Building the future together

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

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

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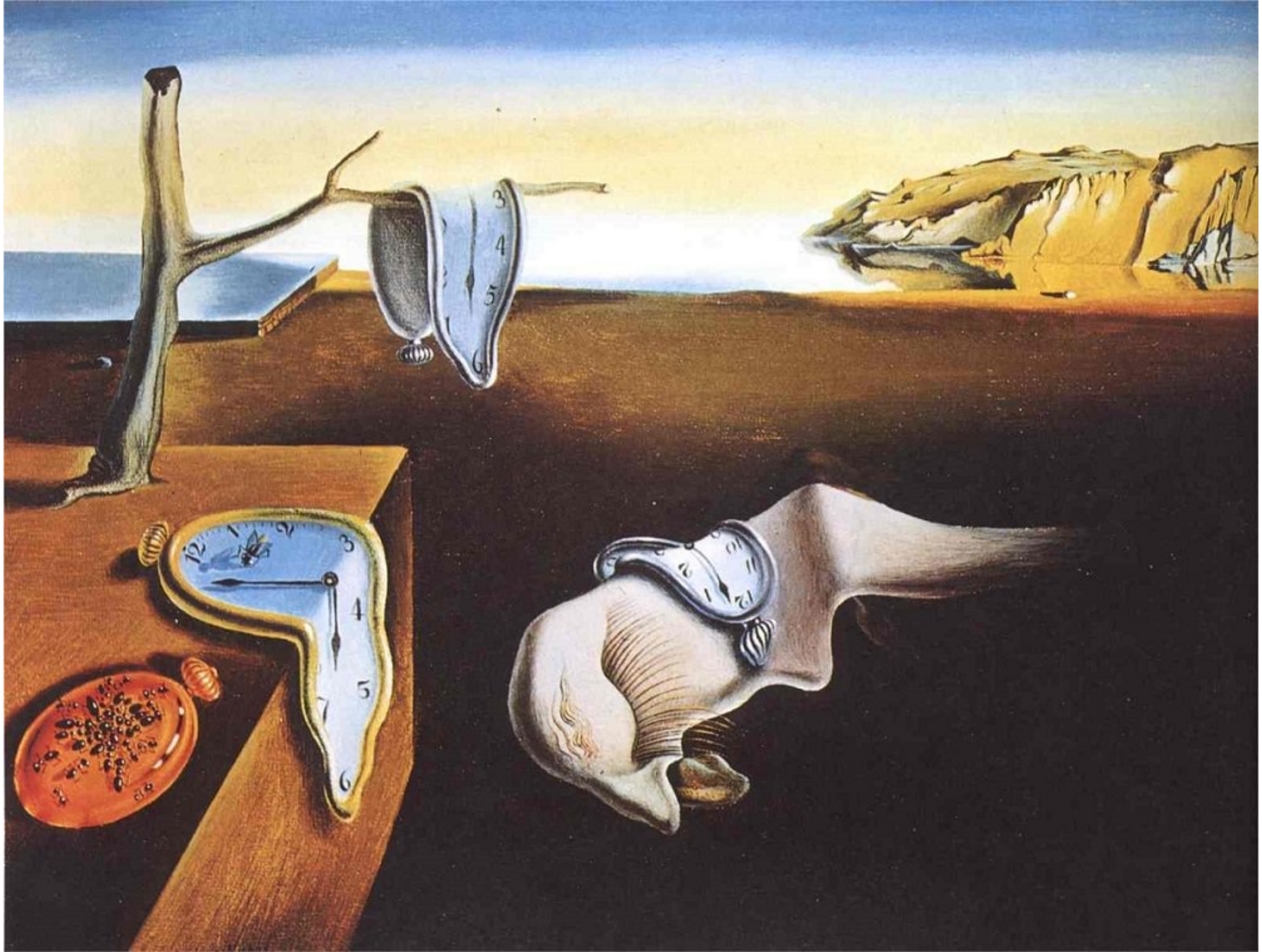
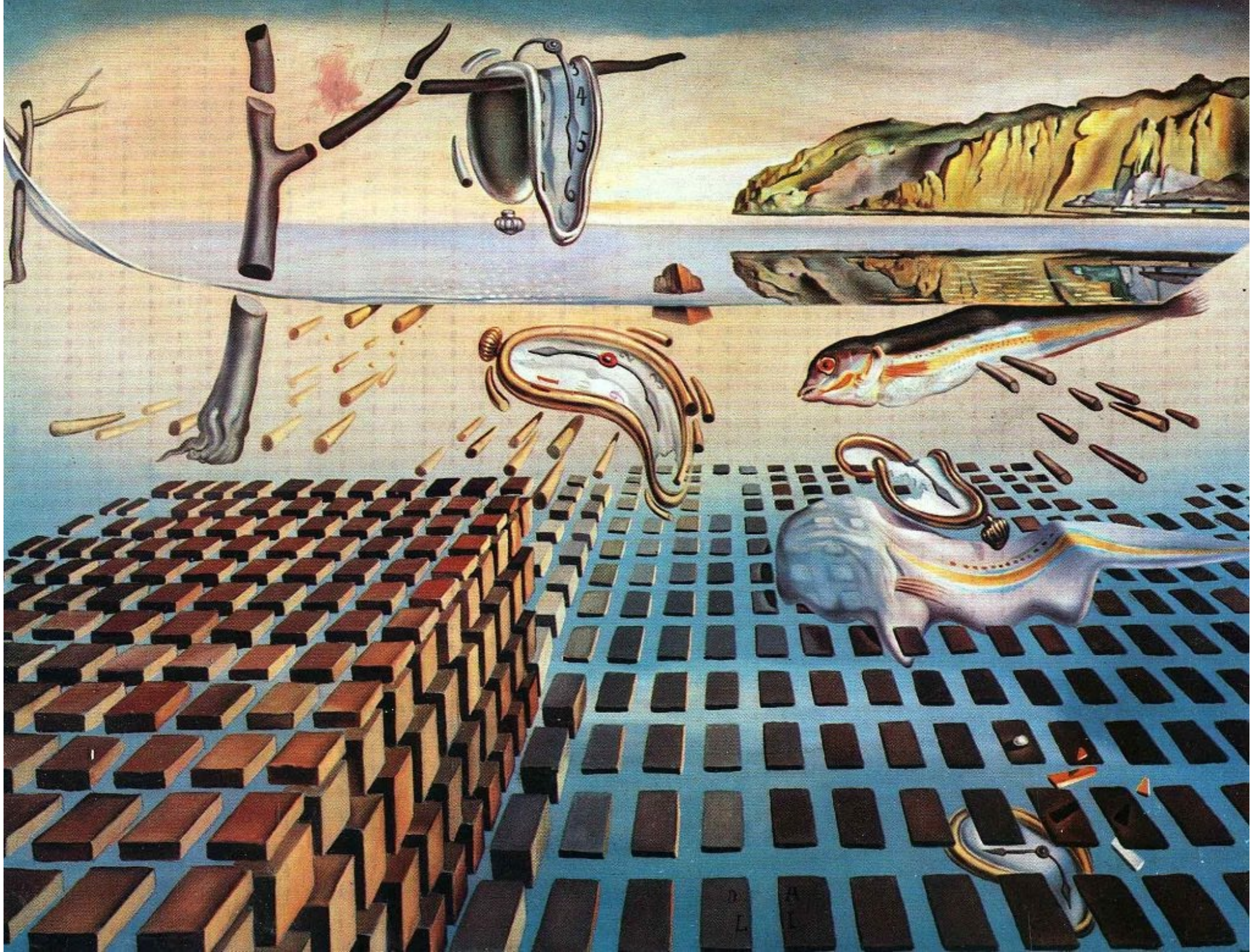
2nd Joint ECFA-NuPECC-APPEC Symposium (JENAS), 3-6 May 2022



S. Dali
1931



S. Dali
1952

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

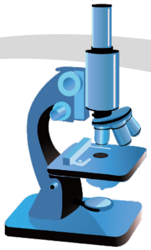
biological cell

atoms

proton neutron

observable universe
8.8 10^{26}m

visible with our own eyes



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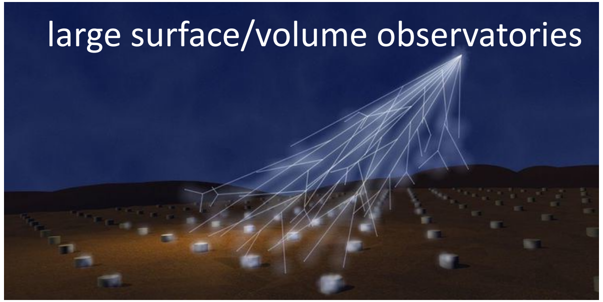

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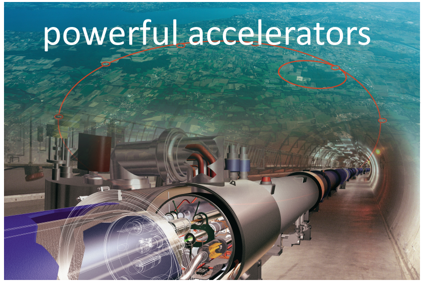

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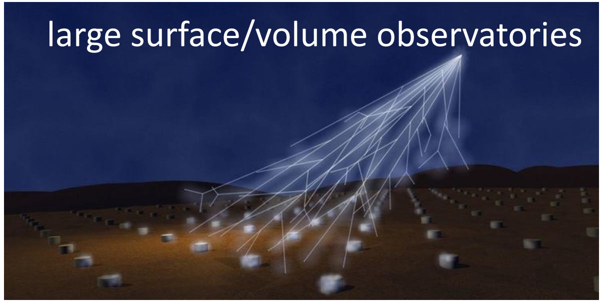
atoms

proton neutron

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

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



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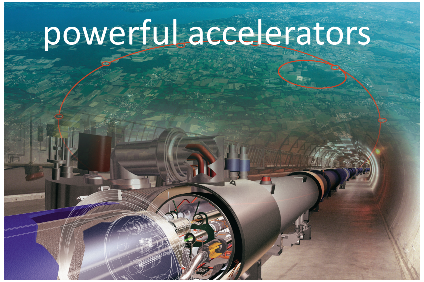

lifetime top quark
$5\ 10^{-25}$ s

quarks
$> 10^{-19}$ m

~ 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

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

Basic Principles → **Fundamental Theories**

MATHEMATICAL FRAMEWORKS HOW OBJECTS BEHAVE

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

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

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Basic Principles

Fundamental Theories

Concrete Models

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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 tinniest 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

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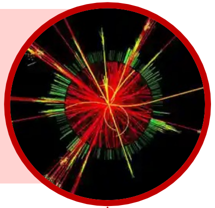
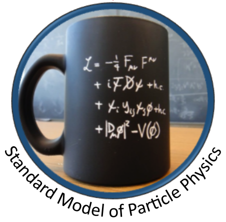
observations how small objects behave in our laboratories





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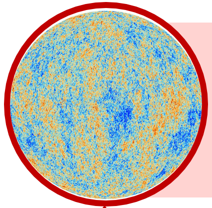
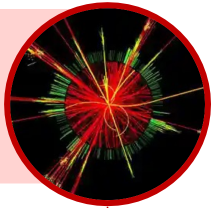
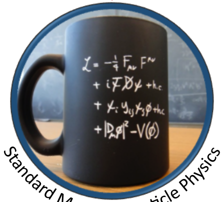


observations how large objects behave in our universe

Standard Model of Cosmology

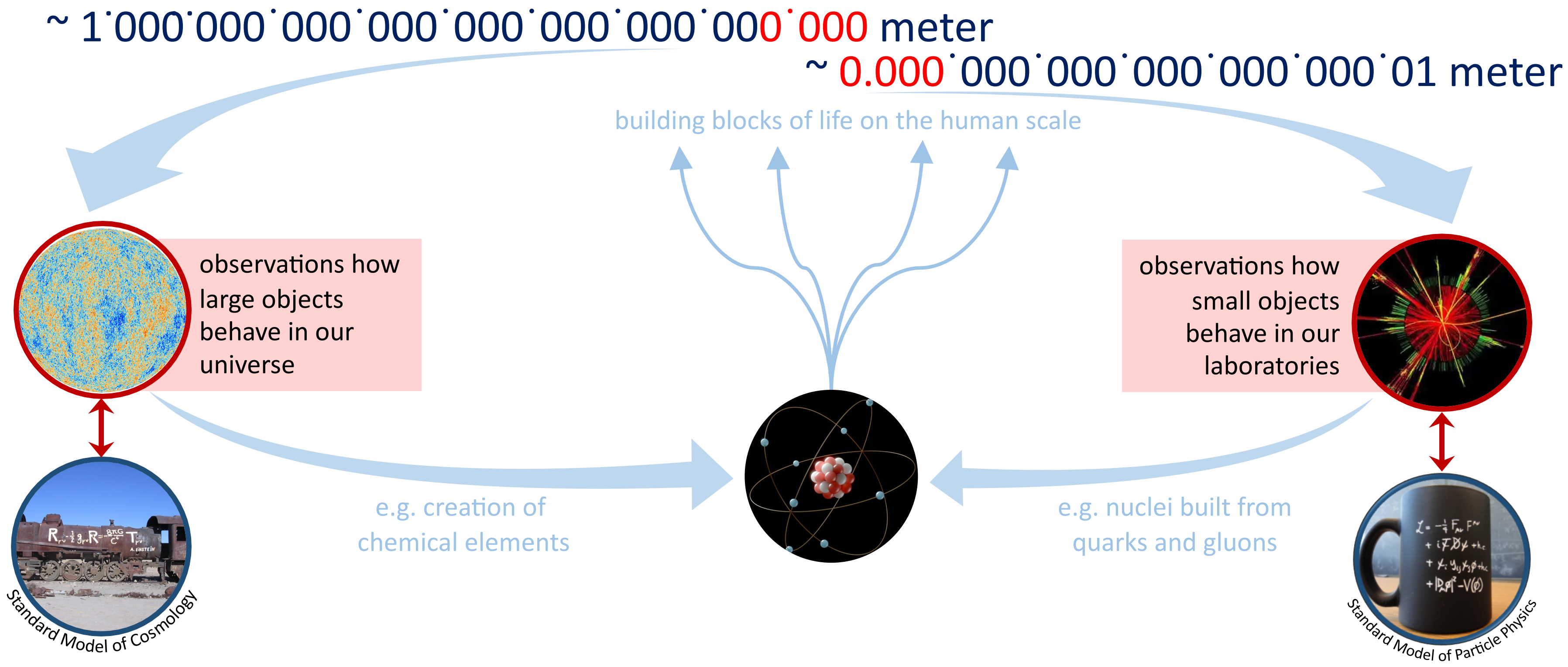


observations how small objects behave in our laboratories



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

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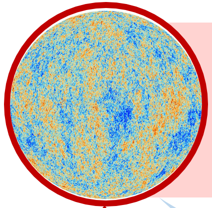
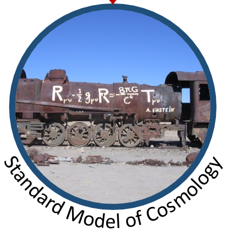
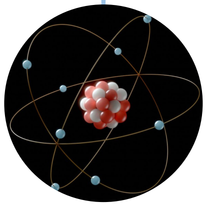
building blocks of life on the human scale



observations how large objects behave in our universe

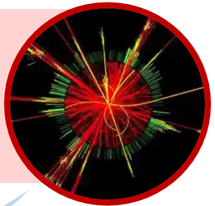


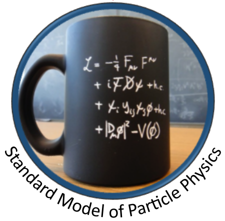
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





communication
satellites
GPS

World Wide Web
touchscreens

A century of scientific revolutions

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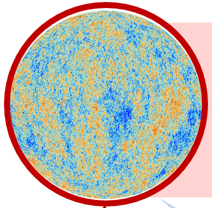
~ 0.000'000'000'000'000'000'01 meter

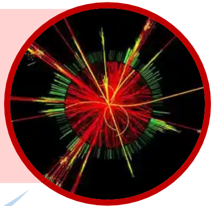
building blocks of life on the human scale

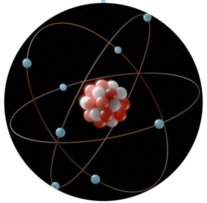


observations how large objects behave in our universe

production of particles and radiation
nuclear diagnosis and medicine

observations how small objects behave in our laboratories

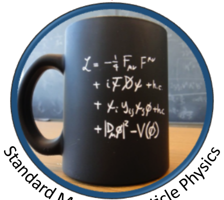




e.g. creation of chemical elements

e.g. nuclei built from quarks and gluons

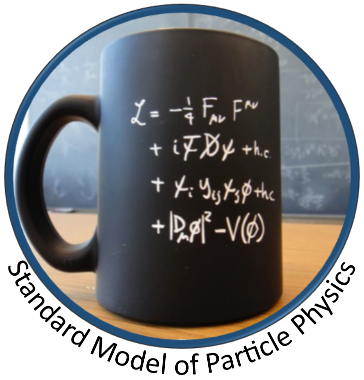
Standard Model of Cosmology



Standard Model of Particle Physics

“Scientific curiosity which ends up in your pocket”
Rolf Heuer (previous Director General of CERN)

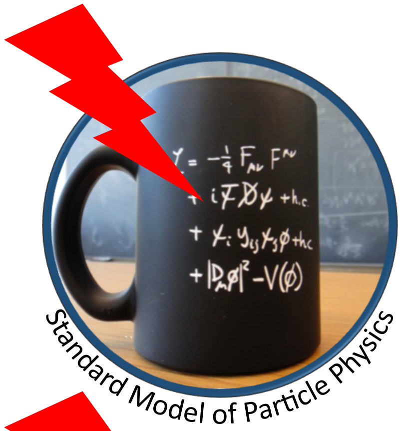
The quest for understanding physics

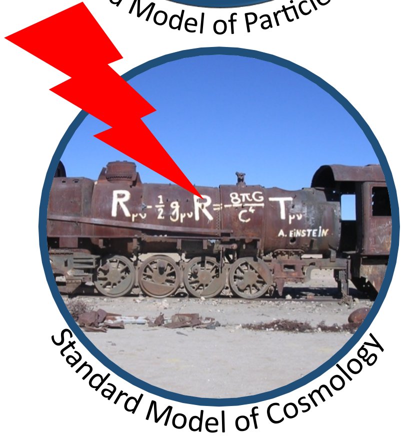


"Problems and Mysteries"

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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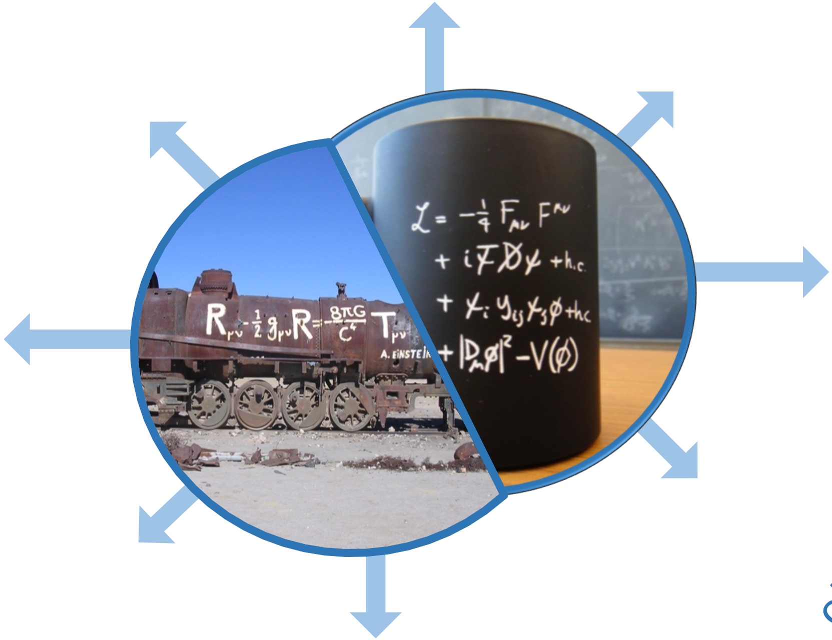
- Dynamics of Electro-Weak symmetry breaking?
- How do quarks and gluons give rise to properties of nuclei?…

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

higher energy interactions
in the lab

earlier universe

rarer processes

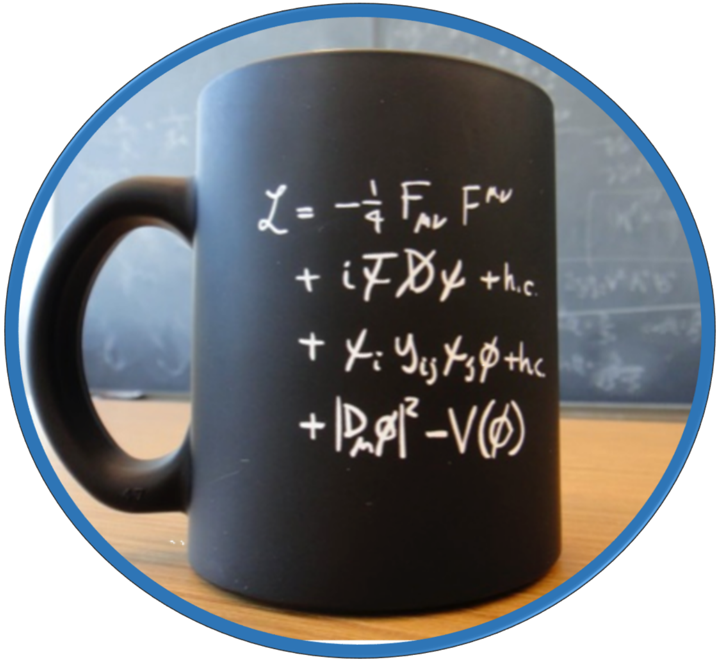
higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

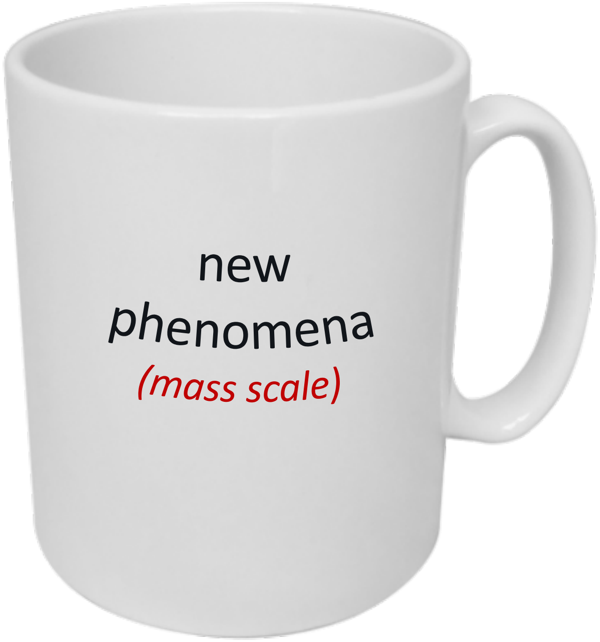
Extending our models with new phenomena

(assuming our basic principles and theoretical frameworks hold)



connection

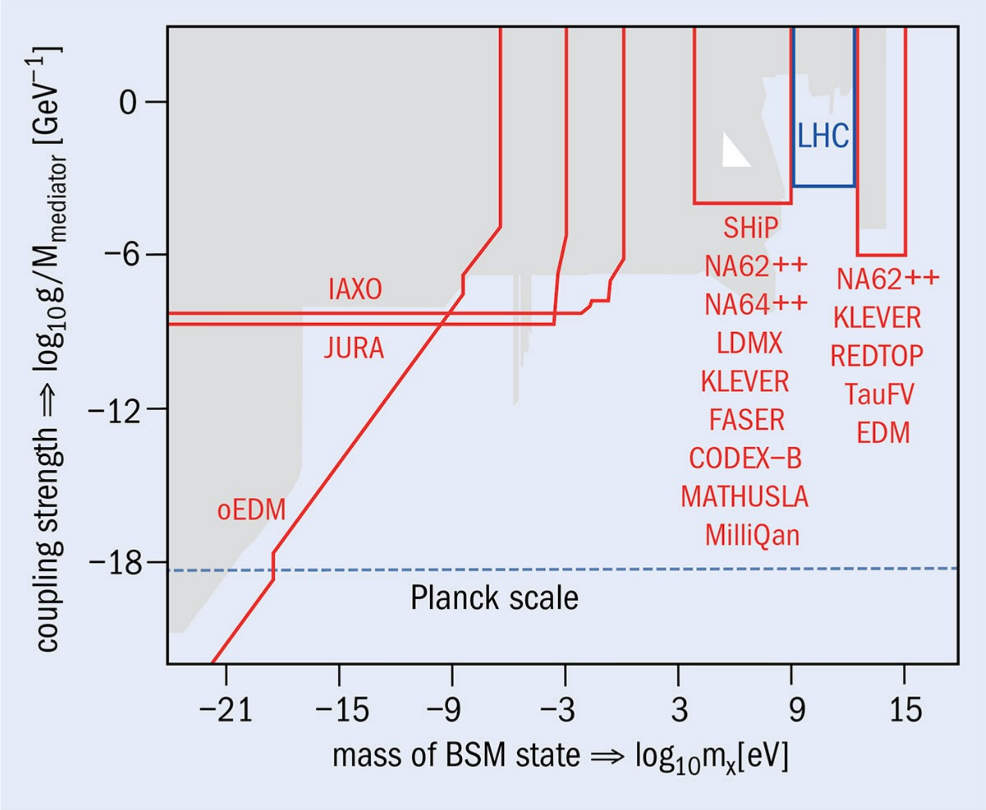
(coupling strength)



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 hidding



Most recent European Strategies

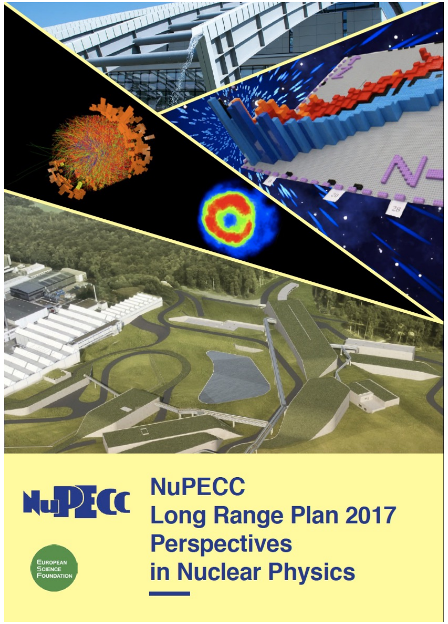
the large …

weblink

2017-2026 European Astroparticle Physics Strategy

… the connection …

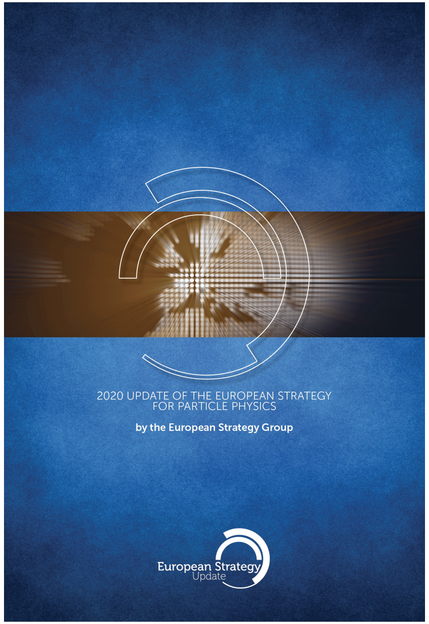
weblink



Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink

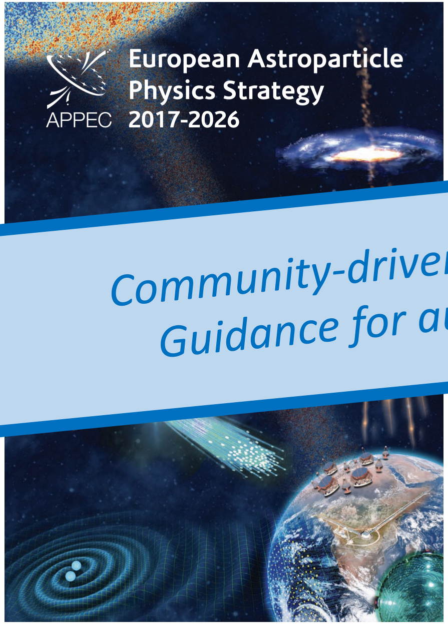


2020 Update of the European Particle Physics Strategy

Most recent European Strategies

the large …

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

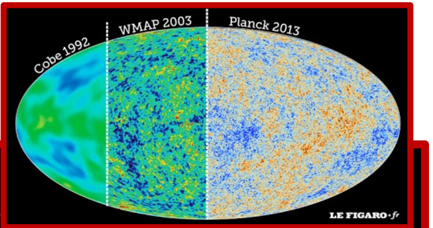
Community-driven strategies reflecting our ambition to address open questions.
Guidance for authorities to develop resource-loaded research programmes.

our eyes on the sky

The cosmic frontier: Cosmic Microwave Background precision physics

Previous flagship

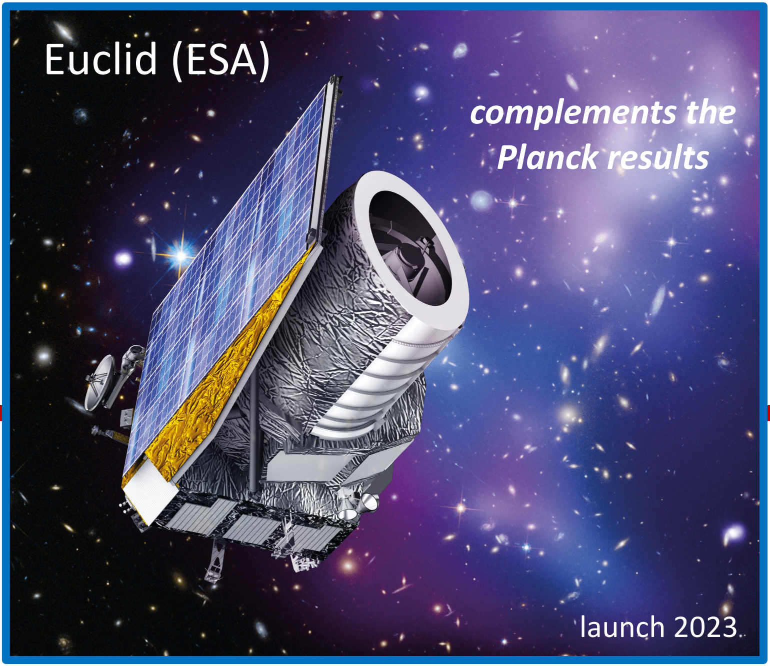
impressive science



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

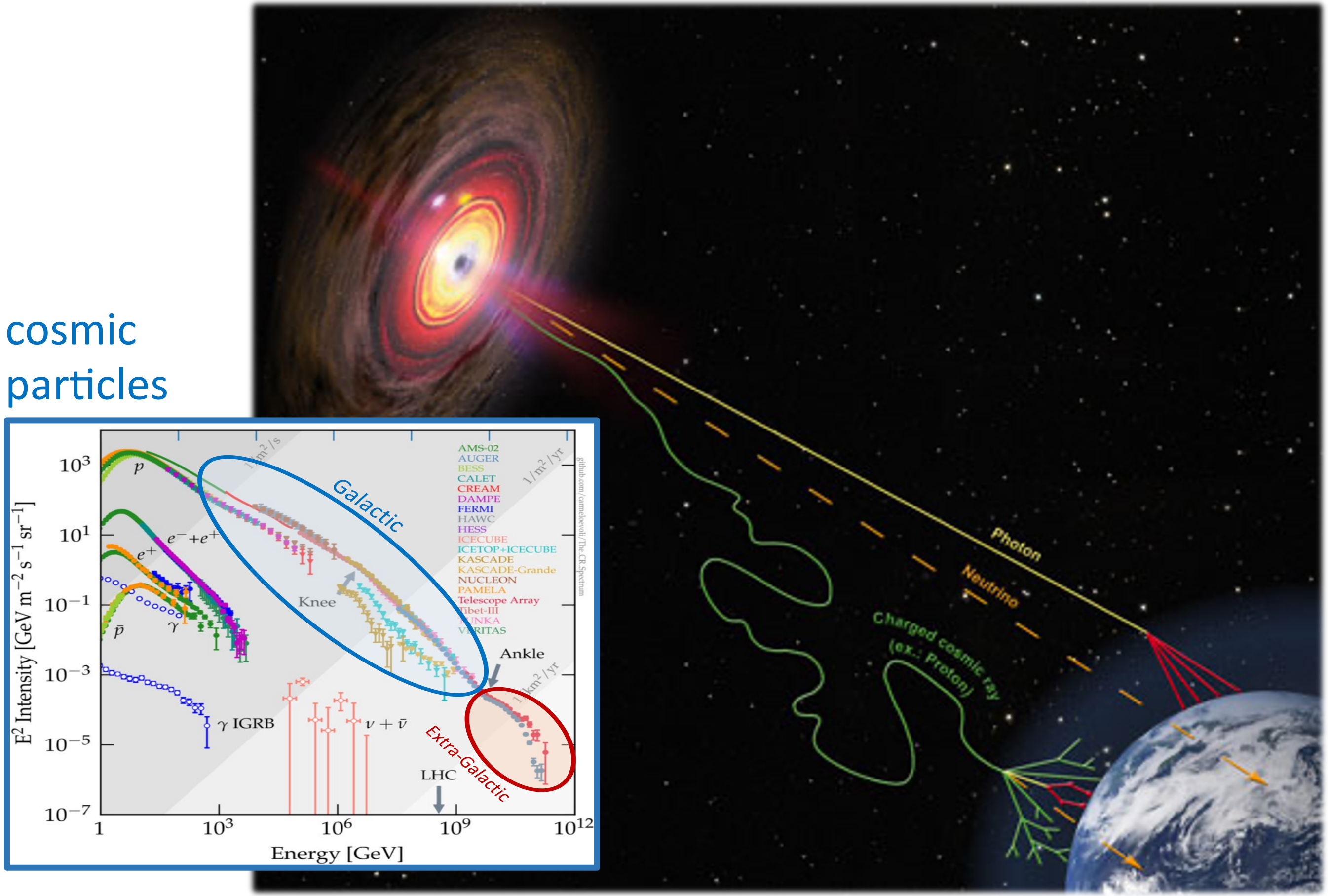


Properties of dark energy, dark matter and gravity

ESA: European Space Agency

A variety of very high-energy particles from our universe

cosmic particles



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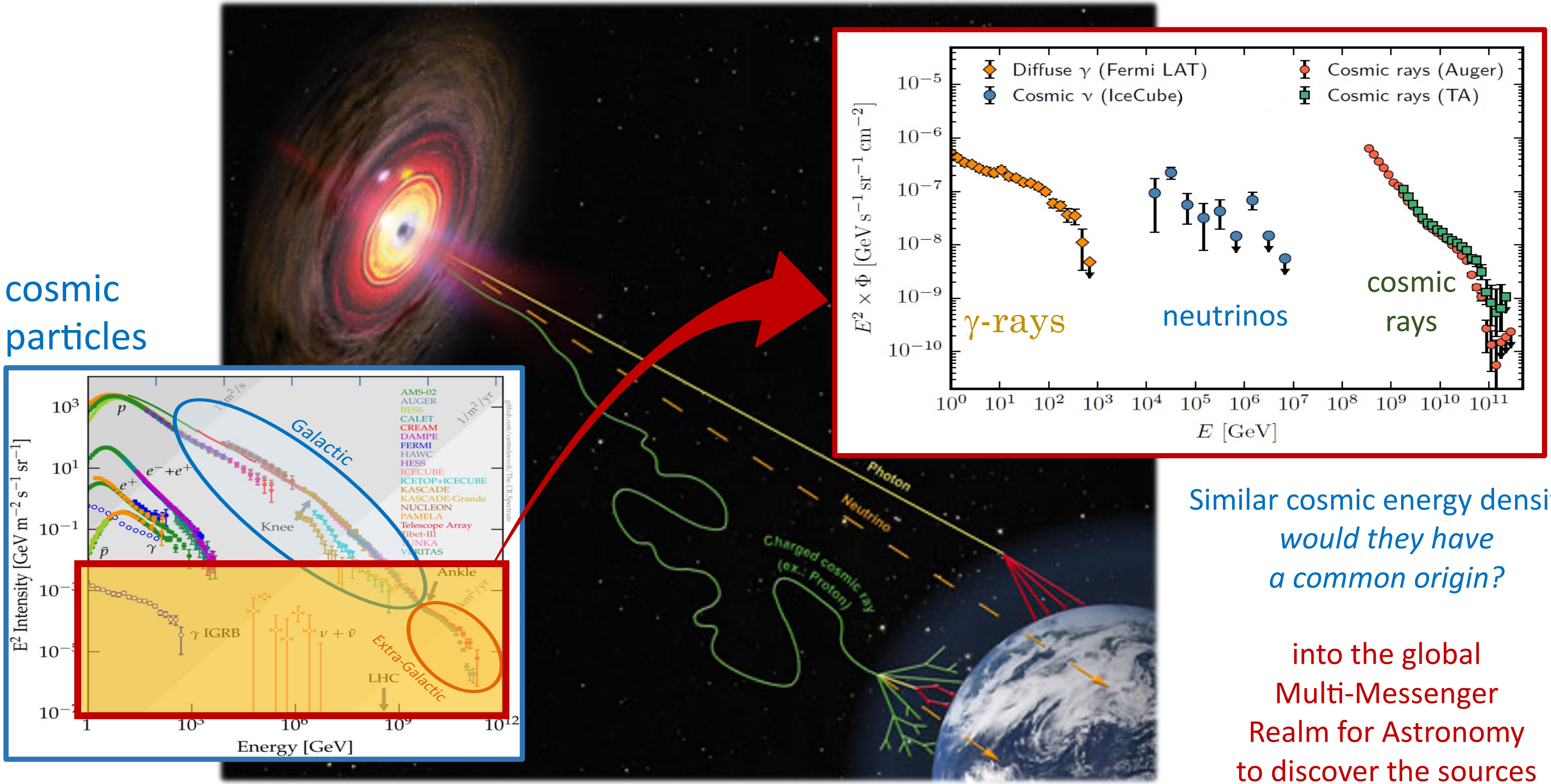


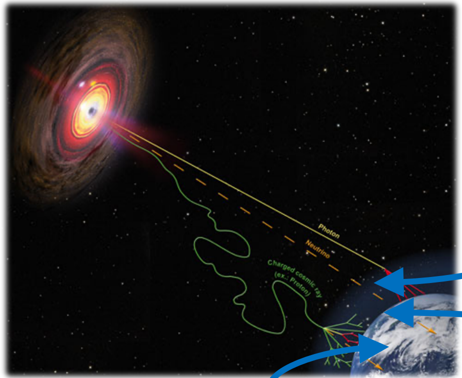
Similar cosmic energy density:

would they have a common origin?

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

Major Cosmic Particle Facilities in Europe

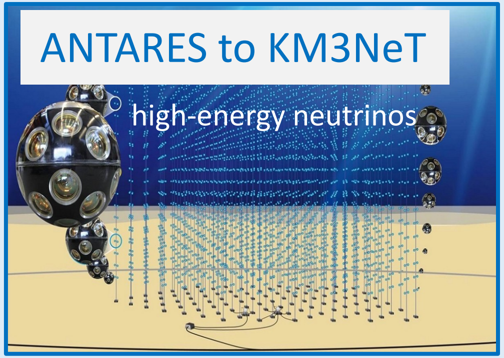
advance our major participation outside Europe: Pierre Auger Observatory, IceCube(-Gen2), …



observatory in orbit

data taking

observatory below surface



construction, partially operational

construction, partially operational

observatory on the surface

construction, start observations >2023

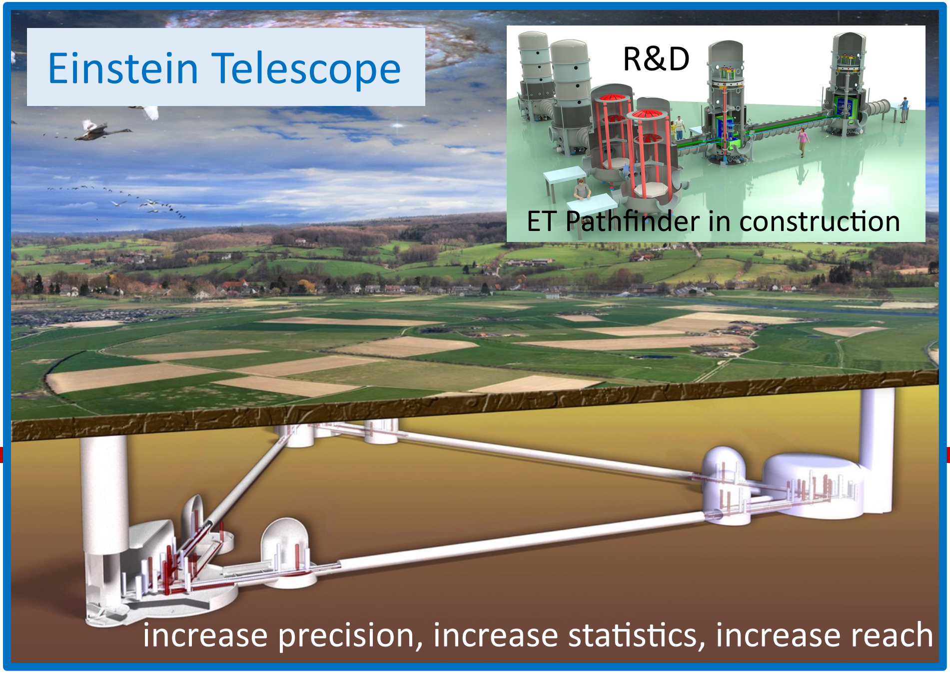
Gravitational Wave Facilities in Europe

Current flagships

Advanced & Plus upgrades up to 2035

3^{rd} generation interferometer, beyond 2035

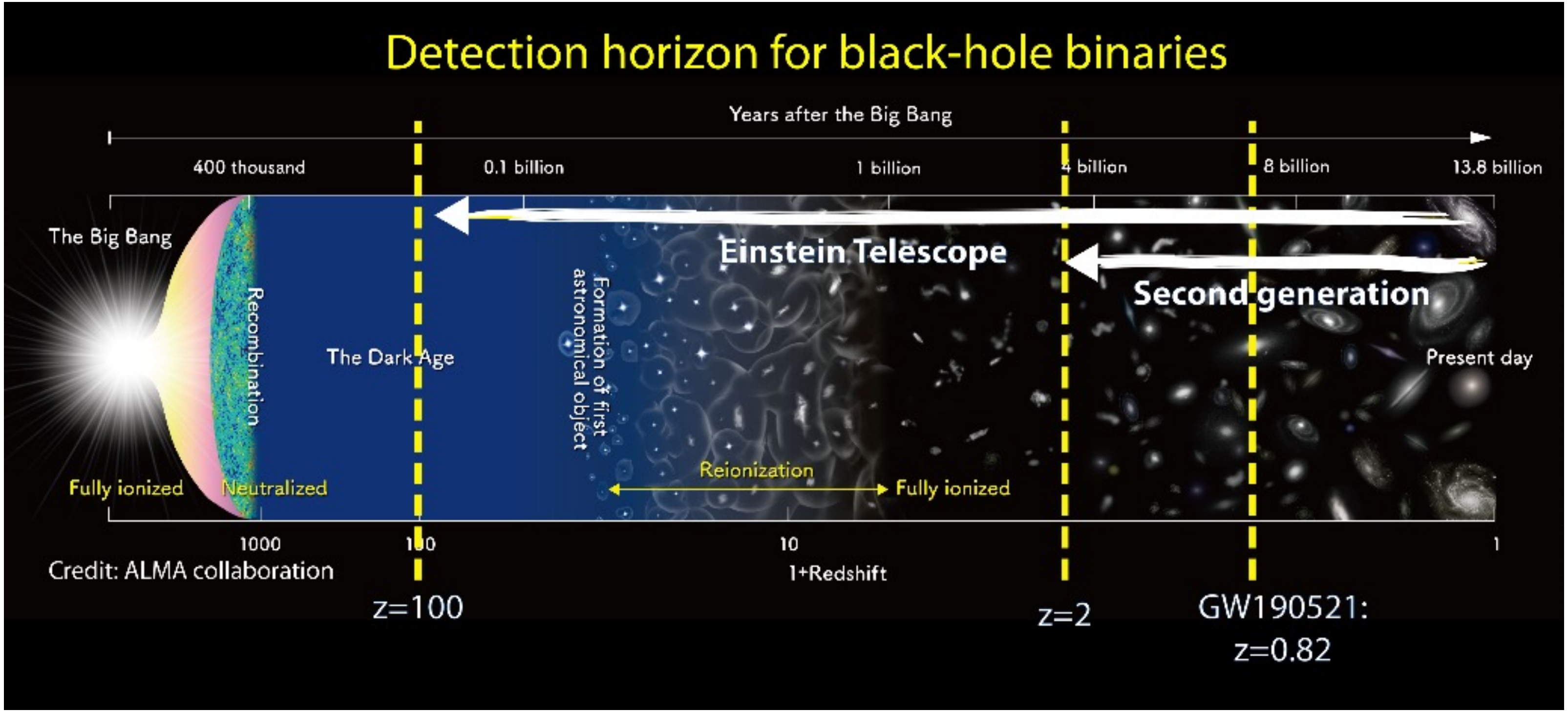
underground – triangle (10km arms) – cryogenic



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?

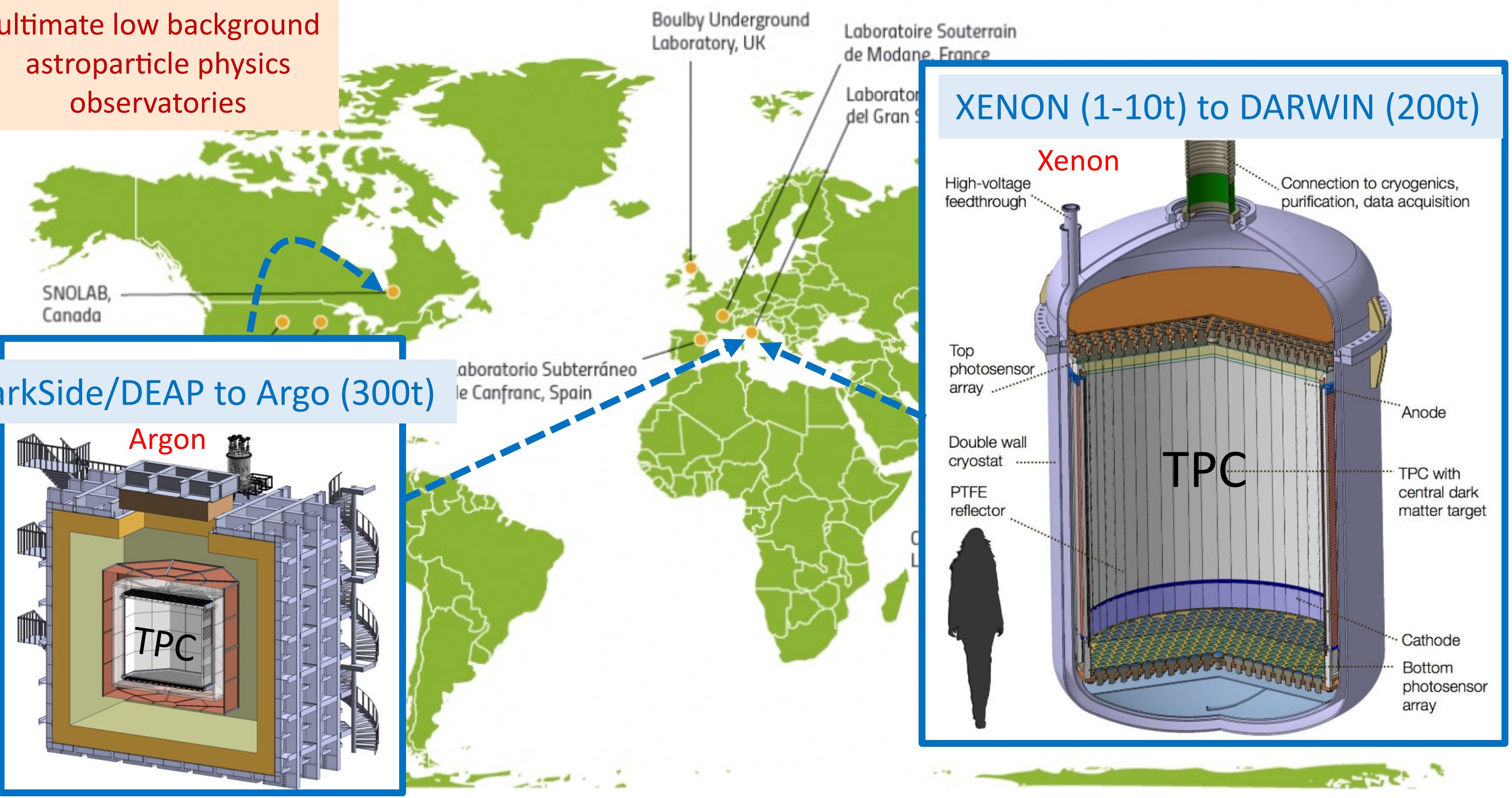
our eyes on the invisible

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

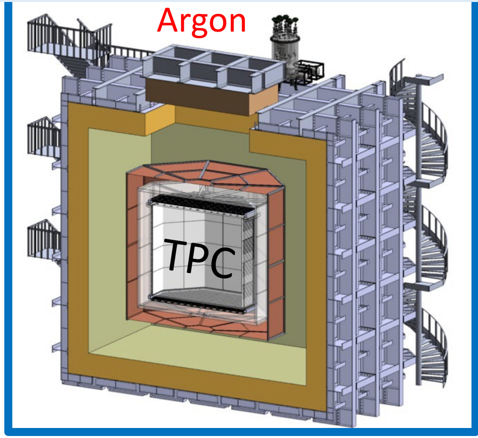
XENON (1-10t) to DARWIN (200t)

proposal towards CDR (beyond 2027)

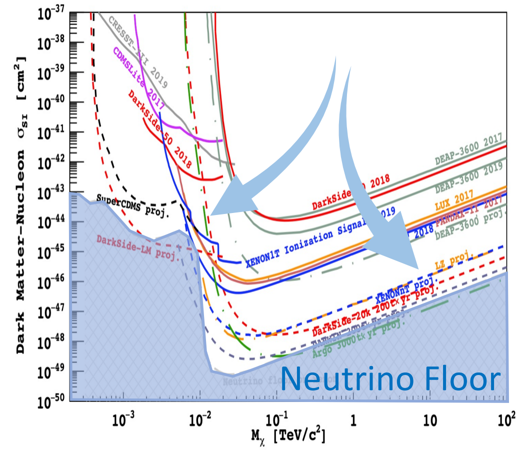
Major underground Facilities in Europe – Dark Matter

ultimate low background astroparticle physics observatories

DarkSide/DEAP to Argo (300t)

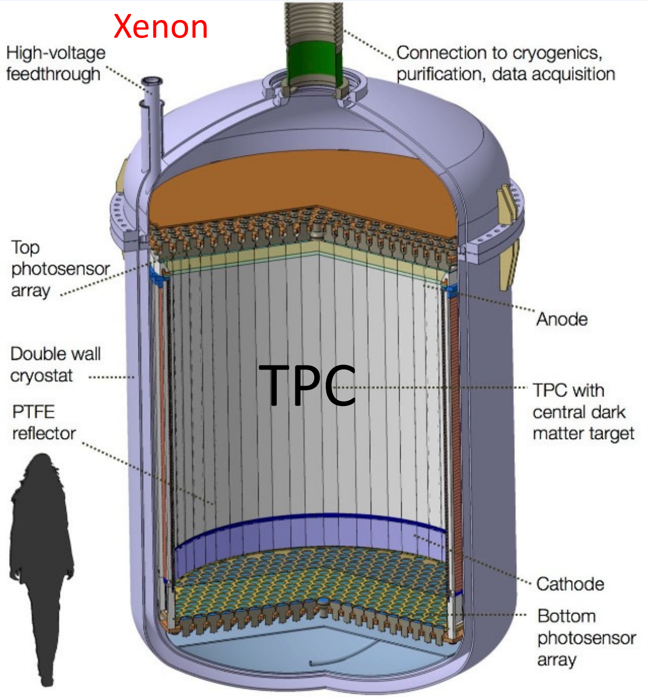


proposal



reaching the "neutrino floor"
where the neutrino backgrounds dominate

XENON (1-10t) to DARWIN (200t)



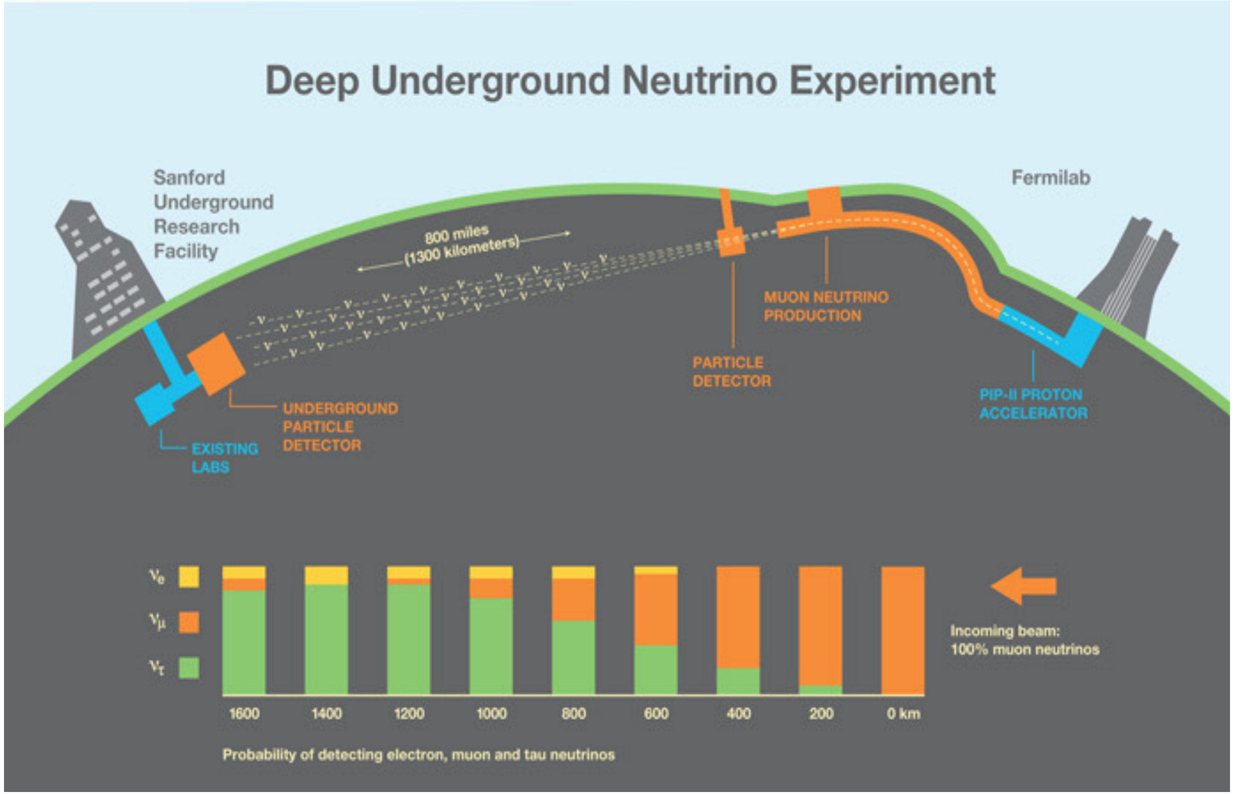
proposal towards CDR (beyond 2027)

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 looks like?*

Measure the oscillation probabilities of neutrinos and antineutrinos will ultimate precision, e.g. at the Long-Baseline Neutrino Facility (LBNF) with the DUNE experiment.

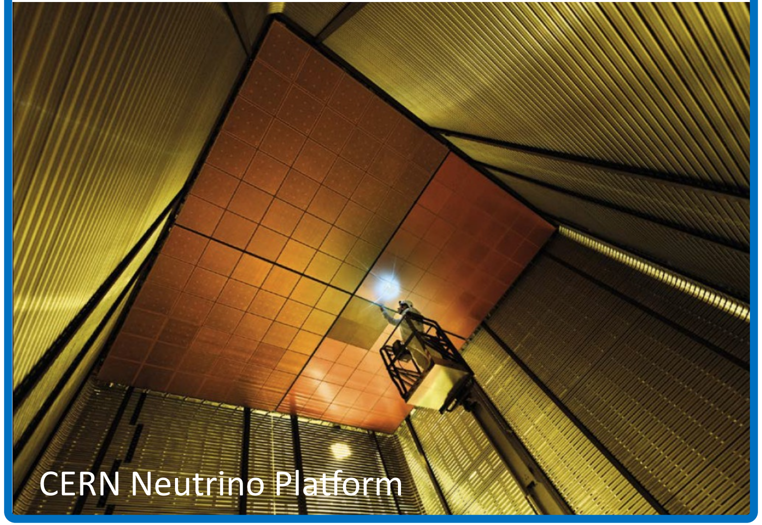


Neutrino beams in Japan and in the US

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

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC


CERN Neutrino Platform

BabyMIND @ T2K (near detector)

Prototype for Magnetised Iron Neutrino Detector


CERN Neutrino Platform

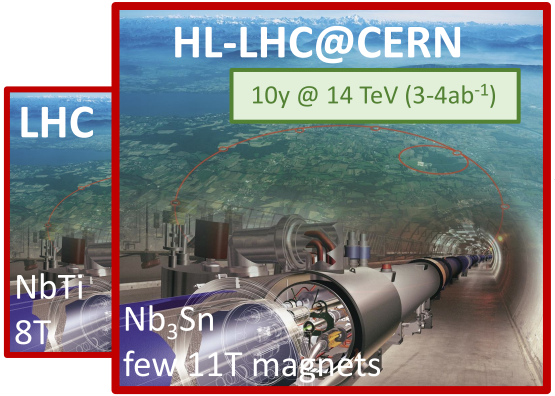
Within the next decade, we will now much more how to develop the neutrino sector to extend the Standard Model

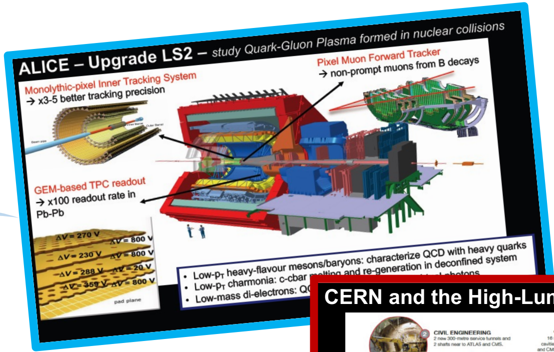
our eyes on direct discoveries

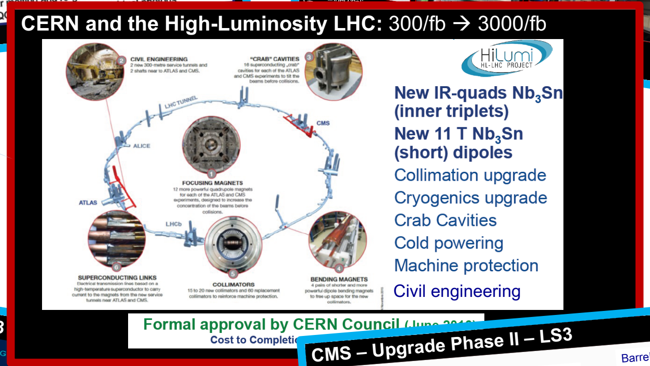
Today's Flagship: from LHC to HL-LHC

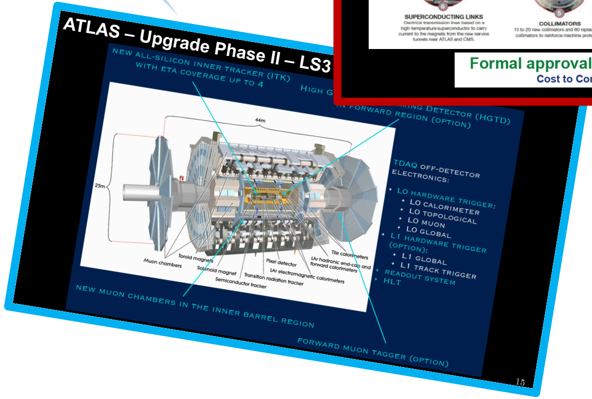
Current flagship (27km)

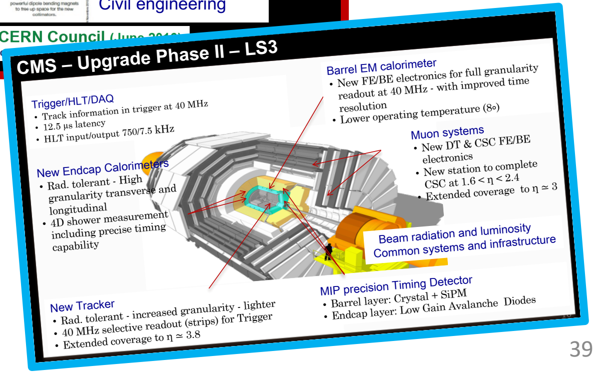
impressive programme up to 2040











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

Today's Flagship: from LHC to HL-LHC

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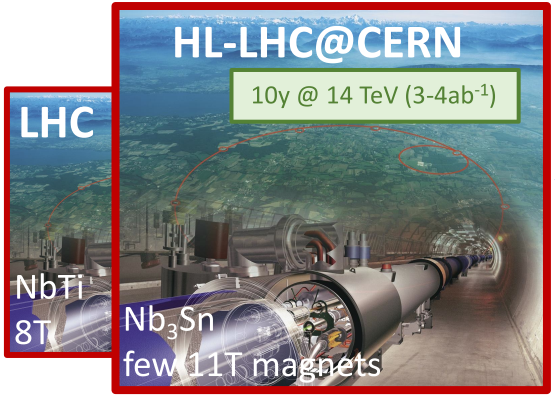
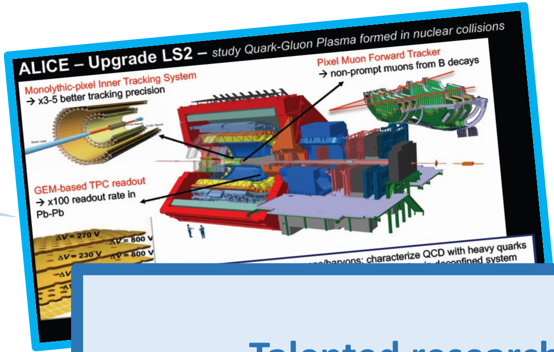


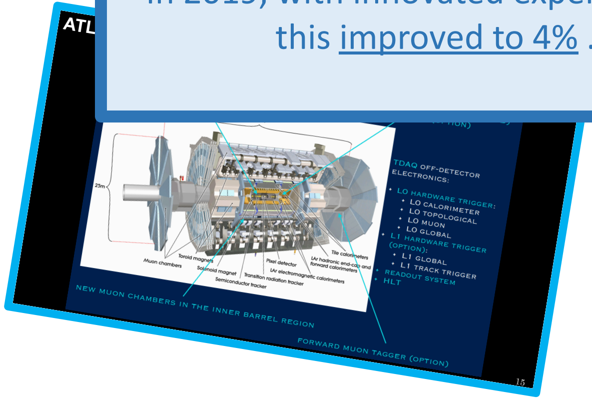
continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

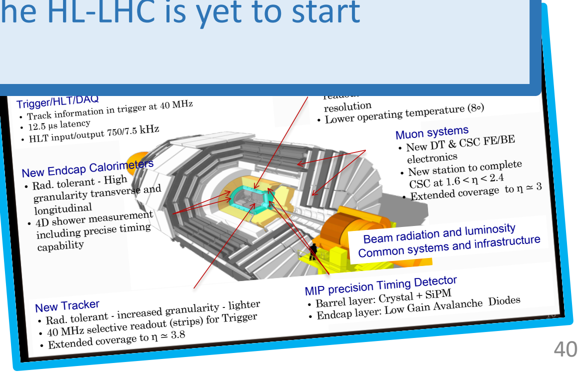


Talented researchers make the difference

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



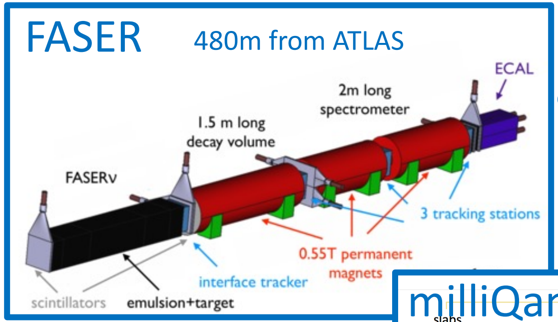


(HL-)LHC as a catalyser for dedicated experiments

Current flagship (27km)

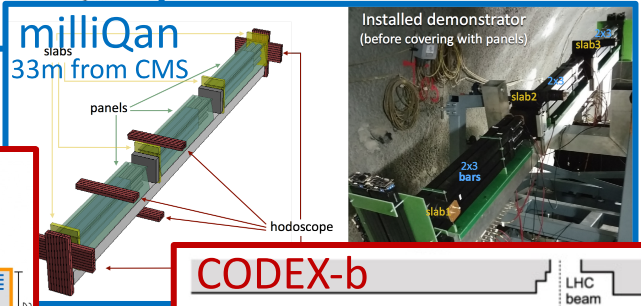
impressive programme up to 2040

Additional opportunities with high-energy proton collisions

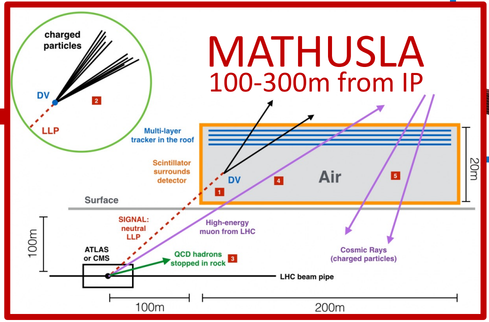


being installed

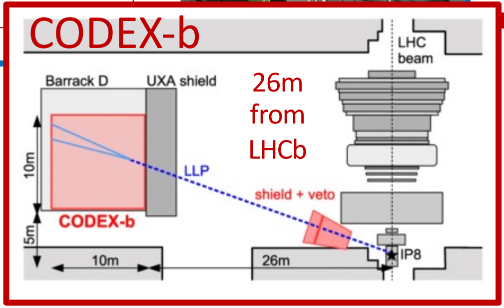
Long Lived Particles
Light & weakly coupling particles
Milli-charged particles
Magnetic Monopoles (MoEDAL)



being demonstrated



proposal



proposal

(HL-)LHC as a catalyser for dedicated experiments

Current flagship (27km)

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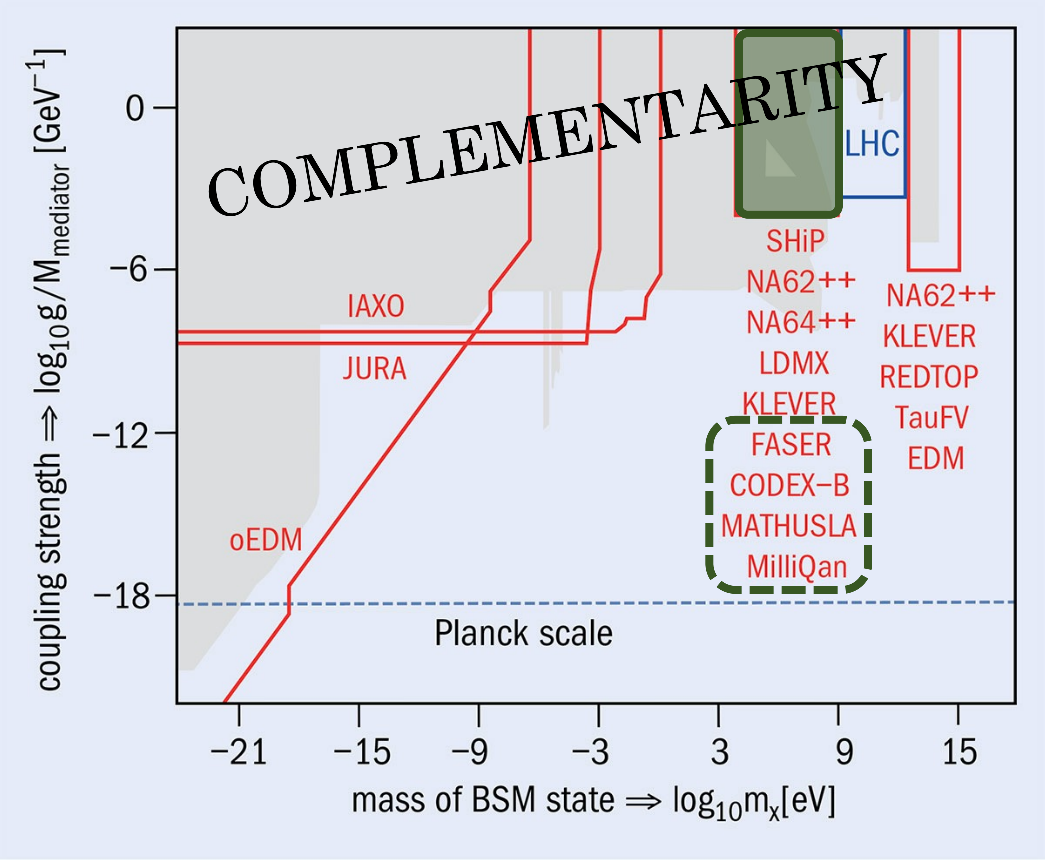
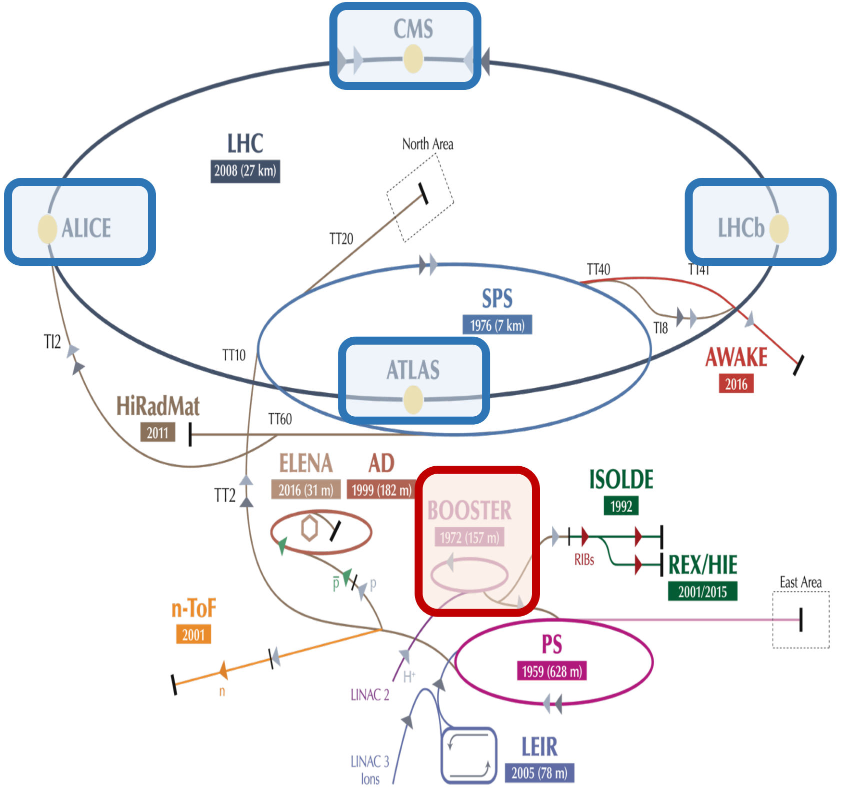
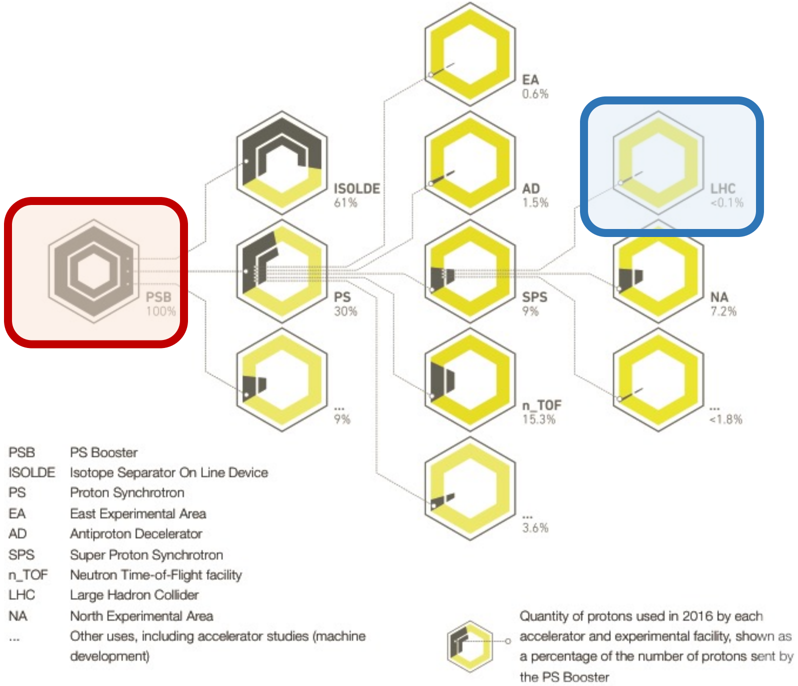


While running the (HL-)LHC: Accelerated Beams at CERN

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





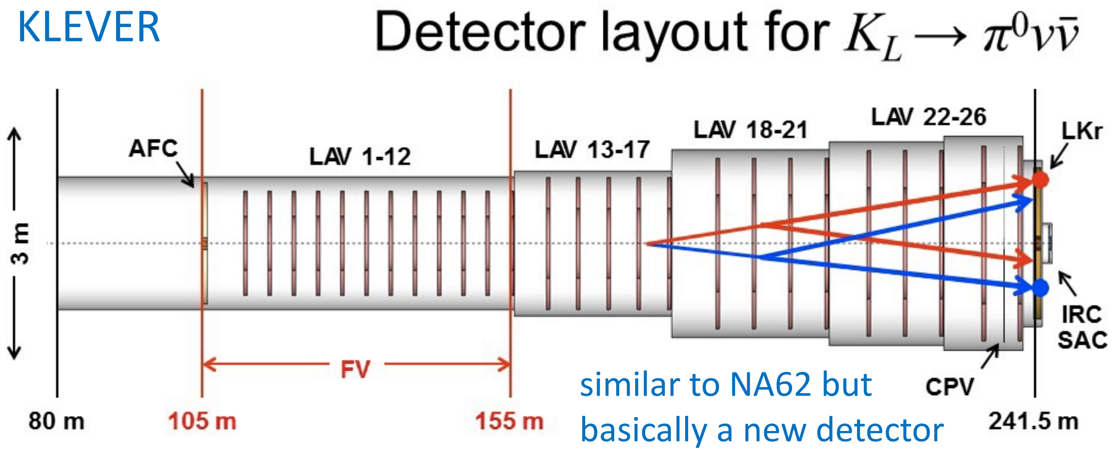
Kaon physics from NA62 to KLEVER @ SPS-CERN

During LHC era

running

During HL-LHC era

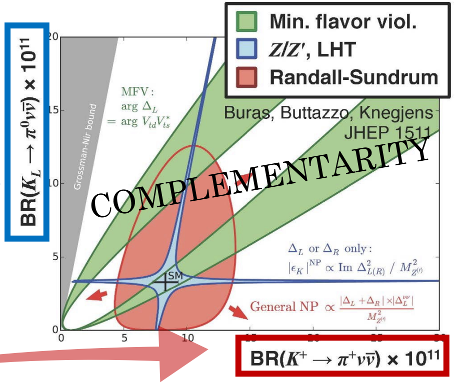
KLEVER



similar to NA62 but basically a new detector

proposal

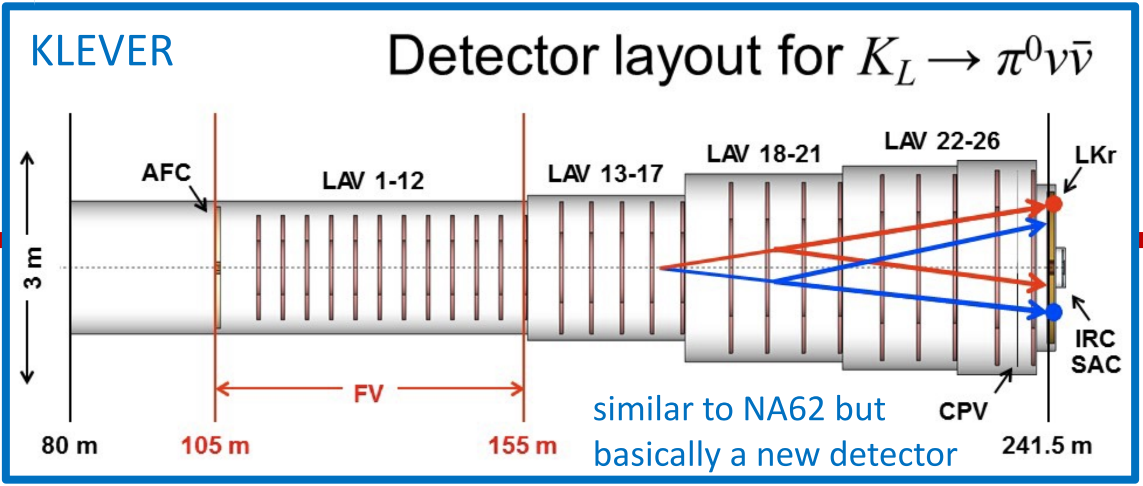
Kaon physics from NA62 to KLEVER @ SPS-CERN



During LHC era

running

During HL-LHC era



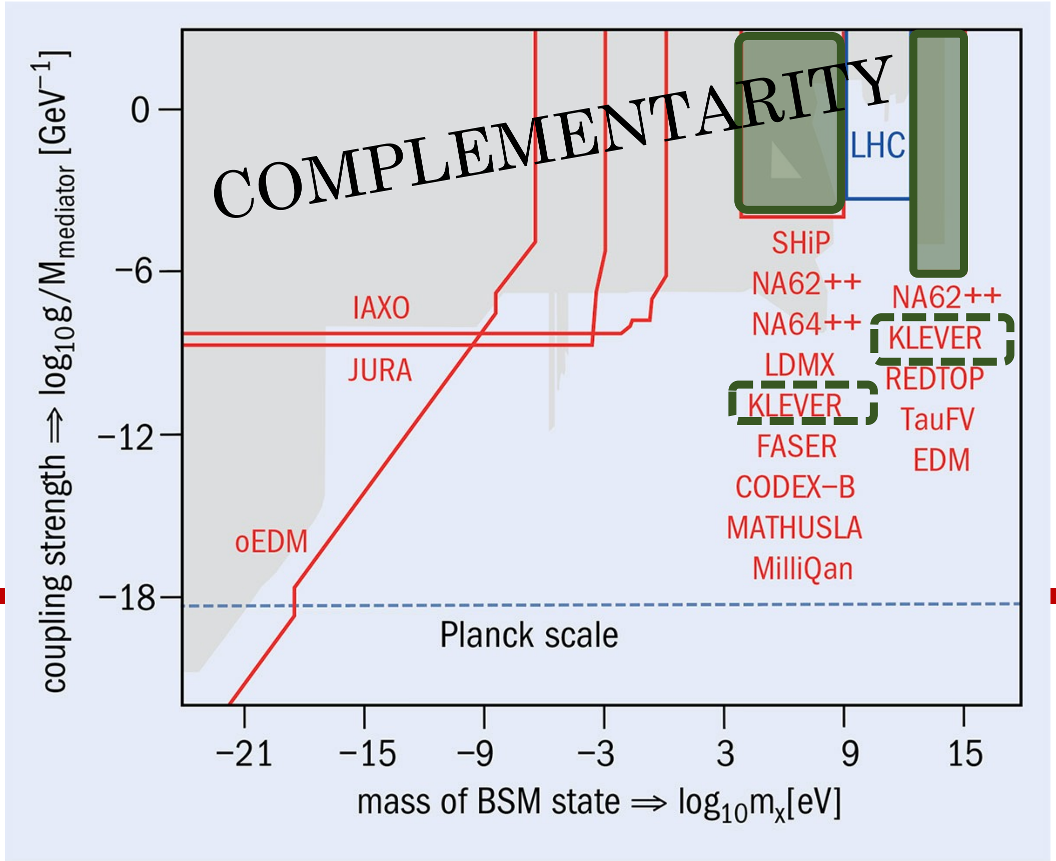
proposal

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

Current flagship (27km)

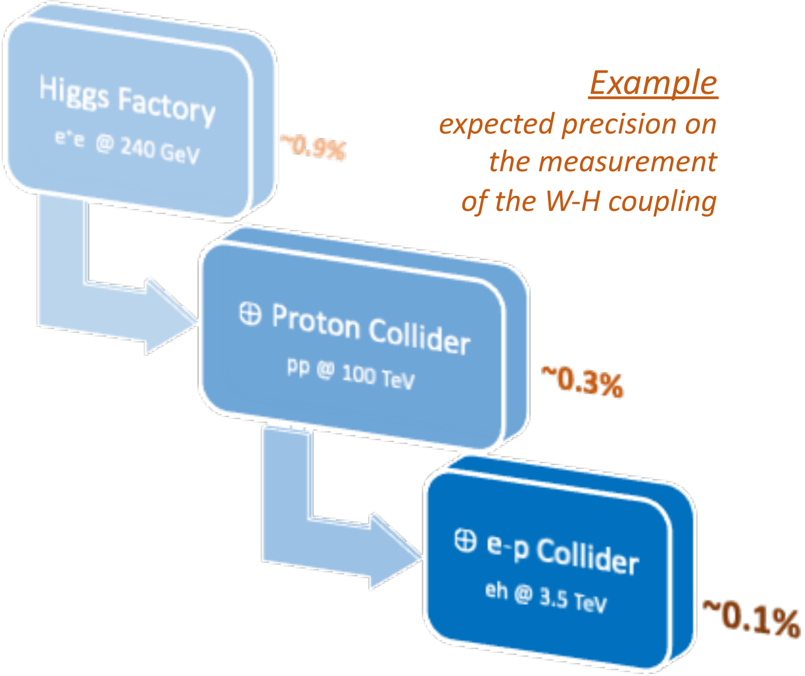
impressive programme up to 2040

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



Future high-energy particle colliders

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



Example
expected precision on the measurement of the W-H coupling

complementarity

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

ep-option with HL-LHC: LHeC

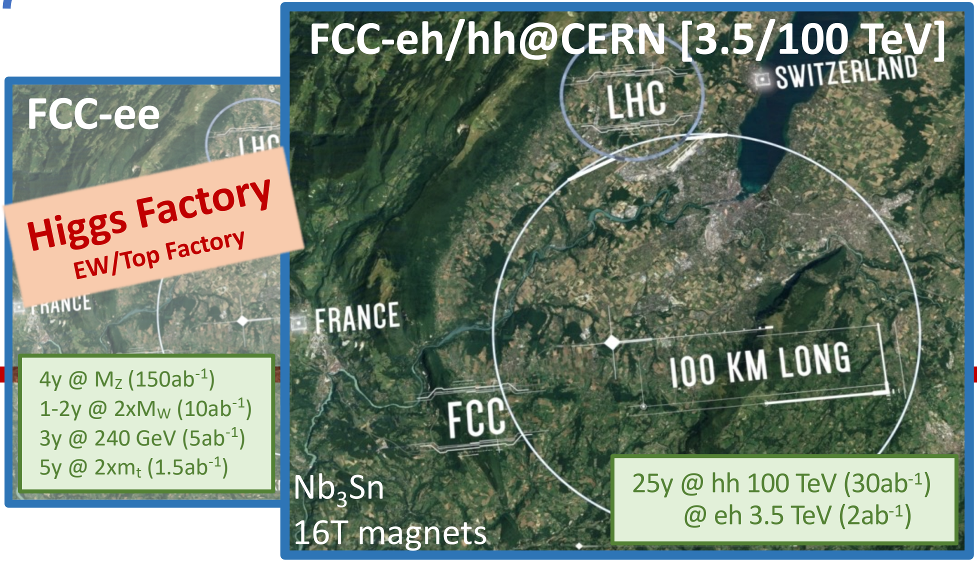
10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



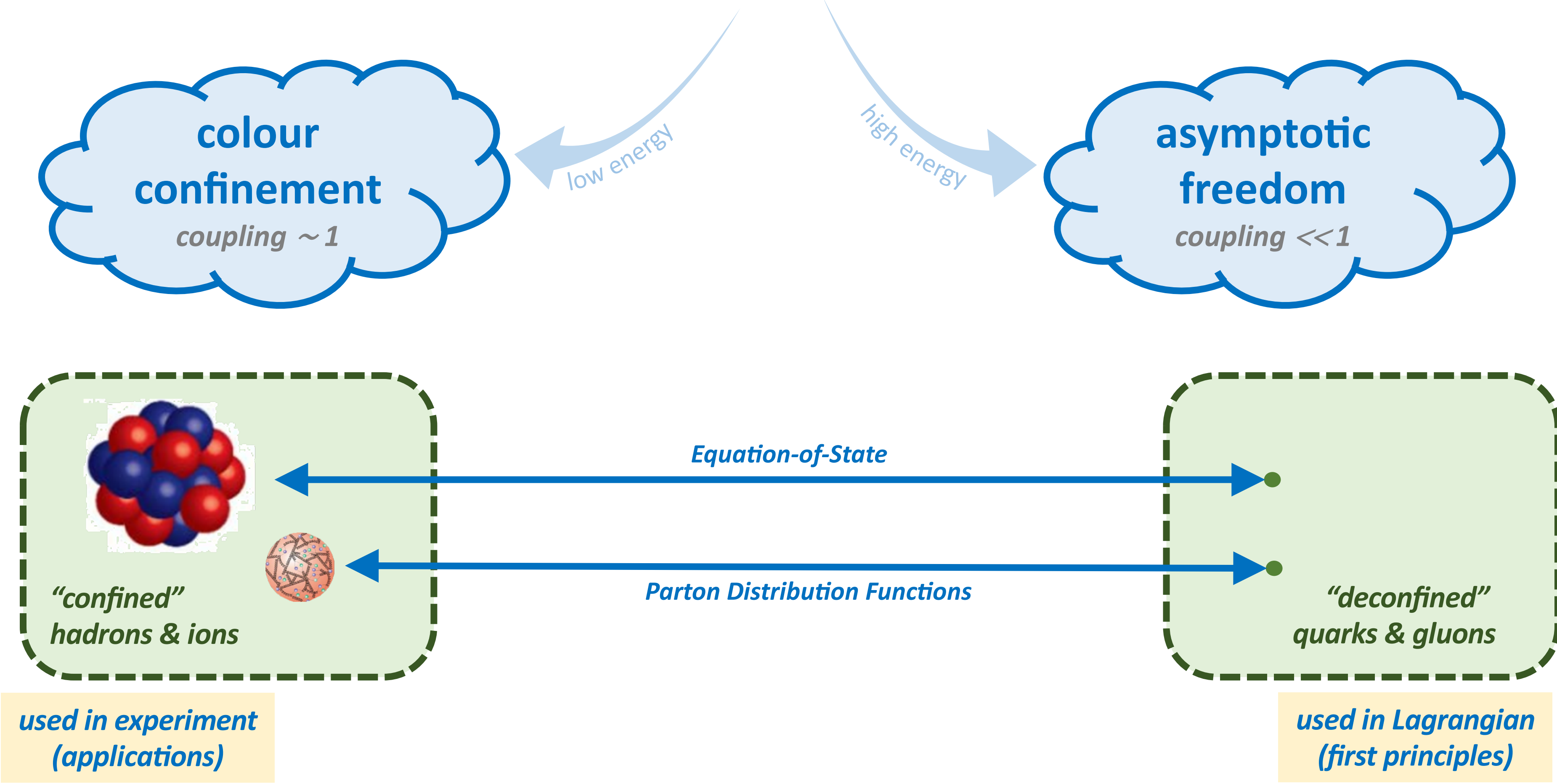
numbers assume 2 IPs for each collider (only one for FCC-eh)

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

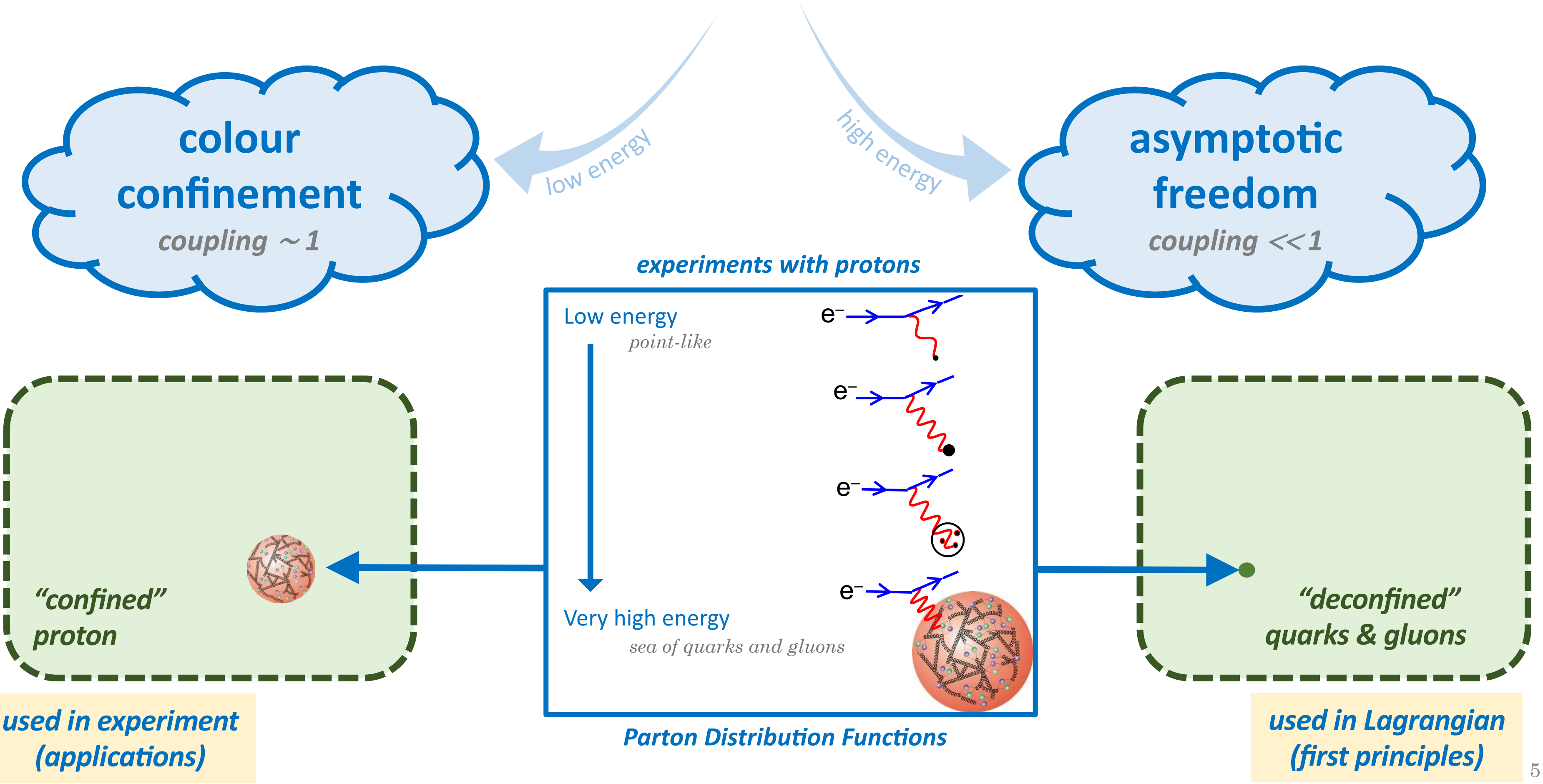
potential alternatives pursued @ CERN: CLIC & muon collider

our eyes on the structure of things

Quarks & gluons built up hadrons & ions

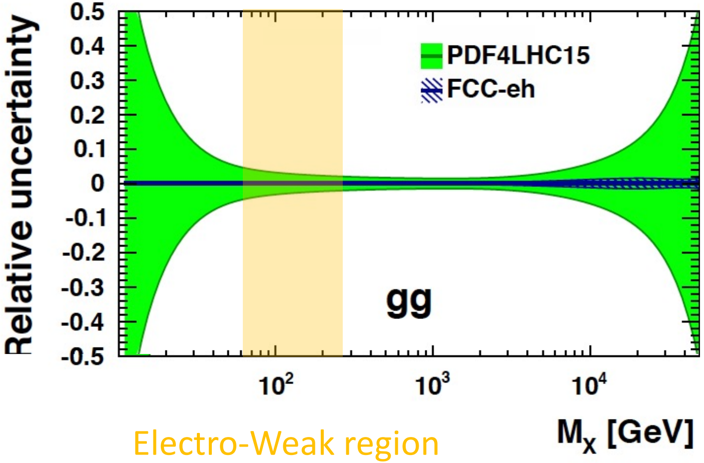


Quarks & gluons built up hadrons & ions



Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV



Electro-Weak region

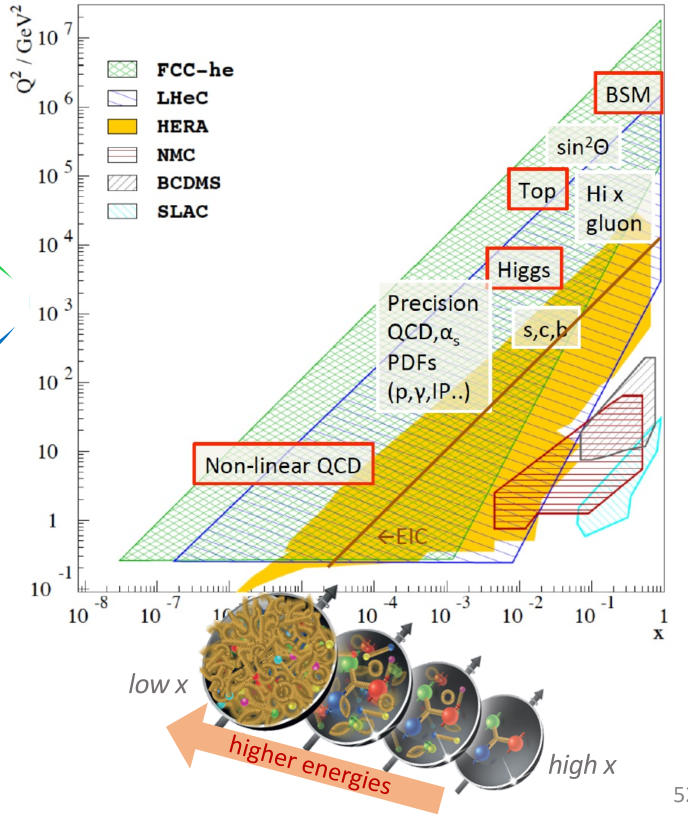
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

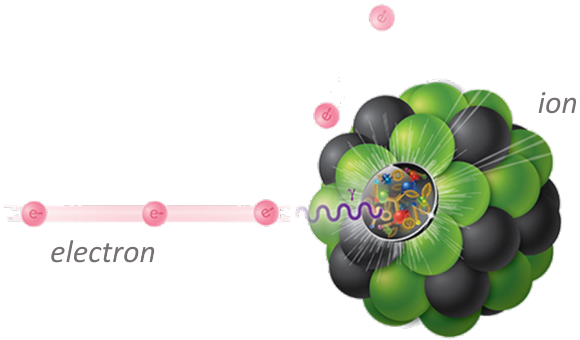
Kinematic range Parton Distribution Functions



Electron-Ion Collider (EIC)

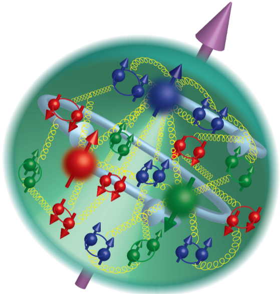
World's 1st polarized e-p/light-ion & 1st eA collider

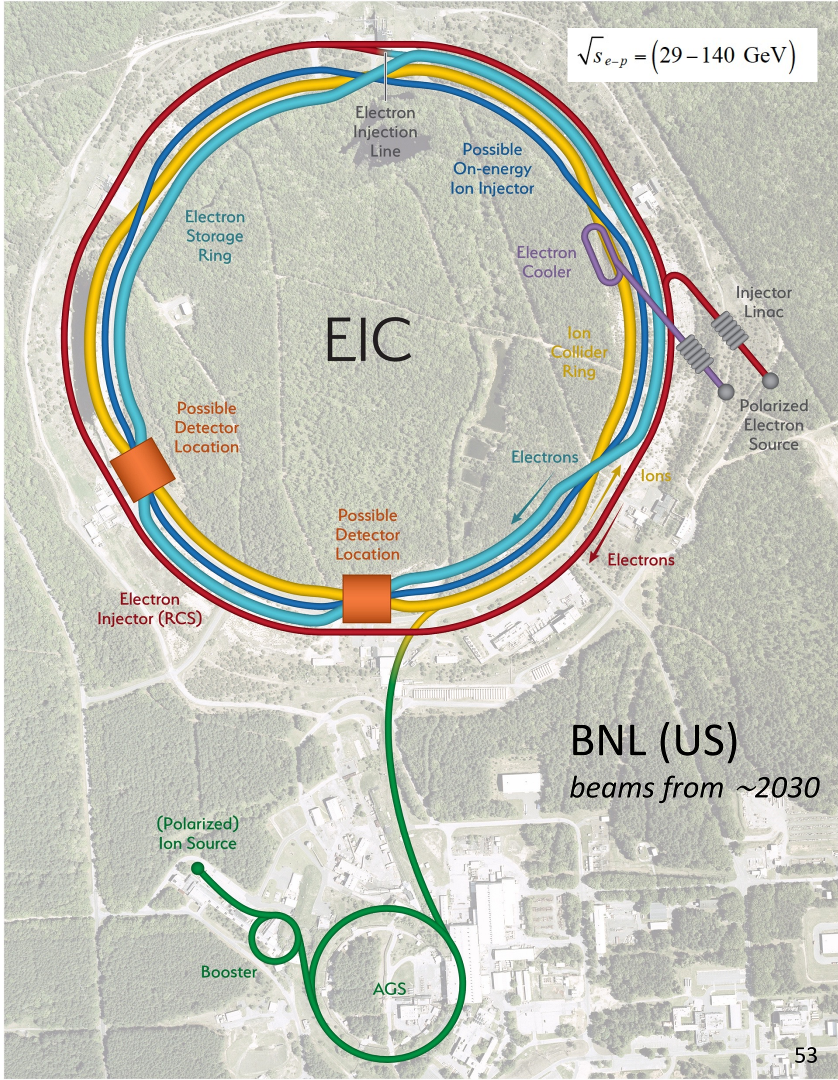
User Group >1000 members: http://eicug.org



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

Towards a 3D partonic image of the proton





Quarks and gluons built up hadrons and ions

low energy

high energy

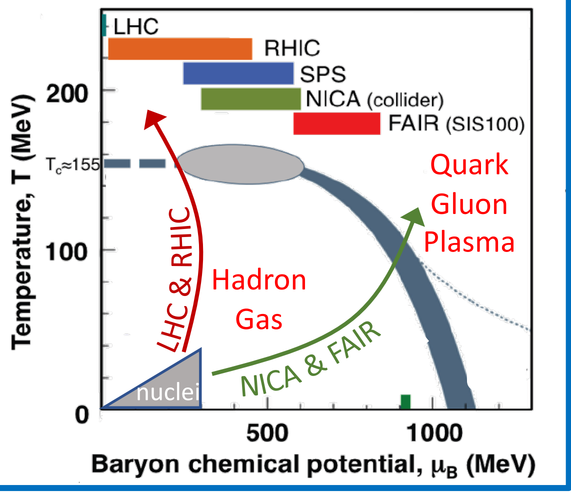
colour confinement

coupling ~ 1

asymptotic freedom

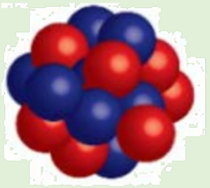
coupling << 1

experiments with heavy ions



Equation-of-State

(from a gas state to a quark-gluon plasma)



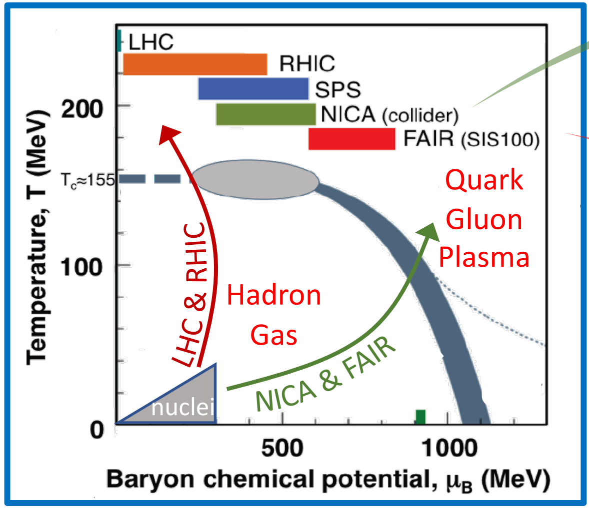
"confined" ions

used in experiment (applications)

"deconfined" quarks & gluons

used in Lagrangian (first principles)

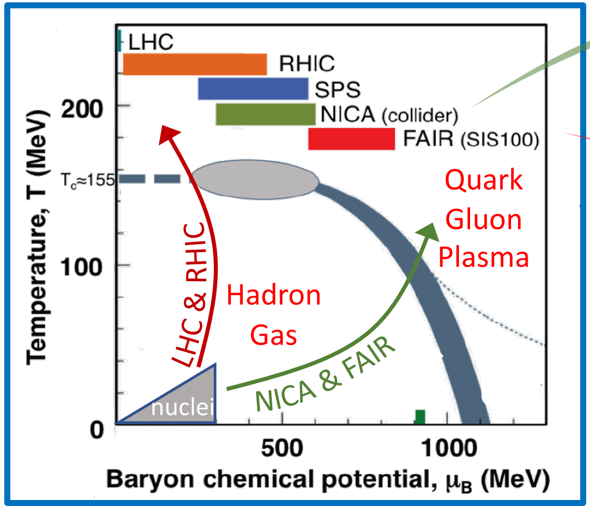
Heavy Ion physics from RHIC & SPS to NICA & FAIR



Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

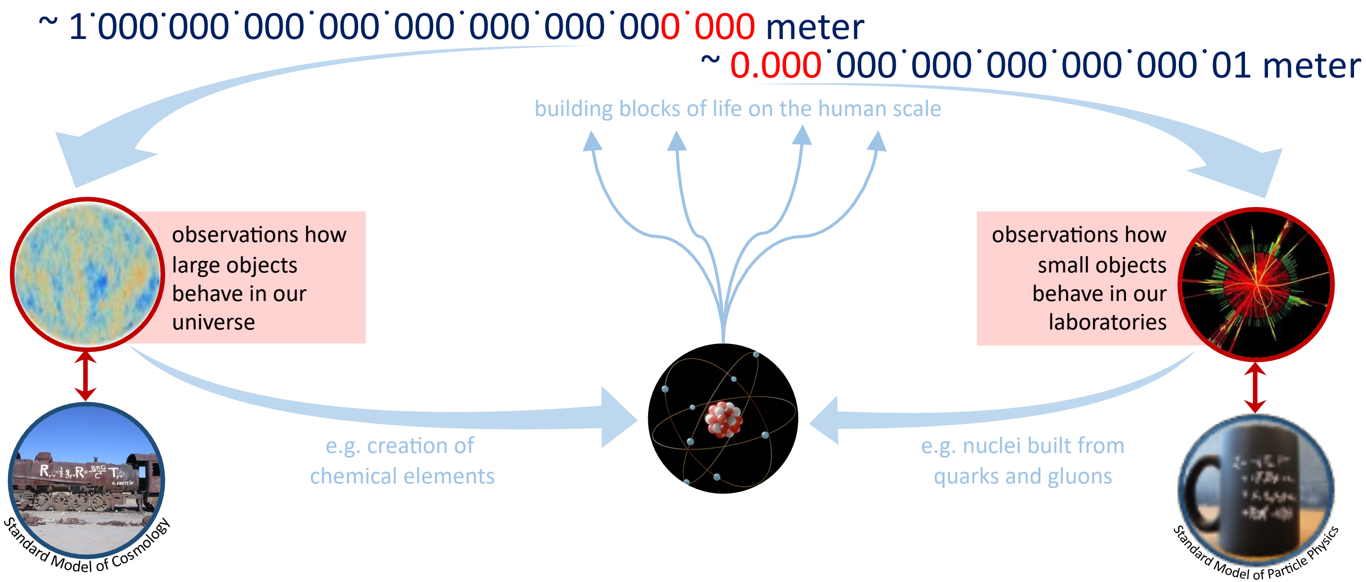
Heavy Ion physics from RHIC & SPS to NICA & FAIR



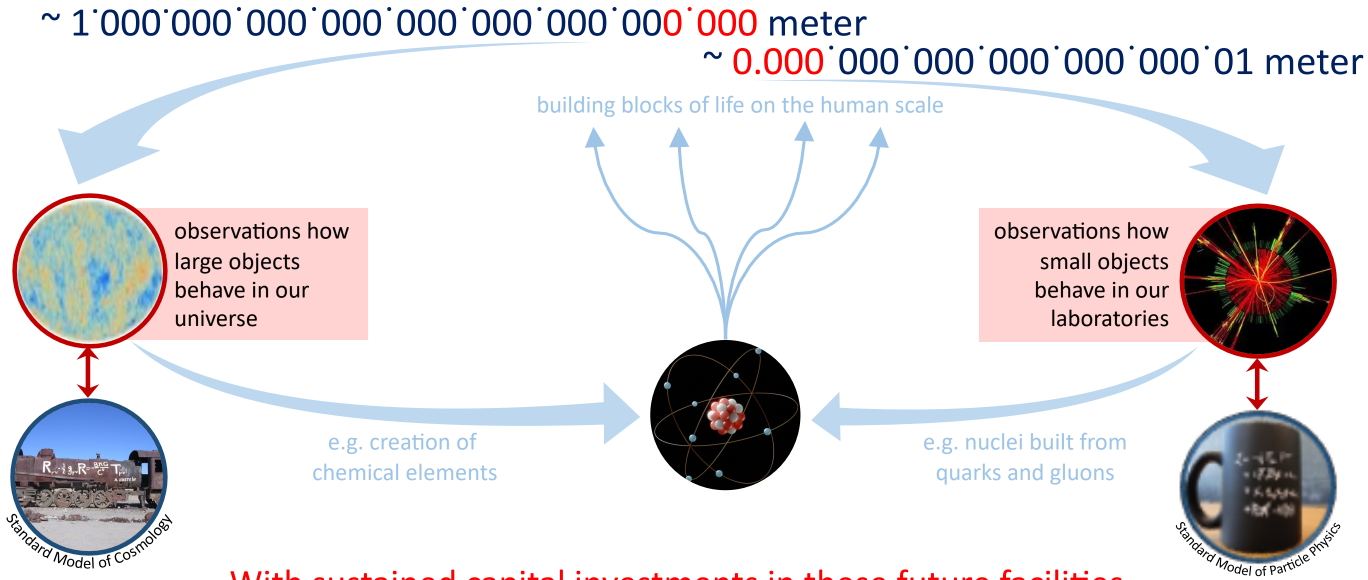
Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

Multi-faceted research to deepen our knowledge of how matter and complexity emerges from the fundamental building blocks of matter and the forces among them and will open a new era in the understanding of the evolution of our Universe and the origin of the elements.


~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter
~ 0.000˙000˙000˙000˙000˙000˙01 meter
building blocks of life on the human scale
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

Building the future together



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 basic principles and/or our theoretical frameworks.

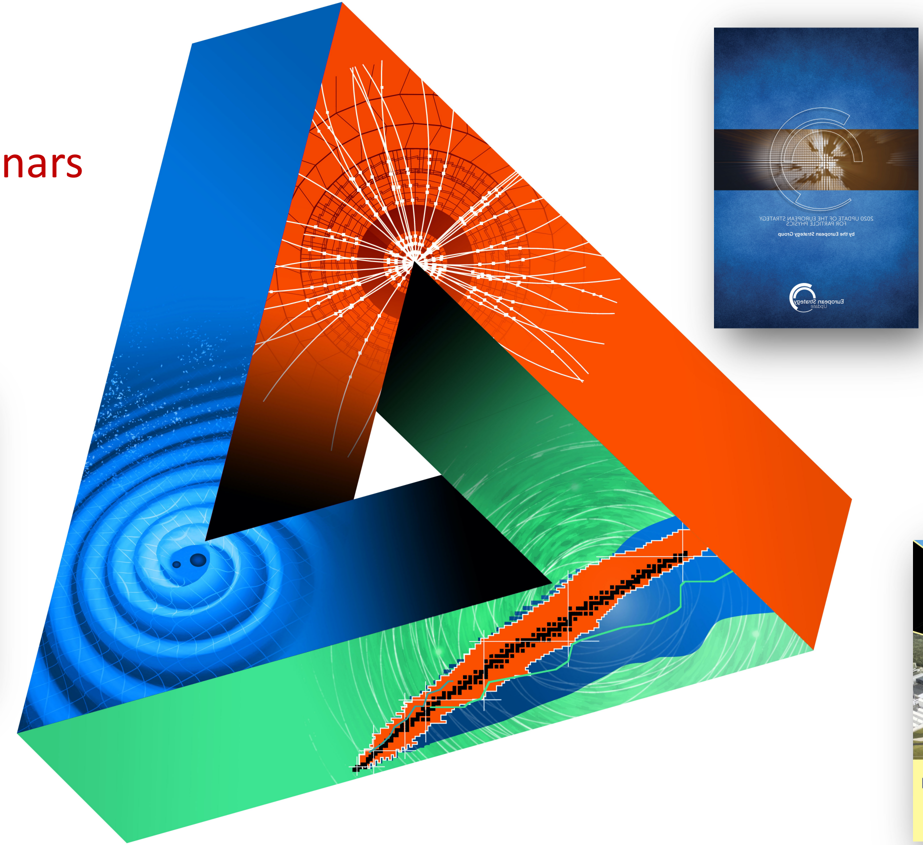
HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be

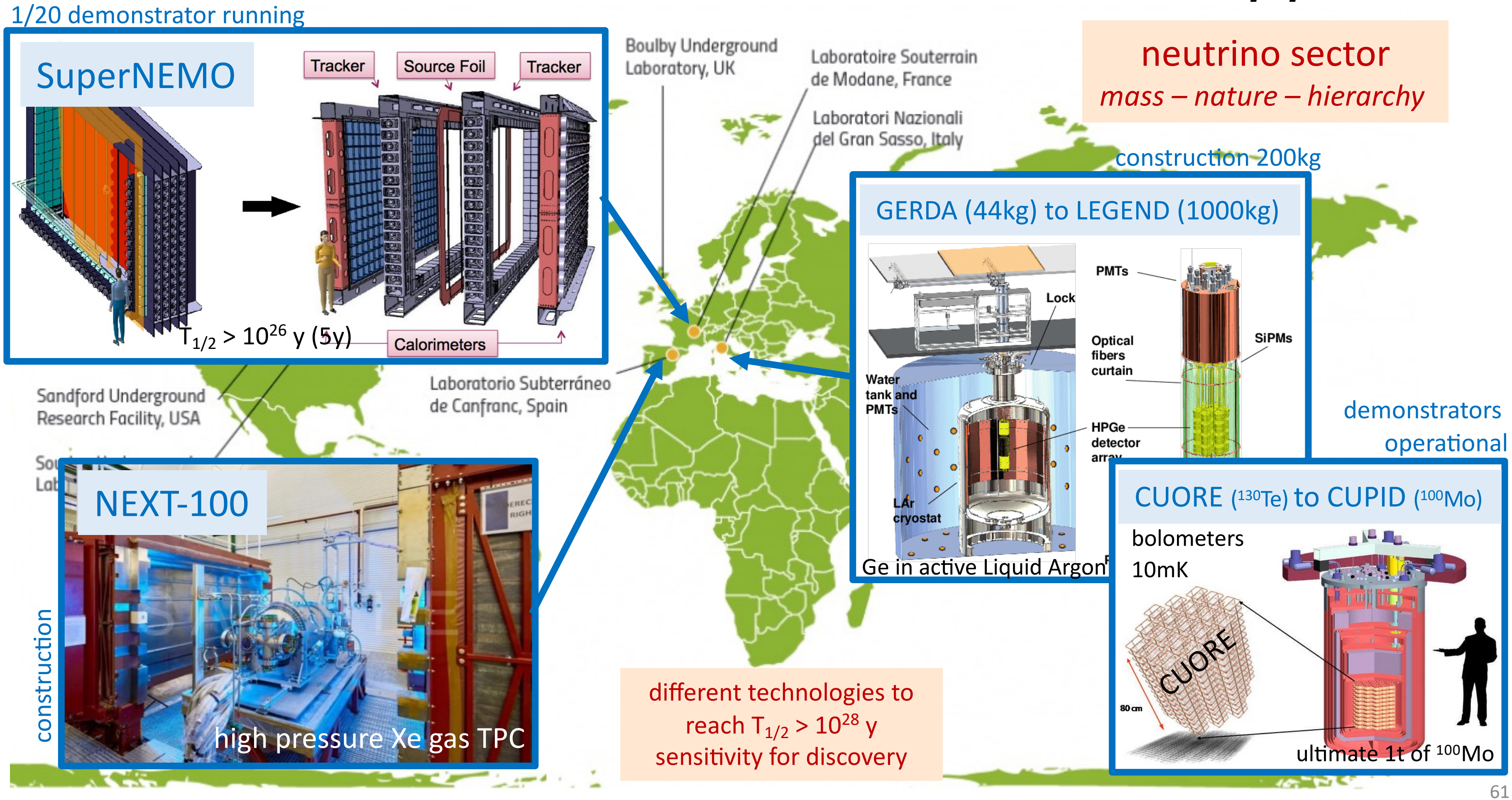
Exploring and strengthening synergies

Initiated a series of
Joint ECFA-NuPECC-APPEC Seminars
(JENAS)



ECFA: European Committee for Future Accelerators
NuPECC: Nuclear Physics European Collaboration Committee
APPEC: Astroparticle Physics European Consortium
First JENAS event at Orsay, 2019: https://jenas-2019.lal.in2p3.fr

Major underground Facilities in Europe – 0νββ



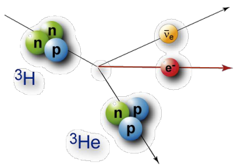
The absolute mass of the neutrino (ν_e)

KATRIN experiment at KIT (Germany) – a 70m long experimental setup

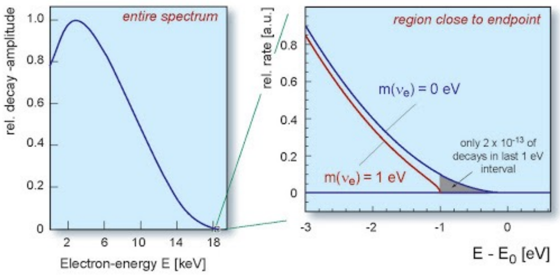
KATRIN

spectroscopic energy measurement of the β-electrons from ^3H β-decay

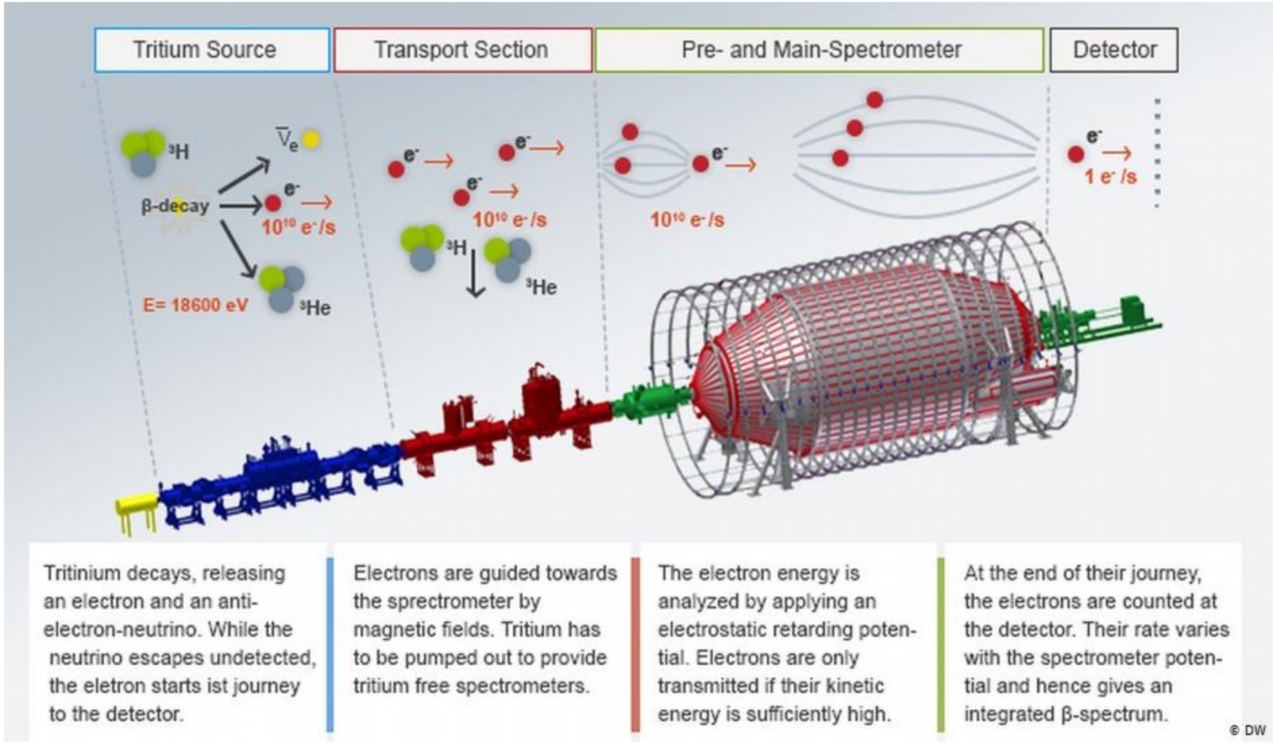
sensitivity down to about 0.35 eV (5σ)



kinematic parameters
&
energy conservation

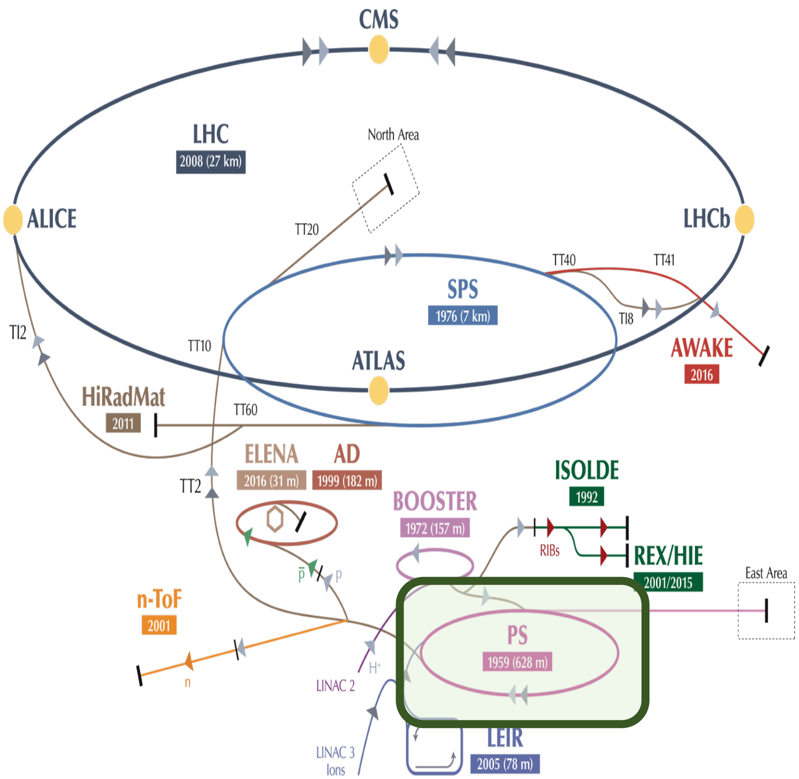


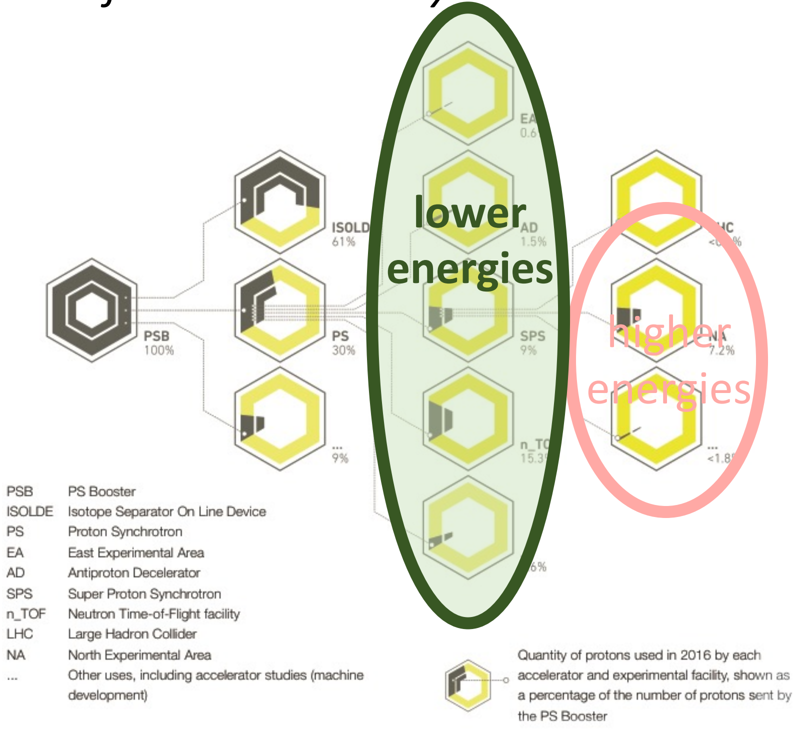
running



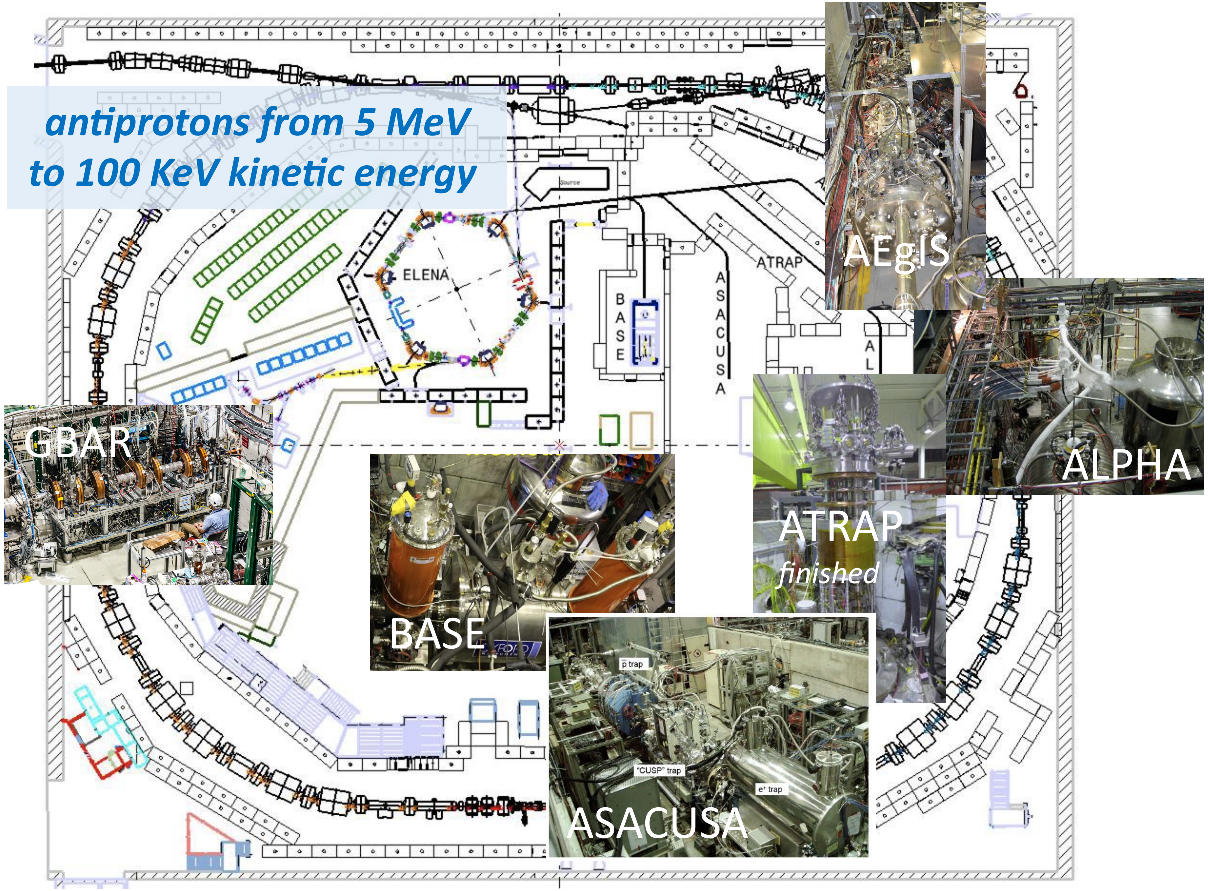
While running the (HL-)LHC: Accelerated Beams at CERN

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



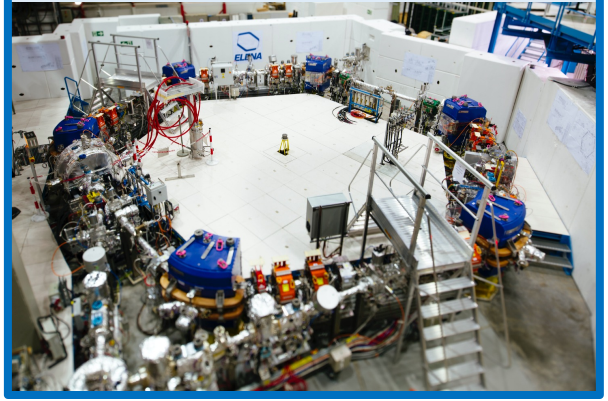


Precision physics with antimatter @ CERN



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

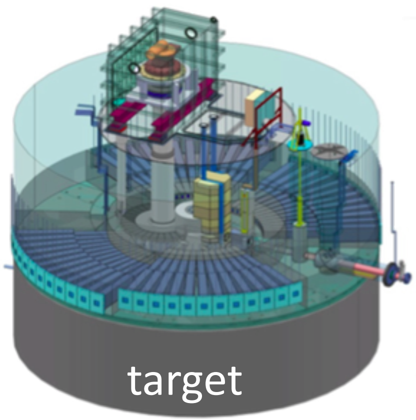
European Spallation Source (ESS) at Lund (Sweden)

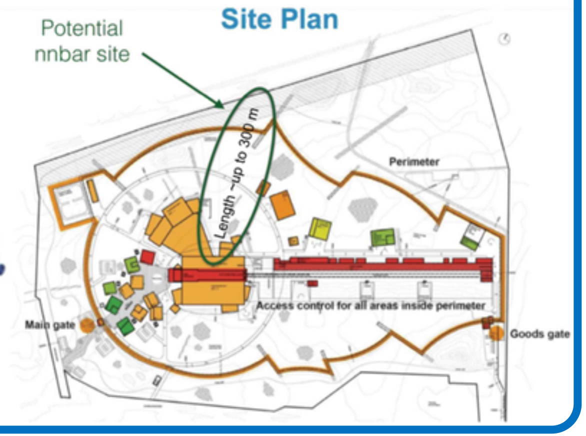
Fundamental Physics Beamline – Physics with Cold Neutrons

NNBAR experiment – from 2030 onwards

Baryon Number Violation with neutron-antineutron oscillations (up to 300m)

(3 orders of magnitude more sensitivity)





proposal

Linear Accelerator producing up to 5 MW beam of 2 GeV protons

(first science from 2023, full operation 2026)

Charged Lepton Flavour Violation

Towards the MEG-II and Mu3e experiments @ PSI (Switzerland)

Flavour Physics

Mu3e experiment

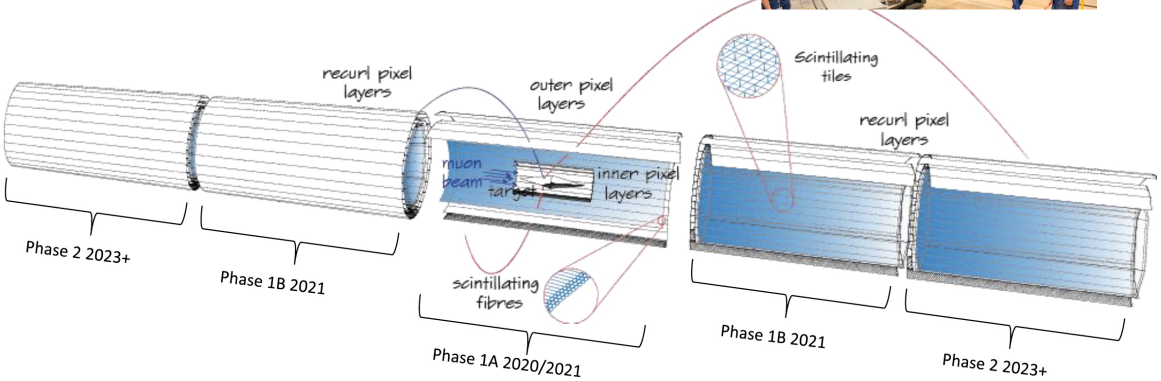
search for $\mu^+ \rightarrow e^+e^-e^+$

new beamline in next 5-10 years with most intense muon beam with >10^9 muons/s decaying in the Mu3e detector

sensitivity to BR($\mu^+ \rightarrow e^+e^-e^+$) ~ 10^{-16}
(10^4 improvement)

being installed

magnet arrival – July 2020



Technical Design: https://arxiv.org/abs/2009.11690

Neutrinos

Experiments at reactors

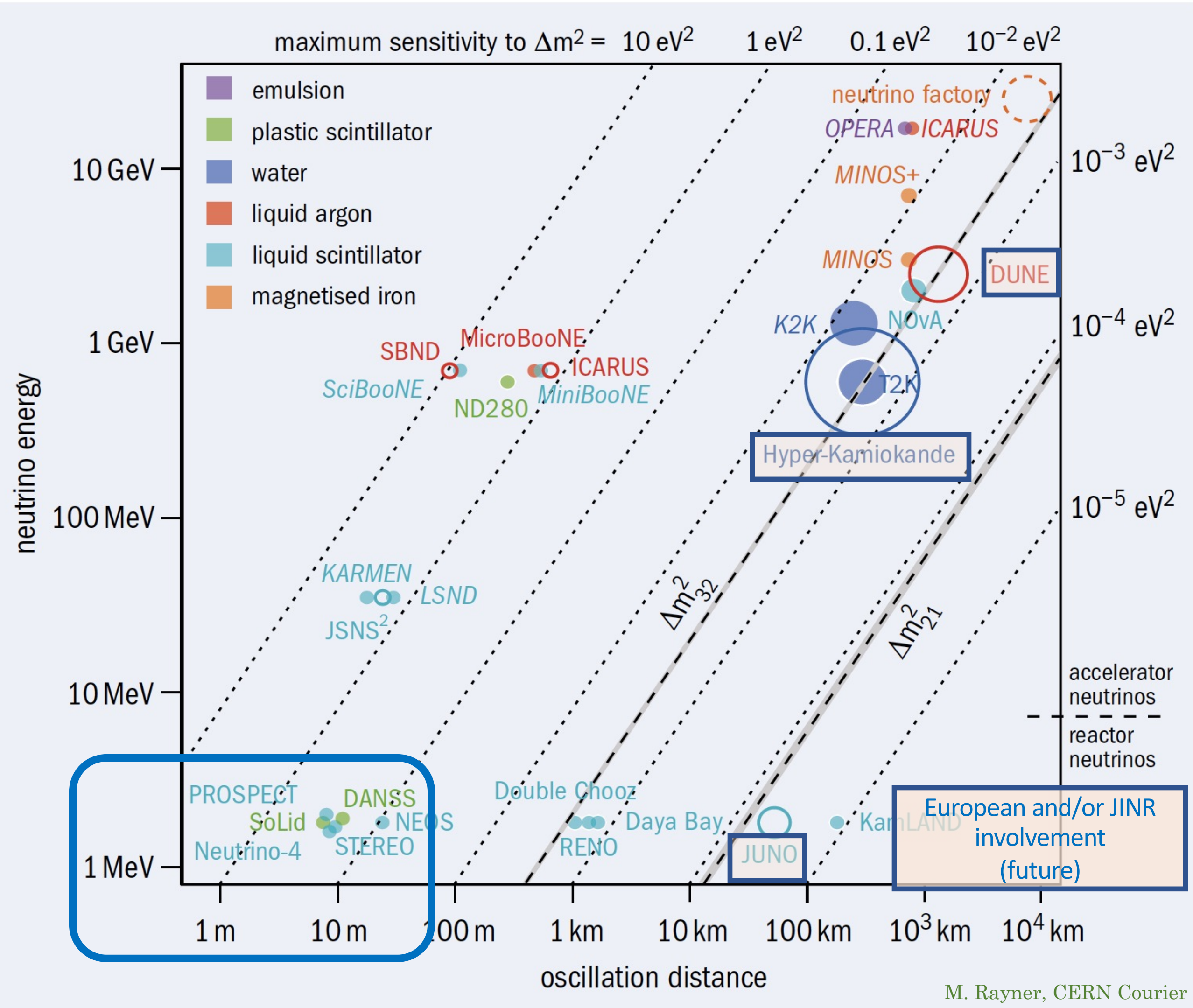
From very short to long baseline

Running in Europe/Russia

- *DANSS (Russia)*
- *Neutrino-4 (Russia)*
- *SoLid (Belgium)*
- *STEREO (France)*

Zooming into anomalies

Sterile neutrinos



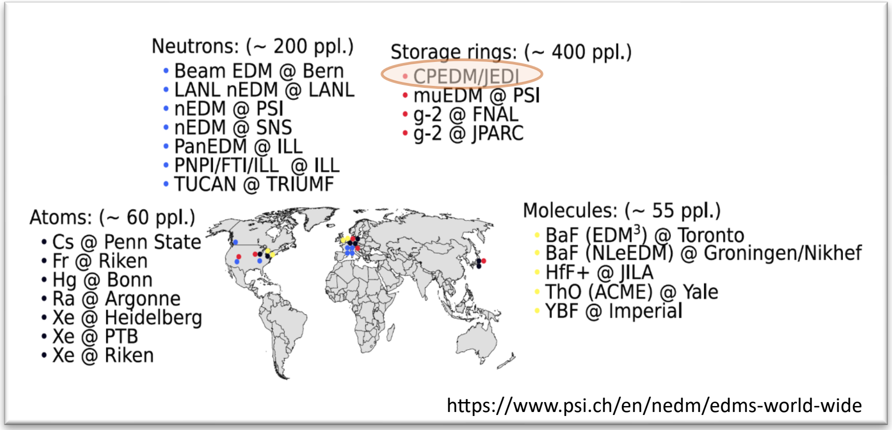
Neutrino-oscillation experiments using neutrinos from nuclear reactors or accelerator beams, as a function of the distance from source to detector and the peak energy of the neutrinos. Open markers indicate future projects (for detectors in excess of 5 kton, the area of the marker is proportional to the detector mass) and italics indicate completed experiments. The experiments are coloured according to target material. The "magic-baseline" neutrino factory proposed in the 2011 international design study is plotted for reference.

Charged-Particle EDMs (CPEDM & JEDI Collaborations)

Towards a prototype storage ring – Flavour Physics & Axion Physics via oscillating EDMs

Feasibility studies

Extensive EDM activity throughout Europe



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)

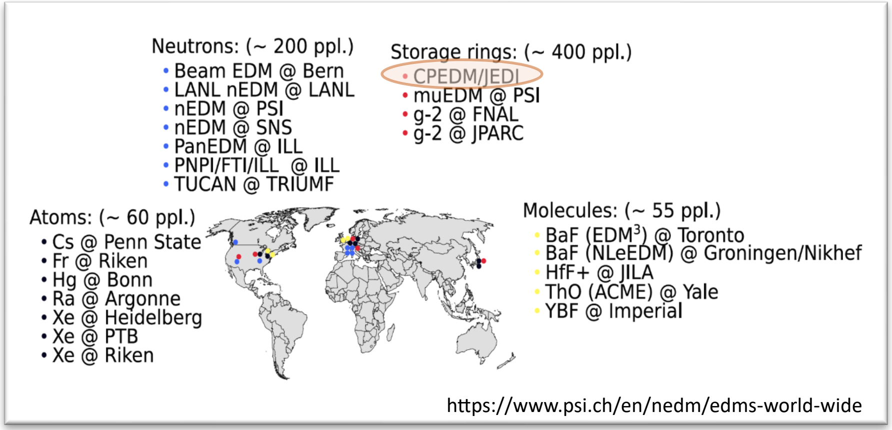
Opportunity to modify the COSY storage ring at the Forschungszentrum Jülich (Germany) towards a demonstrator and R&D for small EDMs

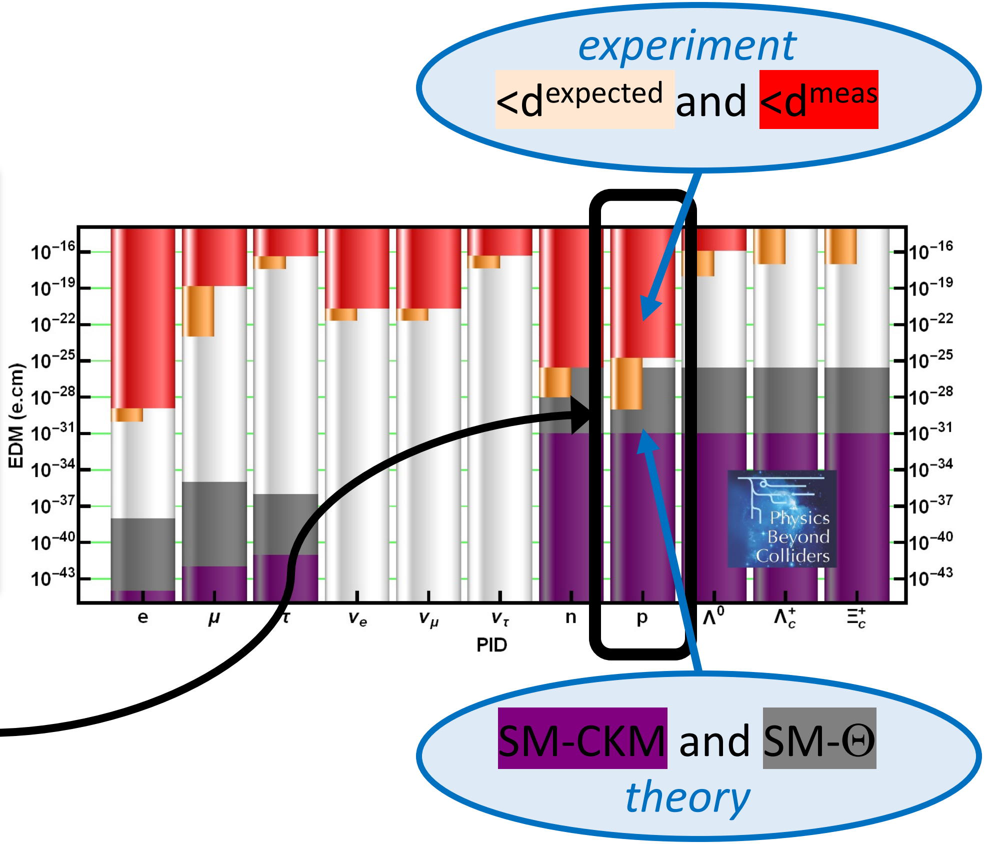
Charged-Particle EDMs (CPEDM & JEDI Collaborations)

Towards a prototype storage ring – Flavour Physics & Axion Physics via oscillating EDMs

Feasibility studies

Extensive EDM activity throughout Europe





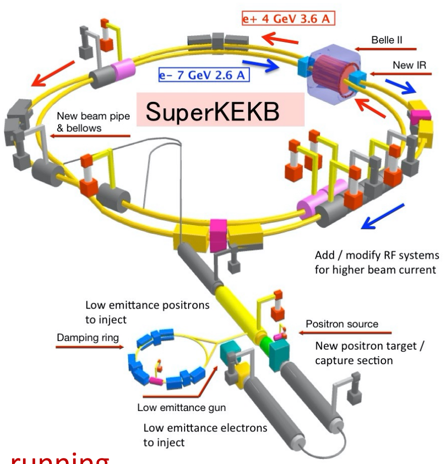
Ultimate goal of a dedicated storage ring with 400-500m circumference is pEDM sensitivity down to 10^{-29} e cm

(today 10^{-26} e cm)

Europeans at current and future colliders elsewhere

B-factory with e^+e^- at Υ(4S)≈10.5GeV

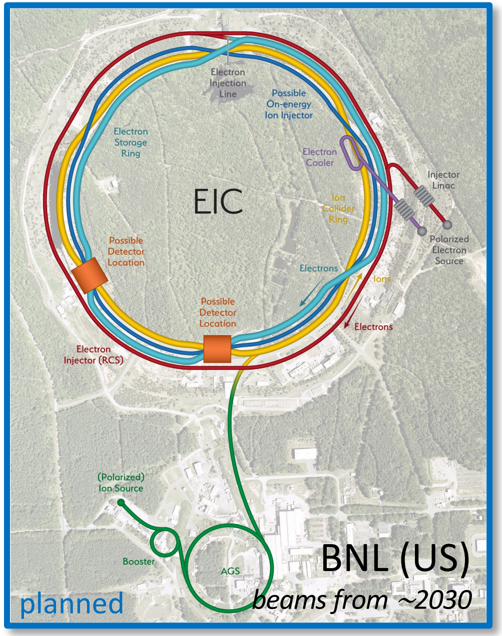
SuperKEKB (Japan)



running

Large European participation in the Belle II experiment

electron-ion collider



BNL (US)

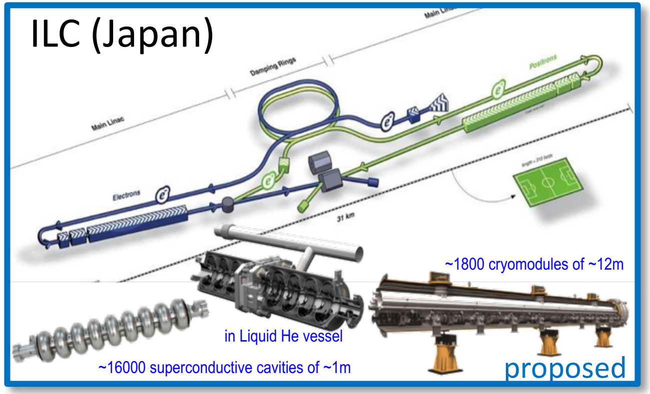
beams from ~2030

planned

Sizeable European fraction in the EIC User Community

e^+e^- Higgs Factory

ILC (Japan)



proposed

ESPP: "The timely realisation of the ILC in Japan would be compatible with [the European ambition for a the FCC programme] and, in that case, the European particle physics community would wish to collaborate."

China has plans for CepC/SPPC similar to FCC

Jaeckel, J., Lamont, M. & Vallée, C. The quest for new physics with the Physics Beyond Colliders programme. *Nat. Phys.* **16**, 393–401 (2020). https://doi.org/10.1038/s41567-020-0838-4

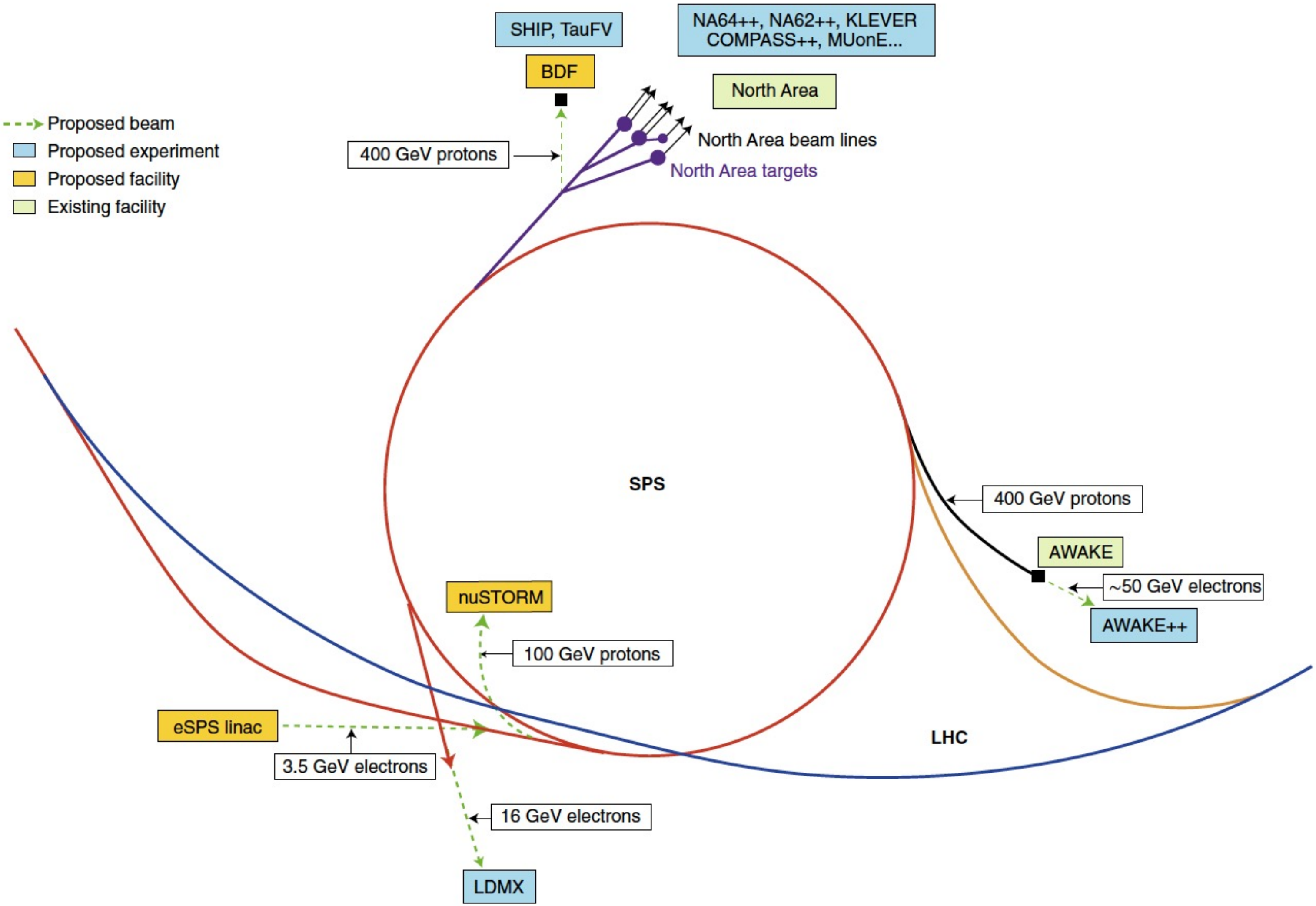


Table 1 | List of projects submitted to the PBC study group

Experiment	Physics case	Status	Time scale
NA61++	Charm in QCD phase transition	Operational/upgrade studies	Near
NA60++	Caloric curve of QCD phase transition	Feasibility study	Medium
DIRAC++	QCD with pionic and kaonic atoms	Feasibility study	Medium
COMPASS++	QCD dynamics	Operational/upgrade studies	Near
MUonE	Hadronic vacuum polarization for $(g-2)_\mu$	Prototype/tests with beam	Near
LHC FT (gas storage cell)	QCD dynamics and phase transition	Installation/further studies	Near
LHC FT (bent crystal)	Magnetic and electric dipole moment of short-lived baryons	Prototype planned/studies	Medium
KLEVER	Ultra-rare decays of neutral kaons	Feasibility studies	Medium
TauFV	Ultra-rare decays of tau leptons	Design study in progress	Long
REDTOP	Ultra-rare decays of eta meson	Proposal	Medium
NA64++	Dark photon searches with electron and/or muon beam dump	Operational/upgrade studies	Near
LDMX	Dark photon searches	Design study in progress	Medium
AWAKE++	Dark photon searches	Exploratory studies	Long
NA62++	Dark sector searches with proton beam dump	Beam dump option studies	Near
SHiP	Dark sector, study of tau neutrinos	Design study complete	Medium
BabyIAXO/IAXO	Axion search (helioscope)	Conceptual design/ prototyping	Medium
JURA	Axion and axion-like particle searches	Exploratory studies	Long
VMB@CERN	Vacuum magnetic birefringence	Letter of intent/studies	Medium
Facility	**Beam type**	**Status**	**Time scale**
BDF	High intensity 400 GeV protons for SHiP and TauFV	Design study complete	Medium
eSPS	16 GeV electrons	Design study in progress	Medium
nuSTORM	Neutrino beam from a muon storage ring for cross-section measurements	Feasibility study complete	Long
EDM ring	Polarized proton storage ring for EDM measurement	Feasibility study complete	Medium
Gamma Factory	High intensity gamma-ray beam	Design study in progress	Long

The level of maturity (status) and approximate time-line (time scale) for each experiment/facility is indicated as in ref. [1]: near term, before 2025; medium term, 2025–2030; long term, after 2030. See main text for discussion of the individual projects.

Jaeckel, J., Lamont, M. & Vallée, C. The quest for new physics with the Physics Beyond Colliders programme. *Nat. Phys.* **16**, 393–401 (2020). https://doi.org/10.1038/s41567-020-0838-4

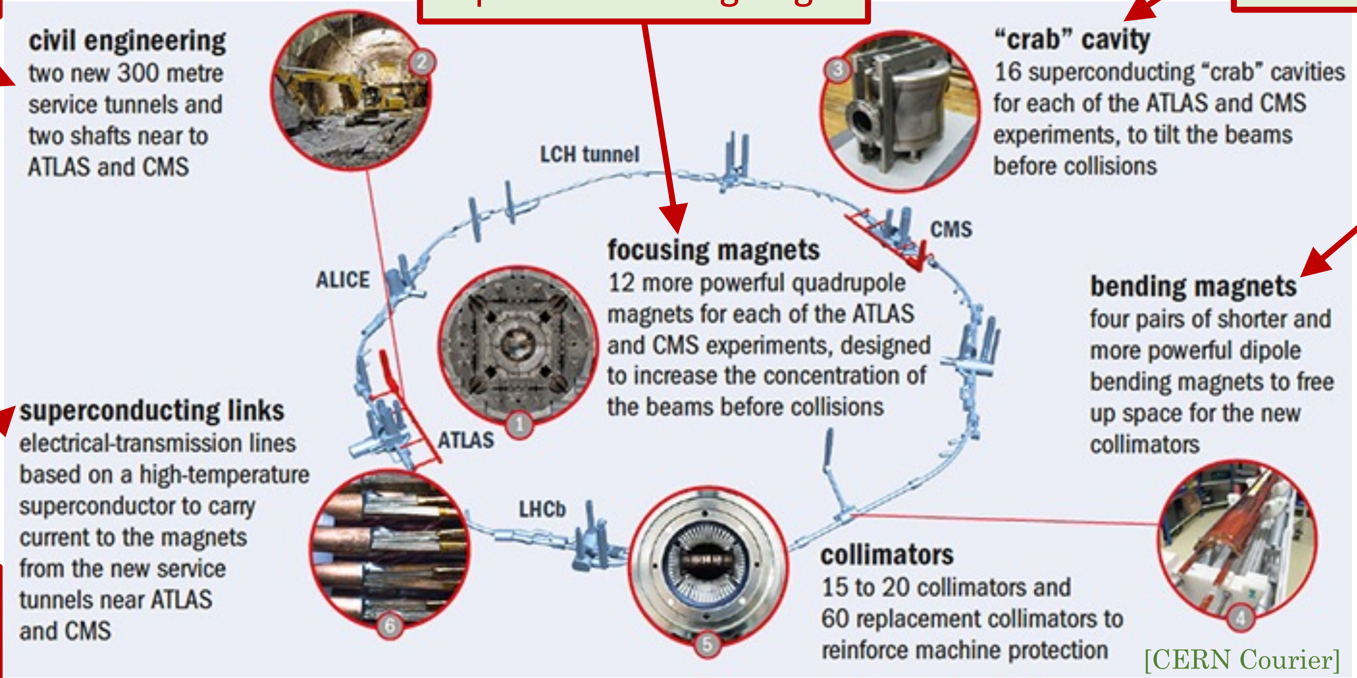
From the LHC to the High-Luminosity LHC @ CERN

excavation mostly done

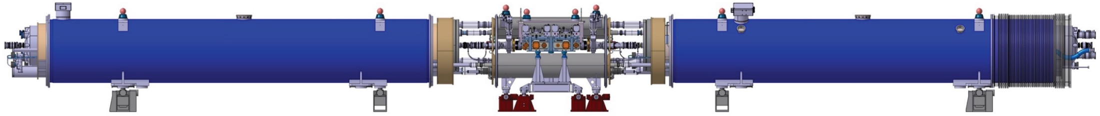
successfully tested (US) production ongoing

successfully tested at SPS (CERN)

ongoing tests on bench, some qualified (CERN)

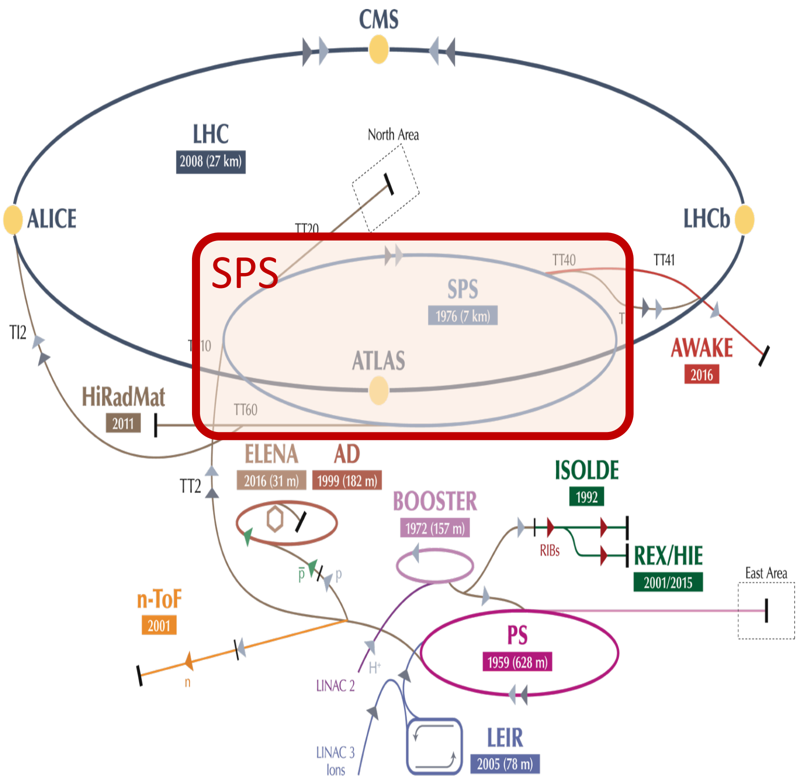


60m system demonstrator successful (CERN)

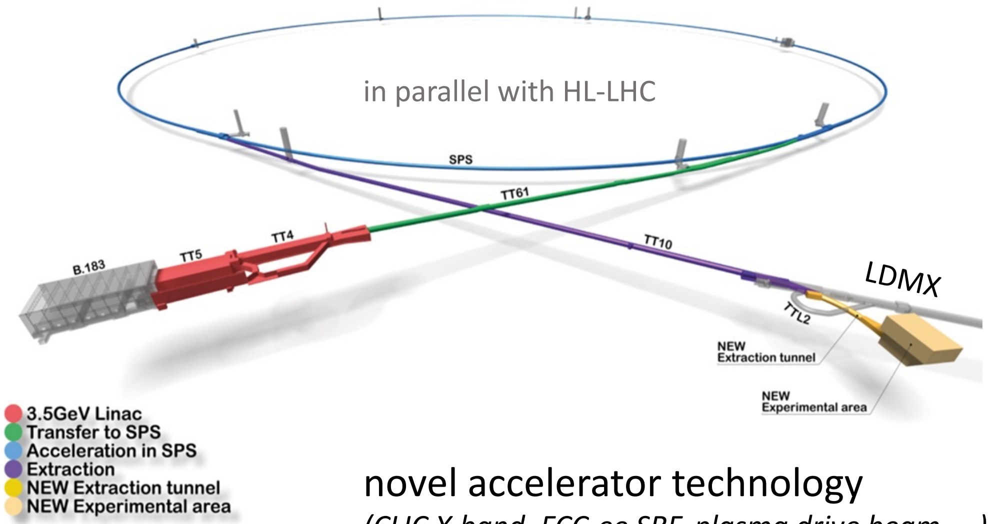


Accelerated Beams (Beyond Colliders) at CERN

The CERN accelerator complex and the LHC – from protons to electrons in the SPS



eSPS accelerator
&
Light Dark Matter eXperiment (LDMX)



novel accelerator technology

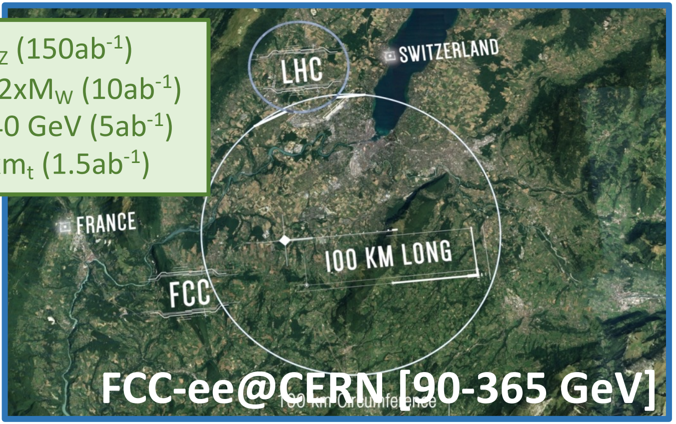
(CLIC X-band, FCC-ee SRF, plasma drive beam, …)

proposal, CDR just submitted

e^+e^- Higgs Factories

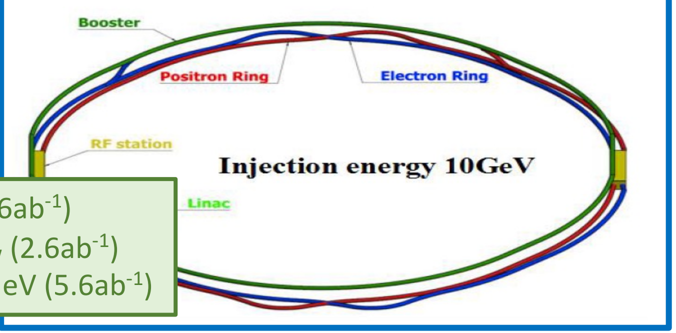
circular colliders

4y @ M_Z ($150ab^{-1}$)
1-2y @ $2xM_W$ ($10ab^{-1}$)
3y @ 240 GeV ($5ab^{-1}$)
5y @ $2xm_t$ ($1.5ab^{-1}$)



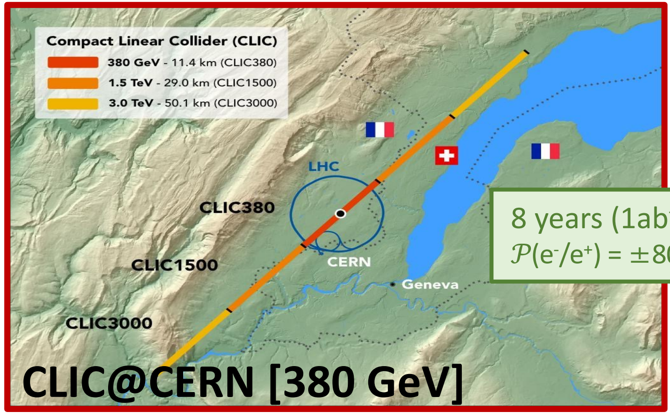
FCC-ee@CERN [90-365 GeV]

CEPC@China [90-240-(350) GeV]



2y @ M_Z ($16ab^{-1}$)
1y @ $2xM_W$ ($2.6ab^{-1}$)
7y @ 240 GeV ($5.6ab^{-1}$)

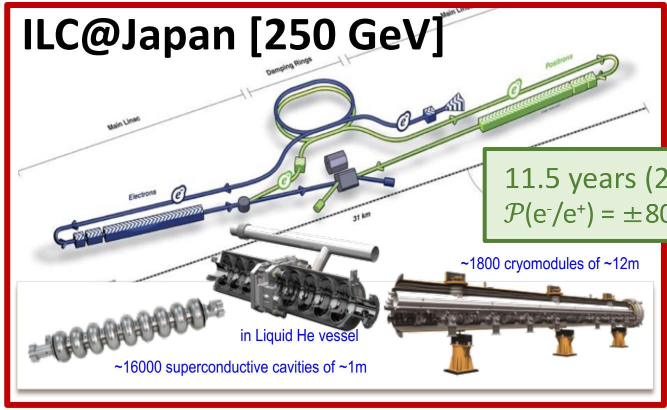
linear colliders



CLIC@CERN [380 GeV]

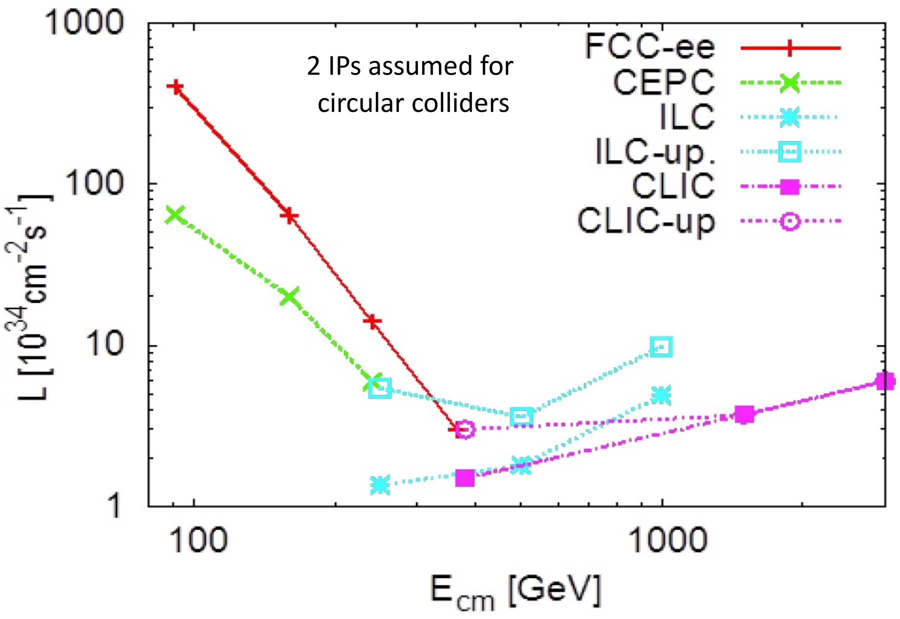
8 years ($1ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/0\%$

ILC@Japan [250 GeV]



11.5 years ($2ab^{-1}$)
$\mathcal{P}(e^-/e^+) = \pm 80\%/\pm 30\%$

e^+e^- Higgs Factories



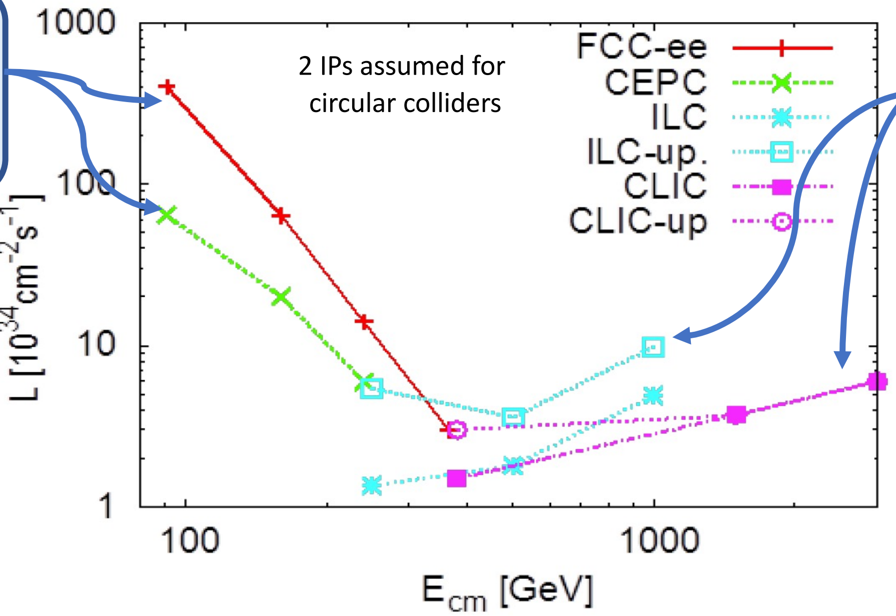
e^+e^- Higgs Factories

precision frontier

circular colliders

linear colliders

energy frontier



synchrotron radiation

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})

e^+e^- Higgs Factories

precision frontier

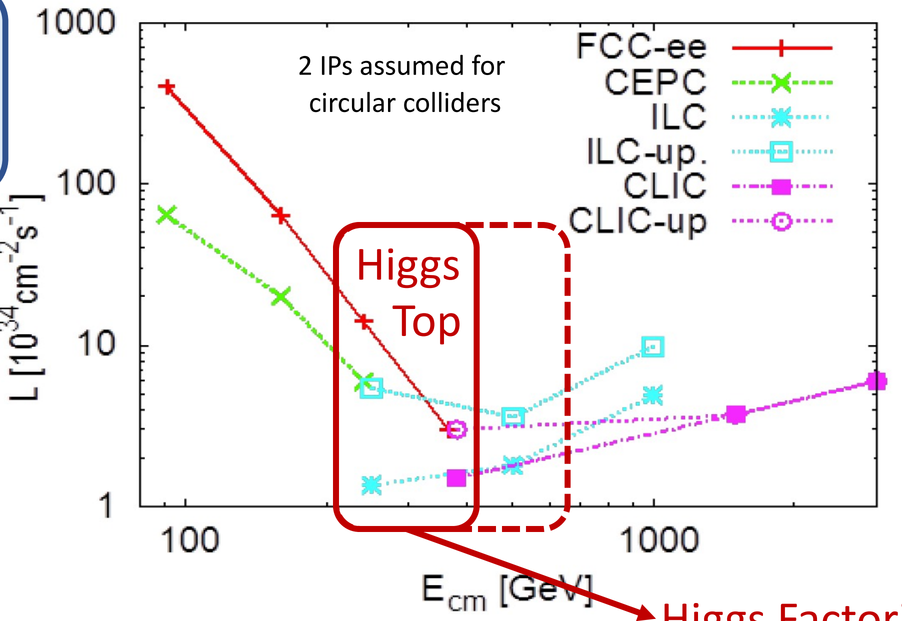
circular colliders

synchrotron radiation

↓

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



linear colliders

energy frontier

Higgs Factories with complementarity

- g_{HZZ} (250GeV) versus g_{HWW} (380GeV)
- top quark physics
- beam polarization for EW precision tests

(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)

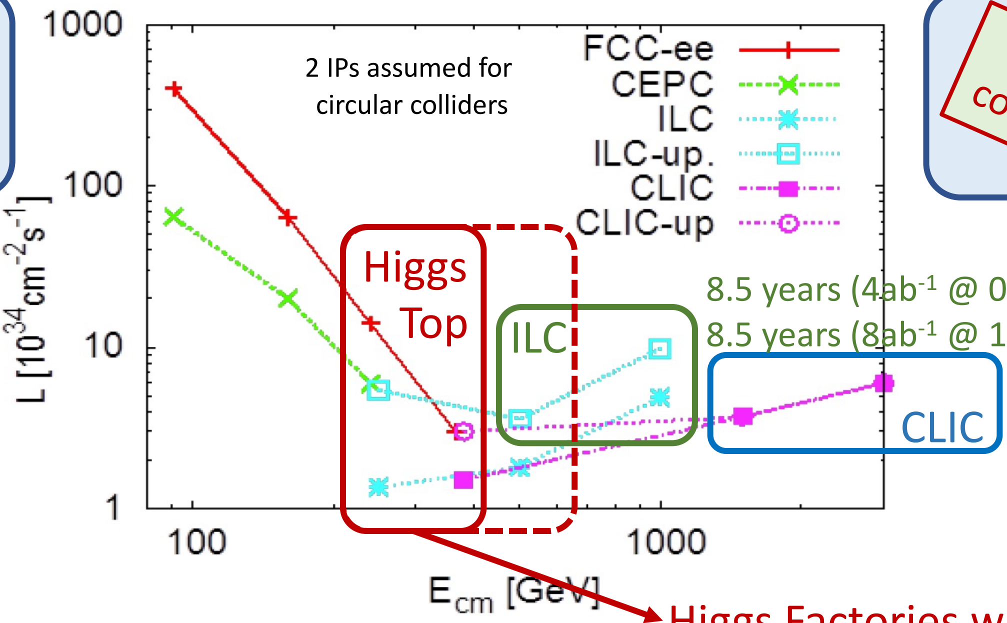
e^+e^- Higgs Factories

precision frontier — circular colliders

synchrotron radiation

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



8.5 years ($4ab^{-1}$ @ 0.5 TeV)

8.5 years ($8ab^{-1}$ @ 1 TeV)

7 years ($2.5ab^{-1}$ @ 1.5 TeV)

8 years ($5ab^{-1}$ @ 3 TeV)

linear colliders — energy frontier

Higgs Factories with complementarity

- g_{HZZ} (250GeV) versus g_{HWW} (380GeV)
- top quark physics
- beam polarization for EW precision tests

(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)

e^+e^- Higgs Factories (incl. B/c/τ/EW/top factories)

precision frontier

circular colliders

linear colliders

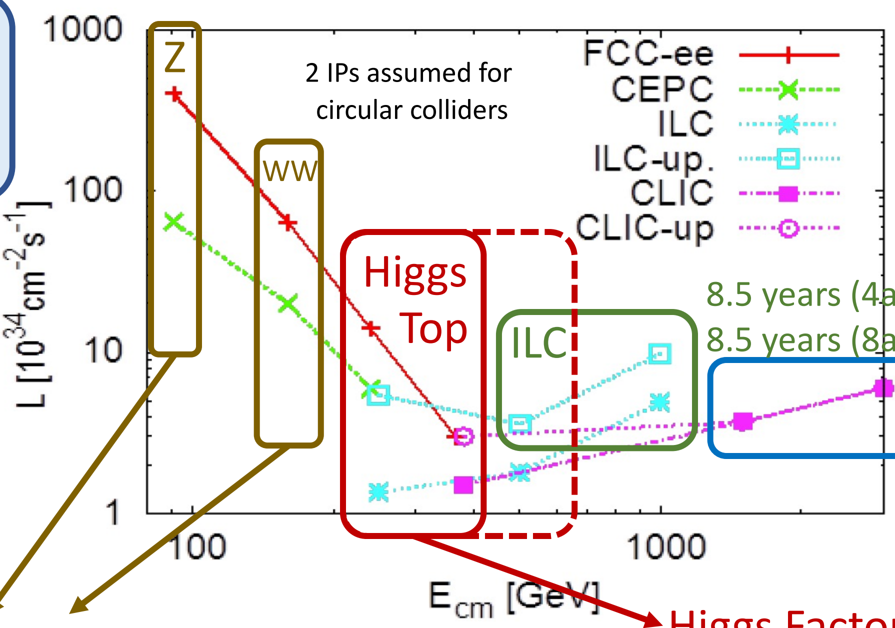
energy frontier

synchrotron radiation

↓

for the same power, less luminosity at higher E_{cm}

(Energy Recovery Linac technology might mitigate this & allow to go to higher E_{cm})



8.5 years ($4ab^{-1}$ @ 0.5 TeV)

8.5 years ($8ab^{-1}$ @ 1 TeV)

7 years ($2.5ab^{-1}$ @ 1.5 TeV)

8 years ($5ab^{-1}$ @ 3 TeV)

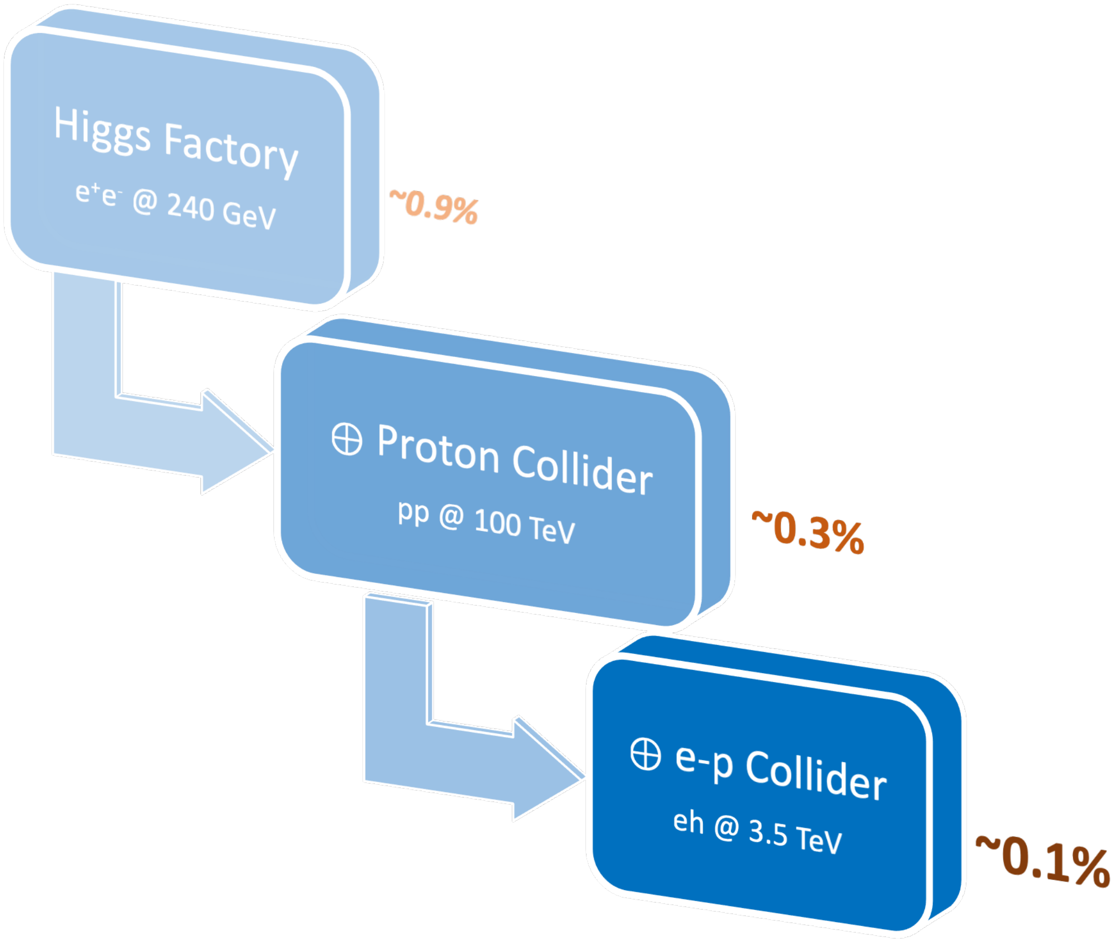
B/c/τ/EW Factories

per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	2 x 10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5 x 10^{12}	7.5 x 10^{11}	2 x 10^{11}	6 x 10^{11}	1.5 x 10^8

Higgs Factories with complementarity

- g_{HZZ} (250GeV) versus g_{HWW} (380GeV)
- top quark physics
- beam polarization for EW precision tests

(transverse polarization in circular e^+e^- colliders only at lower E_{cm} while longitudinal polarization at linear colliders)


Higgs Factory
e+e- @ 240 GeV
~0.9%
⊕ Proton Collider
pp @ 100 TeV
~0.3%
⊕ e-p Collider
eh @ 3.5 TeV
~0.1%

Today's Flagship: from LHC to HL-LHC

Current flagship (27km)

impressive programme up to 2040

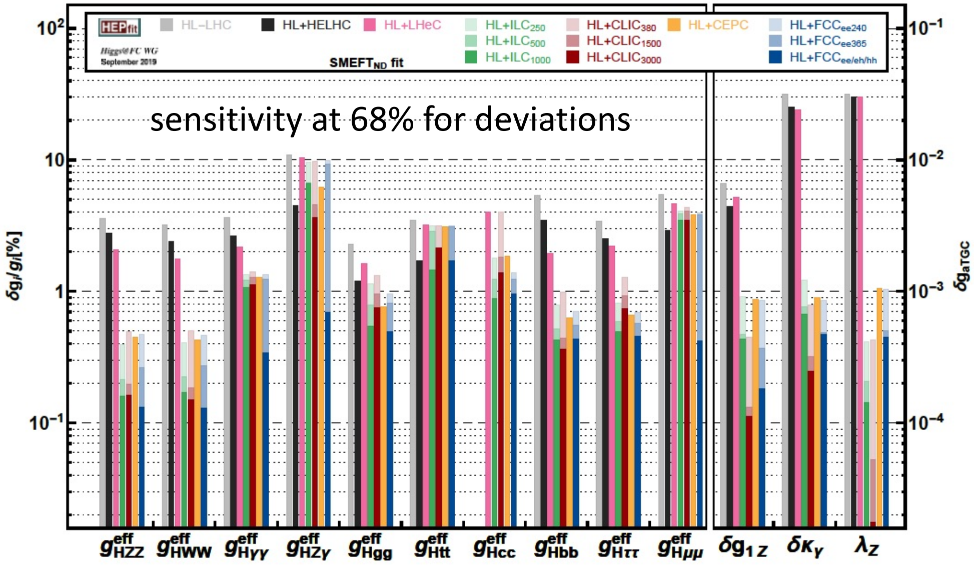
The Higgs couplings are expected to improve significantly with the HL-LHC data

ESPP: "Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a "Higgs factory". The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges."

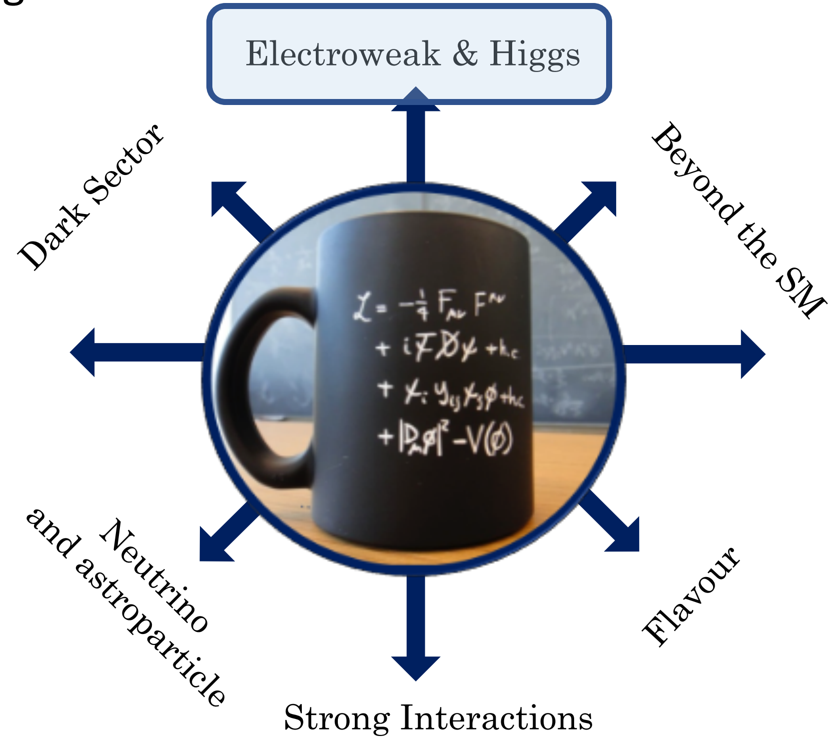
- With only 6 years of experimental and theoretical innovations a factor of 2 improvement, and yet 20 years to go into the research program

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings
(from a global EFT fit – dim-6 SM Effective Field Theory)



Results of the SMEFT fit projected in effective couplings: $g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{SM}}$

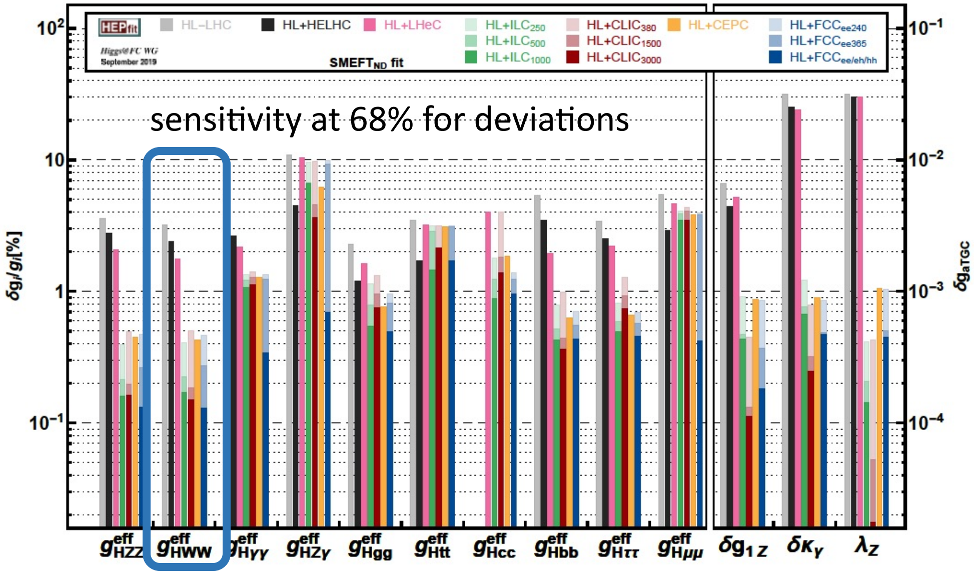


Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

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

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings
(from a global EFT fit – dim-6 SM Effective Field Theory)



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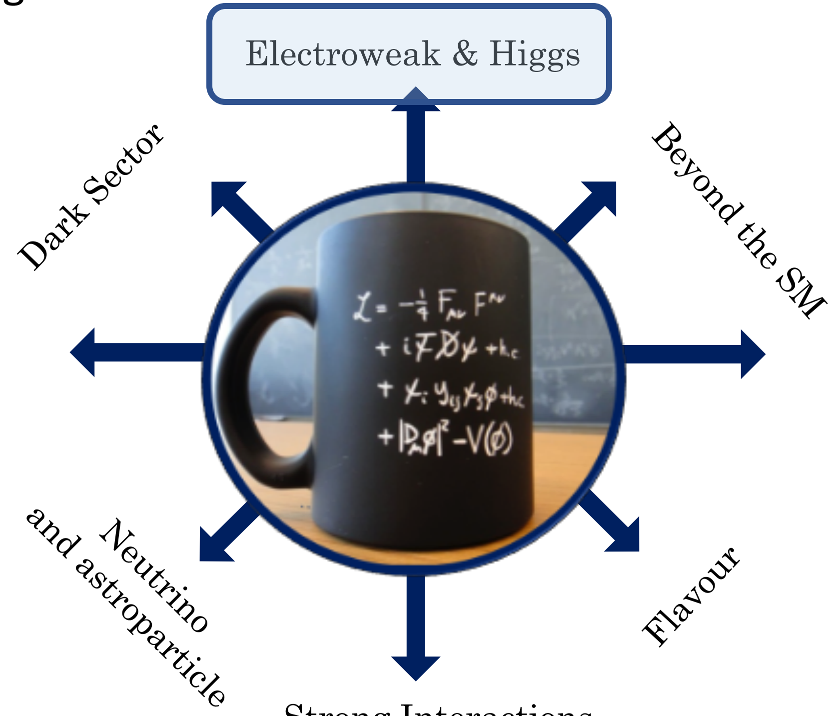
[J. de Blas et al., JHEP 01 (2020) 139]

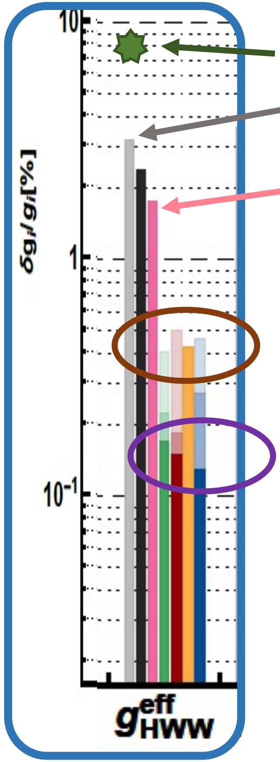


Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings

(from a global EFT fit – dim-6 SM Effective Field Theory)



today

HL-LHC expectation (6000fb^{-1})

HL-LHC ⊕ LHeC expectation

HL-LHC ⊕ e^+e^- Higgs Factories (~250 GeV)

HL-LHC ⊕ e^+e^- Higgs Factories (~250 GeV)
⊕ Energy Frontier
(ILC@1TeV, CLIC@3TeV, FCC-pp@100TeV)

The improvement is in the complementarity!

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

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

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

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

only FCC-ee@240GeV

only FCC-hh

ALL COMBINED

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

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

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

the coupling we looked at on the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+	ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
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ALL COMBINED

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

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

(Higgs coupling strength modifier parameters κ – assuming no BSM particles in Higgs boson decay)

(expected relative precision)

the coupling we looked at on the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
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Γ_H[%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

Zooming into the Higgs sector with colliders

Complementarity between ee/eh/hh colliders – case for the FCC project

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

the coupling we looked at on the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+[illegible]	[illegible]ee/hh	HL+FCC[illegible]	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	[illegible]	[illegible]	0.39	0.14
κ_Z[%]	0.15	0.14	[illegible]	[illegible]	[illegible]	0.63	0.12
κ_g[%]	1.1	0.88	[illegible]	[illegible]	[illegible]	0.74	0.46
κ_γ[%]	1.3	[illegible]	[illegible]	[illegible]	[illegible]	0.56	0.28
$\kappa_{Z\gamma}$[%]	10.	[illegible]	[illegible]	[illegible]	[illegible]	0.89	0.68
κ_c[%]	1.5	[illegible]	[illegible]	[illegible]	[illegible]	—	0.94
κ_t[%]	3.1	[illegible]	[illegible]	[illegible]	[illegible]	0.99	0.95
κ_b[%]	0.94	[illegible]	[illegible]	[illegible]	0.52	0.99	0.41
κ_μ[%]	4.	[illegible]	[illegible]	0.41	0.45	0.68	0.41
κ_τ[%]	0.9	[illegible]	0.39	0.49	0.63	0.9	0.42
Γ_H[%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

complementarity between
e$^+$e$^-$ Higgs Factories
and
high-energy proton colliders

adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

Zooming into the Higgs sector with colliders

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{\mathrm{eff}}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{\mathrm{eff}}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{\mathrm{eff}}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{\mathrm{eff}}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta \kappa_{\gamma}[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

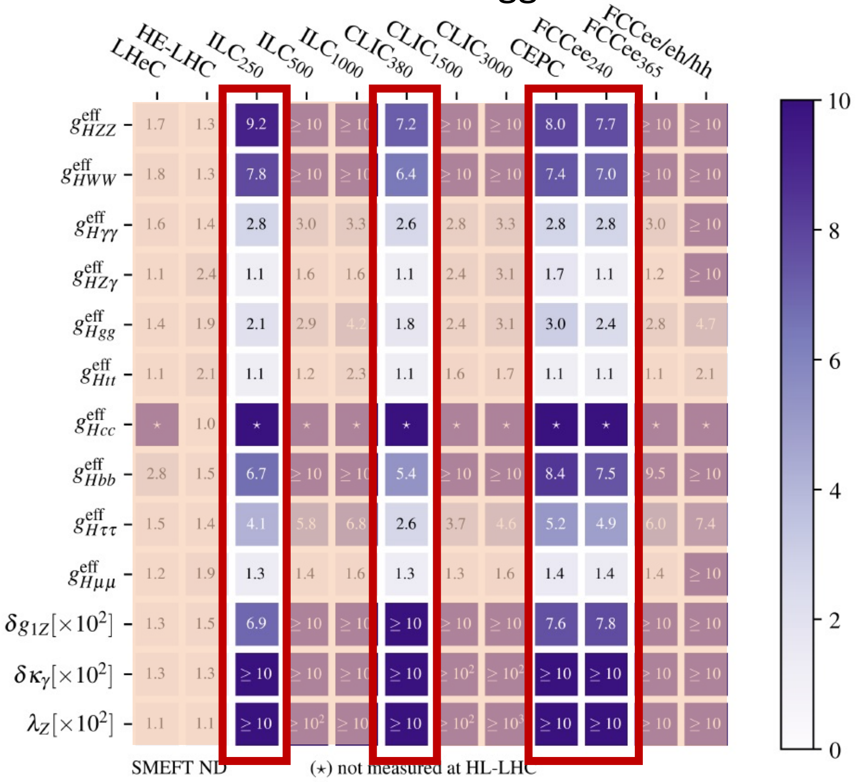
SMEFT ND (⋆) not measured at HL-LHC

improvement factor adding
CEPC results additional to HL-LHC results

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

Zooming into the Higgs sector with colliders

Comparable improvement from HL-LHC to e^+e^- Higgs Factories

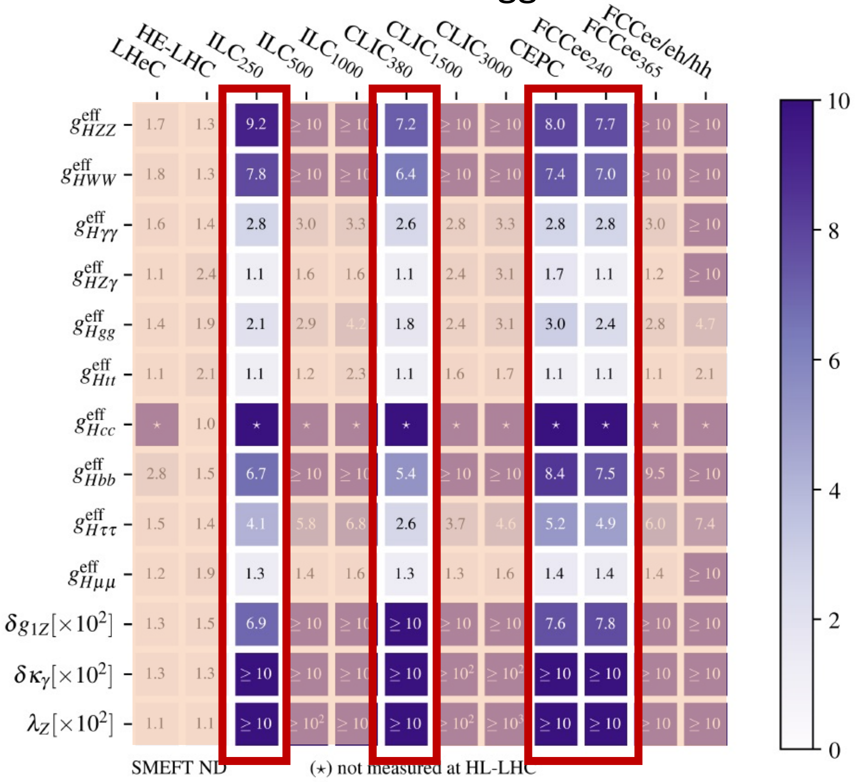


[J. de Blas et al., JHEP 01 (2020) 139]

Zooming into the Higgs sector with colliders

the coupling we looked at on the previous slides

Comparable improvement from HL-LHC to e^+e^- Higgs Factories



Results from a global EFT fit for FCC-hh with any of the four e^+e^- Higgs Factories proposed

$SMEFT_{ND}$	HL+ILC$_{250}$+FCC-hh	HL+CLIC$_{380}$+FCC-hh	HL+CEPC+FCC-hh	HL+FCC-ee$_{365}$+hh
$g^{eff}_{HZZ}[\%]$	0.35	0.46	0.38	0.21
$g^{eff}_{HWW}[\%]$	0.36	0.46	0.36	0.21
$g^{eff}_{H\gamma\gamma}[\%]$	0.47	0.55	0.48	0.38
$g^{eff}_{HZ\gamma}[\%]$	0.78	0.83	0.76	0.72
$g^{eff}_{Hgg}[\%]$	0.73	0.88	0.54	0.56
$g_{Htt}[\%]$	3.1	2.2	3.1	1.7
$g_{Hcc}[\%]$	1.8	3.9	1.8	1.2
$g_{Hbb}[\%]$	0.75	0.95	0.58	0.51
$g_{H\tau\tau}[\%]$	0.78	1.2	0.61	0.54
$g_{H\mu\mu}[\%]$	0.54	0.61	0.53	0.46
$\delta g_{1Z}[\times 10^2]$	0.078	0.04	0.08	0.028
$\delta\kappa_\gamma[\times 10^2]$	0.12	0.079	0.089	0.048
$\lambda_Z[\times 10^2]$	0.042	0.043	0.1	0.047

Differences at e^+e^- colliders:

model independent total width Γ_H measured at circular (1.1%@FCC-ee) and linear (2.2%@ILC250)

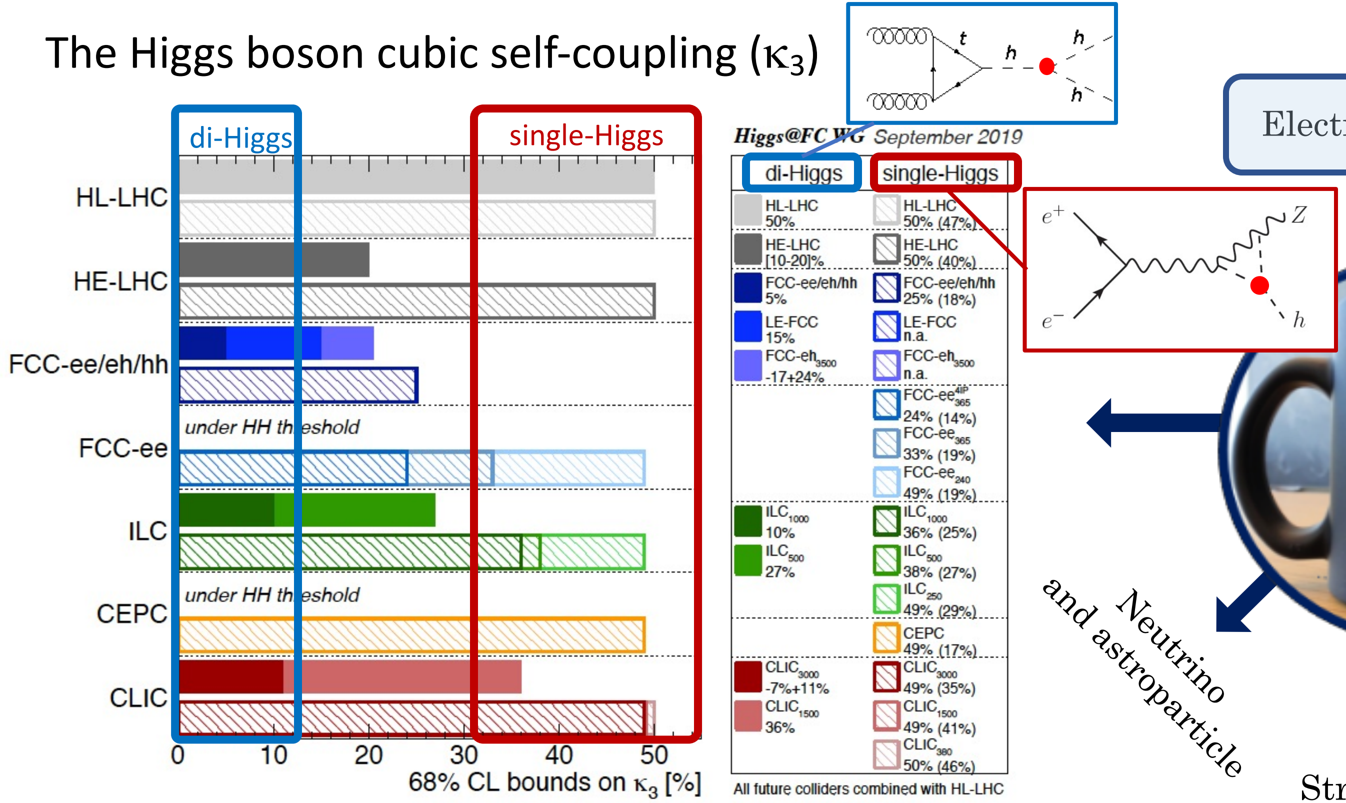
the combination of 250 GeV and >250 GeV e^+e^- data is relevant

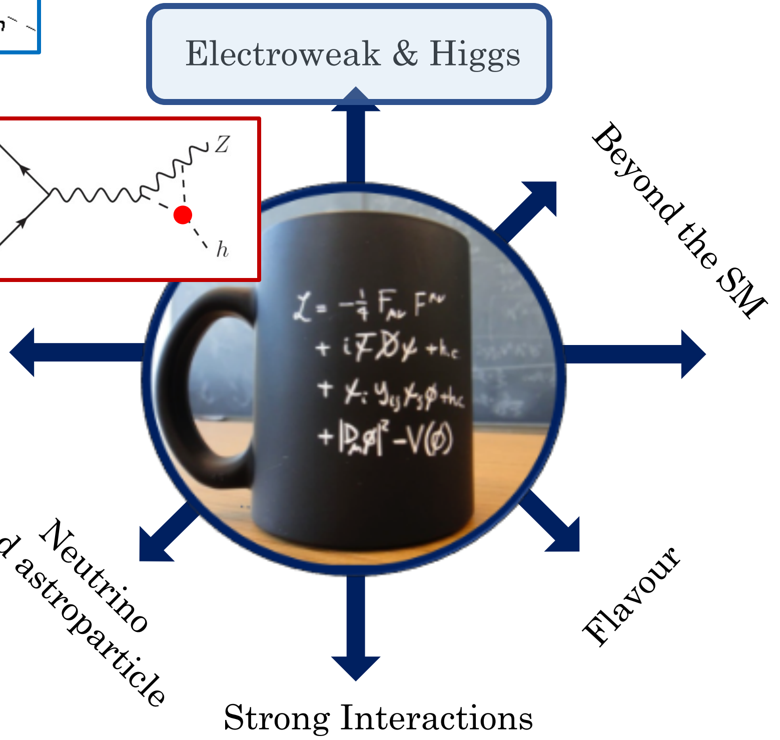
ILC @ 250+500 GeV would reach 1.1%

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

Zooming into the Higgs sector with colliders

The Higgs boson cubic self-coupling (κ_3)



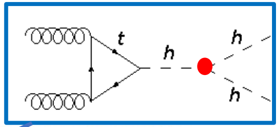


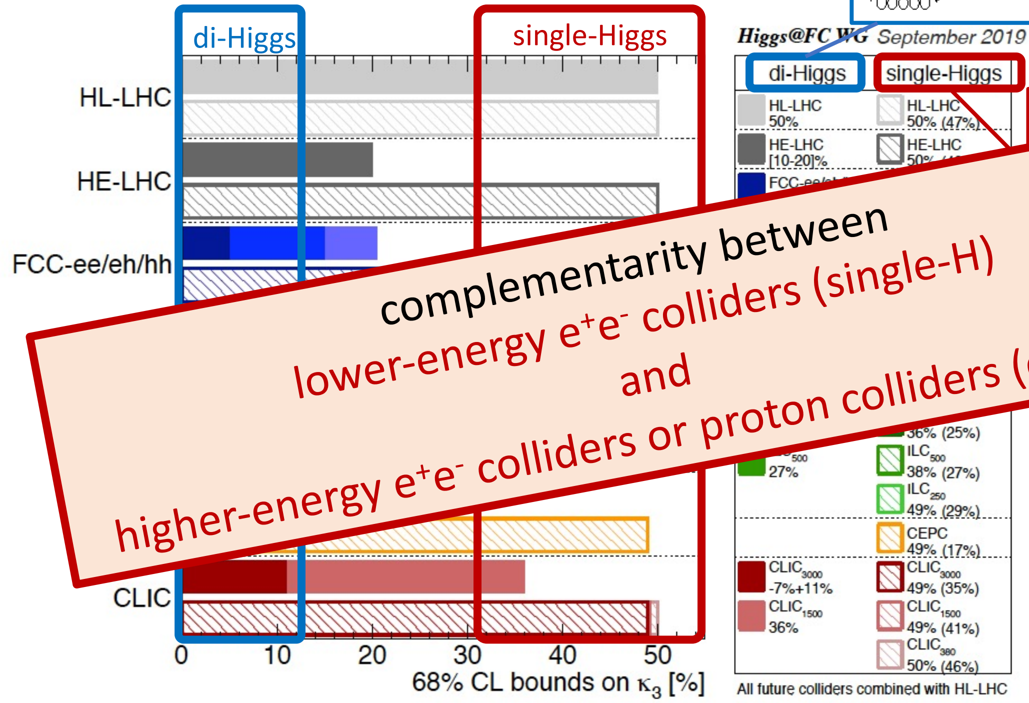
[J. de Blas et al., JHEP 01 (2020) 139]

Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

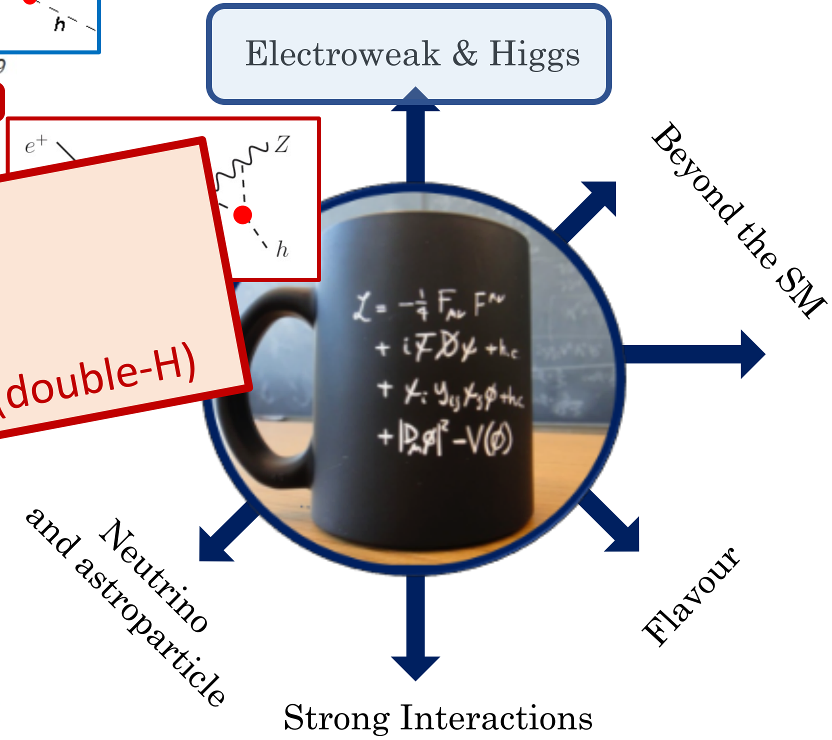
Zooming into the Higgs sector with colliders

The Higgs boson cubic self-coupling (κ_3)





complementarity between
lower-energy e^+e^- colliders (single-H)
and
higher-energy e^+e^- colliders or proton colliders (double-H)



Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

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

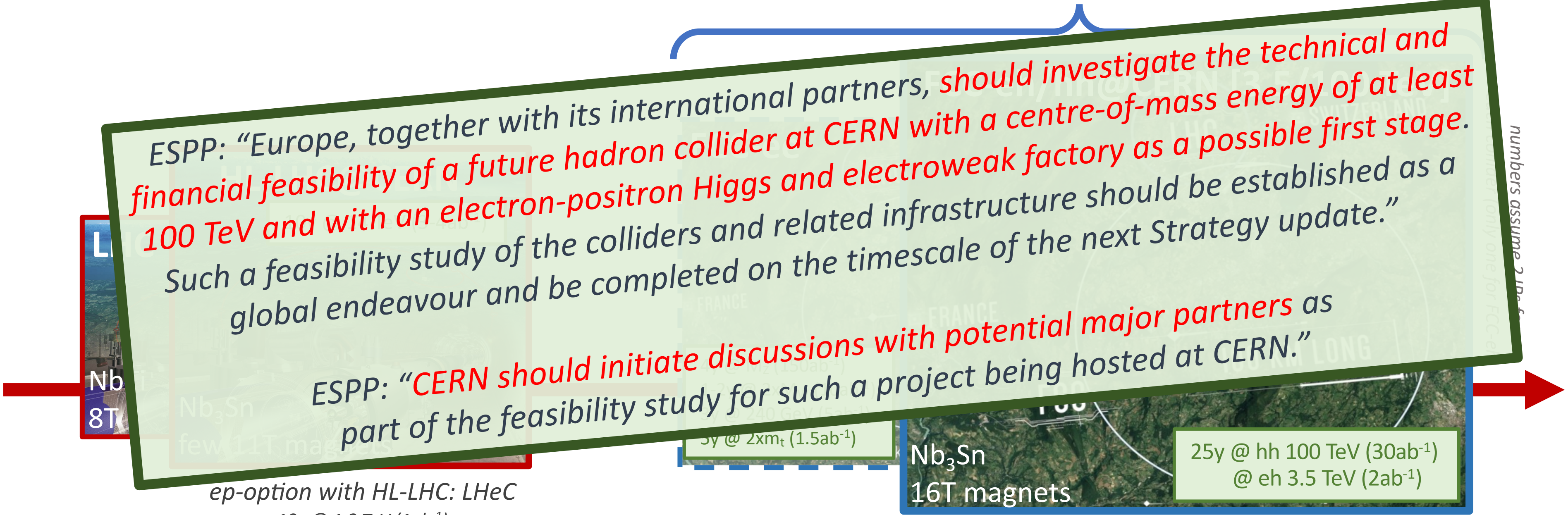
Colliders in Europe at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

Big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



ESPP: "Europe, together with its international partners, *should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.* Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

ESPP: "*CERN should initiate discussions with potential major partners* as part of the feasibility study for such a project being hosted at CERN."

ep-option with HL-LHC: LHeC

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

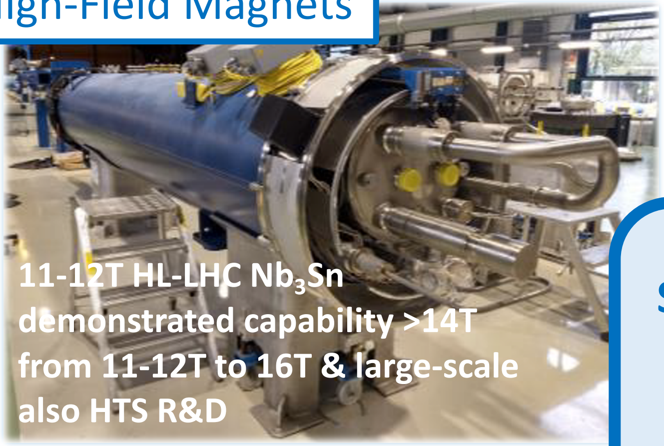
updated CDR 2007.14491

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

potential alternatives pursued @ CERN: CLIC & muon collider

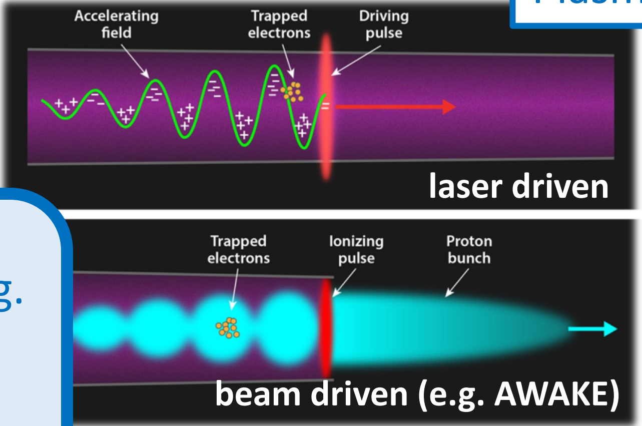
Advancing Accelerator Technologies

High-Field Magnets

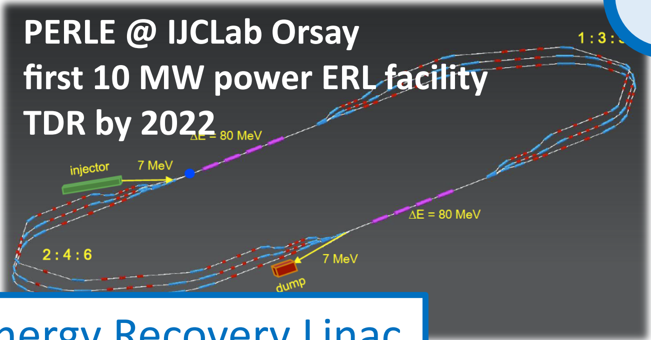


continue the development of CLIC accelerator technology and other high-gradient accelerating structures

Plasma

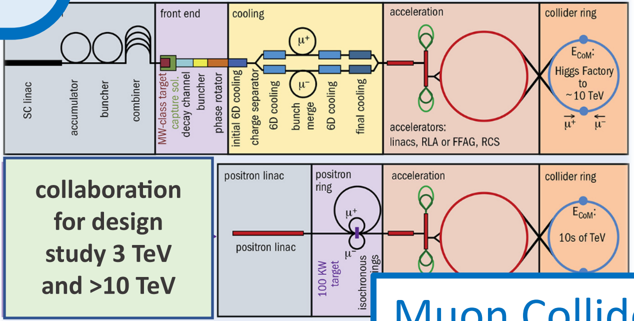


Strong EU support, e.g.
EuPRAXIA, EuroCircol, FCC IS, ARIES, EuCARD, EASITrain, E-JADE, …



Energy Recovery Linac

Accelerator and Detector R&D Roadmaps will be developed (2021)

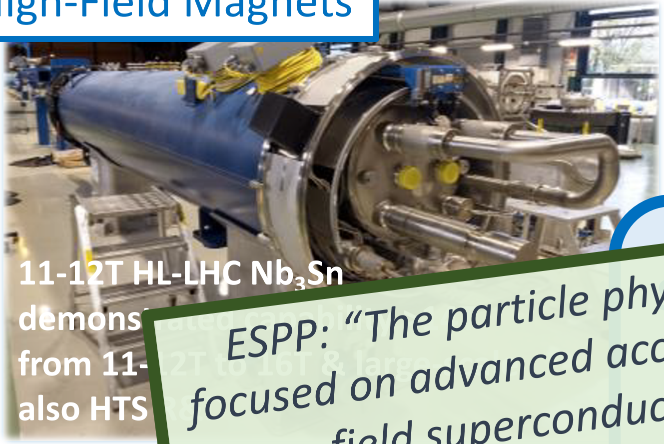


collaboration for design study 3 TeV and >10 TeV

Muon Collider

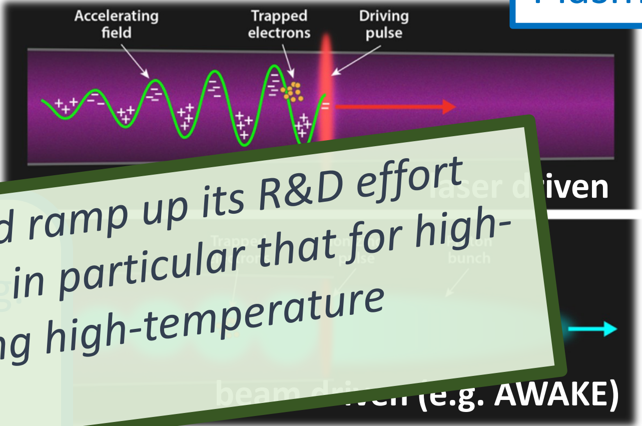
Advancing Accelerator Technologies

High-Field Magnets



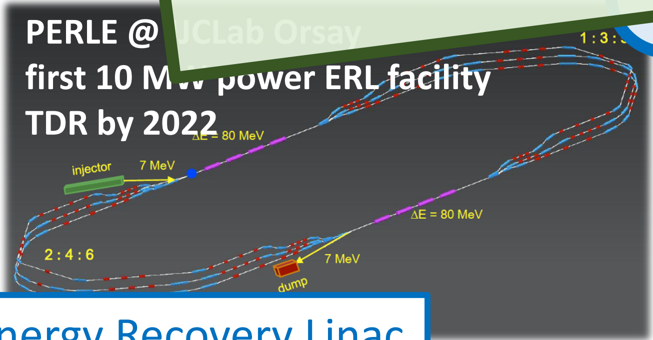
continue the development of CLIC accelerator technology and other high-gradient accelerating structures

Plasma



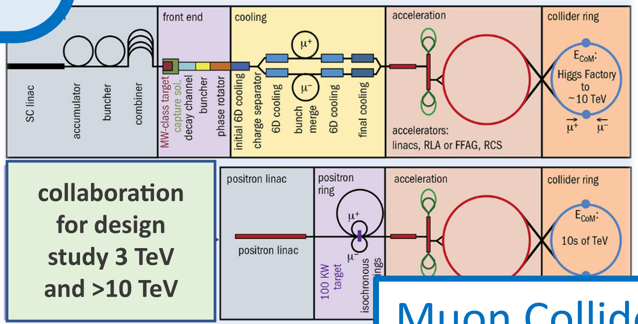
ESPP: "The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors ."

Energy Recovery Linac



Accelerator and Detector R&D Roadmaps will be developed (2021)

Muon Collider

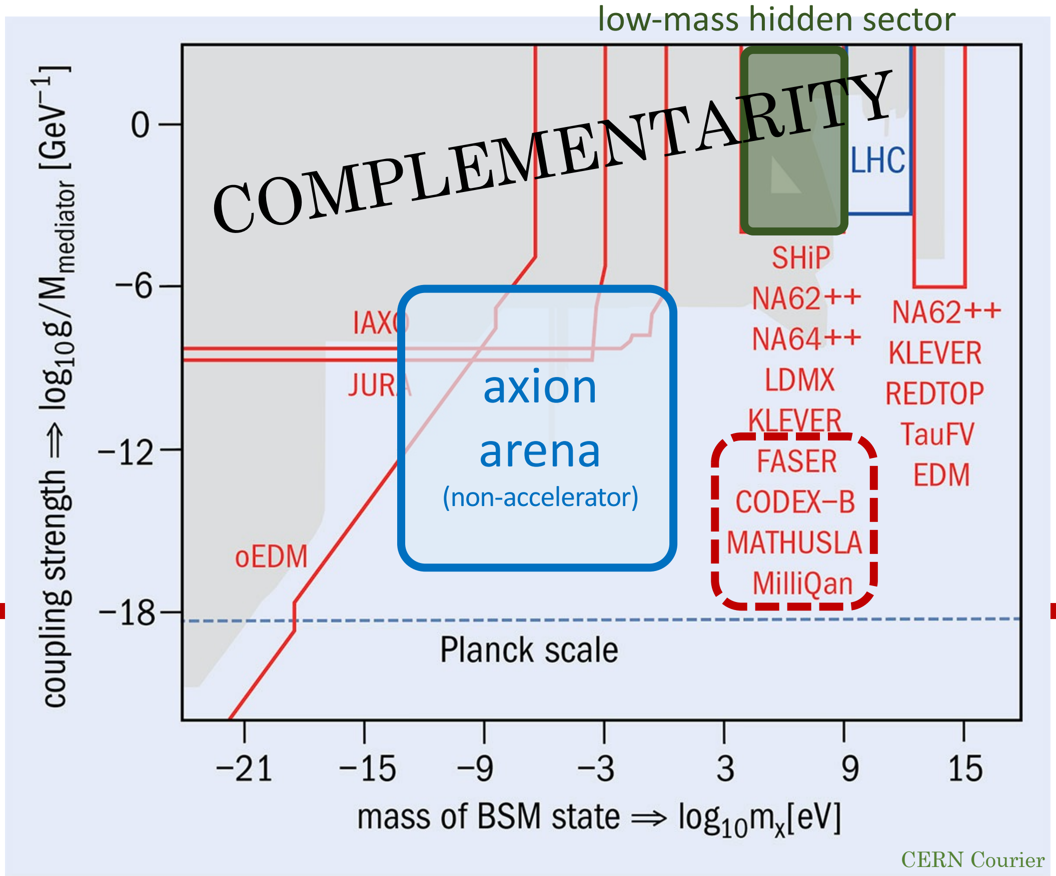


collaboration for design study 3 TeV and >10 TeV

Colliders in Europe at the energy & precision frontier

Current flagship (27km)

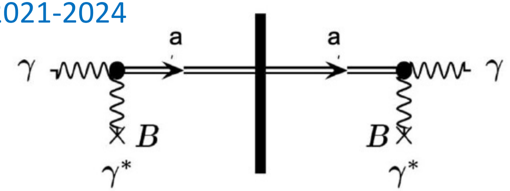
impressive programme up to 2040



“portal” representation of physics potential to demonstrate complementarity

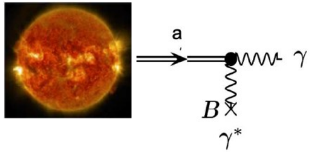
Axion Physics with “old” and new magnets in Europe

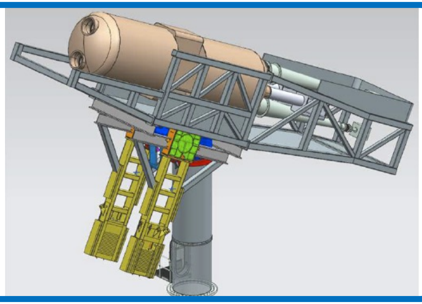
Light-shine-through-Wall
ALPS-II @ DESY
2021-2024



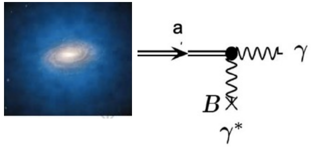
CAST @ CERN
(helioscope)
running

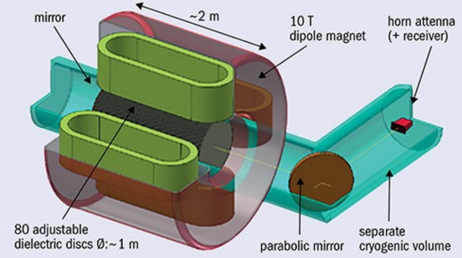
BabyIAXO & IAXO @ DESY
looking at the Sun, helioscope
2024-2030+

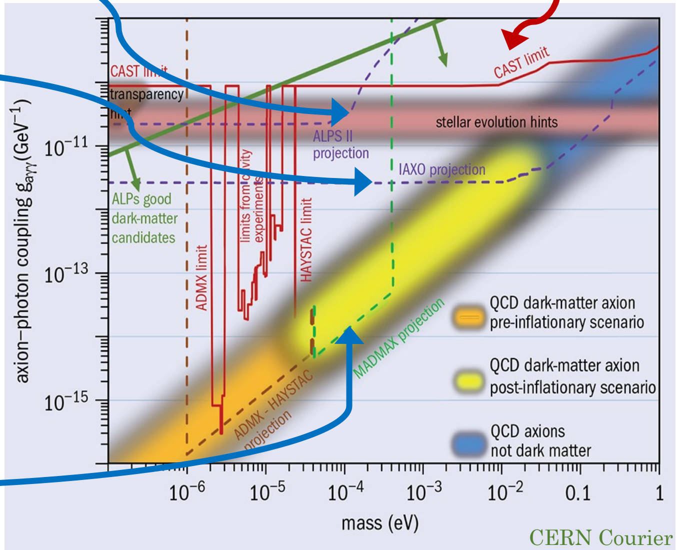




MADMAX @ DESY
looking at the galactic halo, haloscope
2026-2030+

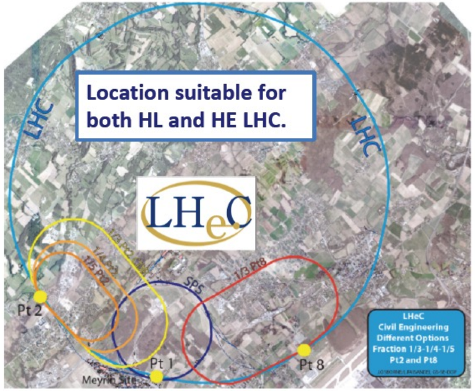






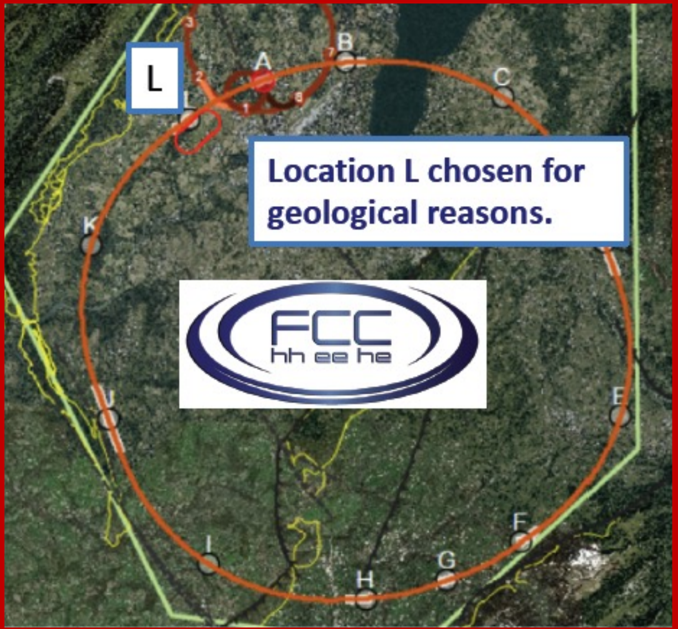
High energy ep collisions – from LHeC to FCC-eh

together with HL-LHC



Smaller PERLE demonstrator for high power ERL at Orsay with maximal beam energy of 0.5 GeV operation within the decade.

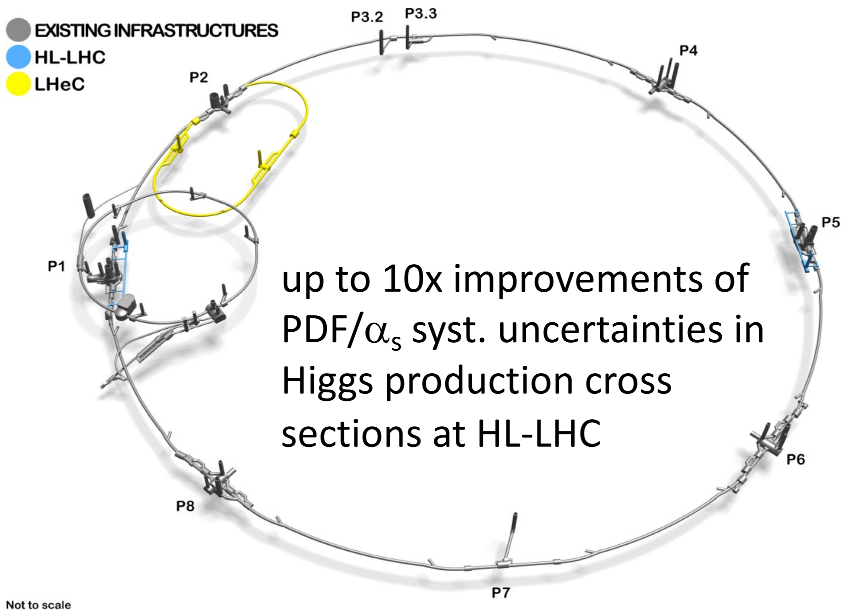
together with FCC-hh



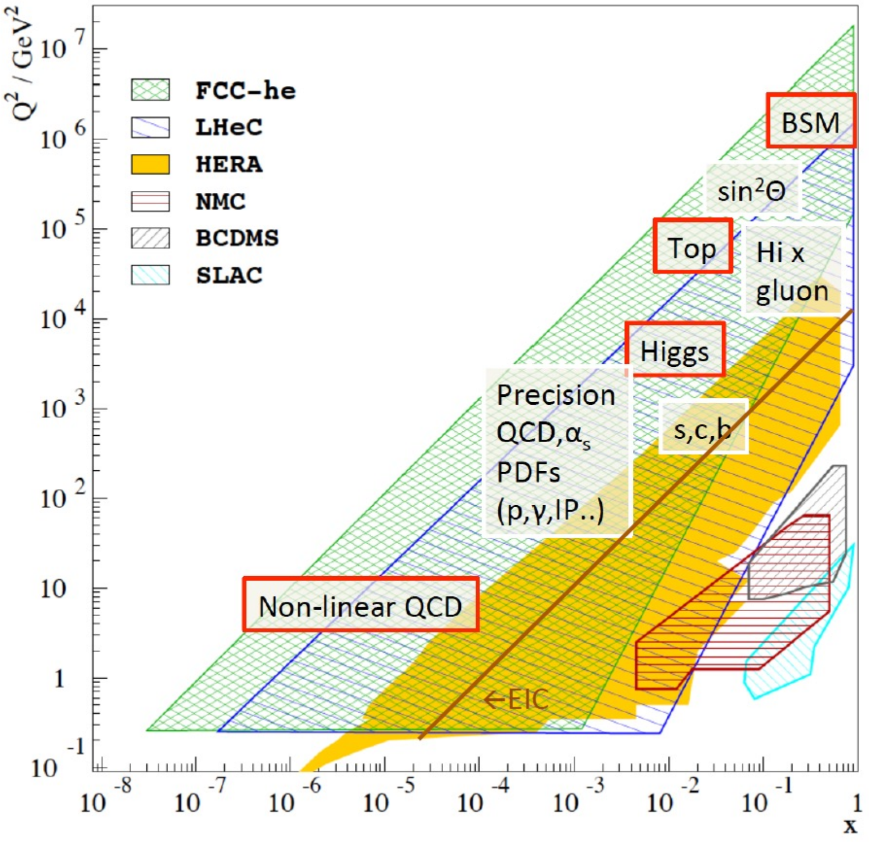
E

Empowering the HL-LHC program with the LHeC

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



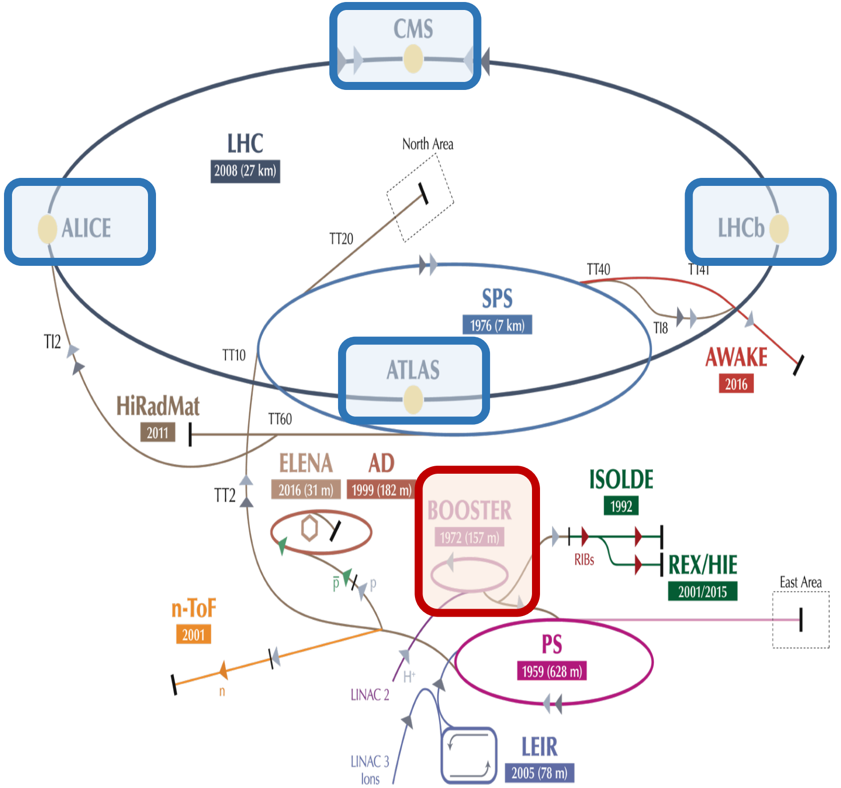
up to 10x improvements of PDF/α_s syst. uncertainties in Higgs production cross sections at HL-LHC

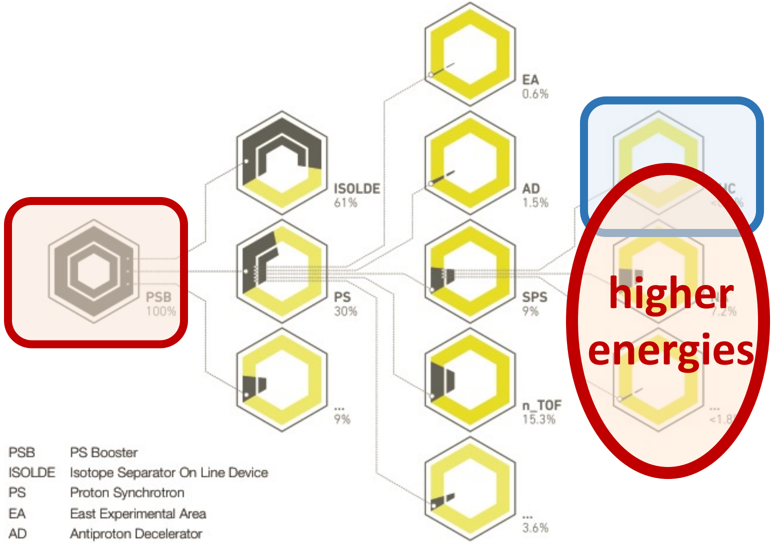


[updated CDR submitted: https://arxiv.org/abs/2007.14491]

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

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





PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

Fascination for what is discovered at the frontiers of knowledge