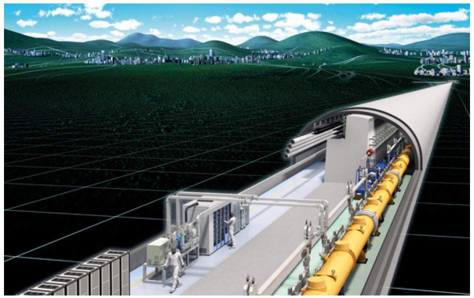
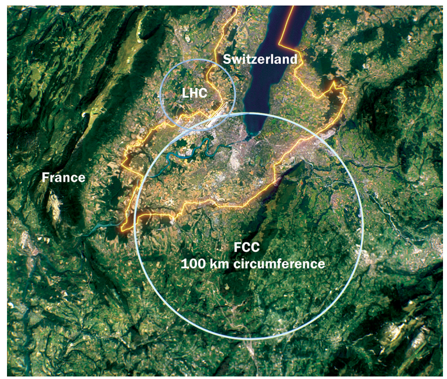
The Future of Particle Physics



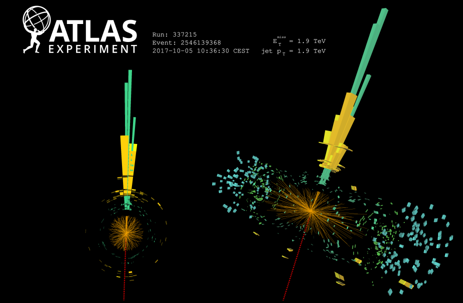


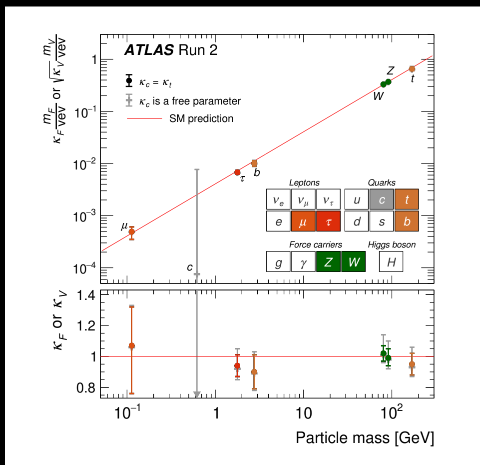
Karl Jakobs
European Committee for Future Accelerators

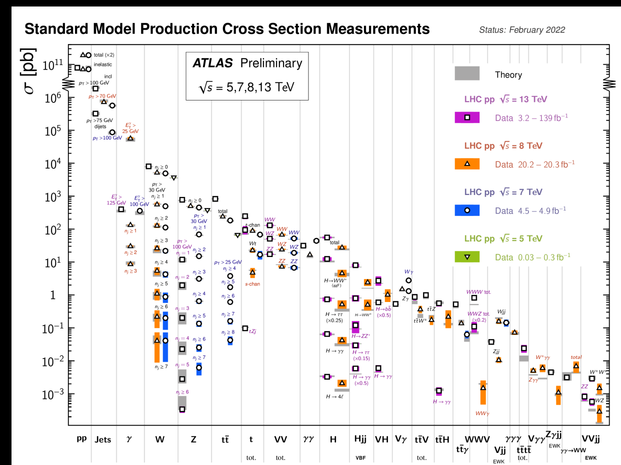
VERTEX 2023
Sestri Levante, 16th October 2023

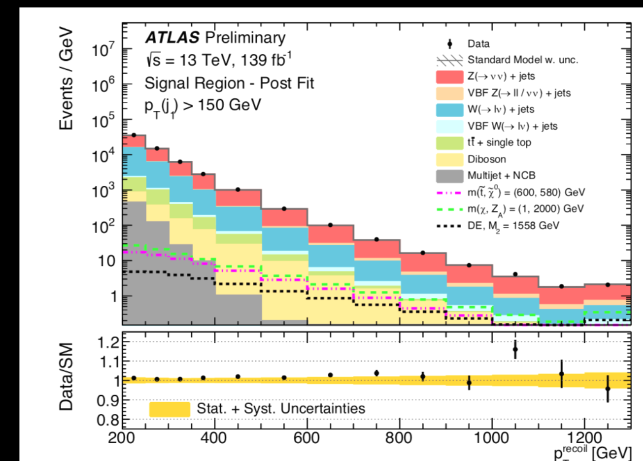
Where do we stand today?

Why do we need a new collider?









- The properties of the Higgs boson are in excellent agreement with the predictions of the Standard Model; Impressive precision already reached
- All measurements at the LHC are well described by the predictions of the Standard Model
- No indications for physics beyond the Standard Model (despite some spectacular events)

Important Open Questions

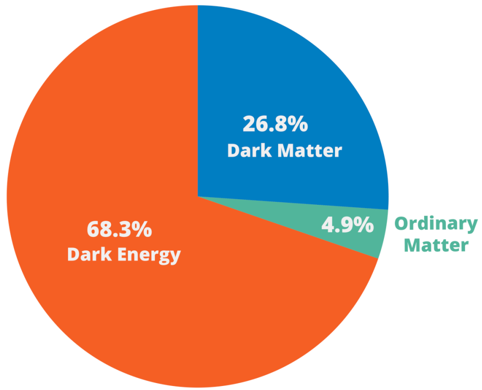
1. Mass

The Higgs boson exists!

Does it have the predicted properties?

Why is it so light?

* Fundamental scalar → large quantum corrections
* “Hierarchy” or “naturalness” problem
* Is it a fundamental particle or a composite scalar?

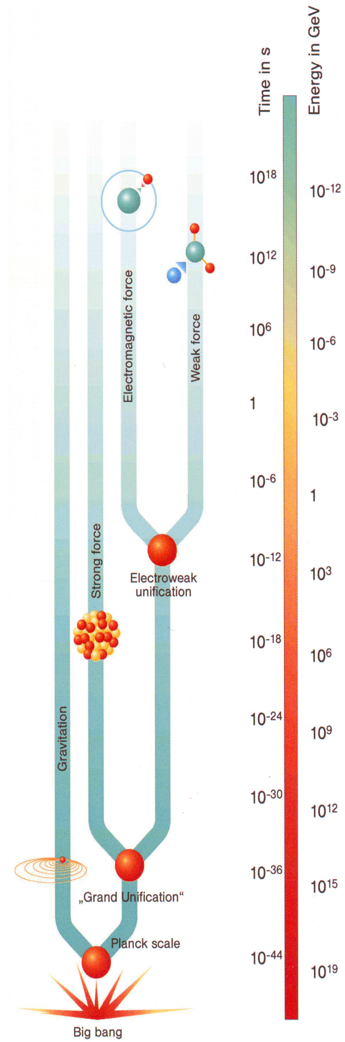


2. Unification

Can the different interactions be unified?
How can gravity be incorporated?
Why is gravity so weak?

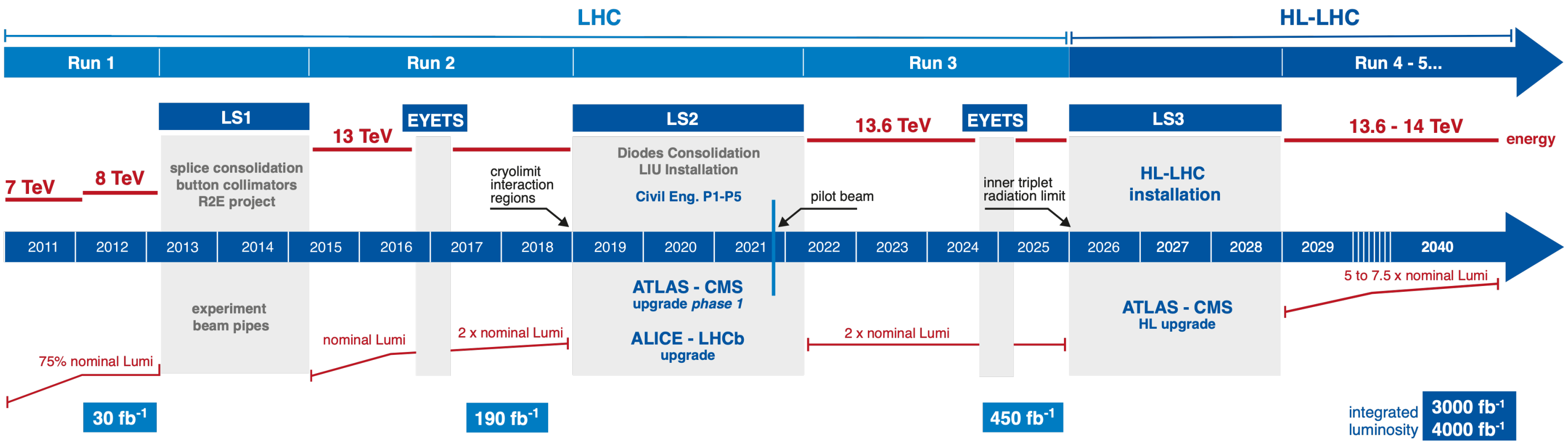
3. Structure and composition of matter

- Are there new forms of matter, e.g. **supersymmetric particles**?
- Are they responsible for the **Dark Matter in the Universe**?
- What is the origin of the matter-antimatter asymmetry?
- Why are there three families of fermions?
- What is the origin of neutrino masses?



New physics required, but no clear indication of the energy scale

The near future

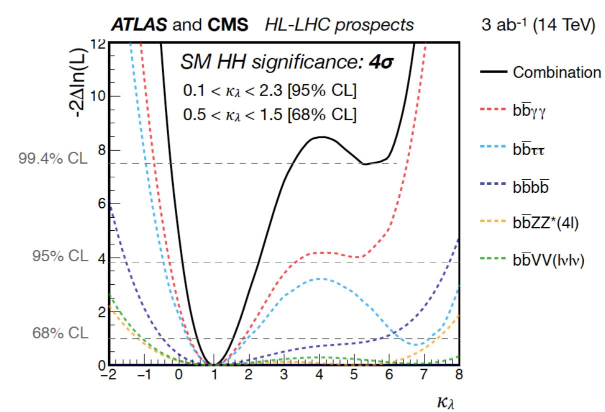


Luminosity Upgrade of the LHC → High Luminosity LHC (HL-LHC):

→ Increase of integrated luminosity by factor of ~ 20 (→ 3000 fb^{-1})

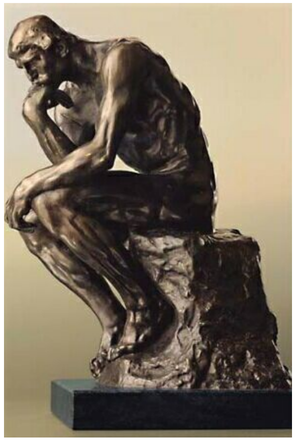
- Higgs boson
(increased precision, Higgs boson self-coupling)

- Direct searches for new physics



First sensitivity on the Higgs boson self coupling (±50% uncertainty)

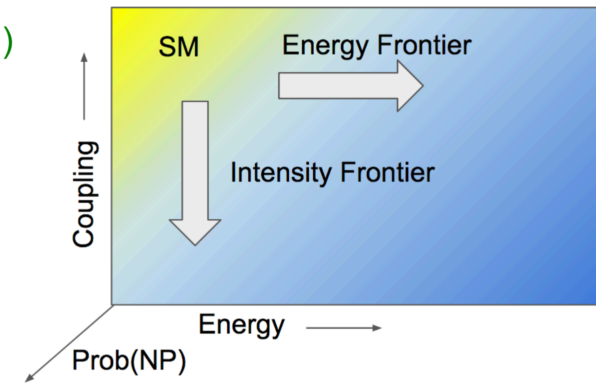
Towards the long-term future



- New physics required, but no clear indication of the energy scale

Energy Frontier → high-energy colliders remain essential;

In addition the **Intensity Frontier** needs to be explored
(e.g. search for Feebly Interacting Particles,
Neutral Heavy Leptons, Flavour anomalies,…)



No strong guidance from theory

Experiments must show the way!

Understanding the **Higgs Sector** is vital:
the Higgs particle is not just "another particle"

- Profoundly different from all elementary particles discovered so far;
- The only spin-0 particle; carries a different type of "force";
- Related to the most obscure sector of the Standard Model
- Linked to some of the deepest structural questions (flavour, naturalness, vacuum, …)

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \lambda H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

↑ flavour ↑ naturalness ↑ stability ↑ C.C.

G. Giudice, CERN

→ It provides a unique door into new physics,
… and calls for a very broad and challenging experimental programme

Fabiola Gianotti, LHCP Conference 2021

	High-E colliders	Dedicated high-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
H, EWSB	×	×		×	
Neutrinos	× (ν_R)		×	×	×
Dark Matter	×			×	×
Flavour, CP, matter/antimatter	×	×	×	×	×
New particles, forces, symmetries	×	×		×	
Universe acceleration					×

High-energy accelerators are one of the best tools for exploration; unique in studying the Higgs boson

Needed: Precision + Energy

2020 Update of the European Strategy for Particle Physics

Statements from last ESPP relevant to ECFA

3. High-priority future initiatives

An **electron-positron Higgs factory is the highest-priority next collider**. **For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy**.

Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

4. Other essential scientific activities for particle physics

C. The ***success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.*** *To prepare and realise future experimental research programmes, the community must* ***maintain a strong focus on instrumentation***. ***Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities.*** …

Deliberation Document:
"Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields. .."

US Snowmass process (2022)

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

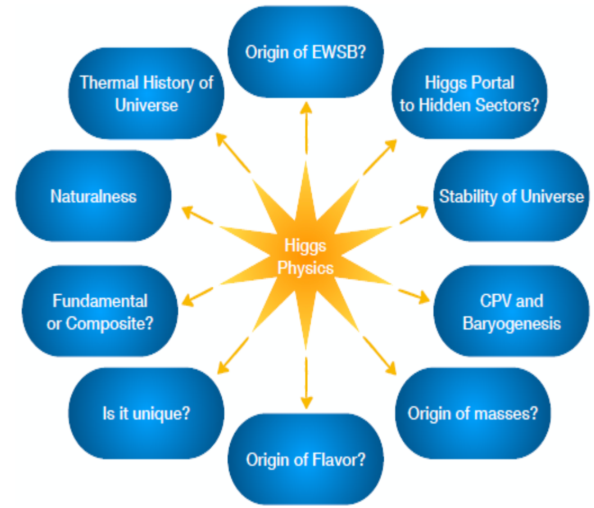
1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

Snowmass Summary Report

- **e^+e^- Higgs factory as highest priority** next collider re-emphasized

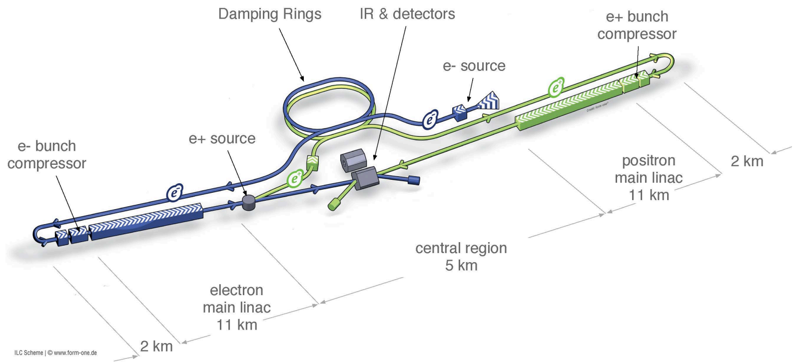


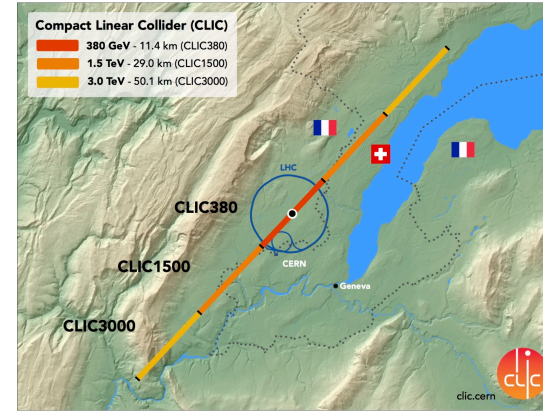
arXiv:2209.07510

- In addition: prioritisation of the **HL-LHC physics** exploitation programme and R&D towards a **TeV-scale Muon Collider**
- P5 (Particle Physics Project Prioritization Panel) recommendations expected in early Dec. 2023

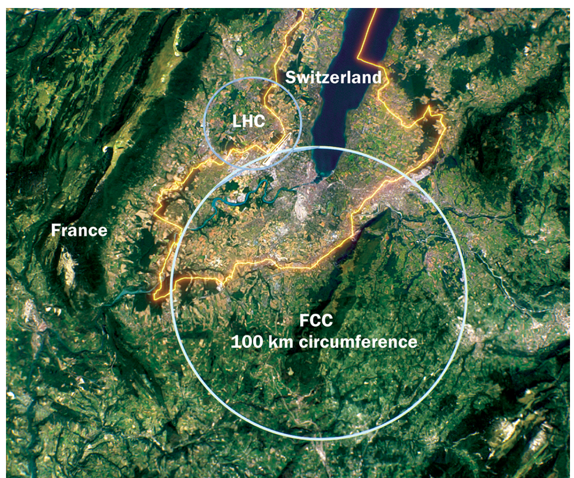
High-energy e^+e^- collider projects

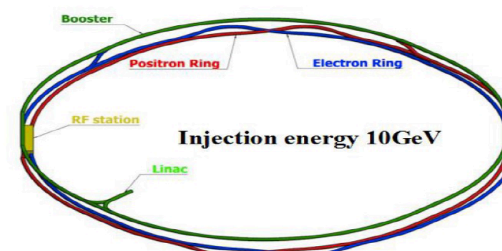
Linear Colliders





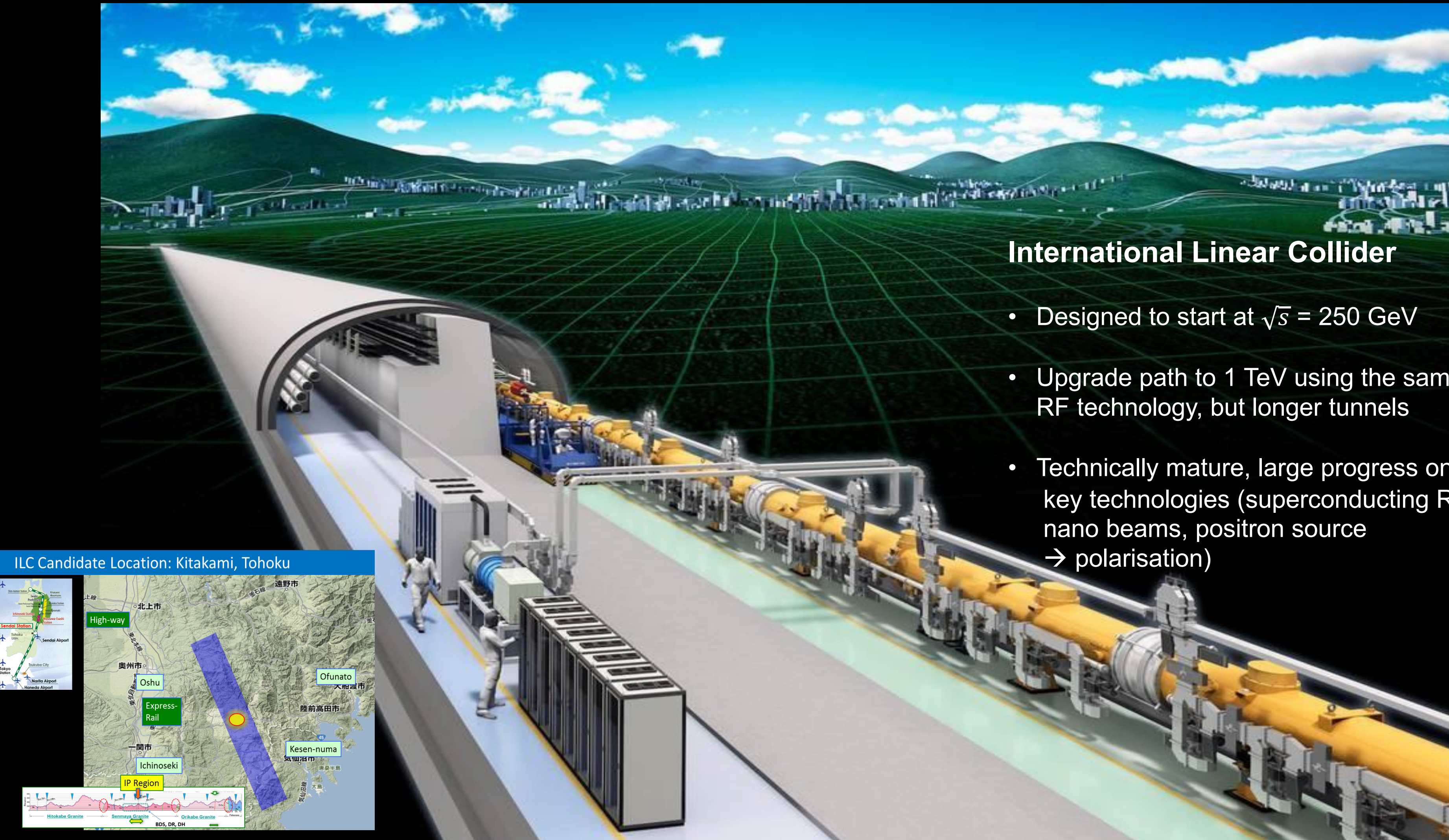
Circular Colliders





The same rings could be used in a second stage to host a ~100 TeV pp collider

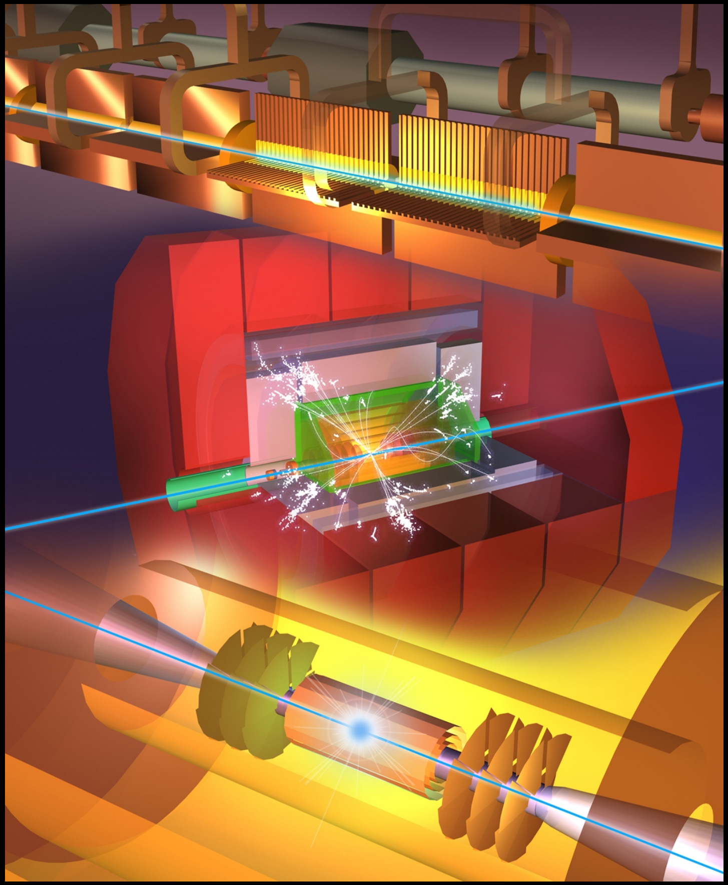
Status of the ILC project

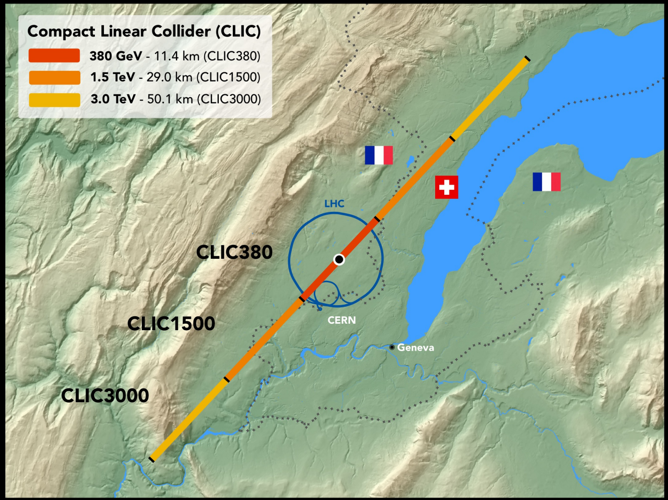


International Linear Collider

- Designed to start at $\sqrt{s}$ = 250 GeV
- Upgrade path to 1 TeV using the same RF technology, but longer tunnels
- Technically mature, large progress on key technologies (superconducting RF, nano beams, positron source → polarisation)

CLIC: Compact Linear Collider





Compact Linear Collider

- Designed to start at $\sqrt{s}$ = 380 GeV
- Upgrade path to 3 TeV
- Novel and unique two-beam acceleration, 72 MV/m → 11.4 km in initial phase
- Many technical developments successfully carried out

FCC: Future Circular Collider

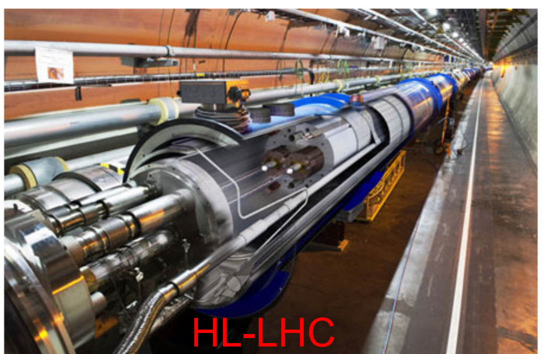
FCC integrated programme

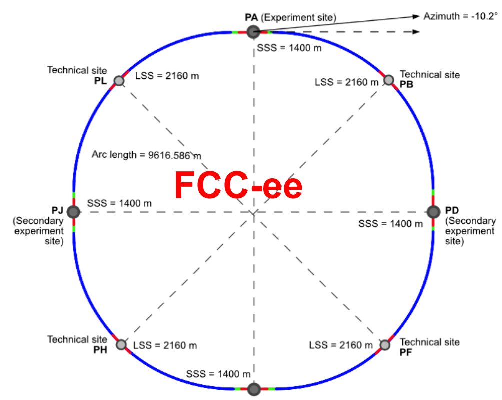
Comprehensive long-term programme maximising physics opportunities:

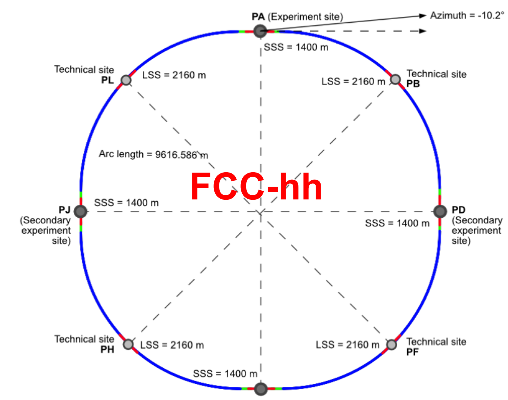
- Stage 1: FCC-ee : e^+e^- Higgs, electroweak & top factory at highest luminosities [91 GeV → 365 GeV]
  Build on large progress made at circular e^+e^- colliders over the past decades → reach luminosities beyond 10^{34} cm^{-2} s^{-1}

- Stage 2: FCC-hh : 100 TeV pp collider, energy frontier machine (in addition: eh and ion options)

- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC project start is coupled to HL-LHC programme (→ start operation of FCC-ee around 2048)







2029 - 2042 | **2048 - 2065** | **2070 - 2095**

FCC Feasibility Study

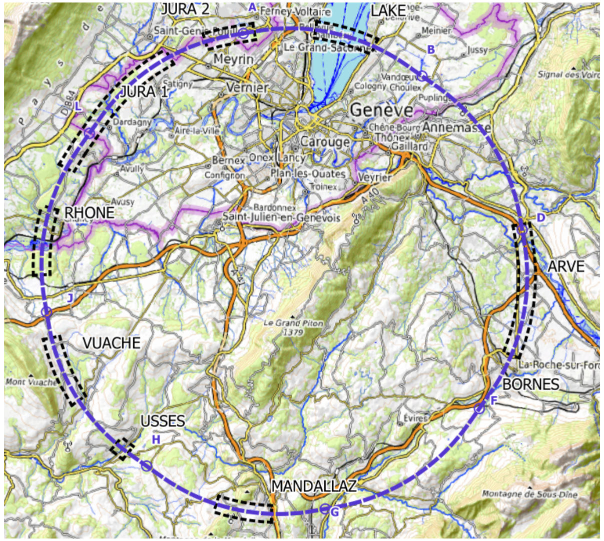
Explore the feasibility for an integrated FCC-ee / FCC-hh programme at CERN

- Study and its organisational structure have been approved by CERN Council in June 2021

- Report to be released by end of 2025
  → Basis for a decision at the next Strategy Meeting 2026/27
  (mid-term report by end of 2023)

- Major deliverables and milestones
  - Understand the realisation (geology, infrastructure, political, …)
  - Collider design, with clear focus on FCC-ee
  - Timeline and cost for FCC-ee
  - Contributions from outside CERN
  - Physics case and experiment design
  - Sustainable operational model for the colliders and experiments (environmental aspects, energy efficiency, …)

- Address technical issues of Hadron Collider
  Large technological challenges, 16 T superconducting magnets not yet available

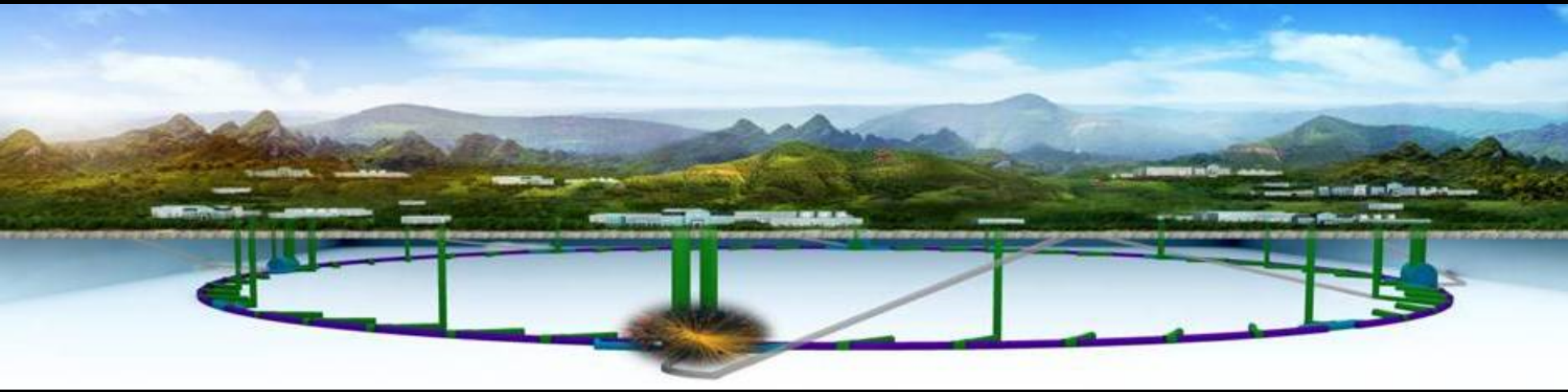


Converging on a "low risk" placement with circumference of 91 km

(4-fold symmetry, 8 surface points, 2-4 e^+e^- experiments)

Significant progress on many fronts,
→ talk by M. Benedikt at next ECFA Plenary meeting on 17 Nov. 2023 at CERN (open to full community)

CEPC: Circular Electron-Positron Collider in China

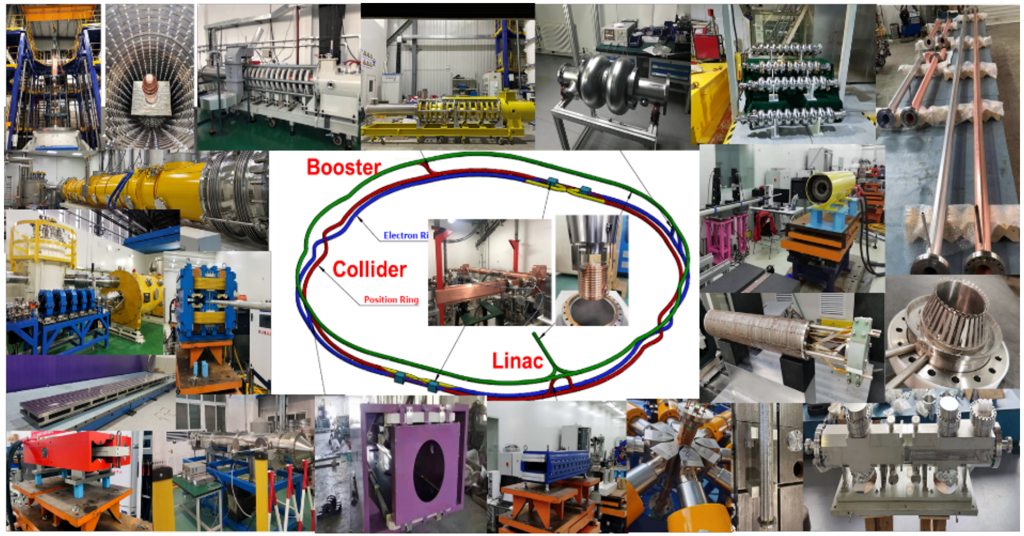


- Stage 1: CEPC: Higgs / el.weak / top factory [91 GeV → 360 GeV]
- Stage 2: SppC: pp energy-frontier machine ~100 TeV
  (integrated programme, similar to FCC)

Key technology readiness

Yifang Wang, CEPC Meeting, UK, June 2023

Huge R&D and prototyping programme ongoing



Key technology R&D spans all components needed for CEPC

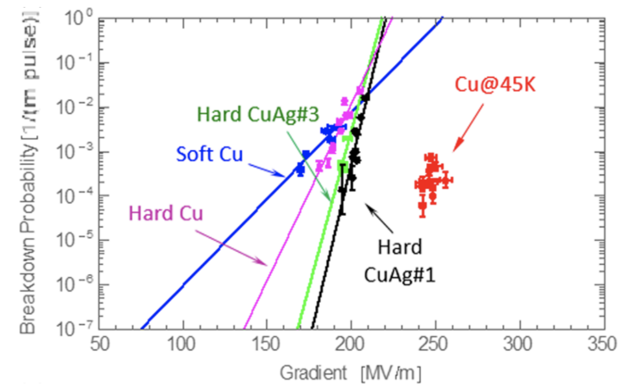
Will be ready for construction by 2026

Specification Met ✓ Prototype Manufactured ✓

Accelerator	Fraction
✓ Magnets	27.3%
✓ Vacuum	18.3%
✓ RF power source	9.1%
✓ Mechanics	7.6%
✓ Magnet power supplies	7.0%
✓ SC RF	7.1%
✓ Cryogenics	6.5%
✓ Linac and sources	5.5%
✓ Instrumentation	5.3%
✓ Control	2.4%
✓ Survey and alignment	2.4%
✓ Radiation protection	1.0%
✓ SC magnets	0.4%
✓ Damping ring	0.2%

A new, recent proposal: Cold Copper Collider C^3

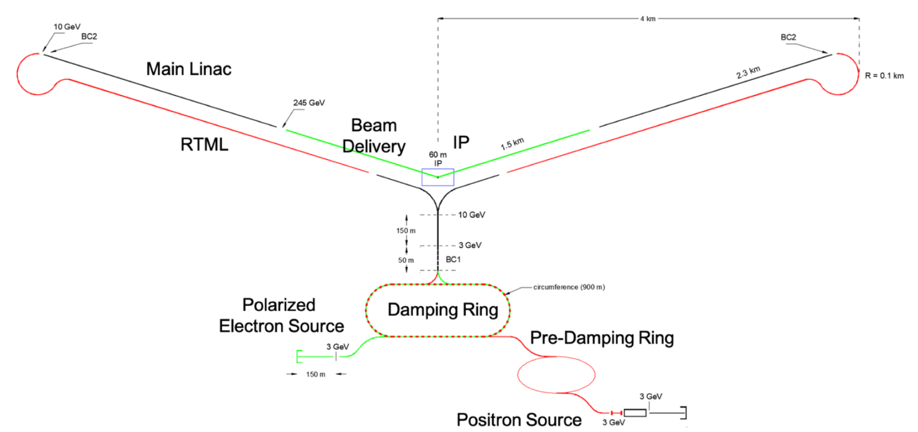
- Proposal was discussed in US Snowmass process arxiv:2110.15800
- Based on observation that cryogenic temperatures elevate the RF performance (larger gradients)
  Linked to: - increased material strength for higher gradients
  - increased electrical conductivity
- Operation at 77 K (liquid nitrogen temperature) can be considered



CCC design:

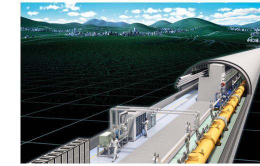
- 8 km footprint for $\sqrt{s}$ = 250 / 550 GeV requires gradients of 70 / 120 MV/m
  Possible site: **Fermilab**
- Large portions of the accelerator complex are compatible with ILC technologies
  (Beam delivery, damping ring and injectors will be optimised with ILC or CLIC as baseline)

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR



The Approval status

- **ILC:** - Under consideration by the Japanese Ministry / Government as a **global project**
  - 2023: increased resources, ILC Technology Network established, incl. CERN (coordination for Europe)

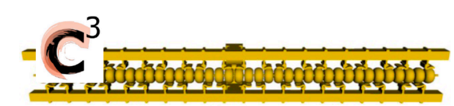


- **FCC-ee**: - Feasibility study ongoing, very good progress in many areas, mid-term report expected in November 2023;
  - **Priority 1 for CERN / Europe (CERN Council)**
  - Outcome (technical feasibility, costs,…) decisive for Europe

- **CEPC:** **-** TDR in preparation, incl. cost review
  - A lot of progress on the technical side
  - **Aiming for approval in next 5-year plan (2025)**
  - Ranked 1st in Chinese HEP preselection

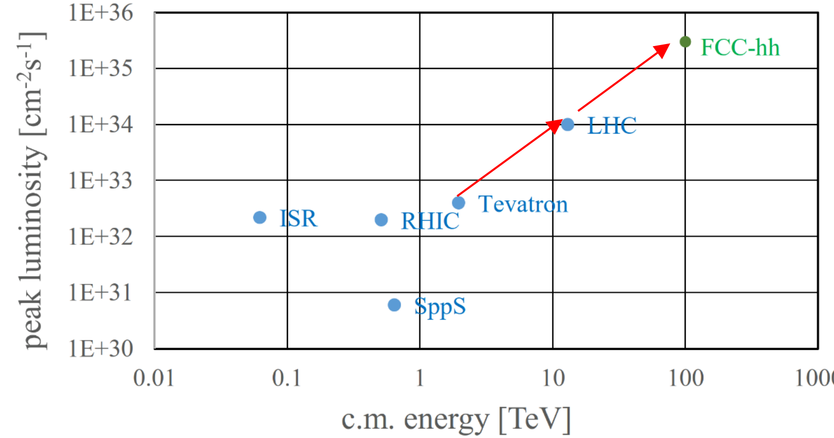
- **CLIC**: - Possible alternative for CERN
  CLIC community is preparing a Project Readiness Report (PRR) for the next ESPP (2026/27)

- **CCC:** - R&D towards a demonstrator moving forward at SLAC;
  Waiting for P5, and for a commitment of a laboratory to host it



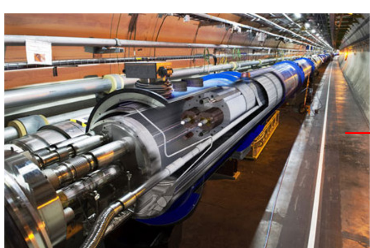
Stage 2: FCC-hh

- High energy frontier exploration machine, reaching **100 TeV pp collisions**
- Performance increase by an order of magnitude in energy and luminosity w.r.t. LHC
- Planned to accumulate ~20 ab^{-1} per experiment, over 25 years



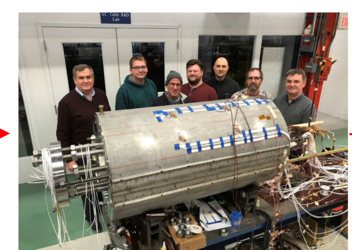
- Large challenges: - High bending power → high-field magnets with field strength of 16 – 20 T;
  - Costs (linked to magnets)

From LHC technology
8.3 T NbTi dipole



via HL-LHC technology
12 T Nb_3Sn quadrupole

via large R&D programme
(e.g. FNAL 14.5 T Nb_3Sn dipole demonstrator, 2019)



.. to high-field, high performance, industrially mass-produced FCC-hh dipole magnets

?
16 – 20 T
High-field magnets,
HTS technology?
(High Temperature Superconductors)

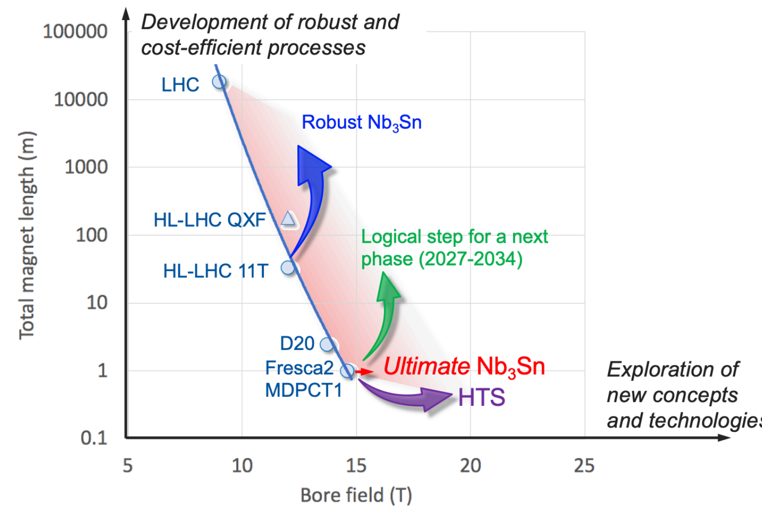
→ accelerator R&D roadmap

High-field Superconducting Magnets

- Key technology for future accelerators (hadron colliders, muon colliders, neutrino beams, …)
- To reach the required field strength of 16 – 20 T for FCC-hh, new technologies have to be **established and brought into industrial production**
  (Present candidates: Nb_3Sn and High-Temperature Superconductors (HTS), …)

Accelerator Roadmap:

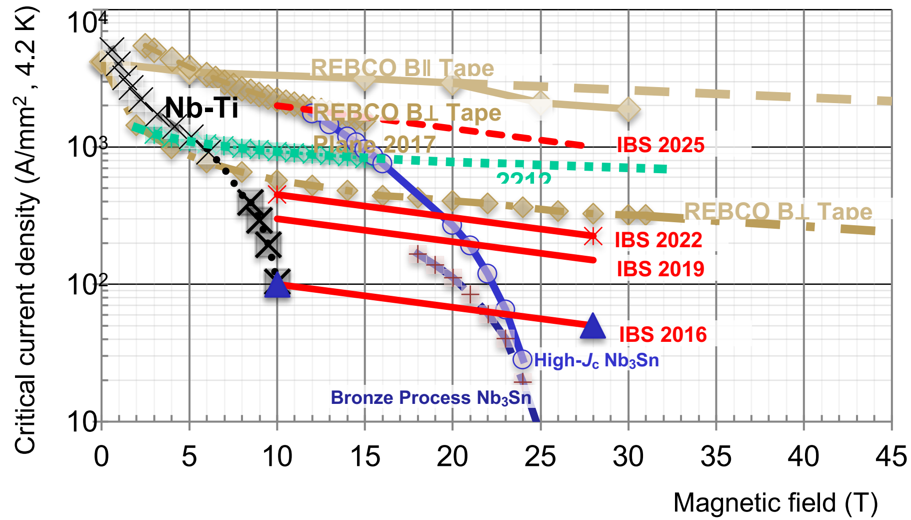
- Encompass Nb_3Sn and HTS (REBCO) developments
  - Demonstrate Nb_3Sn magnet technology for large-scale deployment
  - Demonstrate the suitability of HTS for accelerator magnet applications
- "Vertically integrated" approach to R&D
  - Development of all aspects from conductors to cables to magnets to systems
  - Emphases: full system optimisation, fast turnaround for R&D, modelling

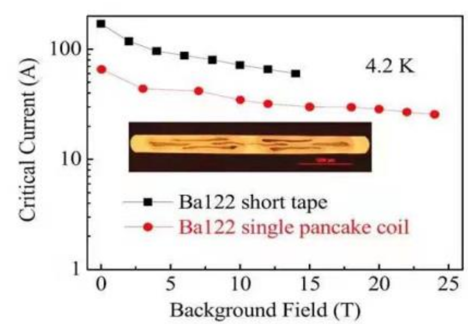


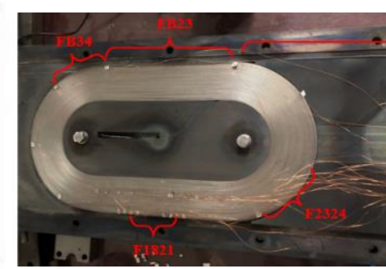
R&D for High-Field Superconductors for SppC

Yifang Wang, CEPC Meeting, UK, June 2023

- **Iron-based superconducting materials** are very promising for high-field magnets
  - Isotropic
  - May go to very high field
  - Raw materials are cheap
  - Metal, easy for production
- Technology spin-off can be enormous
- Major R&D goals
  - High J_c: > 1000 A/mm^2@4.2K
  - Long cable: > 1000 m
  - Low cost: < 5 \$/kA·m
- A collaboration formed in 2016 by IHEP, IOP, IOEE, SJTU, etc., and supported by CAS
- World first: 1000 m IBS cable, IBS coil,
  → magnet

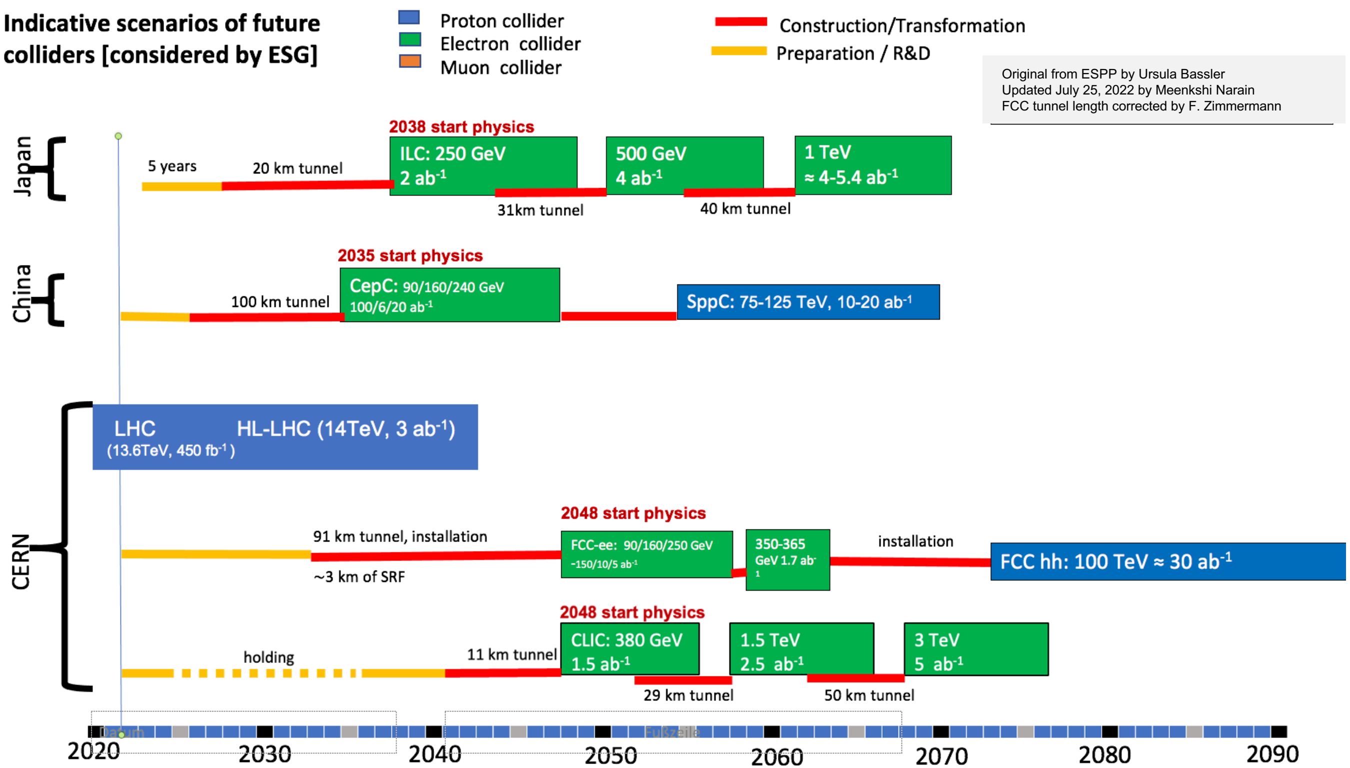






1st iron-based superconducting solenoid coil at 24T

Timelines



Comments:

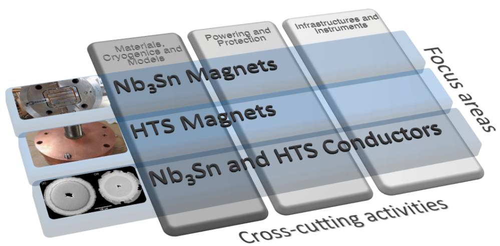
- e^+e^- timelines are limited by approval processes
- CEPC and ILC projects need to pass approval processes in the near future to maintain these schedules
- CERN projects are linked to completion of the HL-LHC
- hh timelines are limited by technology issues, costs, proceeding e^+e^- projects

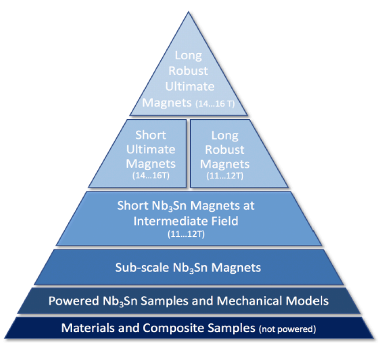
Research and Development on Accelerator Technologies

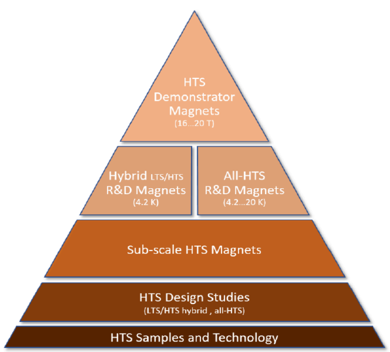
From the European Strategy:

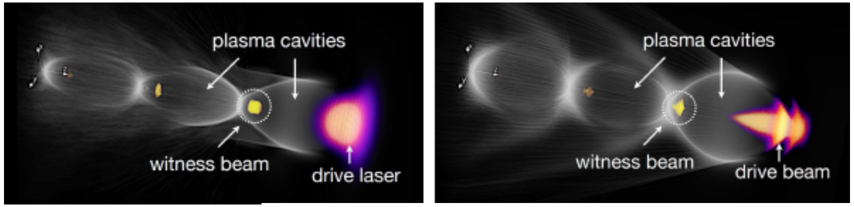
Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry.

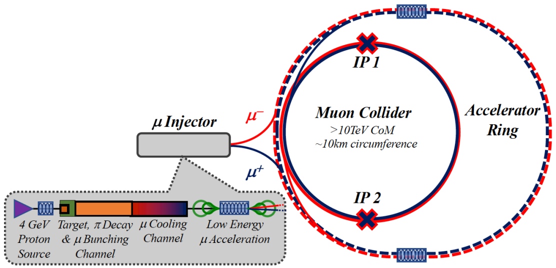
The technologies under consideration: **High-field magnets, high-temperature superconductors**
Plasma / Laser acceleration
Bright muon beams (→ Muon collider)
Energy recovery linacs
+ High-gradient RF structures











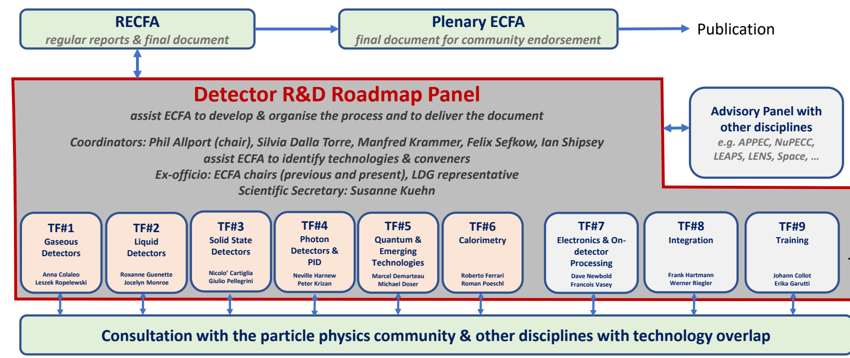
ECFA Roadmap on Detector R&D

- As suggested by the 2020 Update on the European Strategy a Roadmap for Detector R&D has been developed;
  Released at the end of 2021: https://cds.cern.ch/record/2784893

- The implementation of the roadmap foresees the formation of Detector R&D Collaborations (DRDs) at CERN;
  One for each of the six technology areas + electronics

- Five proposals have been submitted and are under review by the newly established Detector R&D Committee (DRDC) with support by the ECFA Detector Panel
  (co-chaired by P. Allport, D. Contardo)

  - DRD1: gaseous detectors
  - DRD2: liquid detectors
  - DRD3: solid state detectors
  - DRD4: particle identification and photon detection
  - DRD6: calorimeters



DRD5 (quantum, emerging technologies) and
DRD7 (electronics, transversal activity) will submit proposals by the end of this year
(later timescale due to: internal coord. (DRD5), coordination with other DRDs (DRD7))

- Collaborations are open for world-wide collaboration; participation from outside Europe is very welcome!

- DRDC has been set up and is complete: http://committees.web.cern.ch

- Recommendations on approval are expected to be issued by the DRDC early December

  → Final decision on approval by the CERN Research Board shortly after

- Start-up of new Collaborations in January 2024;

- During 2024 Memoranda of Understanding with Funding Agencies are expected to be signed.

  Funding-agency involvement is planned via RRB-like meetings
  (Details are still under discussion with CERN management)

Detector R&D Committee (DRDC)

BERGAUER, Thomas	HEPHY, Vienna, **Chairperson**
TROSKA, Jan	CERN, **Scientific Secretary**
Members - Referees	
BENTVELSEN, Stan	NIKHEF
BRESSLER, Shikma	Weizmann Institute of Science
BUDKER, Dimitry	Helmholtz Institute Mainz and Johannes Gutenberg University
FORTY, Roger	CERN
GEMME, Claudia	INFN and University, Genoa
GIL BOTELLA, Ines	CIEMAT
MERKEL, Petra	Fermilab
PESARESI, Mark	Imperial College
SERIN, Laurent	IJCLab - Laboratoire de physique des 2 infinis
Members Ex-officio	
ALLPORT, Phil	ECFA Detector Panel (EDP) Co-Chair
CONTARDO, Didier	ECFA Detector Panel (EDP) Co-Chair

Detector R&D Roadmap: General Strategic Recommendations

GSR 1 - Supporting R&D facilities (e.g. testbeams, irradiation facilities, …)

GSR 2 - Engineering support for detector R&D

GSR 3 - Specific software for instrumentation

GSR 4 - International coordination and organisation of R&D activities

GSR 5 - Distributed R&D activities with centralised facilities (e.g. ASIC developments, ..)

GSR 6 - Establish long-term strategic funding programmes

GSR 7 - Blue-sky R&D

GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts → ECFA Training Panel

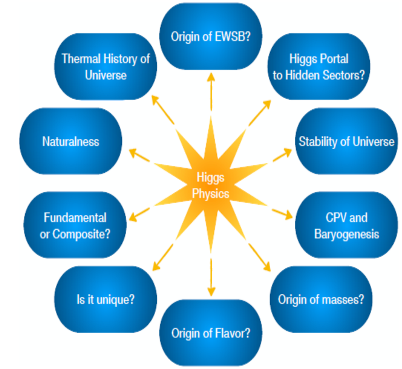
GSR 9 - Industrial partnerships

GSR 10 - Open Science

ECFA-LDG Working group to address the remaining General Strategic Recommendations has started its work

Chairs: Stan Bentvelsen (Nikhef) and Marko Mikuz (Ljubljana)

Conclusions on Future Colliders



- High-energy future colliders will play a key role in the exploration of crucial fundamental questions of physics

- Consensus:
  - Exploration of the Higgs sector is vital
  - To be addressed with an e^+e^- collider in a first stage

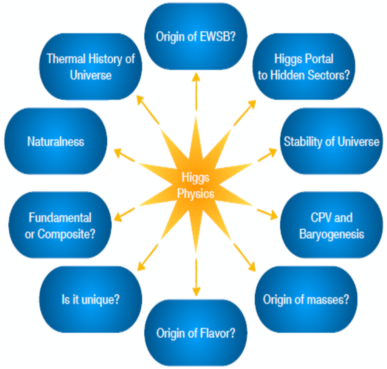
  Mature options for the realisation of such a collider exist: CLIC, FCC-ee, ILC, CEPC

  Long timescales → approval process must converge soon!
  (next ESPP in 2026/27?, convergence in other areas of the world?)

- Longer-term options: High-energy Hadron Collider (FCC-hh, SppC) or a Muon Collider
  For both significant R&D is required and will be pursued!

- Further R&D on accelerator technologies and development of innovative approaches are vital (plasma/laser acceleration, energy-recovery linacs, …)

Conclusions on Future Colliders



- **Important for the realisation of future colliders:**

  * Convince decision makers of the incredible physics case and of the vital role of high-energy colliders

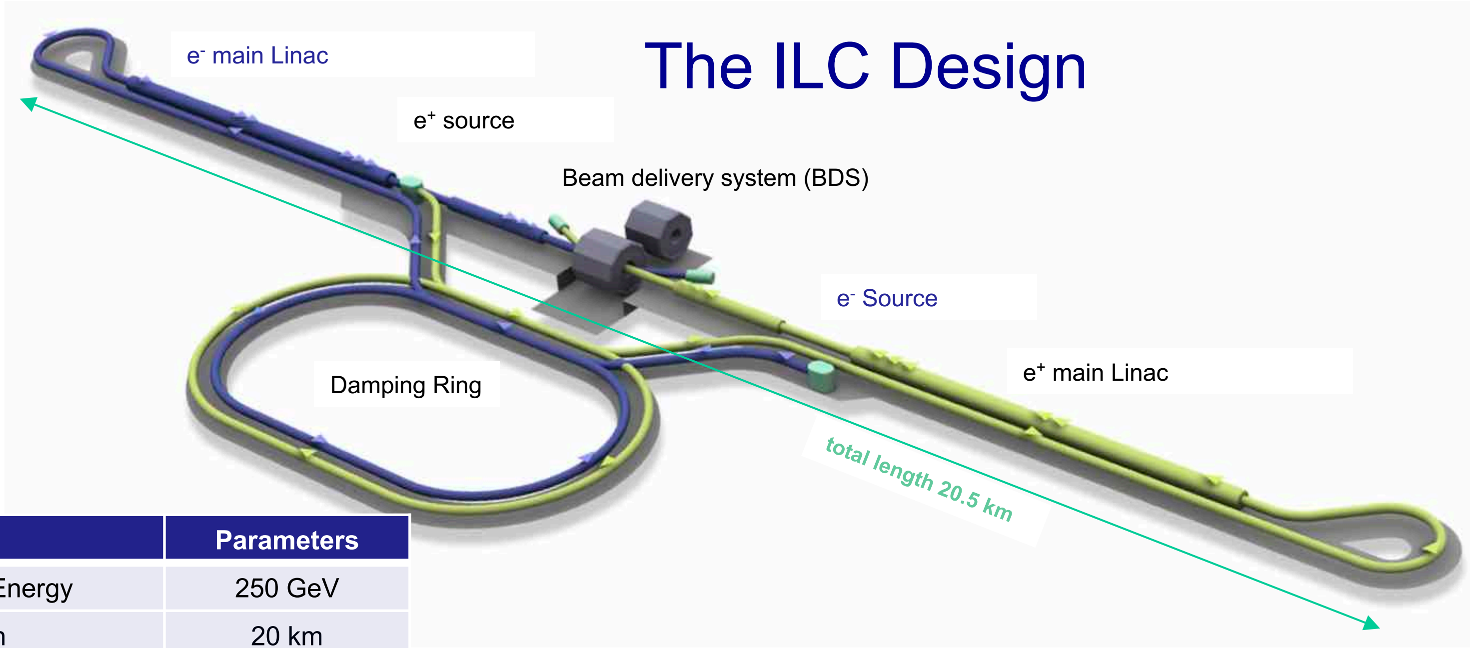
  → more efforts needed

  * Broad support within the HEP community is needed!

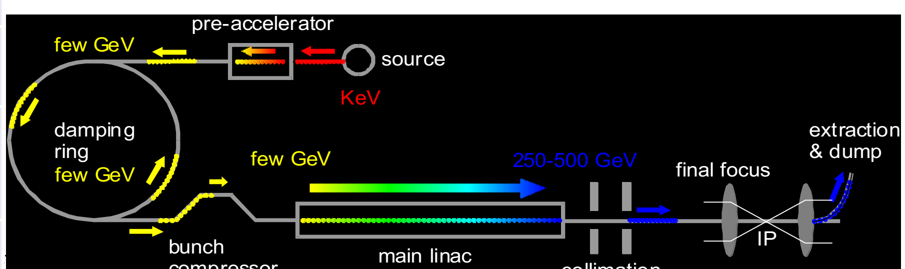
  * Continue optimisation efforts on power reduction!

Backup Slides

The ILC Design



Item	Parameters
C.M. Energy	250 GeV
Length	20 km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at final focus	**7.7** nm@250GeV
SRF Cavity G. Q_0	**31.5** MV/m (**35** MV/m) Q_0 = 1x10^{10}
Power	129 MW (250 GeV)



Key Technologies:

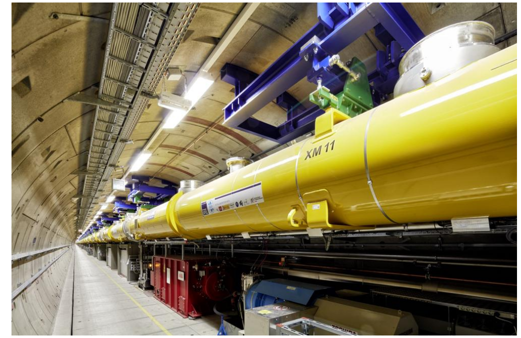
- Superconducting RF
- Nano-beam technology
- Positron source (polarised positrons)

Status of Key Technologies

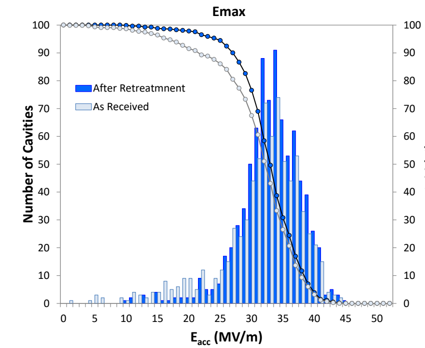
(i) Superconducting RF

1.3 GHz, 9 cell cavity

- Capitalize on the massive developments done for light sources worldwide, in particular via the European XFEL at DESY / Hamburg
- Ongoing: Optimisation of the RF performance
  (surface treatment, improve efficiency in
  cavity production, automation of cavity cleaning, …)



European XFEL (~800 cavities, 100 modules)
~ 10% of ILC needs



Good perf. reached on acc. gradient

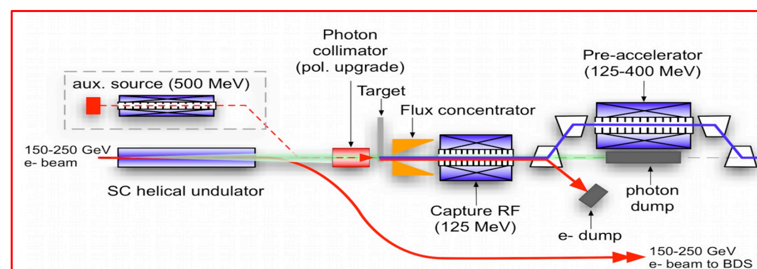
(ii) Nano Beams

ILC final focus method established
(with same optics and comparable beamline tolerances)

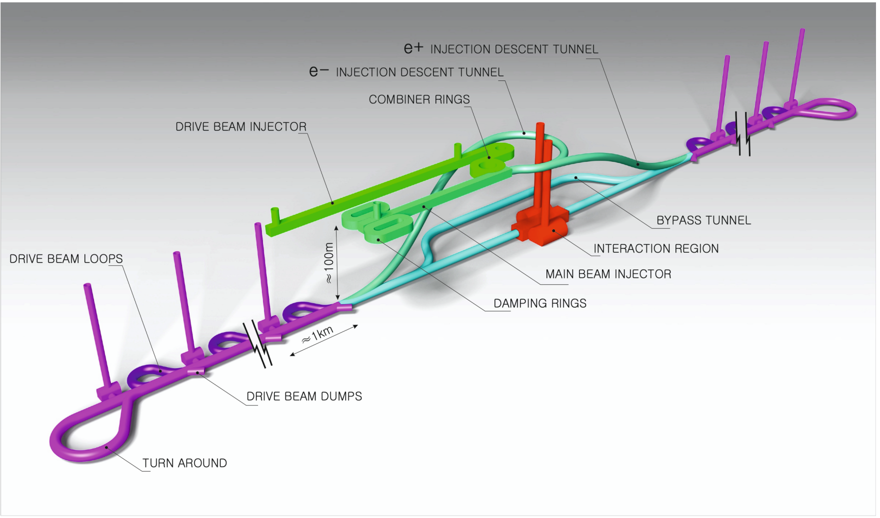
- ATF2 Goal: 37 nm → ILC 7.7 nm (at ILC250)
- Achieved 41 nm (2016)

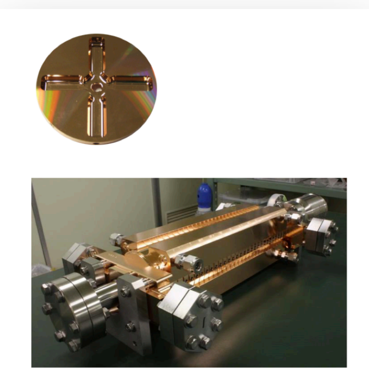
(iii) Positron Source

Undulator-driven positron source under study;
Important for the production of **polarised positrons**



The Compact Linear Collider

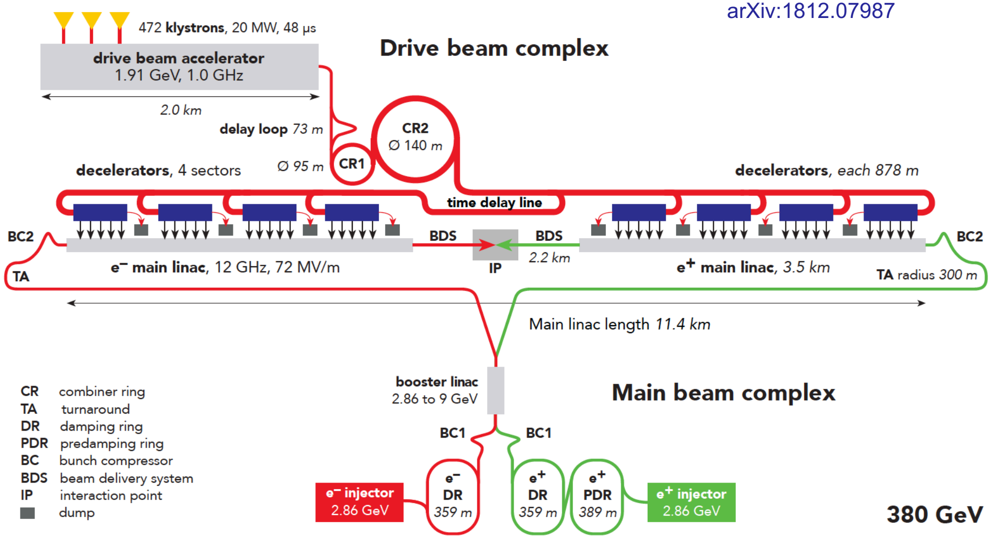




Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)

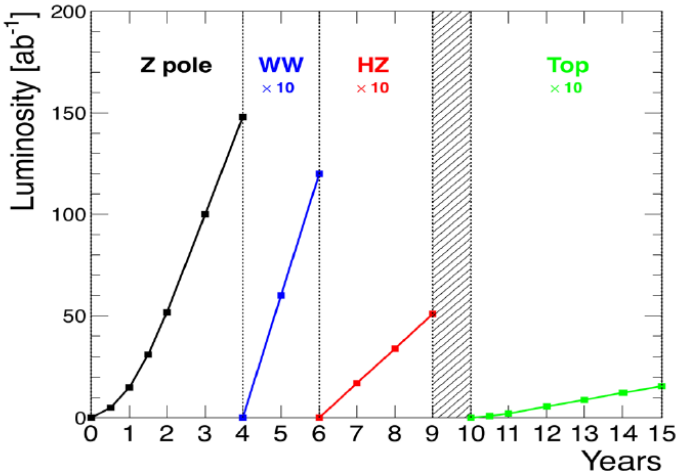
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact: Novel and unique two-beam accelerating technique** with high-gradient room temperature RF cavities (~20'500 cavities at 380 GeV)
  Achieve **accelerating gradients of 72 MV/m**
  → **11.4 km in its initial phase**
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)
- **Power: 168 MW at 380 GeV**, some further reductions possible
- Many technical developments have been carried out over the past decades (see backup slides)
  → also the CLIC accelerator studies are mature
- CLIC community is preparing a **Project Readiness Report (PRR)** for the next ESPP (2026/27)

CLIC acceleration concept



- Use low-frequency klystrons to efficiently generate long RF pulses
- Energy is stored in a long, high-current drive-beam pulse
- Beam pulse is used to generate many short, high-intensity pulses alongside the main linac
- Stored energy is released via transfer structures and transferred into the accelerating structures
  → high gradients of 72 MV/m (100 MV/m) can be reached

FCC-ee Running scenarios and Physics Yield



Studies ongoing whether operation can be switched, i.e. HZ first

arXiv:2203.06520

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\to$ H		(6000)

Dedicated run to measure the **electron Yukawa coupling** via s-channel $e^+e^- \to$ H production

Under study!

Needs strong monochromatisation of the beams

- Huge potential at Z peak: $5 \cdot 10^{12}$ events (10^5 times LEP)
- WW and $t\bar{t}$ threshold scan (→ precision mass measurements of m_W and m_t)
- 10^6 HZ events (at 240 GeV) + 25.000 H$\nu\nu$ events (via W fusion)
- s-channel run at $\sqrt{s}$ = m_H considered → may give access to electron Yukawa coupling
- Precise mass scale; high precision of beam energy due to resonant depolarisation (δE (91 GeV) ~ 100 keV, δE (350 GeV) ~ 2 MeV)

Precision on Higgs boson couplings

Precision on Higgs coupling strength modifiers κ_i
(assuming no BSM particles in Higgs boson decays)

J. De Blas et al. JHEP 01 (2020) 139

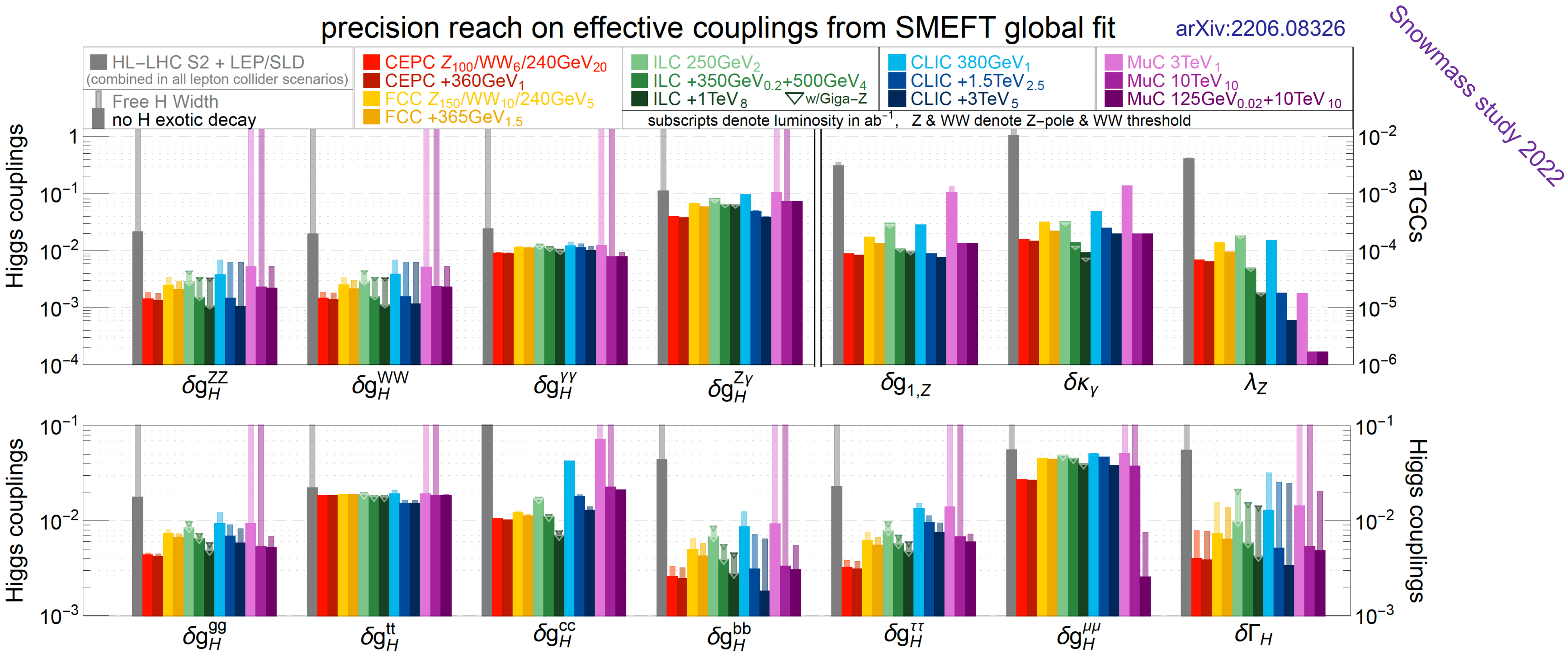
kappa-3 scenario	HL-LHC+ ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4∗	1.3	1.2	1.3	1.3	1.3	0.31
* $\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
* κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
* κ_μ [%]	4.2	3.9	3.6	4.4∗	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR$_{inv}$ (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR$_{unt}$ (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

$$\sigma_{ZH} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HZZ} \times g^2_{HX\overline{X}}}{\Gamma_H}$$

$$\sigma_{H\nu_e\overline{\nu}_e} \times \mathcal{B}(H \to X\overline{X}) \propto \frac{g^2_{HWW} \times g^2_{HX\overline{X}}}{\Gamma_H}$$

- Large improvement with future e^+e^- colliders (compared to (HL)-LHC)
- Powerful ability to measure Higgs boson production without any assumptions on its decay;
- Higgs boson width within a few percent (via ZH cross section)
- **Comparable precision between different e^+e^- colliders at early stage**
- Complementarity to hadron collider * → ultimate precision (sub %) from FCC-hh

Higgs and anomalous couplings (SMEFT interpretation)



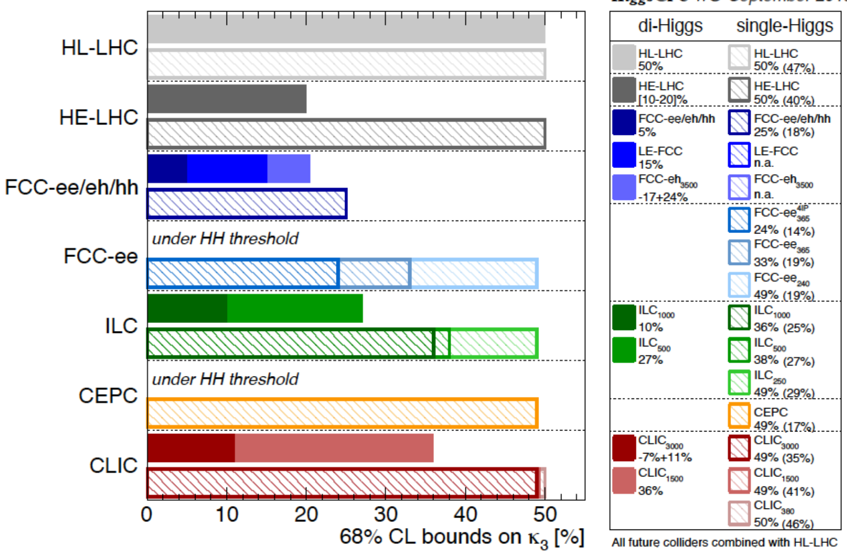
- All e^+e^- colliders show comparable performance (higher luminosities partly compensated by beam polarisation)
- Several couplings well below 1% level: Z, W, g, b, τ

  Others at ~ 1% level: γ, c

  Comparable precision as HL-LHC for: γ, t, μ

Precision on Higgs boson self coupling

J. De Blas et al. JHEP 01 (2020) 139

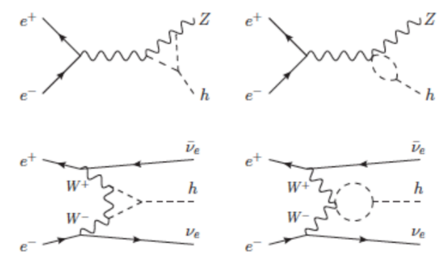


Precision on λ parameter:	
HL-LHC:	$\pm 50\%$
ILC (1 TeV):	$\pm 10\%$
CLIC (3 TeV):	$\pm (7-10)\%$
FCC-ee:	$\pm 35\%$
FCC-hh:	$\pm$ **5%**

Results confirmed in Snowmass study arXiv:2211.11084

- At low-energy lepton collider, no direct di-Higgs production possible

  → sensitivity via loop effects

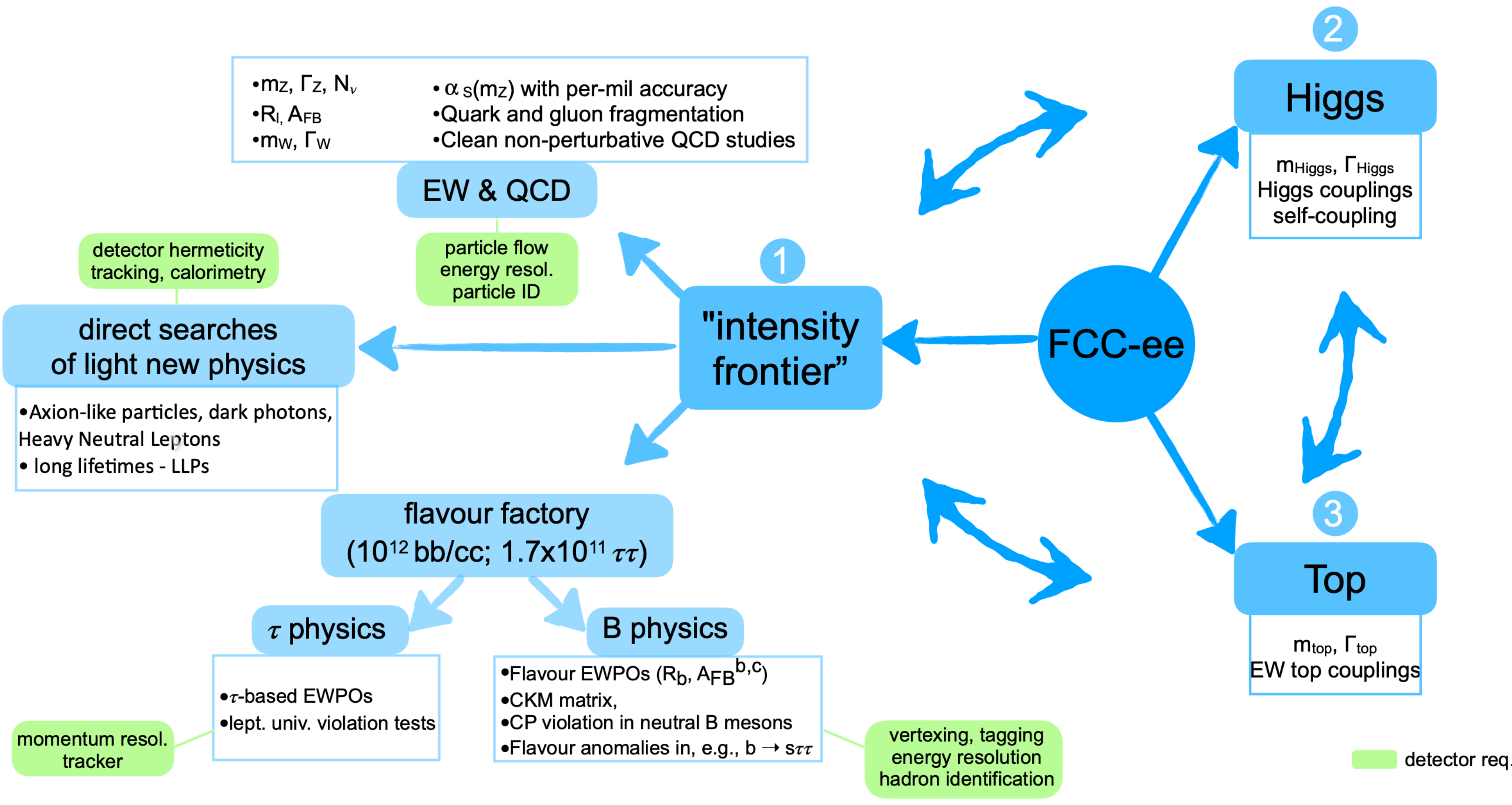


Precise cross section measurements required at 240 and 360 GeV

- Higher sensitivity can be reached at high-energy lepton colliders (ILC, CLIC)

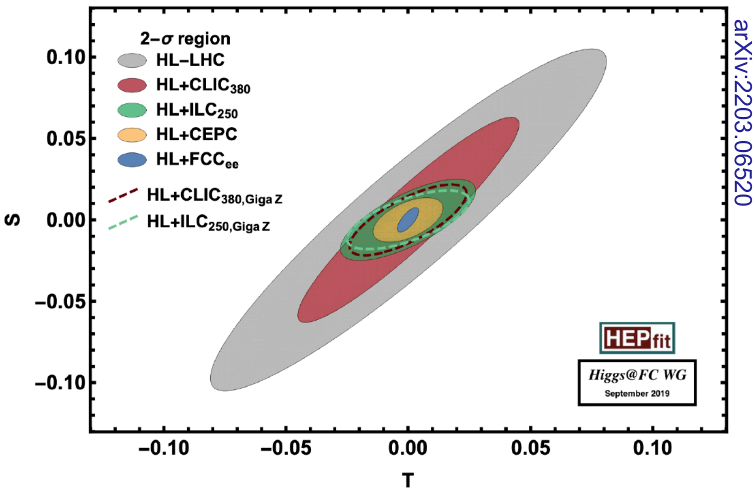
FCC-ee (and CEPC) Z-physics programme

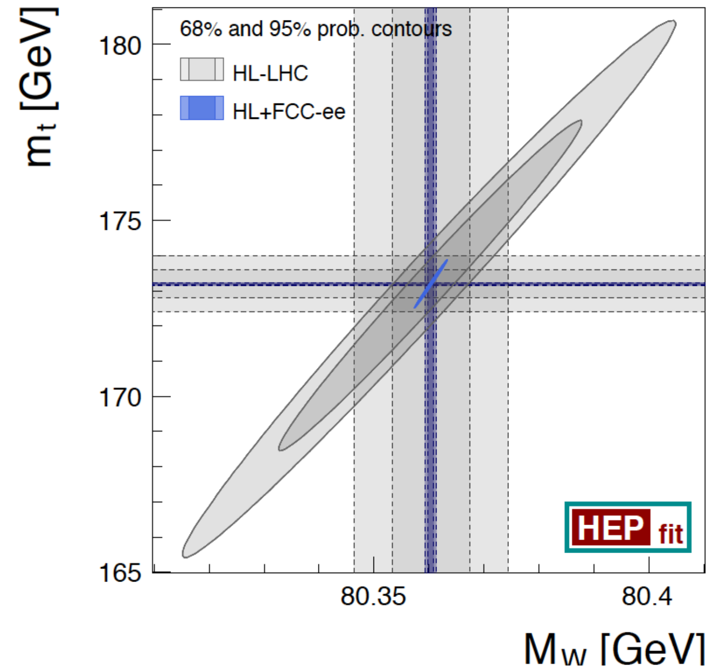
Christophe Grojean, FCC week 2022



Precision of electroweak observables

FCC-ee: Impressive precision on el.weak observables:
δm_Z ~ 100 keV, $\delta\Gamma_Z$ ~ 25 keV
δm_W < 500 keV (from WW threshold scan)
δm_t ~45 MeV (from $t\bar{t}$ threshold scan)
(more numbers in backup slides)





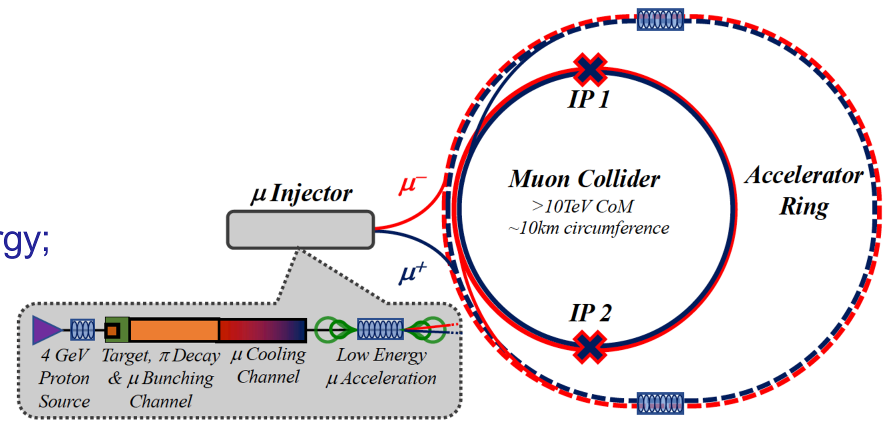
- Importance of el.weak precision:
  - (i) Improve **sensitivity to new physics** (e.g: $\delta S \sim 10^{-2} \rightarrow M \sim 70$ TeV)
  - (ii) **Reduce parametric uncertainties** for other measurements, global fits

Muon Collider

- Potentially interesting path to realise high-energy lepton colliders, however, the muon-collider technology must overcome several significant challenges

- Advantages: - luminosity / beam power improves with energy;
  - compact collider

- Challenges: muon brightness, ionisation cooling, neutrino radiation, magnets & RF, machine detector interface, beam background…



Significant progress over the past years, but still a lot to demonstrate

- **Roadmap Objectives**: again focussed on the "plausibility case"

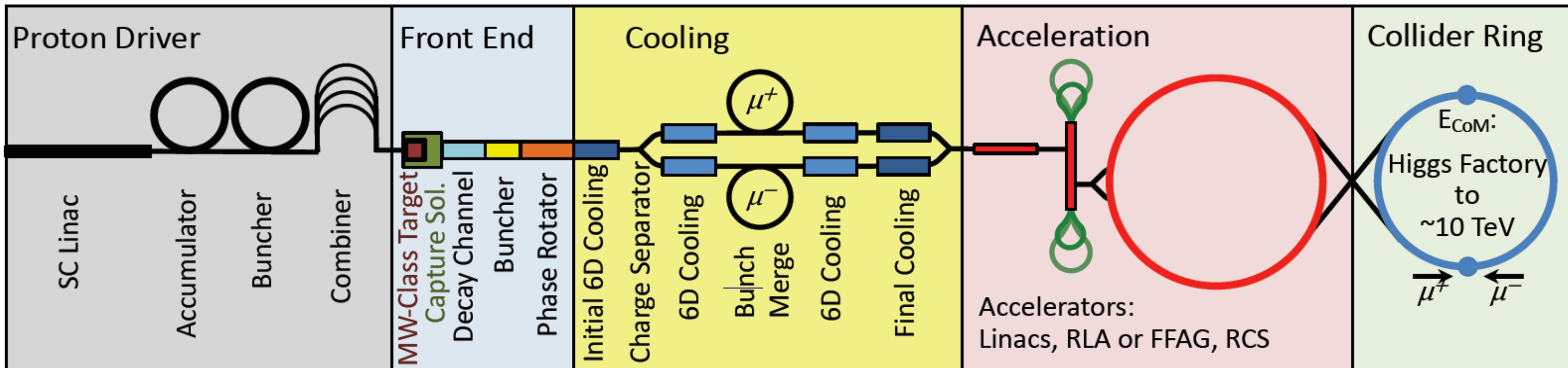
→ Examine the key technical barriers and cost drivers before the next strategy update

→ Planning towards a muon beam demonstrator

Muon Collider Concept

Daniel Schulte, Plenary ECFA 2021

Fully driven by muon lifetime



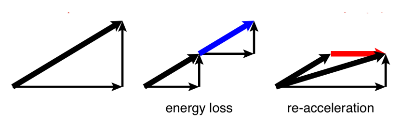
Short, intense proton bunch

Ionisation cooling of muon in matter

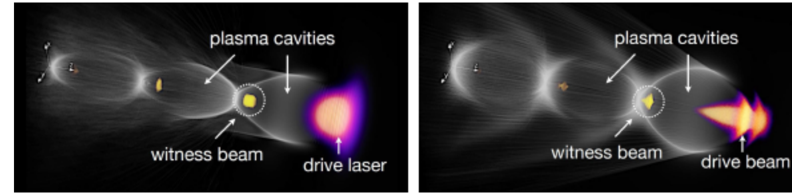
Acceleration to collision energy

Collision

Protons produce pions which
decay into muons
muons are captured



High-gradient Plasma and Laser Acceleration

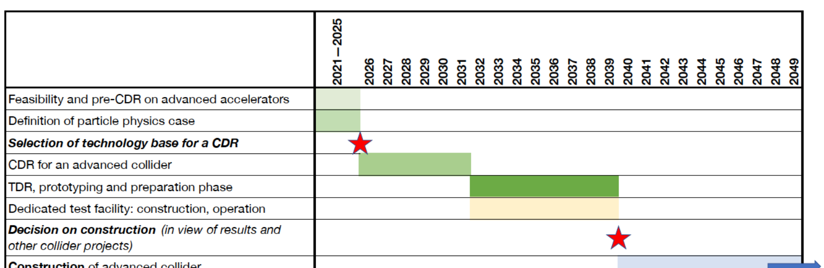


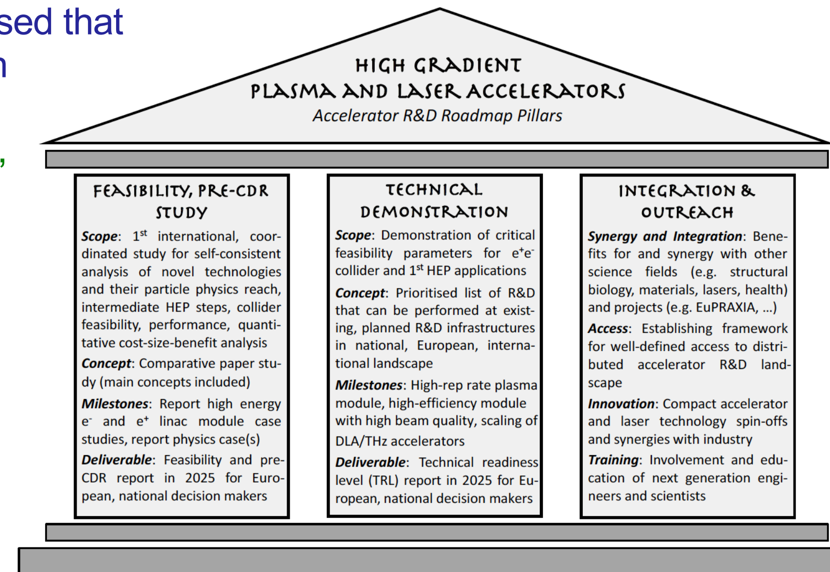
- Novel high-gradient accelerators have demonstrated acceleration of electrons with E-field strength of 1 to >100 GeV/m

- Potential for significant reduction is size and, perhaps, cost of future accelerators, however, feasibility of a collider based on plasma acceleration remains to be proven
  Key challenges: acceleration of bunch charge sufficient to reach high luminosity, emittance preservation, staged designs of multiple structures

- A plasma and laser accelerator R&D roadmap has been proposed that should be implemented and delivered in a three pillar approach

  By next strategy: A feasibility and pre-conceptual design report, i.e. evaluate the potential and performance reach for colliders, plus four experimental demonstrations



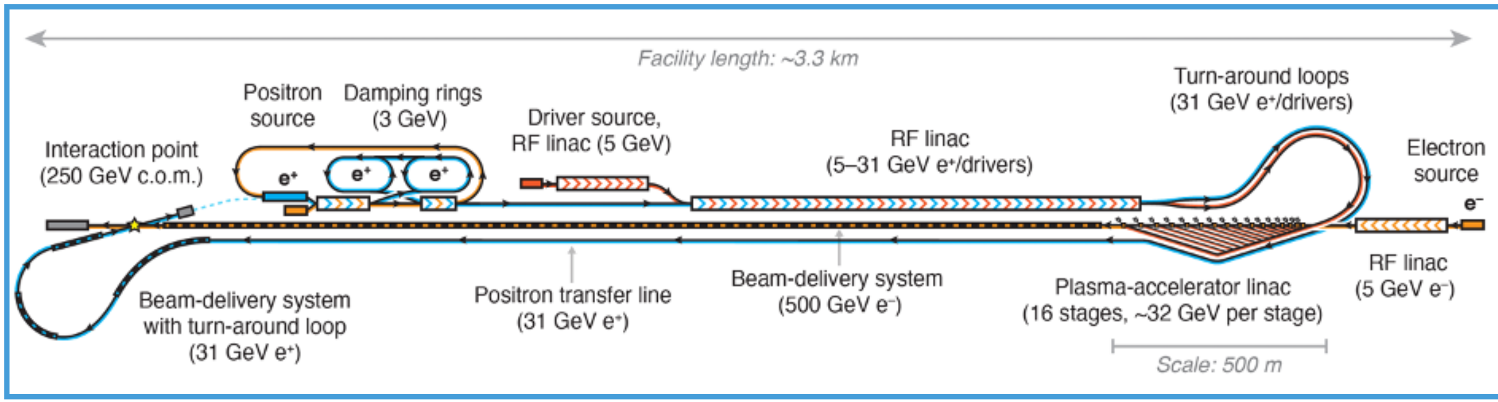


A new plasma-based proposal

- Hybrid, Asymmetric, Linear Higgs Factory (HALHF)

arXiv:2303.10150

- Beam-driven plasma-wakefield acceleration for electrons (very high gradients, 1.2 GV/m) + conventional RF acceleration to low-energy for positrons (31.5 GeV e^+ , 500 GeV e^-)



- First studies on detector / physics estimate ~10 years for R&D for plasma wakefield part

"HALHF cannot be built tomorrow: many unsolved problems remain. The major challenge is to produce plasma accelerators with the characteristics required. We believe that the HALHF concept should act as a spur to the improvement of specific plasma-acceleration techniques…. The necessary R&D should be vigorously pursued as soon as possible."

Costs

- ILC 250 GeV: 6 BCHF (incl. tunnel 1.1 BCHF)
- CLIC 380 GeV: 6 BCHF
  3000 GeV: +11 BCHF (if 380 GeV collider is extended, standalone 18 BCHF)
- FCC-ee: 10.7 BCHF (incl. tunnel 5.4 BCHF)

- All costs estimated in a traditional European way (no personnel costs of institutes / laboratories included);
- Numbers taken from 2020 ESPP, improved estimates (reduced uncertainties) upcoming
  (Estimates agree well with recent numbers calculated in US Snowmass study*, based on empirical cost model encompassing many parameters, based on experience from construction of previous colliders)

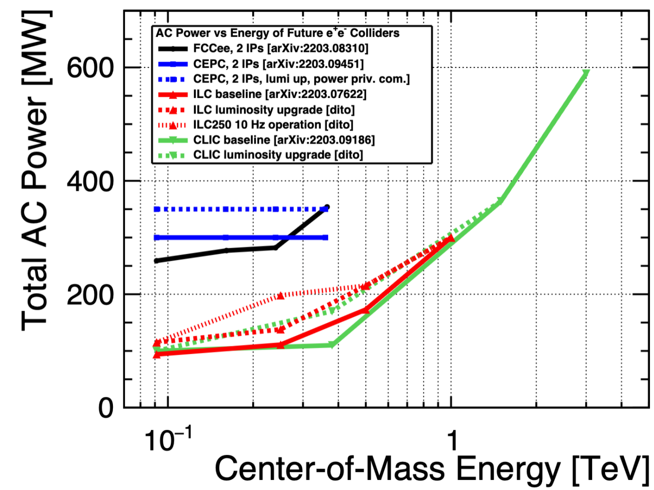
* *"On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force"*
  JINST 18 (2023) P05018 [arXiv: 2208.06030]

Power consumption

Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II

arXiv:2208.06030

Numbers on power consumption and size quoted in collider proposals;
Categories of power consumption, size, complexity and required radiation mitigation as ranked in the Snowmass study;
(colour scheme: lighter to darker meaning lower to higher risk)



These power consumptions are significant!

With standard running scenario every 100 MW correspond to an energy consumption of ~0.6 TWh
(as reference: CERN's yearly consumption today: 1.2 TWh)

→ Further power optimisation is essential!
e.g. technical developments targeting higher efficiency klystrons and RF systems, RF cavity design and optimisation, as well as magnets (operation at higher temperatures?)

CERN is well aware and studies in these directions are ongoing (e.g. see recent seminar by R. Losito https://indico.cern.ch/event/1317615/)