Future colliders

SFS Accelerator Section Workshop

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What will be the next collider at CERN? (after the HL-LHC)

We are about to answer that question

In the coming months

European Strategy
for Particle Physics

- The European Strategy for Particle Physics (ESPP) is about to be updated (for the 3rd time).
  - https://europeanstrategyupdate.web.cern.ch/
- Previous update (2020):
  - Summary & Briefing book: https://cds.cern.ch/record/2691414?ln=en

2020 update of the European Strategy for Particle Physics
“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.”

2023 US P5 Report
Advocates for substantial US participation and effort to support development of an offshore Higgs factory, with the goal of leading and potentially hosting a muon collider beyond it.

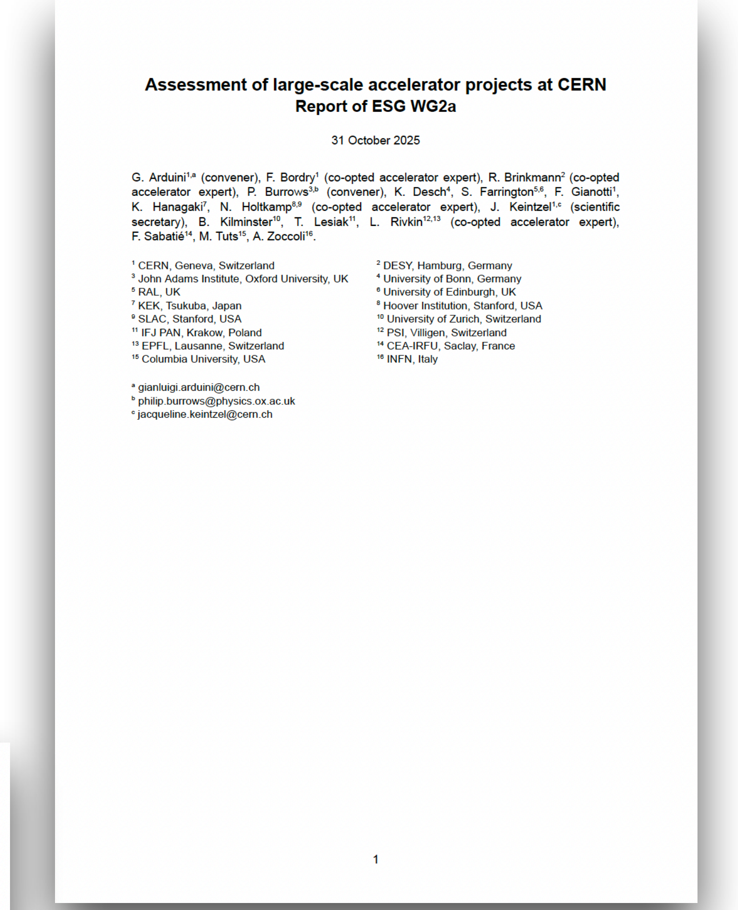
The process
Is getting close to the end

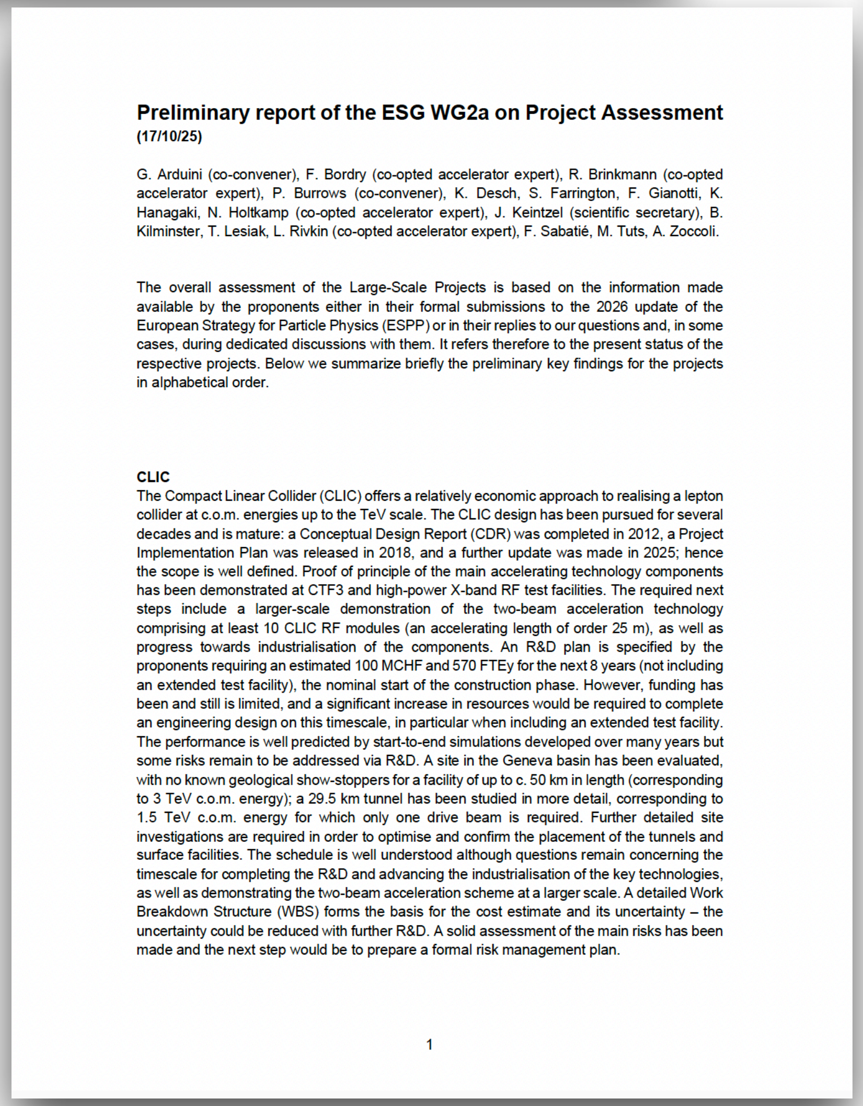
- Everything started last year:
  - In march 2024, CERN Council launched the process
  - In June 2024 The European Strategy Group (ESG) and the Strategy Secretariat were established
  - One year later June 2025 we had a **major milestone**: the Venice symposium!
    - 277 inputs from countries, facilities, individuals: https://eppsu-explorer.app.cern.ch/
    - https://agenda.infn.it/event/44943/
    - All talks in YouTube: Link

An even bigger milestone

The Briefing Book

- Released in cds at the beginning of October:
  - https://cds.cern.ch/record/2944678
- Last week uploaded to the arXiv
  - https://arxiv.org/abs/2511.03883
- A set of supplemental documents is on the way, starting by :
  - Preliminary report of the ESG WG2a on Project Assessment:
    - https://cds.cern.ch/record/2947131
  - Assessment of large-scale accelerator projects at CERN - Report of ESG WG2a
    - https://cds.cern.ch/record/2947728





End September 2024

Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024

Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025

Deadline for the submission of main input from the community

26 May 2025

Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025

Open Symposium

End September 2025

Submission of the “Briefing Book” to the **ESG**

14 November 2025

Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025

ESG Strategy Drafting Session

End January 2026

Submission of the draft strategy document to the Council

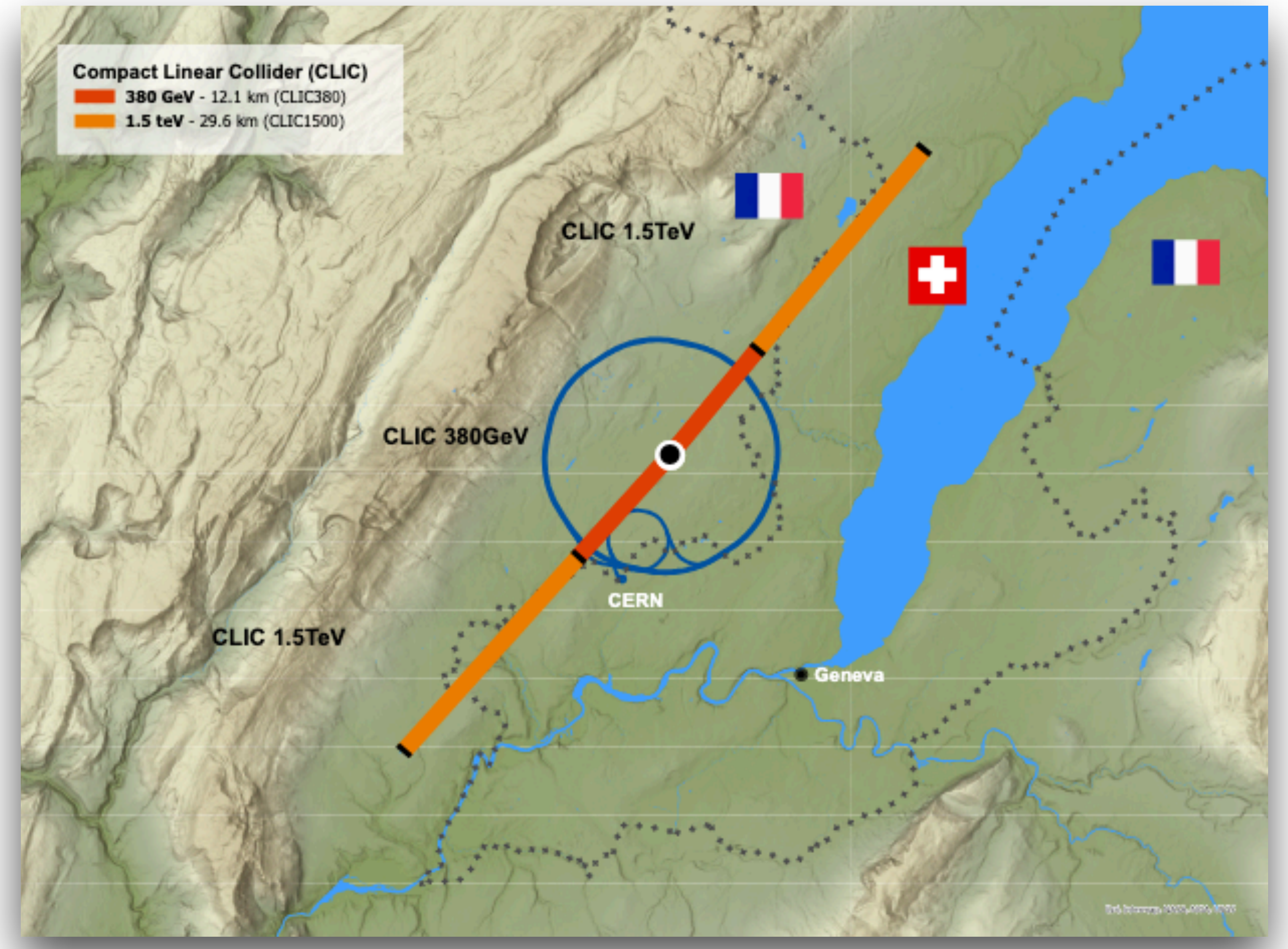
March and June 2026

Discussion of the draft strategy document by the Council and **updating of the Strategy**

The options on the table

CLIC

Compact Linear e+e- Collider

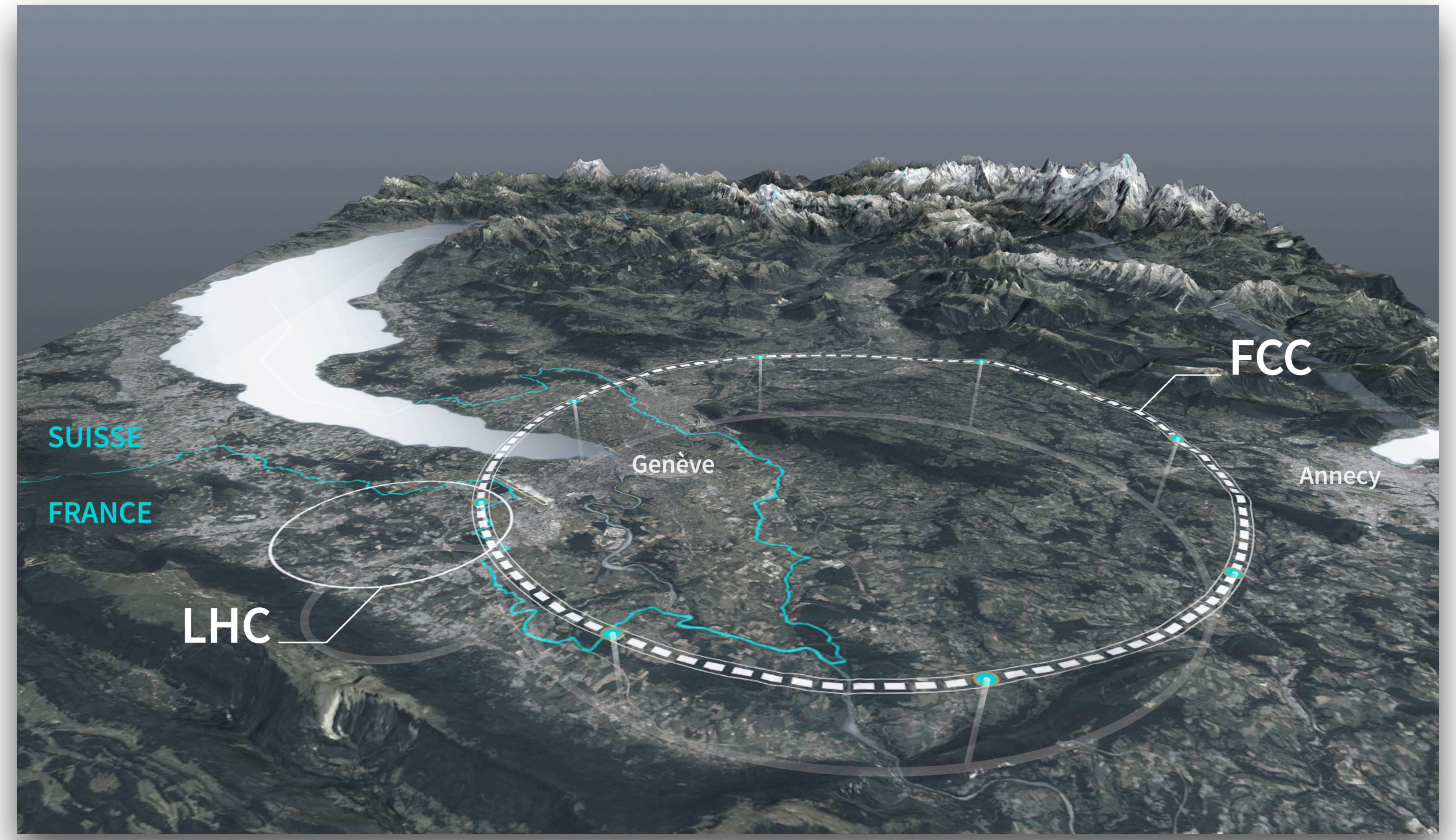


- Staged e+e- linear collider based on a Two-Beam Acceleration scheme
- 12.1/29.4 km tunnel for collision energies from 380 GeV/1.5 TeV
- 2 IPs considered for the lower energy stages
- CLIC design has been pursued for several decades and is mature → scope is well defined
- **In Sweden:** **Uppsala University** (Maja Olvegård, Marek Jacewicz)
    - Extensive work in novel acceleration methods for the **CLIC feasibility study**
    - Building/operation of the two-beam test stand, at the CLIC Test Facility 3 (CTF3)
    - Design of beam diagnostics systems for CLIC and CTF3
    - Investigating vacuum breakdown in high-gradient accelerating cavities
    - Developing a simulation framework for the drive beam complex for beam performance studies.

FCC

Future Circular Collider at CERN

- Integrated programme
  - **Stage 1: FCC-ee**
    - e+e- collisions at 91.2 (Z), 160 (WW), 240 (ZH), 365 (tt) GeV
    - collision energy can be varied seamlessly
    - highest luminosity of all proposed facilities
    - 4IPs
    - 2046 - 2065
  - **Stage 2: FCC-hh**
    - Hadron collisions at energy frontier (~85TeV), pp/AA
    - 2070 - 2100
  - Common tunnel (90.7 km circumference), civil engineering, and technical infrastructures



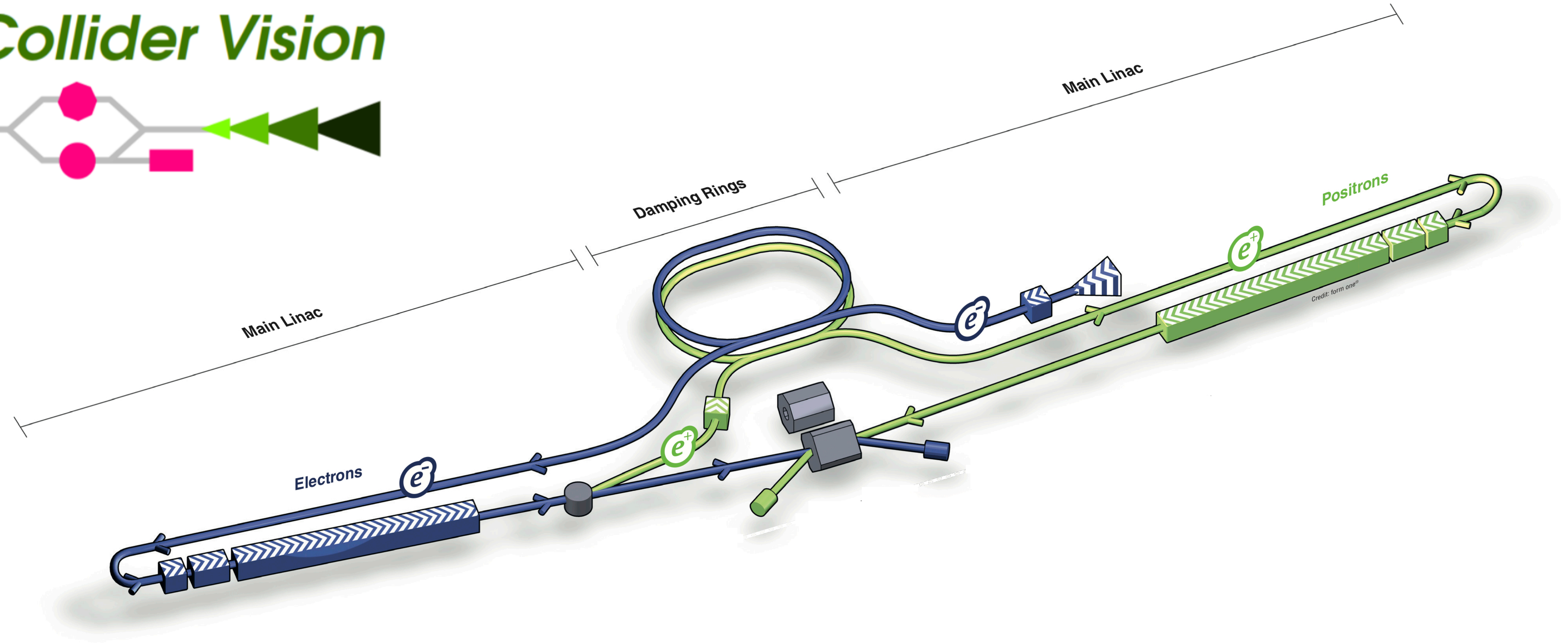
FCC
In Sweden

- **Work in FCC has been ramping up in the last few years**
  - **All universities eager to contribute (mostly physics analysis and detector R&D), work ongoing in UU, KTH, and SU**
- Vetenskapsrådet created a reference group to follow the FCC process and European Strategy Update in 2023:
  - Sara Strandberg, Lars Börjesson, Anders Karlhede, Lisbeth Olsson and Mattias Marklund.
- Swedish authors prominent in midterm report and FCC Feasibility Study
  - Feasibility Study completed in spring
  - Volume II Accelerators, Technical Infrastructure and Safety https://arxiv.org/abs/2505.00274
- 2 MoUs: Uppsala signed early 2024, **ESS signed this year!**
  - Håkan Danared, Ciprian Plostinar, Paolo Pierini
  - Possible contribution in **superconducting RF**

Linear Collider Vision

LCF

Linear Collider Facility

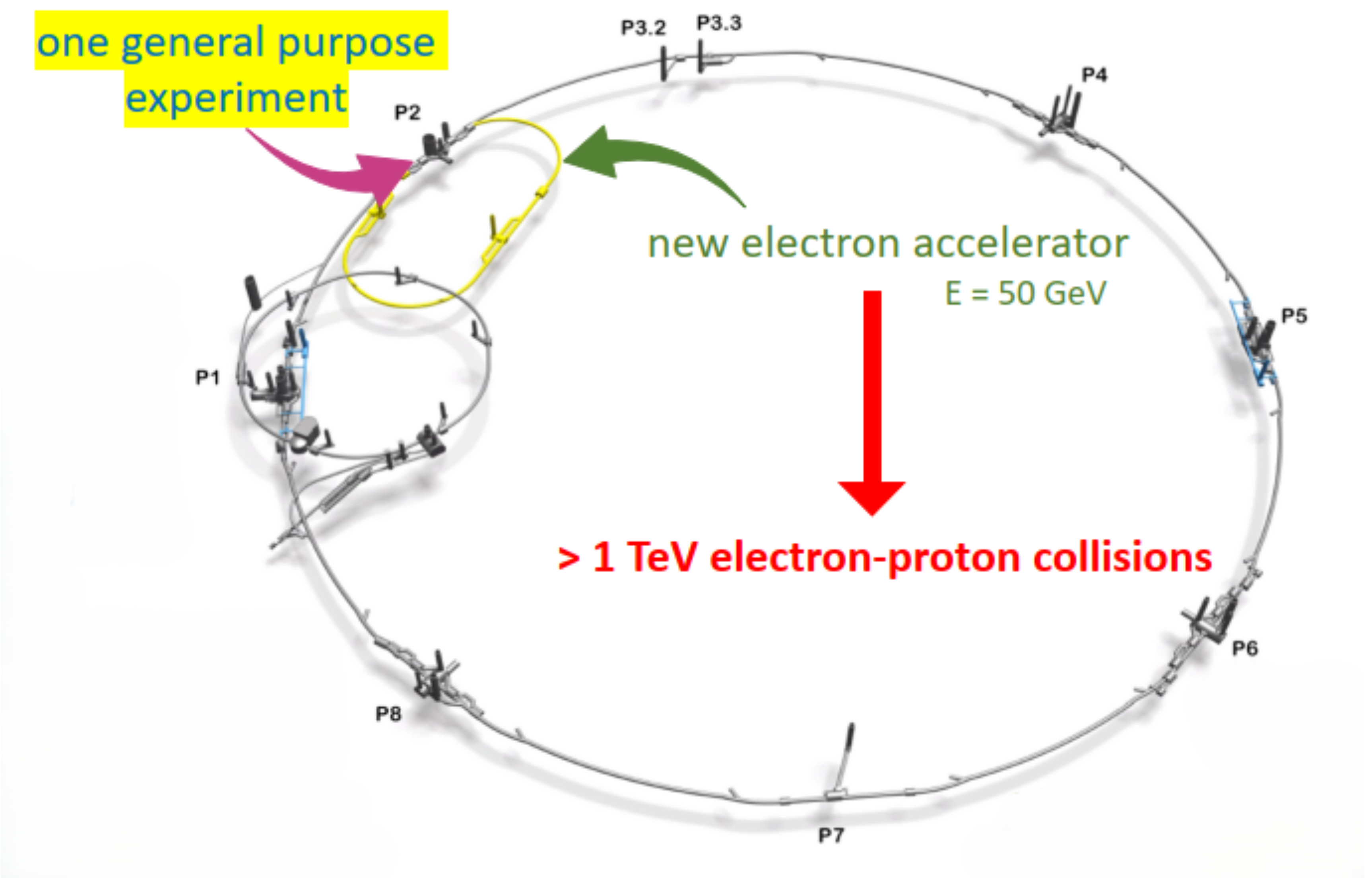


- 250/550 GeV e+e- linear collider
- Based on International Linear Collider design (250 GeV) considered for Japan but:
  - Double repetition rate: 5 → 10 Hz (upgrade option to double number of bunches)
  - 2 IPs
  - Longer (smaller diameter) tunnel (33.5 km) to accommodate extension to 550 GeV
- In Sweden:
  - From the **detector** side: **Lund University** involved in detector development at the ILC (Leif Joensson, Anders Oskarsson)

LEP 3 and LHeC

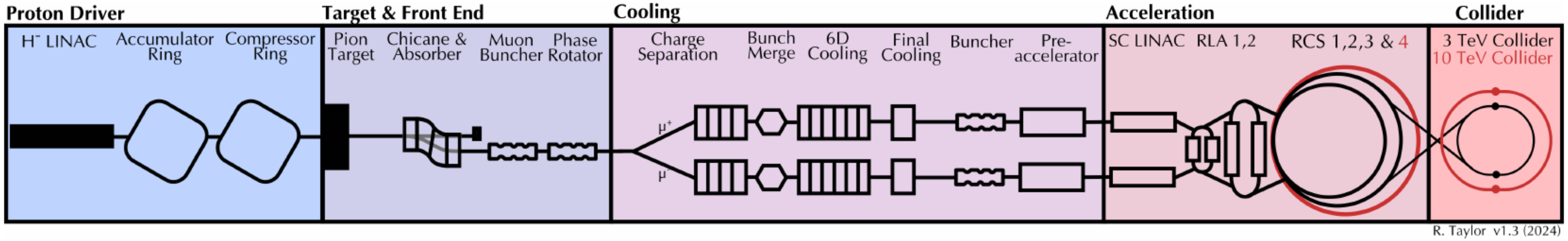
Both propose to re-use the LHC tunnel

- Infrastructure conflicts
- LEP 3:
  - Squeezes FCC-ee into the LHC tunnel
  - Downsized: 2IPs instead of 4, limited to 230 GeV (no top)
  - Limited physics reach, lack of an upgrade path
  - Lack of feasibility studies
- LHeC:
  - Electron-hadron collisions: 7 TeV HL-LHC proton beam with a 50 GeV, 50 mA electron beam accelerated by a multi-pass ERL after the end of the HL-LHC programme
  - Relies on the ERL technology that is still to be demonstrated at the required level of power



MC
Muon Collider

- Energy-efficient path toward high-luminosity collisions at 10 TeV in a reduced footprint.
    - Never done before, exciting physics potential.
    - Not yet the level of maturity of the other Large-Scale Project proposals.
- Main focus: assessment of key technological/operational challenges in preparation for a possible conceptual design study.
- Uppsala and ESS are part of the **European Consortium MuCol**
- ESS: lead institute and coordinator (Natalia Milas) of **WP3 → Proton Complex (or Proton Driver)**
- ESS and UU (Maja Olvegård, Vitaliy Goryashko) to design a proton accumulator and compressor.



First comparisons

	CLIC			FCC-ee				FCC-hh	LCF				LEP3			LHeC	MC	
									LP	FP								
Particles colliding [-]	e^+/e^-			e^+/e^-				p/p	e^+/e^-				e^+/e^-			e^-/p	μ^+/μ^-	
C.o.m. energy [GeV]	380	550	1500	91.2	160	240	365	84600	250	91.2	250	550	91.2	160	230	1180	3200	7600
Length [km]	12.1	15	29.6	90.7				90.7	33.5				27.6			9.2/27.6	11/4.8	11/8.7
#IPs [-]	2	2	1	4				4	2				2			1	2	
Peak inst. lumi/IP [$10^{34}cm^{-2}s^{-1}$]	2.2	3.2	3.7	140	20	7.5	1.4	30	1.35	0.28	2.7	3.85	40	6.2	1.6	2.3	0.9/2	7.9/10.1
Peak power consumption [MW]	166	210	287	251	276	297	381	355	143	123	182	322	200	226	250	220	117	182
Cost [BCHF][a]	7.2	+30%[b]	+7.1	15				+19[c]	8.3	+0.8		+5.5	3.9			2	12	17

[a] Total installation and construction cost quoted by the proponents of the projects in 2024 prices. The cost includes the technical components, materials, contracts, services, civil construction and conventional systems and associated implicit labour such as that provided by a company to produce components. It does not include labour provided by the host institution and the collaborating laboratories, contingency, any potential future inflation, the costs prior to project approval (construction and R&D), off-line computing, spares, maintenance, beam commissioning. The cost of the experiments is not included. The cost of land acquisition, site activation (e.g. external roads, water supplies, power lines) and spoil removal are not included for CLIC and LCF though they are expected to represent a minor contribution to the total cost (at the percent level). The additional cost of each individual upgrade is indicated.

[b] Cost of the upgrade from 380 GeV.

[c] Cost estimated if FCC-hh follows FCC-ee. The cost for standalone FCC-hh is given as 28.4 BCHF.

Table 1: Overview of the main parameters submitted to the ESPP2026 and considered for this assessment. Data compiled from Refs. [ID40, ID78, ID188, ID207, ID214, ID233, ID247,2,3,4,5]. LP=Low Power, FP=Full Power.

Technical Readiness Level of major sub-systems

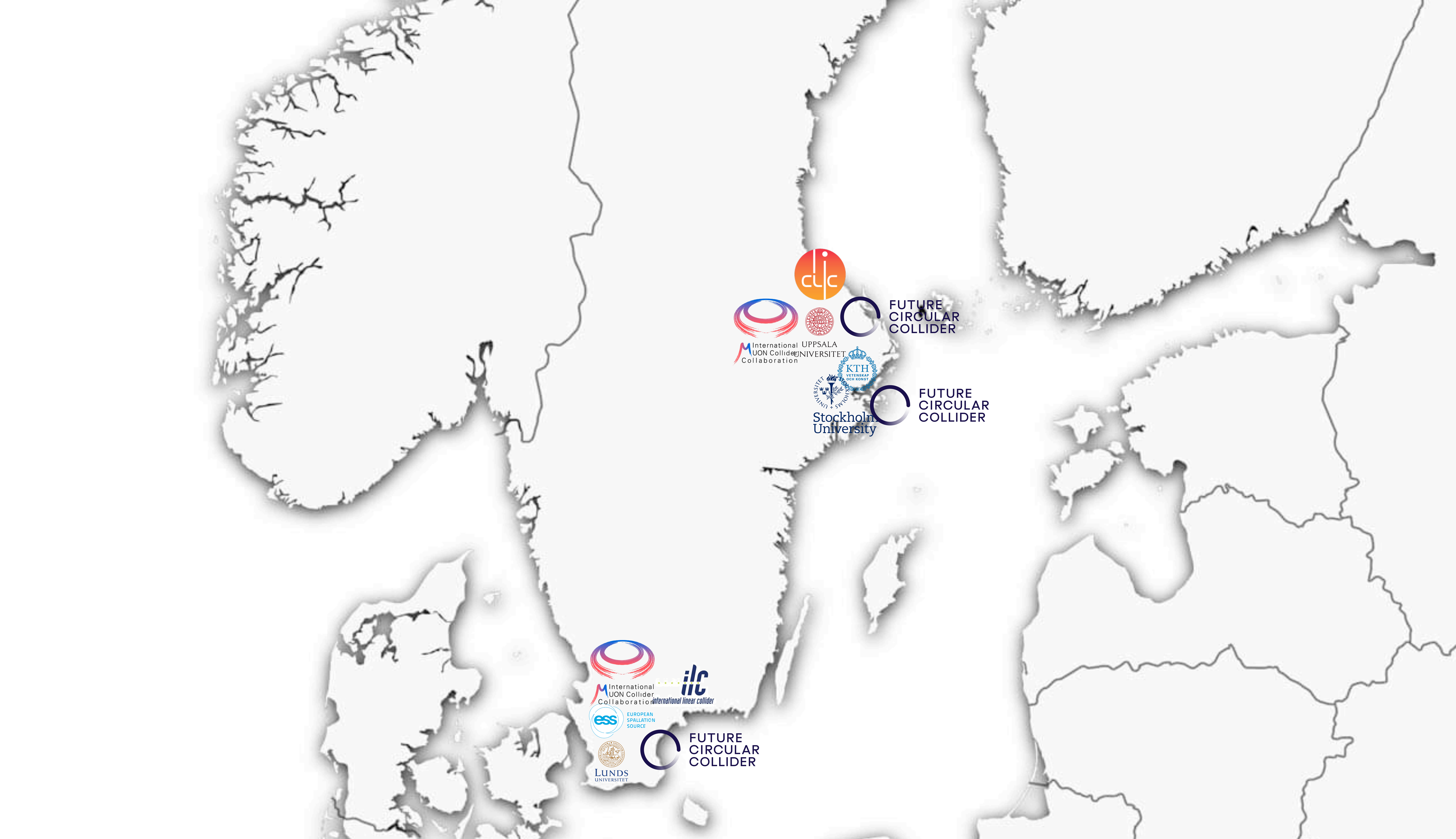
Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
CLIC 380 GeV, 1.5 TeV		4 - 6 / 5.2							
FCC-ee 91-365 GeV		4 - 7 / 6.0							
FCC-hh 85 TeV		4 - 7 (Nb_3Sn) / 4.3 2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

Table 16: Summary table schematically representing the key findings of the WG according to the assessment criteria and based on the present status of the large-scale collider project proposals as submitted to the ESPP2026. Scope=Scope level-of-definition; TDR=Technical Readiness Level score - the range of values and the cost-weighted average for the baseline scenarios are listed; the colour code is selected based on on the cost-weighted average TRL score (TRL≥ 6 - green, 4≤TRL<6 - yellow, TRL<4 - red); R&D=R&D requirements, R&D plan level-of-definition, R&D funding status; Test facilities=need of test facilities or demonstrators and (if needed) level-of-definition of their scope; Performance=Performance uncertainty; Site preparation=Site preparation status; Schedule=Schedule uncertainty; Cost=Cost uncertainty; Risk=Risk level-of-definition. The cost-weighted average TRL score could not be estimated for the MC project as there is no detailed cost breakdown by sub-system. The colour code for the various criteria is defined according to the summary assessment in the Tables A.1 to A.8.

How about the physics?

That is for another talk!

Thanks so much!

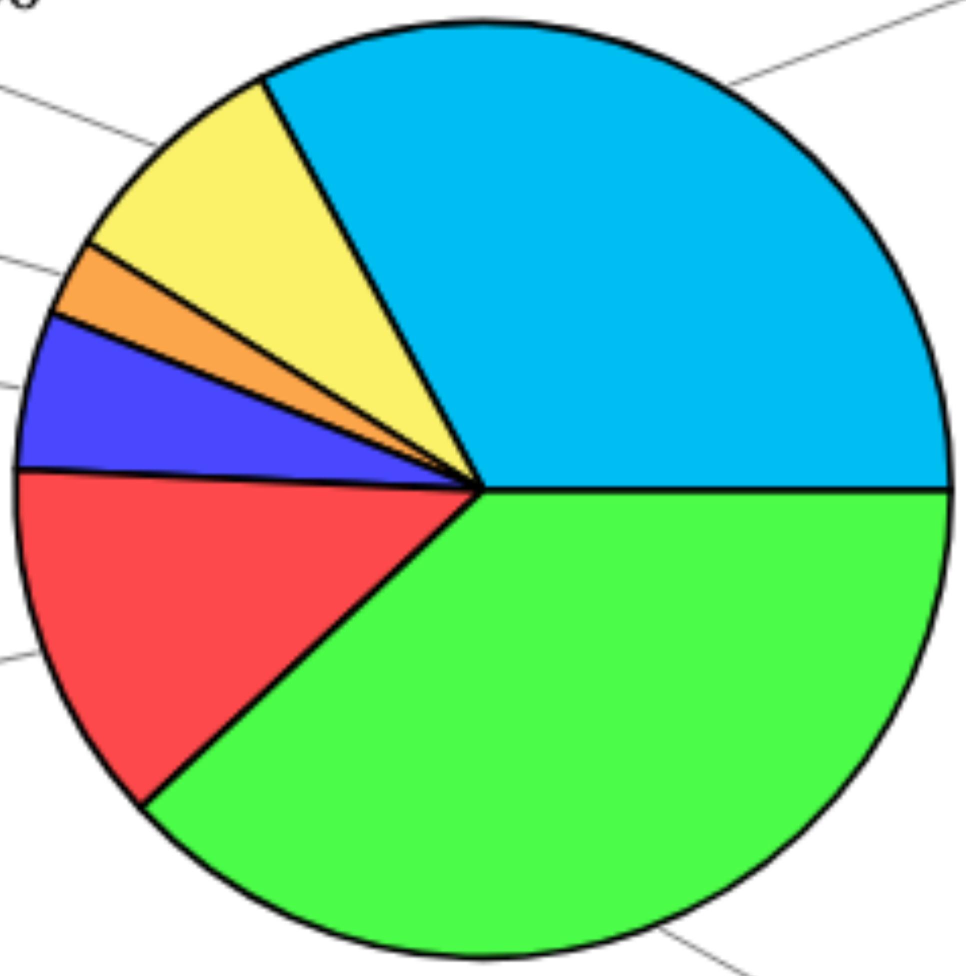

CLIC
International
MUON Collider
Collaboration
UPPSALA
UNIVERSITET
FUTURE
CIRCULAR
COLLIDER
KTH
VETENSKAP
OCH KONST
Stockholm
University
FUTURE
CIRCULAR
COLLIDER
International
MUON Collider
Collaboration
ilc
international linear collider
ess
EUROPEAN
SPALLATION
SOURCE
FUTURE
CIRCULAR
COLLIDER
LUNDS
UNIVERSITET

Backup

Performance comparison

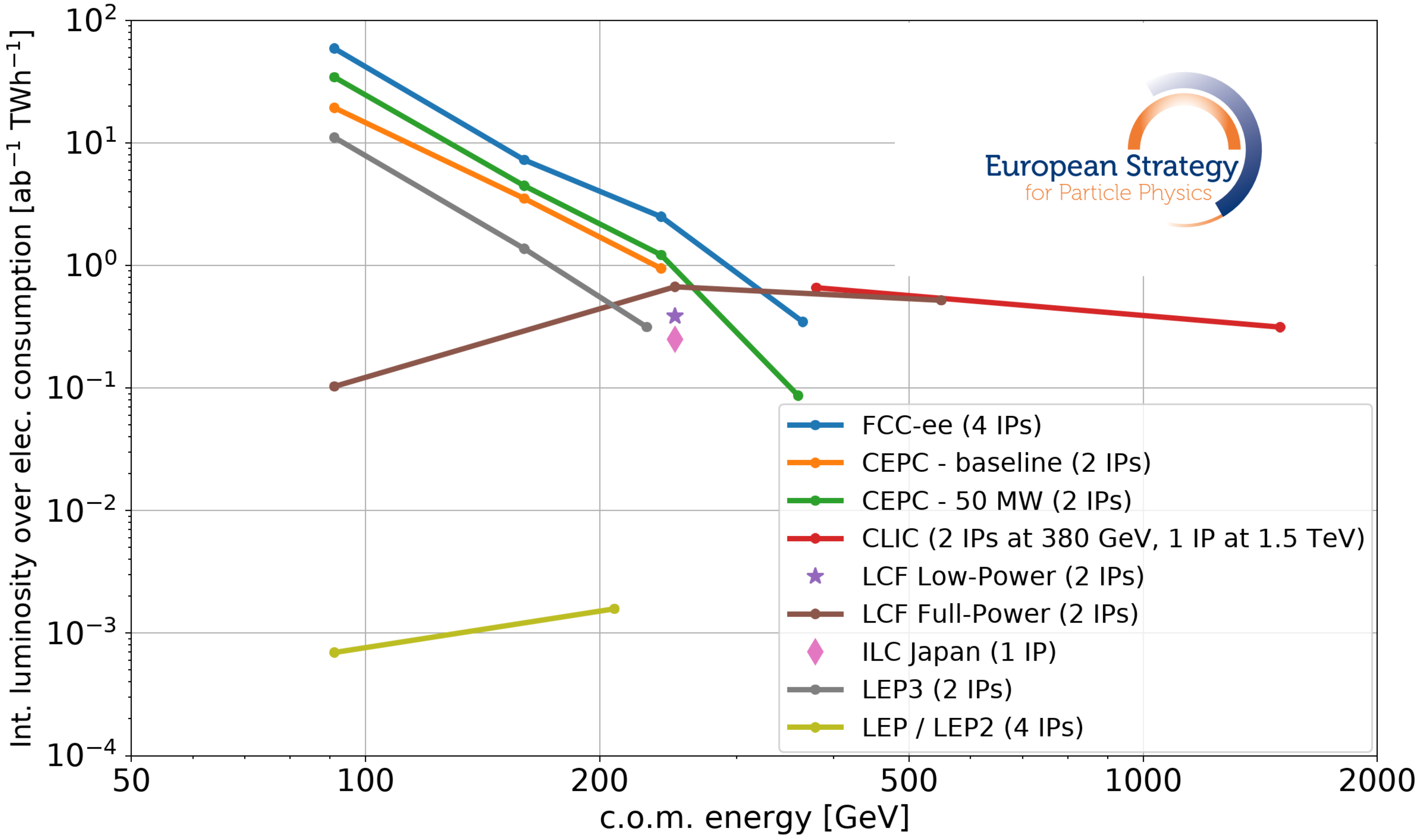
Common assumptions for the operational scenarios for e+/e- colliders

- integrated luminosity estimate per year (summed over all IPs)
- electricity consumption per year, knowing the peak wall plug power and the fraction used during each operation phase, provided by the projects.



Operational phase	Number of days	Fraction of the peak power consumption [%]								
		circular				CLIC		LCF		
		Z	W	ZH	$t\bar{t}$	380 GeV	1.5 TeV	250 LP	250 FP	550 FP
Annual shutdown	120	12	12	11	11	6	5	28	18	25
Commissioning	30	58	60	60	62	55	55	77	72	72
Technical stops	10	27	28	27	28	55	55	54	45	44
Machine development	20	39	45	50	61	55	55	77	72	72
Downtime (faults)	46	30	36	42	55	55	55	54	45	44
Data taking	**139**	100								

Performance comparison
(e^+/e^- colliders)



- Circular colliders (CC) are more efficient than Linear Colliders (LC) at energies up to at least 300 GeV. Note the improvement w.r.t. LEP/LEP2
- LC (CLIC) can reach the O(TeV) region (no synchrotron radiation loss)
- CC can accommodate more experiments operating in parallel
- FCC-ee collision energy can be varied between 90 and 240 GeV seamlessly at unparalleled luminosity.
- LC baselines include polarized e^- beam. For LCF e^+ too.
- LEP3 proposal still at pre-conceptual design level: larger uncertainty on luminosity, power consumption

Project timeline

- Financial and personnel commitments for HL-LHC operations imply that a future collider cannot realistically start operation before mid 40s
- FCC feasibility study completed and detailed timeline established considering the above constraints
- CLIC, and particularly LCF@CERN, would require a preparation phase (with corresponding resources) to reach a level of detail comparable to the FCC FS → Difficult to conduct two territorial implementation studies in parallel in the Host States
- CLIC/LCF: only relative timelines with respect to decision points (and considering the above constraint)

Milestone	FCC-ee
Conceptual Design Study	2014 – 2018
Definition of the placement scenario	2022
Preliminary implementation with the Host states	2024 – 2025
Feasibility Report ready	2025
Earliest Project Approval[a]	2028
Environmental evaluation & project authorisation processes	2026 – 2031
Main technologies R&D completion[b]	2031
Technical Design Report ready[c]	2032
Civil engineering	2033 – 2041
TI installation	2039 – 2043
Accelerator installation	2041 – 2045
HW commissioning	2042 – mid 2046
Beam commissioning – collider	mid 2046 – 2047
Physics operation start	2048

Milestone	CLIC	LCF
Conceptual/Reference Design Report	2004 – 2012	2002 – 2007
Site-independent TDR for ILC 500 GeV		2007 – 2013
Project Implementation Plan, Readiness Report	2013 – 2025	
ILC 250 GeV reports and Prelab planning		2013 – 2025
Project Preparation Phase 1	2026 – 2028	
Definition of the placement scenario Design optimisation and finalization Main technologies R&D conclusions Technical Design Report - two IPs at CERN		
Project Preparation Phase 2	$T_0 - (T_0+5)$	
Site investigation and preparation Implementation studies with the Host states Environmental evaluation & project authorisation processes Industrialisation of key components Engineering design completion		
Construction Phase (from ground breaking)	$T_1 - (T_1+10)$	
Civil engineering Construction of components Installation and hardware commissioning		
Beam commissioning and physics operation start	T_1+11	

Project timeline

- As a 2nd phase after FCC-ee, FCC-hh could start operation in mid 2070s
- On a technically-limited timescale (assuming accelerated R&D) a stand-alone FCC-hh with 14 T Nb3Sn dipoles could start operation around mid 2050s

Milestone	FCC-hh
Conceptual Design Study	2014 – 2018
Definition of the placement scenario	2022
Feasibility Report ready	2025
Main technologies R&D completion	2054
Technical Design Report ready	2054
Latest Project Approval	2054
Environmental evaluation & project authorisation processes	2054 – 2058
Industrialization & magnet production	2054 – 2069
Civil engineering - collider	2060[a] – 2068
FCC-ee dismantling	2063 – 2064
TI installation – collider	2065 – 2069
Accelerator installation – collider	2068 – 2072
HW commissioning – collider	2071 – 2073
Beam commissioning – collider	2073
Physics operation start	2074

[a] The starting date corresponds to the start of the surface CE works.

Table 6.4: FCC-hh timeline as a second phase after FCC-ee.

Milestone	FCC-hh
Conceptual Design Study	2014 – 2018
Definition of the placement scenario	2022
Feasibility Report ready	2025
Latest Project Approval	2033
Environmental evaluation & project authorisation processes	2026 – 2035
Main technologies R&D completion	2037[a]
Technical Design Report ready	2037
Industrialization & magnet production	2038 – 2053
Civil engineering - collider	2037 – 2046
TI installation – collider	2043 – 2050
Accelerator installation – collider	2046 – 2052
HW commissioning – collider	2049 – 2053
Beam commissioning – collider	2054
Physics operation start	2055

[a] Assuming an accelerated R&D programme.

Table 6.5: Fastest possible FCC-hh timeline as a stand-alone project.