Future Colliders

addressing open questions in fundamental physics with future particle colliders

Jorgen D'Hondt

Vrije Universiteit Brussel

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iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

Rencontres de Blois, Particle Physics and Cosmology

14-19 May 2023

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

quarks
$< 10^{-19}m$

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

~ 0.000˙000˙000˙000˙000˙000˙01 meter

distance to galactic center

distance light travels in one year

farthest human object from Earth (Voyager 1)

distance Earth-sun

biological cell

atoms

proton
neutron

observable universe

8.8 10^{26}m

visible with our own eyes

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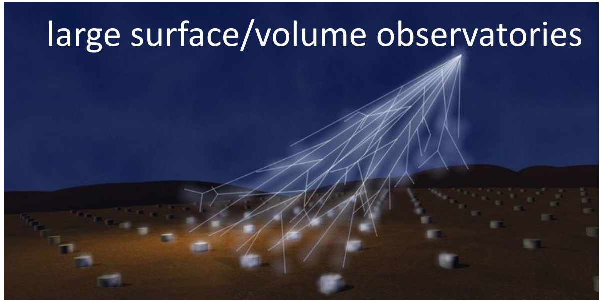

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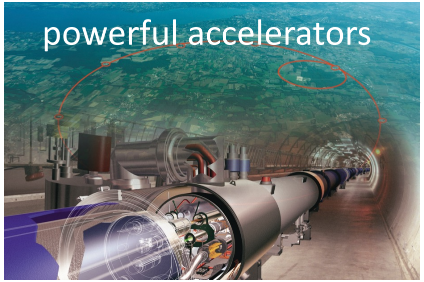

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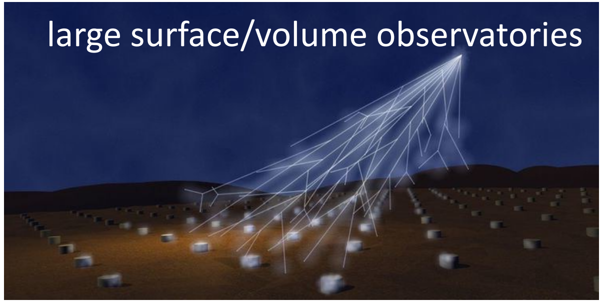
age universe
$4.4\ 10^{18}$ s

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



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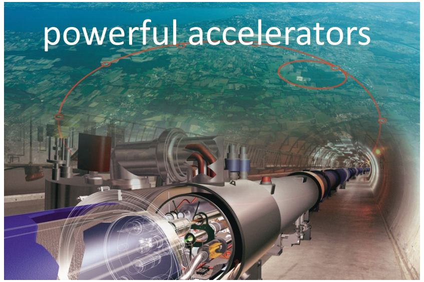

lifetime top quark
$5\ 10^{-25}$ s

quarks
$< 10^{-19}$m

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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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Concrete Models

APPLY MATHEMATICAL FRAMEWORKS ON OBJECTS

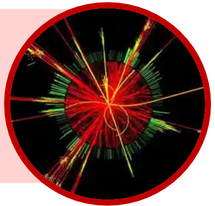
① ***General Relativity → Standard Model of Cosmology***
② ***Quantum Field Theory → Standard Model of Particle Physics***

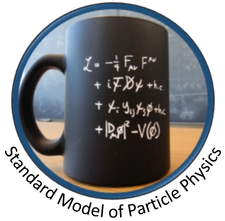
need to be valid into even the tiniest cracks of space and time and for all energies or masses of the objects… even at the extremes

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

~ 0.000˙000˙000˙000˙000˙000˙01 meter

observations how small objects behave in our laboratories





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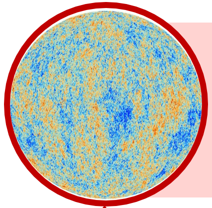
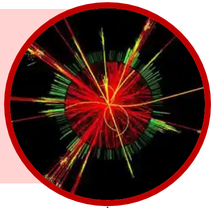
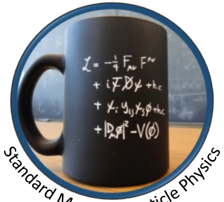


observations how large objects behave in our universe

Standard Model of Cosmology

observations how small objects behave in our laboratories





Standard Model of Particle Physics

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

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

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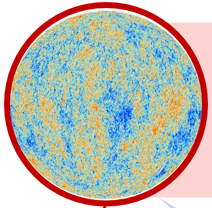
building blocks of life on the human scale



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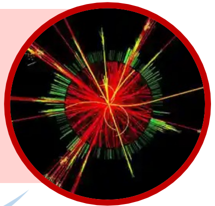
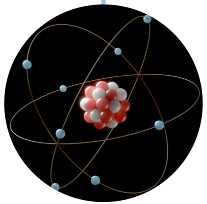


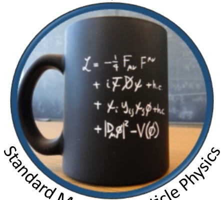
observations how small objects behave in our laboratories



e.g. creation of chemical elements

e.g. nuclei built from quarks and gluons

Standard Model of Cosmology



Standard Model of Particle Physics

A century of scientific revolutions

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

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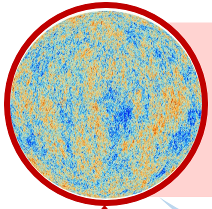
building blocks of life on the human scale



observations how large objects behave in our universe

Standard Model of Cosmology

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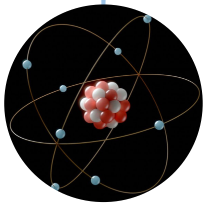
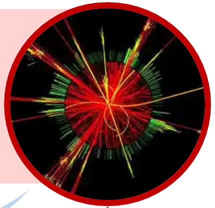
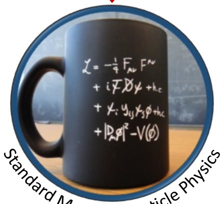


e.g. nuclei built from quarks and gluons

observations how small objects behave in our laboratories





Standard Model of Particle Physics

communication
satellites
GPS

A century of scientific revolutions

World Wide Web
touchscreens

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

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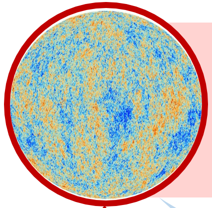
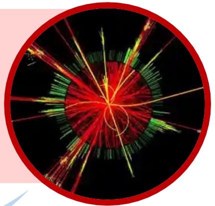
building blocks of life on the human scale



observations how large objects behave in our universe

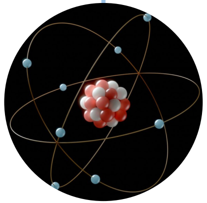
production of particles and radiation
nuclear diagnosis and medicine

observations how small objects behave in our laboratories



Standard Model of Cosmology

e.g. creation of chemical elements



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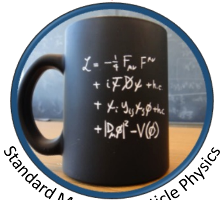
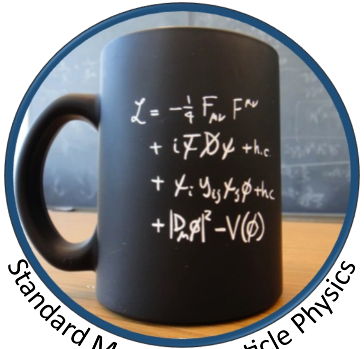


Standard Model of Particle Physics

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

The quest for understanding physics



Standard Model of Particle Physics

Standard Model of Cosmology

"Problems and Mysteries"

e.g. Abundance of dark matter?

Abundance of matter over antimatter?

What is the origin and engine for high-energy cosmic particles?

Dark energy for an accelerated expansion of the universe?

What caused (and stopped) inflation in the early universe?

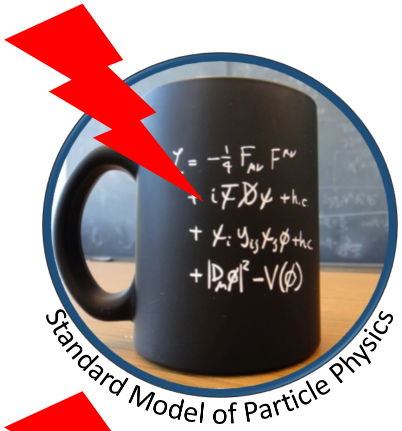
Scale of things (why do the numbers miraculously match)?

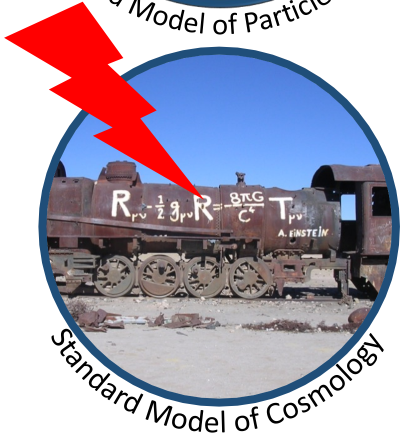
Pattern of particle masses and mixings?

Dynamics of Electro-Weak symmetry breaking?

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

The quest for understanding physics





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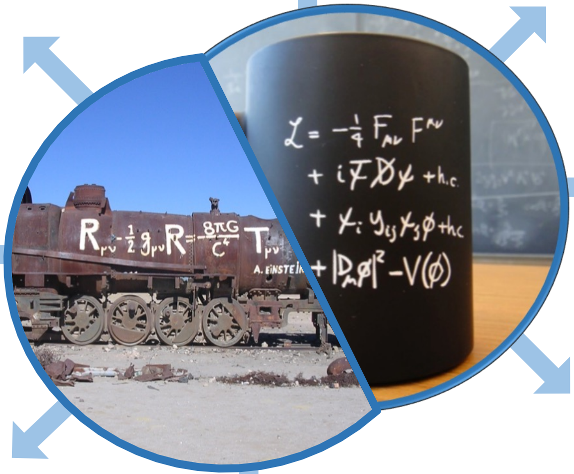
Observations of new physics phenomena and/or deviations from the Standard Models are expected to unlock concrete ways to address these puzzling unknowns

higher energy interactions
in the lab

earlier universe

rarer processes



higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

RF cavities, high-field magnets, plasma wakefield acceleration

higher energy interactions
in the lab

squeezed-light sources to
deal with quantum noise
in gravitational-wave
detectors

earlier universe

rarer processes

solid-state devices with
fast read-out electronics

Innovate Technology

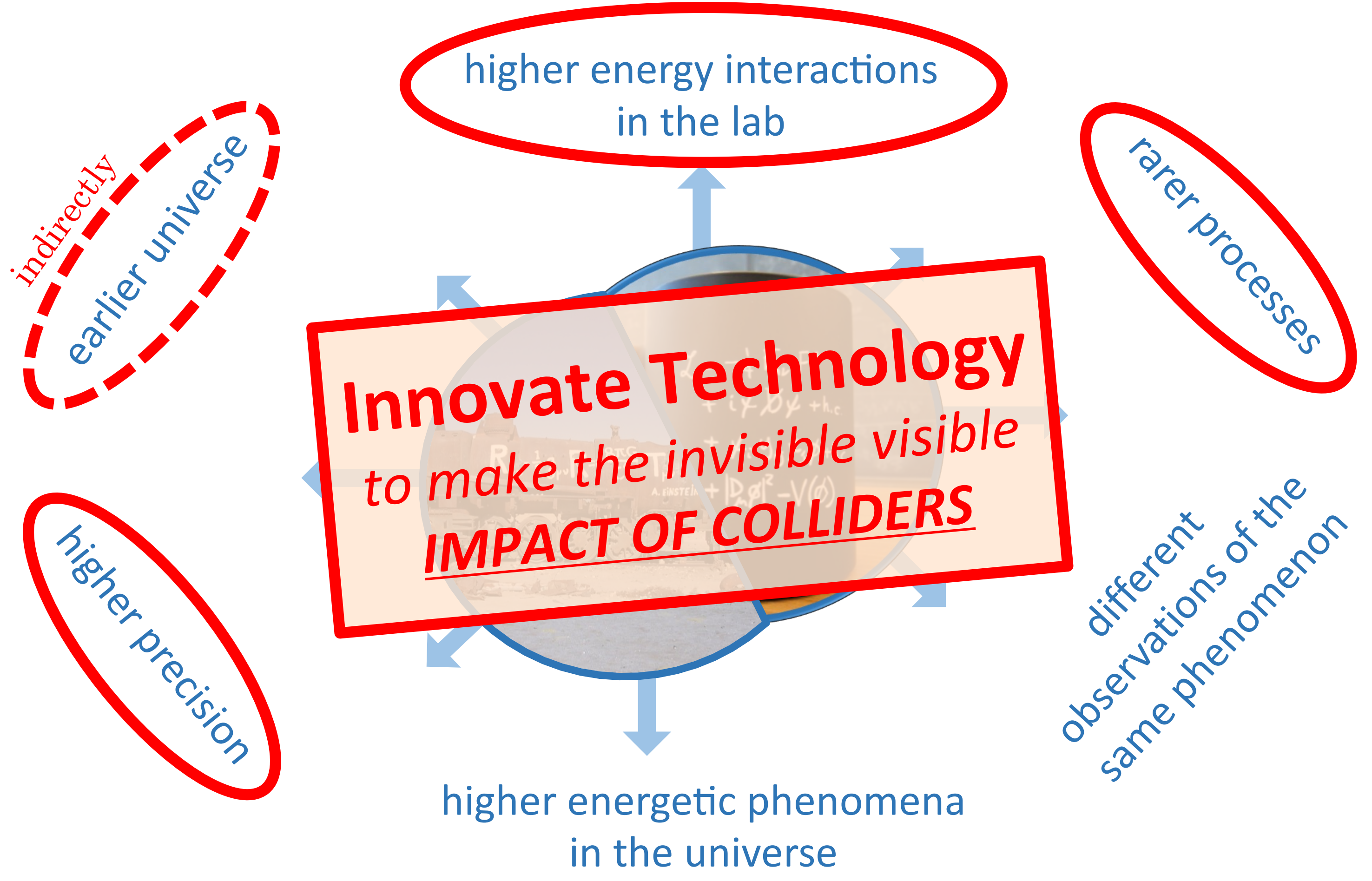
to make the invisible visible

higher precision

different
observations of the
same phenomenon

higher energetic phenomena
in the universe

computing and software challenge for Multi-Exabyte Data Infrastructures



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

Some key uncharted territories where colliders have unique impact:

Higgs sector

Flavour sector

Structure of matter

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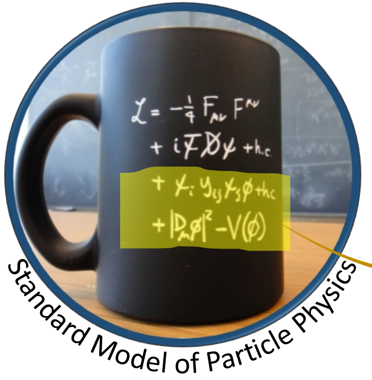
Higgs sector

Flavour sector

Structure of matter

The Higgs field fills the vacuum as a scalar field



window to new physics

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

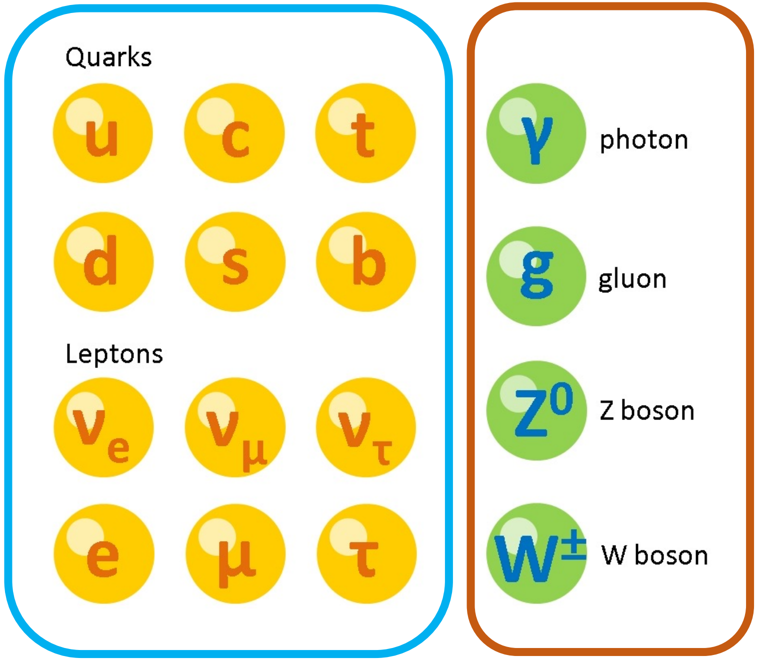
The scalar H field is home to the scalar H boson which is deeply intertwined with the vacuum structure throughout space-time and its mass is wildly sensitive to quantum fluctuations emerging from new physics phenomena at (higher) energies.

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

Hence the argument to built new colliders dedicated to produce copiously Higgs bosons in order to map precisely its interactions with other particles and itself.

Higgs couplings today

A unique window of opportunnity to probe for new physics phenomena



building blocks of matter (fermions *f*)

forces between them (bosons *V*)

Theory prediction

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

$$y_f \propto m_f$$

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

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

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

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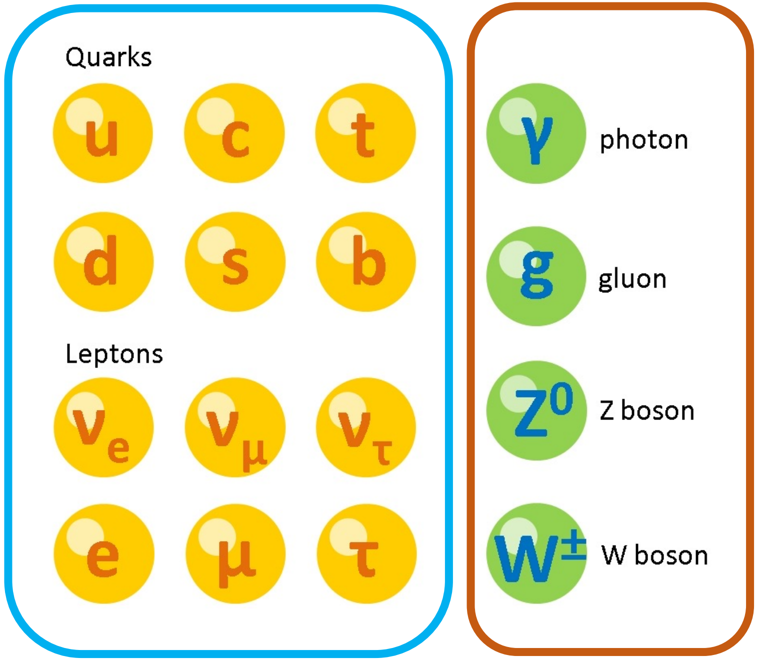

building blocks of matter
(fermions *f*)

forces between them
(bosons *V*)

Theory prediction

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

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

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

simple coupling modifiers

involving new particles and/or new interactions

Higgs couplings today

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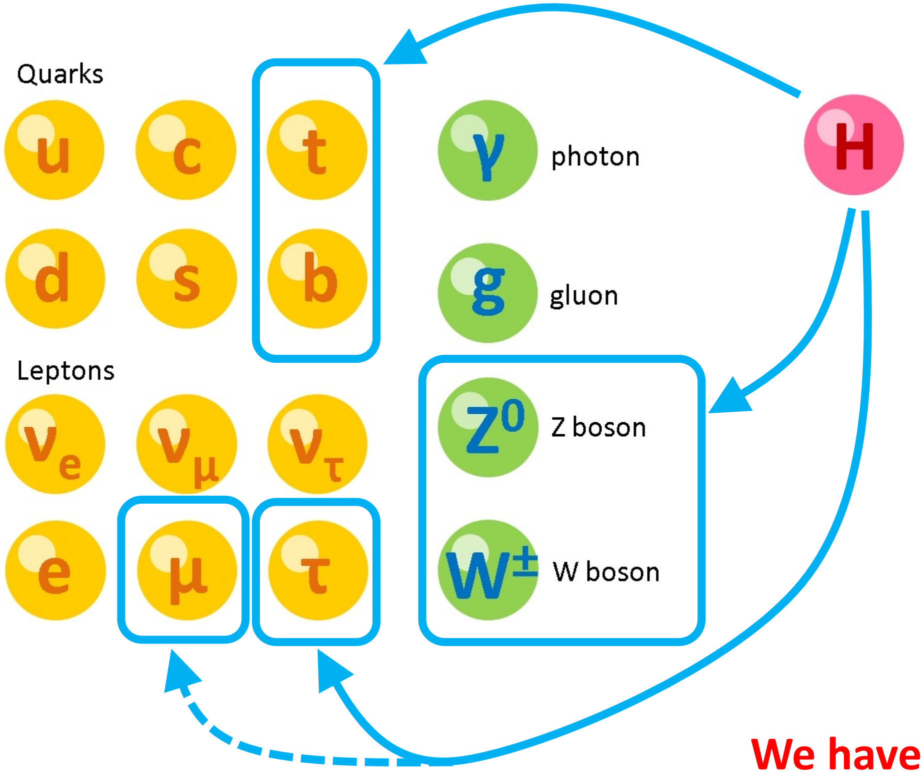
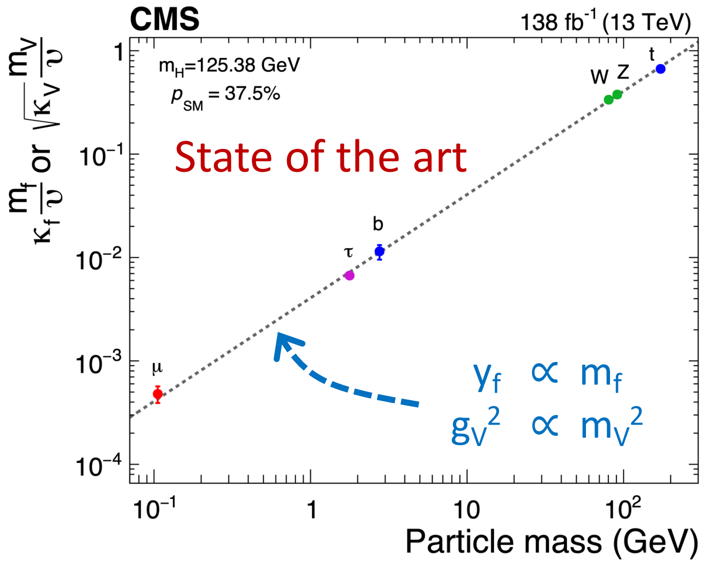




We have only seen a first glimpse of the H sector

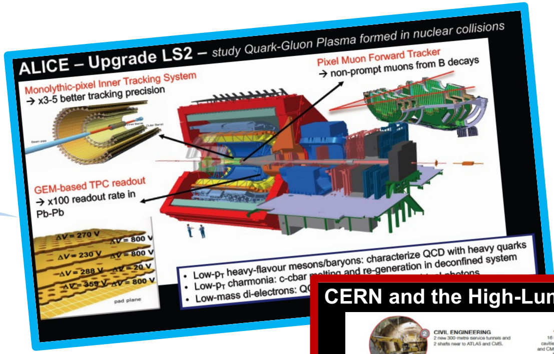
planned upgrade of today's flagship collider

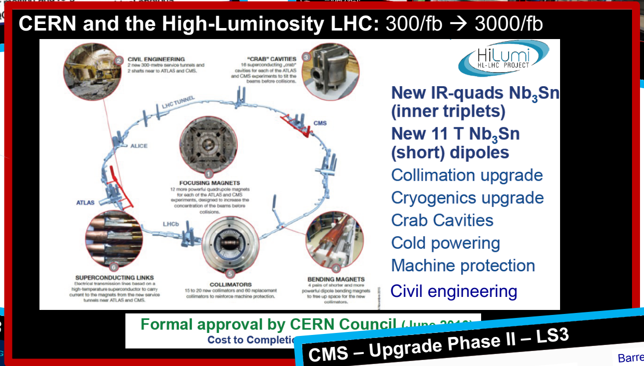
Today's Flagship: from LHC to HL-LHC

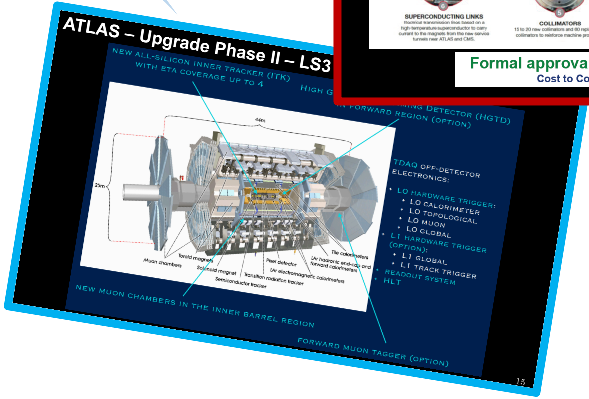
Current flagship (27km)

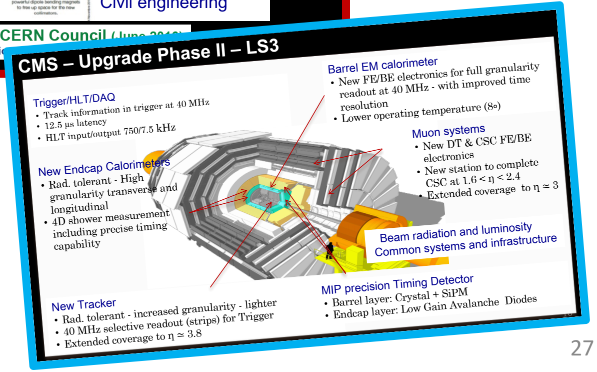
impressive programme up to 2042

dataset x10









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

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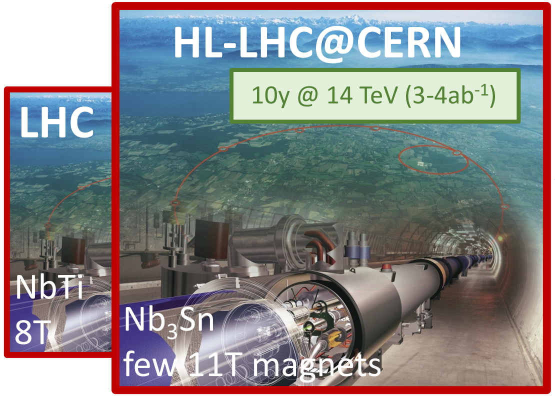


continued innovations in experimental techniques will keep the (HL-)LHC at the focal point to seek new physics at the energy and intensity frontiers

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

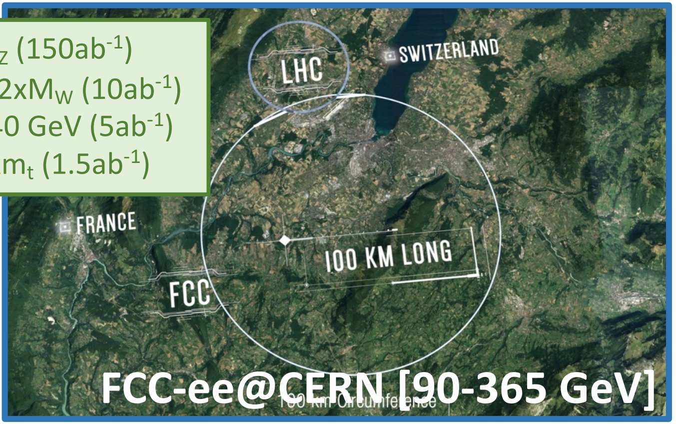
future colliders concepts

Higgs Factories

e^+e^- Higgs Factories

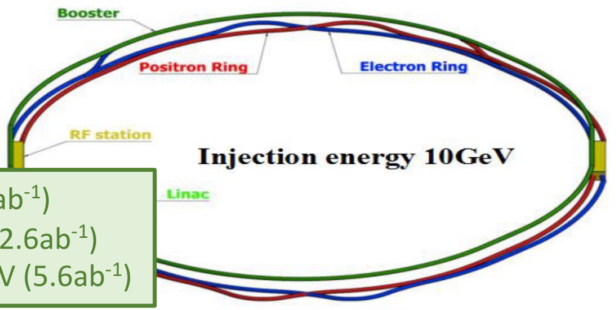
circular colliders

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



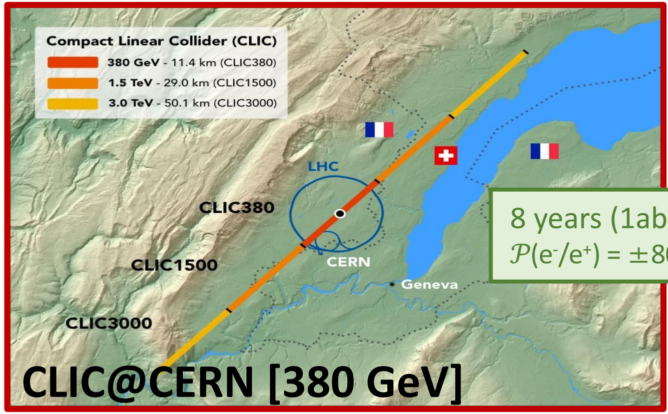
FCC-ee@CERN [90-365 GeV]

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



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

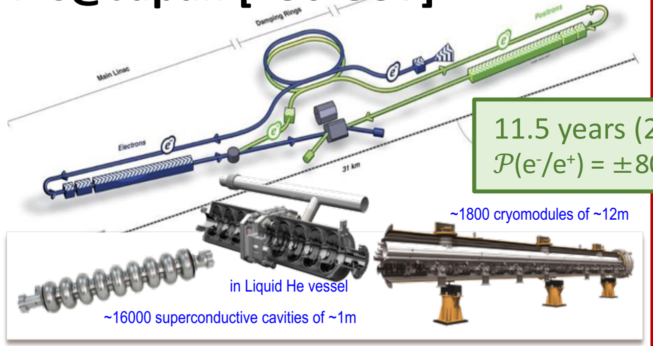
linear colliders



CLIC@CERN [380 GeV]

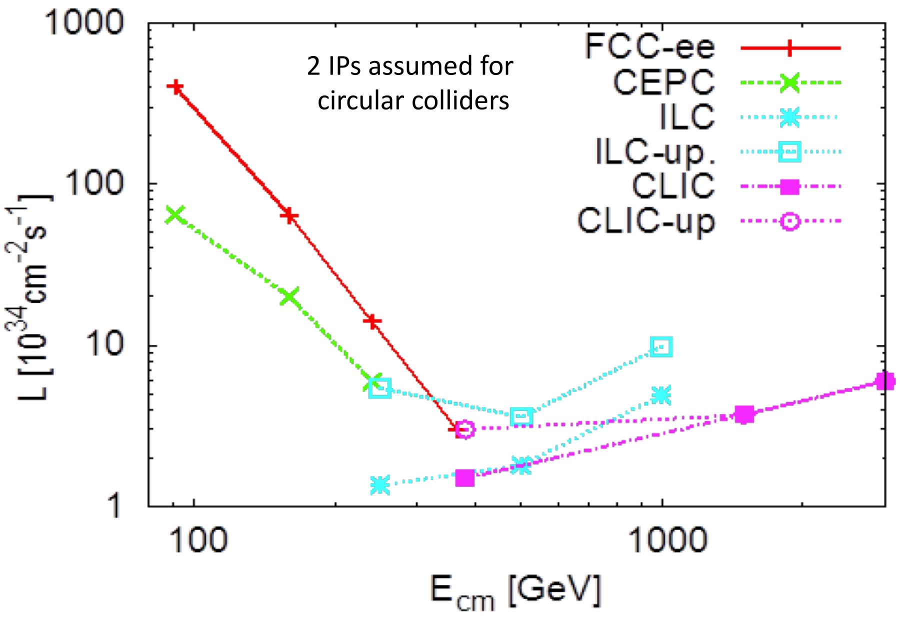
8 years (1ab^{-1})
$\mathcal{P}(e^-/e^+) = \pm 80\%/0\%$

ILC@Japan [250 GeV]



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

e^+e^- Higgs Factories



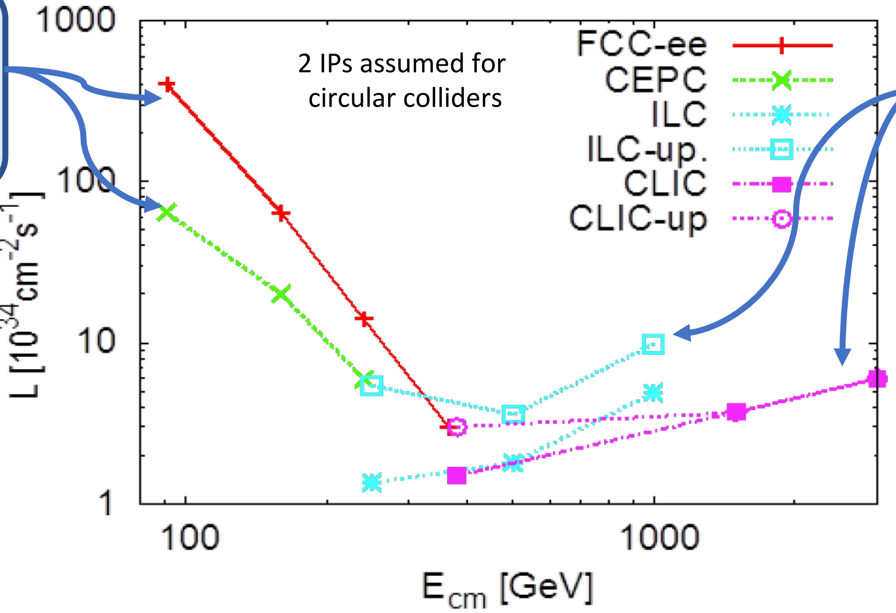
e^+e^- Higgs Factories

precision frontier

circular colliders

synchrotron radiation

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



linear colliders

energy frontier

e^+e^- Higgs Factories

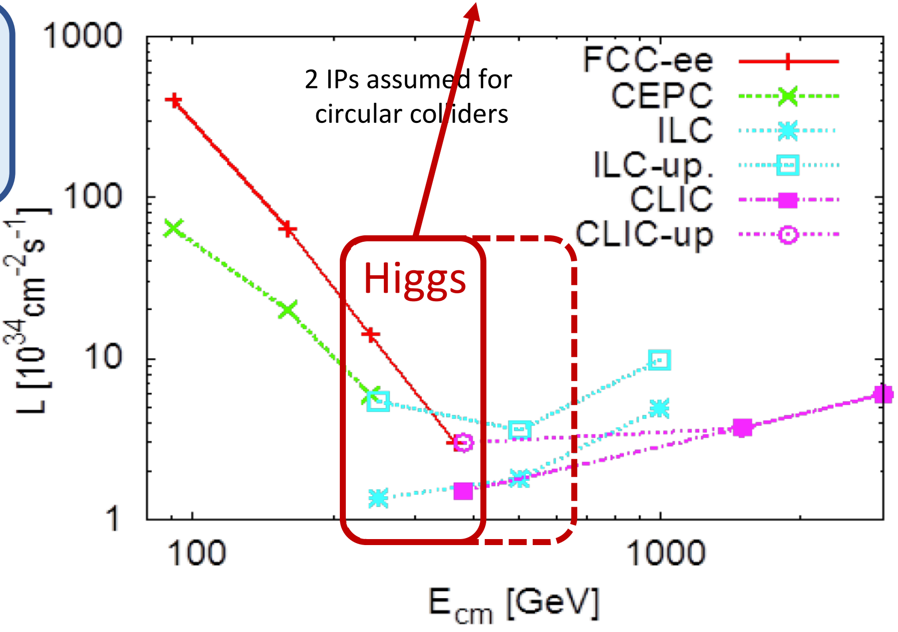
precision frontier

circular colliders

synchrotron radiation

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

Higgs Factories



linear colliders

energy frontier

e^+e^- Higgs Factories

precision frontier

circular colliders

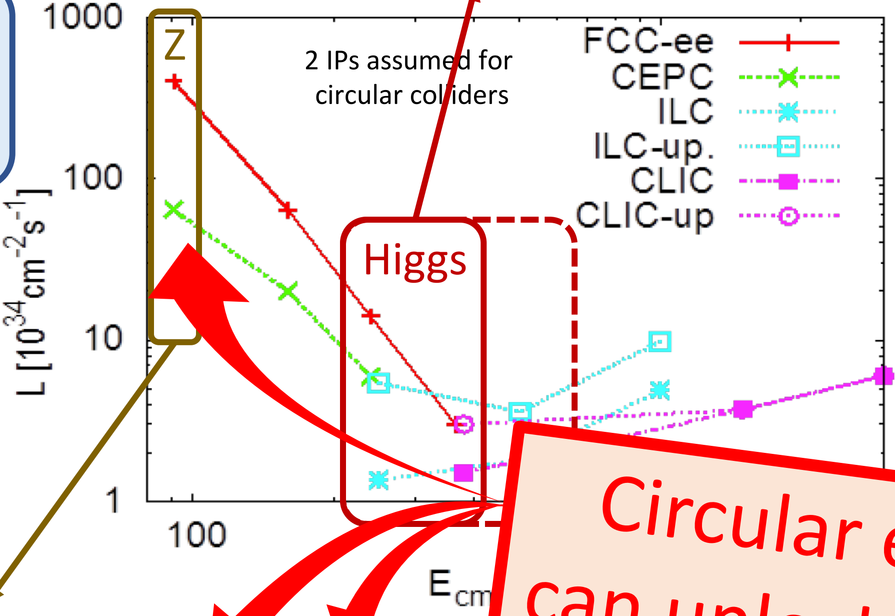
linear colliders

energy frontier

synchrotron radiation

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

Higgs Factories

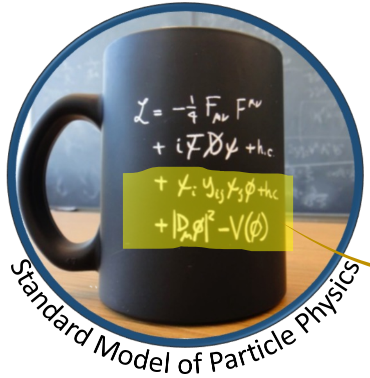


Circular e^+e^- colliders can unlock new territory in flavour physics

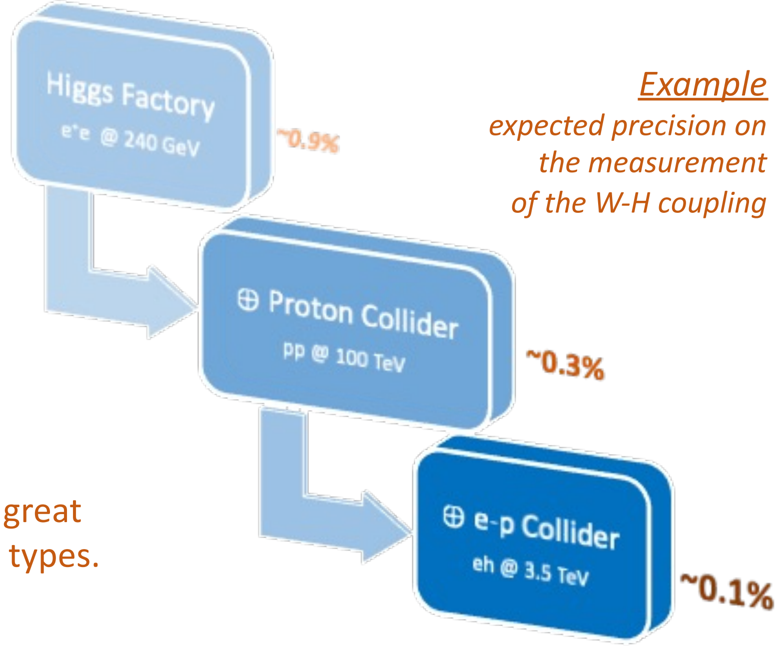
Flavour Factories

per detector in e^+e^-	# Z	# B	# τ	# charm	
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	
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

Aditional future high-energy particle colliders



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 complementarity among the science reach of different collider types.

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

Future flagship at the energy & precision frontier

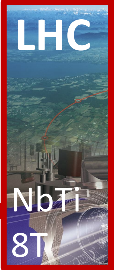
Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

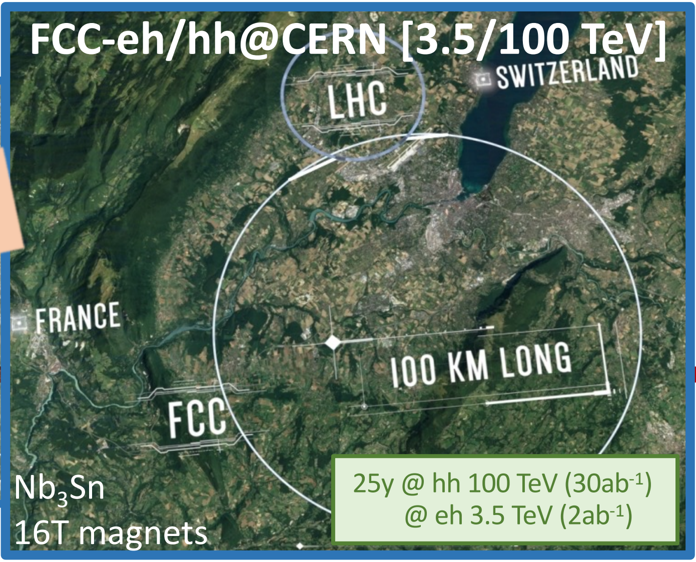
attractive combination of precision & energy frontier



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

Zooming into the Higgs sector with the FCC

Complementarity between ee/eh/hh colliders

(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

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

Zooming into the Higgs sector with the FCC

Complementarity between ee/eh/hh colliders

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

the one from the previous slide

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL	+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
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ALL COMBINED

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(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
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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 the FCC

Complementarity between ee/eh/hh colliders

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

kappa-0-HL	HL+FCC...	...	...	...e/eh/hh
Γ_H		0.61	1.3	0.44

complementarity between
e$^+$e$^-$ Higgs Factories
and
high-energy pp & ep colliders

only FCC-ee@240GeV

adding 365 GeV runs

adding FCC-ep

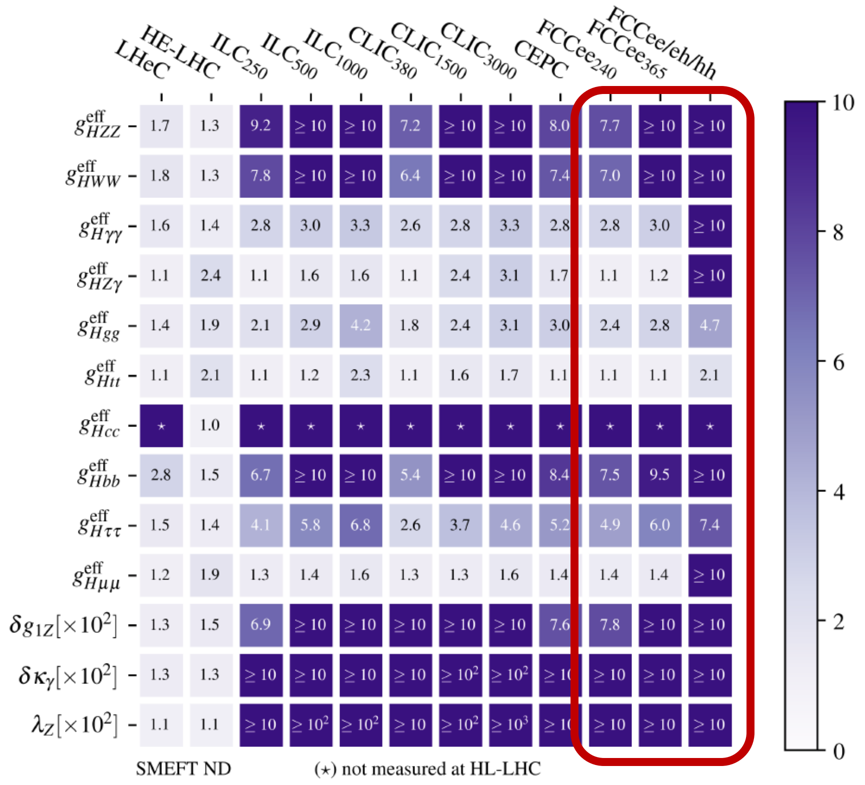
only FCC-hh

ALL COMBINED

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

Ultimate Higgs Factory = {ee + eh + hh}

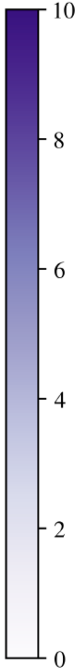
improvement factor adding FCC results additional to HL-LHC



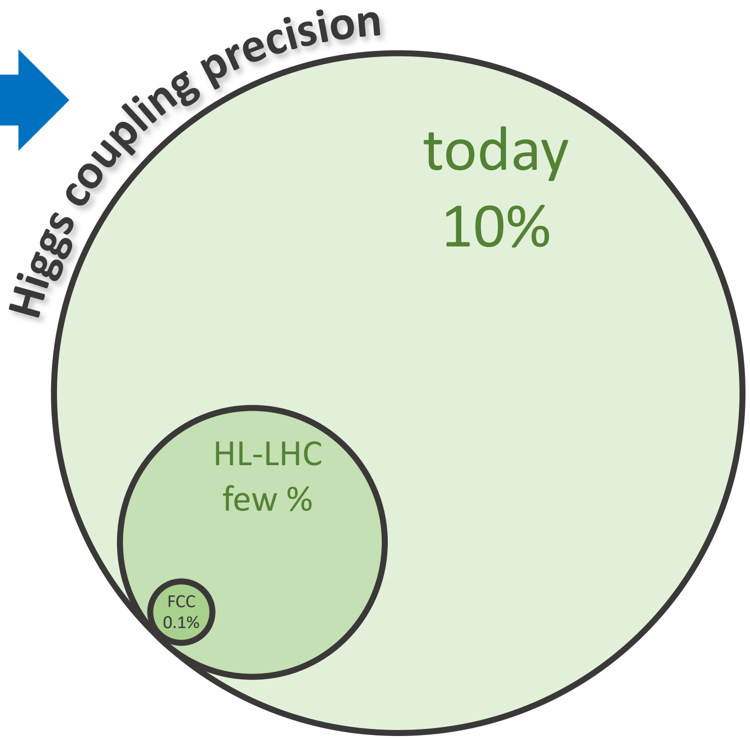
[J. de Blas et al., JHEP 01 (2020) 139]

Ultimate Higgs Factory = {ee + eh + hh}

	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
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{eff}_{HZ\gamma}$	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
$g^{eff}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{eff}_{H\mu\mu}$	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

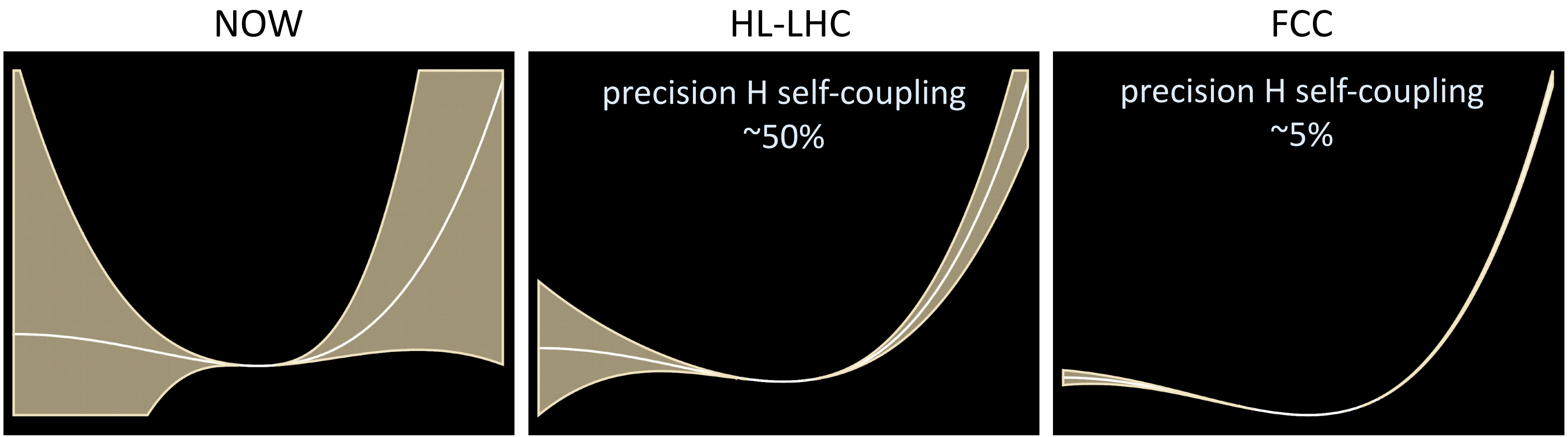


SMEFT ND (⋆) not measured at HL-LHC



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

Ultimate Higgs Factory = {ee + eh + hh}

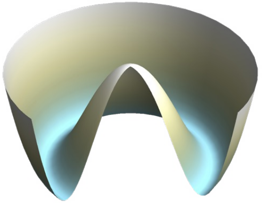


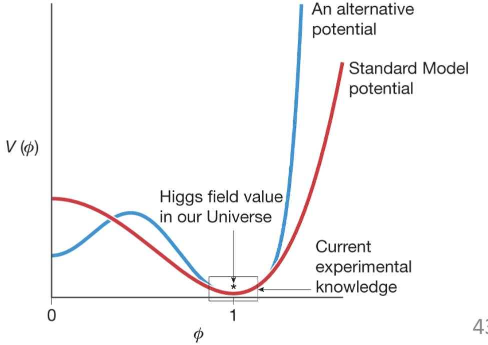
Adapted from Nathanial Craig

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

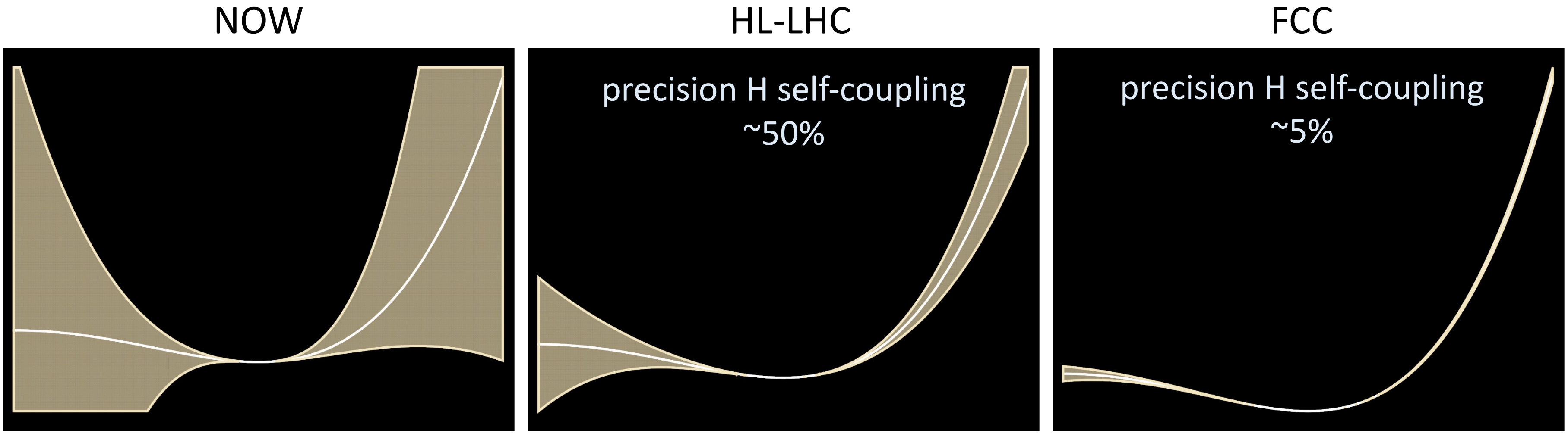
$$V_{higgs} = -\frac{1}{2}m^2|\varphi|^2 + \frac{\lambda}{4}|\varphi|^4$$

m_H *H self-coupling*





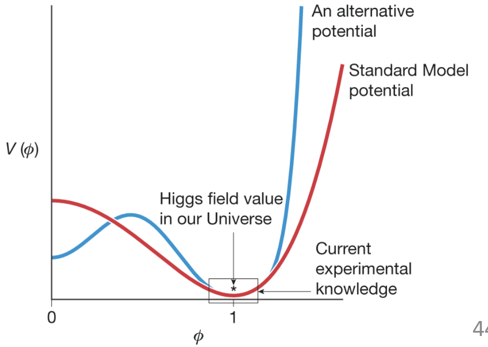
Ultimate Higgs Factory = {ee + eh + hh}



Adapted from Nathanial Craig

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

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



Breakthroughs with more precise observations

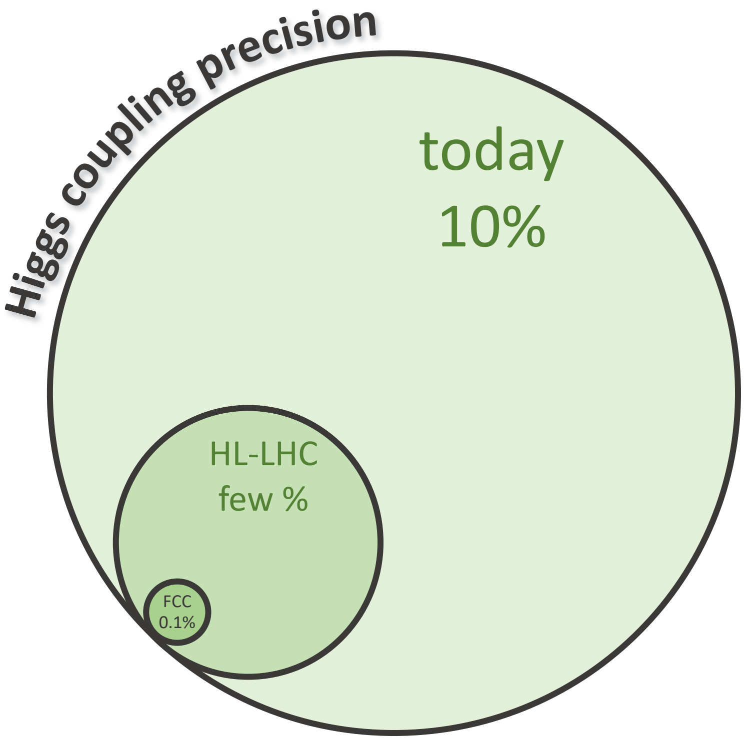
e.g., a more precise analysis of measured UV light reaching Earth revealed the ozone hole

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

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

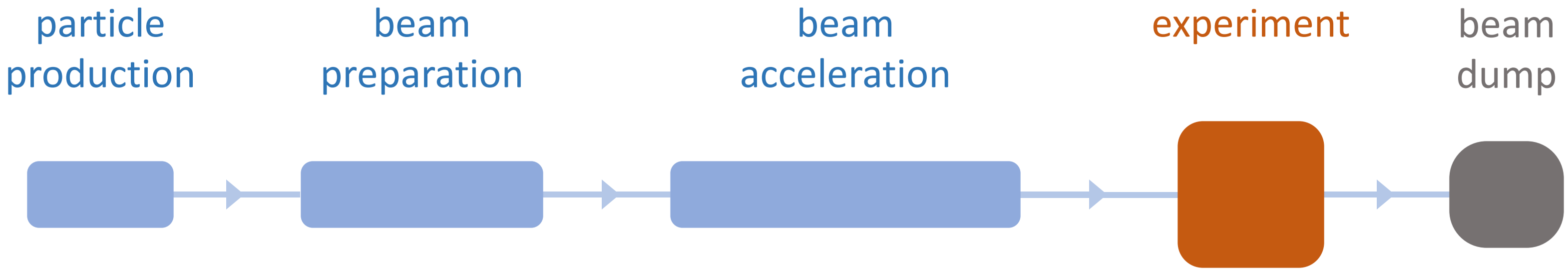
Unless dramatic new insights appear, we have to built a Higgs Factory to ever be able to answer our open fundamental problems.

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

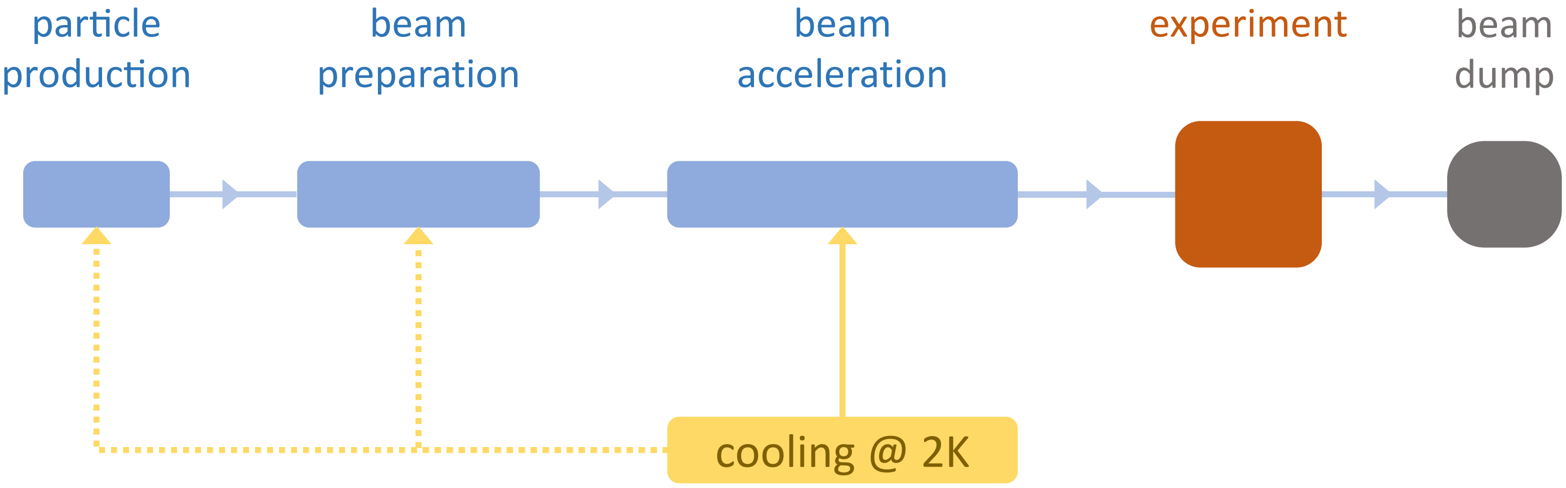


Caveat
Sustainable Accelerating Systems

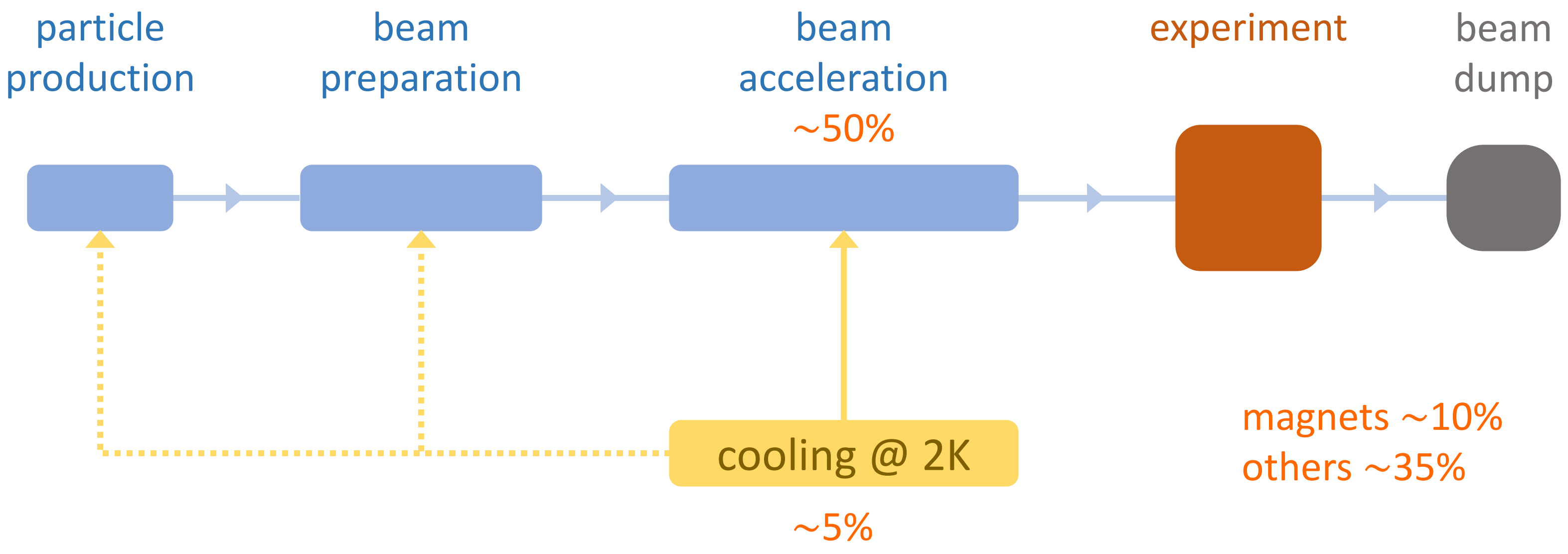
Basic structures of a particle accelerator



Basic structures of a particle accelerator



Basic structures of a particle accelerator

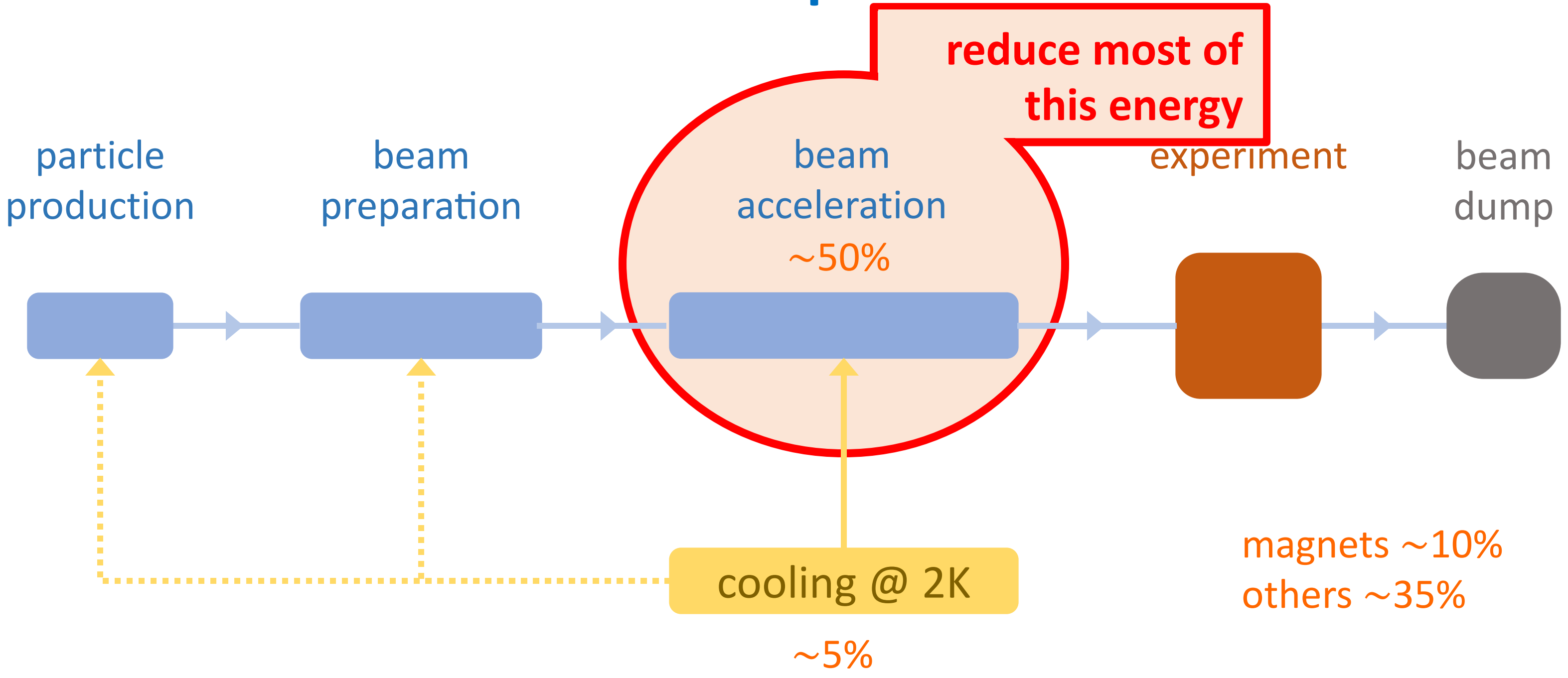


Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



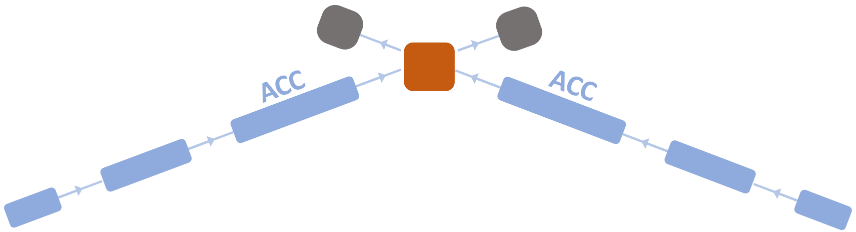
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

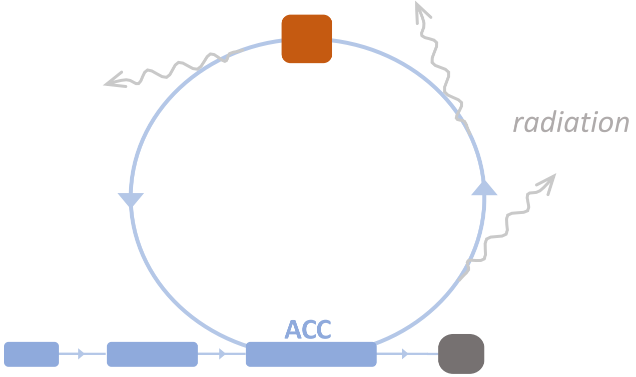
example FCC@250GeV

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 $\simeq$ 300 MW

~2% of annual electricity consumption in Belgium

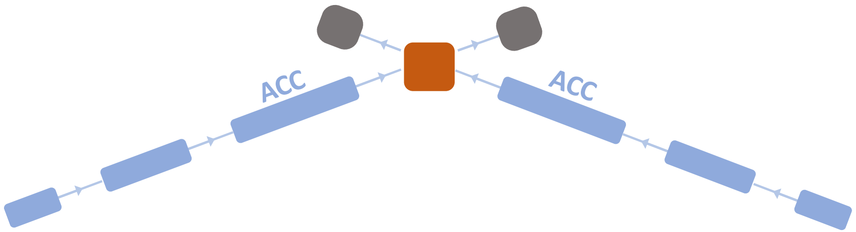
radiate away very quickly the beam power

about half of this is dumped or lost due to radiation

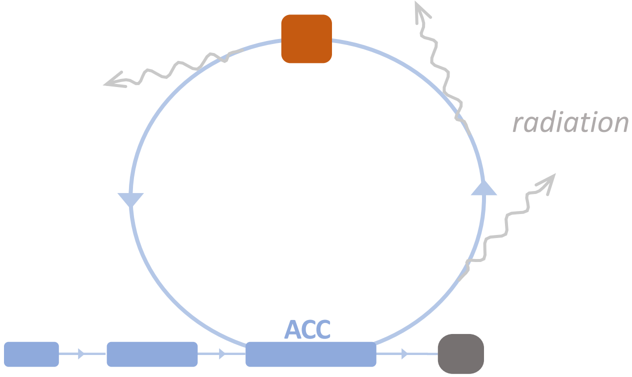
OBJECTIVE: develop new accelerating systems that save power with an impact of saving ~1% of Belgium's electricity

Impact for the current designs of Higgs Factories

Linear colliders



Circular colliders



dump >99.9999% of the beam power

FCC-ee@250 ≃ 300 MW

~4% of annual electricity consumption in Belgium

radiate away very quickly the beam power

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

about half of this is dumped or lost due to radiation

OBJECTIVE: develop new accelerating systems that save power with an **impact of saving ~2% of Belgium's electricity**

Importance highlighted in the European Strategy for Particle Physics 2020

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

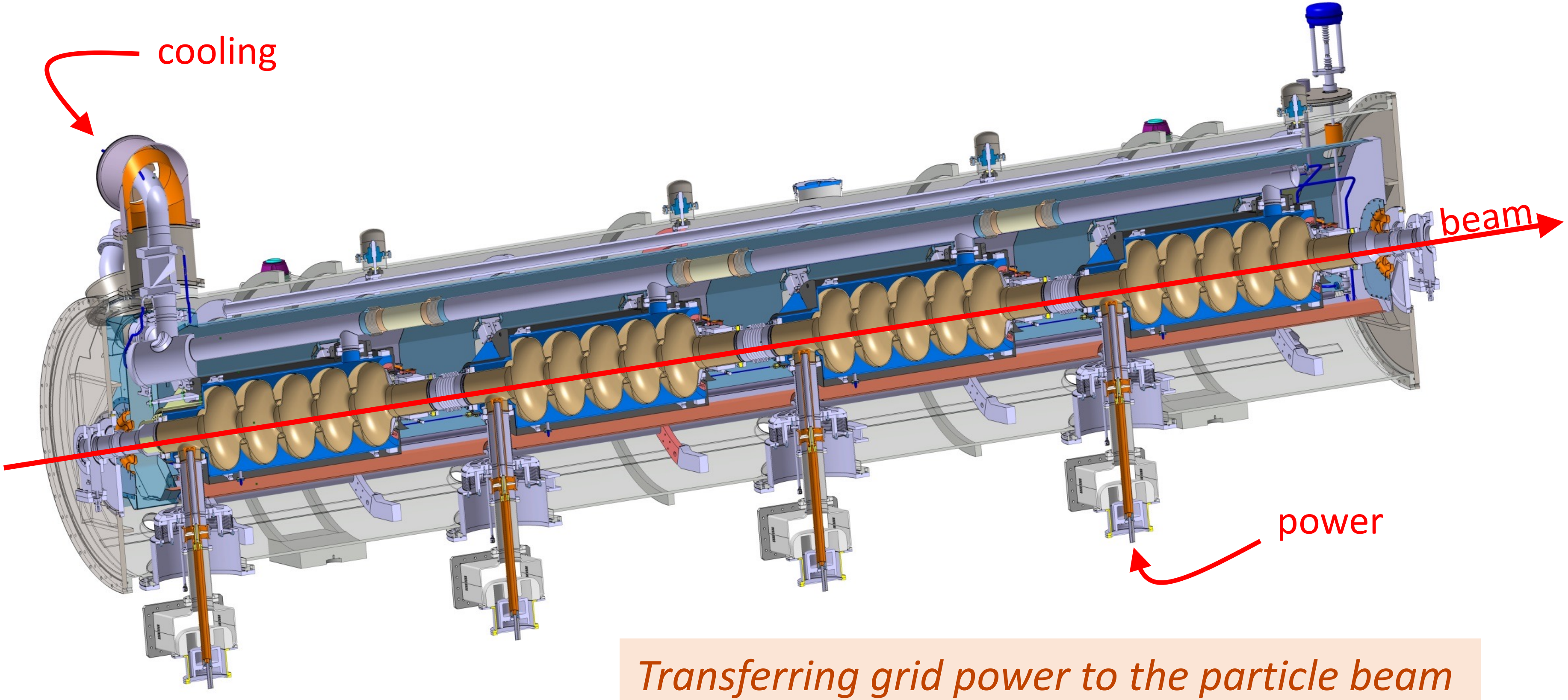
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

A detailed plan for the […] saving and re-use of energy should be part of the approval process for any major project.

European Strategy for Particle Physics 2020

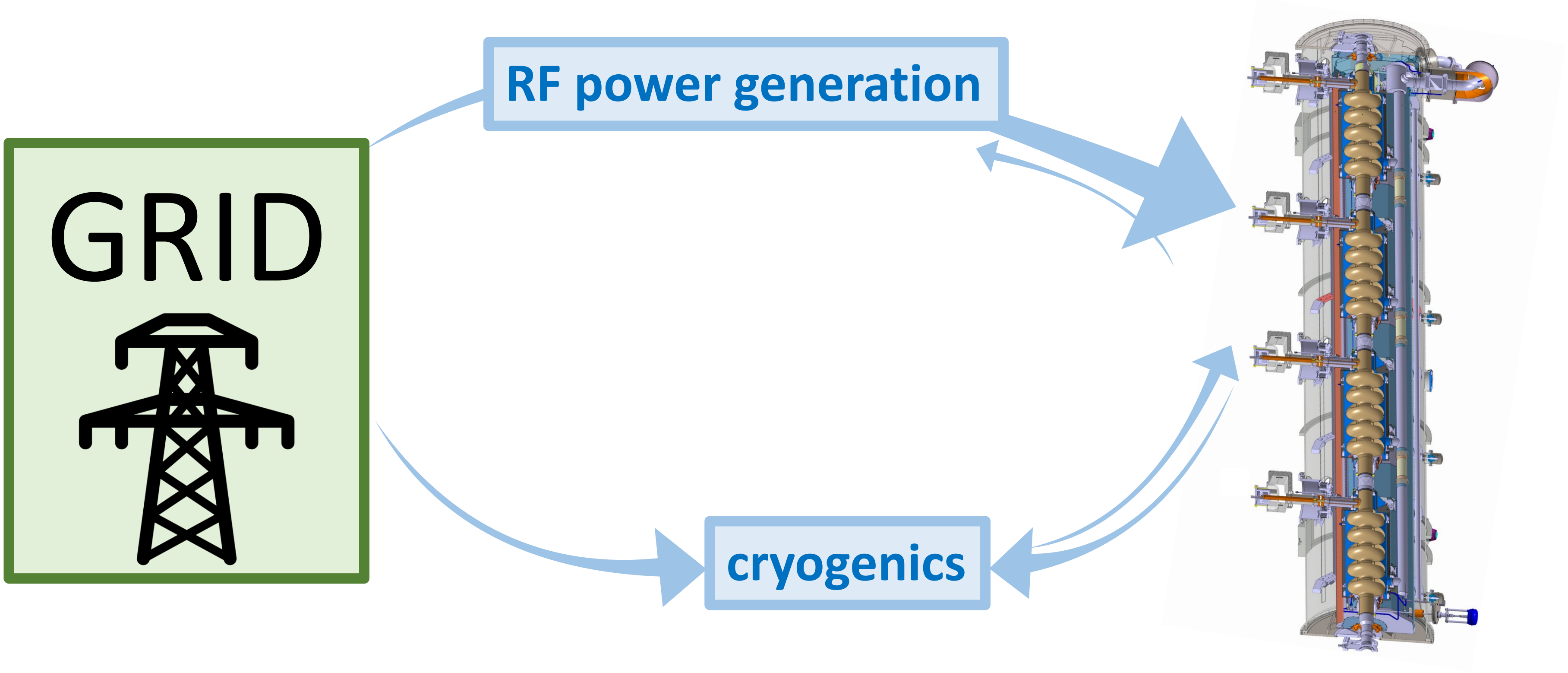
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency



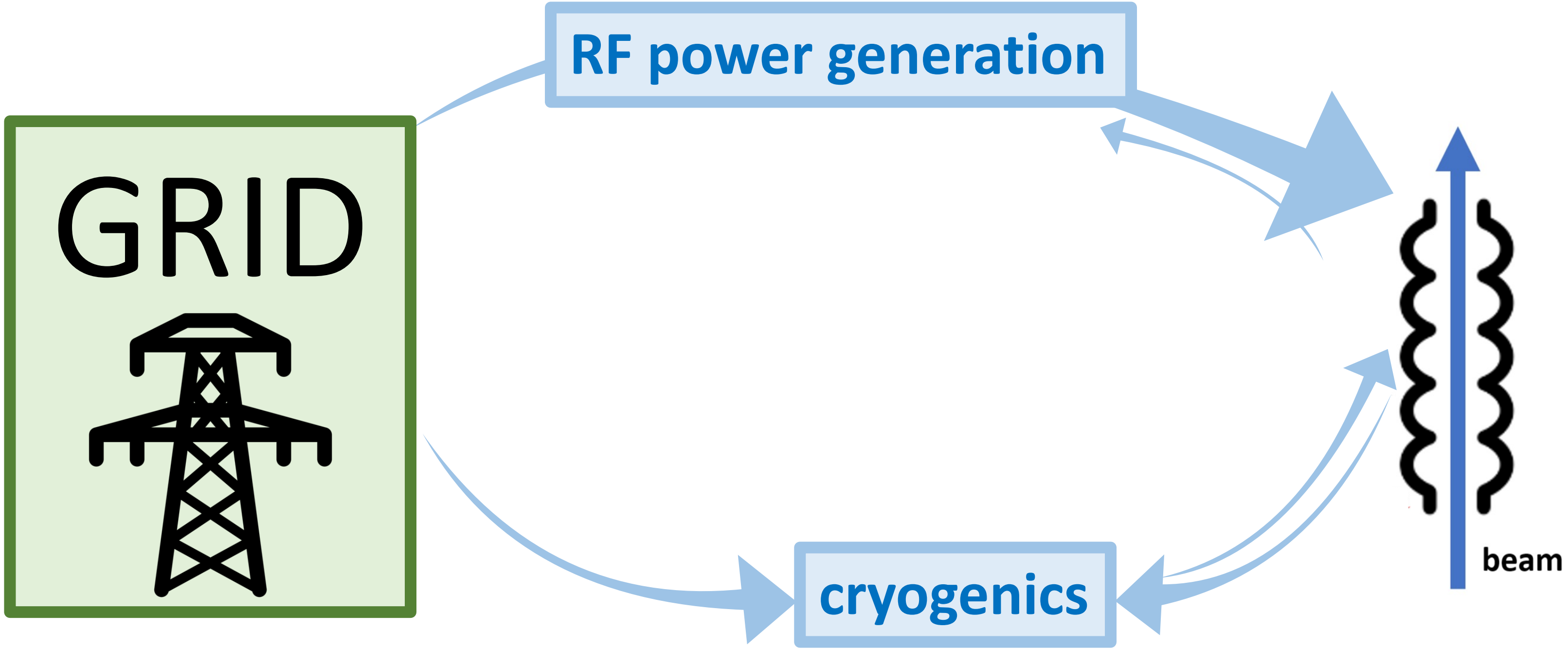
Transferring grid power to the particle beam

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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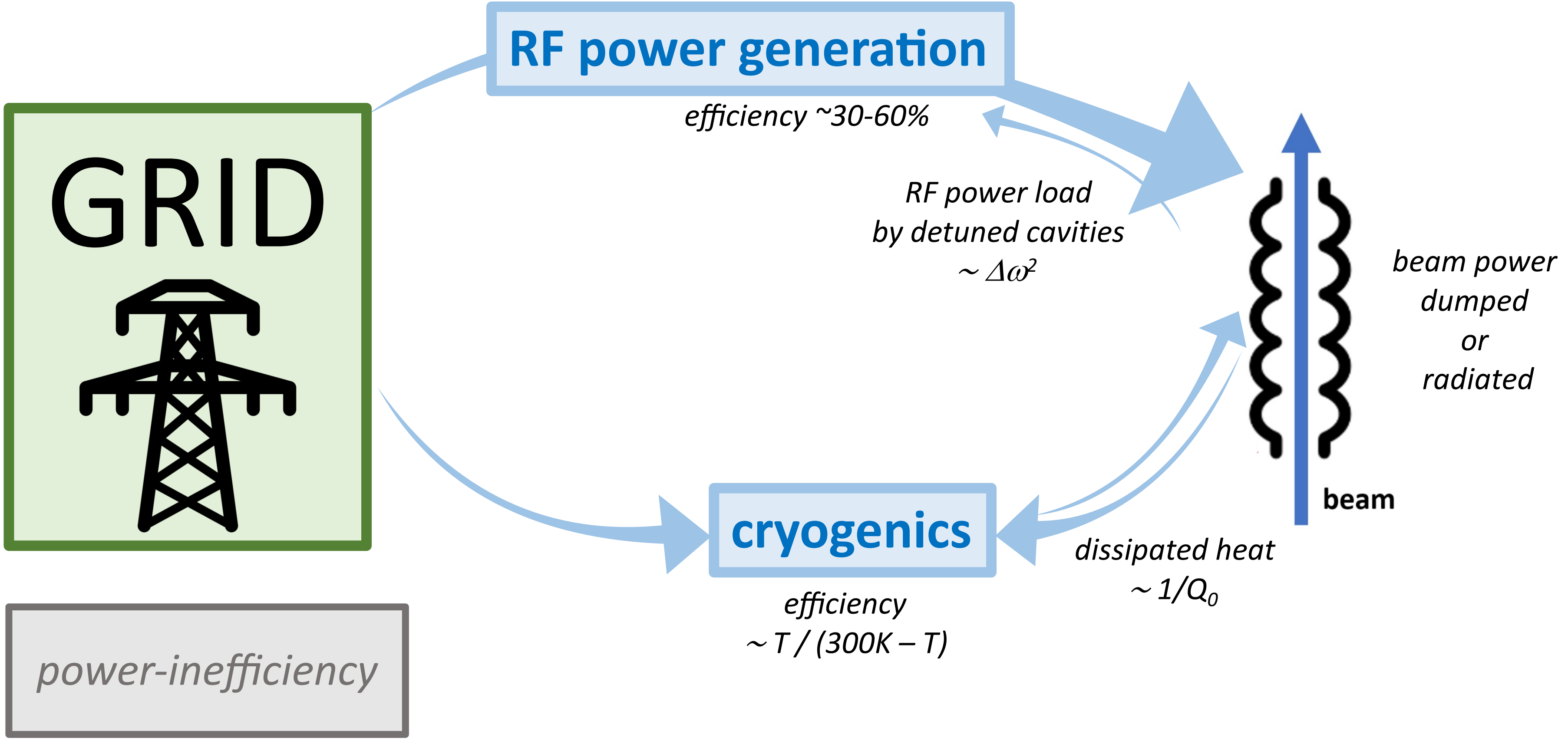
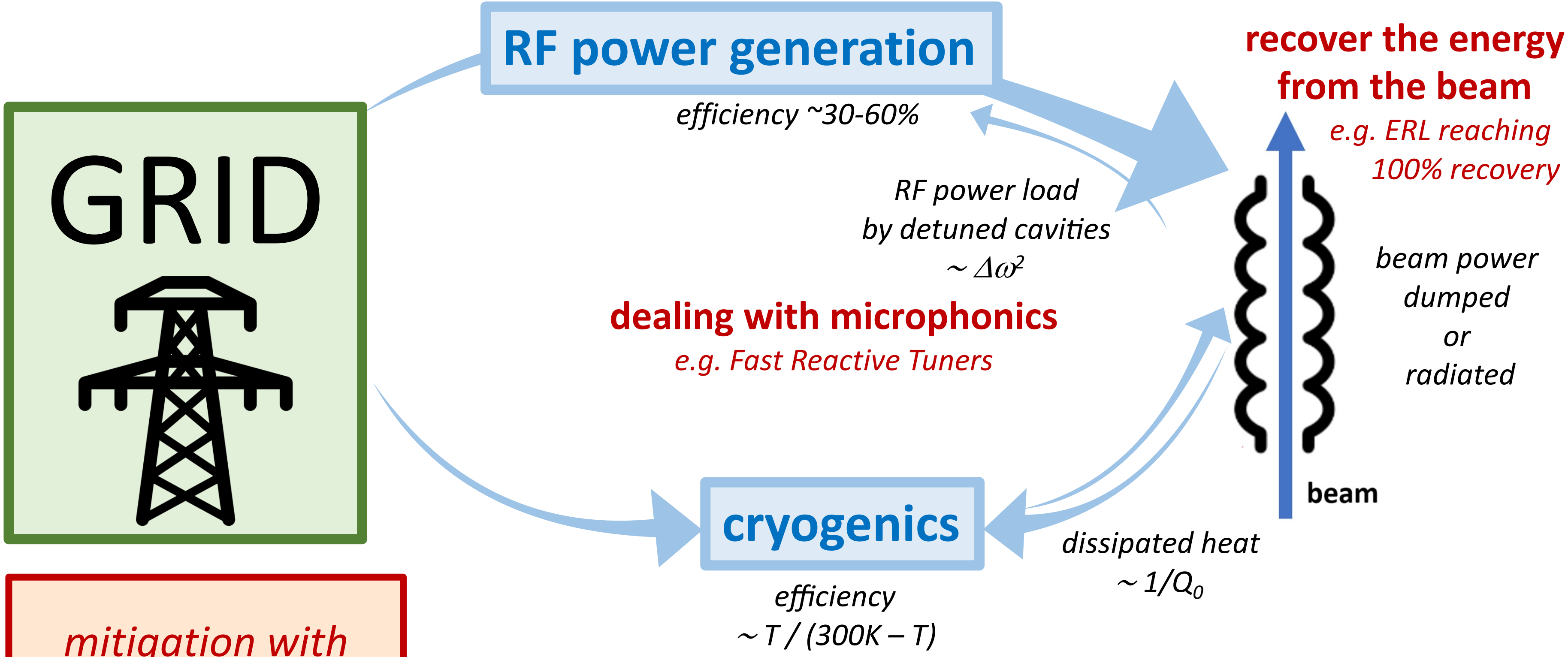
From Grid to Beam



From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

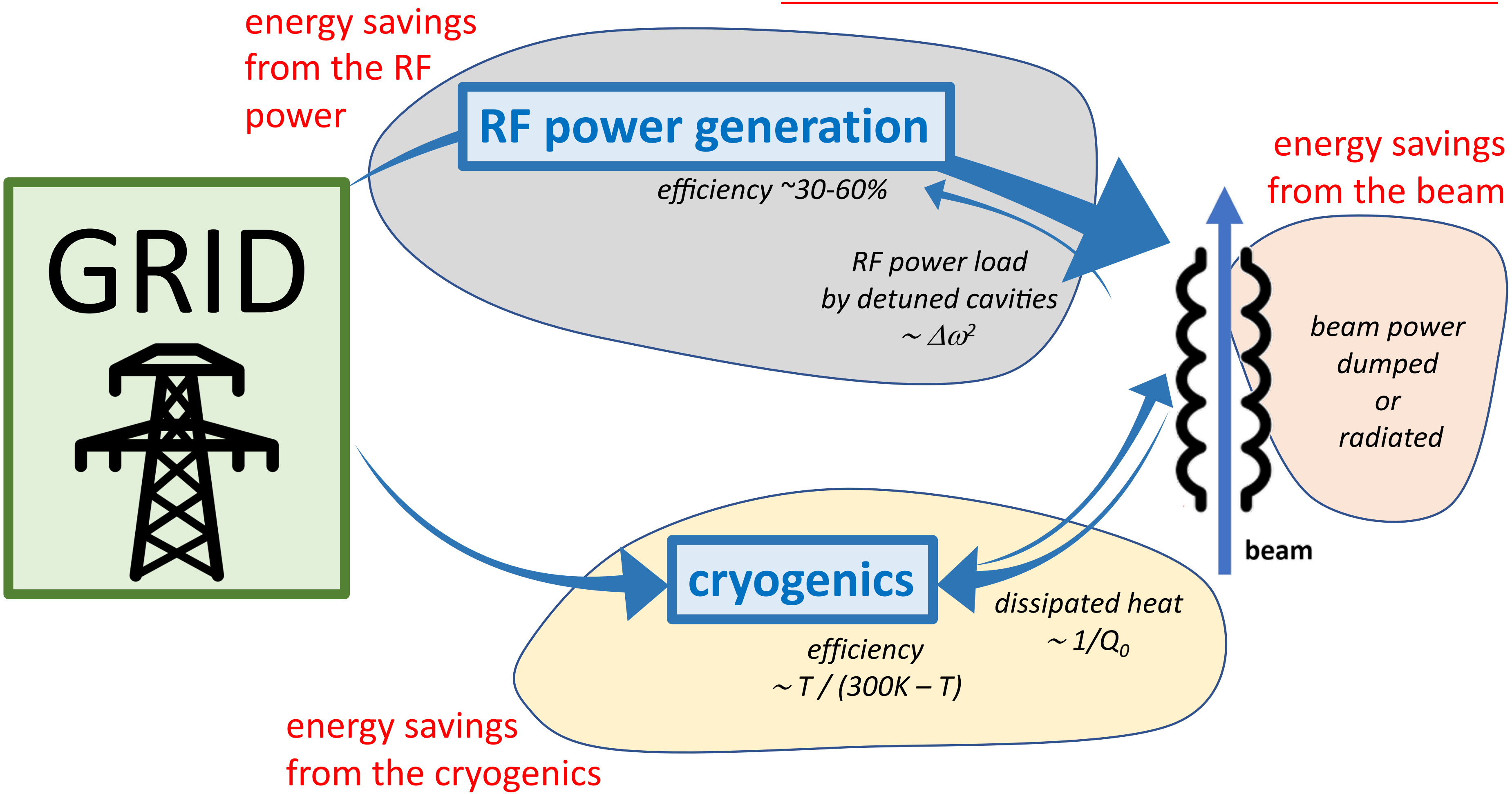


operate cavities at higher T & improve Q_0 of cavities

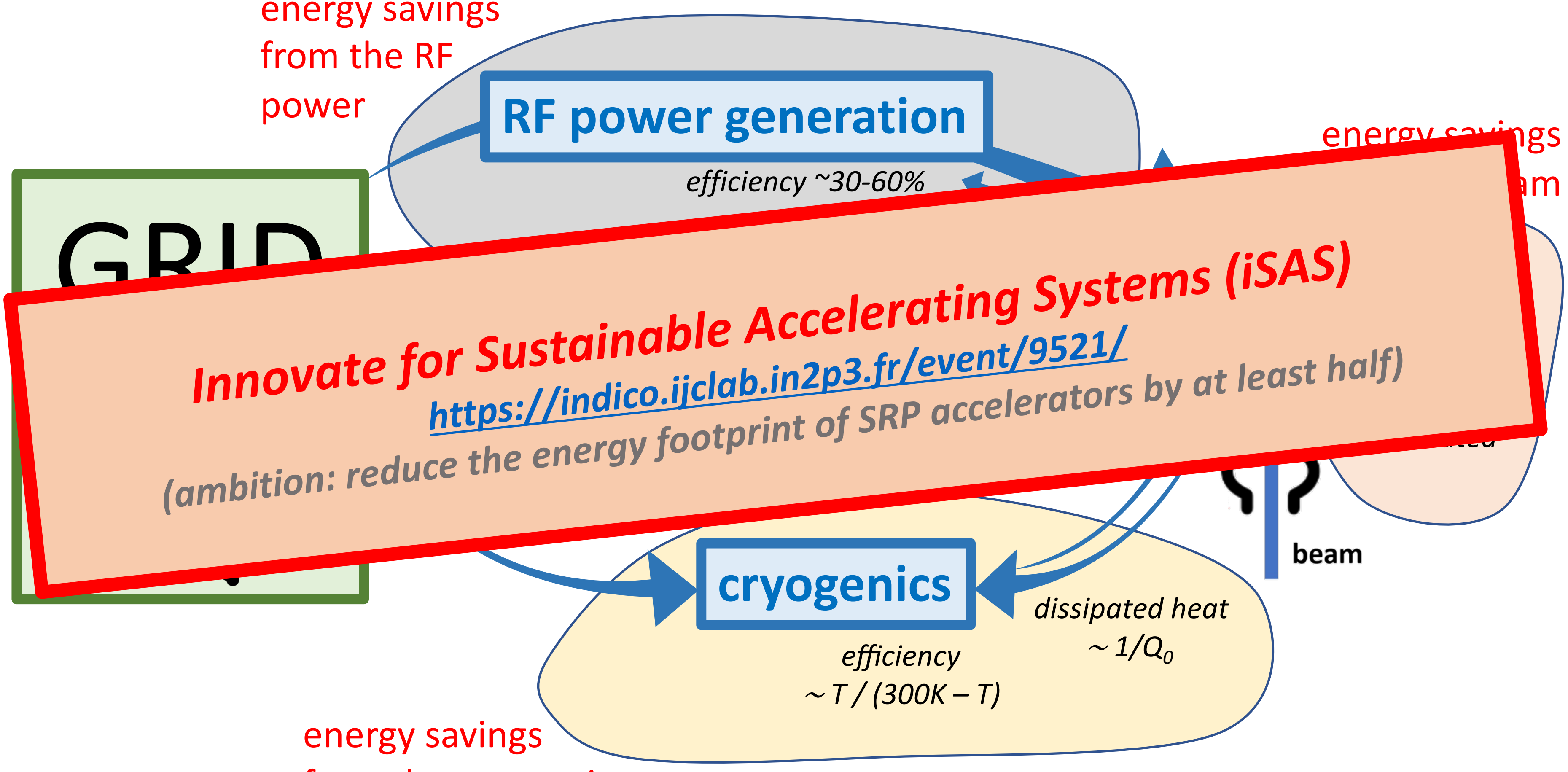
e.g. Nb_3Sn from 2K to 4.2K ➔ 3x less cooling power needed

mitigation with novel technologies

Three main innovation directions



Three main innovation directions



Innovate for Sustainable Accelerating Systems (iSAS)

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

(ambition: reduce the energy footprint of SRP accelerators by at least half)

new (re)emerging collider concepts

some examples:

ERL-based, C^3 and HELEN H-factories, muon collider to high energies, …

Impact of iSAS technologies on HEP e^+e^- colliders

example future e^+e^- Higgs Factories

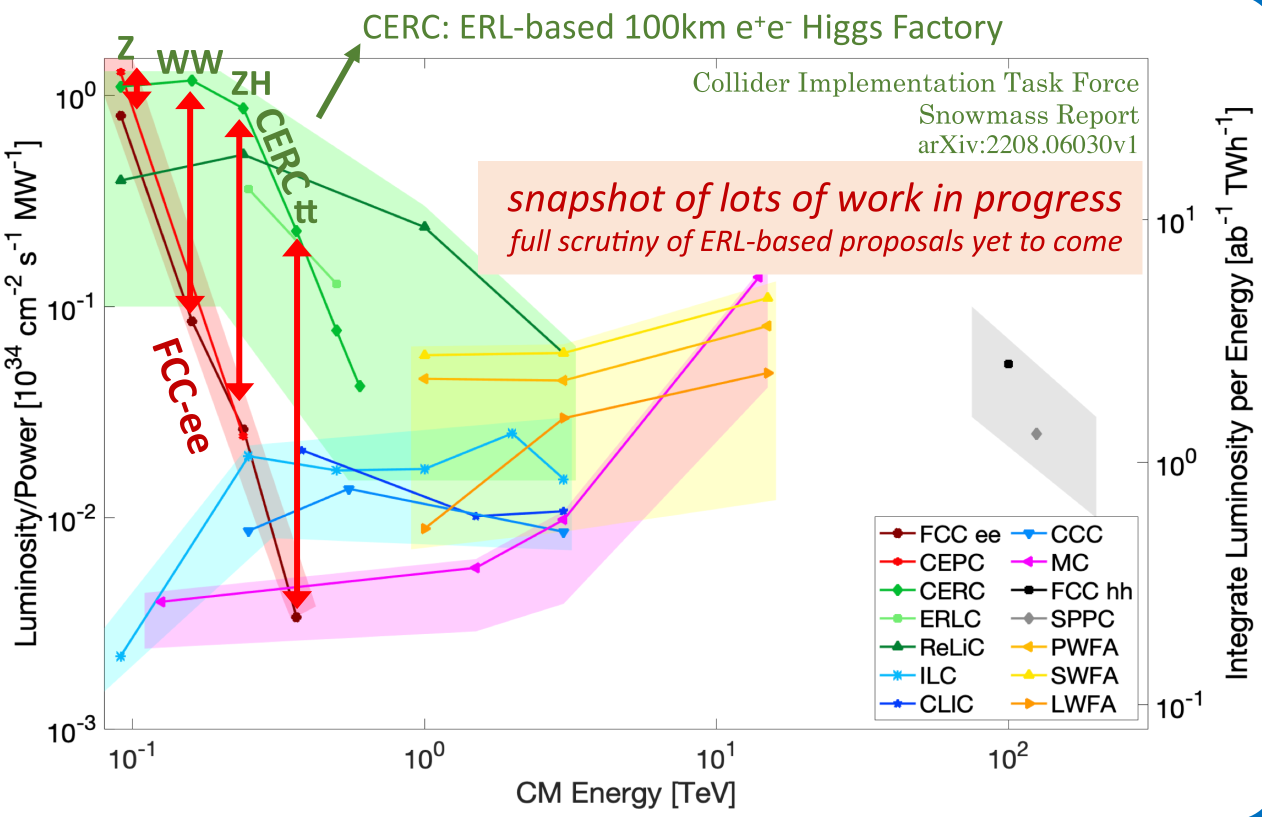
This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

x10 more Higgs bosons

or

x10 less electricity costs

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



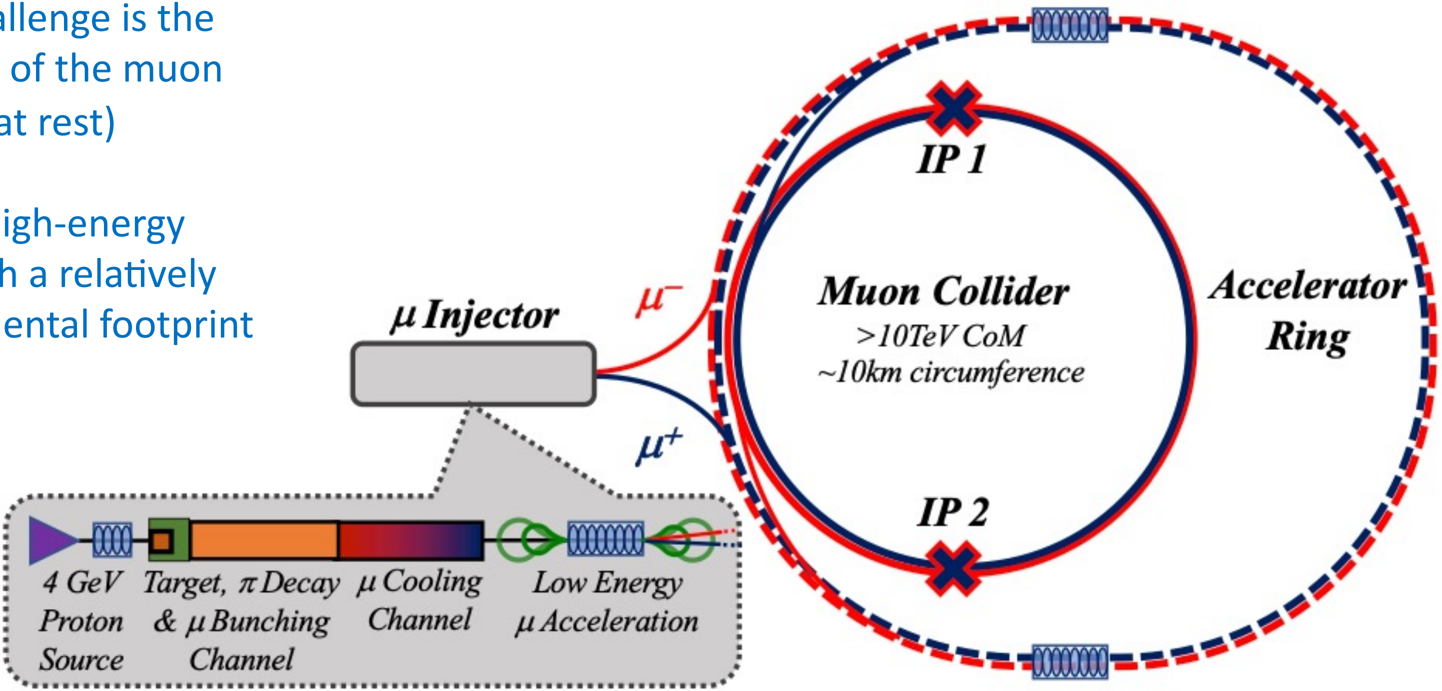
References for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Colliding muons rather than electrons

larger mass, hence much less synchrotron radiation

The main challenge is the short lifetime of the muon (2.2μs at rest)

Impactful high-energy collisions with a relatively small environmental footprint



https://muoncollider.web.cern.ch/

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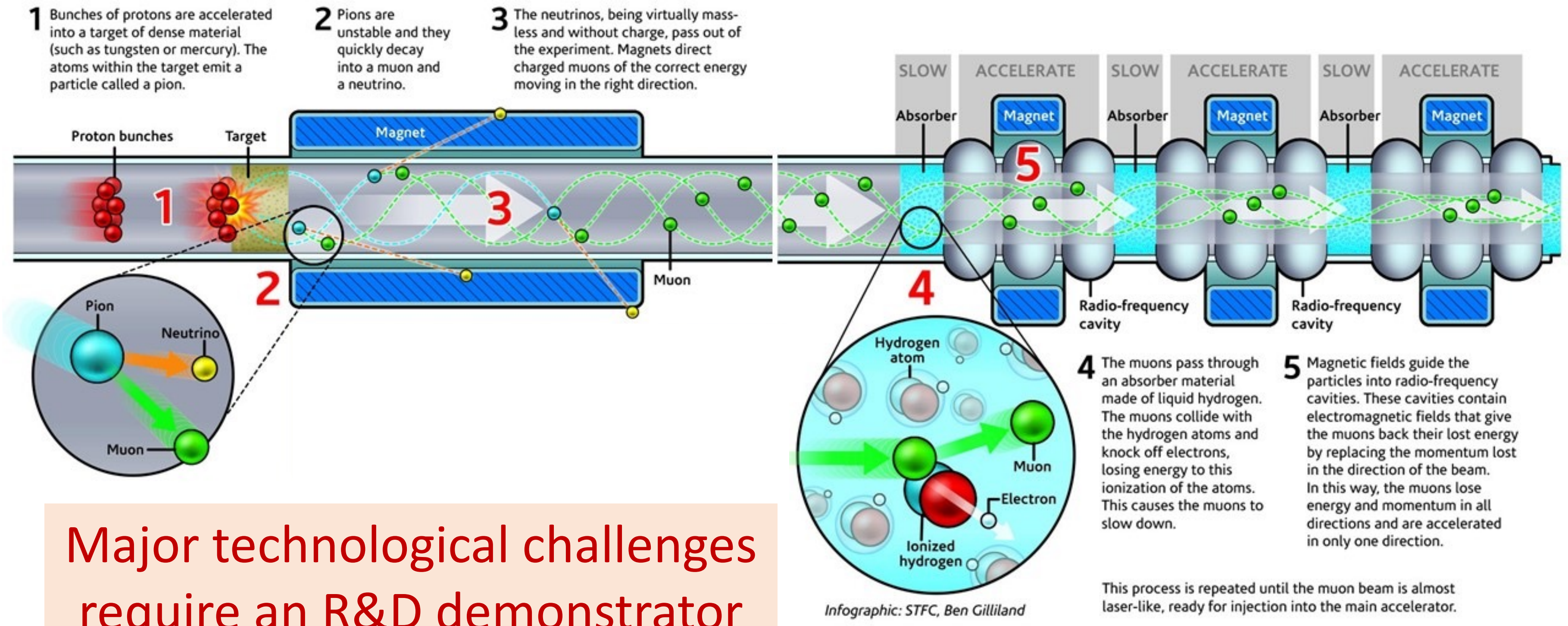
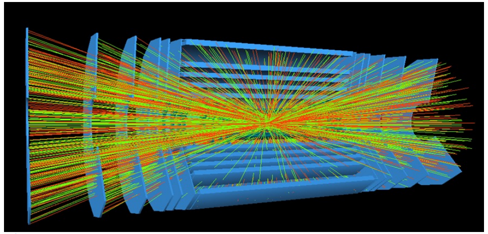


Major technological challenges require an R&D demonstrator

https://muoncollider.web.cern.ch/

Colliding muons rather than electrons

larger mass, hence much less synchrotron radiation

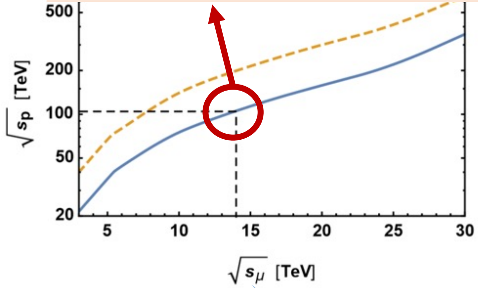


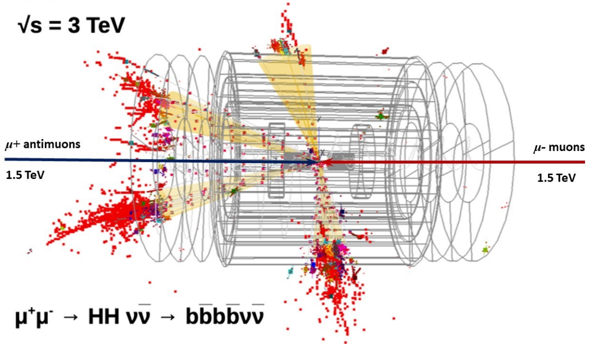
proton collisions

The energy at which the proton collider cross-section equals that of a muon collider for heavy particles.

The plot compares the pair production cross-sections for heavy particles with mass M approximately equal to half the muon collider energy $\sqrt{s_\mu}/2$. The dashed yellow line assumes comparable processes for muon and proton production, while the continuous blue line accounts for the possible QCD enhancement on the proton production.

14 TeV μμ = 100 TeV pp





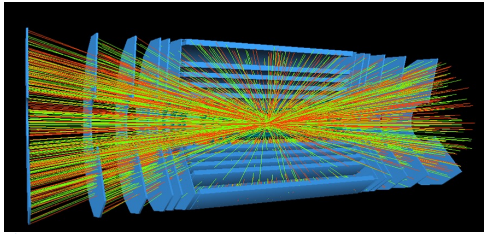
$\mu^+\mu^- \rightarrow HH\, \nu\bar{\nu} \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$

muon collisions

https://muoncollider.web.cern.ch/

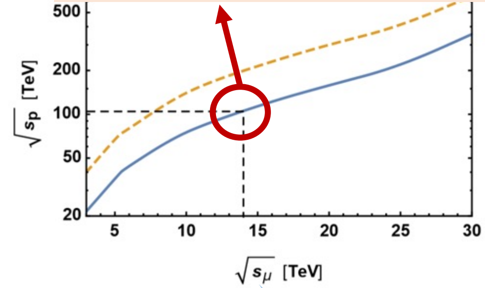
Colliding muons rather than electrons

larger mass, hence much less synchrotron radiation



proton collisions

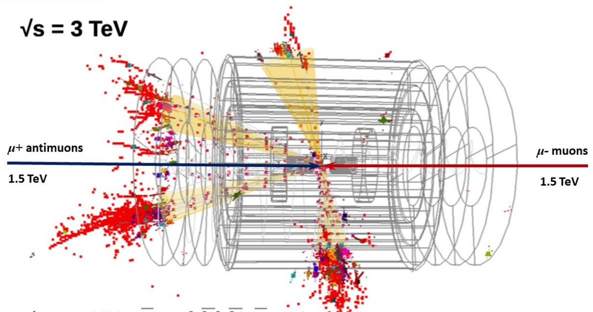
14 TeV μμ = 100 TeV pp



muon collisions

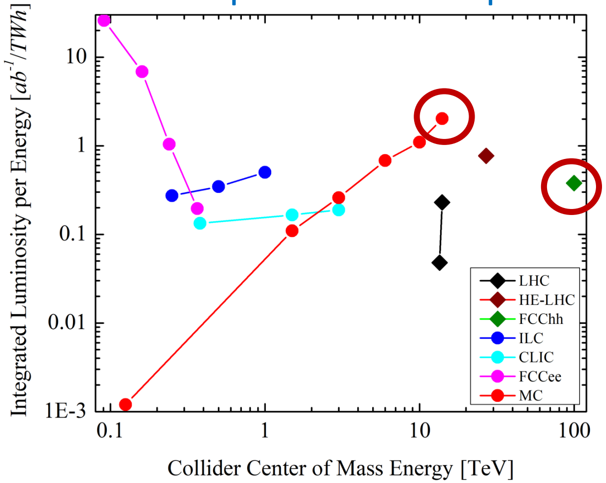
The energy at which the proton collider cross-section equals that of a muon collider for heavy particles.

The plot compares the pair production cross-sections for heavy particles with mass M approximately equal to half the muon collider energy $\sqrt{s_\mu}/2$. The dashed yellow line assumes comparable processes for muon and proton production, while the continuous blue line accounts for the possible QCD enhancement on the proton production.



$\mu^+\mu^- \to HH\,\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$

Annual integrated luminosity per electric power consumption.



https://muoncollider.web.cern.ch/

new collider concepts emerge which also continuously challenge and accordingly lead to improvements of our main FCC ambition

future collider plans and concepts

Structure of Matter

Hadrons & Ions are made up of Quarks & Gluons

low energy

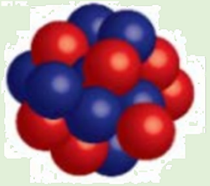
high energy

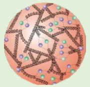
colour confinement

coupling ~1

asymptotic freedom

coupling <<1





"confined"
hadrons & ions

Equation-of-State

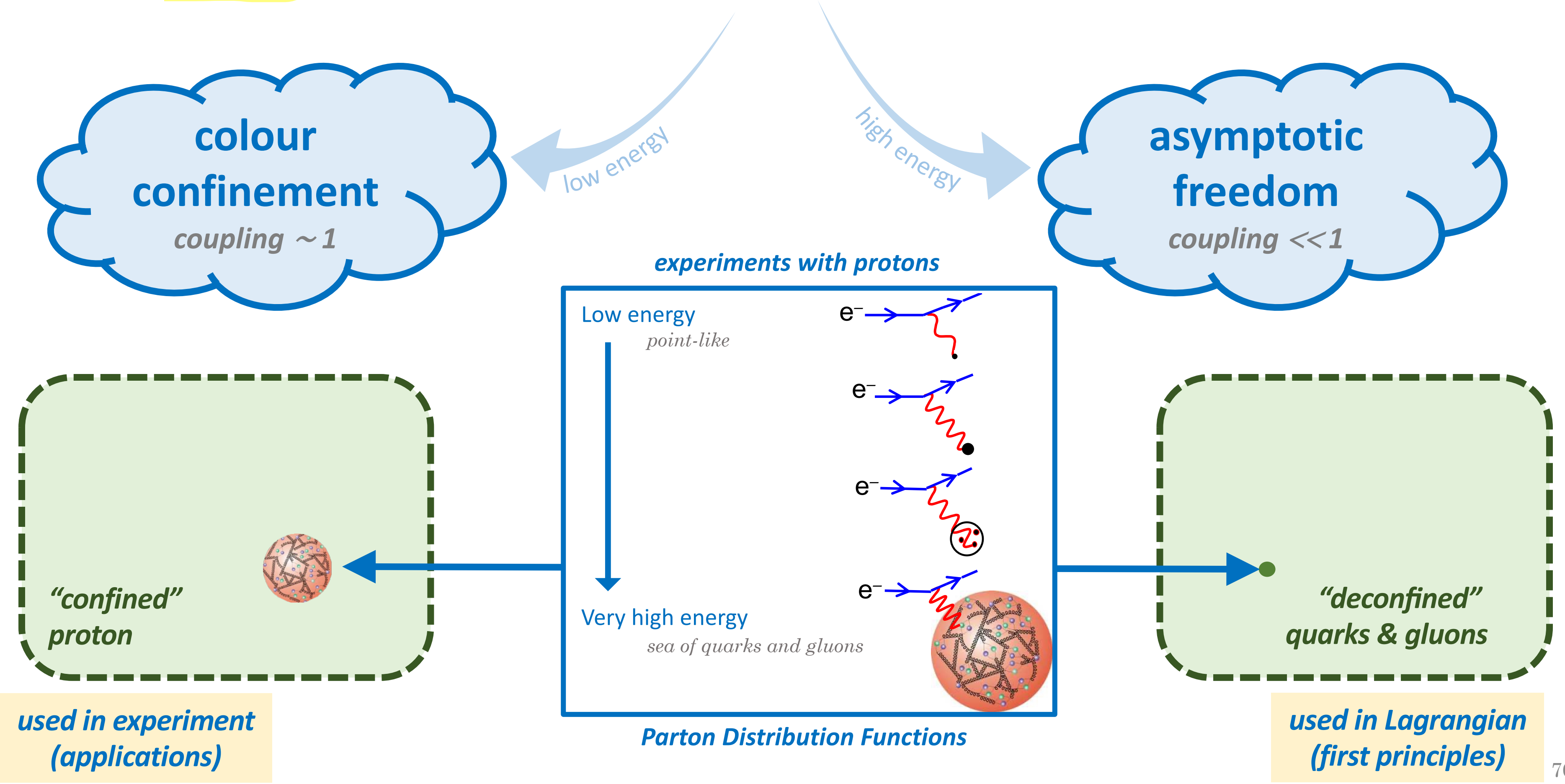
Parton Distribution Functions

"deconfined"
quarks & gluons

used in experiment (applications)

used in Lagrangian (first principles)

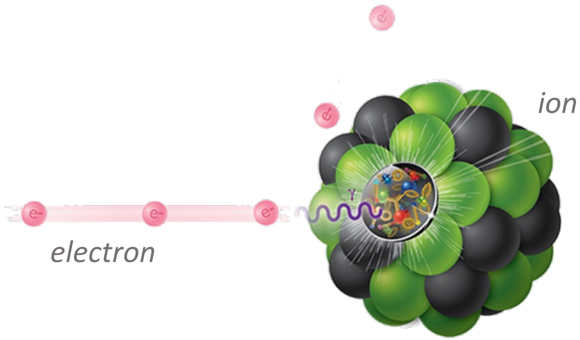
Hadrons & Ions are made up of Quarks & Gluons



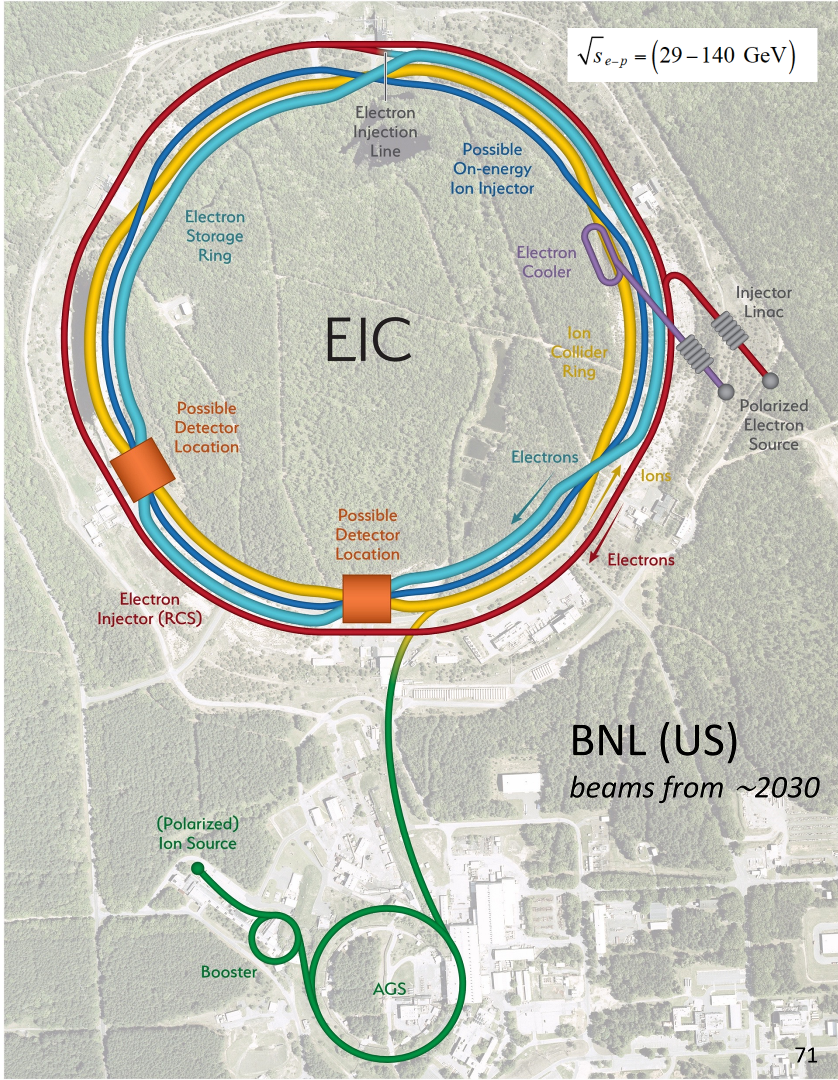
Electron-Ion Collider (EIC)

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

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



Now a planned future collider!



BNL (US)

beams from ~2030

Electron-Ion Collider (EIC)

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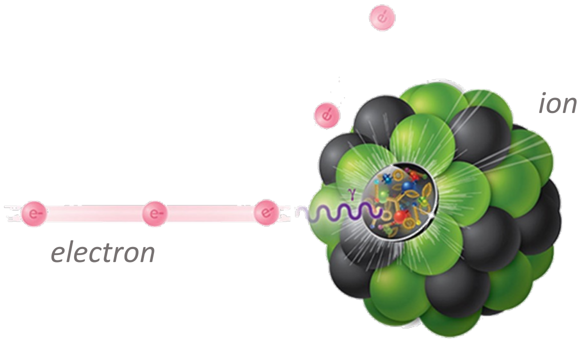
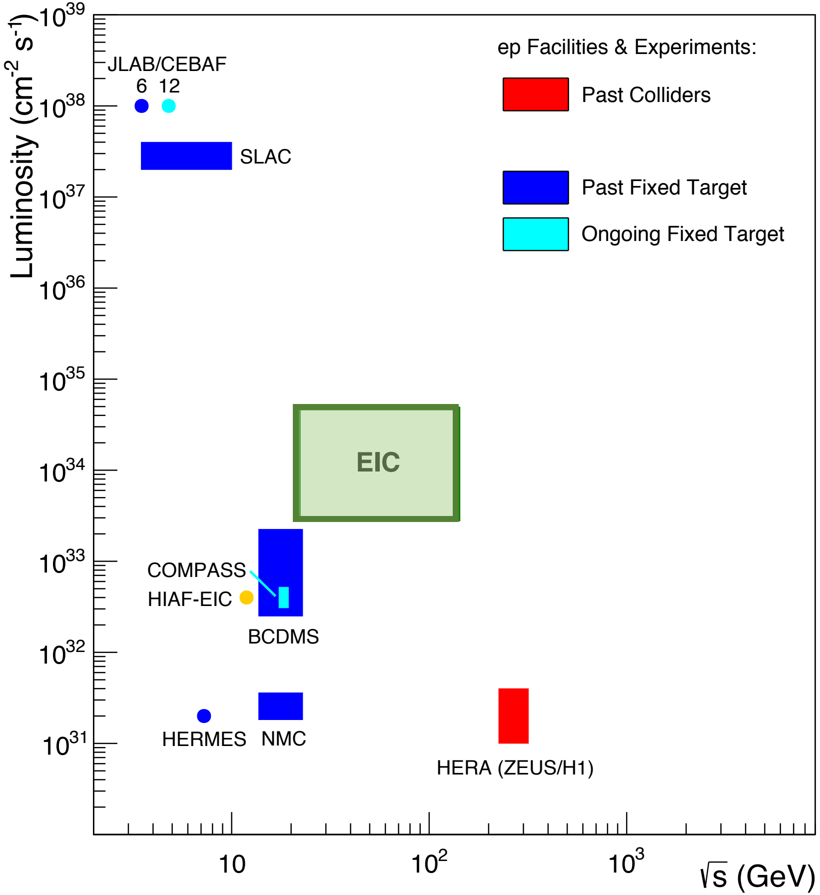
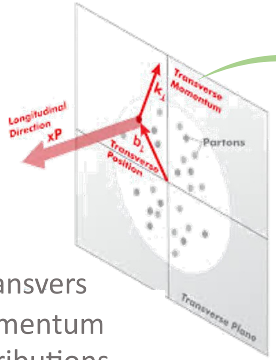


- High luminosity
- Wide range in beam energy
- Polarized lepton & hadron beam
- Nuclear beam

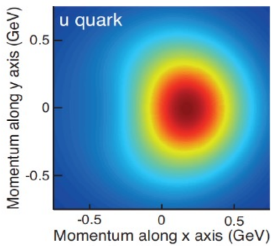
Unique in the landscape of Deep Inelastic Scattering (DIS)



Electron-Ion Collider (EIC)

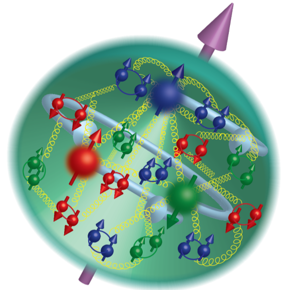


Transvers Momentum Distributions

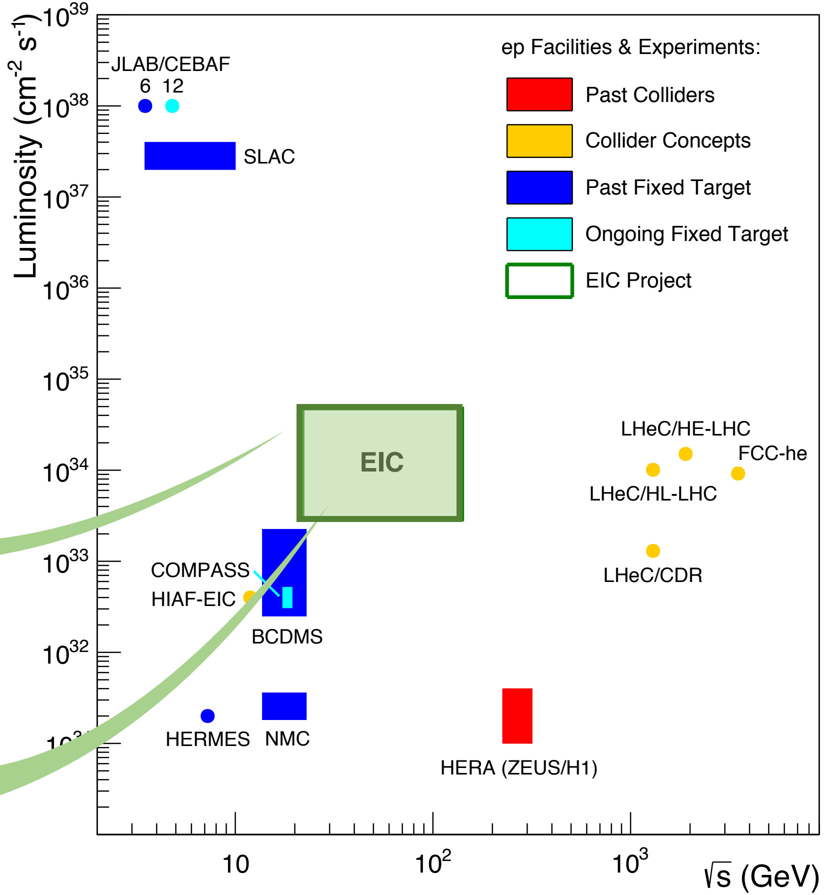


How do the properties of proton and neutrons arise from its constituents?

Towards a 3D partonic image of the proton



Unique in the landscape of Deep Inelastic Scattering (DIS)



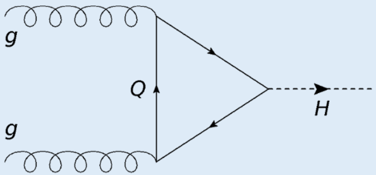
Electron-Ion Collider (EIC)

Unique in the landscape of Deep Inelastic Scattering (DIS)

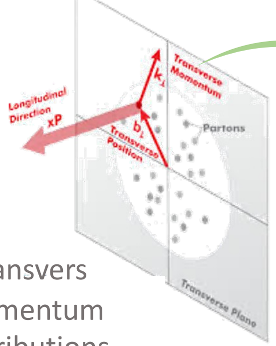
Snowmass 2021 White Paper

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

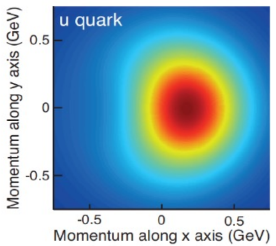
improved gg→H @ LHC

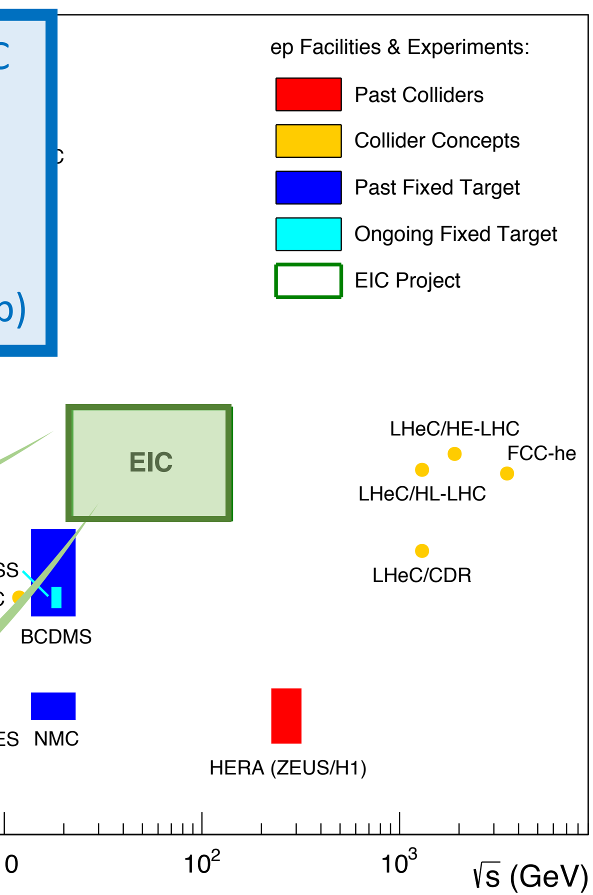


improved W mass (in pp)



Transvers Momentum Distributions





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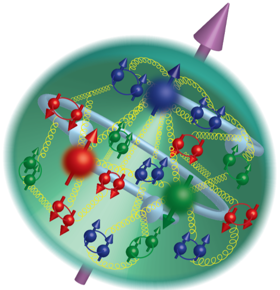
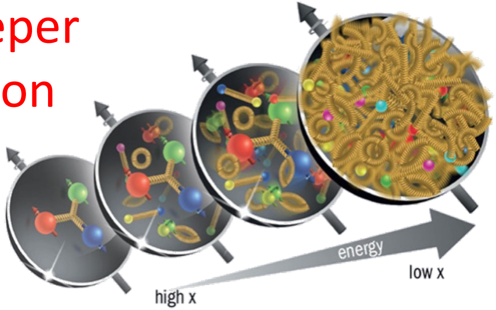


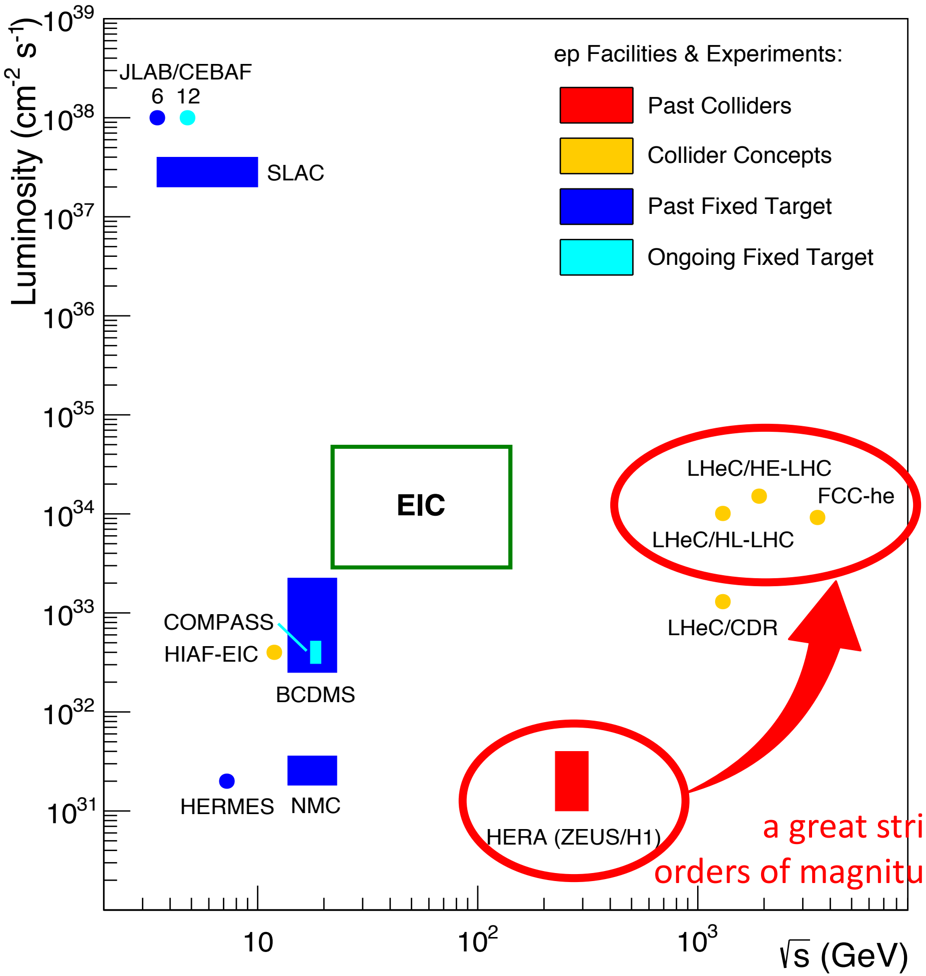
A future scope

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

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

reaching deeper into the proton





a great stride
orders of magnitude

The challenge

High-intensity electron beam

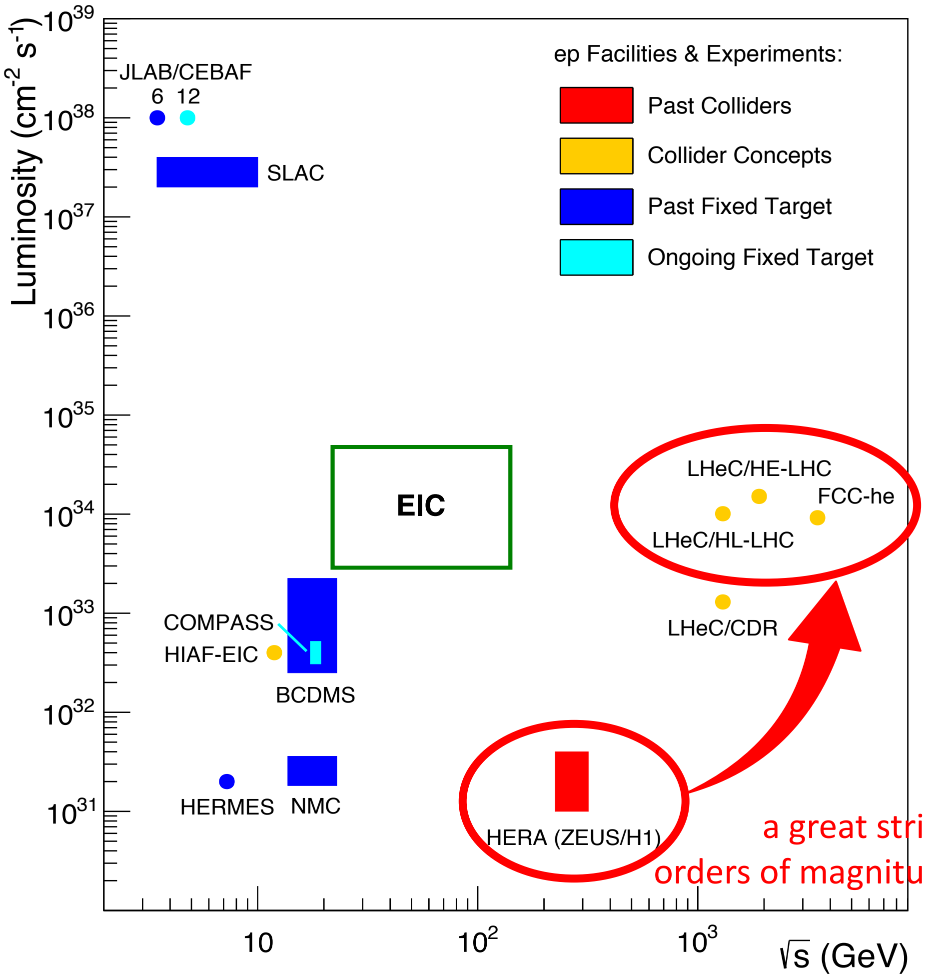
HERA@DESY to LHeC/FCC-eh@CERN

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

beam current × beam energy
= beam power

LHeC ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant



a great stride
orders of magnitude

The challenge

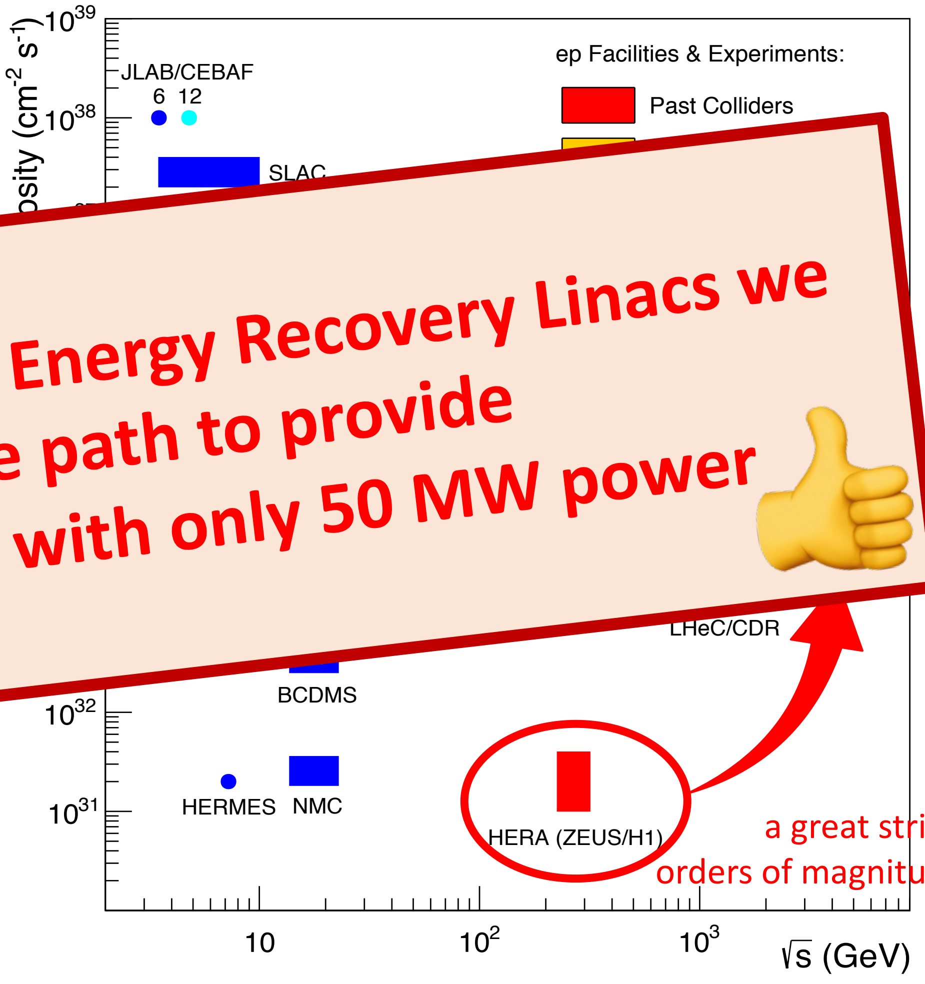
High-intensity electron beam

HERA@DESY to LHeC/FCC-eh@C

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

1 GW beam power

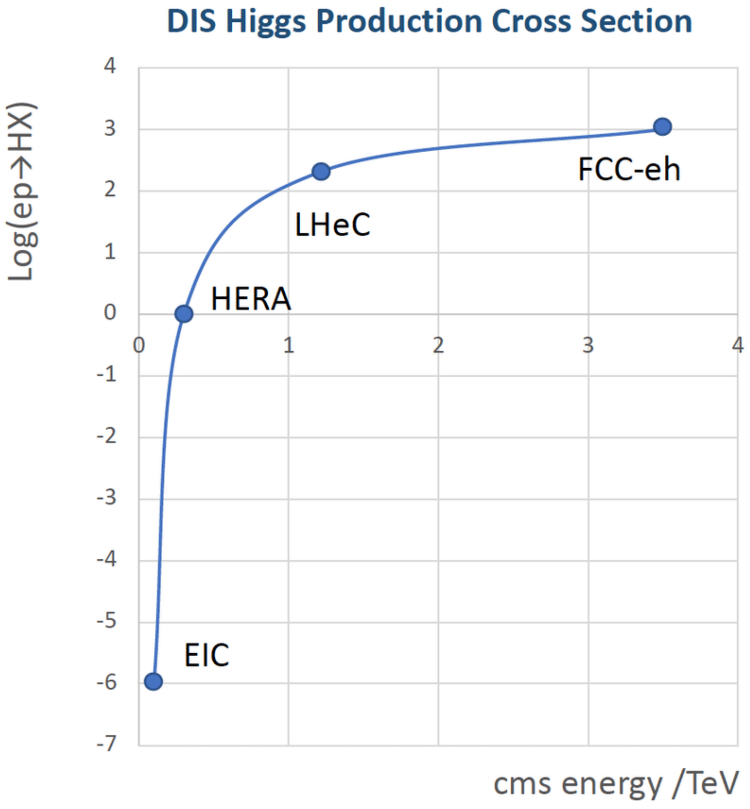
equivalent to the power delivered by a nuclear power plant



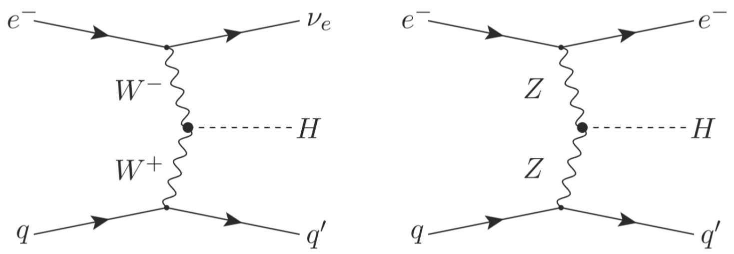
a great stride
orders of magnitude

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



The real game change between HERA and LHC/FCC

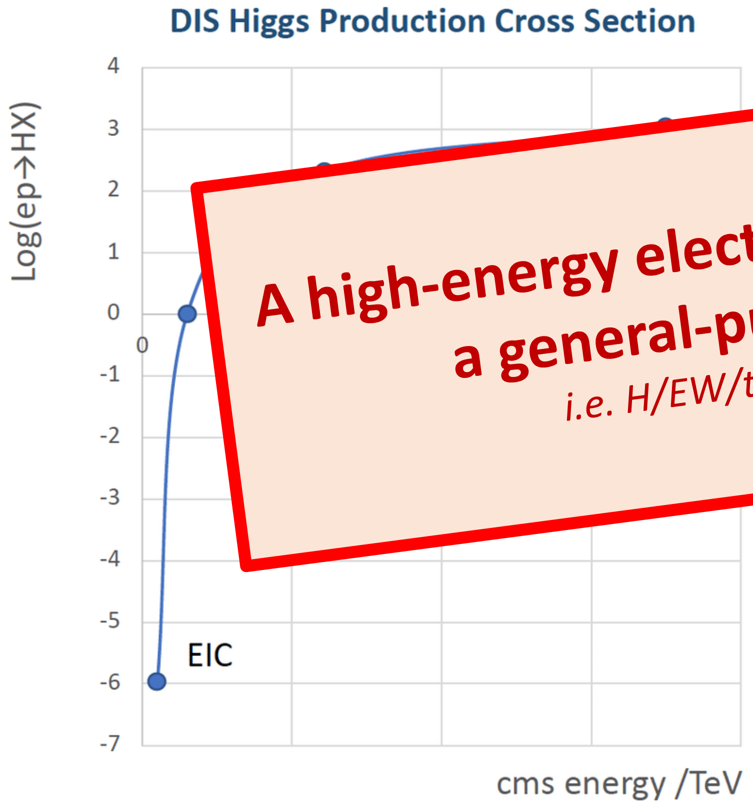


Compared to the LHC, these are reasonably clean Higgs events with much less backgrounds

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

Collision energy above the threshold for EW/Higgs/Top

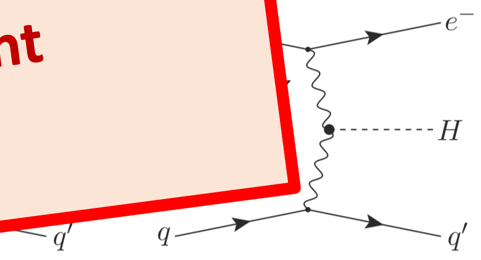
from mostly QCD-oriented physics to General-Purpose physics



The real gam ge between
/FCC

A high-energy electron-proton experiment is a general-purpose experiment

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



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

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

Hadrons & Ions are made up of Quarks & Gluons

low energy

high energy

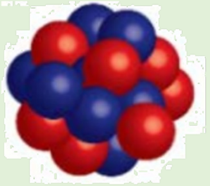
colour confinement

coupling ~1

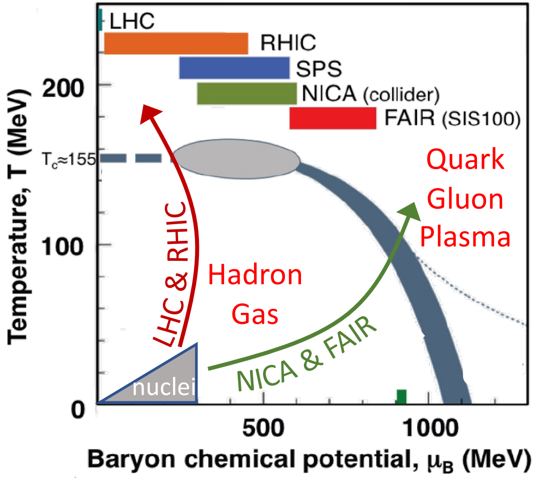
asymptotic freedom

coupling <<1

experiments with heavy ions



"confined" ions



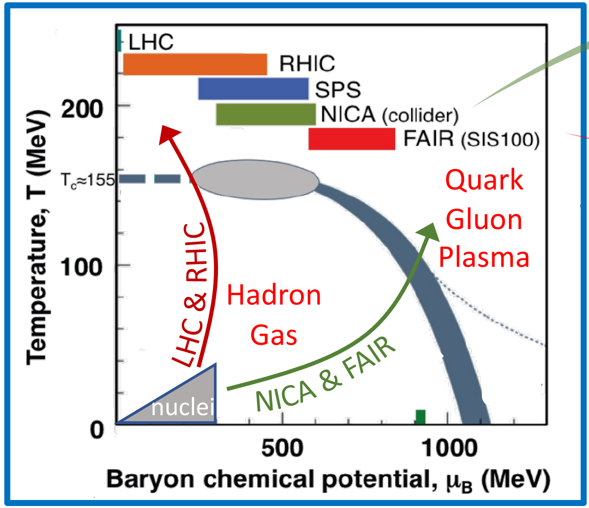
"deconfined" quarks & gluons

used in experiment (applications)

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

used in Lagrangian (first principles)

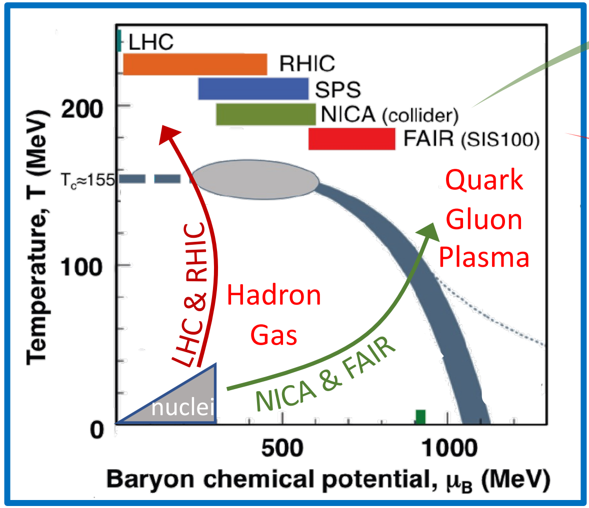
Heavy Ion physics from RHIC & SPS to NICA & FAIR



Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

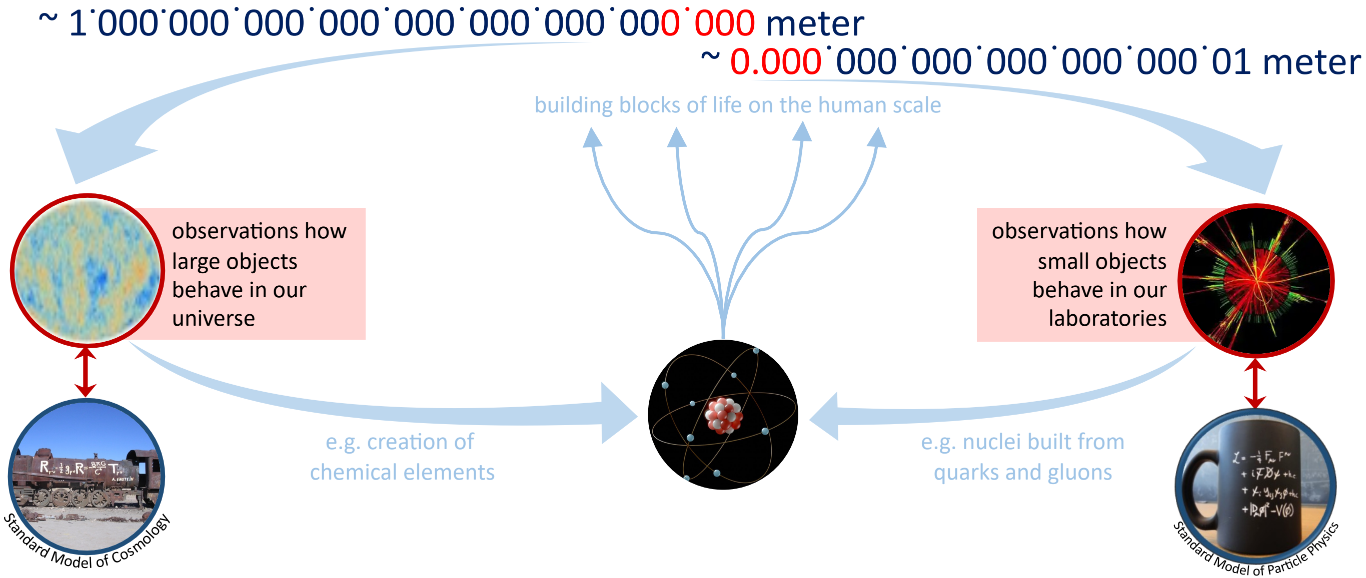
Heavy Ion physics from RHIC & SPS to NICA & FAIR



Nuclotron-based Ion Collider Facility @ JINR

SIS100/300 @ FAIR

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

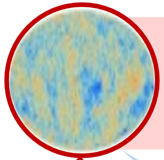

~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter
~ 0.000˙000˙000˙000˙000˙000˙01 meter
building blocks of life on the human scale
observations how large objects behave in our universe
observations how small objects behave in our laboratories
e.g. creation of chemical elements
e.g. nuclei built from quarks and gluons
Standard Model of Cosmology
Standard Model of Particle Physics

an impactful future with particle colliders

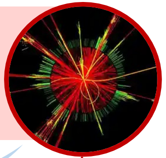
~ 1˙000˙000˙000˙000˙000˙000˙000˙000˙000 meter

~ 0.000˙000˙000˙000˙000˙000˙01 meter

building blocks of life on the human scale

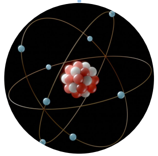


observations how large objects behave in our universe

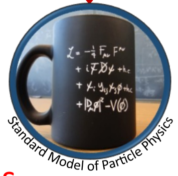


observations how small objects behave in our laboratories

e.g. creation of chemical elements



e.g. nuclei built from quarks and gluons



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

HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be