Accelerating Nuclear & Particle Physics

united in a quest for fundamental knowledge with synergies at a scientific and technical level

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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Kick Off Meeting, EURO-LABS, Bologna, 3-5 October 2022

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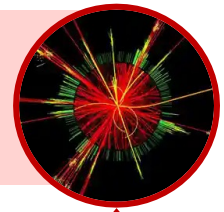
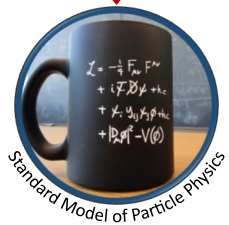
observations how small objects behave in our laboratories





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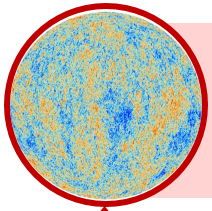
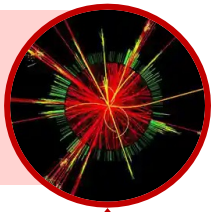
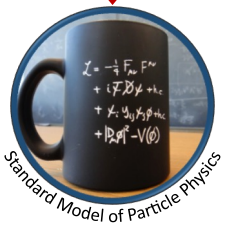


observations how large objects behave in our universe

observations how small objects behave in our laboratories





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

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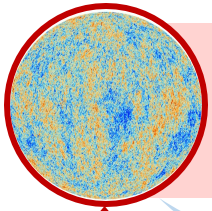
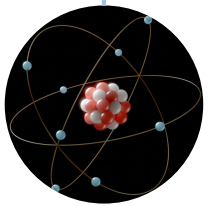
building blocks of life on the human scale



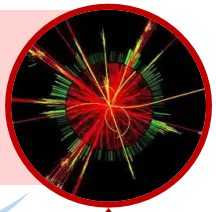
observations how large objects behave in our universe

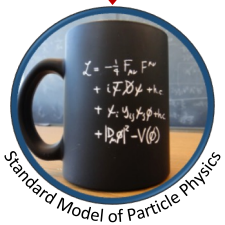
e.g. creation of chemical elements



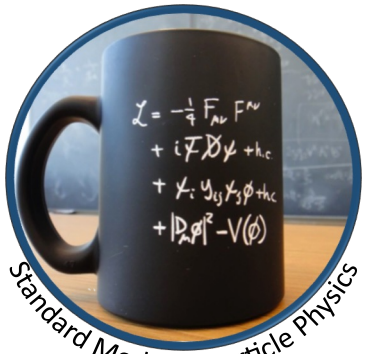
e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





The quest for understanding physics



“Problems and Mysteries”

e.g. Scale of things (why do the numbers miraculously match)?
Pattern of particle masses and mixings?
Dynamics of Electro-Weak symmetry breaking?
Abundance of dark matter?
Abundance of matter over antimatter?
How do quarks and gluons give rise to properties of nuclei?
What caused (and stopped) inflation in the early universe? …

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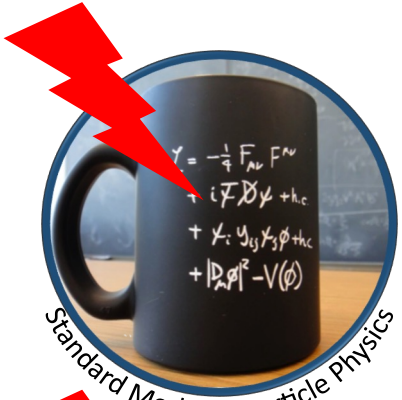

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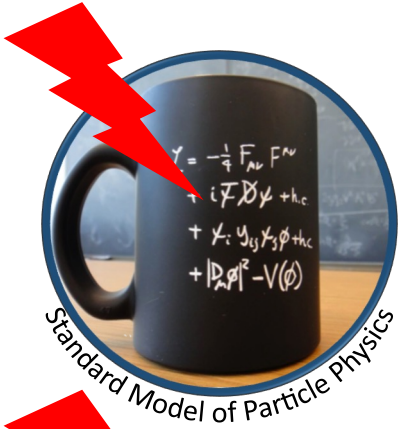
Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

The quest for understanding physics



"Problems and Mysteries"

Accordingly, researchers question among others:

The structure of matter ?

The symmetries in nature ?

The invisible part of nature ?

When we enter terra incognita along these three scientific axes, there are essential synergies between nuclear and particle physics

①

the structure of matter

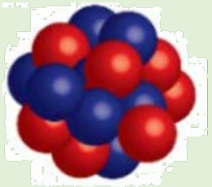
Hadrons & Ions are made up of Quarks & Gluons

colour confinement
coupling ~1

low energy

high energy

asymptotic freedom
coupling <<1



Equation-of-State

Parton Distribution Functions

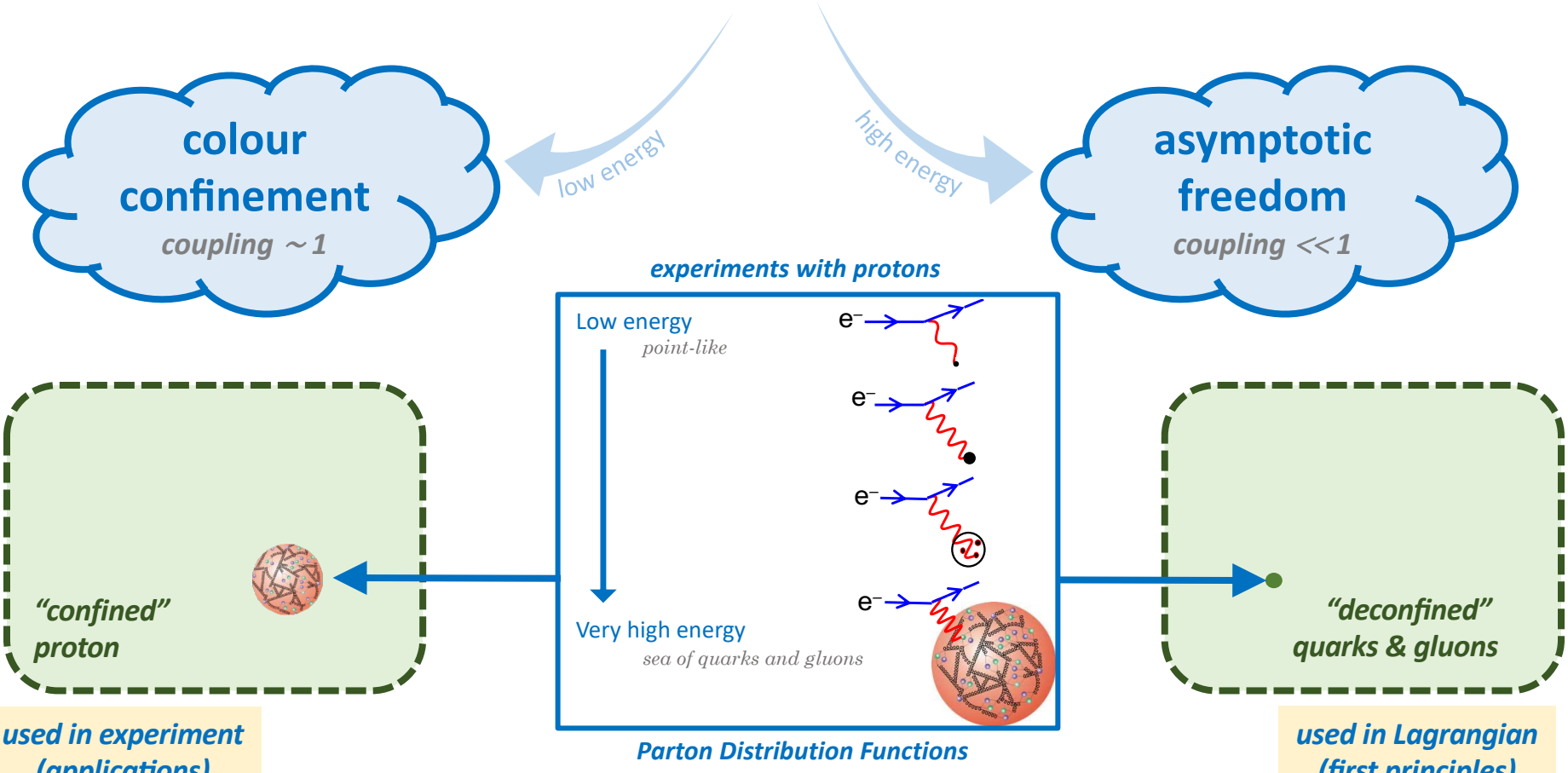
"confined" hadrons & ions

"deconfined" quarks & gluons

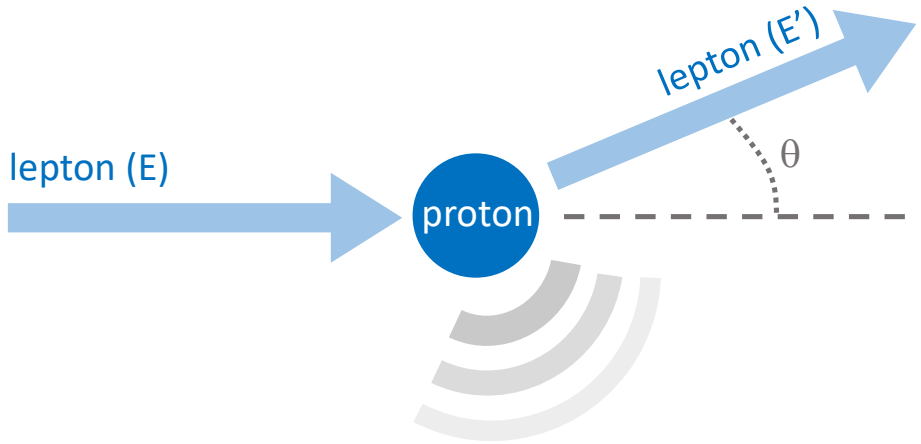
used in experiment (applications)

used in Lagrangian (first principles)

Hadrons & Ions are made up of Quarks & Gluons



The 50+ years success story of DIS



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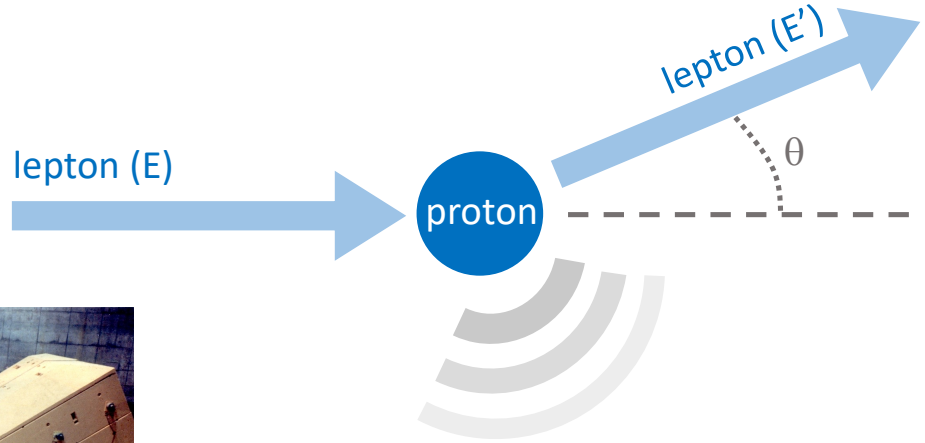

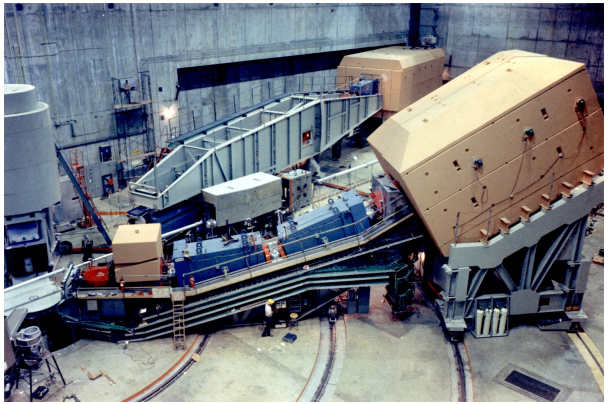

Discovery of quarks

(1968, ep@MIT-SLAC experiment)

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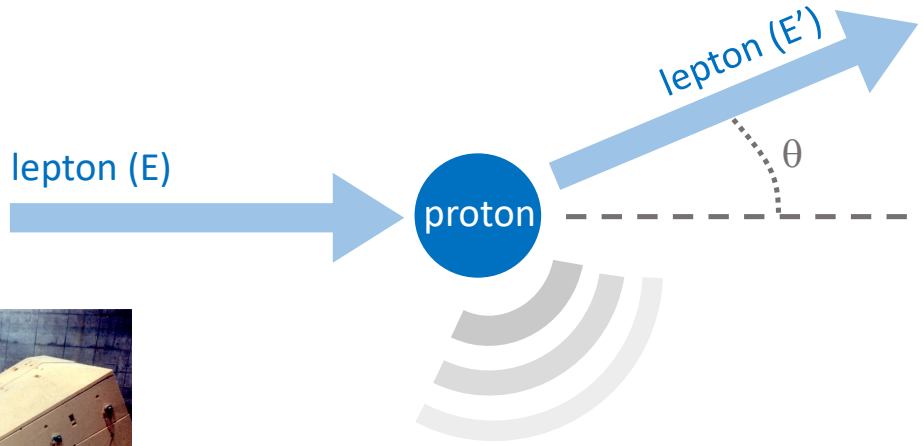

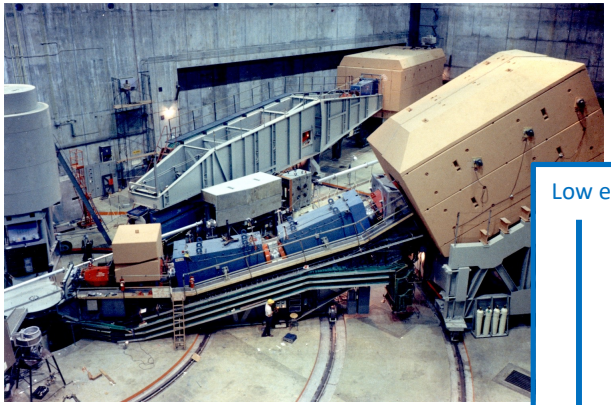

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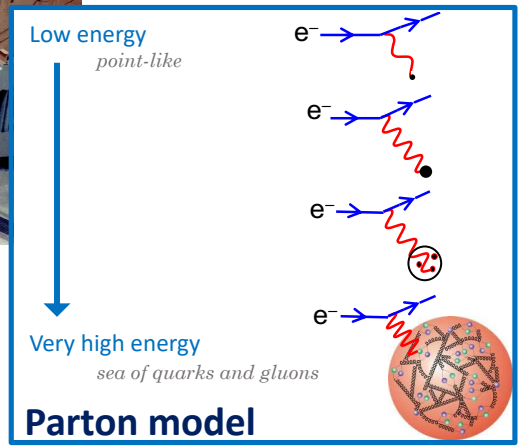

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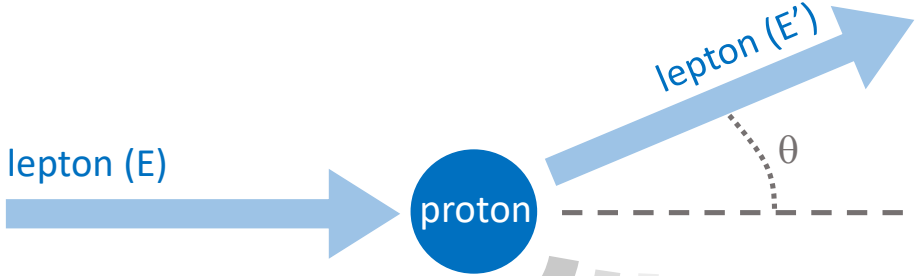

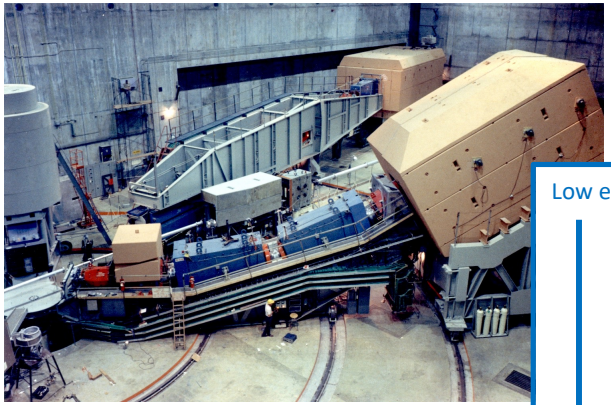

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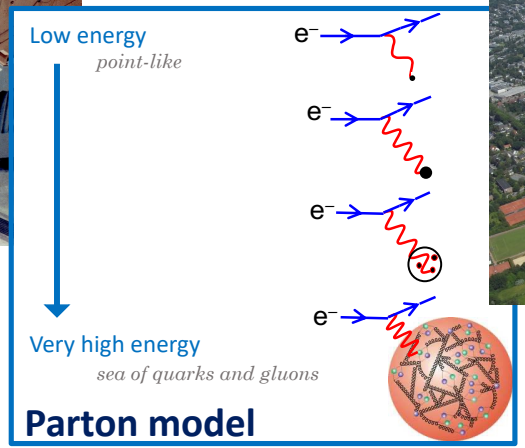

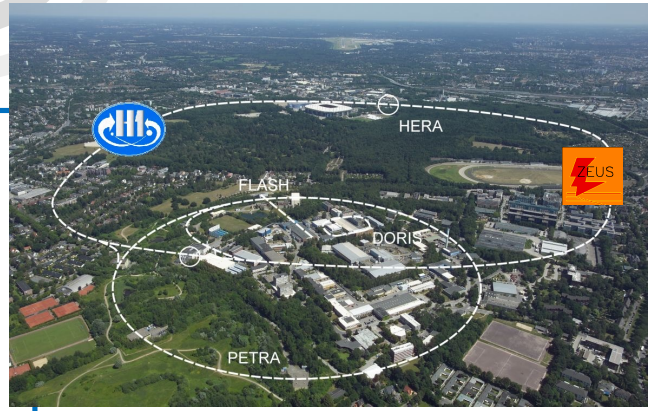

The DIS precision era

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

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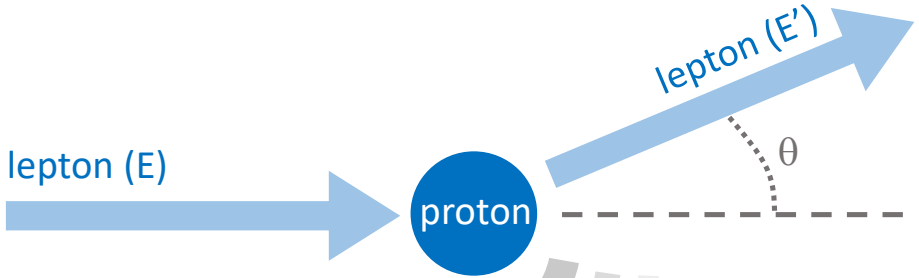

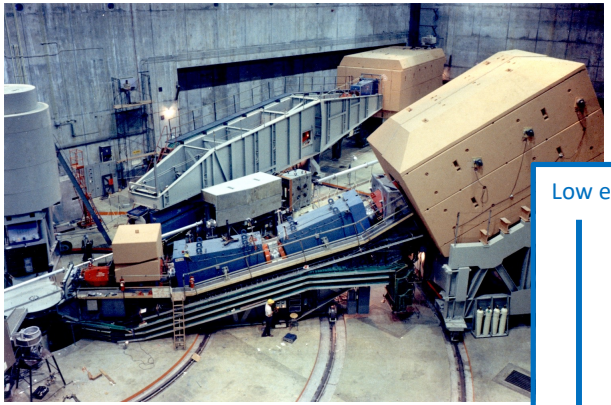

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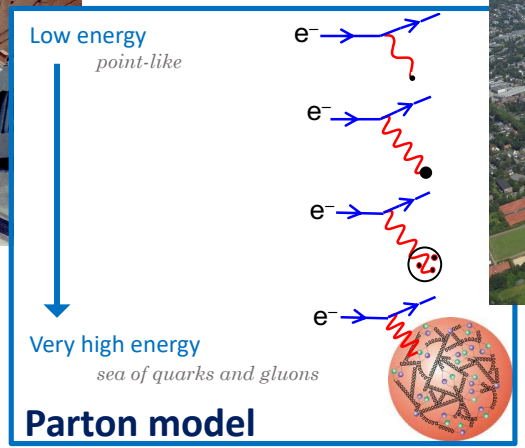

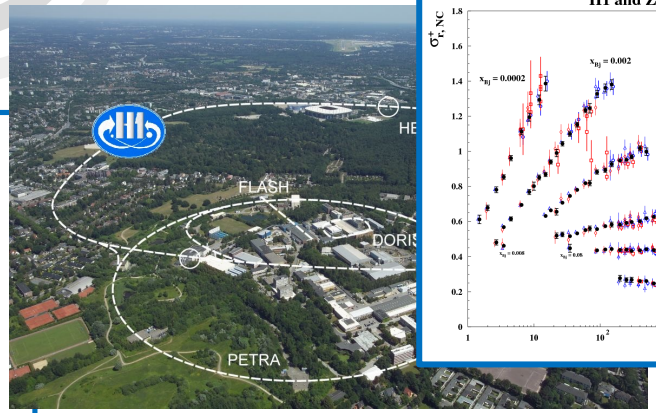

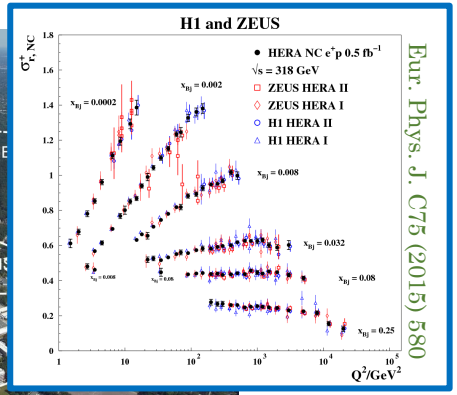

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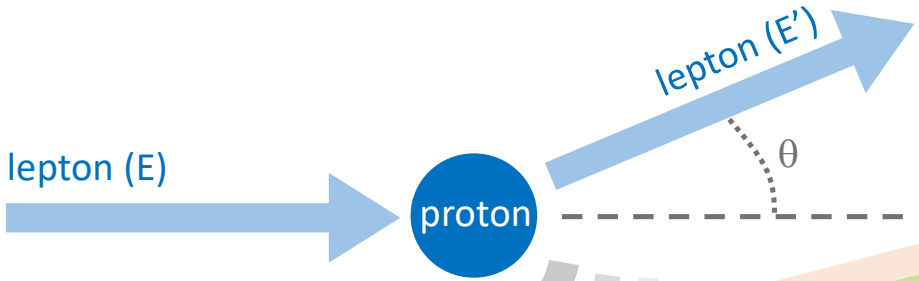

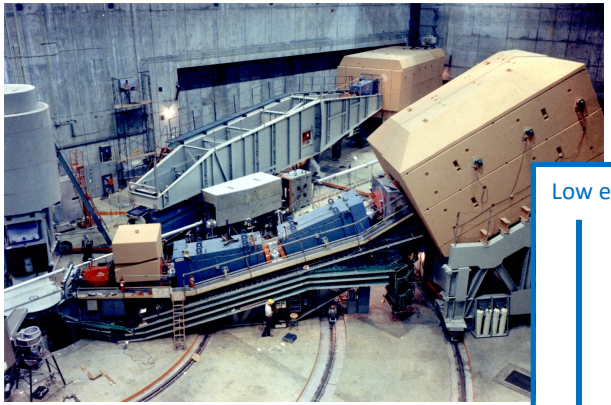

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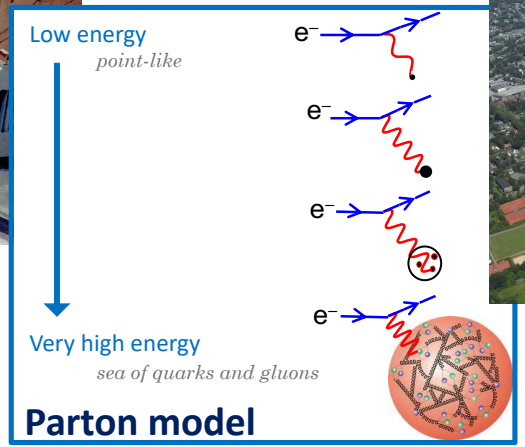
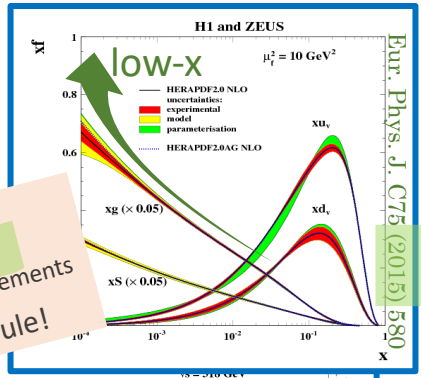


Parton model

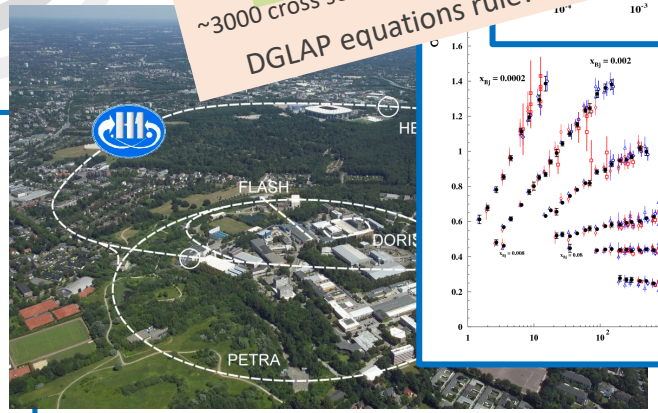
Parton Distribution Functions



the HERA legacy

~3000 cross section measurements

DGLAP equations rule!



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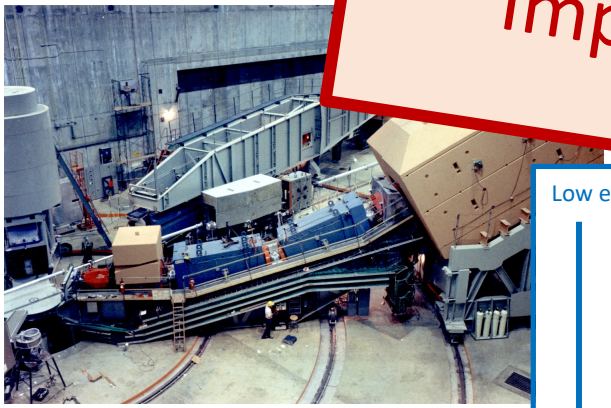

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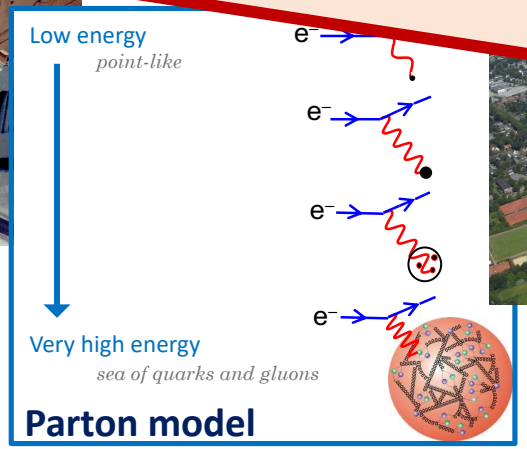

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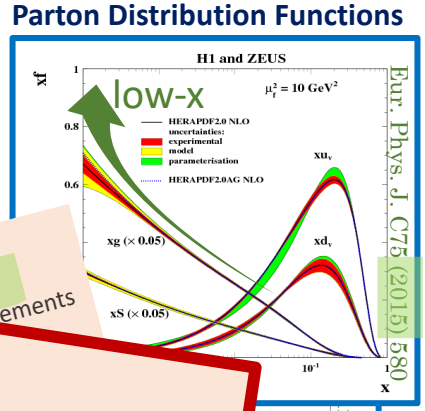
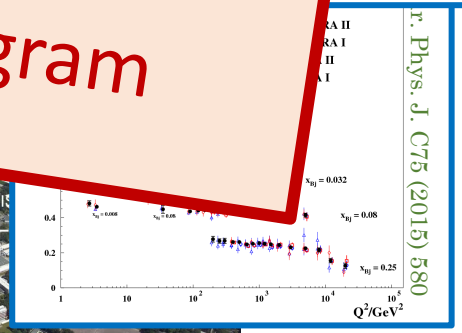


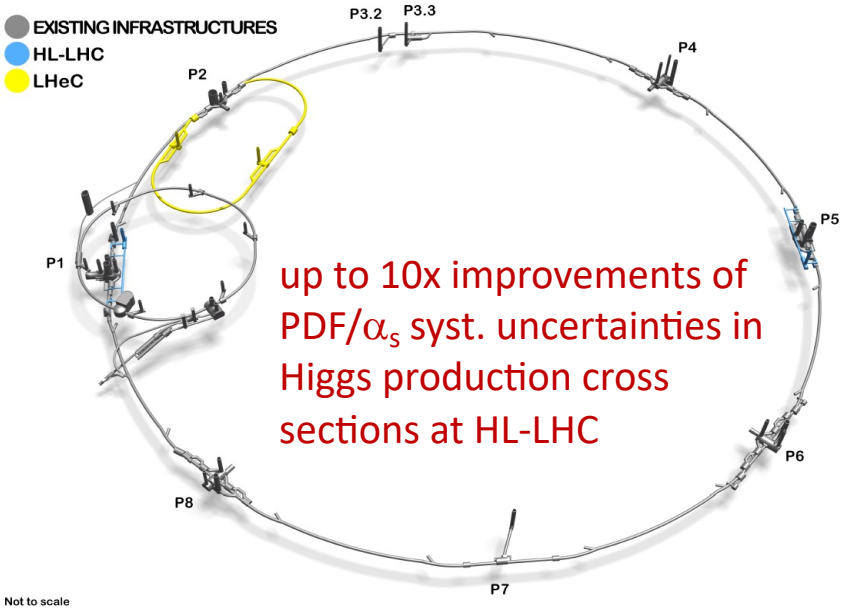


Important for the LHC program

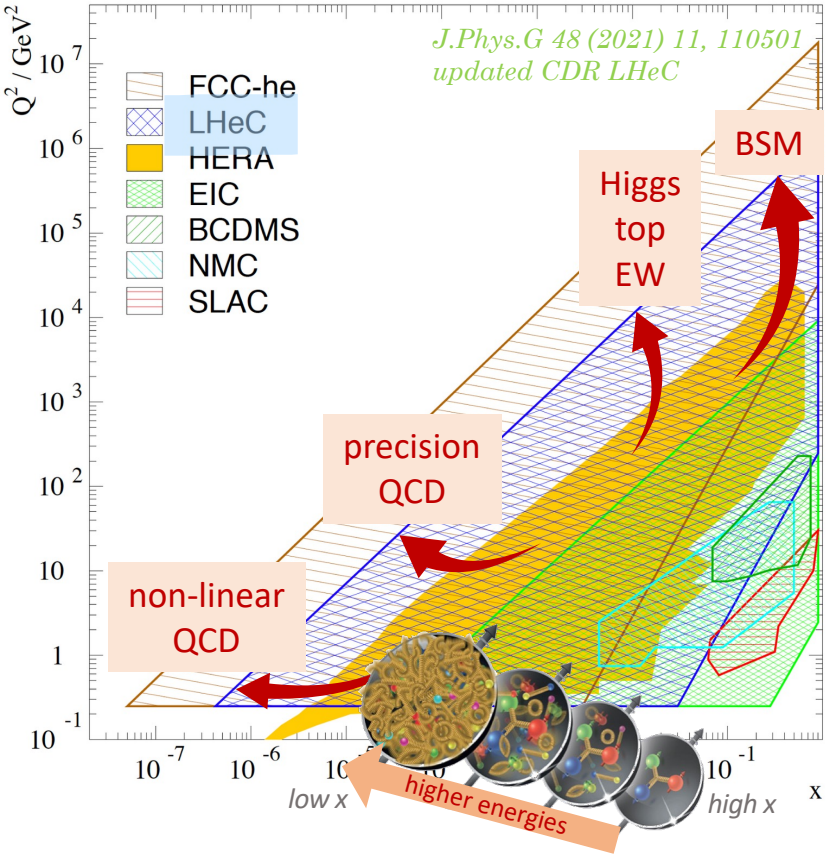
Empowering the (HL-)LHC program with the LHeC

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

LHeC (up to 60 GeV e^-)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA run with the HL-LHC ($\gtrsim$ Run5)

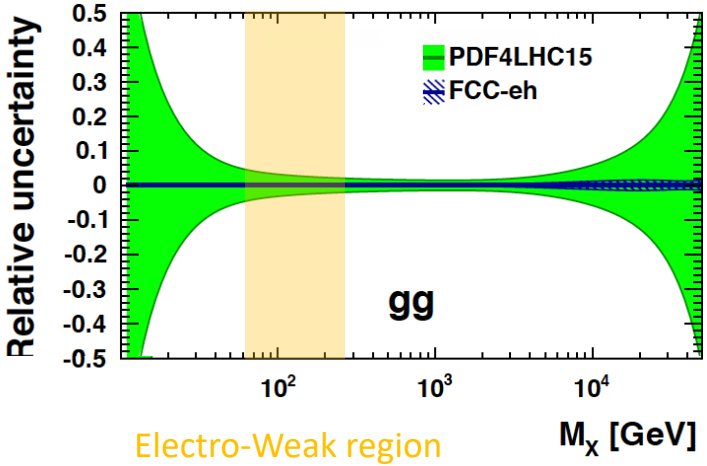


up to 10x improvements of PDF/α_s syst. uncertainties in Higgs production cross sections at HL-LHC



Empowering the FCC-hh program with the FCC-eh

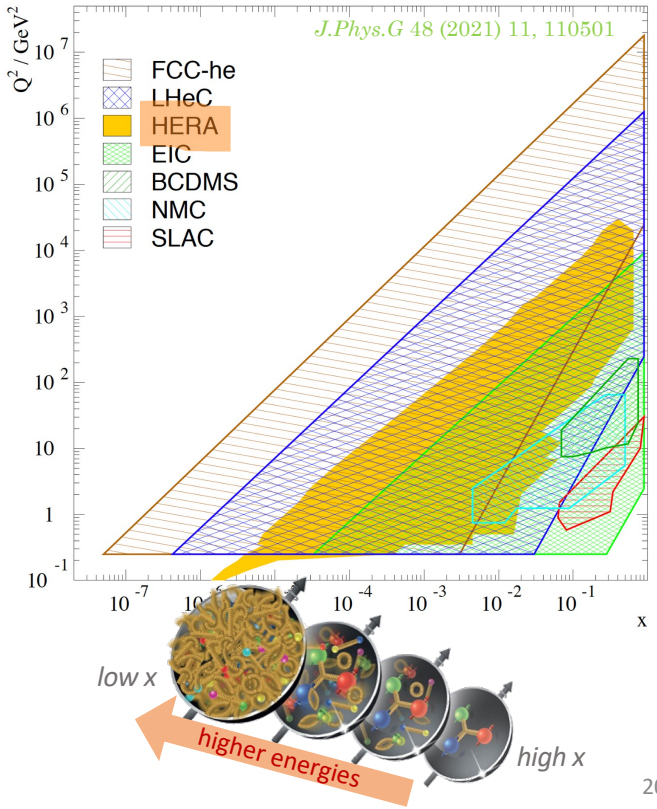
pp @ 100 TeV



Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



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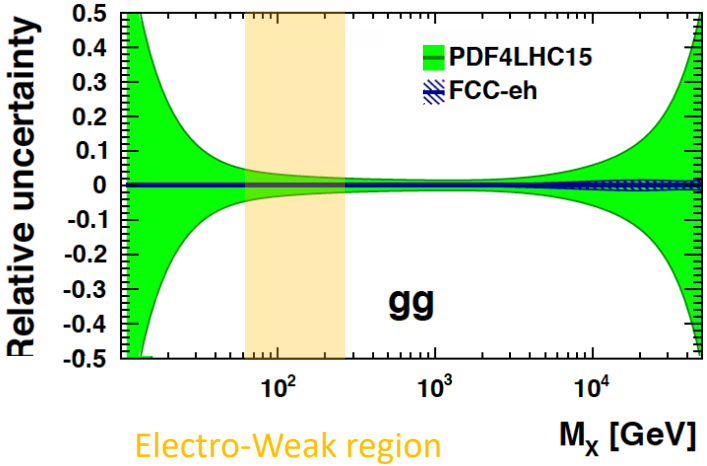


Electro-Weak region

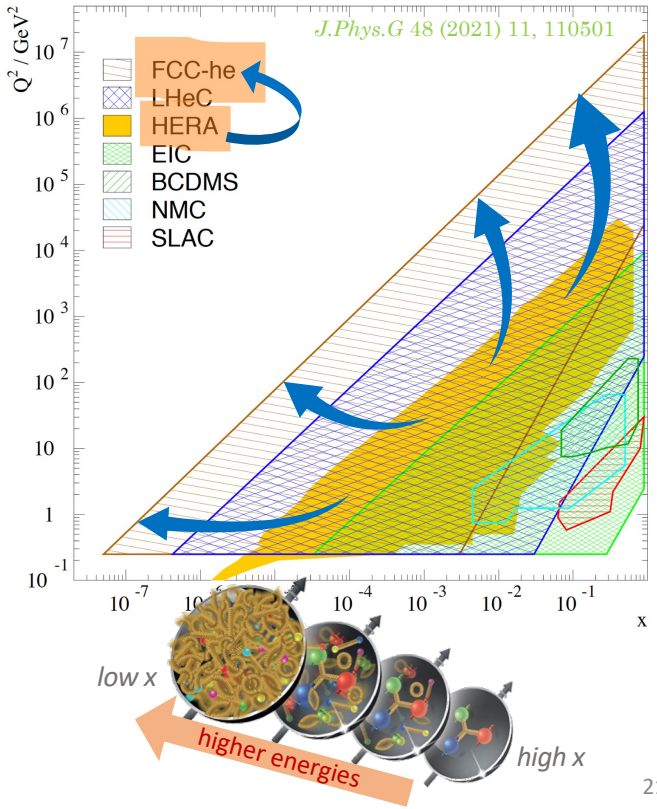
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions

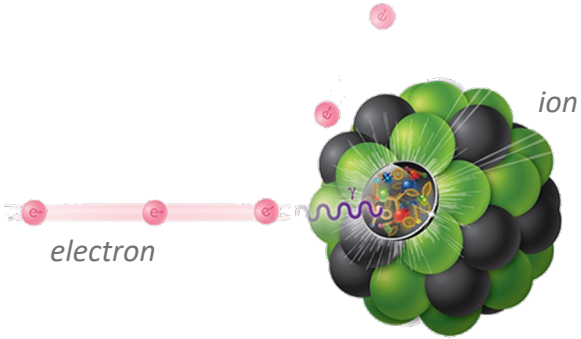


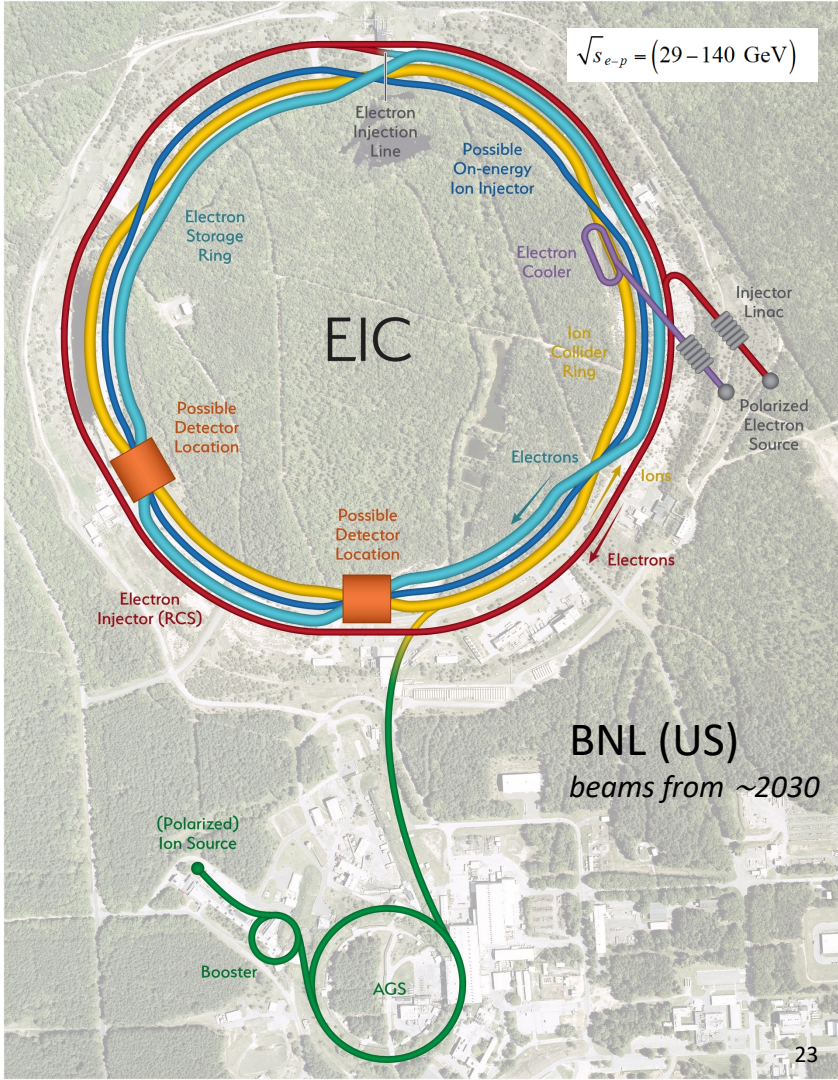
around the corner:
a unique ep & eA scattering facility

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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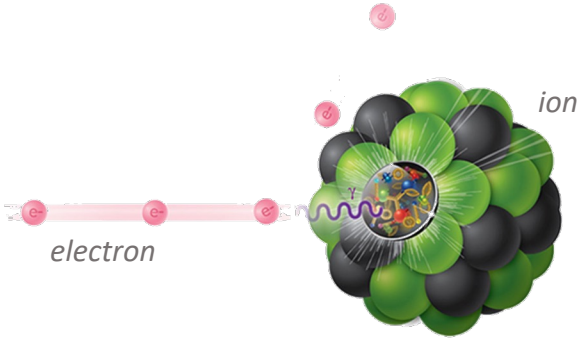
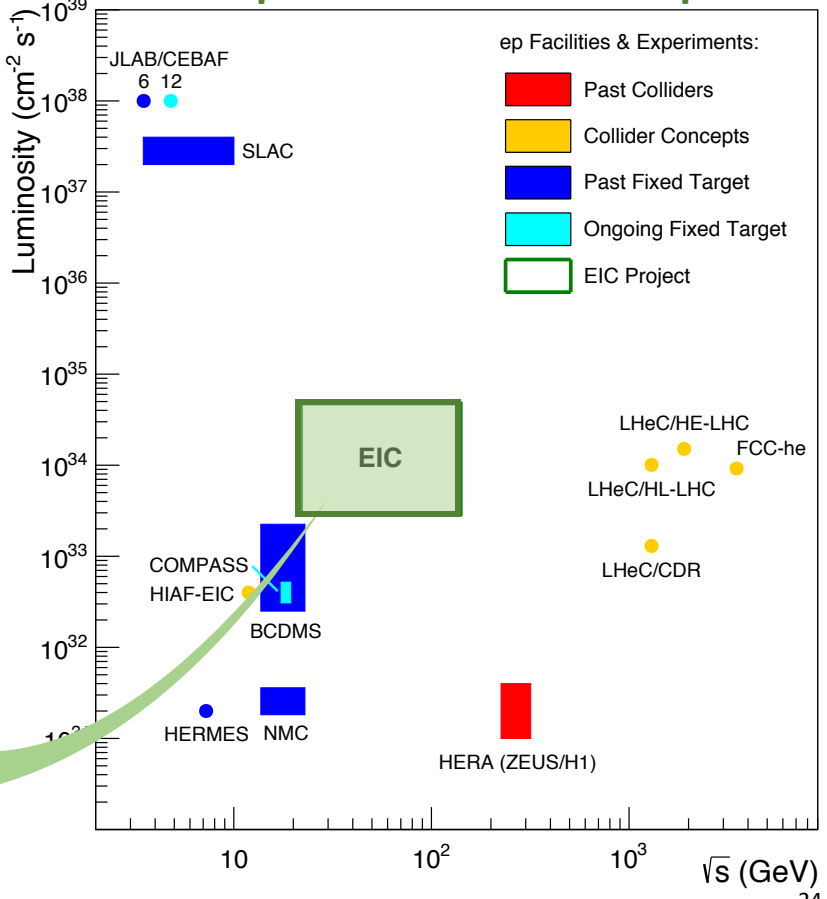


- High luminosity
- Wide range in beam energy
- Polarized lepton & hadron beam
- Nuclear beam

Unique in the DIS landscape

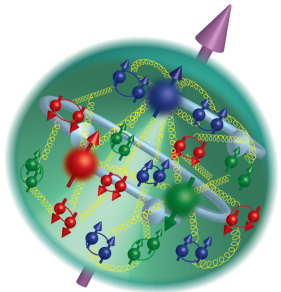


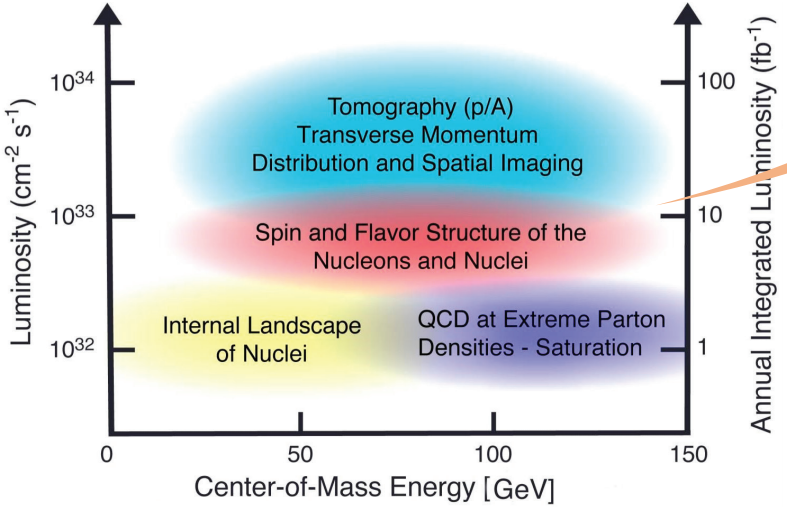
Electron-Ion Collider (EIC)

Unique in the DIS landscape

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

Towards a 3D partonic image of the proton





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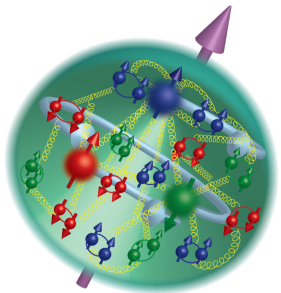
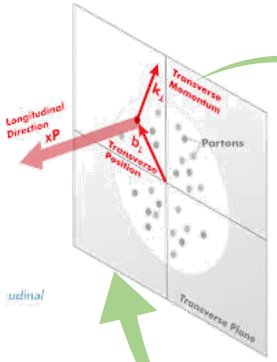
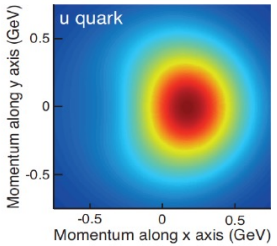
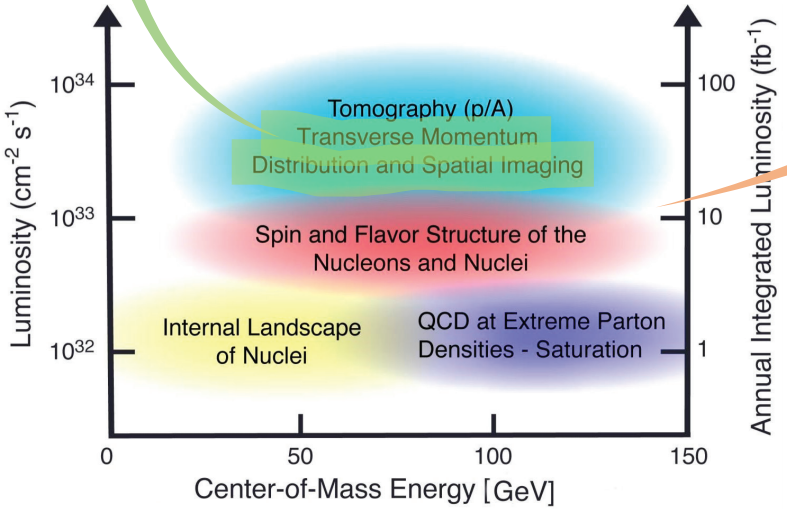
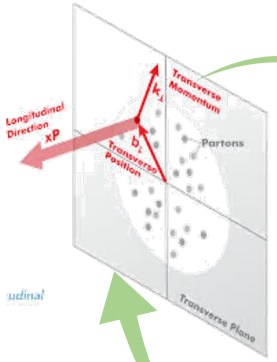


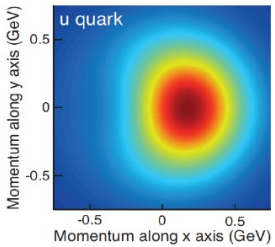






Electron-Ion Collider (EIC)





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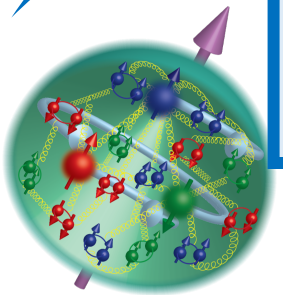
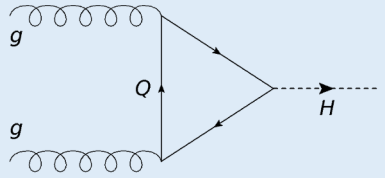
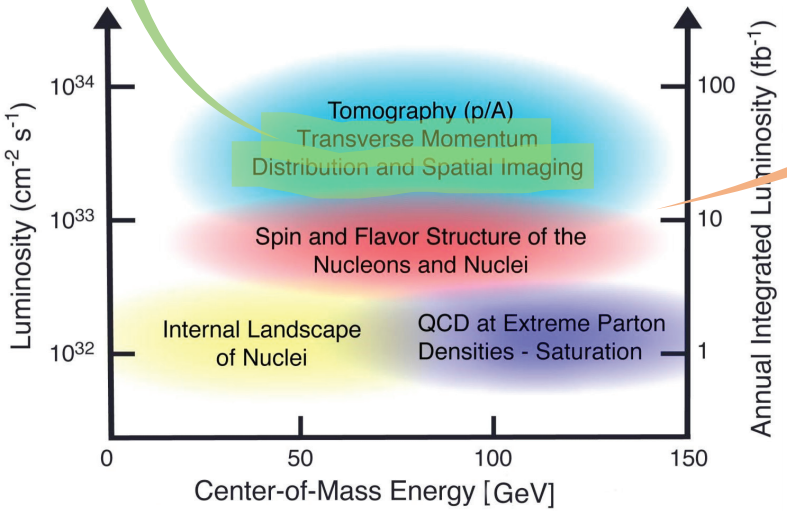
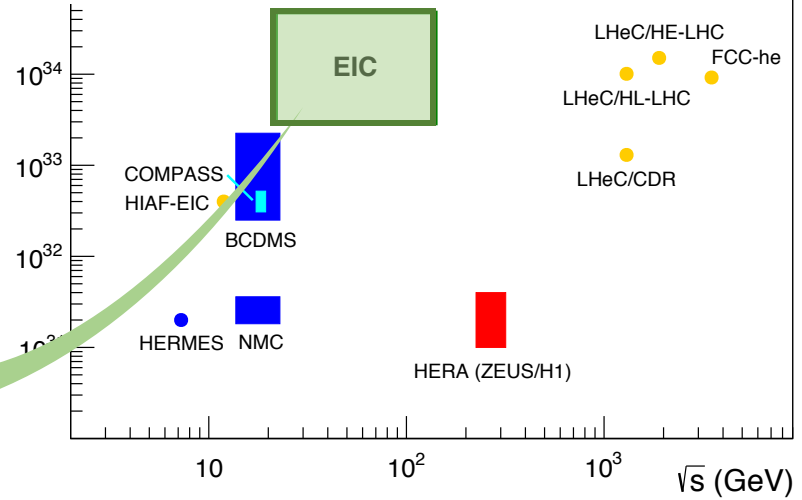


improved gg→H @ LHC



improved W mass (in pp)





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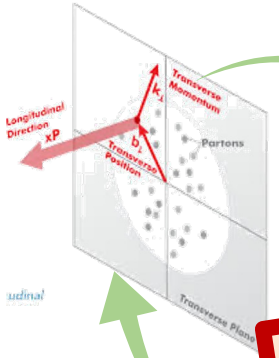

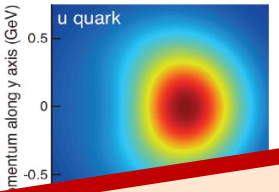

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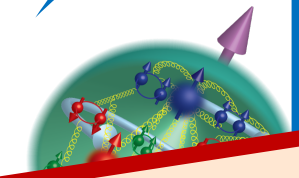

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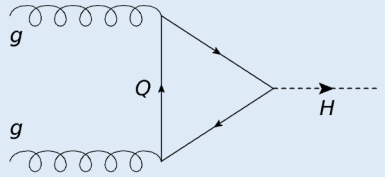
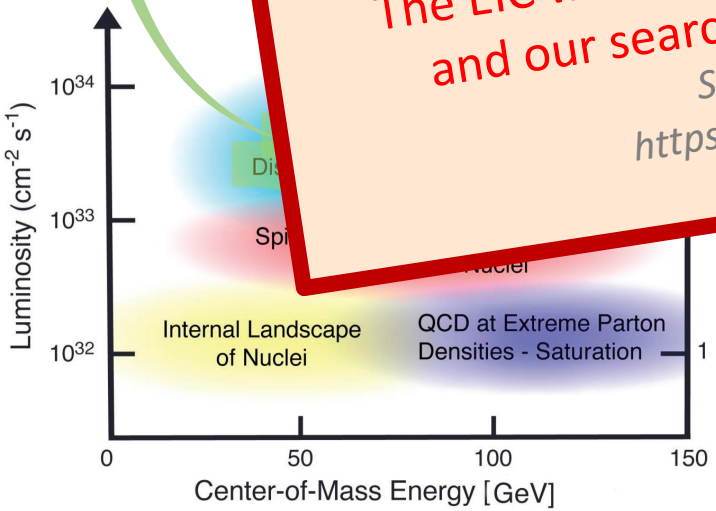


mass (in pp)

The EIC will empower the (HL-)LHC physics program and our search for new physics at high energies

Snowmass 2021 White Paper

https://arxiv.org/pdf/2203.13199.pdf



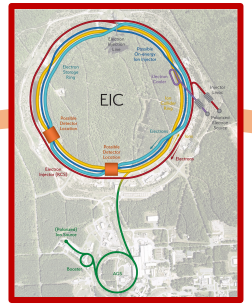
From lower to higher energy scattering experiments

A global ep/eA/μA program bridging nuclear & particle physics for a profound understanding of the structure of matter

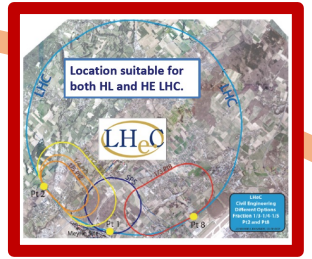
2020'ies

Lower-energy scattering
MESA, COMPASS++/AMBER, NA61, …

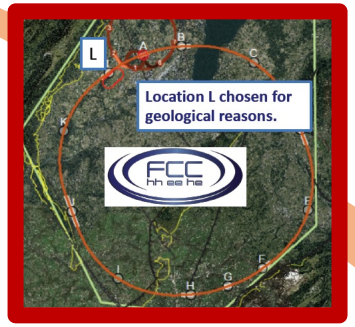
2020-2030'ies



2030-2040'ies



> 2050



Driven by unique science
nuclear structure
ElectroWeak & Higgs
new physics searches
theory & experiment

Driven by remarkable technology
energy recovery & RF structures
precision detectors
leverage on other colliders

the symmetries in nature

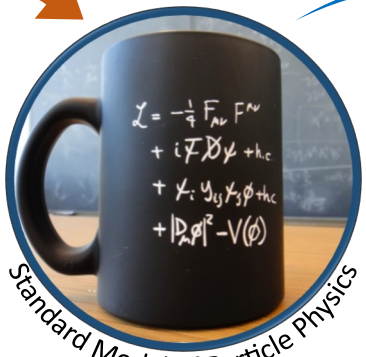
Mathematical description of nature based on its symmetries

Our understanding is not complete… hence where and how do these symmetries break

(Broken) Symmetries

Discrete: C, P, T, CP, CPT

Gauge: U(1) x SU(2) x SU(3)



Search for the tiniest cracks

(e.g.)

Matter vs antimatter

Baryon Number Violation

Lepton Number Violation

Electric Dipole Moments

Interpretations in theoretical frameworks covering nuclear and particle physics

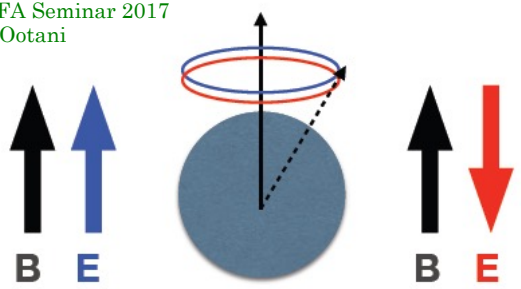
Electric Dipole Moment (EDM)

Separation of particle charge along angular momentum axis

The EDM in the Standard Model is negligible (SM EDM electron 10^{-38} e-cm).
If non-zero it violates symmetries like P, T, CP.

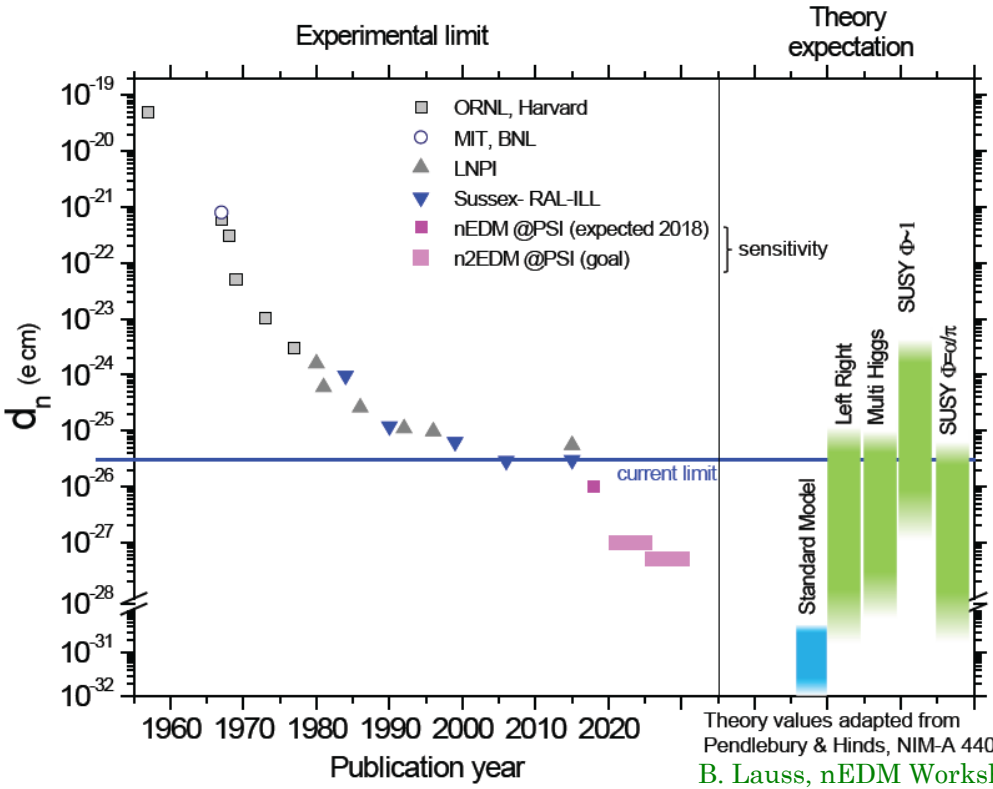
Measure Larmor frequency shift

ICFA Seminar 2017
W.Ootani



$$h\nu_{\uparrow\uparrow} = 2(\mu \cdot B + d \cdot E)$$
$$h\nu_{\uparrow\downarrow} = 2(\mu \cdot B - d \cdot E)$$
$$\Rightarrow \quad h\Delta\nu = 4d \cdot E$$

Various systems are used from protons, neutrons and electrons to atoms and molecules.



Theory values adapted from
Pendlebury & Hinds, NIM-A 440 (2000) 471

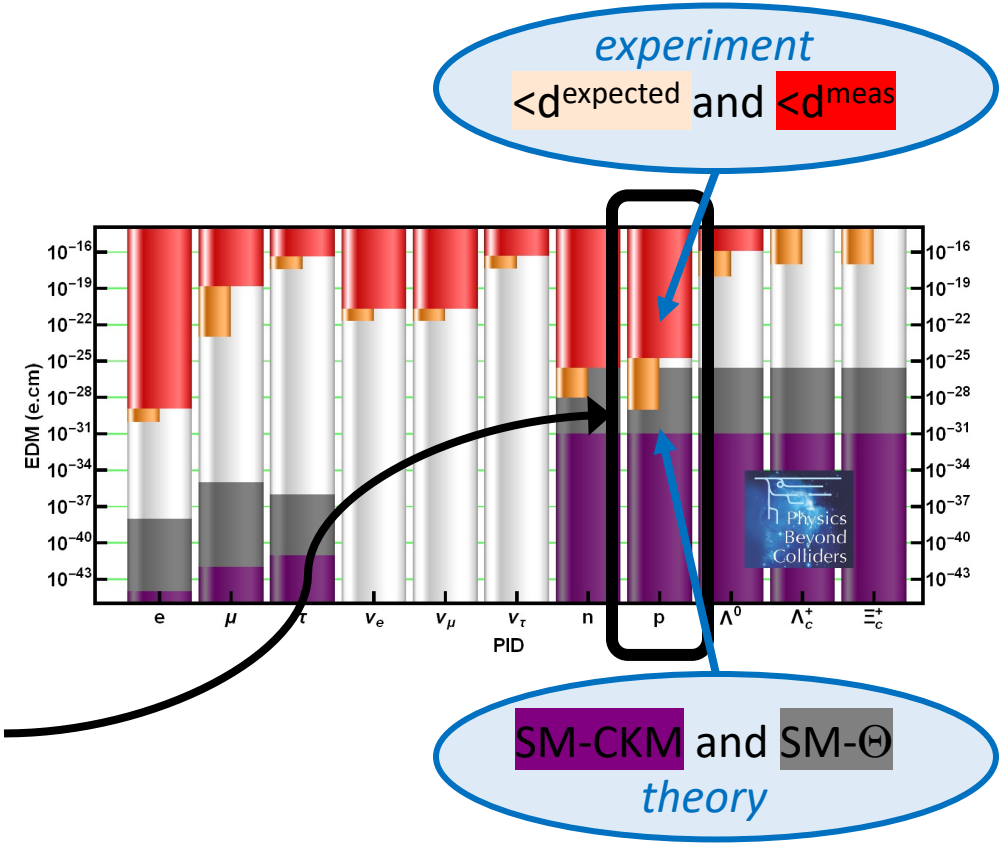
B. Lauss, nEDM Workshop 2017

Charged-Particle EDMs (CPEDM & JEDI Collaborations)

Towards a prototype storage ring – Feasibility studies

Ultimate goal of a dedicated storage ring with 400-500m circumference is pEDM sensitivity down to 10^{-29} e cm

(today 10^{-26} e cm)



Probing the fundamental symmetries of nature

Larger and smaller objects are used in nuclear & particle physics, but interpreted in a common framework

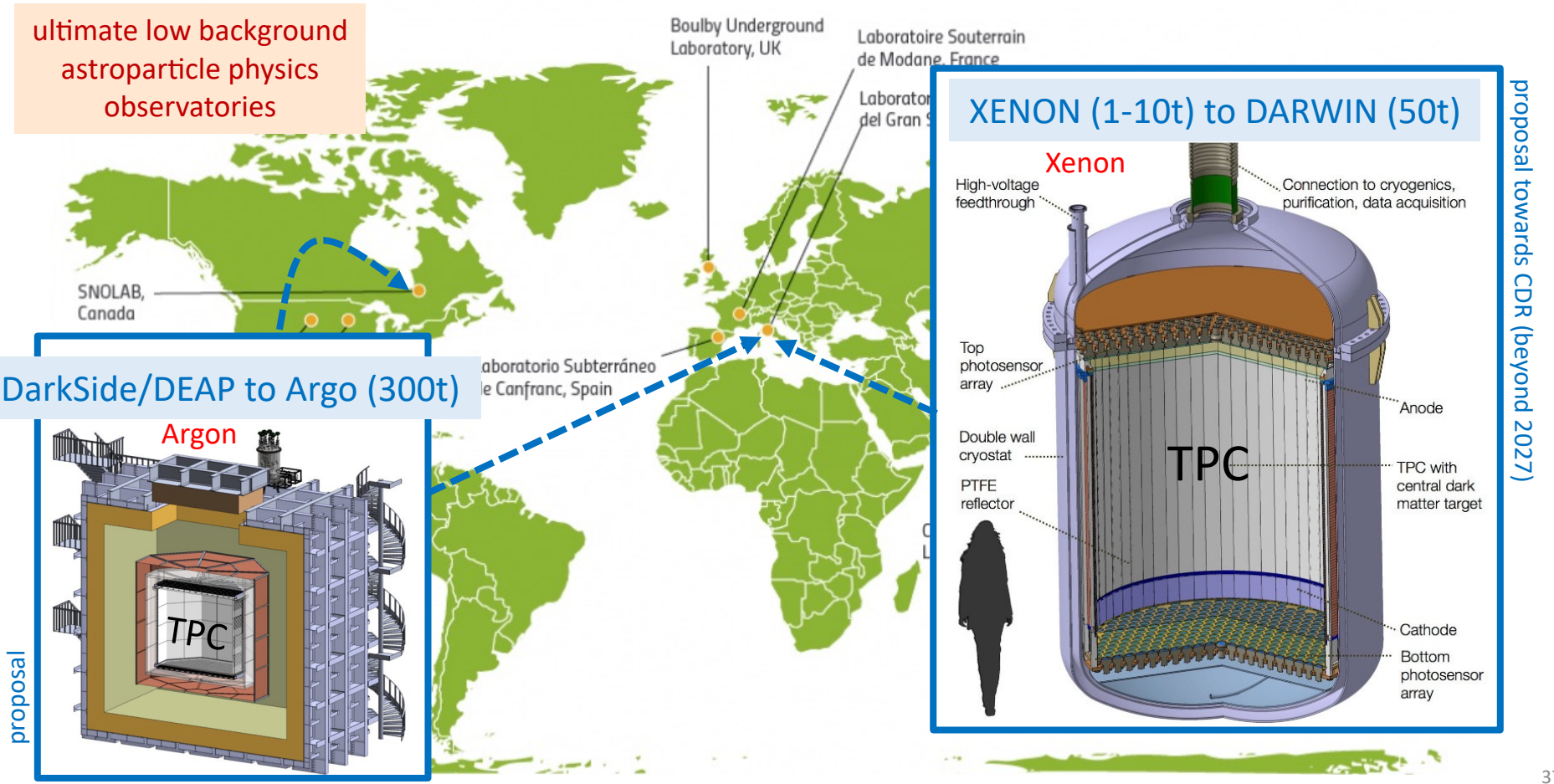
the invisible part of nature

Major underground Facilities – shielding the visible

image courtesy of Susana Cebrián, "Science goes underground"

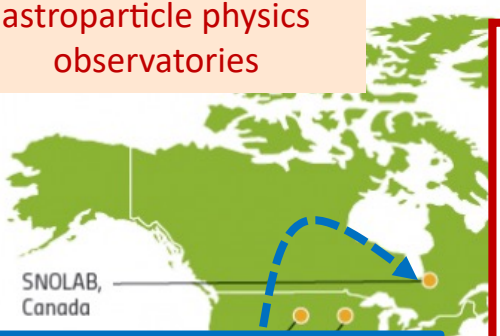
Major underground Facilities – Dark Matter (WIMP)

ultimate low background astroparticle physics observatories



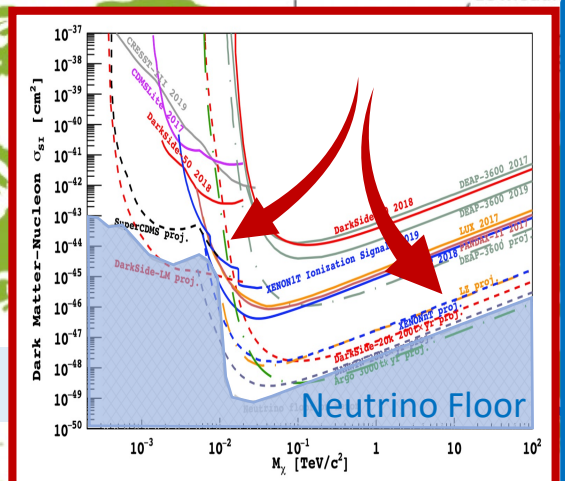
Major underground Facilities – Dark Matter (WIMP)

ultimate low background astroparticle physics observatories



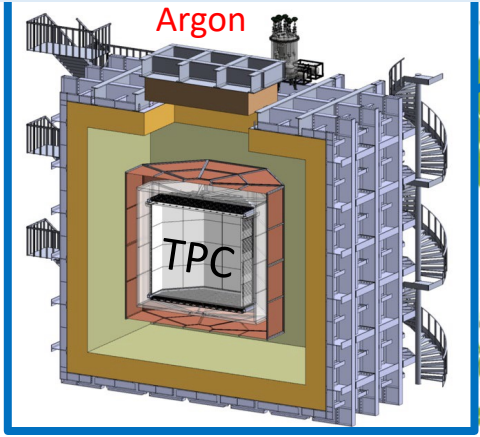
Boulby Underground Laboratory, UK

Laboratoire Souterrain de Modane, France

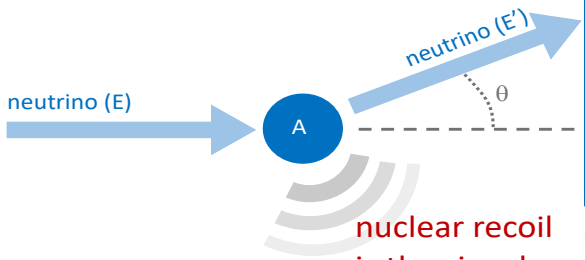


reaching the "neutrino floor"
where the νA backgrounds dominate

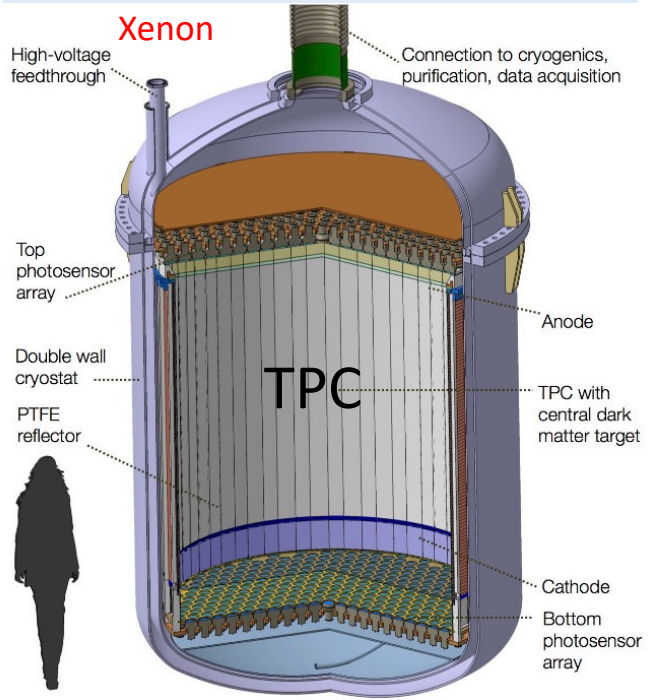
DarkSide/DEAP to Argo (300t)



proposal



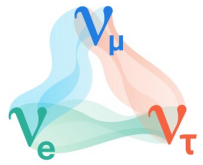
XENON (1-10t) to DARWIN (50t)



proposal towards CDR (beyond 2027)

Neutrino sector extends the Standard Model

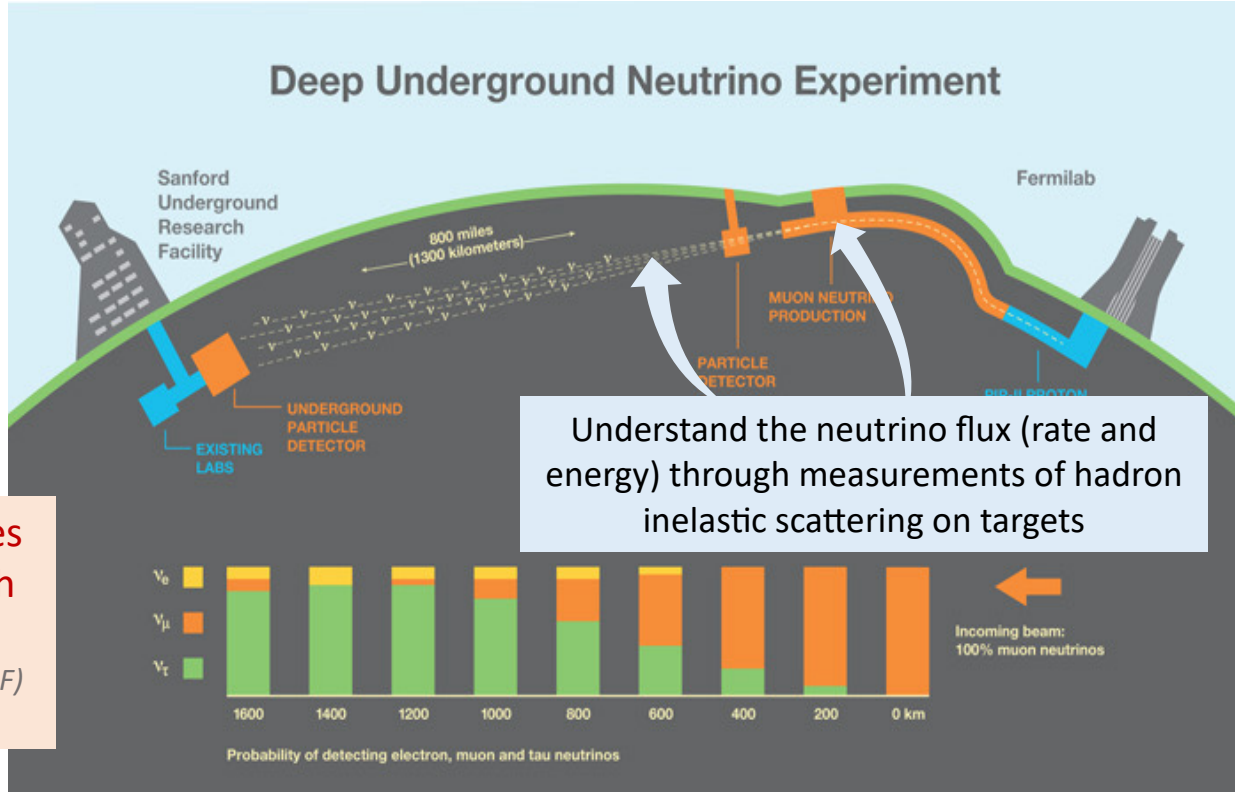
Because neutrinos oscillate, they have mass… but how to extend the Standard Model?



- *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

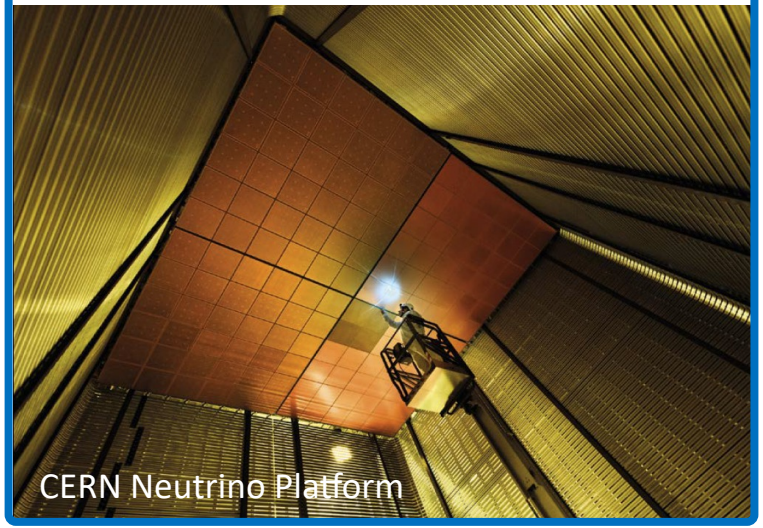


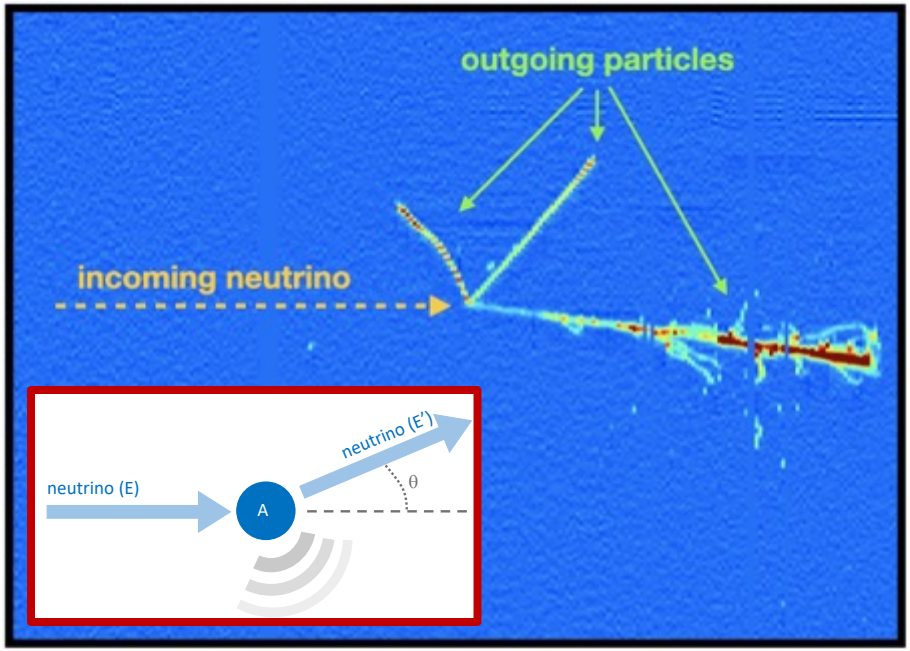
Empowering the neutrino/dark sector quest with DIS

Measurements of νA cross sections are vital to improve the precision

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC

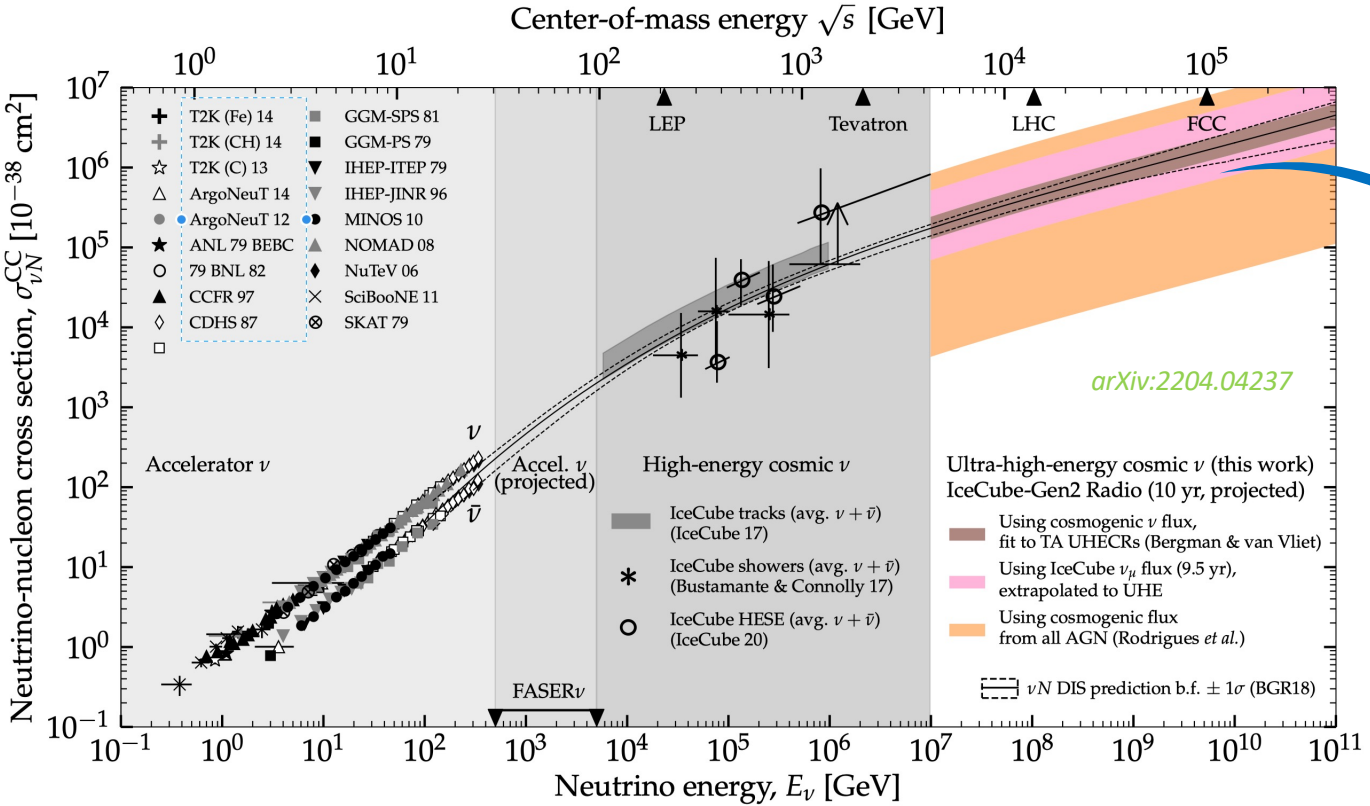




Precise low-energy neutrino DIS-like scattering measurements on nuclear targets are required for DUNE, Super-K/Hyper-K, IceCube, JUNO, …

Scattering with high-energy cosmic neutrinos

Measuring νN cross sections at ultra-high neutrino energies (>100 PeV) offers novel insight into the deep structure of protons and neutrons



IceCube's forecast of measurements of the neutrino charge current cross section through absorption by Earth (>10TeV)

From lower to higher energy ν scattering experiments

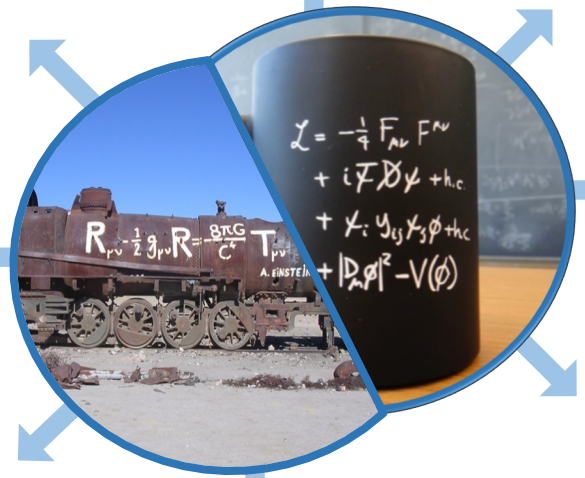
A global νN program bridging nuclear & particle physics for a profound understanding of the invisible sector

novel technologies are required to enable these scientific programs

higher energy interactions
in the lab

earlier universe

rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

ACCELERATORS

higher energy interactions
in the lab

earlier universe

rarer processes

DETECTORS

higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

COMPUTING, SOFTWARE AND SIMULATIONS

ACCELERATORS

higher energy interactions
in the lab

earlier universe

rarer processes

DETECTORS

Innovate Technology
to make the invisible visible

higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

COMPUTING, SOFTWARE AND SIMULATIONS

Advancing Accelerator Technologies

High-energy & high-intensity beams are required for nuclear and particle physics

European Accelerator R&D Roadmap (2021)

https://arxiv.org/pdf/2201.07895.pdf

- High-field magnets
- RF accelerating structures
- Plasma acceleration
- Muon colliders
- Energy Recovery Linacs (ERL)

Continuous innovations are required in accelerating structures to achieve more bright, energetic and powerful beams for nuclear and particle physics

A high-energy muon collider is as well on the mind
(at CERN… towards a μp/μA DIS program at high energies)

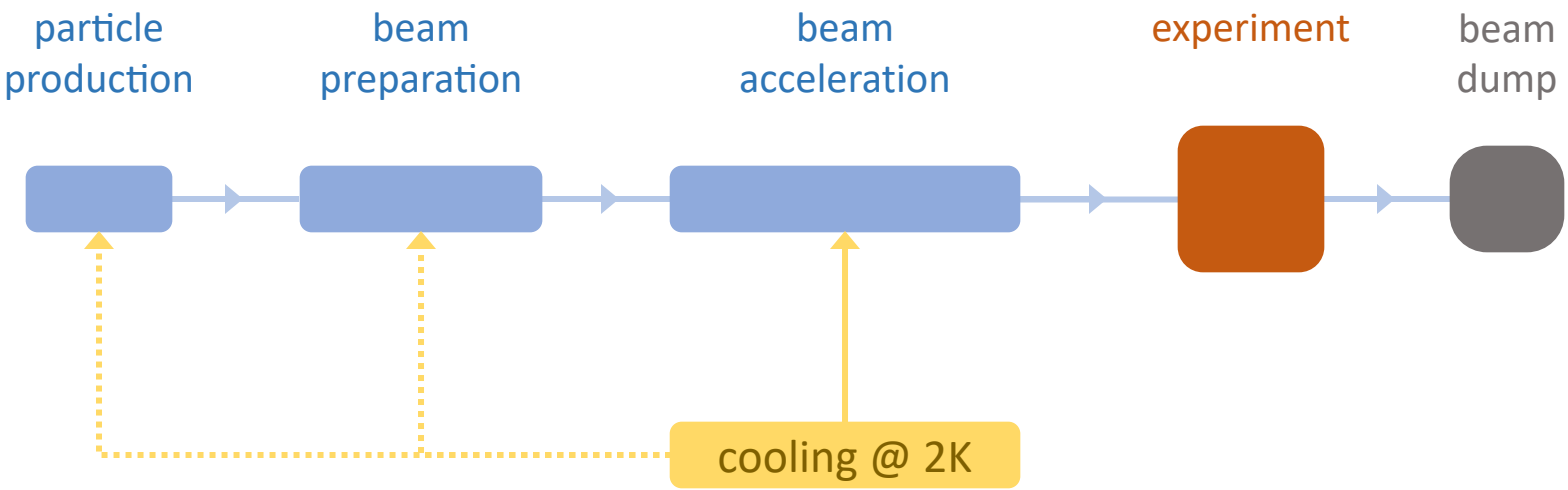
Efficiently recovering the energy from the accelerated particle beam

An overarching theme is the development of
Sustainable Accelerating Structures

less energy, less cooling, less power loss, recover beam energy

a critical duty and common goal for nuclear and particle physics

Basic structures of a particle accelerator



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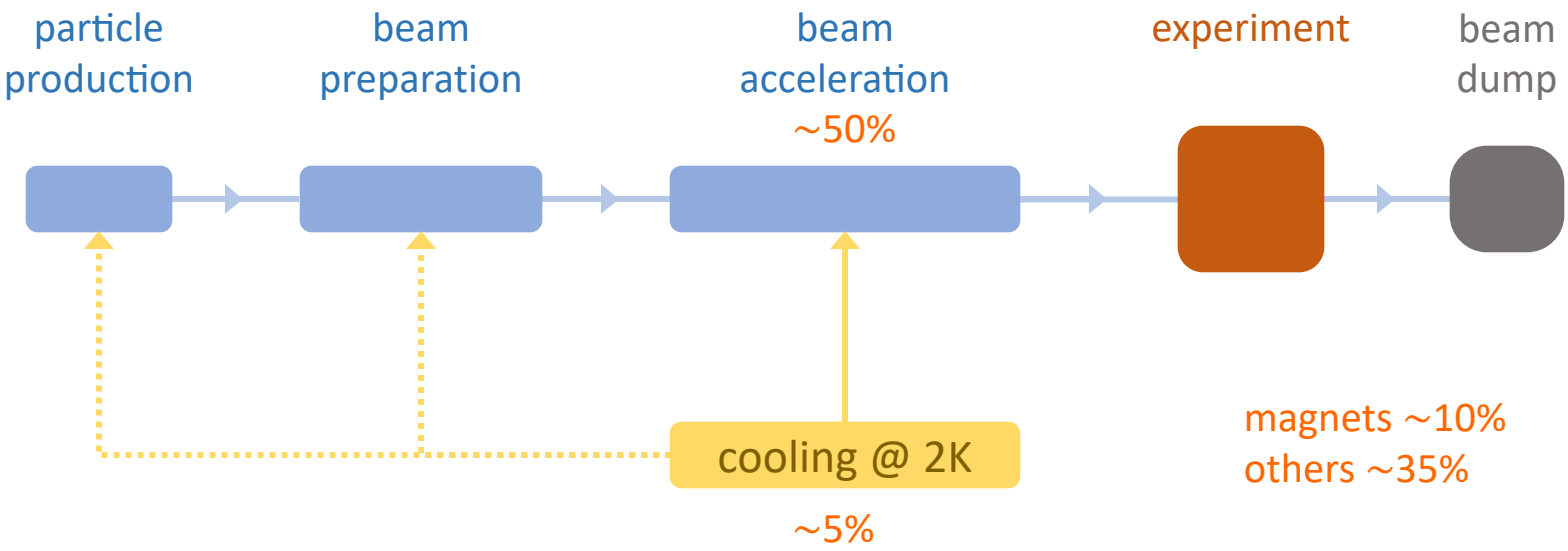
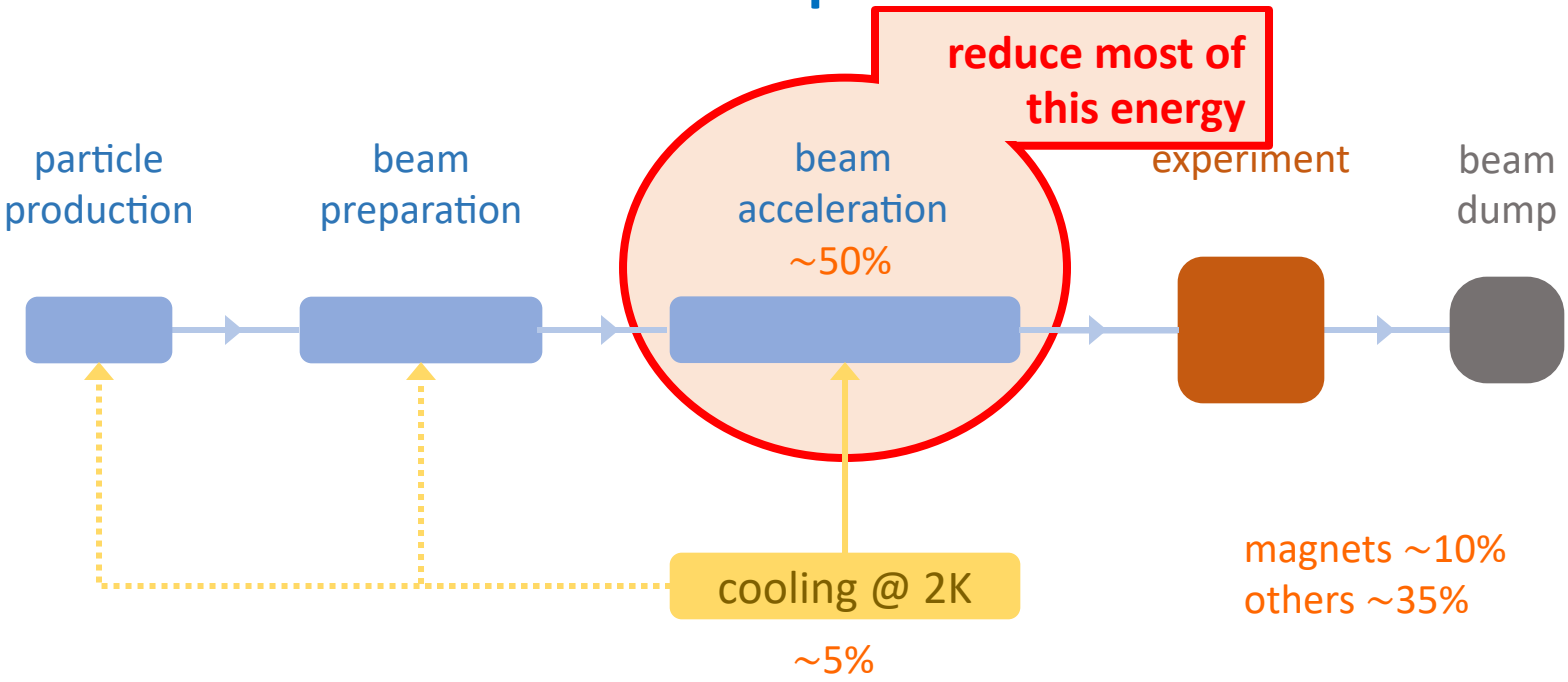


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



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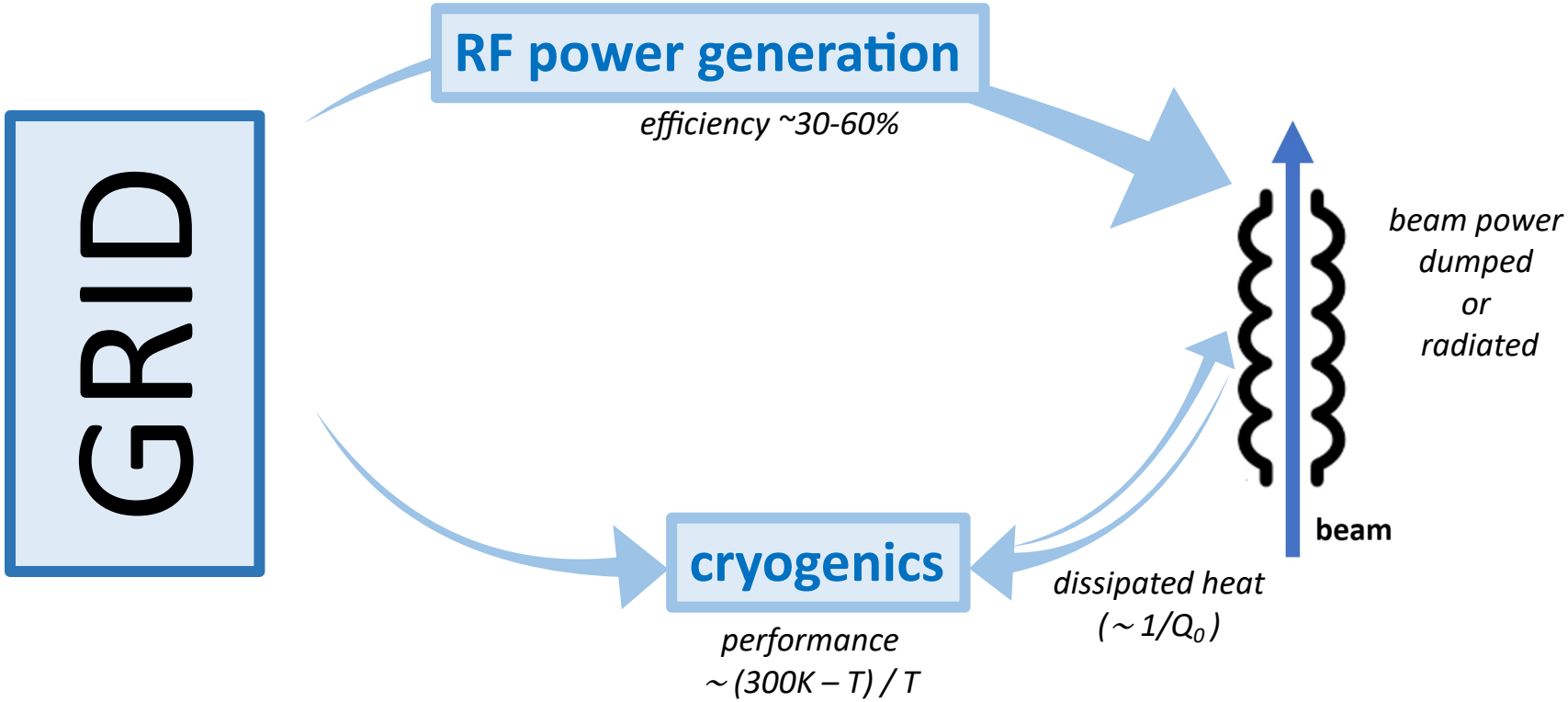
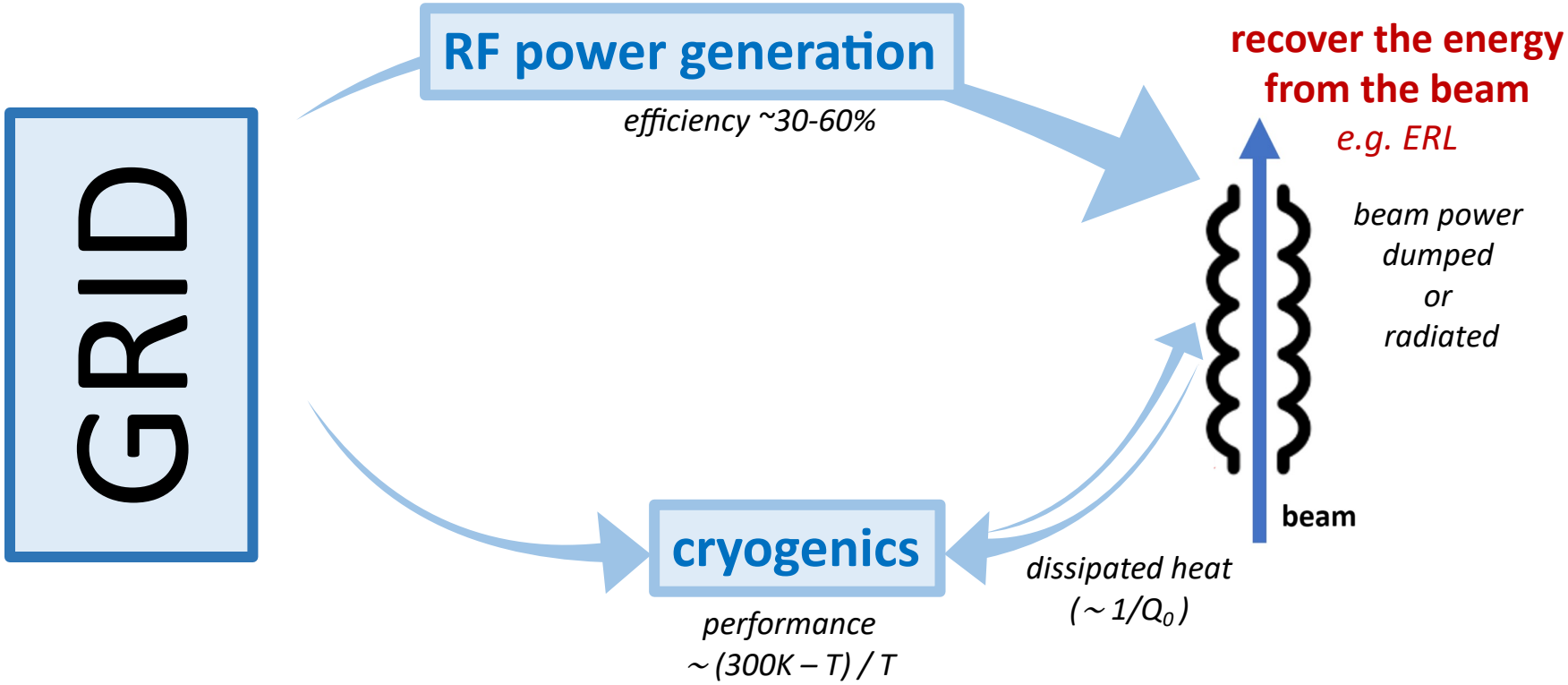
From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam

improve amplifier efficiency
e.g. solid state amplifiers

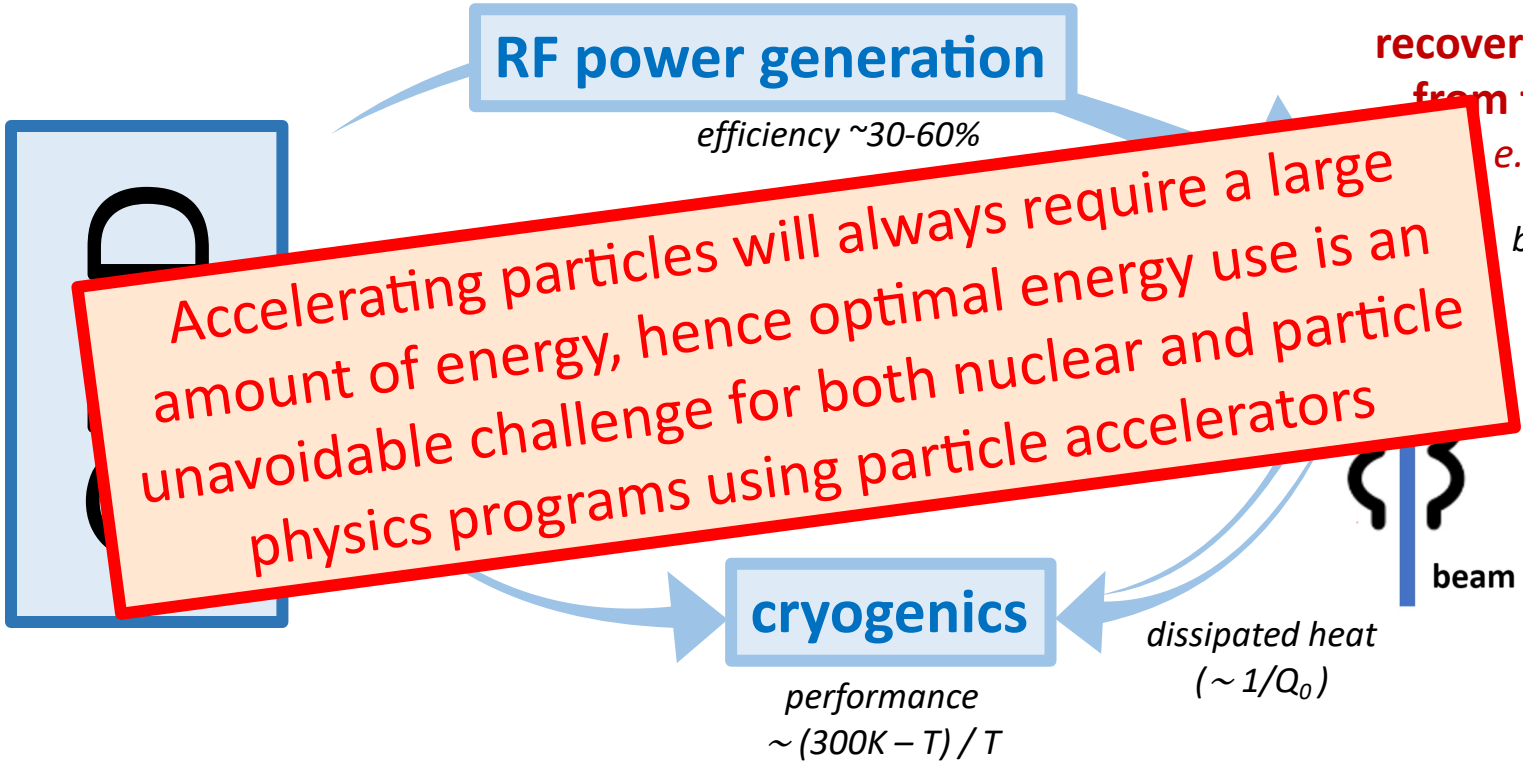


improve Q_0 cavities & operate cavities at higher T
e.g. Nb_3Sn from 2K to 4.4K

Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam

improve amplifier efficiency
e.g. solid state amplifiers



Accelerating particles will always require a large amount of energy, hence optimal energy use is an unavoidable challenge for both nuclear and particle physics programs using particle accelerators

improve Q_0 cavities & operate cavities at higher T
e.g. Nb_3Sn from 2K to 4.4K

Picture adopted from M. Seidel (IPAC 2022)

Get together for Sustainable Accelerating Structures

If we had to learn something from this energy crisis…

We are fascinated to discover physics beyond the frontiers of knowledge

Unlocking the terra incognita of fundamental physics requires researchers from across disciplines to exchange the results they achieve

I am delighted to see that EURO-LABS enables the essential next step to foster scientific (exp & th) and technological collaboration while achieving these results

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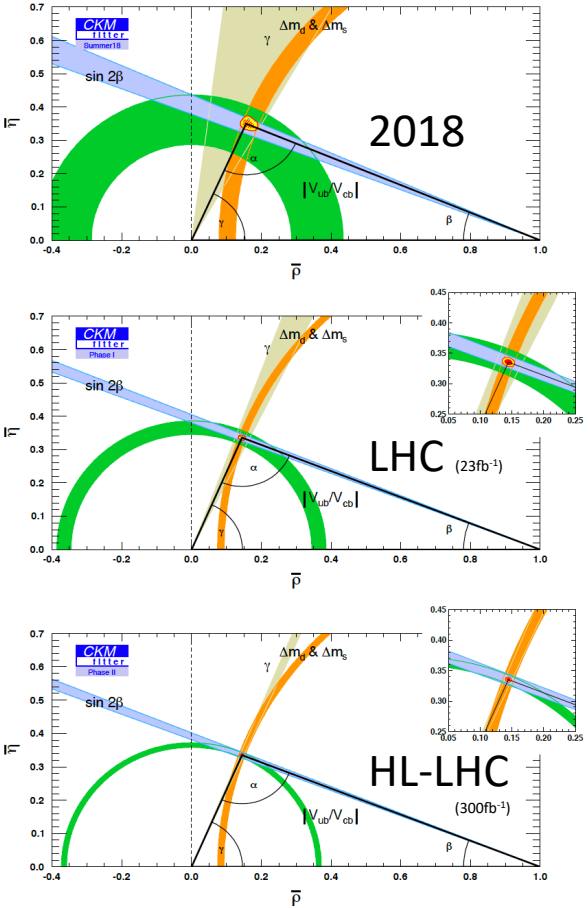
VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

fwo

Thank you for your attention!
Jorgen.DHondt@vub.be

Symmetries matter vs antimatter @ LHC of CERN

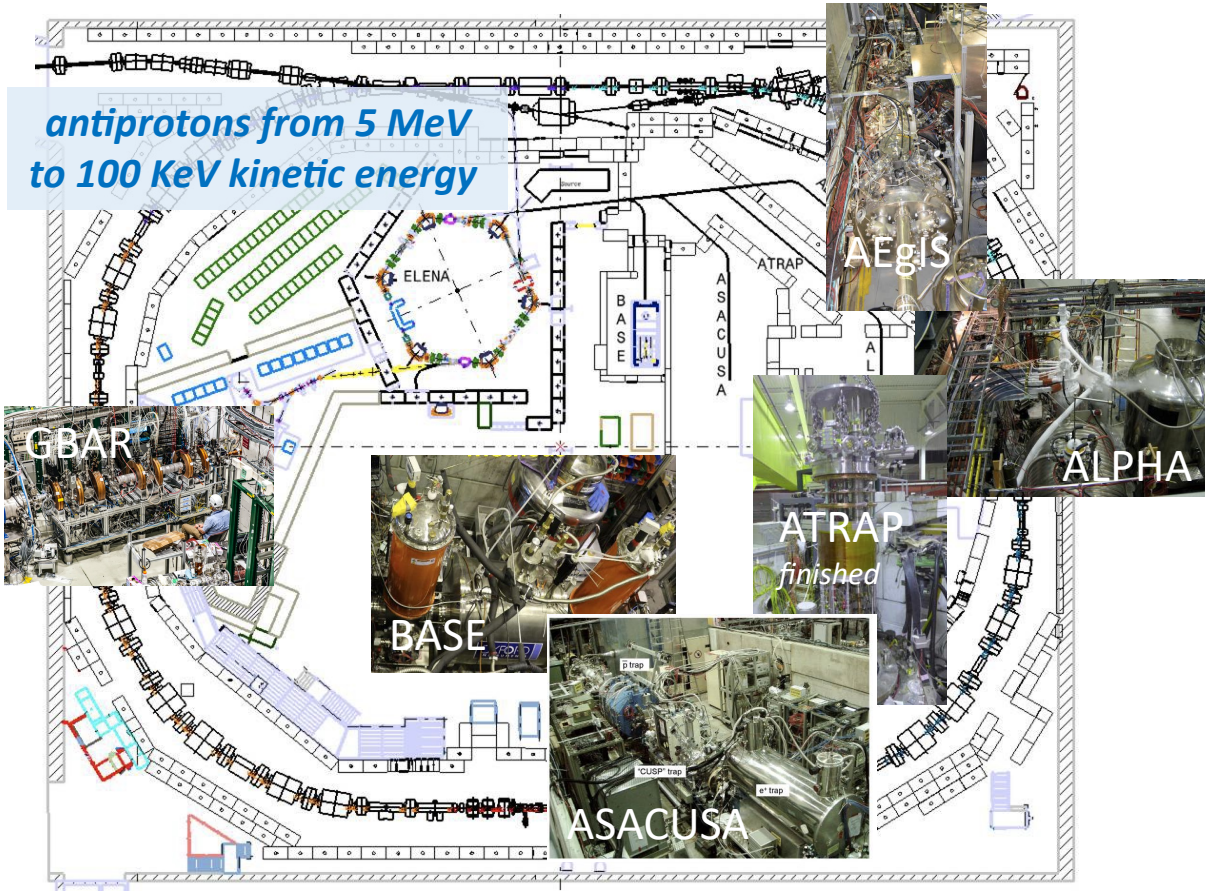


[Physics case for an LHCb Upgrade II, https://arxiv.org/pdf/1808.08865.pdf]

At the highest energies

- Constraining the parameters of the unitary CKM matrix (not predicted by the SM) will provide an extremely precise test of symmetries
- Upcoming improvements from LHC and Belle II
- Sensitivity to new physics up to 10^3-10^6 TeV assuming $\mathcal{O}(1)$ coupling strength, depending on flavour

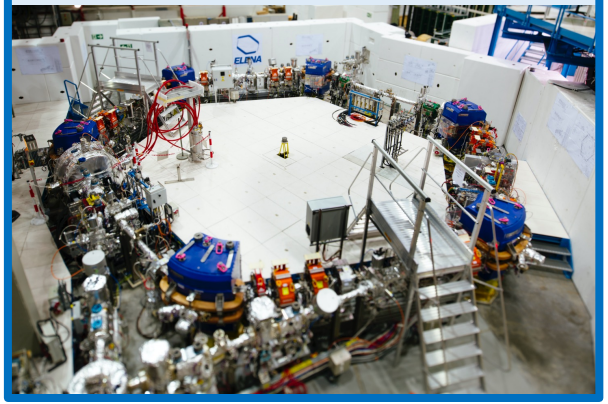
Symmetries matter vs antimatter @ PS of CERN



At low energies

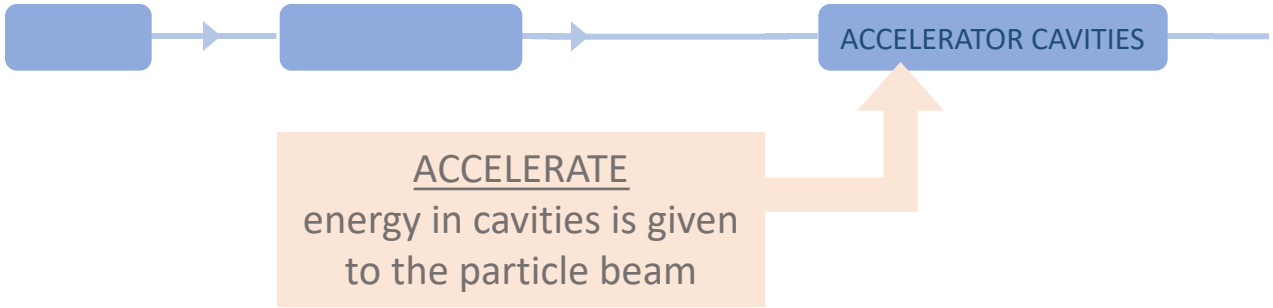
Devoted to antiproton and antihydrogen properties

ELENA secures antimatter physics for the next decade

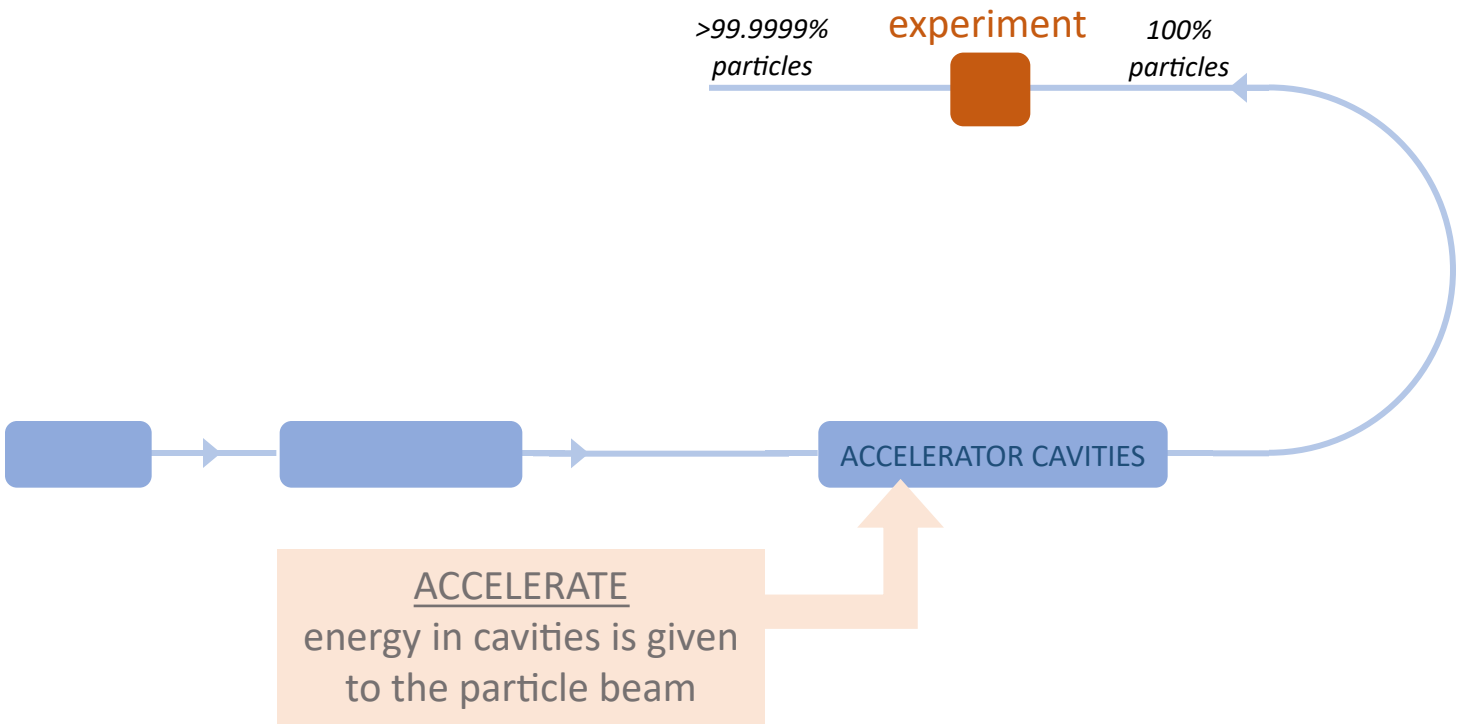


AEgIS – Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy
ALPHA – Antihydrogen Laser PHysics Apparatus
ASACUSA – Atomic Spectroscopy And Collisions Using Slow Antiprotons
ATRAP – Antihydrogen TRAP
GBAR – Gravitational Behaviour of Antihydrogen at Rest
BASE – Baryon Antibaryon Symmetry Experiment

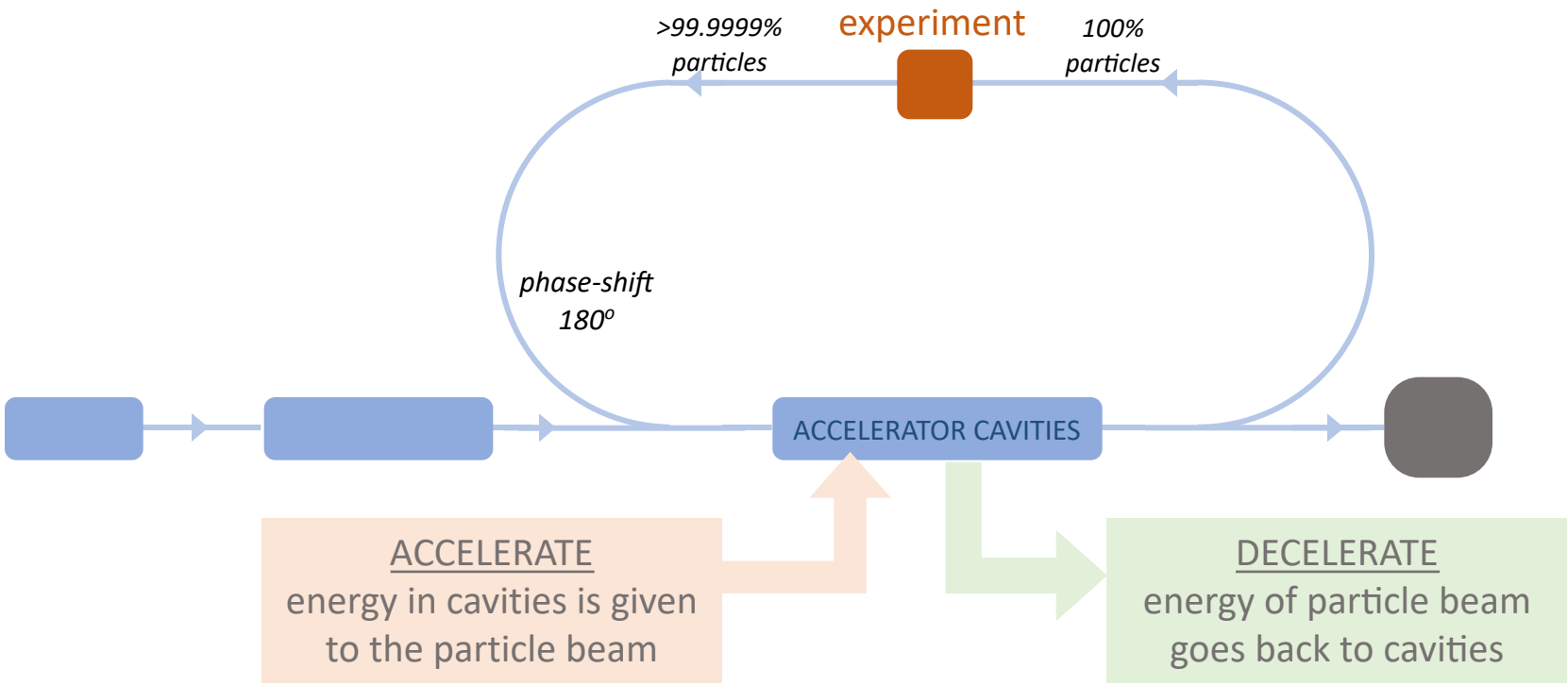
The principle of Energy Recovery



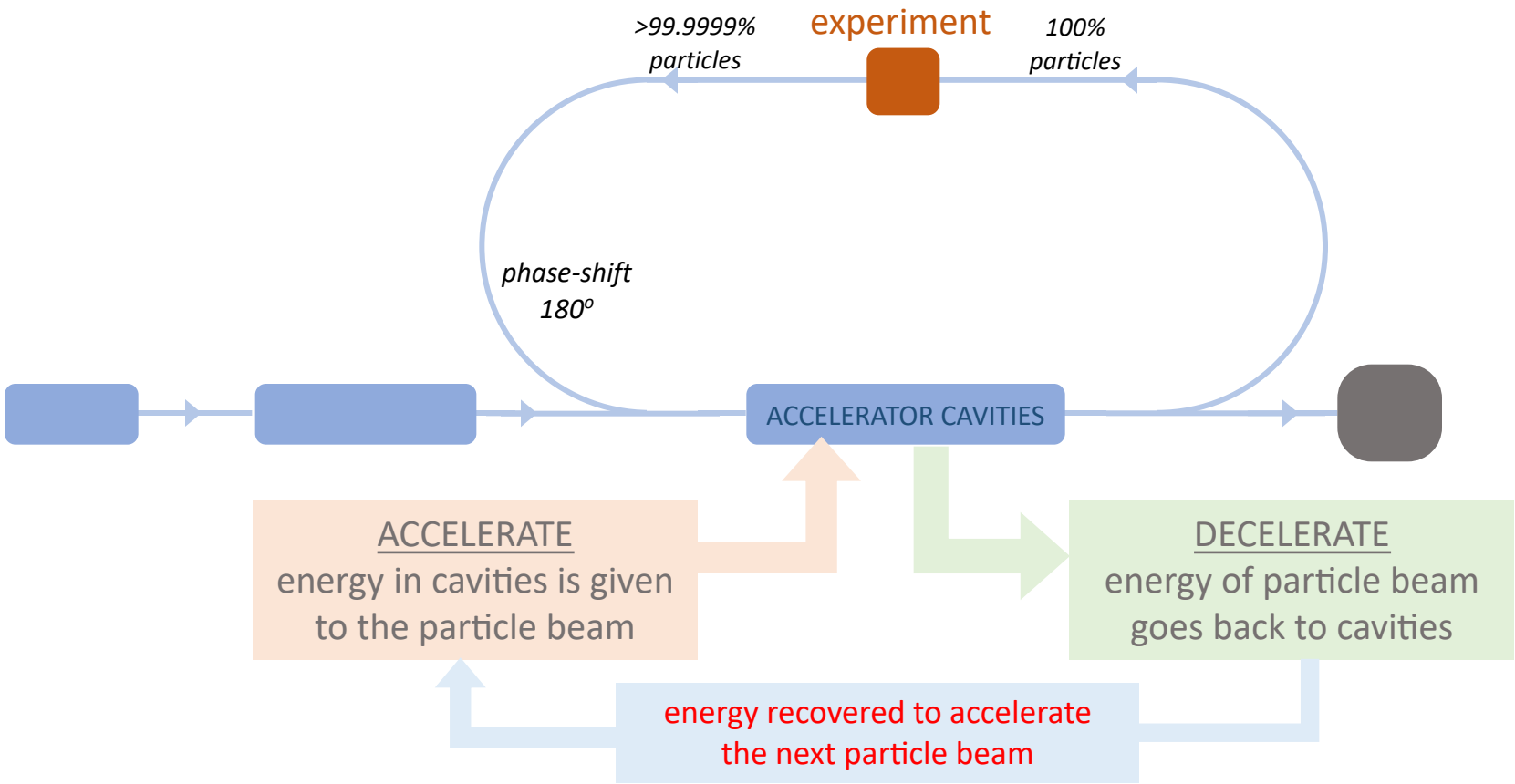
The principle of Energy Recovery



The principle of Energy Recovery

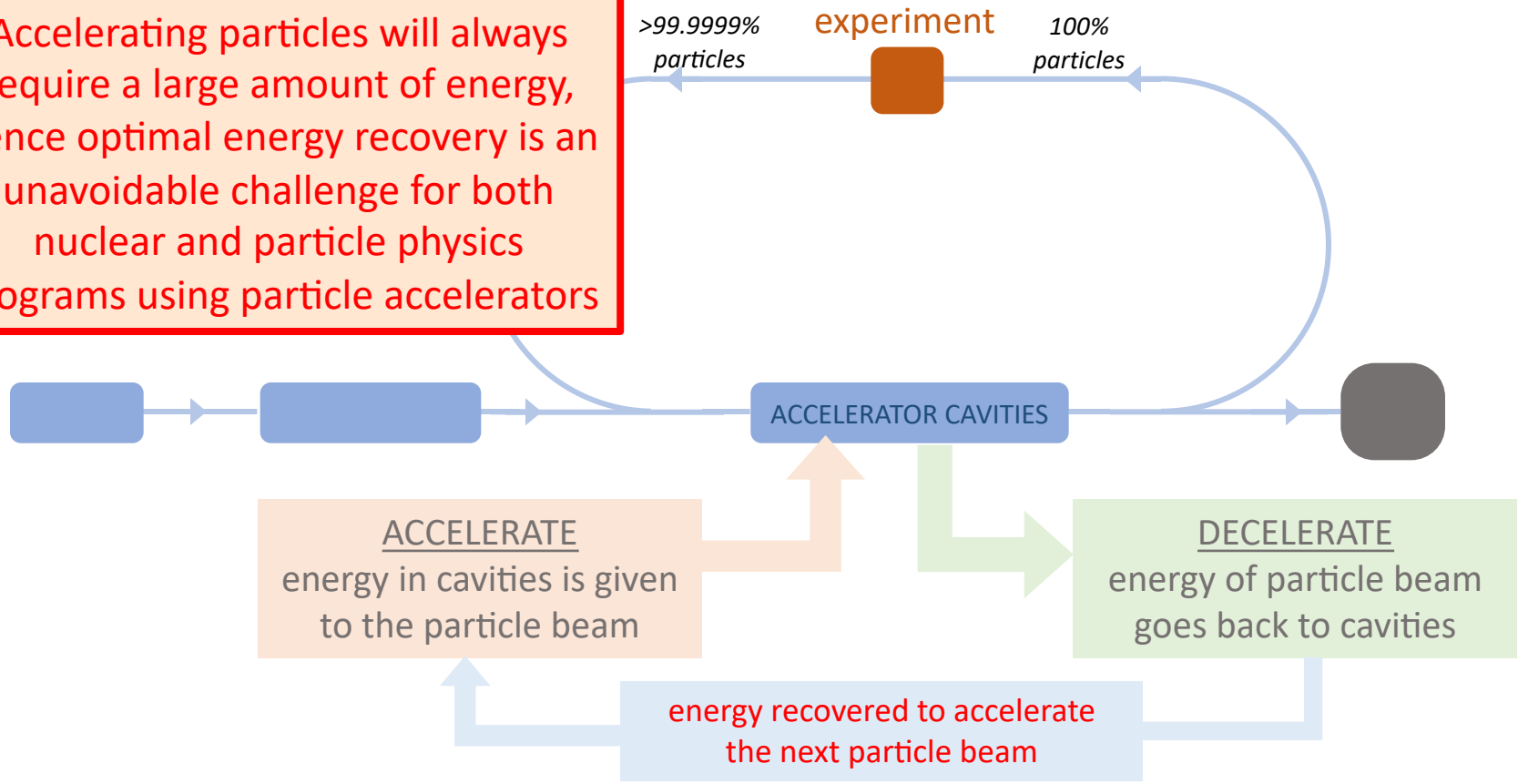


The principle of Energy Recovery



The principle of Energy Recovery

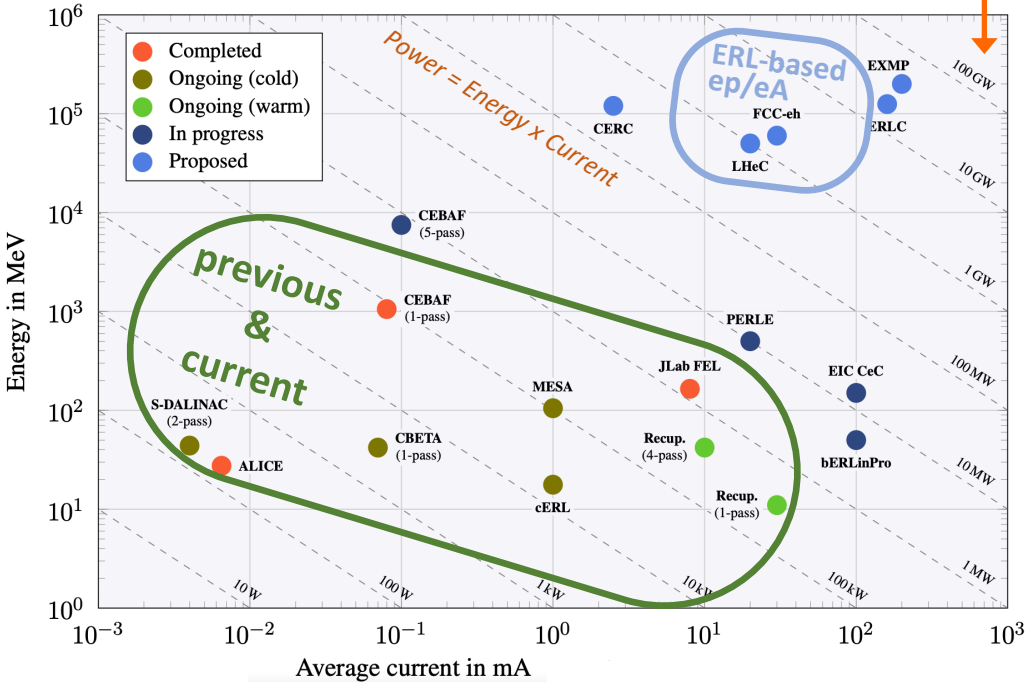
Accelerating particles will always require a large amount of energy, hence optimal energy recovery is an unavoidable challenge for both nuclear and particle physics programs using particle accelerators



Energy Recovery – 50 years of innovation

essential to realise the future ep/eA program

would be the required external power supply without Energy Recovery



Energy Recovery

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

Energy Recovery – 50 years of innovation

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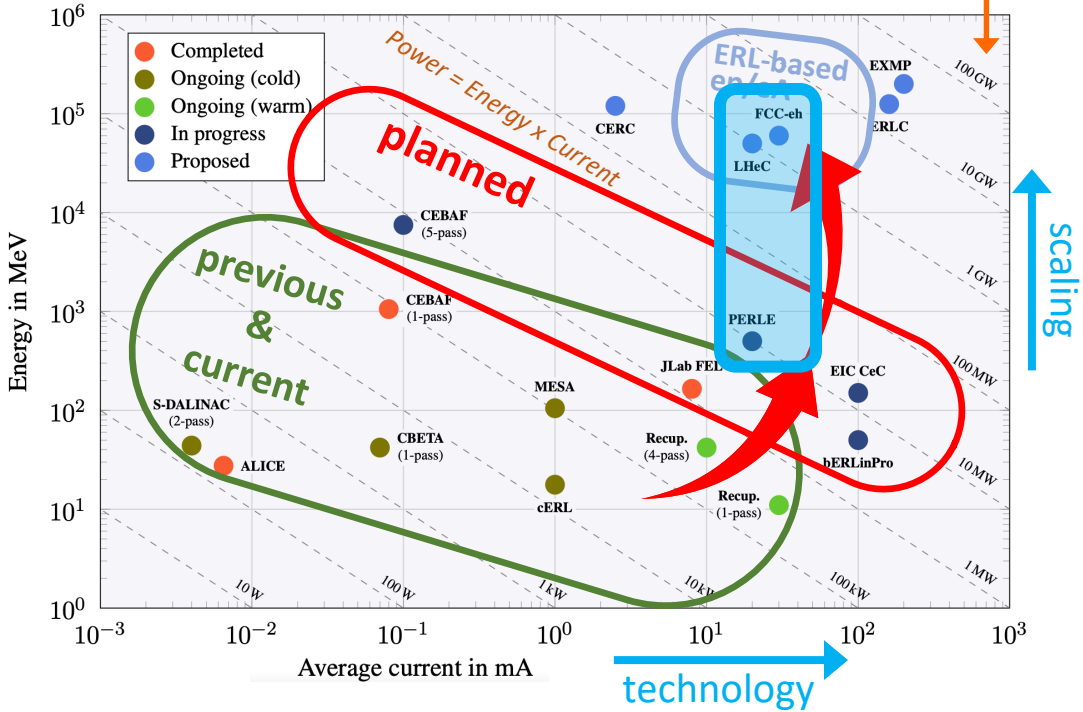

Energy Recovery

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

bERLinPro & PERLE

essential technology stepping stones for future ep/eA (and other) implementations of Energy Recovery accelerators

towards high power

The Development of Energy-Recovery Linacs

arXiv:2207.02095, 237 pages, 5 July 2022