Overview of future colliders (FCC, CEPC, ILC, CLIC)

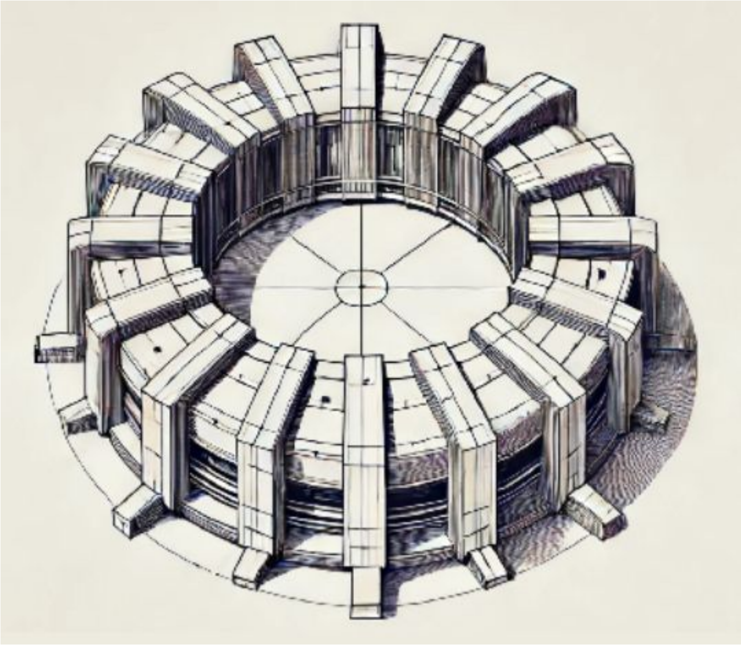
J. Faltová (Charles University)

27th September 2024, Future Colliders for Early-Career Researchers: CZ/SK Edition

Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Future Colliders



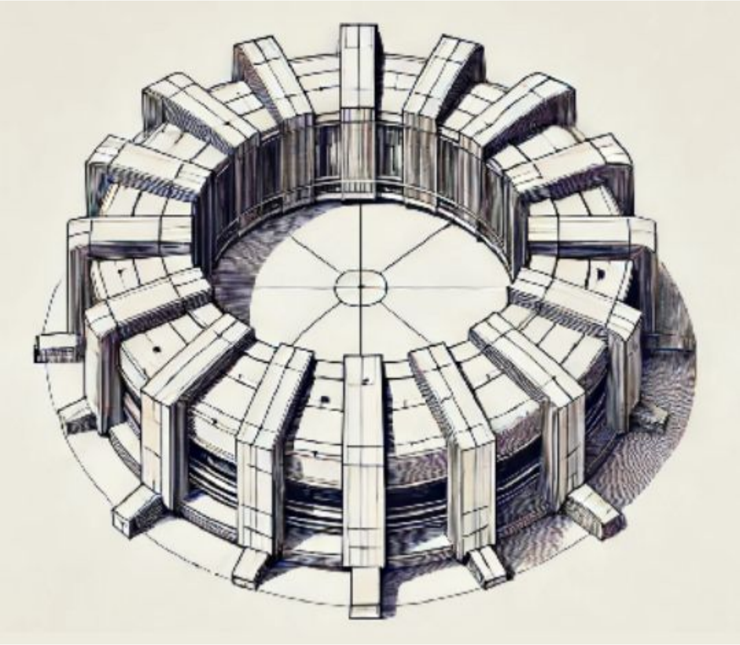
FCC

CEPC

ILC

CLIC

Future Colliders



FCC

CEPC

ILC

CLIC

Let’s talk about the future

Next generation of colliders in the world

Let’s talk about the future

Next generation of colliders in the world

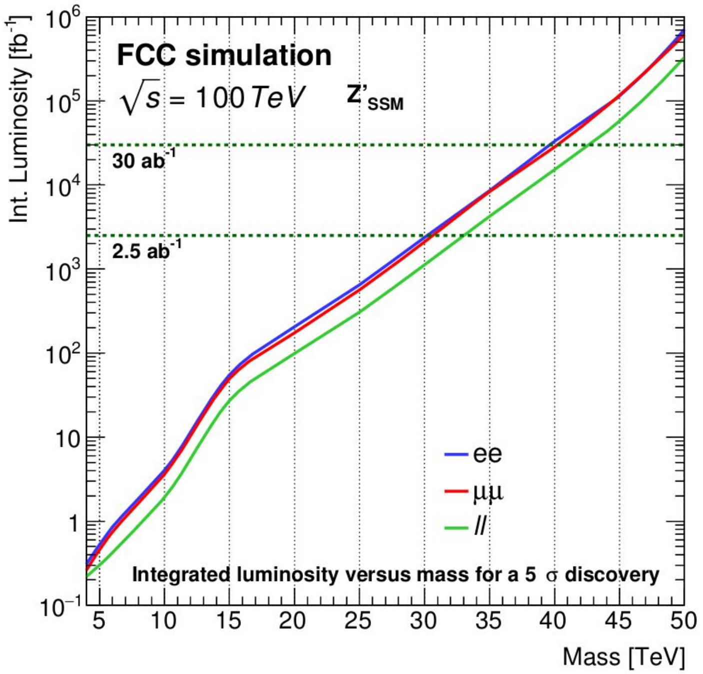
European Strategy of Particle Physics 2020

- New e+ e- collider (Higgs factory) as the highest-priority
- Hadron collider with Ecms at least 100 TeV at CERN as a longer term

Why new hadron collider?

Hadron collider as a discovery machine

Open questions in particle physics



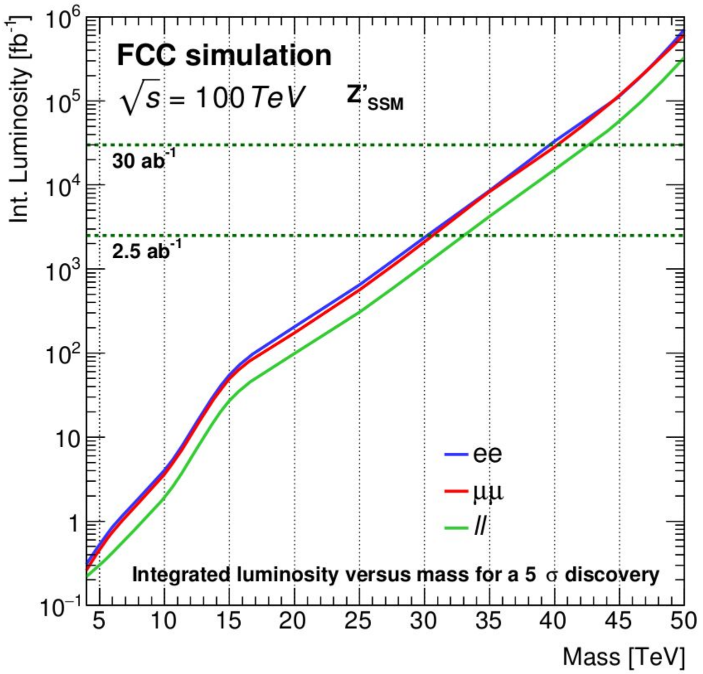
Why new hadron collider?

Hadron collider as a discovery machine

Open questions in particle physics

Hadron collider can give answers if

- Mass of new particles is in its reach
- The detectors are sensitive enough



Why new lepton collider?

More in the talk by Matej

Electroweak Precision

push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

The Higgs Boson

model-independent study of all accessible couplings

The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

Flavour Physics

use extremely large data sets to explore, resolve and understand the puzzles in the flavour sector

New Particles

searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Colliders at the market

Circular Colliders (lepton and potentially hadron colliders)

- FCC (Future Circular Collider, CERN)
- CEPC (Circular Electron Positron Collider, China)

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Circular Colliders (lepton and potentially hadron colliders)

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- CEPC (Circular Electron Positron Collider, China)

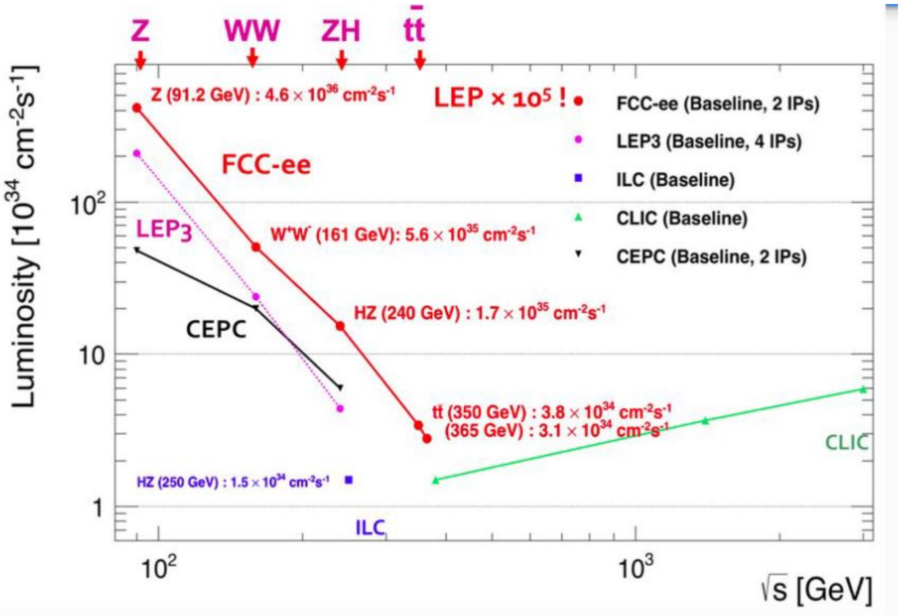
Linear Colliders (lepton colliders)

- ILC (International Linear Collider, Japan)
- CLIC (Compact Linear Collider, CERN)

Circular vs linear

Circular colliders

- High luminosity
- Synchrotron radiation
- Circulating reusable beams
- Synergy with future *pp* collider



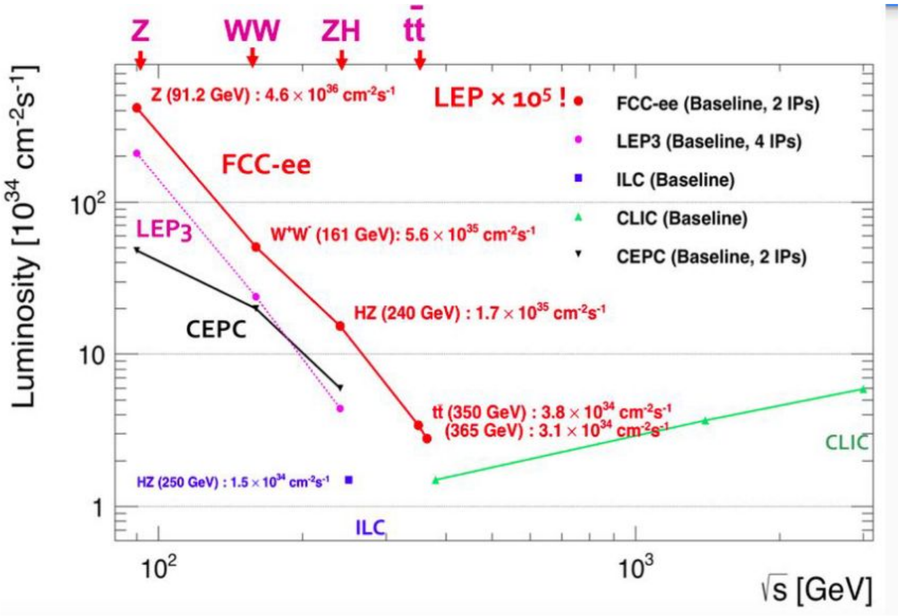
Circular vs linear

Circular colliders

- High luminosity
- Synchrotron radiation
- Circulating reusable beams
- Synergy with future *pp* collider

Linear colliders

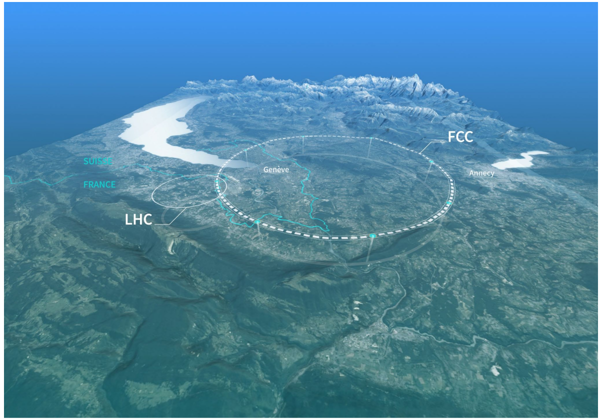
- High energy (extendable)
- No synchrotron radiation
- Beams not reusable

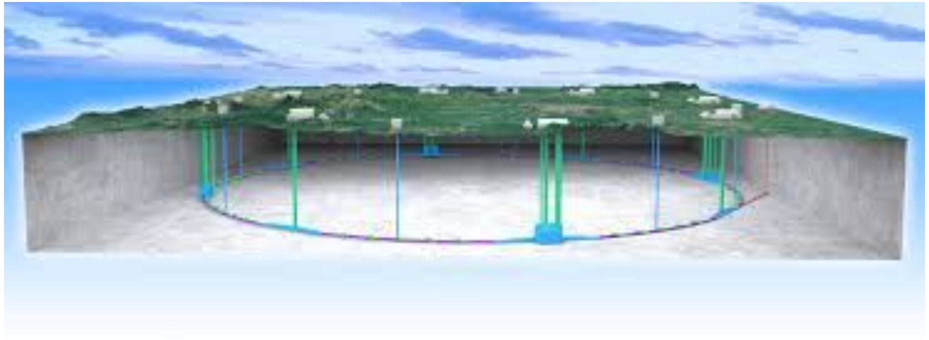


Circular colliders

FCC (CERN), CEPC (China)

- Electron-positron colliders which could be followed by proton-proton collider in ~100 km long tunnel
- Different stages: *Z* pole, *ZH*, *WW* threshold
- Physics programme: Higgs, EW, flavor physics & QCD, probes of physics BSM
- Timeline: CEPC 30's, FCC-ee 40's





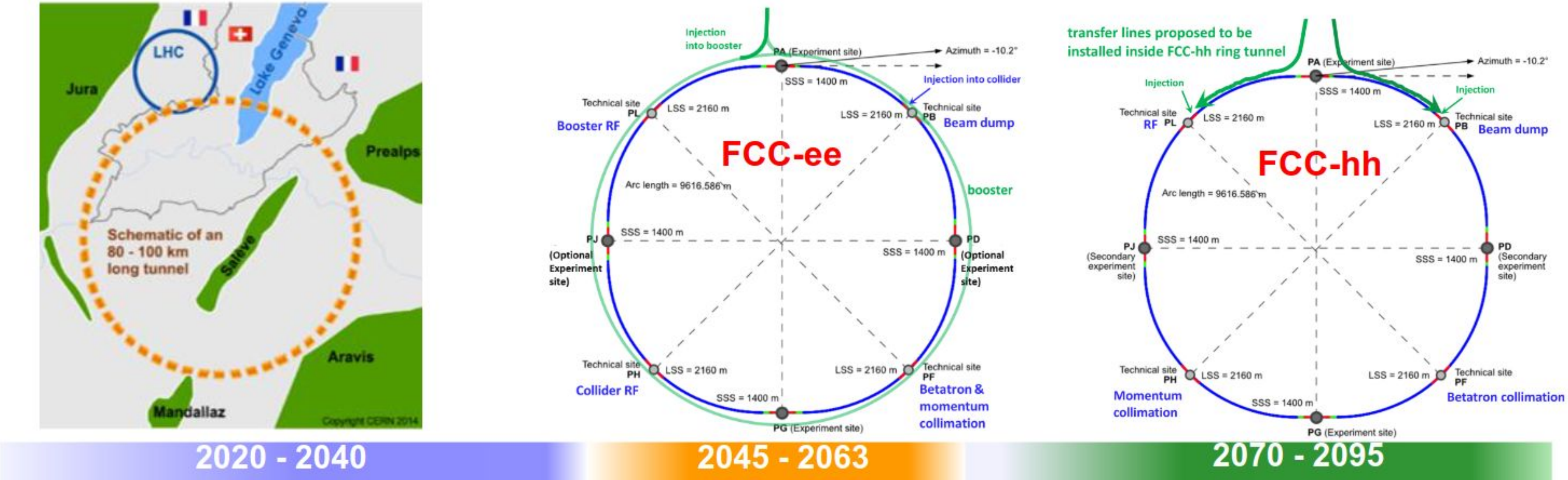
Future Circular Collider (FCC)

[FCC week, San Francisco, June 2024](#)

Higgs factory at CERN, could be followed by *pp* collider

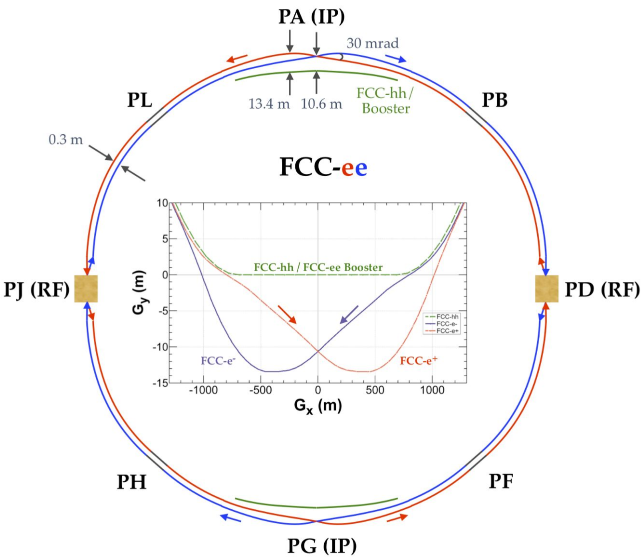
- Highly synergetic and complementary programme boosting the physics reach of both colliders
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure

FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



FCC-ee: Lepton collider

More in the talk by Zdenek



- Double ring e^+e^- collider (91 km)
- Asymmetric IR layout & optics to limit synchrotron radiation

FCC-ee: Lepton collider

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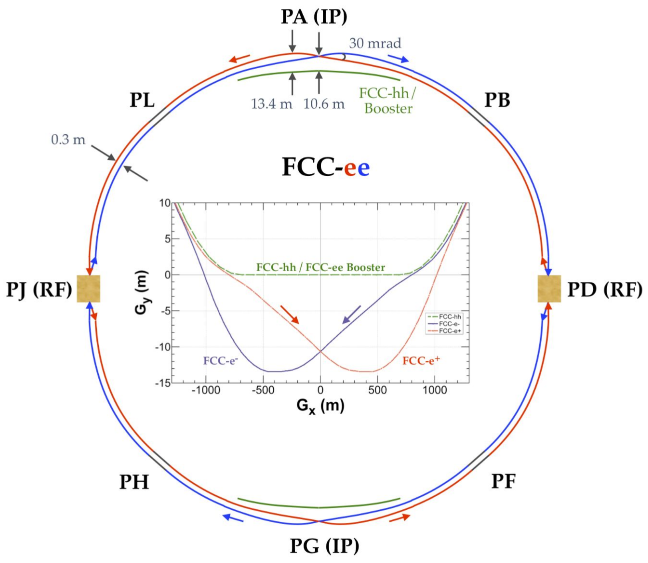
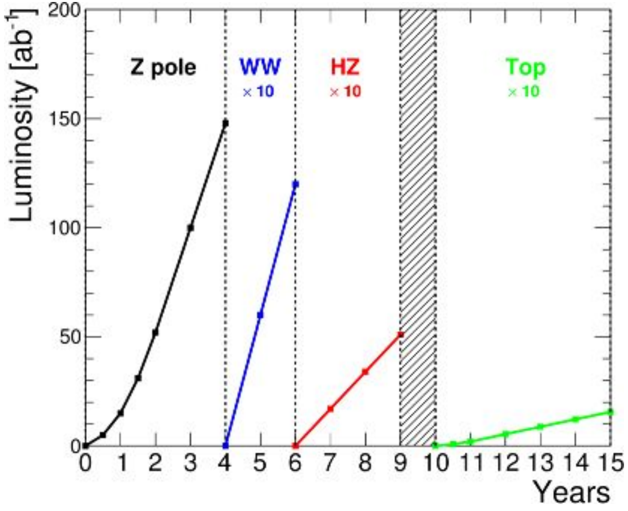
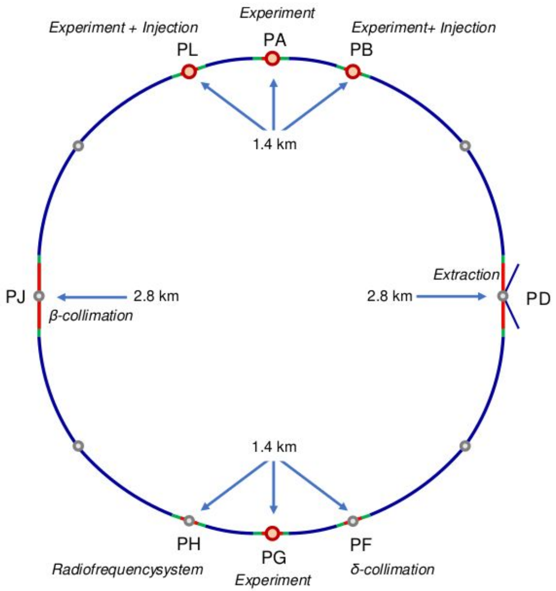




- Double ring e^+e^- collider (91 km)
- Asymmetric IR layout & optics to limit synchrotron radiation

- Up to four working points
- 10^5 × more Z bosons compared to LEP

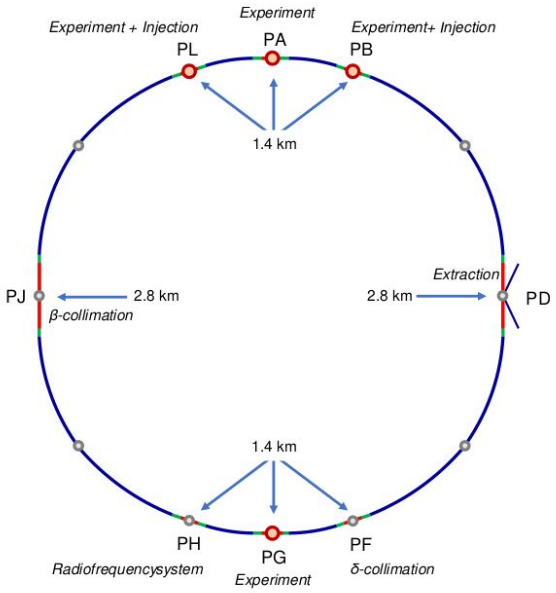
FCC-hh: Hadron collider

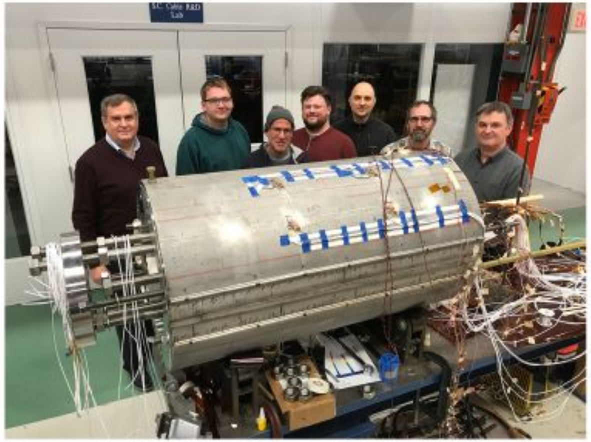


Order of magnitude increase wrt HL-LHC

- Centre of mass energy: 14 TeV → 100 TeV
- Total integrated luminosity: 4 ab^{-1} → 20 ab^{-1}

FCC-hh: Hadron collider





Order of magnitude increase wrt HL-LHC

- Centre of mass energy: 14 TeV → 100 TeV
- Total integrated luminosity: 4 ab^{-1} → 20 ab^{-1}

Key technology: 16 T dipole magnets

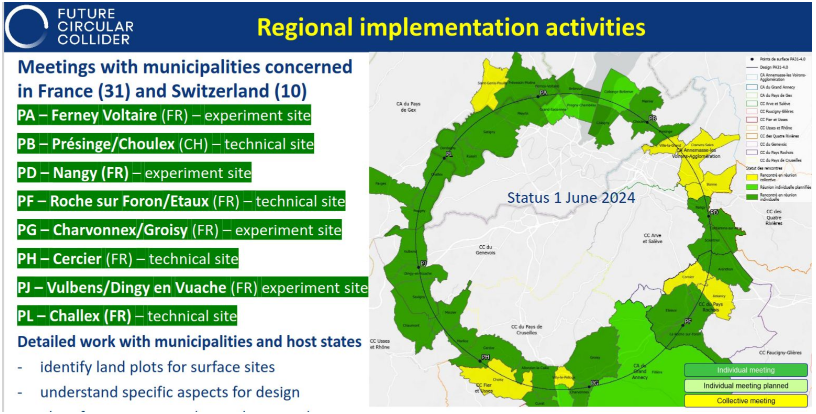
- Prototype of 14.1 T Nb_3Sn dipole magnet (Fermilab)

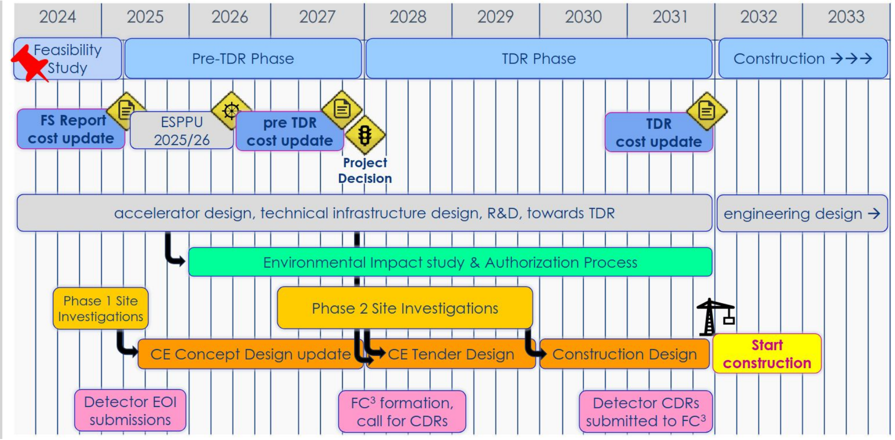
FCC Feasibility study

Feasibility study (2021–2025)

- Optimised placement (lowest risk baseline 90.7 km)
- Optimisation of RF, optics, layout
- Cost estimation
- Meetings with local authorities
- Connection to the electrical grid infrastructure
- Environmental studies and preparation of geological investigations (drillings and seismics) ongoing
- Studies on environmental aspects

R&D studies for the *pp* accelerator are ongoing





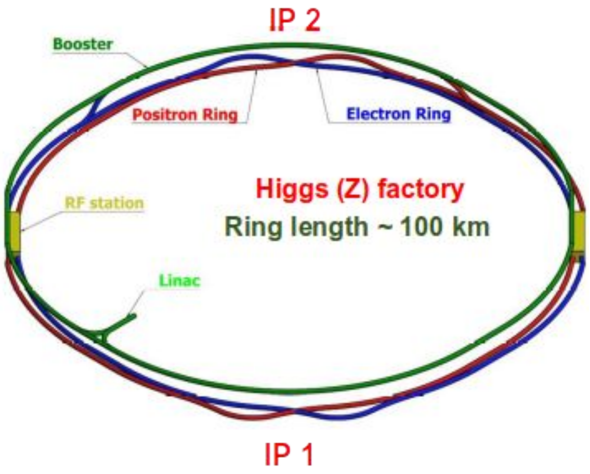
Circular Electron Positron Collider (CEPC)

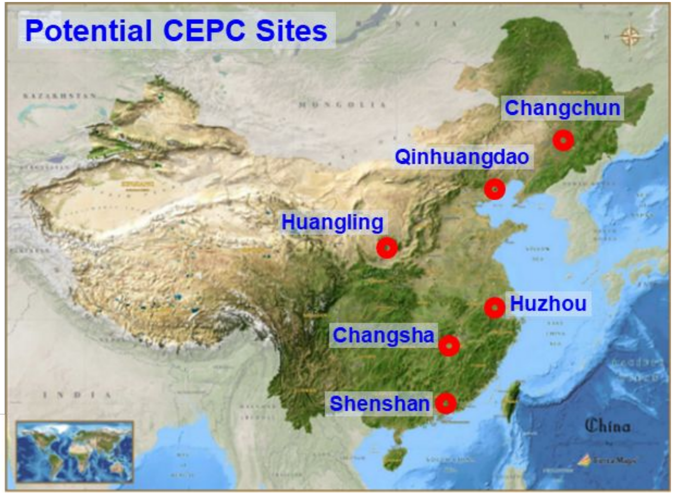
[CEPC workshop, Nanjing, Oct 2023]

The CEPC aims to start operation in 2030's, as a Higgs (*Z*/*W*) factory in China

Physics programme: Higgs, EW, flavor physics & QCD, probes of physics BSM

Possible *pp* collider (SppC) of ~ 50–100 TeV in the far future

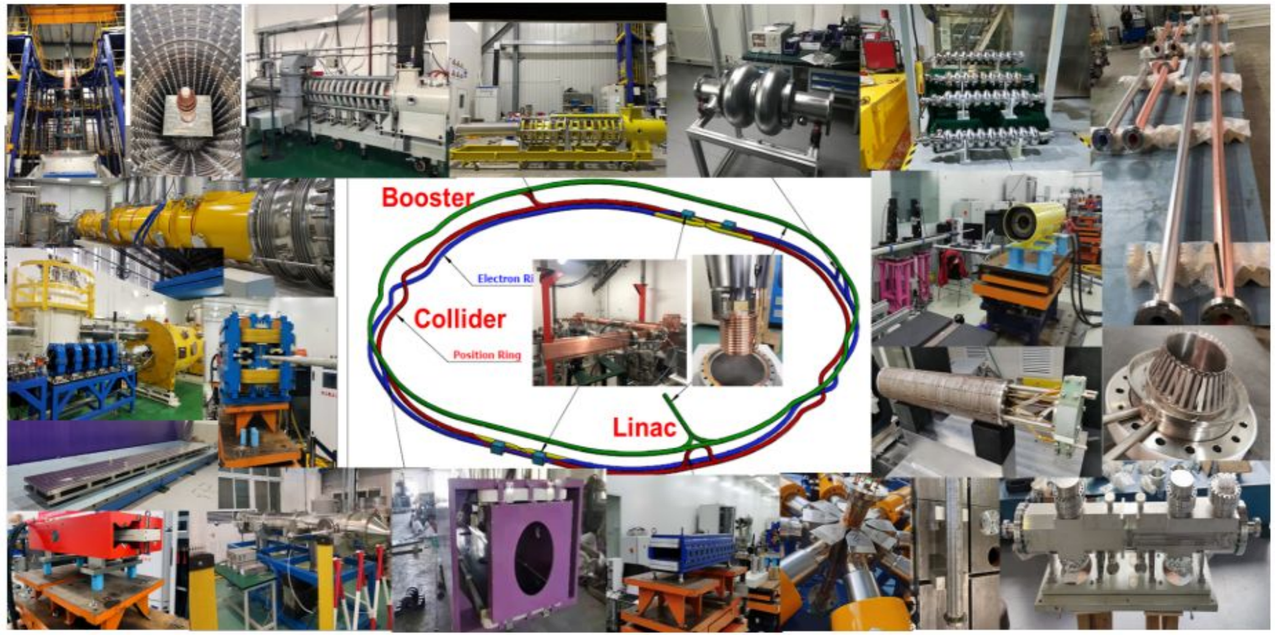




CEPC accelerator R&D

Specification Met ✓ Prototype Manufactured ✓

Represented Key Technologies for the CEPC



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

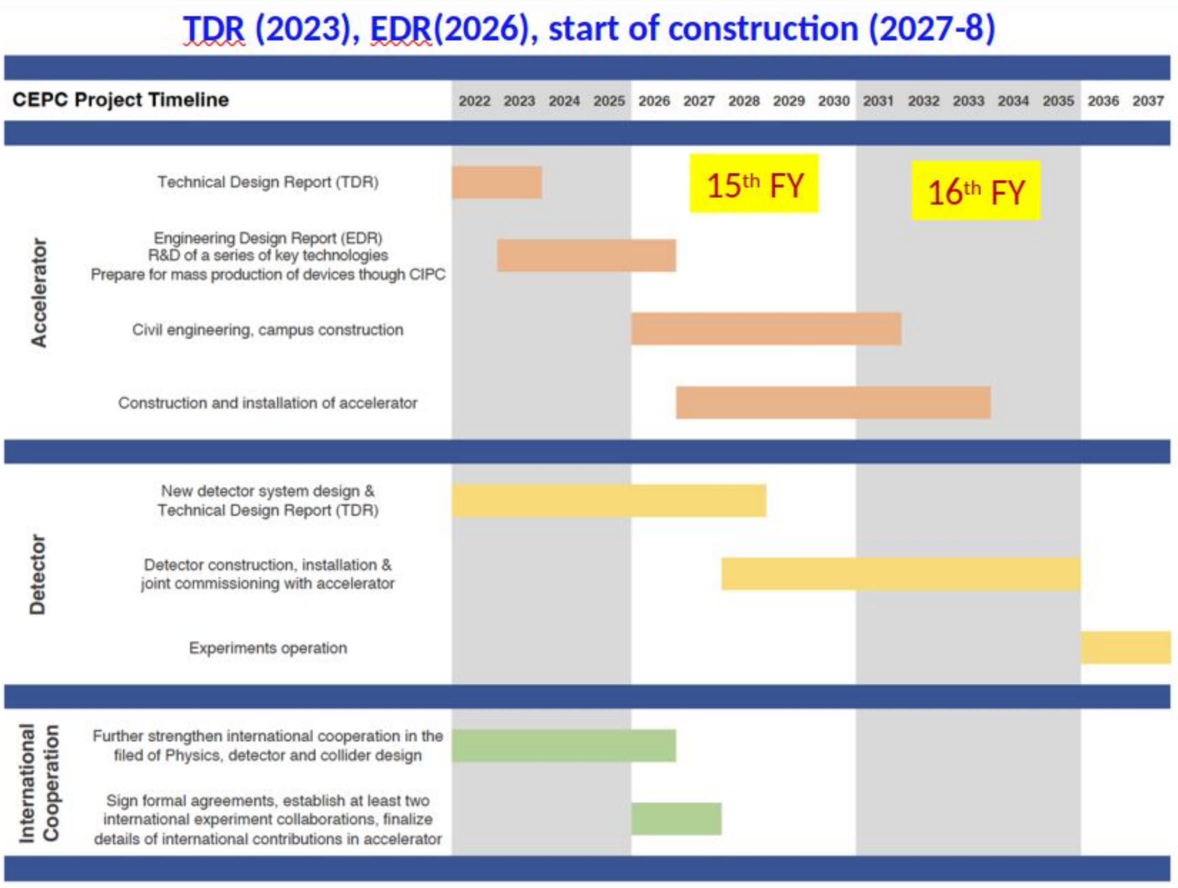
Key technology R&D spans all component lists in CEPC CDR

CEPC timeline

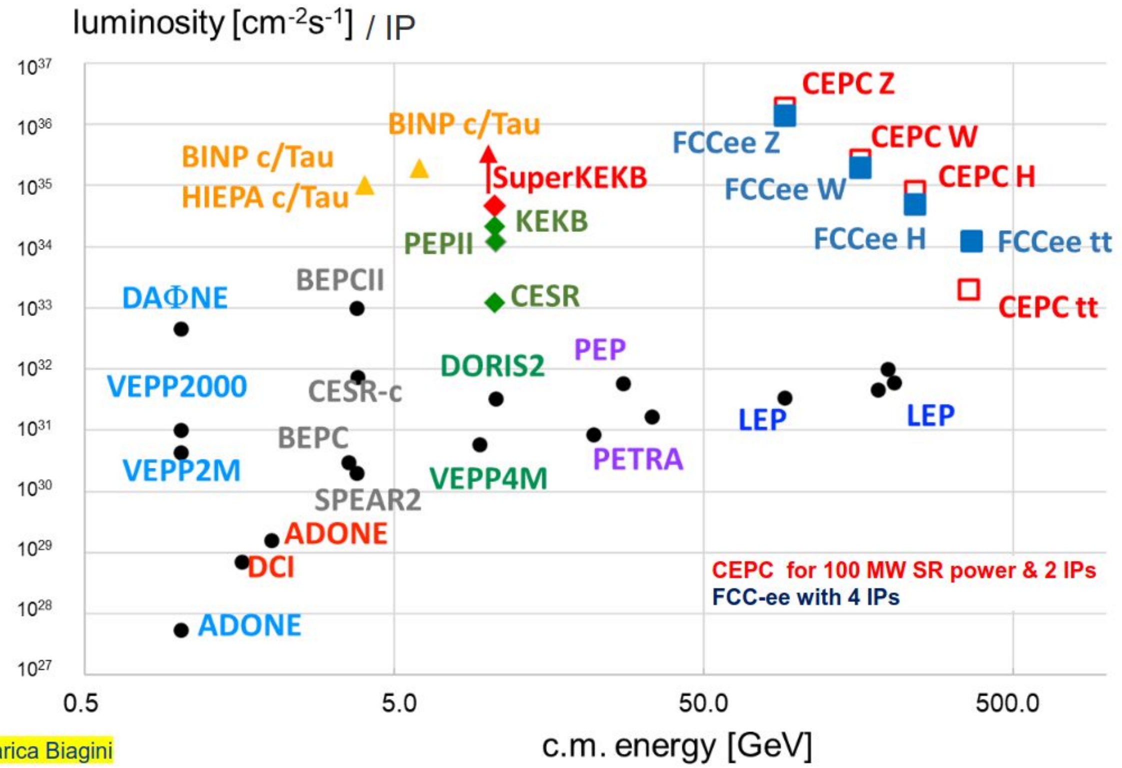
[**CEPC Accelerator Technical Design Report**]() (TDR) released (Dec 2023)

TDR of a reference detector: preparation starts in Jan 2024, official release by June 2025

Start of experiments ~2036



FCC vs CEPC



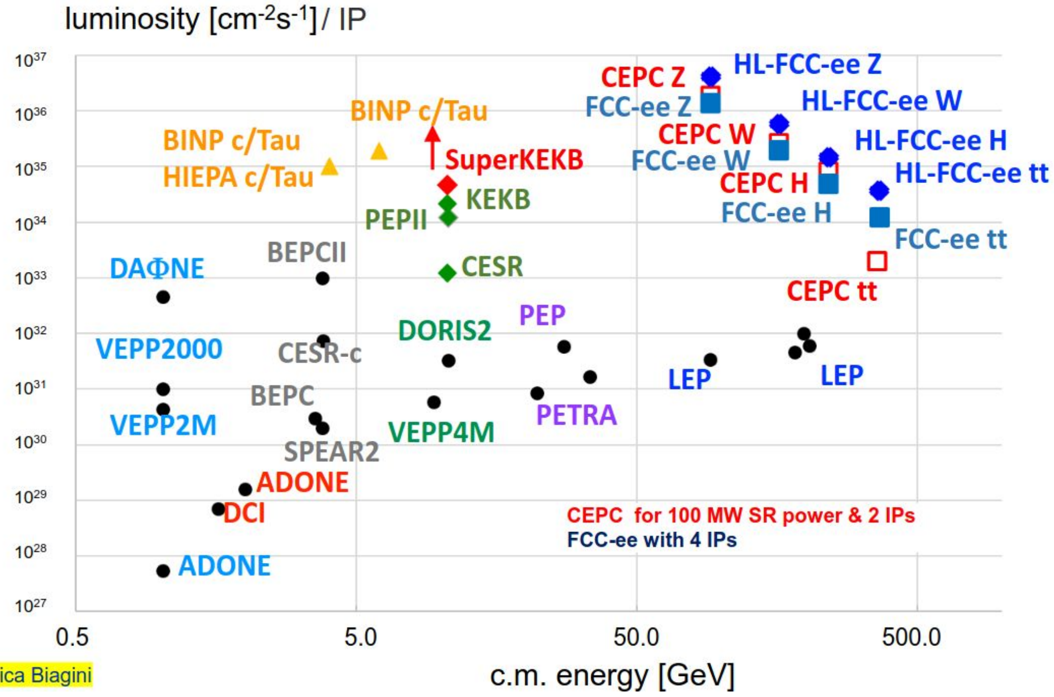
Marica Biagini

~ same accelerator design as twin machine CEPC

a few differences

	FCC-ee	CEPC
#IPs	4 or 2	2
collider SRF up to ZH	400 MHz, 1- & 2-cell, Nb/Cu, 4.5 K	650 MHz, 2-cell, Nb, 2 K
collider SRF ttbar	800 MHz 5-cell, Nb, 2 K	650 MHz, 5-cell, Nb, 2 K
booster SRF	800 MHz 5-cell, Nb, 2 K	1.3 GHz, 9-cell, Nb, 2 K
top-up	in collider	in booster

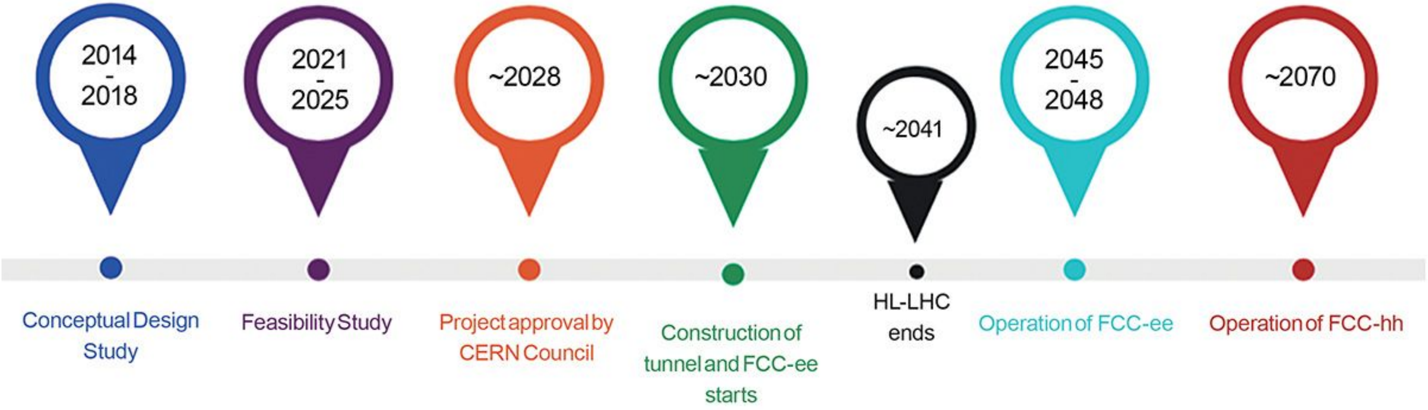
"HL-FCC-ee"



Marica Biagini

FCC-ee vs CEPC: timeline

FCC



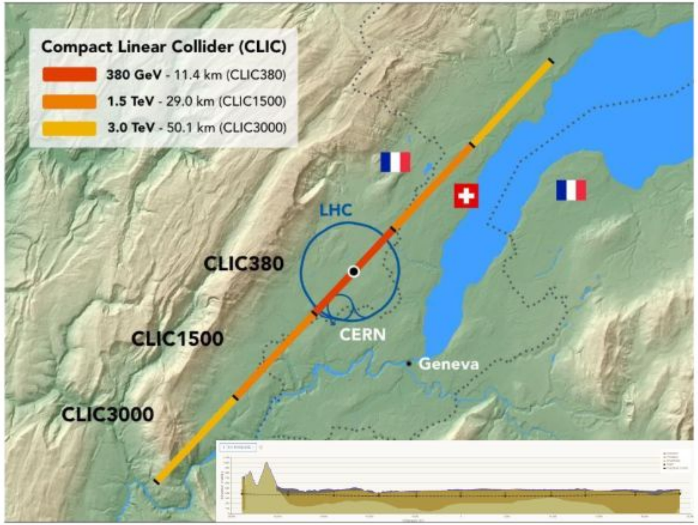
CEPC

- 2013-2025: Key technology R&D, from CDR to TDR, site selection, international collaboration etc.
- Ideal case: Approval in the 15th Five-Year Plan, and start construction (~8 years)

Linear colliders - ILC, CLIC

- Energy extendability to TeV scale lies in the heart of linear colliders: ILC focuses on $\sqrt{s}$ from 250 GeV to 1 TeV; CLIC 380 GeV to 3 TeV; keeping options to run at Z-pole ("GigaZ")
- Complementary approaches: "Warm" & "Cold" accelerating technologies; 72MeV/m @ CLIC380; 31.5MeV/m @ ILC250
- Polarized beams: both offering 80% for electron; 30% for positron in ILC default design

ILC250 ~ 20km



Compact LInear Collider (CLIC)

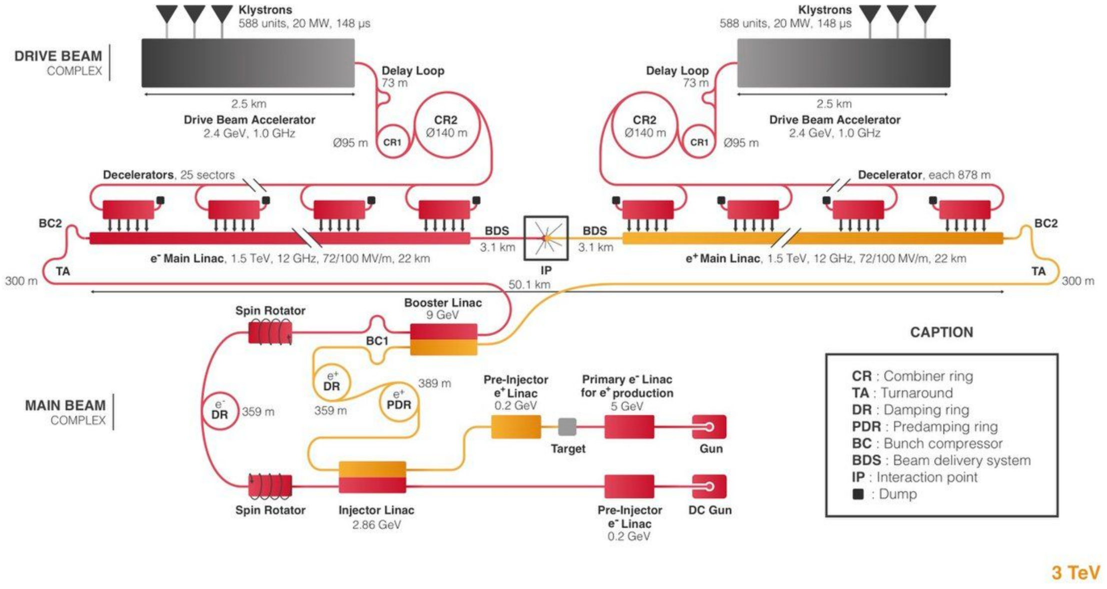
Alternative plan @ CERN

Two beam acceleration techniques with an acceleration gradient of 100 MV/m

Acceleration cavities operating at room temperature

Machine is extendable

- Three energy stages (380 GeV, 1.5 TeV, 3 TeV)

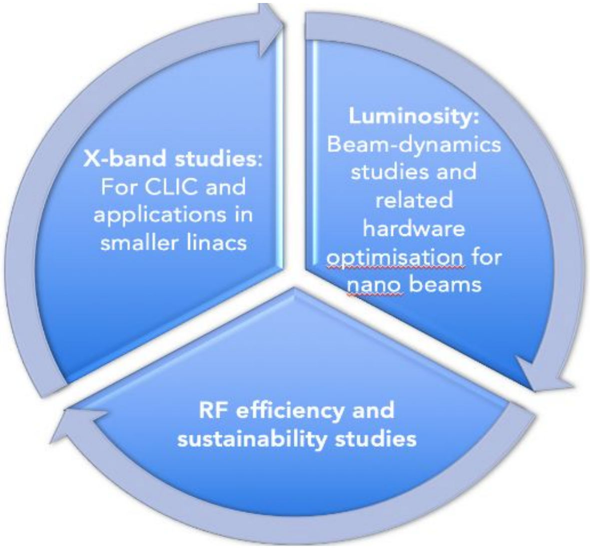


CLIC status

CLIC is working towards a Project Readiness Report 2025/26 as a step toward a TDR (for next ESPP)

Focusing on:

- X-band technology readiness for the 380 GeV CLIC initial phase
- Optimizing the luminosity at 380 GeV
- Improving power efficiency for both initial phase & high energies



CLIC development

The CLIC accelerator studies are mature:

Optimised design for cost and power

Many tests in CTF3, FELs, lightsources and test-stands

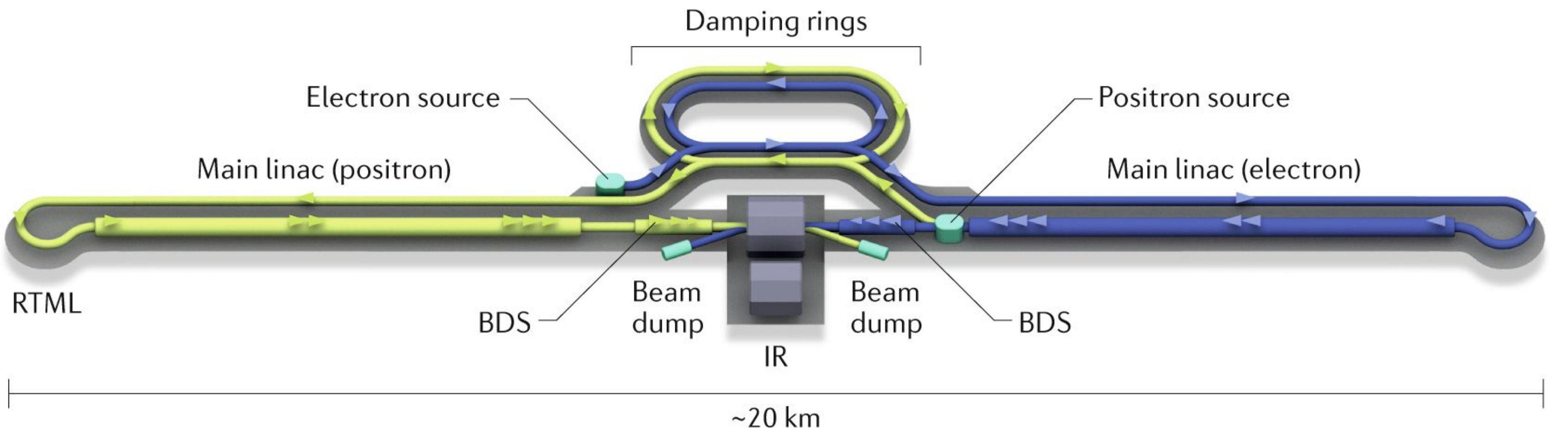
Technical developments of "all" key elements

International Linear Collider (ILC)

Location: Japon

Collision energy of 500 GeV, extendable to 1 TeV

Key technologies: SRF accelerating, nano-beam



ILC status

TDR published in 2013, progress towards to final technology choice and engineering design, optimization of the cost

Approval of the project

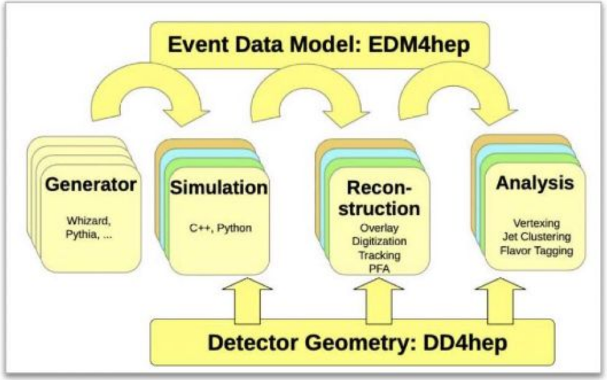
- MEXT (represents Japanese government) didn’t approve the original Pre-Lab proposal (Feb 2022, newsline)
- April 2023: factor of 2 increase on KEK funding for ILC R&D by MEXT
- ILC Technology Network (ITN) is launched: memorandum between KEK & CERN signed
- Promotion under leadership by International Development Team (IDT), KEK and ILC-Japan

If ILC project does not seem very likely, new linear collider proposals sited in US (discussed in Snowmass 2022): C3

Common software

More in the talk by Juraj

- **Key4HEP** framework being developed with support from AIDAInnova, adopted (fully developing and/or migrating to) in all Higgs Factories (CLIC, FCCee, ILC, CEPC, C^3) and even beyond (Muon collider, EIC)



- Trend towards common event data (**EDM4HEP**) and geometry (**DD4HEP**) models, MC event format (**HepMC3**, w/ EDM4HEP converter)

G. Ganis

- Simulations and reconstruction are maturing to be become cross usable in Key4HEP (develop once, use many)

List of generators currently available in key4hep

T Mandlener, Oct 2022

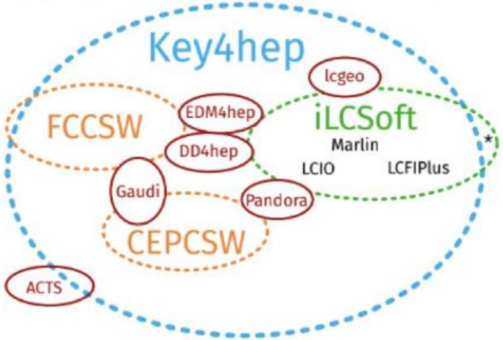
- Generators

babayaga*†	baurmc†	bhlumi*†	crmc†	evtgen	genie†
gosam†	guinea-pig*†	herwig3	herwigpp†	kkmcee*	madgraph5amc
photos	pythia6†	pythia8	sherpa	starlight†	superchic†
tauola†	vbfnlo	whizard			

- "Generator tools"

agile†	alpgen†	ampt†	apfel†	ccs-qcd†	chaplin†
collier†	cuba†	dire†	feynhiggs†	form†	hepmc
hepmc3	heppdt	hoppet†	hztool†	lhapdf	lhapdfsets†
looptools	openloops	professor†	prophecy4f†	qd†	qgraf†
recola†	rivet	syscalc†	thepeg	unigen†	yoda

Installed with current Key4hep stack
* Available from key4hep-spack repository
† Single version only



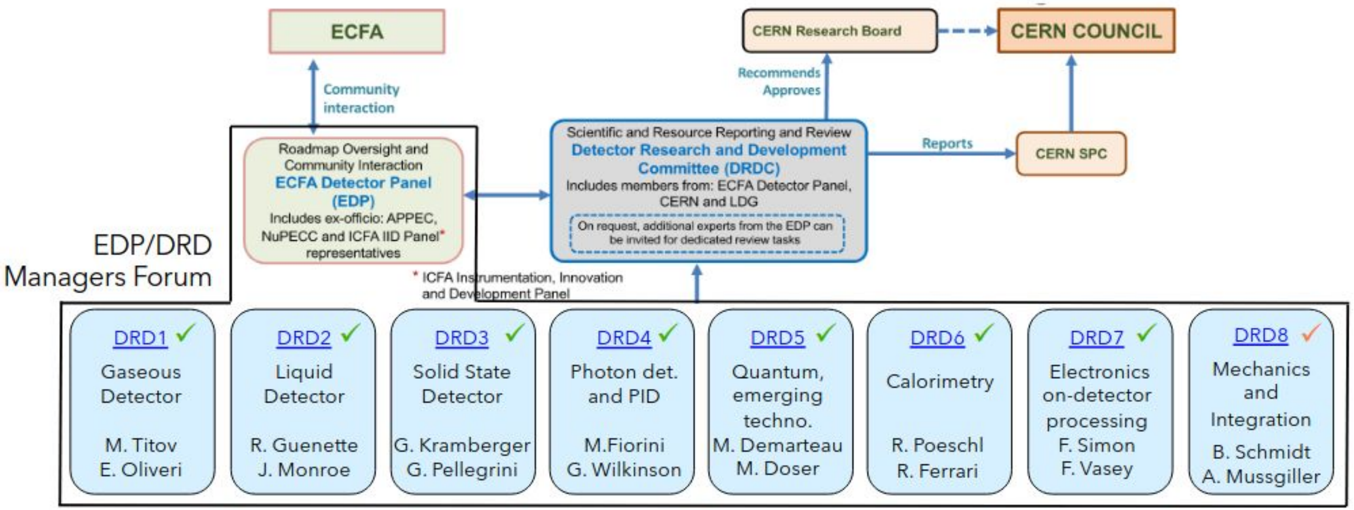
Detectors for future facilities

More in the talk by Filomena

Common effort started by ECFA

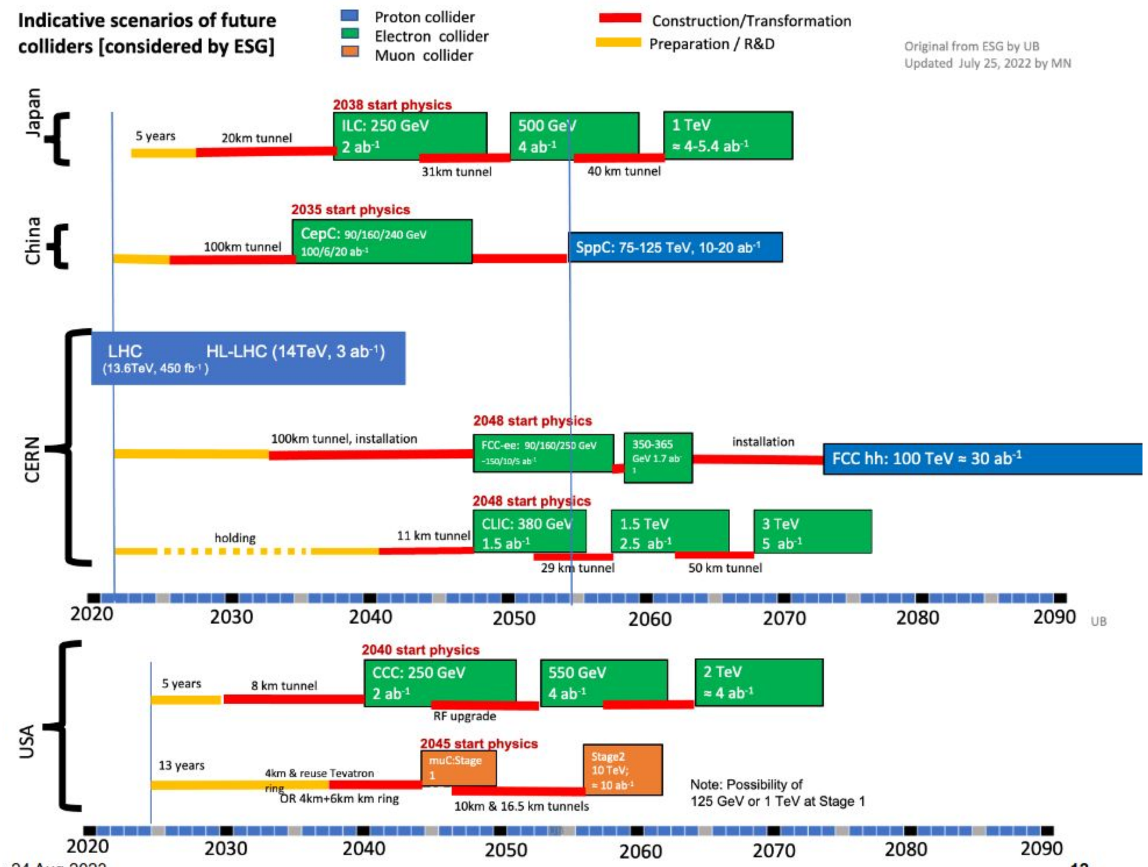
Detector R&D Collaborations

- Hosted at CERN
- Several CZ/SK institutions are parts of these collaborations



✓ approved by CERN RB*, ✓ DRD8 LoI submitted to DRDC, proposal aims end-2024

Timelines



Indicative scenarios of future colliders [considered by ESG]
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated July 25, 2022 by MN
Japan
5 years
20km tunnel
2038 start physics
ILC: 250 GeV 2 ab-1
500 GeV 4 ab-1
1 TeV ≈ 4-5.4 ab-1
31km tunnel
40 km tunnel
China
100km tunnel
2035 start physics
CepC: 90/160/240 GeV 100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
CERN
LHC (13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
350-365 GeV 1.7 ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
holding
11 km tunnel
2048 start physics
CLIC: 380 GeV 1.5 ab-1
1.5 TeV 2.5 ab-1
3 TeV 5 ab-1
29 km tunnel
50 km tunnel
2020 2030 2040 2050 2060 2070 2080 2090
UB
USA
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV 2 ab-1
550 GeV 4 ab-1
2 TeV ≈ 4 ab-1
RF upgrade
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage 1
Stage2 10 TeV; ≈ 10 ab-1
10km & 16.5 km tunnels
Note: Possibility of 125 GeV or 1 TeV at Stage 1
2020 2030 2040 2050 2060 2070 2080 2090

Words by F. Gianotti (director of CERN)

FUTURE CIRCULAR COLLIDER

Why FCC ?

F. Gianotti

1) **Physics : best overall physics potential of all proposed future colliders; matches the vision of the 2020 European Strategy:** "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."

- ❑ FCC-ee : **ultra-precise** measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- ❑ FCC-hh : **only** machine able to explore next **energy frontier** directly (~ x10 LHC)
- ❑ Also provides for heavy-ion collisions and, possibly, ep/e-ion collisions
- ❑ **4 collision points** → robustness; specialized experiments for maximum physics output

2) **Timeline**

- ❑ **FCC-ee technology is "mature"** → construction can start in the early 2030s and physics a few years after the end of HL-LHC operation (currently 2048, earlier if more resources available) → This would keep the community, in particular the young people, engaged and motivated.
- ❑ **FCC-ee before FCC-hh** would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - **20 years of R&D work towards affordable magnets providing the highest achievable field (HTS)**
  - **optimization of overall investment** : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the **only facility commensurate with the size of the CERN community** (4 major experiments)

Is it feasible? Isn't it too ambitious?

-- Ongoing Feasibility Study showing spectacular progress

-- **FCC is big and audacious project, but so were LEP and LHC when first conceived** → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects

-- FCC is the **best project for future of CERN** (for above reasons) → **we have to work to make it happen**

More words by F. Gianotti

FUTURE CIRCULAR COLLIDER

Should we change our plans ?

F. Gianotti

1) Only a new European Strategy can modify the plans of a previous one, taking into account Europe's ambitions within the global context (e.g. P5/US support for an off-shore Higgs factory, CEPC in China, etc.)

2) Recommendation of 2020 European Strategy for future colliders:
"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."
Note: the Strategy does not state that a Higgs factory should be built in Europe. However, a Higgs factory is the highest priority for the European community → wherever it will be built, it should allow for significant participation from Europe

3) Furthermore, skipping FCC-ee and going directly to FCC-hh implies a long gap (>> 10 years) between the end of HL-LHC and beginning of next collider at CERN, for reasons of cost and of readiness of high-field magnet technology
→ risk to lose the community, in particular the young generations.

4) The only colliders that are technically mature enough to start operation in early 2040s are e^+e^- Higgs factories, and to be time-competitive with the CEPC (if approved), a circular Higgs factory is needed (much higher luminosity than linear colliders)

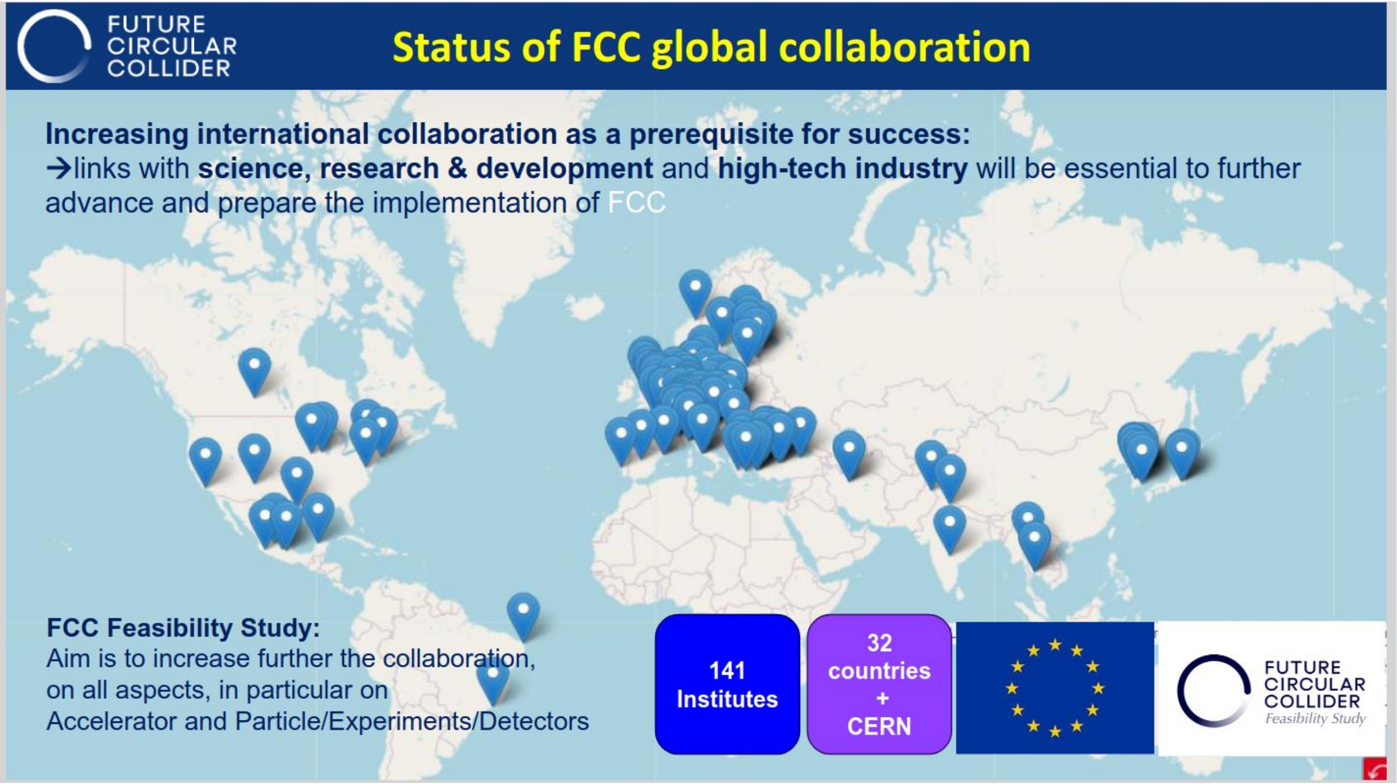
⬇

Should we change our plans ? **NO**

Should we accelerate our planning ? **YES**
→ CERN Directorate will discuss these matters with the CERN Council in the coming months

Future colliders and CZ/SK

Charles Uni (CZ) is a member of **FCC Collaboration**



To conclude

FCC is the main future CERN project

Would you like to join?

- Many areas where you can contribute (physics studies, theoretical calculations, detector development, accelerator physics, common software, …)
- Our group at Charles Uni will be happy to help you as much as we can

To conclude

FCC is the main future CERN project

Would you like to join?

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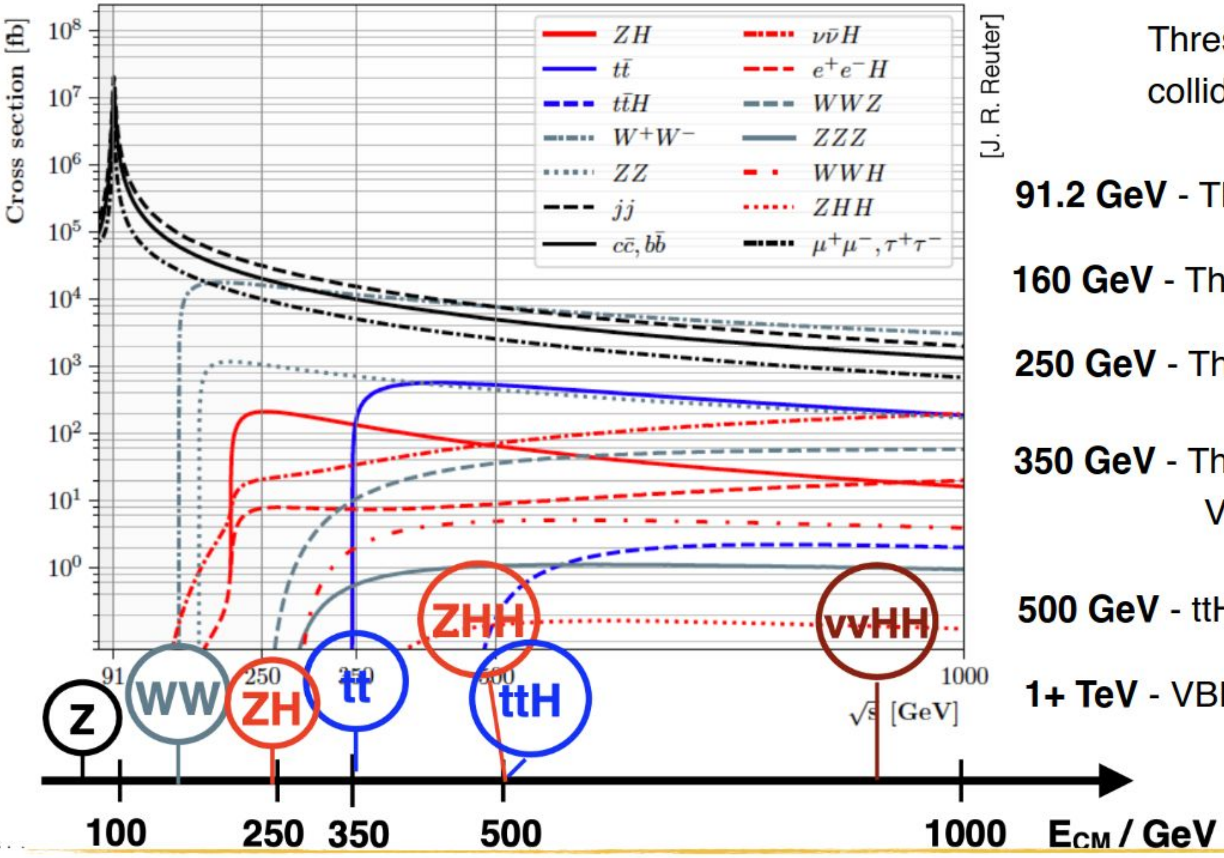
Talk with your university teachers and supervisors about joining the FCC Collaboration

It’s your future

BACKUP

Future e+e- colliders



Thresholds and cross sections set collider energy targets:

91.2 GeV - The Z pole

160 GeV - The WW threshold

250 GeV - The ZH maximum

350 GeV - The top threshold, VBF Higgs production

500 GeV - ttH, ZHH

1+ TeV - VBF double Higgs

Precision electroweak, Flavour, QCD, …

Higgs properties & couplings

Top properties, Top as probe

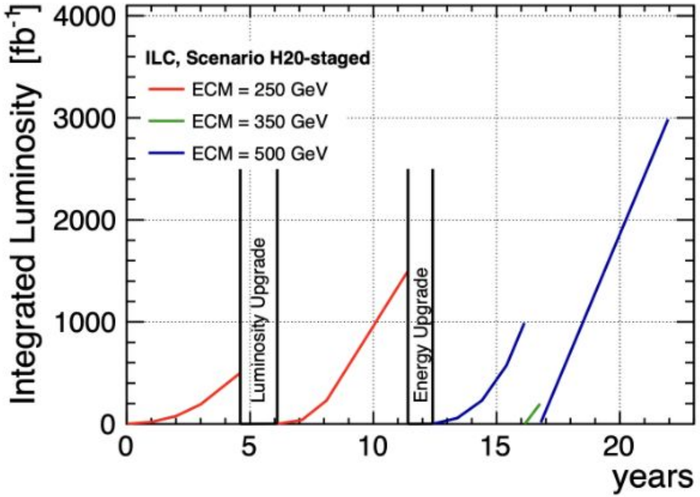
Direct top Yukawa Higgs selfcoupling

Search at the energy frontier

Linear Colliders

running scenarios for benchmark studies

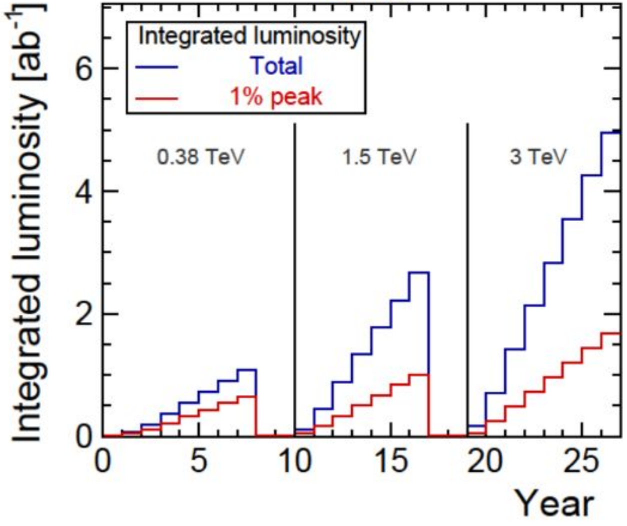
ILC



	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(LL, LR, RL, RR) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5

[arXiv:2203.07622]

CLIC

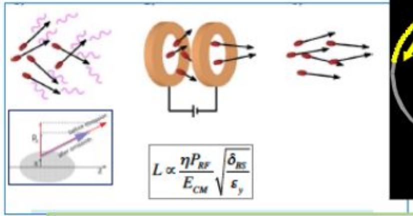


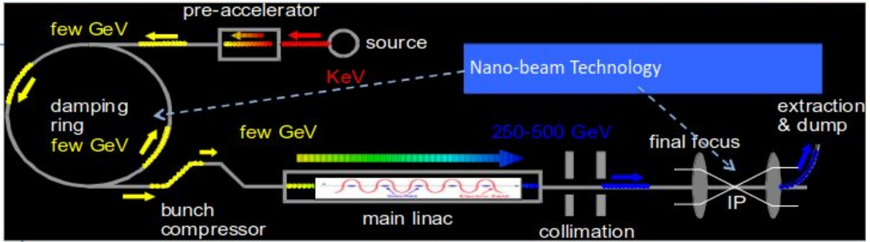
	380 GeV	1.5 TeV	3 TeV
∫L (ab^{-1})	1	2.5	5
P(e-,e+;%)	80/0	80/0	80/0
(LR,RL)	(50,50)	(80,20)	(80,20)

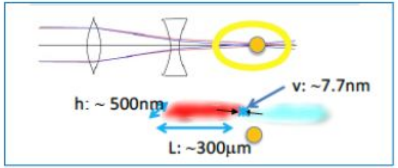
[arXiv:2203.07622]

Progress in Nano-beam Technology

Damping ring & Final focus







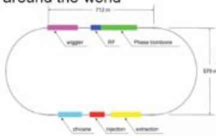
Progress in DR

~2017	2018~

DR — Eng. design

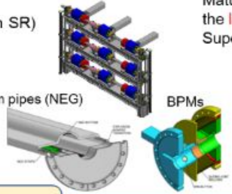
Design based on experience with circular accelerators (4th generation SR) around the world

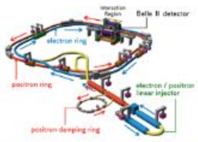
Maturing technology for beams in the latest ring accelerators such as SuperKEKB



Beam pipes (NEG)

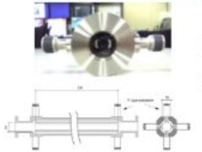
BPMs

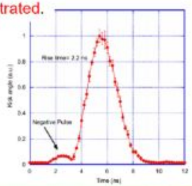




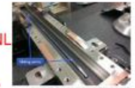
Inj./Ext. — Eng. Design, Equipment verification

Beam extraction demonstrated.





LBNL



CERN-CLIC

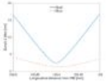
Fast kicker technology

Progress in Final Focus

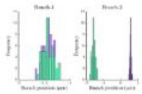
~2017	2018~

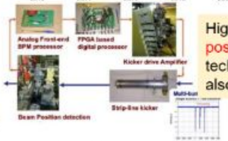
Tech. design completed
Spec. almost achieved

Wakefield effects



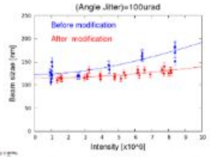
Distribution of bunch positions measured at IPB, with two-BPM FB off (green) and on (purple)

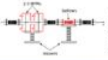




High-speed beam position control technology was also demonstrated.

FONT feedback system





ATF2 wakefield knobs system be-tween BPM QD10BFF and QD10AFF

Wakefield effect was evaluated at ATF.
-confirm no serious problem at ILC
-demonstrate a technique to reduce the wakefield effect

ATF International Review (Committee)*
-The committee highly evaluated the achievements of ATF so far.
-The committee pointed out the importance of continuing research to contribute to the detailed design of the ILC final convergence.

*https://agenda.linearcollider.org/event/8626/

Progress in SRF Technology

~1.3 GHz worldwide SRF accelerators

European XFEL
(in operation, 2017~)

800 cavities
100 CMs
17.5 GeV (Pulsed)

ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)

ILC (planned)

8,000 9-cell cavities
900 CMs
2 x 125 GeV (Pulsed)

LCLS-II -HE
(in commissioning)

-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)

> 2,000 SRF cavities being realized!

ILC Promotion

Paradigm shift: from "international" to "global"

東京大学 THE UNIVERSITY OF TOKYO

Global project: Starts and evolves as a collaborative project of partner countries who make collective decisions on all aspects of the project, such as the scheme for cost and responsibility sharing, project organisation, and host and site location. The ownership is shared among the partners.

ILC

SKA

ITER

[S. Asai]

International project: Initiated as a project of a laboratory with a limited international participation, a total of O(10~20%) of the accelerator, like HERA (started as a DESY project) and LHC (started as a CERN project). This fraction may become larger but the ultimate ownership remains with the initiator.

Our usual approach

Linear Colliders - New Players

ILC “backup”

- If ILC is not moving forward as expected…
- New linear collider proposals sited in US as discussed in Snowmass 2022

C3 Workshop 2022

[V.Sheltsev @ Snowmass 2022]

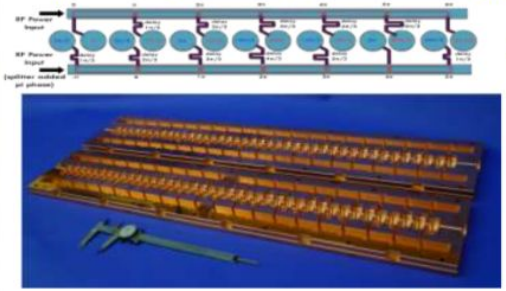
arxiv:2203.08211 arxiv:2110.15800

Must fit ~7 km including BDS

Required gradients of at least **70MV/m**

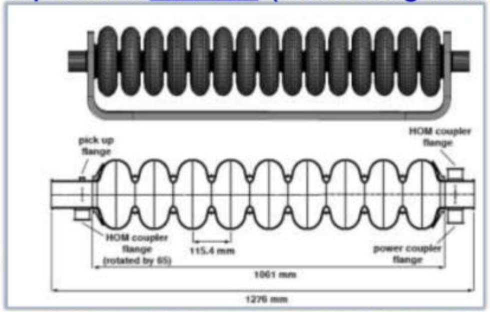
Compact → lower cost (wrt ILC/CLIC)

Option 1: Cool Copper Collider (C^3)



5.7GHz 77K

Option 2: *HELEN* (Travelling Wave ILC)



1.3GHz 2 K

FCC Feasibility Study mid-term review

The goal of the FCC FS mid-term review was to assess the progress of the Study towards the final report

Deliverables (approved by Council in Sept 2022):

D1 : Definition of the baseline scenario
D2 : Civil engineering
D3 : Processes and implementation studies with the Host States
D4 : Technical infrastructure
D5 : FCC-ee accelerator
D6: FCC-hh accelerator
D7: Project cost and financial feasibility
D8: Physics, experiments and detectors

FS scope is actually much broader than just the project feasibility

Documents:

- ❑ Mid-term report (all deliverables except D7; ~ 700 pages)
- ❑ Executive Summary of mid-term report (~ 50 pages)
- ❑ Updated cost assessment (D7)
- ❑ Funding model (D7)

Conclusion

- ❑ Extremely positive feedback from all committees
- ❑ Mid-term deliverables and goals met
- ❑ No technical show-stopper found at this stage.
- ❑ "The Council … congratulated and thanked all the teams involved in the Study for the excellent and significant work done so far and for the impressive progress, and looks forward to receiving the final report in 2025."

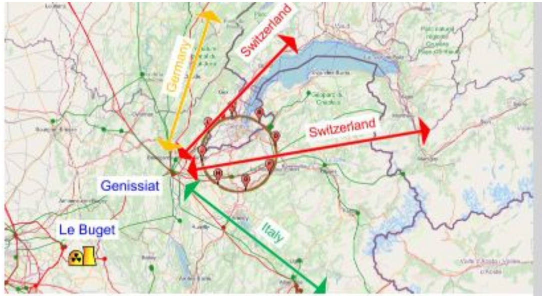
Review steps:

- ❑ Oct 2023: FCC FS Scientific Advisory Committee (scientific and technical aspects) and Cost Review Panel (ad hoc committee; cost and financial aspects)
- ❑ Nov 2023: CERN Scientific Policy Committee (SPC) and Finance Committee
- ❑ 2 Feb 2024: Council

← Many thanks to all of them!

FCC: electricity

Updated FCC-ee energy consumption	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Max. power during beam operation (MW)	222	247	273	357
Average power / year (MW)	122	138	152	202
Total yearly consumption (TWh)	**1.07**	**1.21**	**1.33**	**1.77**

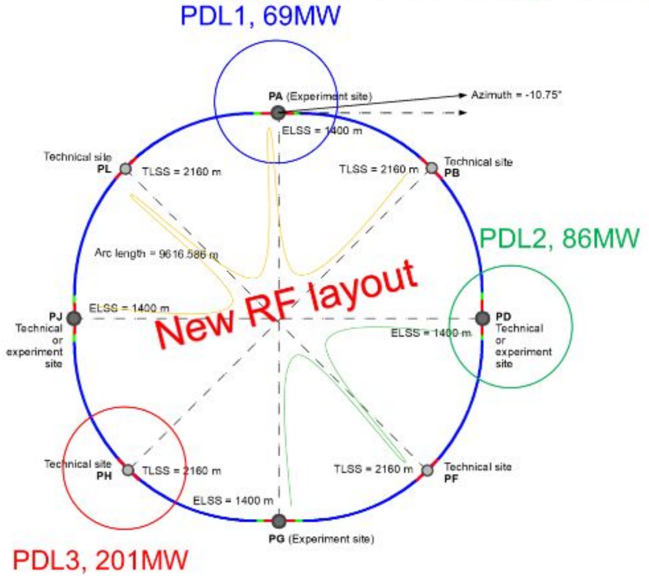


Powering concept and max power load by sub-stations:

The loads could be charged on the three sub-stations (optimum connections to existing regional HV grid):

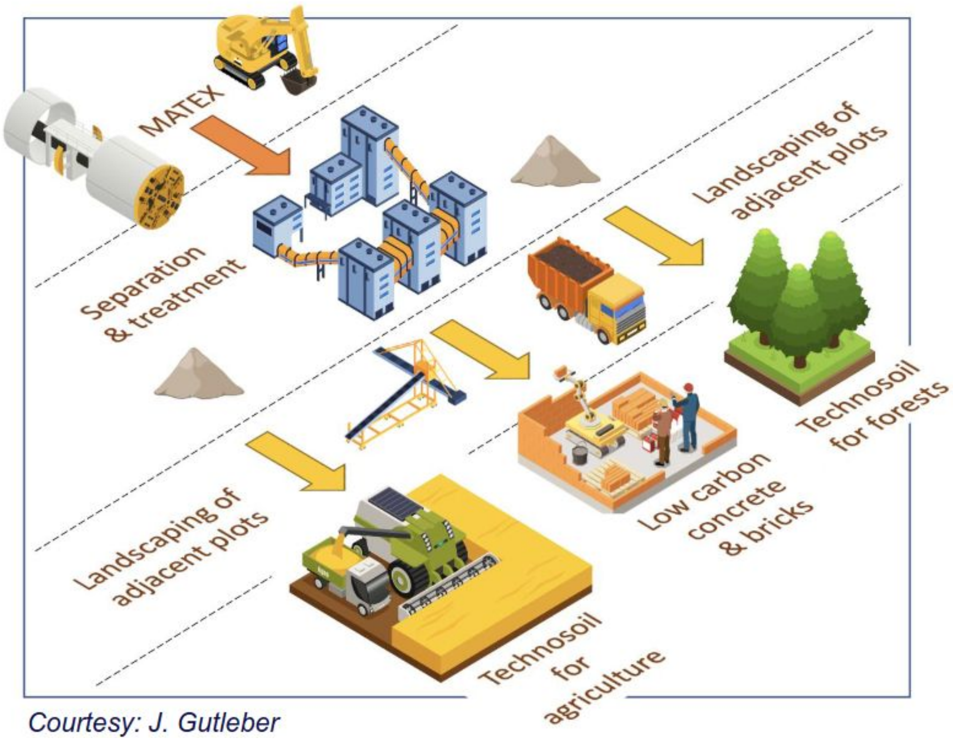
- **Point D, with a new sub-station** covering PB – PD – PF – PG
- **Point H with a new dedicated sub-station** for collider RF
- Point L, with a sub-station covering PJ – PL – PA
- → Alternative to new sub-station at Point L is **reusing the existing CERN Prevession station to PA**

- **All options pursued with RTE**
- **Powering concept and max. power rating of the three sub-stations compatible FCC-hh.**



Excavation material management

An innovative local approach for excavated materials:



Courtesy: J. Gutleber

Excavated material from FCC subsurface infrastructures: 6.5 Mm³ in situ, 8.4 Mm³ excavated (bulk factor 1.3)

2021-2022: International competition " **Mining the Future",** launched with the support of the EU Horizon 2020 grant agreement 951754**, to find innovative and realistic ideas for the reuse of Molasse (95% of excavated materials)**

2023: **Definition of the "OpenSky Laboratory" project:**

- **Objective**: Develop and test an innovative process to transform sterile "molasse" into fertile soil for agricultural use and afforestation.
- Duration: **4 years (2024-2027)**

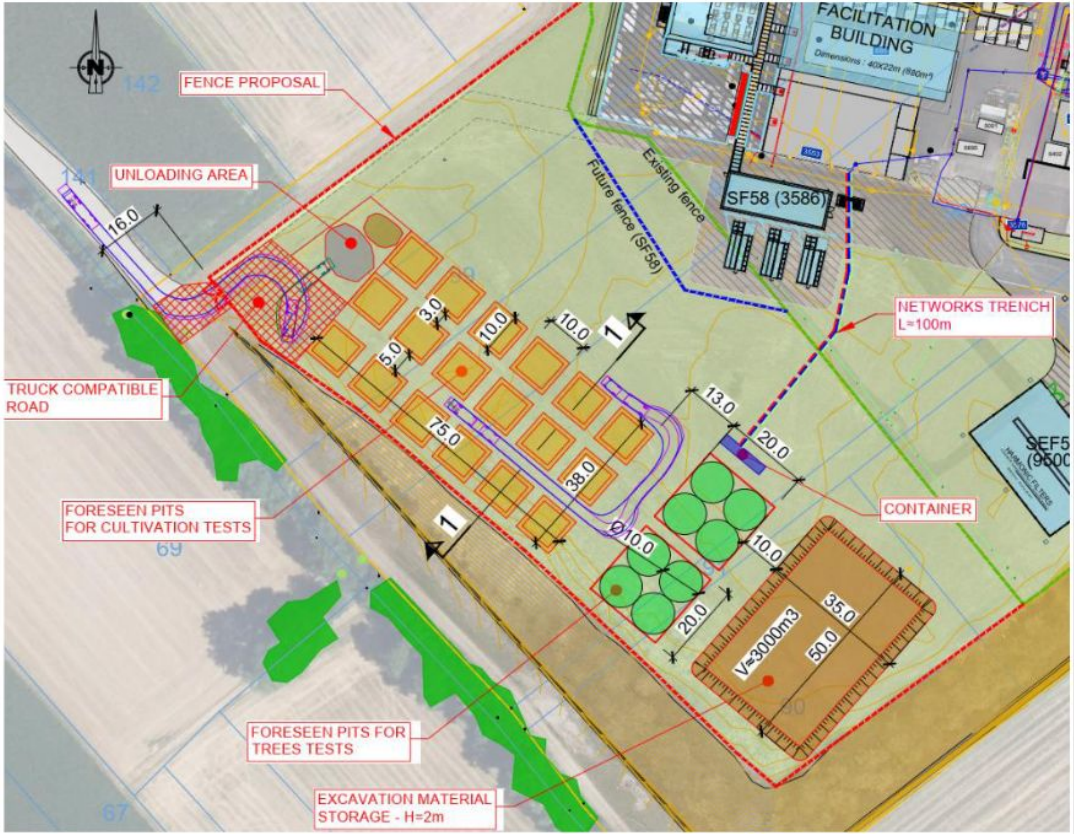
OpenSky Laboratory : HOW?

- 3’000 m^2 at LHC P5 in Cessy, France.
- **Trial with 5 000 t of excavated local molasse**
- 18 cells for agriculture trials (10*10 m)
- 2 cells for forestry trials (20*20 m)
- Different types of plants selected as function of regional specificities

1) Initial laboratory analysis to **identify** the **most suitable mixing** of molasse and amendments,

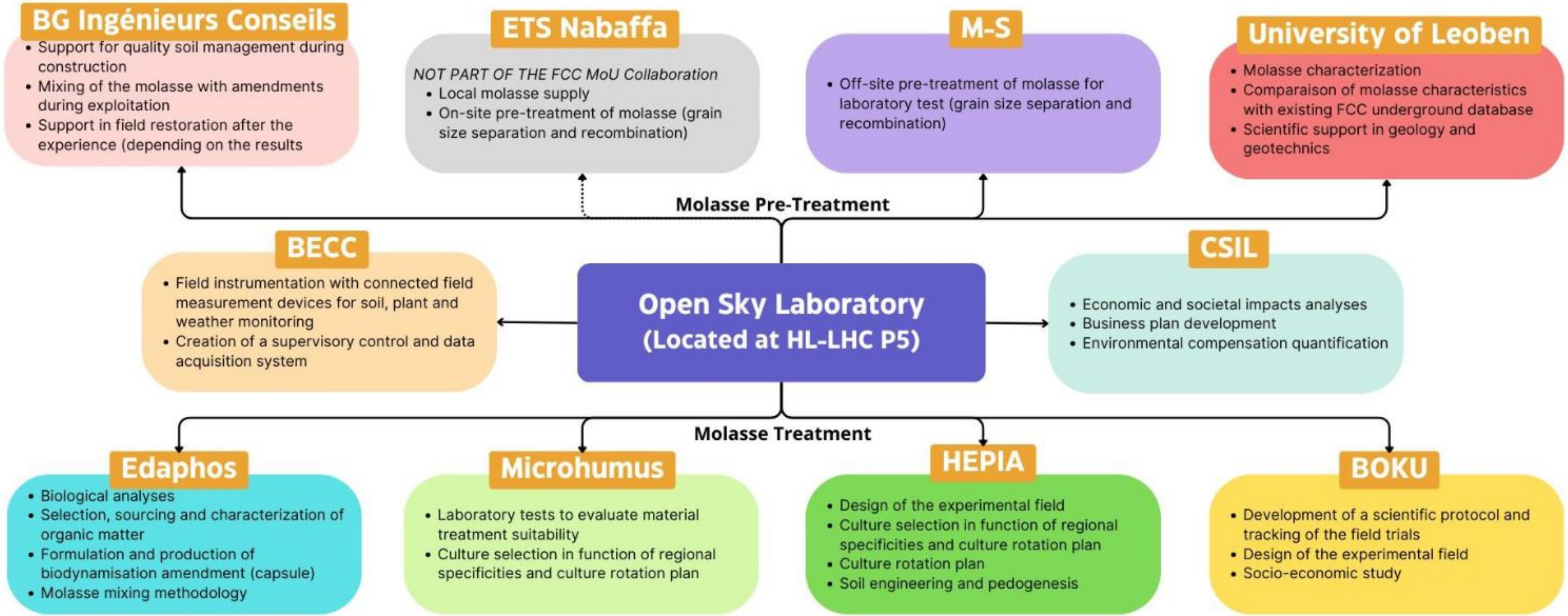
2) **Mixing/spreading** of the molasse with amendments on the trial cells,

3) **Planting and treatment with monitoring** of the field conditions in a **controlled environment.**



OpenSky Laboratory : WHO?

A collaborative effort of industry and academic/educational institutes



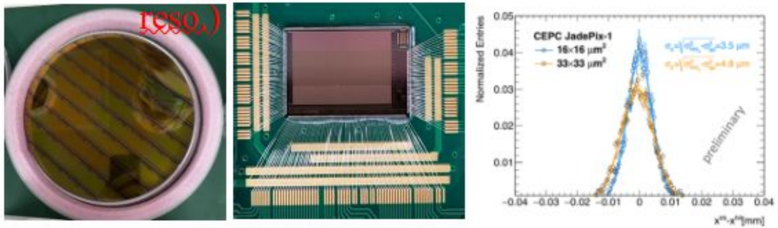
CEPC detector R&D

- Lots of R&D benefitted from past experience
  - Silicon strip detector: Experience from ATLAS upgrade
  - Drift chamber: Lots of Experience from BESIII
  - Super-conducting magnet: Experience from BESIII
- New R&D on key technology
  - Vertex detector
  - TPC drift chamber
  - PFA calorimeter

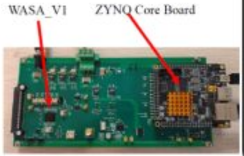
Prototype Manufactured

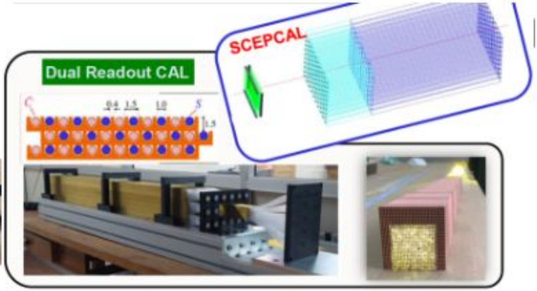
	Sub-detector	Specification	Requirement	World-class level	CEPC prototype
✓	Pixel detector	Spatial resolution	$\sim 3\ \mu m$	$3-5\ \mu m$ [12, 13]	$3-5\ \mu m$ [14–16]
✓	TPC/drift chamber	dE/dx (dN/dx) resolution	$\sim 2\%$	$\sim 4\%$ [17, 18]	$\sim 4\%$ [19–21]
✓	Scintillator-W ECal	Energy resolution Granularity	$< 15\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2\ \mathrm{cm}^2$	12.5% [22]	Prototype built to be measured $0.5 \times 0.5\ \mathrm{cm}^2$
✓	4D crystal ECal	EM energy resolution 3D Granularity	$\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$	$2\%/\sqrt{E(\mathrm{GeV})}$ [23, 24] N/A	Prototyping [25] $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$
✓	Scintillator-Steel HCal	Support PFA, Single hadron σ_E^{had}	$< 60\%/\sqrt{E(\mathrm{GeV})}$	$57.6/\sqrt{E(\mathrm{GeV})}\%$ [26]	Prototyping
✓	Scintillating glass HCal	Support PFA Single hadron σ_E^{had}	$\sim 40\%/\sqrt{E(\mathrm{GeV})}$	N/A	Prototyping $\sim 40\%/\sqrt{E(\mathrm{GeV})}$
✓	Low-mass Solenoid magnet	Magnet field strength Thickness	2 T – 3 T < 150 mm	1 T – 4 T [27–29] > 270 mm	Prototyping

Vertex detector R & D (3- 5 µm reso.)



TPC prototype (low power electronics)





4,5 prototypes, 15⁺ years of R&D, all [to be] tested

Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL

Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS