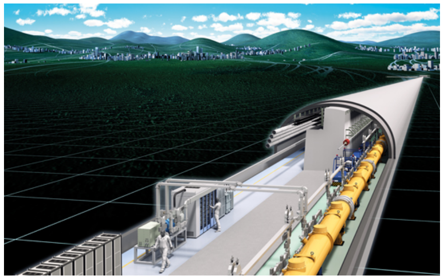
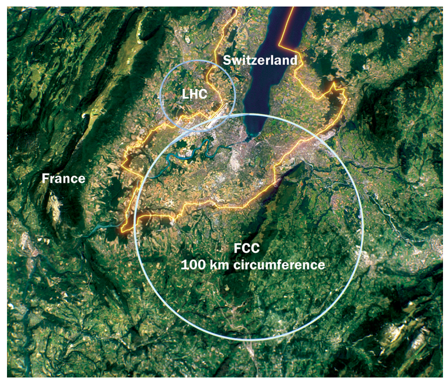
Future Colliders





Karl Jakobs
European Committee for Future Accelerators (ECFA Chair)
University of Freiburg

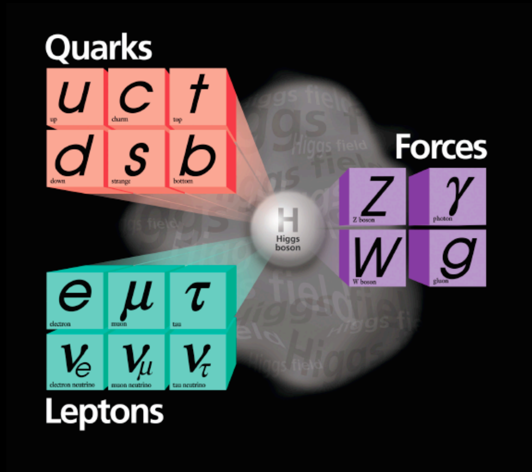
CERN-FNAL School
31st August 2023

Where do we stand today?
Why do we need a new collider?

4 July 2012

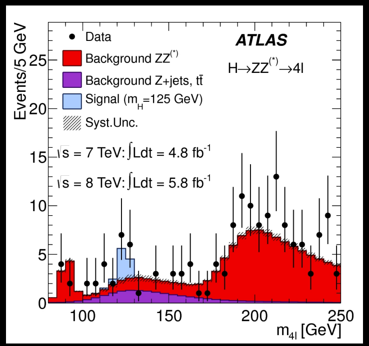
- The Higgs boson has been discovered

  → Last missing piece of the Standard Model

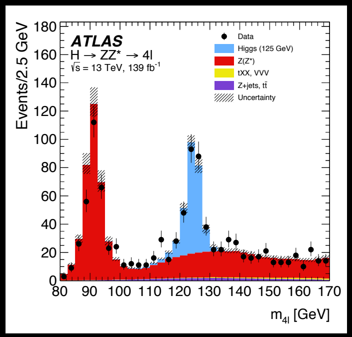


- Huge progress on exploring its properties over the last ~10 years (LHC Run 1 and Run 2)

  … and it will continue with the ongoing Run 3 and with much higher precision at HL-LHC

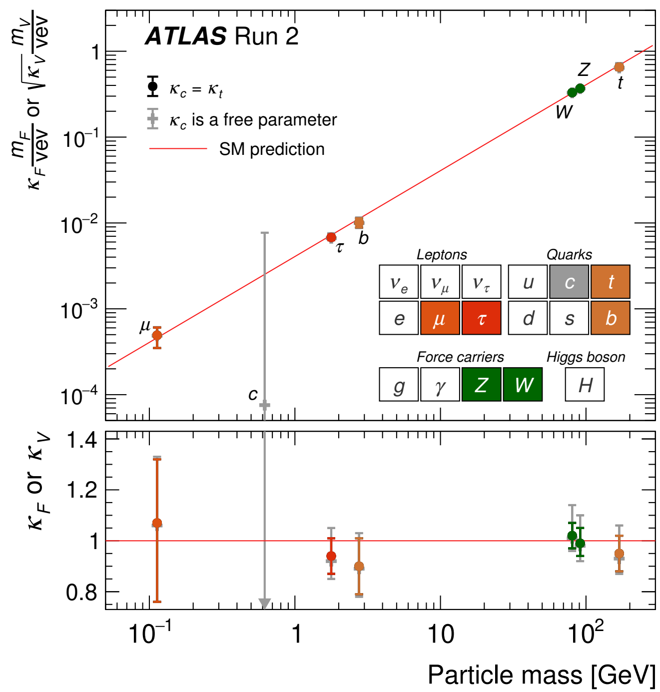


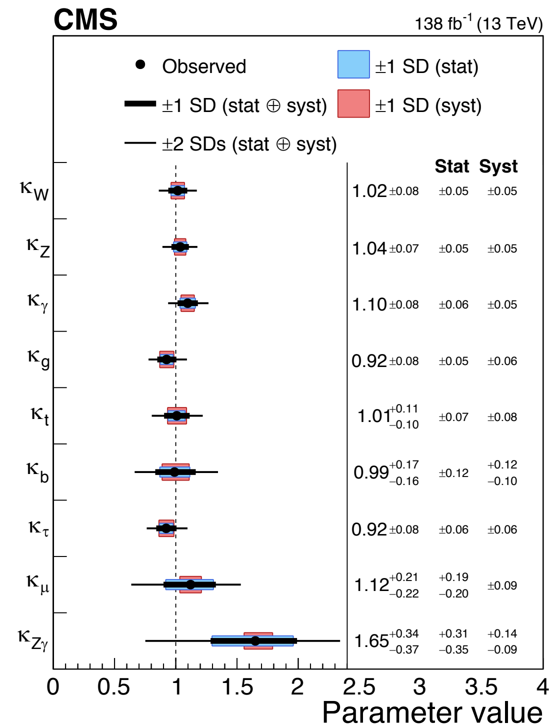
2012



2022

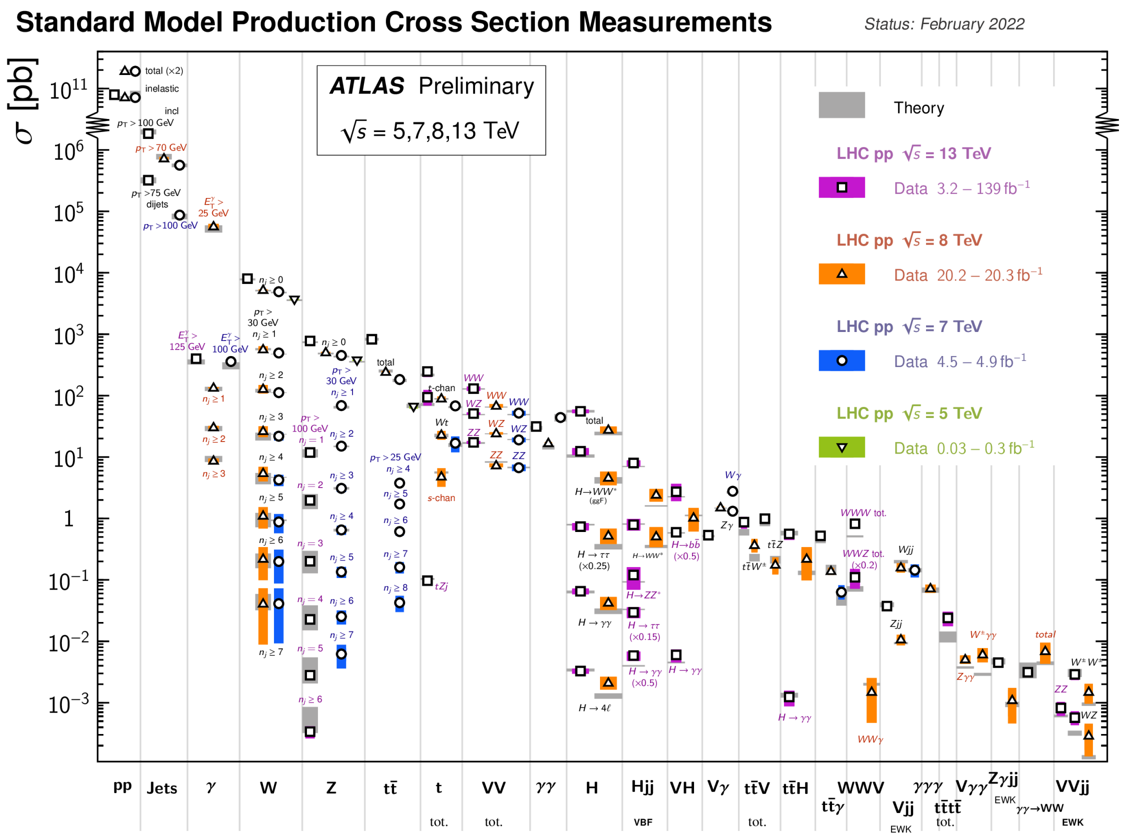
Test of the Standard Model Higgs sector





- Impressive precision already reached on measuring Higgs boson properties
- All measurements are in agreement – within uncertainties – with SM predictions

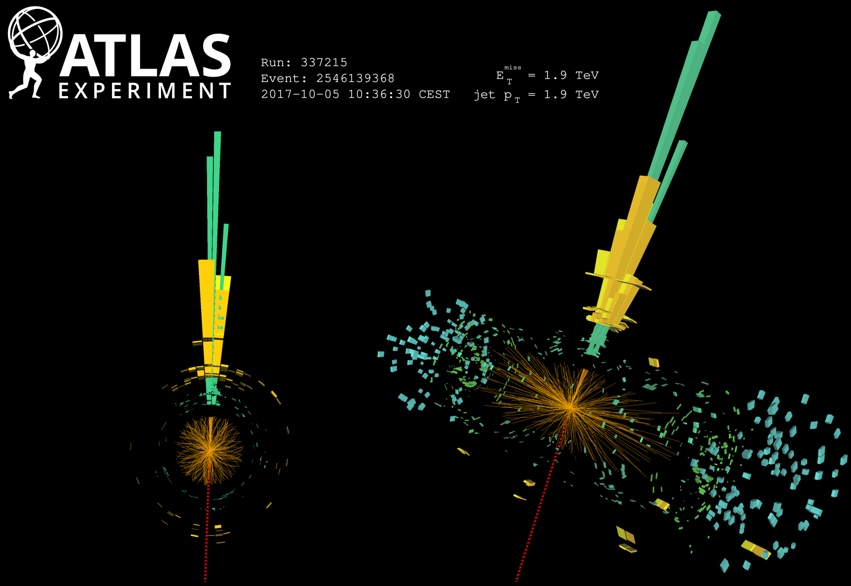
Precision test of the Standard Model



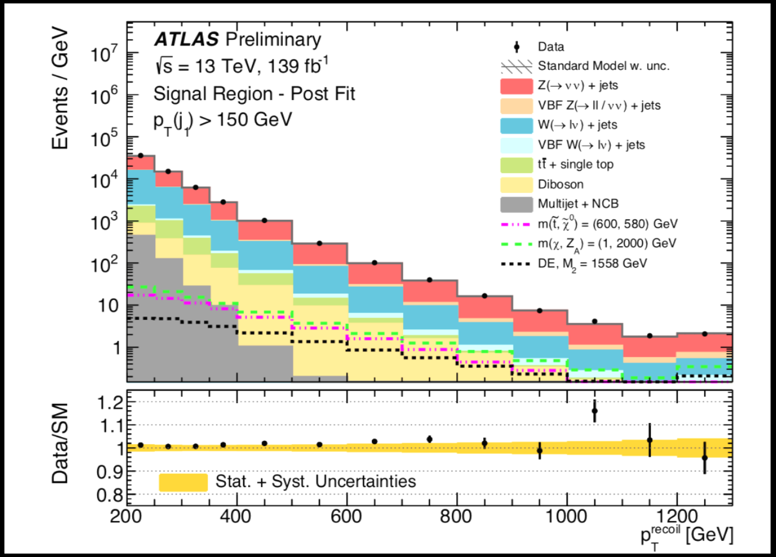
- Triumph of **experiment** and **theory**
- The Standard Model provides a successful description of the data

Huge progress as well on the theory side, NNLO calculations (NNLO revolution!)

Search for Physics Beyond the Standard Model



Data: events with at lest one jet (E_T>150 GeV) and E_T^{miss} >200 GeV



Good agreement between data and expectations from SM processes

→ No hints for BSM contributions

Important Open Questions

1. Mass

The Higgs boson exists!

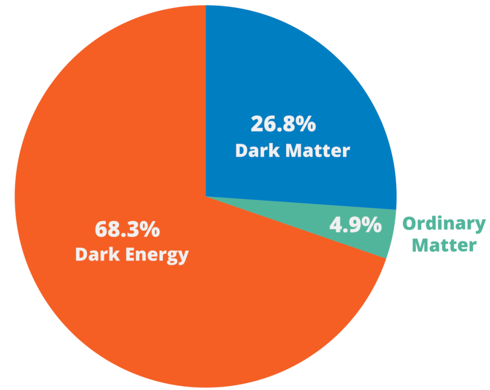
Does it have the predicted properties?

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

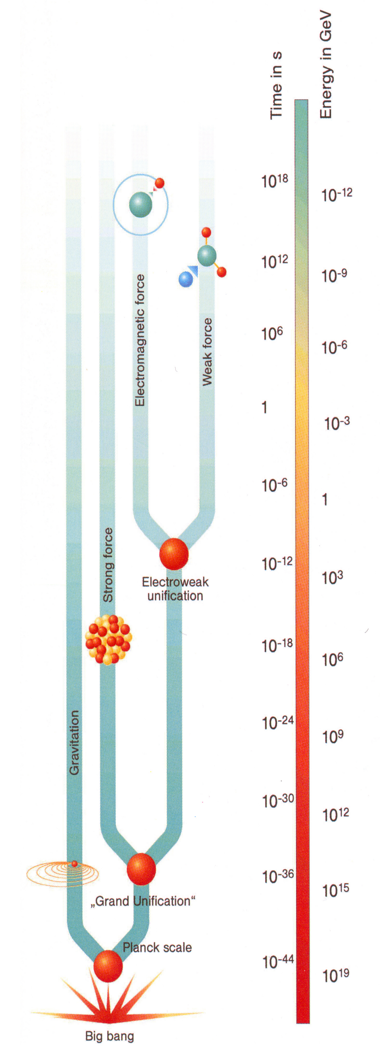
Can the different interactions be unified?

How can gravity be incorporated?

Why is gravity so weak?

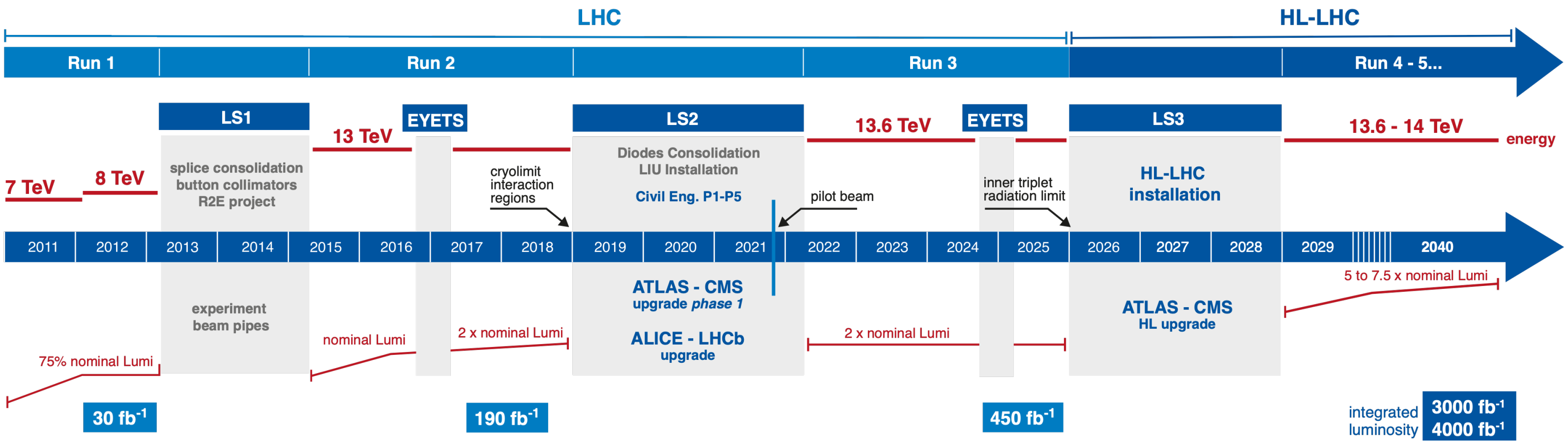
3. Structure and composition of matter

- 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})

Major focus: - **Higgs boson**

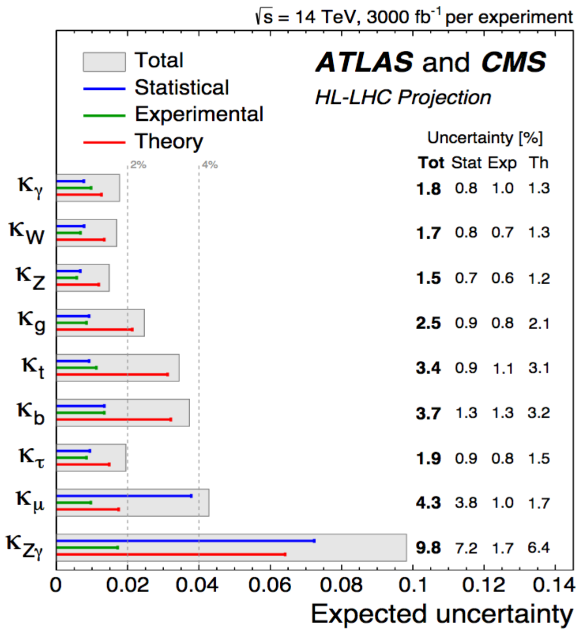
(more precise measurements, differential cross sections, EFT interpretations, Higgs self coupling)

- **Direct searches for new physics** (more exotic scenarios, e.g. long life times)

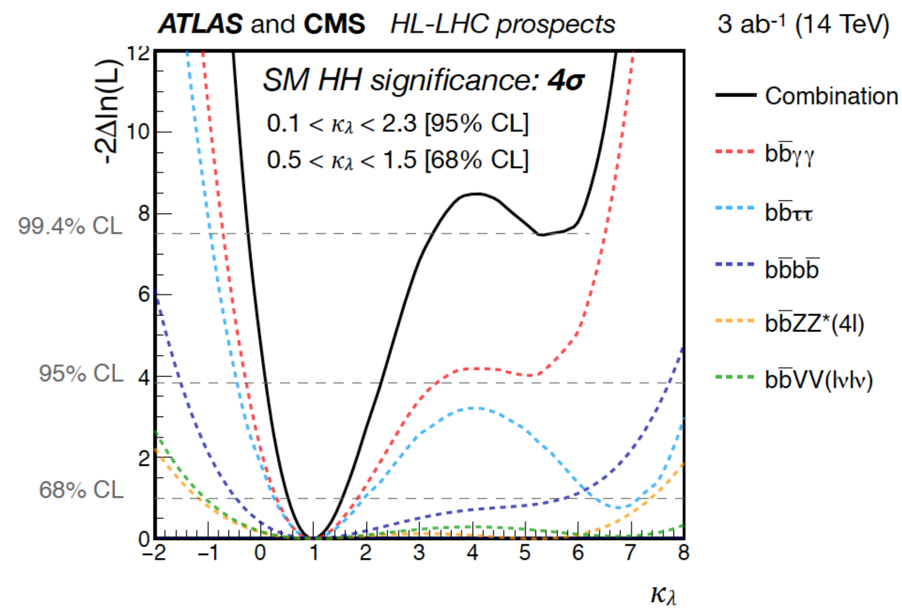
Expected HL-LHC sensitivity: Higgs

Precision on Higgs coupling strength modifiers κ_i

(assuming no BSM particles in Higgs boson decays)



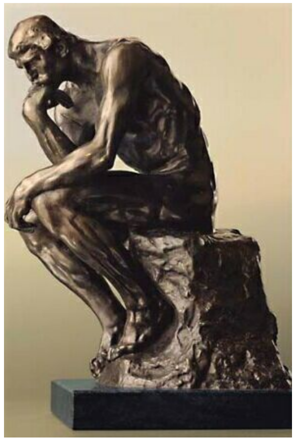
Higgs boson self-coupling?



HL-LHC:

- Very significant improvement of the precision on the Higgs boson couplings (reach level of few %)
- First sensitivity on the Higgs boson self coupling (±50% uncertainty)

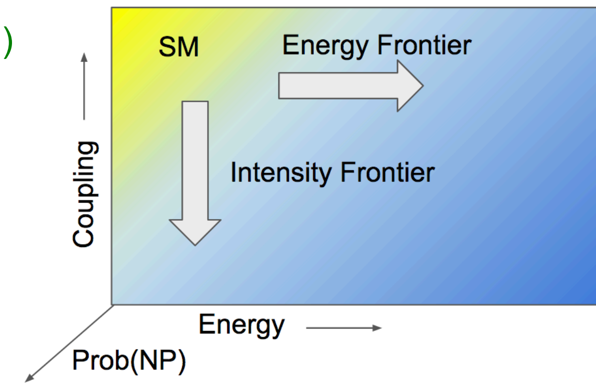
Towards the long-term future



- 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,…)



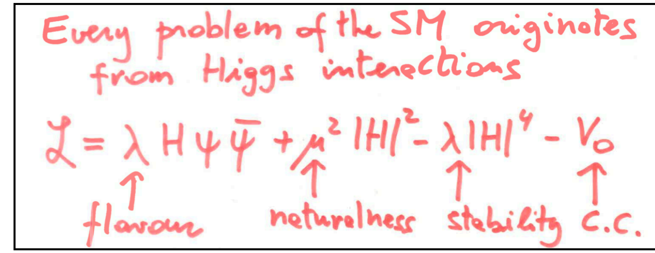
No strong guidance from theory

Experiments must show the way!

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

Fabiola Gianotti, LHCP Conference 2021

- 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, …)



G. Giudice, CERN

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

- Precision measurements of couplings (as many generations as possible, decays via loops, …)
- Higgs boson self coupling → Higgs potential
- Forbidden, rare and exotics decays, e.g. H → $\tau\,\mu$ → flavour structure and source of fermion masses
- Other Higgs boson properties (CP admixture?)
- Probe of compositeness
- Search for additional Higgs bosons

The outstanding questions are compelling, difficult and interrelated

→ They can only be successfully addressed through a **variety of approaches**

- Particle colliders
- Dark matter direct and indirect searches
- Neutrino experiments
- Cosmic surveys
- Measurements of rare processes
- Dedicated searches (e.g. axions, dark-sector particles, feebly interacting particles, …)

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

(1) **Scientific diversity**, and the **combination of complementary approaches**, are crucial to explore directly and indirectly the largest range of energy scales and couplings, and to properly interpret signs of new physics to reach the goal to build a coherent picture of the underlying theory

(2) **Global coordination and optimisation** of the particle physics programme is necessary to maximise the opportunities of the field, given the exciting physics questions, the cost and complexity of the projects

2020 Update of the European Strategy for Particle Physics

Update of the European Strategy for Particle Physics

2. General considerations for the 2020 update

…

Europe, through CERN, has world leadership in accelerator-based particle physics and related technologies. ***The future of the field in Europe and beyond depends on the continuing ability of CERN and its community to realise compelling scientific projects.*** *This Strategy update should be implemented to ensure Europe's continued scientific and technological leadership.*

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.

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:

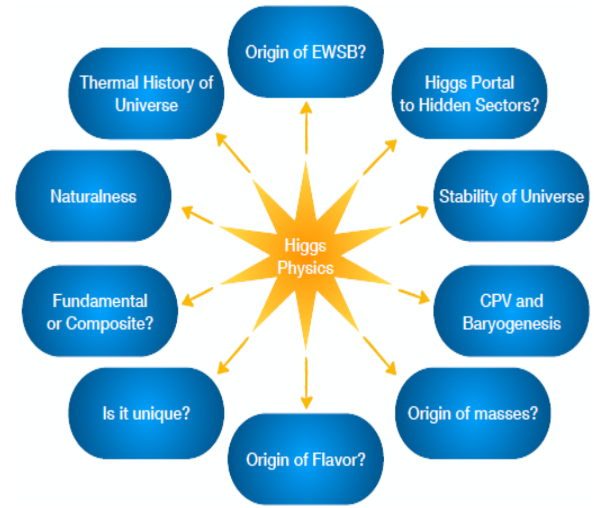
1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

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

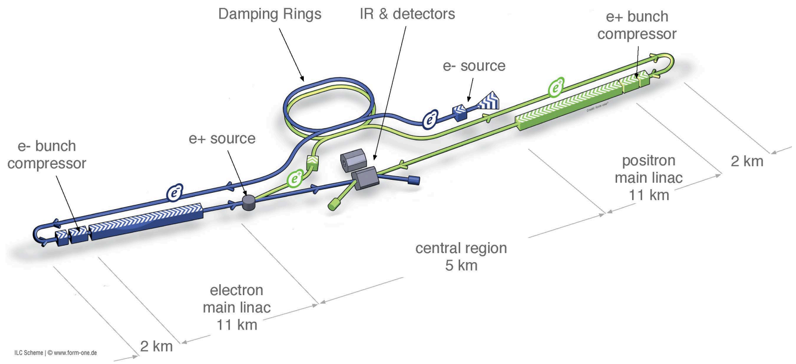
- In addition: prioritisation of the **HL-LHC physics** exploitation programme

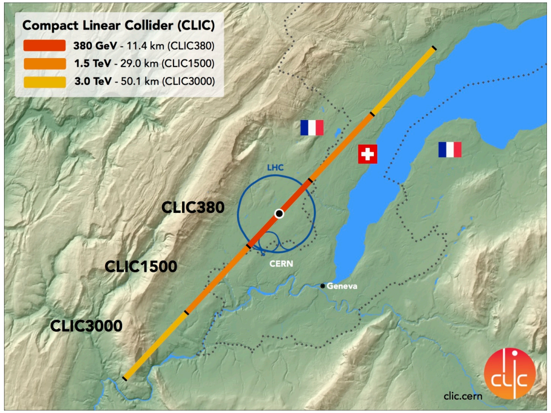
  and

  R&D towards a **TeV-scale Muon Collider**

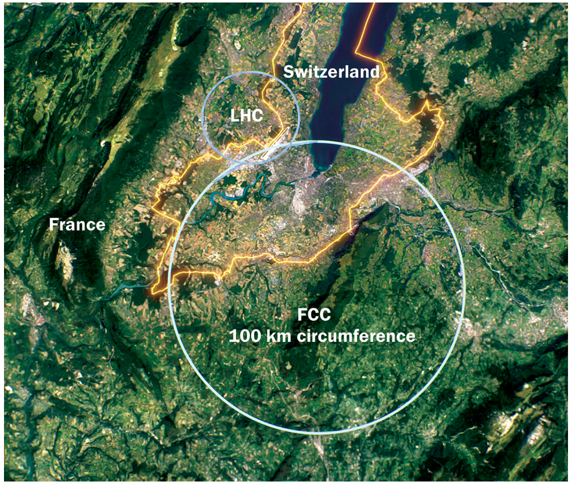
High-energy e^+e^- collider projects

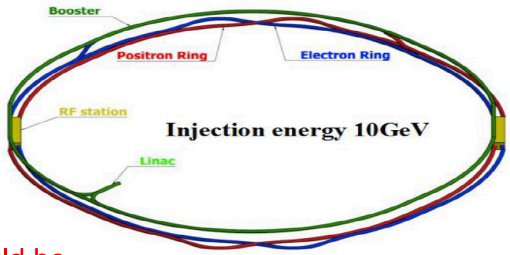
Linear Colliders





Circular Colliders



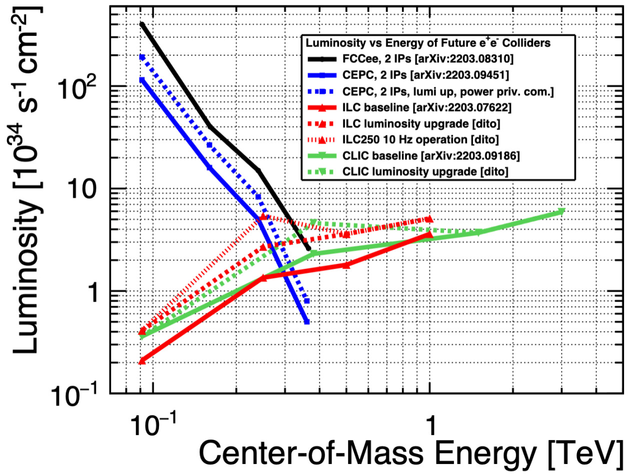


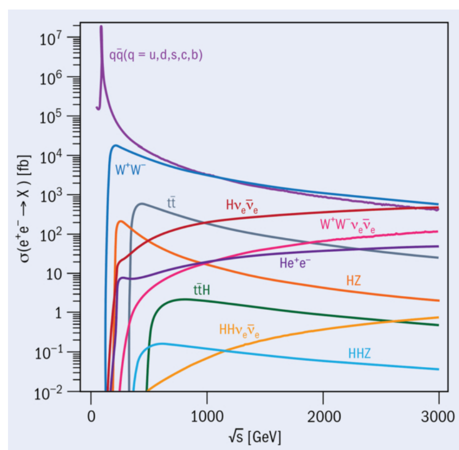
The same rings could be used in a second stage to host a ~100 TeV pp collider

Circular or linear e^+e^- colliders?

Circular e^+e^- colliders

- FCC-ee, CEPC
- Circumference: 90 - 100 km
- High luminosity & power efficiency at **low energies;**
  → huge rates at Z pole (table below)
- Less luminosity at higher E_{CM} (synchrotron radiation)
- Multiple interaction regions
- Very clean: little beamstrahlung





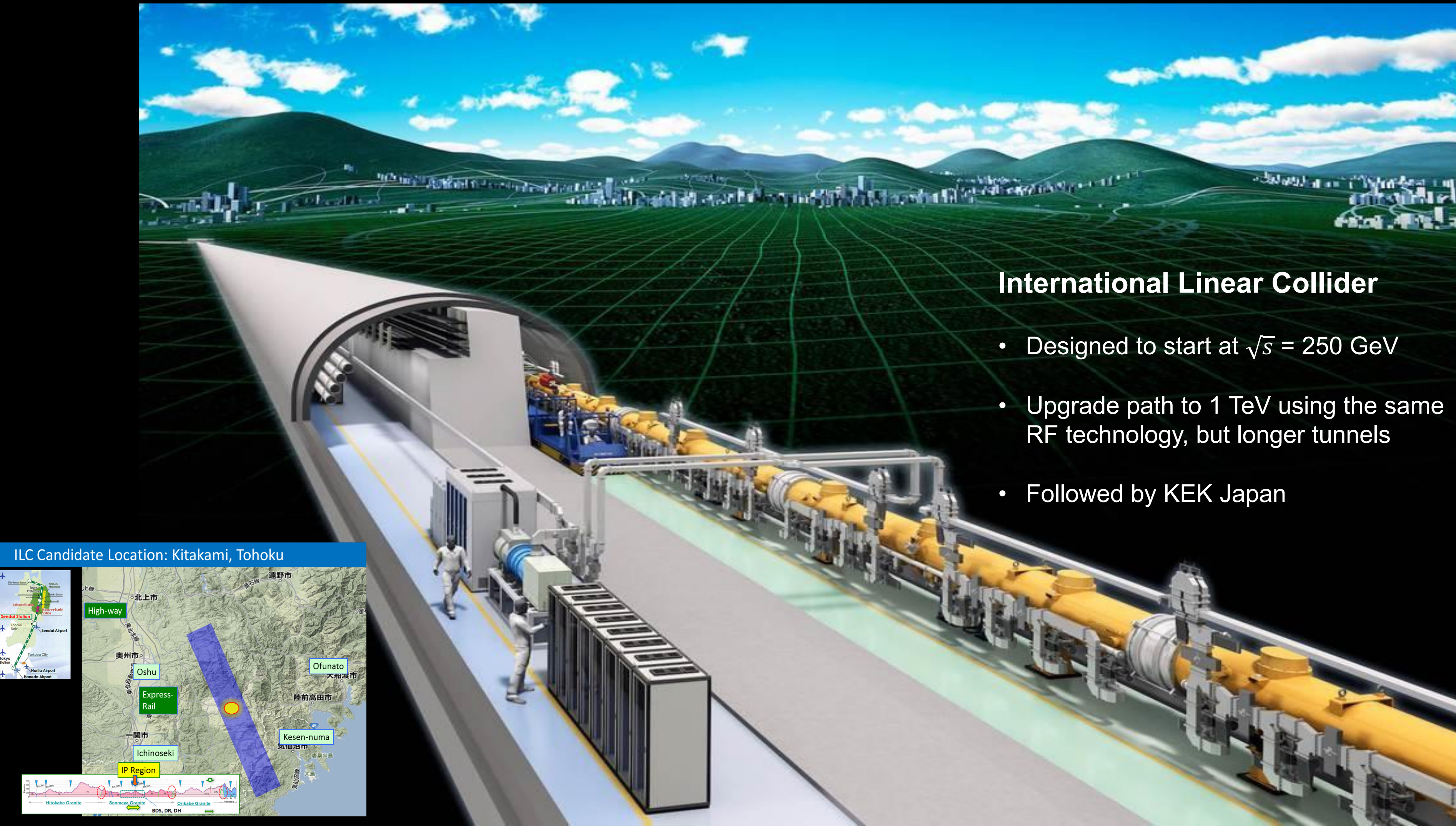
per detector in e^+e^-	# Z	# B	# τ	# charm	# WW
LEP	4 x 10^6	1 x 10^6	3 x 10^5	1 x 10^6	2 x 10^4
SuperKEKB	-	10^{11}	10^{11}	10^{11}	-
FCC-ee	2.5 x 10^{12}	7.5 x 10^{11}	2 x 10^{11}	6 x 10^{11}	1.5 x 10^8

Linear e^+e^- colliders

- ILC, CLIC, C^3 (new idea)
- Length
  ILC: 250 GeV – 1 TeV: 20.5 → 40 km
  CLIC: 380 GeV – 3 TeV: 11.4 → 50 km
- High luminosity & power efficiency at **high energies;**
- **Longitudinally spin-polarised beams**
- Long-term energy upgrades possible

  - longer tunnel, same technology
    and/or
  - replacing accelerating structure with advanced technologies
    (RF cavities with higher gradients, plasma acceleration?)

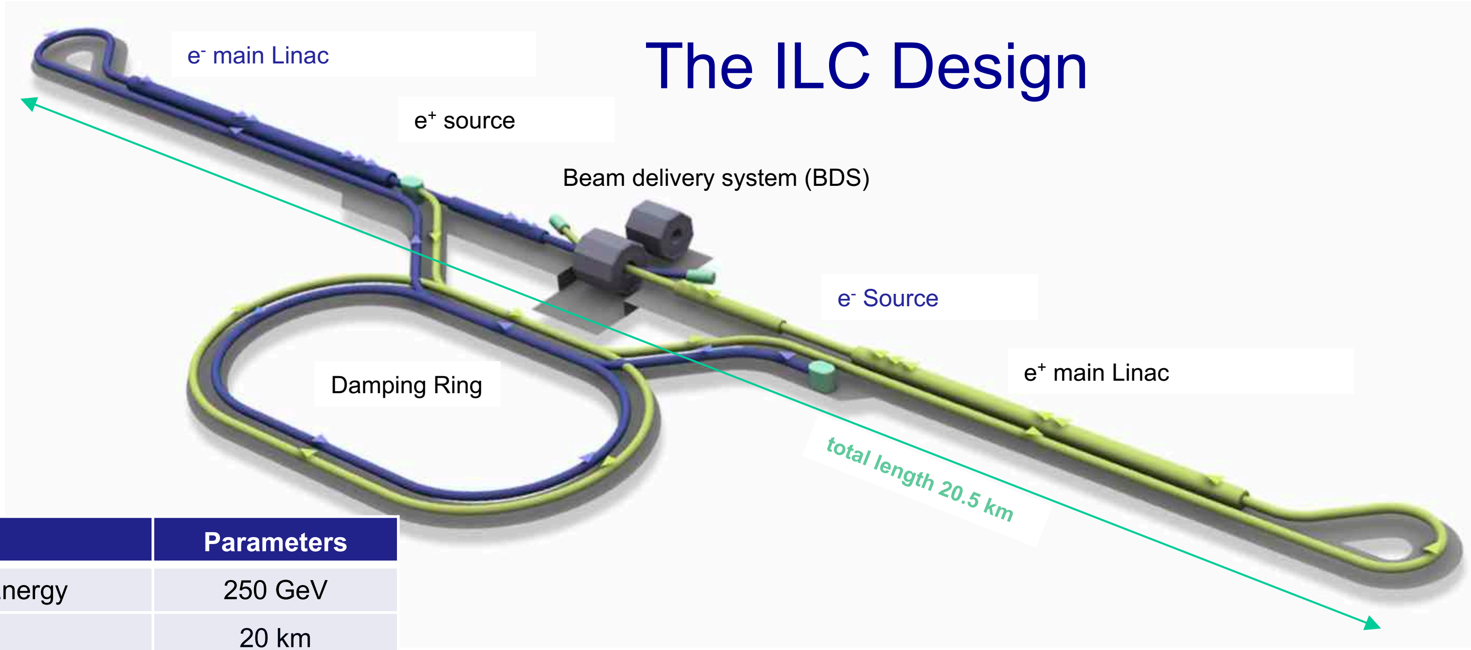
Status of the ILC project



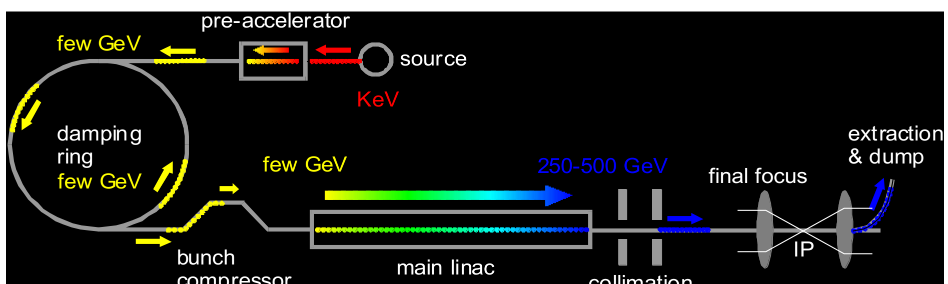
International Linear Collider

- Designed to start at $\sqrt{s}$ = 250 GeV
- Upgrade path to 1 TeV using the same RF technology, but longer tunnels
- Followed by KEK Japan

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}



Key Technologies:

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

Status of Key Technologies

(i) **Superconducting RF**

1.3 GHz, 9 cell cavity

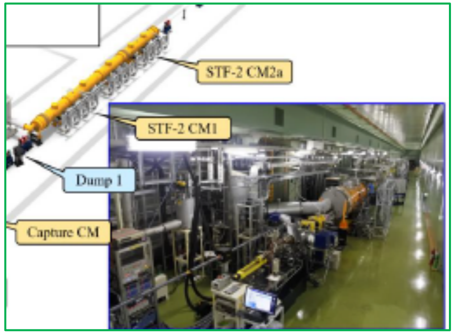
- Capitalize on the massive developments done for light sources worldwide, in particular via the European XFEL at DESY / Hamburg

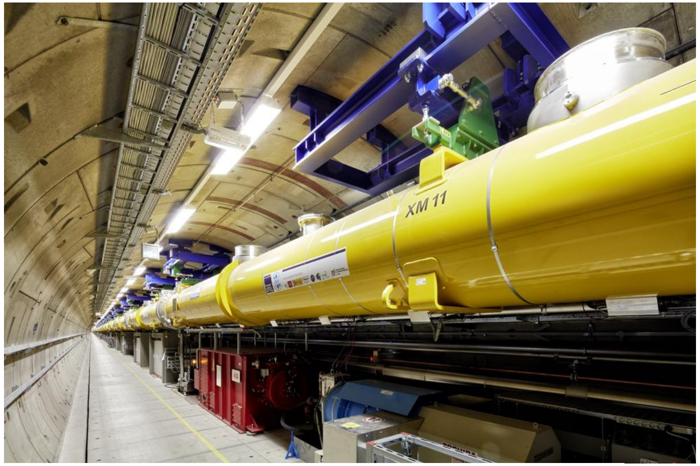
- Ongoing: Optimisation of the RF performance
  (surface treatment, improve efficiency in cavity production, automation of cavity cleaning, …)

  With international participation: Japan, France, Germany, US,…

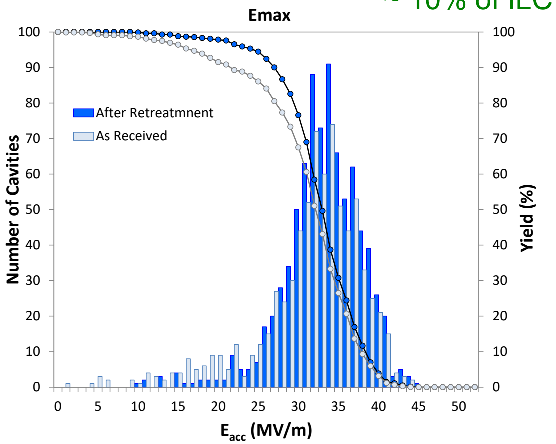
  → higher performance, reduced cost

- Verification of accelerator performance at KEK test facility (KEK-STF2)





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



Good perf. reached on acc. gradient

Cryomodules

Status of Key Technologies

(i) **Superconducting RF**

1.3 GHz, 9 cell cavity

Aim and interest in R&D for (S)RF:

- Higher quality factor Q_0
  → Less power (heat losses) → lower operation cost
- Simpler production → lower construction cost
- Higher gradient → shorter linac

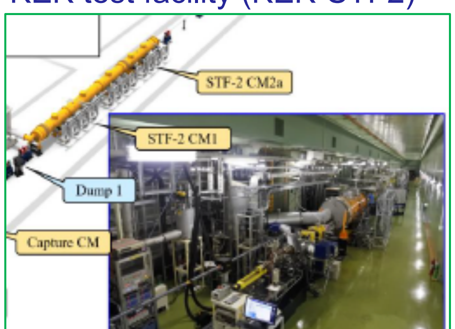
- Capitalize on the massive developments done for light sources worldwide, in particular via the European XFEL at DESY / Hamburg

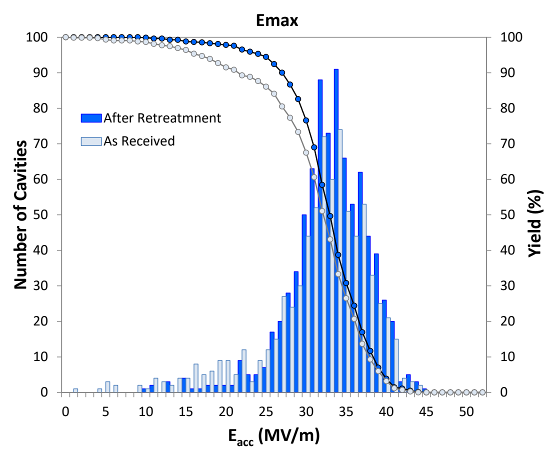
- Ongoing: Optimisation of the RF performance
  (surface treatment, improve efficiency in cavity production, automation of cavity cleaning, …)

  With international participation: Japan, France, Germany, US,…

  → higher performance, reduced cost

- Verification of accelerator performance at KEK test facility (KEK-STF2)





Good perf. reached on acc. gradient

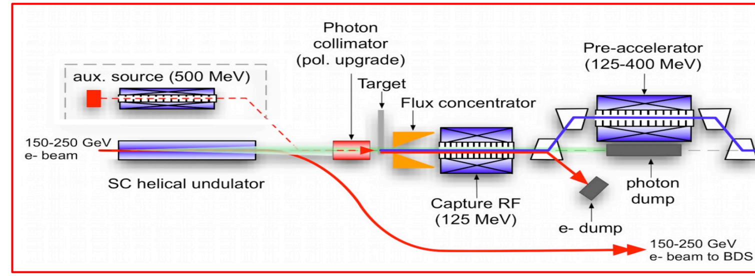
Cryomodules

(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**)

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

Good perf. reached on acc. gradient

Energy and Luminosity upgrade scenarios

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

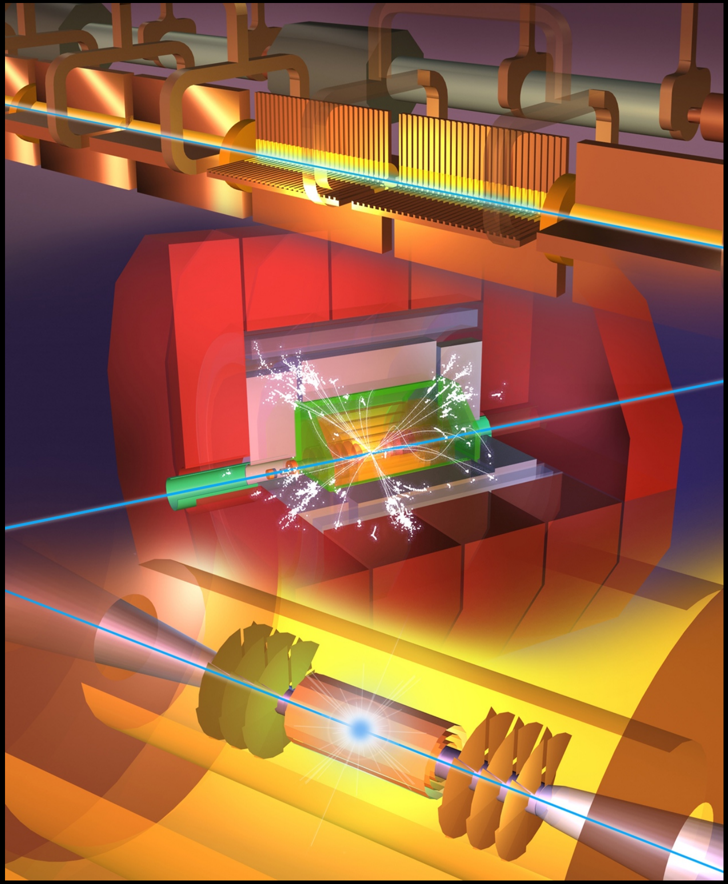
Luminosity: 1.35 10^{34} cm^{-2} s^{-1} → 4.9 10^{34} cm^{-2} s^{-1}

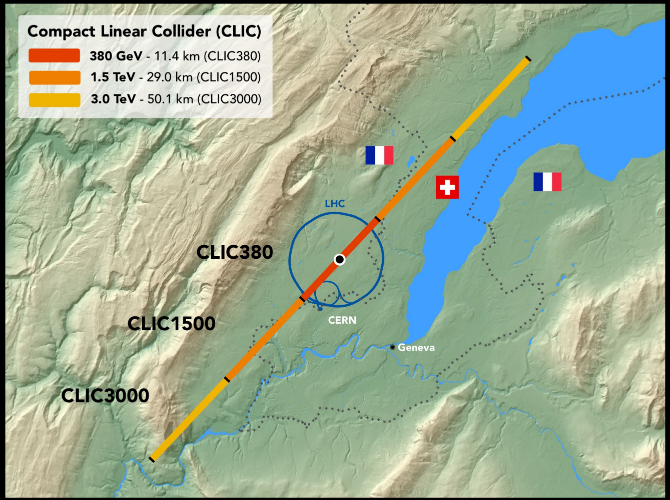
High degree of polarisation

Length: 20.5 km → 40 km

Power: **129 MW (250 GeV) → 300 MW (1 TeV)**

CLIC: Compact Linear Collider

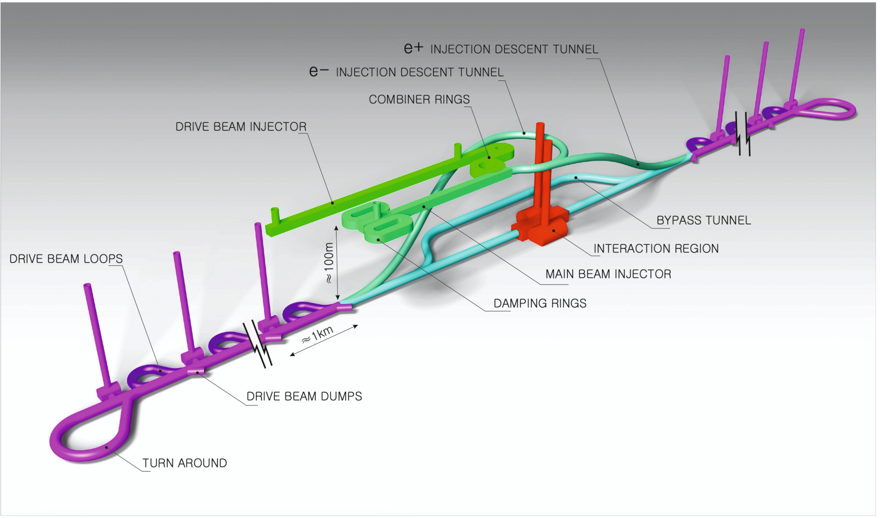


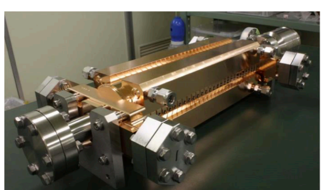


Compact Linear Collider

- Designed to start at $\sqrt{s}$ = 380 GeV
- Upgrade path to 3 TeV
- Studied at CERN / CLIC Collaboration

The Compact Linear Collider





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

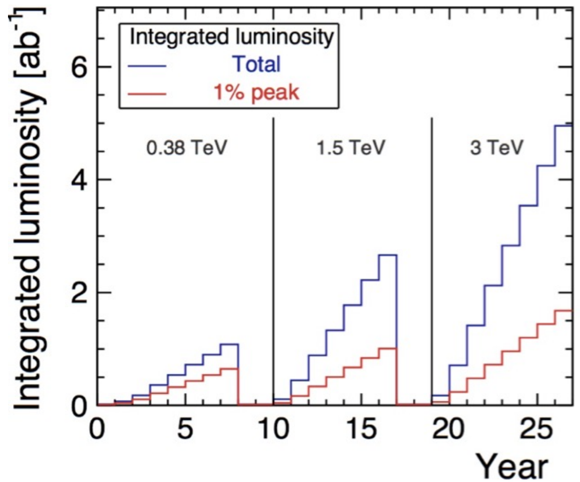
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC (~2035 Technical Schedule)
- **Compact: Novel and unique two-beam accelerating technique** with high-gradient room temperature RF cavities (~20’500 cavities at 380 GeV)

  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

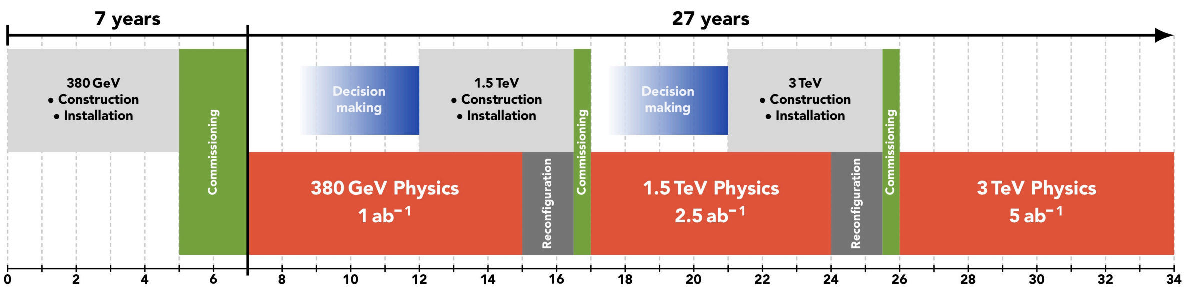
CLIC parameter and timeline

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

arXiv:1810.13022



Ramp-up and up-time assumptions



Technology-driven schedule from start of construction (5 years preparation phase + 2 years initial commissioning)

Technical developments and next steps

Many technical developments have been carried out over the past decades

→ Also the CLIC accelerator studies are mature:

- Many tests in CLIC Test Facility (CTF3)
- Technical developments of "all" items

Key issues to be addressed:

- The CLIC community is preparing a **Project Readiness Report (PRR)** for the next ESPP (2026/27)
- Focus of ongoing R&D on operation in initial 380 GeV phase:
  RF technology readiness
  Optimisation of luminosity
  Improving the power efficiency

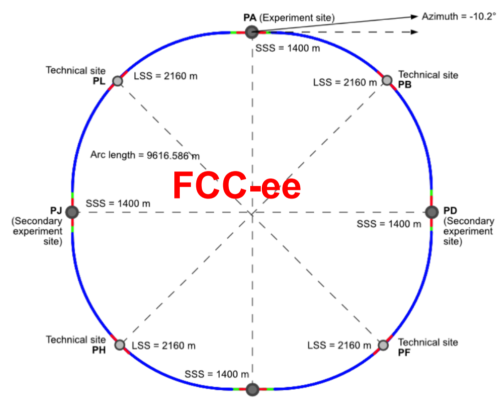
FCC: Future Circular Collider

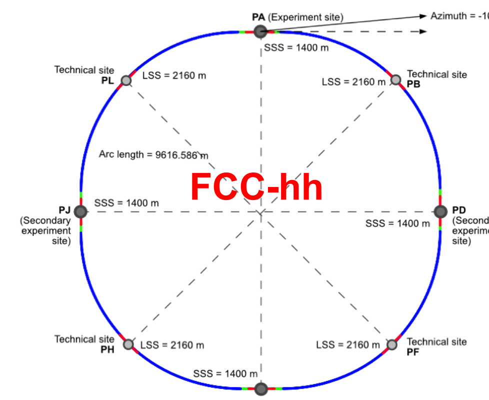
FCC integrated programme

Comprehensive long-term programme maximising physics opportunities:

- Stage 1: FCC-ee : e^+e^- Higgs, electroweak & top factory at highest luminosities [91 GeV → 365 GeV]
- 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

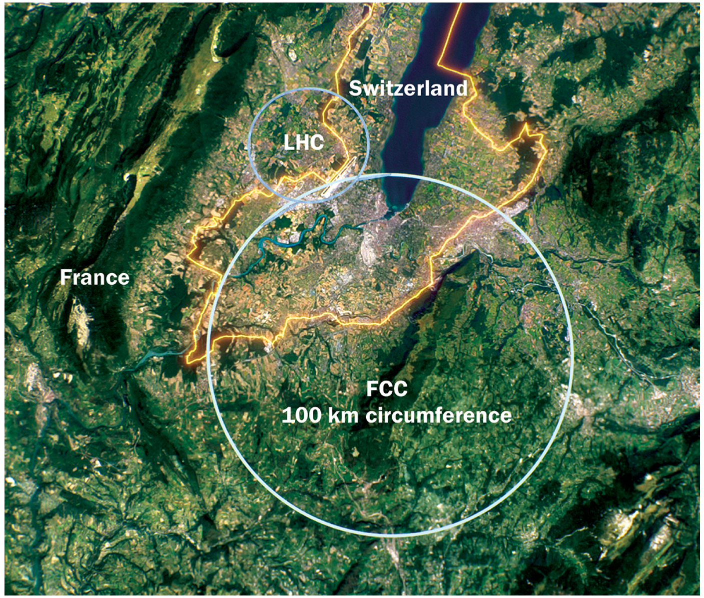
Explore the feasibility for an integrated FCC-ee / FCC-hh programme at CERN

- 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



FCC Feasibility Study

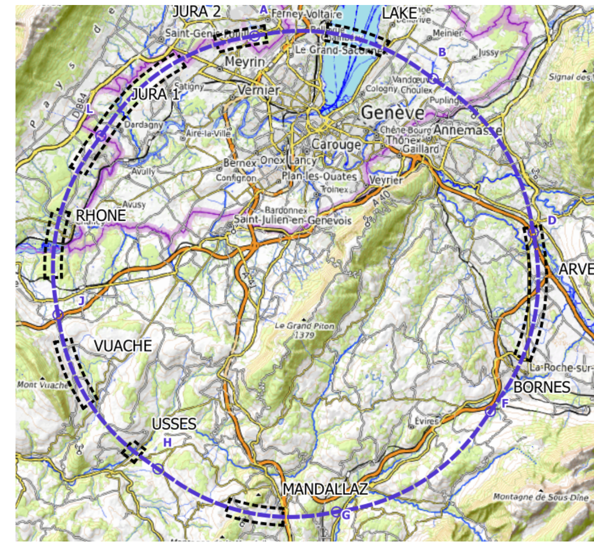
Explore the feasibility for an integrated FCC-ee / FCC-hh programme at CERN

- 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



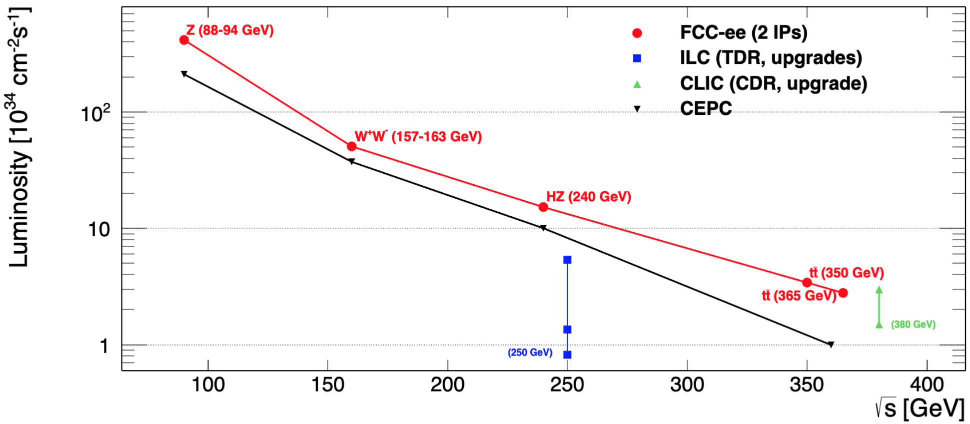
Converging on a "low risk" placement with circumference of 91 km

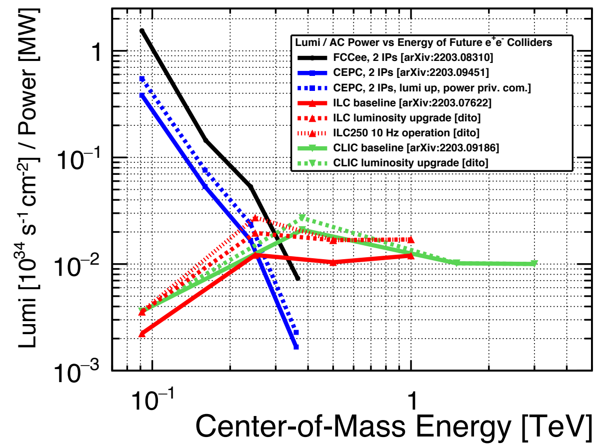
(4-fold symmetry, 8 surface points, 2-4 e^+e^- experiments)

FCC-ee Luminosity

- FCC-ee can cover the full energy range from the Z pole to the $t\bar{t}$ threshold with high luminosity; Efficient luminosity / power ratio

arXiv:2203.06520



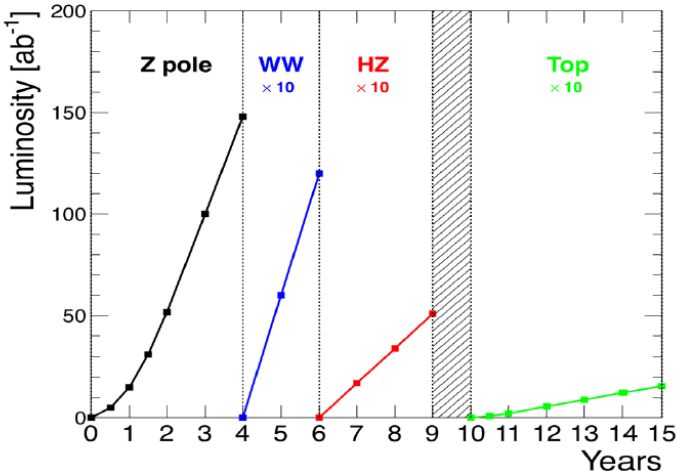


- Built on large progress made at circular e^+e^- colliders over the past decades → reach luminosities beyond 10^{34} cm^{-2} s^{-1}
  (e+e- B factories, SuperKEKb, … + EIC in the US (approved, to be realised before FCC-ee))

- Important ingredients: high-Q superconducting RF, efficient RF power system, twin-aperture magnets, efficient injection, ...

- Technology to build FCC-ee is available; optimisation done to increase efficiency on RF power sources, SC cavities, power consumption, injection, …
  + design and optimisation of machine-detector interface

FCC-ee Running scenarios and Physics Yield



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} cm^{-2}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 → H	10^6 $t\bar{t}$ +200k HZ +50k WW → H		(6000)

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

Under study!

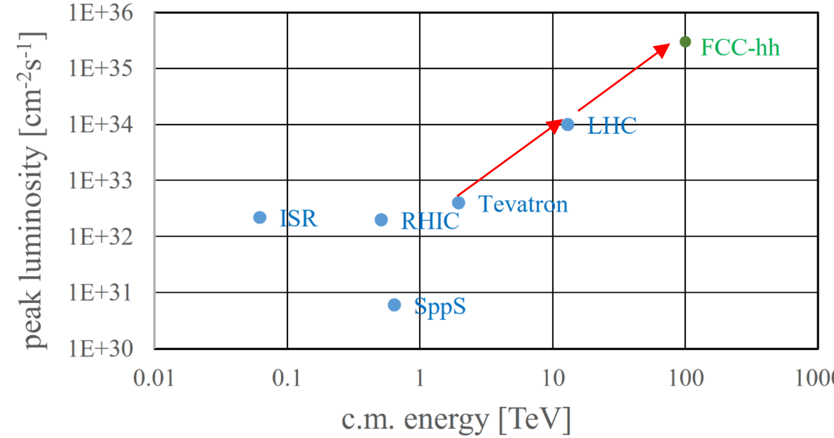
Needs strong monochromatisation of the beams

- 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 Hνν 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)

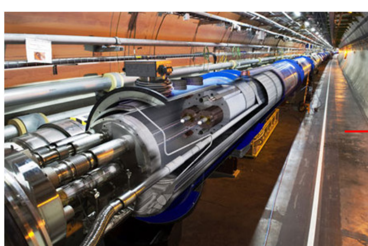
Stage 2: FCC-hh

- 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



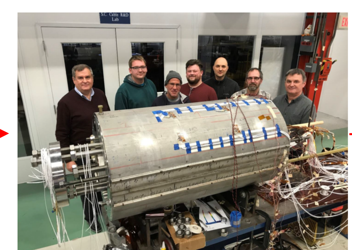
- Large challenges: - High bending power → high-field magnets with field strength of 16 – 20 T;
  - Costs (linked to magnets)

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)



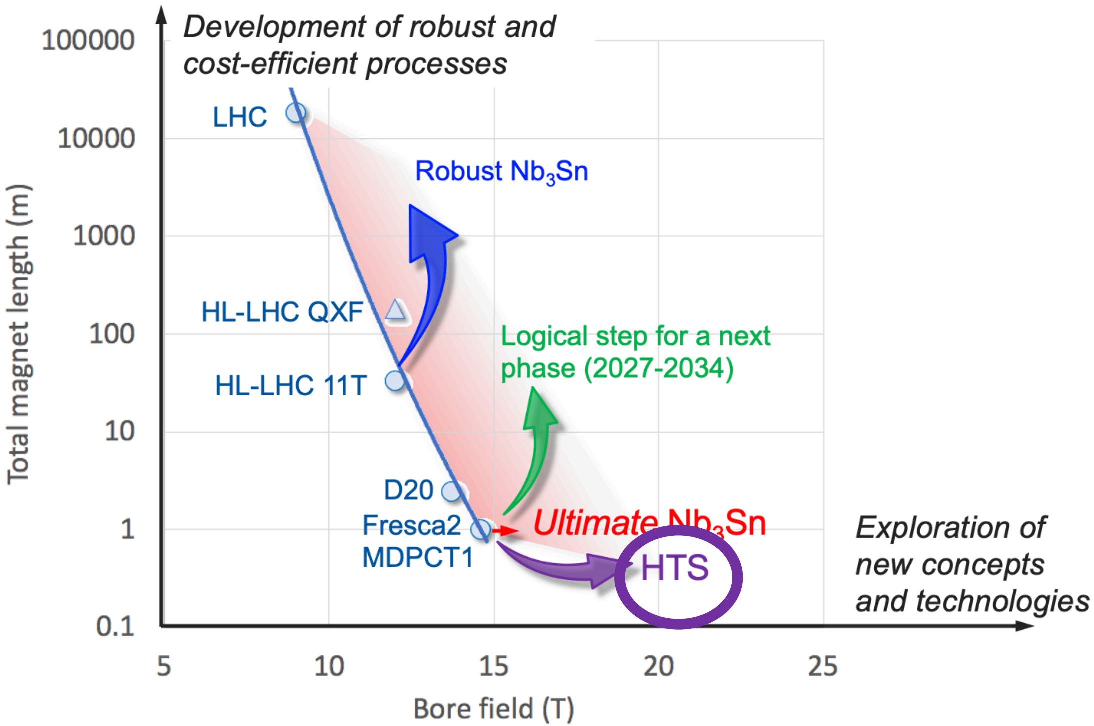
.. to high-field, high performance, industrially mass-produced FCC-hh dipole magnets

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

→ more later, accelerator R&D roadmap

FCC-hh: High-field magnet development programme

In parallel to FCC-ee studies, CERN and other labs are pursuing a long-term High-Field Magnet development programme (embedded in European Accelerator R&D roadmap process)



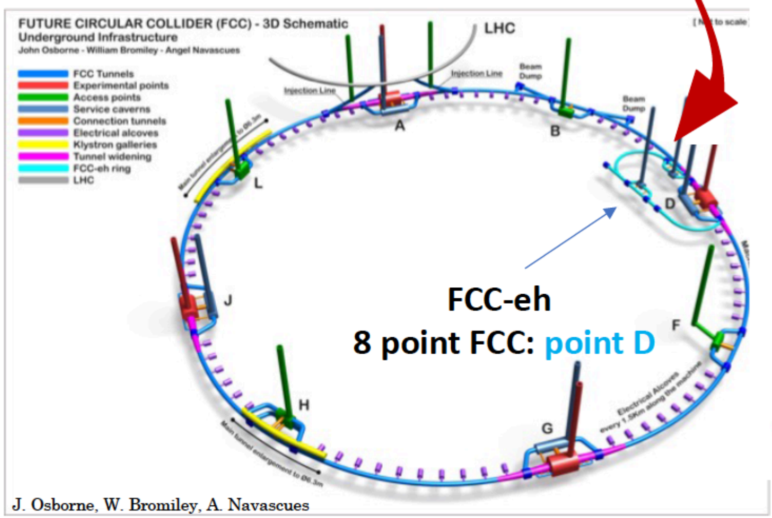
Main R&D activities:

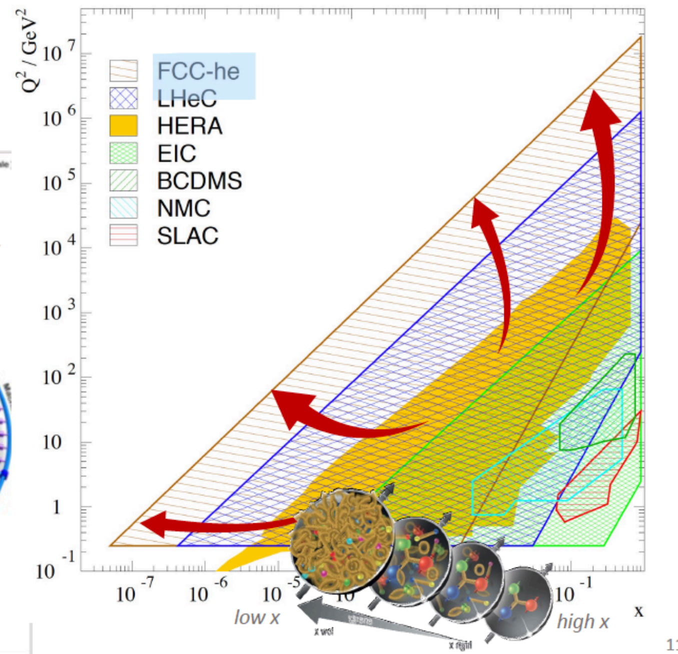
- Materials: goal is ~16 T for Nb_3Sn, at least ~20 T for HTS inserts
- Magnet technology: engineering, mechanical robustness, insulating materials, field quality
- Production of models and prototypes: to demonstrate material, design and engineering choices, industrialisation and costs
- Infrastructure and test stations: for tests up to ~ 20 T and 20-50 kA

Possible stage 2b: FCC-eh

Jorgen D'Hondt, FCC Meeting, UK, June 2023

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



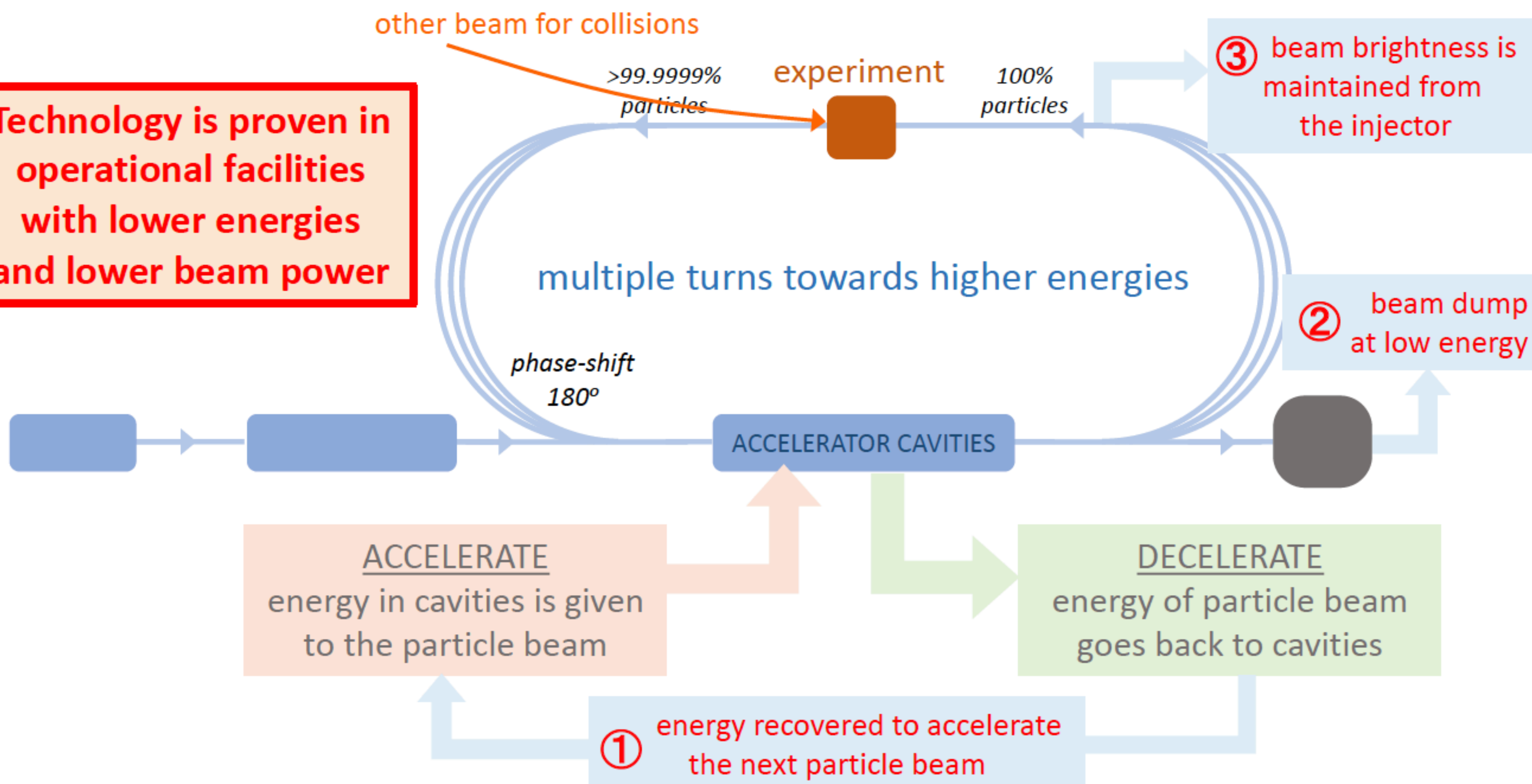


- Requires addition of an electron ring (layout as Energy Recovery Linac, → next slide)
- Complements physics programme: QCD, pdfs, but also large potential in el.weak physics!

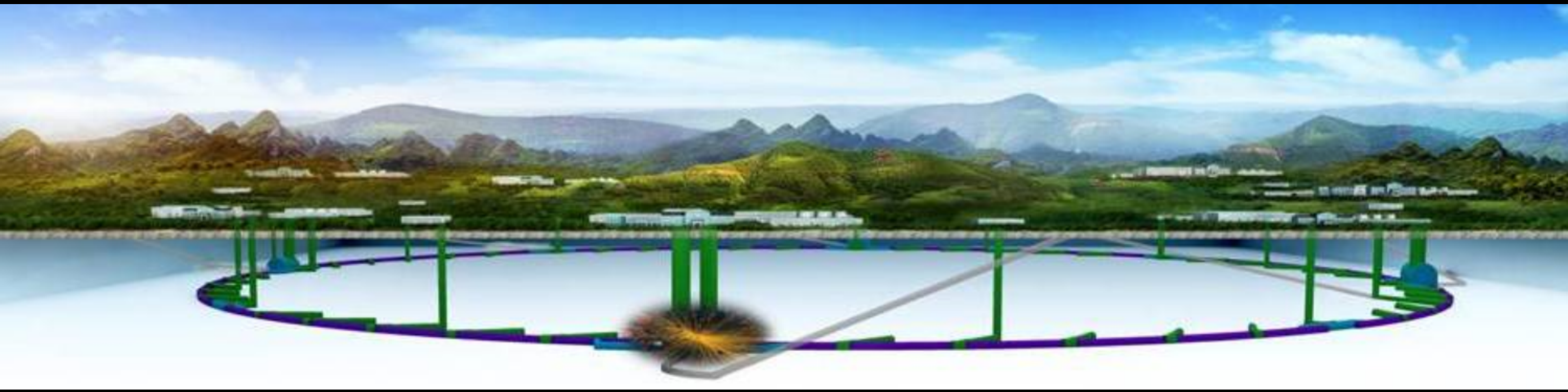
The principle of Energy Recovery Linacs

Jorgen D'Hondt, FCC Meeting, UK, June 2023

Technology is proven in operational facilities with lower energies and lower beam power



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)

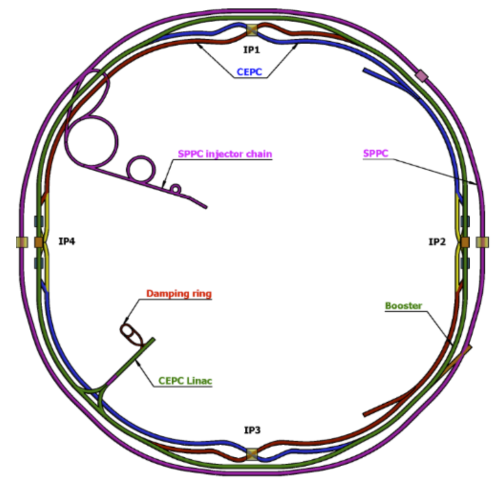
Approval status:

- TDR in preparation, incl. cost review
- Aiming for approval in next 5-year plan (2025)
- Ranked 1st in Chinese HEP preselection

CEPC layout and running scenarios

Yifang Wang, CEPC Meeting, UK, June 2023

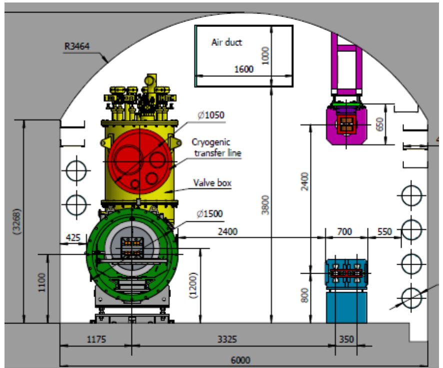
- 100 km circumference: Optimum for total cost
- Shared tunnel: Compatible design for CEPC and SppC
  (Super proton-proton Collider)
- Switchable operation: Higgs, W/Z, top (lattice optimisation for all energies)
- Accelerator complex comprised of a Linac,
  100 km booster and collider rings



- CEPC will commence its operation with a focus on **Higgs boson physics as top priority**
  → Large samples of Higgs bosons during initial phase
  $(2.6 – 4.3) \cdot 10^6$ events collected over 10 years

  → Large samples of Z bosons: $(2.5 – 4.1) \cdot 10^{12}$ events collected later

  (details in backup material)



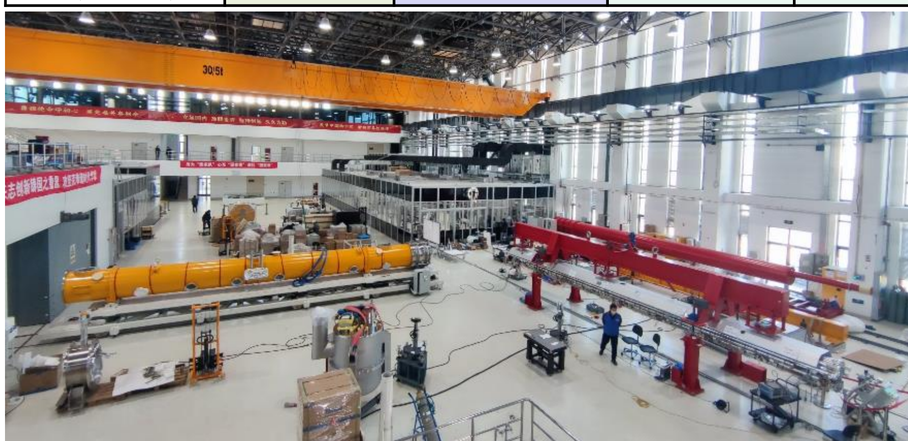
Common tunnel for booster/collider & SppC

Example for technical developments: SRF Modules

Yifang Wang, CEPC Meeting, UK, Jun 2023

- 650 MHz test cryomodules including cavities, couplers, HOM absorbers, tuners..., was built and tested OK
- A full eight 1.3 GHz 9-cell cavities with input couplers, tuners, SC magnet, BPM, cryostat, module cart, feed/end-cap, volve-box … was built and tested OK

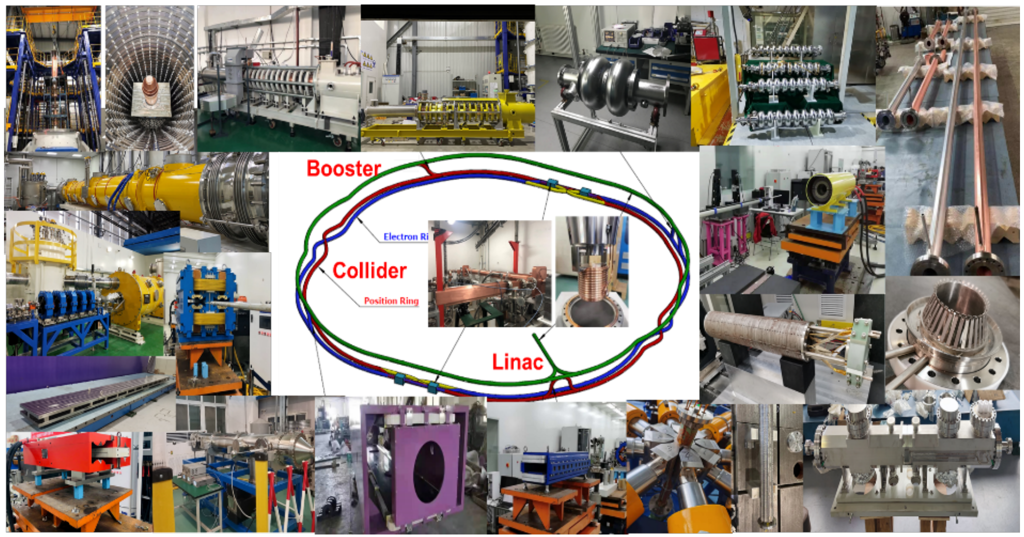
Parameters	Horizontal test results	CEPC Booster Higgs	LCLS-II, SHINE	LCLS-II-HE
Average Q_0 @ 21.8 MV/m	3.4×10^{10}	3.0×10^{10} @ 21.8 MV/m	2.7×10^{10} @ 16 MV/m	2.7×10^{10} @ 20.8 MV/m
Average CW E_{acc} (MV/m)	23.1			



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 ✓ (green)   Prototype Manufactured ✓ (red)

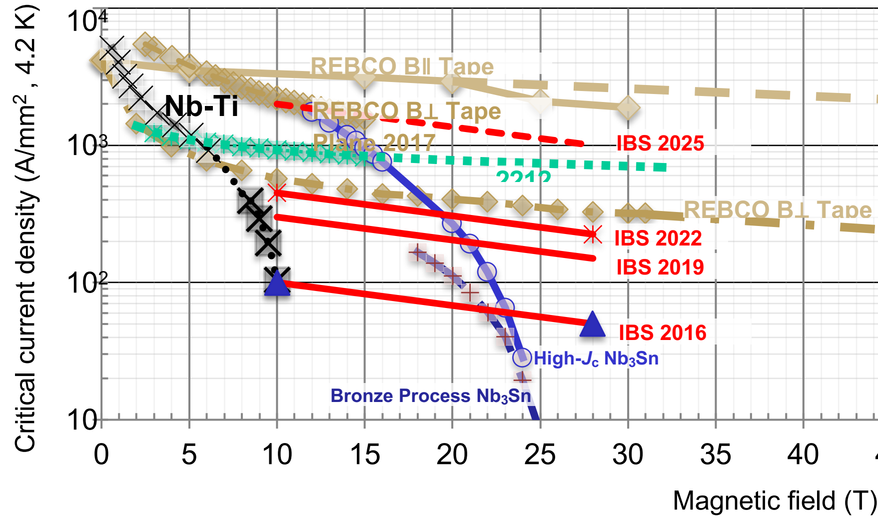
	Accelerator	Fraction
✓ Specification Met	Magnets	27.3%
✓ Specification Met	Vacuum	18.3%
✓ Prototype Manufactured	RF power source	9.1%
✓ Specification Met	Mechanics	7.6%
✓ Specification Met	Magnet power supplies	7.0%
✓ Specification Met	SC RF	7.1%
✓ Specification Met	Cryogenics	6.5%
✓ Specification Met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

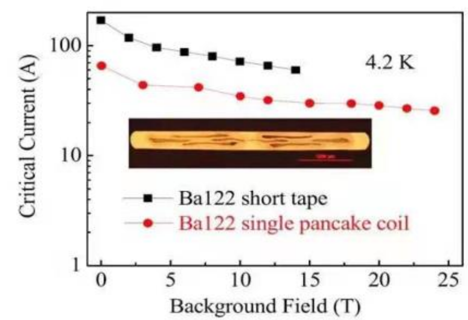
R&D for High-Temperature Superconductors for SppC

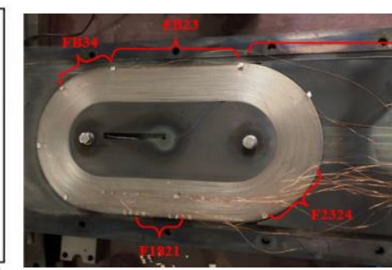
Yifang Wang, CEPC Meeting, UK, June 2023

- **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



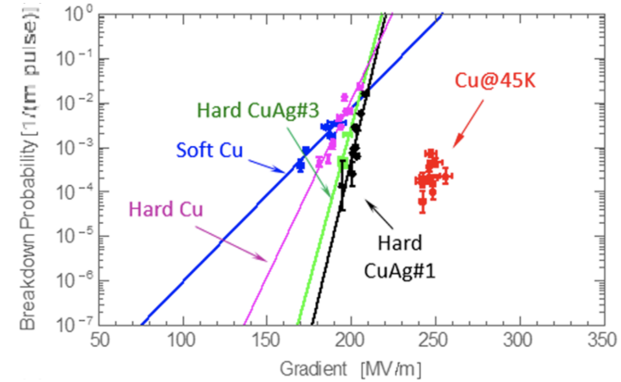




1st iron-based superconducting solenoid coil at 24T

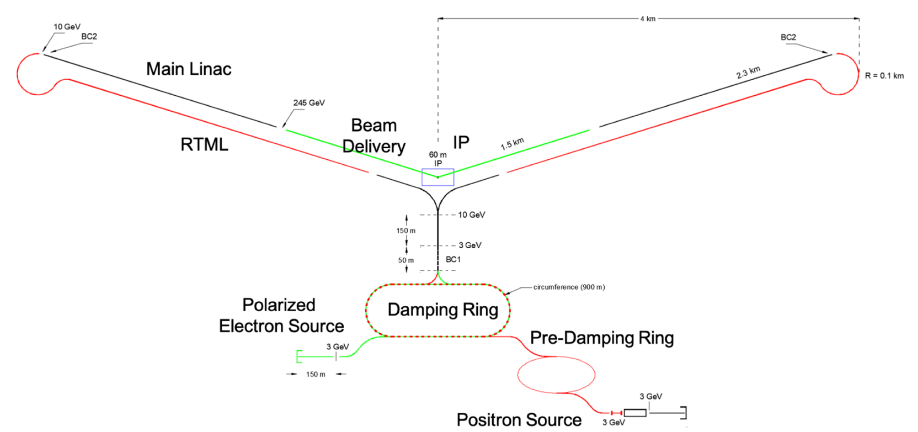
A new, recent proposal: Cold Copper Collider C^3

- 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

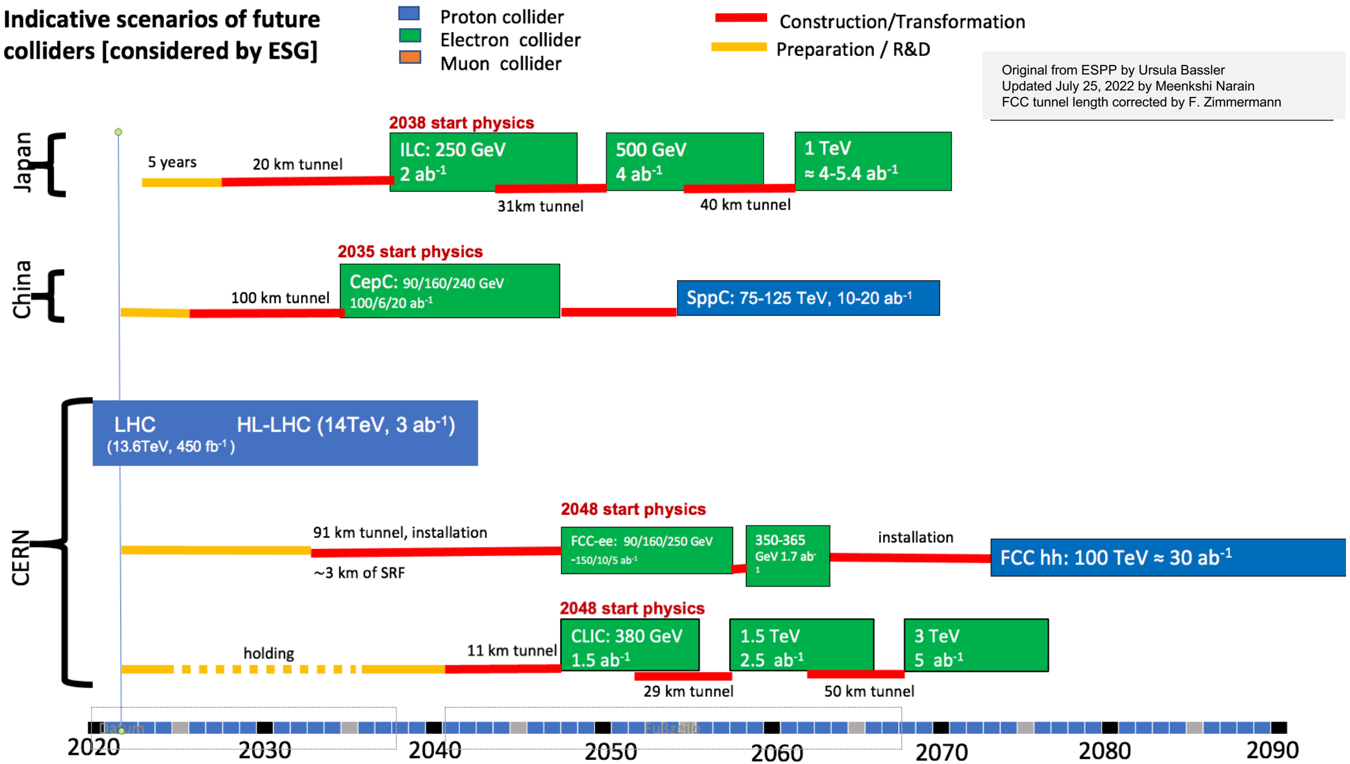


CCC design:
- 8 km footprint for $\sqrt{s}$ = 250 / 550 GeV requires gradients of 70 / 120 MV/m
  Possible site: **Fermilab**
- Large portions of the accelerator complex are compatible with ILC technologies
  (Beam delivery, damping ring and injectors will be optimised with ILC or CLIC as baseline)

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



Timelines



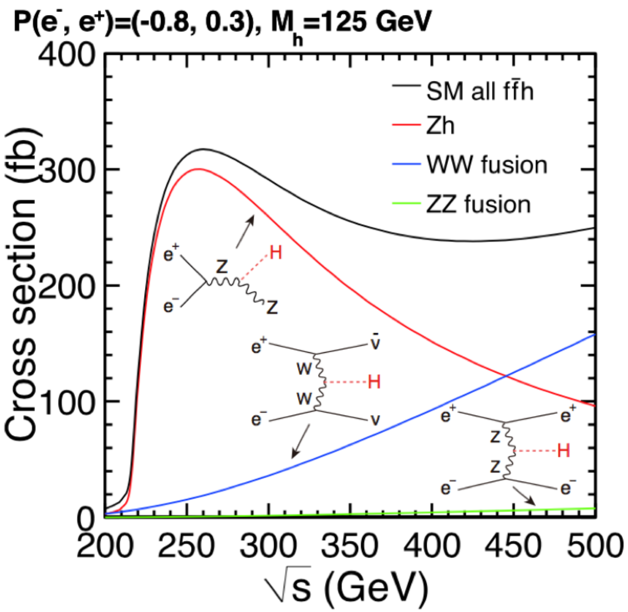
Comments:

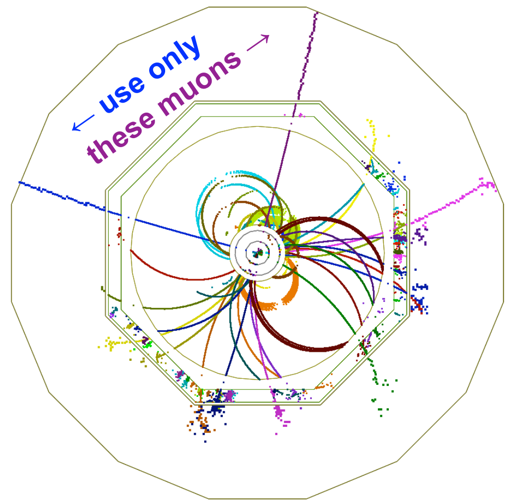
- e^+e^- timelines are limited by approval processes
- CEPC and ILC projects need to pass approval processes in the near future to maintain these schedules
- CERN projects are linked to completion of the HL-LHC
- hh timelines are limited by technological issues, costs, proceeding e^+e^- projects

Physics Potential

- a few selected topics -

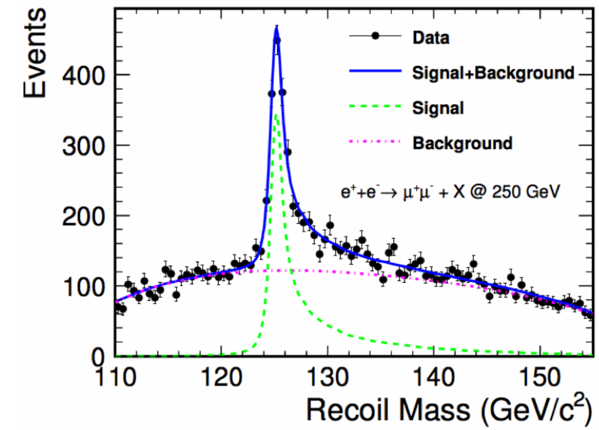
Higgs boson physics





$e^+e^- \to \mu^+\mu^- H \to \mu^+\mu^-\, bb$ (ILD simulation)

(ILD full simulation)



- Higgs physics will start at $\sqrt{s}$ = 240 GeV (cross section for ZH production is maximal)
- Recoil mass fit in $e^+e^- \to$ ZH, with Z $\to \mu^+\mu^-$ $\quad m_{\text{recoil}} = s + m_{f\bar{f}} - 2\sqrt{s}(E_f + E_{\bar{f}})$
  (unique feature at e+e- colliders, the **key to a model-independent normalisation of all Higgs boson couplings**)

→ measurement of **total ZH cross section**
measurement of **excl. Higgs boson final states** → **branching fractions**
→ **model-independent coupling measurements**

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

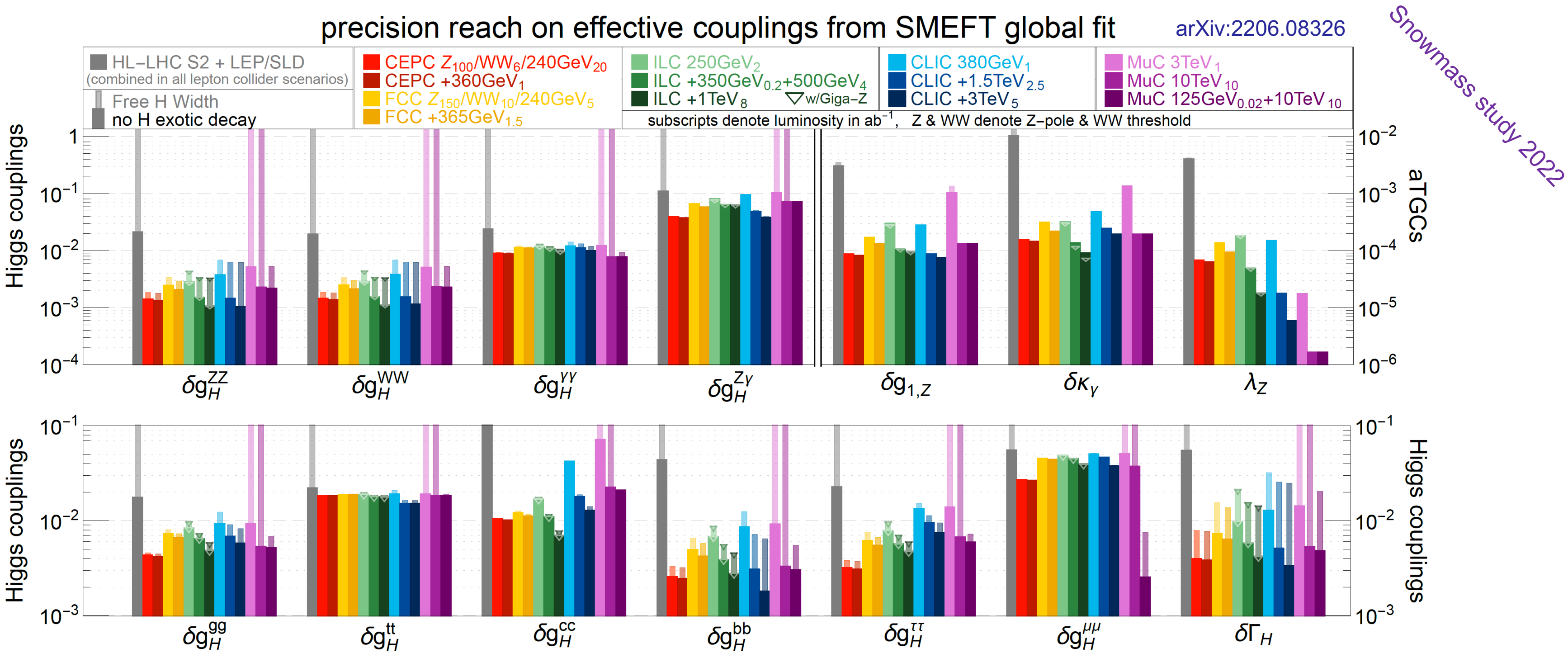
kappa-3 scenario	HL-LHC+									
	ILC_{250}	ILC_{500}	ILC_{1000}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	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
$\mathrm{BR}_{\mathrm{inv}}$ ($<$%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
$\mathrm{BR}_{\mathrm{unt}}$ ($<$%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

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

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

- 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)



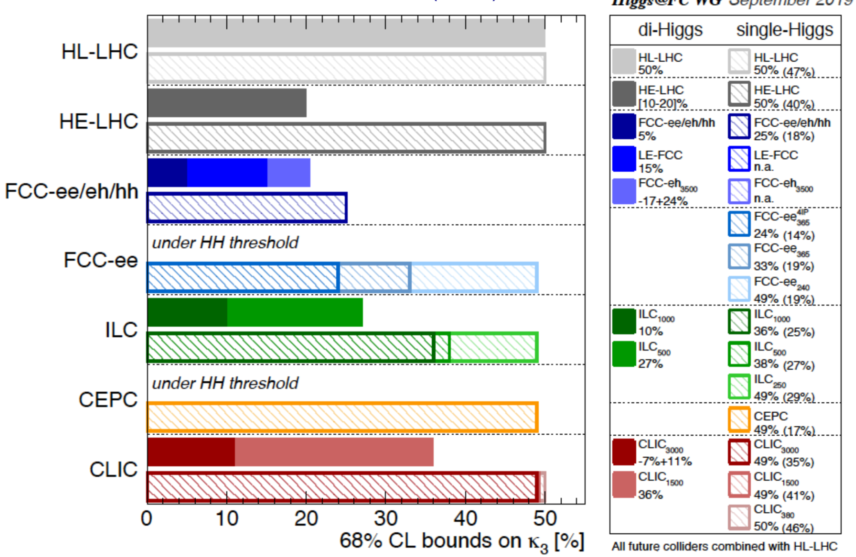
- All e^+e^- colliders show comparable performance (higher luminosities partly compensated by beam polarisation)
- Several couplings well below 1% level: Z, W, g, b, τ

  Others at ~ 1% level: γ, c

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

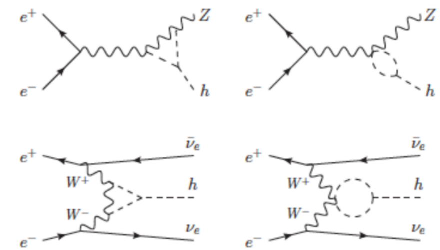
Precision on Higgs boson self coupling

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



- 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

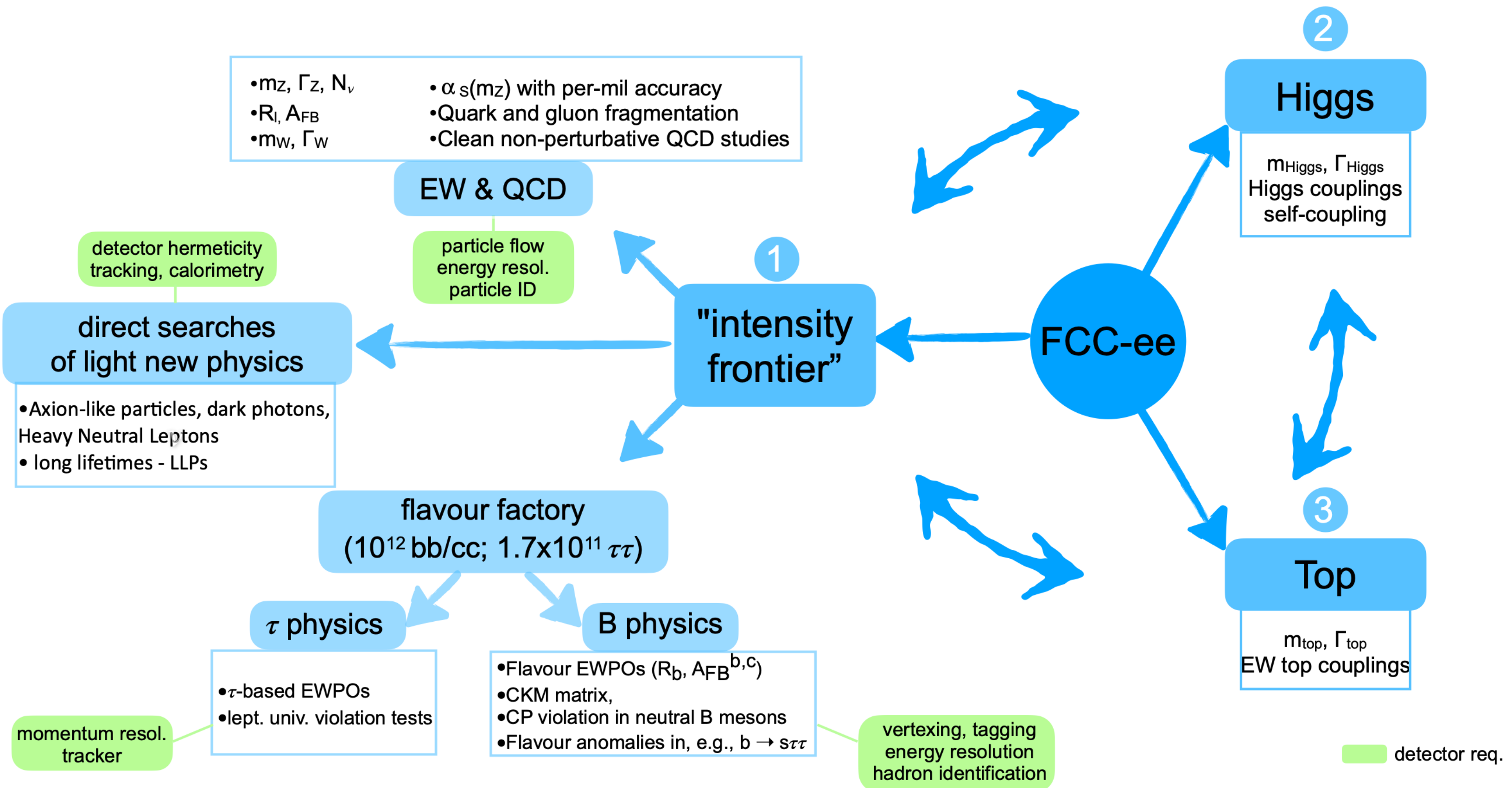
- Higher sensitivity can be reached at high-energy lepton colliders (ILC, CLIC)

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

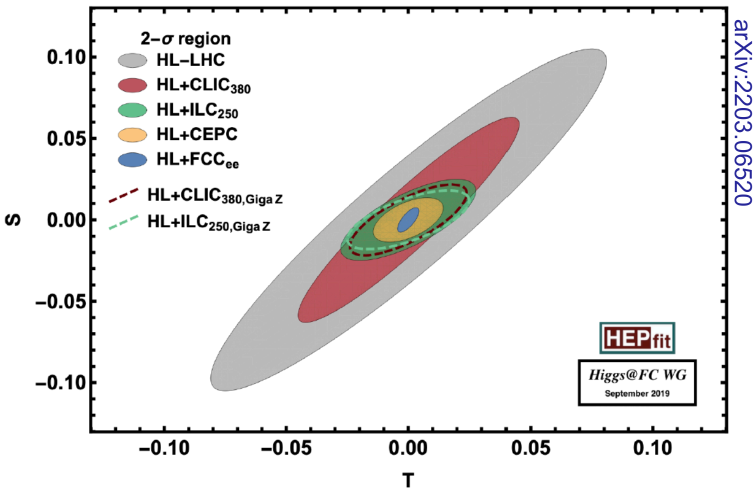
FCC-ee (and CEPC) Z-physics programme

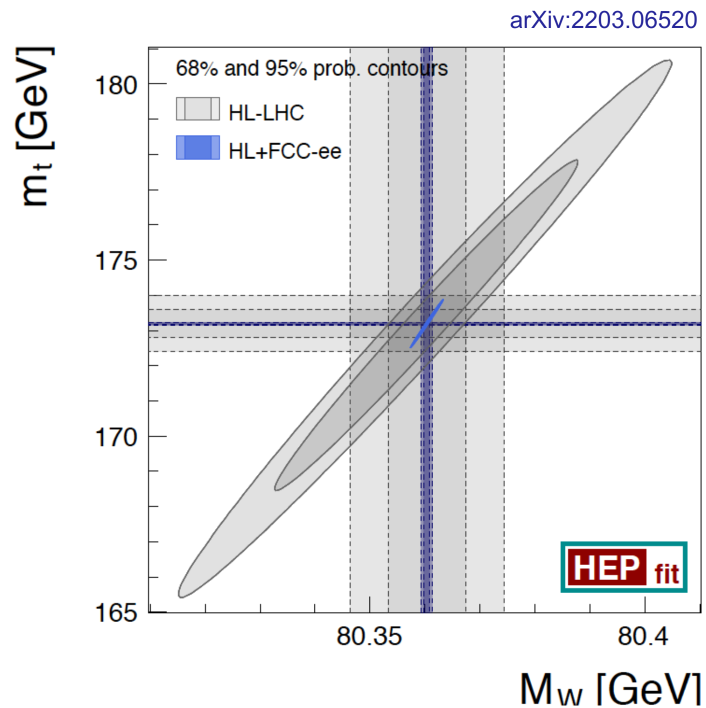
Christophe Grojean, FCC week 2022



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)

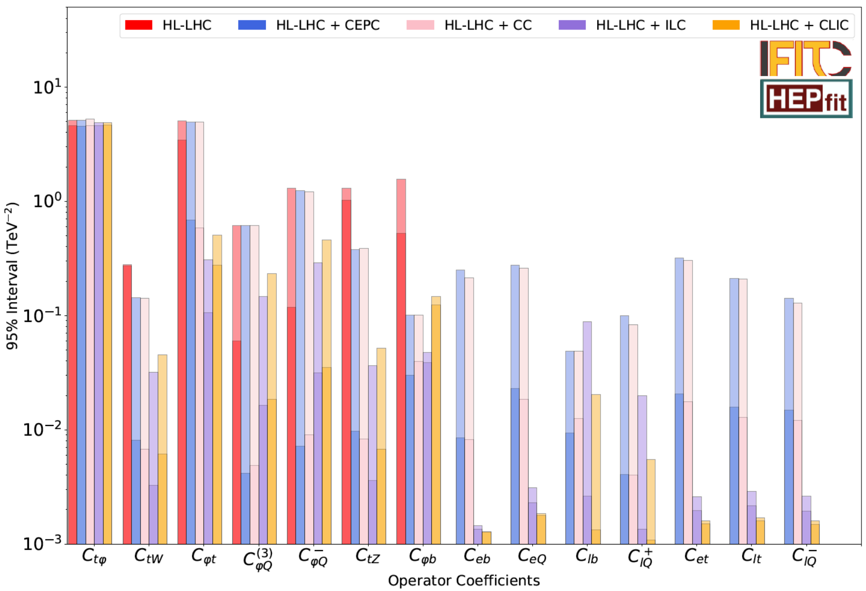




- Importance of el.weak precision:
  - (i) Improve **sensitivity to new physics** (e.g: $\delta S \sim 10^{-2} \rightarrow M \sim 70$ TeV)
  - (ii) **Reduce parametric uncertainties** for other measurements, global fits

Detailed Top-Quark studies

arXiv:2205.02140



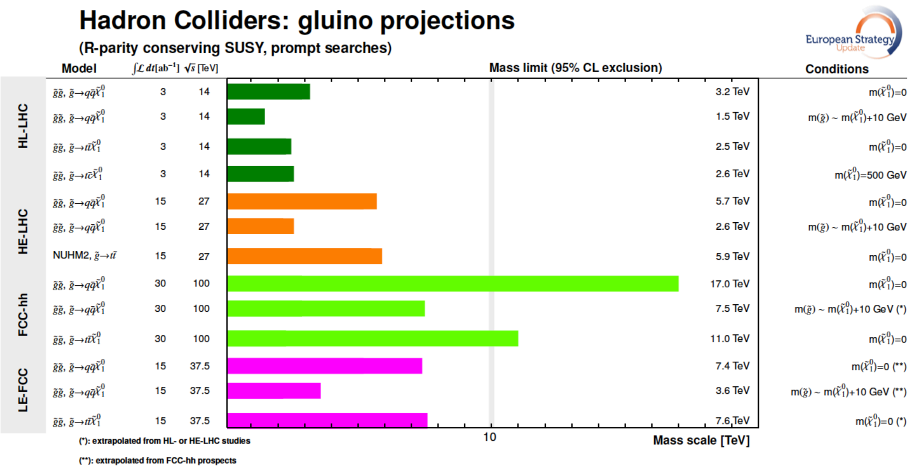
Expected precision on Wilson coefficients for HL-LHC, and combined with various e^+e^- colliders

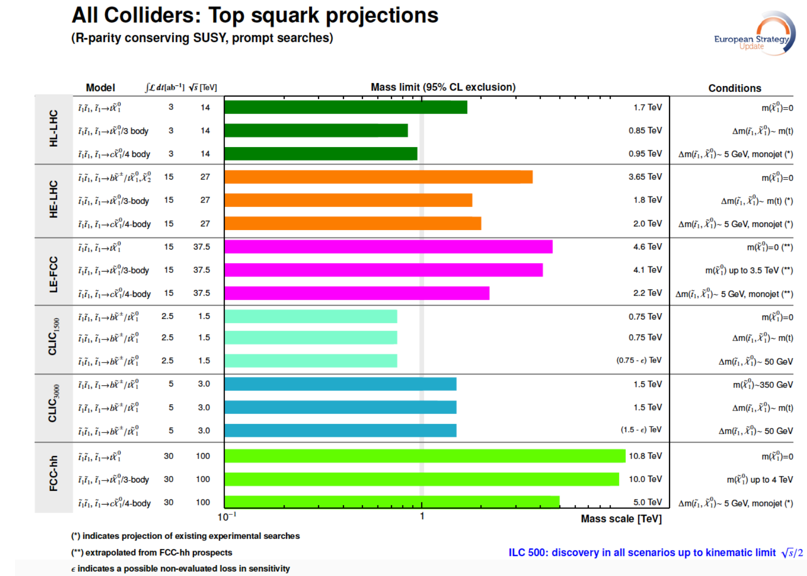
Example for power of high-energy e^+e^- colliders:

SMEFT fit to top quark observables

→ Input from high-energy e^+e^- colliders and power of polarised beams lift degeneracies between operators

Search for new Physics



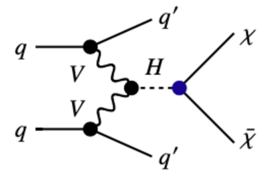


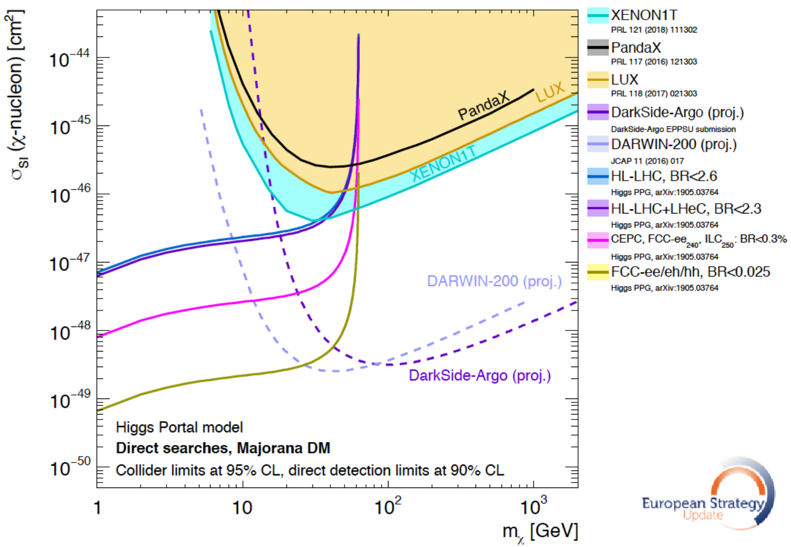
- High-energy hadron colliders have the largest reach for strongly produced **gluinos, squarks**, in particular also **top-squarks**

  Mass range > 10 TeV can be reached

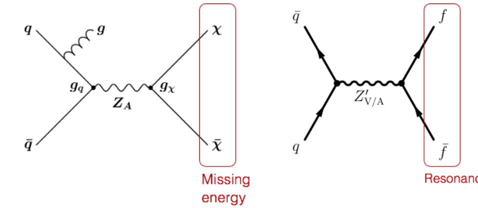
Dark Matter: complementarity between Direct Searches and Future Colliders

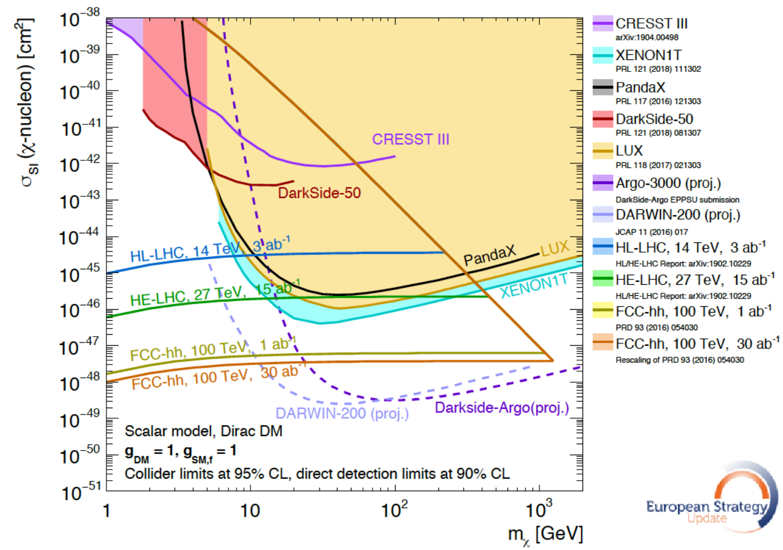
Invisible Higgs boson decays





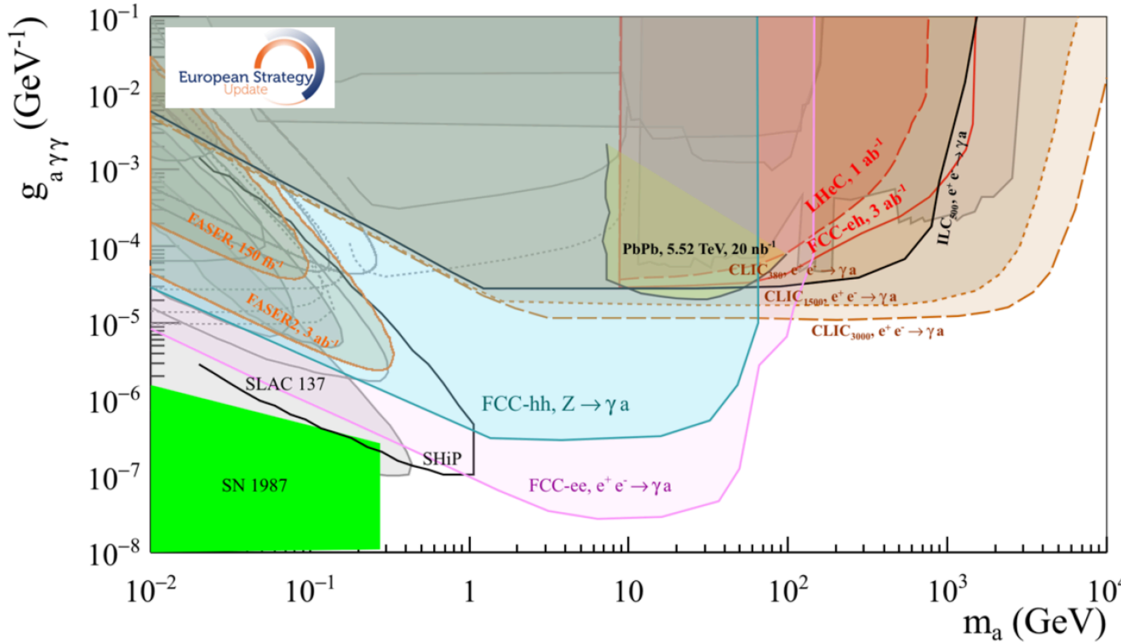
Mediator models





- Future collider experiments are well suited to explore the low mass region, complementary to Direct Detection experiments;

Sensitivity to Axion-like particles



- Production via $Z \to a\gamma$, with $a \to \gamma\gamma$
- Complementarity between ongoing and planned “beam-dump” experiments (low mass, m_a <1 GeV) and collider experiments (FCC: $1 < m_a < m_Z$, ILC, CLIC: high mass region)

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 (values) 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)

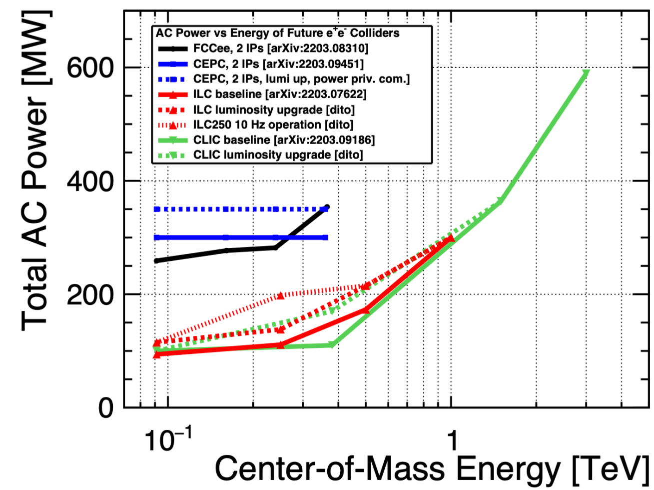
* *"On the feasibility of future colliders: report of the Snowmass'21 Implementation Task Force" JINST 18 (2023) P05018 [arXiv: 2208.06030]*

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 Tuesday's seminar by R. Losito https://indico.cern.ch/event/1317615/)

Other Collider concepts

- No obvious way to reach high energies with lepton collider

  Linear e^+e^- colliders: - cost proportional to energy
  - power proportional to luminosity

- **Alternative: Muon Collider**

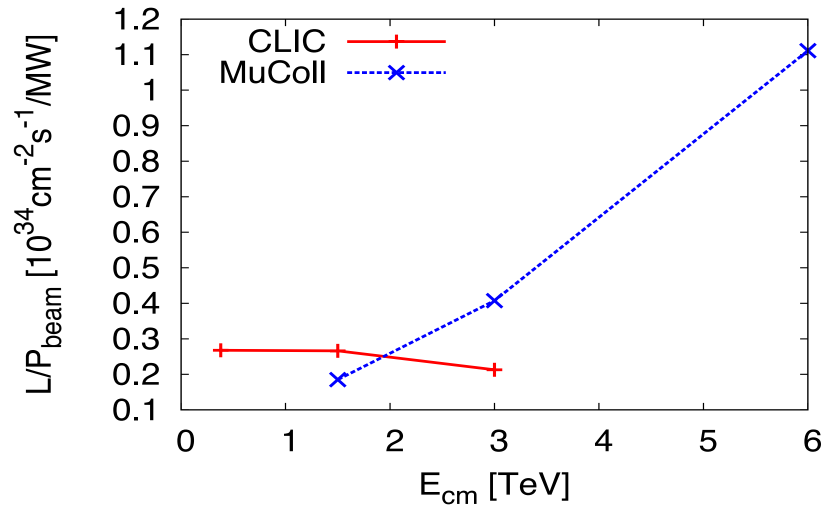
  "10 TeV muon collider has similar reach as 100 TeV hadron collider"

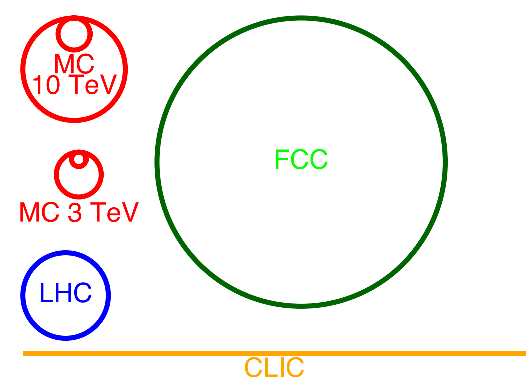
- *Potential first stage: 3 TeV muon collider*

  More efficient (~ factor 2) compared to CLIC (power / luminosity)

- *Can be built more compact → sustainability*

- *However: Technical challenges!!*
  Muons are non-stable particles, lifetime $2.2 \cdot 10^{-6}$ s

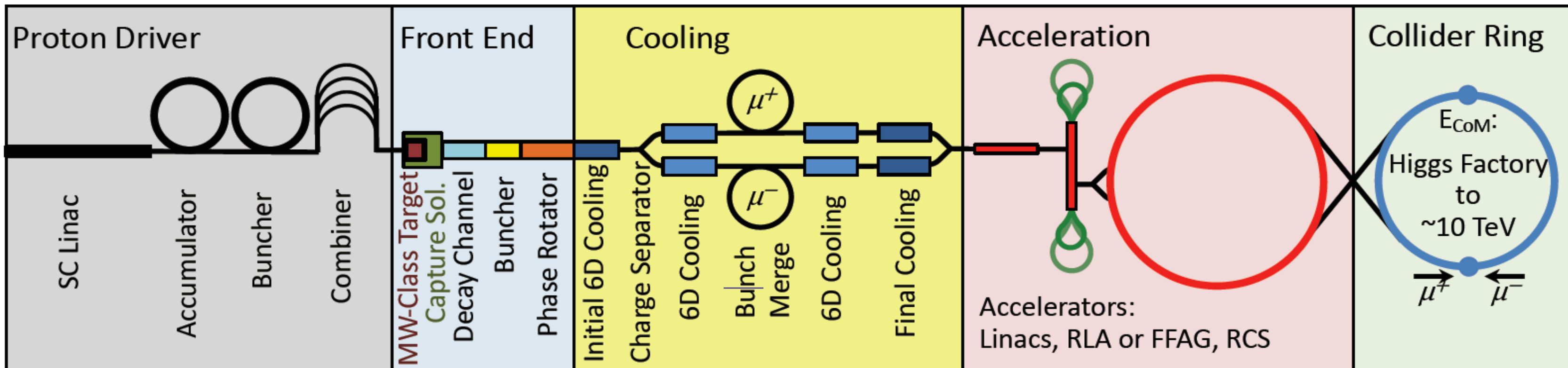




Muon Collider Concept

Daniel Schulte, Plenary ECFA 2021

Fully driven by muon lifetime



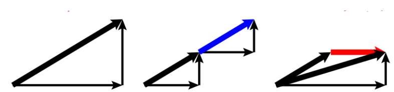
Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

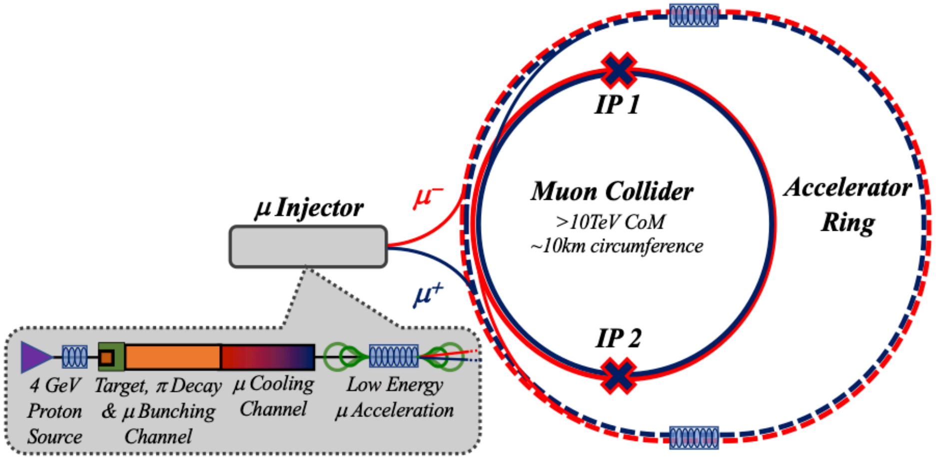
Collision

Protons produce pions which decay into muons
muons are captured



Key Challenges for a Muon Collider

- Muon brightness, ionisation cooling, μ injector (drives beam quality)
- Dense neutrino flux → neutrino radiation!
- High-field magnets, efficient RF
- Beam-induced background
- Machine-detector interface
- Cost and power consumption limit energy reach



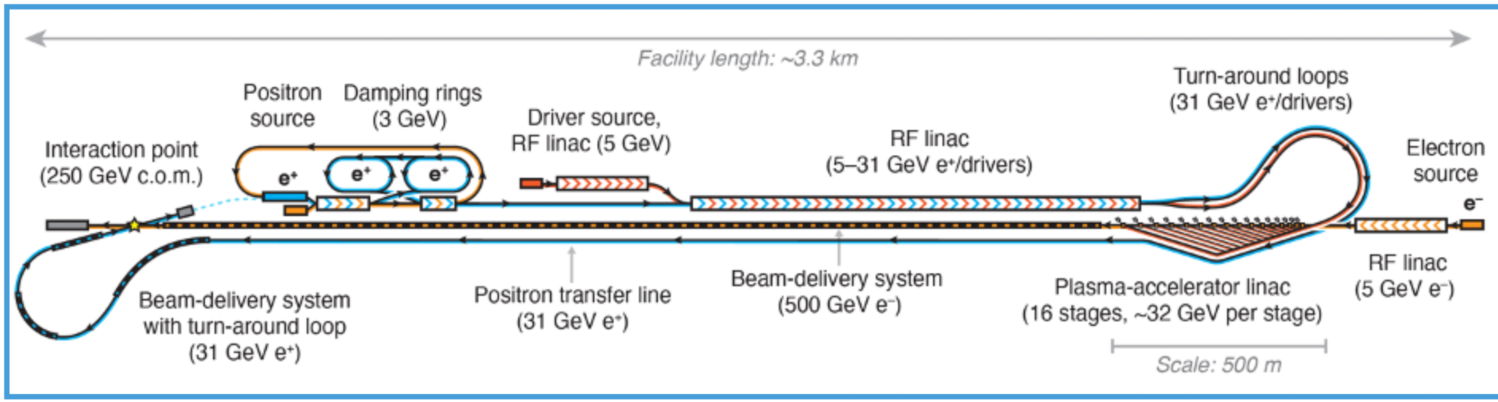
Significant progress over the past years, but still a lot to demonstrate

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

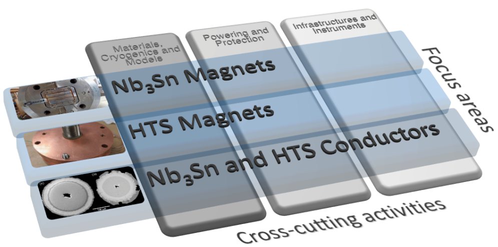
"HALHF cannot be built tomorrow: many unsolved problems remain. The major challenge is to produce plasma accelerators with the characteristics required. We believe that the HALHF concept should act as a spur to the improvement of specific plasma-acceleration techniques…. The necessary R&D should be vigorously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

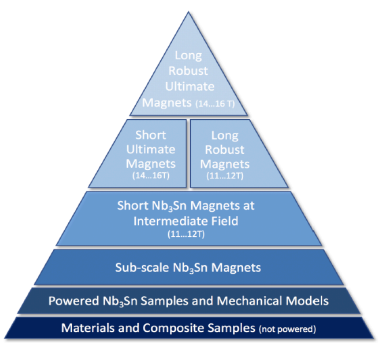
Research and Development on AcceleratorTechnologies

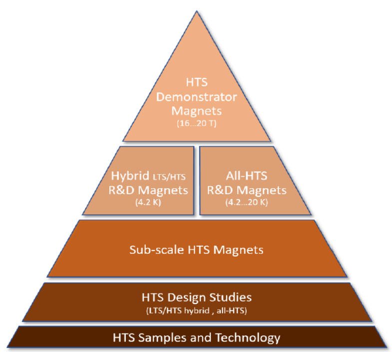
From the European Strategy:

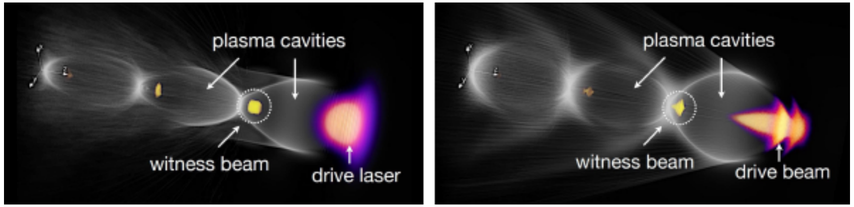
Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry.

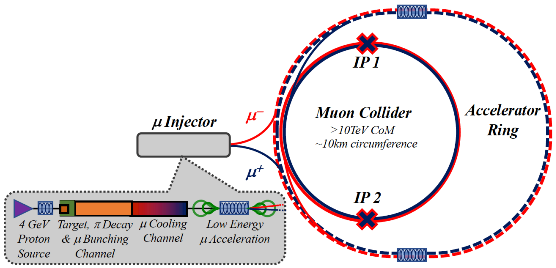
The technologies under consideration: **High-field magnets, high-temperature superconductors**
Plasma / Laser acceleration
Bright muon beams (→ Muon collider)
Energy recovery linacs



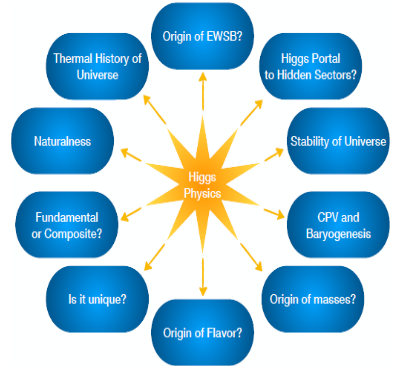








Conclusions on Future Colliders



- 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 address this with an e^+e^- collider in a first stage

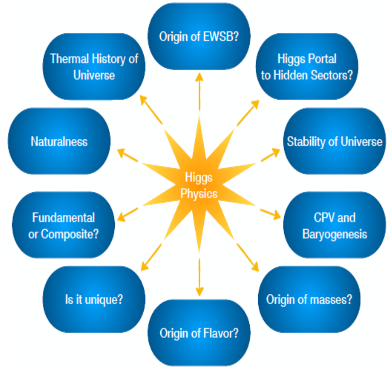
  Mature options for the realisation of such a collider exist: CLIC, FCC-ee, ILC, CEPC, (C^3)

  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 (energy recovery linacs, plasma/laser acceleration, …)

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!

    → get engaged (see examples on the next two slides)

  * Continue optimisation efforts on power reduction!

Acknowledgements: Huge thanks for valuable discussions and sharing of slides to:
Shoji Asai, Michael Benedikt, Jorgen D'Hondt, Christophe Grojean, Karsten Köneke, Jenny List, Daniel Schulte, Steinar Stapnes, Caterina Vernieri, Yifang Wang and Frank Zimmermann,
… and those I have forgotten.

Future Colliders for Early Career Researches

https://indico.cern.ch/event/1293507/

Attend, discuss and engage!

Wednesday, 27th Sept. 2023

Future Colliders for Early-Career Researchers

27 September 2023
CERN
Europe/Zurich timezone

In 2020, the last update of the European Strategy for Particle Physics was approved by the CERN council. In one of its twenty strategy statements, it is stated that an electron-positron Higgs factory is the highest-priority next collider. Studies on such and other colliders are in full swing world-wide. Moreover, we are halfway to the next update of the European strategy in 2026-2027.

*Considering the long timelines that these projects have, we think that it is **of paramount importance for young researchers to participate in an informed way to the many discussions that are currently taking place on the future of our field.***

*The aim of this one-day workshop is to introduce ECRs to the future-collider proposals currently under consideration, so that young researchers can form their opinions about this important matter for the future of our field, and **to foster the discussion within the ECR community** on the same topic.*

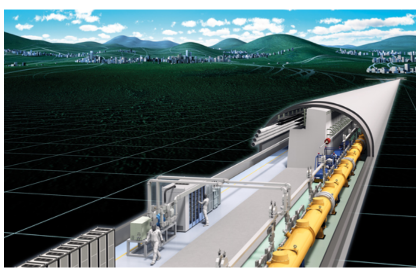
… and get engaged in the

ECFA Study on Physics, Experiments and Detectors at a Future e^+e^- Factory

https://ecfa.web.cern.ch/ecfa-study-higgs-ew-top-factories

"ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather. ***ECFA supports a series of workshops*** *with the aim to* ***share challenges and expertise, to explore synergies in their efforts*** *and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP)."*

Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects; collaborative research programmes are to emerge



Backup Slides

What precision is needed on the Higgs couplings?

- Small corrections expected in many BSM Models

Examples, for scale M of new physics at 1 TeV

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	<6%	<6%	<6%
2HDM (large t_β)	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

S. Dawson

- Generally, new physics effects on couplings are proportional to v^2 / M^2 (6% at 1 TeV)

→ high precision is vital to reach larger energy scales!

Only with HL-LHC we will approach percent-level sensitivity

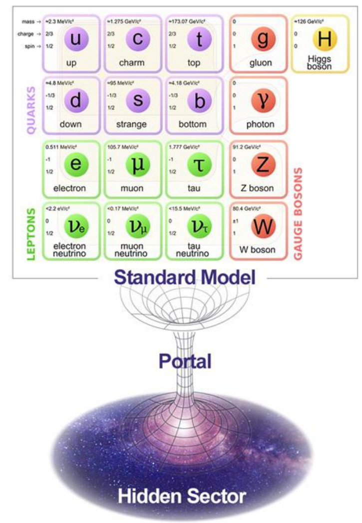
What can future particle-physics experiments contribute

- We are still largely ignorant about the nature of Dark Matter
  - Standard cosmological models: viable masses from ~keV → ~ 100 TeV
  - However, also lighter DM particles masses possible
  - Alternatively: ultralight particles in sub-eV range (Axions, or Axion-like particles)

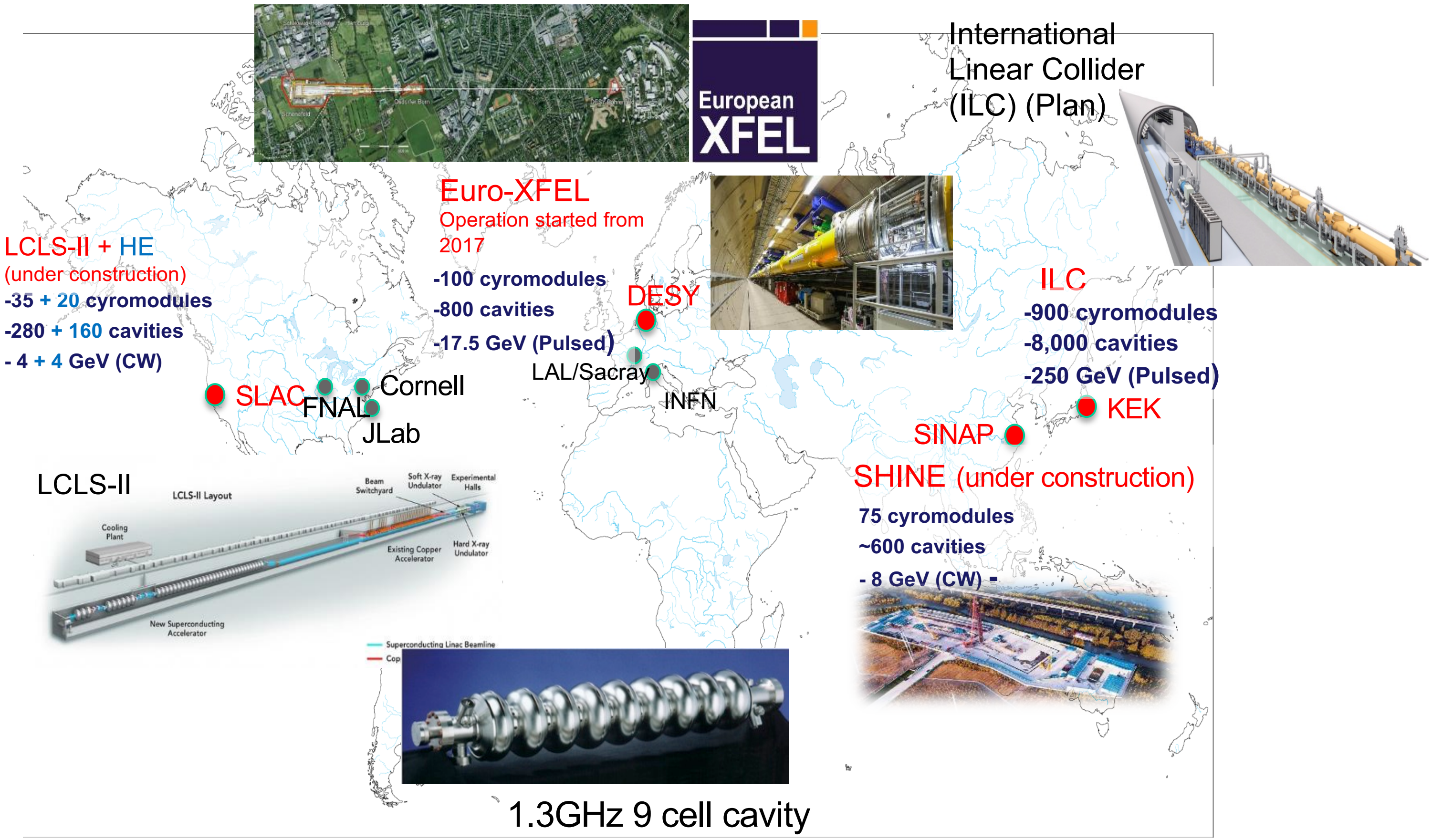
- Future: Open to broad range of scenarios

  Collider focus: **WIMP-type Dark Matter**
  Mediator Models (coupling between dark sector and SM, portal models)
  Invisible Higgs boson decays (Higgs portal models)

  Complemented by **dedicated experiments searching for Light Dark Matter and Feebly Interacting Particles)**

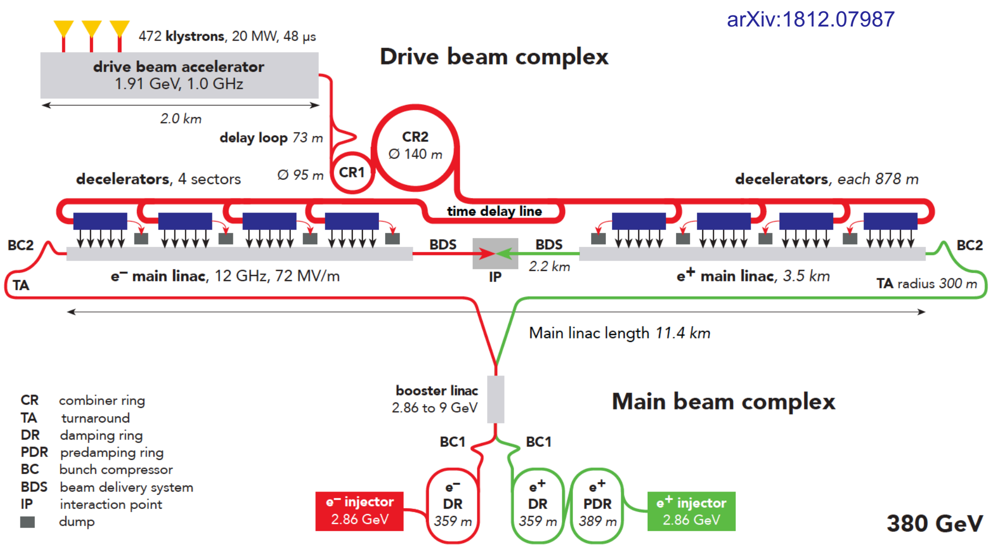


Worldwide usage of SC RF Technology for Light Sources



ILC RF technology is well-matured; scale up by factor of 10 needed

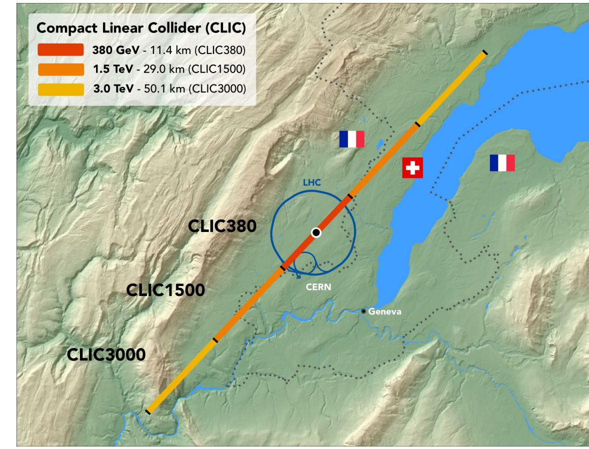
CLIC acceleration concept

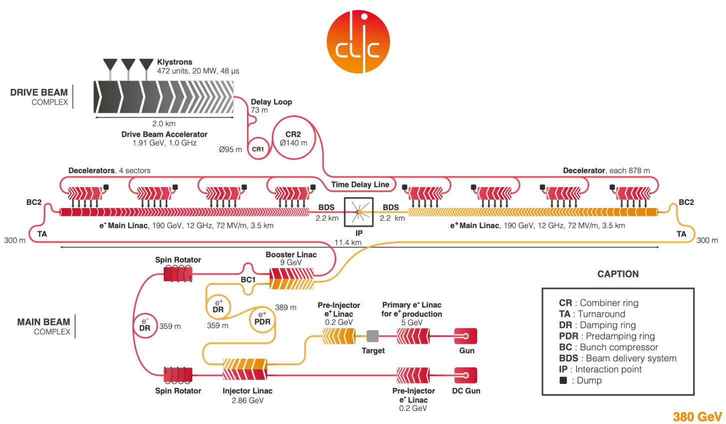


- Use low-frequency klystrons to efficiently generate long RF pulses
- Energy is stored in a long, high-current drive-beam pulse
- Beam pulse is used to generate many short, high-intensity pulses alongside the main linac
- Stored energy is released via transfer structures and transferred into the accelerating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

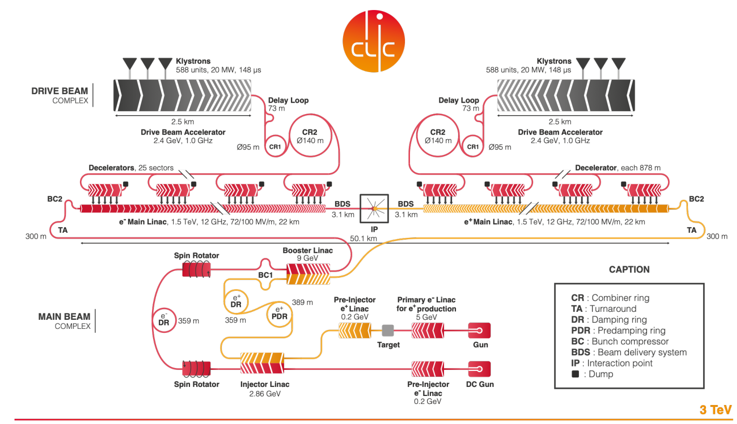
CLIC high-energy running

- CLIC can easily be extended
- Critical elements: - Gradient and power efficiency
  - Costs
- Technical challenges: - Extending main linacs
  - Increase drive-beam pulse length and power
  - A second drive beam is needed to get to 3 TeV





380 GeV



3000 GeV

FCC-ee machine parameter

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Bending radius of arc dipole	[km]	9.937			
SR power / beam	[MW]	50			
Circumference	[km]	91.174117		91.174107	
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		9600	880	248	36
Bunch population	[10^{11}]	2.53	2.91	2.04	2.64
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		Short 90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	150 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.130	0.069 / 0.154	0.103 / 0.185	0.157 / 0.229
Bunch length (SR/BS) σ_z	[mm]	4.37 / 14.5	3.55 / 8.01	3.34 / 6.00	2.02 / 2.95
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
Harmonic number (400 MHz)		121648			
RF frequency (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune $4Q_s$		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.1
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y*		0.0040 / 0.152	0.011 / 0.125	0.014 / 0.131	0.096 / 0.151
Luminosity / IP	[$10^{34}/\text{cm}^2\text{s}$]	189	19.4	7.26	1.33
Lifetime (q + BS)	[sec]	–		1065	2405
Lifetime (lum)	[sec]	1089	1070	596	701

FCC-ee precision on electroweak observables

arXiv:2203.06520

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

Impressive precision!

CEPC Operation Plan

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

Yifang Wang, CEPC Meeting, UK, June 2023

** Detector solenoid field is 2 T during Z operation, 3 T for all other energies

*** Calculated using 3.600 h per year for data collection

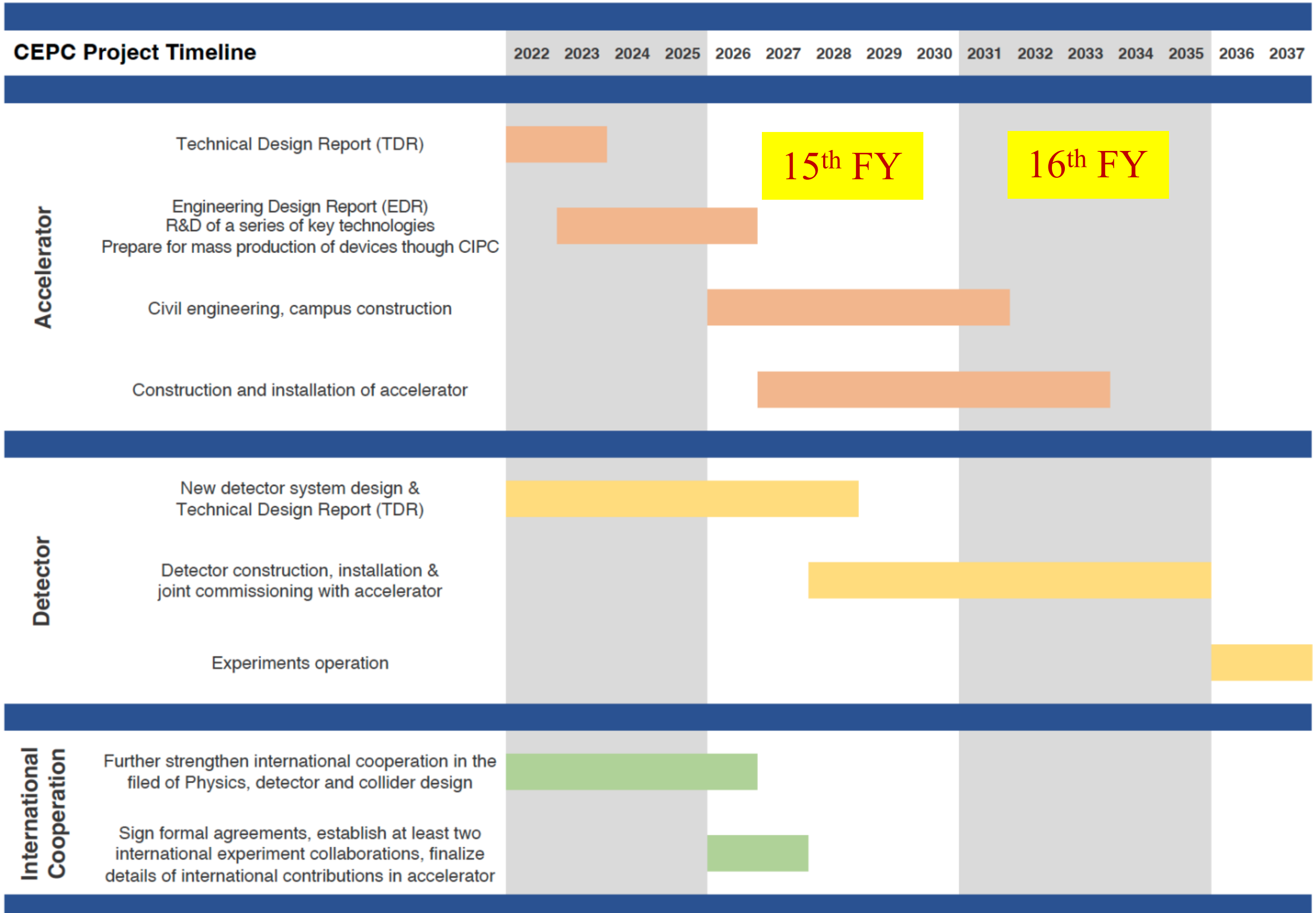
CEPC will commence its operation with a focus on **Higgs boson physics as top priority**

→ Large samples of Higgs bosons during initial phase (2.6 – 4.3) · 10^6 events collected over 10 years

Large samples of Z bosons: (2.5 – 4.1) · 10^{12} events collected later

CEPC Timeline ("ideal schedule")

Yifang Wang, CEPC Meeting, UK, Jun 2023



Complementarity of different colliders in the FCC program

Complementarity for Higgs physics between ee/eh/hh colliders

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

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W[%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z[%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g[%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ[%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$[%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c[%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t[%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b[%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ[%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ[%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H[%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

only FCC-ee@240GeV

only FCC-hh

ALL COMBINED

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

18

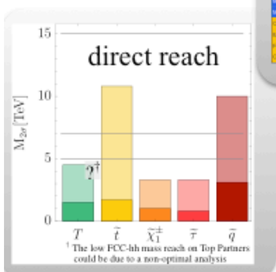
New interest in muon colliders

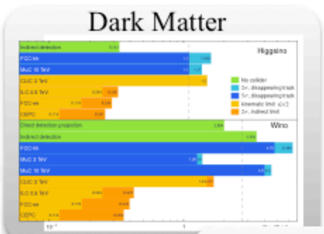
From, e.g., Snowmass21 EF report draft:

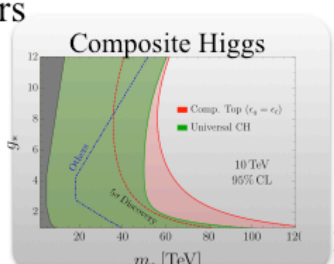
"A 10-TeV scale muon collider with sufficient integrated luminosity provides an energy reach similar to that of a 100 TeV proton-proton collider. […] muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. […] Multi-TeV muon colliders will have the benefit of excellent signal to background […] One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential."

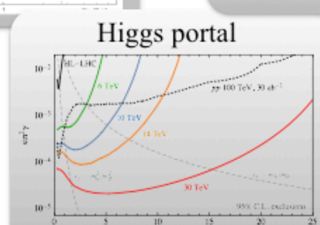
Selected summary plots, from Snowmass21 reports:

2 IMCC reports, plus Muon Collider Forum report. Total of 15 editors, ~150 authors, based on ~100 papers from 3 past years









Higgs couplings

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for μ collider