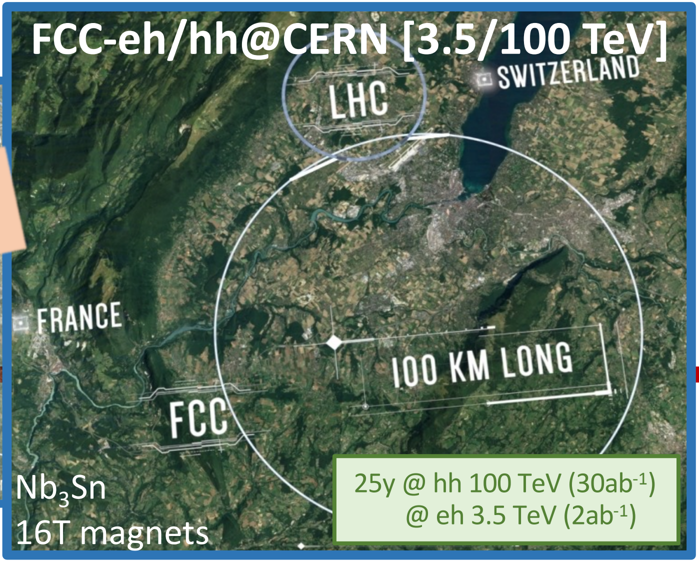
Future flagship at the energy & precision frontier

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 2007.14491



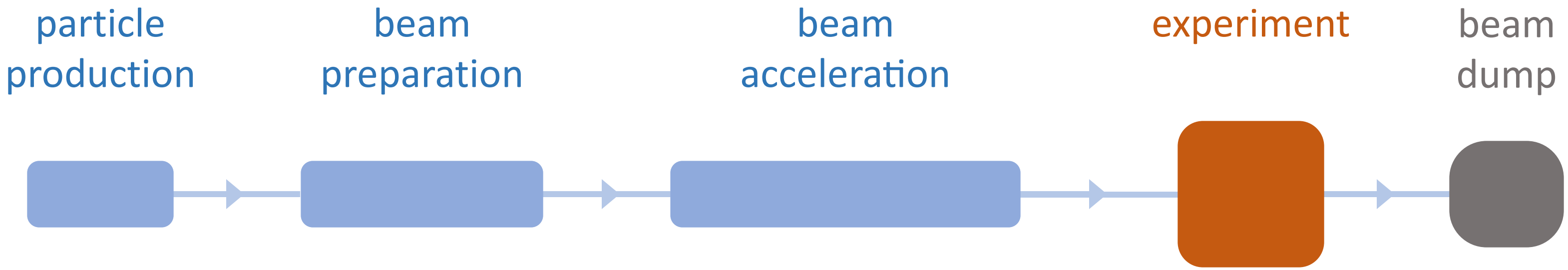
numbers assume 2 IPs for each collider (only one for FCC-eh)

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

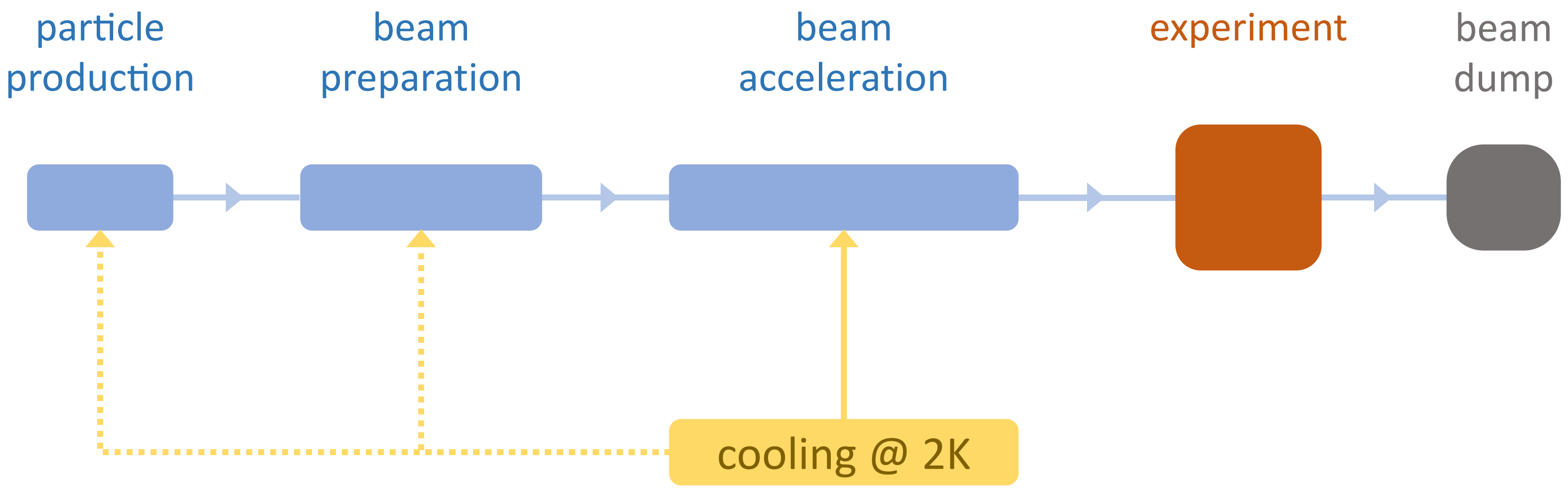
potential alternatives pursued @ CERN: CLIC & muon collider

Sustainable Accelerating Structures

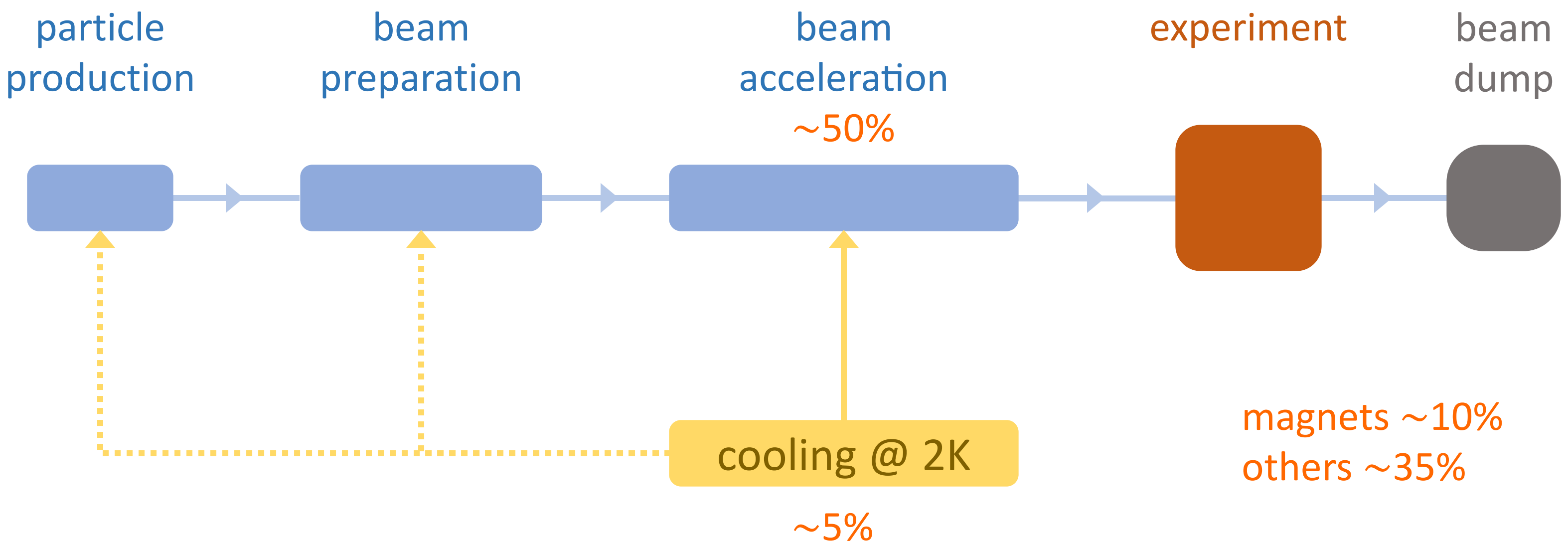
Basic structures of a particle accelerator



Basic structures of a particle accelerator



Basic structures of a particle accelerator



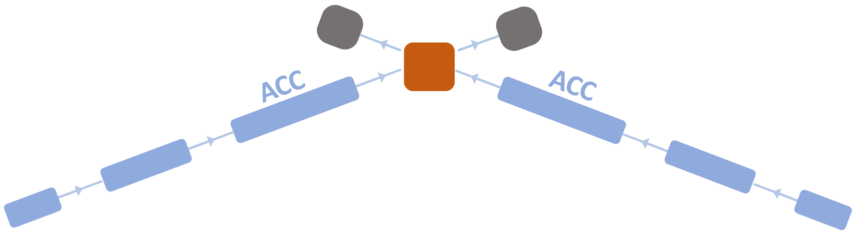
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

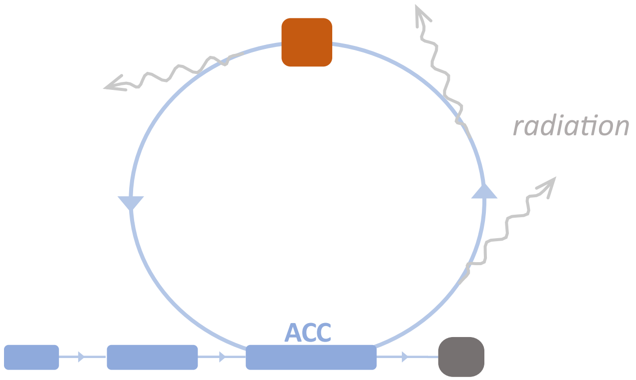
example FCC@250GeV

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

∼2% of annual electricity consumption in Belgium

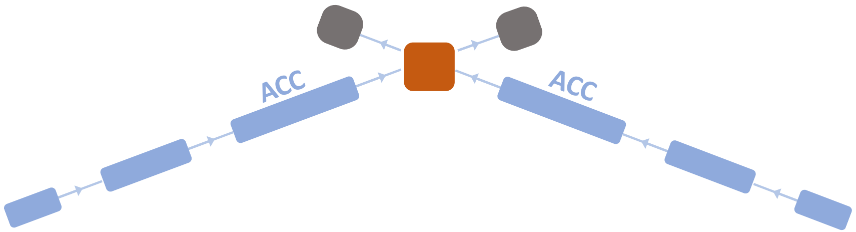
radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

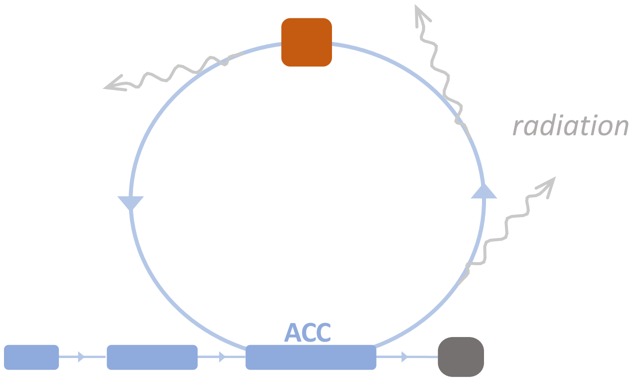
OBJECTIVE: develop accelerator technologies that recover the beam energy with an impact of saving ∼1% of Belgium's electricity

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

radiate away very quickly the beam power

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

about half of this is dumped or lost due to radiation

OBJECTIVE: develop accelerator technologies that recover the beam energy with an **impact of saving ~2% of Belgium's electricity**

Importance highlighted in the European Strategy for Particle Physics 2020

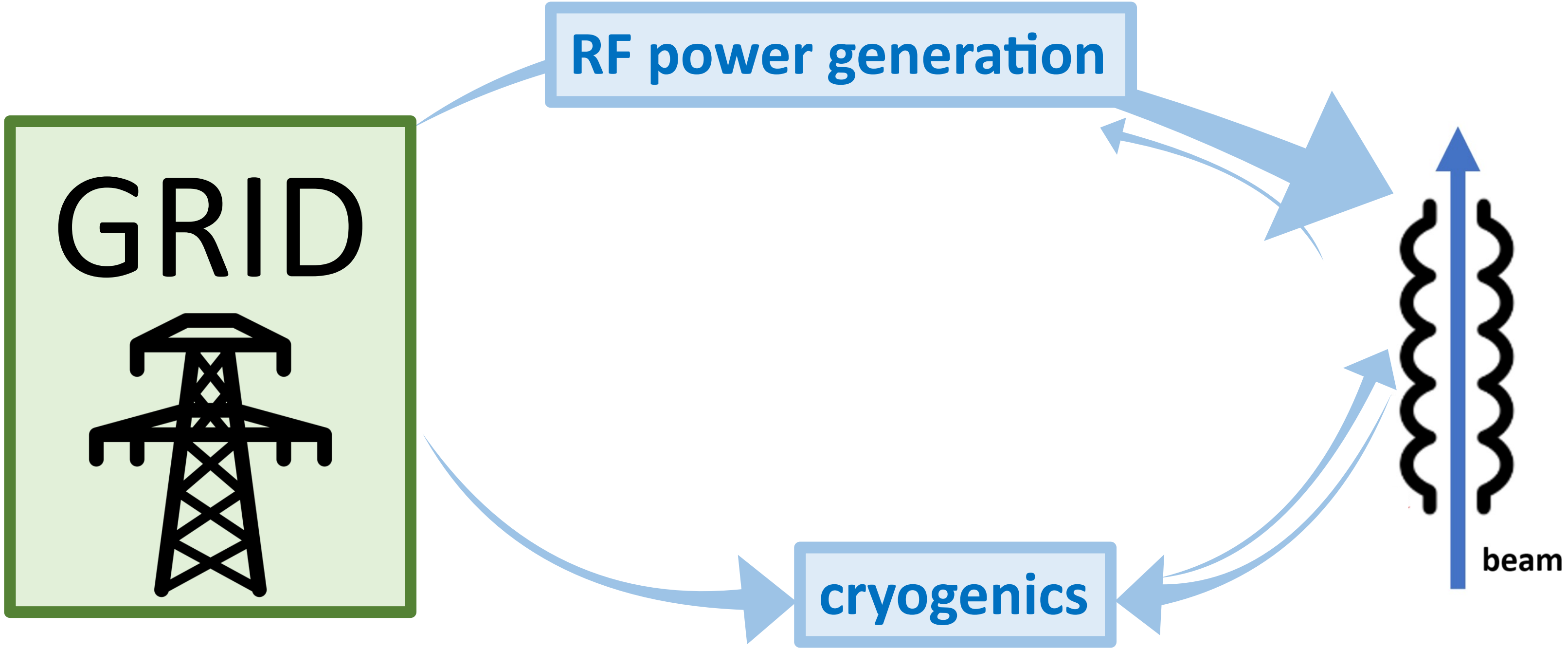
An electron-positron Higgs factory is the highest-priority next collider.

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.

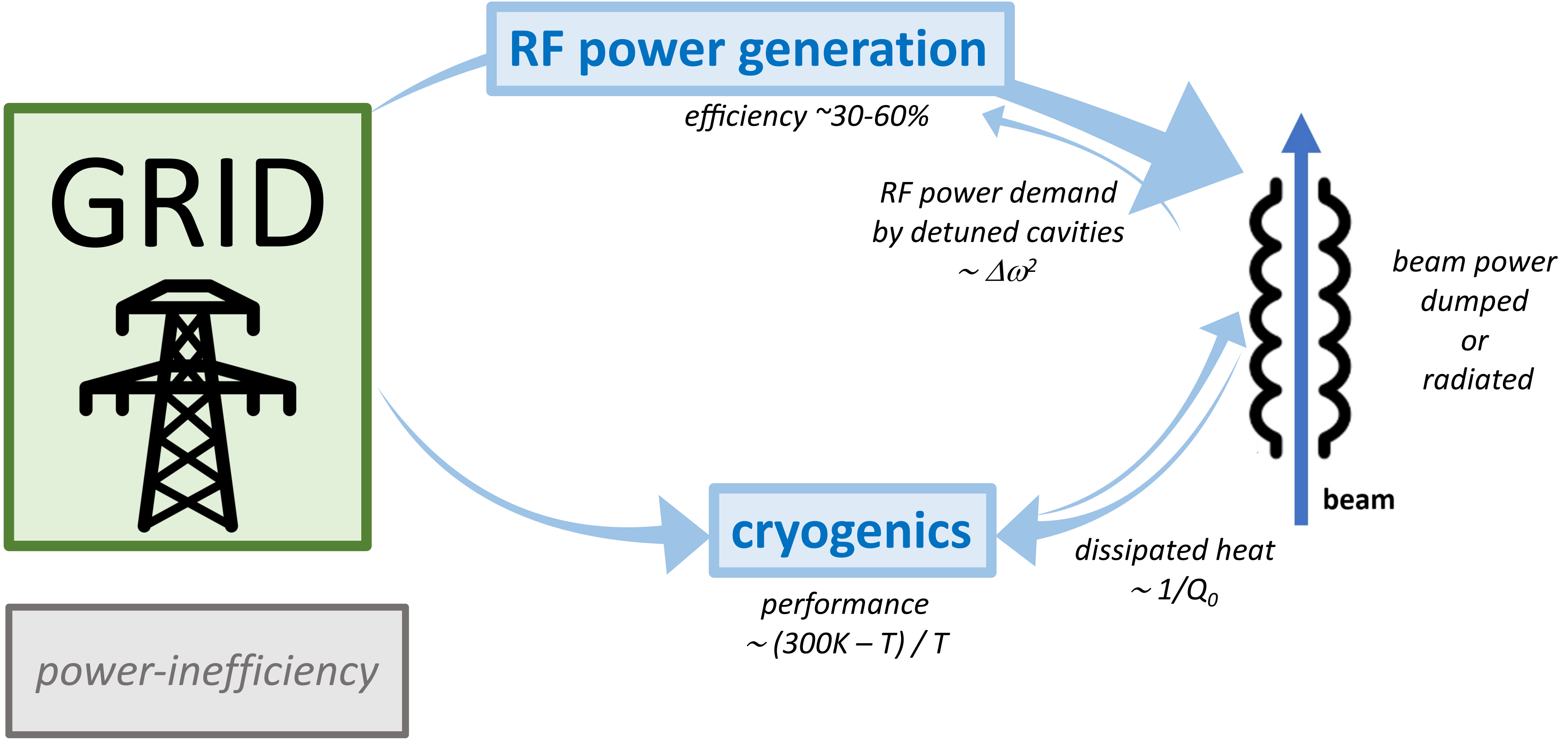
European Strategy for Particle Physics 2020

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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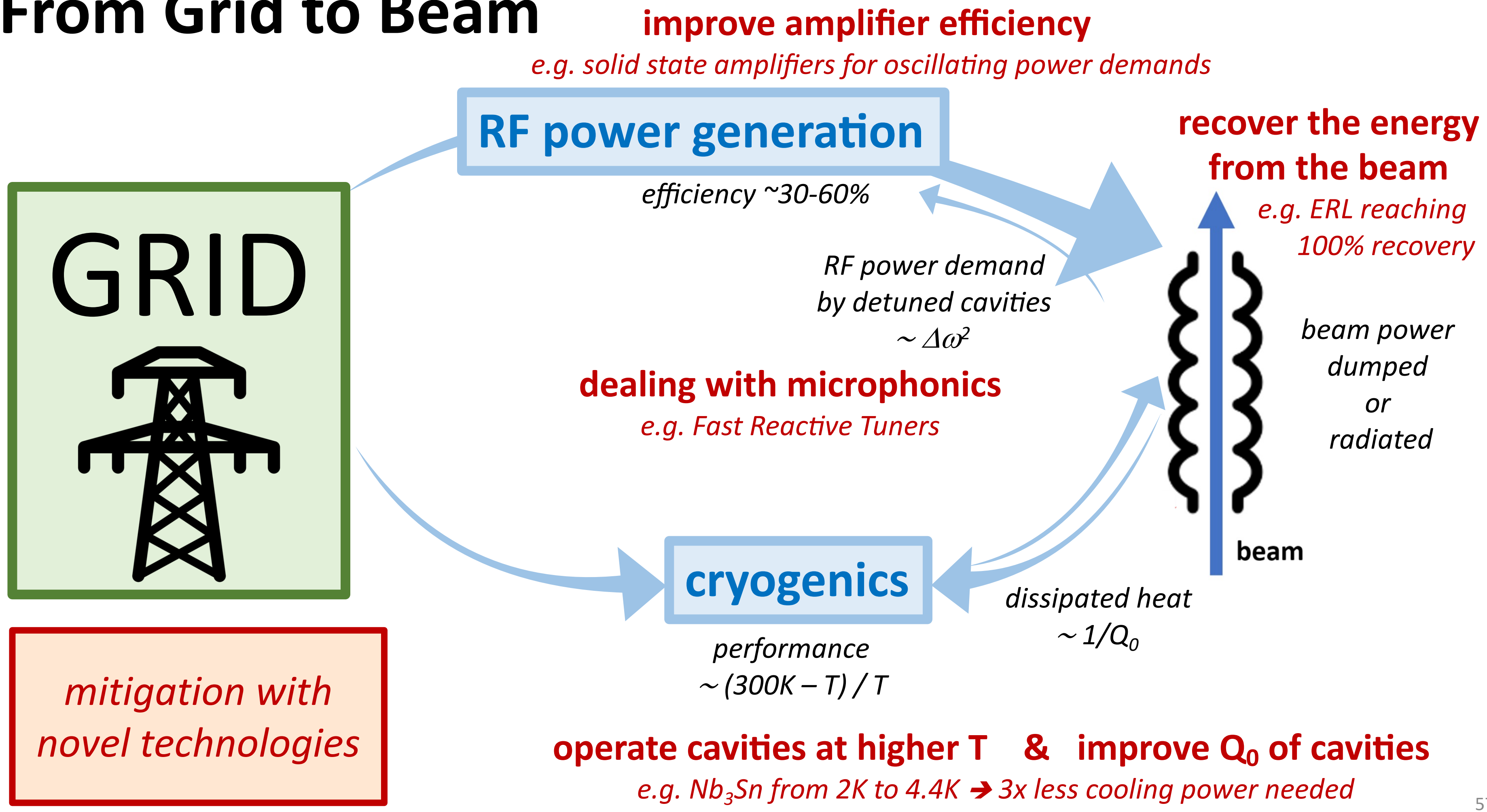

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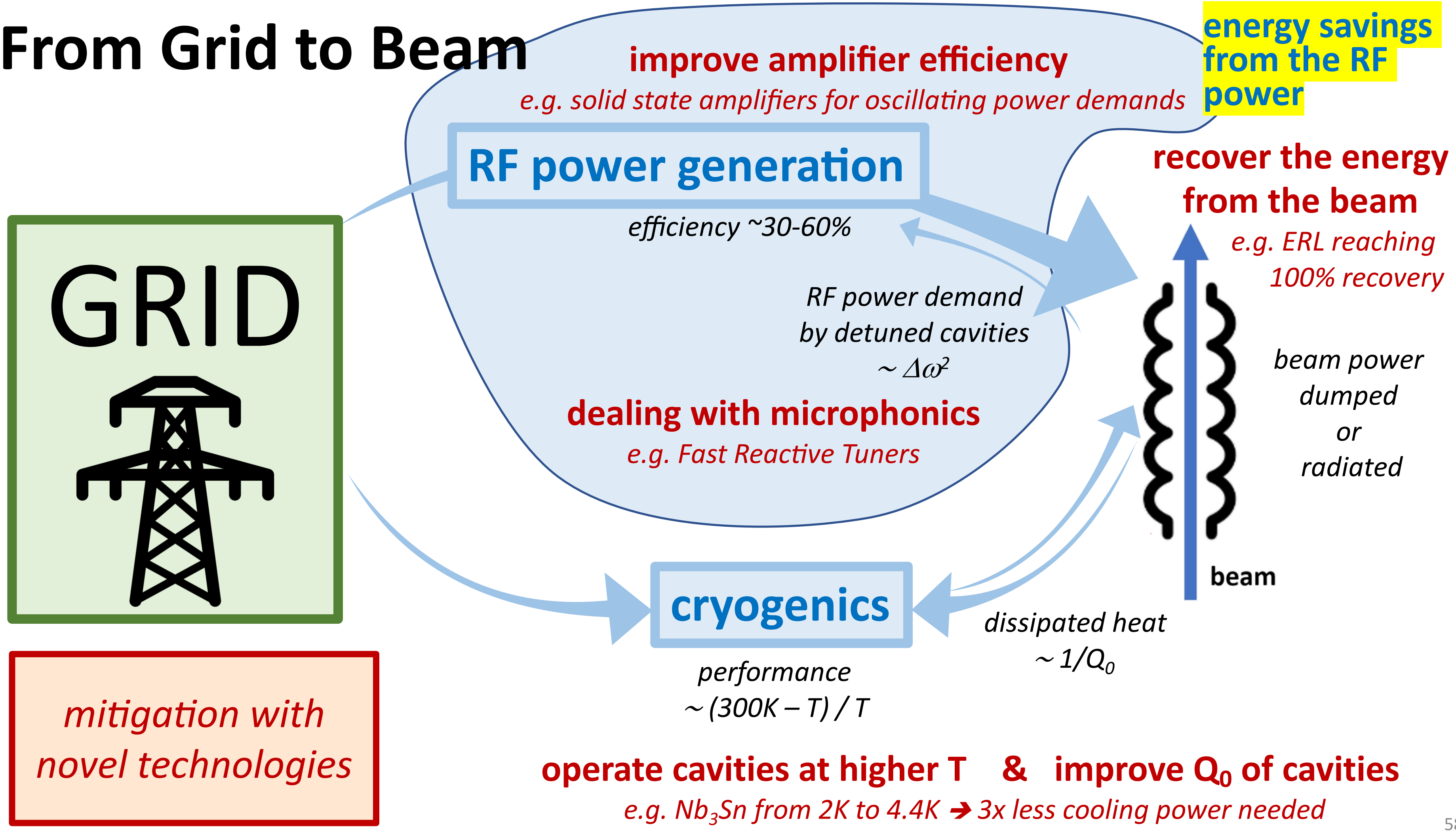

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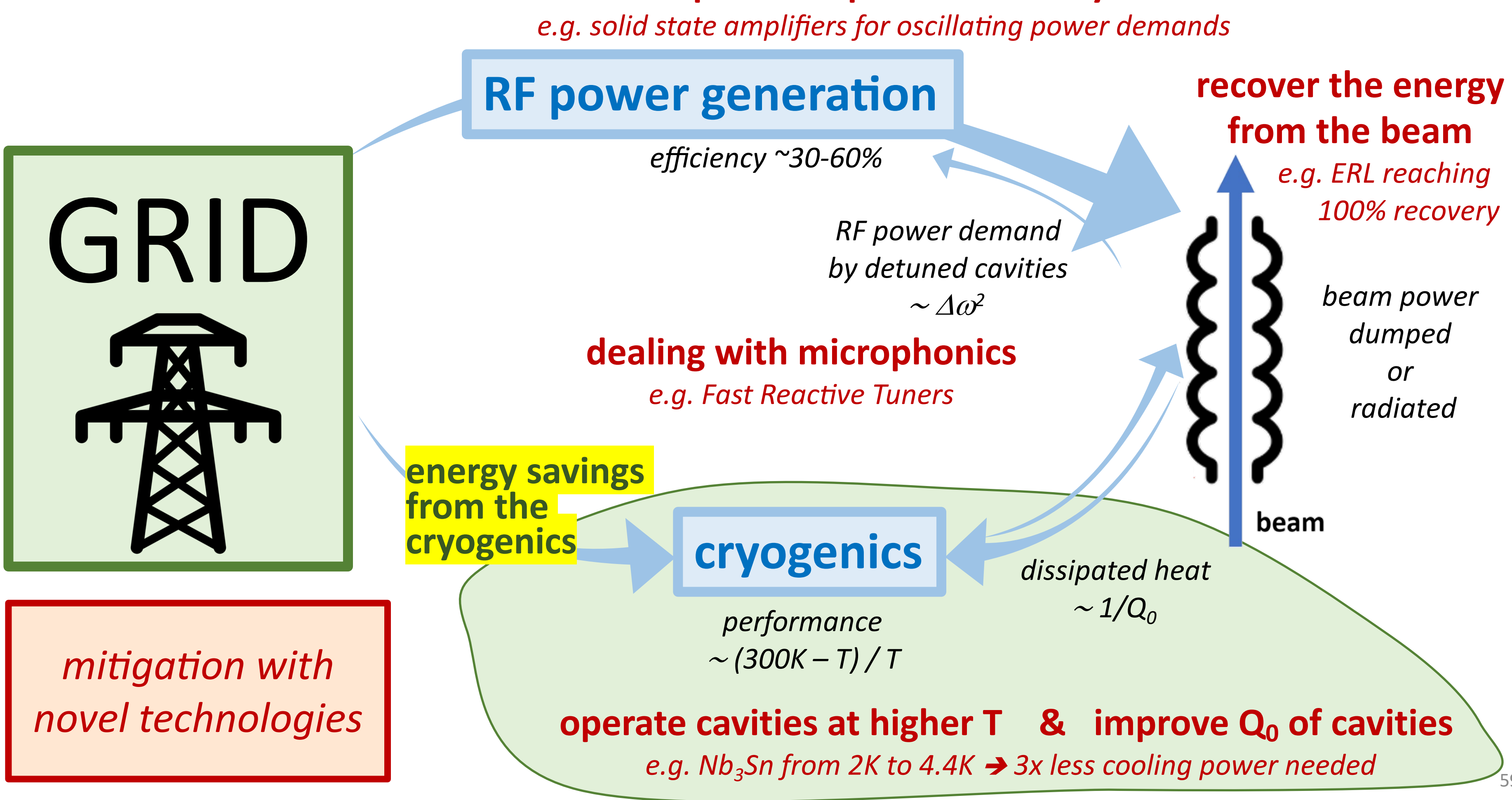
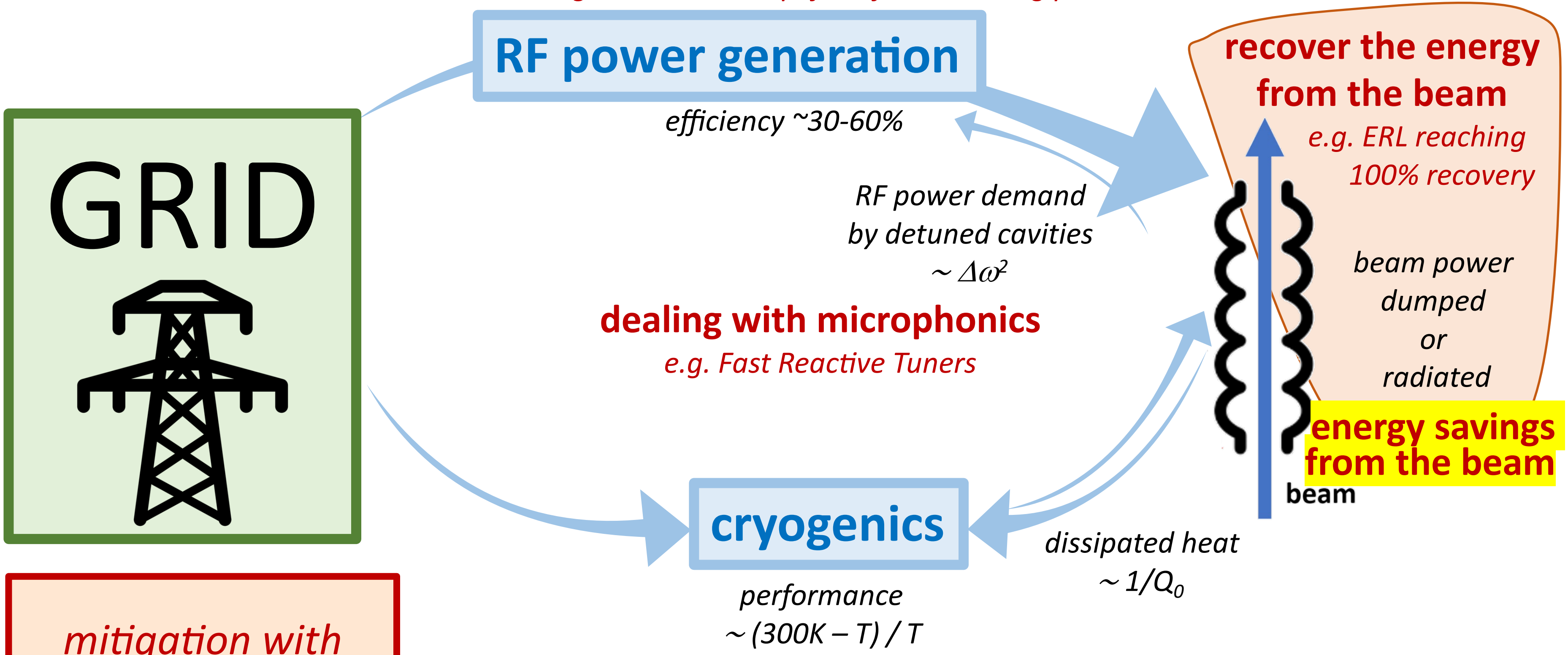


From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

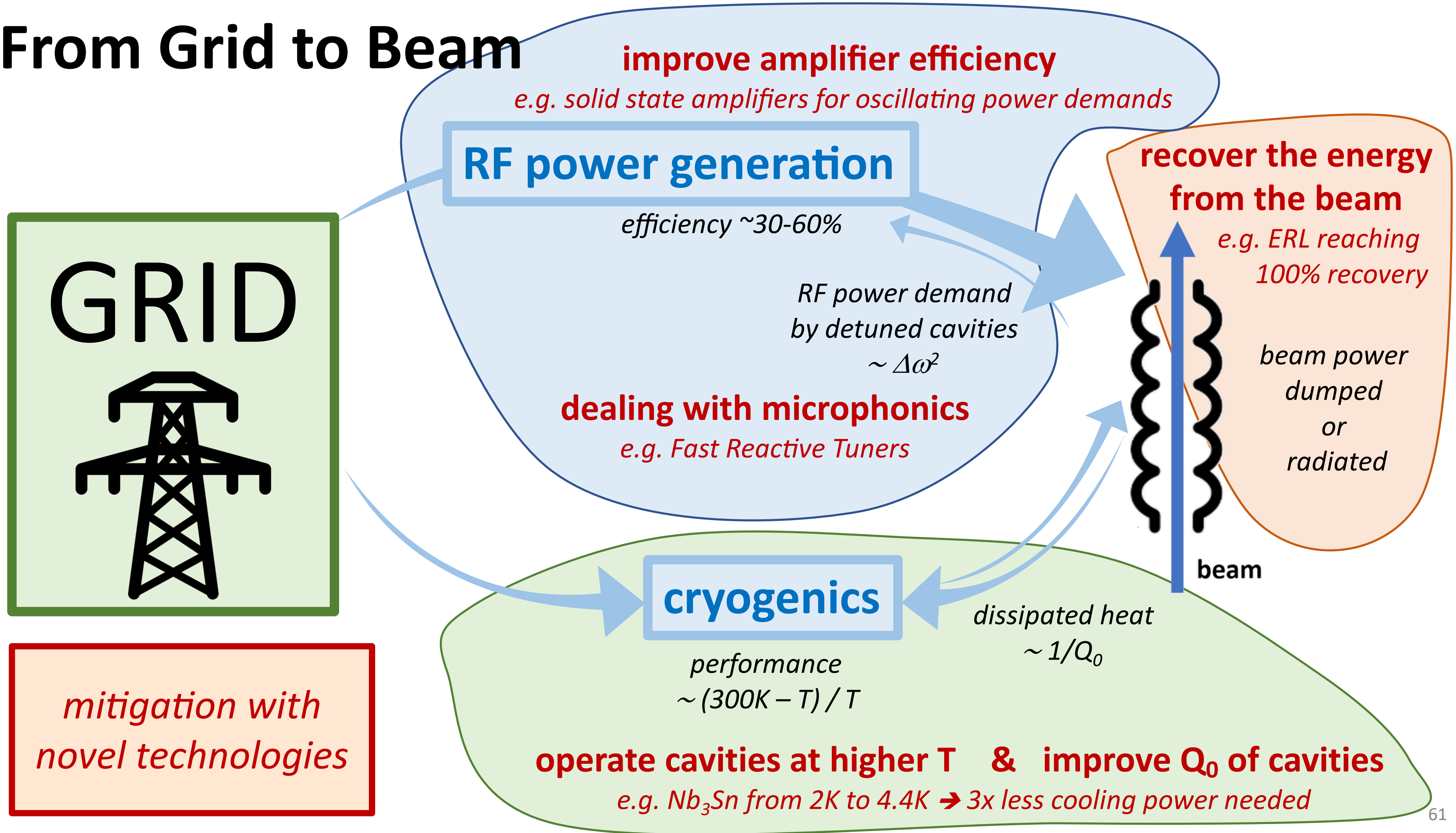


mitigation with novel technologies

operate cavities at higher T & improve Q_0 of cavities

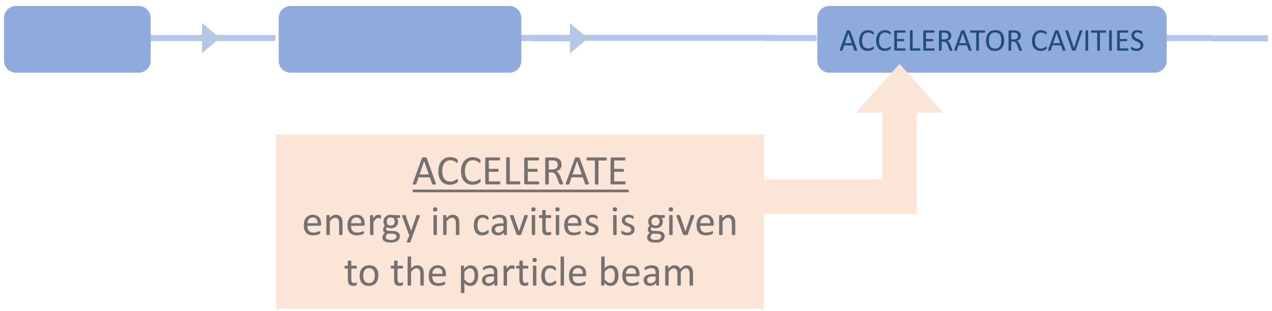
e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

From Grid to Beam



Impact of Energy Recovery

The principle of Energy Recovery



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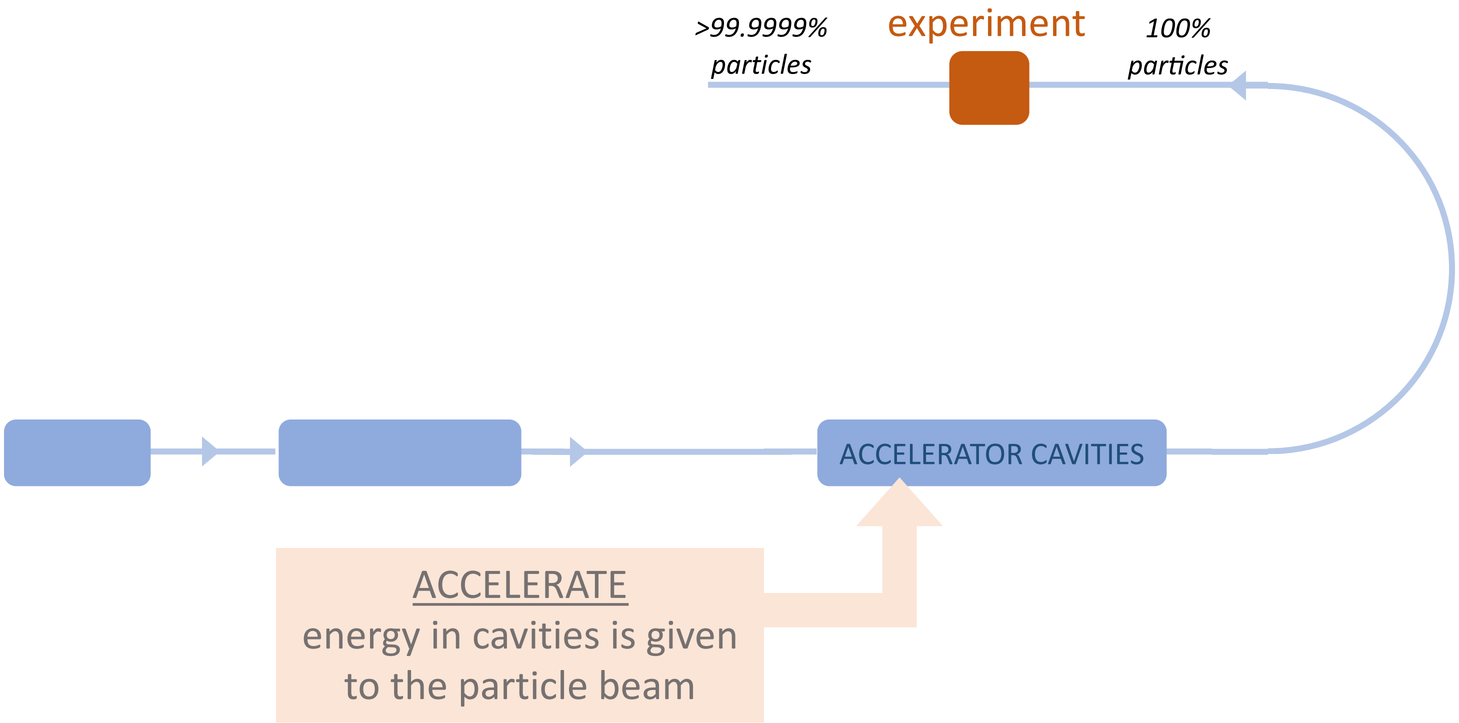

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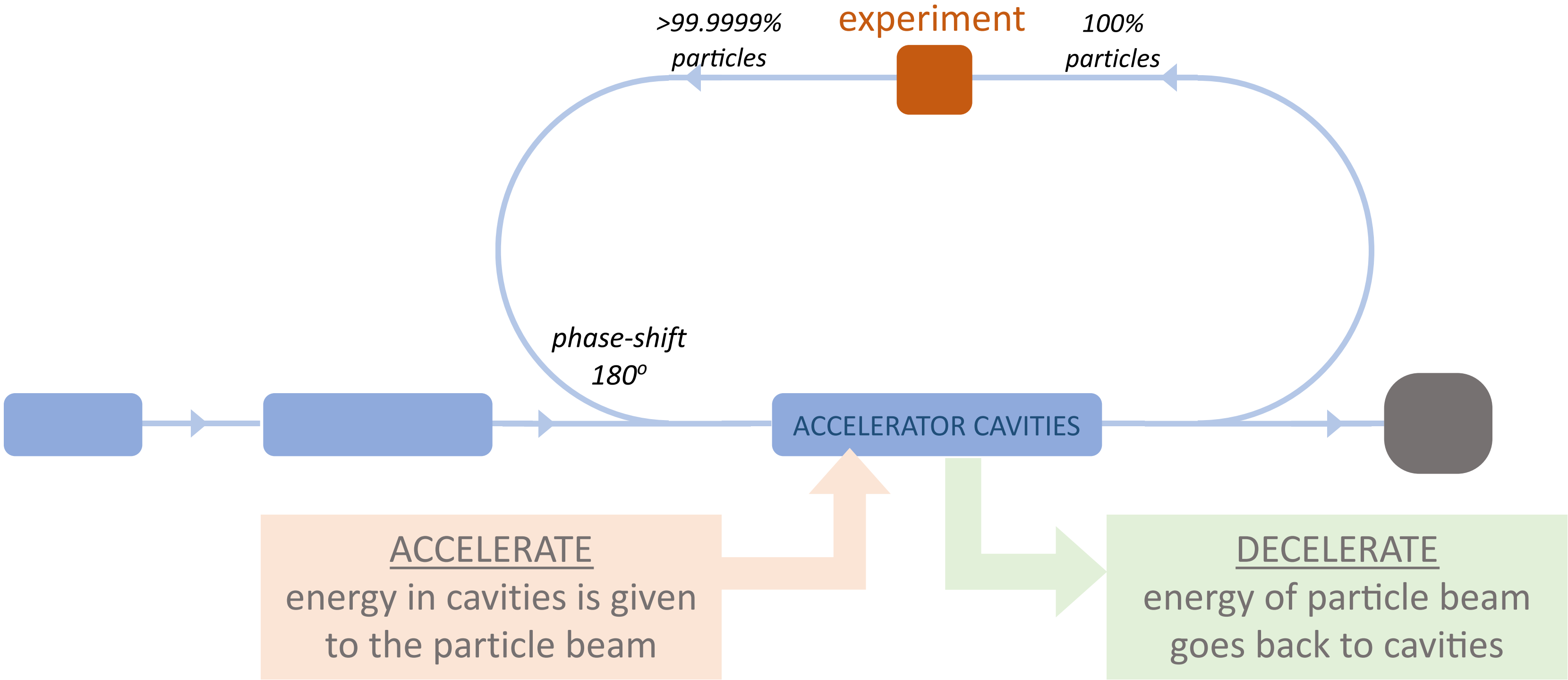

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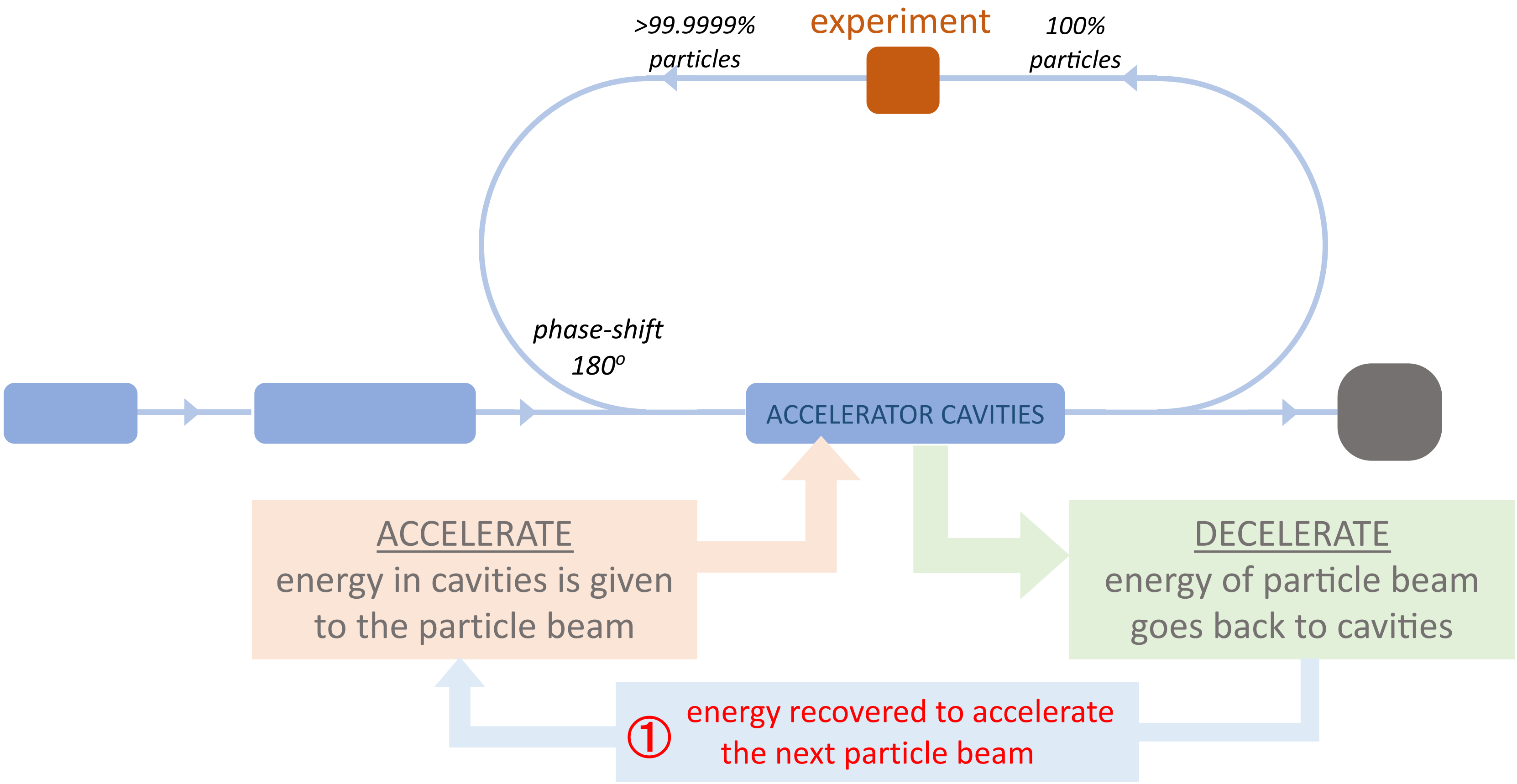

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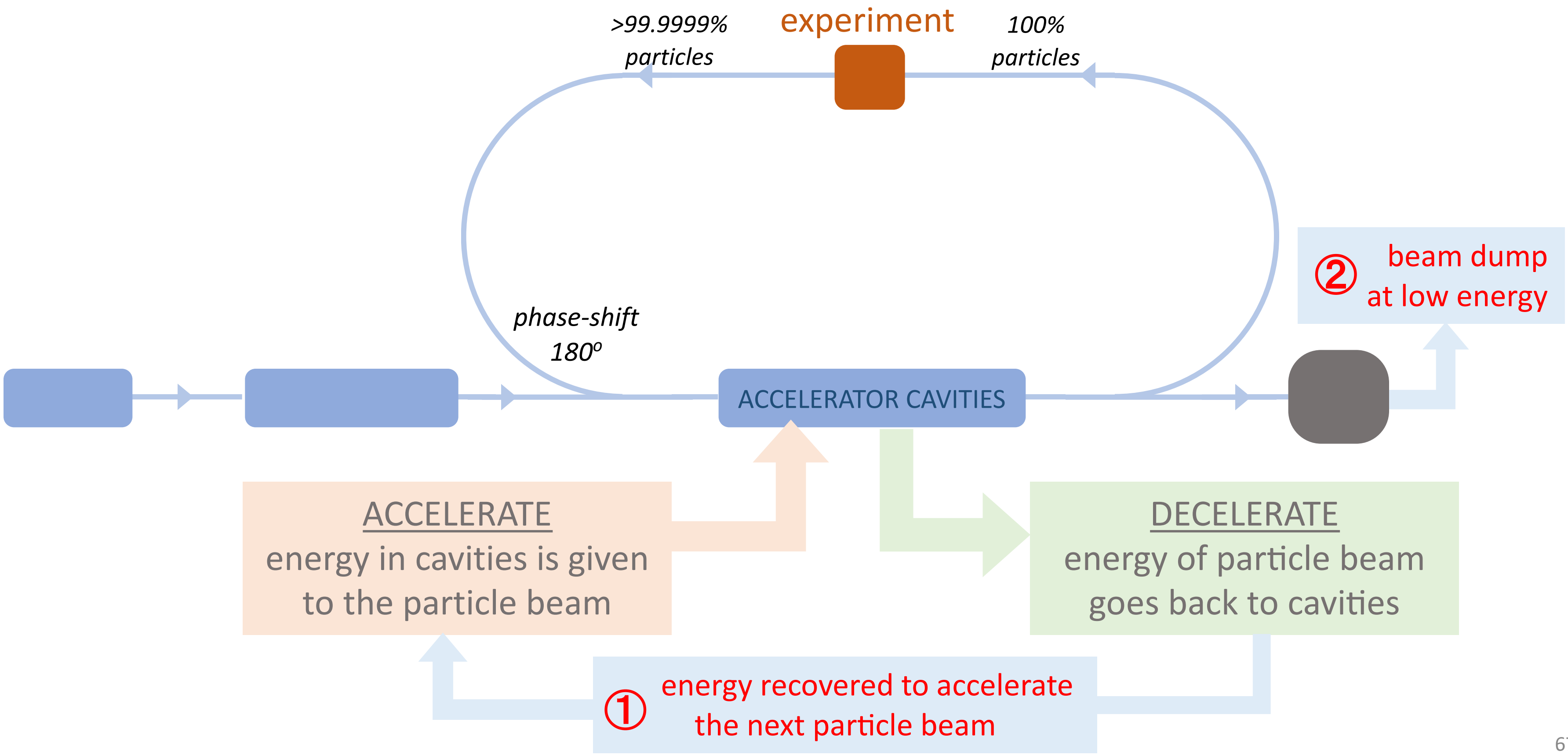

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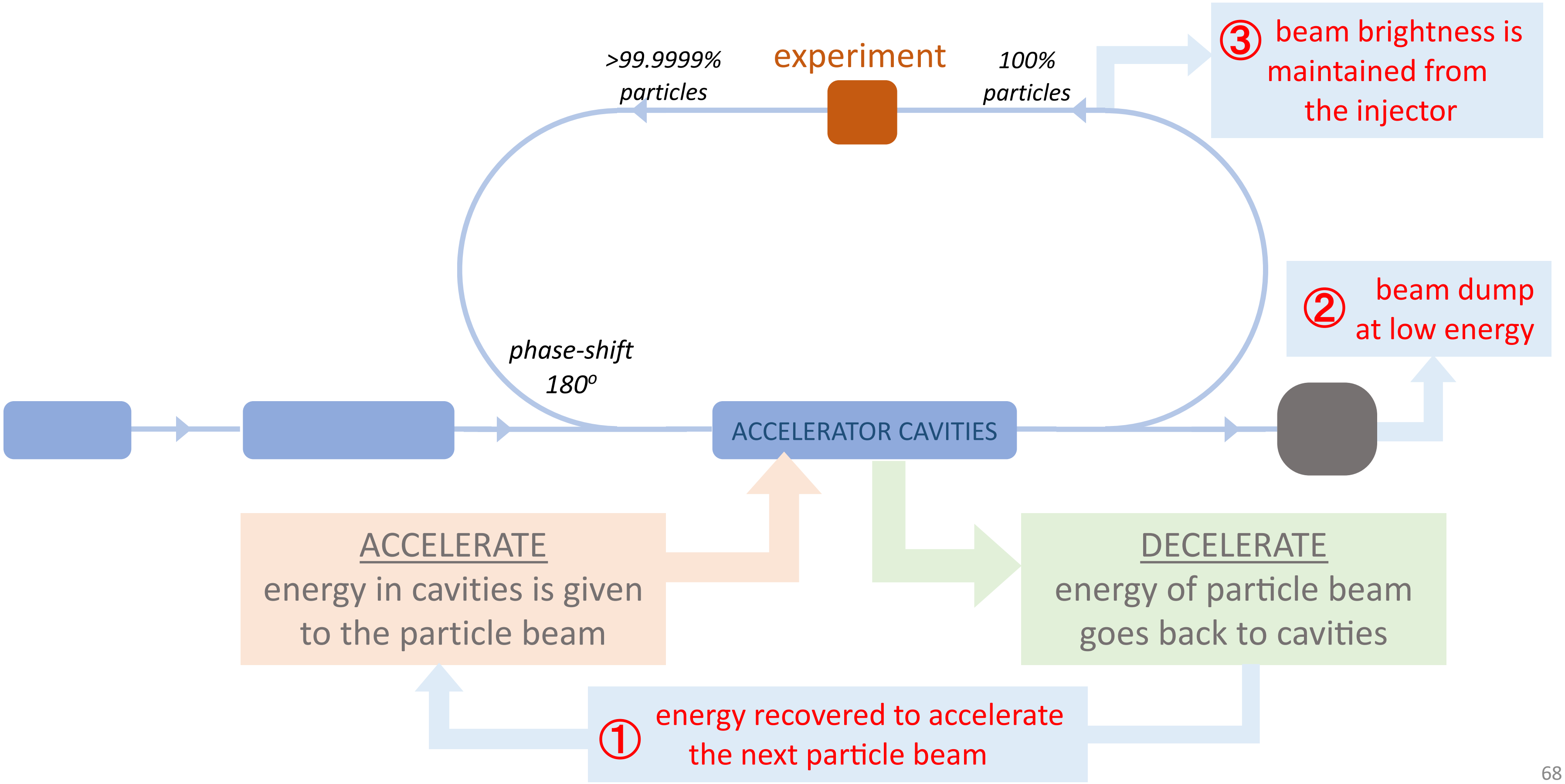

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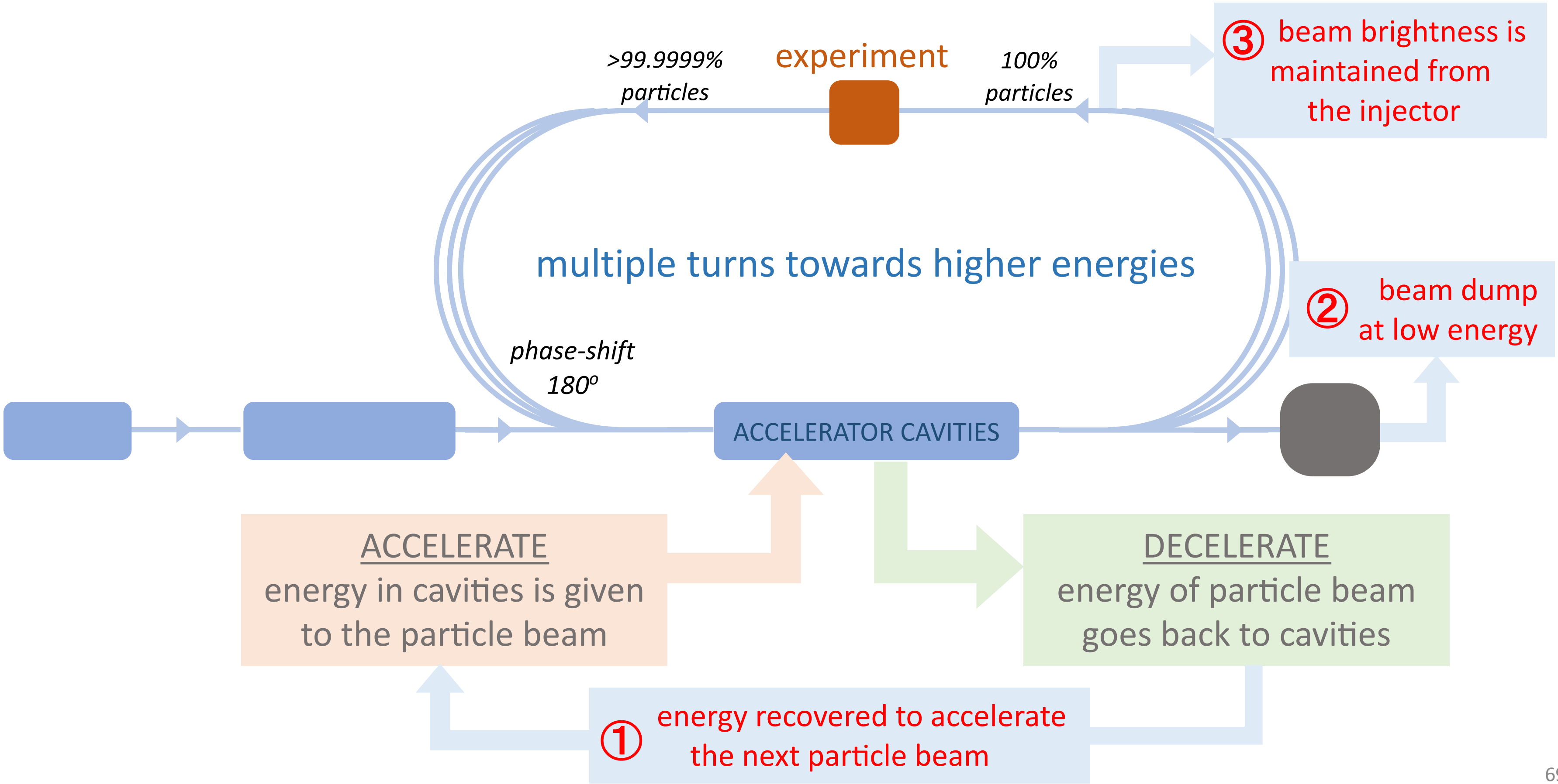

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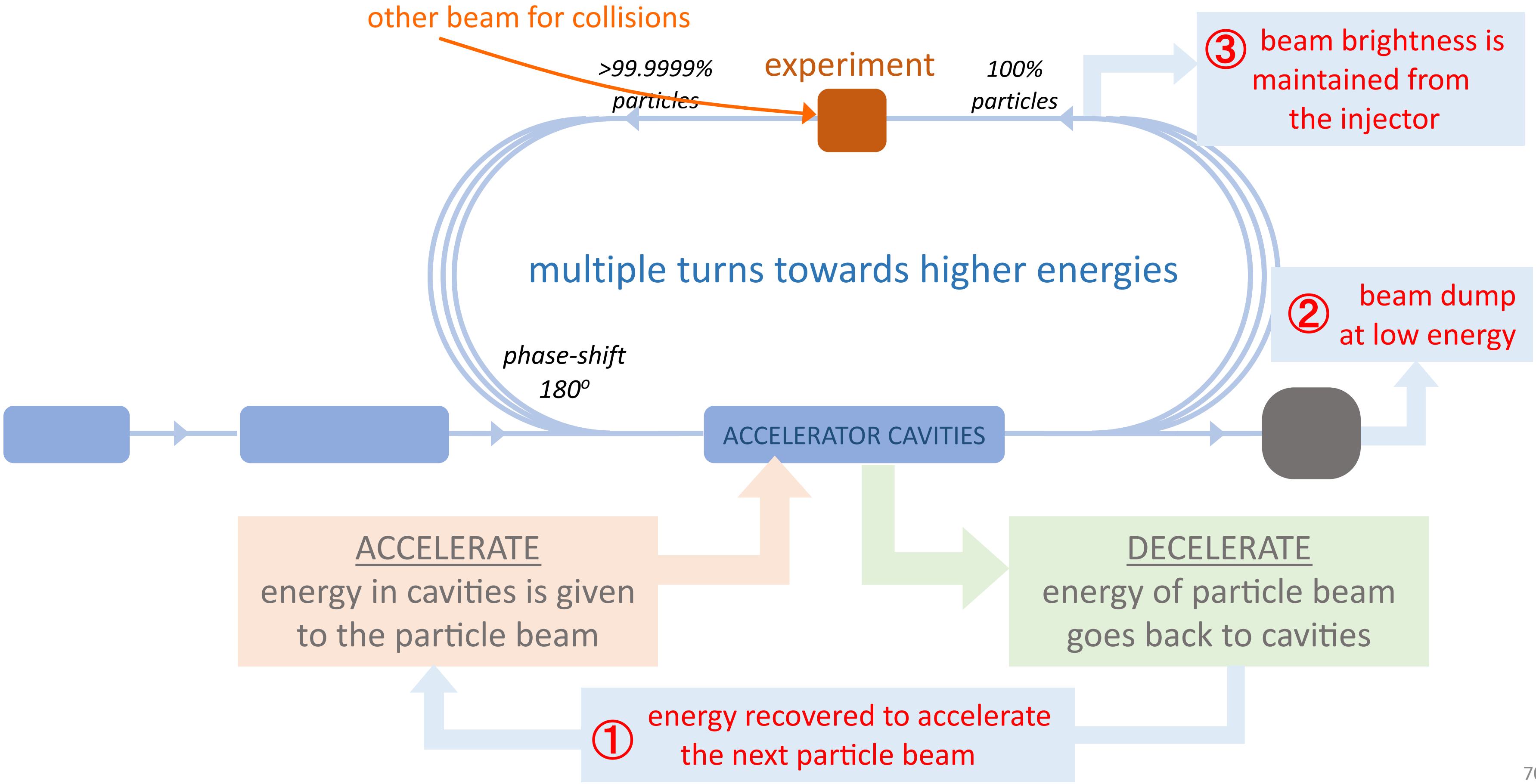

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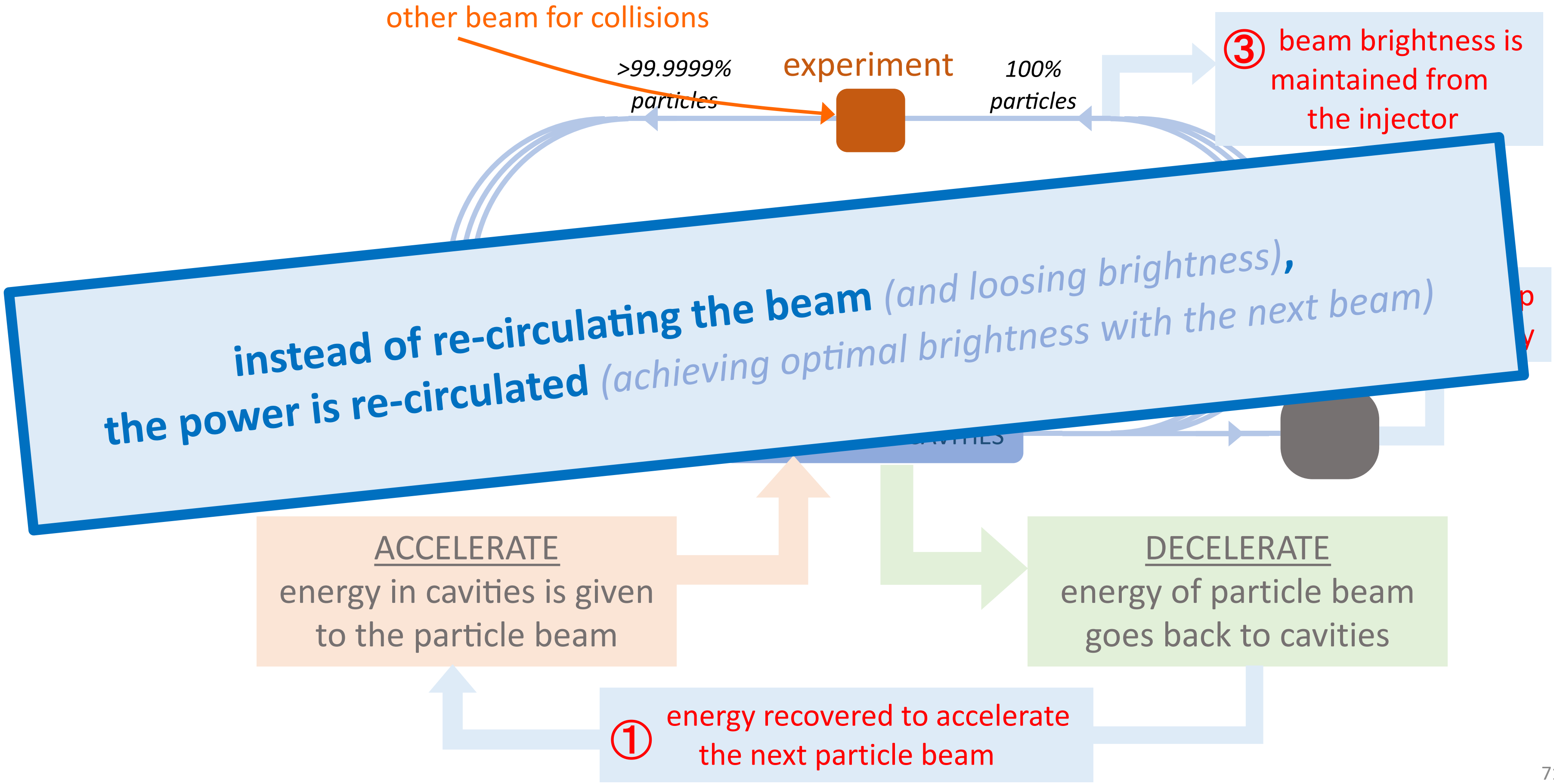

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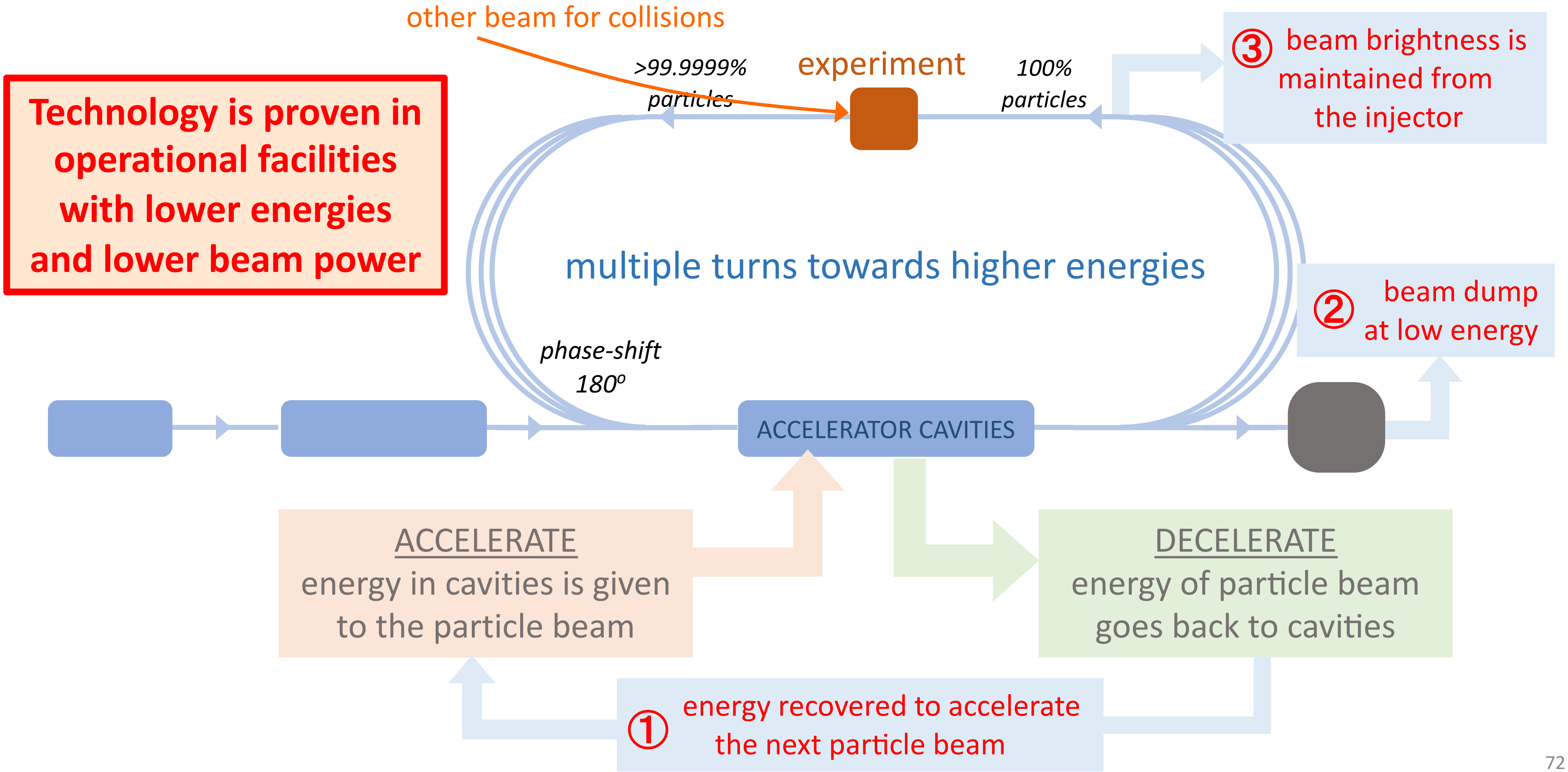


Energy Recovery Linac (ERL) applications for HEP e^+e^- colliders

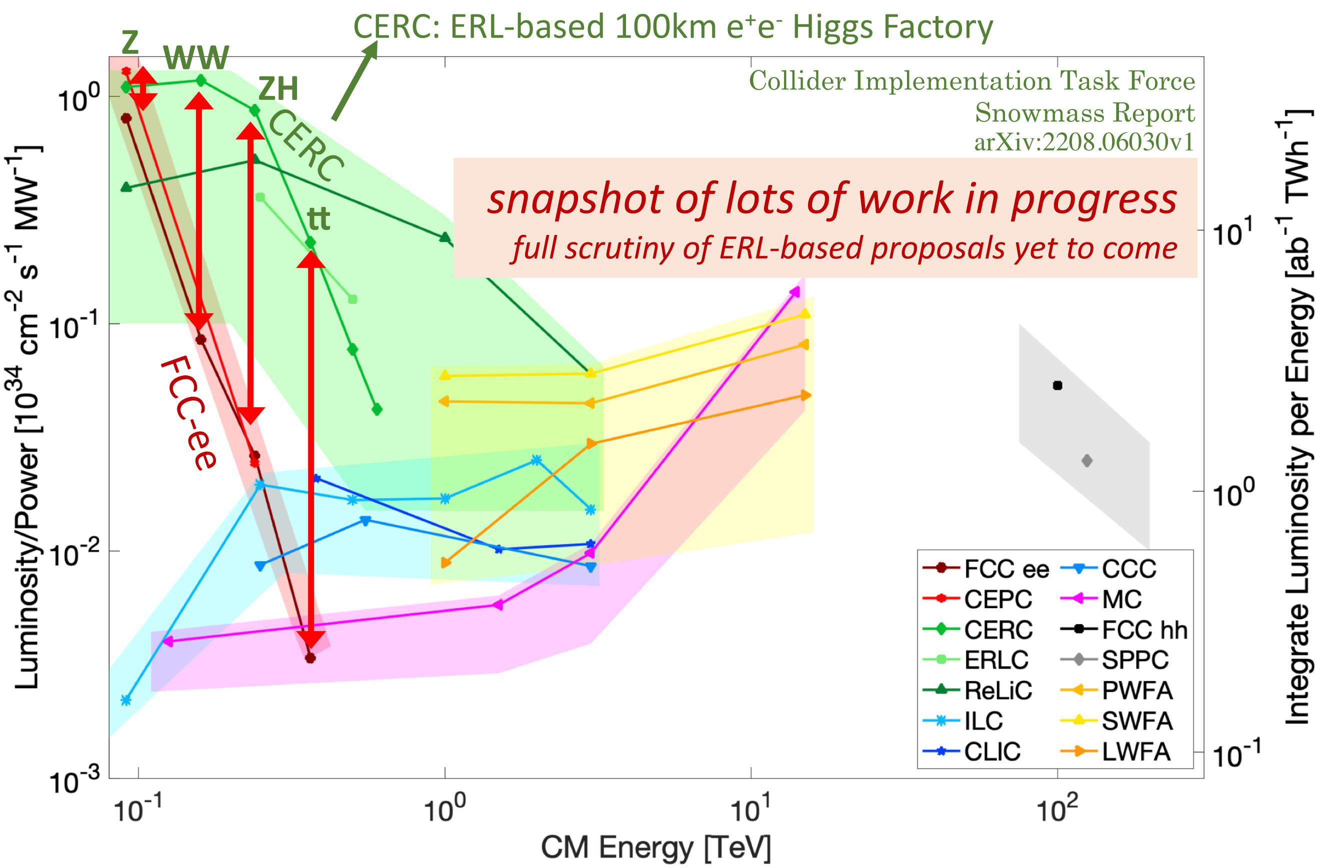
This plot suggests that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



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

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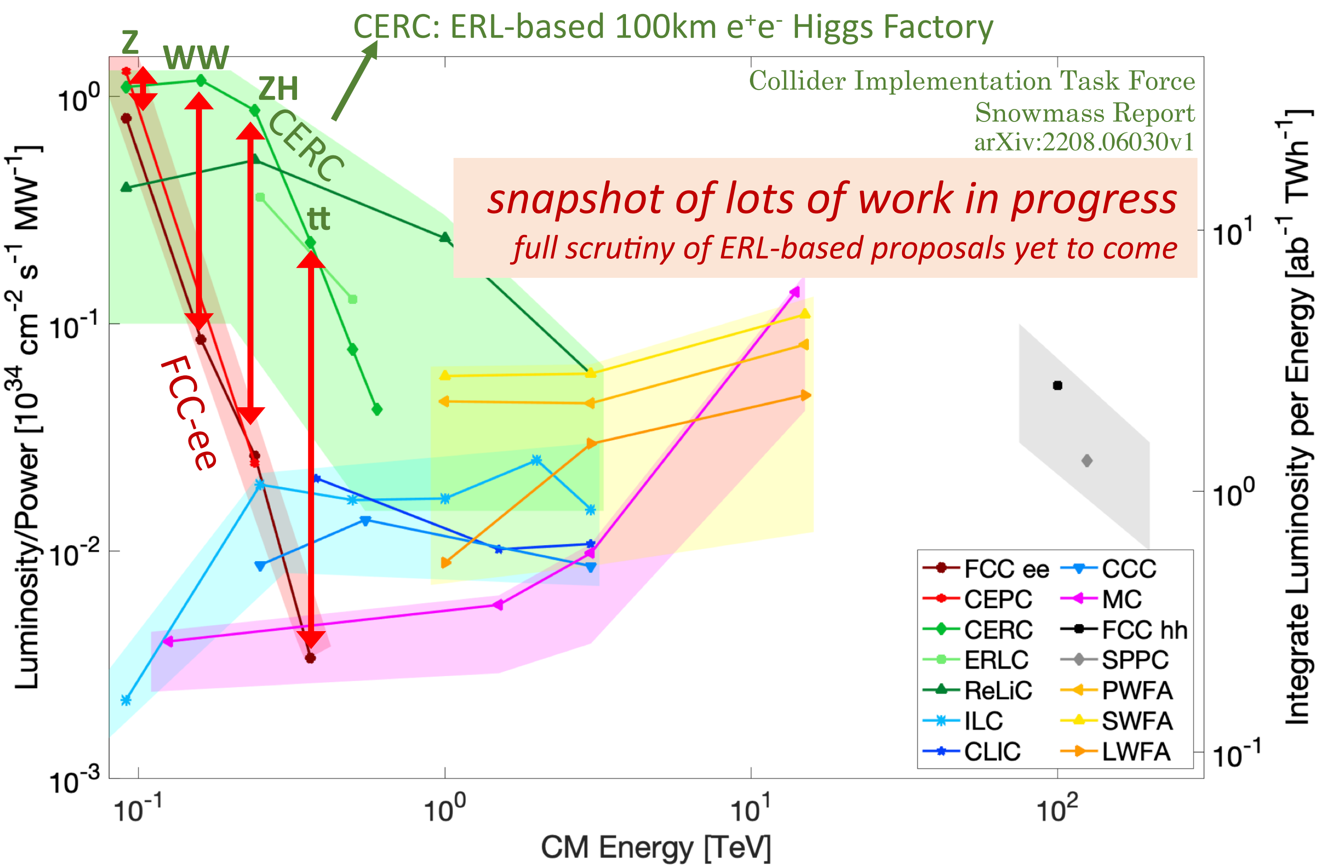
next slide: what would be the concrete impact

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



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Energy Recovery Linac (ERL) applications for HEP

invest today an additional R&D budget
to avoid a 100x larger spending on electricity bills

budget for <u>ERL R&D 40 MCHF</u> for this decade

15y of FCC-ee (1.4 TWh per year from FCC website, was 1.9 TWh/y in CDR)
~0.25 EUR/kWh (average number in Europe in Sept 2022)
~0.35 BCHF per year
5.25 BCHF/15y

With ERL 10x less energy = <u>electricity bill savings of 4.5 BCHF</u>

the previous factor of 10x

x100

Tl
a
F

x1

ReLIC PWFA
ILC SWFA
CLIC LWFA

Integrate Luminosity per Energy [ab^{-1} TWh^{-1}]

10^{-1}

10^{-1} 10^{0} 10^{1} 10^{2}

CM Energy [TeV]

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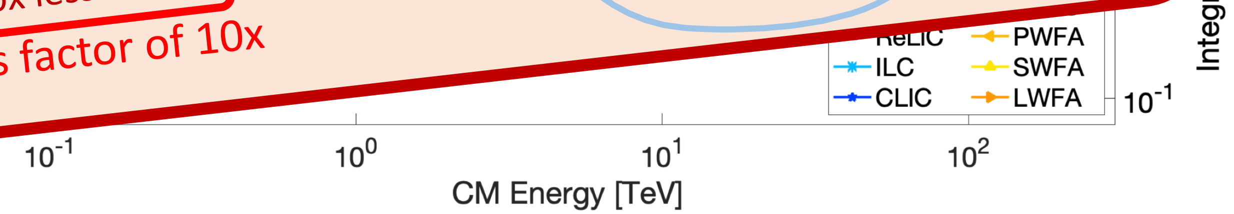
With ERL 10x less energy = <u>electricity bill savings of 4.5 BCHF</u>

x100

the previous factor of 10x

even with only a factor of 2x
the impact is huge, >2.5 BCHF



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Energy Recovery Linac (ERL) applications f… s

This … an … Fa…

x10 …

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

Power of Synchrotron Radiation ~ 1/R

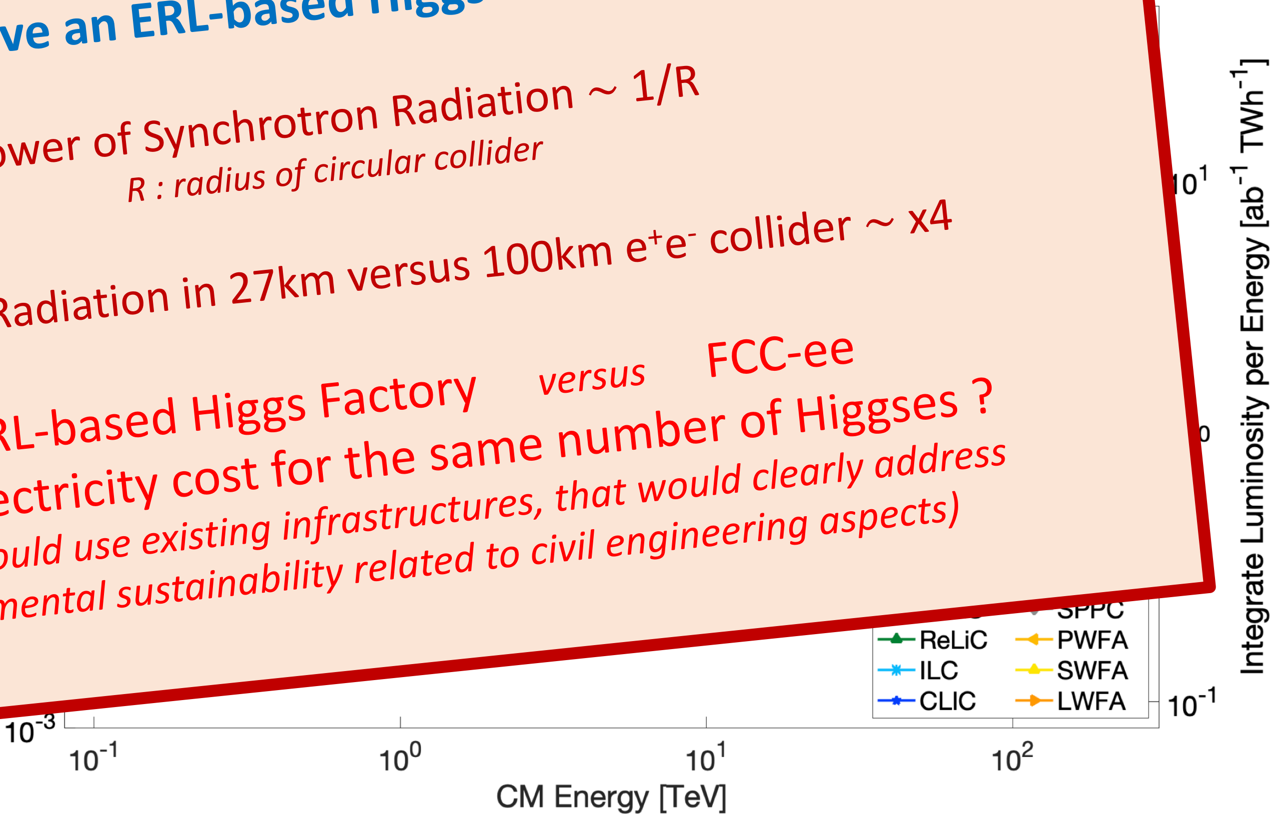
R : radius of circular collider

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

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

the same electricity cost for the same number of Higgses ?

(because we would use existing infrastructures, that would clearly address the environmental sustainability related to civil engineering aspects)



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

... same number of Higgses ?

Several very challenging aspects are to be verified in these initial thoughts, but it demonstrates the potential impact of new technologies, and motivates R&D support for sustainable accelerating systems to further explore

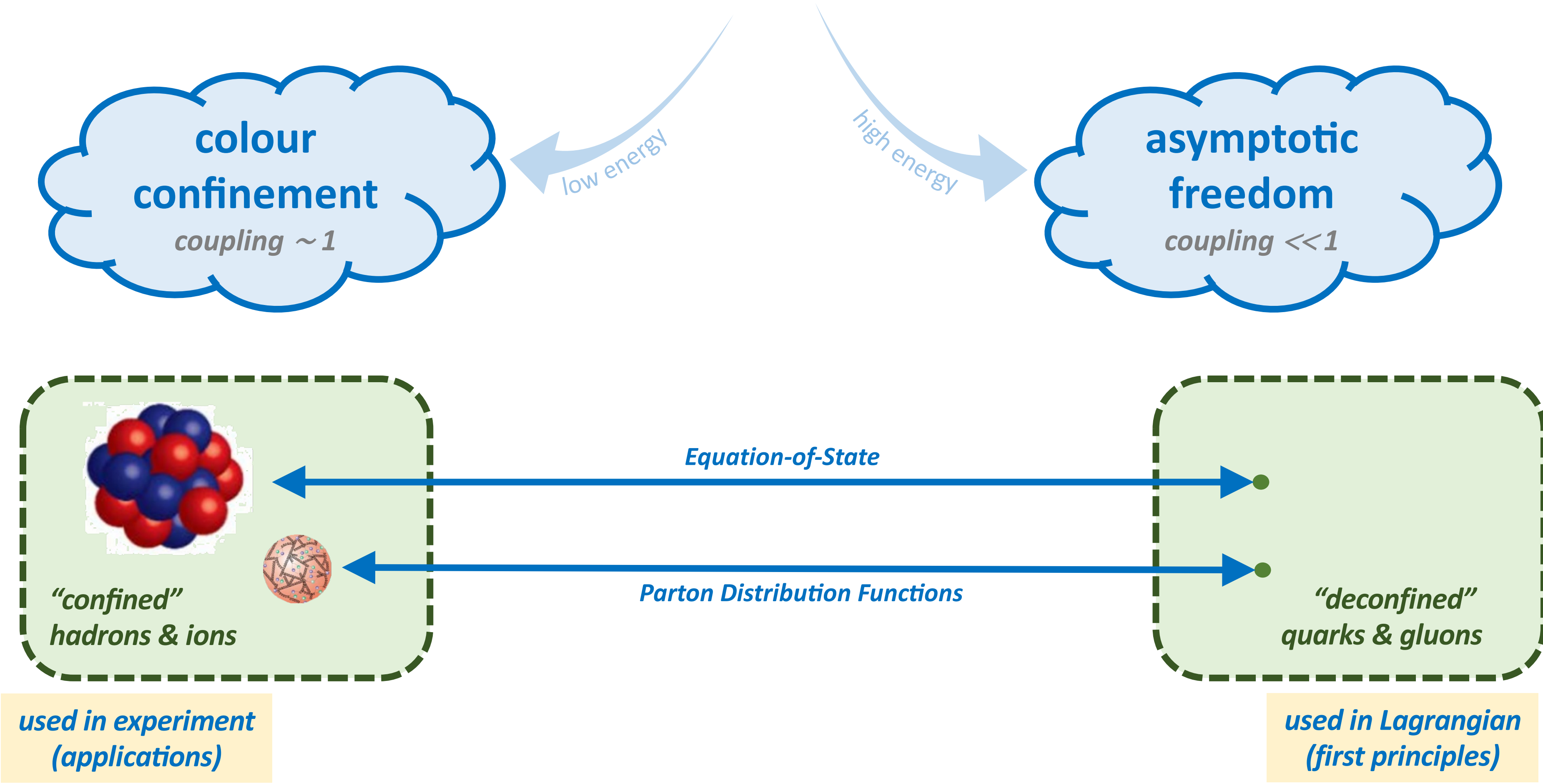
...sity per Energy [ab^{-1} TWh^{-1}]

10^1

...0

our eyes on the structure of things

Hadrons & Ions are made up of Quarks & Gluons



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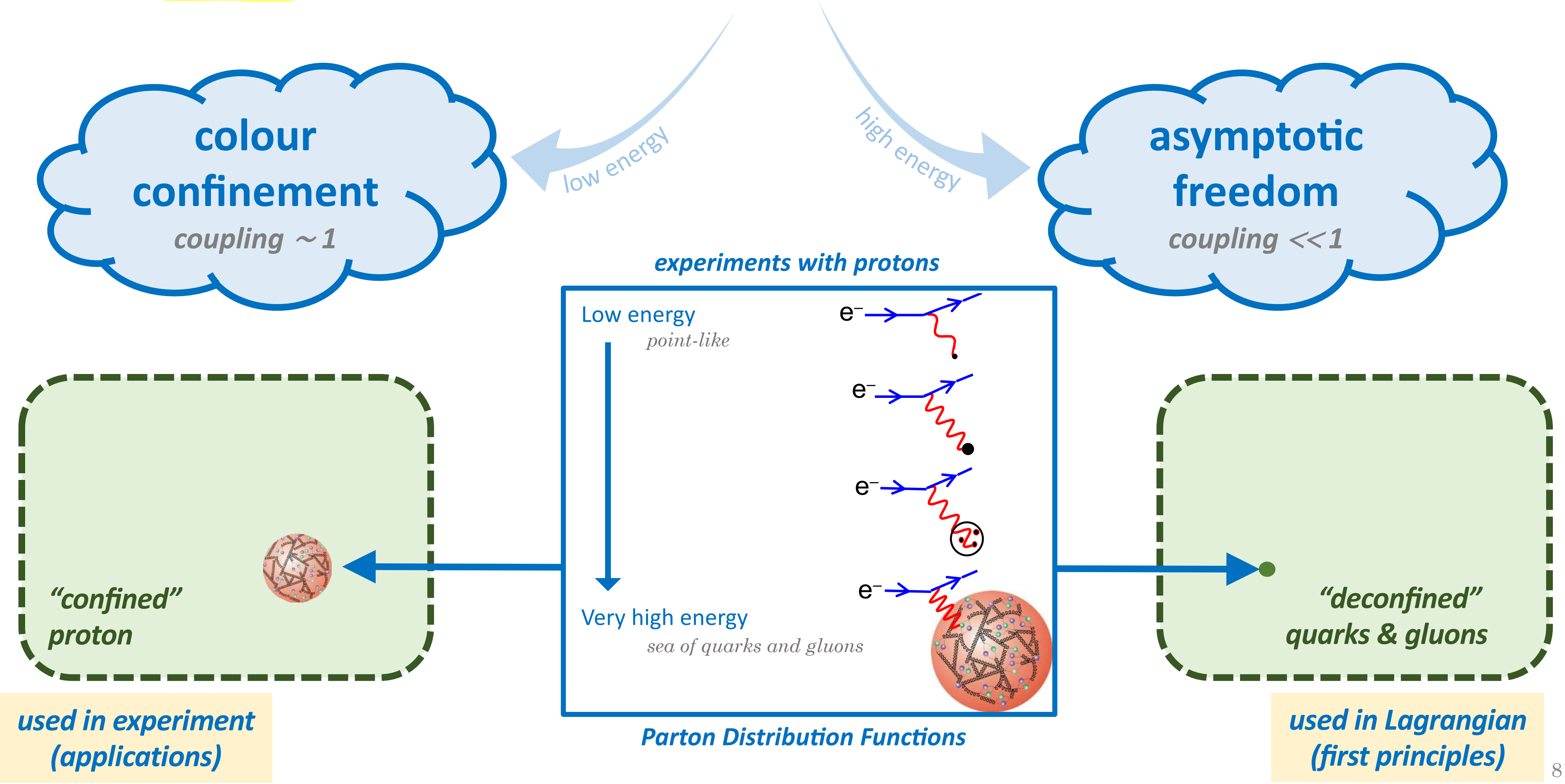
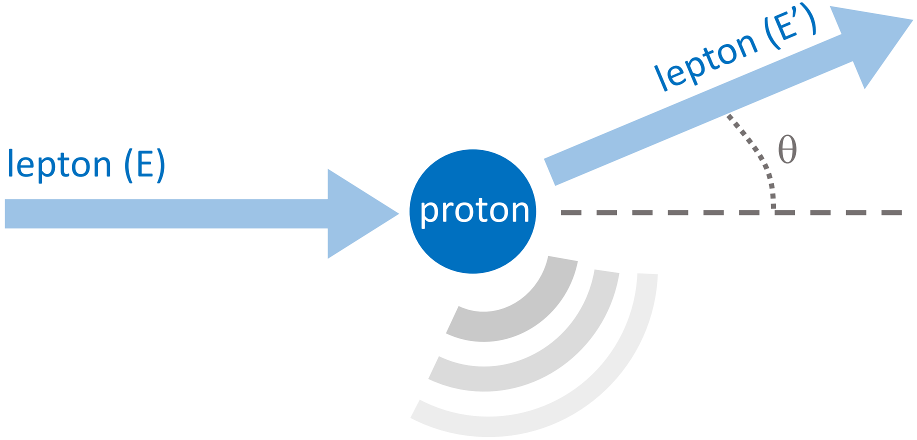


The 50+ years success story of DIS



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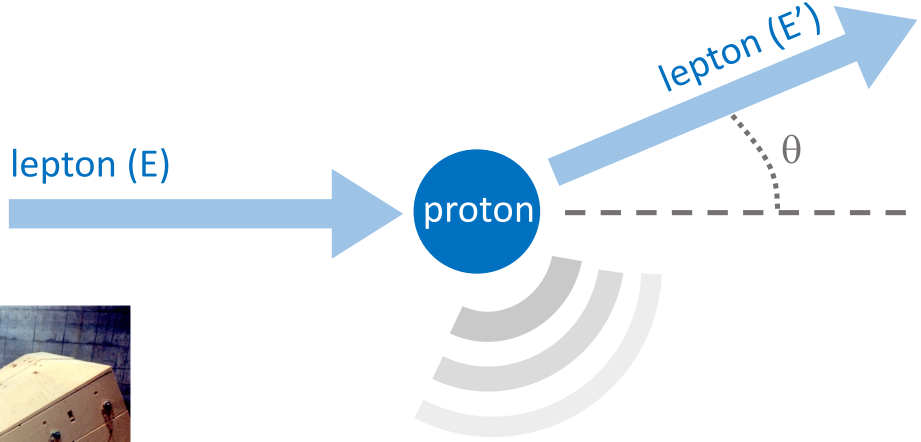
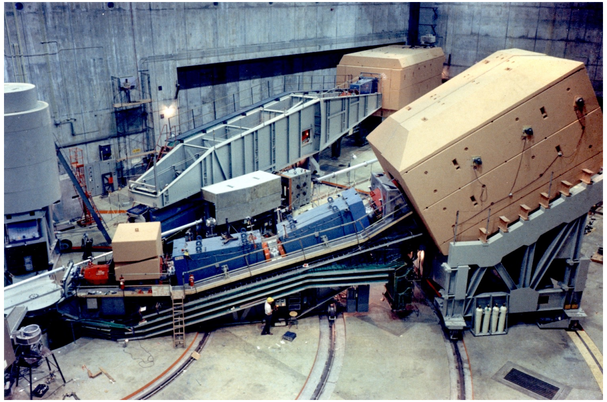
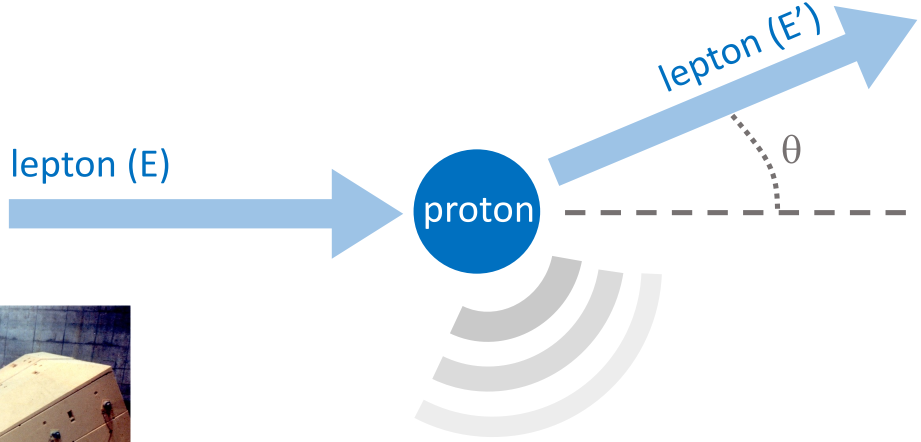


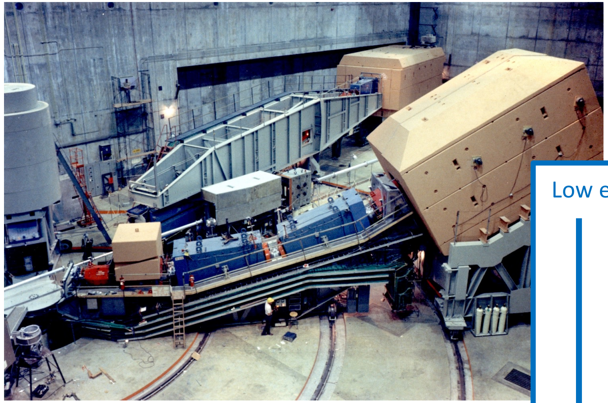


Discovery of quarks

(1968, ep@MIT-SLAC experiment)

The 50+ years success story of DIS





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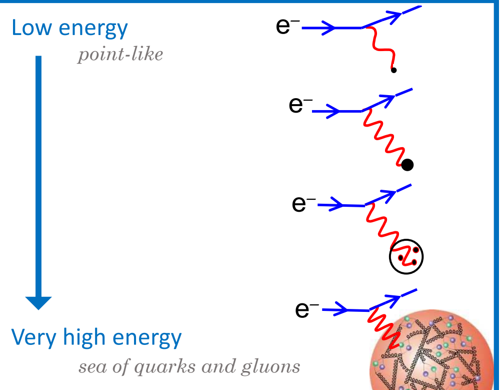
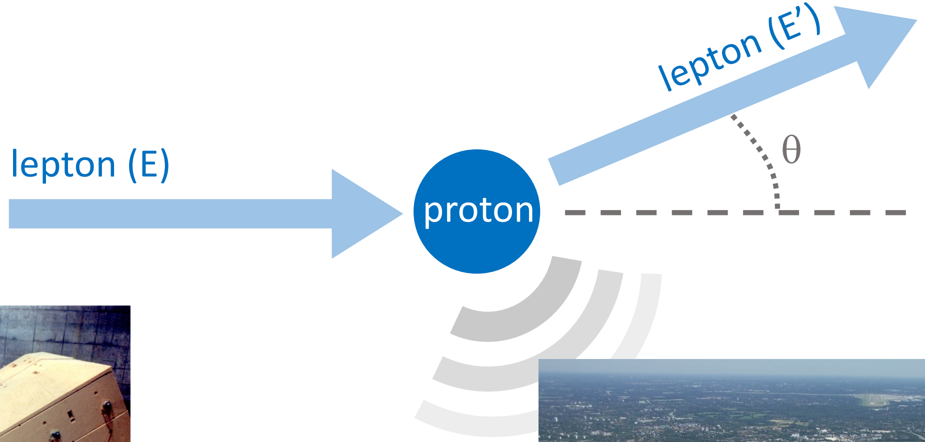
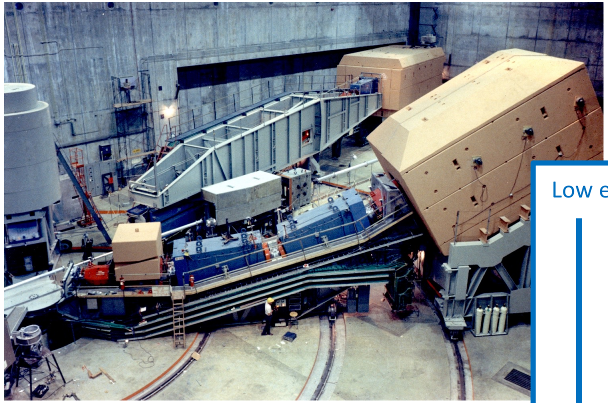


Parton model

The 50+ years success story of DIS





Discovery of quarks

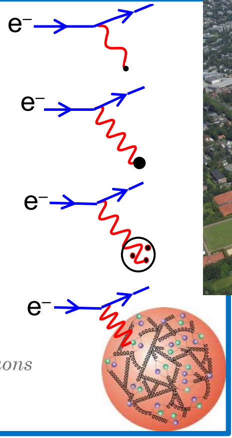
(1968, ep@MIT-SLAC experiment)

Low energy

point-like

Very high energy

sea of quarks and gluons



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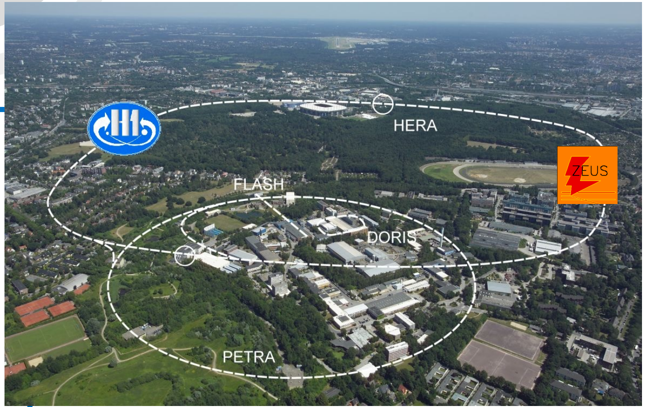
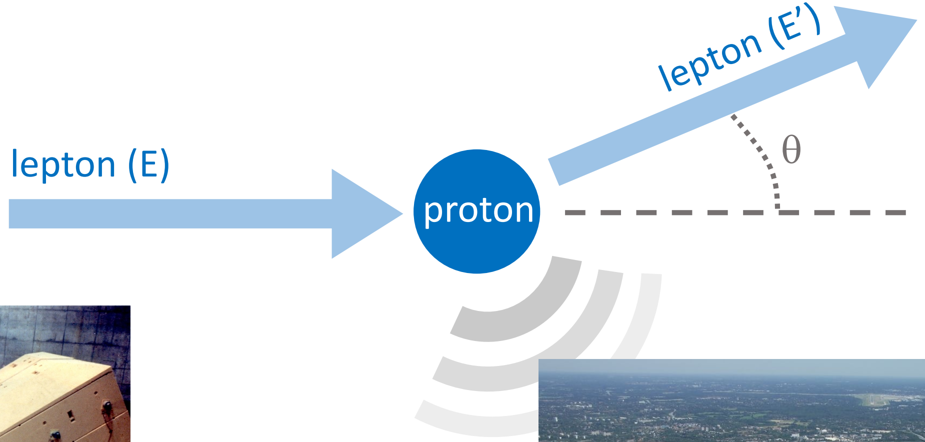
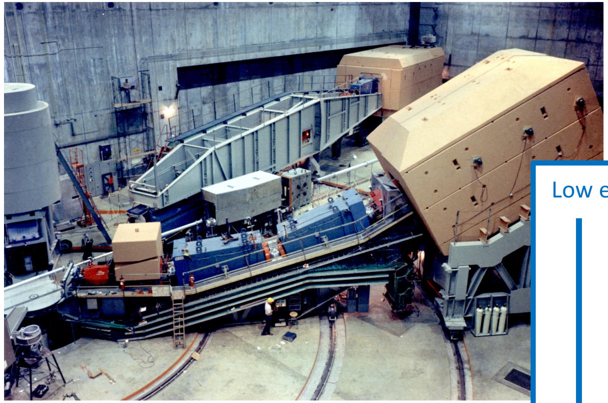


The DIS precision era

(1992-2007, $e^{\pm}p$@HERA)

The 50+ years success story of DIS





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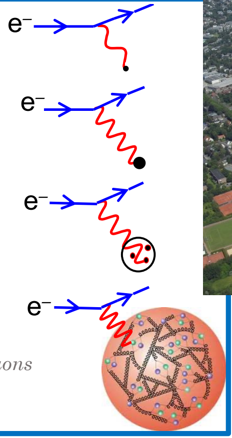

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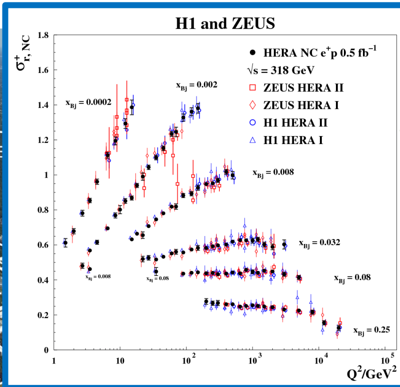

Eur. Phys. J. C75 (2015) 580

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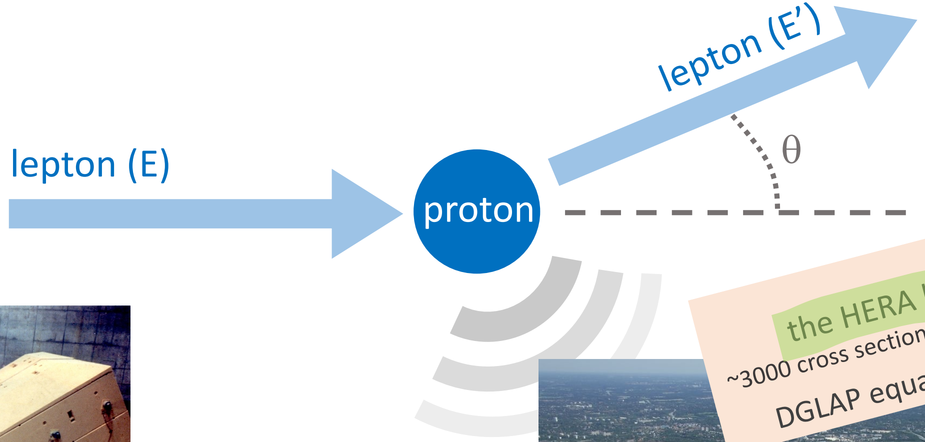
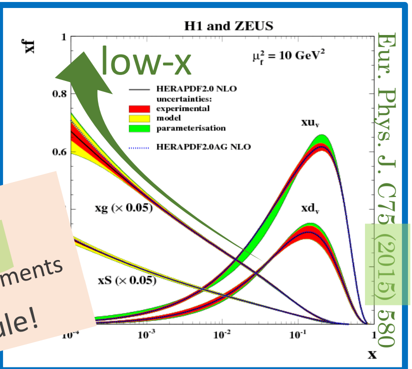
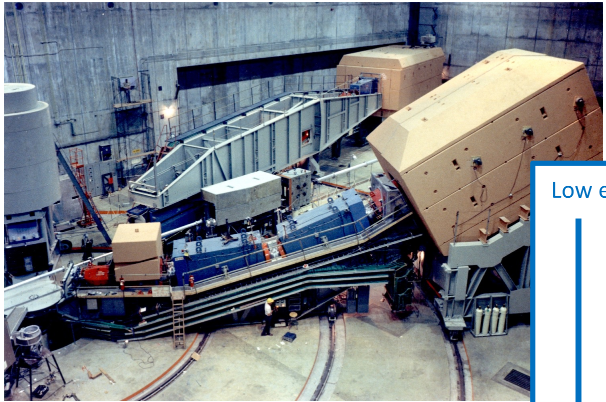


Parton Distribution Functions



the HERA legacy
~3000 cross section measurements
DGLAP equations rule!



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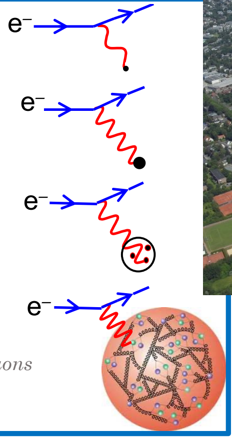

Very high energy
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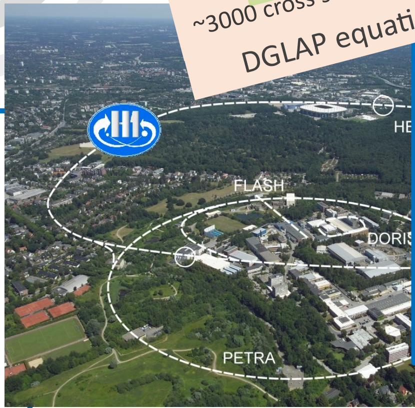
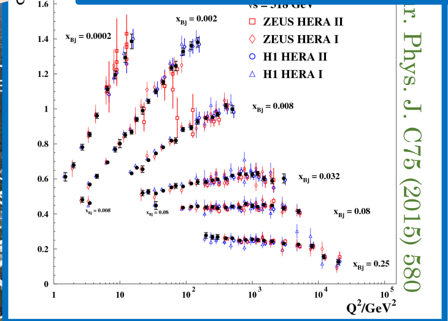
Parton model

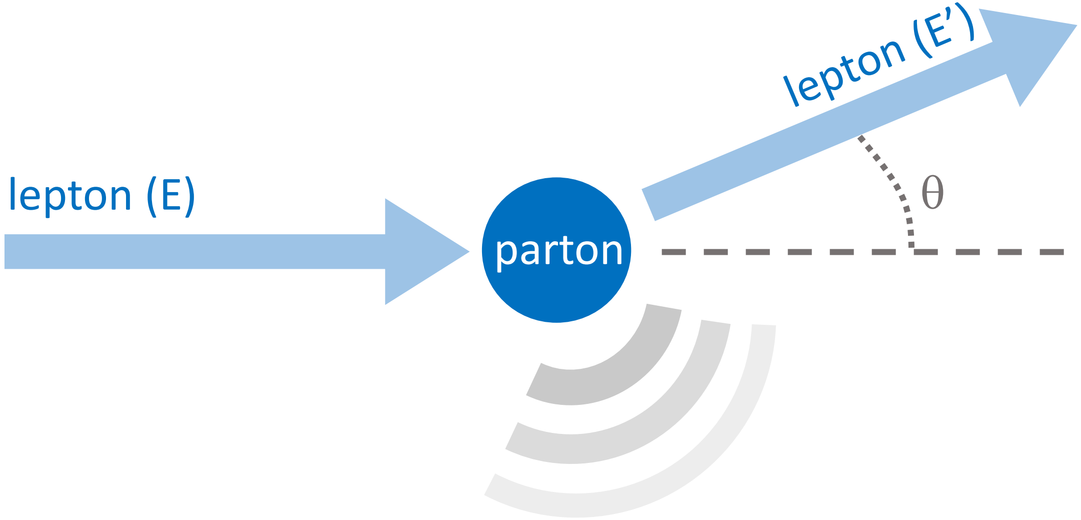




The DIS precision era

(1992-2007, e±p@HERA)

Why study this for another 50 years?



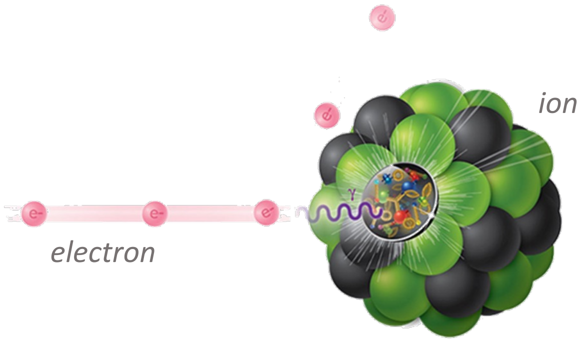
DIS is alive!

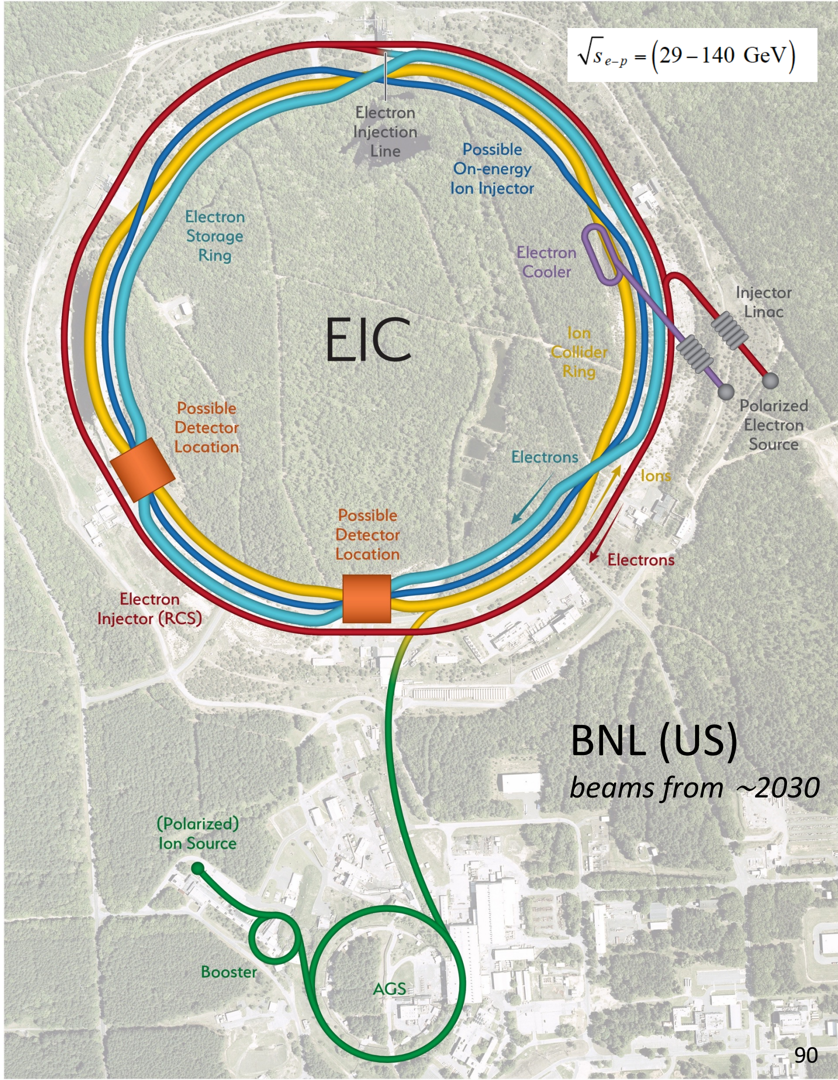
381 registrations for DIS2022

Electron-Ion Collider (EIC)

World's 1st polarized e-p/light-ion & 1st eA collider

User Group >1000 members: http://eicug.org





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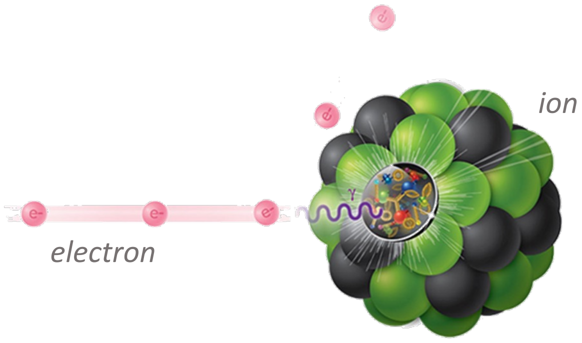
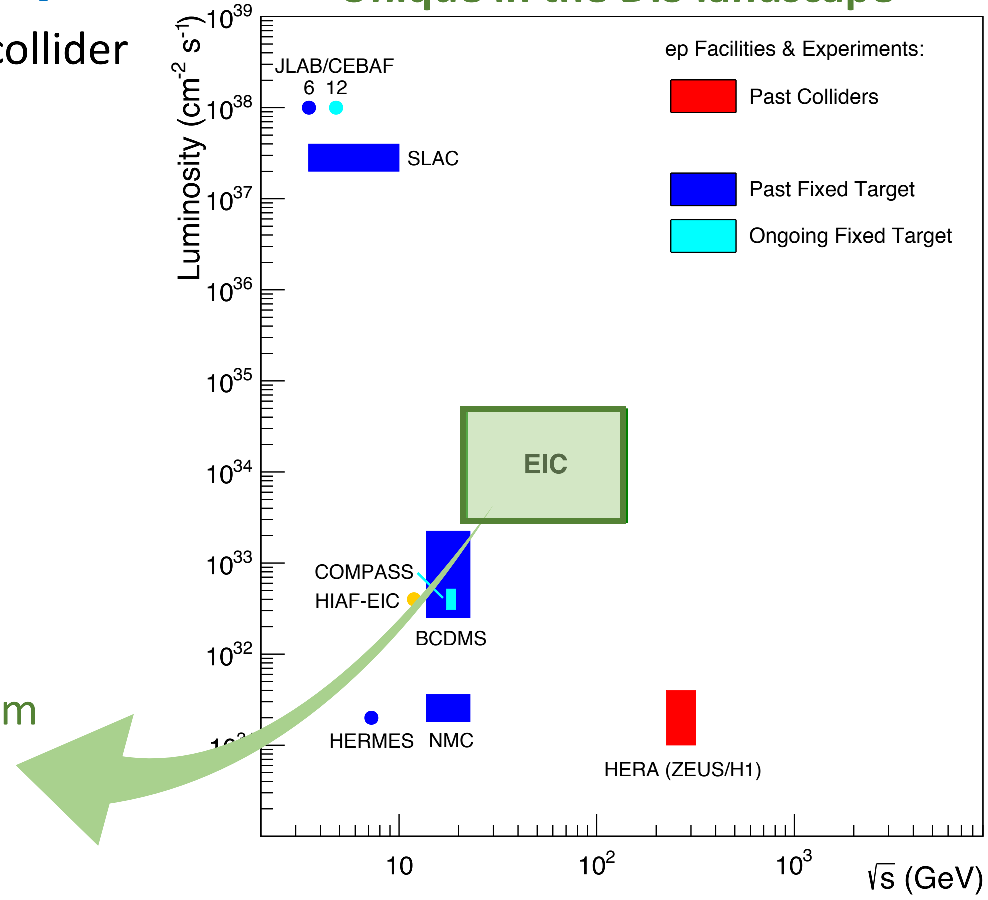


- High luminosity
- Wide range in beam energy
- Polarized lepton & hadron beam
- Nuclear beam

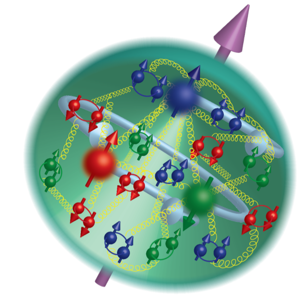
Unique in the DIS landscape



Electron-Ion Collider (EIC)

How do the properties of proton and neutrons arise from its constituents?

Towards a 3D partonic image of the proton



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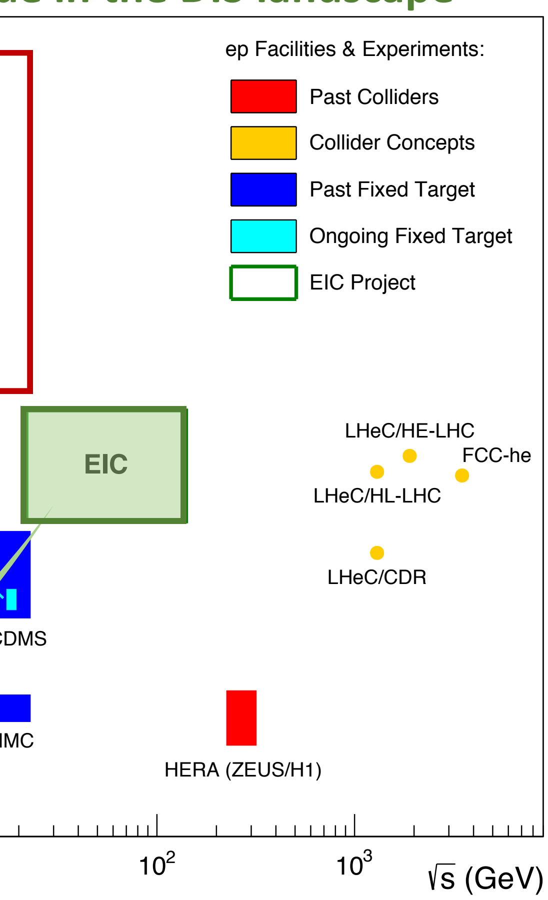

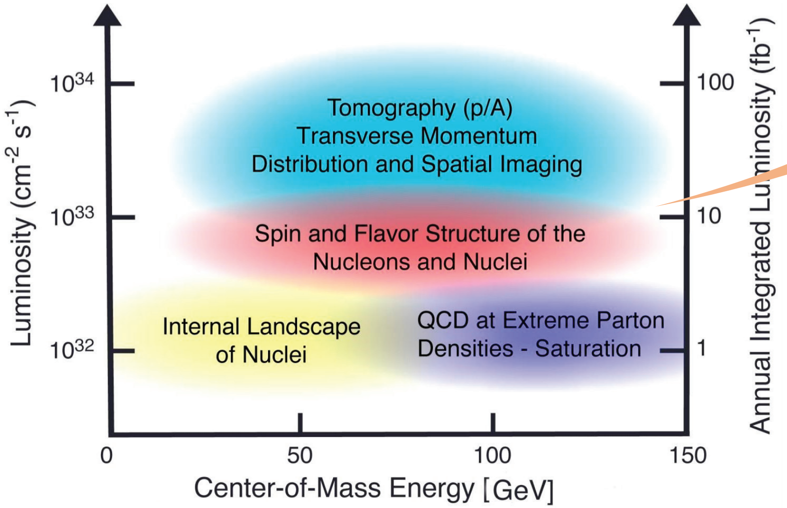

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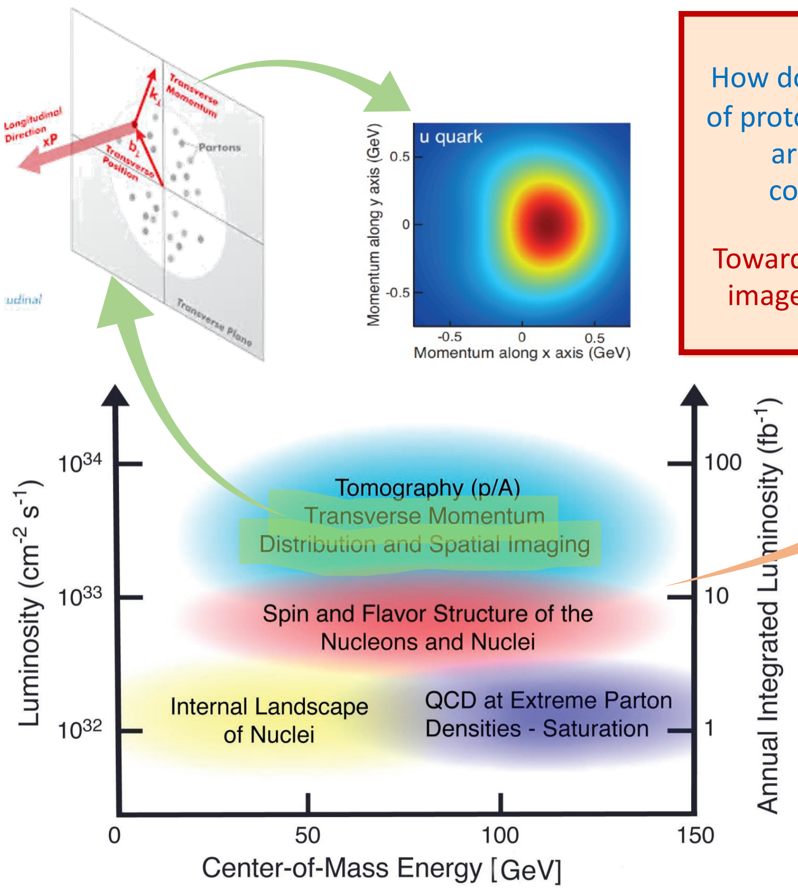

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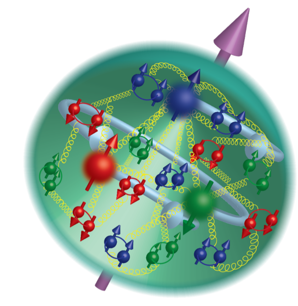

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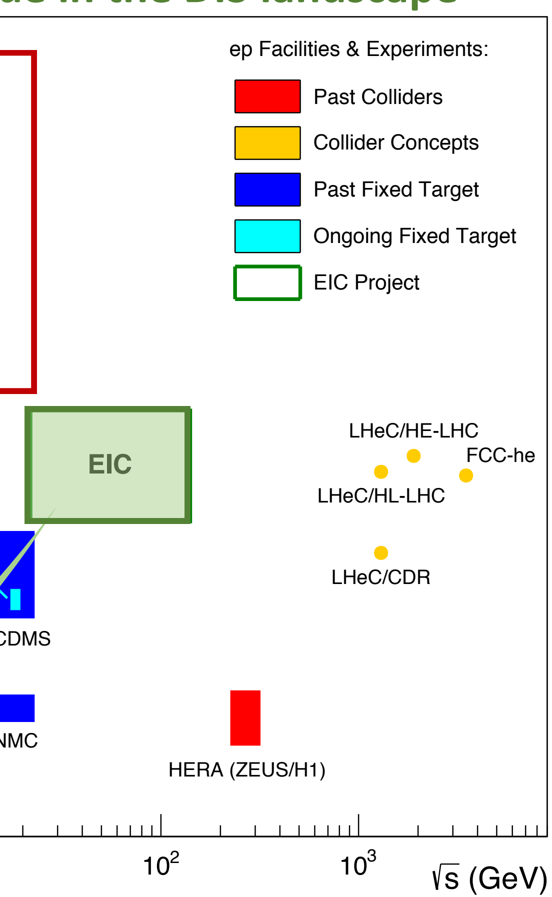

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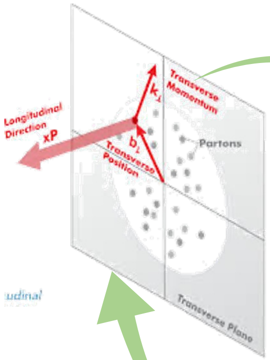

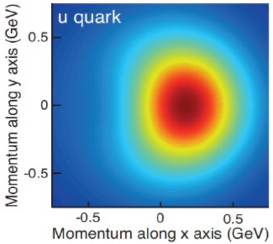

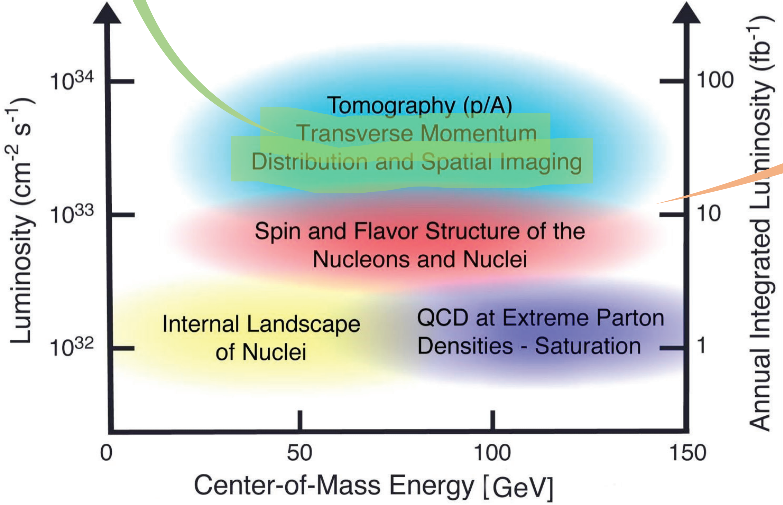

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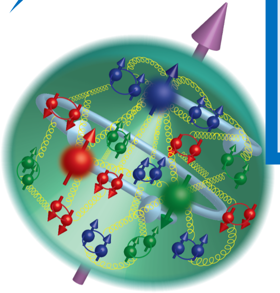
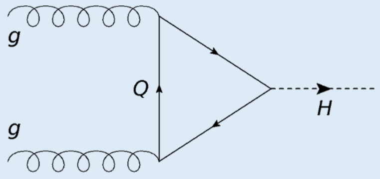
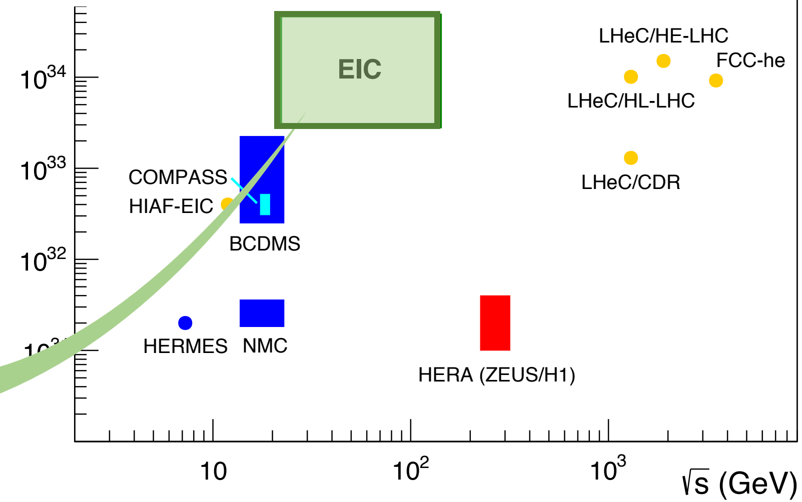


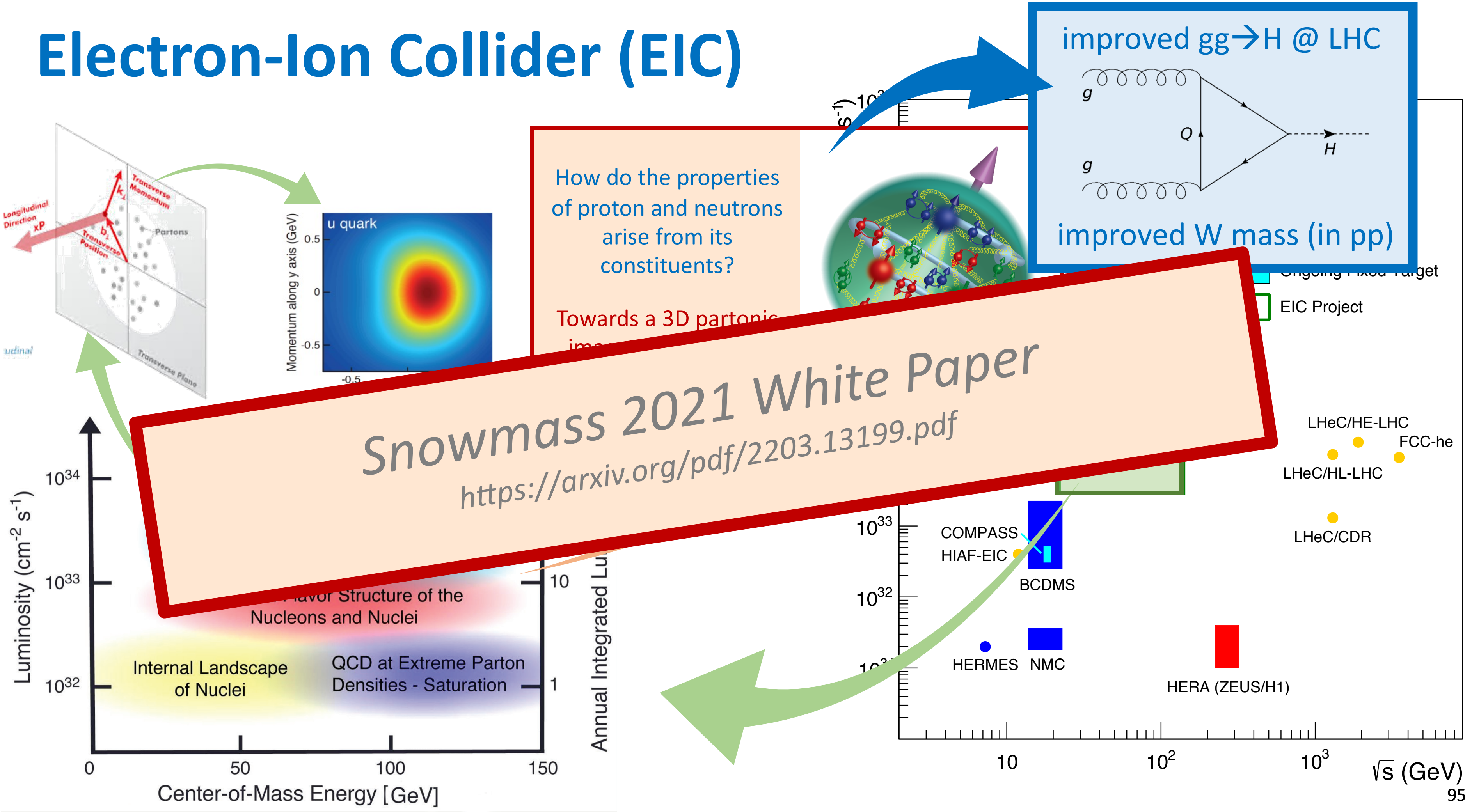
improved gg→H @ LHC



improved W mass (in pp)



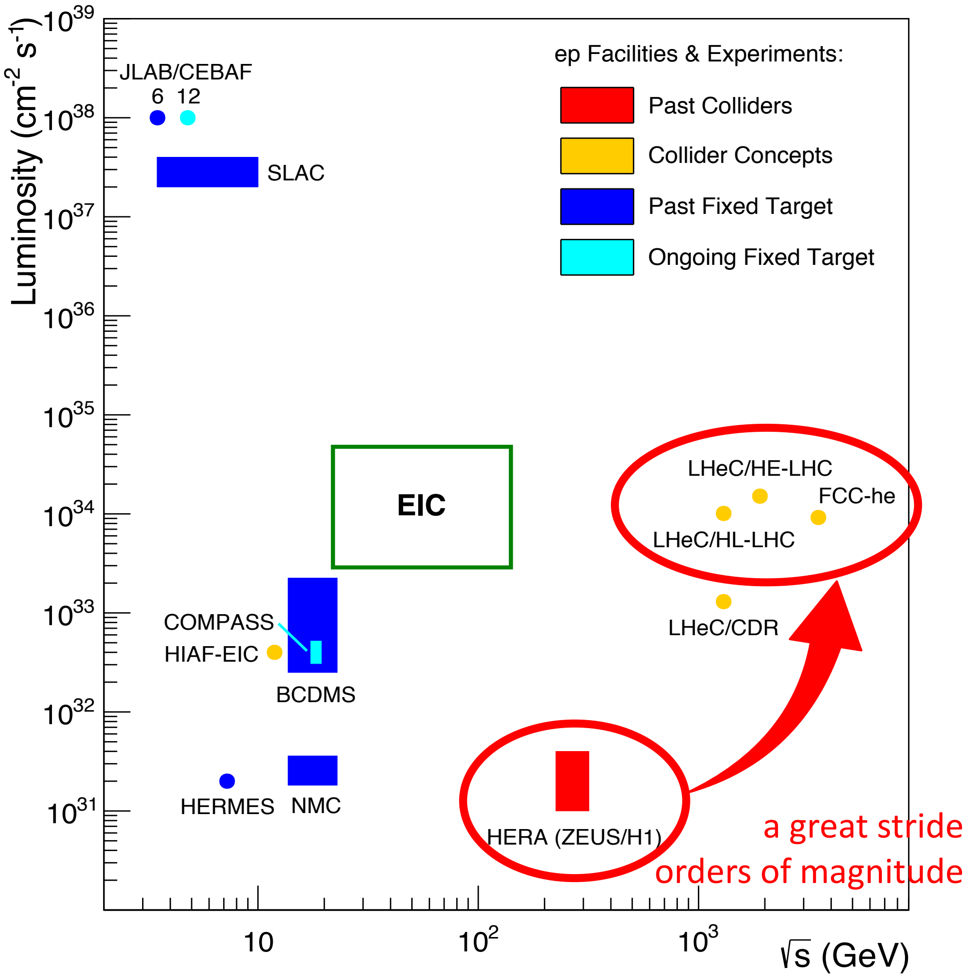
Electron-Ion Collider (EIC)



A future scope

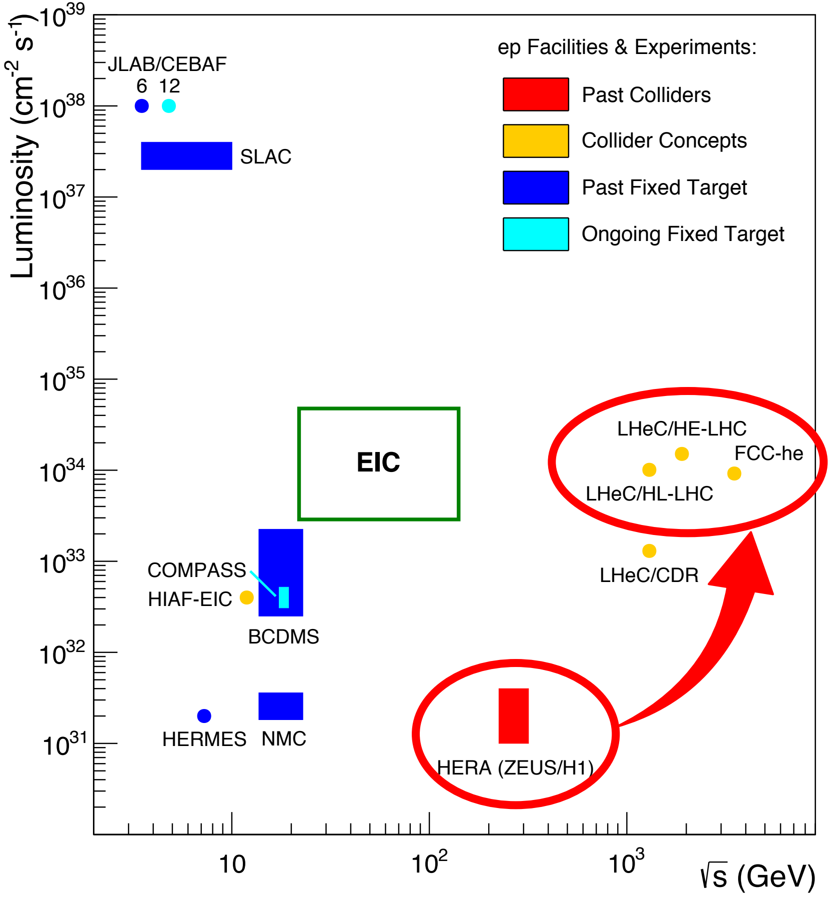
For ep/eA physics, the 2030'ies will be the decade of the EIC

The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

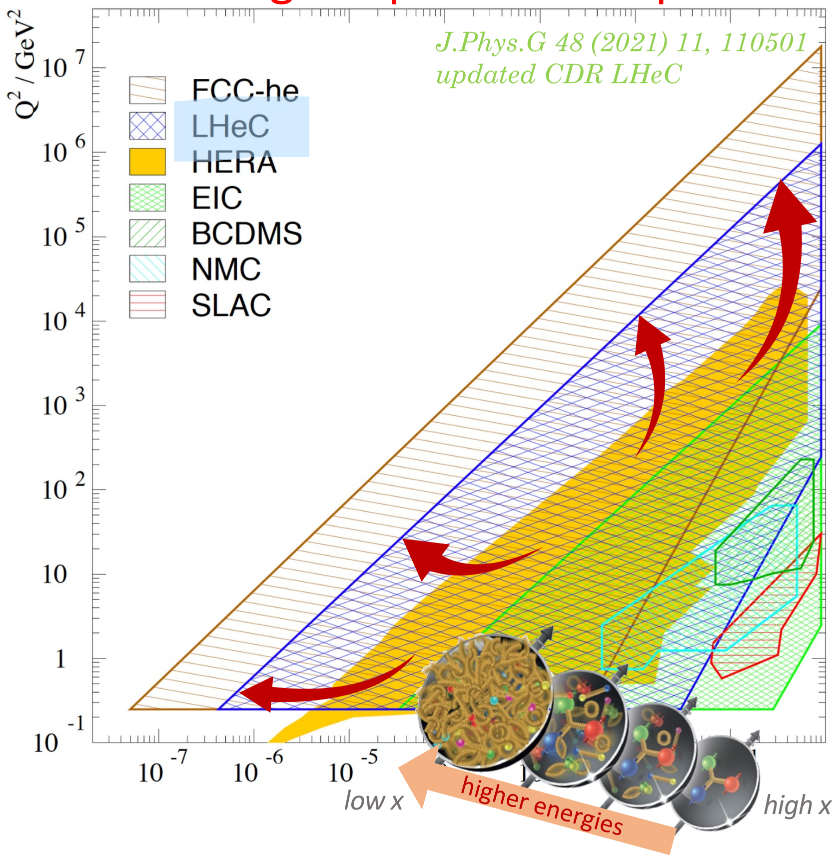


From HERA onwards to high-energy proton beams

measurements of proton Parton Distribution Functions are vital to improve the precision



reaching deeper into the proton



The challenge

High-intensity electron beam

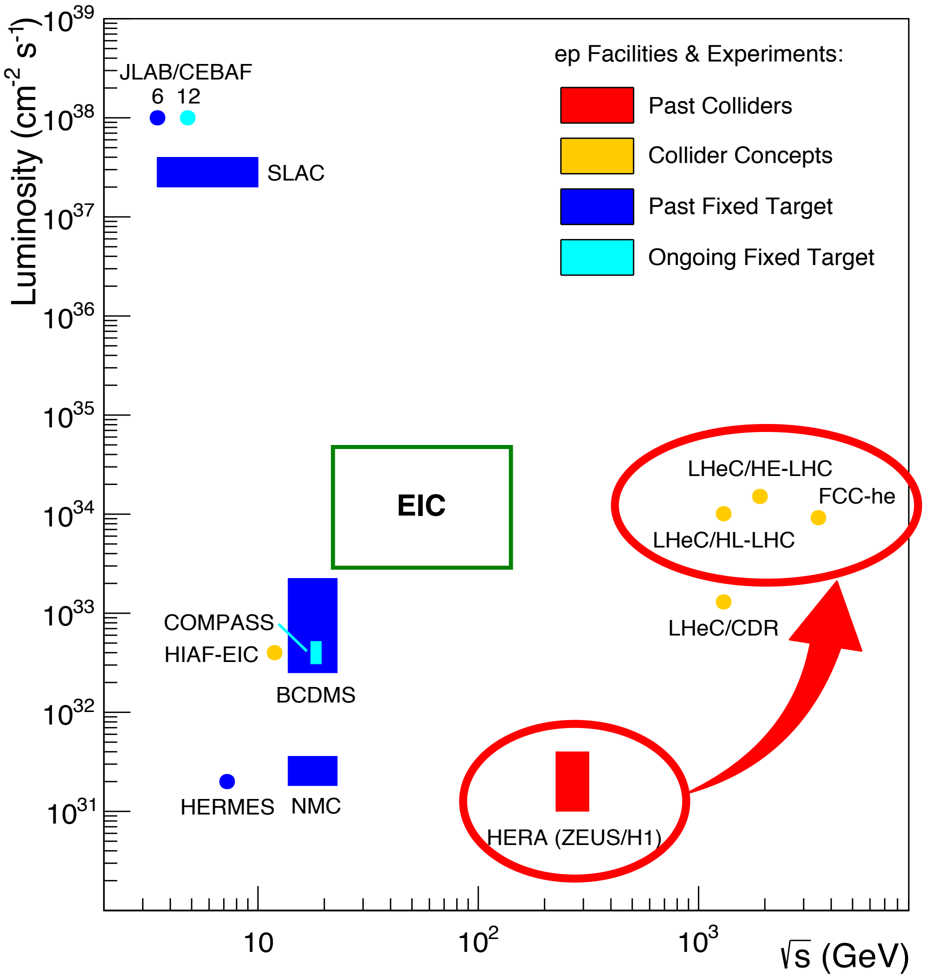
From HERA@DESY to LHeC@CERN

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



The challenge

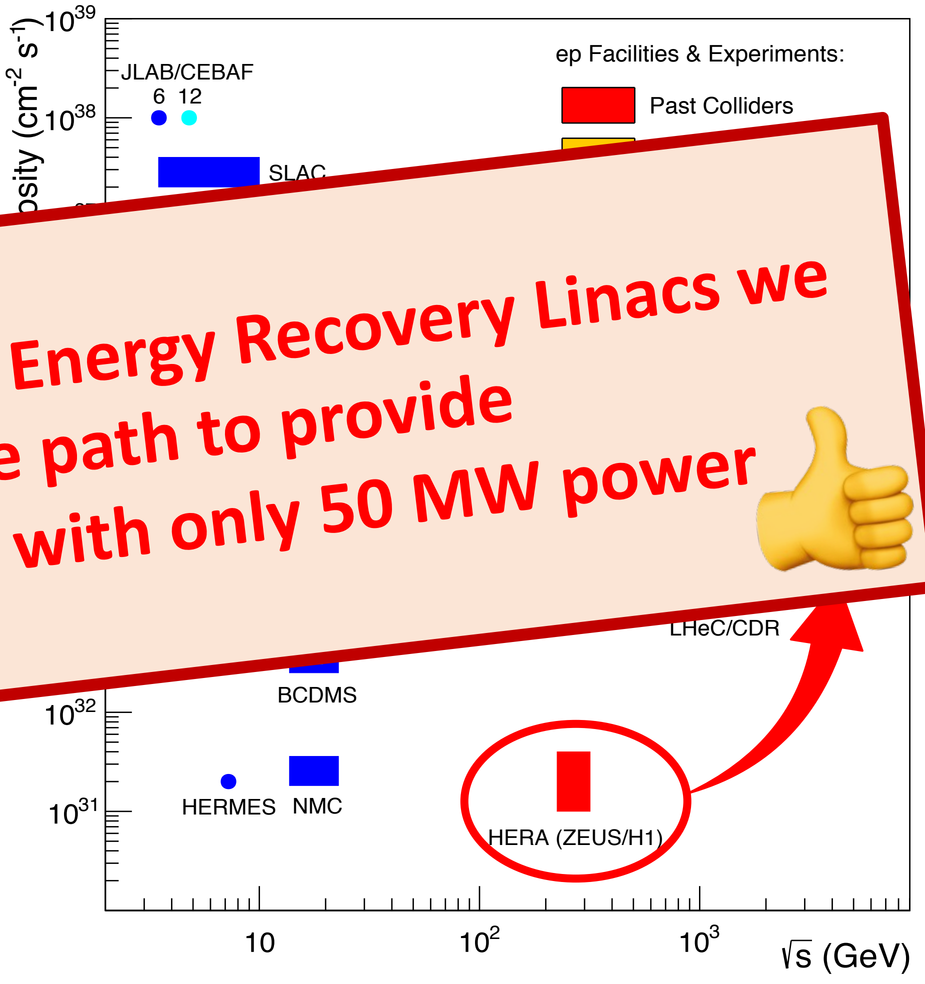
High-intensity electron beam

From HERA@DESY to LHeC@...

1 GW beam power

equivalent to the power delivered by a nuclear power plant

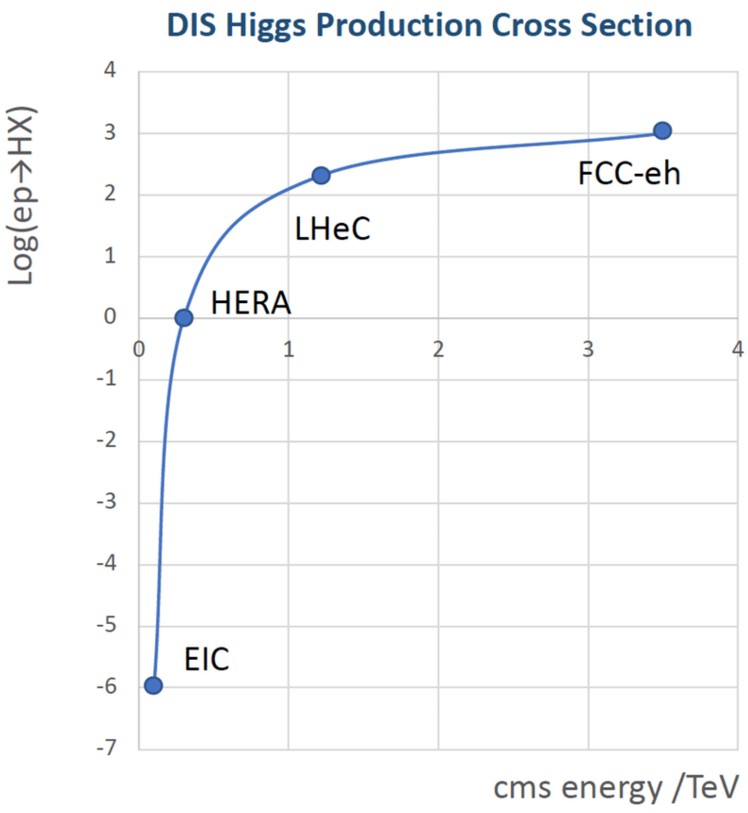
With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 50 MW power



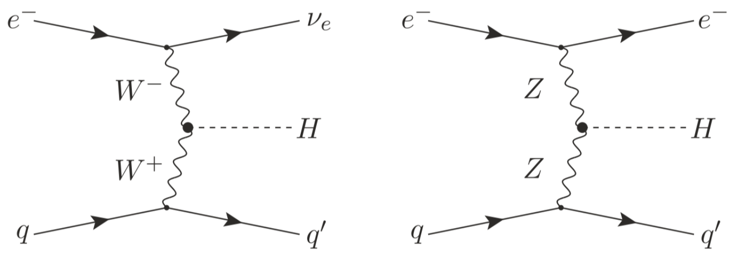
at high energies
electron-proton colliders provide
a General-Purpose experiment

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



The real game change between HERA and LHC/FCC



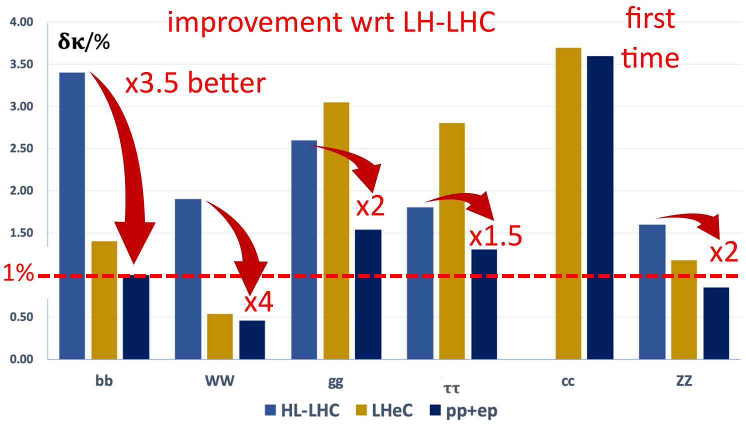
Compared to the LHC, these are reasonably clean Higgs events with much less backgrounds

at these energies, interactions with all particles in the Standard Model can be measured precisely

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



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

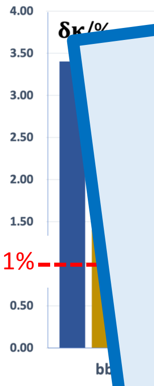
- α_s precision of 0.1%
- low-x: a new discovery frontier

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

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

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

Higgs physics



improve...

for EW/Higgs/top physics improvement factor from LHC → HL-LHC similar to HL-LHC → LHeC

...eV)

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

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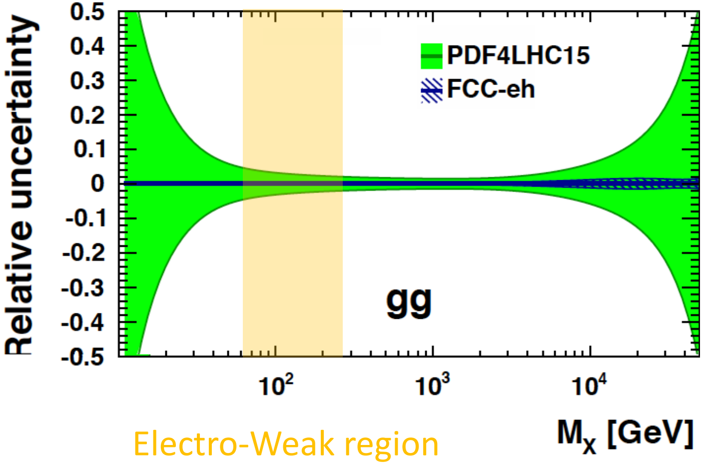
Empowering the FCC-hh program with the FCC-eh

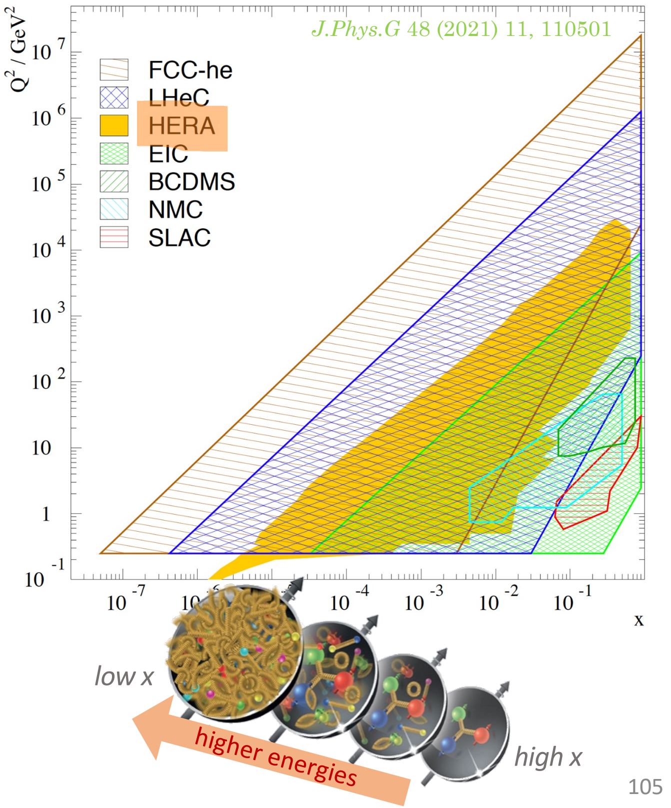
pp @ 100 TeV



~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



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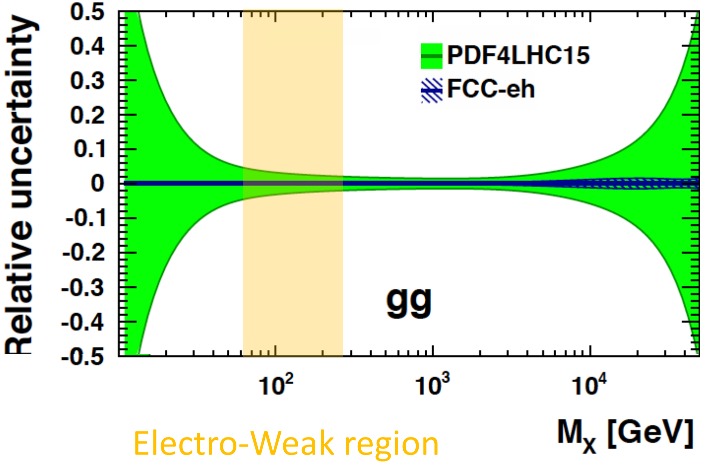


Electro-Weak region

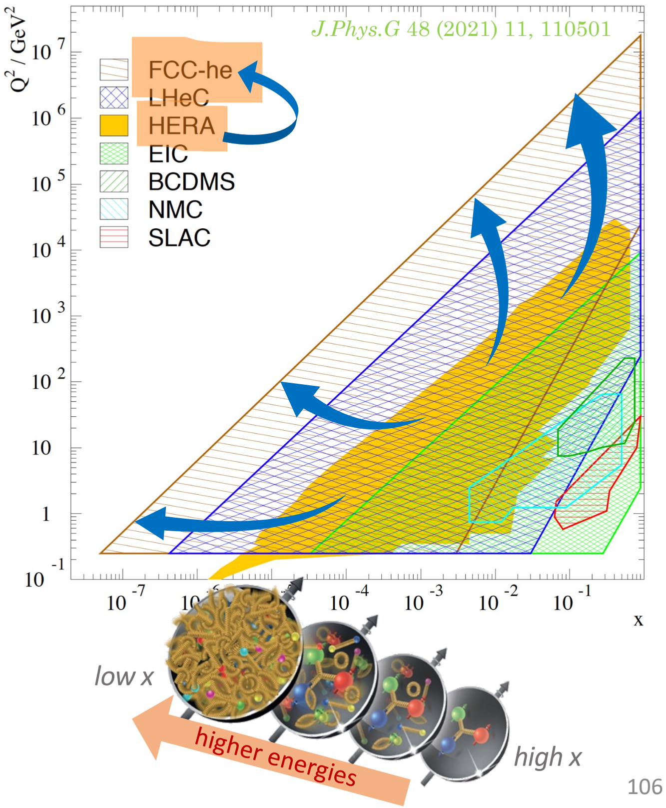
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

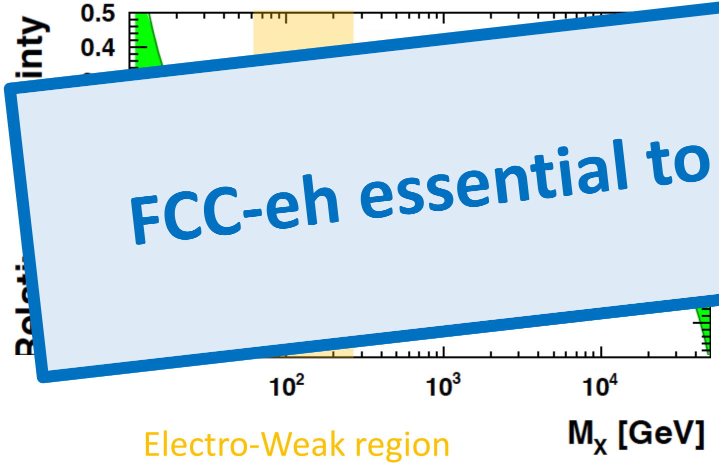
Kinematic range Parton Distribution Functions



Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

~5-7% uncertainty on the σ(W,Z,H)



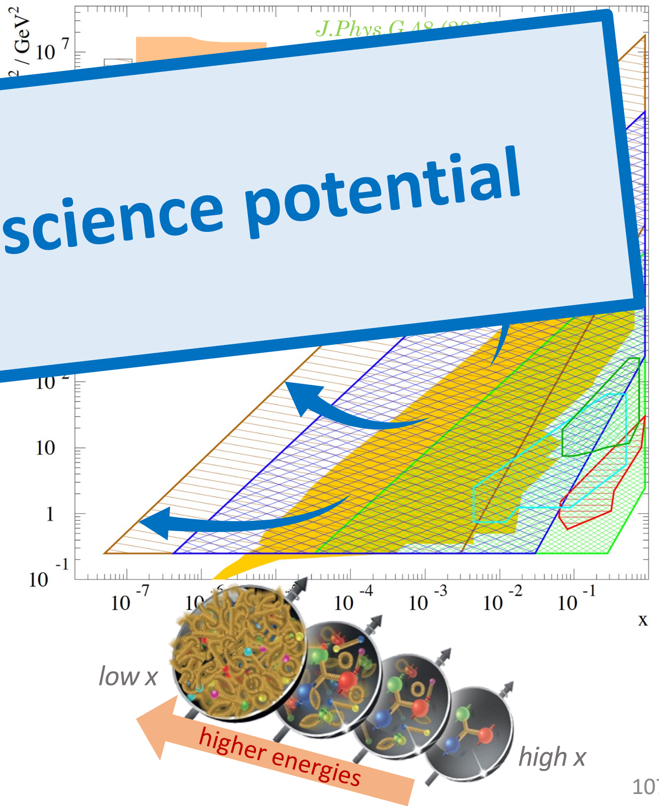
Electro-Weak region

FCC-eh essential to unlock FCC-hh science potential

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



Hadrons & Ions are made up of Quarks & Gluons

low energy

high energy

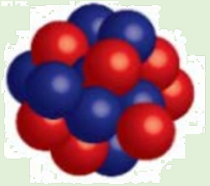
colour confinement

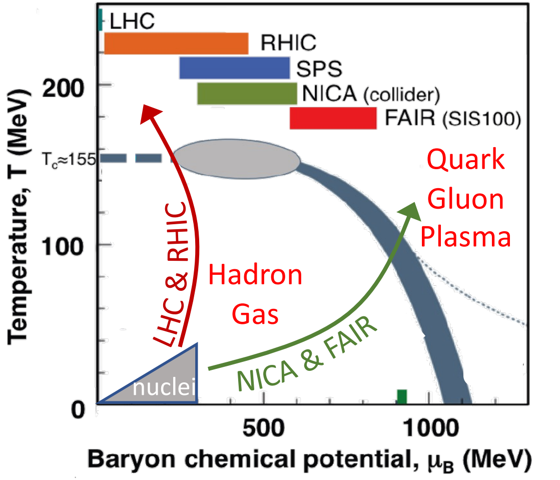
coupling ~1

asymptotic freedom

coupling <<1

experiments with heavy ions





Equation-of-State
(from a gas state to a quark-gluon plasma)

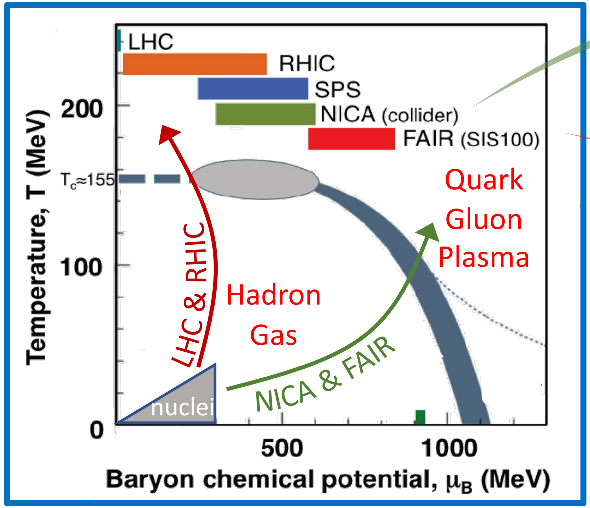
"confined" ions

"deconfined" quarks & gluons

used in experiment (applications)

used in Lagrangian (first principles)

Heavy Ion physics from RHIC & SPS to NICA & FAIR



Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

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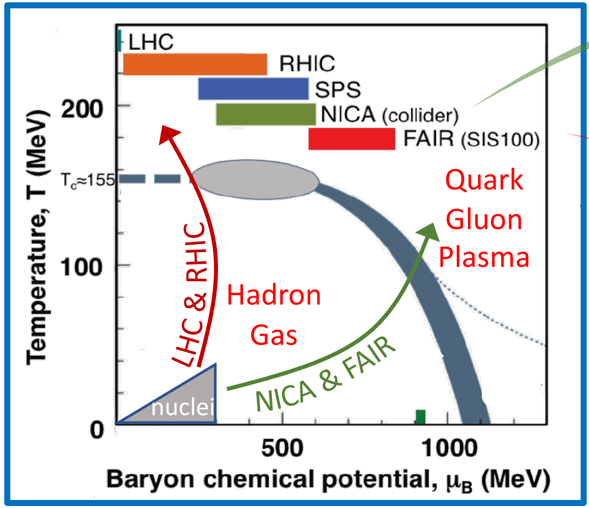
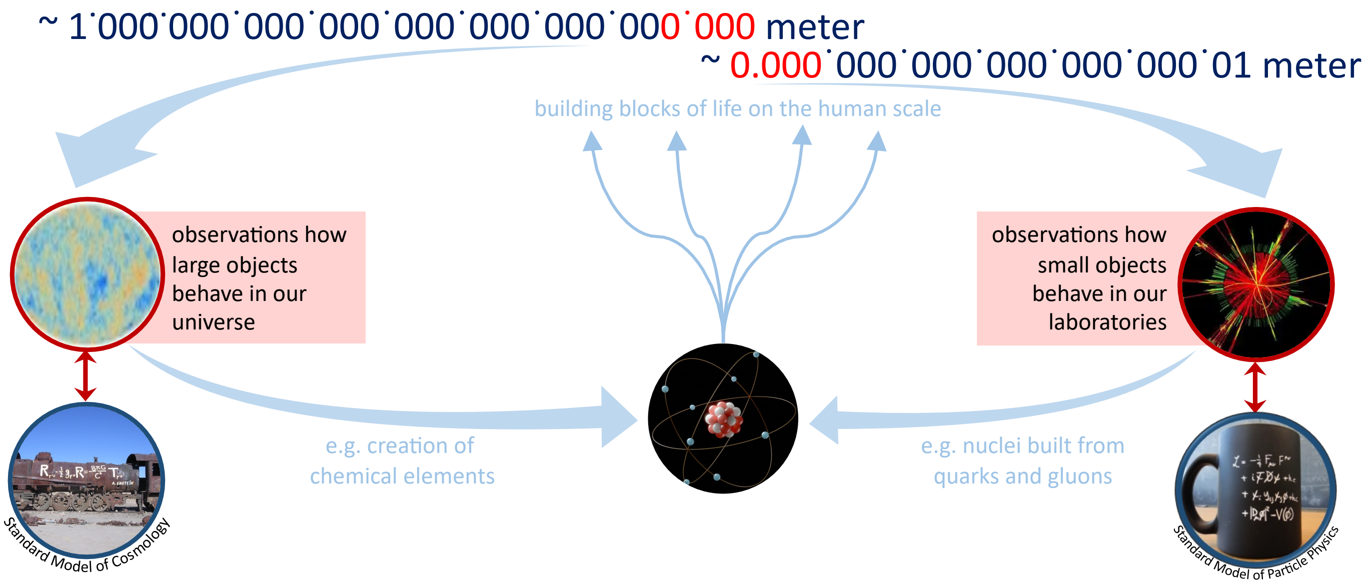


Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

- how matter and complexity emerge
- evolution of our Universe
- origin of the chemical elements



~ 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
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

Building the future together

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

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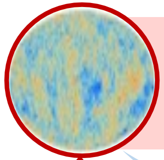
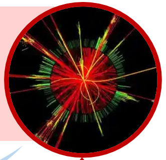
building blocks of life on the human scale

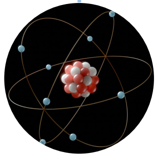


observations how large objects behave in our universe

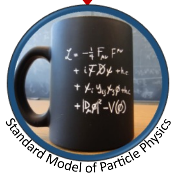


observations how small objects behave in our laboratories

e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons



With sustained capital investments in these future facilities,
we know that we must discover new physics phenomena to add to our standard models.
… if not, we might have to revisit our theoretical frameworks and/or our basic principles.

HIGH-ENERGY PHYSICS RESEARCH CENTRE

iihe BRUXELLES BRUSSEL

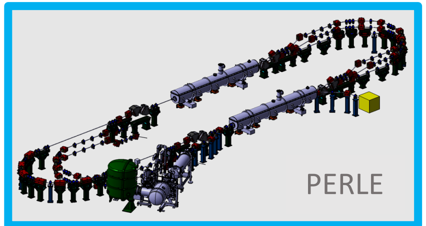
Thank you for your attention!

Jorgen.DHondt@vub.be

The future of ERL colliders

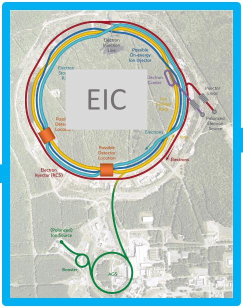
With stepping stones for innovations in technology to boost our physics reach

2020’ies



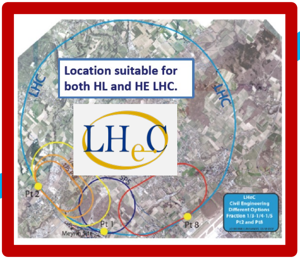
high-power ERL demonstrated

2020-2030’ies



ERL application electron cooling

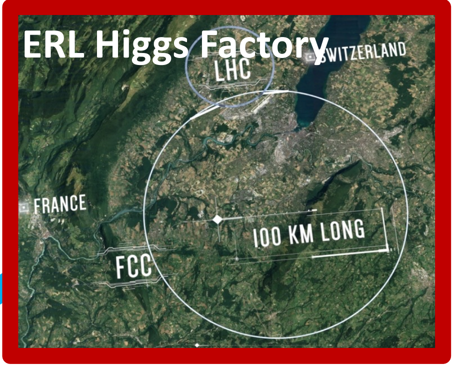
2030-2040’ies



1 ERL beam

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

2040-2050’ies



2 ERL beams

with high-power ERL
e^+e^- Higgs Factory
(Z/W/H/top program)

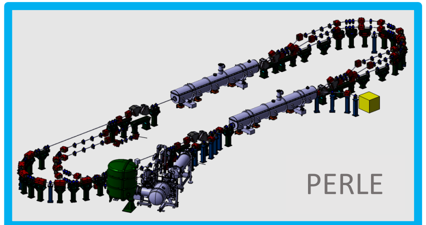
very challenging

The future of ERL colliders

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

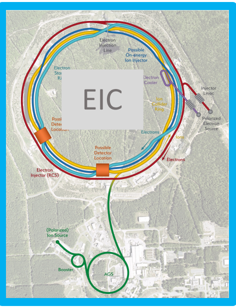
the ultimate upgrade of the LHC programme

2020'ies



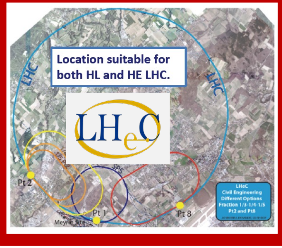
high-power ERL demonstrated

2020-2030'ies



ERL application electron cooling

2030-2040'ies



1 ERL beam

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

2040-2050'ies

2 ERL beams

with high-power ERL
e^+e^- Higgs Factory
(Z/W/H/top program)

the next major collider