The Future of DIS

Leading and empowering the search for new physics

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VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

beh

29th International Workshop on Deep-Inelastic Scattering and Related Subjects

DIS2022 – 2-6 May 2022

Where are we in fundamental physics?

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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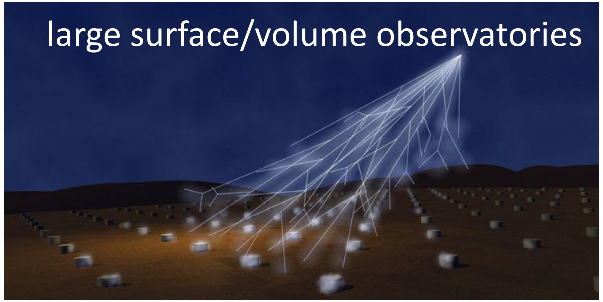
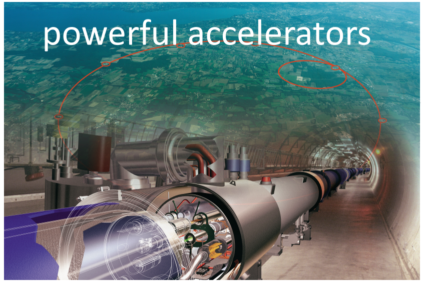


visible with our own eyes



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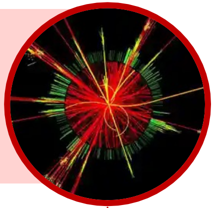
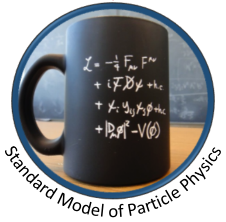
observations how small objects behave in our laboratories





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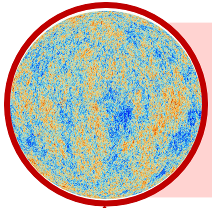
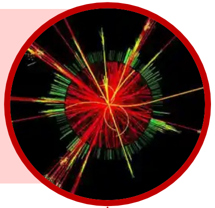


observations how large objects behave in our universe

Standard Model of Cosmology



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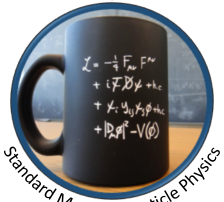


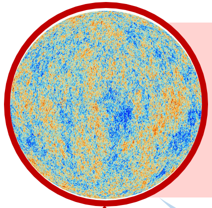
Standard Model of Particle Physics

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

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

~ 0.000˙000˙000˙000˙000˙000˙01 meter

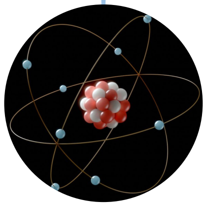
building blocks of life on the human scale



observations how large objects behave in our universe

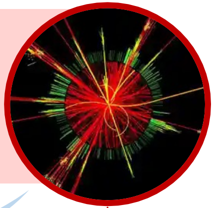
Standard Model of Cosmology

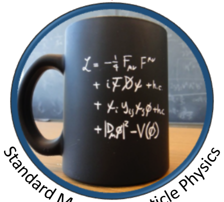
e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





Standard Model of Particle Physics

A century of scientific revolutions

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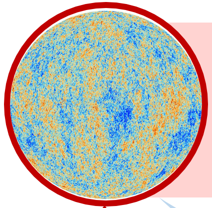

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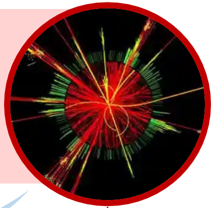

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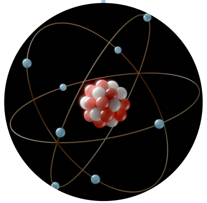
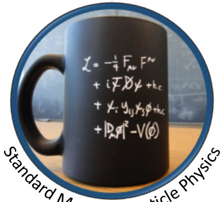


e.g. creation of chemical elements

e.g. nuclei built from quarks and gluons

Standard Model of Cosmology



Standard Model of Particle Physics

communication
satellites
GPS

A century of scientific revolutions

World Wide Web
touchscreens

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

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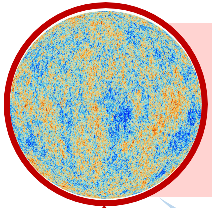
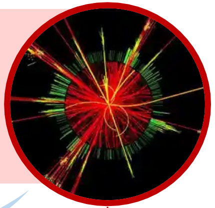
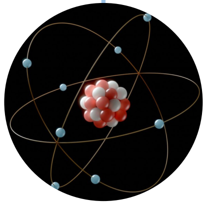


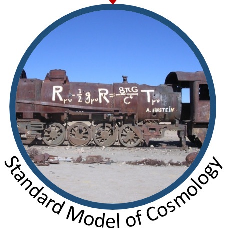
observations how large objects behave in our universe

production of particles and radiation
nuclear diagnosis and medicine

observations how small objects behave in our laboratories







e.g. creation of
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e.g. nuclei built from
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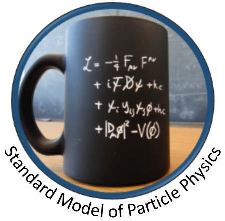
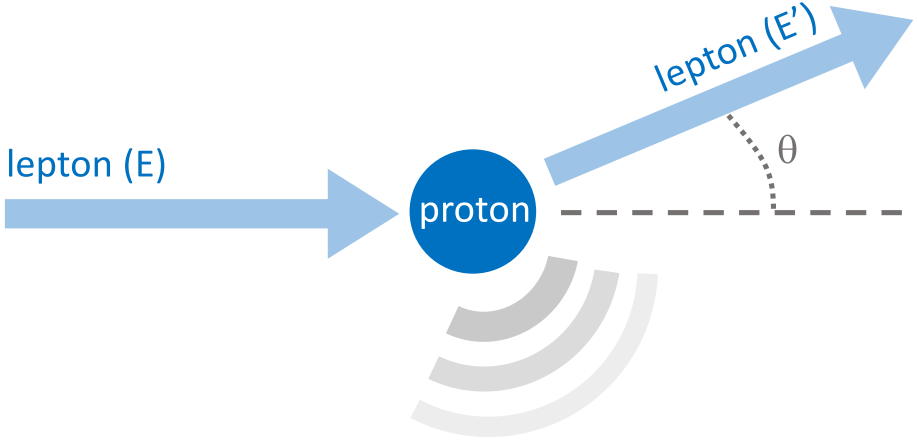
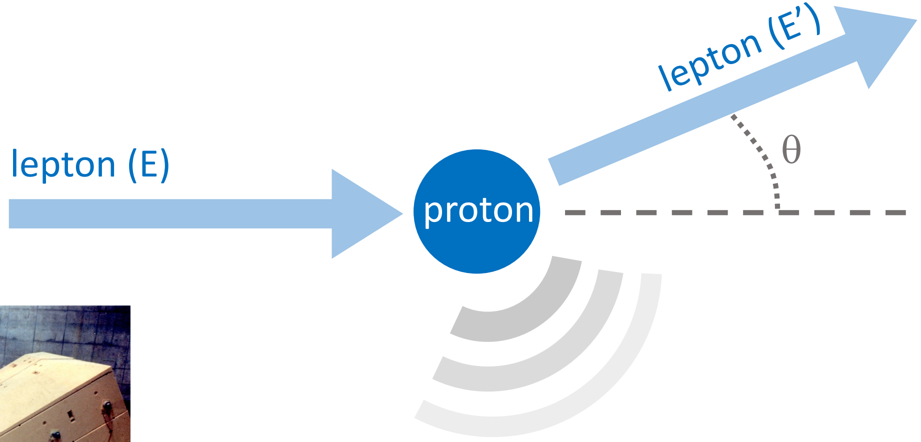


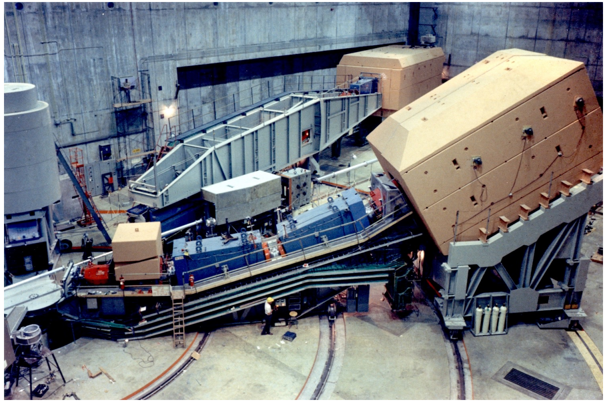
“Scientific curiosity which ends up in your pocket”
Rolf Heuer (previous Director General of CERN)

The 50+ years success story of DIS



The 50+ years success story of DIS





Discovery of quarks

(1968, ep@MIT-SLAC experiment)

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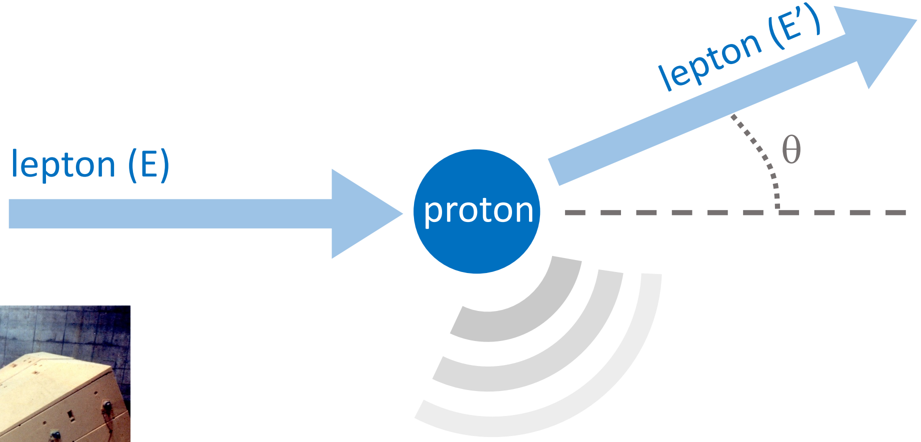

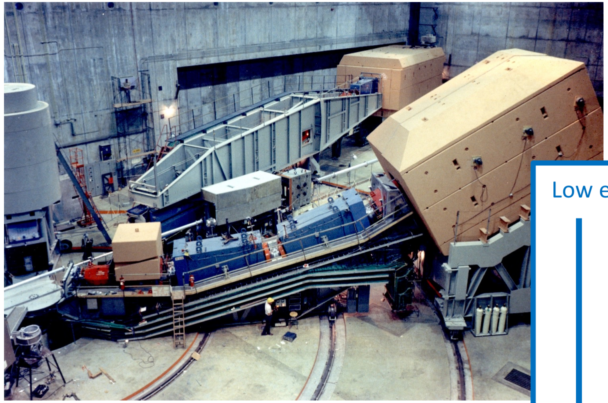

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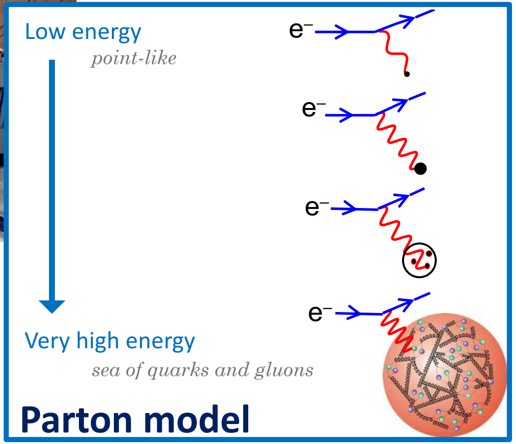

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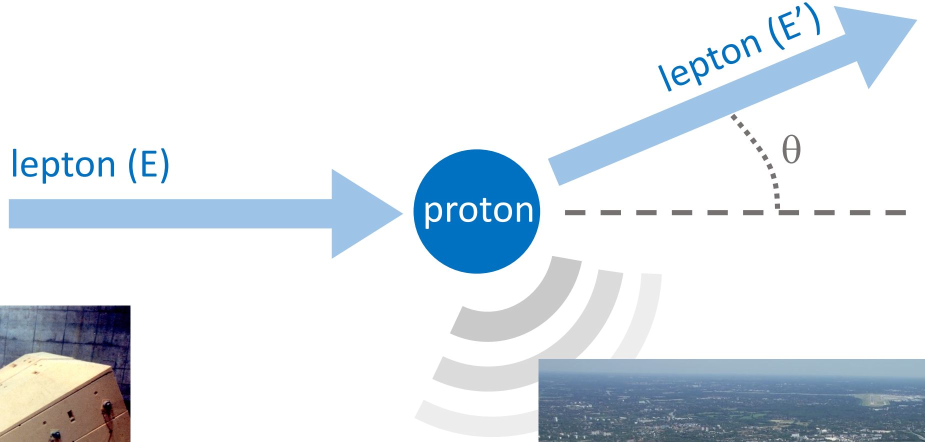

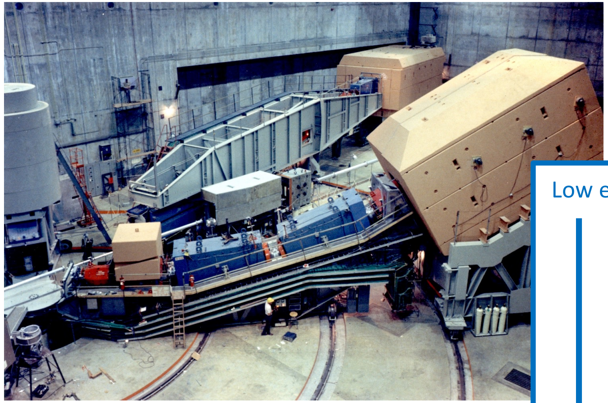

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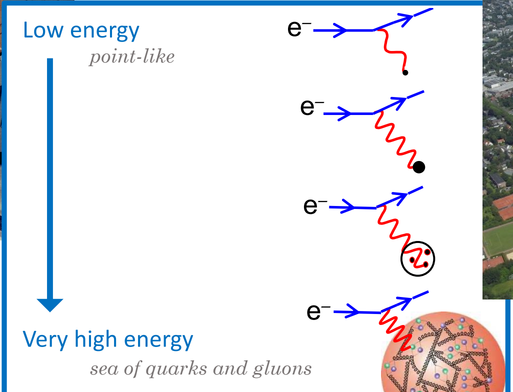
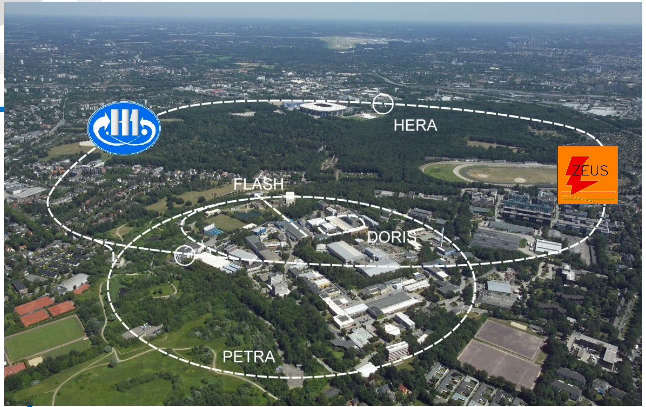


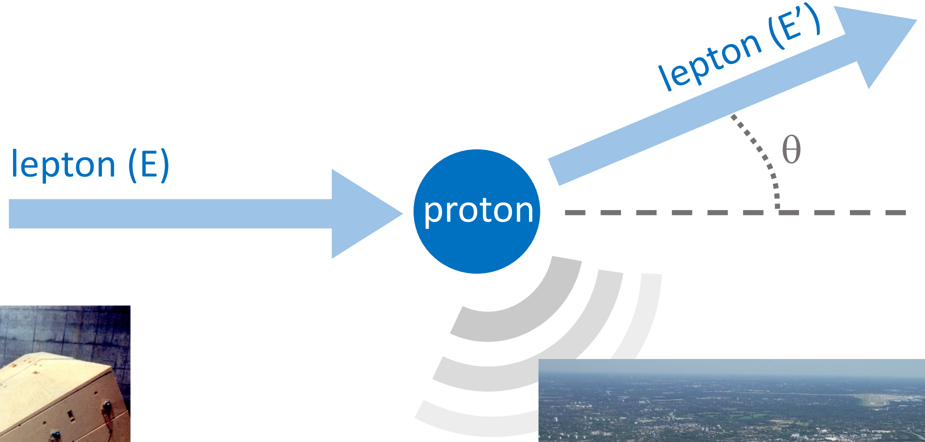
Parton model

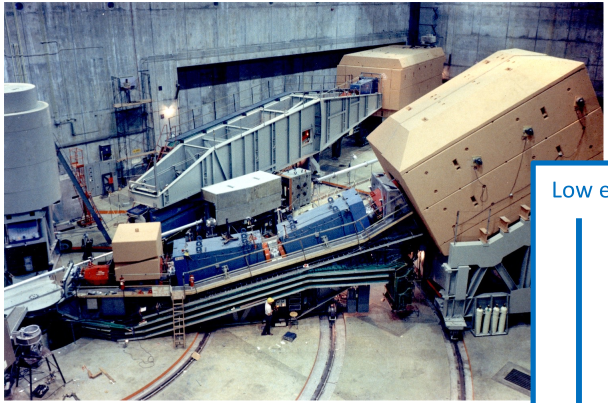


The DIS precision era

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

The 50+ years success story of DIS





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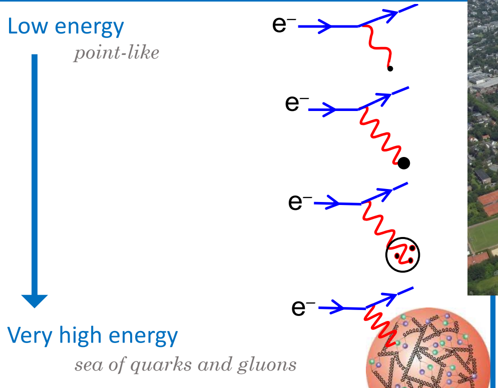

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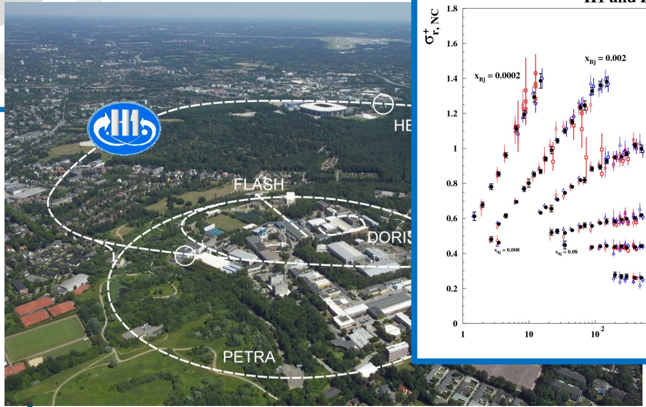

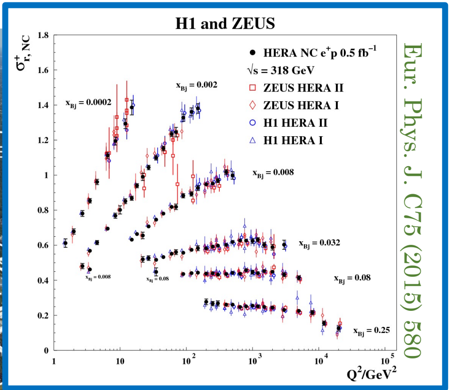

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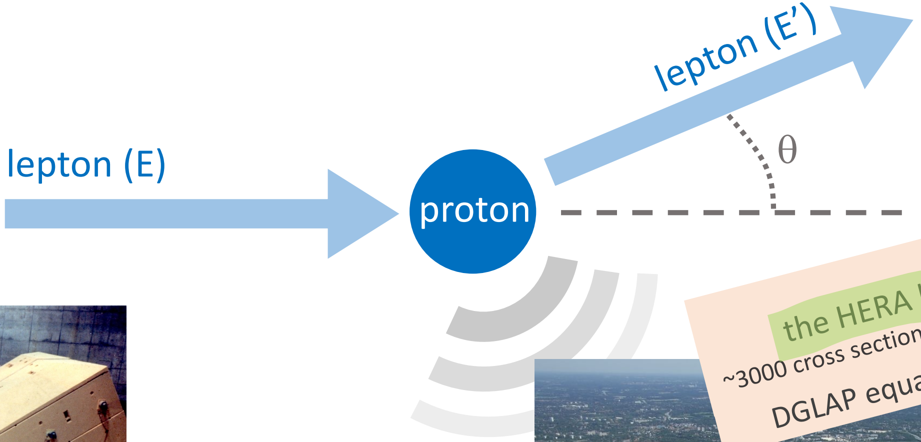
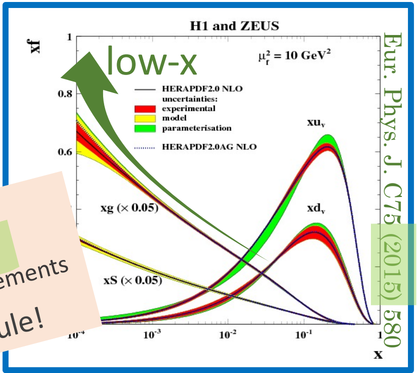
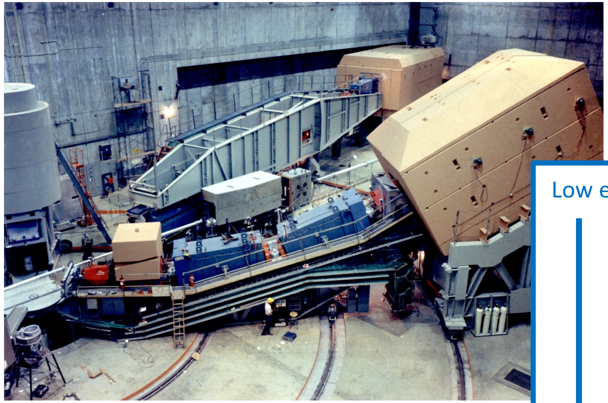


Parton Distribution Functions



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



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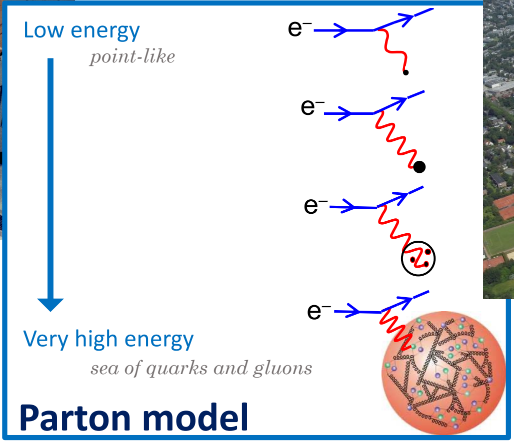
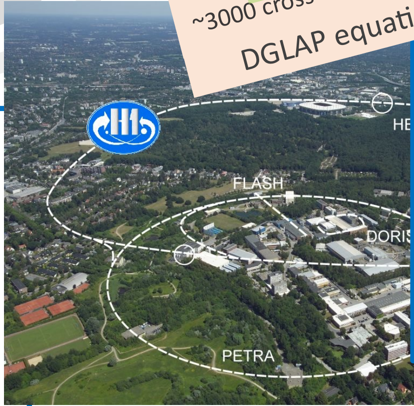
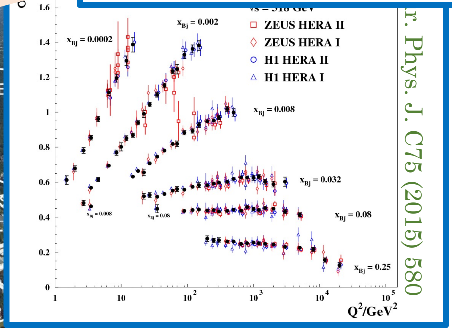






The DIS precision era

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

Precise picture how quarks and gluons built up protons

low energy

high energy

colour confinement

coupling ~1

asymptotic freedom

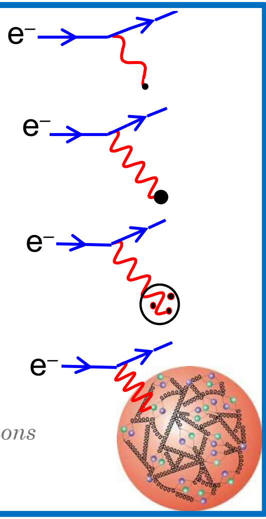
coupling <<1

Low energy

point-like

Very high energy

sea of quarks and gluons



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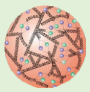


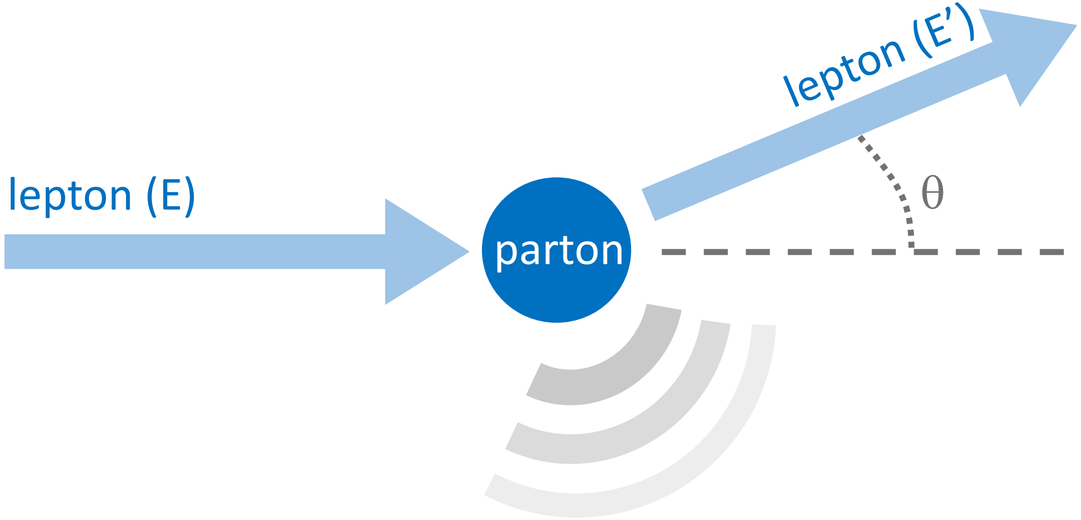
"confined" proton

"deconfined" quarks & gluons

used in experiment (applications)

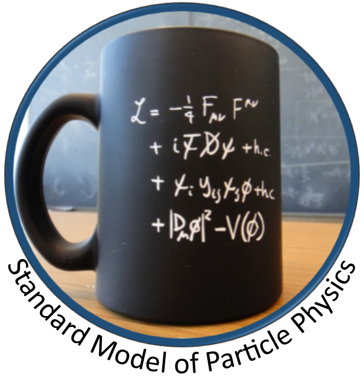
used in Lagrangian (first principles)

Why study this for another 50 years?



I believe a broad DIS program can enable our search for new physics in various ways (directly & indirectly)

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)?

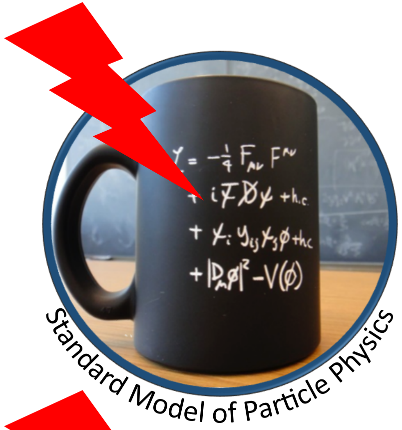
Pattern of particle masses and mixings?

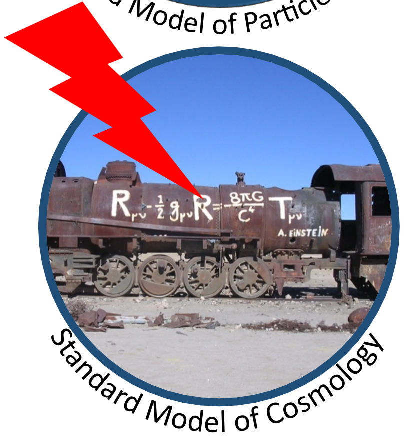
Dynamics of Electro-Weak symmetry breaking?

How do quarks and gluons give rise to properties of nuclei?

Resolution of the structure and dynamics inside hadrons? …

The quest for understanding physics





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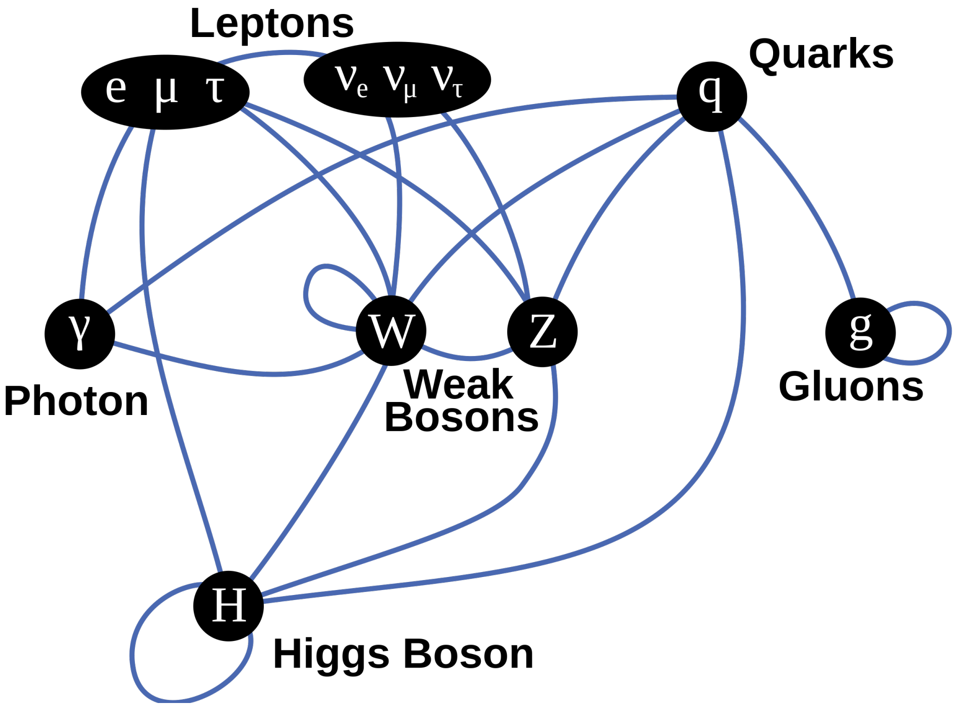
Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

Zooming into the fundamental interactions

- New physics is hiding somewhere
- Extend the SM in a QFT framework



Zooming into the fundamental interactions

- New physics is hiding somewhere
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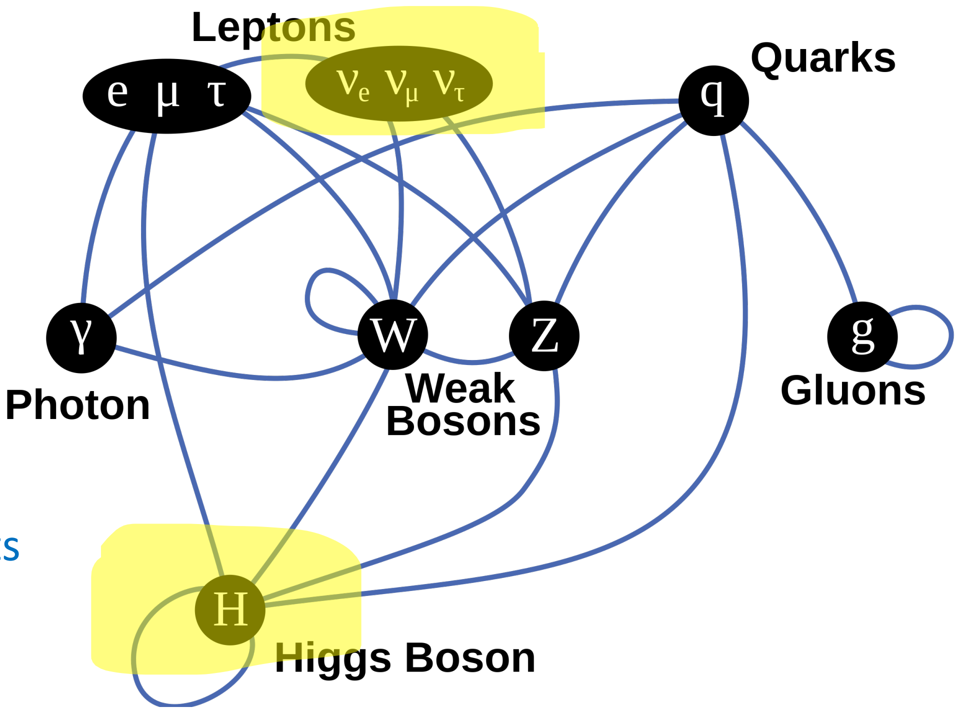
- Windows to new physics, e.g.:
  - the Higgs sector… ?
  - the neutrino sector… ?

- Make H and ν interactions visible, e.g.:
  - H: today with proton colliders
  - ν: long-baseline neutrino experiments



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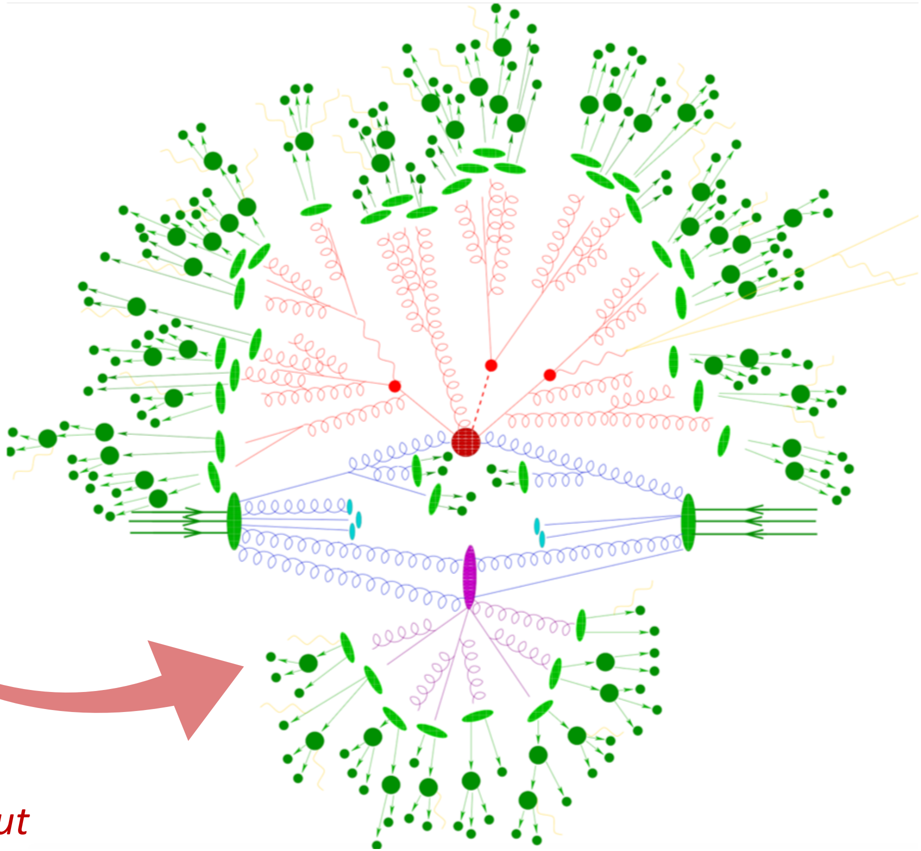

analyzing the observable information to learn about
the hard interaction requires precise knowledge on the structure of the proton

Zooming into the fundamental interactions

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  - H: today with proton colliders
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e.g. J-PARC beam to Kamioka

capturing the invisible in large volume detectors
requires precise knowledge of νA interactions

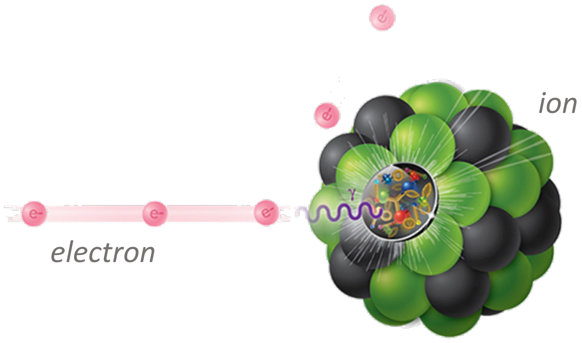
Hyper-K = 10x Super-K volume

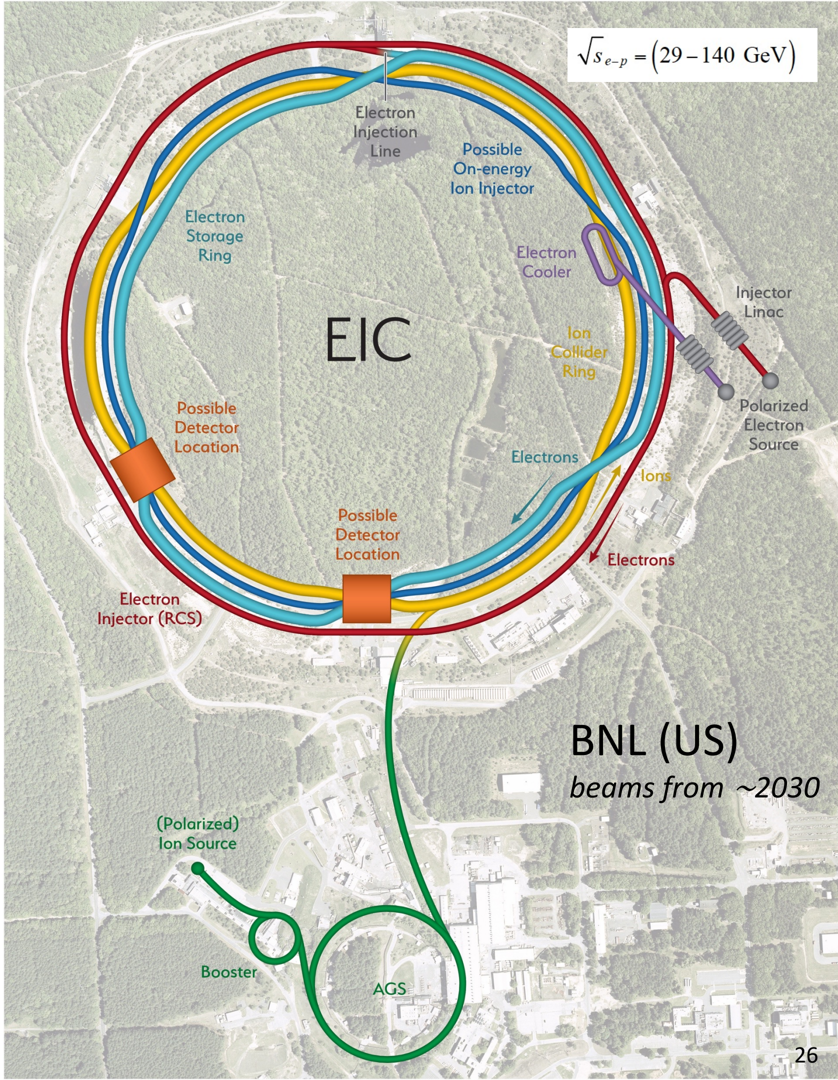
new DIS around the corner

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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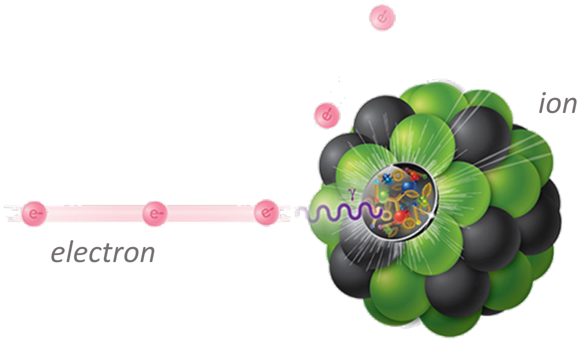
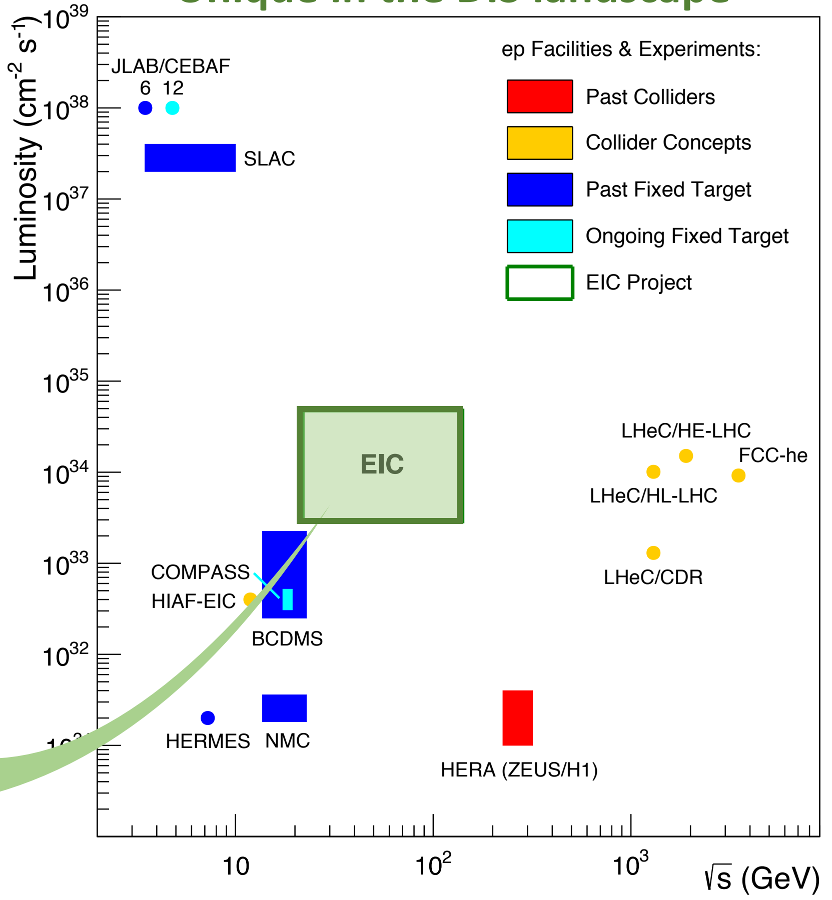


- High luminosity
- Wide range in beam energy
- Polarized lepton & hadron beam
- Nuclear beam

Unique in the DIS landscape



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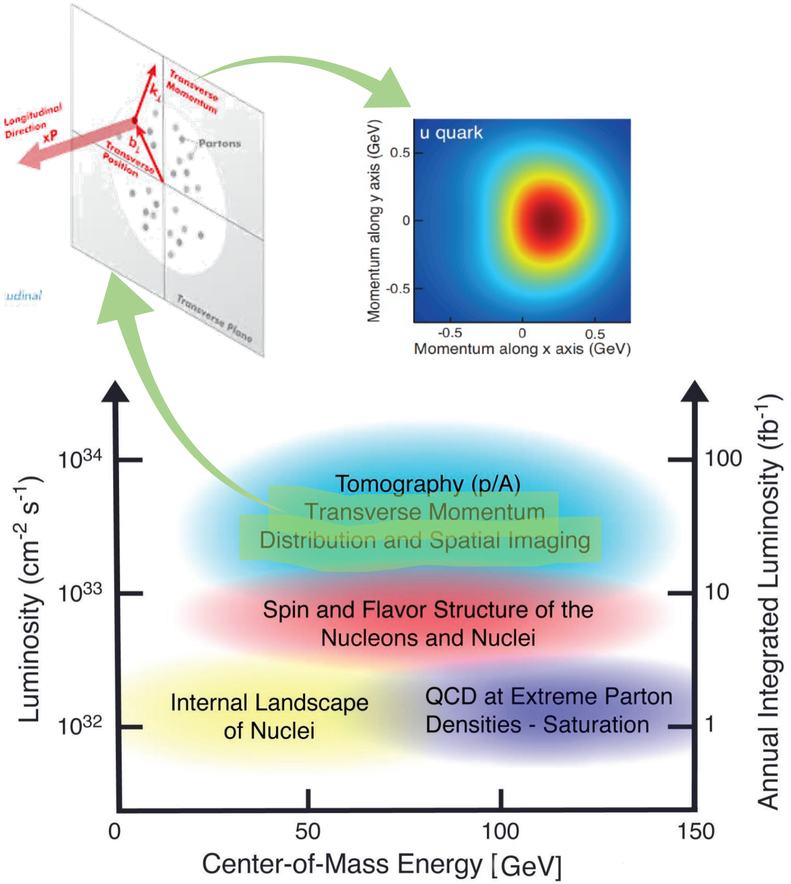
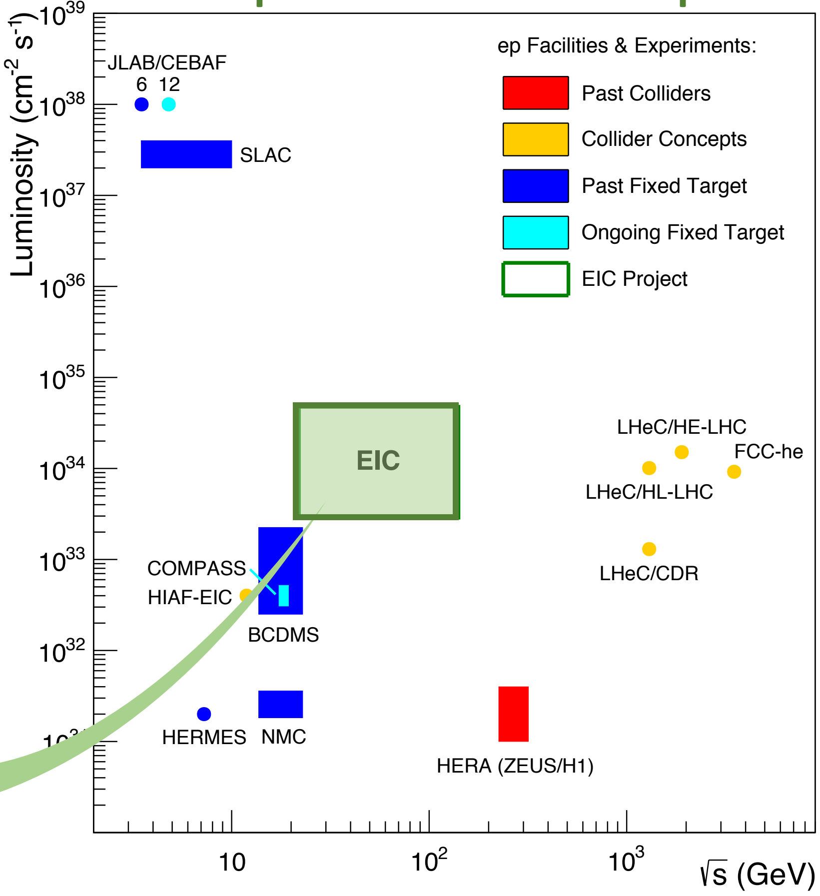
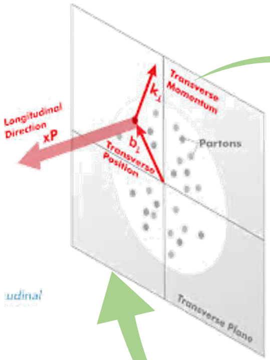
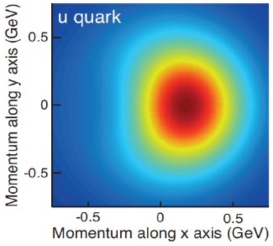


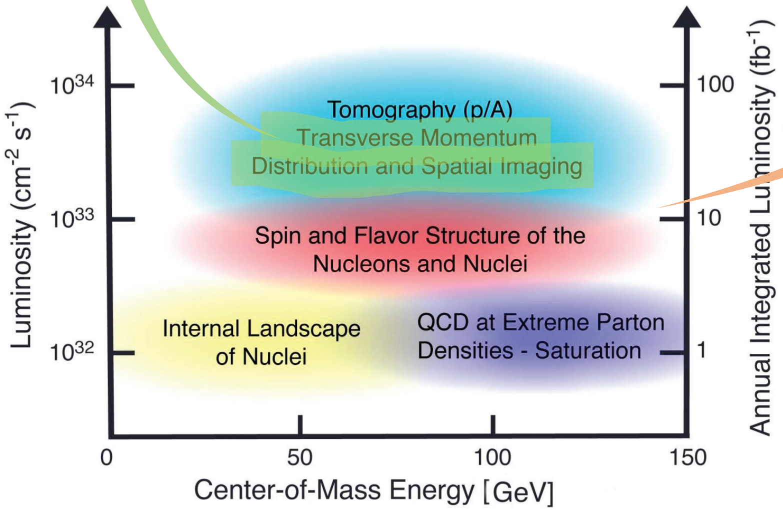
Unique in the DIS landscape



Electron-Ion Collider (EIC)



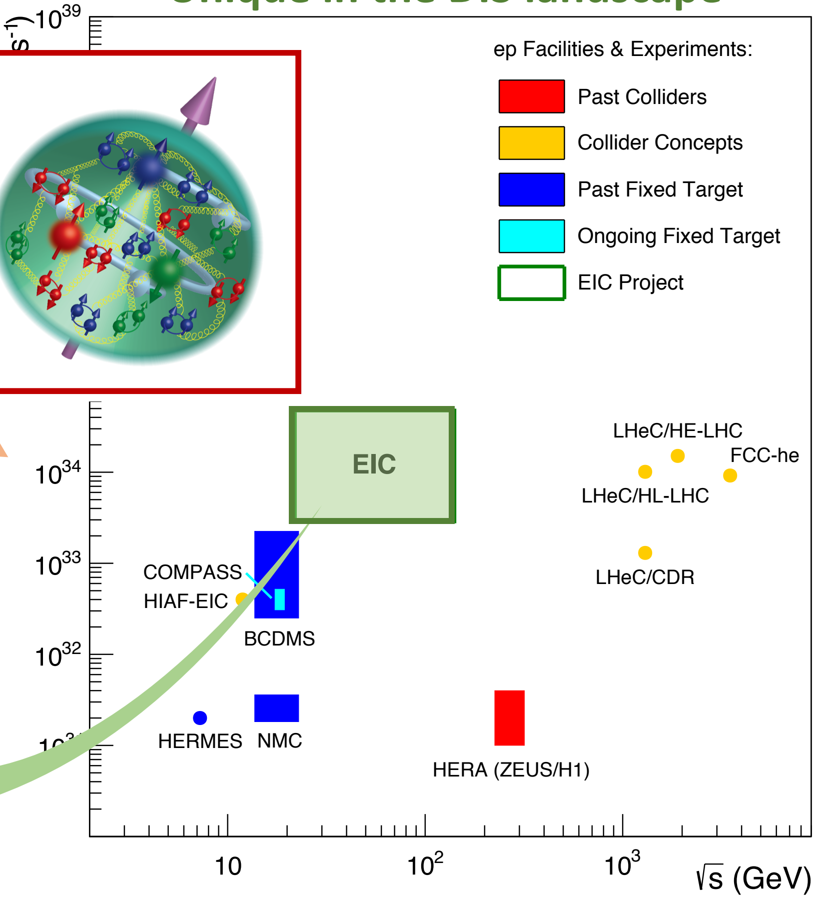




How do the properties of proton and neutrons arise from its constituents?

Towards a 3D partonic image of the proton

Unique in the DIS landscape



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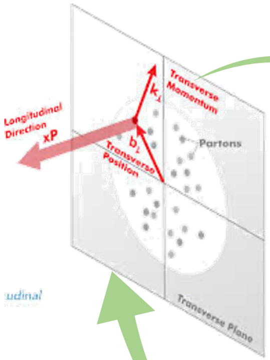

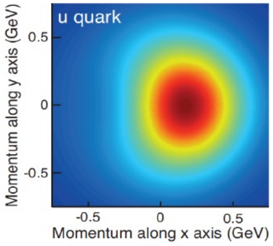

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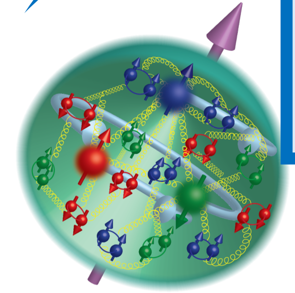
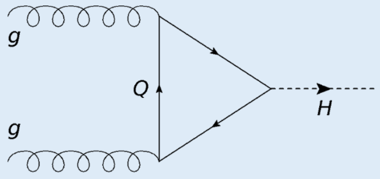
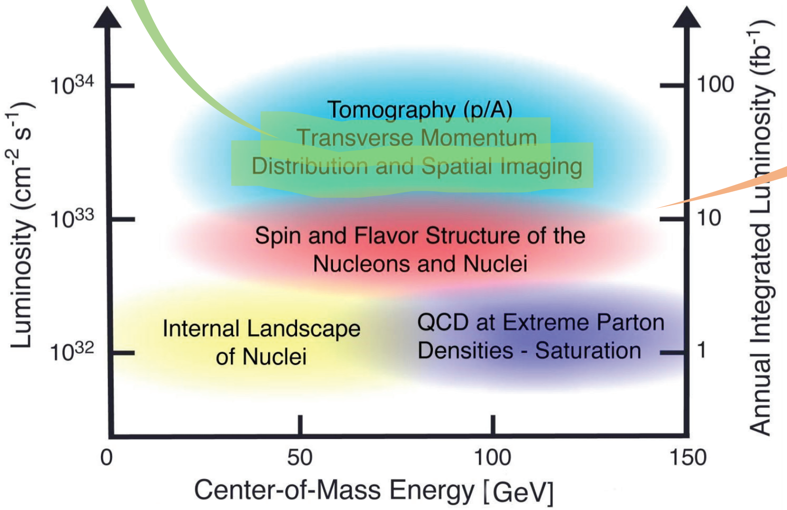
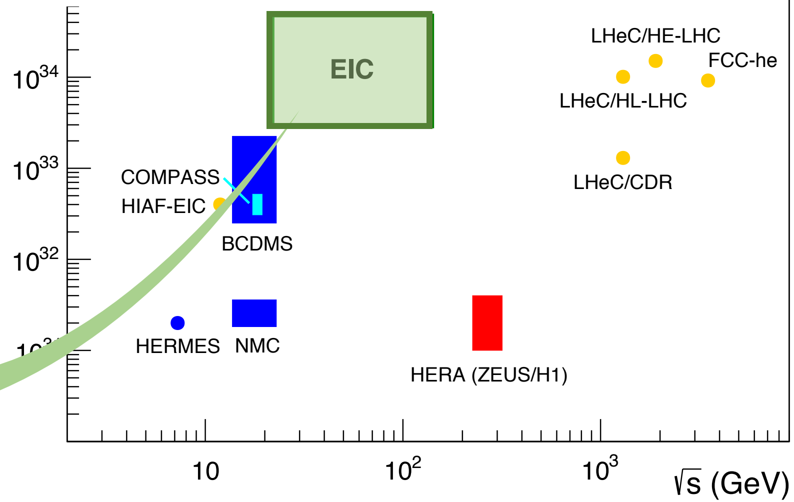


improved gg→H @ LHC



improved W mass (in pp)





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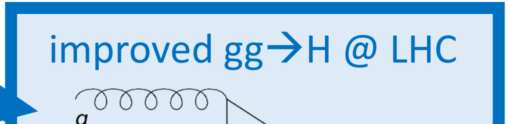
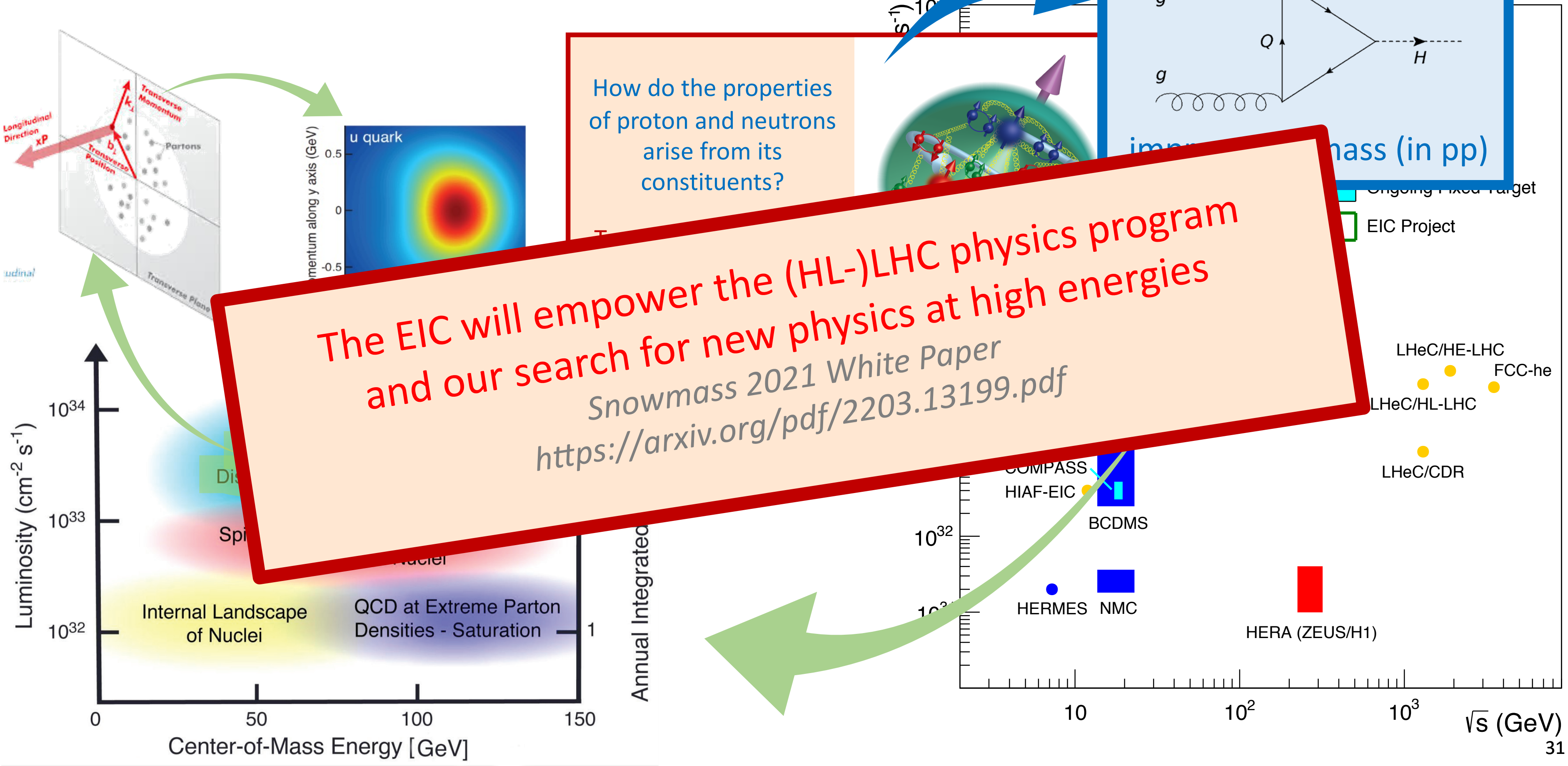




The EIC will empower the (HL-)LHC physics program and our search for new physics at high energies

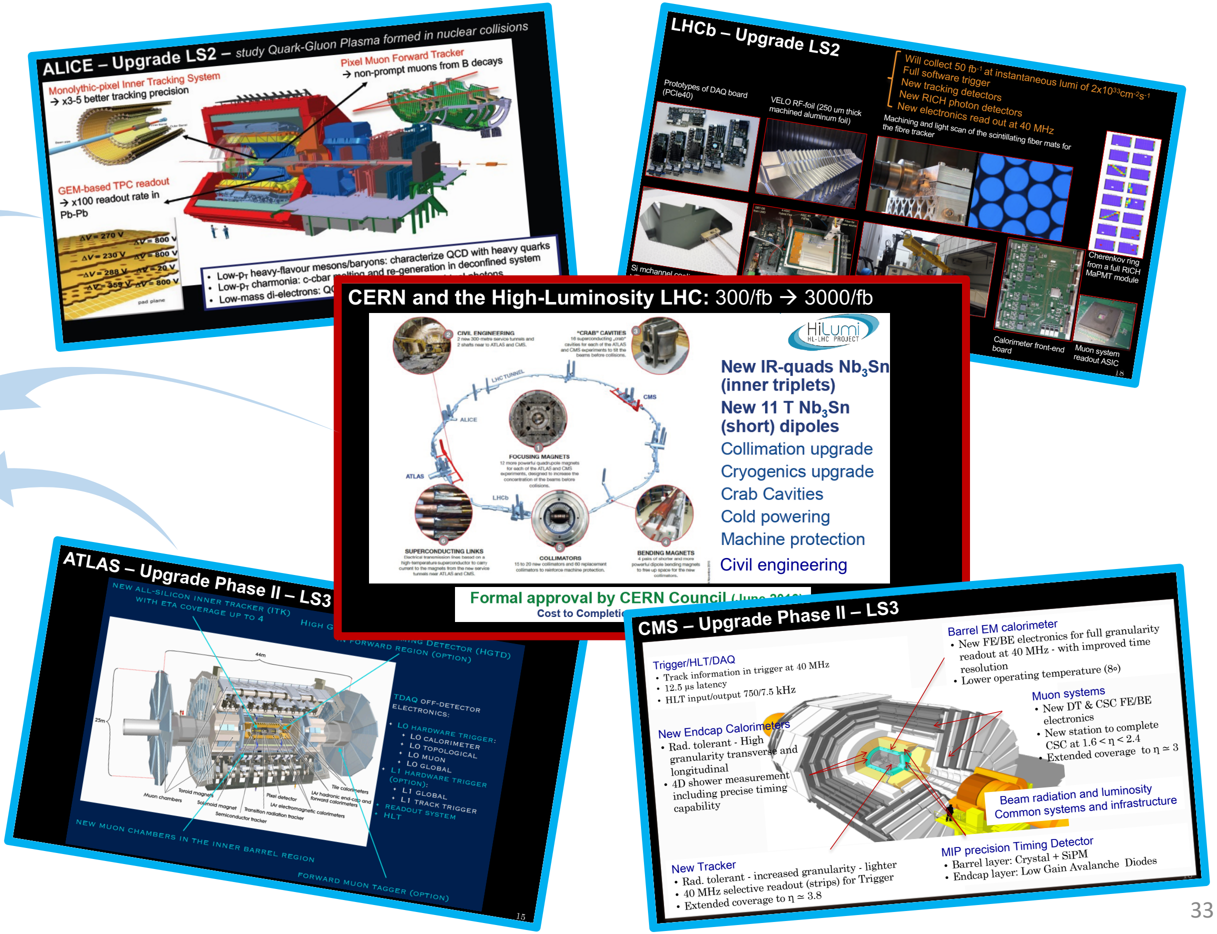
Snowmass 2021 White Paper
https://arxiv.org/pdf/2203.13199.pdf

our current eyes on the Higgs sector

Today's "Higgs Factory": from LHC to HL-LHC

Current flagship (27km)

impressive programme up to 2040

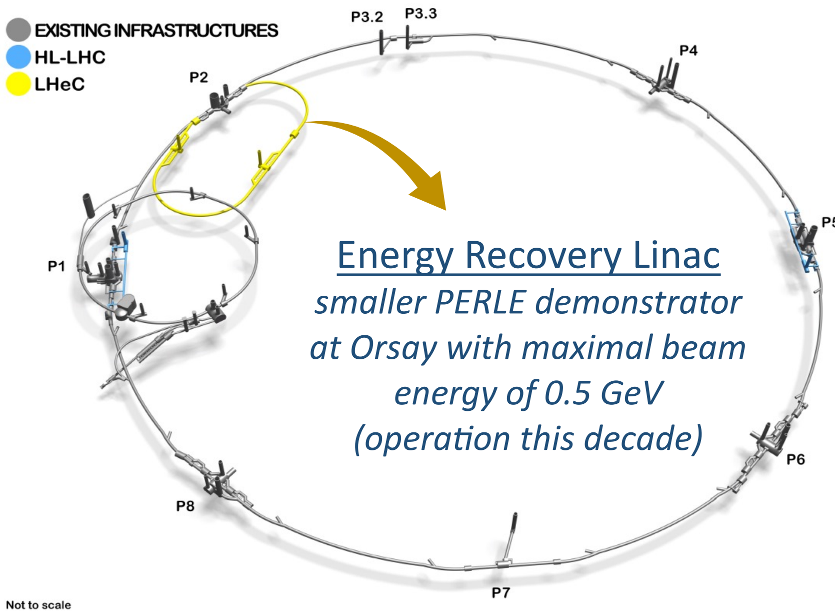


continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

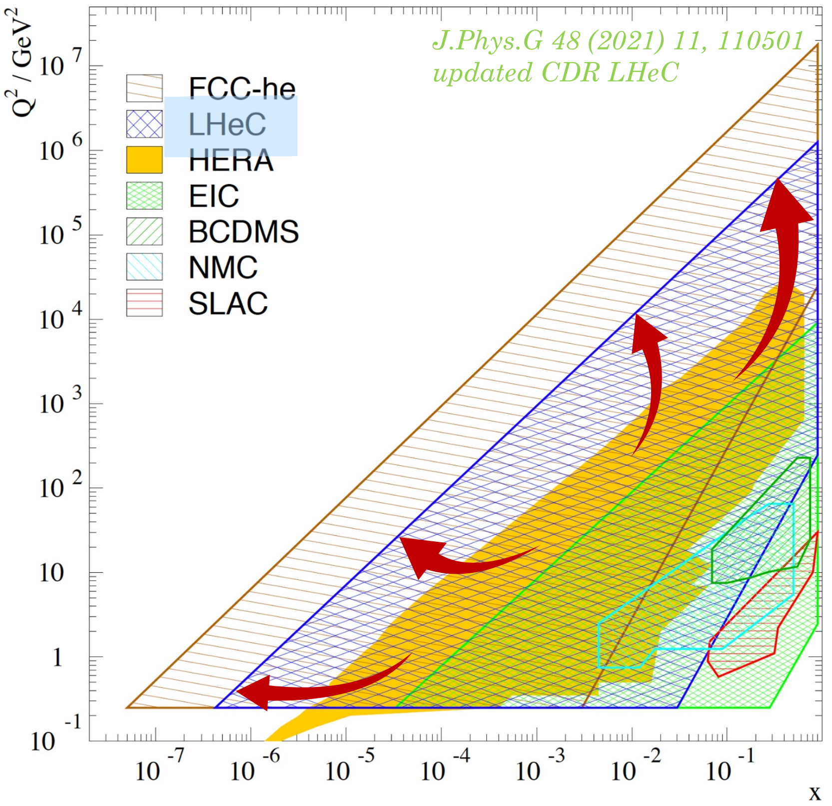
Empowering the (HL-)LHC program with the LHeC

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

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



Energy Recovery Linac
smaller PERLE demonstrator at Orsay with maximal beam energy of 0.5 GeV (operation this decade)



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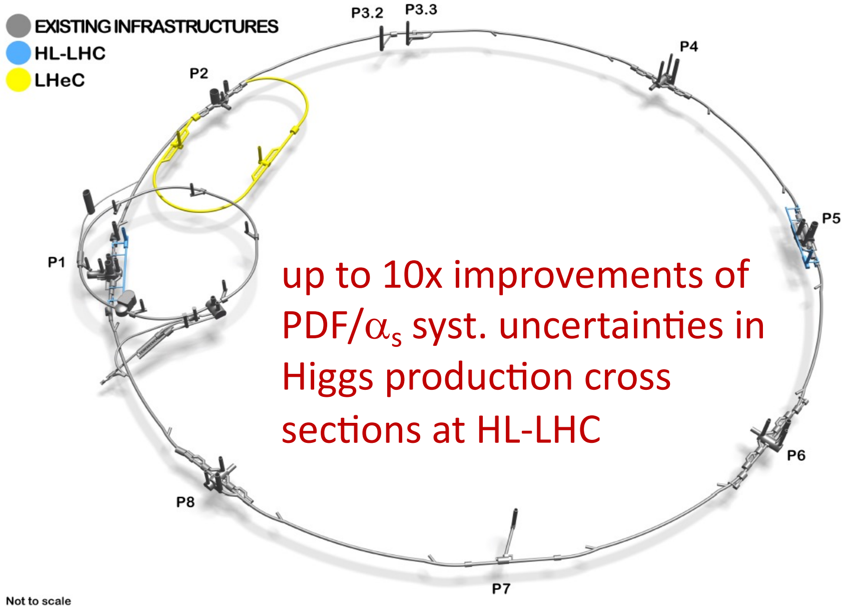
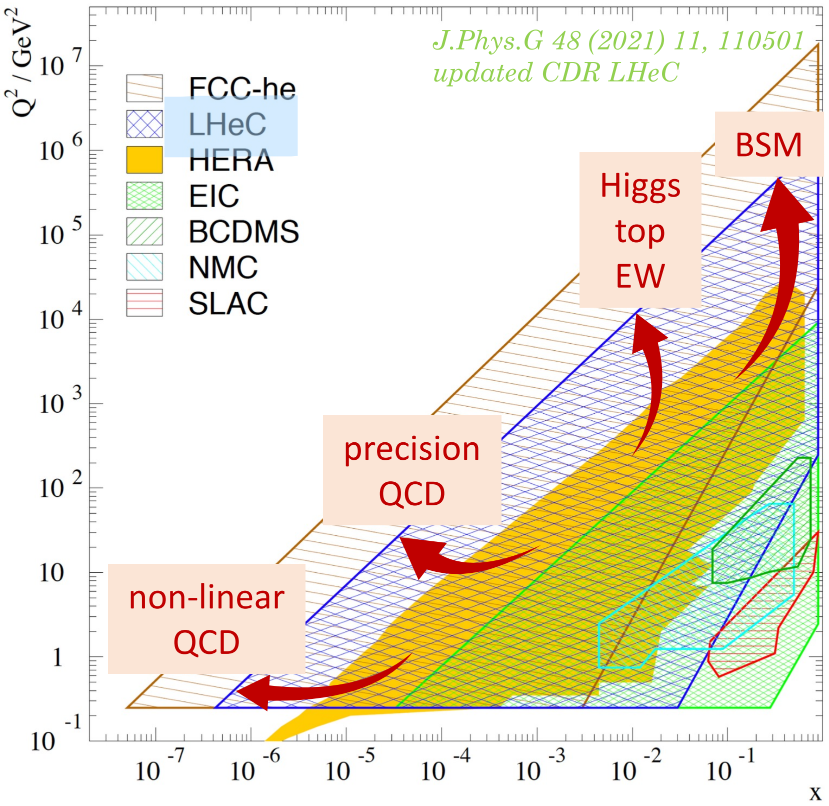


up to 10x improvements of PDF/α_s syst. uncertainties in Higgs production cross sections at HL-LHC



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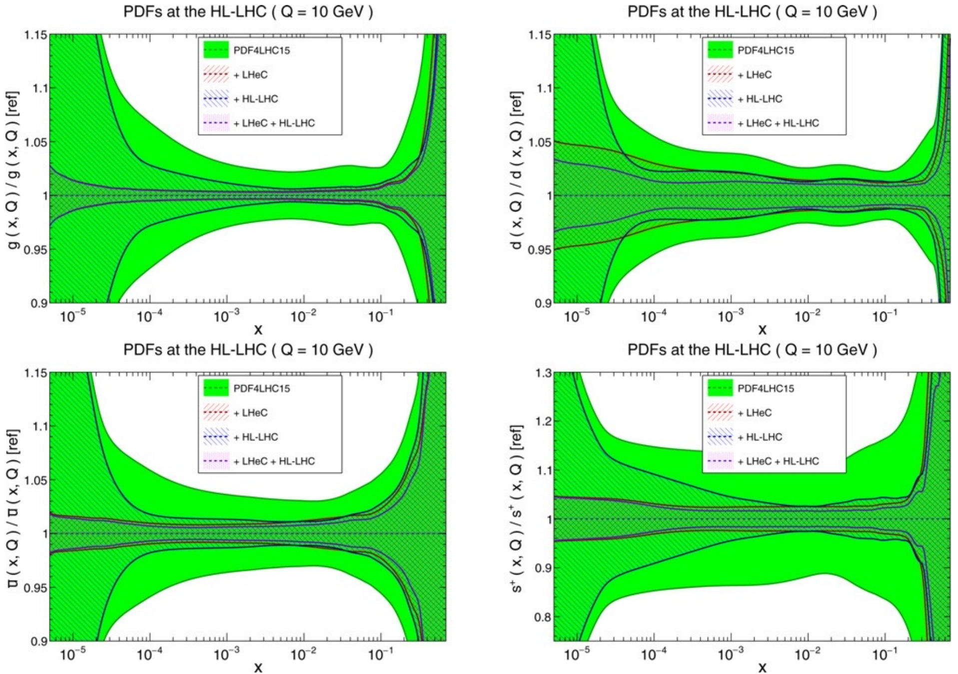

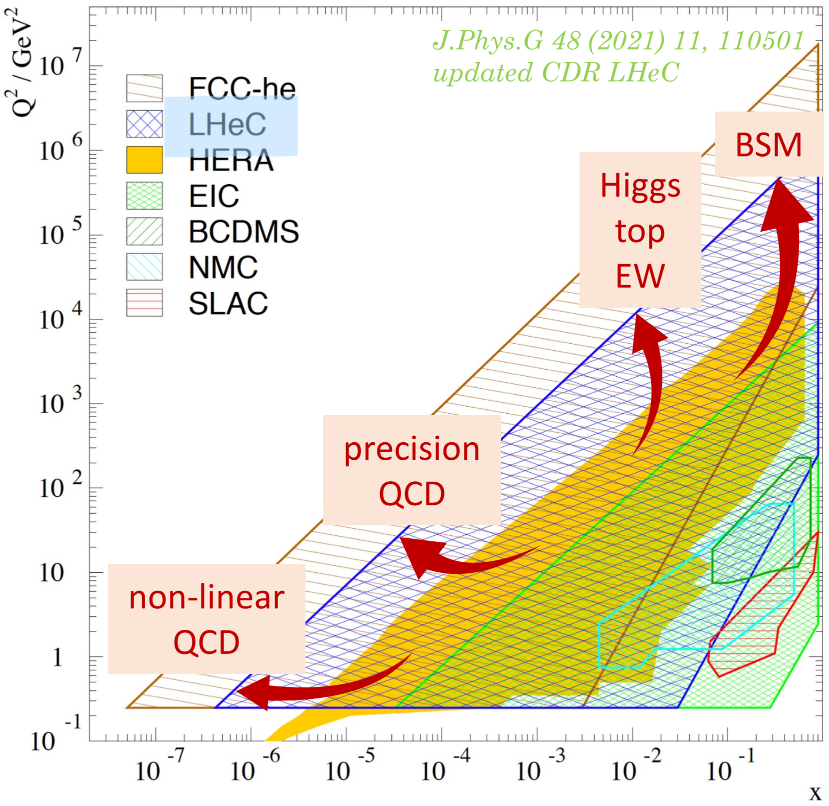

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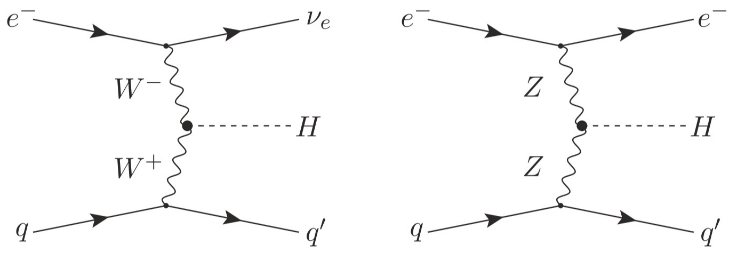
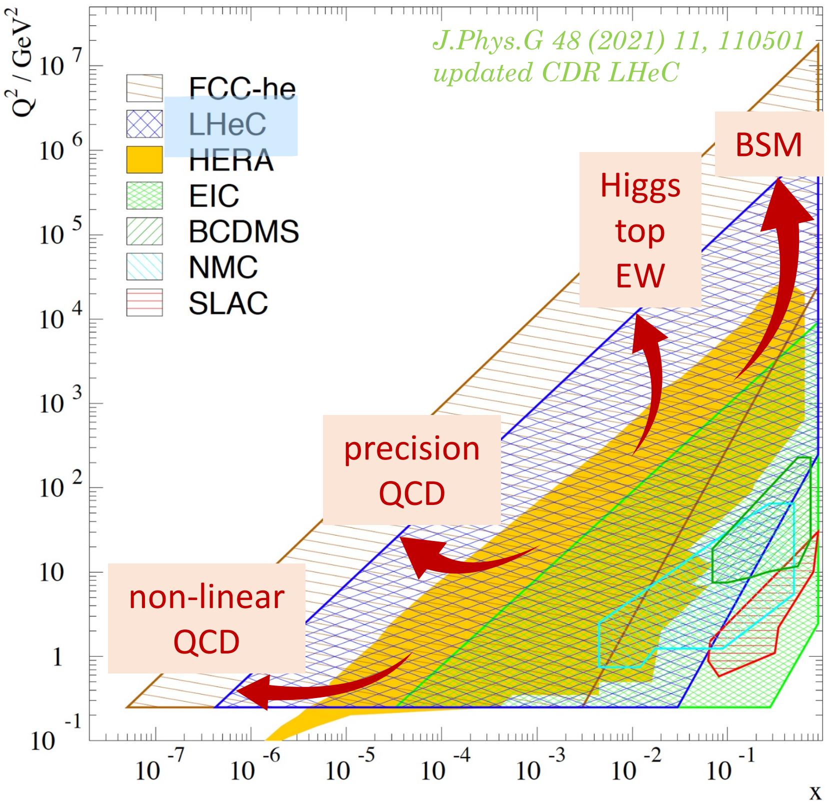
Higgs physics at LHeC itself



With respect to the full HL-LHC expectations, the LHeC improves up to a factor of 2-3 for several effective Higgs couplings

e.g. HZZ, HWW, Hγγ, Hcc, Hbb, Hττ



More DIS-like opportunities with the SPS and LHC

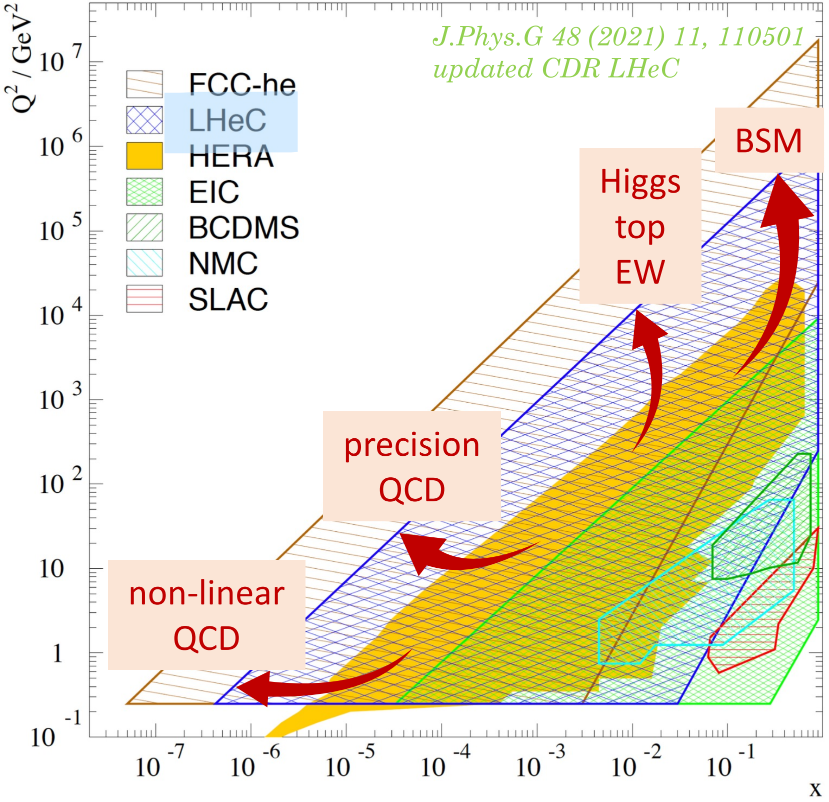
Unique measurements

LHC Fixed Target (ALICE, LHCb, LHCSpin, AFTER@LHC)
the most energetic fixed-target experiment ever

- High-x (x>0.5) frontier for gluon and heavy-quark content in the nucleon and nucleus
  (relevant for new physics searches at the LHC and for ultra-high-energy cosmic rays)
- Transverse dynamics and spin of gluons and quarks inside (un)polarised nucleons

COMPASS++/AMBER (at SPS) → multipurpose QCD facility
elastic (low-Q^2) muon-proton scattering *(hydrogen target)*

- Solving the proton radius puzzle



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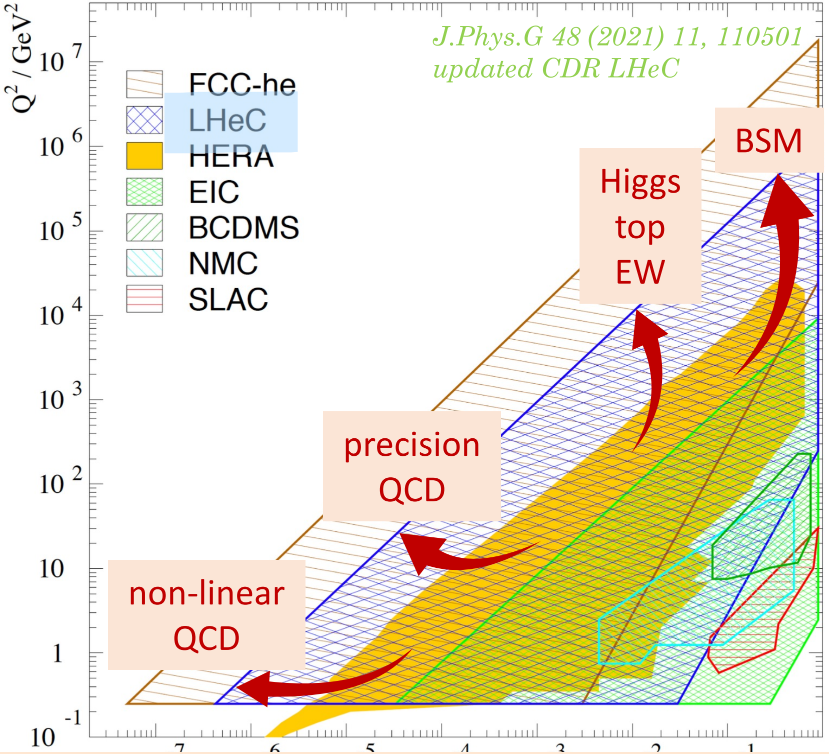


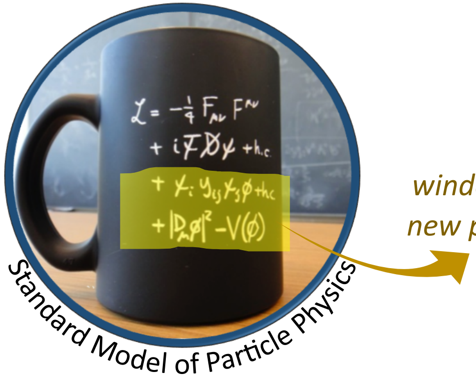
Many essential DIS opportunities around the world at lower energies, e.g. MESA, …

our future eyes on the Higgs sector

Future high-energy particle colliders

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

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



window to new physics

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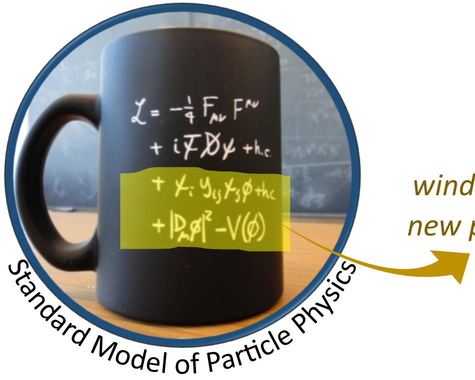
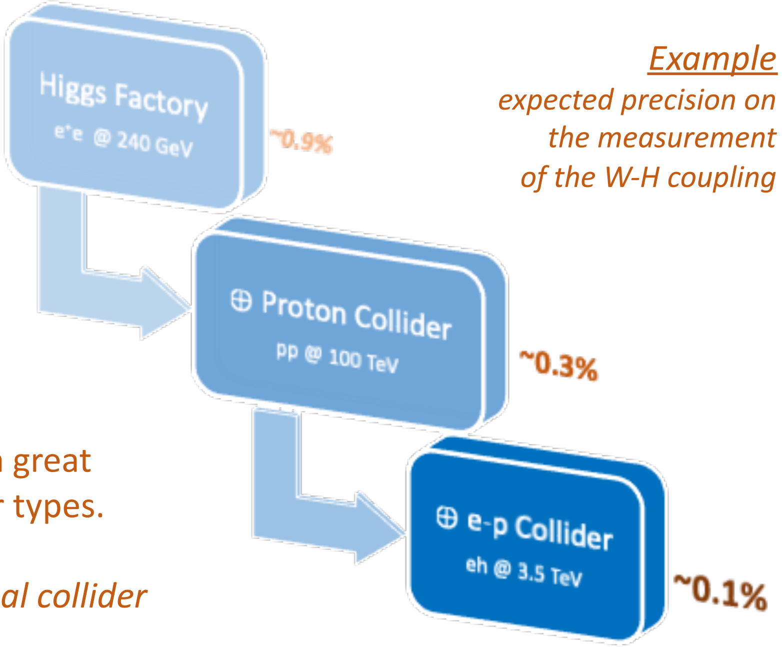


window to new physics



Example

expected precision on the measurement of the W-H coupling

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

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

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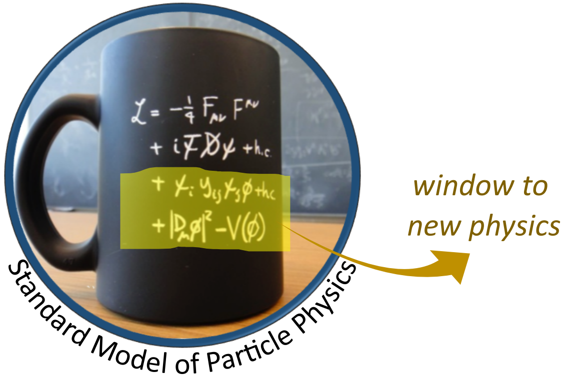

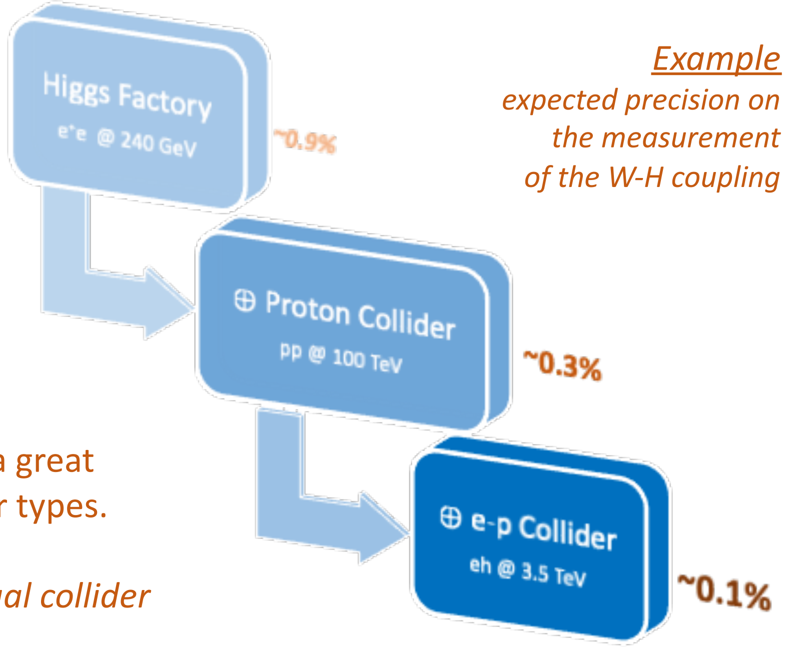

Example

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

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

Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

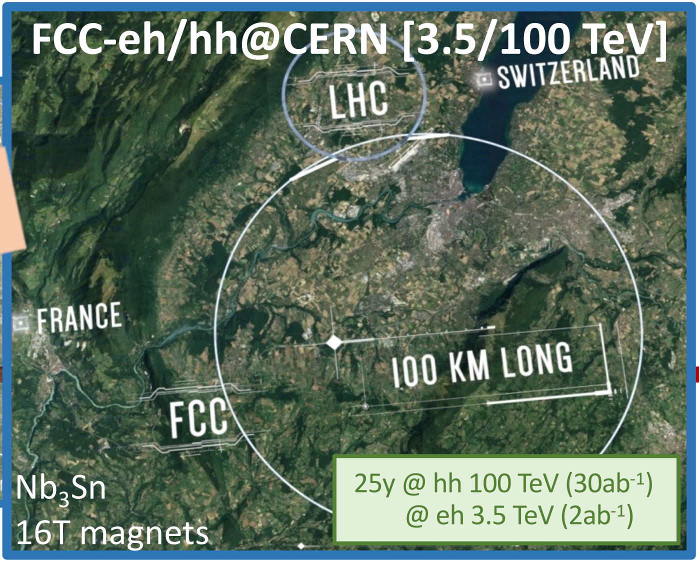
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

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

updated CDR 2007.14491



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

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

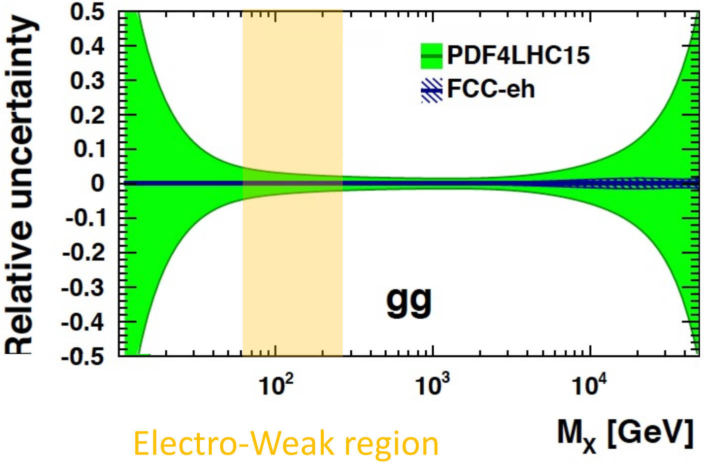
potential alternatives pursued @ CERN: CLIC & muon collider

Empowering the Higgs sector quest with DIS

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

~5-7% uncertainty on the σ(W,Z,H)

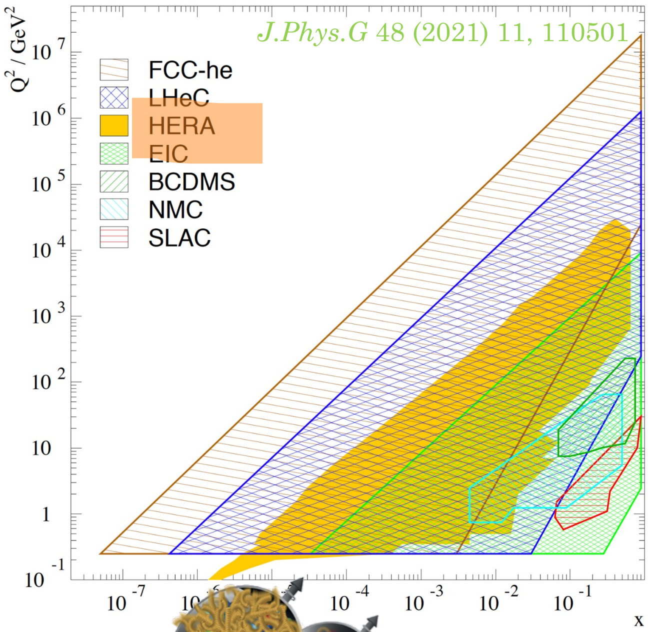
pp @ 100 TeV

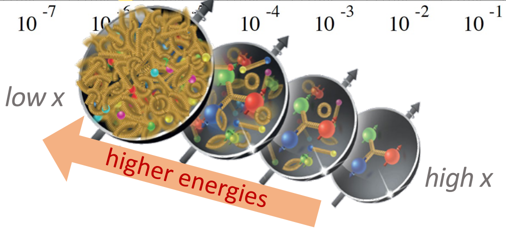


Electro-Weak region

no FCC-eh

Kinematic range Parton Distribution Functions





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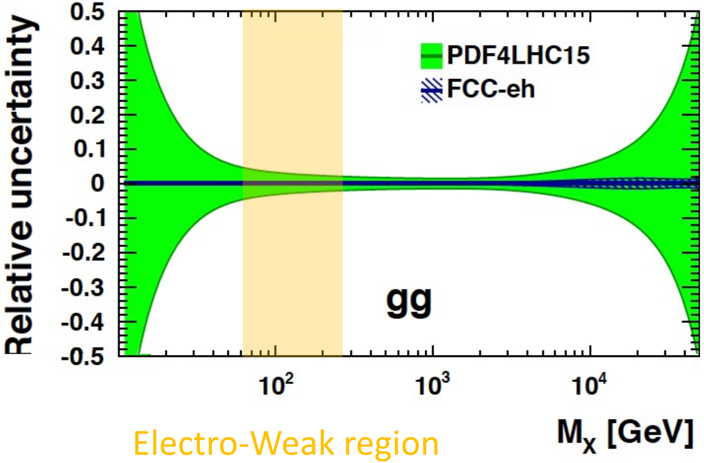


Electro-Weak region

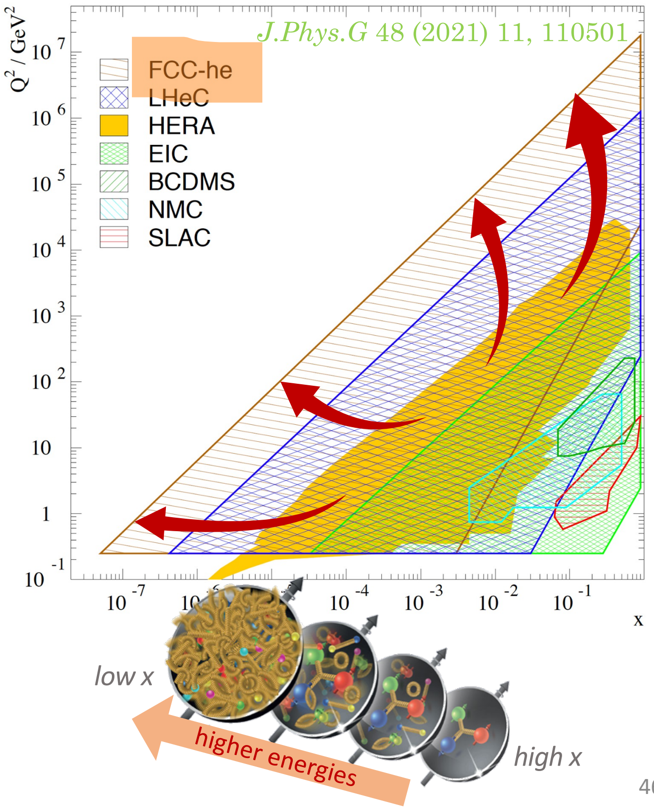
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions



our eyes on the neutrino & dark sector

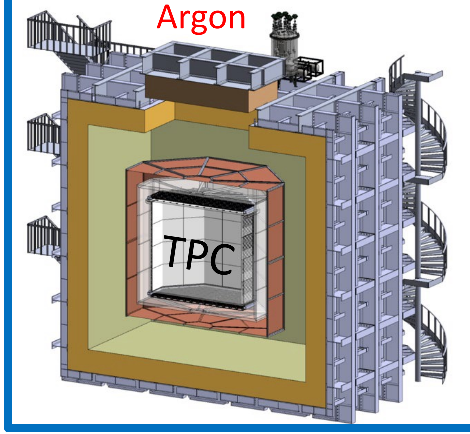
Major underground Facilities – shielding the visible

image courtesy of Susana Cebrián, "Science goes underground"

Major underground Facilities – Dark Matter (WIMP)

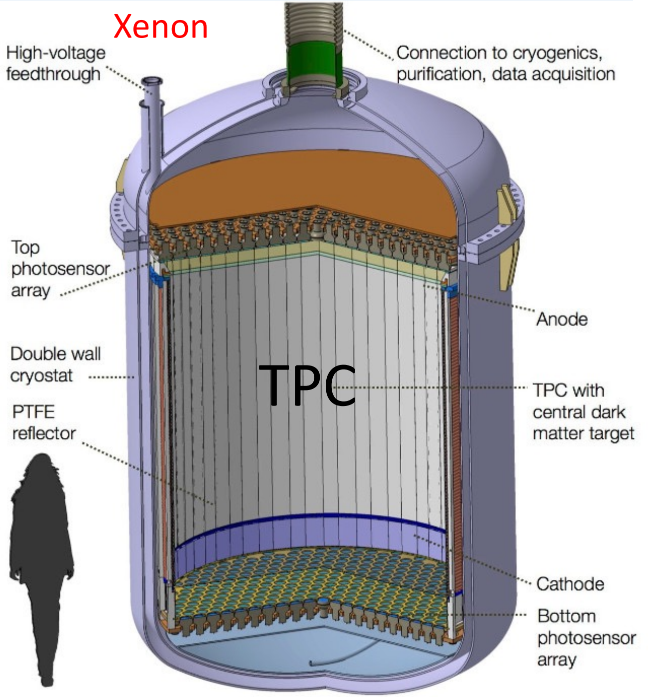
ultimate low background astroparticle physics observatories

DarkSide/DEAP to Argo (300t)



proposal

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



proposal towards CDR (beyond 2027)

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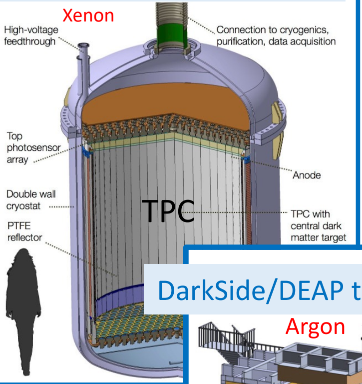

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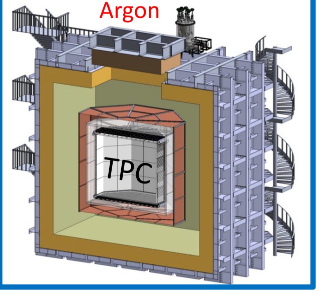
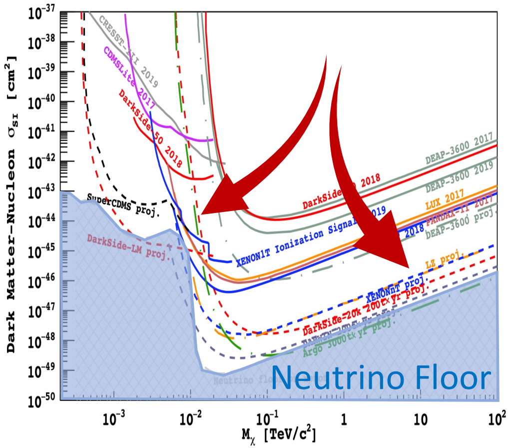
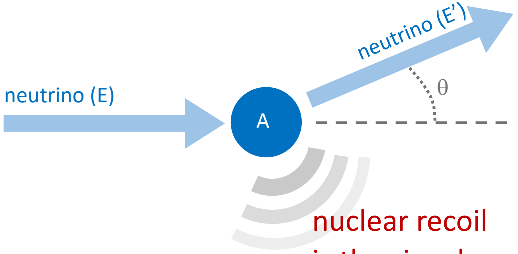




reaching the "neutrino floor"

where the νA backgrounds dominate



nuclear recoil is the signal

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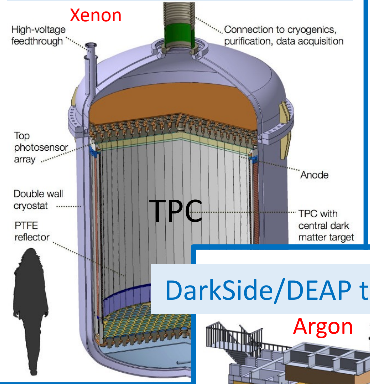

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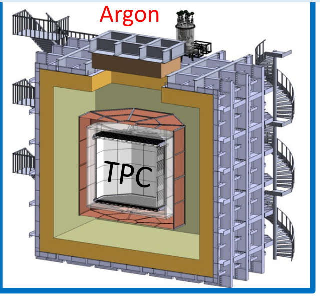
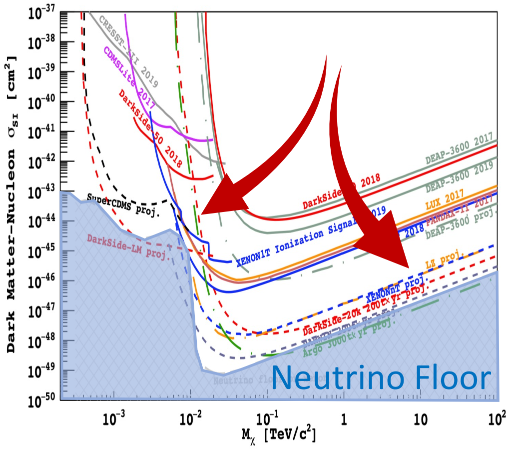


proposal



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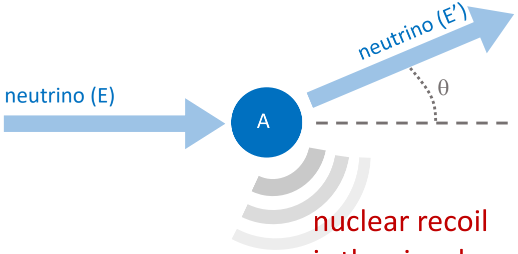
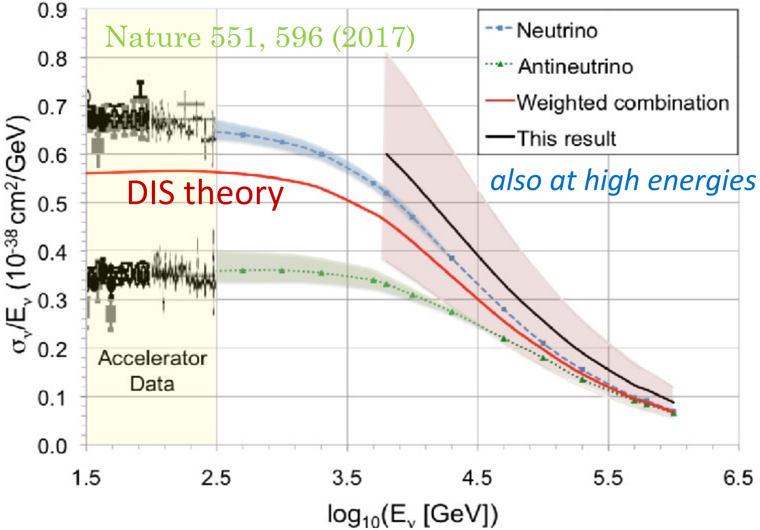


nuclear recoil is the signal

Understand νA interactions much better



also at high energies

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

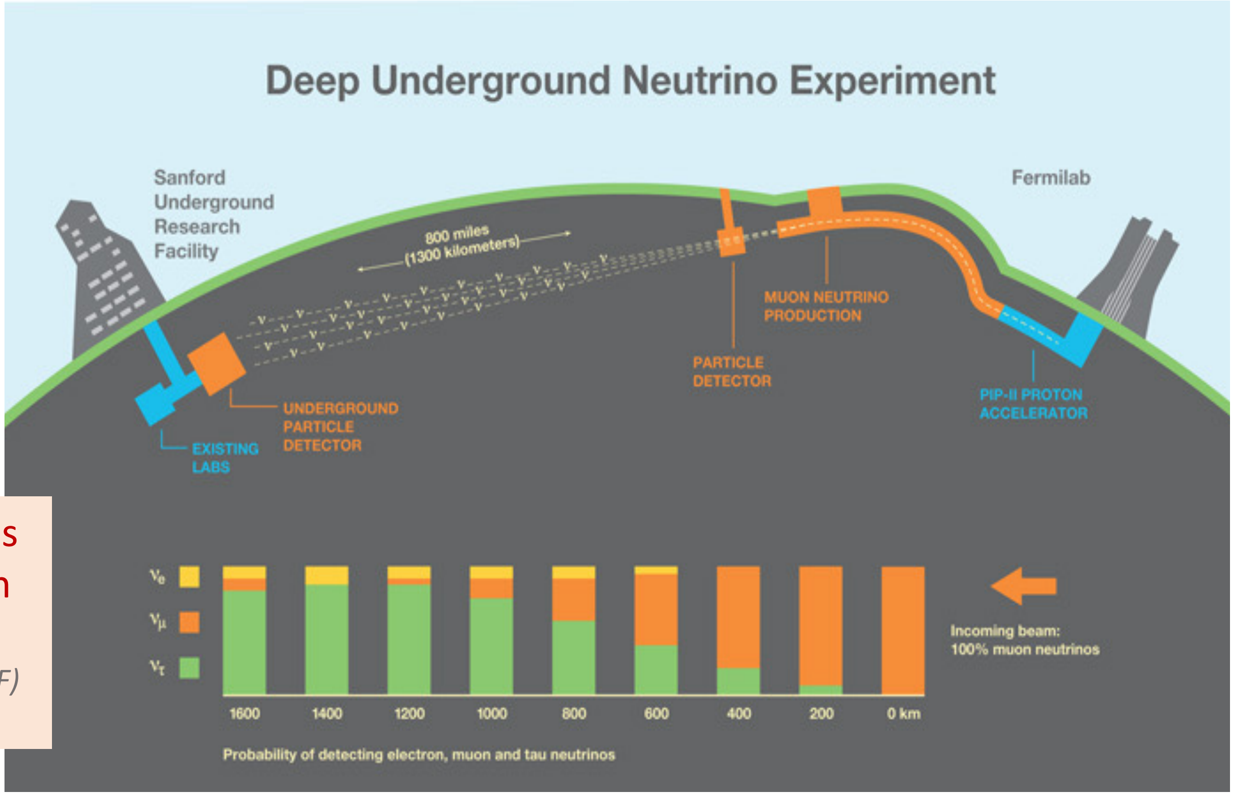
more to come from DUNE, JUNO, …

more to come with IceCube-Gen2 arXiv:2204.04237

Neutrino sector extends the Standard Model

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

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



Measure the oscillation probabilities of neutrinos and antineutrinos with ultimate precision

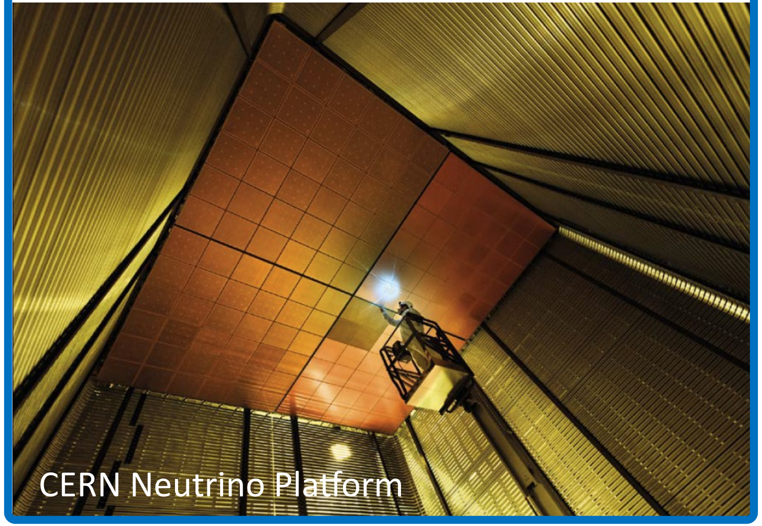
e.g. at the Long-Baseline Neutrino Facility (LBNF) with the DUNE experiment

Neutrino beams in Japan and in the US

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

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC



BabyMIND @ T2K (near detector)

Prototype for Magnetised Iron Neutrino Detector

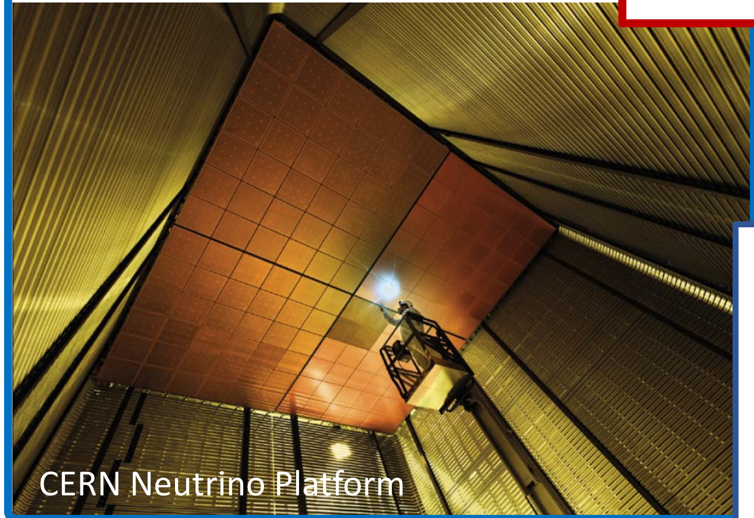
Within the next decade, we will now much more how to develop the neutrino sector to extend the Standard Model

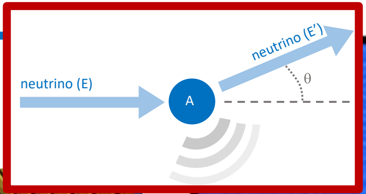
Empowering the neutrino/dark sector quest with DIS

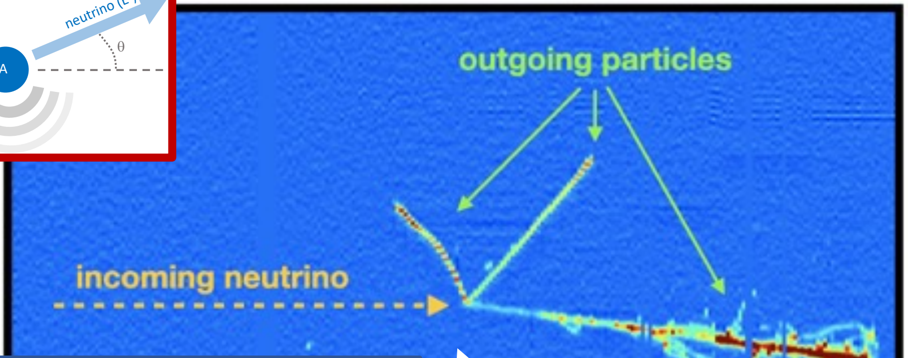
Measurements of νA cross sections are vital to improve the precision

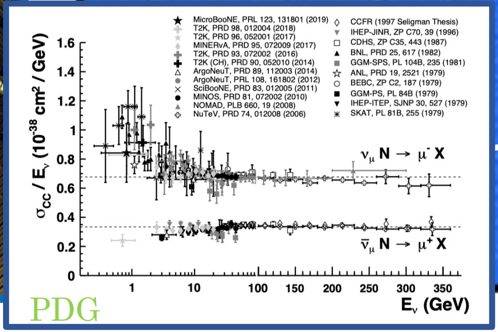
DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC









$\nu_\mu N \rightarrow \mu X$ cross section not well known

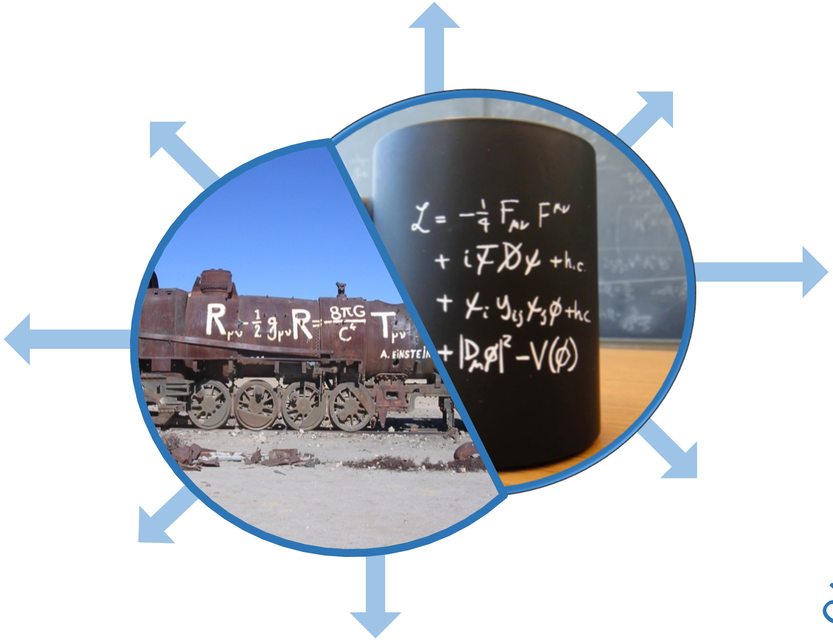
Precise low-energy neutrino DIS-like scattering measurements on nuclear targets are required for DUNE, Super-K/Hyper-K, IceCube, JUNO, …

our eyes on new physics

higher energy interactions
in the lab

earlier universe

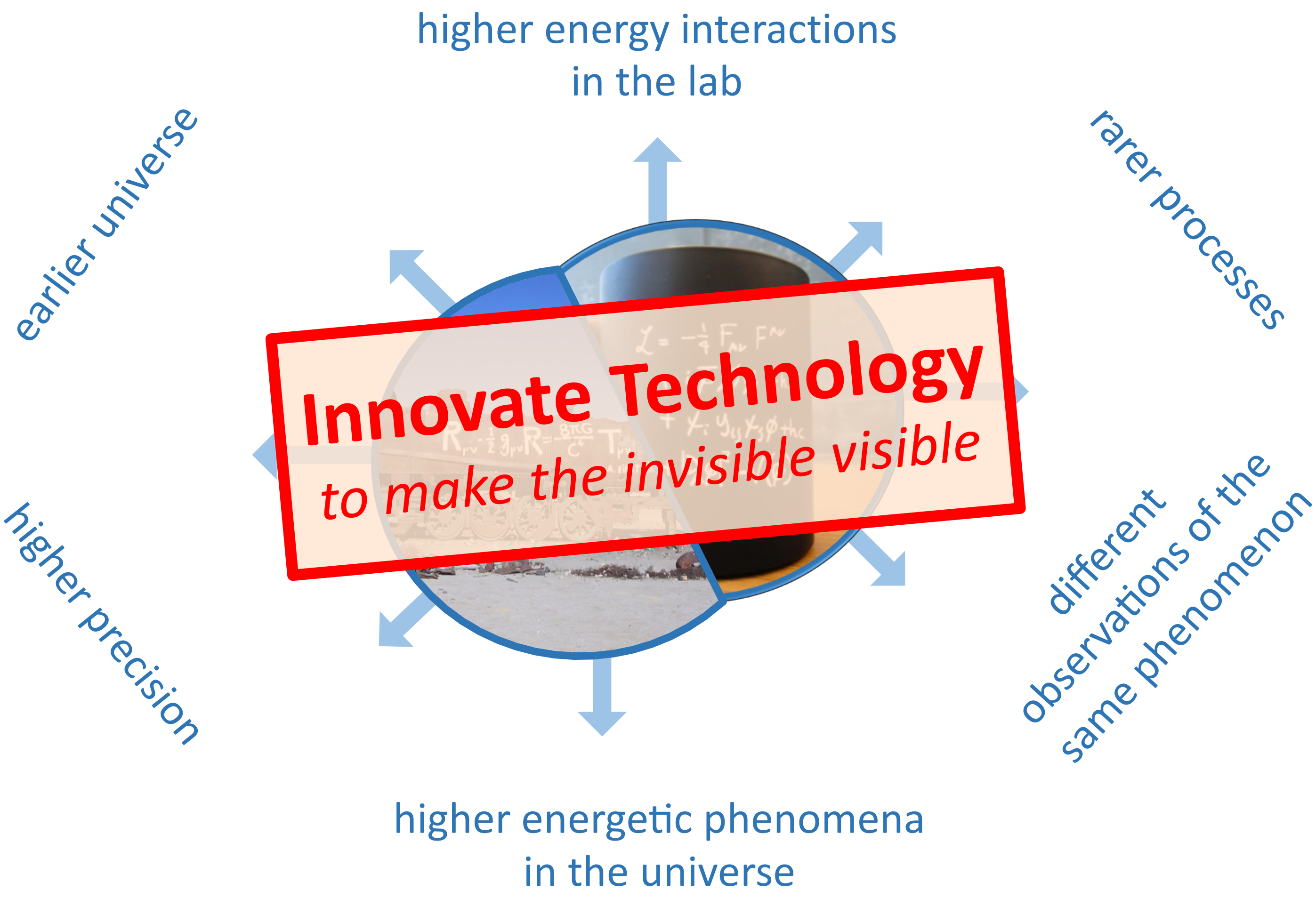
rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

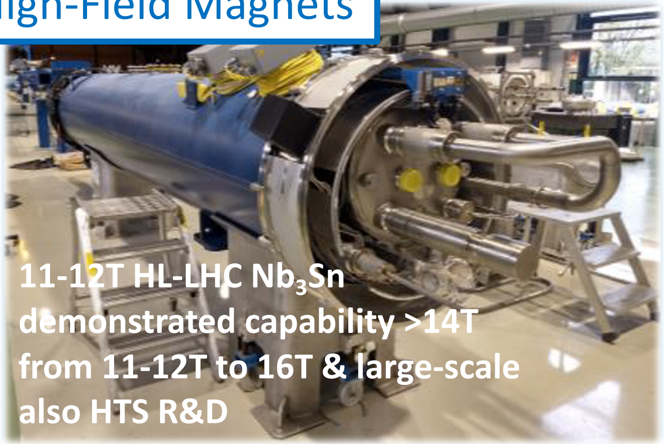

higher energy interactions
in the lab
earlier universe
rarer processes
Innovate Technology
to make the invisible visible
higher precision
different
observations of the
same phenomenon
higher energetic phenomena
in the universe

Advancing Accelerator Technologies

High-energy & high-intensity beams are required for a DIS program

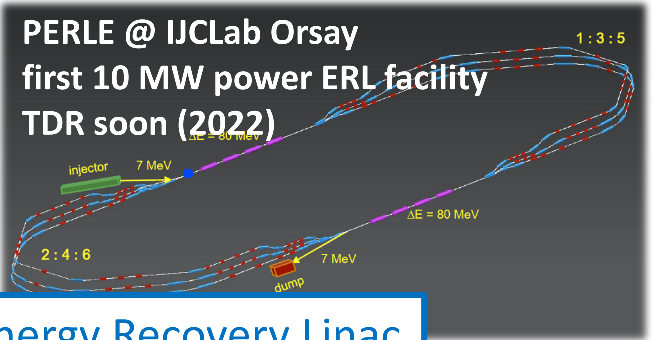
European Accelerator R&D Roadmap (2021)
https://arxiv.org/pdf/2201.07895.pdf

High-Field Magnets



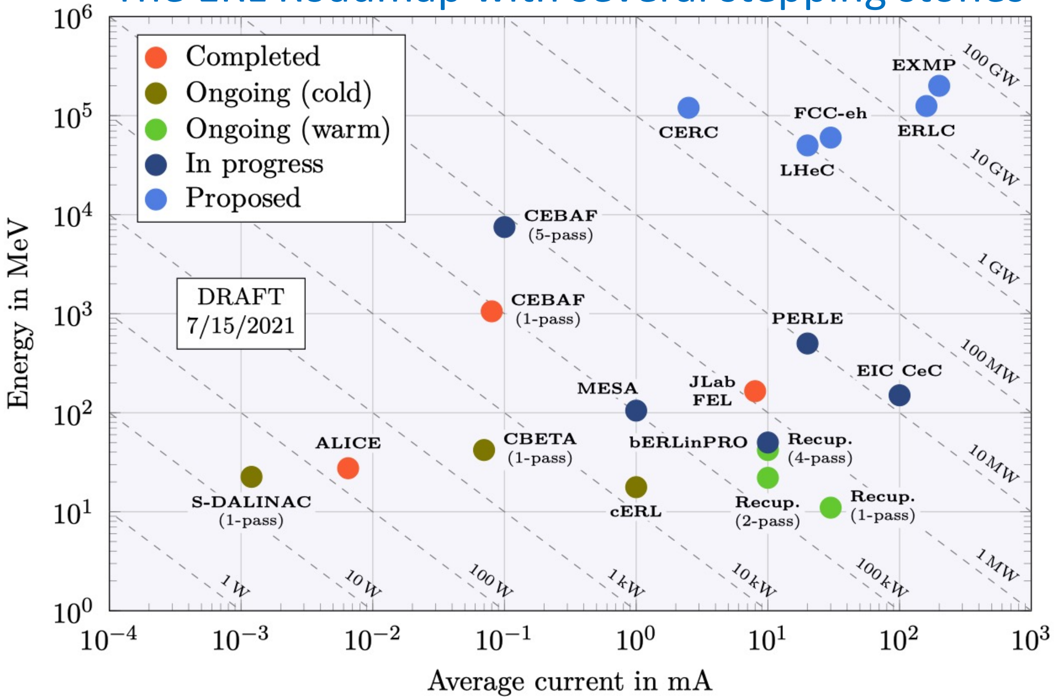
11-12T HL-LHC Nb_3Sn
demonstrated capability >14T
from 11-12T to 16T & large-scale
also HTS R&D

PERLE @ IJCLab Orsay
first 10 MW power ERL facility
TDR soon (2022)



Energy Recovery Linac

The ERL Roadmap with several stepping stones



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

Make the invisible visible – Detector R&D for DIS

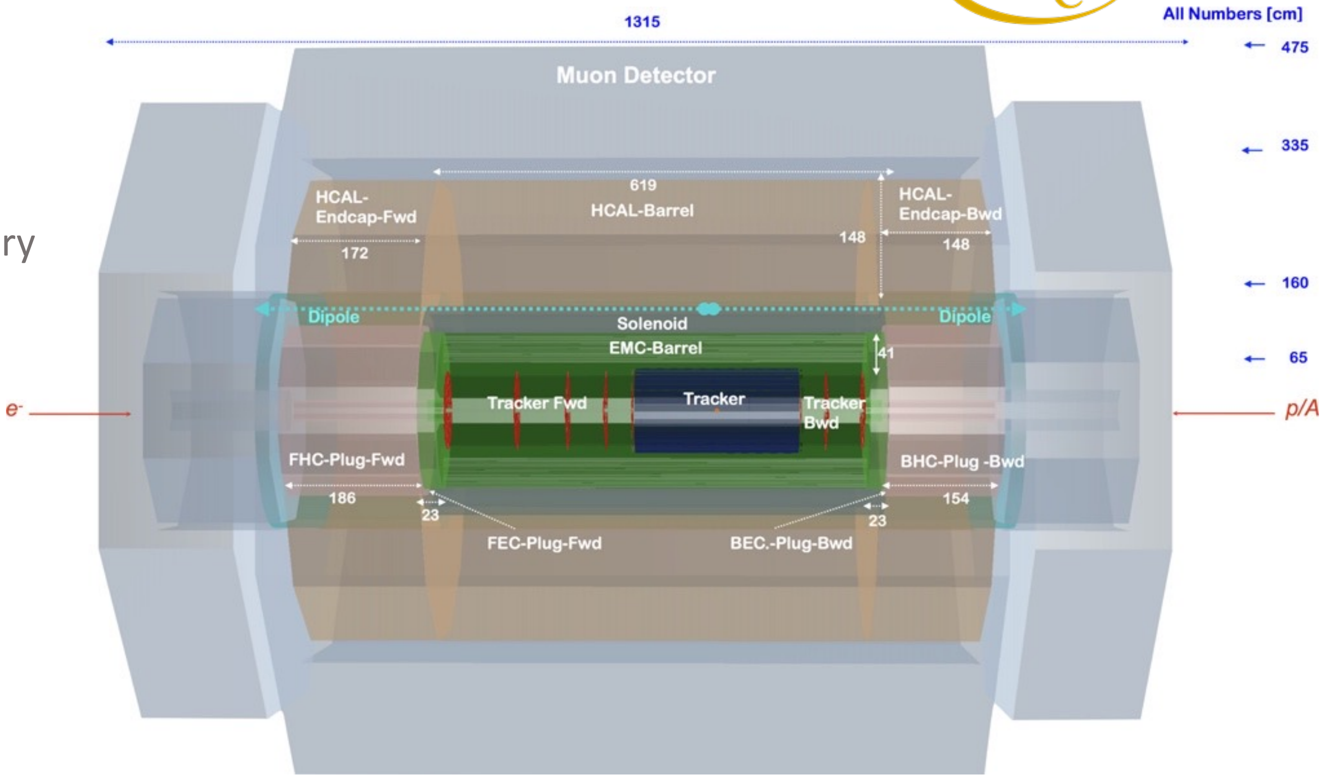
Dedicated detector R&D efforts are to continue

Major challenges:

- Tracking & Vertexing
- 1^{o} close to the beamline
- High-resolution calorimetry

Solid State Detectors

e.g. Monolithic Active Pixel Sensors



Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

European Detector R&D Roadmap (2021)

Major challenges:

- Tracking & Vertexing
- 1° close to the beamline
- High-resolution calorimetry

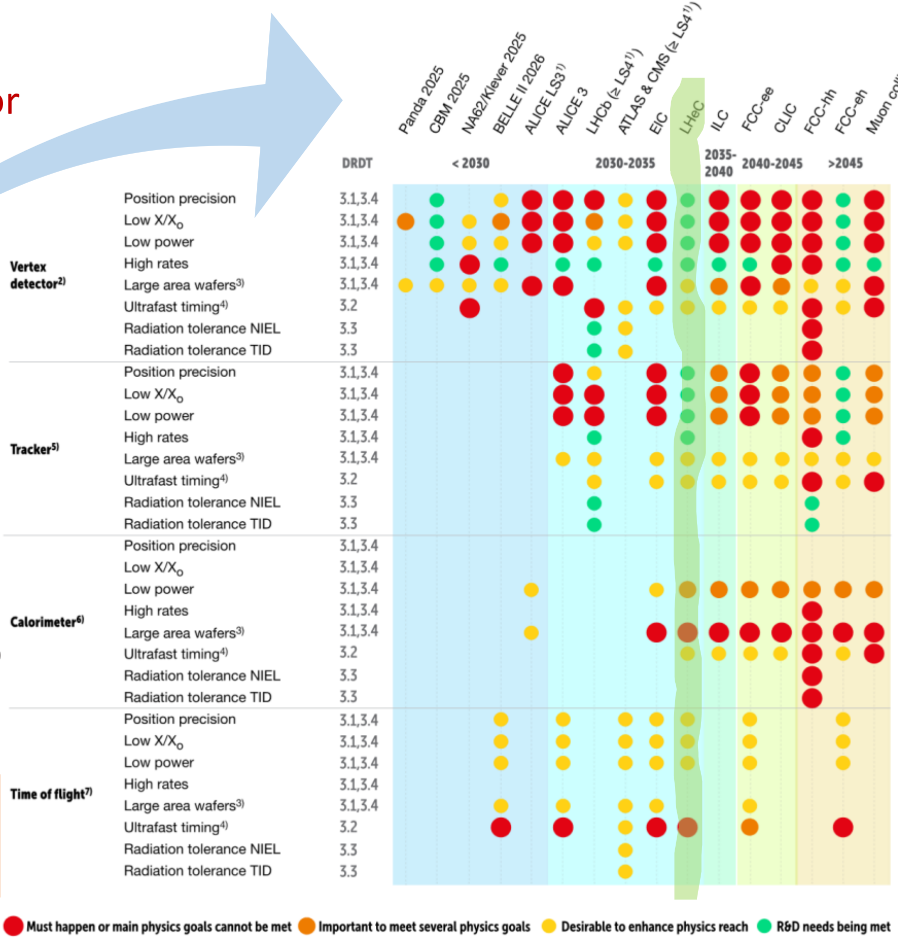
Solid State Detectors

e.g. Monolithic Active Pixel Sensors

Synergies with many other major projects, potentially as stepping stones

Detector Requirements

e.g. Solid State Devices



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

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

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

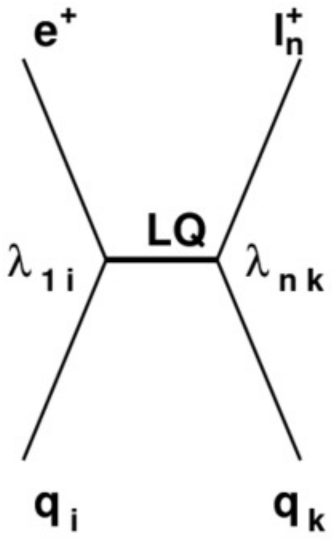
The DIS program as a search engine for new physics

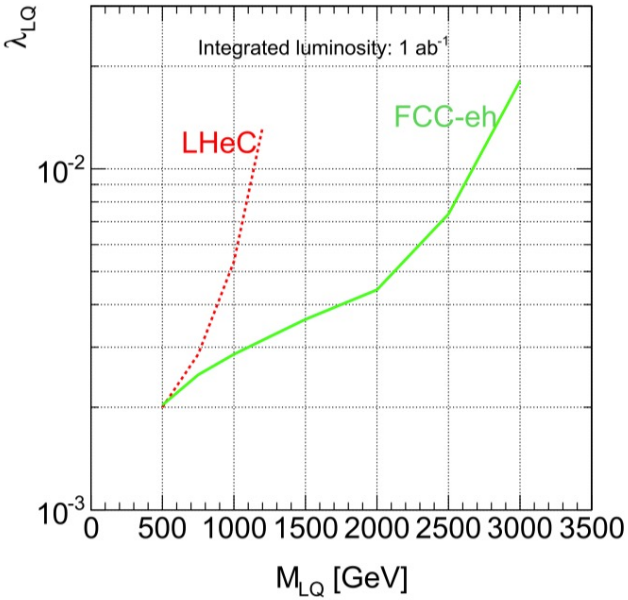
With adequate instrumentation a DIS program can be a prime gateway to discoveries

An high-energy ep collider is ideal to study features where leptons and quarks interact

e.g. s-channel production of leptoquarks (LQ)

In general, low production rate but with small background



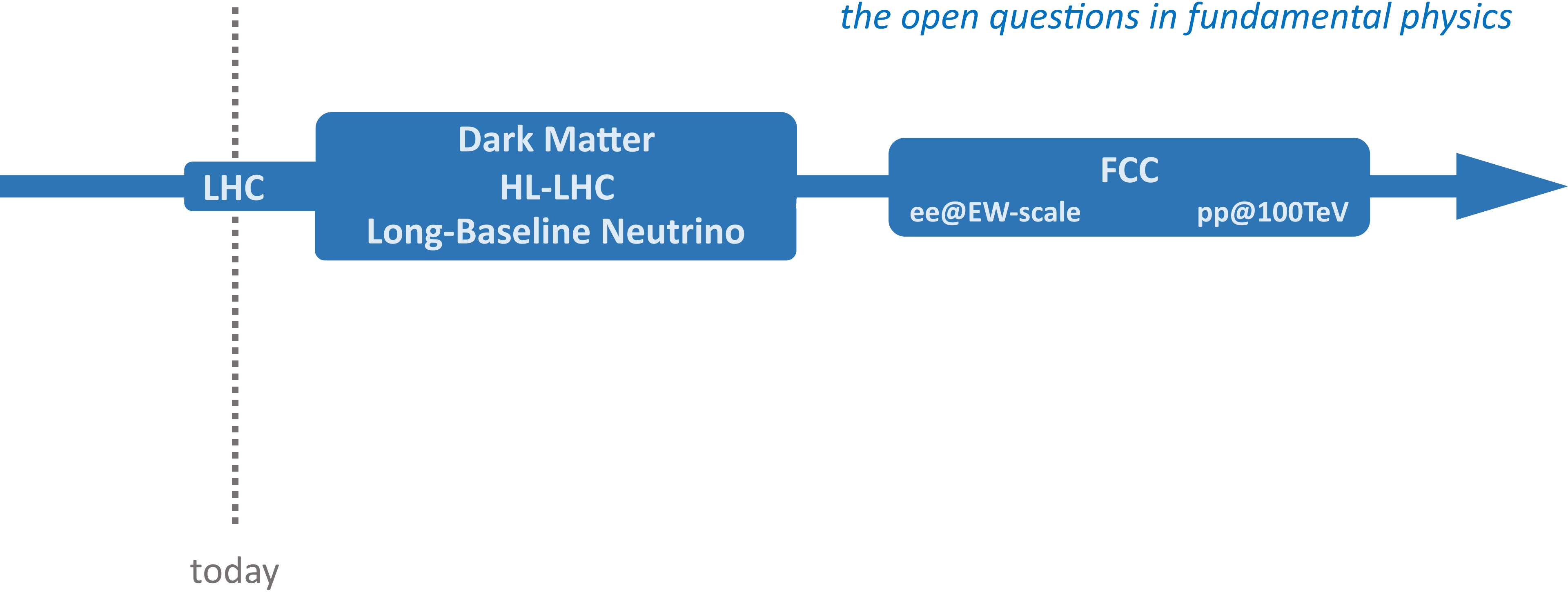


Our community should be able to respond when clear signs of new physics appear

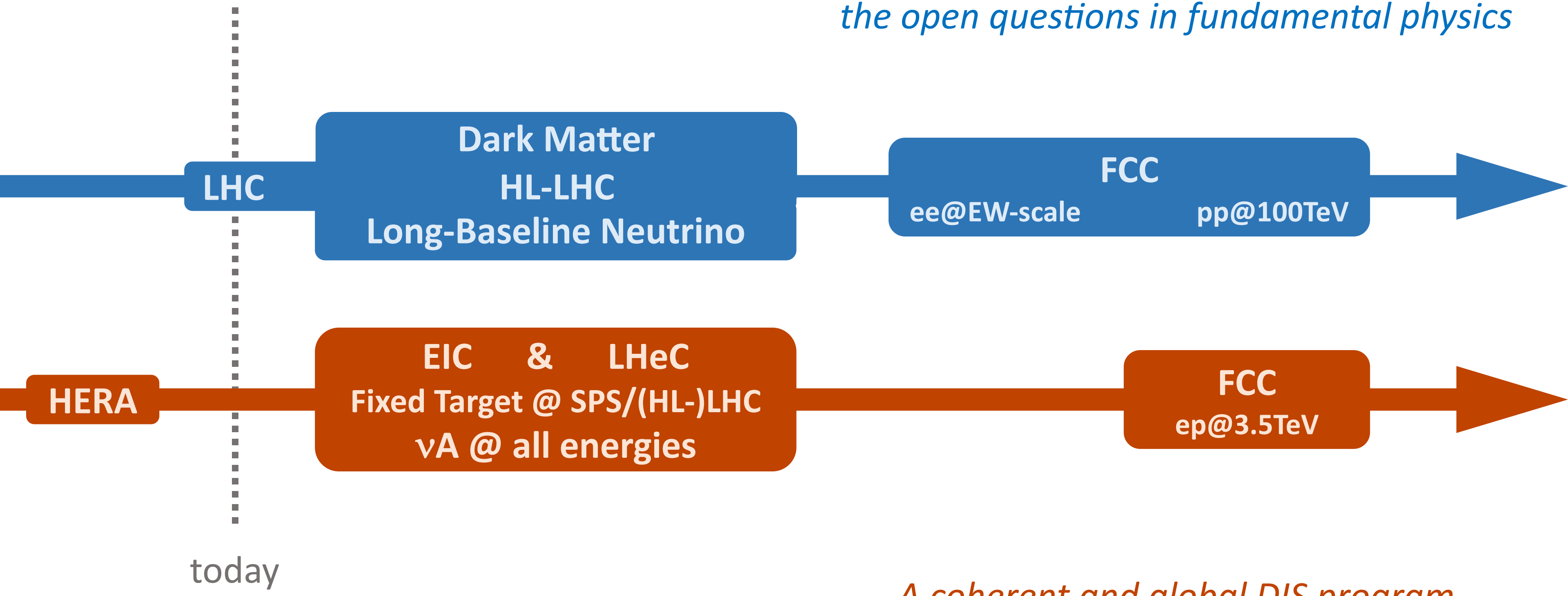
What would be our roadmap if indeed lepton flavour universality is violated? Search for leptoquarks?

e.g. recent LHCb results comparing B-meson decays of muons and electrons, the muon's anomalous magnetic moment g-2…

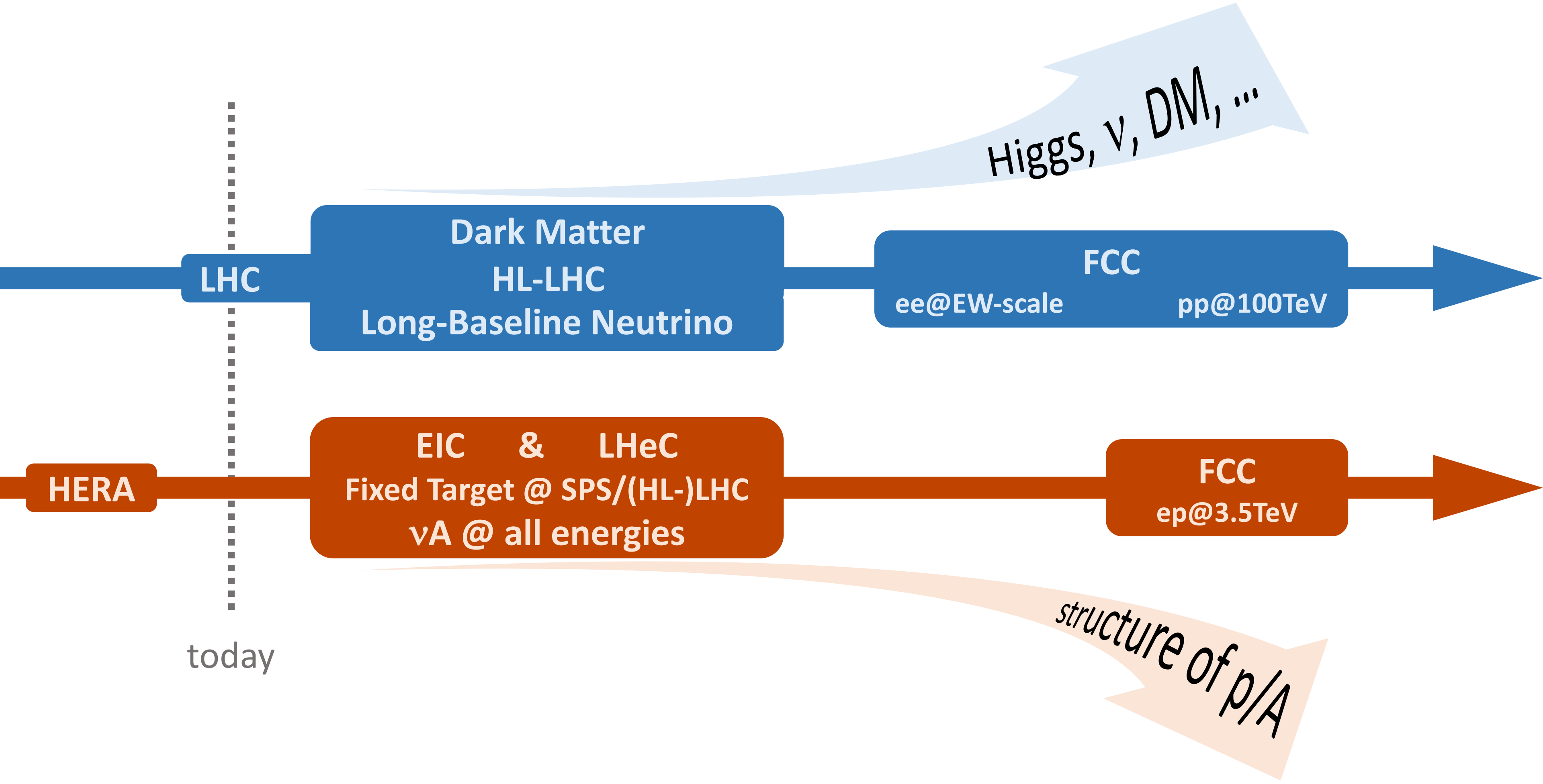
Our communnity is gearing up to future research programs addressing the open questions in fundamental physics

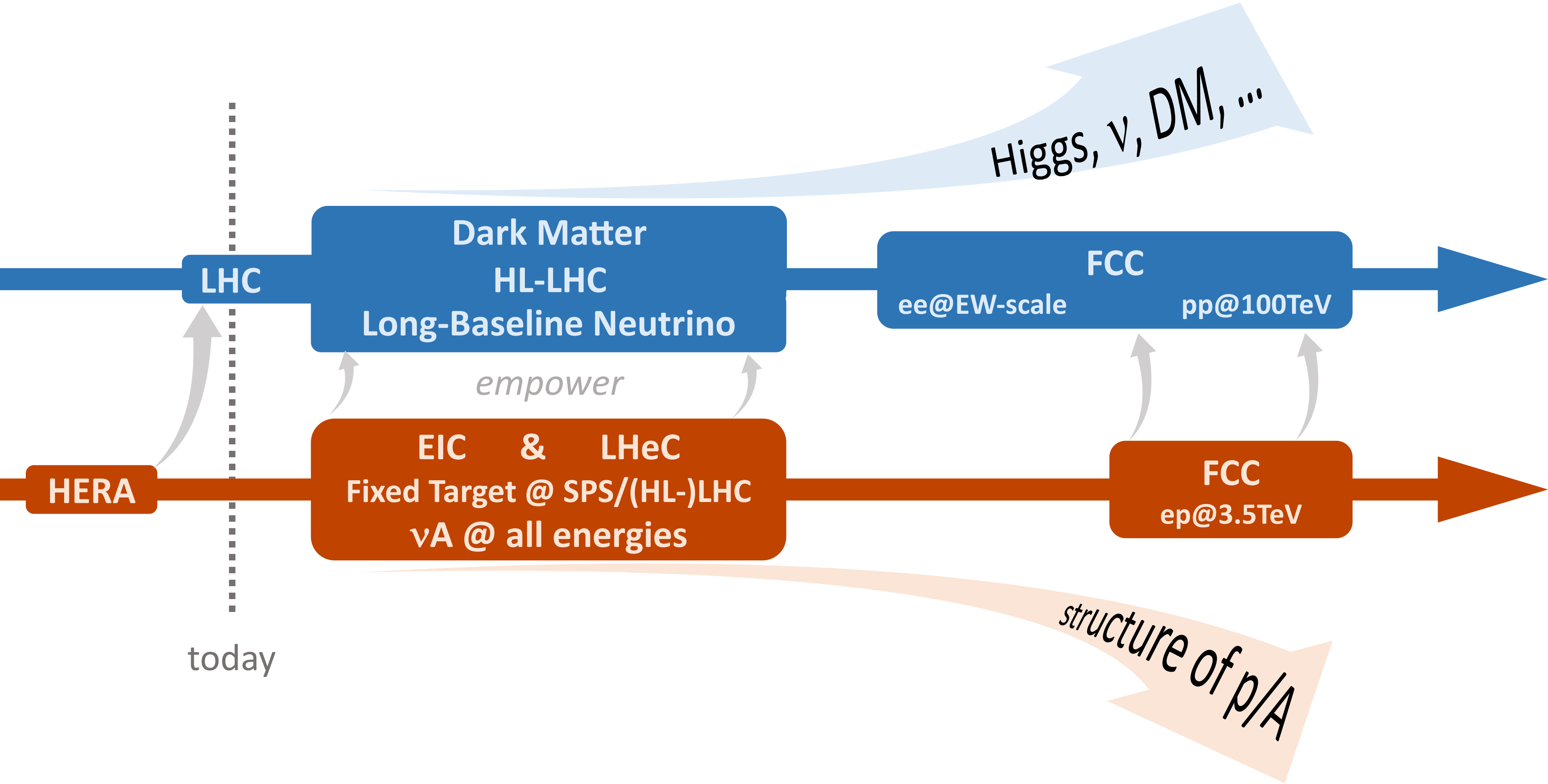


Our communnity is gearing up to future research programs addressing the open questions in fundamental physics



A coherent and global DIS program is a major part of this endeavour (experimental & theoretical)


Higgs, ν, DM, …
Dark Matter
HL-LHC
Long-Baseline Neutrino
LHC
FCC
ee@EW-scale
pp@100TeV
HERA
EIC & LHeC
Fixed Target @ SPS/(HL-)LHC
νA @ all energies
FCC
ep@3.5TeV
structure of p/A
today



Higgs, ν, DM, …
LHC
Dark Matter
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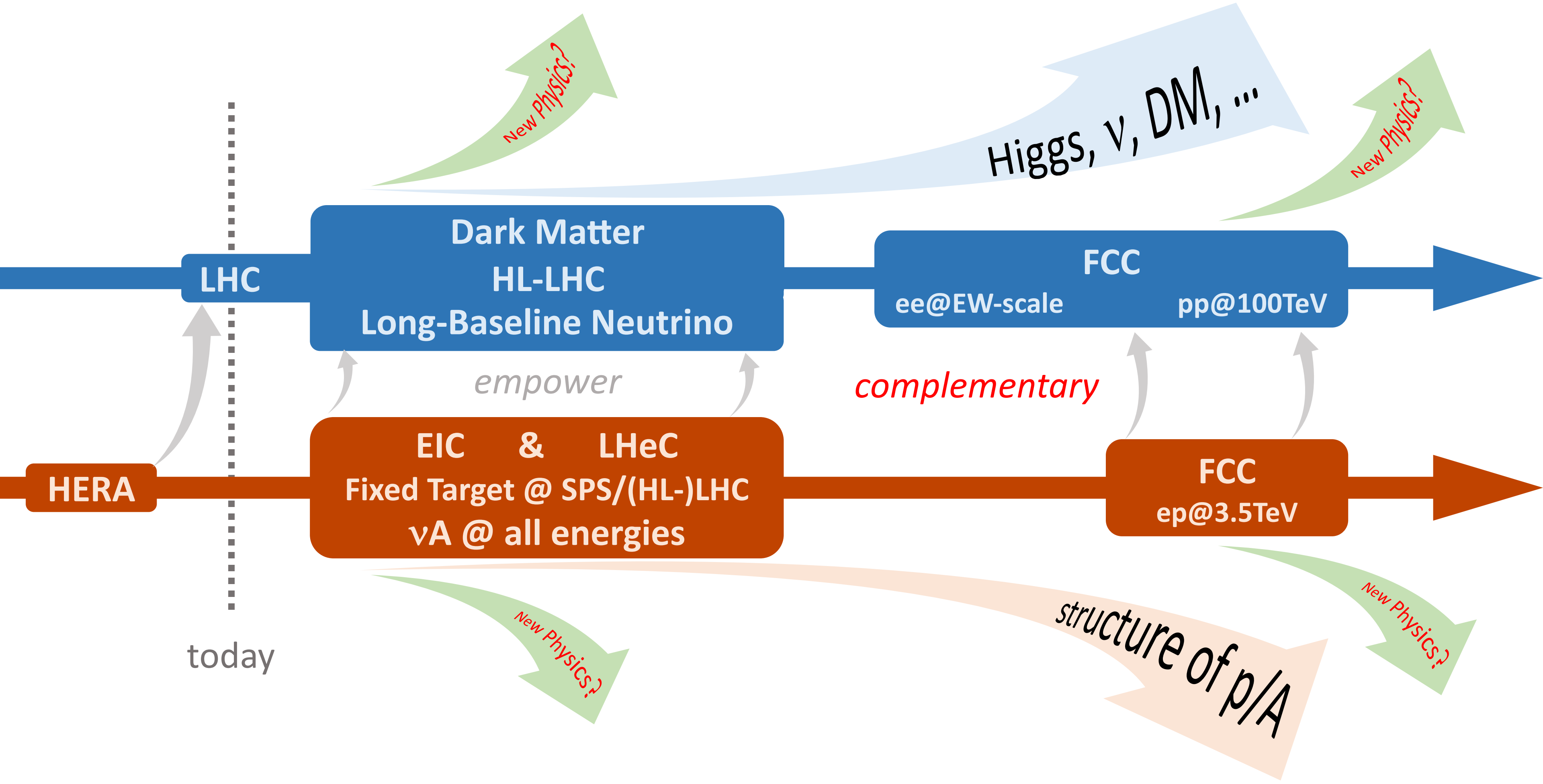
New Physics?
Higgs, ν, DM, ...
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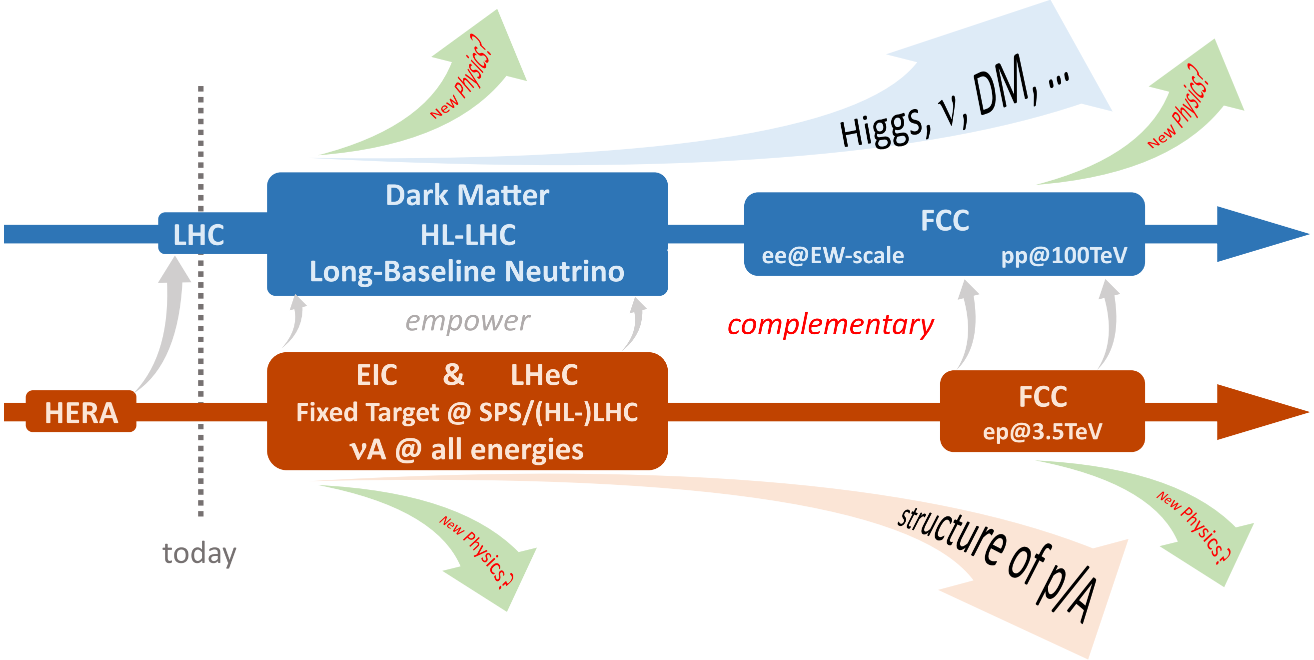
New Physics?

Building the DIS future together



Sustain a strong global DIS program is vital for particle physics

HIGH-ENERGY PHYSICS RESEARCH CENTRE

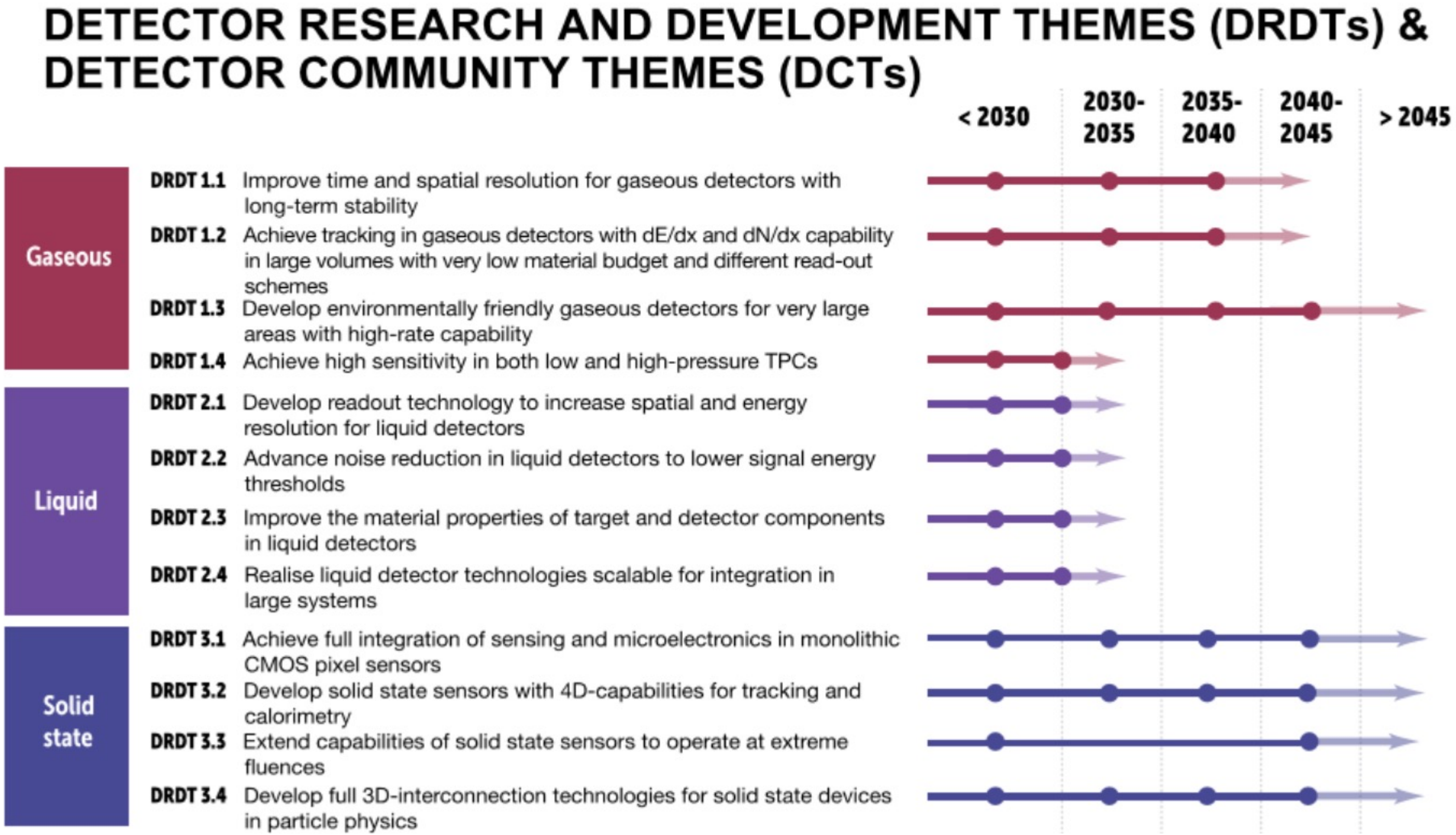
Thank you for your attention!

Jorgen.DHondt@vub.be

Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

European Detector R&D Roadmap (2021)



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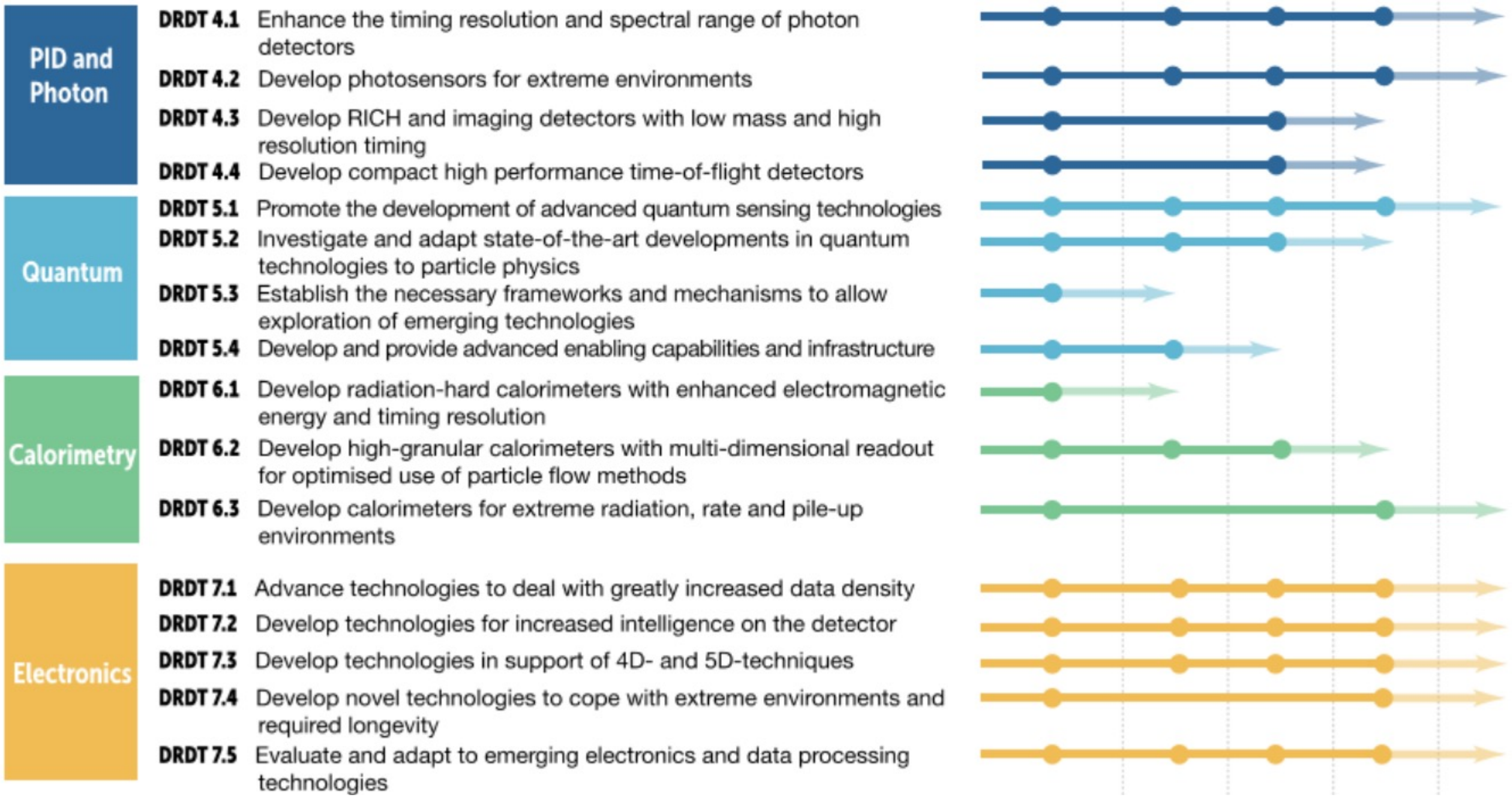

Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

European Detector R&D Roadmap (2021)

Electronics	DRDT 7.1	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	DRDT 8.1	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
Training	DCT 1	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation