”What is Next in Particle Physics ?”– Experimental (Collider) Perspective

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High Energy Physics - Theoretical and Experimental CHALLEGES” (“HEP-TEC-2025”)
Kyiv, Ukraine, January 21-22, 2025

Large-Scale Research Infrastructures

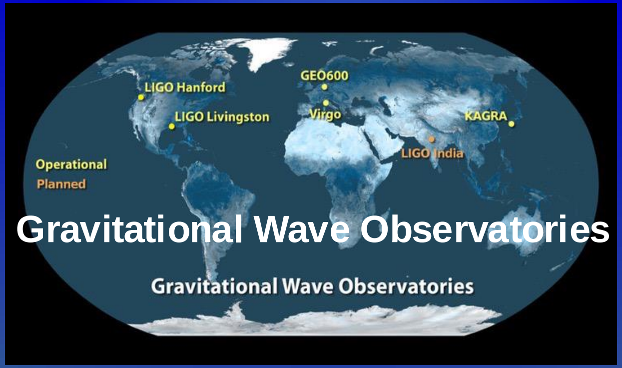
(International Collaborations, Global Laboratories)

- **Address:**
  - fundamental science questions at the forefront of research and technology

- **Require:**
  - large and sustained infrastructures of great operational complexity
  - global collaboration on long time scales of many decades from theory to observations

- **Provide:**
  - fantastic sensitivities (LHC: 1 out 10^{10} Higgs ev.; LIGO: 10^{-23} strain, EHT: 10 μarcsec res.)
  - challenging requests for high technology and innovation
  - stimulating ideas which in turn attract good people
  - occasion to bring people together


CMS Experiment



Gravitational Wave Observatories

Event Horizon Telescope

Excellence, Cooperation and Sociology

- **Scientific Excellence** is key
  → world-class, excellent infrastructures need excellent staff
  intellectual challenges for all staff in RIs important

- **Large International Collaborations**
  - a place where people learn to work together
  - collaboration and competition
  - cultural exchange: good opportunity to recognize differences, accept them and learn to use them
  - influence the way of thinking, planning at general level
  - information sharing: role of internationalization and communication
  - experience can be used by individuals and in other fields

→ management through "common goals"

→ management by "convincing partners"

If ***Management*** is concerned with **doing things right,** ***Leadership*** is concerned with **doing the right things**

5* Scientific Discoveries of the Last Two Decades In Fundamental Physics

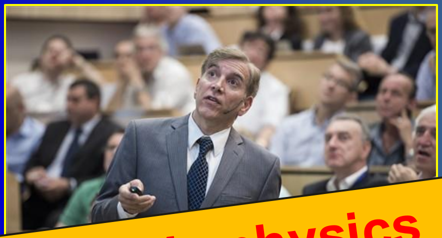
- ✓ *Higgs Boson (CERN, 2012)*
- ✓ *Gravitational Waves (LIGO, 2016)*
- ✓ *Black Hole Event Horizon (EVT, 2019)*

We have a "virtuous cycle", which must remain strong and un-broken: from fundamental science comes applied research and technological breakthrough, enabling novel Instrumentation concepts and techniques, which in turn lead to a greater physics discoveries and better understanding of our Universe.

Image Credit: National Geographic

Higgs Discovery at Large Hadron Collider @ CERN (2012)

"As a layman I would now say… I think we have it – It is a Discovery" (Rolf-Dieter Heuer, CERN DG)



The unique organizational structure and culture of particle physics contributed to this scientific breakthrough

Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

The HIGGS BOSON is part of our "origin".

We did not know on that day and still have to establish if it is – "THE HIGGS BOSON" of the SM or comes from one of the SM extensions

Our Journey: As Seen by Outside

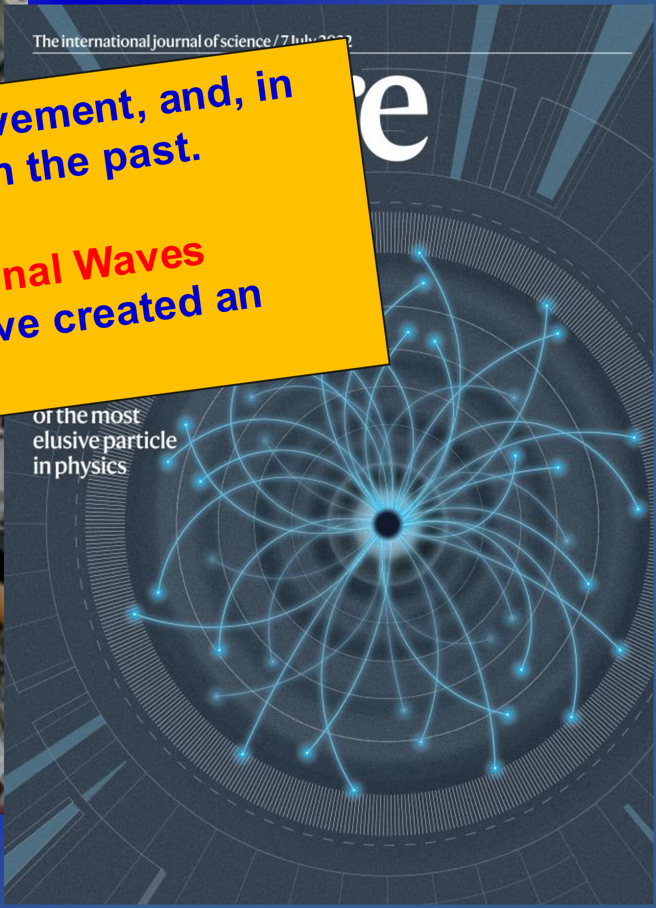
During Construction (Sep. 2008):

The "Gothic Cathedrals" of the 21st Century

Upon Discovery (Dec. 2012):

A Giant Leap for Science

Higgs Turned Ten (Jul. 2022):

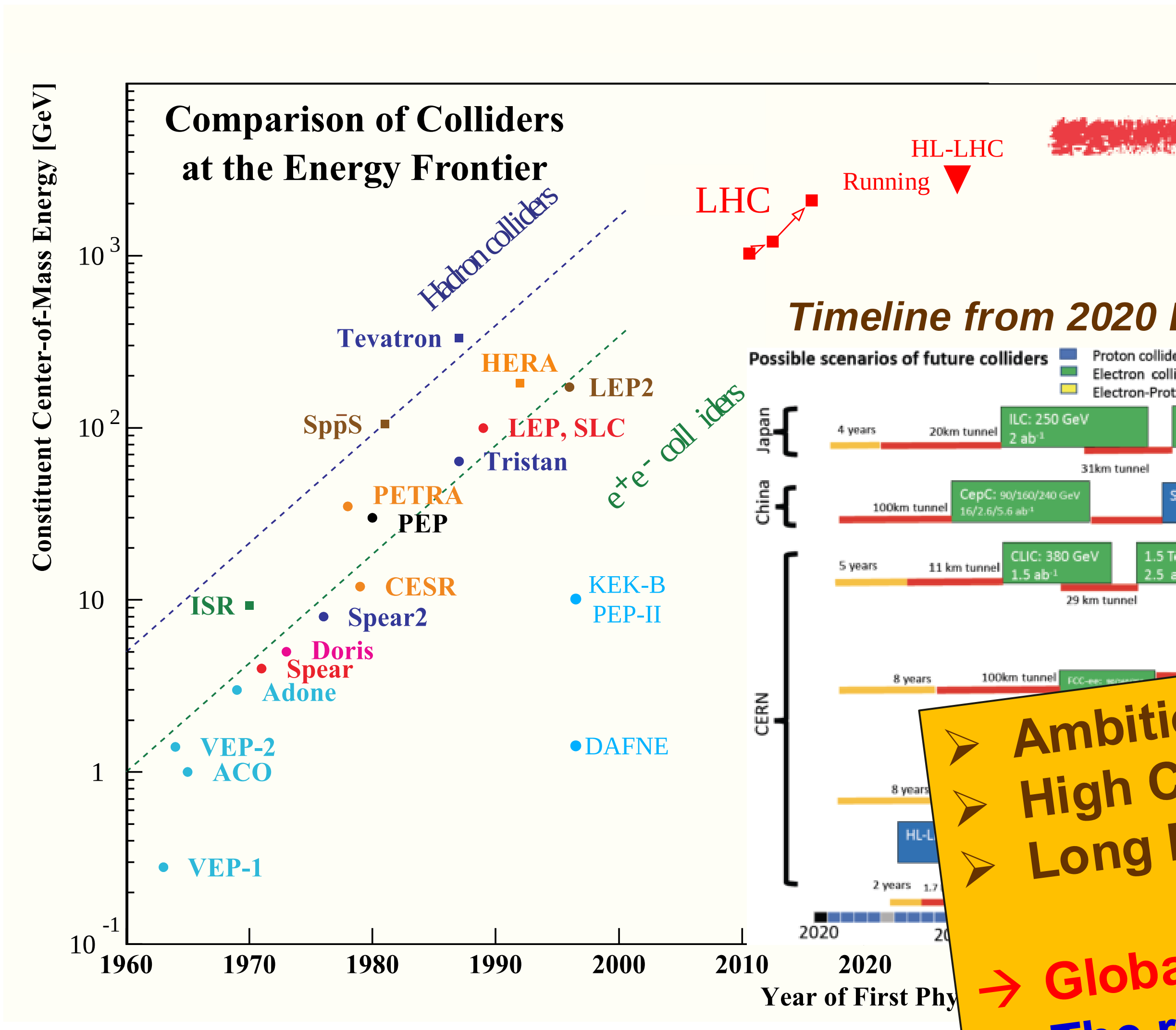


Our instrumentation represents both a towering achievement, and, in some cases, a scaled-up version of techniques used in the past.

Recent discoveries of the Higgs boson and Gravitational Waves required increasingly sophisticated detectors and have created an exceptionally positive environment in society.

The HEP Field is Facing a Defining Moment in its History

We are on a verge of a phase transition …



Plans
Dreams
Aspirations
Hopes

Timeline from 2020 EPPSU Update:

- ➢ **Ambitious Scope**
- ➢ **High Costs**
- ➢ **Long R&D Times**

→ Global Projects (POLITICS!)

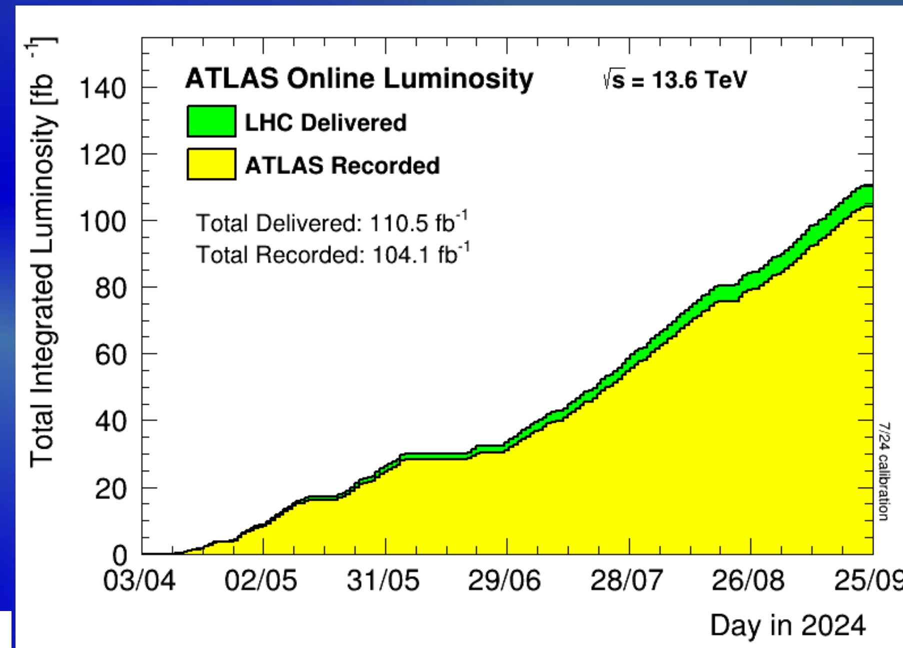
→ The real challenge is GETTING THE FUNDING !

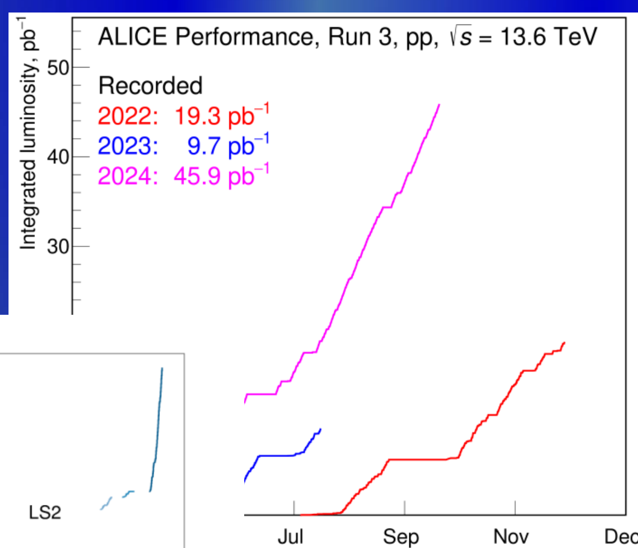
Clear and Exciting Prospects for the Next Two Decades: LHC & CERN at the Energy Frontier

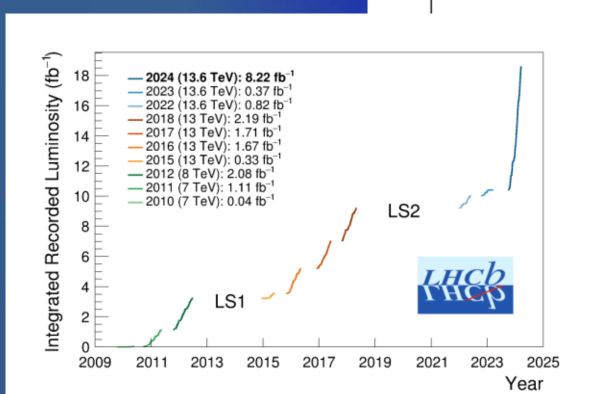
LHC Accelerator Complex: Glorious Run 2

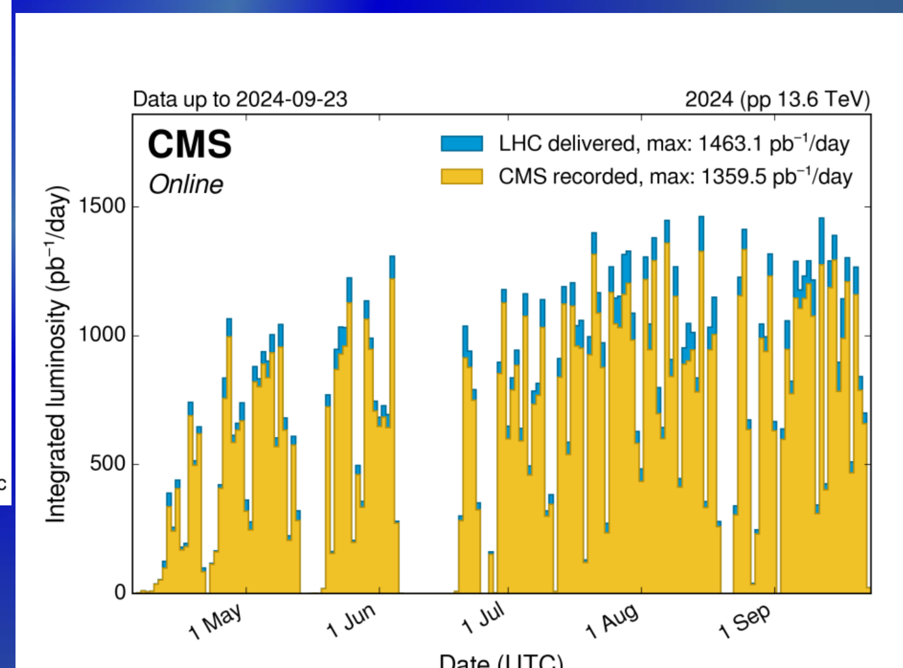
2024 - High availability operation, Full mastery of considerable inherent operational risks

- ✓ >110 fb^{-1} pp luminosity delivered so far in 2024 to ATLAS & CMS!
- ✓ Up to almost 1.5 fb^{-1} in a day!
- ✓ All Phase I (LS2) upgrades are now fully operational
- ✓ Beta* and separation: luminosity levelling time 7-8 h (ATLAS & CMS)







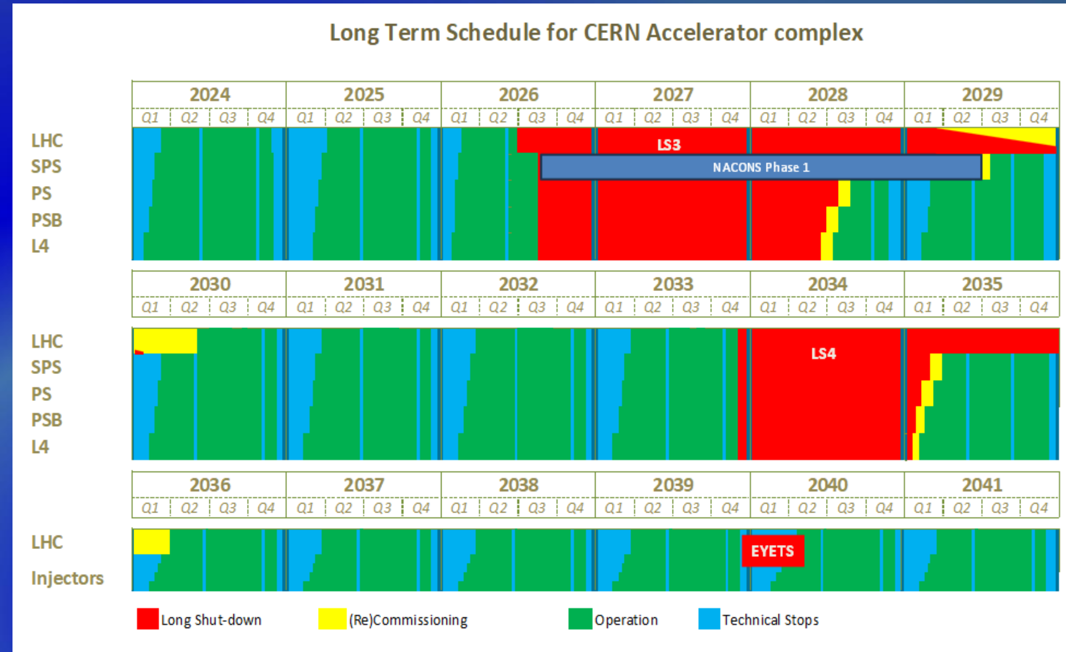


J. Mnich

Long-Term Schedule of LHC Accelerator Complex

CERN Council approved in Sep. 2024 a holistic plan for LS3 (HL-LHC):

- Extension of Run 3 until Summer 2026
- Shift of start of Run 4 by 1 year to mid-2030
- Shift LS4 by 1 year, maintaining length of Run 4
- No LS5 – replace by EYETS



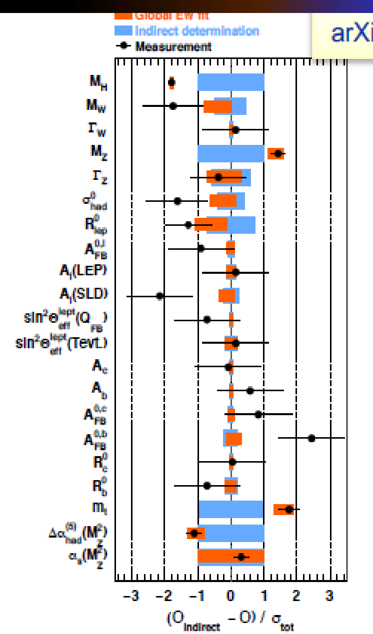
***Towards HL-LHC:* Upgrades to many detector components ongoing**

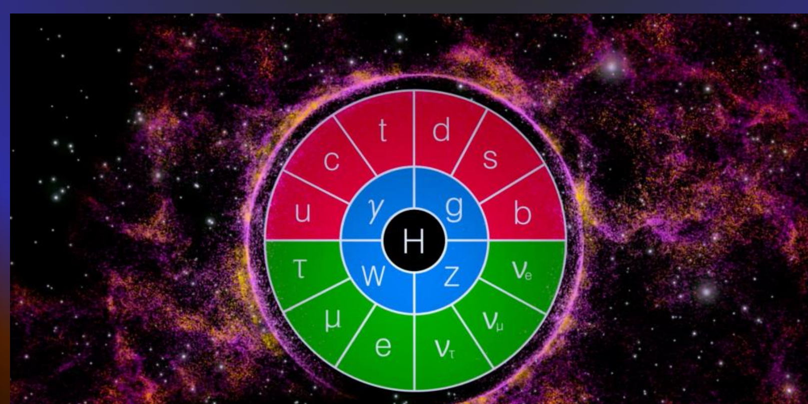
LHC will guide the way →
the only Higgs (top, Z, W…) factory for a decade(s) to come

= Cosmic DNA OF THE UNIVERSE

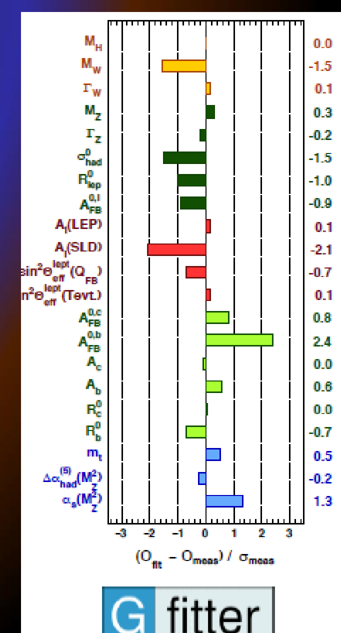
The Standard Model of Particle Physics

Some background and history



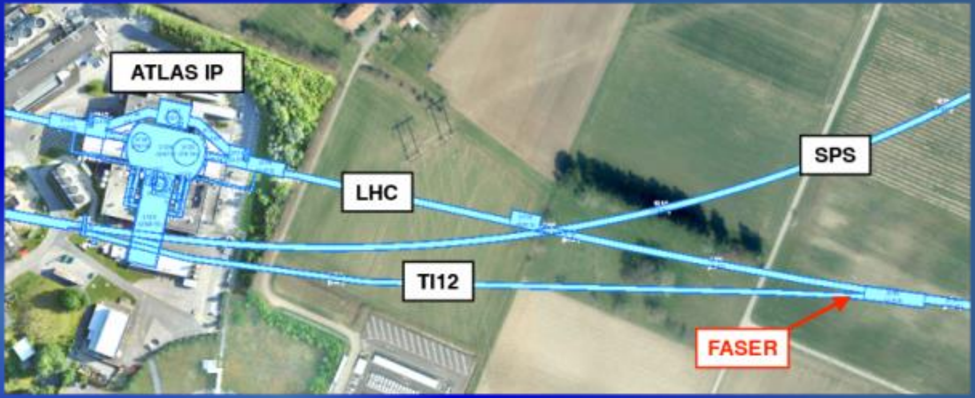


Walter Murch for the 2013 film *Particle Fever*

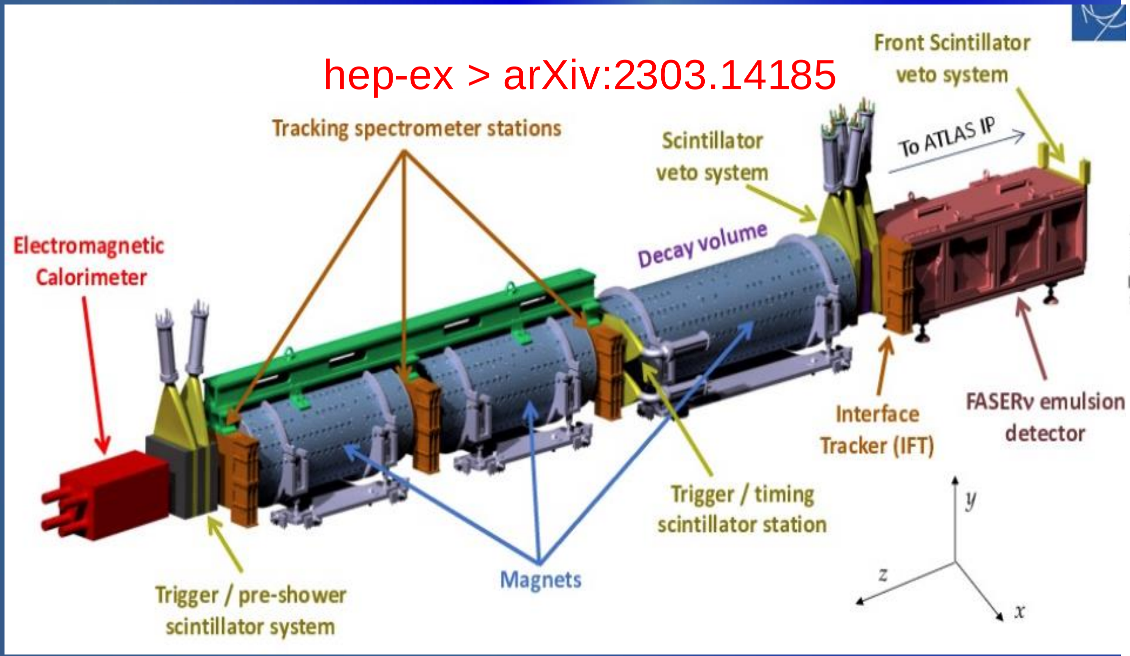


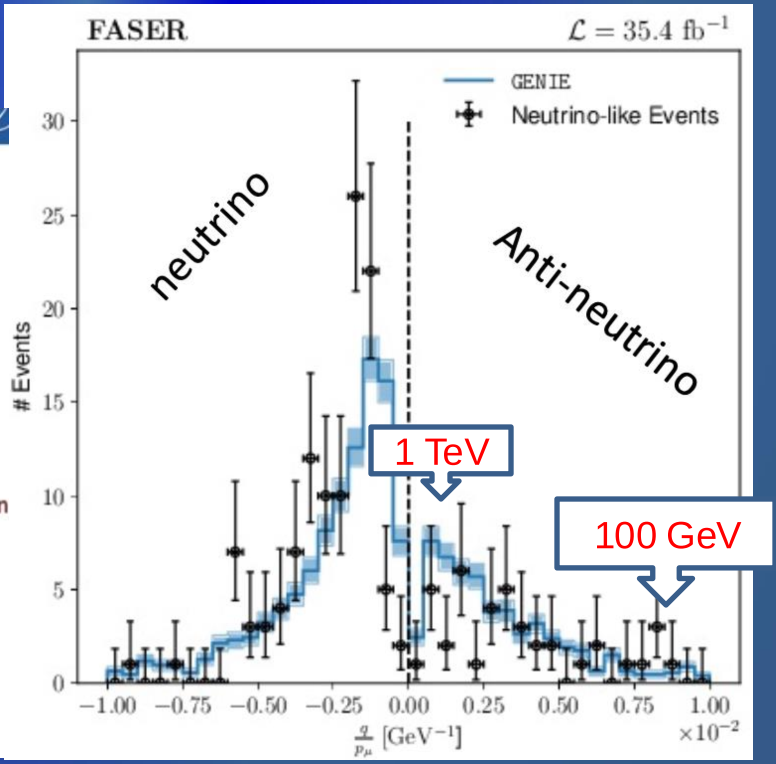
The Birth of Collider Neutrinos (FASER @ CERN)

- First Direct Observation of Collider Neutrinos with FASER at the LHC
- ✓ Expect 151 ± 40 events
- ✓ Background estimate: 0.2 events
- ✓ 153 event observed (16 σ)



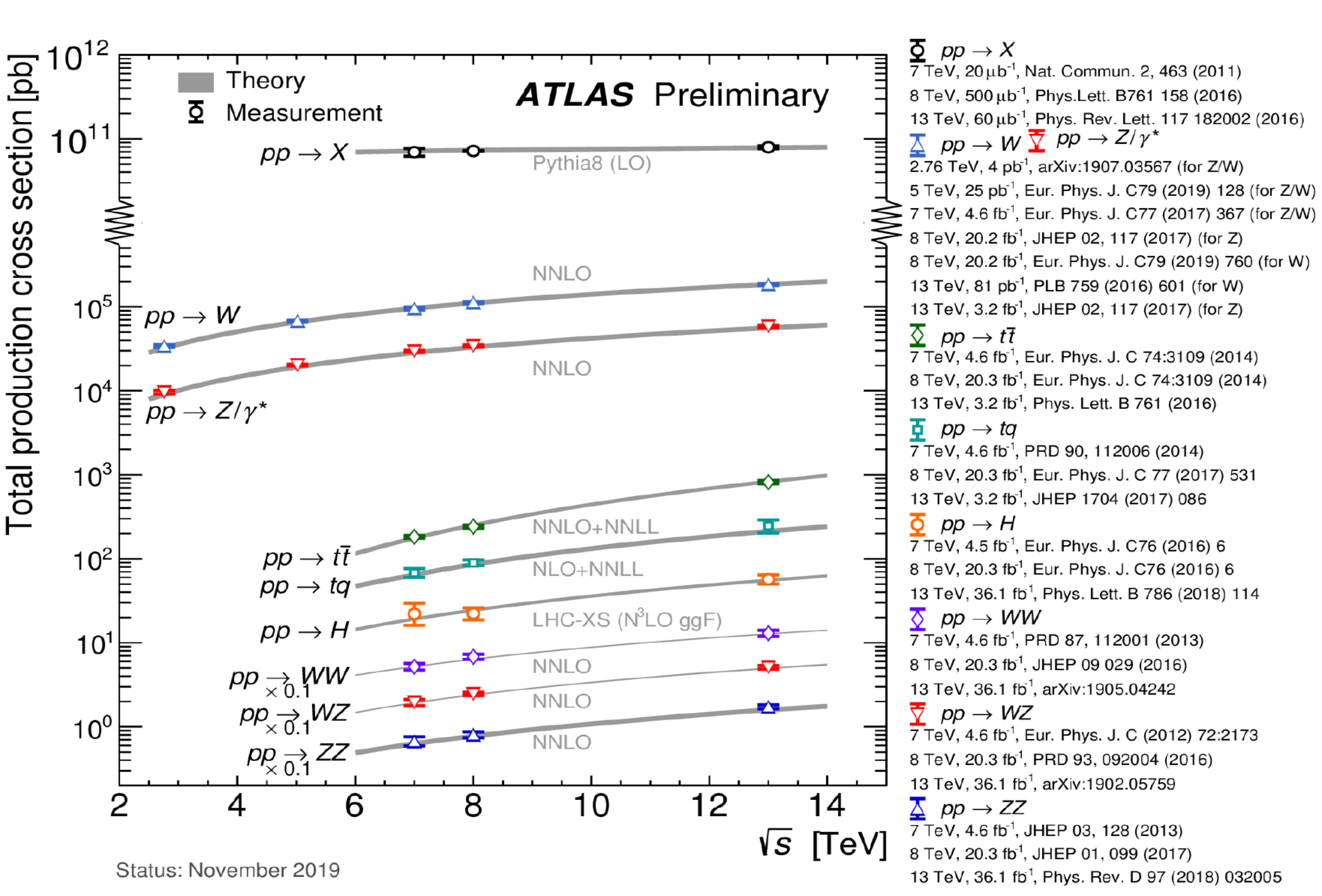
FASER is ideally positioned to detect the particles into which light and weakly interacting particles will decay. FASER also has a subdetector called FASERν, which is specifically designed to detect neutrinos.





SM Still Going Very Strong: Remarkable Agreement …

Improvements in theoretical calculations to NNLO level **complement** these results



THE HIGGS BOSON
FINAL PIECE IN THE PUZZLE?

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

What protects its mass and sets it to the EWK scale, when it should be Λ_{PL}

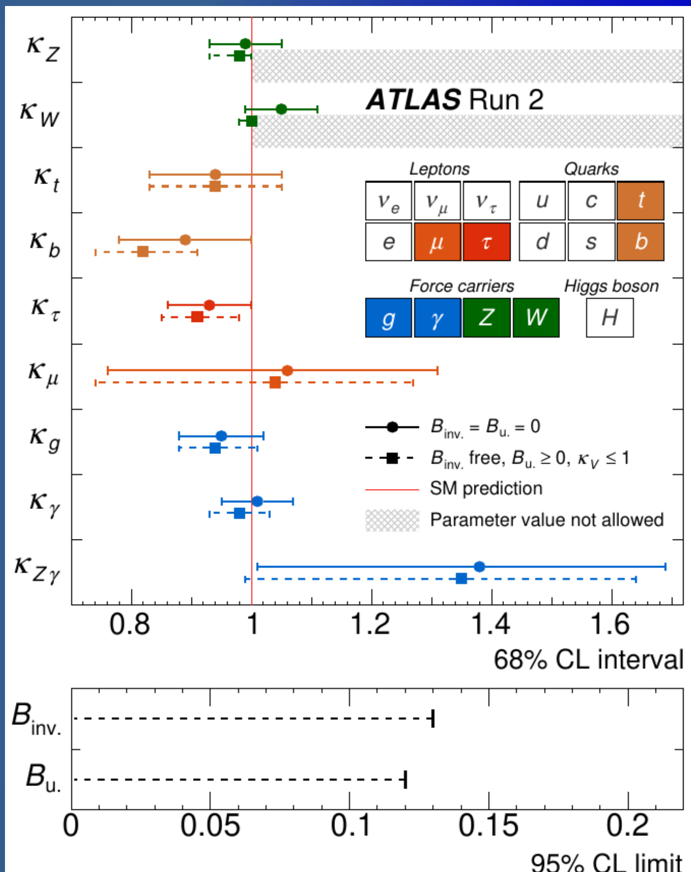
… is it "THE Higgs Boson" (of the Standard Model) ? or one of several ?

… its properties could give information on Dark Matter ? New "Portal" ?

… its properties could give first hints on Dark Energy

From Discovery to Precision: THE Higgs or A Higgs

Measurements of Higgs properties with increasing precision are a formidable tool to look for new-physics manifestations → experimental precision approaching theory precision even before using full Run 2 statistics

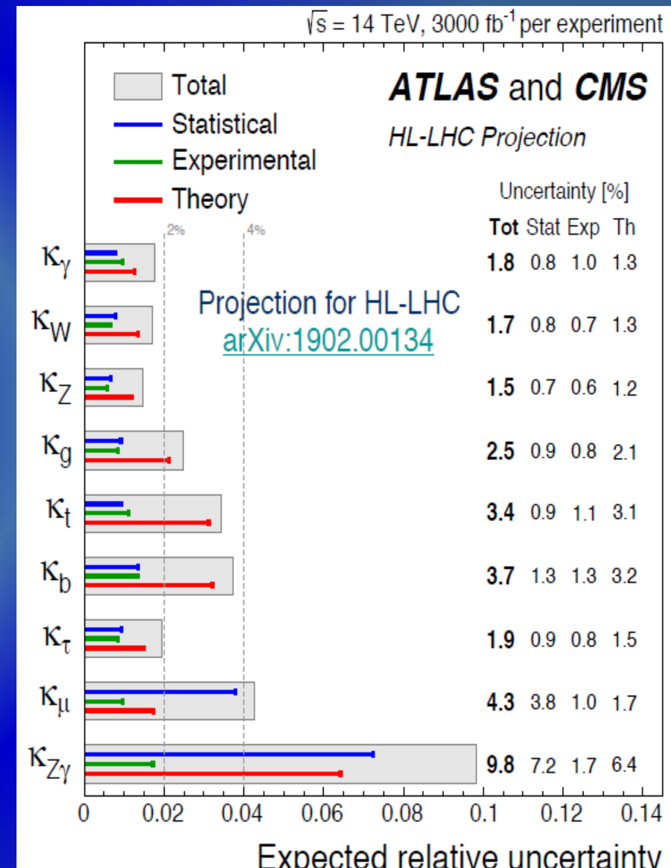


TODAY:

Most precise measurements of (most) Higgs couplings to-date from combinations of Run2 data: from 6% (to weak bosons) to 7-12% (for third generation fermions)

FUTURE:

20x increase in statistics



- ✓ The newly found boson has all properties as expected for a SM Higgs, AS OF TODAY!
- ✓ We *continue to look for anomalies*, i.e. unexpected decay modes or couplings,multi-Higgs production, heavier Higgses, charged Higgses…

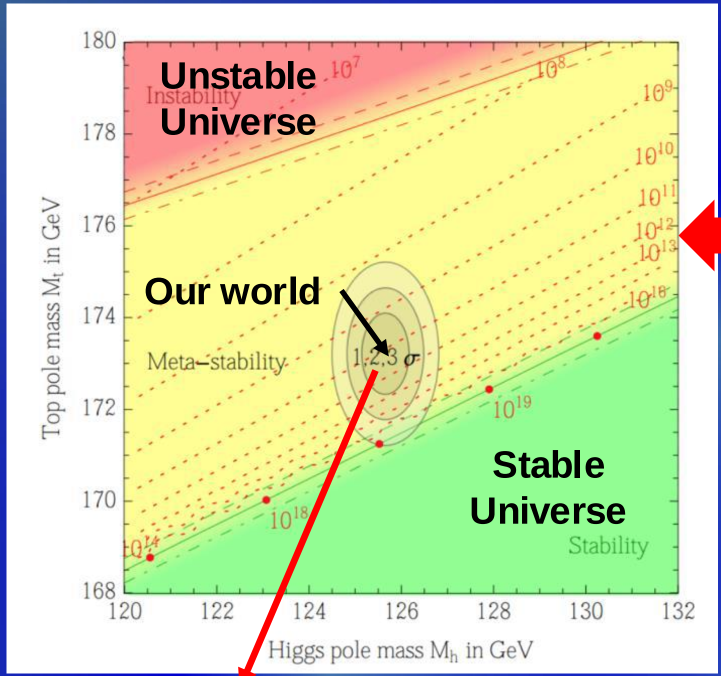
The "Fate of Our Universe" & Higgs Boson

Is Empty Space Stable ?

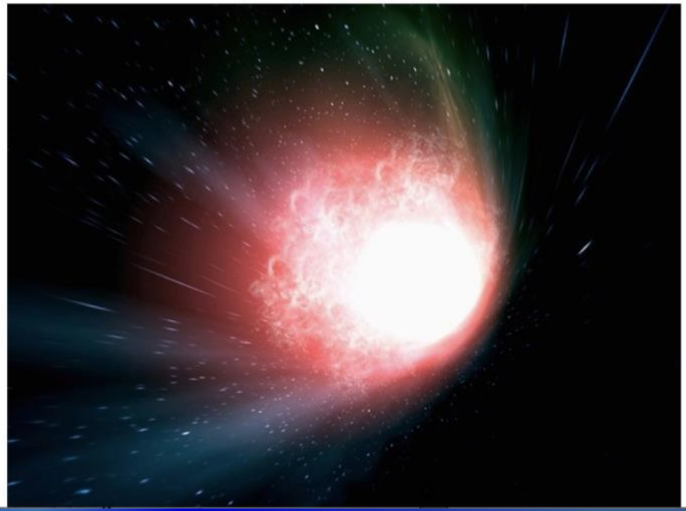
« Stability of the EW vacuum »

arXiv: 1403.6535

The universe seems to live near a critical condition

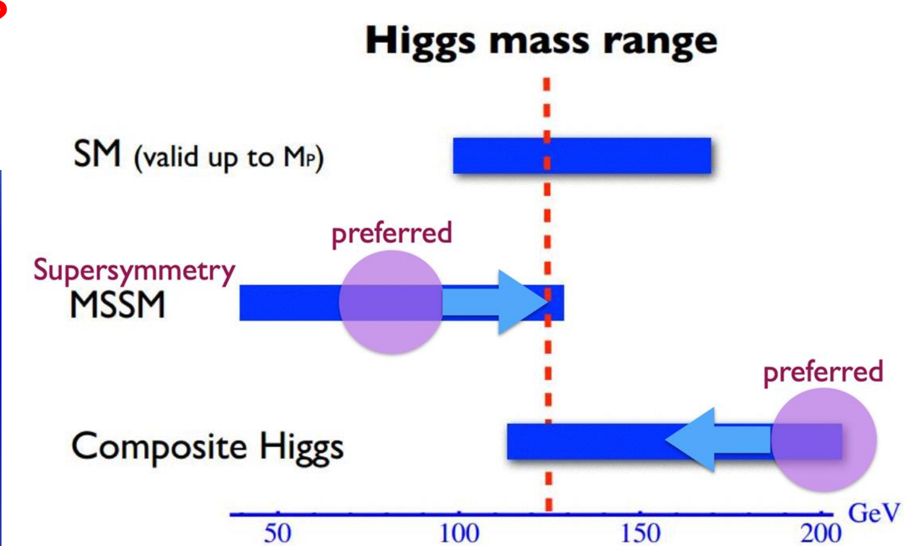


Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



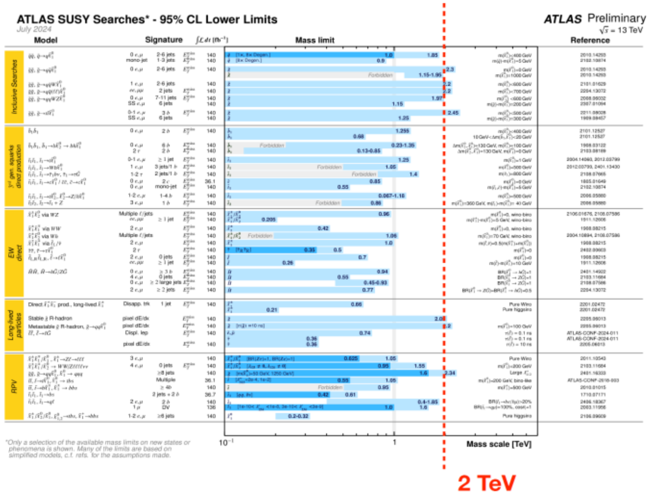
Is m_H = 125 GeV special ?

Higgs Mass is finely-tuned observable …

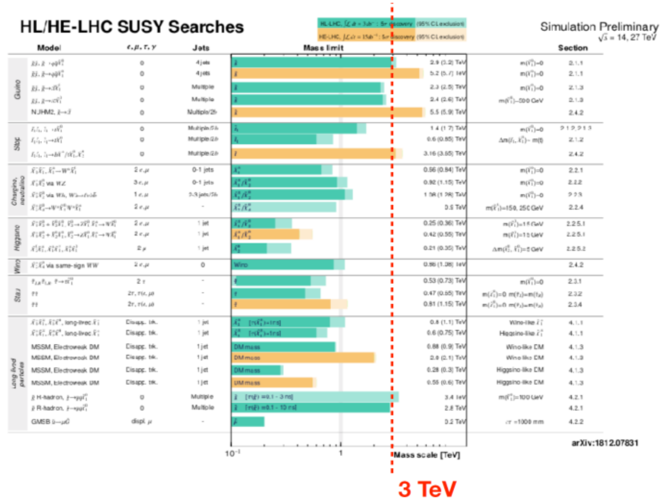


The Never-Ending Search for New Physics: SUSY, Exotica …

(in a large variety of topologies and models)



Example from ATLAS (similar for CMS)



HL-LHC YR
1812.07831

Still Room for Discoveries @ HL-LHC:

- gluinos up to O(2-3 TeV)
- stops up to O(1.5 TeV)
- EW SUSY up to O(1 TeV)
- Z' and W' up to 6 -8 TeV
- LQ up to 1.5 - 2 TeV

HL-LHC YR
1812.07831

Example from CMS (similar for ATLAS) - latest plot in the backup!

Where do we go from here ?

- Are we looking at a right place ?
- Complementary searches?
- Are we leaving any stone unturned ?

There is no anymore a "no-loose" theorem that connects naturalness to discoveries at colliders

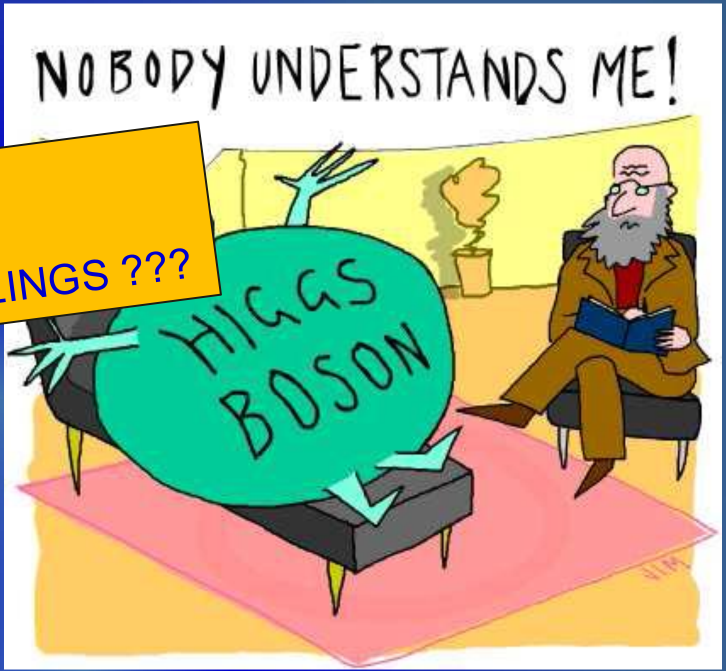
LHC and Diversification of the HEP Field

Main results from LHC:

- ✓ **We have <u>consolidated</u> the Standard Model** (wealth of SM measuremen… includi…
- ✓ …ndard Model: …y of the Higgs-field messenger
- ✓ **We have no evidence of new physics (YET), beyond the SM → *No argument yet for a particular energy scale beyond the SM***

WHERE IS "EVERYBODY" ?

AT HIGHER MASSES ??? – OR AT SMALLER COUPLINGS ???



HEP getting closer to other fields of science

SUSY
Composite Higgs
Extra dimensions
Neutral naturalness
Relaxion models
Clockwork
NNaturalness
UV/IR mixing

WIMP
Axion DM
Dark sectors
Sterile neutrinos
Strongly interacting DM
Feebly interacting particles
Primordial black holes

Effective field theories

Axions &
Axion-like-particles

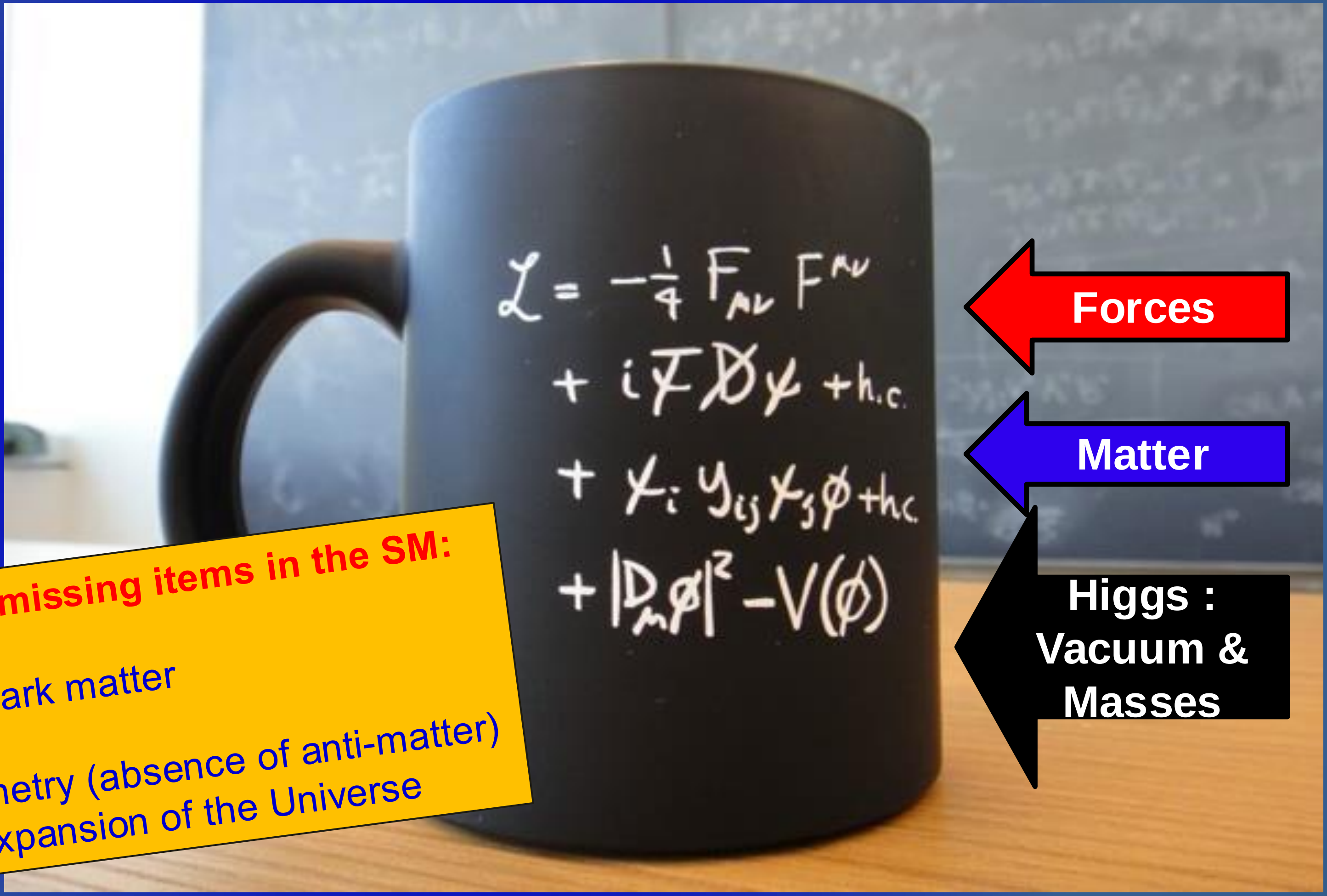
Extended Higgs sectors

Leptoquarks

We Know There Must be New Physics: Puzzle is Sharpened

With a discovery of M_H ~ 126 GeV, we have a *self-consistent theory that can be extrapolated to exponentially high energies* (e.g. Plank scale)

Lagrangians
&
coffee mugs



Forces

Matter

Higgs : Vacuum & Masses

There are several missing items in the SM:

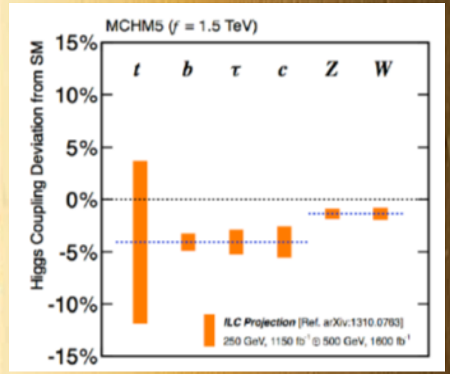
- non-baryonic dark matter
- neutrino mass
- baryon asymmetry (absence of anti-matter)
- accelerated expansion of the Universe

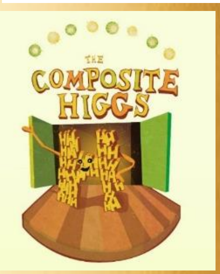
REALLY NEW IDEAS NEEDED
Beyond Paradigms of Spacetime + Internal Symmetries

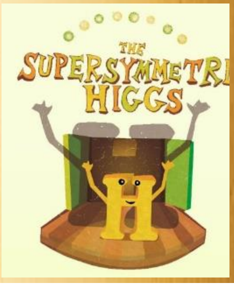
H

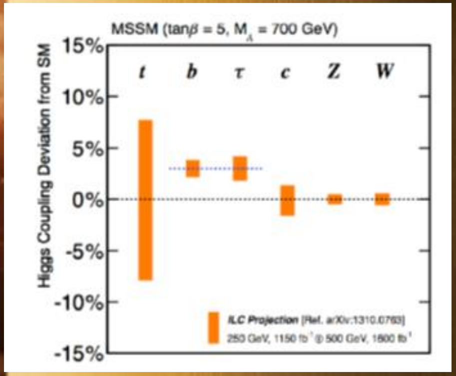
We have only just started to understand the Higgs boson …

… and we need to look from every angle









Future Electron-Positron Colliders: " Higgs Factory"

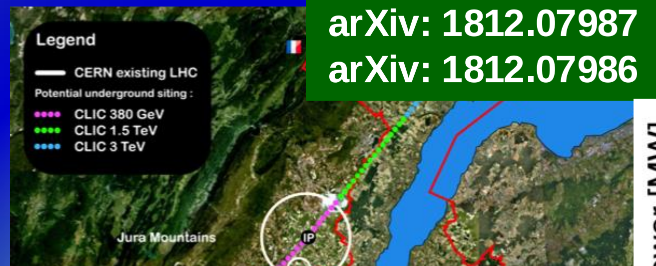
Linear colliders: *ILC, CLIC* (technical extendability to TeV regime)

More collider concepts emerging: C3 & HALHF

arXiv: 1901.09829
arXiv: 1901.09825

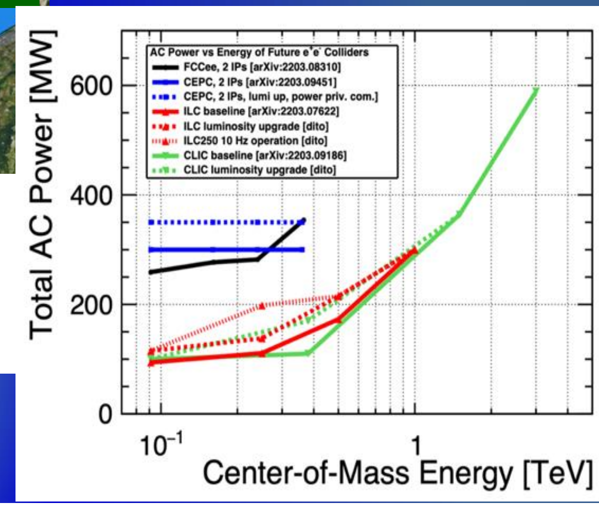
International Linear Collider (ILC): Japan (Kitakami)
√s = 250 - 500 GeV (1 TeV)
Length: 21 km - 31 km (50 km)

arXiv: 1812.07987
arXiv: 1812.07986



Compact Linear Collider (CLIC): CERN
√s = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

Power proportional to luminosity:

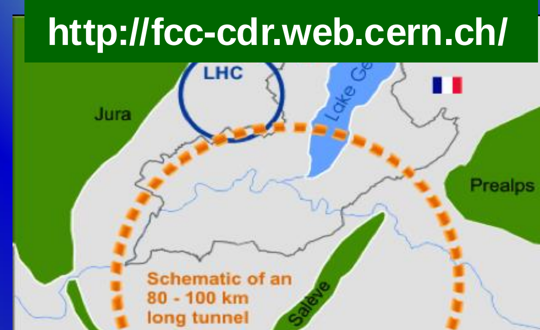


Circular colliders: *CEPC, FCC-ee*

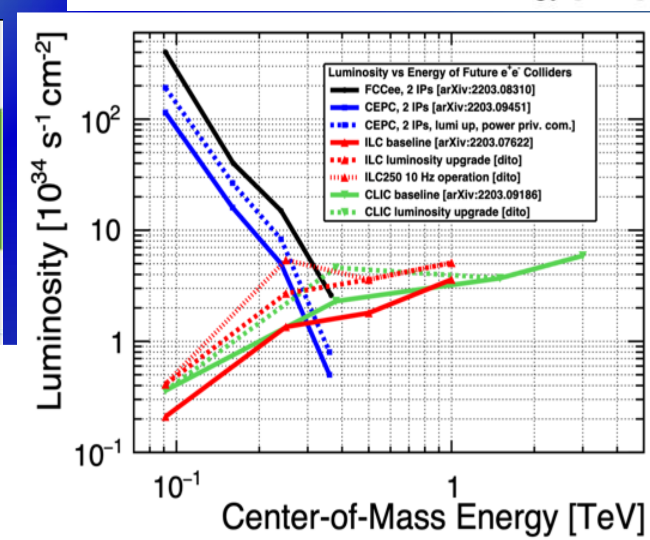
arXiv: 1901.03169
arXiv: 1901.03170

Circular Electron-Positron Collider (CEPC): China
√s = 90 - 350 GeV
Circumference: 100 km

http://fcc-cdr.web.cern.ch/



Future Circular Collider (FCC-ee): CERN
√s = 90 - 350 GeV
Circumference: ~100 km



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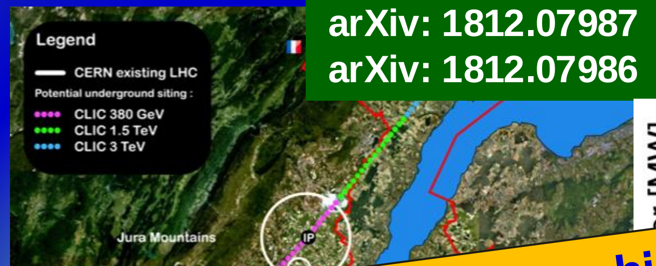

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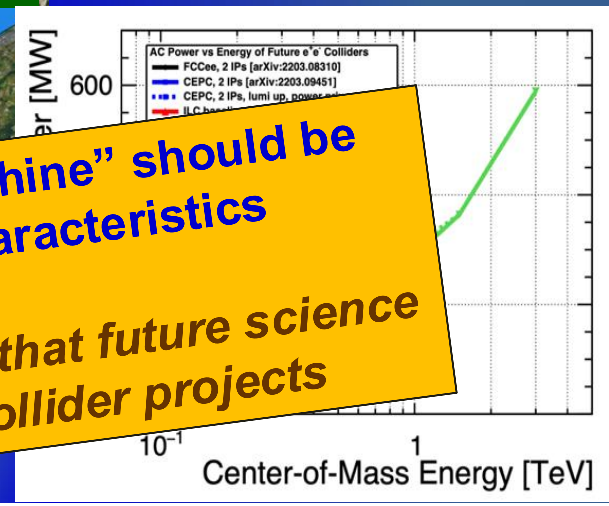


ESPPU2020 general consensus: next "big machine" should be e+e- collider to scrutinize Higgs boson characteristics

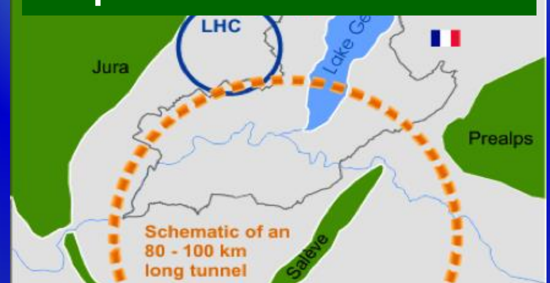
Perhaps the elephant in the room is the impact that future science diplomacy relations could have on these collider projects

Circu

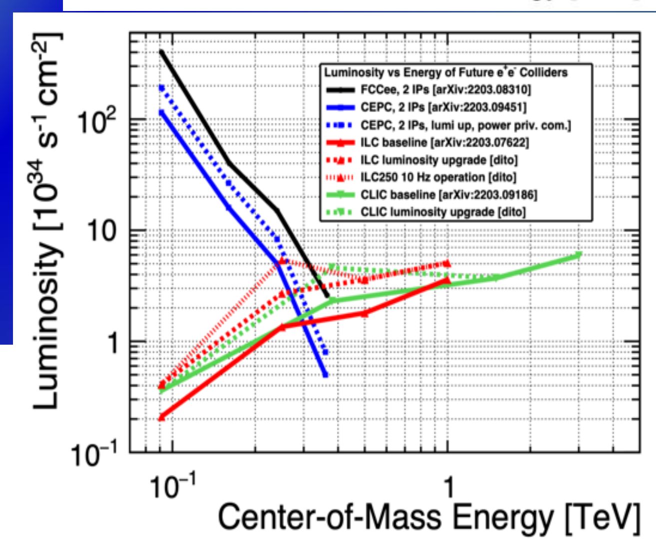
arXiv: 19
arXiv: 19

Circular Electron-Positron Collider (CEPC): China
√s = 90 - 350 GeV
Circumference: 100 km

http://fcc-cdr.web.cern.ch/



Future Circular Collider (FCC-ee): CERN
√s = 90 - 350 GeV
Circumference: ~100 km



Charting the Future of Particle Physics – EPSSU 2026

- ✓ Mar. 2025: deadline for submission of community input
- ✓ June 23-27 2025: Open Symposium
- ✓ Dec 2025: Strategy Drafting Session
- ✓ June 2026: approval of the Strategy update by CERN Council

https://europeanstrategyupdate.web.cern.ch/

- ✓ Strategy update should include the ***preferred option for the next collider at CERN*** and ***prioritised alternative options*** to be pursued ***if the chosen preferred plan turns out not to be feasible or competitive (due to cost, timing, international developments, etc…)***

- ✓ Strategy update should also indicate areas of priority for exploration complementary to colliders and for other experiments to be considered at CERN and at other laboratories:
  - National Inputs: physics program, role in accelerator R&D, detector R&D, interaction with CERN and other labs, …
  - European LDG: accelerator R&D roadmap – which topics (e.g. high-field magnet, RF technology, alternative8 accelerators/colliders) should be pursued; LDG Sustainability WG

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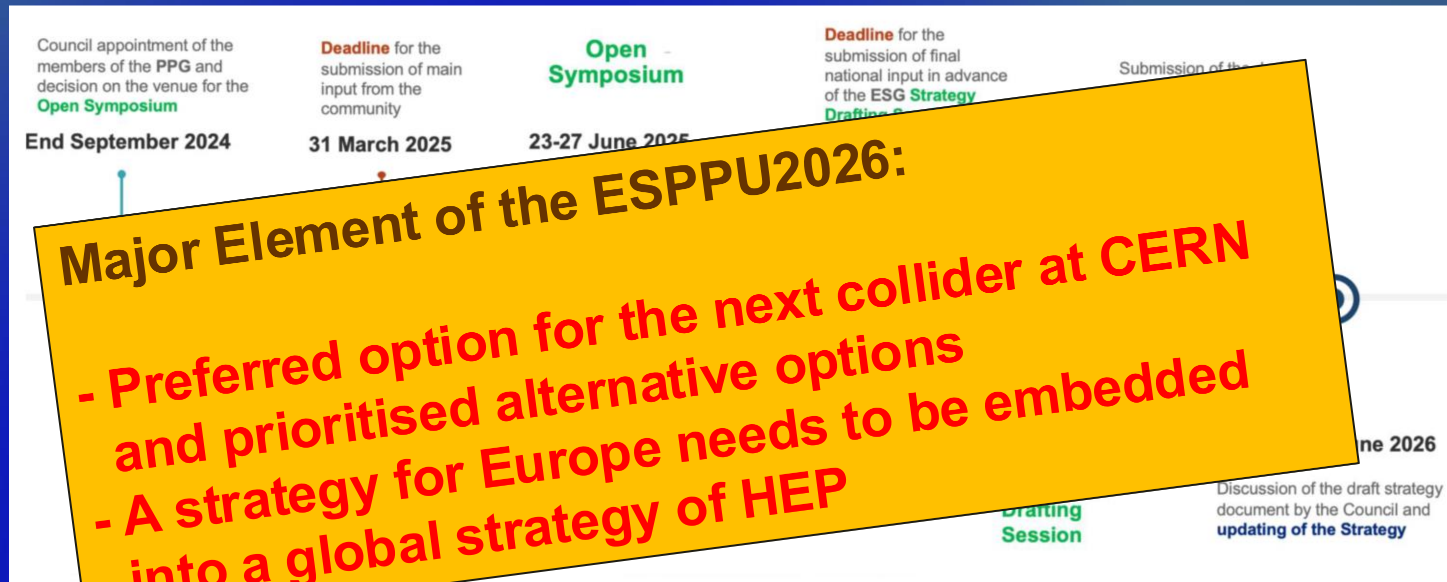

Major Element of the ESPPU2026:

- Preferred option for the next collider at CERN and prioritised alternative options

- A strategy for Europe needs to be embedded into a global strategy of HEP

https://europeanstrategyupdate.web.cern.ch/

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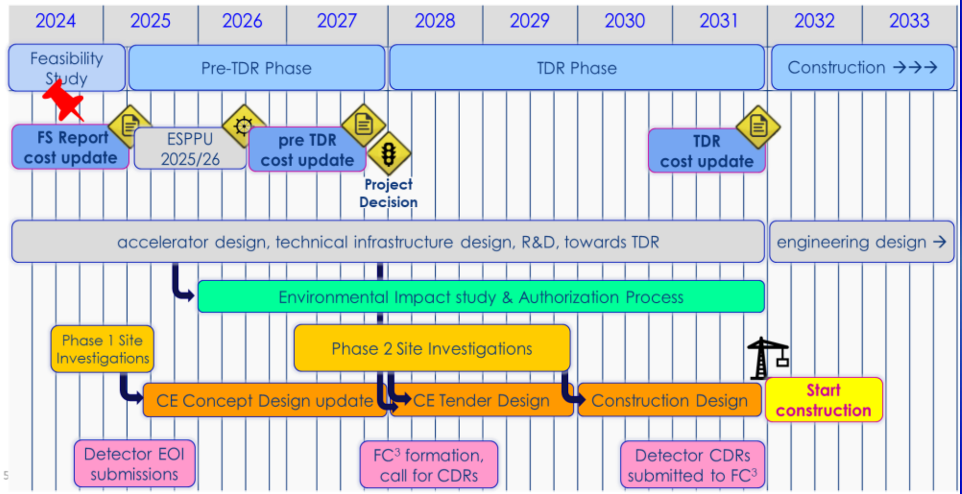
FCC Status and Recent Highlights

Expected time line till start of construction



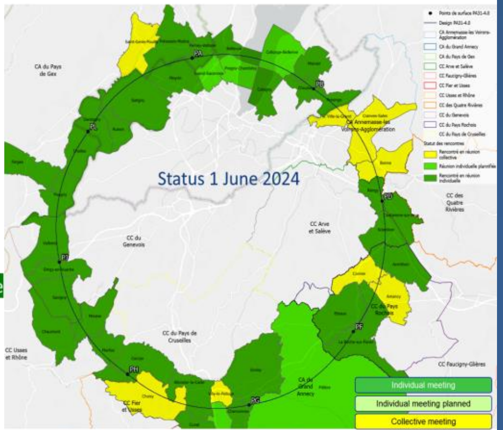
Regional implementation activities

Meetings with municipalities concerned in France (31) and Switzerland (10)

- **PA – Ferney Voltaire** (FR) – experiment site
- **PB – Présinge/Choulex** (CH) – technical site
- **PD – Nangy (FR)** – experiment site
- **PF – Roche sur Foron/Etaux** (FR) – technical site
- **PG – Charvonnex/Groisy** (FR) – experiment site
- **PH – Cercier** (FR) – technical site
- **PJ – Vulbens/Dingy en Vuache** (FR) experiment site
- **PL – Challex (FR)** – technical site

Detailed work with municipalities and host states

- identify land plots for surface sites
- understand specific aspects for design
- identify opportunities (waste heat, tec.)
- reserve land plots until project decision



The support of the host states is greatly appreciated and essential for the study progress!

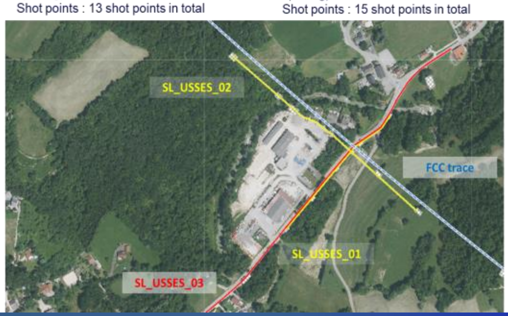
Start of site investigations – field work ongoing

First seismic line

Seismic line SL_USSES_02 :
Acquisition date : 01/10/2024
Length : 480 meters
Method(s) : Explosive and Seismic gun
Geophones : 96 units (5 meters of spacing)
Shot points : 13 shot points in total

Second seismic line

Seismic line SL_USSES_01 :
Acquisition date : 02/10/2024
Length : 300 meters
Method(s) : Weight drop
Geophones : 60 units (5 meters of spacing)
Shot points : 15 shot points in total



The CNDP, created in 1995, is an **independent French authority that ensures public participation in the definition and decision process of major projects in France,** impacting the environment by providing a neutral and transparent framework for discussions between decision-makers and citizens.

On July 2, 2024, the **CERN DG requested the CNDP to undertake an advisory mission** on public participation for the FCC. On July 3, the president of the CNDP appointed two guarantors to:

- **Assist CERN in preparing the first information meetings** on the ongoing studies in the region.
- **Provide non-binding advice to CERN** on the next steps for **public participation regarding the FCC.**

FCC Main Goals for Coming Years

The first part of the FCC Feasibility Study has been concluded with the mid-term review

Next milestone: completion of the FCC FS by March 2025

F. Zimmermann

FCC Project & Accelerator Key R&D Items – Next 5 Years

FUTURE CIRCULAR COLLIDER

By 2027-2028, possible FCC project approval:

- **specifications to enable CE tender design by 2028**
- **refined input for environm'l evaluation and project authorisation process**
- **requires overall integration study and designs based on technical pre-design**

By 2031-32, possible start of CE construction:

- **CE groundbreaking**
- **TDR to enable prototyping, industrialization towards component production**

FCC-ee arc half-cell mock-up at CERN
FCC-ee IR mock-up at INFN-LNF

FCC-ee SC RF system
2-cell 4.5 K Nb/Cu 400 MHz cavity & cryomodule
6-cell 2 K Nb 800 MHz cavity & cryomodule
thin film coating, seamless cavity production
efficient RF power sources (klystrons, IOTs, SSAs)

FCC-ee IR
SC IR magnet system and cryostat design
MDI 3D integration

FCC-ee beam-intercepting devices
collimator design
beamstrahlung dump
radiation shieldings

F. Zimmermann

FCC-ee optics and parameters
ongoing effort
code development for combined effects

FCC-ee alignment
initial tolerances & beam-based procedures
alignment & survey systems

FCC-ee beam diagnostics
BPMs, BLMs
Beam-size monitors
polarimeter

FCC-hh arc magnets
Nb_3Sn at 12 T and 14 T
HTS conductor and magnet developments

Key Acc. R&D items

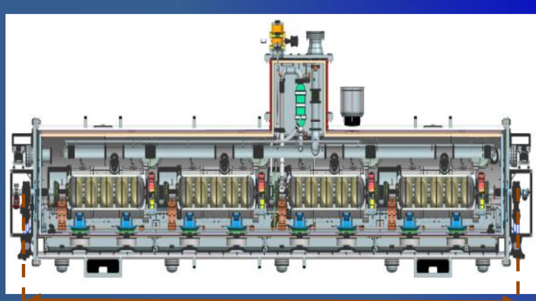
FCC RF R&D Activities

RF system R&D is key for increasing energy efficiency of FCC-ee

- Nb on Cu 400 MHz cavities, seamless cavity production, coating techniques
- Bulk Nb 800 MHz cavities, surface treatment techniques, cryomodule design
- RF power source R&D in synergy with HL-LHC.

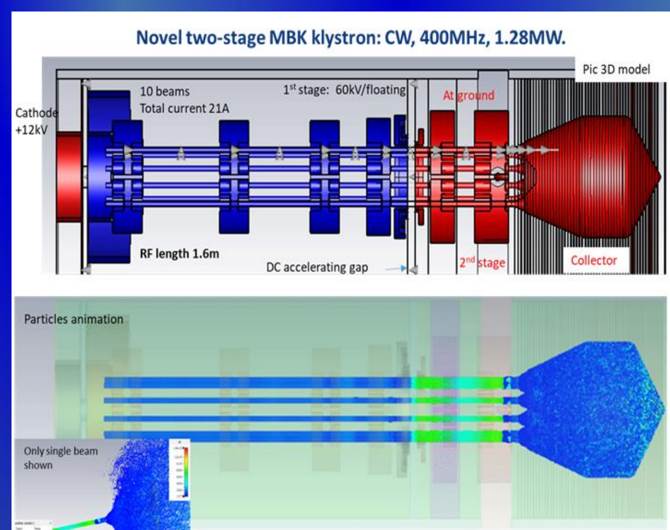
800 MHz cavity and CM design
collaborations with **JLAB and FNAL**

800 MHz segmented design,
based on PIP-II

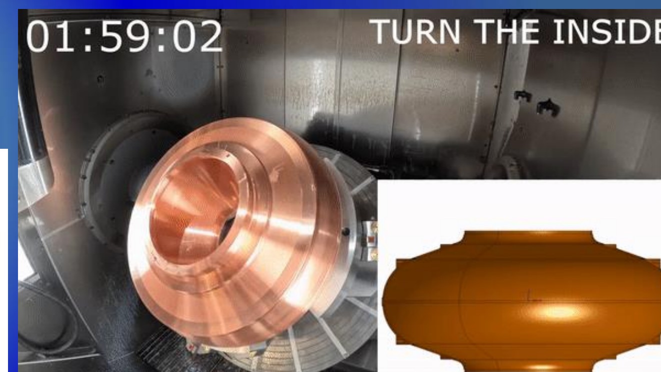


7 m

high-efficiency klystron
R&D in collaborations with
THALES & CANON

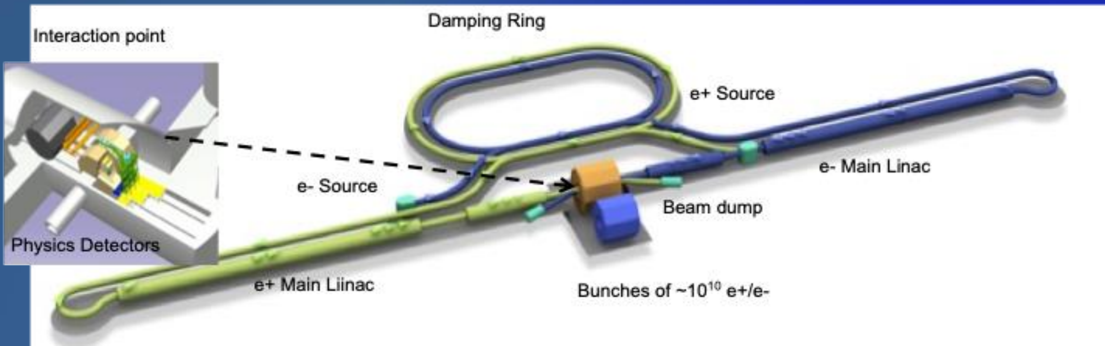


400 MHz cavity production
in coll. w **German industry**



F. Zimmermann

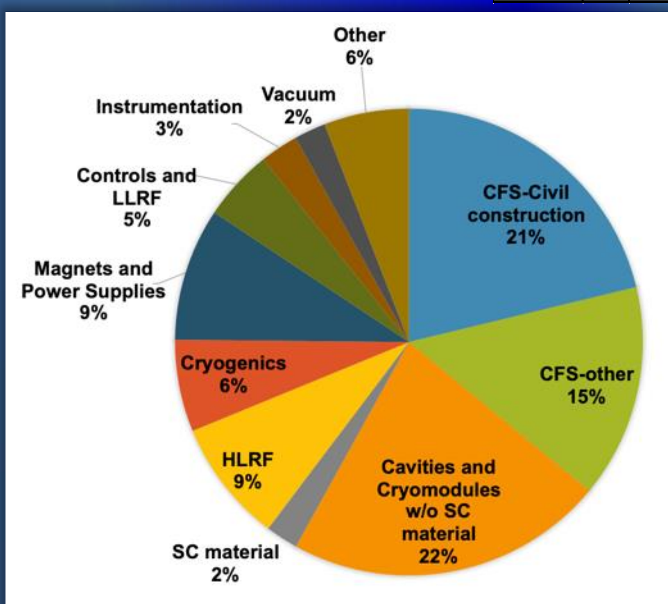
The ILC (250 GeV) Accelerator Facility in Japan



Technical Progress in ILC Technology Network (ITN):
interest/capability matrix from 28 labs/universities

Cost matrix, updating SCRF and CFS (~75%), escalation and currency updates for the rest (~25%)

SRF	WPP	1	Cavity production	√		√	√	√			√	√	√				√	√	√		√	√		√	√	
	WPP	2	CM design	√				√				√			√	√	√	√	√			√		√	√	
	WPP	3	Crab cavity			√	√							√					√			√	√		√	√
Sources	WPP	4	E-source			√						√							√		√			√		
	WPP	6	Undulator target				√												√	√			√			
	WPP	7	Undulator focusing				√												√	√			√			
	WPP	8	E-driven target	√		√												√	√							
	WPP	9	E-driven focusing	√														√	√							
	WPP	10	E-driven capture	√															√					√		
	WPP	11	Target replacement	√																						
Nano-beams	WPP	12	DR System design	√	√				√	√		√							√				√	√		
	WPP	14	DR Injection/extraction	√					√										√				√	√		
	WPP	15	Final focus	√			√		√		√							√			√			√		
	WPP	16	Final doublet	√	√													√								
	WPP	17	Main dump	√			√					√														



European ITN studies are distributed over five main activity areas:

ML related tasks
- SRF and ML elements: Cavities and Cryo Module, Crab-cavities, ML quads and cold BPMs (INFN, CEA, DESY, CERN, IJCLAB, UK, CIEMAT, IFIC)

Sources
- Pulsed magnet and wheel/target (Uni.H, DESY, CERN)

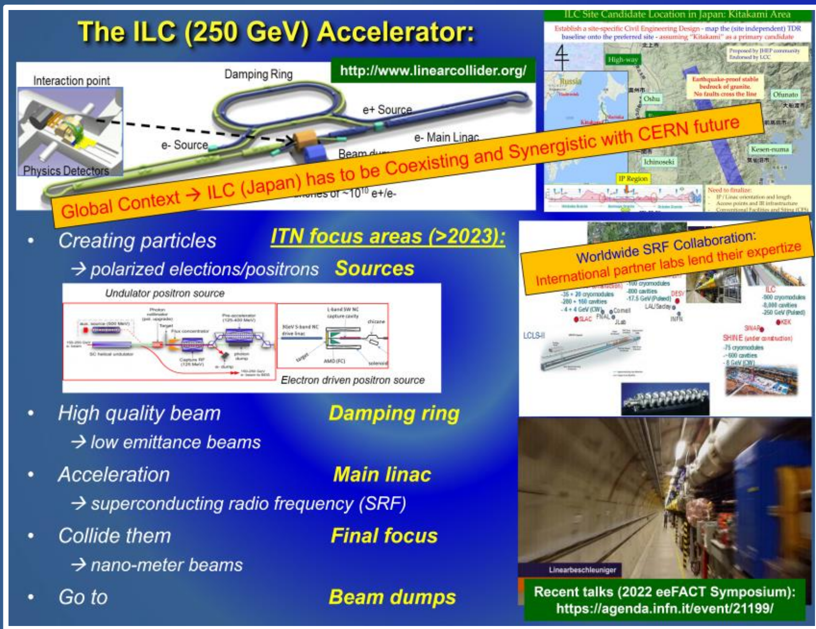
Damping Ring including kickers
- Low Emittance Rings (UK)

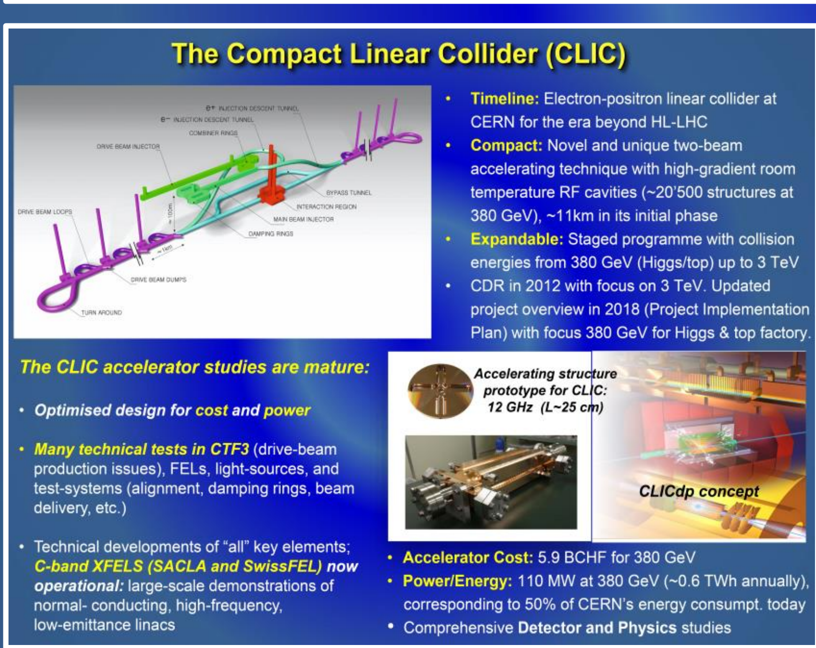
ATF activities, final focus and nanobeams
- ATS and MDI (UK, DESY, IJCLAB, CERN, IFIC)

Implementation
- Dump, CE, Cryo – follow up efforts at CERN
- Sustainability, Life Cycle Assessment (CERN, DESY, CEA, UK groups)
- EAJADE started (EU funding) (DESY, UK, CEA, CNRS, IFIC, INFN, UHH, CERN)

S. Stapnes

ILC / CLIC: Inputs to the ESPPU in 2026





ILC ESPP Update:

- ILC in Japan with updated technology results, updated CFS (CE and Conv. Systems), environmental studies and costing
- New: An LC starting with ILC technology at 250 GeV with upgrade options (site independent), and an implementation of such a facility at CERN

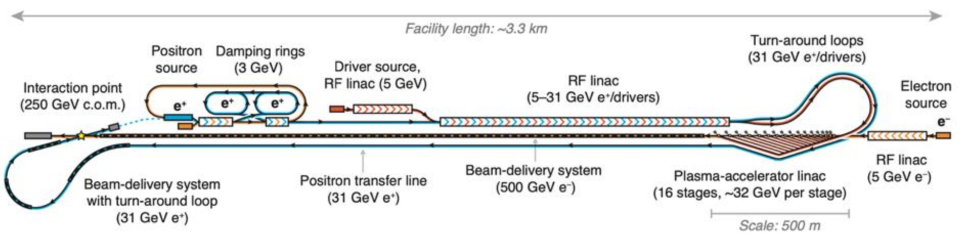
CLIC ESPP Update: Preparing "Project Readiness Report" as a step toward a TDR

- Energy scales: 380 GeV and 1.5 TeV with one drivebeam
- Consider also 100 Hz running at 250 GeV (i.e. two parallel experiments, two BDSs)
- Several updates on parameters (injectors, damping rings, drive-beam) based on new designs, results and prototyping (e.g. klystrons, magnets) - however no fundamental changes beyond staying at one drivebeam
- Technology results updates, including more on use of them in other projects (e.g. alignment, instrumentation, X-band RF is small linacs)
- Update costing and power – interplay between inflation and CHF
- Life Cycle Assessments
- More detailed prep phase planning (next 5-7 years)

S. Stapnes

Hybrid Asymmetric Linear Higgs Factory (HALHF)

Schematic layout of HALHF



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

>Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

>Length dominated by e⁻ beam-delivery system

- Exploit high gradient of e- acceleration in PWFA and avoid difficulty of e+ acceleration by using conventional RF linac, reducing cost by low E(e+) (31 GeV)=> high E(e-) (500 GeV), boost g ~ 2.7 => ECM ~ 250 GeV.
- Reduce running costs by increasing current I(e+) and reducing I(e-); this & asymmetric emittance (increased for e-) ease PWFA req.
- ~ 400m length PWFA stage (PWFA gradient~ 6.4 GV/m; <gradient>~ 1.2 GV/m) => facility length ~ 3.3 km and cost ~ ¼ of ILC/CLIC - $1.9B (2022 $).

Several key plasma acc. challenges:
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling, reduced plasma density (increased beam length, reduced gradient), etc…

Conventional beam(s) challenges:
Ppolarized positron source, damping rings, RF linac, beam delivery system

Experimental challenges with asymmetric beams

New concept aiming for: "pre-CDR" input to European Strategy and to LC Facility/Vision. Longer term – CDR by early 2026.

Erice workshop (Oct. 3-8, 2024)

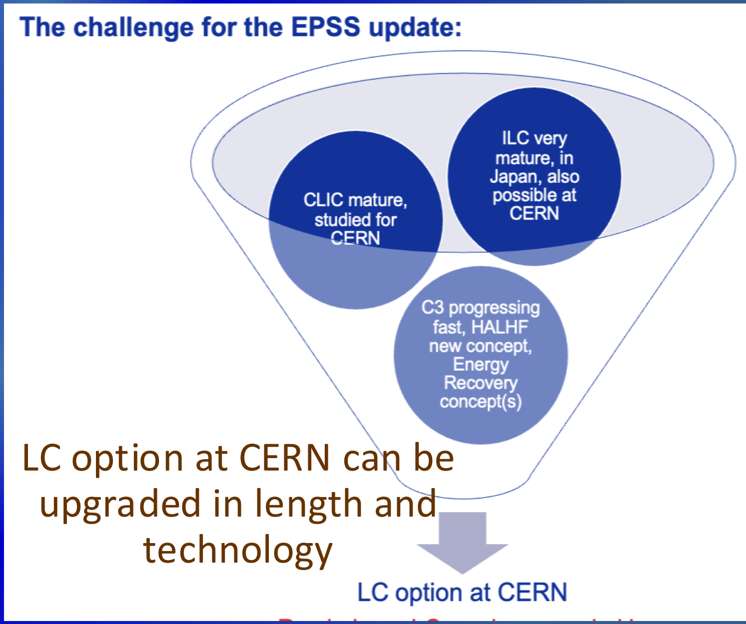
Energy recovery options, potentially very large luminosities but early stage of development

B. Foster

An Adaptable (ILC + CLIC) Linear Collider Facility @ CERN

LC facility @ CERN can be upgraded in energy & luminosity, using the same or improved versions of the same technology (ILC, CLIC, C3, HALHF):

- Starting with ILC (EUXFEL) technology, change to more performant (usually higher gradient) technologies in an upgrade, e.g. plasma and ERL
- Implementation at CERN in footprint studied for CLIC (and ILC back in the TDR days), with two BDS, and experimental area at Prevessin
- Such a programme can run in parallel with future hadron and/or muon colliders that can be developed, optimised and implemented as their key technologies mature

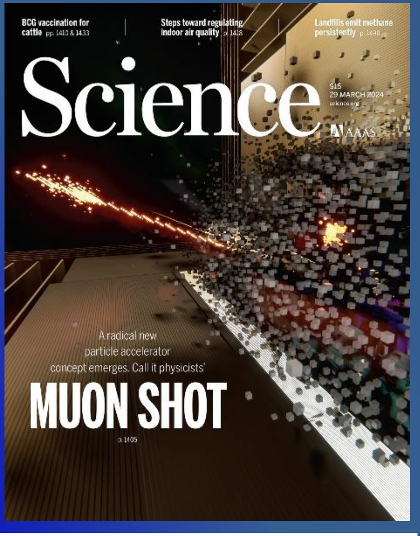


"ILC model" could be exploited to reduce load on CERN during the HL-LHC period (lab support from outside for cryomodules)

S. Stapnes

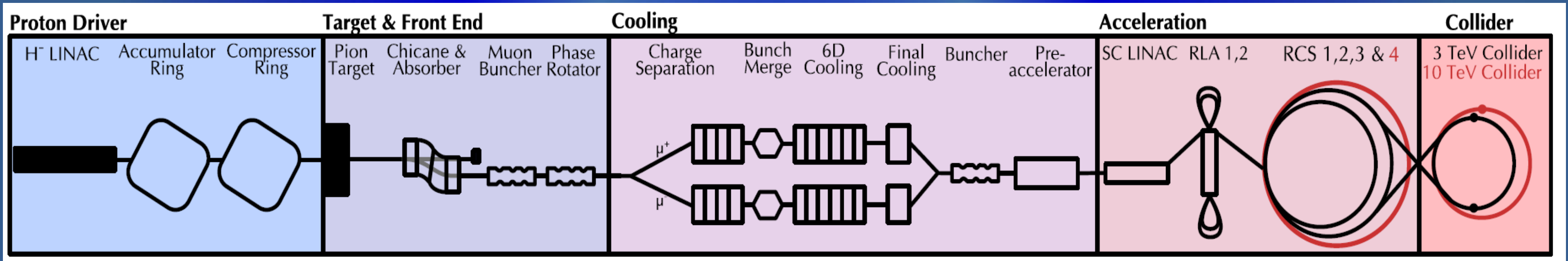
Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$

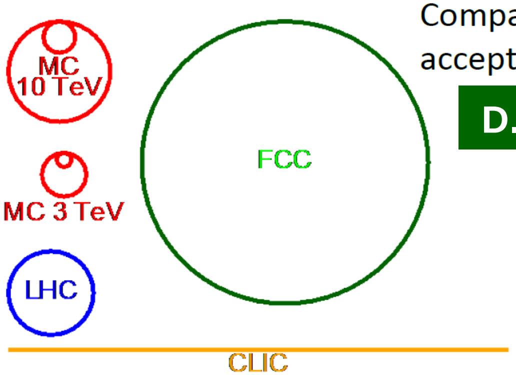


MAJOR CHALLENGES:

- Muon generation
- Colling of muons
- Cost-efficient acceleration
- Collider ring and backgrounds from decays



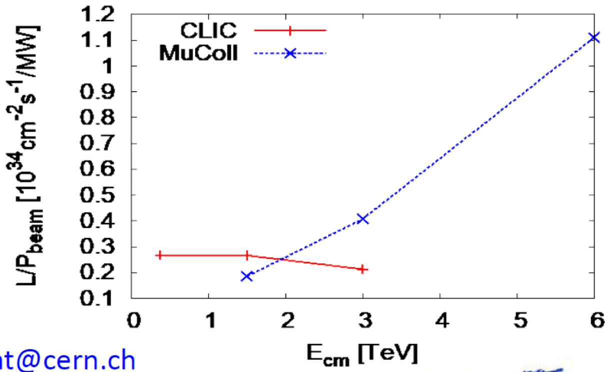
Short, intense proton bunch	Protons to pions to muons, which are captured	Ionisation cooling of muon in matter	Acceleration to collision energy	Collision



Compact, expect acceptable cost

D. Schulte, Muon Collider, 2024

Luminosity to power increases with energy



To join contact muon.collider.secretariat@cern.ch

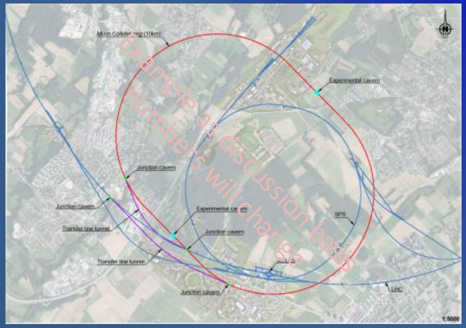
Muon Collider Collaboration Goals

IMCC (International Muon Collider Collaboration)

About 60 full members and several additional contributors
EU cofinances design study
US is ramping up involvement after P5 recommendation
Deliver input to ESPPU in 2025

Siting/environemental impact

- Aim for negligible impact on environnement
  - e.g. mitigate neutrino flux
- Promising reuse of LHC and SPS tunnels
- Appears to fit on FNAL site

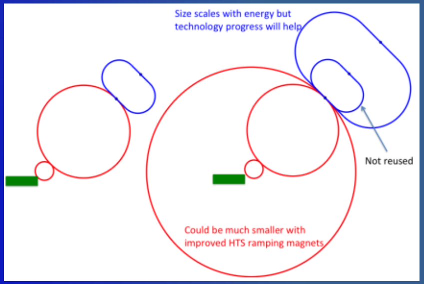


Goal

Staged collider starting physics by 2050
Final stage 10 TeV, 10 ab^{-1}
Initial stage with lower energy/luminosity

Appears consistent with key timeline drivers

- Detector
- Magnets
- Cooling technology



Appears consistent with key timeline drivers

- No showstopper identified
- Good progress
- Need to ramp-up effort for all key areas

Two detector concepts are being studied

Mitigation of beam-induced background is promising
Can do the physics, but improvement potential

D. Schulte, Muon Collider, 2024

Key Muon Collider R&D Examples

Muon cooling technology

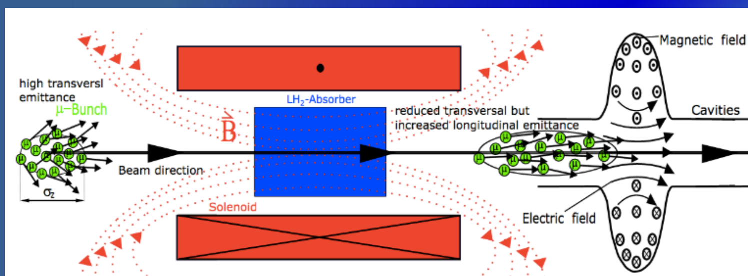
- RF cavities in high magnetic field
- Cost effective strong solenoids
- Absorbers
- Compact integration

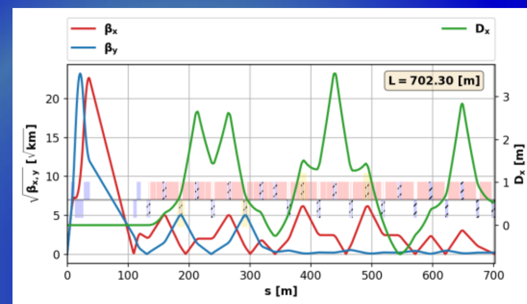
Muon production/cooling demonstrator

CERN example: PS/SPS beam

FNAL: will be studied

Accelerator Design



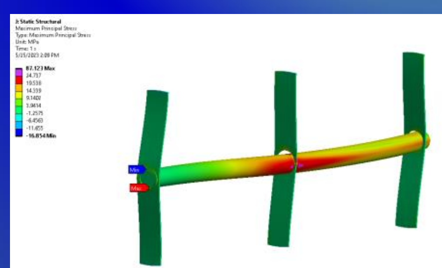


Windows and Absorbers

Very bright muon beam

Experimental studies promising

High-power Target Design



Fast-ramping magnets/power converter

Efficient energy recovery

Normal-conducting, HTS as alternative

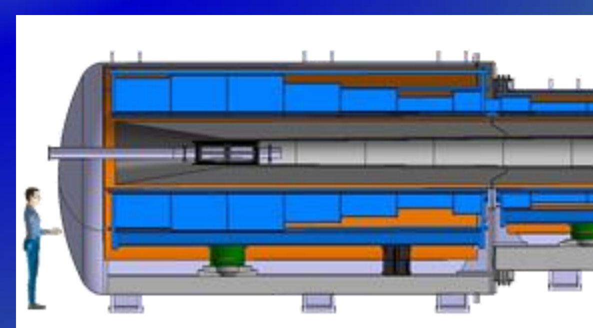
Collider ring dipoles/magnets

Nb_3Sn for fast-track, HTS for final stage

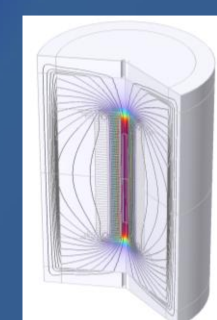
HTS solenoids

20 T HTS target solenoid

Strong synergy with fusion reactor R&D



40+ T HTS solenoid



D. Schulte, Muon Collider, 2024

Industry Connection & Beyond CLIC: X-Band RF Technology

Main benefits for CLIC: much strengthened industrial base and strong increase in research/experience on/with X-band technology and associated components

Compact Linacs have many uses:

- As part of research accelerators (e.g. in FELs as main technology or special elements), or in medical or industrial linacs
- Many/most of these developments are driven by CLIC collaborators, for their "local" applications

Global X-band and High-Gradient Deployment

Trieste, Fermi	Linearizer	KEK	NEXTEF	TU Eindhoven	Smart*Light, ICS
SwissFEL	Linearizer and Polarix deflector	CERN	XBox-2,3 and SBox	Tsinghua.	VIGAS, ICS
SARI:	Linearizer, deflectors	Tsinghua	TPot	CERN:	AWAKE electron injector
CERN:	Xbox-1 with CLEAR, accelerator	Valencia	IFIC VBox	INFN Frascati	EuPRAXIA@SPARC LAB, accelerator
DESY:	PolariX deflectors in FELs	Trieste	FERMI S-Band	DESY:	SINBAD/ARES, deflector
SLAC:	NLCTA, XTA	SLAC	Cryo-systems	CHUV/CERN.	DEFT, medical accelerator
Argonne	AWA	LANL	CERF-NM	Daresbury	CLARA, linearizer
Arizona	CXLS, ICS	INFN Frascati.	TEX	Trieste:	FERMI energy upgrade
		Melbourne	AusBox	+ more	

L. Wroe @ ICHEP2024

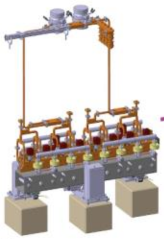
Non-exhaustive list

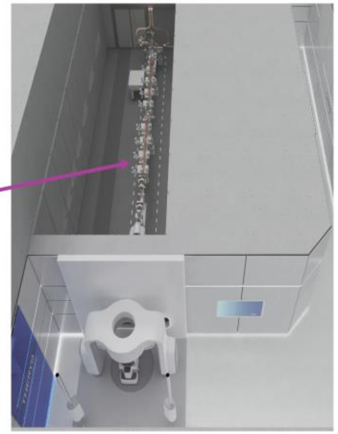
Laurence Wroe | Compact Electron Linacs for Research, Medical, and Industrial Application:
(https://indico.cern.ch/event/1291157/contributions/5890088/attachments/2899569/5084489/240719_Wroe_ICHEP.pdf)

Compact Linacs: Research, Medical and Industrial Applications

Medical - DEFT (Deep Electron Flash Therapy)

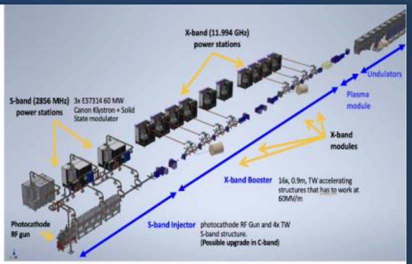
- **CERN-CHUV-THERYQ collaboration**
  - VHEE (100 – 250 MeV)
  - FLASH (>40 Gy/s, < 100 ms)
  - Clinical trials planned for 2025
- **Accelerator technology**
  - S-band photoinjector
  - X-band accelerating structures mounted on girders
  - X-band klystrons with pulse compressor



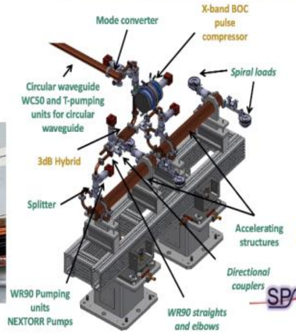


L. Wroe @ ICHEP2024

Research - EuPRAXIA@SPARC_LAB

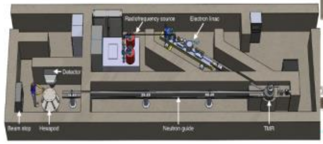


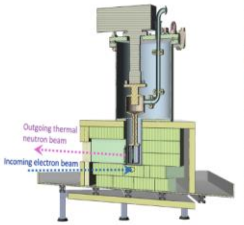
- **41 laboratory collaboration, hosted at INFN Frascati**
  - FEL facility driven by plasma acceleration
  - 1 GeV X-band electron linac driver of a plasma wakefield accerator
  - Expected ready for operation in 2028
- **Accelerator technology**
  - S-band injector
  - 50 MW X-band klystrons
  - X-band pulse compressor
  - X-band accelerating structures



Industrial - VULCAN (Versatile ULtra-Compact Advanced Neutron Generator)

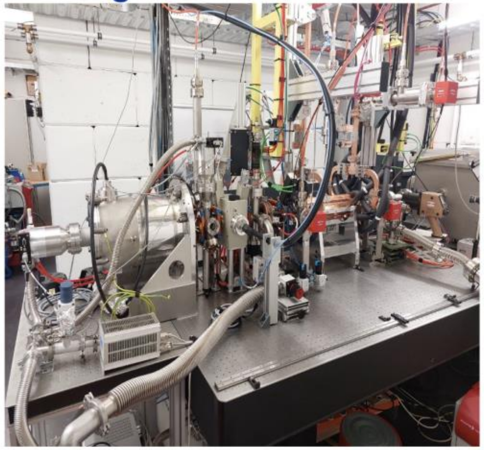
- **CERN-DAES-DTI-Xnovotech collaboration**
  - 35 MeV, kW-scale electron linac
  - Target-moderator-reflector for converting electrons to thermal neutrons
  - Stress-strain measurements, battery & fuel-cell investigations
  - Proof of concept testing in CLEAR this year, complete prototype construction by mid-late 2020s
- **Accelerator technology**
  - High-gradient accelerating structures and pulse compressor optimized for compactness, cost, beam power and efficiency
  - High-power, high-efficiency klystrons





Research / Industrial - Smart*Light

- **Dutch-Flemish collaboration, at Eindhoven University of Technology**
  - Inverse Compton Scattering
  - 30 MeV electrons producing 40 keV X-rays through laser interaction
  - Upgrading to Smart*Light 2.0 with 60 MeV and 100x higher repetition rate
  - Table-top device in operation
- **Accelerator technology**
  - Single X-band accelerating structure
  - 6 MW X-band klystron with pulse compressor



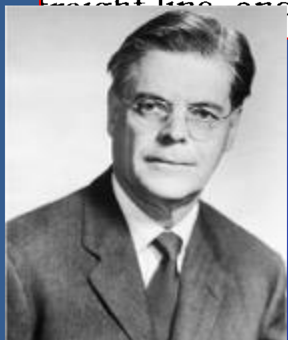
Wide-spread adoption benefits the original CLIC research and society at large!

Advanced Accelerator Technologies: Past, Present, Future

Radiology 47:487–91 (1946)

in tissue … ev proton … protons can penetrate to … ody. … ceeds through the tissue … and the tissue

nsity, i.e., 15 … r cent water. … can be easily extended t … and densities.² The accu … per cent. However, exa … ious tissues can be quic

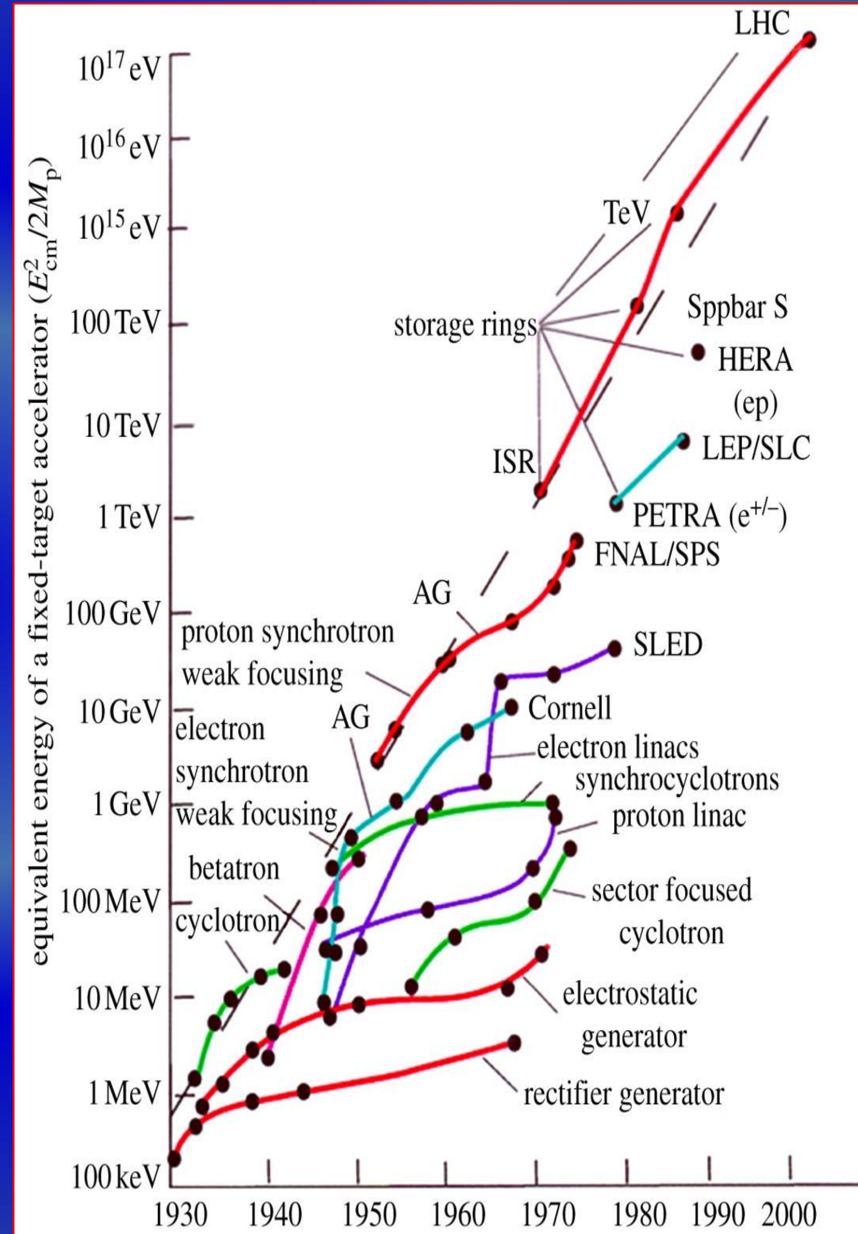


Wilson, at Harvard designing 150 MeV cyclotron:

- Identified benefits and properties of proton beams for RT
- Pointed out potential of ions (carbon) and electrons

Promote industrial base and application of advanced accelerator technologies as part of the R&D strategy (innovate through applications):

- *Compact and robust accelerators with different parameters requiring different RF and design solutions*
- *Focus on low cost and energy efficient accelerator technologies*
- *Maintain and Strengthen industrial base and capabilities*
- *Recruitment & retention, education, and training of accelerator physicists*
- *Future Plasma acceleration platforms: synergies between HEP (HALHF) & applications (EUPRAXIA, LhARA)*



Wide Choice of Detector Technologies to Reveal the SM Secrets

JINST15 C10023 (2020)

Published by IOP Publishing for Sissa Medialab
Received: June 12, 2020
Accepted: June 28, 2020
Published: October 22, 2020

International Conference on Instrumentation for Colliding Beam Physics
Novosibirsk, Russia
24–28 February, 2020

Next frontiers in particle physics detectors: INSTR2020 summary and a look into the future

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E-mail: maxim.titov@cea.fr

- ✓ The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision Si-vertex & tracking;
- ✓ CMOS sensors offers low mass and (potentially) radiation-hard technology for future colliders;
- ✓ MPGDs have become a well-established technique in the fertile field of gaseous detectors;
- ✓ Several novel concepts of picosecond-timing detectors (LGAD, LAPPD) will have numerous powerful applications in PID & pile-up rejection:
- ✓ The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method (PFA);
- ✓ The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed;
- ✓ Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge;

Social – Economic Benefit Analysis of Particle Physics

- ✓ ***Social - Economic Benefits of HEP accelerator-based Research Infrastructures:***
  in relation to the UN Sustainability Development Goals (environment, economy, society)
  - SDG Reference Matrix from UN (2024)
    - Fundamental Physics Knoweledge, Accelerator and Detector R&D
    - Economic Growth (regional, international, developing countries)
    - Education, Innovation, International Cooperation, Cultural Exchange

- ✓ ***Comprehensive sustainability assessment based on quantitative Cost-Benefit Analysis:***
  state-of-the-art economics knowledge that integrates total costs, negative environmental externalities, industrial, social and environmental benefits

Reference for the integrated model FCC

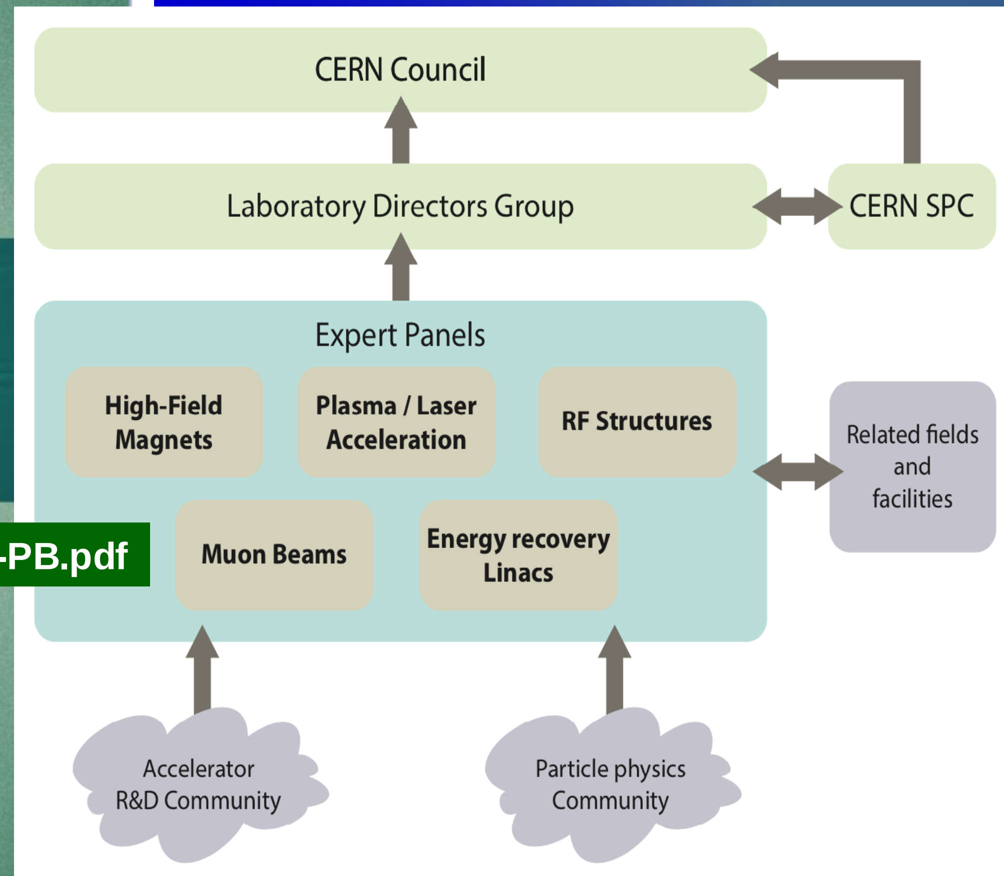
EU Policies
- Global Reporting Initiative
- European Sustainability Reporting Standards
- European Union Eco-Management and Audit Scheme (EMAS)
- EC Economic Appraisal Vademecum
- National Guidelines (France, Germany, Switzerland, …)

Carbon Footprint Accounting and Reporting
- Shadow Carbon Cost

- ✓ ***European Strategy Forum for Research Infrastructures (ESFRI):***
  socio-economic impact has become one of important considerations in the roadmap process that identifies European investment priorities in Research Infrastructures

CERN Council has mandated the Laboratory Directors Group (LDG) to *define and maintain a prioritized accelerator R&D roadmap* towards future large-scale facilities for particle physics.

https://cds.cern.ch/record/2800190/files/146-138-PB.pdf



Sustainability Working Group (added to 5 LDG Expert Panels) since January 2024

LDG Sustainability WG Mandate and Composition

Development of guidelines and a minimum set of key Indicators for the sustainability assessment of future accelerators

Panel consisting of 15 members with technical expertize in evaluation of accelerator sustainability and future collider project representatives

Ensuring broad community representation:

- Sustainability Lab. Panels established at CERN, DESY, ESS, NIKHEF, STFC
- ICFA Sustainability Panel
- EU- Horizon Programs
- Future accelerator projects: FCC, ILC, CePC, CLIC/Muon, LHeC, C3
- Invited experts on specific topics

- Walib Kaabi - PERLE, EU-iSAS
- Mats Lindroos - ESS (deceased May 2, 2024)
- Roberto Losito - CERN Sust. Panel
- Ben Shepherd - STFC Sust. Task Force
- Andrea Klumpp - DESY Sust. Panel, EU-iFAST
- Hannah Wakeling - ISIS-II Neutron & Muon Source
- Patrick Koppenburg - NIKHEF Sust. Panel

- Johannes Gutleber - FCC
- Yuhui Li - CePC
- Benno List - ILC
- Emilio Nanni - ICFA Sust. Panel & C3
- Vladimir Shiltsev - LHeC
- Steinar Stapnes - CLIC & Muon collider

- Caterina Bloise - Co-Chair
- Maxim Titov - Co-Chair, EU-EAJADE

in the Editorial Board also

- Enrico Cennini (CERN), Luisa Ulric (CERN).
- Beatrice Mandelli (CERN), Niko Neufeld (CERN)
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Sustainability Working Group

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✓ *Draft is expected for the LDG review early 2025*

✓ ***Executive summary as an input to the ESPPU due by March 2025*** → *some tables with parameter numbers might be complemented at a later stage*

Caveat:
- *not all of these topics can be addressed in details in a limited time*
- ***A homogeneous evaluations of all issues will probably need more time to develop and deserves a strategy to be pursued***

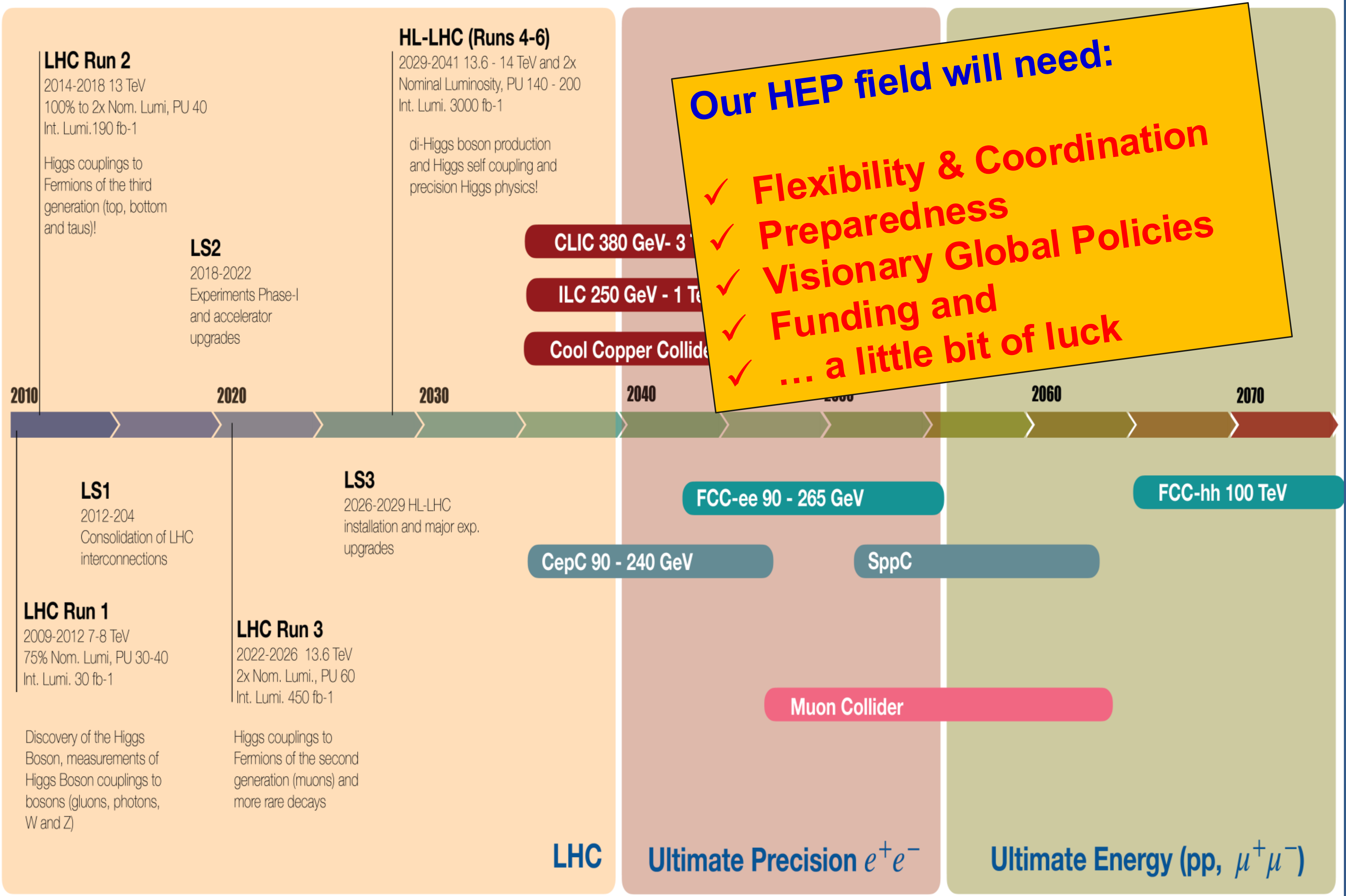
Report Structure and Sustainability Assessment Guidelines:

Sustainability WG report is advancing, the bulk of issues elaborated pertain to:
- *socio-economic benefits of accelerators-based research infrastructures*
- *basis of sustainability assessment*
- *methodology and reporting of LCA for future HEP accelerators*
- *evaluation of Greenhouse gas (GHG) emissions in construction, operation, decommissioning*
- *mitigation & compensation strategies*

Content for each chapter will contain:
- *description of landscape & highlights*
- *recommendations (major and more technical ones)*
- *the list of open questions*

Sustainability assessment for future large-scale accelerator infrastructures is quite complex:
- *assessment criteria needs to be properly tuned to the maturity of the project (stage)*
- *differently developed for Researchers, Management and Society*

HEP Scientific Mission for the 21st Centery



Outlook

- ✓ We need to define the most appropriate organizational form for future HEP collider projects and need to be open and inventive (scientists, funding agencies, politicians. . .)
- ✓ Mandatory to have accelerator laboratories in all regions as partners in accelerator development / construction / commissioning / exploitation
- ✓ We need to have excellent communication and outreach accompanying all projects