Future Circular Collider ++

In view of the update of European Strategy for Particle Physics Update (ESPPU) 2026

K. Österberg,

Particle Physics Days, Lammi, 27.11.2024

Material & slides from M. Benedikt (FCC), J. Gao (CEPC) , F. Gianotti (FCC), C. Grojean (FCC physics), K. Huitu (ESPPU) & J. Zhu (FCC detectors)

ESPPU 2020

About LHC: “The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics…. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.“

About future high-energy frontier:
”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.”

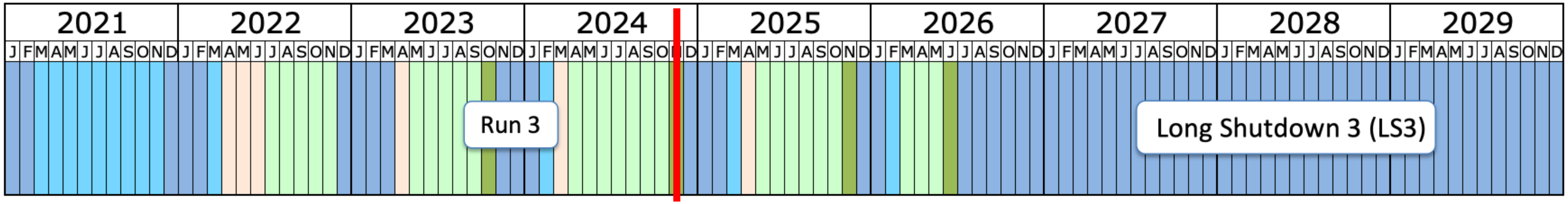
“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.”

“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.”

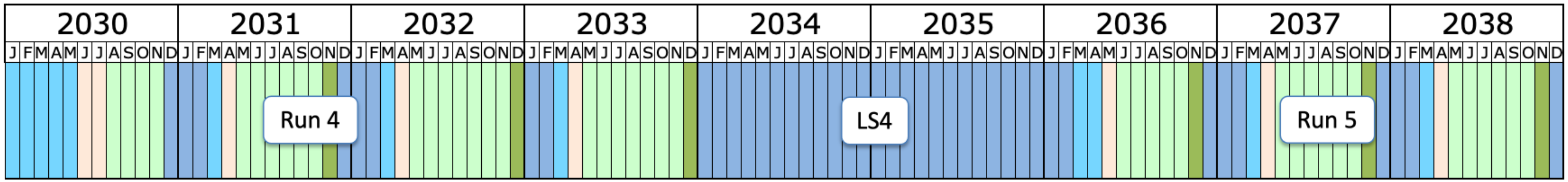
LHC & HL-LHC

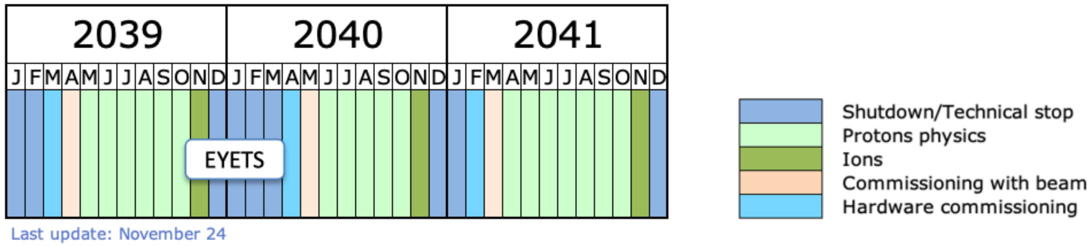
Current high energy frontier: LHC @ CERN

- High luminosity phase (HL-LHC): Increase integrated luminosity by a factor 10 ($\sim 3000\ \mathrm{fb}^{-1}$)
- Plan to run LHC & HL-LHC until 2041



we are here !





What after 2041 ?

What next @ CERN?

Future Circular Collider (FCC)

—

CERN’s next flagship project?

- **Stage 1: FCC-ee – precision physics**: e^+e^- collider for Z, W, Higgs & top quark precision measurements
- **Stage 2: FCC-hh – discovery machine**, a $\sqrt{s} = 100$ TeV proton-proton & ion-ion collider (with an e^+/e^--hadron option)

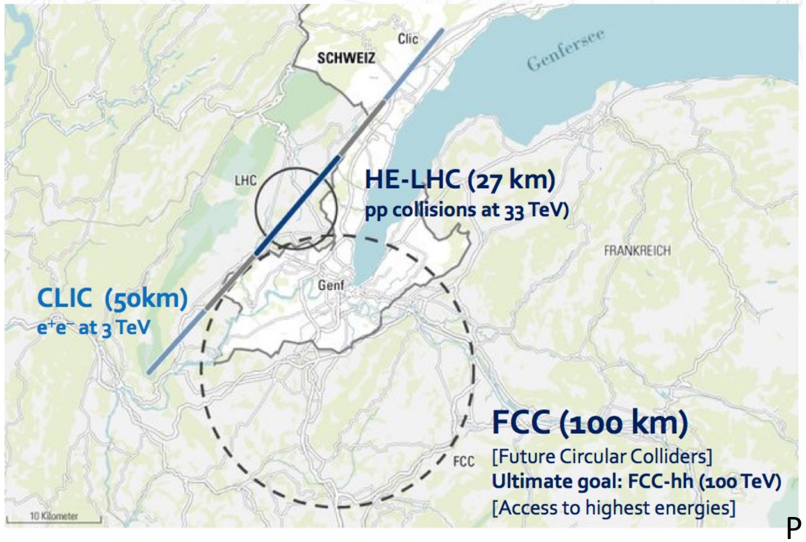
Next high energy frontier machine candidates

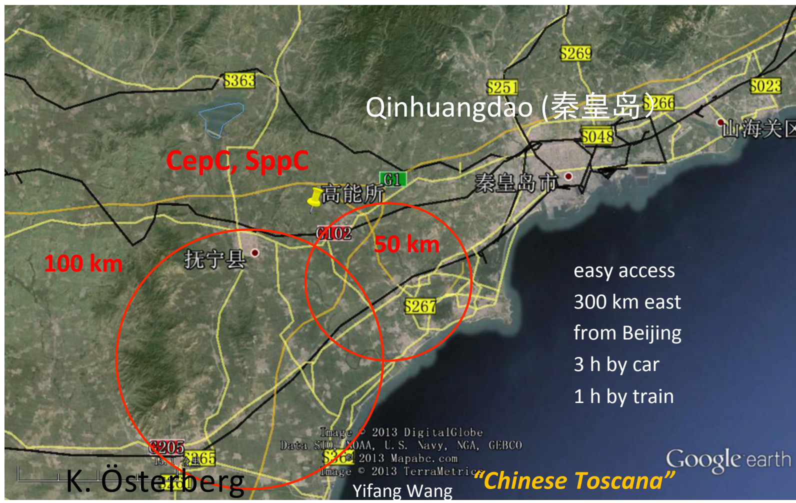
Circular colliders:

- FCC (Future Circular Collider), CERN hosts
  - FCC-hh: $\sqrt{s} = 100$ TeV proton-proton collider, ion operation possible
  - FCC-ee: First step $\sqrt{s} = 90 - 365$ GeV e^+e collider
- CEPC (Circular Electron-Positron Collider) : e^+e^- $\sqrt{s} = 90 - 240$ GeV, China hosts
- SppC (Super proton-proton Collider): proton-proton $\sqrt{s} = 70$ TeV, China hosts

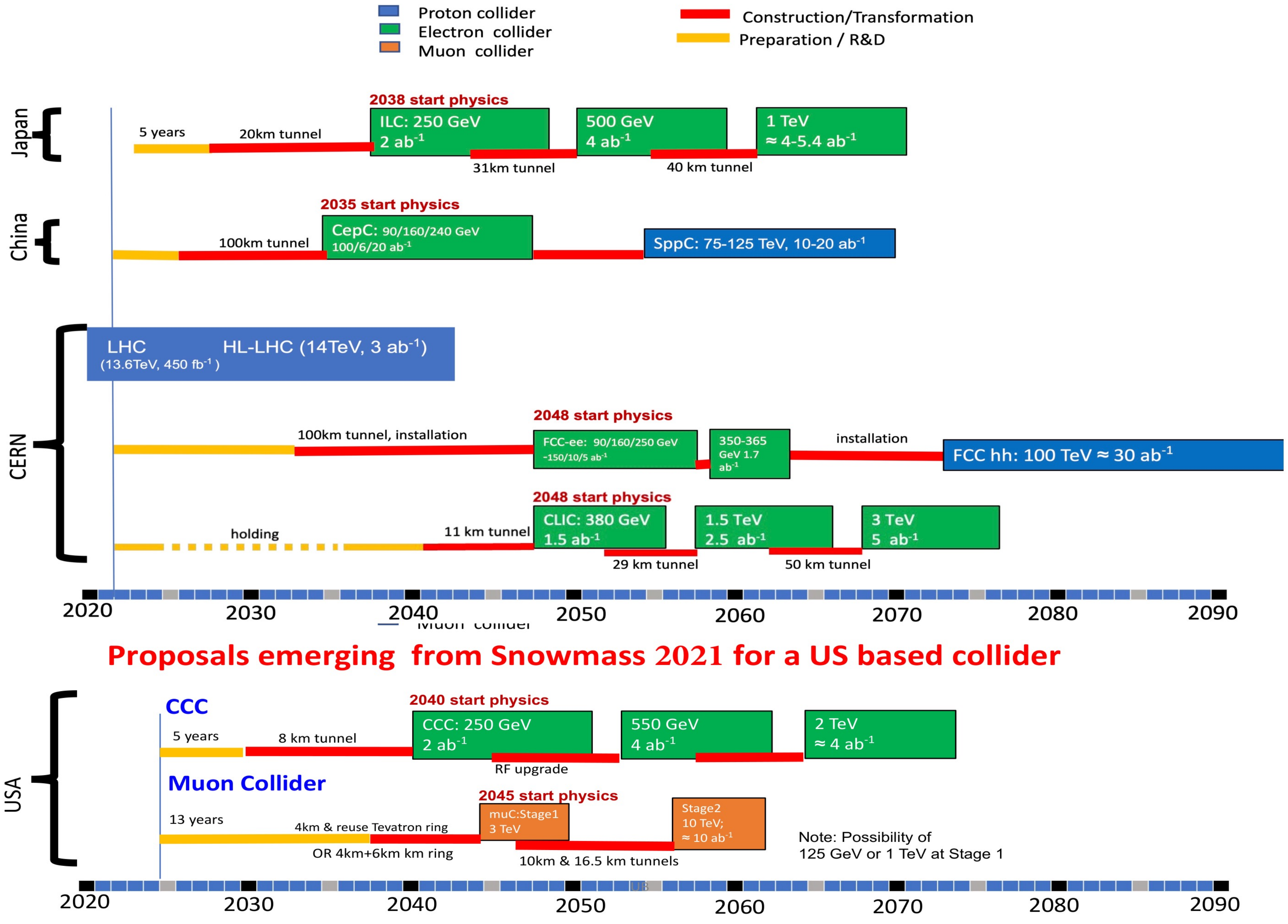
Linear colliders:

- ILC (International Linear Collider): e^+e^- $\sqrt{s} = 250 - 500$ GeV, Japan hosts
- CLIC (Compact Linear Collider): e^+e^- $\sqrt{s} = 380$ GeV - 3 TeV, CERN hosts
- CCC (Cool copper collider): e^+e^- $\sqrt{s} = 250$ GeV - 2 TeV, US hosts
- HALHF: asymmetric e^+e^- using plasma wake-field acceleration $\sqrt{s} = 250 - 550$ GeV, host?
- Muon collider: $\mu^+\mu^-$ $\sqrt{s} = 3$ - 10 TeV, US hosts





Next high energy frontier machine timelines



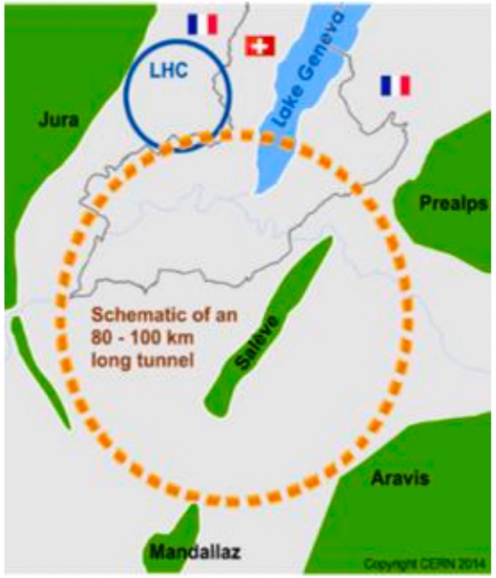
FCC program spanning until end of centary

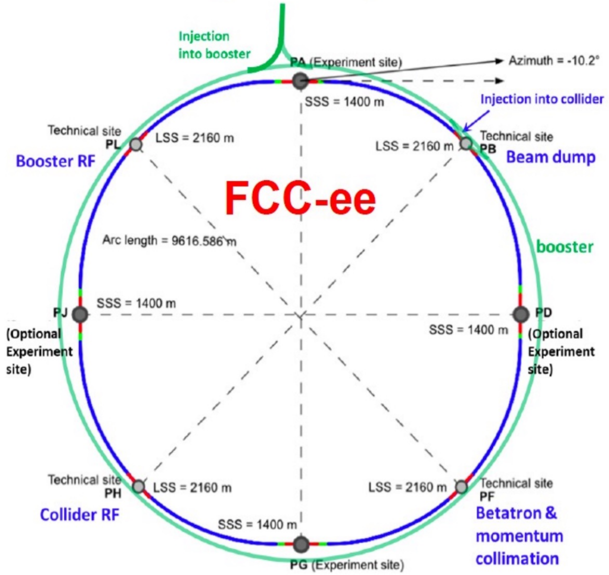
FCC integrated program

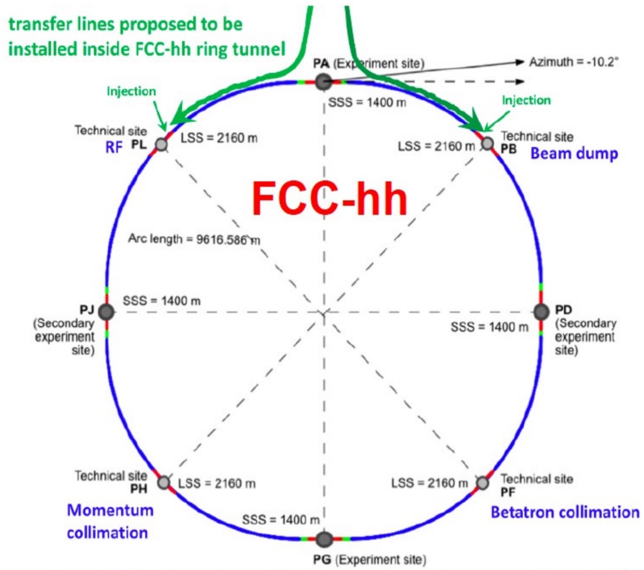
FUTURE CIRCULAR COLLIDER

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







2020 - 2046 | **2048 - 2063** | **2074 -**

FCC Feasibility Study Mid-Term Status
Michael Benedikt
RC, 2 February 2024

FCC decision ~2028 ⟹ an FCC-ee by 2048

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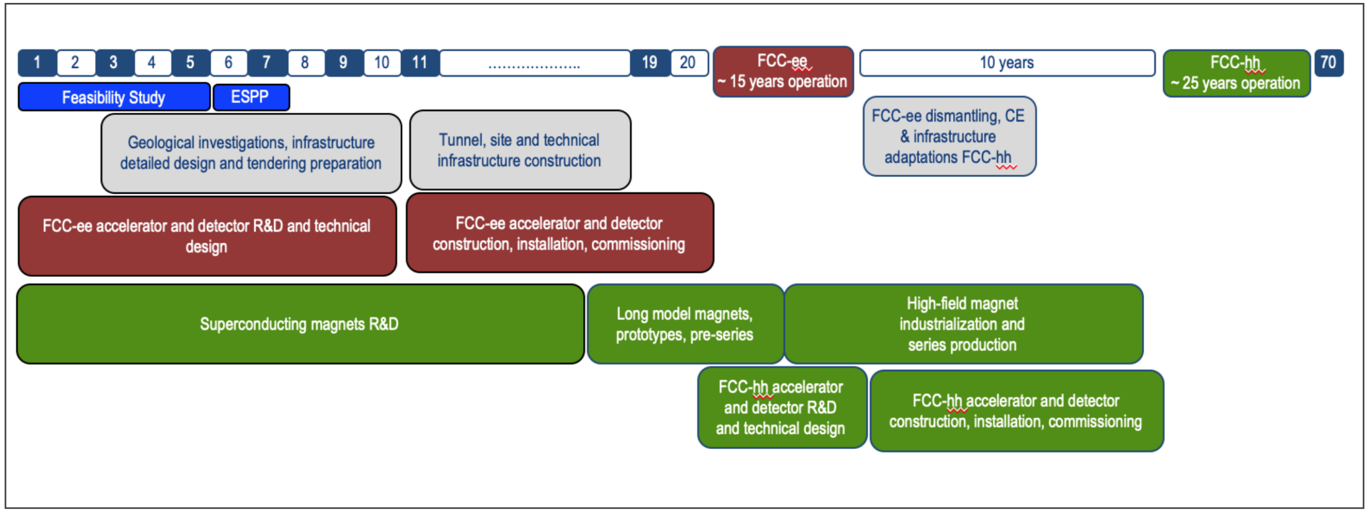
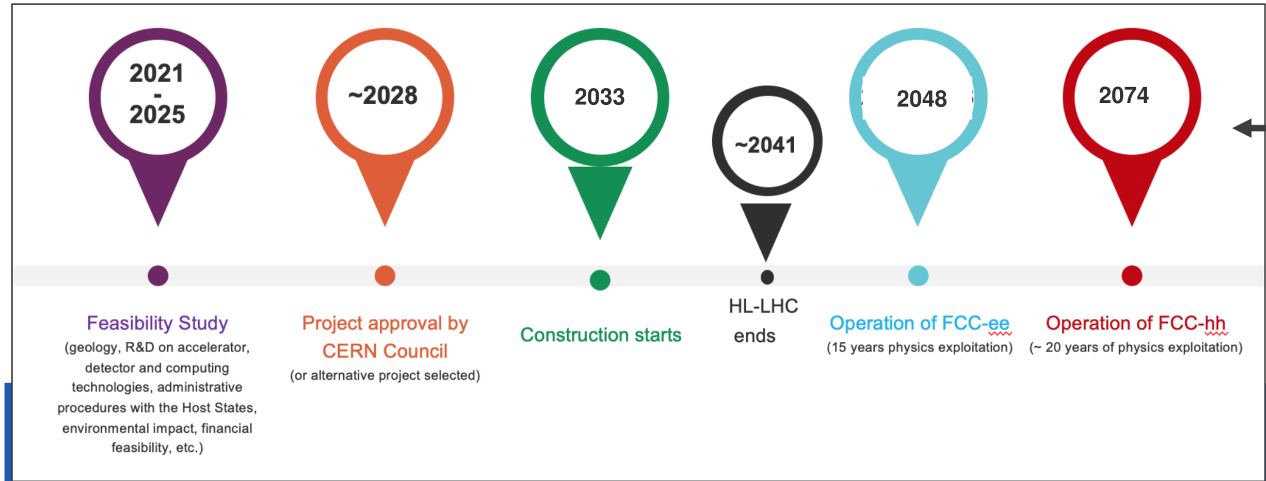
FCC integrated program - timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



“Realistic” schedule taking into account:
- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until 2041

Can be accelerated if more resources available

FCC described in detail in 3 volume CDR

FUTURE CIRCULAR COLLIDER

European Strategy for Particle Physics

2013 Update of European Strategy for Particle Physics:

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines."

→ FCC Conceptual Design Reports (2018/19)

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

2020 Update of European Strategy for Particle Physics:

"Europe, together with its international partners, should investigate 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."

CERN

FCC Feasibility Study Mid-Term Status
Michael Benedikt
CERN, 13 February 2024

FCC feasibility study made to facilitate a decision

FUTURE CIRCULAR COLLIDER — FCC Feasibility Study (2021-2025): high-level objectives

- demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- consolidation of the physics case and detector concepts for both colliders.

Results will be summarised in a Feasibility Study Report to be released in 2025

FCC Feasibility Study Mid-Term Status
Michael Benedikt
CERN, 13 February 2024

Optimized FCC: a 90.7 km tunnel ring

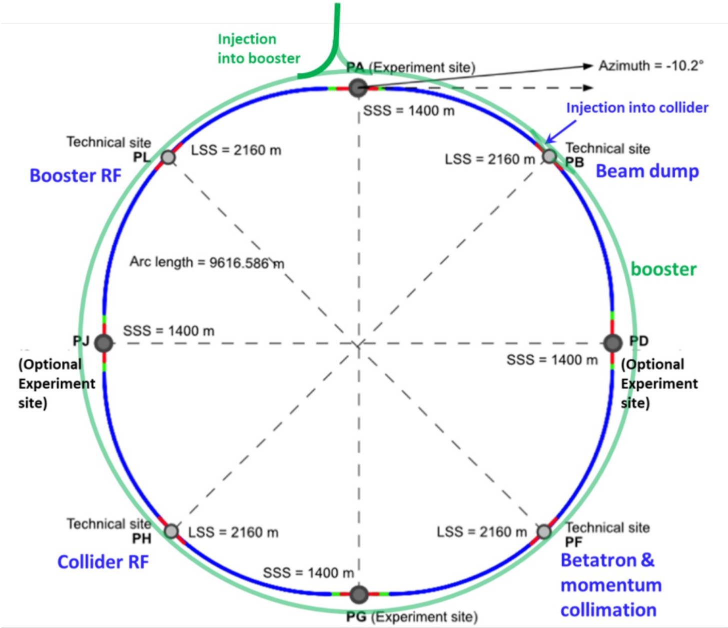
FUTURE CIRCULAR COLLIDER

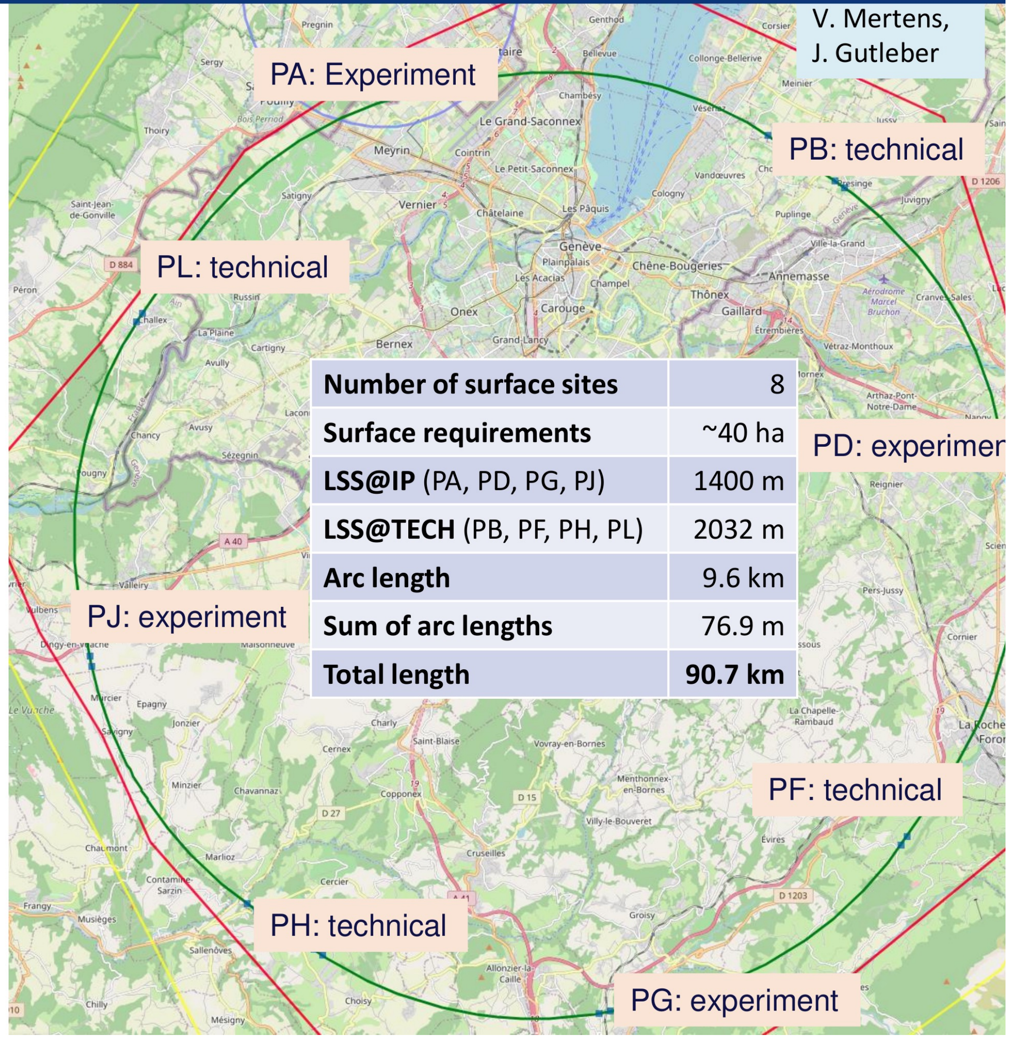
Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce-compensate" principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC-ee: > 10 x precision of LEP & HL-LHC

FUTURE CIRCULAR COLLIDER

FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

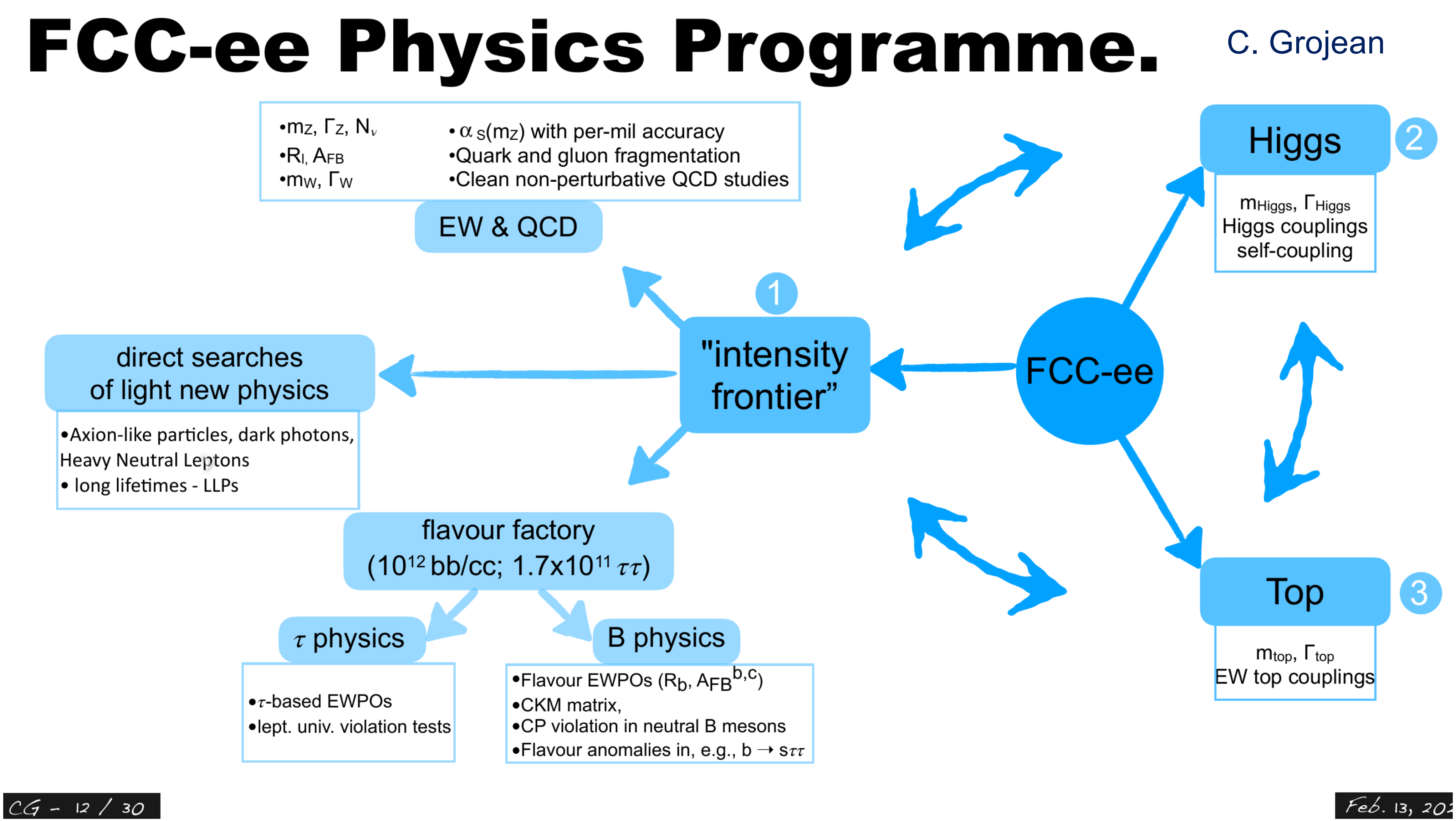
Design and parameter dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

FCC-ee: verstile physics programme with 3 pillars



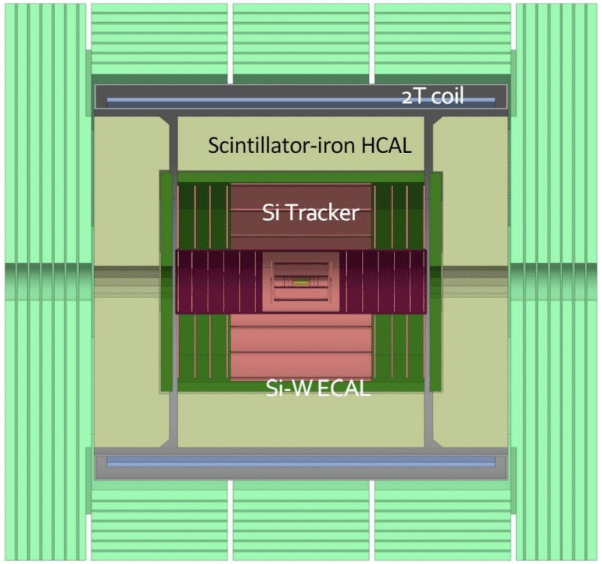
FCC-ee: pursued detector concepts

J. Zhu

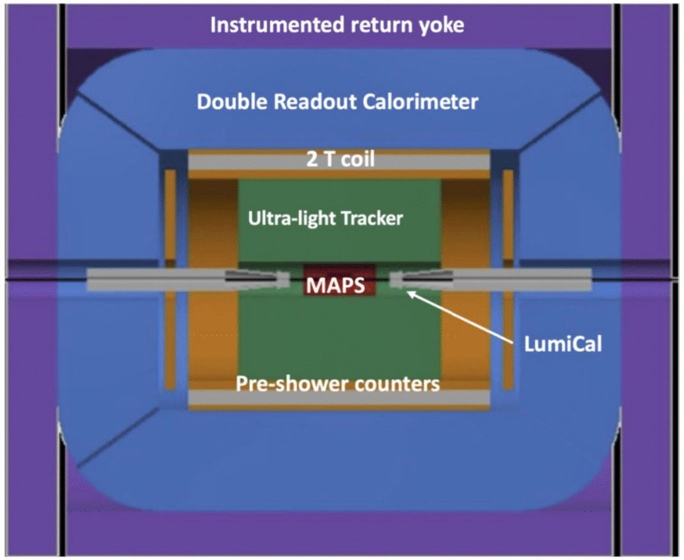
Detector benchmarks

Four detectors considered for FCC-ee

CLD



IDEA



ALLEGRO

- Full silicon vertex + strip tracker
- CALICE-like 3D-imaging high-granular calorimetry with Si-W for ECAL and Sci-iron for HCAL
- Muon system with RPCs
- Coil outside of calorimeters

- Silicon vertex + ultra-light tracker
- Monolithic dual readout calorimeter with Cu-fibers (possibly augmented by dual-readout crystal ECAL)
- Muon system with μ-RWELL
- Coil inside calorimeters

- Silicon vertex + ultra-light tracker
- High granularity noble liquid ECAL (LAr or LKr with Pb or W absorbers)
- CALICE-like or TileCal-like HCAL
- Muon system
- Coil outside of ECAL

Four detector benchmark sessions on Tuesday and Thursday afternoons

FCC-hh: direct discoveries up to ~ 40 TeV

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FCC-hh parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

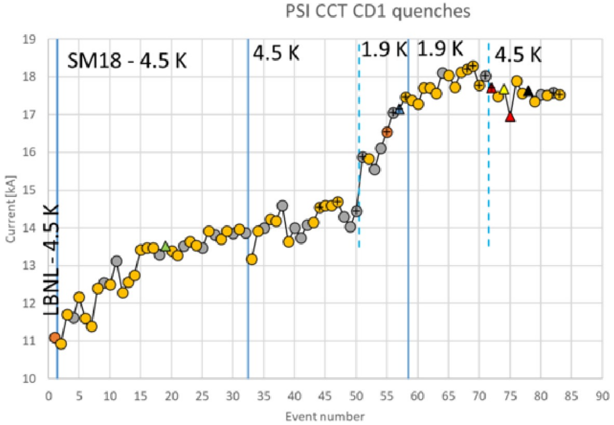
Formidable physics reach, including:
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)
- ❑ Final word about WIMP dark matter

F. Gianotti

FCC-hh: biggest challenge – high-field magnets

FUTURE CIRCULAR COLLIDER — high-field magnets for FCC-hh: Nb_3Sn & HTS R&D

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23



It trained ***A LOT***. **It reached 100% of maximum field at 4.5 K.** No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

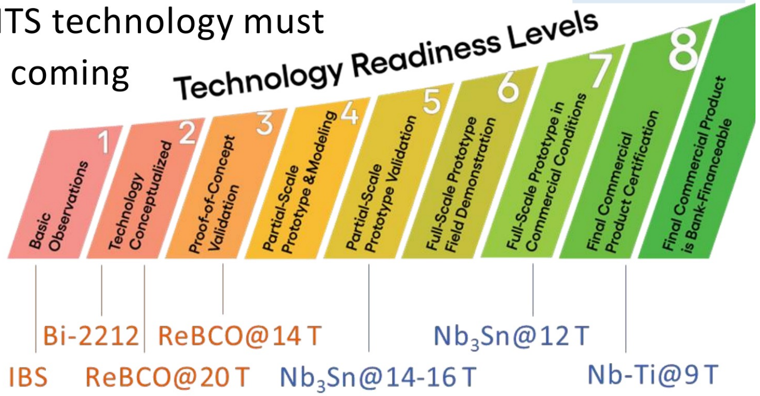
Stress-management works, CD1 is a robust magnet.

B. Auchmann

Rough estimates

Bottom line: HTS technology must catch over the coming 10 years in TRL to LTS

B. Auchmann



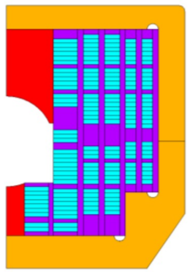
Next: FCC-hh SM-CC Demonstrator

Goal: demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.

Novel concept: Stress-managed and asymmetric common coils.

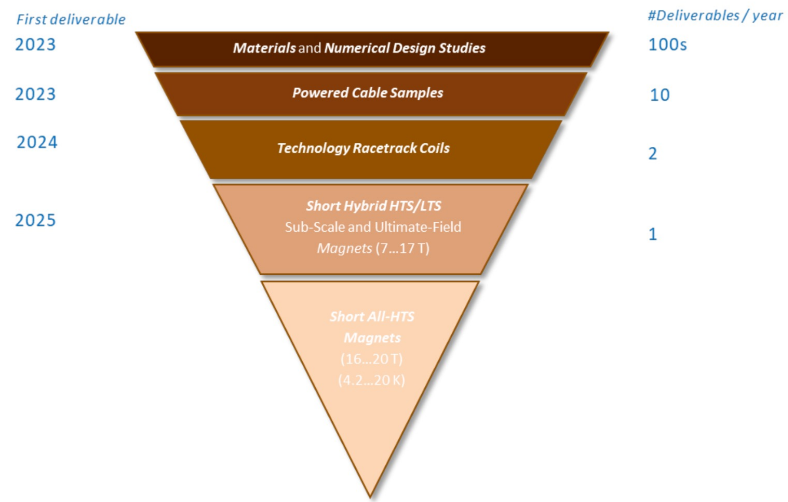
D. Araujo

Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor

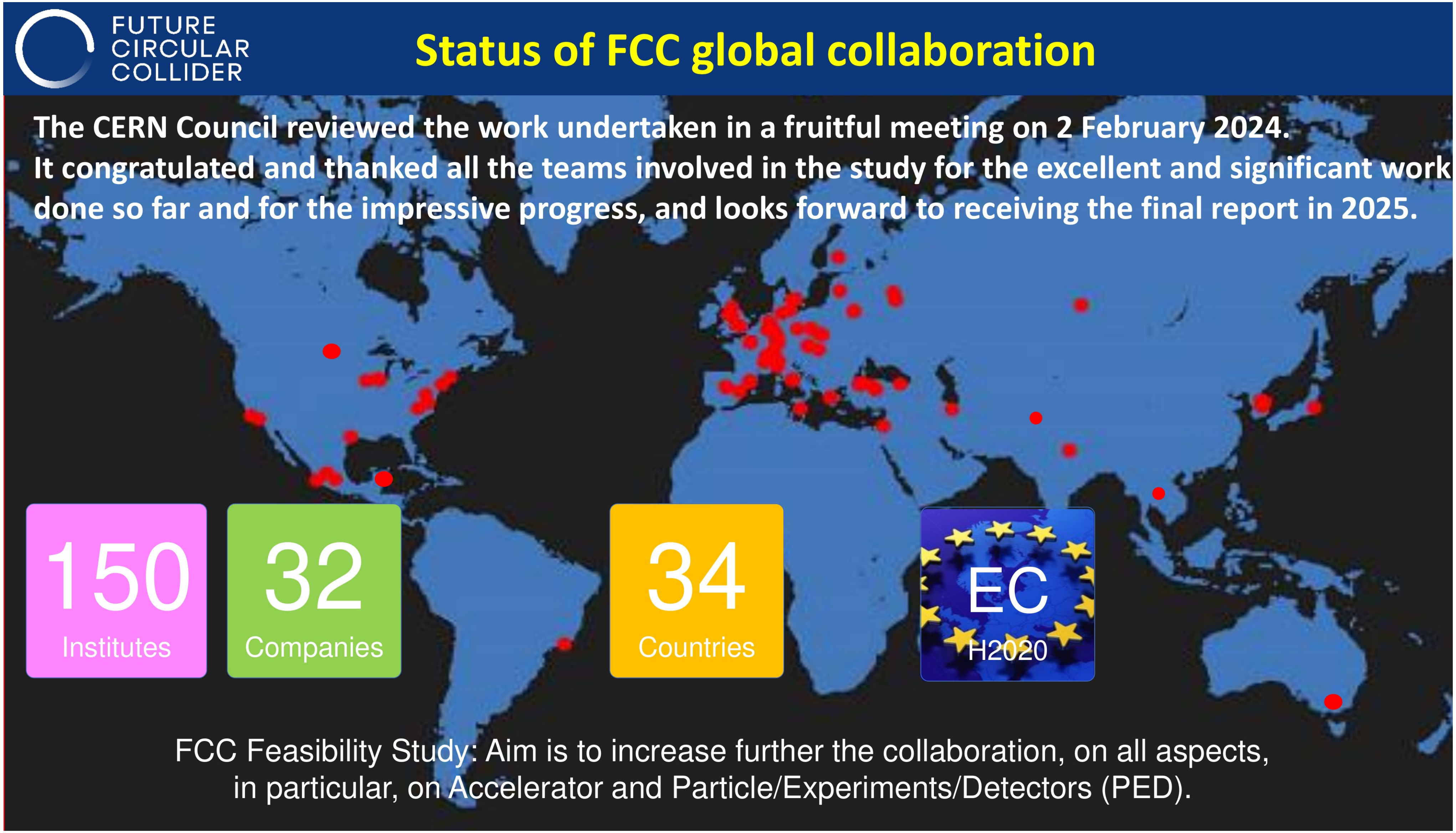


B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

HTS Innovation Funnel for HFM



FCC: already a global endevour



How much does the fun cost & how pays?

FCC-ee cost and funding

F. Gianotti

FCC-ee construction cost up to operation at ZH : ~ 15 BCHF

Does not include upgrade to ttbar operation (~ 1.5 BCHF)

Includes:

- Civil engineering (tunnel, experimental caverns, surface sites, etc.)
- FCC-ee collider and injectors
- Technical infrastructure
- Other infrastructure (roads, power lines, land, etc.)
- 4 detectors

Updated cost assessment made in 2023, reviewed by dedicated Cost Review Panel of experts (chair N. Holtkamp), which concluded:

- cost estimates are appropriate for this stage of the study
- uncertainty estimates are realistic; most items are class 4 (- 30% to + 50%) or class 3 (-20% to +30%).
  Aim at class 3 for all main items at the end of the Feasibility Study

Note: **care should be taken when comparing with other proposed future colliders, whose cost estimates are in most cases not so detailed and complete, and have not been re-assessed recently** (high inflation over past years!)

Funding

CERN Budget can cover more than half of the cost. Contributions expected from non-Member States with interested communities (e.g. US) and from Member States (beyond their contributions to CERN Budget).
Other contributions may come from the European Commission and private donors.

Preliminary funding model (including construction and operation expenses) and funding scenarios studied
→ will be further developed in the coming year based on discussions in Council and with potential partners.

What happens between 2025 & 2028 ?

Preparing for next step: pre-TDR phase (April 2025 - end 2027)

F. Gianotti

Main goal of Feasibility Study is to determine if there are any showstoppers for the implementation of the FCC.

More detailed technical studies and documentation are needed to allow the Council to take a decision, possibly at end 2027/beg 2028, on whether or not the project should go ahead

⬇

The pre-TDR phase (April 2025 - end 2027) should prepare the needed input for a decision (note: construction start requires a full TDR)

Main goal of "pre-TDR" phase would be to further develop civil engineering and technical components and their integration, so as to provide a more detailed cost estimate with reduced uncertainties:

-- R&D and design studies of all main components of accelerators and technical infrastructure
-- full project integration study, including detector requirements
-- proto-collaborations around detector conceptual design activities

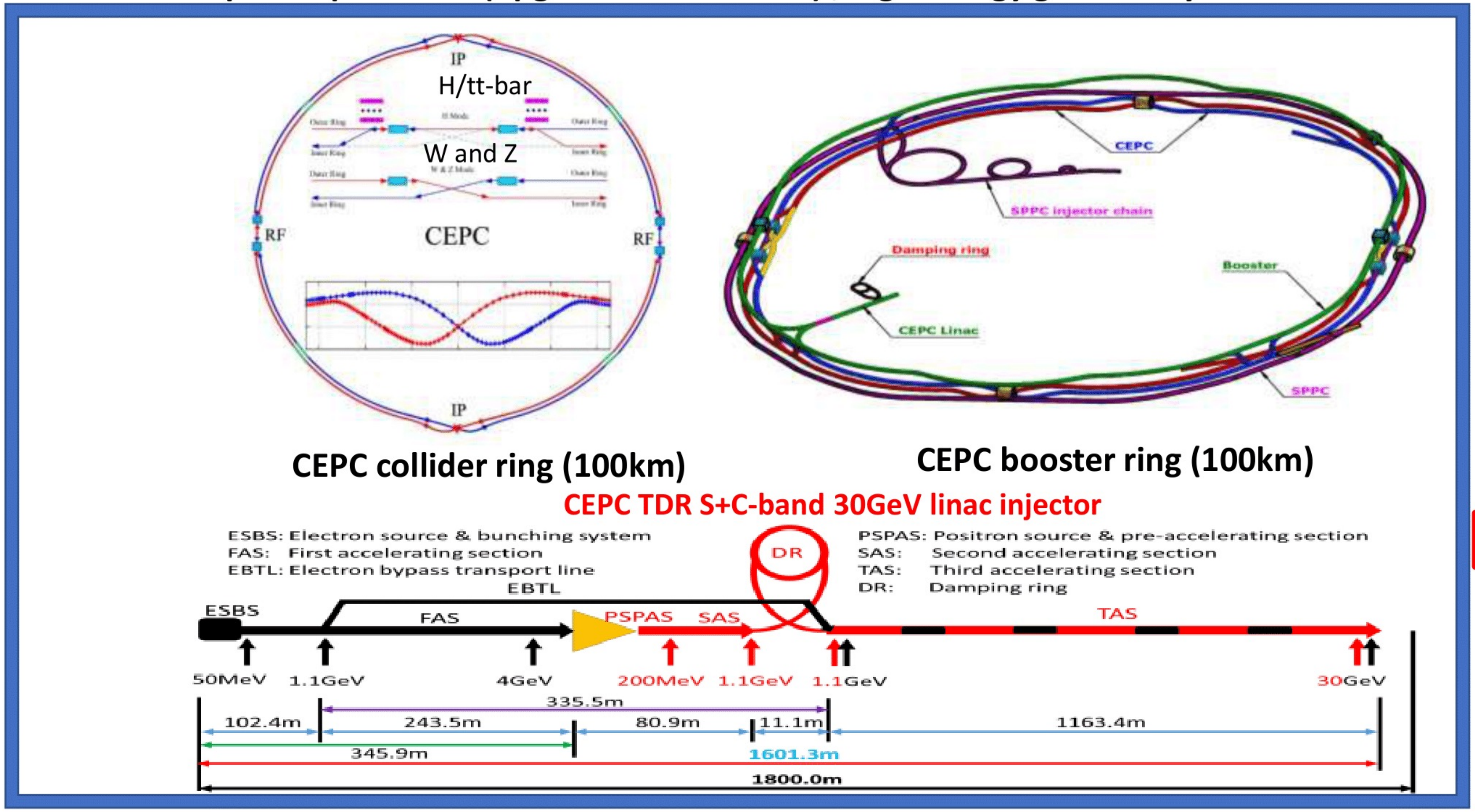
Another crucial goal of the pre-TDR phase would be to start a deeper environmental impact study (quantitative analysis of impact of FCC-ee components and mitigation measures)

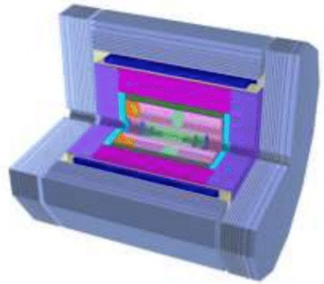
The Council will consider the pre-TDR phase based on the final report of the FCC Feasibility Study; in the meantime, allocation of the necessary resources until that time will be considered for approval by Council next week.

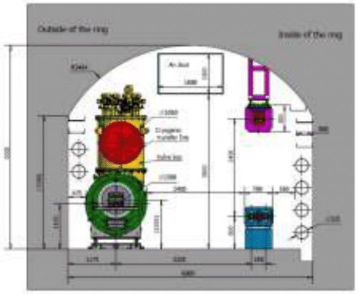
Main competitor: CEPC & SppC in China

CEPC Higgs Factory and SppC Layout in EDR

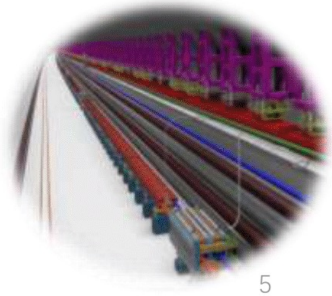
CEPC as a Higgs Factory： H, W, Z, upgradable to ttbar, followed by a SppC (a Hadron collider) ~125TeV
30MW SR power per beam (upgradable to 50MW) , high energy gamma ray 100Kev~100MeV







CEPC/SppC in the same tunnel



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CEPC focuses on Higgs

CEPC Operation Plan and Goals in TDR

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (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

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

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

*** Calculated using 3,600 hours per year for data collection.

Status of the CEPC Projects-J. Gao LCWS2024, July 8, 2024, Tokyo University, Japan 7

CEPC included in China's next 5 year plan?

CEPC Engineering Design Report (EDR) Goal

2012.9	2015.3	2018.11	2023.10	2025	2027	15th five year plan
CEPC proposed	Pre-CDR	CDR	TDR	CEPC Proposal CEPC Detector reference design	EDR	Start of construction

CEPC EDR Phase General Goal: 2024-2027

After completion CEPC accelerator TDR in 2023, CEPC accelerator will enter into the Engineering Design Report (EDR) phase (2024-2027), which is also the preparation phase with the aim for CEPC proposal to be presented to and selected by Chinese government around 2025 for the construction start during the "15th five year plan (2026-2030)" (for example, around 2027) and completion around 2035 (the end of the 16th five year plan).

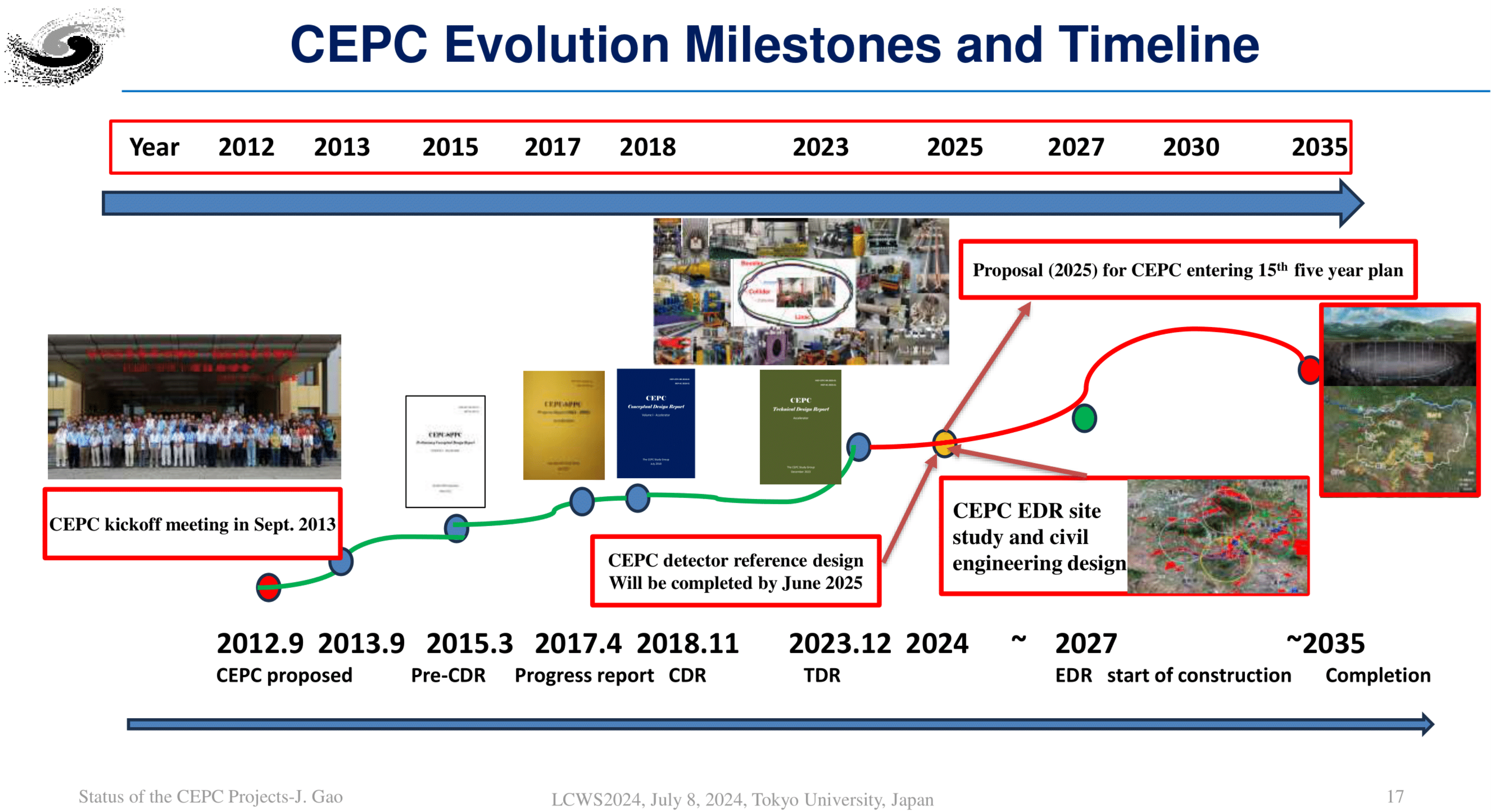
CEPC EDR includes accelerator and detector (TDRrd)
CEPC detector TDR reference design (rd) will be released by June 30, 2025

CEPC Accelerator EDR goals, scope and the working plan (preliminary) of 35 WGs summarized in a documents of 20 pages, EDR progress be reviewed by IARC in Sept. 18-20, 2024

Cost estimate: 36.4 B RMB
(of which accelerator: 19 B)

1 RMB ≈ 0.13 € so ~5 B €

CEPC ready by 2035 (> 10 years before FCC-ee)?



CEPC: becoming an international endevour?

CEPC International Collaboration

CEPC attracts significant International participation and collaborations

Accelerator TDR report: 1114 authors from 278 institutes (including 159 International Institutes, 38 countries) arXiv: 2312.14363

- More than 20 MoUs have been signed with international institutions and universities
- CEPC International Workshop since 2014
- EU-US versions of CEPC WS since 2018
- Annual working month at HKUST-IAS (mini workshops and HEP conference) since 2015

Possible items for discussion:

- FCC essential for CERN's future & CERN also a Finnish laboratory: should we mainly focus on FCC-ee (after HL-LHC)?
- If FCC-ee engagement: what FCC-ee detector concept to engage in – should we seek Nordic concensus?
- If CEPC progresses as planned: any Finnish interest to participate in the detector open (?) for international collaboration?
- Change completely direction & do something different?

Backup

Next high energy frontier machine(s)?

D. Schulte

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	0.06 / 7	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

ILCU = 1€ (2012)

FCC-ee: detector requirements

Summary

- Very broad ranges of interesting physics to study at the FCC-ee
- Physics goals we want to achieve put strong constraints on detector design and performances
- Momentum resolution: **$\sigma(p_T)/p_T^2 \sim 3\text{-}4\times10^{-5}$** to match the beam energy spread
- Jet energy resolution: **$\sigma_E/E \sim 30\%/\sqrt{E}$** to separate W and Z hadronic decays
- Electron/photon energy resolution: **$\sigma_E/E < 15\%/\sqrt{E}$** enough for jet resolution and m_h measurement, better resolution needed for low-energy photon and π^0 reconstruction
- Impact parameter resolution:

$$\sigma(d_0) = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

a ~ 5 μm, b ~ 15 μm·GeV (FCC-ee)

- Particle identification: **μ-π, π-K, K-p separation, e/γ/μ/π^0 identification for a wide momentum range**
- Magnetic field: **≤ 2 Tesla**
- Absolute luminosity measurement: **10^{-4}**, and relative measurement between energy scan points: **10^{-5}**, set strong constraints on the design and mechanical assembly of the LumiCal detector
- Track angular resolution: **<0.1 mrad**
- Stability of the magnetic field: **$<10^{-6}$**
- Fine granularity for ECAL and HCAL
- Large detector acceptances for the tracker, ECAL, HCAL, and muon systems
- …
- More discussions about requirements and the three detector benchmarks can be found in the FCC-ee feasibility study mid-term report
- Continuing work to better understand physics requirements on detector performance and to optimize detector designs