Future Colliders

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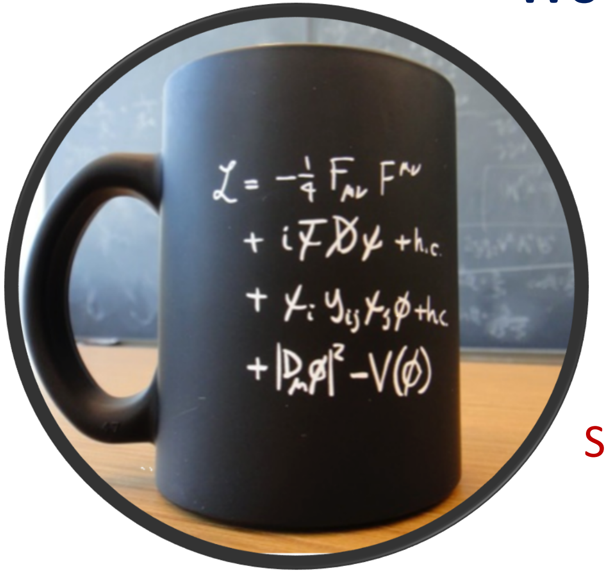
Vrije Universiteit Brussel

International Doctorate Network in Particle Physics, Astrophysics and Cosmology
10^{th} IDPASC School, online, Portugal
6-17 September 2021

The quest for understanding particle physics



Picture from Flip Tanedo @ Quantum Dairies

Wonderful description of fundamental interactions

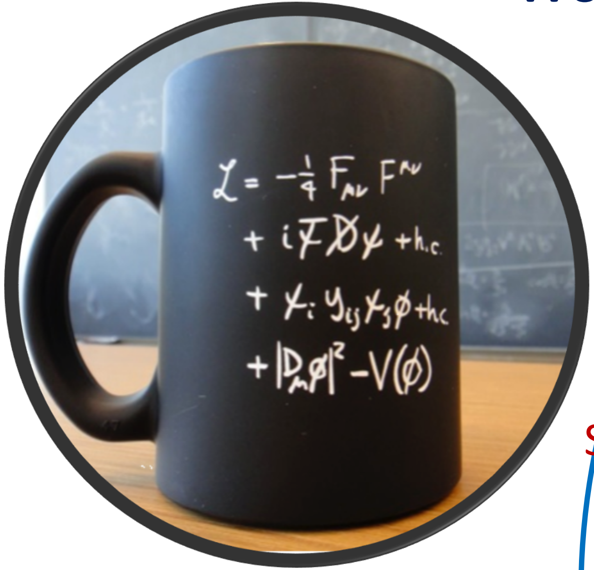
e.g. The Standard Models of Particle Physics and Cosmology
together do not describe all our observations of the universe.

“Problems and Mysteries”

[Riccardo Rattazzi]

e.g. Abundance of dark matter?
Abundance of matter over antimatter?
Scale of things (EW hierarchy problem / strong CP problem)?
Pattern of fermion masses and mixings?
Dynamics of EW symmetry breaking?…

The quest for understanding particle physics



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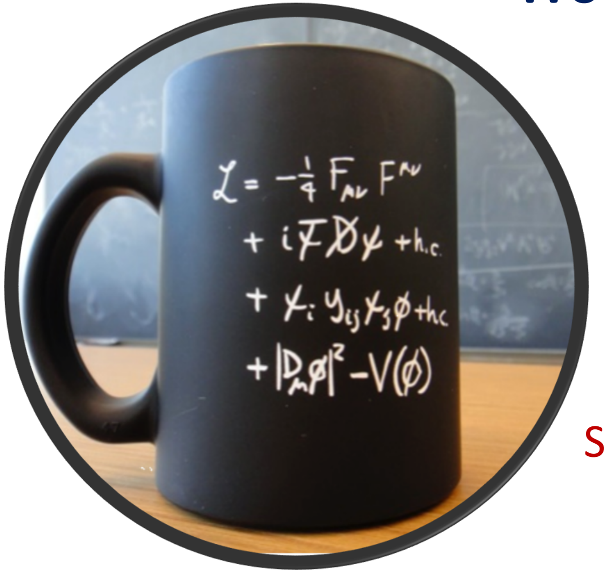
Important research in ph & th relates these to a portfolio of concrete observable phenomena at colliders and elsewhere

In many cases synergies emerge between astro(particle), cosmology, nuclear and particle physics

The quest for understanding particle physics



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Observations of new physics phenomena are expected to unlock concrete ways to address these puzzling unknowns

The quest for understanding particle physics

although there is no lack of novel theoretical ideas,
there are no clear indications where new physics is hiding

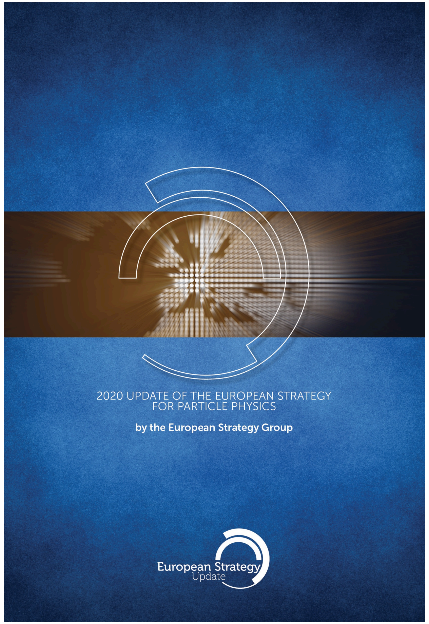
no “*no lose theorem*” for experiments

need a strong and diverse, yet coherent
and concerted empirical exploration

Most recent European Strategies

the small …

weblink



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

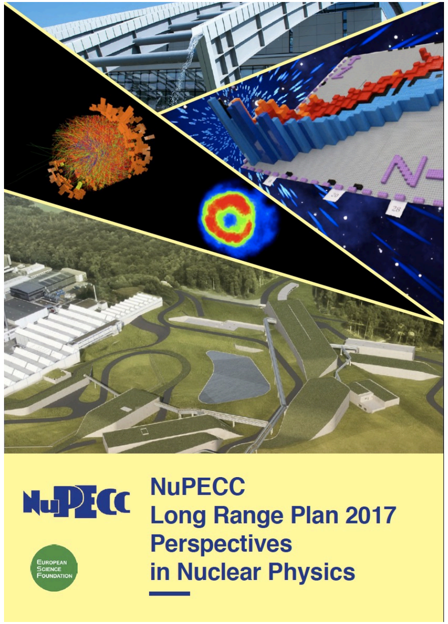
by the European Strategy Group

European Strategy Update

2020 Update of the European Particle Physics Strategy

… the connection …

weblink



NuPECC

Long Range Plan 2017

Perspectives

in Nuclear Physics

European Science Foundation

Long Range Plan 2017 Perspectives in Nuclear Physics

… the large

weblink

APPEC

European Astroparticle Physics Strategy 2017-2026

2017-2026 European Astroparticle Physics Strategy

Most recent European Strategies

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by the European Strategy Group

European Strategy Update

2020 Update of the European Particle Physics Strategy

… the connection …

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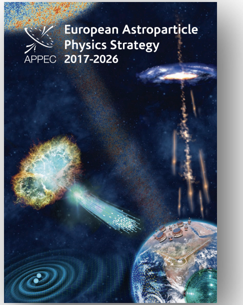
European Astroparticle

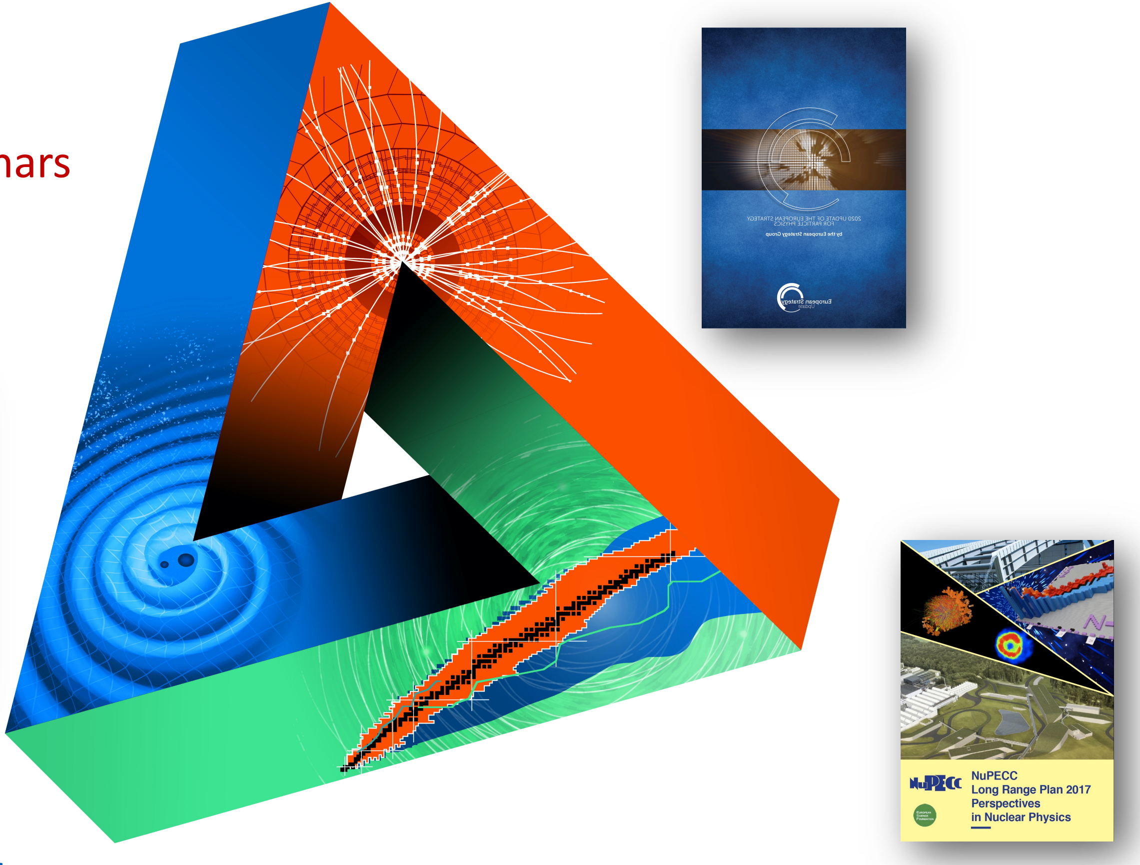
2017-2026 European Astroparticle Physics Strategy

Community-driven strategies reflecting our coherent ambition to address the open questions in particle/nuclear/astroparticle physics and they serve as guidance for funding bodies to develop resource-loaded research programmes.

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

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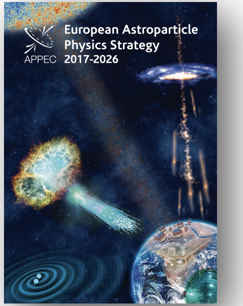
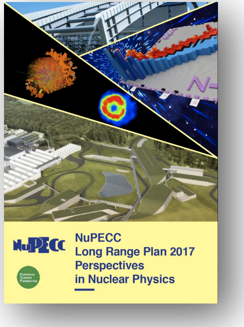
SOME EXAMPLES
Machine Learning tools
Gravitational Waves for fundamental physics
Dark Matter community
Open Science and Data (ESCAPE project)

More topical synergy projects: http://www.nupecc.org/jenaa/





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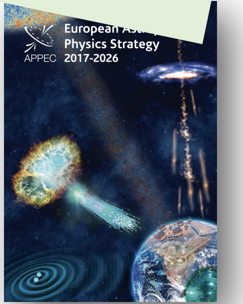
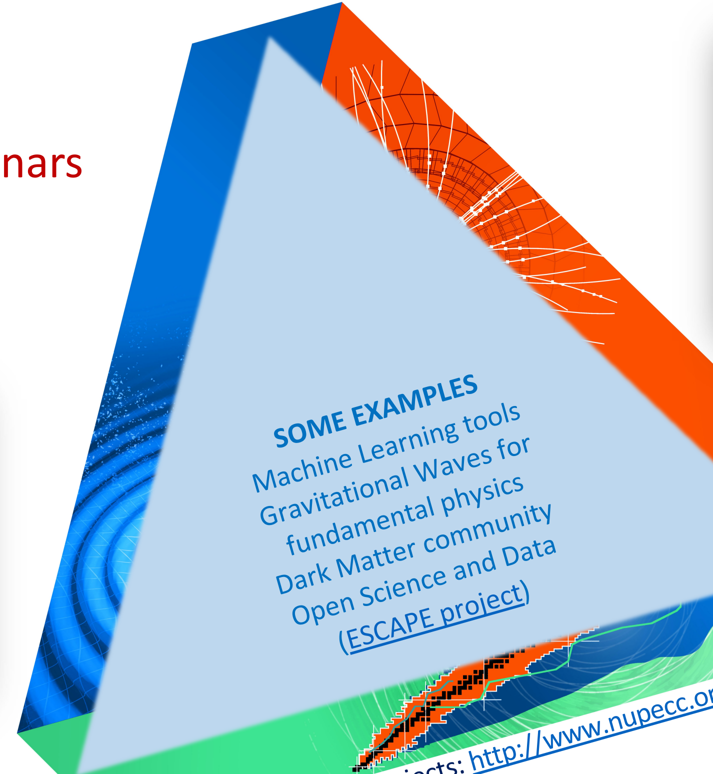
next JENAS in Madrid
3-6 May 2022





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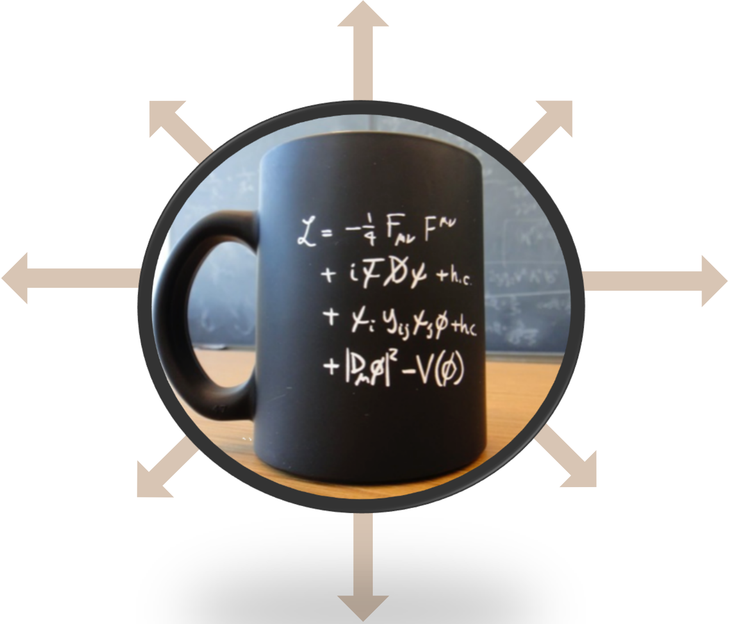
higher energy interactions in the lab

earlier universe



rarer processes

higher energetic phenomena in the universe

higher energy interactions in the lab

earlier universe

Innovate Technology

make the invisible visible

rarer processes

higher energetic phenomena in the universe

higher energy interactions in the lab

RF cavities, high-field magnets, plasma wakefield acceleration

Innovate Technology
make the invisible visible

earlier universe

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

solid-state devices with fast read-out electronics

rarer processes

computing and software challenge for
multi-messenger and multi-instrument astrophysics

higher energetic phenomena in the universe

higher energy interactions in the lab

RF cavities, high-field magnets, plasma wakefield acceleration

this presentation

earlier universe

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

Innovate Technology

make the invisible visible

solid-state devices with fast read-out electronics

rarer processes

e.g. DAQ lecture of Clara Gaspar this school

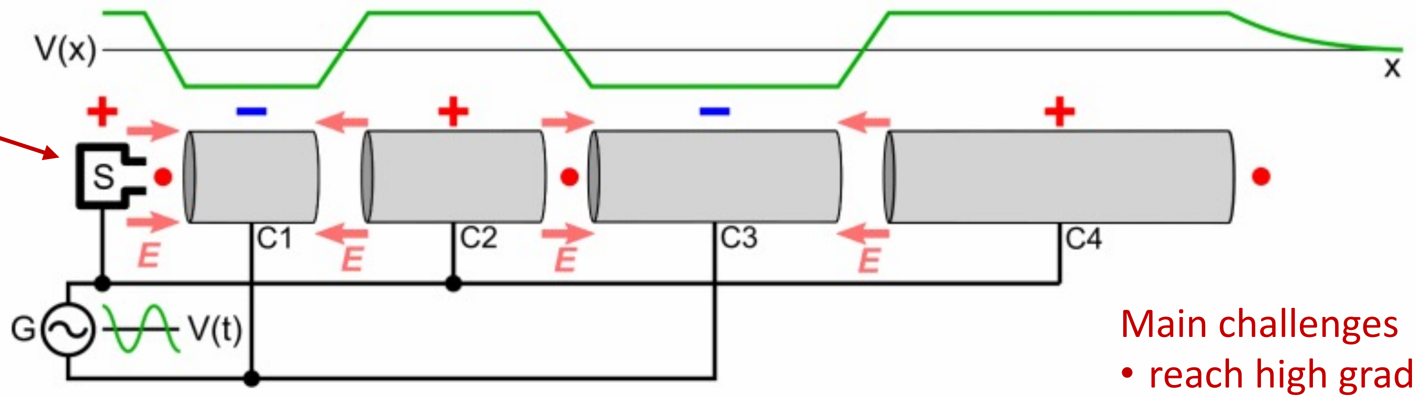
computing and software challenge for multi-messenger and multi-instrument astrophysics

higher energetic phenomena in the universe

Accelerator technology – *the basics*

Particles are accelerated along x in the gaps where there is an accelerating gradient of V(x)
As their speed v=βc increases, the distance between the gaps is to increase synchronously

particle source



RF source

Main challenges
- reach high gradients
- reach high-field magnets

At some moment β~constant, and the distance between the gaps can be fixed
Thereafter, a circular accelerator with high-field magnets can be used with fixed accelerator points around the circle (with a very limited range of the RF frequency)
→ synchrotron radiation: energy loss per turn: $\Delta E \sim E^4 / (m^4 \rho)$ with ρ = radius circular accelerator

Accelerator technology – *the basics*

For circular colliders:

Electrons/positrons → increase collider radius to reduce the synchrotron energy loss
Protons → increase collider radius to reduce requirement on B-field strength of magnets

The collider radius is constrained by many parameters, not in the least a financial one.

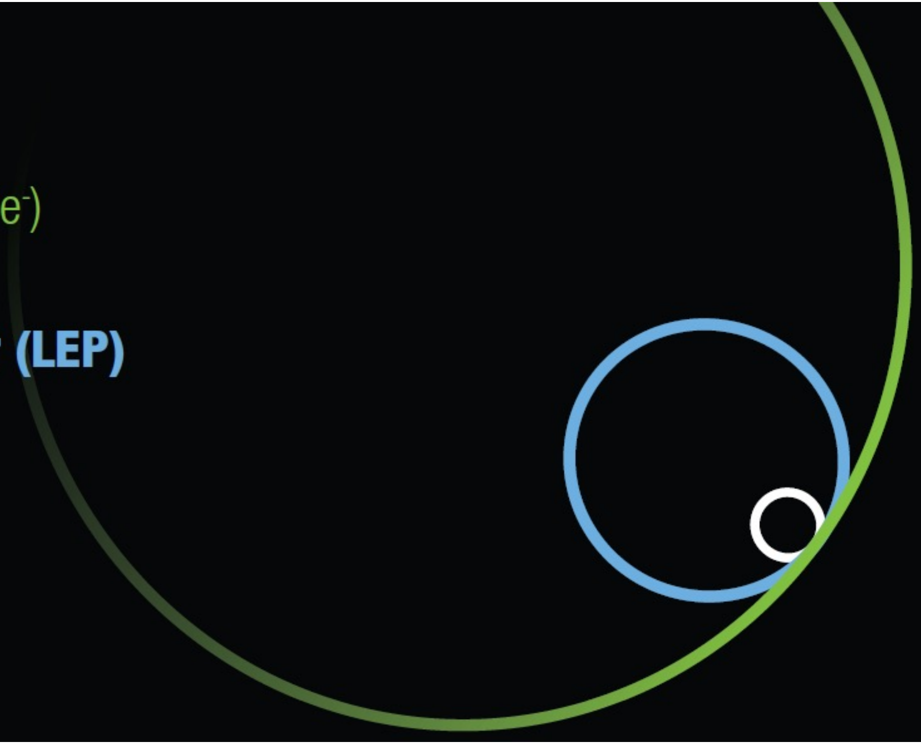
LEP/LHC (r = 4.3km, circumference 27km)

→ radius defined to deal with the synchrotron radiation of LEP
→ maximum LHC collision energy 14 TeV reachable depends on the highest B-field possible (~8Tesla)

FCC-ee/FCC-hh (r = 15.9km, circumference 100km)

→ radius defined to reach 100 TeV proton collisions with to be developed magnet technology (~16Tesla)

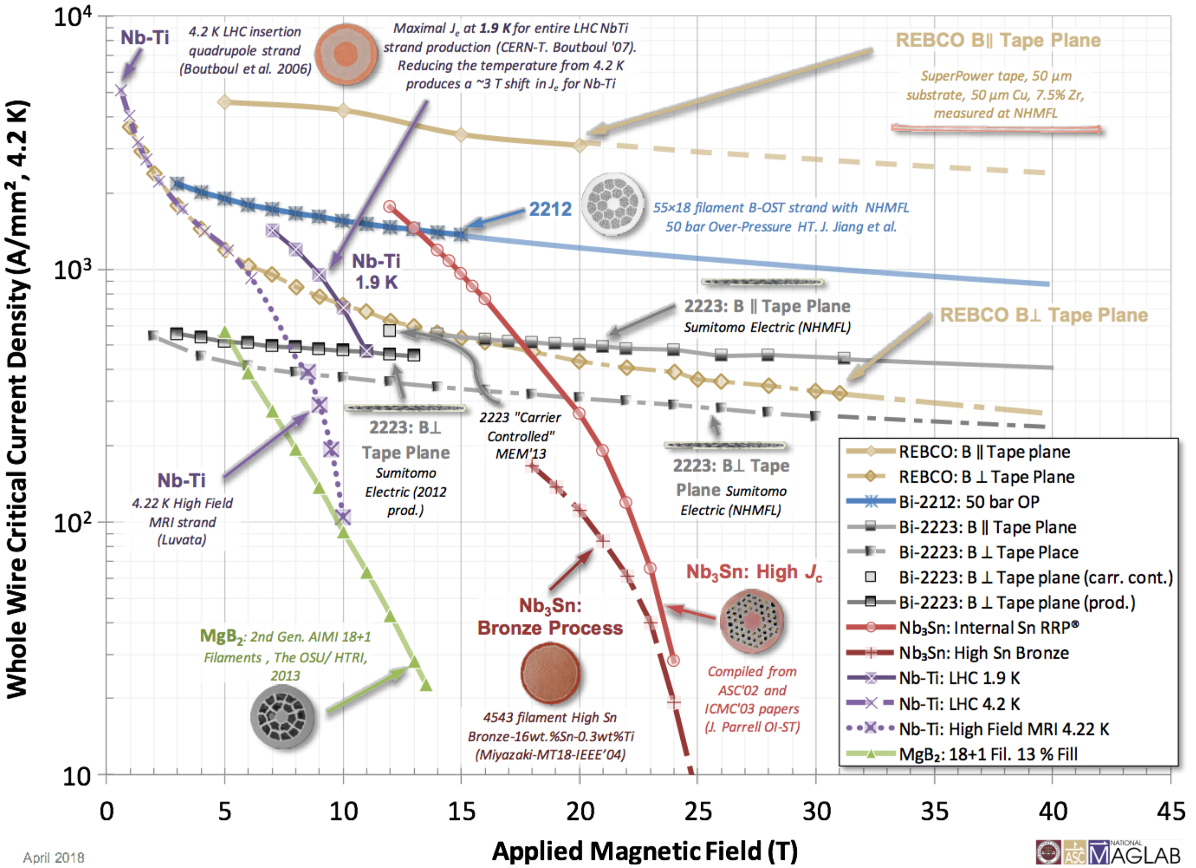
Accelerator technology – *the basics*



- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)
- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)
- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)

… important to develop high-field magnets to get to the highest energies

Accelerator technology – *the basics*



Superconducting magnets

Properties (J_c) and cost (EUR/kAm) of the conductor

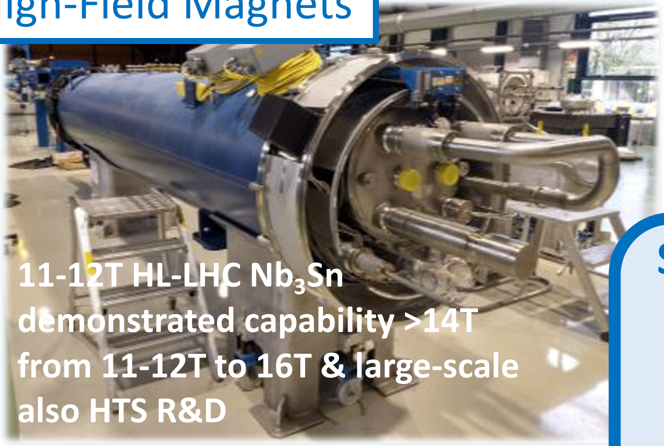
Cost-effective design of mechanical support structure

Training curve (# quenches) and magnet protection

A world-wide R&D effort

Advancing Accelerator Technologies

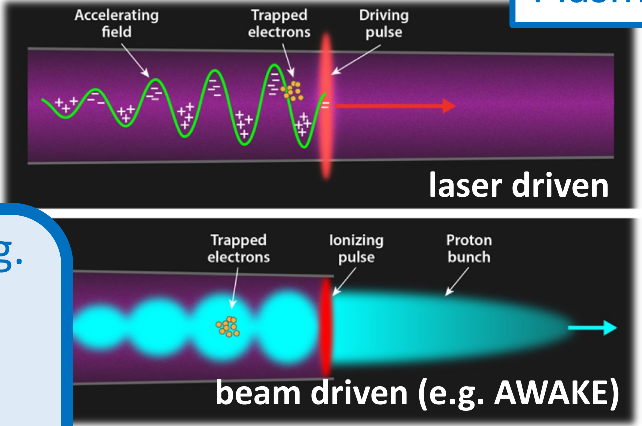
High-Field Magnets



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

continue to develop high-gradient accelerating technologies

Plasma

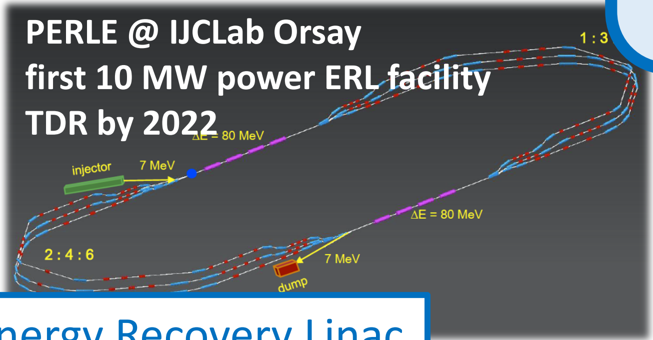


APS/Alan Stonebraker

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

A vibrant field!

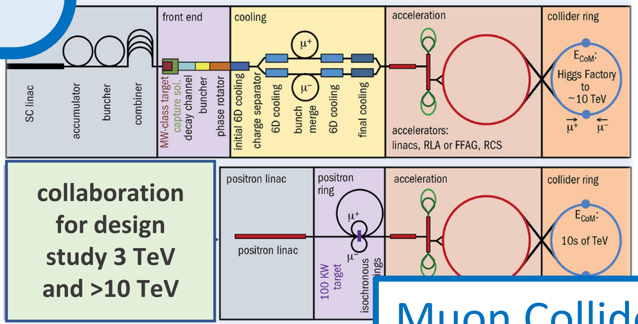
Energy Recovery Linac



PERLE @ IJCLab Orsay
first 10 MW power ERL facility
TDR by 2022

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

Muon Collider



collaboration for design study 3 TeV and >10 TeV

Towards an international muon collider design study

benefits

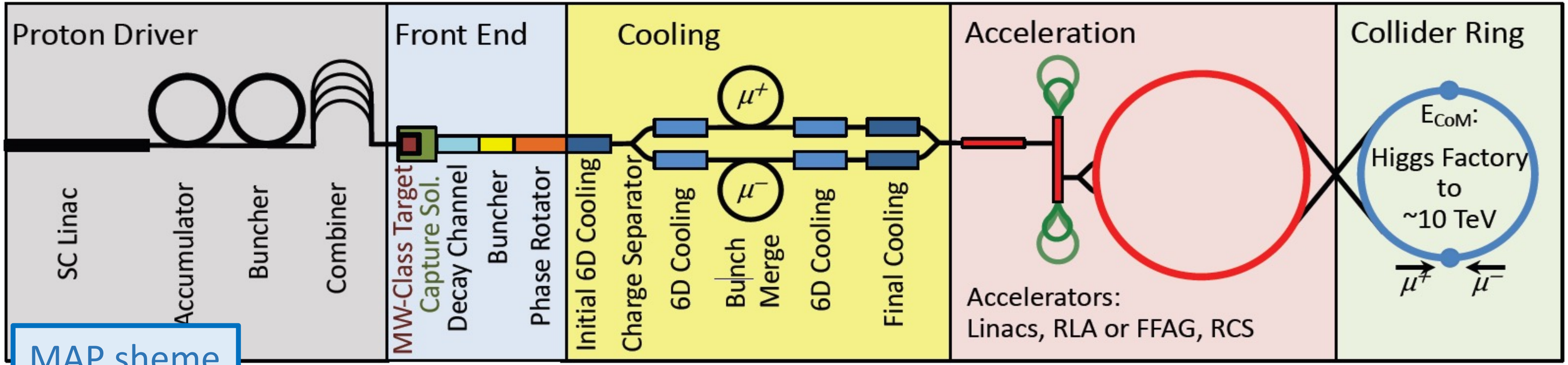
- Suppressed synchrotron radiation wrt electrons
- Luminosity can increase linearly with energy
- For the production of heavy particle pairs 14 TeV lepton collisions are comparable to 100 TeV proton collisions

international collaboration being formed towards
a design study for a 3 TeV and >10 TeV muon collider
(incl. exploring synergies with Higgs Factories & neutrino experiments)

muon collider

main challenge:
muon lifetime at rest
only 2.2 μs

http://muoncollider.web.cern.ch



MAP sheme

Additionally, an alternative LEMMA scheme with 45 GeV positrons that produce muon pairs

Advancing Accelerator Technologies

High-Field Magnets

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continue to develop high-gradient accelerating technologies

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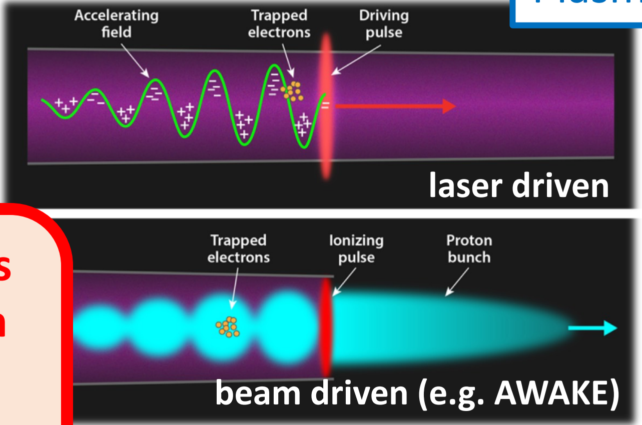
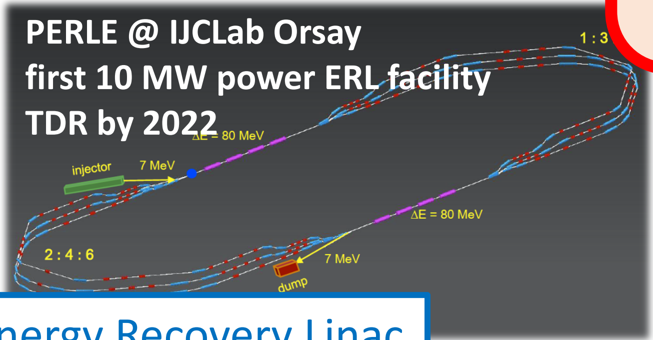


Various opportunities to contribute with an engineering mind to realise future accelerators



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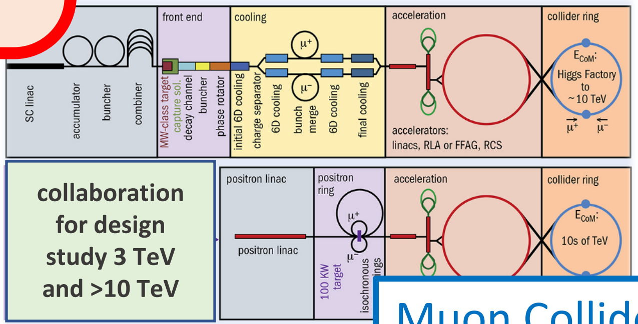
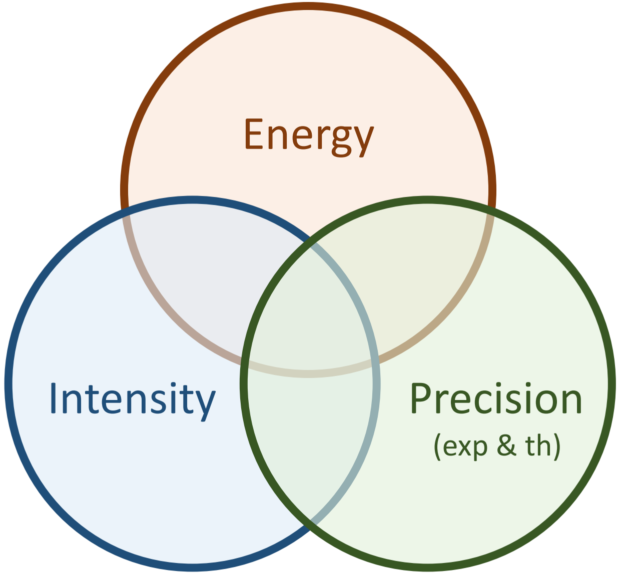


collaboration for design study 3 TeV and >10 TeV

Muon Collider

Three frontiers on the collider route to BSM

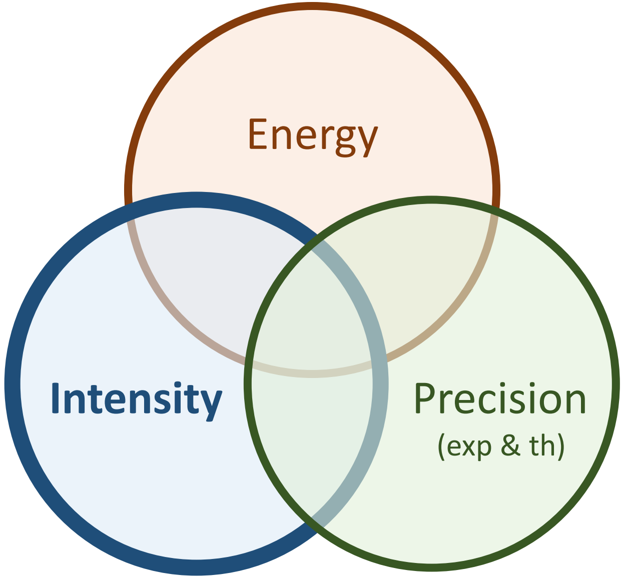


The performance of colliders can be defined with several technical parameters, of which three are key to map the physics potential

Intensity – e.g. SuperKEKB (indirect path to BSM)
Energy – e.g. from LHC to FCC-hh (direct path)
Precision – e.g. FCC-ee (could be both paths)

Extending these collider frontiers remains our prime route to unlock those BSM phenomena related to the most important open questions

Three frontiers on the collider route to BSM



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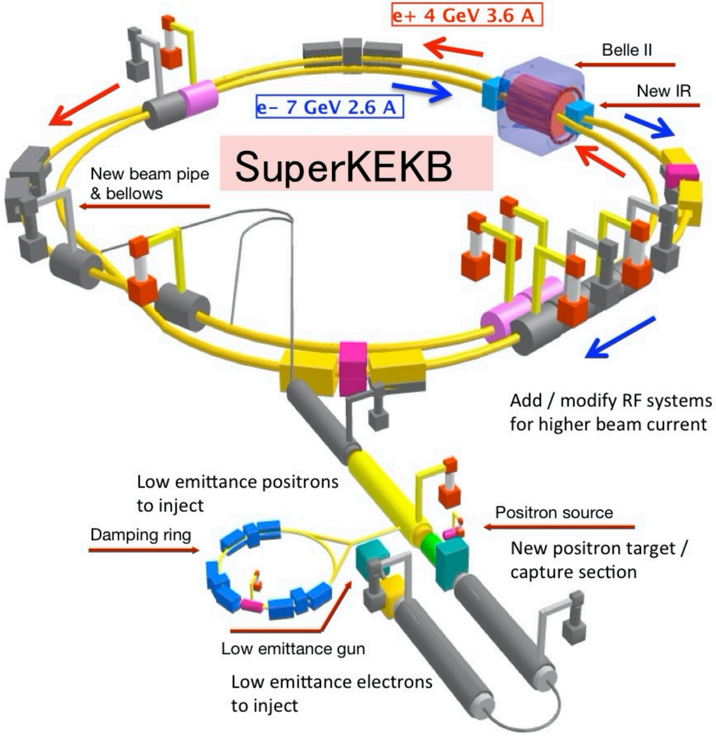
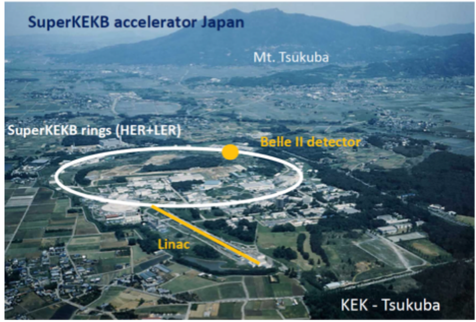
SuperKEKB in Japan

e^+e^- collider at the Υ(4S)≈10.5GeV
B-Factory for the Belle II experiment

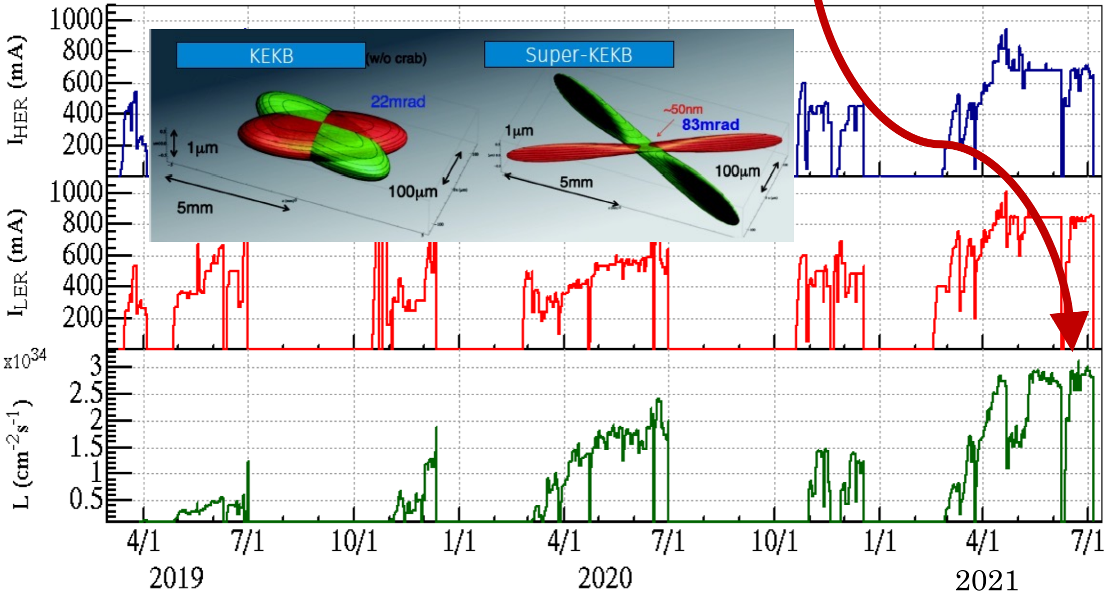




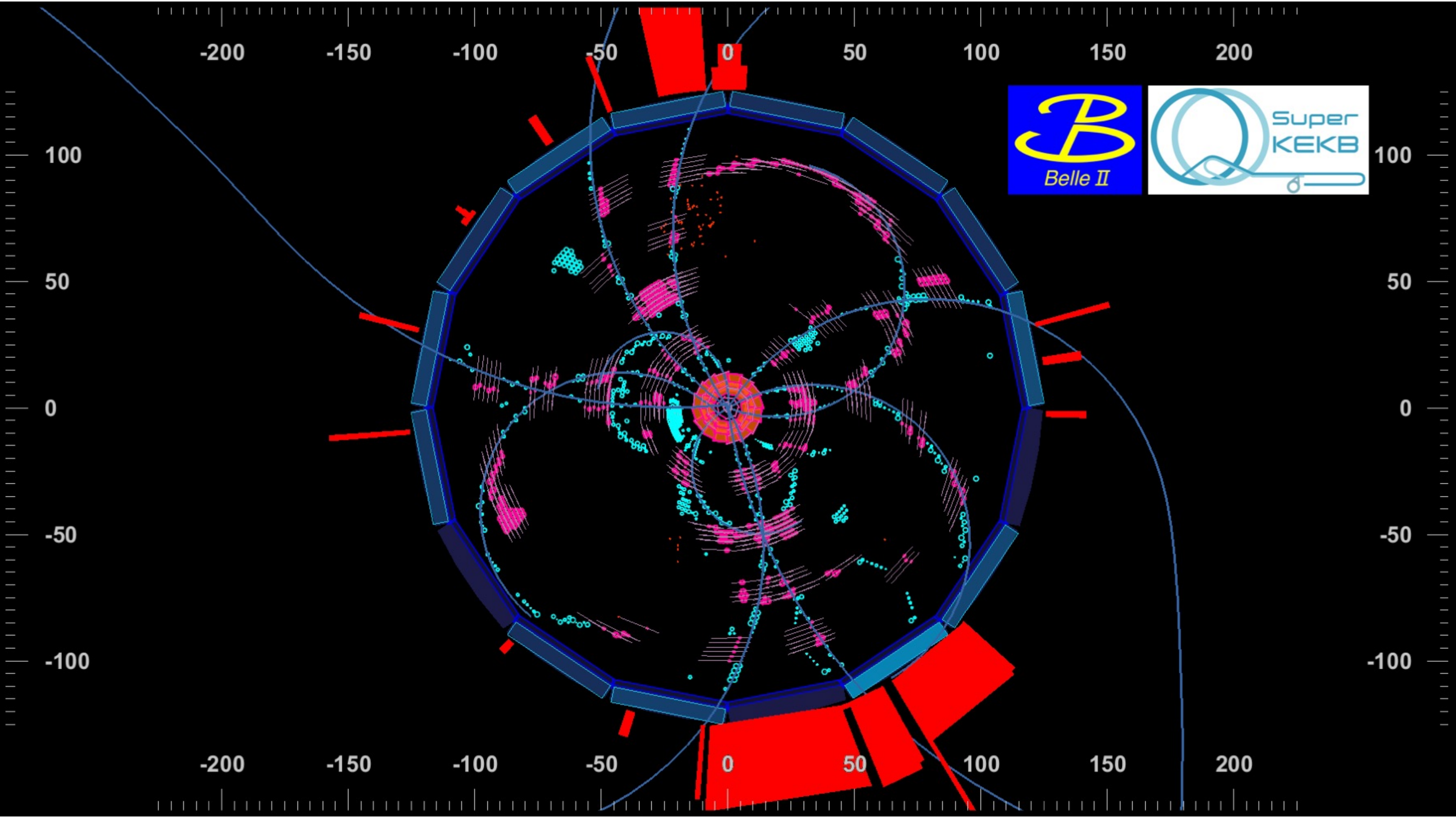
world record luminosity

$3.1\ 10^{34}\ cm^{-2}s^{-1}$ (June 2021)
(ultimate target $8\ 10^{35}\ cm^{-2}s^{-1}$)

1st ever nano-beam scheme



Note: SuperKEKB takes over the luminosity record from the LHC



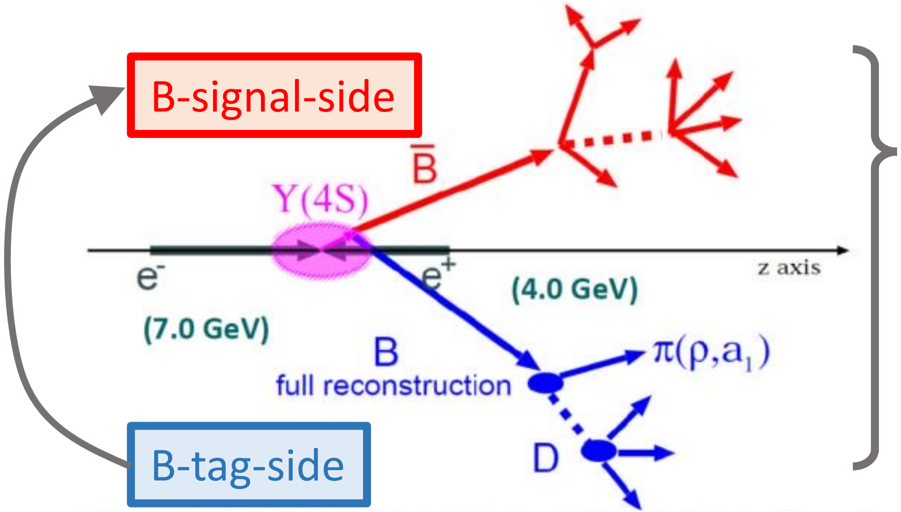
Belle II

Super KEKB

Physics with e^+e^- collisions @ SuperKEKB

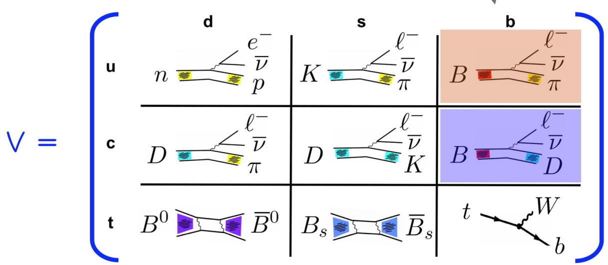
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ (~5 x 10^{10} b pairs in a decade, and c and τ pairs)

fixing the flavor, charge and momentum of the signal side

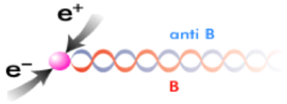


using multivariate techniques to reconstruct and identify the tag side, following a full event interpretation

V =



Quantum entangled neutral B meson pair production



CKM matrix

e.g. ~1% level accuracy on $|V_{ub}|$ with full data set

The Belle II Physics Book – Prog. Theor. Exp. Phys. 2019, 123C01

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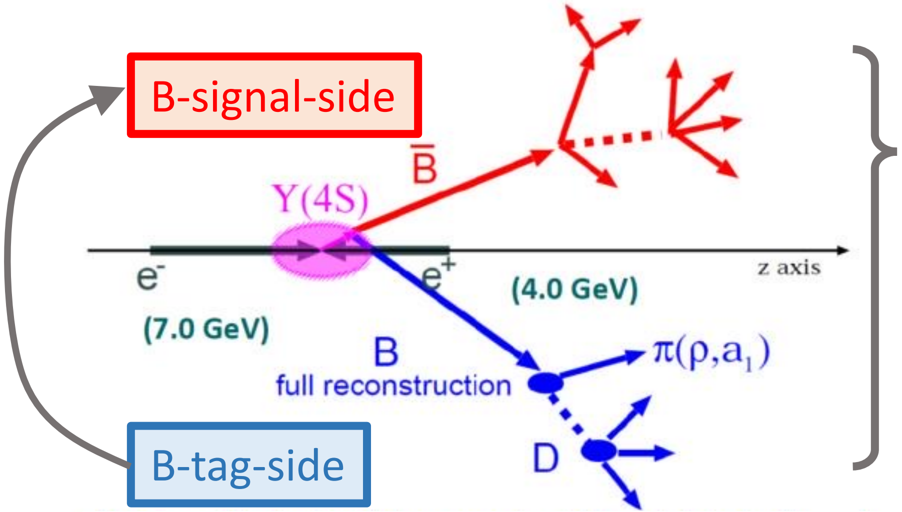

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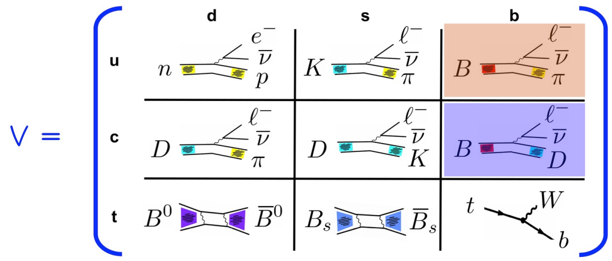

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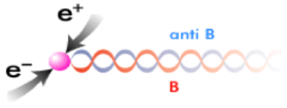

Belle II @ SuperKEKB will be a major experiment during this decade with a wide physics program

CKM matrix

e.g. ~1% level accuracy on $|V_{ub}|$ with full data set

More on Flavour Physics in the lecture of Stéphane Monteil Fuks this school

The Belle II Physics Book – Prog. Theor. Exp. Phys. 2019, 123C01

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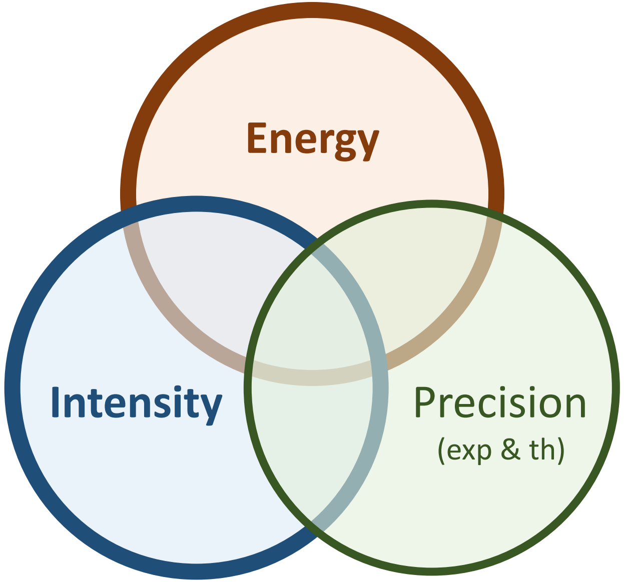

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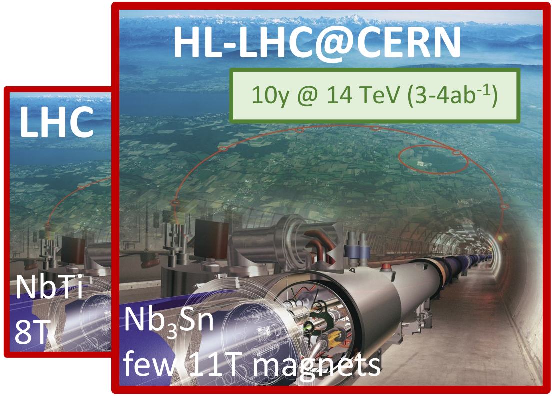
Today’s Flagship: from LHC to HL-LHC

Current flagship (27km)

impressive programme up to 2040



LHC

NbTi
8T

HL-LHC@CERN

10y @ 14 TeV (3-4ab^{-1})

Nb_3Sn
few 11T magnets

ALICE – Upgrade LS2 – *study Quark-Gluon Plasma formed in nuclear collisions*

Monolythic-pixel Inner Tracking System
→ x3-5 better tracking precision

Pixel Muon Forward Tracker
→ non-prompt muons from B decays

GEM-based TPC readout
→ x100 readout rate in Pb-Pb

- Low-p_T heavy-flavour mesons/baryons: characterize QCD with heavy quarks
- Low-p_T charmonia: c-cbar melting and re-generation in deconfined system
- Low-mass di-electrons: QC

LHCb – Upgrade LS2

Will collect 50 fb^{-1} at instantaneous lumi of 2x10^{33}cm^{-2}s^{-1}
Full software trigger
New tracking detectors
New RICH photon detectors
New electronics read out at 40 MHz

Prototypes of DAQ board (PCIe40)

VELO RF-foil (250 um thick machined aluminum foil)

Machining and light scan of the scintillating fiber mats for the fibre tracker

Si mchannel cooli

Cherenkov ring from a full RICH MaPMT module

Calorimeter front-end board

Muon system readout ASIC

18

CERN and the High-Luminosity LHC: 300/fb → 3000/fb

New IR-quads Nb_3Sn (inner triplets)

New 11 T Nb_3Sn (short) dipoles

Collimation upgrade

Cryogenics upgrade

Crab Cavities

Cold powering

Machine protection

Civil engineering

Formal approval by CERN Council (June 2016)
Cost to Completi

ATLAS – Upgrade Phase II – LS3

NEW ALL-SILICON INNER TRACKER (ITK) WITH ETA COVERAGE UP TO 4

HIGH G… TIMING DETECTOR (HGTD) IN FORWARD REGION (OPTION)

TDAQ OFF-DETECTOR ELECTRONICS:
- L0 HARDWARE TRIGGER:
  - L0 CALORIMETER
  - L0 TOPOLOGICAL
  - L0 MUON
  - L0 GLOBAL
- L1 HARDWARE TRIGGER (OPTION):
  - L1 GLOBAL
  - L1 TRACK TRIGGER
- READOUT SYSTEM
- HLT

NEW MUON CHAMBERS IN THE INNER BARREL REGION

FORWARD MUON TAGGER (OPTION)

15

CMS – Upgrade Phase II – LS3

Trigger/HLT/DAQ
- Track information in trigger at 40 MHz
- 12.5 μs latency
- HLT input/output 750/7.5 kHz

Barrel EM calorimeter
- New FE/BE electronics for full granularity readout at 40 MHz - with improved time resolution
- Lower operating temperature (8∘)

New Endcap Calorimeters
- Rad. tolerant - High granularity transverse and longitudinal
- 4D shower measurement including precise timing capability

Muon systems
- New DT & CSC FE/BE electronics
- New station to complete CSC at $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Beam radiation and luminosity
Common systems and infrastructure

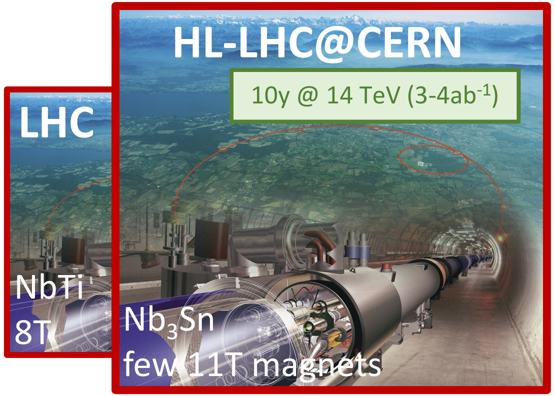
New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout (strips) for Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP precision Timing Detector
- Barrel layer: Crystal + SiPM
- Endcap layer: Low Gain Avalanche Diodes

Today’s Flagship: from LHC to HL-LHC

Current flagship (27km)

impressive programme up to 2040



ALICE – Upgrade LS2 – *study Quark-Gluon Plasma formed in nuclear collisions*

Monolythic-pixel Inner Tracking System
→ x3-5 better tracking precision

Pixel Muon Forward Tracker
→ non-prompt muons from B decays

GEM-based TPC
→ x100 readout
Pb-Pb

LHCb – Upgrade LS2

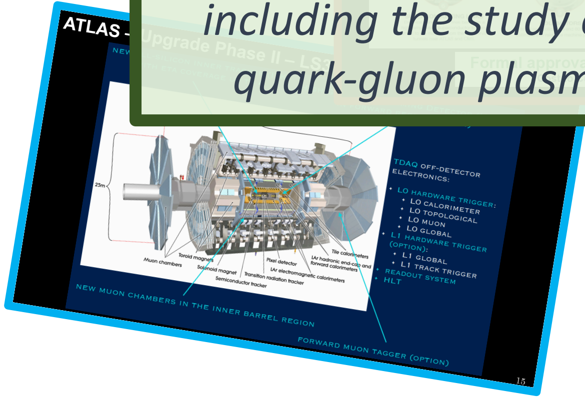
Will collect 50 fb^{-1} at instantaneous lumi of 2x10^{33}cm^{-2}s^{-1}
Full software trigger
New tracking detectors
New RICH photon detectors
New electronics read out at 40 MHz

Prototypes of DAQ board (PCIe40)

Machining and light scan of the scintillating fiber mats for the fibre tracker

European Strategy for Particle Physics (ESPP)

ESPP: “The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.”



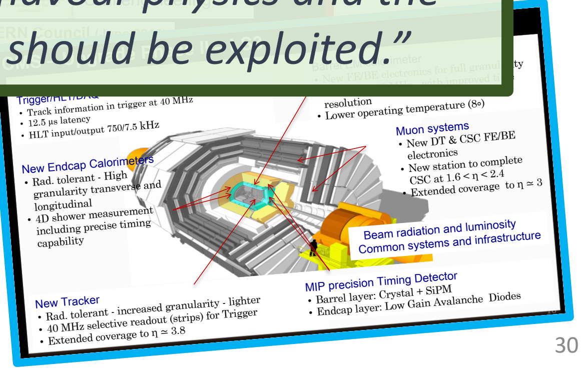
ATLAS –

TDAQ OFF-DETECTOR ELECTRONICS:
- L0 HARDWARE TRIGGER:
  - L0 CALORIMETER
  - L0 TOPOLOGICAL
  - L0 MUON
  - L0 GLOBAL
- L1 HARDWARE TRIGGER (OPTION):
  - L1 GLOBAL
  - L1 TRACK TRIGGER
- READOUT SYSTEM
- HLT

NEW MUON CHAMBERS IN THE INNER BARREL REGION

FORWARD MUON TAGGER (OPTION)

15



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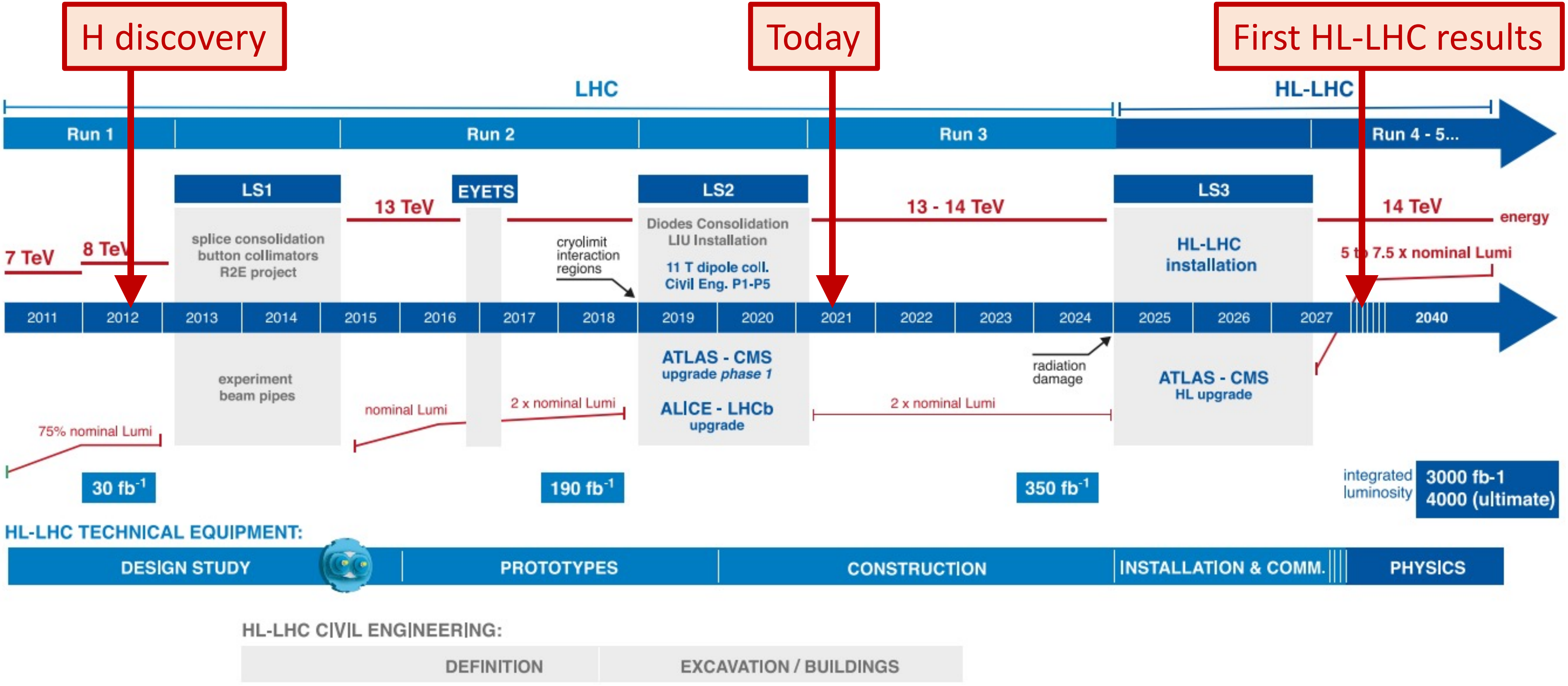
From the LHC to the High-Luminosity LHC @ CERN



H discovery

Today

First HL-LHC results

LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

EYETS

LS2

LS3

7 TeV

8 TeV

13 TeV

13 - 14 TeV

14 TeV

energy

splice consolidation
button collimators
R2E project

cryolimit
interaction
regions

Diodes Consolidation
LIU Installation

11 T dipole coll.
Civil Eng. P1-P5

HL-LHC
installation

5 to 7.5 x nominal Lumi

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2040

experiment
beam pipes

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

radiation
damage

ATLAS - CMS
HL upgrade

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

$30\ fb^{-1}$

$190\ fb^{-1}$

$350\ fb^{-1}$

integrated
luminosity

3000 fb-1
4000 (ultimate)

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS

HL-LHC CIVIL ENGINEERING:

DEFINITION | EXCAVATION / BUILDINGS

From the LHC to the High-Luminosity LHC @ CERN

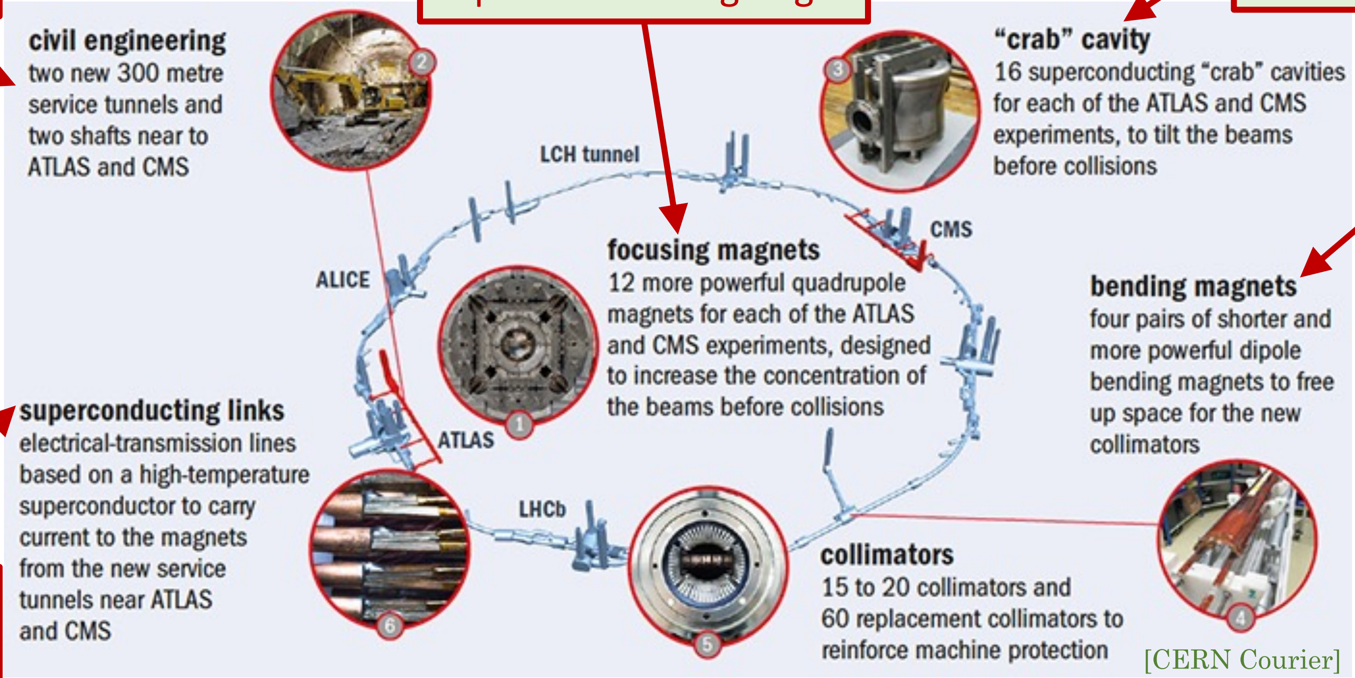
excavation mostly done

successfully tested (US)
production ongoing

successfully tested at SPS (CERN)

ongoing tests on bench, some qualified (CERN)

60m system demonstrator successful (CERN)



civil engineering
two new 300 metre service tunnels and two shafts near to ATLAS and CMS

“crab” cavity
16 superconducting “crab” cavities for each of the ATLAS and CMS experiments, to tilt the beams before collisions

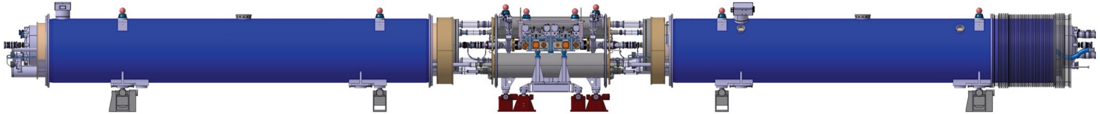
focusing magnets
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions

bending magnets
four pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators

superconducting links
electrical-transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS

collimators
15 to 20 collimators and 60 replacement collimators to reinforce machine protection

[CERN Courier]



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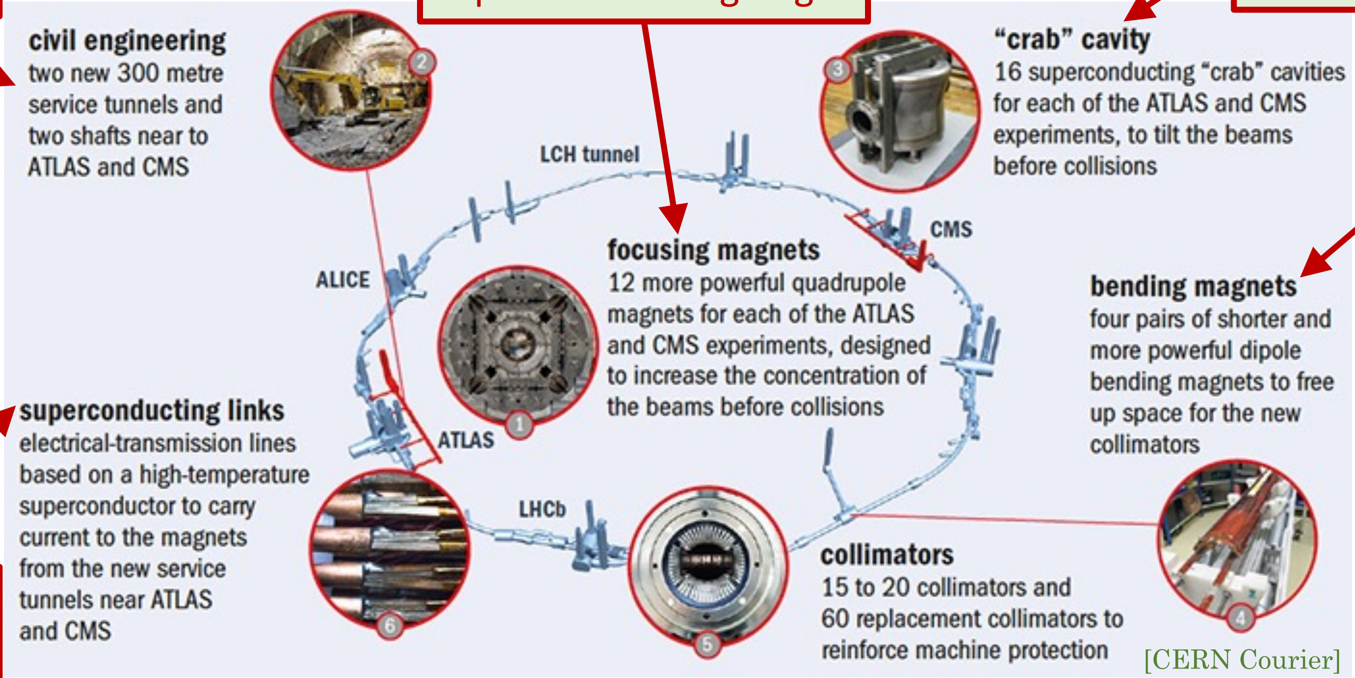

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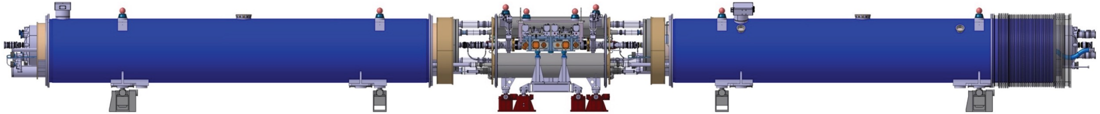
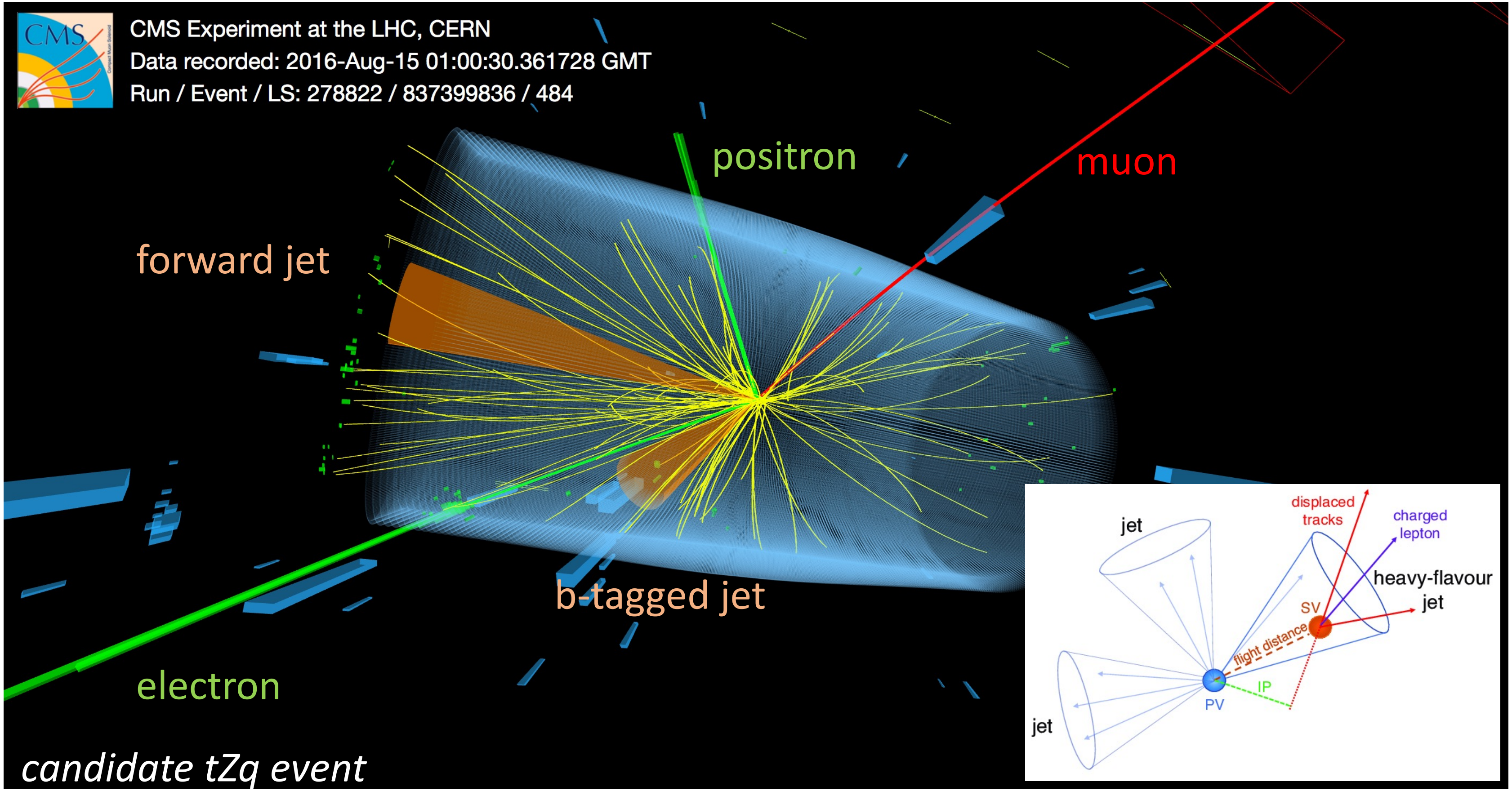
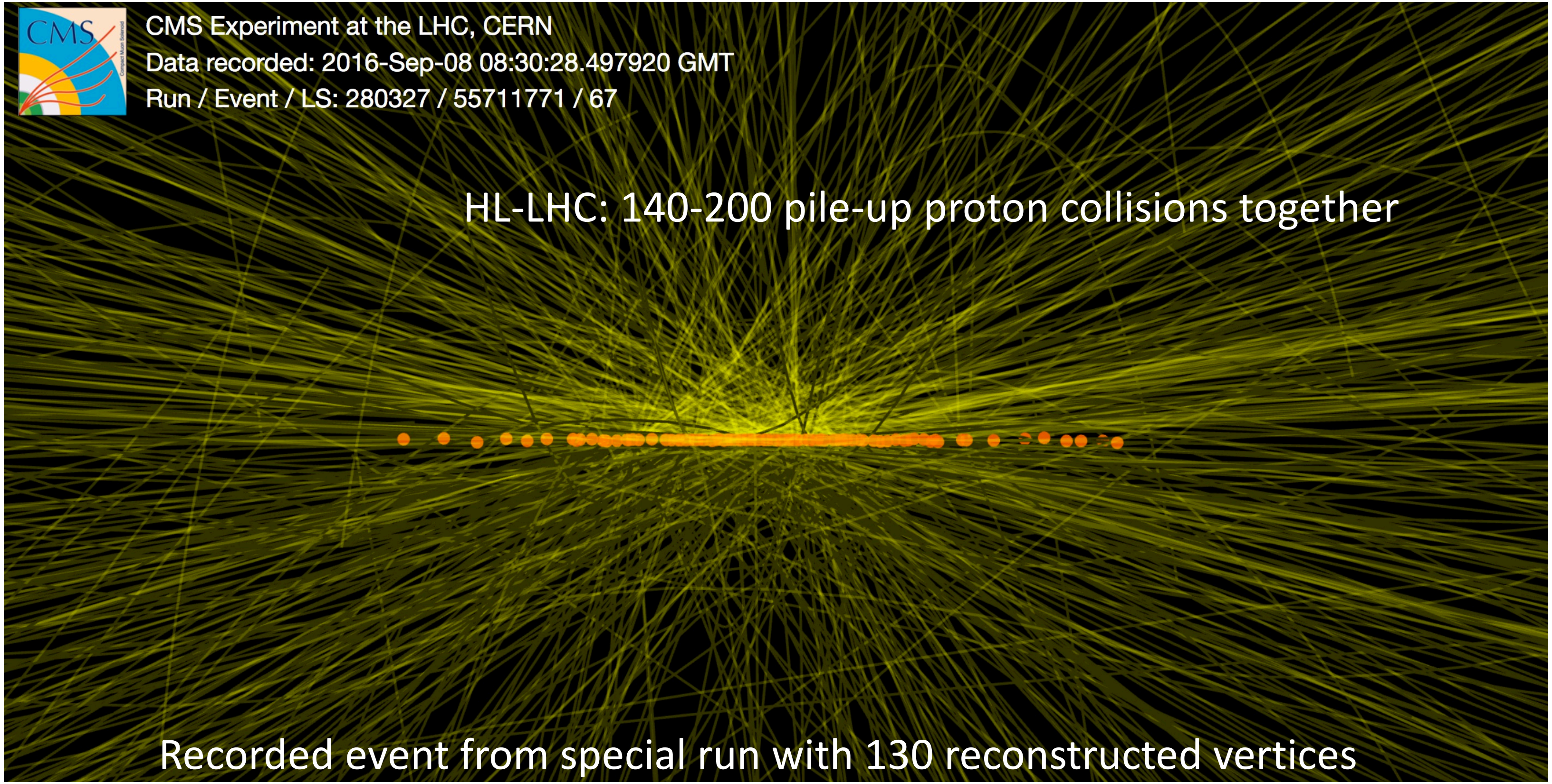


Illustration of a proton collision at the **LHC**



candidate tZq event

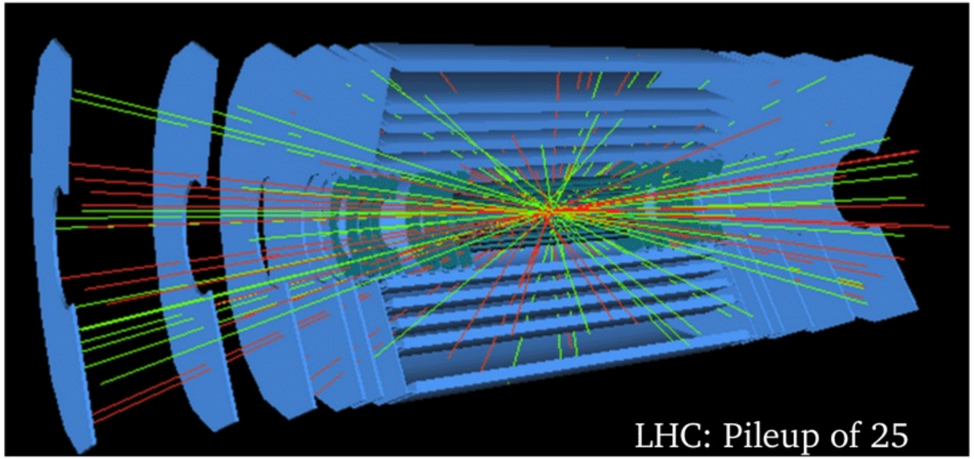
Illustration of a proton collision at the **HL-LHC**

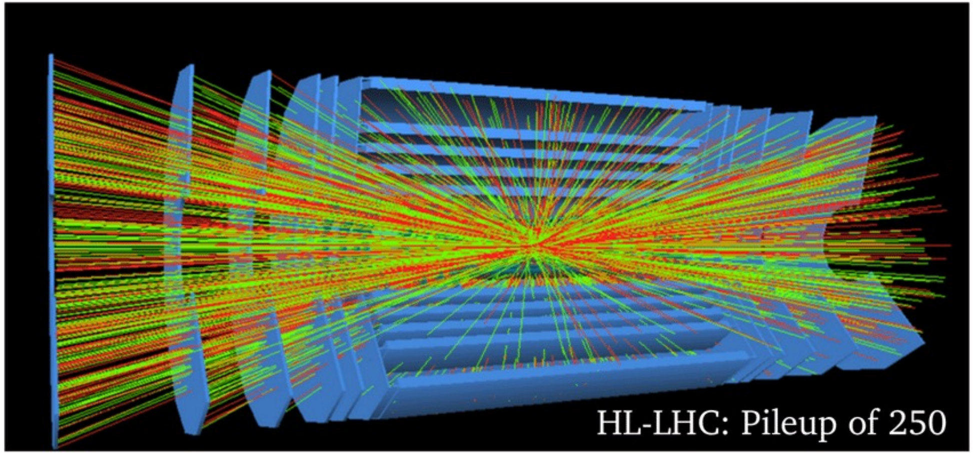


HL-LHC: 140-200 pile-up proton collisions together

Recorded event from special run with 130 reconstructed vertices

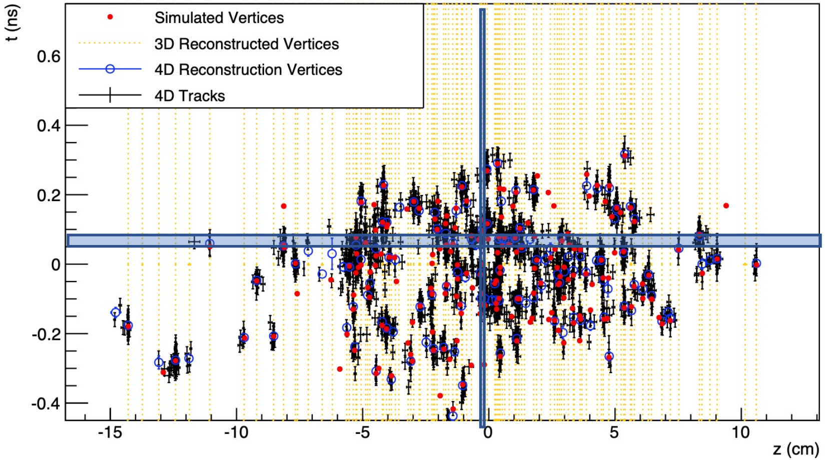
Illustration of a proton collision at the **HL-LHC**





The pile-up challenge is a major driver for innovations in detector instrumentation

3D (space) → 4D (space-time) tracking



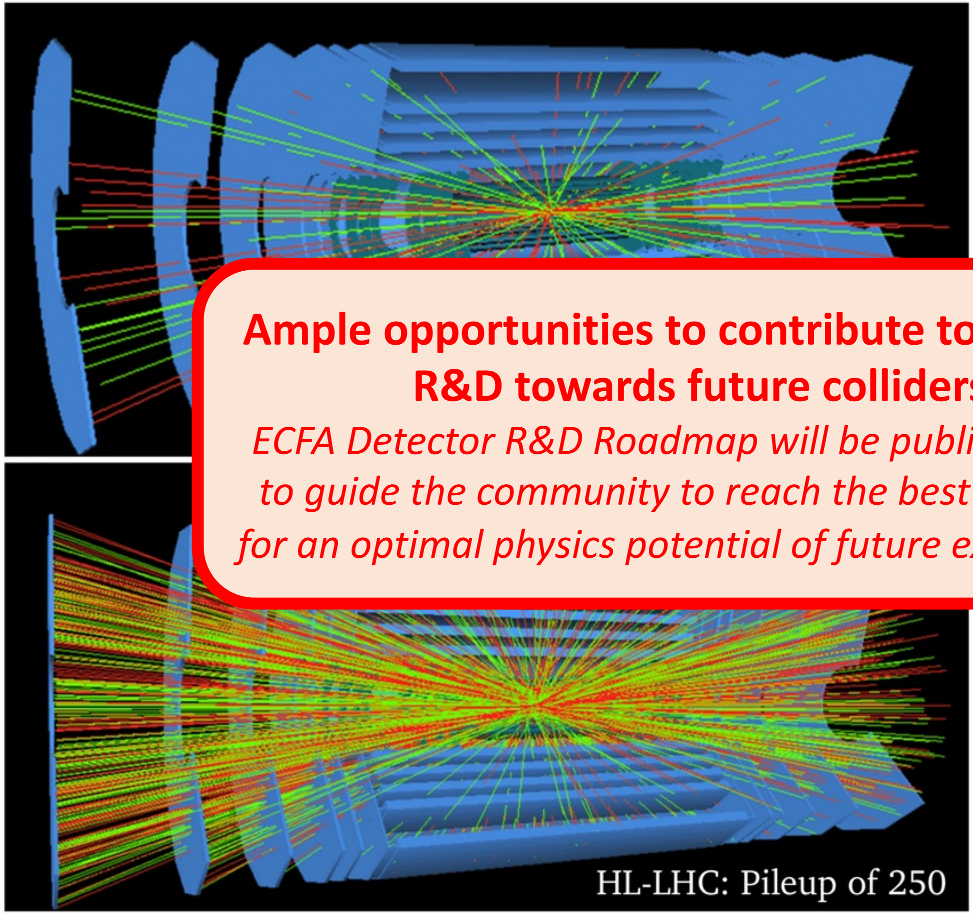
Slice the event in pieces of 30ps time

Additional to the 250μm slices in space

(only 1% probability to have 2 vertices in remaining box)

⟹ recover physics performance of LHC

Illustration of a proton collision at the **HL-LHC**



Ample opportunities to contribute to detector R&D towards future colliders

ECFA Detector R&D Roadmap will be published soon to guide the community to reach the best detectors for an optimal physics potential of future experiments

The pile-up challenge is a major driver for innovations in detector instrumentation

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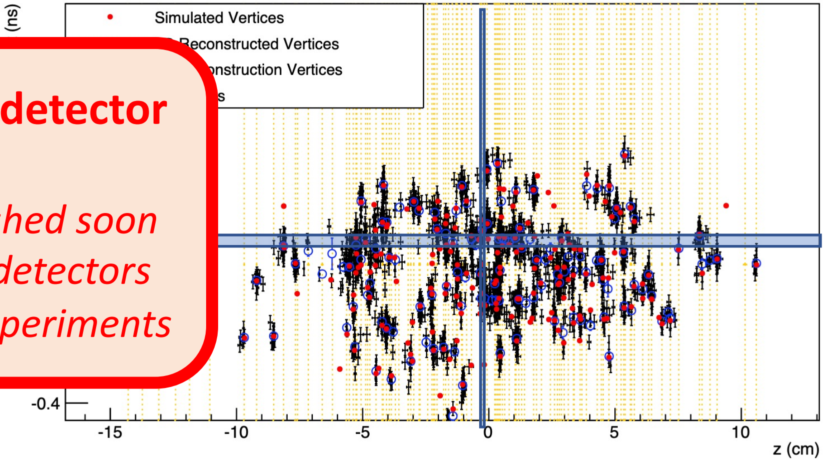

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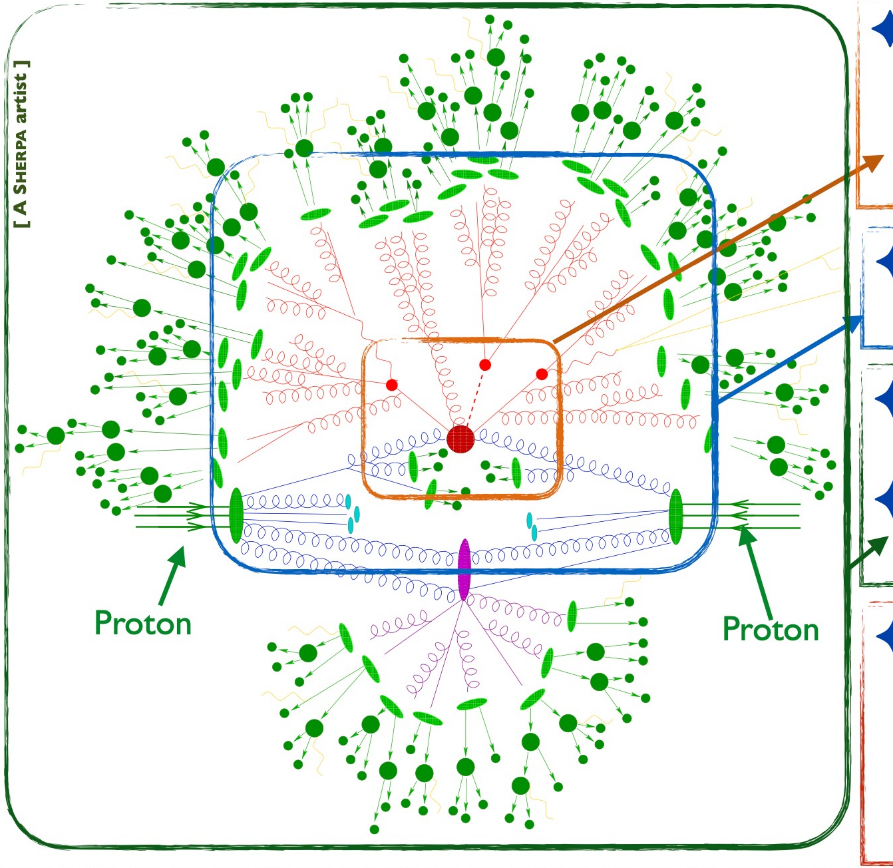
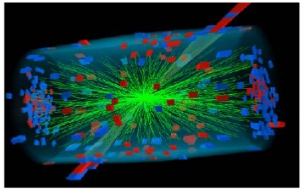
Physics with proton collisions @ HL-LHC



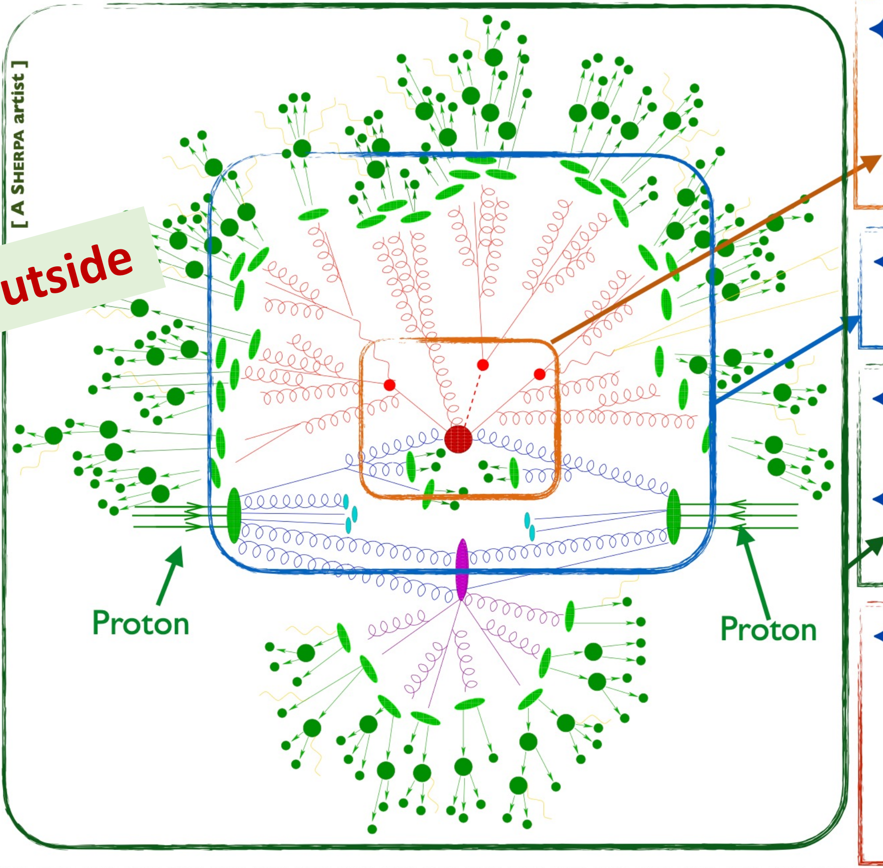
- **Hard process**
  - Depends on the physics model (SM, BSM,…)
  - Perturbative QCD
- **Parton showering**
  - Universal (QCD)
- **Hadronisation**
  - Model-based, universal
- **Underlying event**
  - Model-based, non-universal
- **Detector simulation**



Lecture of
Benjamin Fuks this school

Physics with proton collisions @ HL-LHC

From inside to outside



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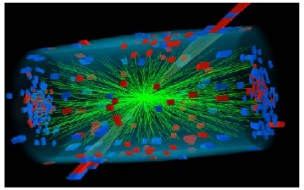
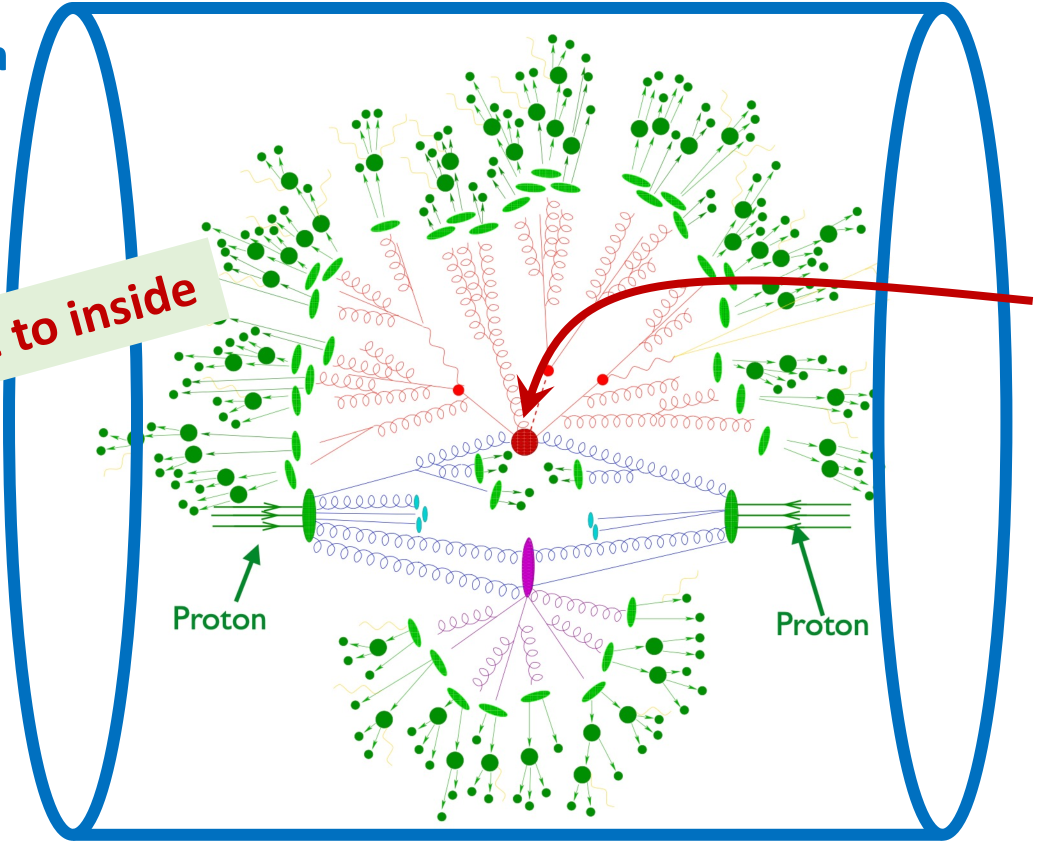


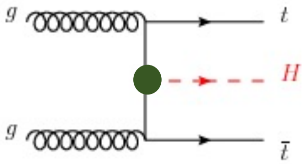
Physics with proton collisions @ HL-LHC

Observed collision with detector



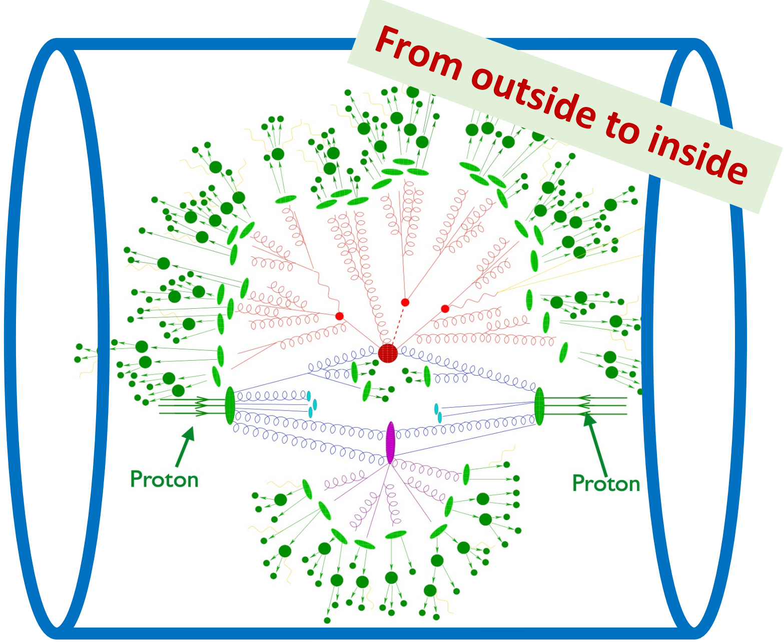
Feature to measure
(e.g. in ME of hard process)

$pp \rightarrow ttH$



sensitive to top quark Yukawa

Physics with proton collisions @ HL-LHC



From the observed collision
- identify the observed particles
- which particles from which quark → jets
- calibrate the observed features & performance
- is there an underlying event topology

Assume you observe
2 muons ⊕ 3 b-jets ⊕ 2 light-quark jets

Such an event could come from

ttH ➔ μνb μνb bb = signal (κ_t sensitive)

where one b-quark is not observed as a b-jet, but as a light-quark jet that radiated

Develop an optimal test statistics to differentiate such signal events from all backgrounds

Extract from the observed (differential) rate of signal events to value of the feature

Try to do this as much as possible independent from detector and theory assumptions

Physics with proton collisions @ HL-LHC

From the observed collision

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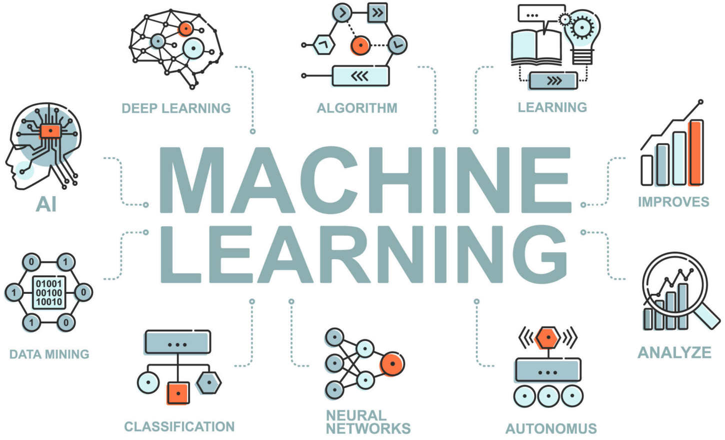
Yann Coadou this school



Latest CERN Courier on AI
https://cerncourier.com/p/magazine/

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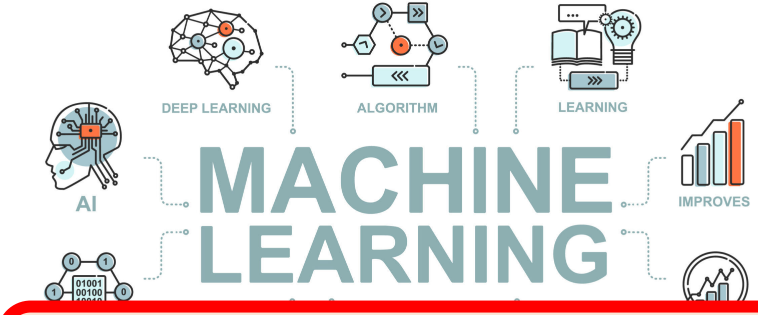

From sequential steps in an analysis to a more integrated approach

Latest CERN Courier on AI
https://cerncourier.com/p/magazine/

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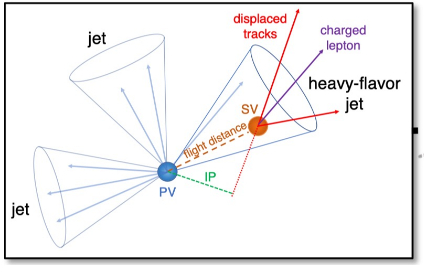
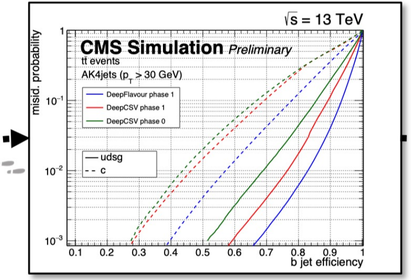
Physics with proton collisions @ (HL-)LHC

example
pp → ttcc

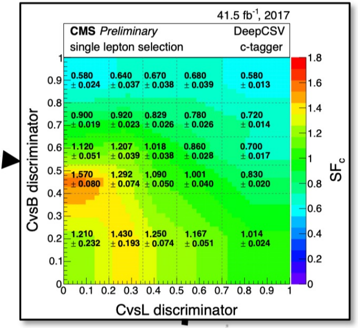
① c, b and t quarks require jets and heavy flavor tagging (new c-tagger)



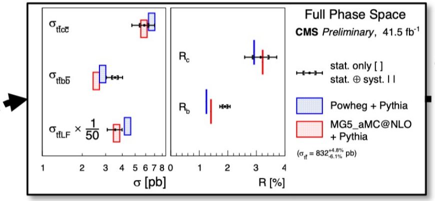
② Improved Machine Learning techniques for HF tagging

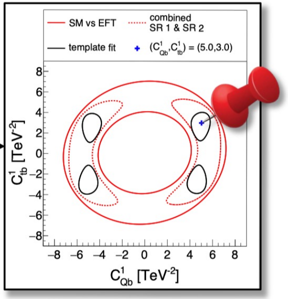


③ Calibration performance (charm tagger shape)

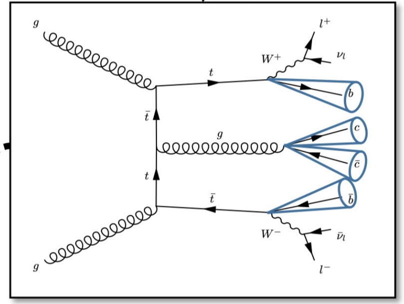


⑥ Resulting cross section measurement

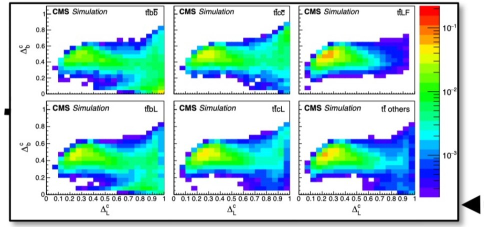




⑦ Search for new physics (SMEFT)



④ Selection and reconstruction of the tt̄+HF topology (jet-parton match)



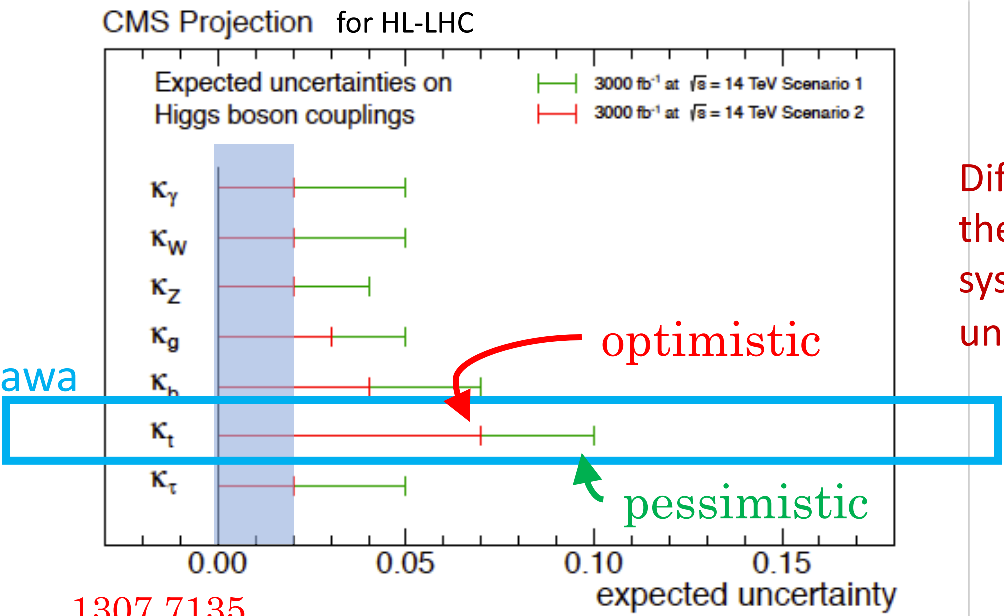
⑤ Differentiating tt̄+HF categories (ML classifier)

Seth Moortgat
CERN-THESIS-2019-051

Physics with proton collisions @ HL-LHC

Expected progress in studying the Higgs sector

situation in 2013



1307.7135

Different scenarios for the evolution of the systematic uncertainties

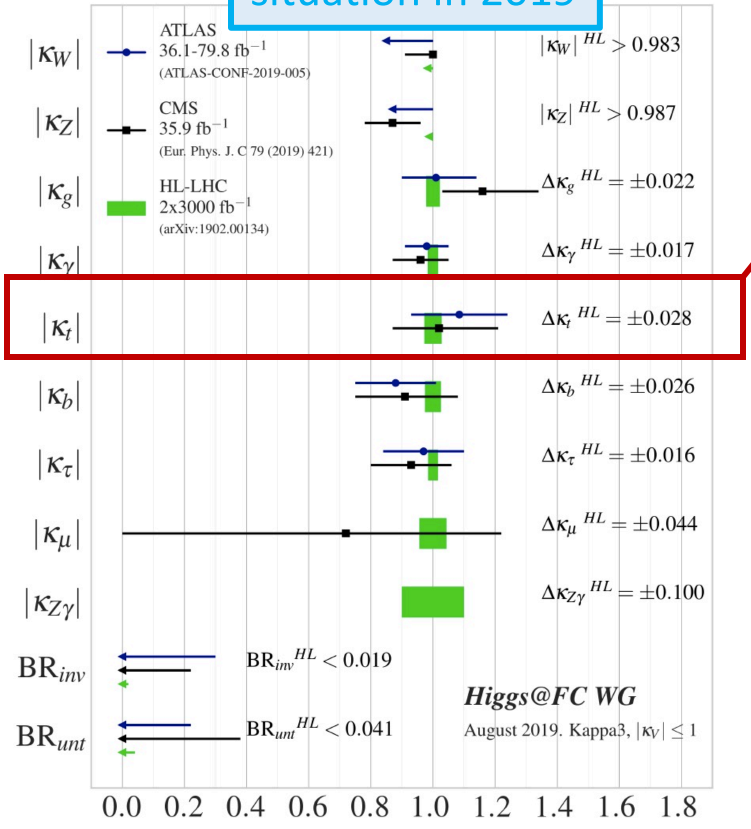
focus on top quark Yukawa

$\kappa_t \sim$ 7-10%

(expected precision)

From the LHC to the High-Luminosity LHC @ CERN

situation in 2019



[Physics Briefing Book, http://cds.cern.ch/record/2691414]

- The Higgs couplings are expected to improve significantly with the HL-LHC data
- The estimate made in 2013 for κ_t was a precision of 7-10% with 3000fb^{-1}, while **now a value better than 4% seems reachable** (for the same integrated luminosity)
- With only 6 years of experimental and theoretical innovations a factor of 2 improvement, and yet 20 years to go into the research program
- Recent innovations in instrumentation, software, computing, analysis and theoretical reasoning unlocked several new avenues for research that were previously thought unreachable…

From the LHC to the High-Luminosity LHC @ CERN

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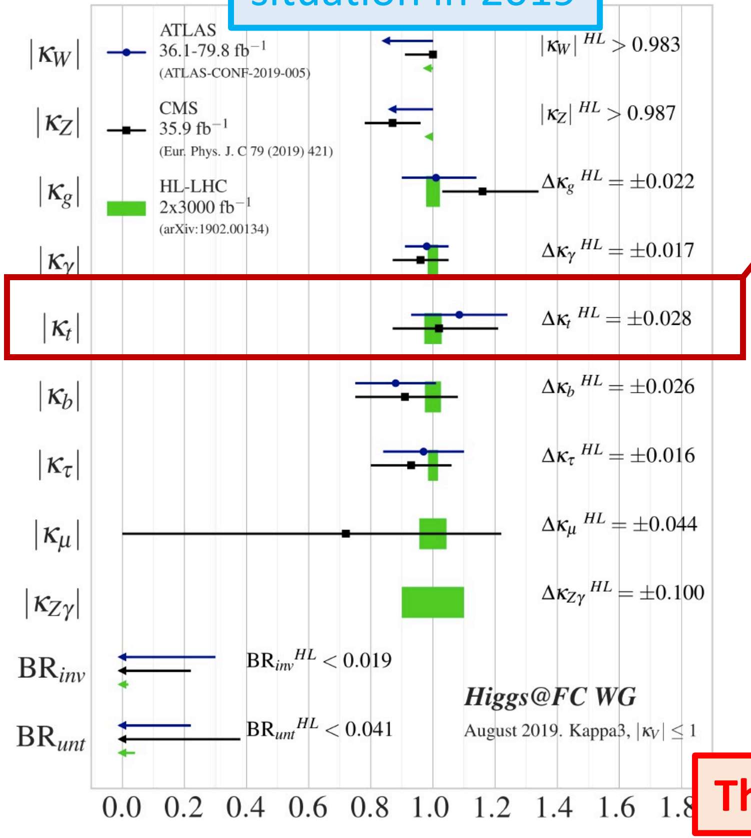

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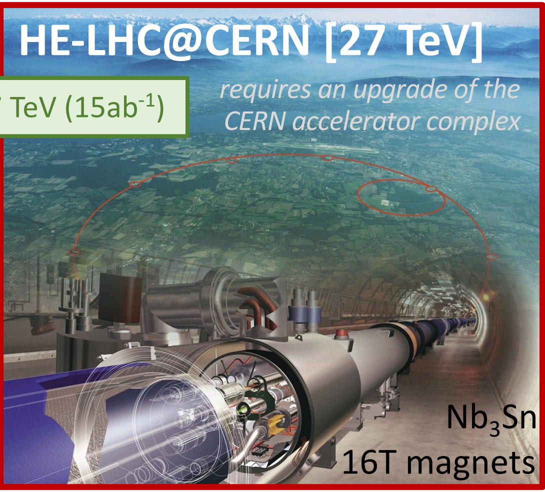
The HL-LHC is an outstanding platform for innovations!

Energy frontier colliders – Hadron Colliders

Direct BSM searches at the highest energies
e.g. addressing the naturalness puzzle

HE-LHC@CERN [27 TeV]

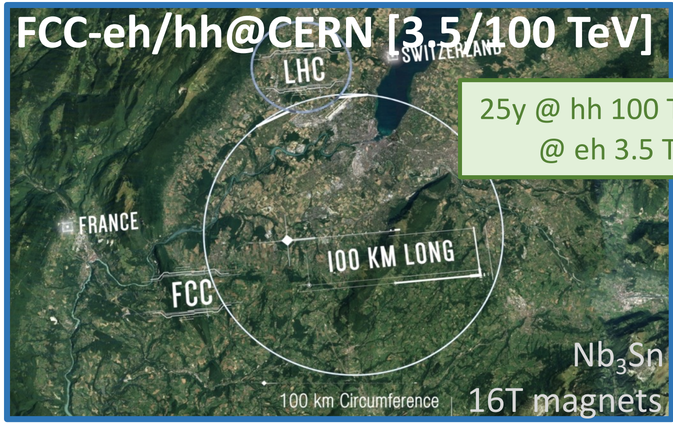
20y @ 27 TeV ($15ab^{-1}$)



requires an upgrade of the CERN accelerator complex

Nb_3Sn
16T magnets

FCC-eh/hh@CERN [3.5/100 TeV]

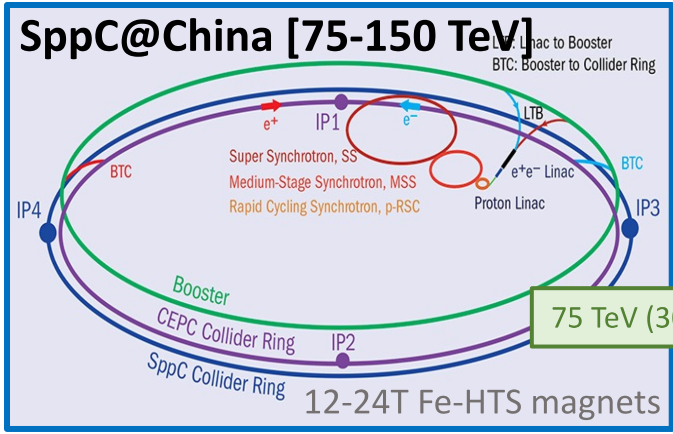


25y @ hh 100 TeV ($30ab^{-1}$)
@ eh 3.5 TeV ($2ab^{-1}$)

Nb_3Sn
16T magnets

E

SppC@China [75-150 TeV]



75 TeV ($30ab^{-1}$)

12-24T Fe-HTS magnets

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

Physics with proton collisions @ FCC-hh

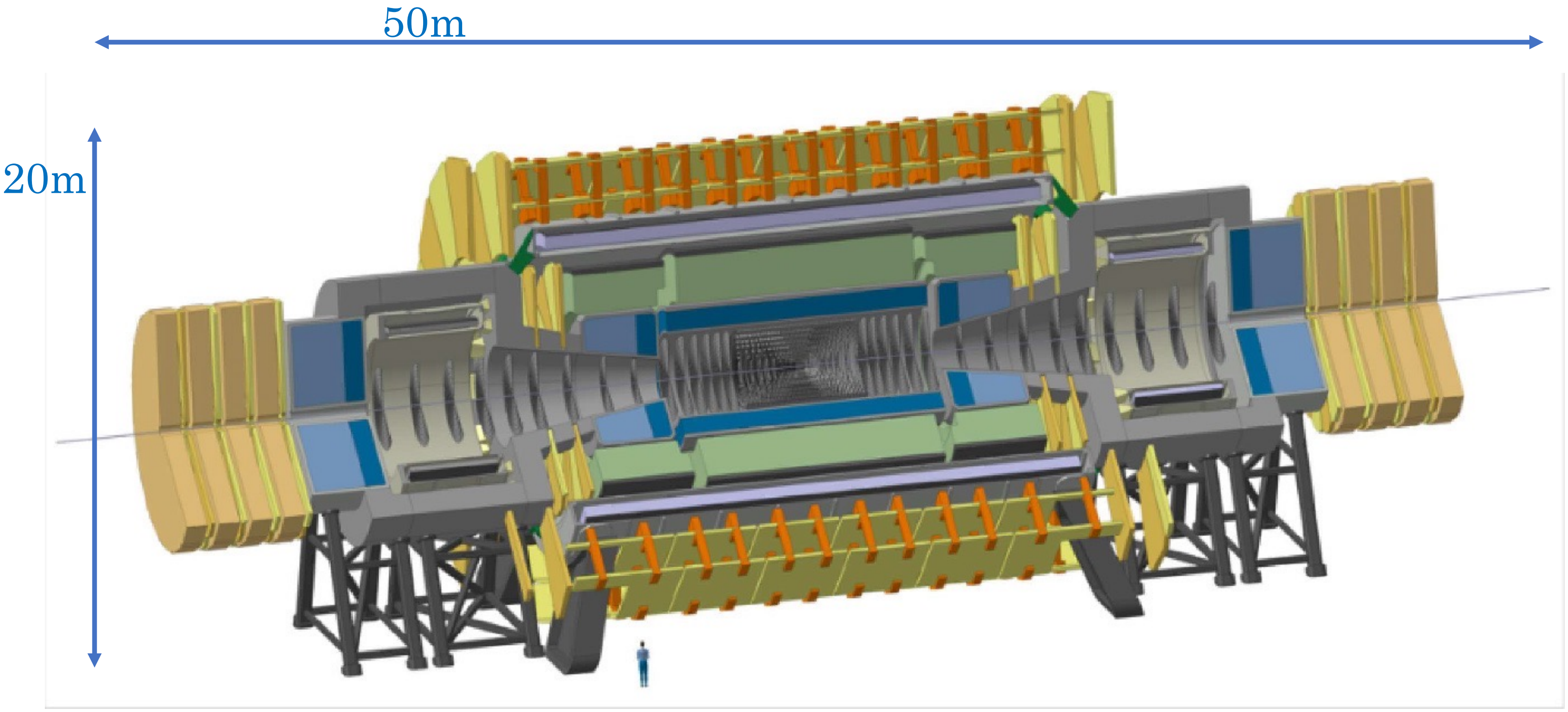
here I would show a simulated event display

but

very challenging today to simulate an event with
∼1000 pile-up proton collisions per beam crossing

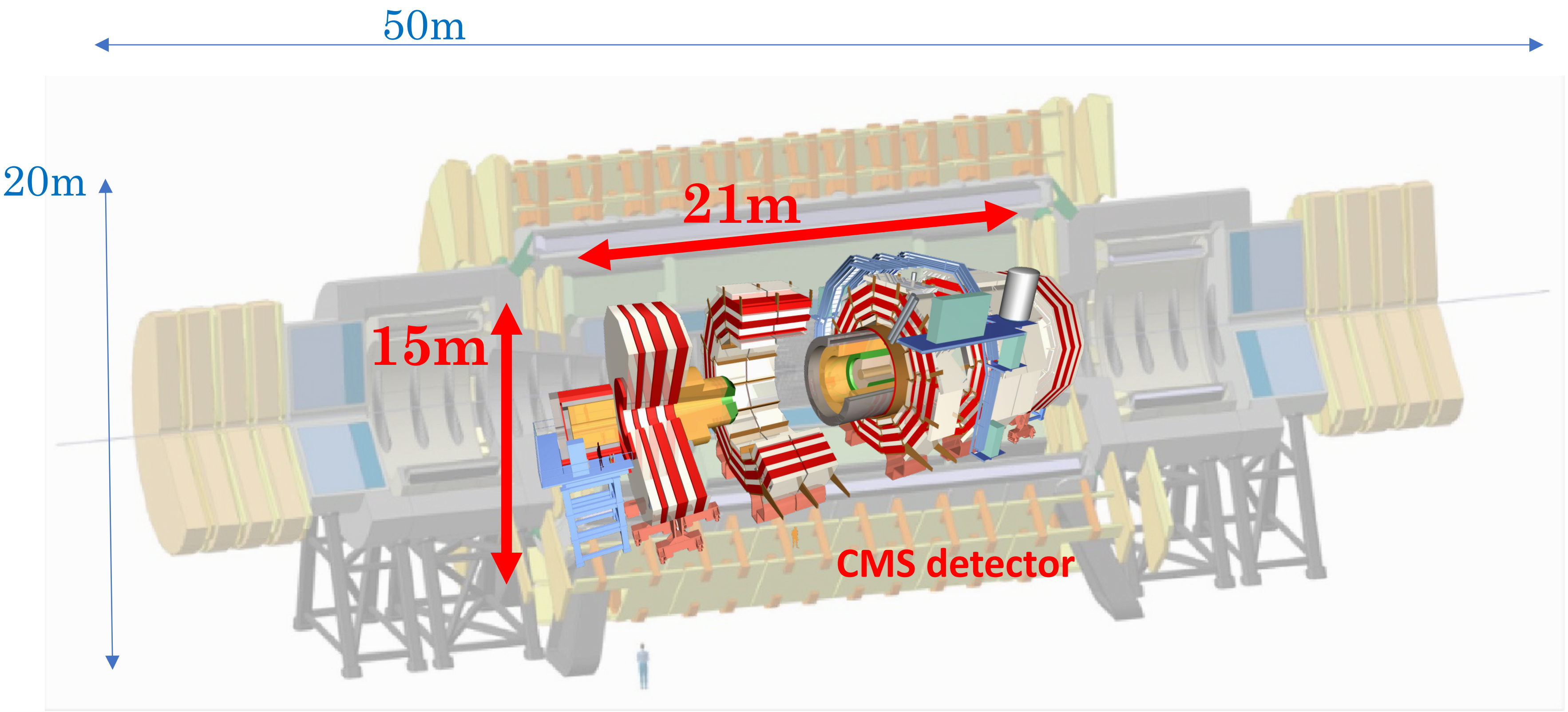
FCC Physics Opportunities, Eur. Phys. J. C (2019) 79:474

Physics with proton collisions @ FCC-hh



FCC Study – Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, CERN-ACC-2018-0058

Physics with proton collisions @ FCC-hh



FCC Study – Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, CERN-ACC-2018-0058

Physics with proton collisions @ FCC-hh

In 25 years of its operation (30ab^{-1}), in total

>10^{10} Higgs bosons (>10^{6} Higgs bosons with FCC-ee)
>10^{5} HH final states (Higgs self-interaction with ∼5% precision)
>10^{3} HHH final states (unique)
>10^{12} top quarks (10^{9} will radiate a Higgs boson → top quark Yukawa with ∼1% precision)

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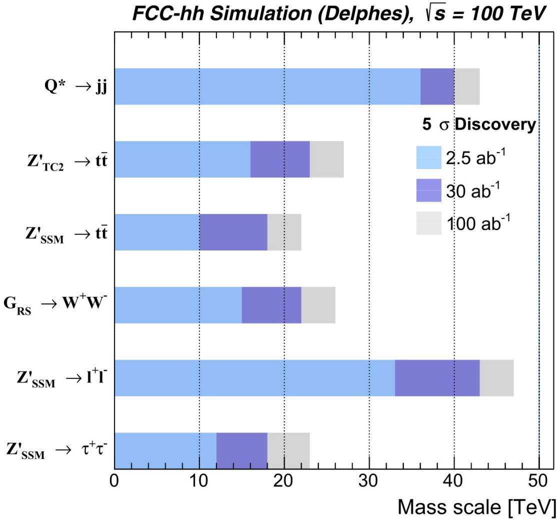

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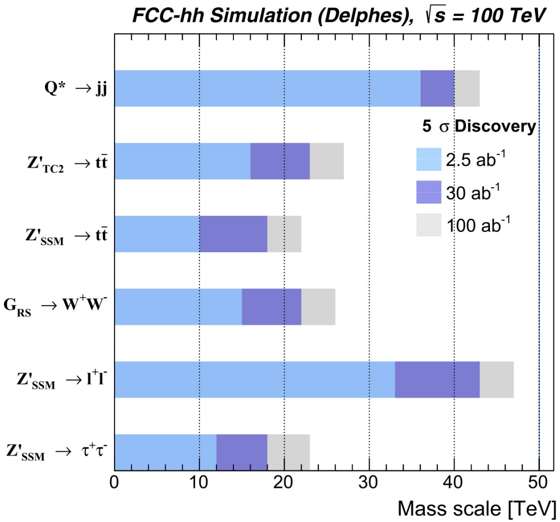


Today: map the physics potential of future colliders with the analysis techniques of today

Must be done: think ahead and invent those analysis methods that might be possible with the technology of the future

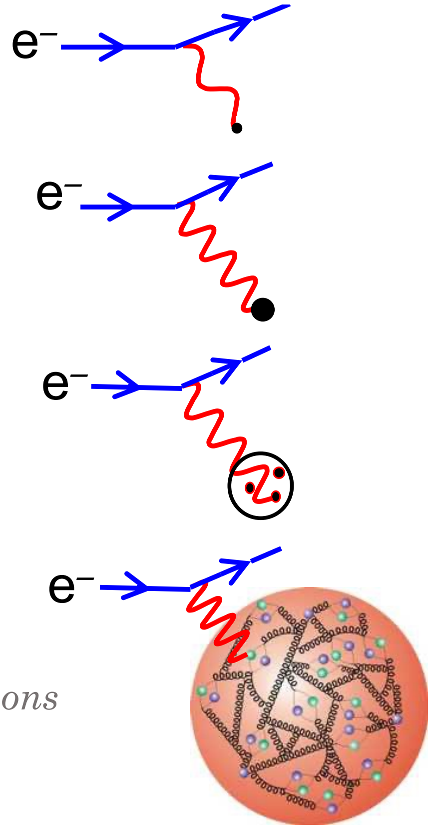
Understanding the inside of the proton

Low energy

point-like

Very high energy

sea of quarks and gluons



Strong interactions

QCD theory: $\mathcal{L}_{\rm QCD} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a + \bar{\psi}(i\not{D} - m)\psi$

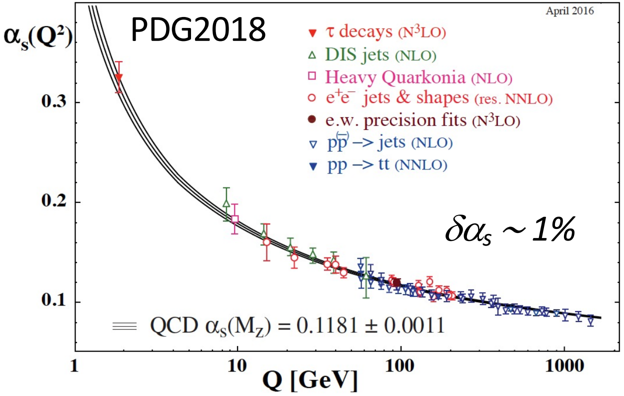
colour confinement

α_s (Q^2 low) ~ 1

key phenomena
(non-Abelian gauge group)

asymptotic freedom

α_s (Q^2 high) << 1



"hot and dense QCD"

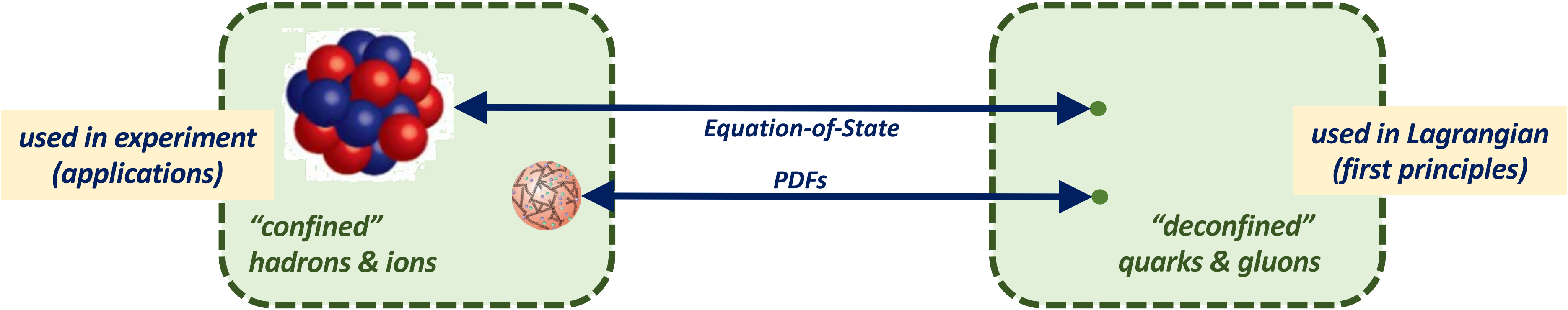
(low energy domain)
(lattice calculations)

"vacuum QCD"

(high energy domain)
(perturbative calculations)

$\alpha_{EW} << \alpha_s$

“hot and dense QCD” ⟷ *“vacuum QCD”*



used in experiment (applications)

“confined” hadrons & ions

Equation-of-State

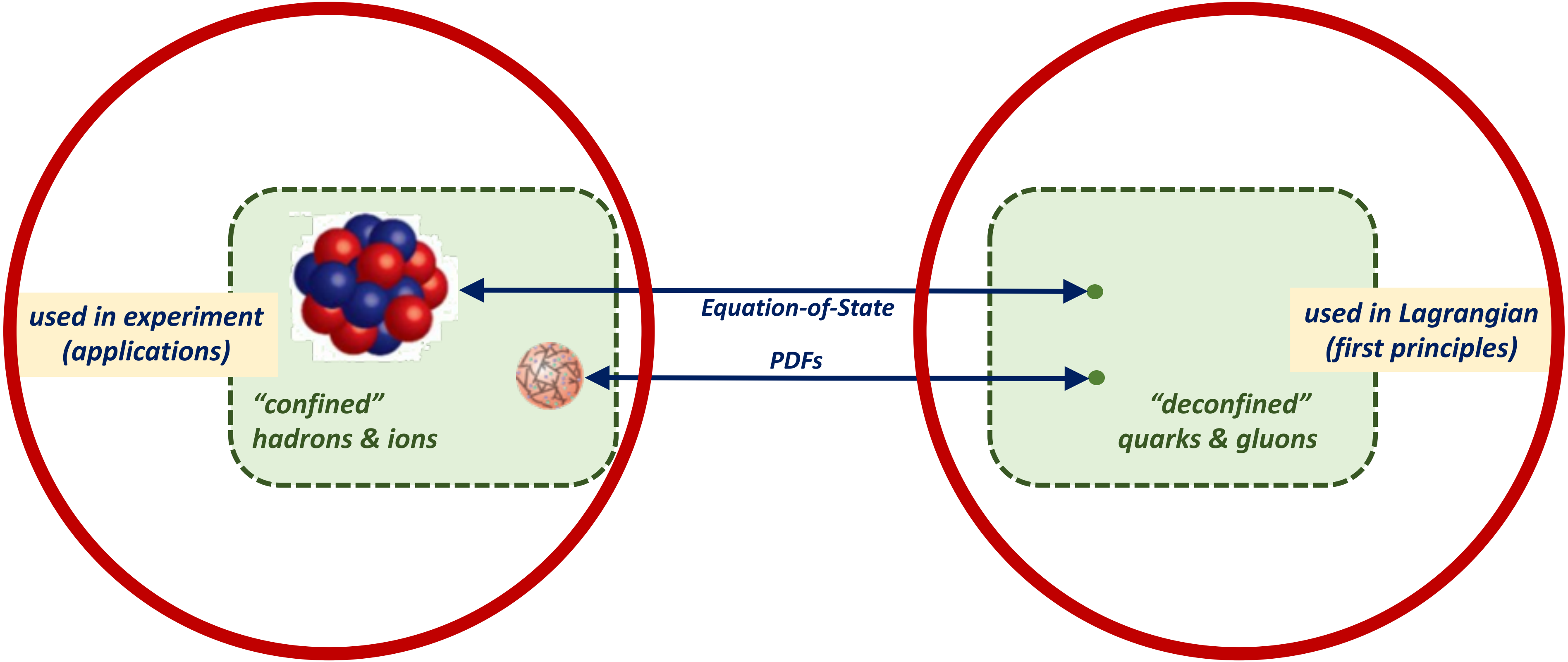
PDFs

“deconfined” quarks & gluons

used in Lagrangian (first principles)

portal to the observable world

portal to the rest of particle physics



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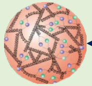
“hot and dense QCD” ⟷ *“vacuum QCD”*



used in experiment (applications)

“confined” hadrons & ions

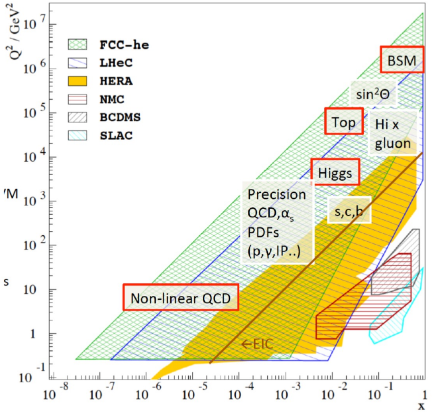
Equation-of-State

PDFs

used in Lagrangian (first principles)

“deconfined” quarks & gluons

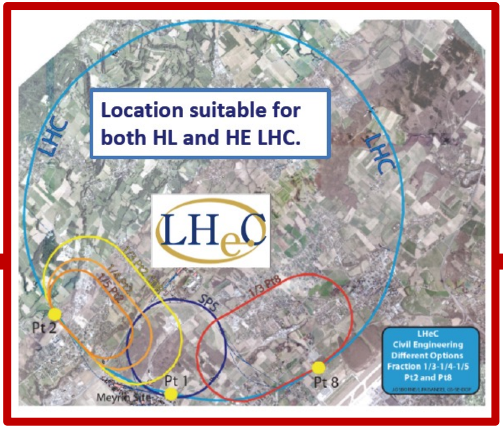
Reach an adequate precision of QCD predictions at the highest energies



Key facilities involve collisions with protons

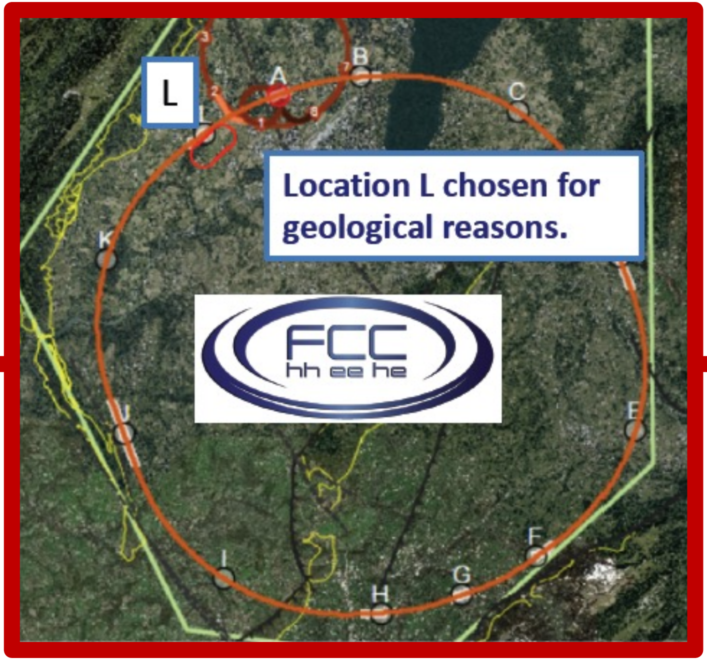
High energy ep collisions – from LHeC to FCC-eh

together with HL-LHC



Location suitable for both HL and HE LHC.

together with FCC-hh

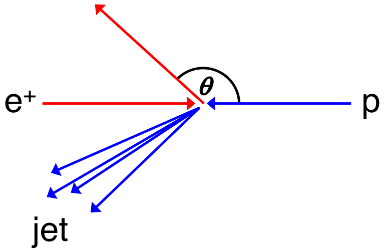


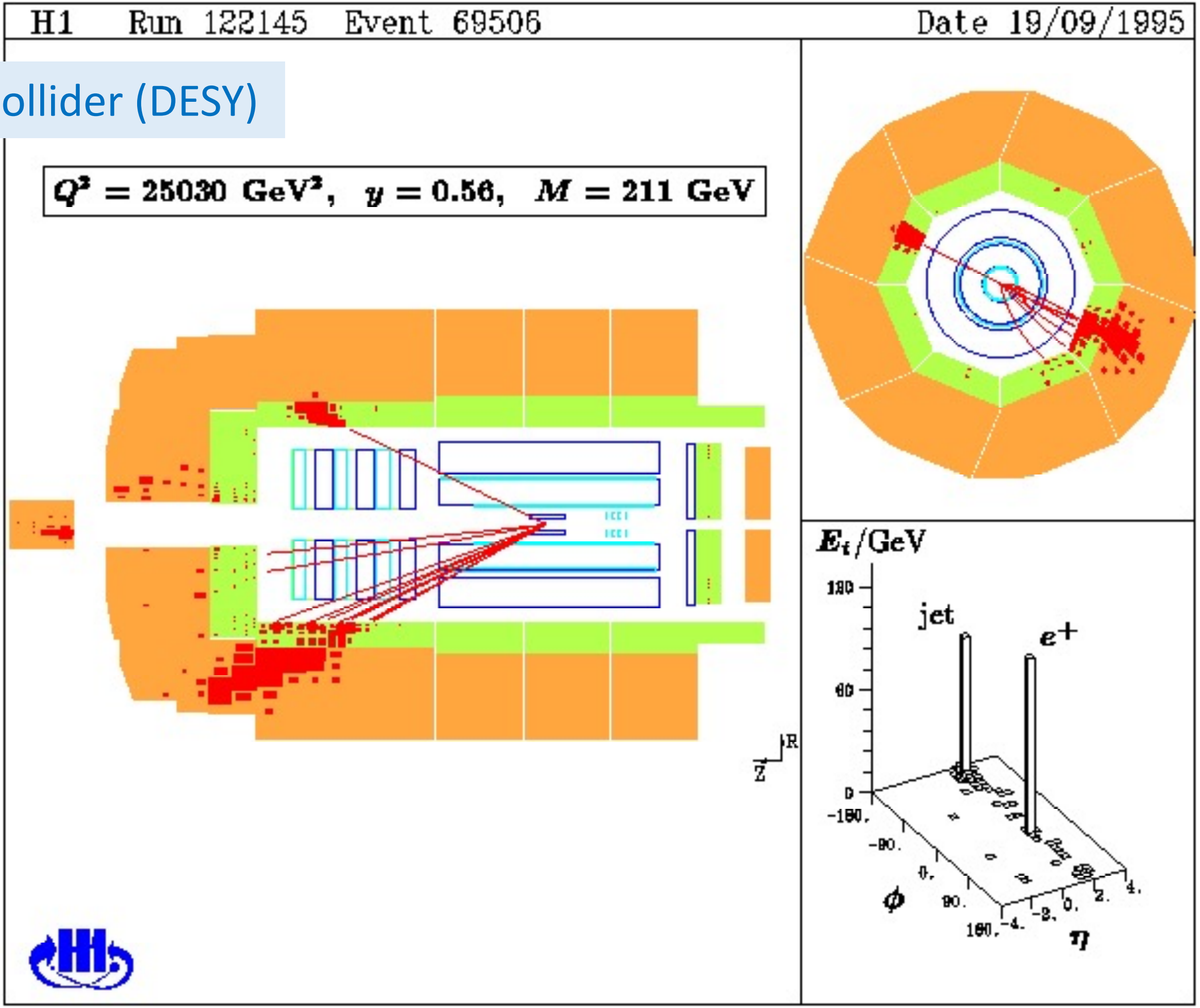
Location L chosen for geological reasons.

E

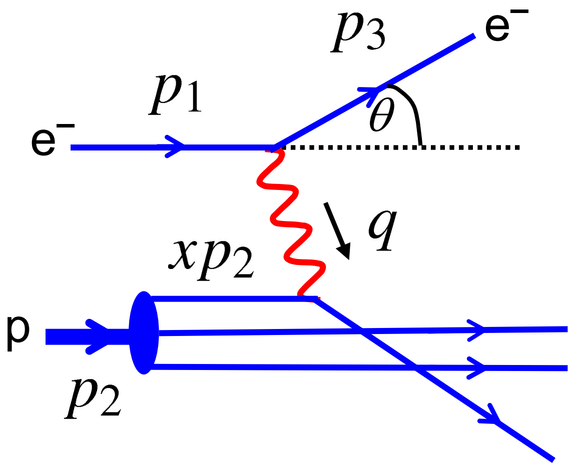
Smaller PERLE demonstrator for high power ERL at Orsay with maximal beam energy of 0.5 GeV operation within the decade.

Previously at the HERA collider (DESY)





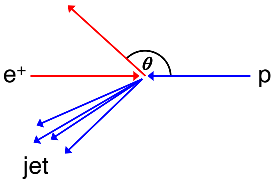
Physics with ep collisions @ LHeC / FCC-eh



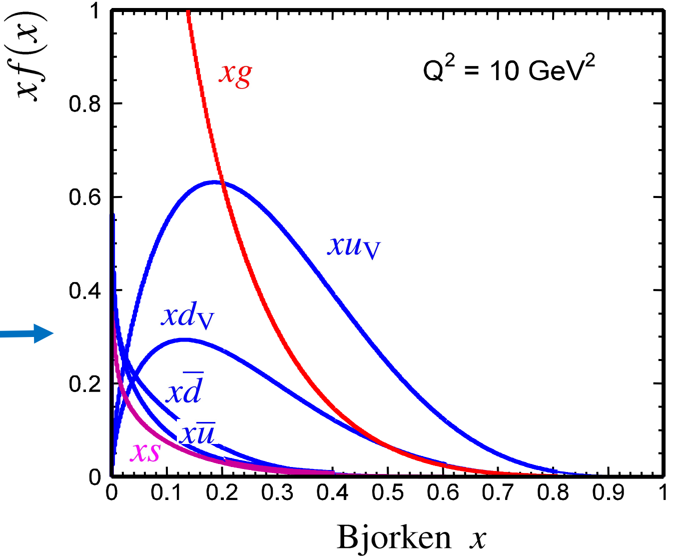
$$\boxed{\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2F_1(x,Q^2)\right]}$$

Structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$ to be measured and related to the momentum distribution of partons in the proton (PDF's).

$$F_2^{\mathrm{p}}(x,Q^2) = 2xF_1^{\mathrm{p}}(x,Q^2) = x\sum_q e_q^2 q^{\mathrm{p}}(x)$$



fit on all data
(e.g. HERA)



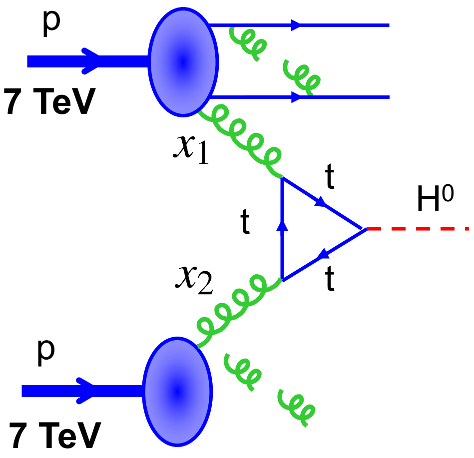
$Q^2 \equiv -q^2$ $\quad x \equiv \frac{Q^2}{2p_2.q}$ $\quad y \equiv \frac{p_2.q}{p_2.p_1}$ $\quad \nu \equiv \frac{p_2.q}{M}$

Bjorken-x
(0 < x < 1)

Two independent variables (x,Q^2)

Physics with ep collisions @ LHeC / FCC-eh

The precision with which we measure the PDF’s is directly related to the precision of proton-proton collision cross sections at the LHC and FCC-hh, e.g. gg→H production



- **Cross section depends on gluon PDFs**

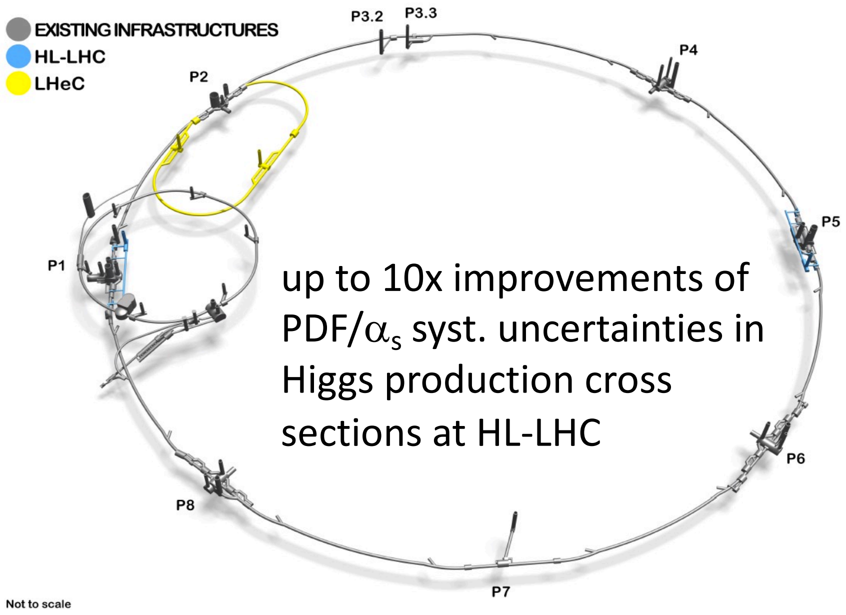
$$\sigma(pp \to HX) \sim \int_0^1 \int_0^1 g(x_1)g(x_2)\sigma(gg \to H)\mathrm{d}x_1\mathrm{d}x_2$$

- **Uncertainty in gluon PDFs lead to a ±5 % uncertainty in Higgs production cross section**

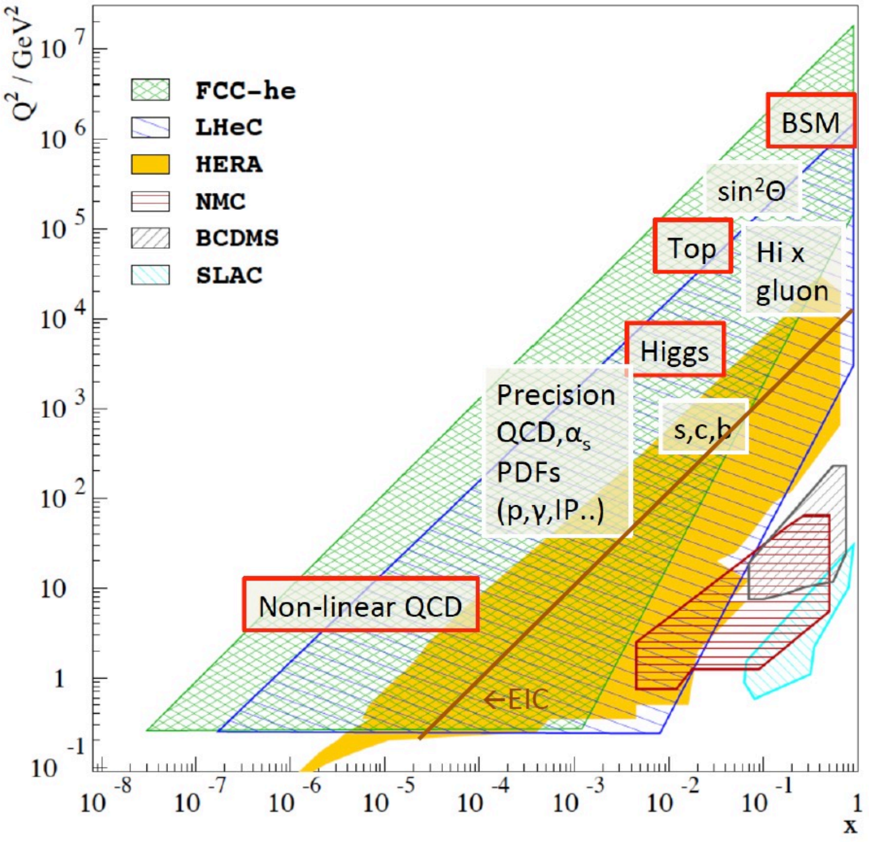
- **Prior to HERA data uncertainty was ±25 %**

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 ($\gtrsim$ Run5)



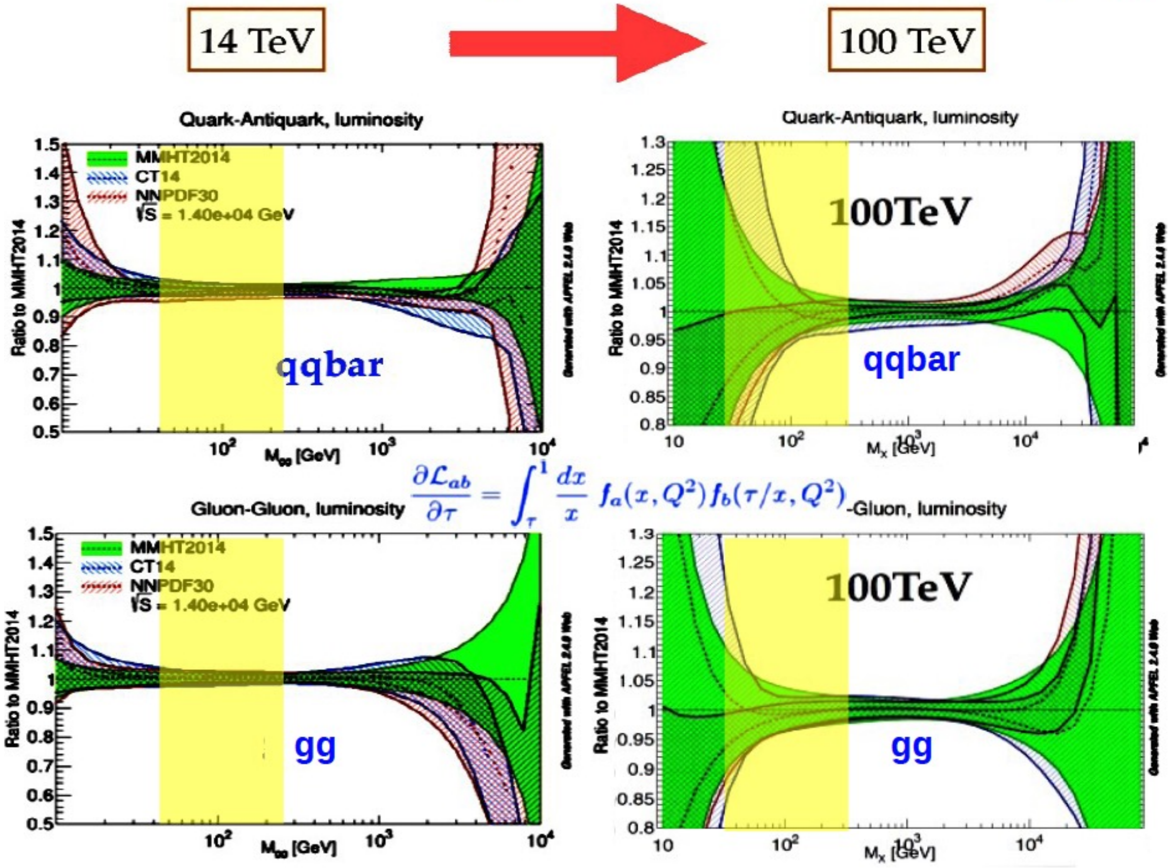
up to 10x improvements of PDF/α_s syst. uncertainties in Higgs production cross sections at HL-LHC



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

The case for ep collisions at high energies (LHeC, FCC-eh)

"Precision" region at FCC-pp: **5–7%** PDF uncertainty for σ(W,Z,H)



$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_{\tau}^{1} \frac{dx}{x} f_a(x,Q^2) f_b(\tau/x,Q^2)$$

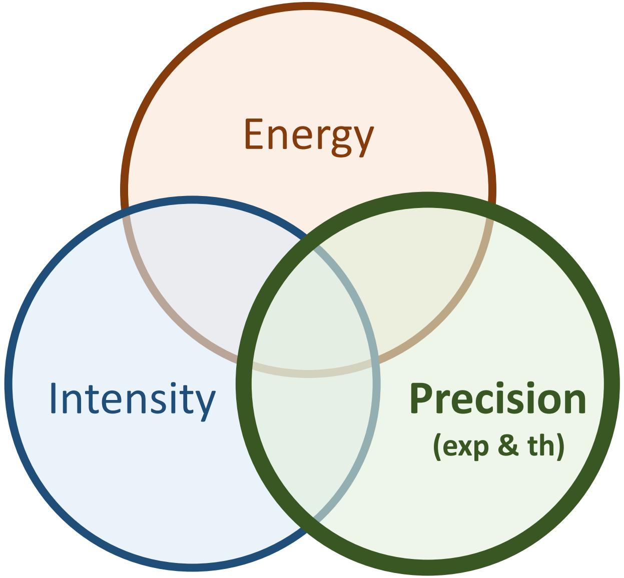
ep collisions essential

- *a clean experimental environment with low multiplicity, no pileup, fully constrained kinematics (x,Q^2) reconstructing the outgoing lepton*
- *a more controlled theoretical setup with many 1st-principles calculations, factorisation tests*

LHeC (60 GeV e^- from ERL)
E_{cms} = 0.2 – 1.3 TeV
run with the HL-LHC (≳Run5)

FCC-ep (60 GeV e^- from ERL)
E_{cms} up to 3.5 TeV
is required to reach O(1%) uncertainty for σ(W,Z,H) at FCC-hh

Three frontiers on the collider route to BSM



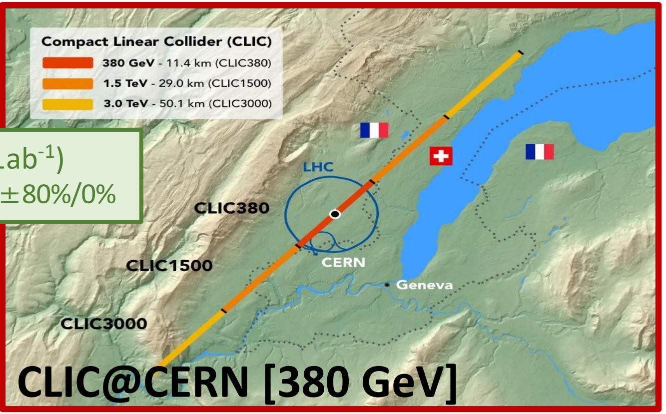
The performance of colliders can be defined with several technical parameters, of which three are key to map the physics potential

- Intensity – e.g. SuperKEKB (indirect path to BSM)
- Energy – e.g. from LHC to FCC-hh (direct path)
- Precision – e.g. FCC-ee (could be both paths)

Extending these collider frontiers remains our prime route to unlock those BSM phenomena related to the most important open questions

e^+e^- Higgs Factories

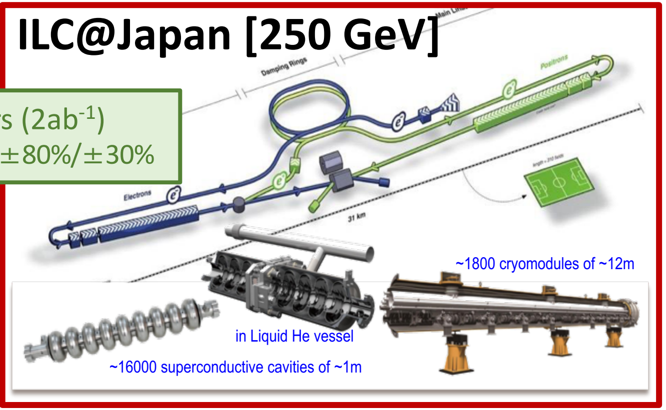
linear colliders



CLIC@CERN [380 GeV]

8 years (1ab^{-1})
$\mathcal{P}(e^-/e^+) = \pm80\%/0\%$

ILC@Japan [250 GeV]



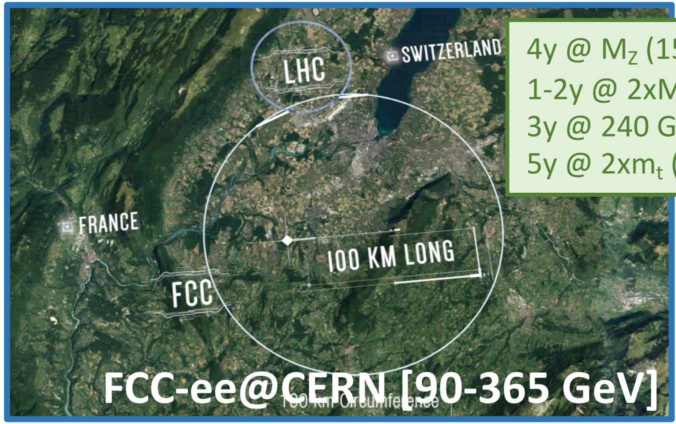
~1800 cryomodules of ~12m

in Liquid He vessel

~16000 superconductive cavities of ~1m

11.5 years (2ab^{-1})
$\mathcal{P}(e^-/e^+) = \pm80\%/\pm30\%$

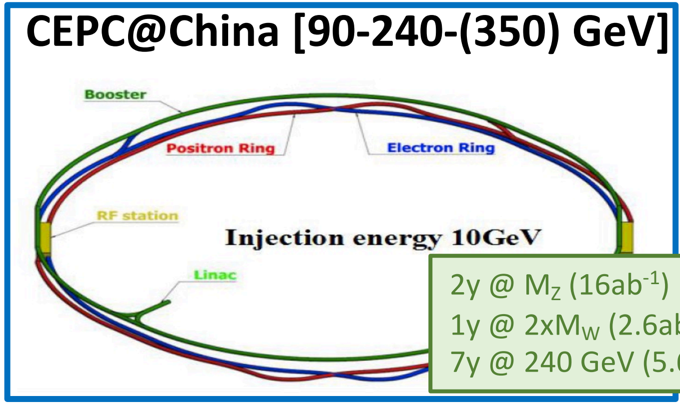
circular colliders



FCC-ee@CERN [90-365 GeV]

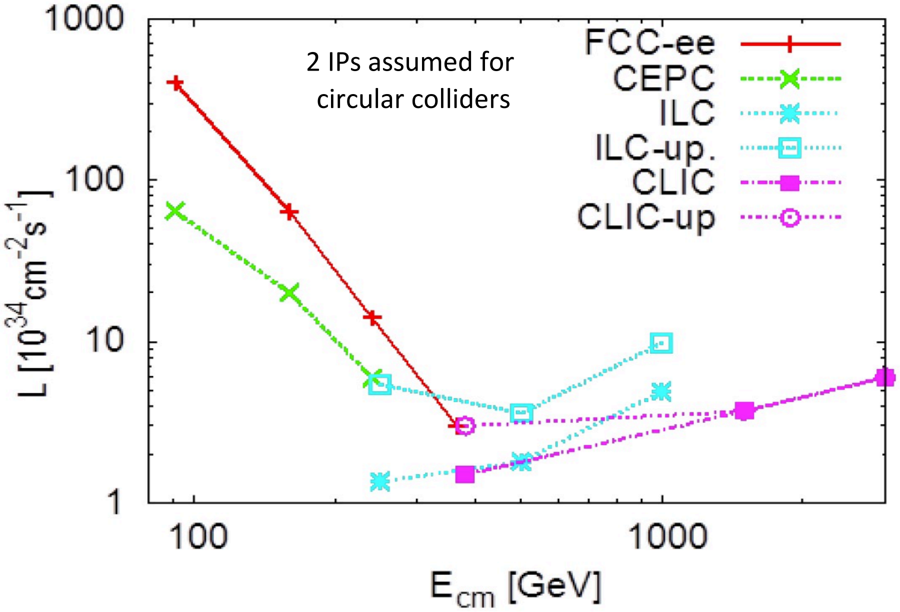
4y @ M_Z (150ab^{-1})
1-2y @ 2xM_W (10ab^{-1})
3y @ 240 GeV (5ab^{-1})
5y @ 2xm_t (1.5ab^{-1})

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



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

e^+e^- Higgs Factories



e^+e^- Higgs Factories

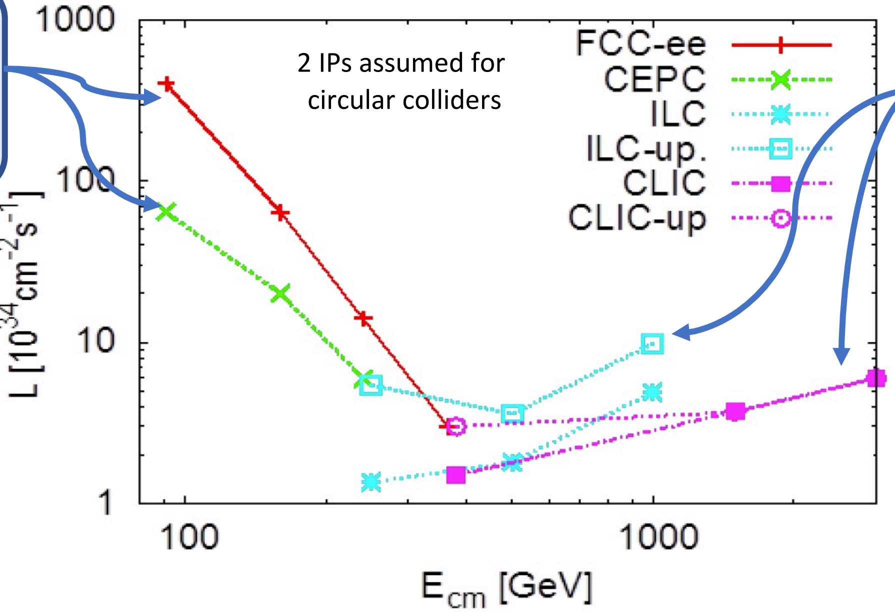
precision frontier

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})



2 IPs assumed for circular colliders

linear colliders

energy frontier

e^+e^- Higgs Factories

precision frontier

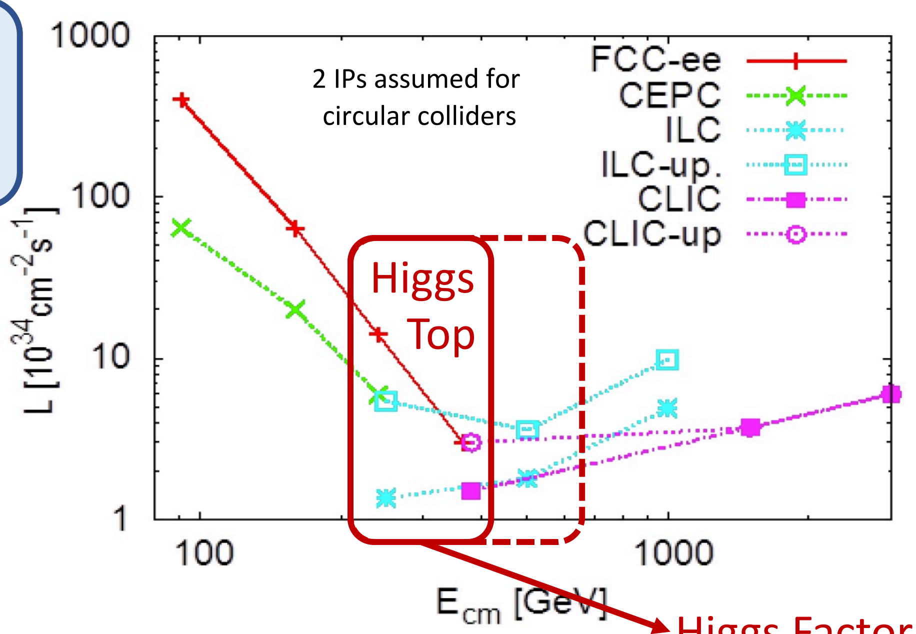
circular colliders

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})



Higgs Factories with complementarity

linear colliders

energy frontier

e^+e^- Higgs Factories

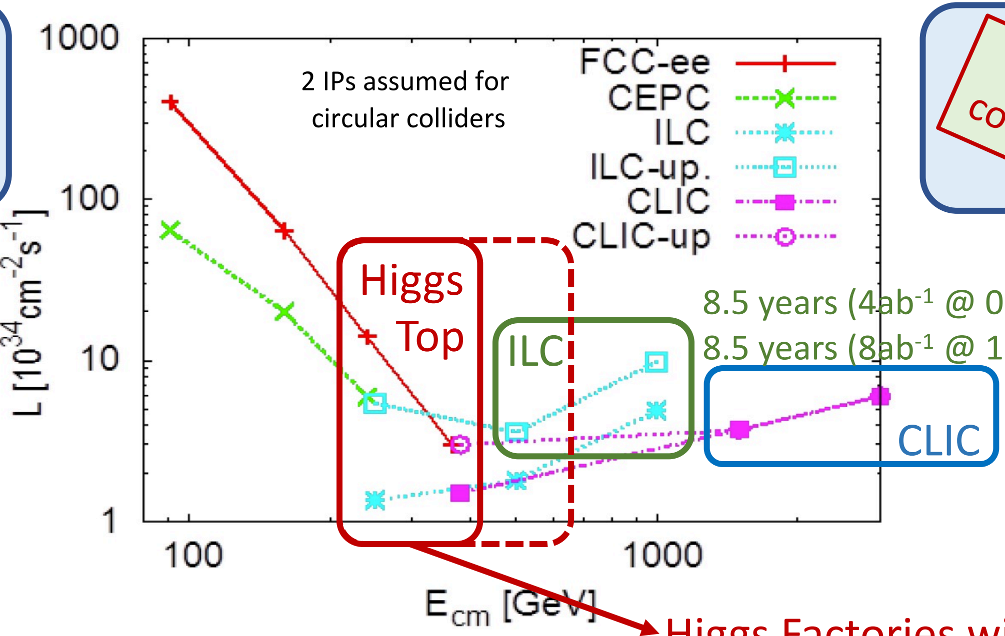
precision frontier

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})



2 IPs assumed for circular colliders

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

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

precision frontier

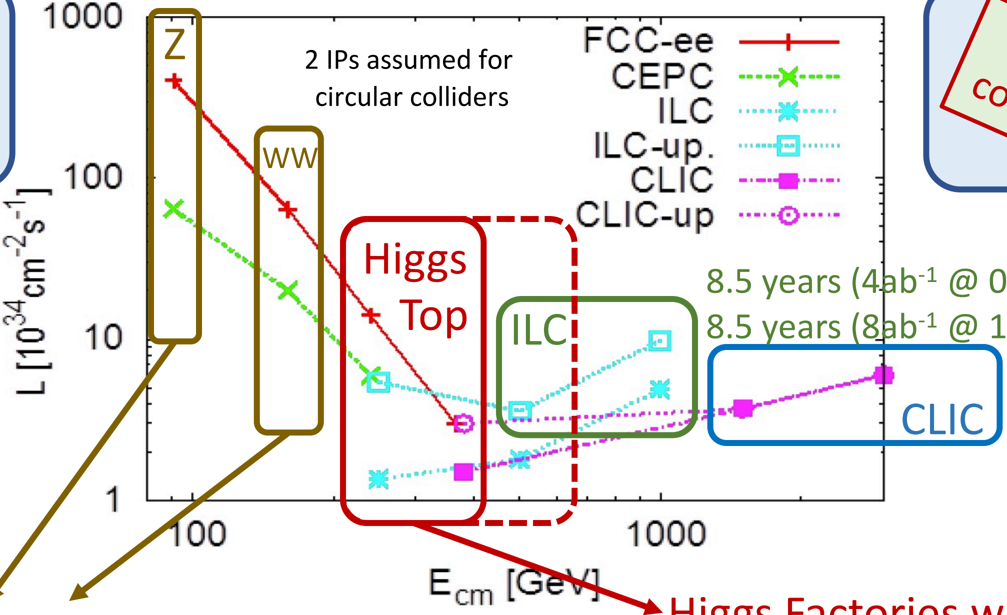
circular colliders

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})



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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

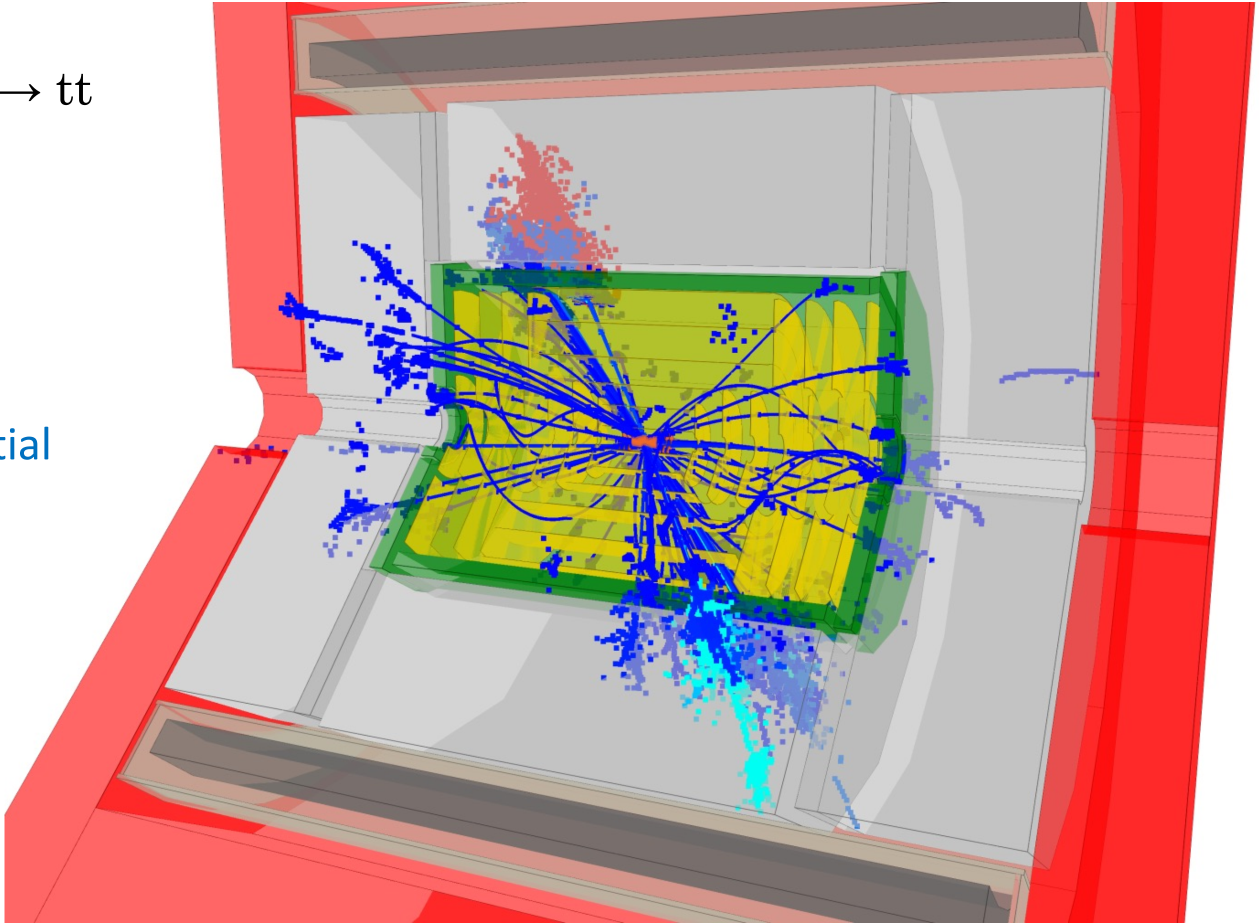
B/c/τ/EW Factories

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

Illustration of a e^+e^- collision at a Higgs Factory

CLIC @ 3 TeV $e^+e^- \rightarrow tt$

- clean event & smaller detector occupancy
- energy & momentum conservation from initial to final state



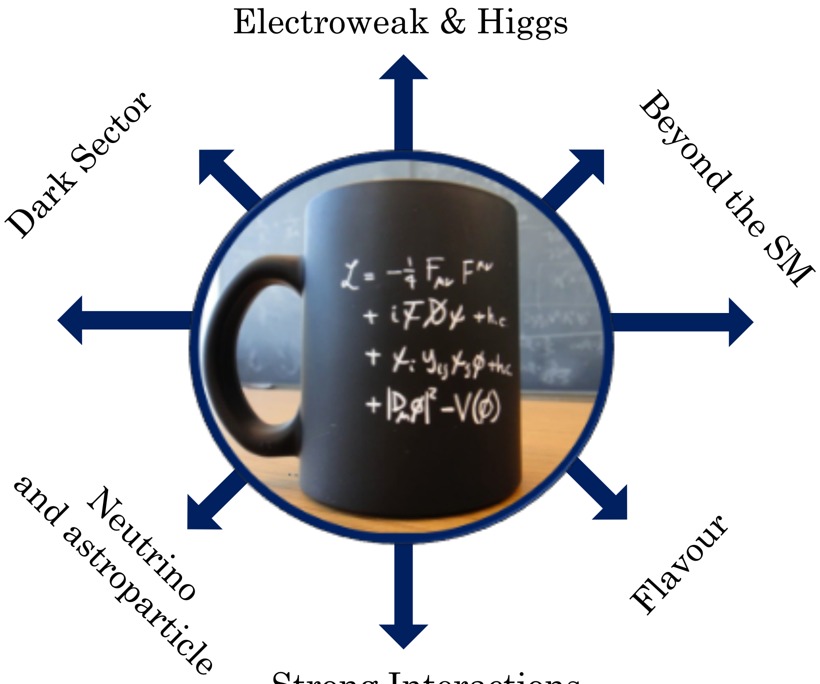
How can all these different collisions help us to find new physics?

Principle collider avenues to seek new phenomena

Open questions quide us to potential new physics ideas and phenomena

Open questions relate to several physics phenomena that can be captures in six principle categories

(surely other sets could be used as well)



Electroweak & Higgs

Dark Sector

Beyond the SM

Neutrino and astroparticle

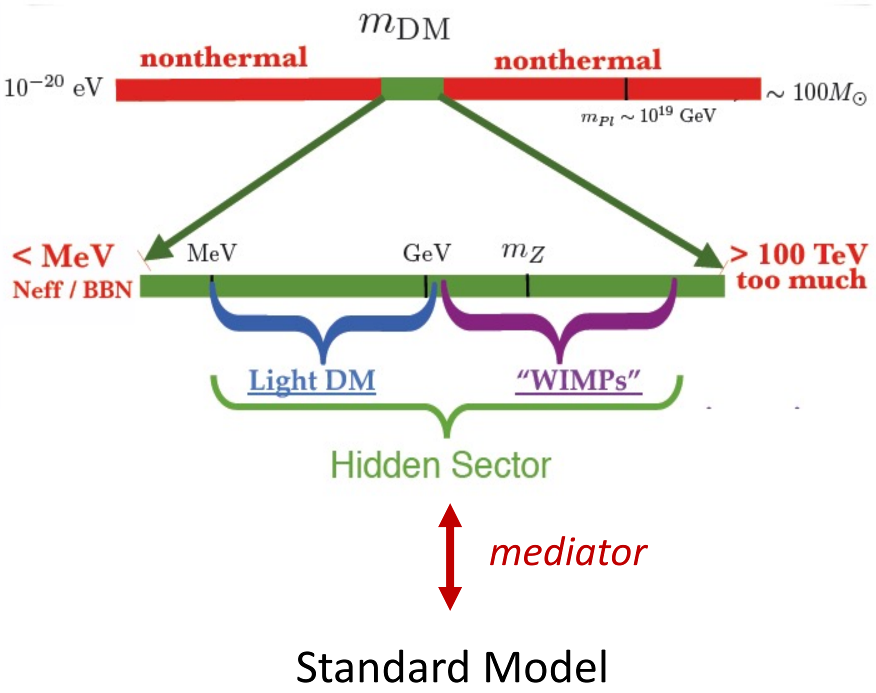
Flavour

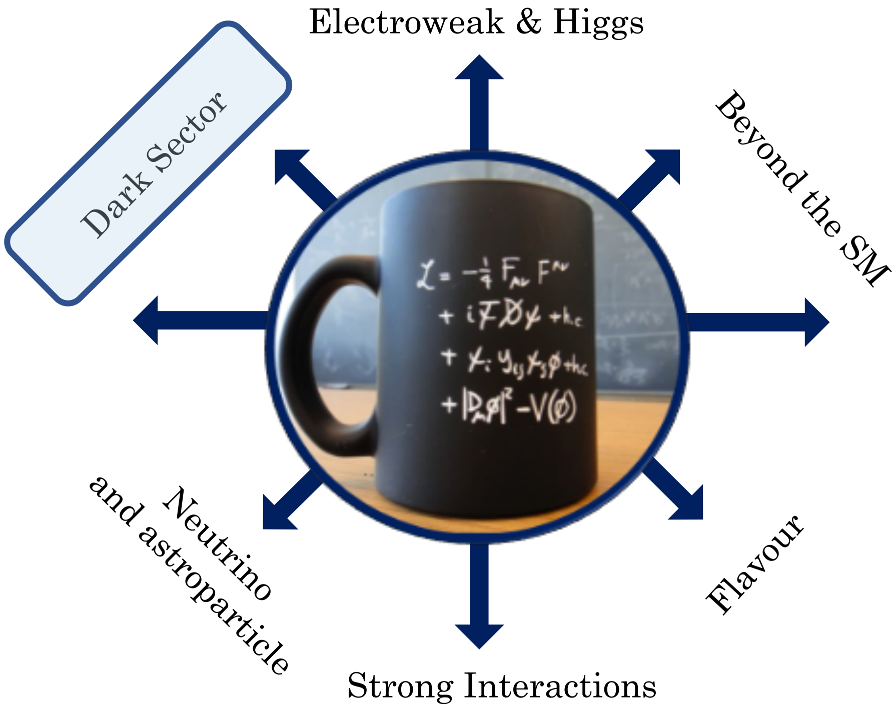
Strong Interactions

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

Searching for dark matter with colliders

The assumption of Thermal Equilibrium in the early Universe narrows the viable mass range

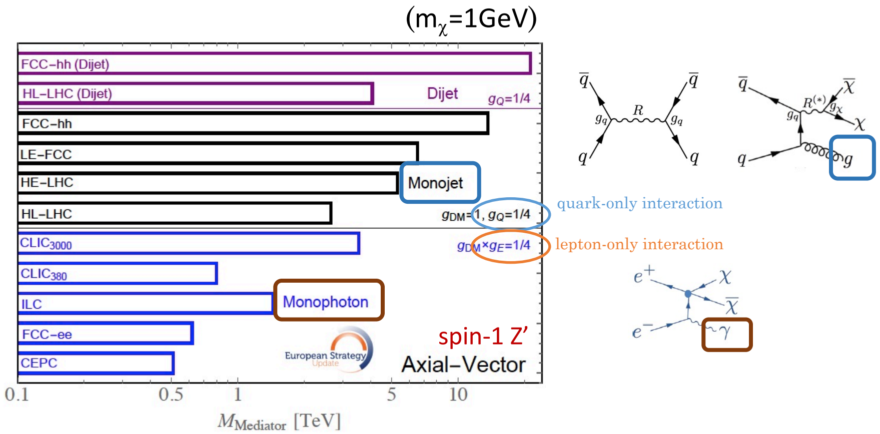




Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Searching for dark matter with colliders

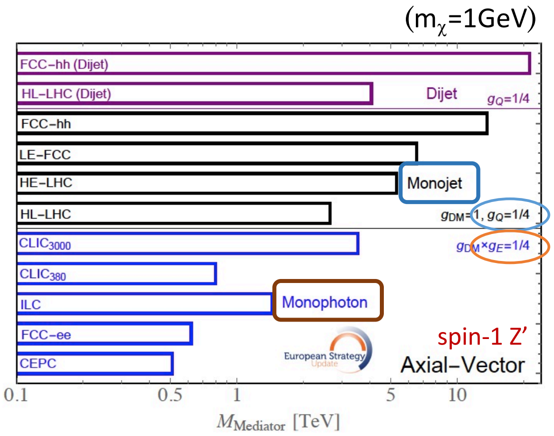
Thermal WIMPs: simplified DM models with one DM particle and one mediator

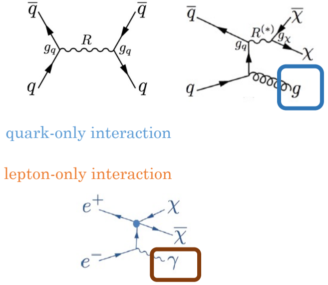


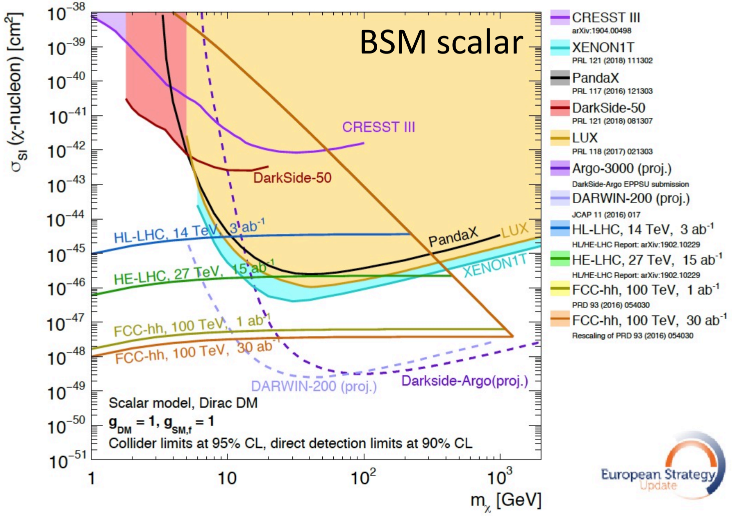
Complementarity:
lepton
and
proton colliders

Searching for dark matter with colliders

<u>Thermal WIMPs:</u> simplified DM models with one DM particle and one mediator



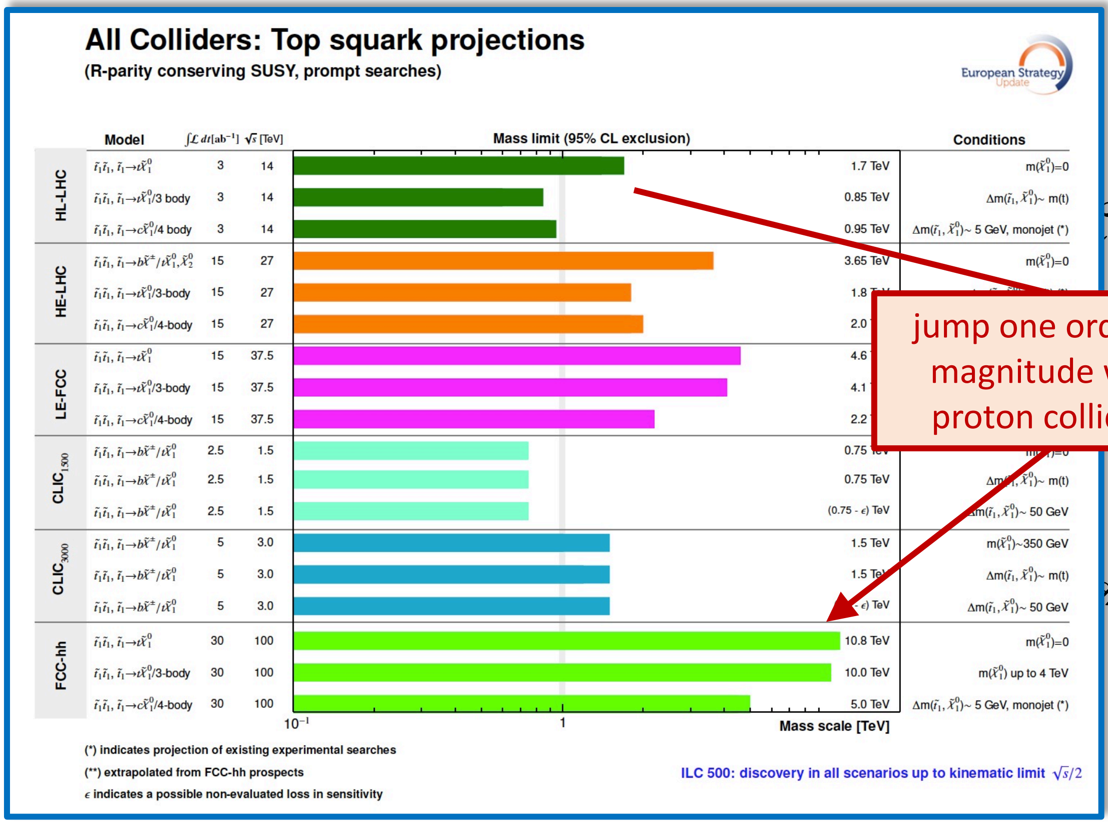




Complementarity:
lepton
and
proton colliders

Maximal overlap with direct & indirect detection sensitivity:
cosmological origin of DM
versus
nature of DM interactions

Addressing the naturalness puzzle with supersymmetry



All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)

	Model	$\int\mathcal{L}\,dt[\mathrm{ab}^{-1}]$	$\sqrt{s}$ [TeV]	Mass limit	Conditions
HL-LHC	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$	3	14	1.7 TeV	$m(\tilde{\chi}_1^0)=0$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$/3 body	3	14	0.85 TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim m(t)$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$/4 body	3	14	0.95 TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim$ 5 GeV, monojet (*)
HE-LHC	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0,\tilde{\chi}_2^0$	15	27	3.65 TeV	$m(\tilde{\chi}_1^0)=0$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	15	27	1.8	
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	15	27	2.0	
LE-FCC	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$	15	37.5	4.6	
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	15	37.5	4.1	
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	15	37.5	2.2	
CLIC_{1500}	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	0.75	
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	0.75 TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim m(t)$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	2.5	1.5	(0.75 - ϵ) TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim$ 50 GeV
CLIC_{3000}	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	1.5 TeV	$m(\tilde{\chi}_1^0)\sim$350 GeV
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	1.5 TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim m(t)$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}_1^0$	5	3.0	- ϵ) TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim$ 50 GeV
FCC-hh	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$	30	100	10.8 TeV	$m(\tilde{\chi}_1^0)=0$
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to t\tilde{\chi}_1^0$/3-body	30	100	10.0 TeV	$m(\tilde{\chi}_1^0)$ up to 4 TeV
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$/4-body	30	100	5.0 TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0)\sim$ 5 GeV, monojet (*)

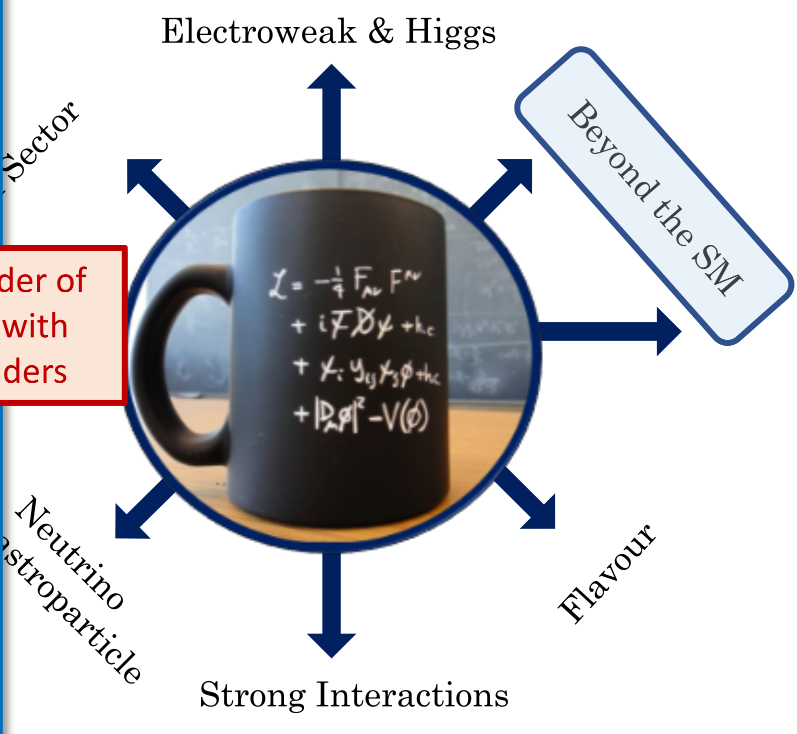
(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

ϵ indicates a possible non-evaluated loss in sensitivity

ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

jump one order of magnitude with proton colliders

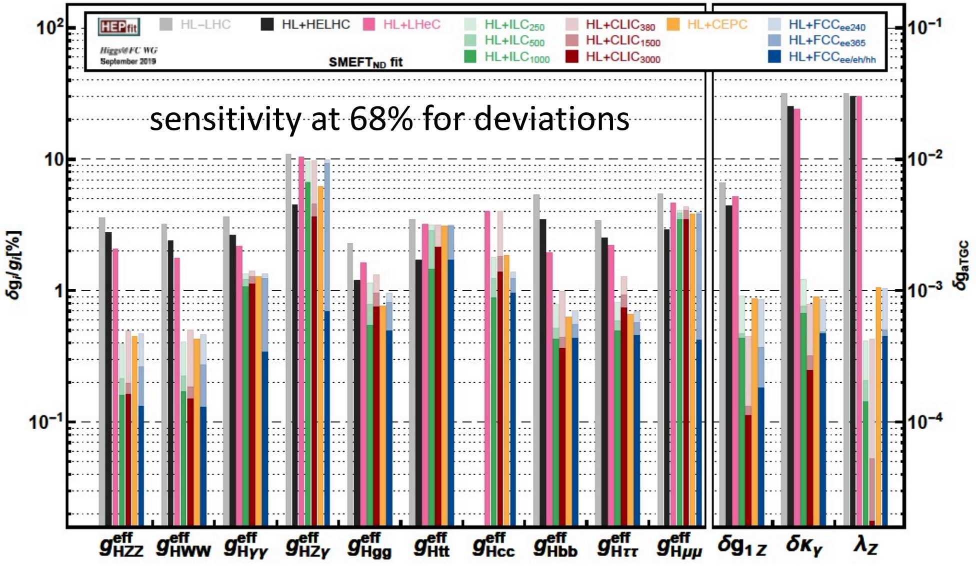


Physics themes of the Open Symposium of the European Strategy for Particle Physics in Granada

Zooming into the Higgs sector with colliders

Sensitivity for deviations in effective Higgs couplings

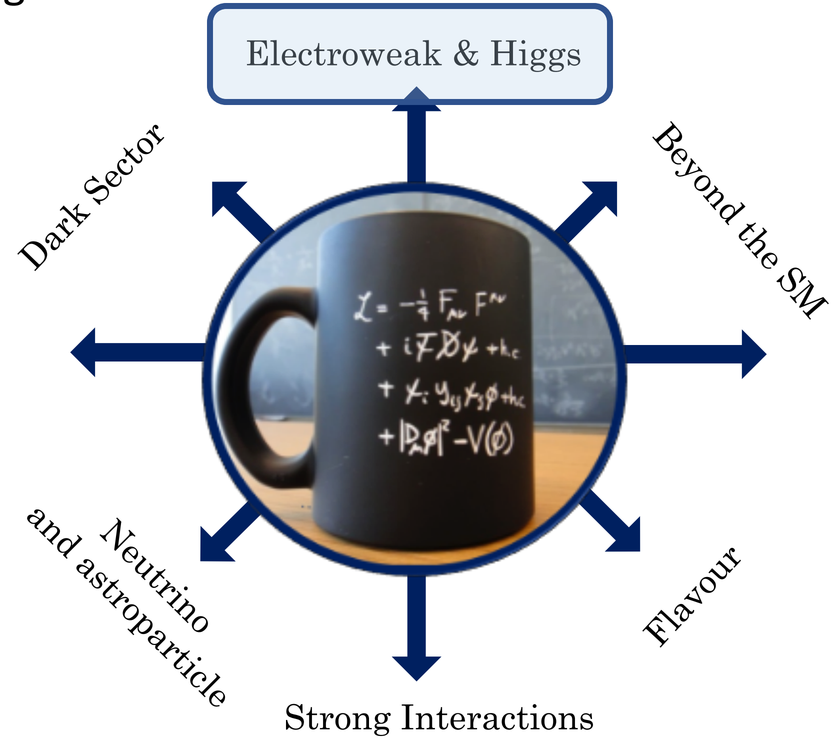
(from a global EFT fit – dim-6 SM Effective Field Theory)



sensitivity at 68% for deviations

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

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



Electroweak & Higgs

Dark Sector

Beyond the SM

Neutrino and astroparticle

Flavour

Strong Interactions

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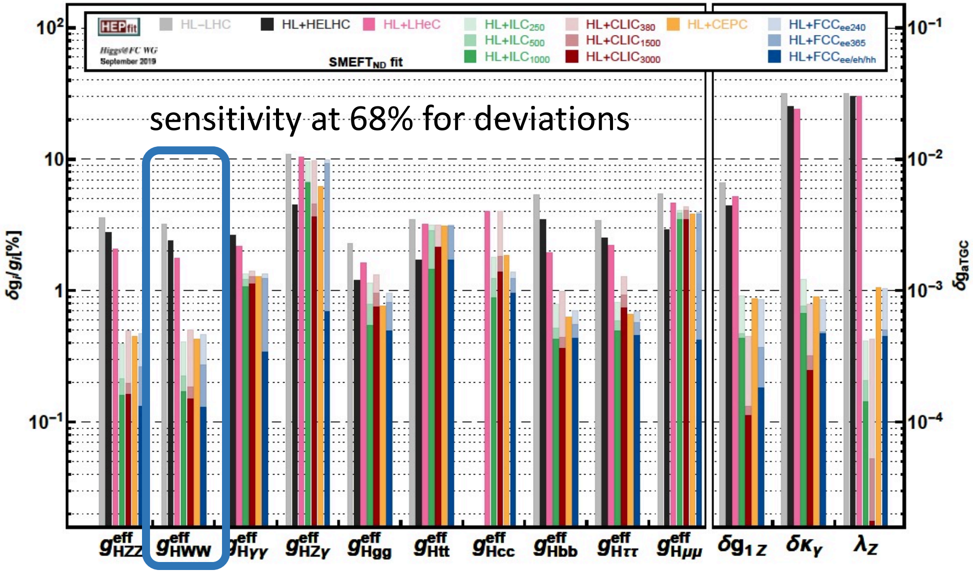

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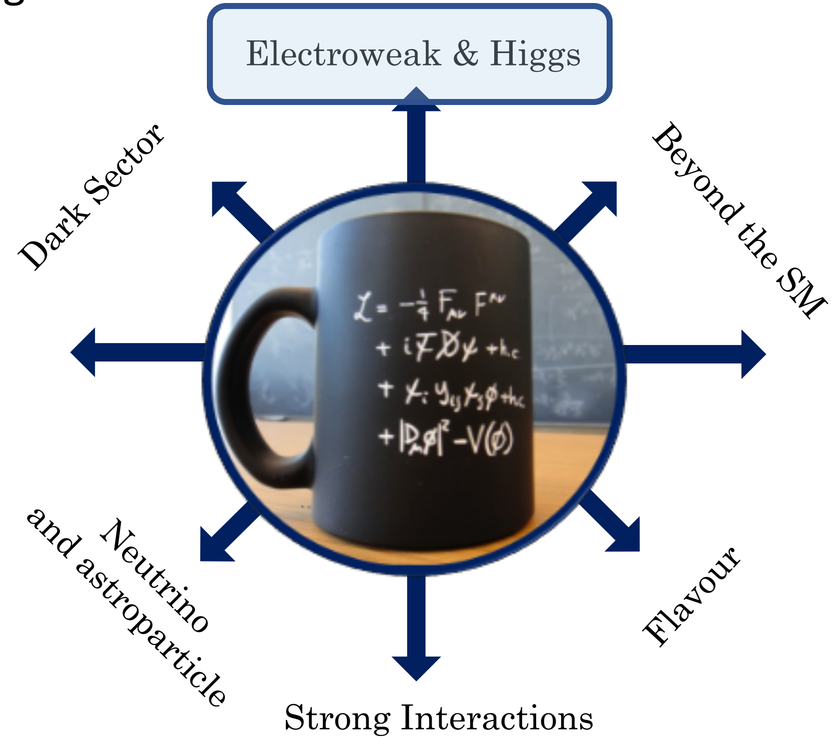

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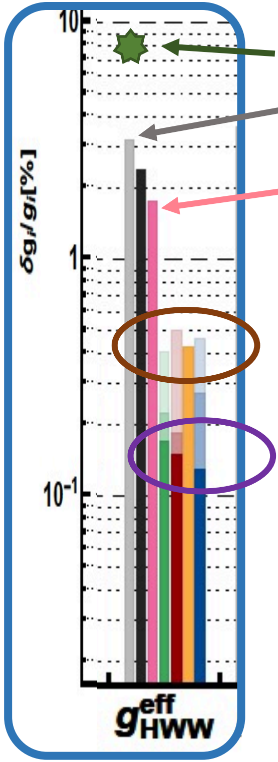


today

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)

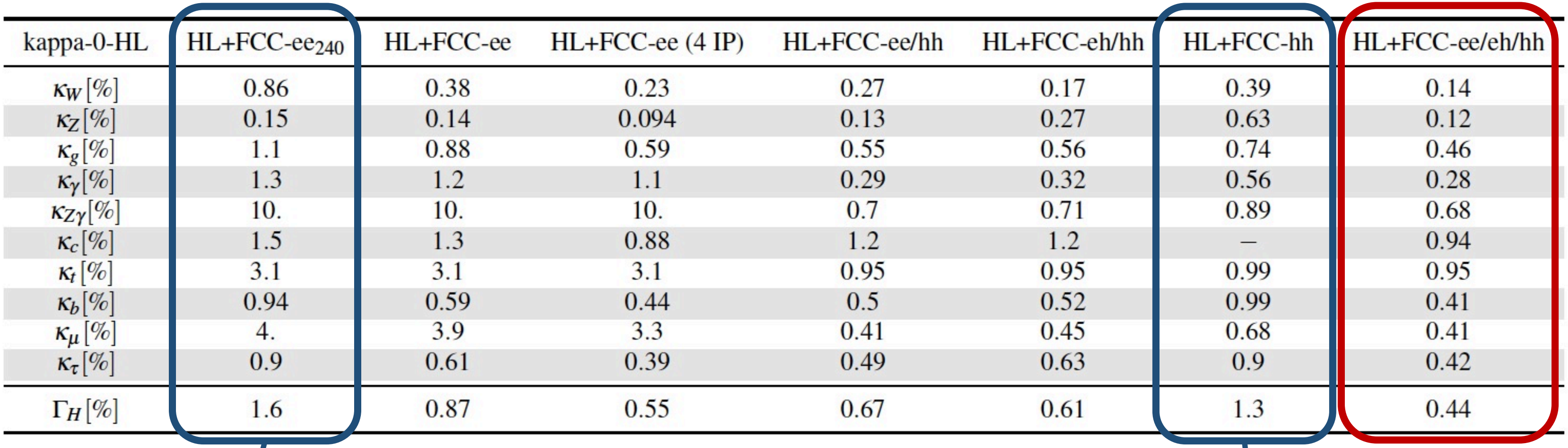
The improvement is in the complementarity!

[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

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

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

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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)*
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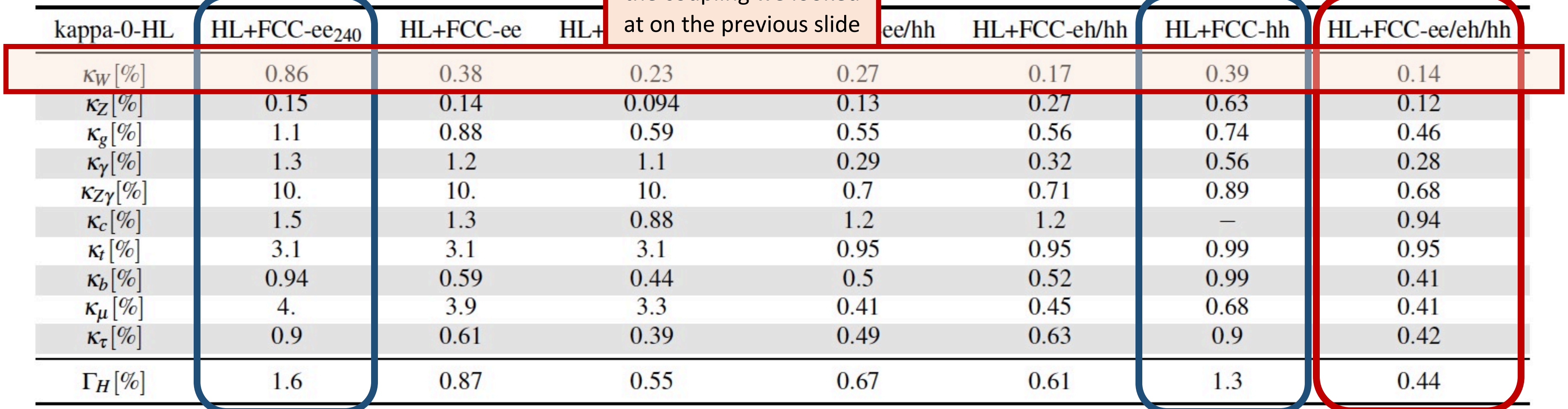
the coupling we looked at on the previous slide



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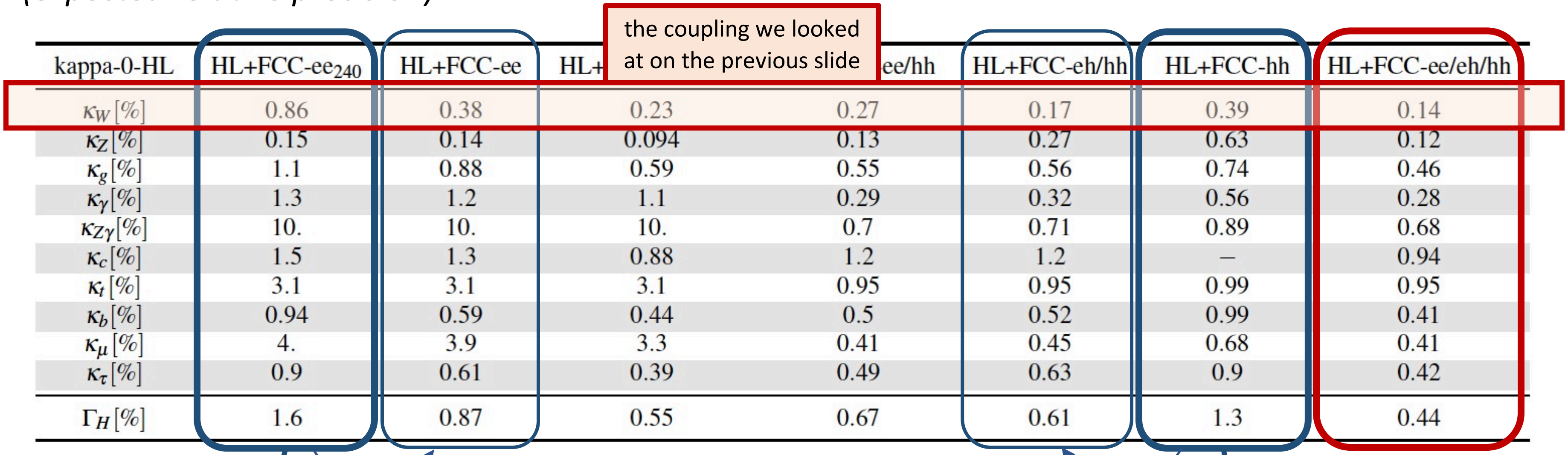

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adding 365 GeV runs

adding FCC-ep

ALL COMBINED

only FCC-ee@240GeV

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

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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
$\kappa_W[\%]$	0.86	0.38	0.23	[illegible]	[illegible]	0.39	0.14
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$\kappa_\mu[\%]$	4.	[illegible]	[illegible]	0.41	0.45	0.68	0.41
$\kappa_\tau[\%]$	0.9	[illegible]	0.39	0.49	0.63	0.9	0.42
$\Gamma_H[\%]$	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

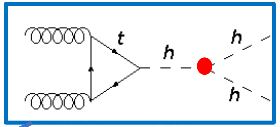
only FCC-ee@240GeV

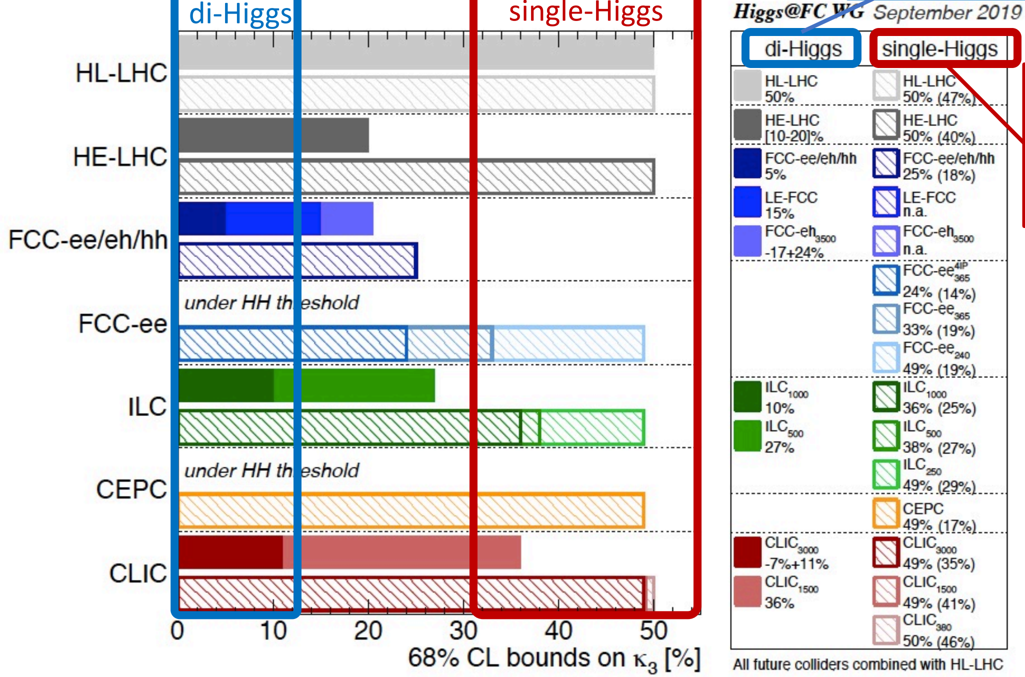
only FCC-hh

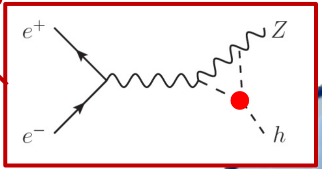
[J. de Blas et al., JHEP 01 (2020) 139]

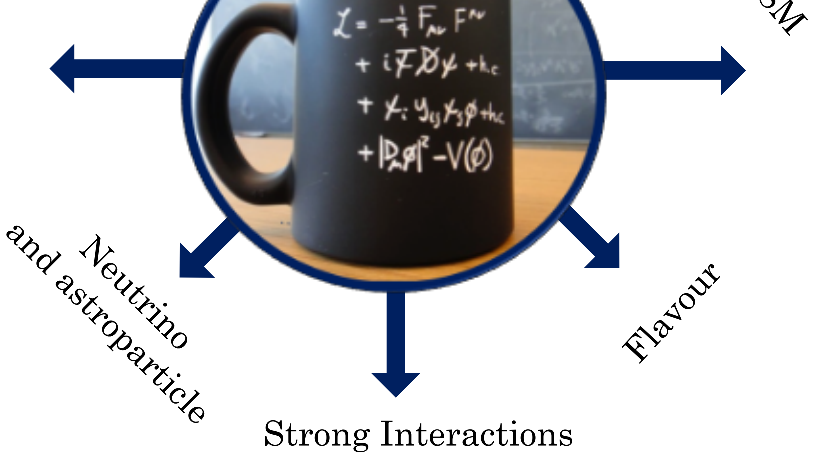
Zooming into the Higgs sector with colliders

The Higgs boson cubic self-coupling (κ_3)









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

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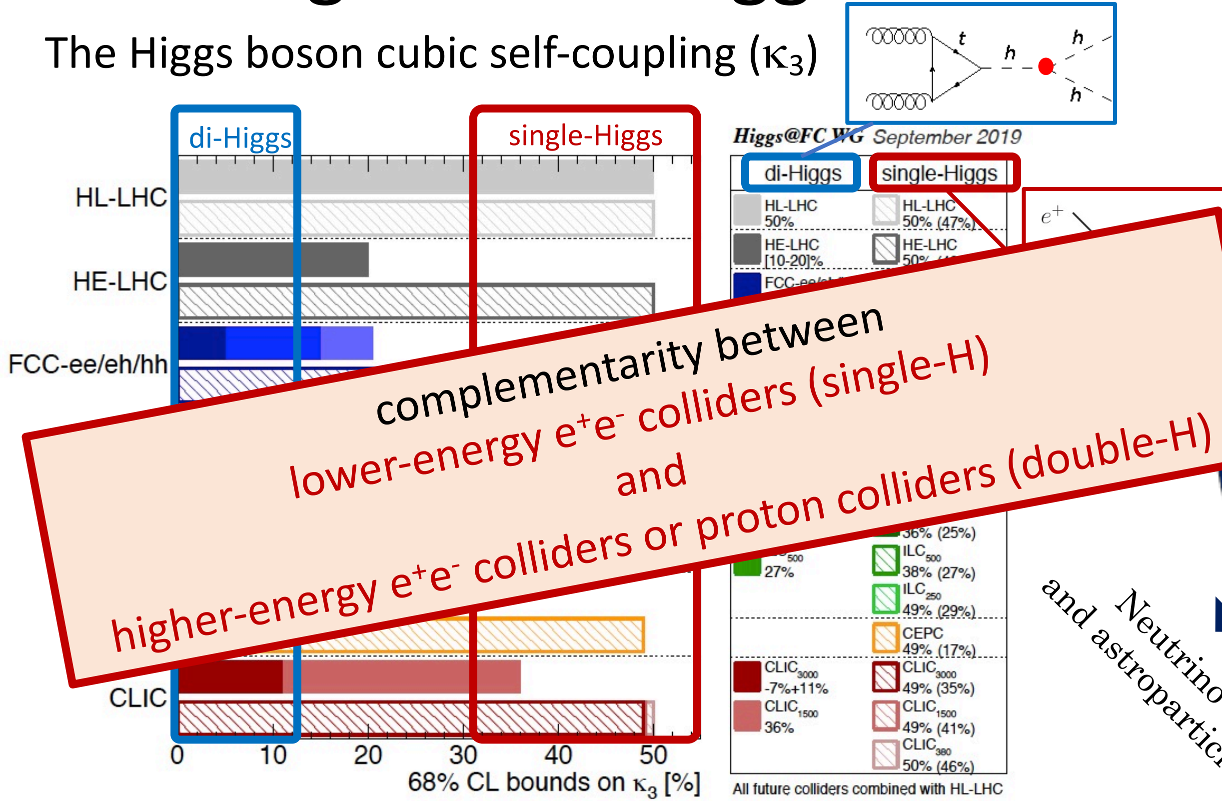
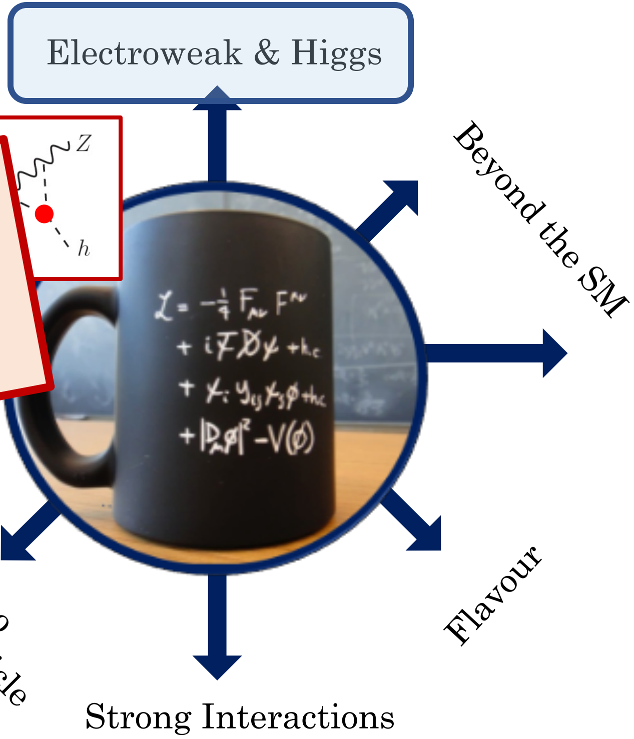


complementarity between
lower-energy e^+e^- colliders (single-H)
and
higher-energy e^+e^- colliders or proton colliders (double-H)



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

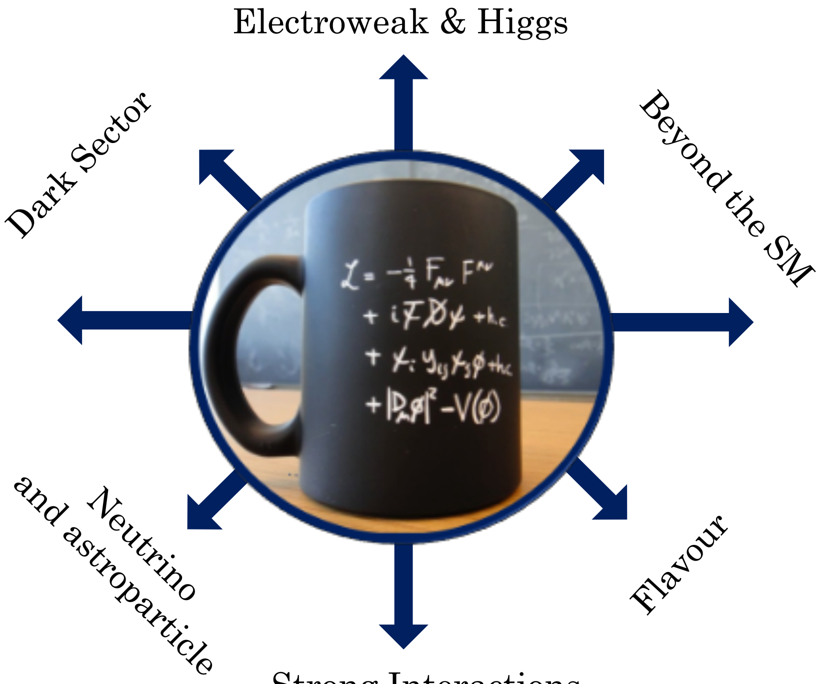
[J. de Blas et al., JHEP 01 (2020) 139]

Principle collider avenues to seek new phenomena

High-energy colliders have a unique capability to address the most profound open questions in particle physics

Although with novel theoretical reasoning we are given several avenues where we could find new physics, we do not know where we will find new physics

This provides an argument, in a global context, for an inclusive collider programme exploiting complementary ee/eh/hh future colliders aiming for broad coverage



Electroweak & Higgs

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The bold and the beautiful of colliders

- With the HL-LHC and SuperKEKB the immediate future for particle physics colliders looks bright, and provides ample opportunities for innovative experimental and theoretical research to unlock physics that was initially thought to be out of reach at these colliders
- Clearly motivated by physics arguments, e^+e^- Higgs Factories are technically ready to become operational in our medium-term future and with the ambition to integrate the concepts of B/c/τ, EW and top quark Factories in their research programs
- Because of the complementary to address the open questions in particle physics, there is a motivation for a new energy frontier machine, potentially at a later stage, to unlock the physics potential of 100 TeV proton collisions

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In my view, we have a few years in front of us to join forces on a global scale
to organize together our concrete ambition for the colliders of the 21st century
… and if we do this together, it better be with a bold moonshot ambition

Join the adventure!

- Various challenging aspects to make happen physics analysis at future colliders

  accelerators, detectors, computing & software, DAQ and electronics, Machine Learning for analysis, reconstruction and even detector controls, new physics models, new interpretation frameworks, … and much more we haven't considered yet

- While engaged in today's projects (EXP and TH), you can also engage with your creativity to prepare for these future colliders

  if you developing a new heavy flavour reconstruction technique for an experiment at the LHC, you might want to apply the technique as well in the settings for a future high energy proton collider... which might result in a few-author publication and additional exposure at conferences

Current and Future Colliders in Europe

Current flagship (27km)

impressive programme up to 2040

Big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

LHC

NbTi
8T

HL-LHC@CERN

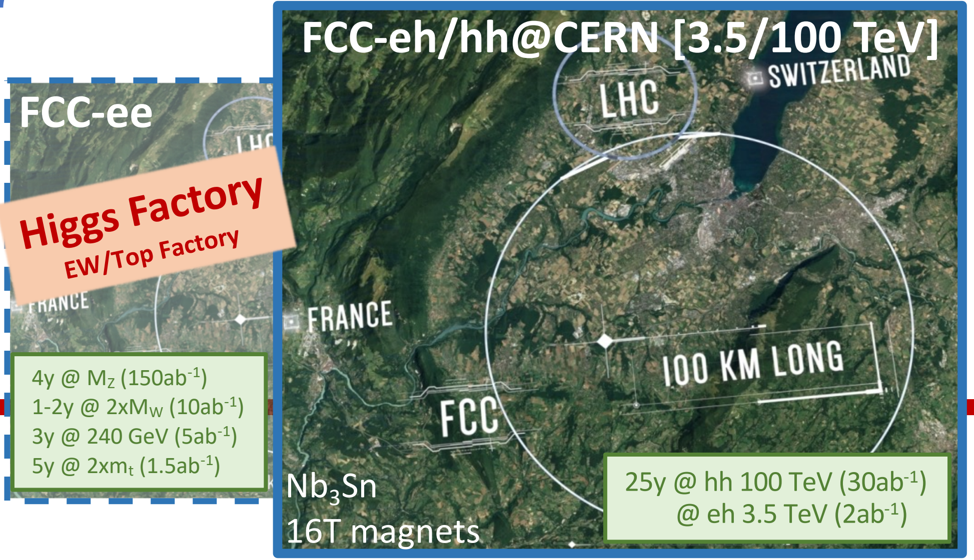
10y @ 14 TeV (3-4ab^{-1})

Nb_3Sn
few 11T magnets

ep-option with HL-LHC: LHeC

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

updated CDR 2007.14491



FCC-ee

Higgs Factory
EW/Top Factory

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

FCC-eh/hh@CERN [3.5/100 TeV]

Nb_3Sn
16T magnets

25y @ hh 100 TeV (30ab^{-1})
@ eh 3.5 TeV (2ab^{-1})

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)

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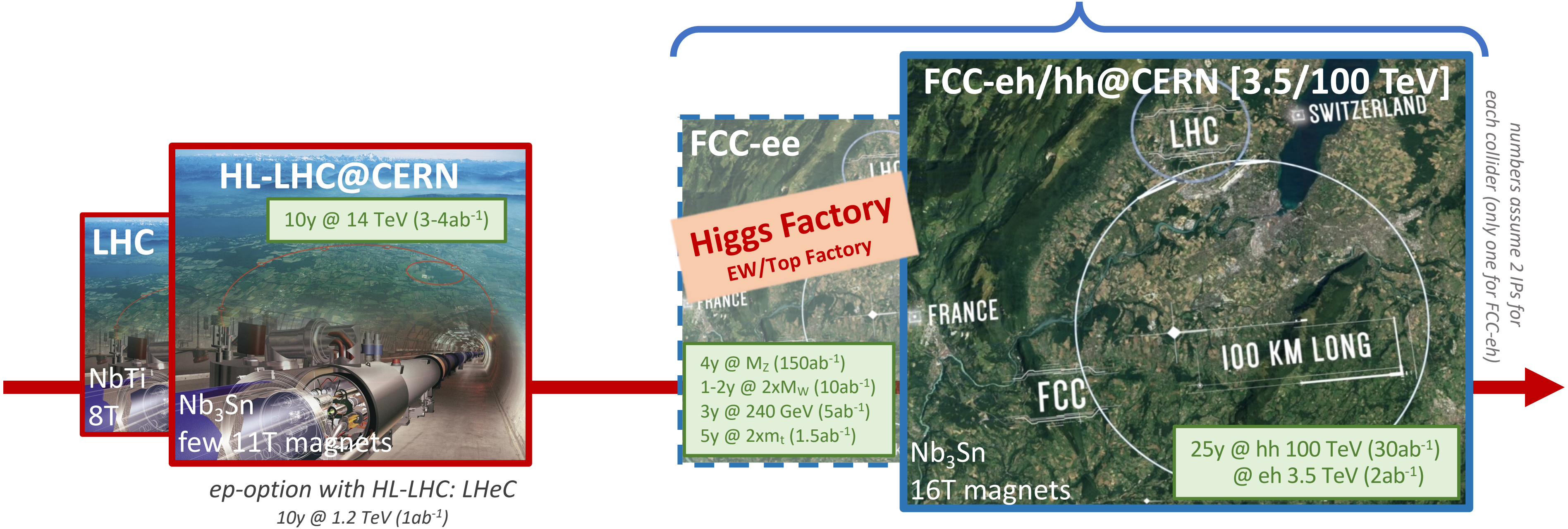

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10y @ 1.2 TeV (1ab^{-1})
updated CDR 2007.14491

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

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

Some extra information/slides

Electron-Ion Collider (EIC)

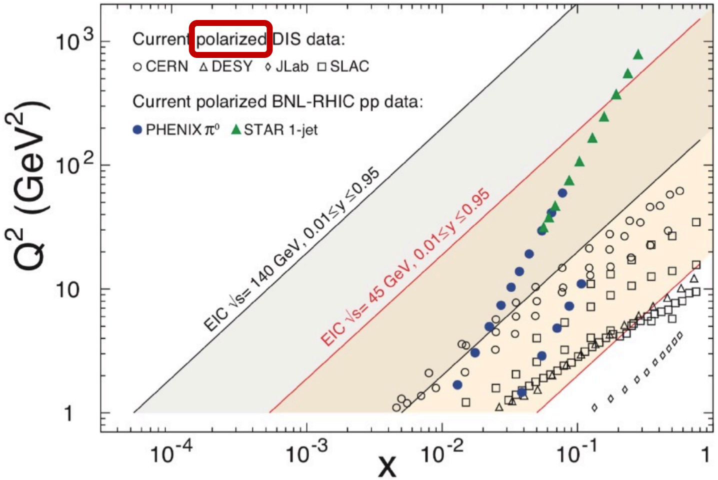
World’s 1st polarized e-p/light-ion & 1st eA collider

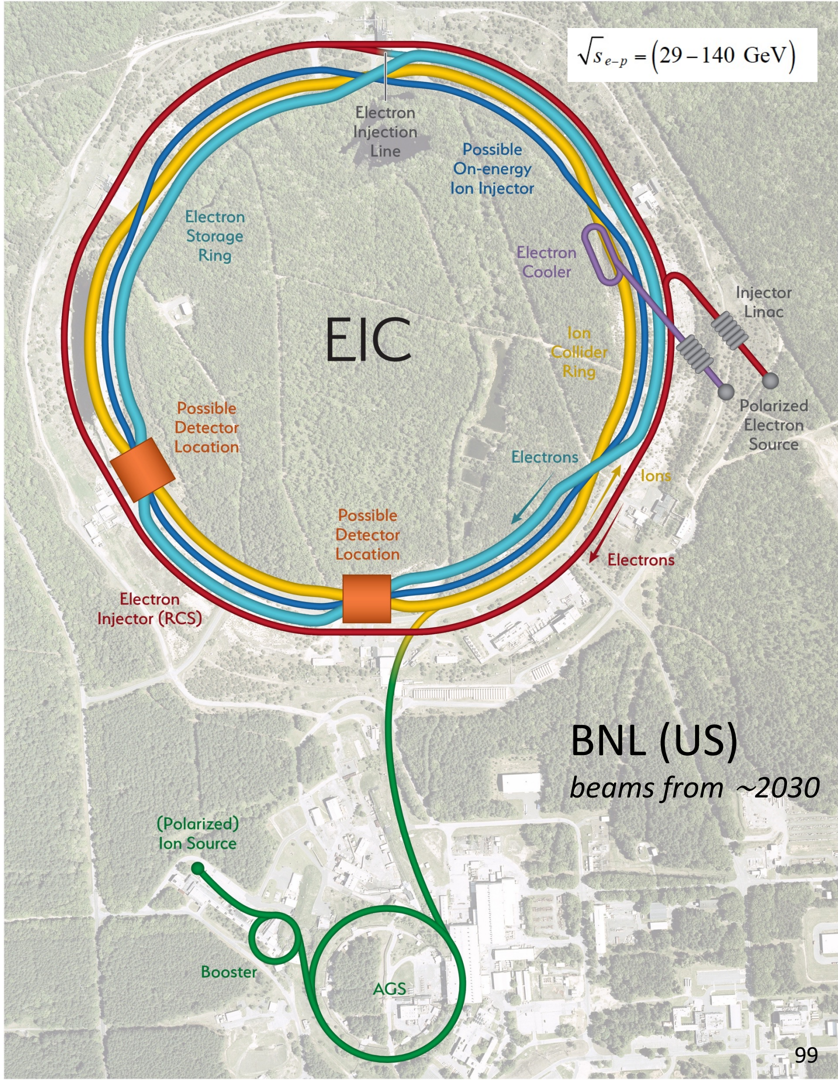
User Group >1000 members: http://eicug.org

The EIC can address three key questions.

- *How does the mass of the nucleon arise?*
- *How does the spin of the nucleon arise?*
- *What are the emergent properties of a dense system of gluons?*

Towards a 3D partonic image of the proton (spin-dependent transverse momentum distributions)



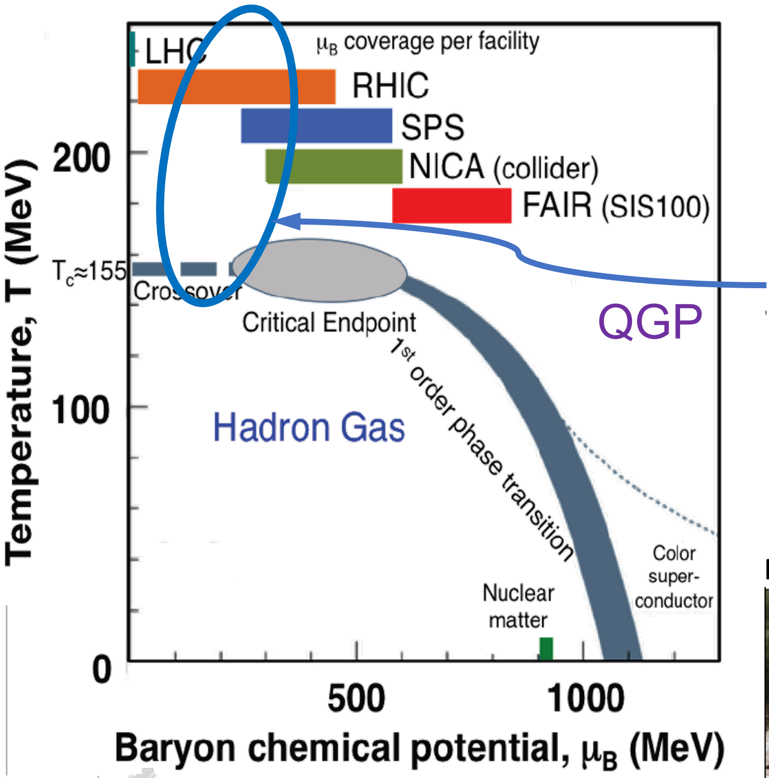


$\sqrt{s_{e-p}} = (29 - 140\ \mathrm{GeV})$

BNL (US)

beams from ~2030

Colliders & fixed-target facilities at the density frontier



BM@N *experiment being prepared at NICA (runs from 2021 onwards)*

Collider experiments @ CERN

- **HL-LHC**: higher luminosity provide new opportunities
- **FCC**: study the QGP at higher energy density and Temp

Fixed-target experiments @ CERN

- **SPS**: QCD at high-μ_B with NA61/SHINE and NA60+
- **(HL-)LHC**: at ALICE and LHCb the most energetic fixed-target experiments to reach quark/gluon high-x PDFs

Facilities @ JINR and FAIR

- **NICA @ JINR**: MPD experiment to start around 2023
- **SIS100 @ FAIR**: CBM & HADES experiments to start around 2025

Nuclotron-based Ion Collider Facility @ JINR

May 2020 - MPD hall is ready for magnet assembly

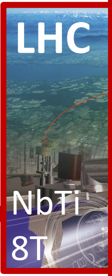
July 2020 - Western half-ring of building 17 and Nuclotron-Collider channels are ready for equipment installation

SIS100 @ FAIR

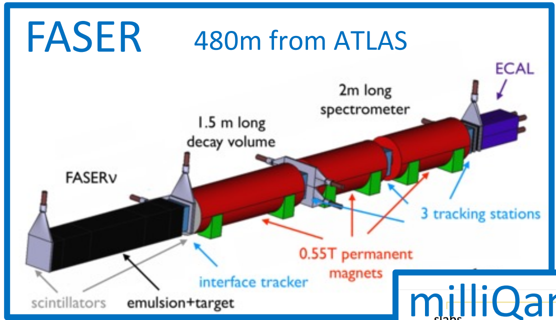
Colliders in Europe at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

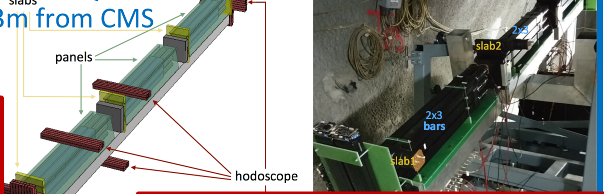


Additional opportunities with high-energy proton collisions

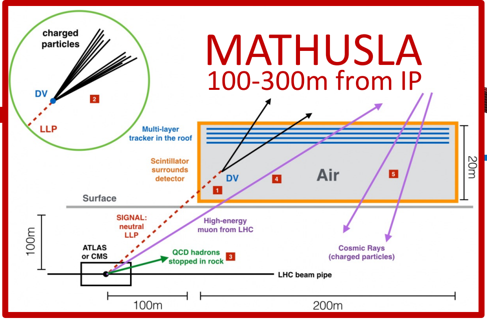


being installed

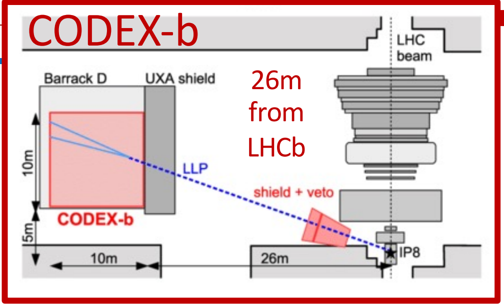
Long Lived Particles
Light & weakly coupling particles
Milli-charged particles
Magnetic Monopoles (MoEDAL)



being demonstrated



proposal



proposal

Colliders in Europe at the energy & precision frontier

Current flagship (27km)

impressive programme up to 2040

LHC

NbTi

8T

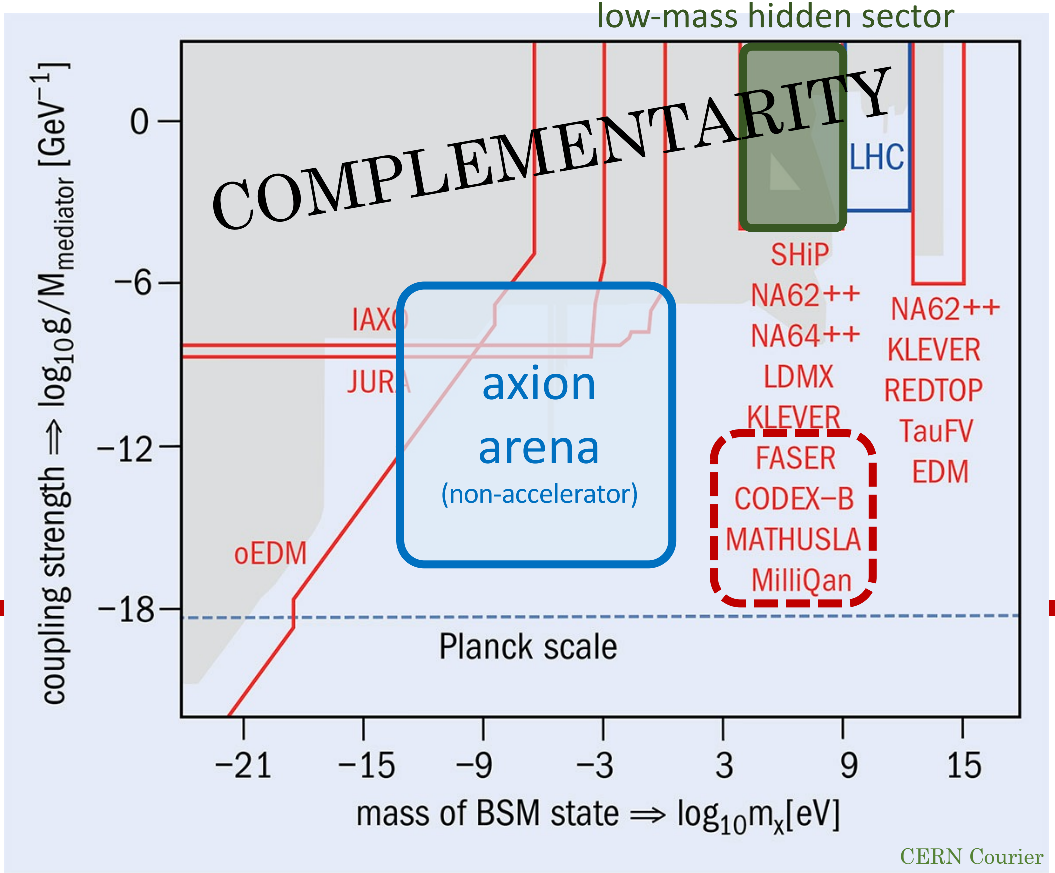
HL-LHC@CERN

10y @ 14 TeV (3-4ab^{-1})

Nb_3Sn

few 11T magnets

low-mass hidden sector

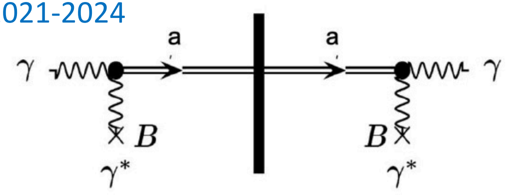


CERN Courier

"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

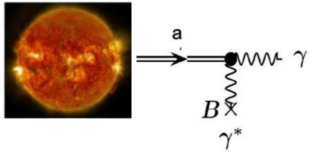


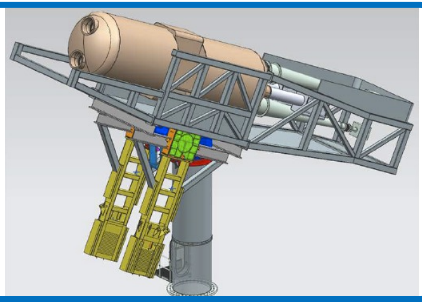

Installation of dipoles around HERA hall North (H1) July 2020

24 HERA dipoles

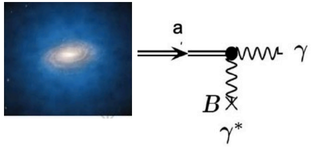
CAST @ CERN
(helioscope)
running

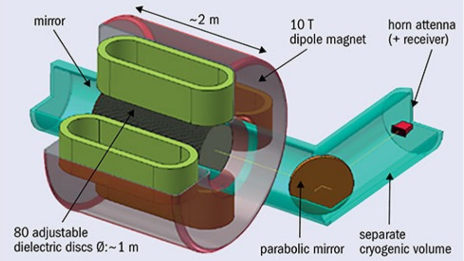
BabyIAXO & IAXO @ DESY
looking at the Sun, helioscope
2024-2030+

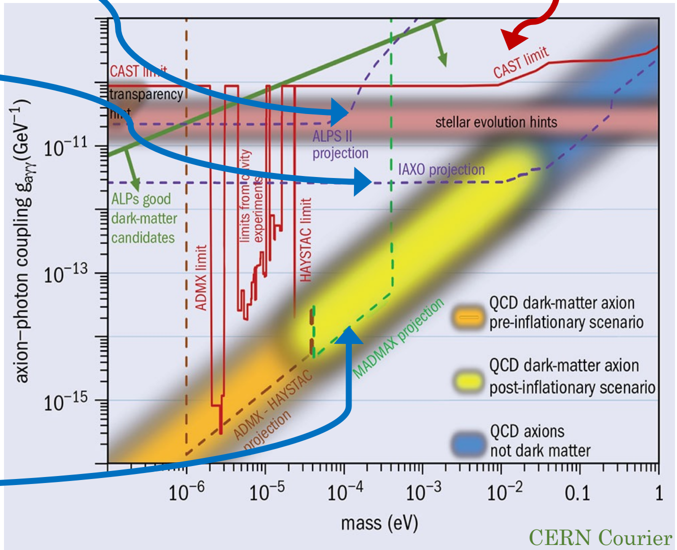




MADMAX @ DESY
looking at the galactic halo, haloscope
2026-2030+



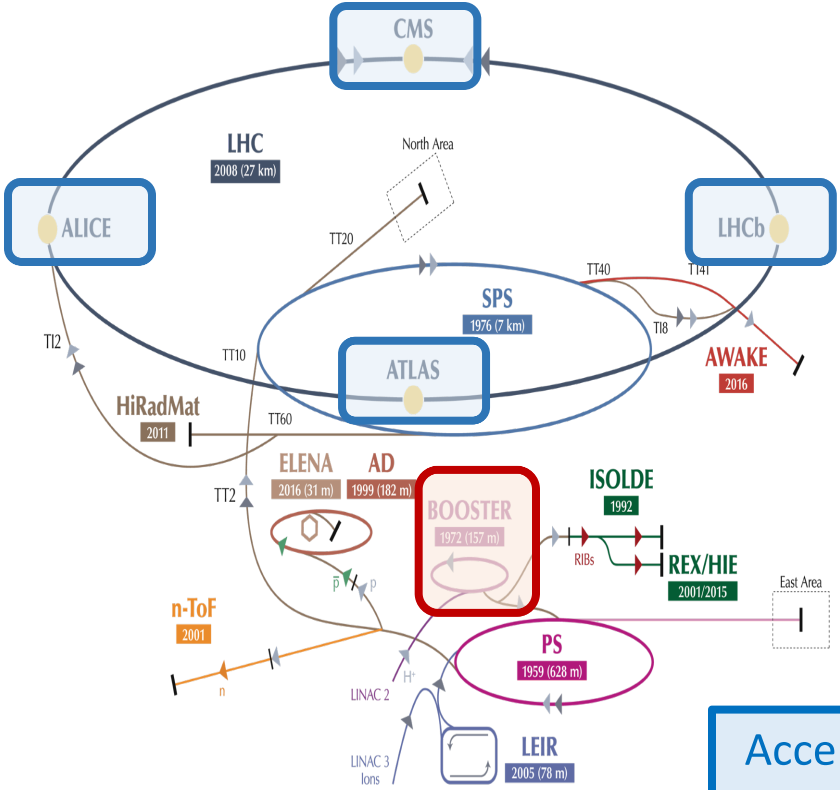


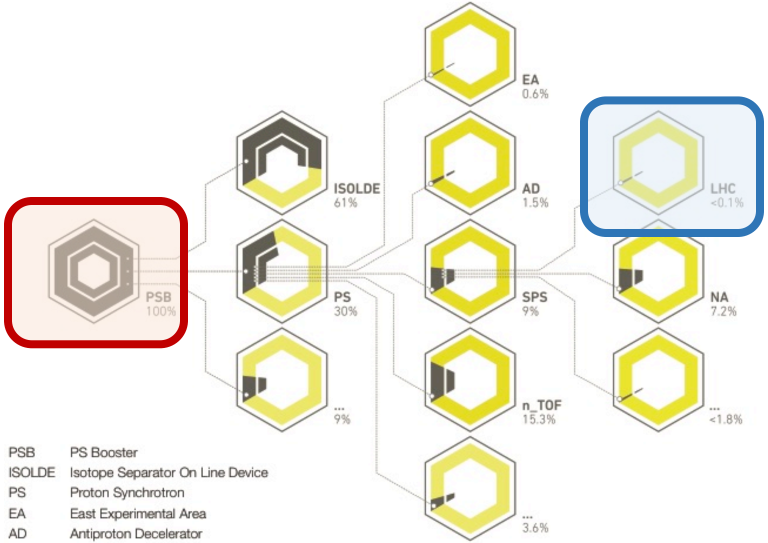


CERN Courier

Accelerated Beams (Beyond Colliders) 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

Accelerated beams unlock unique ways to address the open questions with a complementary methodology

Accelerated Beams (Beyond Colliders) at CERN

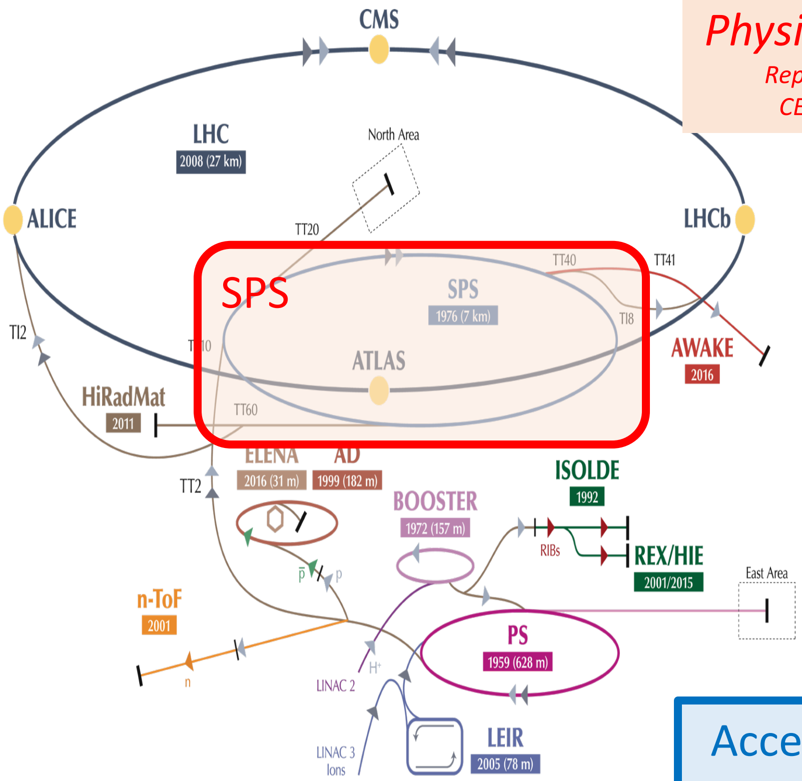
The CERN accelerator complex and the LHC – protons from Booster only <0.1% to LHC

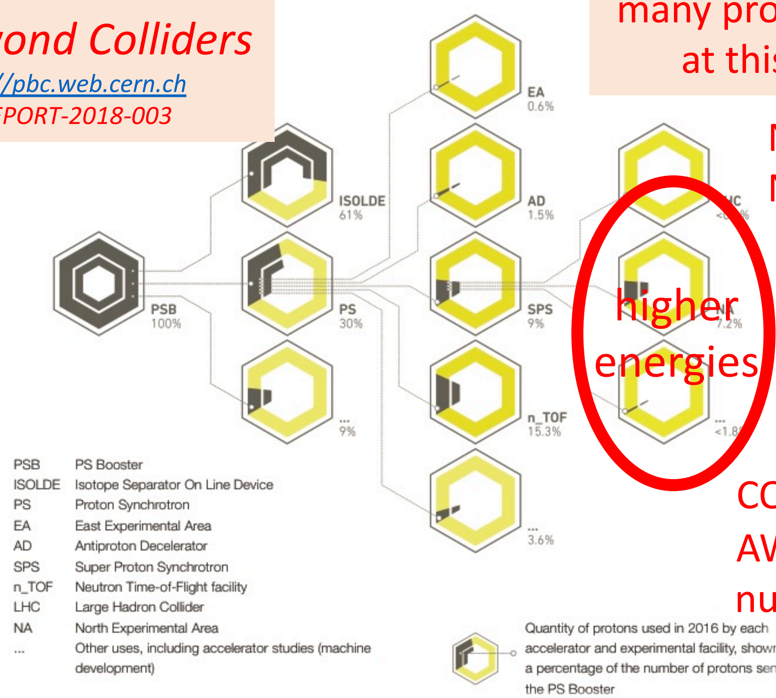
Physics Beyond Colliders

Reports: http://pbc.web.cern.ch

CERN-PBC-REPORT-2018-003

many proposals
at this stage





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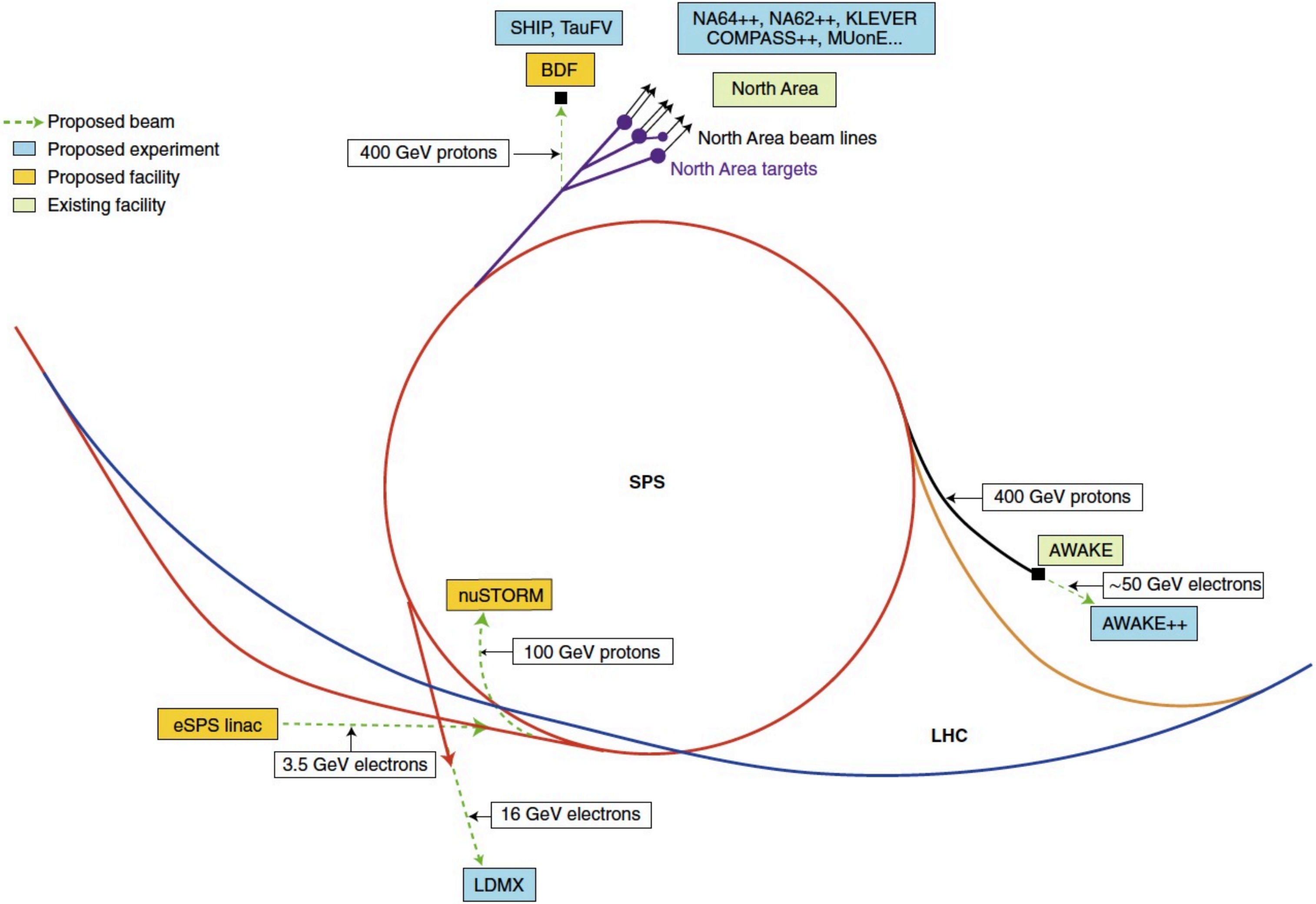
NA62++
NA64++
KLEVER
SHiP
TauFV
eSPS
MUonE
COMPASS
AWAKE++
nuSTORM

Accelerated beams unlock unique ways to address the open questions with a complementary methodology



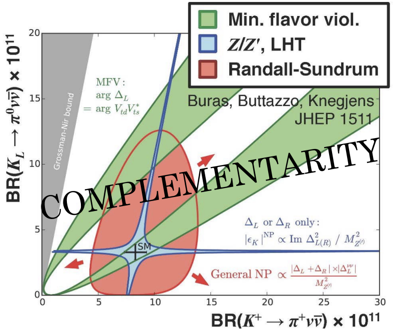
Proposed beam
Proposed experiment
Proposed facility
Existing facility

SHIP, TauFV
BDF
NA64++, NA62++, KLEVER
COMPASS++, MUonE...
North Area
400 GeV protons
North Area beam lines
North Area targets
SPS
400 GeV protons
AWAKE
~50 GeV electrons
AWAKE++
nuSTORM
100 GeV protons
eSPS linac
3.5 GeV electrons
16 GeV electrons
LDMX
LHC

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

Kaon physics with NA62 and KLEVER @ SPS-CERN

Flavour physics (CKM and BSM)



Buras, Buttazzo, Knegjens
JHEP 1511

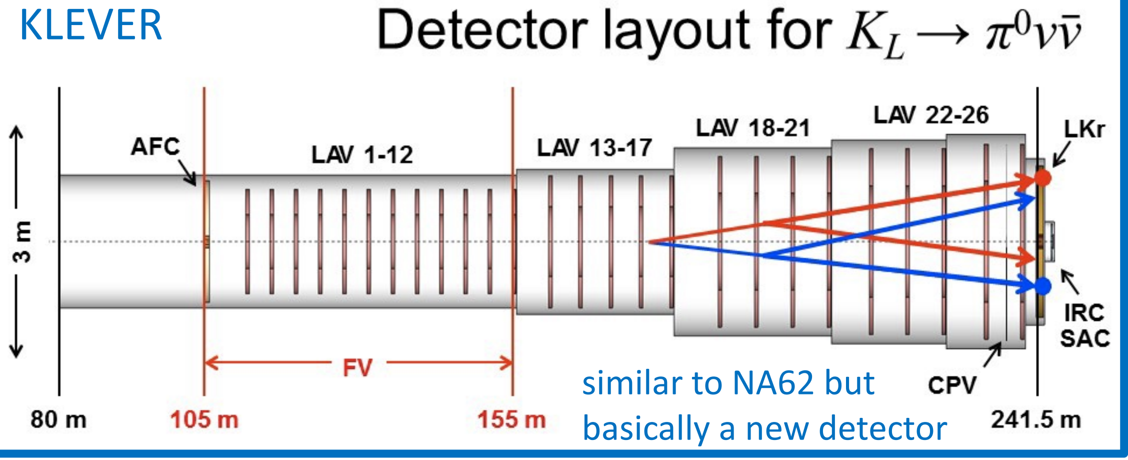
During HL-LHC era

During LHC era

running

NA62++ to run briefly
in beam-dump mode
(dark sector physics)

KLEVER

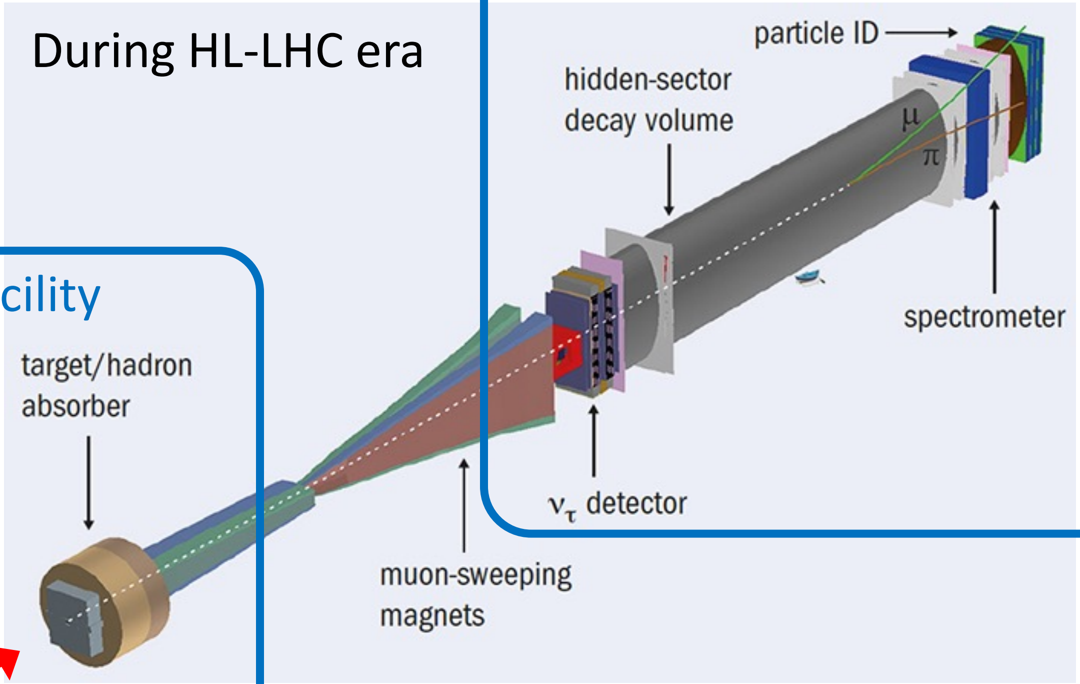


similar to NA62 but
basically a new detector

proposal

Beam Dump Facility @ SPS-CERN

Intensity Frontier & Hidden Sectors



400 GeV protons

SHiP

reconstruct decays of hidden particles in order to reject background to quasi zero

beyond NA62, to reach the charm & beauty mass decay acceptance domain

TauFV

$\tau \rightarrow \mu\mu\mu$ and other rare τ decays on the 10^{-10} level

proposal

Beam Dump Facility

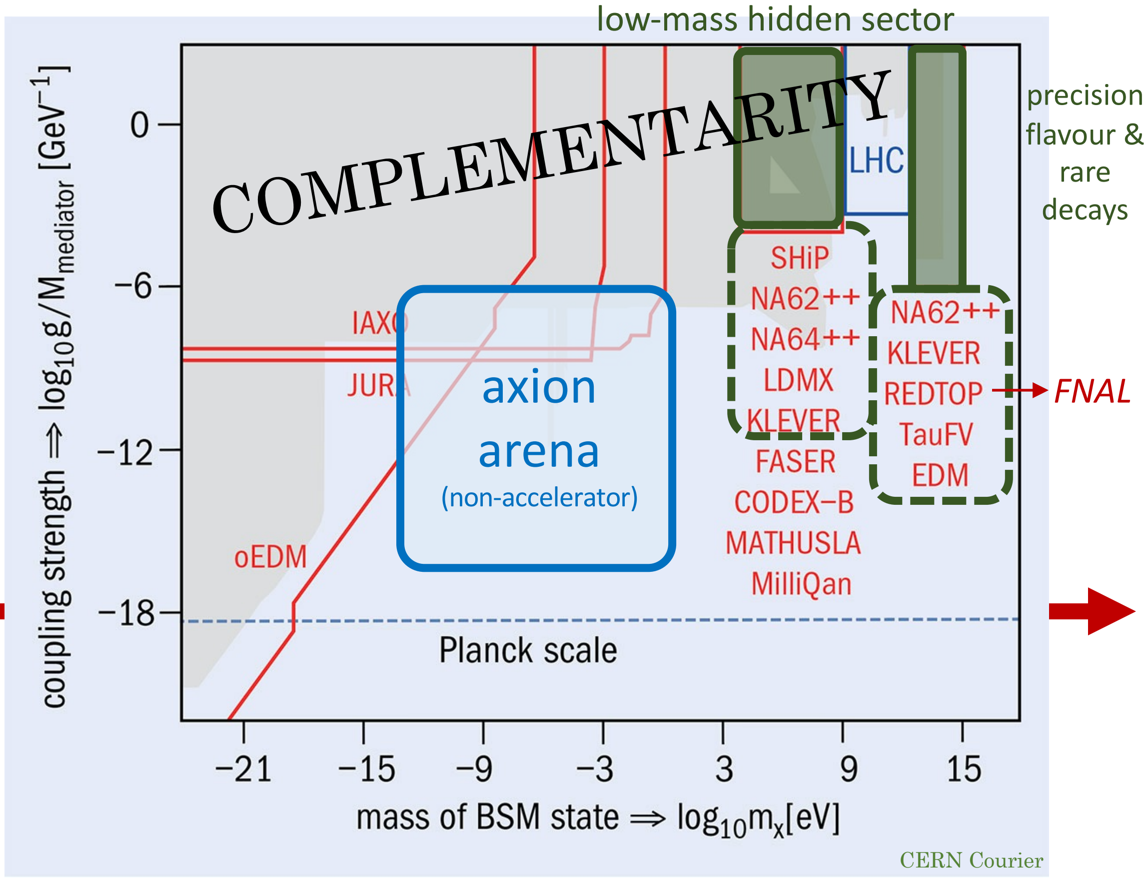
target to contain most of the cascade generated by the primary beam interactions

$PoT/y = 4 \times 10^{19}$

proposal (towards CDR)

Accelerated Beams (Beyond Colliders) at CERN

Flavour Physics
Intensity Frontier

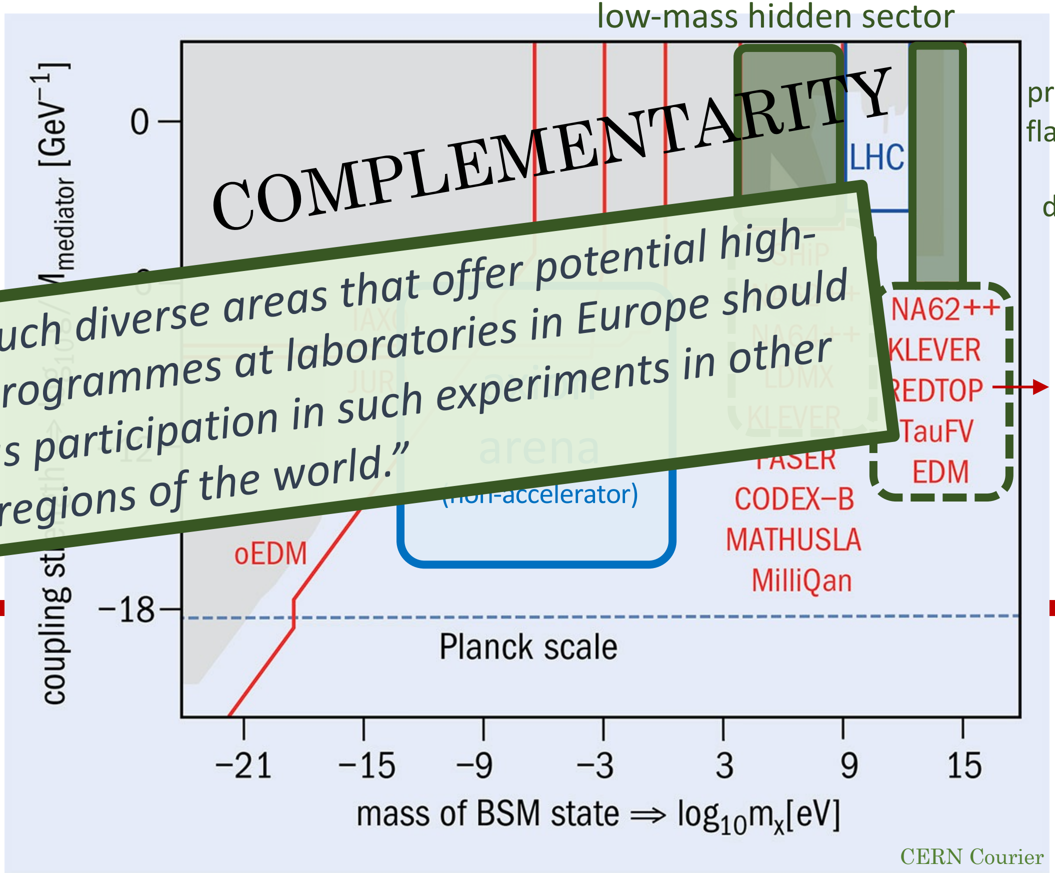


“portal” representation of physics potential to demonstrate complementarity

Accelerated Beams (Beyond Colliders) at CERN

Flavour Physics
Intensity Frontier

low-mass hidden sector



precision
flavour &
rare
decays

→ *FNAL*

“portal” representation of physics potential to demonstrate complementarity

COMPLEMENTARITY

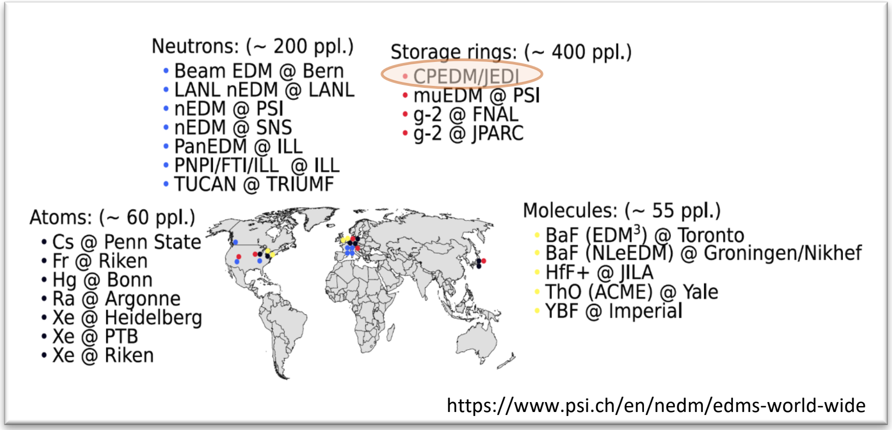
ESPP: “Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.”

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



Neutrons: (~ 200 ppl.)
- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

Atoms: (~ 60 ppl.)
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken

Molecules: (~ 55 ppl.)
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

https://www.psi.ch/en/nedm/edms-world-wide

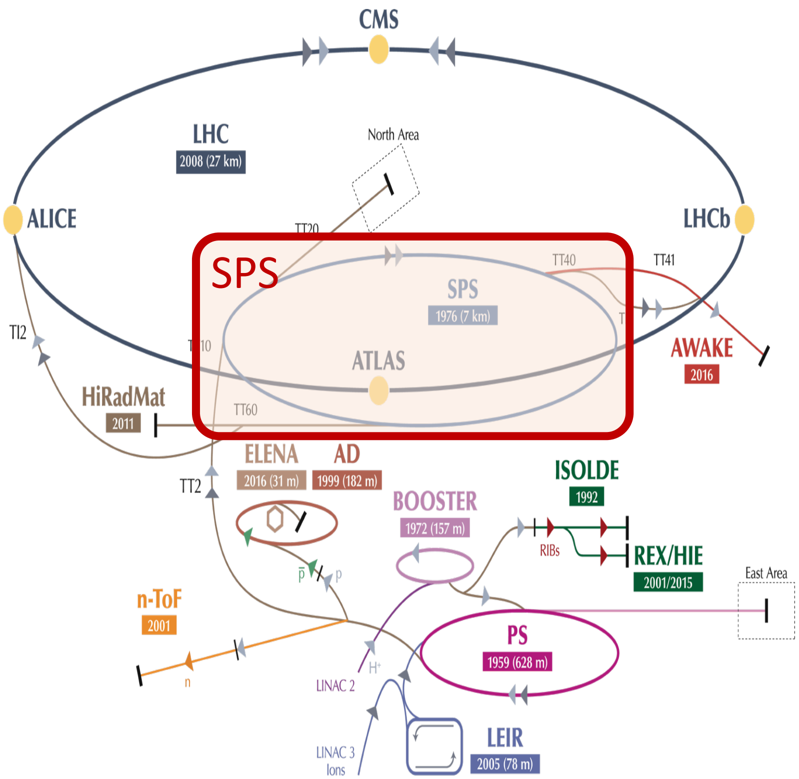
Ultimate goal of a dedicated storage ring with 400-500m circumference is pEDM sensitivity down to 10^{-29} e cm

(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

Accelerated Beams (Beyond Colliders) at CERN

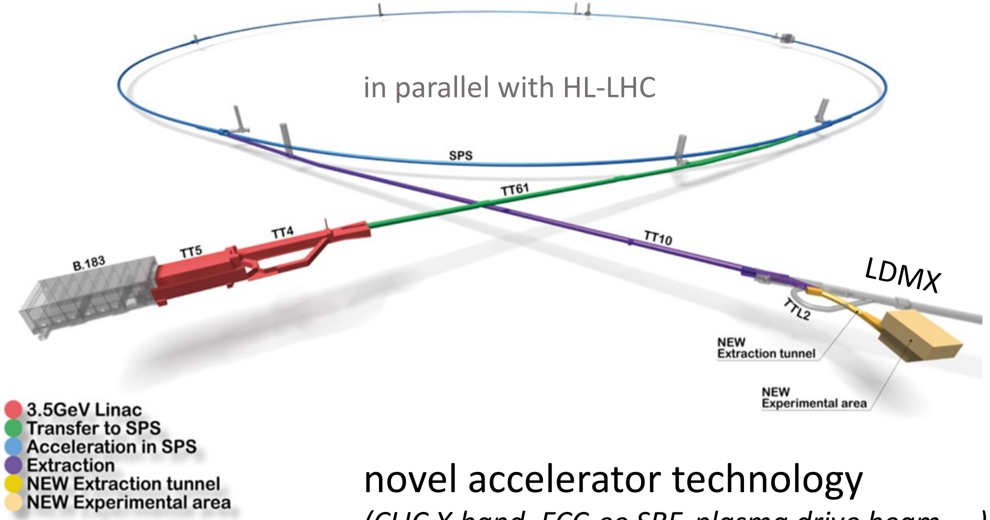
The CERN accelerator complex and the LHC – from protons to electrons in the SPS



eSPS accelerator

&

Light Dark Matter eXperiment (LDMX)



novel accelerator technology

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

proposal, CDR just submitted

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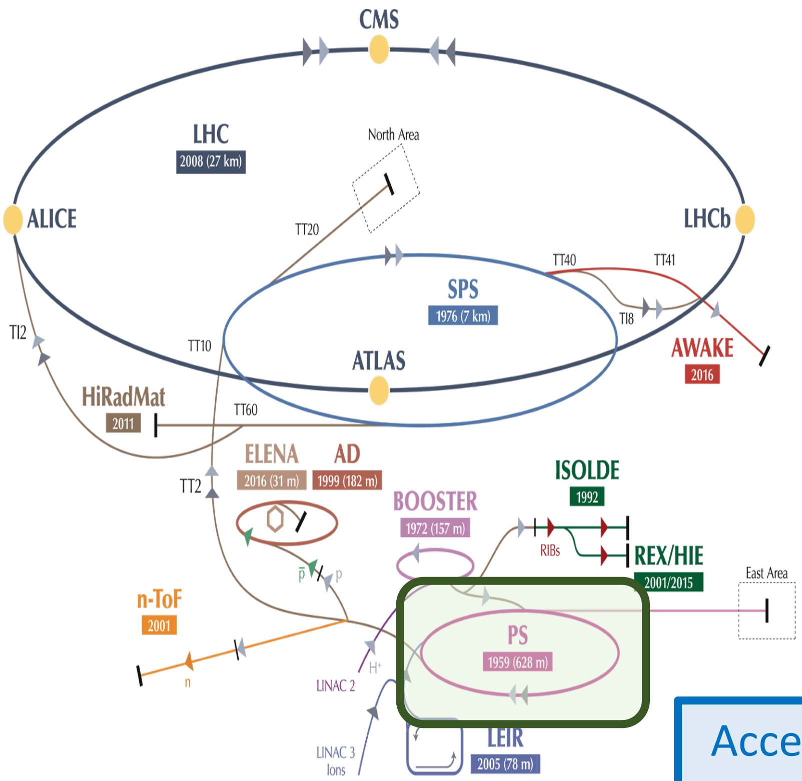
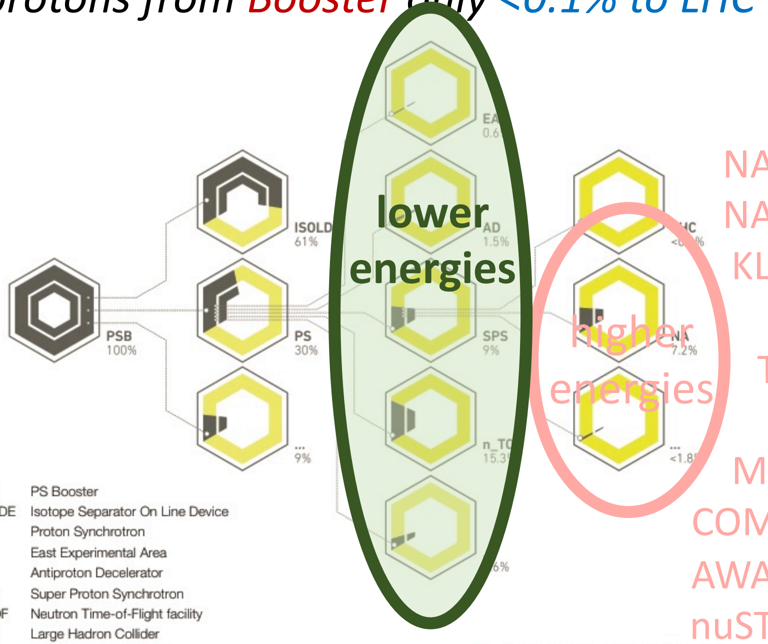
The CERN accelerator complex and the LHC – protons from Booster only <0.1% to LHC





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Accelerated beams unlock unique ways to address the open questions with a complementary methodology

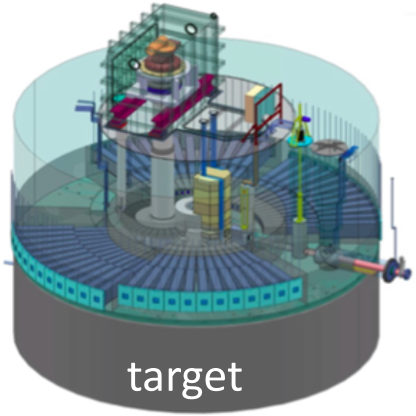
European Spallation Source (ESS) at Lund (Sweden)

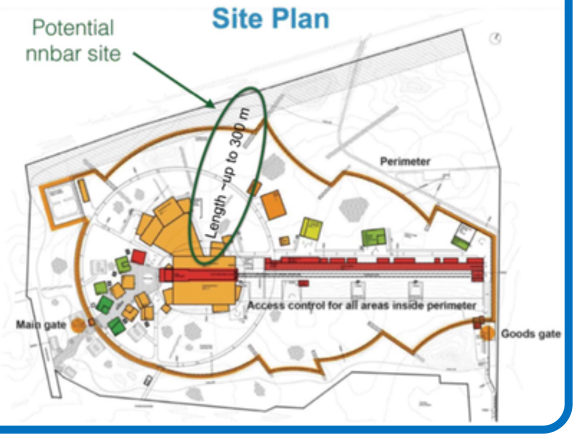
Fundamental Physics Beamline – Physics with Cold Neutrons

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

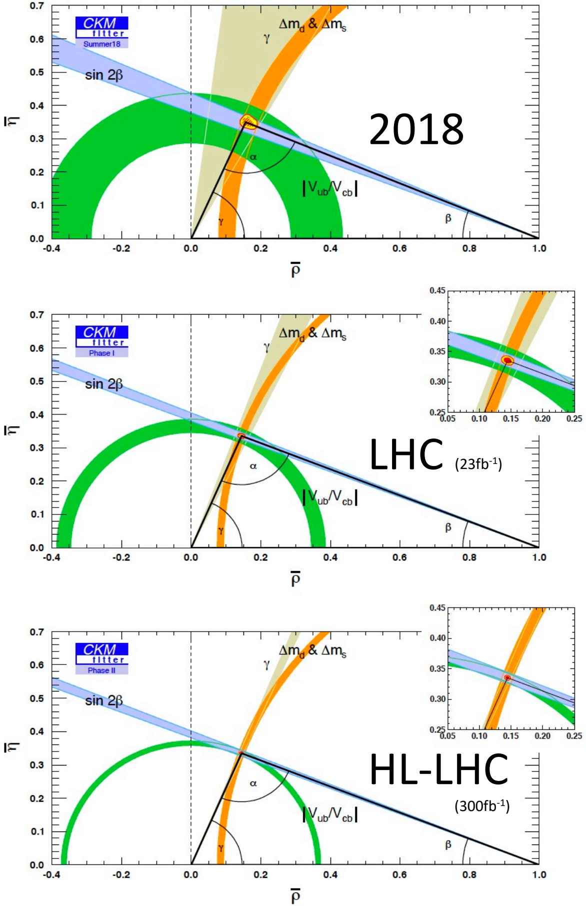
(first science from 2023, full operation 2026)


May 2020 (Courtesy: Perry Nordeng/ESS)

Other particle physics proposals @ ESS: ANNI, HIBEAM, ESSνSB, CEνNS

From the LHC to the High-Luminosity LHC @ CERN

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



2018

LHC (23fb^{-1})

HL-LHC (300fb^{-1})

- Constraining the parameters of the unitary CKM matrix (not predicted by the SM) will provide an extremely precise test of the paradigm, and through loop corrections a powerful sensitivity to BSM physics *(figure from LHCb only)*
- Expected improvement from LHC and Belle II *(table)*

	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
short-term	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
mid-term	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

[arXiv:1812.07638v2]

- In general, not limited by experimental or theoretical systematic uncertainties
- Sensitivity to BSM up to 10^3-10^6 TeV assuming $\mathcal{O}(1)$ coupling strength, depending on flavour
- Addressing significantly the flavour puzzle question