Snowmass 2021

Report of the Snowmass'21 Collider Implementation Task Force

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Physics Colloquium

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AF Collider Implementation Task Force

- The Collider Implementation Task Force (ITF) was charged with the evaluation and **fair and impartial comparison** of future collider proposals, including R&D needs, schedule, cost (using the same accounting rules), and environmental impact.
- Comparison was done for colliders with similar physics goals such as Higgs factories and high parton CM energy colliders.
- ITF effort built on the 2021 report “European Strategy for Particle Physics -- Accelerator R&D Roadmap”
- The full report is available on the arXiv:2208.06030v1.

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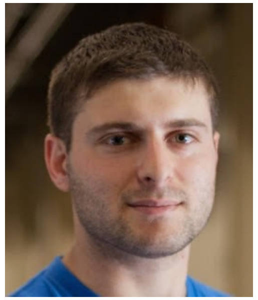

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ITF process

- ITF met over Zoom every other week or more frequently over the last 1.5 years
- ITF focused on collider facilities to keep the task manageable.
- ITF developed a set of metrics to evaluate the proposals and concepts.
- Parameter spreadsheets with more than 60 entries of 24 major collider proposals were collected from proponents. ITF tried to accommodate changing proposal parameters as much as possible.
- ITF held Zoom meetings with all proponents of major proposals to discuss the ITF process and also gave all proponents an opportunity to fact check the draft report.
- ITF did NOT review the ultimate performance of the proposed facilities but focused on technical risk and R&D requirements, estimated cost and plausible, technically limited schedule.
- Four subcommittees analyzed, evaluated, and compared the proposals regarding:
  - Physics reach and impact (CM energy and luminosity reach)
  - Technical risk, technical readiness, and validation
  - Cost and schedule
  - Size, complexity, power consumption, and environmental impact

Approach of evaluation

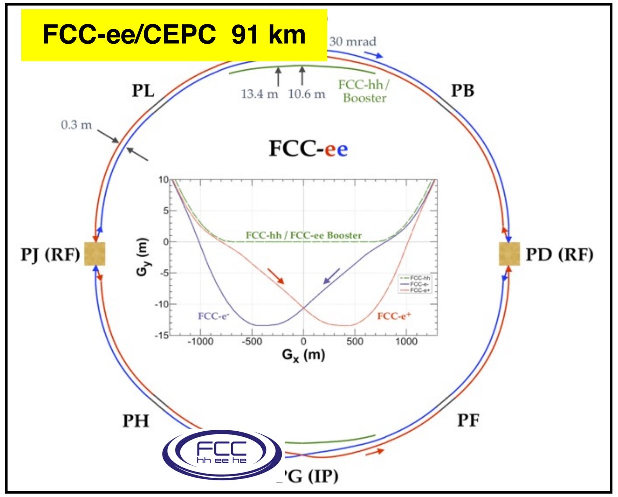
- To facilitate an evaluation that is most useful to Snowmass and P5, proposals were grouped into 4 categories addressing similar physics goals plus an additional group consisting of collider versions that could be located at FNAL:
  - Higgs factory colliders with a typical CM energy of 250 GeV
  - High energy lepton colliders with up to 3 TeV CM energy
  - Lepton and hadron colliders with 10 - 15 TeV parton CM energy
  - Lepton-hadron colliders
  - Collider versions that could be located at FNAL
- ITF evaluated **one** version of each concept as selected by the proponents
- In all tables and figures we show the **luminosity per IP** to facilitate comparing proposals. For proposals with multiple IPs the total luminosity is also shown.
- We did not consider or include staging possibilities of different collider proposals such as FCC-ee followed by FCC-hh. Each proposal was considered on its own. Only exceptions are the lepton-hadron colliders.

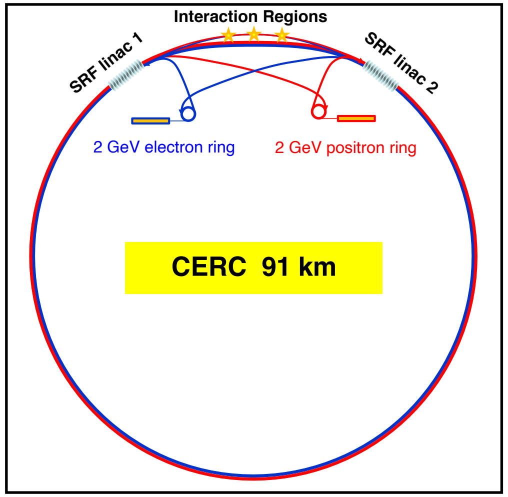
Summary tables of evaluation

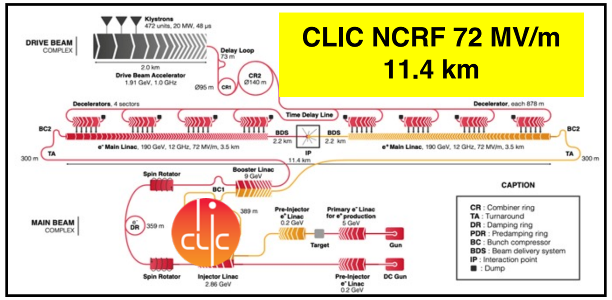
- Summary tables for each group have four columns with summary values for the four areas of evaluations:
  - Years of per-project R&D needed (technical risk and maturity)
    - Provides relevant and comparable measure of maturity and estimate how much R&D is still needed before project start. It includes feasibility R&D, R&D to get technologies to TRL of 5 or higher, and R&D for cost and power consumption reduction. To estimate the time needed for all pre-project R&D we assumed similar progress (and funding) as in the past performance and cost reduction R&D. Focused R&D on energy efficiency of future colliders would be mostly a new effort.
  - Years until first physics (technically limited schedule)
    - This is most useful to compare the scientific relevance of the proposals. It includes pre-project R&D, design, construction, and initial commissioning.
  - Project cost in 2021B$ w/o contingency and escalation (cost)
    - ITF used various models to estimate the cost and also collected cost estimates from the proponents. It uses known costs of existing installations and reasonably expected cost of novel equipment. For future technologies, the cost estimate is quite conservative, and one should expect cost reductions from pre-project cost-reduction R&D.
  - Total operating electric power consumption in MW (environmental impact)
    - This includes all necessary utilities. We used information from proponents, if provided, otherwise we made a rough estimate. One can expect reductions from pre-project R&D to improve energy efficiency and develop more energy efficient concepts, such as energy recovery technologies.

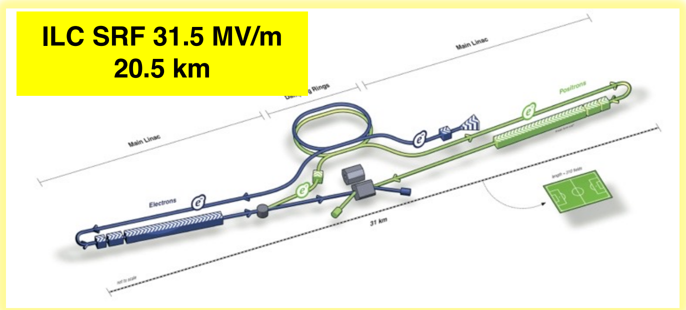
Higgs factory concepts (10)

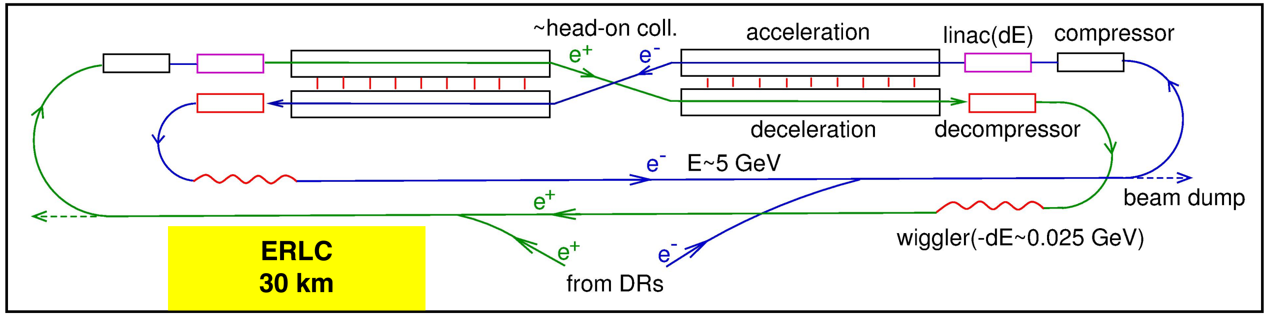
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s}$ = 0.09 – 0.37 TeV
CEPC	e+e-, $\sqrt{s}$ = 0.09 – 0.37 TeV
ILC (Higgs factory)	e+e-, $\sqrt{s}$ = 0.09 – 1 TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s}$ = 0.09 – 1 TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s}$ = 0.25 – 0.55 TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s}$ = 0.09 – 0.60 TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s}$ = 0.25 – 1 TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s}$ = 0.25 – 0.50 TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee ($\gamma\gamma$), $\sqrt{s}$ = 0.125 – 0.14 TeV
MC (Higgs factory)	$\mu+\mu-$, $\sqrt{s}$ = 0.13 TeV

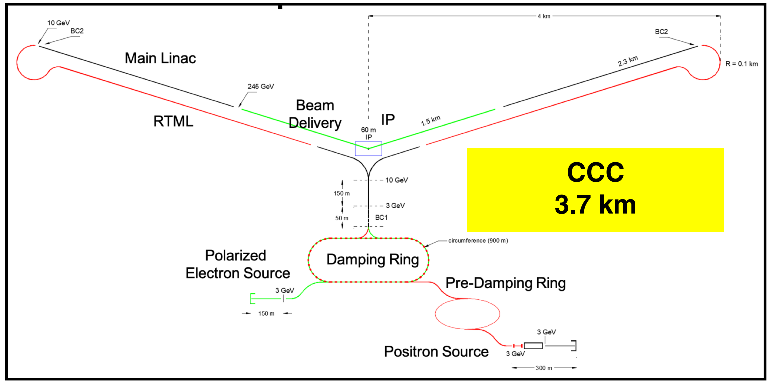


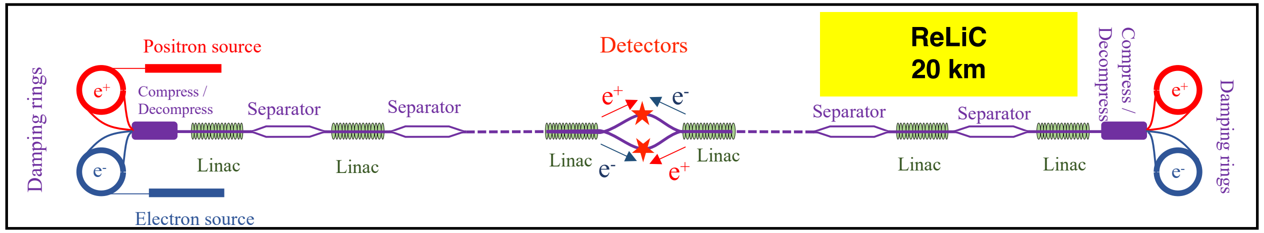












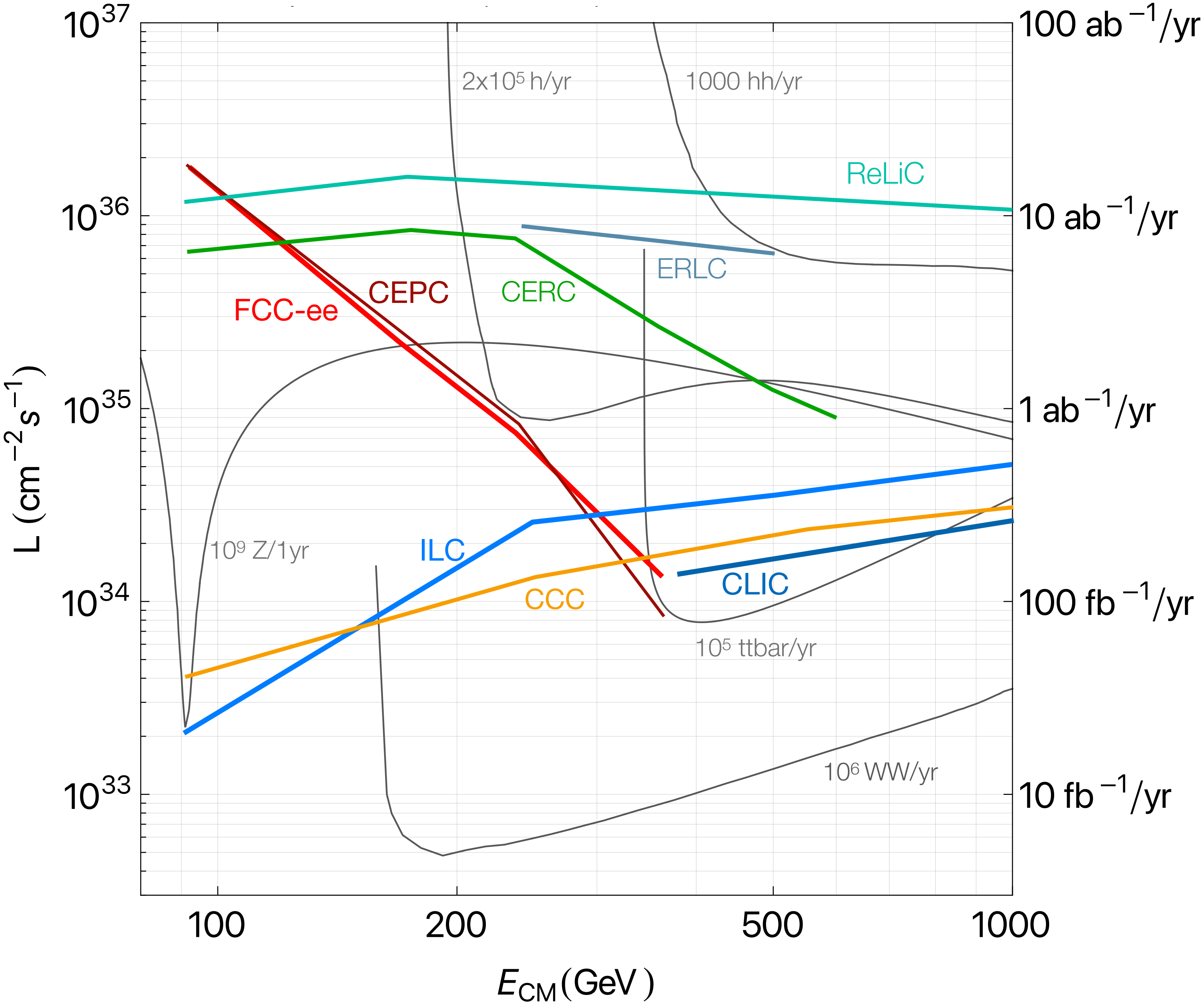
Higgs factory summary table

- Main parameters of the submitted Higgs factory proposals.
- The cost range is for the single listed energy.
- The superscripts next to the name of the proposal in the first column indicate:
  - (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis;
  - (2) Energy calibration possible to 100 keV accuracy for MZ and 300 keV for MW ;
  - (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	$<$12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	$>$25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	$>$25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	$>$10	19-24	4-7	200

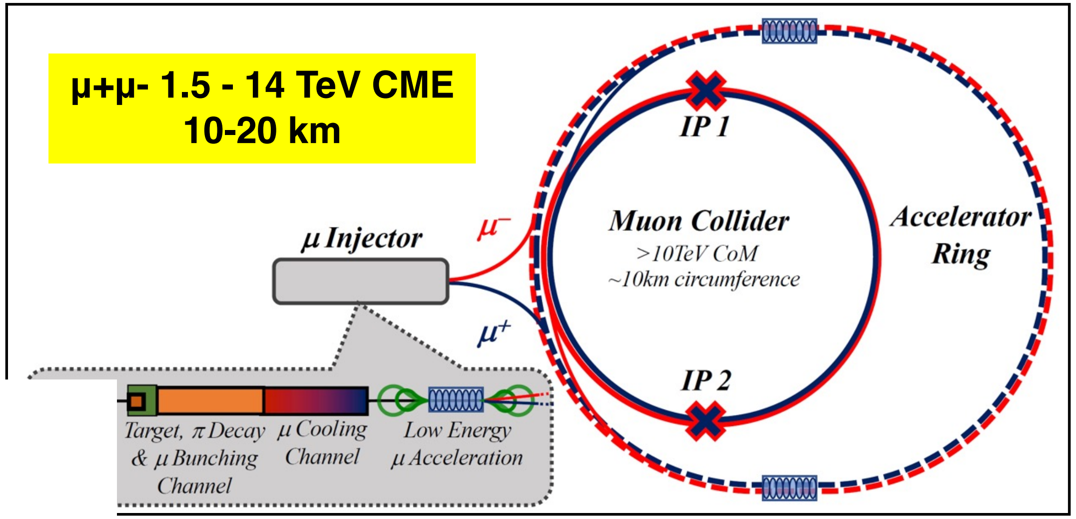
Higgs factory summary plot

- Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents.
- The right axis shows integrated luminosity for one Snowmass year (10^7 s).
- Also shown are lines corresponding to the required luminosity for yearly production rates of important processes.

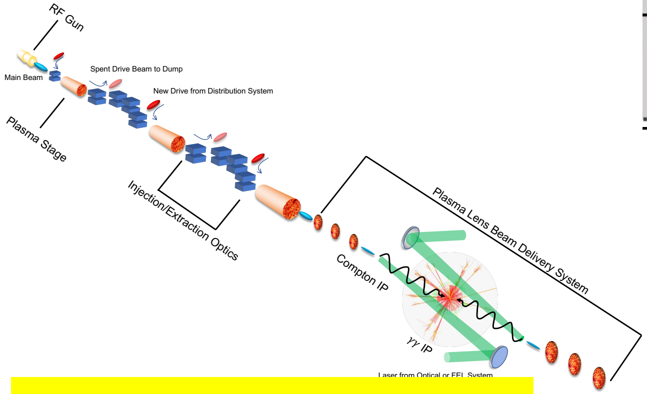


High parton CM energy collider concepts(6)

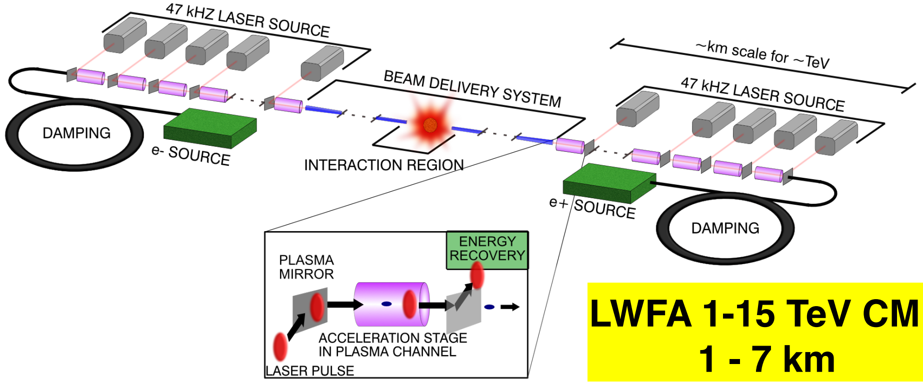
Name	CM energy range
Muon Collider	$\mu+\mu$-, $\sqrt{s} = 1.5 - 14$ TeV
Laser-driven WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV
Particle-driven WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV
Structure WFA - LC	e+e-, $\sqrt{s} = 1 - 15$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV
SPPC	pp, $\sqrt{s} = 75 - 125$ TeV



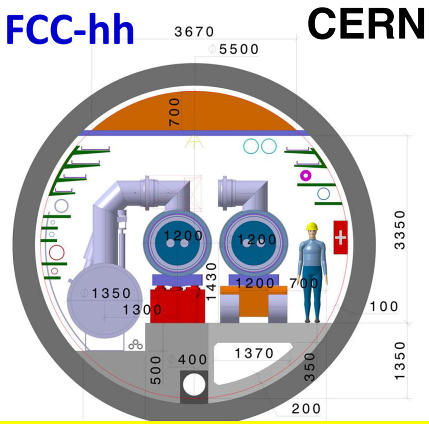
μ+μ- 1.5 - 14 TeV CME
10-20 km

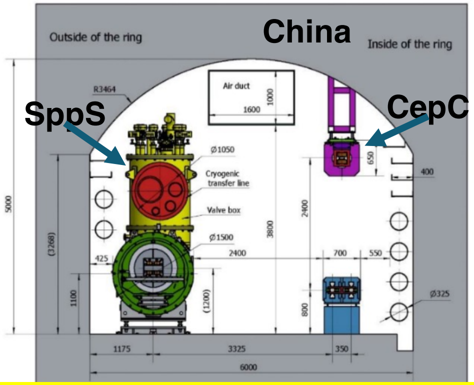


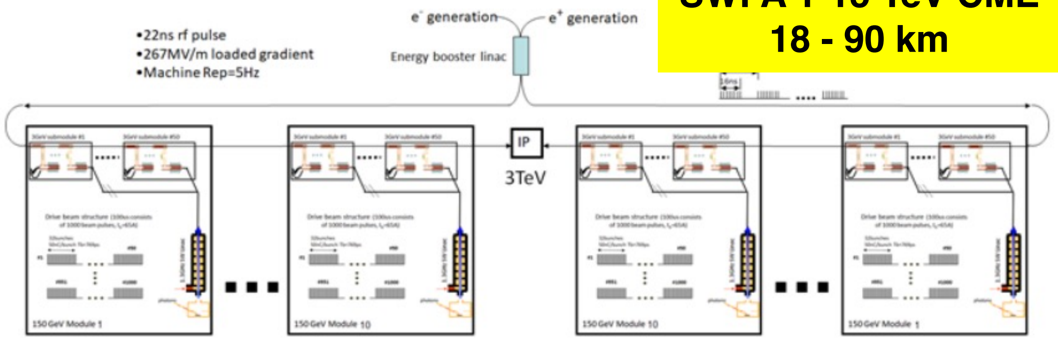
PWFA 1-15 TeV CME
~ 14 km



LWFA 1-15 TeV CME
1 - 7 km







SWFA 1-15 TeV CME
18 - 90 km

FCC-hh 100 TeV, 16 T magnets,
91 km

SPPC 125 TeV, 20 T magnets,
110 km

High energy (3 TeV) lepton colliders summary table

- Main parameters of the lepton collider proposals with CM energy higher than 1 TeV.
- Peak luminosity for multiple IPs is given in parenthesis.
- The cost range is for the single listed energy.
- Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes.

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	$\sim$400
High Energy CLIC	3 (1.5-3)	5.9	$\boxed{3\text{-}5}$	19-24	18-30	$\sim$550
High Energy CCC	3 (1-3)	6.0	$\boxed{3\text{-}5}$	19-24	12-18	$\sim$700
High Energy ReLiC	3 (1-3)	$\boxed{47\ (94)}$	5-10	$>$25	30-50	$\sim$780
Muon Collider	3 (1.5-14)	2.3 (4.6)	$>$10	19-24	$\boxed{7\text{-}12}$	$\sim$230
LWFA - LC (Laser-driven)	3 (1-15)	10	$>$10	$>$25	12-80	$\sim$340
PWFA - LC (Beam-driven)	3 (1-15)	10	$>$10	19-24	12-30	$\sim$230
Structure WFA - LC (Beam-driven)	3 (1-15)	10	5-10	$>$25	12-30	$\boxed{\sim 170}$

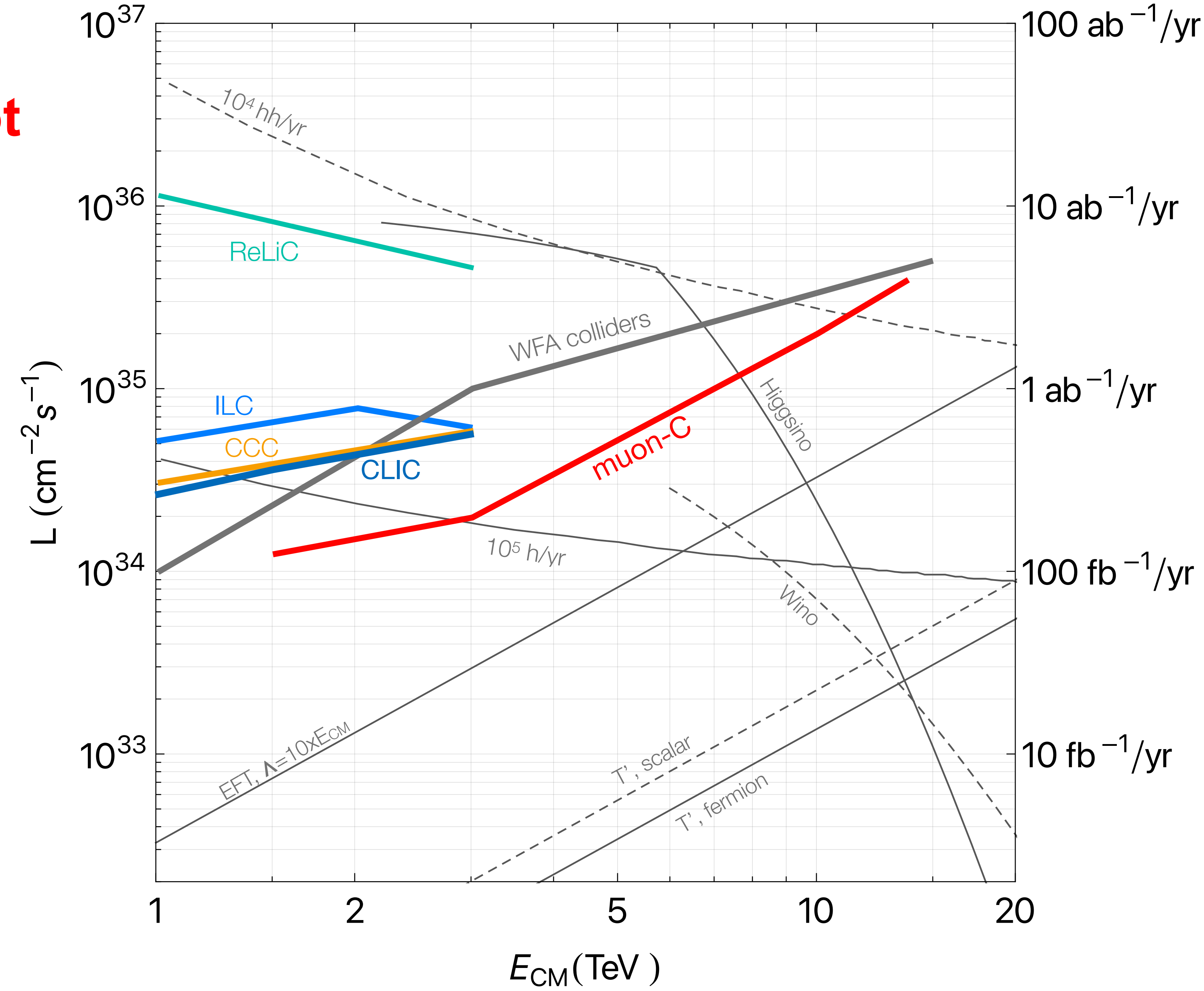
Colliders with high parton CM energy (10 – 15 TeV) summary table

- Main parameters of the colliders with 10 - 15 TeV parton CM energy.
- Total peak luminosity for multiple IPs is given in parenthesis.
- The cost range is for the single listed energy.
- Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes.
- The relevant energies for the hadron colliders are the parton CM energy, which can be substantially less (~ 1/10) than hadron CM energy quoted in the table.

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

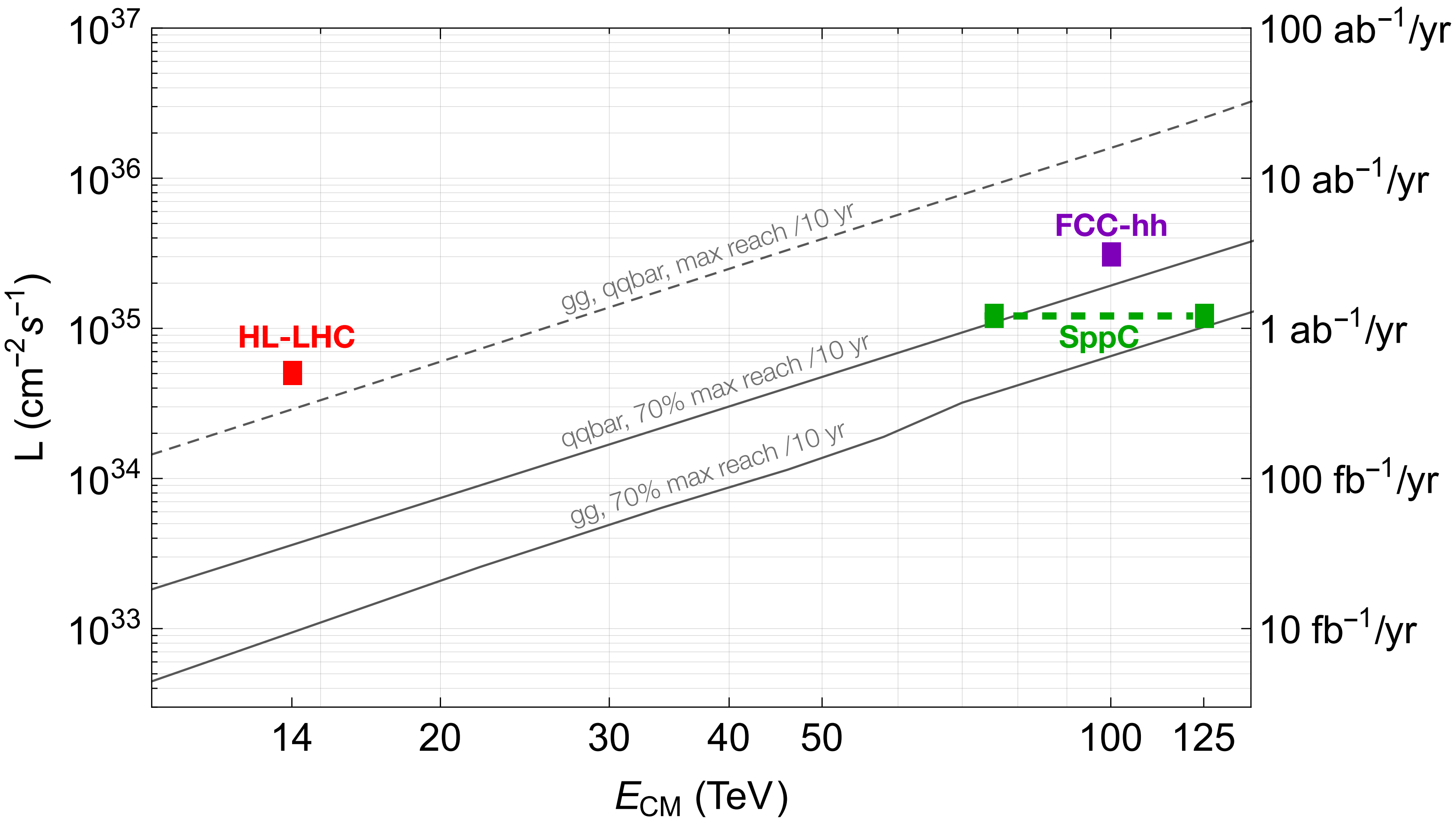
High energy lepton colliders summary plot

- Peak luminosity per IP vs CM energy for the high energy lepton collider proposals as provided by the proponents.
- The right axis shows integrated luminosity for one Snowmass year (10^7 s).
- Also shown are lines corresponding to the required luminosity for yearly production rates of important processes.
- The luminosity requirement for 5σ discovery of the benchmark DM scenarios Higgsino and Wino are also shown.



Hadron colliders summary plot

- Peak luminosity per IP vs CM energy for the high energy hadron collider proposals as provided by the proponents.
- The right axis shows integrated luminosity for one Snowmass year (10^7s).
- Also shown are the luminosity requirements with two possible initial states gg and $q\bar{q}$:
  - The dashed curve represents the luminosity needed (assuming a 10-year run) to have linear increase of new physics mass reach with CM energy.
  - The solid lines represent the luminosity requirements for 70% of this new physics mass reach.



Summary table of collider versions located at FNAL

- Main parameters of the collider proposals located at FNAL.
- Total peak luminosity for multiple IPs is given in parenthesis.
- The cost range is for the single listed energy.
- There is also a recent proposal for a CCC version that can be located at FNAL.
- Other recently developed collider proposals, such as CERC, ReLiC, or wake field accelerators, could also be evaluated for being located at FNAL.

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy LeptoN (HELEN) e^+e^- colider	0.25 (0.09-1)	1.4	5-10	13-18	7-12	$\sim$110
e^+e^- Circular Higgs Factory at FNAL	0.24 (0.09-0.24)	1.2	3-5	13-18	7-12	$\sim$200
Muon Collider at FNAL	10 (6-10)	20 (40)	>10	19-24	12-18	$\sim$300
pp Collider at FNAL	24	3.5 (7.0)	>10	>25	18-30	$\sim$400

Technical readiness of collider proposals

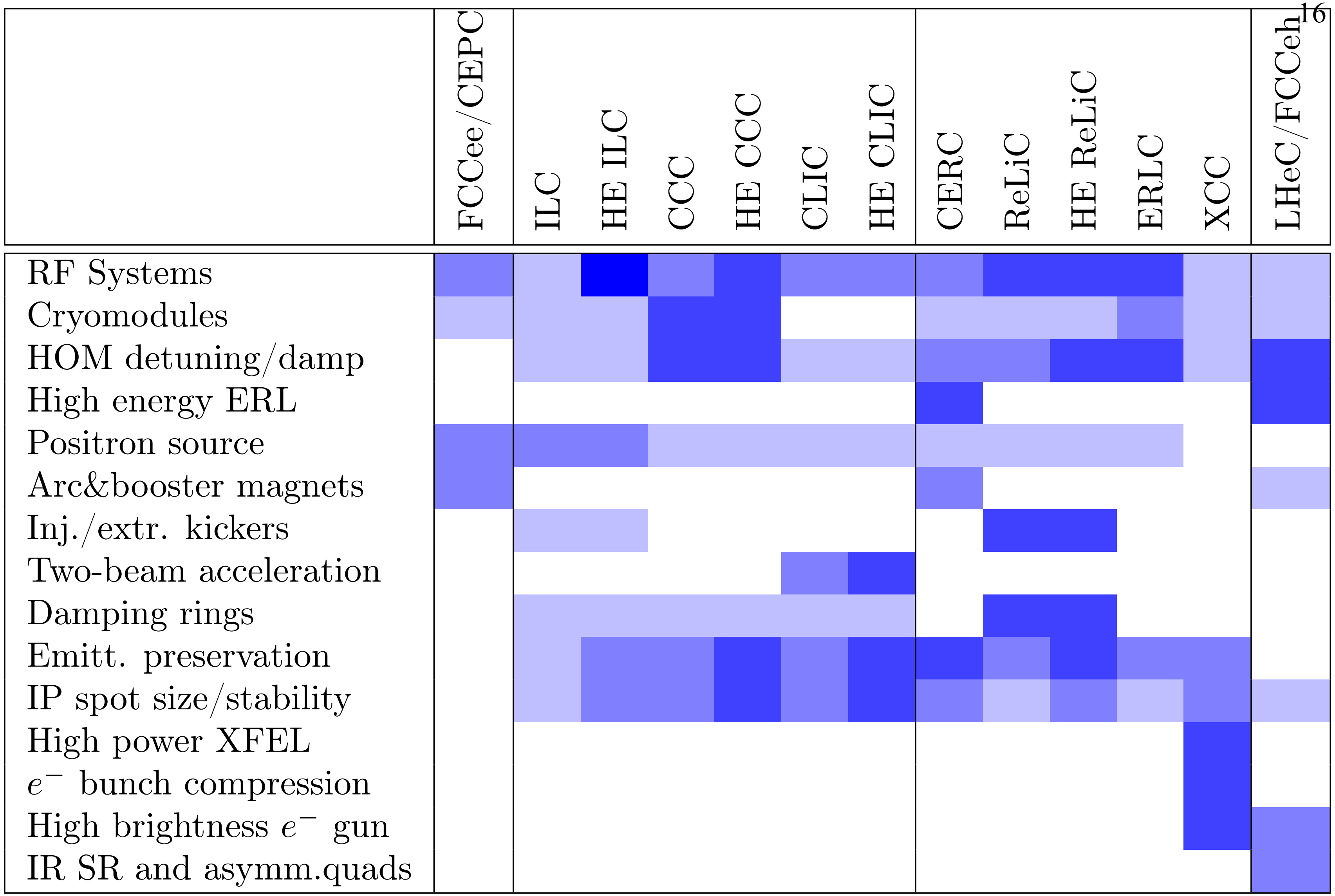
- ITF developed metrics to compare technical risks of key components and systems
- Proponents were asked to select 5 critically enabling technologies and numerically evaluate each in 5 risk categories.
  - Current Technical Readiness Level (TRL): from “Basic principle observed” to “System proven through mission operation”

Technical Risk Factor	Score	Color Code
TRL = 1,2	4	
TRL = 3,4	3	
TRL = 5,6	2	
TRL = 7,8	1	

  - Technology validation requirement: from “full-scale” to “separate component validation”
  - Cost reduction impact: from “critical – a ‘no-go’ w/o cost reduction” to “desirable”
  - Evaluation of performance achievability: from “needs explicit demonstration” to “at state-of-the-art”
  - Technically limited R&D timescale to reach TRL 7-8: from “> 20 years” to “0 – 5 years”

Technical risk registry

- Technical risk registry of accelerator components and systems for **future e⁺e⁻ and ep colliders**: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.

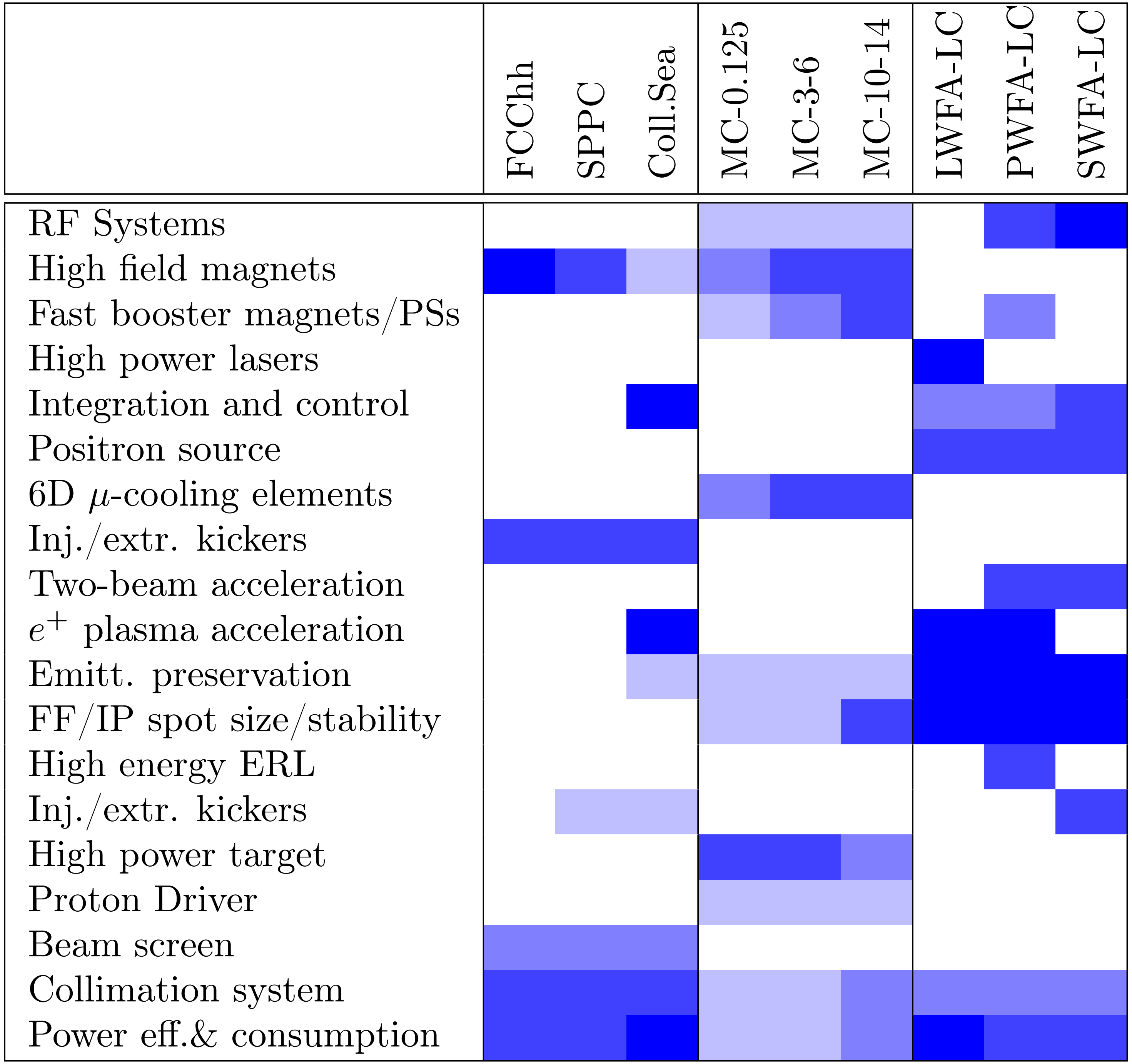


Technical Risk Factor	Score	Color Code
TRL = 1,2	4	
TRL = 3,4	3	
TRL = 5,6	2	
TRL = 7,8	1	

Technical risk registry

- Technical risk registry of accelerator components and systems for **future very high energy pp, muon and WFA colliders**: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.

Technical Risk Factor	Score	Color Code
TRL = 1,2	4	
TRL = 3,4	3	
TRL = 5,6	2	
TRL = 7,8	1	



Technical risk summary table

- Technical risk categories (darker blue is higher risk).
- ”Design status”:
  - I - TDR complete
  - II - CDR complete
  - III - substantial documentation
  - IV - limited documentation and parameter table
  - V - parameter table
- “Overall risk tier”:
  - 1 – lower overall technical risk
  - …
  - 4 – multiple technologies require further R&D

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

R&D Programs and Facilities

- Duration and integrated cost of the past, present, and proposed R&D programs and facilities (the latter indicated by a shift to the right).
- Funding sources for the past and present programs are indicated ("OHEP" - directed R&D in the DOE OHEP, "GARD" - General Accelerator R&D and facilities operation program in the OHEP, "LDG/CERN" - aspirational support requested as part of the European Accelerator R&D Roadmap).
- Inputs with estimates from the proponents on the total cost of demonstration projects and pre-CD2 validations have “tbd” as funding source.

R&D Program Facility Name	Benefiting Concept	Duration (Years)	Integrated Cost (M$)	Funding Source	Key Topics Rationale
Linear e^+e^- colliders					
NLC/NLCTA/FFTB	NLC/C^3	14	120	OHEP	NC RF gradient, final focus
TESLA/TTF	ILC	~10	150	DESY/Collab	SCRF CMs and beam ops
ILC in US/FAST	ILC	6	250	OHEP	SCRF CMs and beam ops
ILC in Japan/KEK	ILC	10	100	KEK	SCRF CMs and beam ops
ATF/AFT2	ILC	15	100	KEK/Intl	LC DR and final focus
CLIC/CTF/CTF3	CLIC	25	500	CERN/Intl	2-beam scheme and driver
General RF R&D	All LCs	8	160	GARD	see RF Roadmap; incl facilities
ILC in Japan/KEK	ILC	5	50	KEK	next 5 yr request
High-G RF & Syst.	CLIC/SRF	5	150	LDG/CERN	NC/SC RF and klystrons
C^3 *input*	C^3	8	200	tbd	72-120 MV/m CMs, design
HELEN *input*	HELEN	n/a	200	tbd	pre-TDR, TW SRF tech
ILC-HE *input*	ILC-HE	20	100	tbd	10 CMs 70MV/m Q=2e10
ILC-HighLumi *input*	ILC-HL	10	75	tbd	31.5 MV/m at Q=2e10
Circular/ERL *ee*/*eh* colliders					
CBB	LCs	6	25	NSF	high-brightness sources
CBETA	ERLCs	5	25	NY State	multi-turn SRF ERL demo
ERLs/PERLE	ERLCs	5	80*	LDG/CERN	NC/SC RF, klystrons
FNALee *input*	FNALee	n/a	100	tbd	design and demo efforts
LHeC/FCC*eh* *input*	*eh*-coll.	n/a	100	tbd	demo facility, design
CEPC *input*	CEPC	6	154	tbd	SRF, magn. cell, plasma inj.
ReLiC *input*	ReLiC	10	70	tbd	demo Q=1e10 at 20 MV/m
XCC *input*	XCC	7	200	tbd	demo and design efforts
CERC *input*	CERC	8	70	tbd	demo high-E ERL at CEBAF
Muon colliders					
NFMCC	MC	12	50	OHEP	design study, prototyping
US MAP	MC	7	60	OHEP	IDS study, components
MICE	MC	12	60	UK/Collab	4D cooling cell demo
IMCC/pre-6D demo	MC-HE	5	70	LDG/CERN	pre-CDR work, components
IMCC/6D cool.	MC-HE	7	150	CERN/Collab	6D cooling facility and R&D
Circular *hh* colliders					
LHC Magnet R&D	LHC	12	140	CERN	8T NbTi LHC magnets
US LARP	LHC	15	170	OHEP	more LHC luminosity faster
SC Magnets General	pp, $\mu\mu$	10	120	GARD	HF-magnets and materials
US MDP	pp, $\mu\mu$	5	40	GARD	see HFM Roadmap
HFM Program	FCChh	7	170	LDG/CERN	16 T magnets for FCChh
FNAL*pp* *input*	FNAL*pp*	n/a	100	tbd	25T magnets demo
FCChh *input*	FCChh	20	500	tbd	large demo, R&D and design
Coll.Sea *input*	CollSea	16	400	tbd	300m magnets underwater
AAC colliders					
SWFA/AWA	SWFA-LC	8	40	GARD	2-beam accel in THz structures
LWFA/BELLA	LWFA-LC	8	80	GARD	laser-plasma WFA R&D
LWFA/DESY	LWFA-LC	10	30	DESY	laser-plasma WFA R&D
PWFA/FACET-I,II	PWFA-LC	13	135	GARD	2-beam PWFA, facility
AWAKE	PWFA-LC	8	40	CERN/Collab	proton-plasma PWFA, facility
EUPRAXIA	LWFA-LC	10	570	EUR/Collab.	high quality/eff. LWFA R&D
LWFA/DESY	LWFA-LC	10	80	DESY	laser WFA R&D
SWFA *input*	SWFA-LC	8	100	tbd	0.5 & 3GeV demo facilities
LWFA *input*	LWFA-LC	15	130	tbd	2nd BL, e^+, kBELLA project
PWFA *input*	PWFA-LC	10	100	tbd	demo and design effort

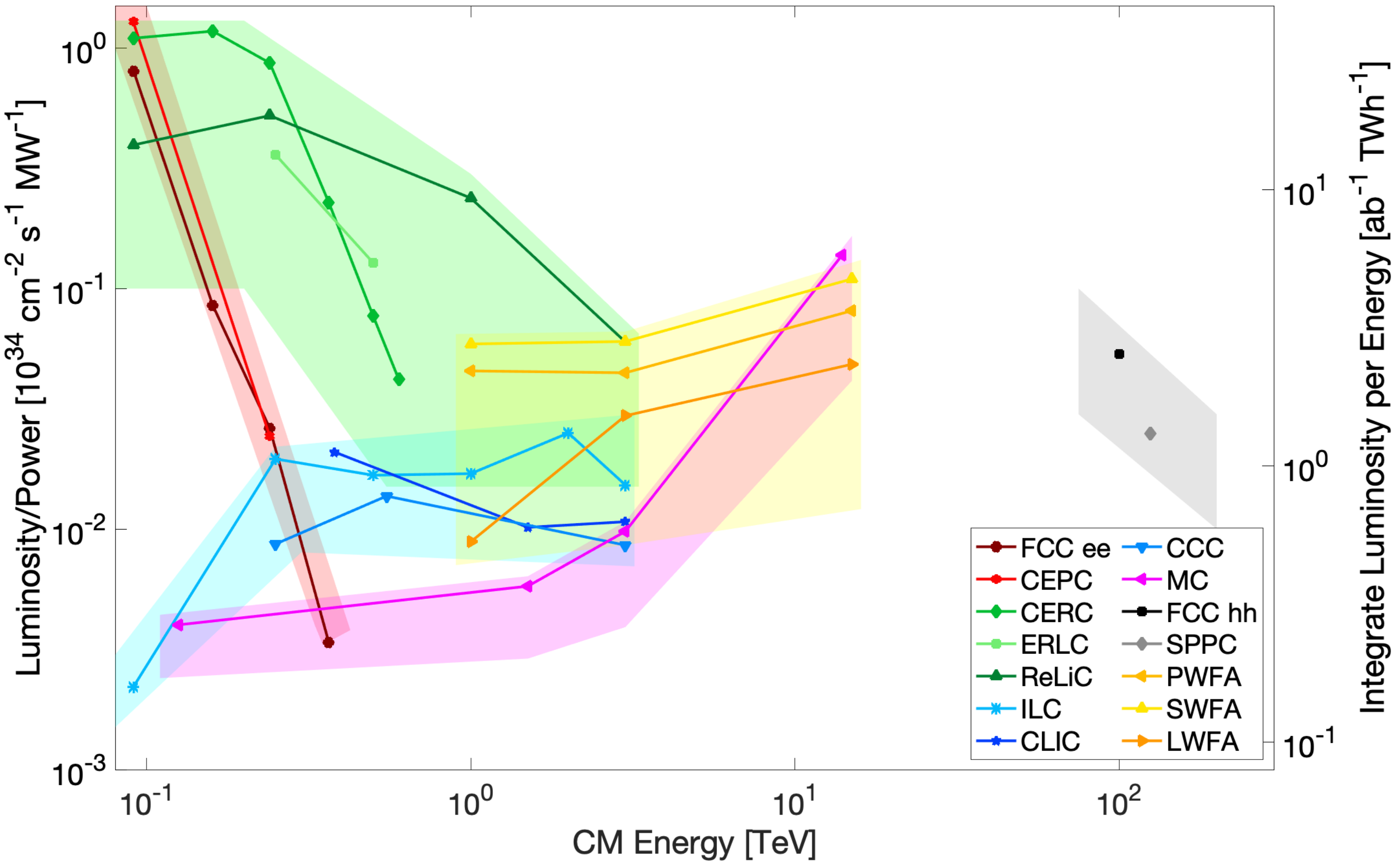
Power, complexity, environmental impact

- Summary table of categories of electric power consumption, size, complexity and required radiation mitigation.
- Darker blue means more impact.
- The WFA at 15 TeV use round beam collisions and have lower power consumption than at 3 TeV with flat beam collisions.

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
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	91 km	II	I
ReLiC (0.24 TeV)	315	20 km	II	I
ERLC (0.24 TeV)	250	30 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	0.3 km	I	II
ILC (3 TeV)	$\sim$400	59 km	II	II
CLIC (3 TeV)	$\sim$550	50.2 km	III	II
CCC (3 TeV)	$\sim$700	26.8 km	II	II
ReLiC (3 TeV)	$\sim$780	360 km	III	I
MC (3 TeV)	$\sim$230	10-20 km	II	III
LWFA (3 TeV)	$\sim$340	1.3 km (linac)	II	I
PWFA (3 TeV)	$\sim$230	14 km	II	II
SWFA (3 TeV)	$\sim$170	18 km	II	II
MC (14 TeV)	$\sim$300	27 km	III	III
LWFA (15 TeV)	$\sim$1030	6.6 km	III	I
PWFA (15 TeV)	$\sim$620	14 km	III	II
SWFA (15 TeV)	$\sim$450	90 km	III	II
FCC-hh (100 TeV)	$\sim$560	91 km	II	III
SPPC (125 TeV)	$\sim$400	100 km	II	III

Luminosity per power consumption

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10^7 seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



Collider Facilities Costs and Time to Construct

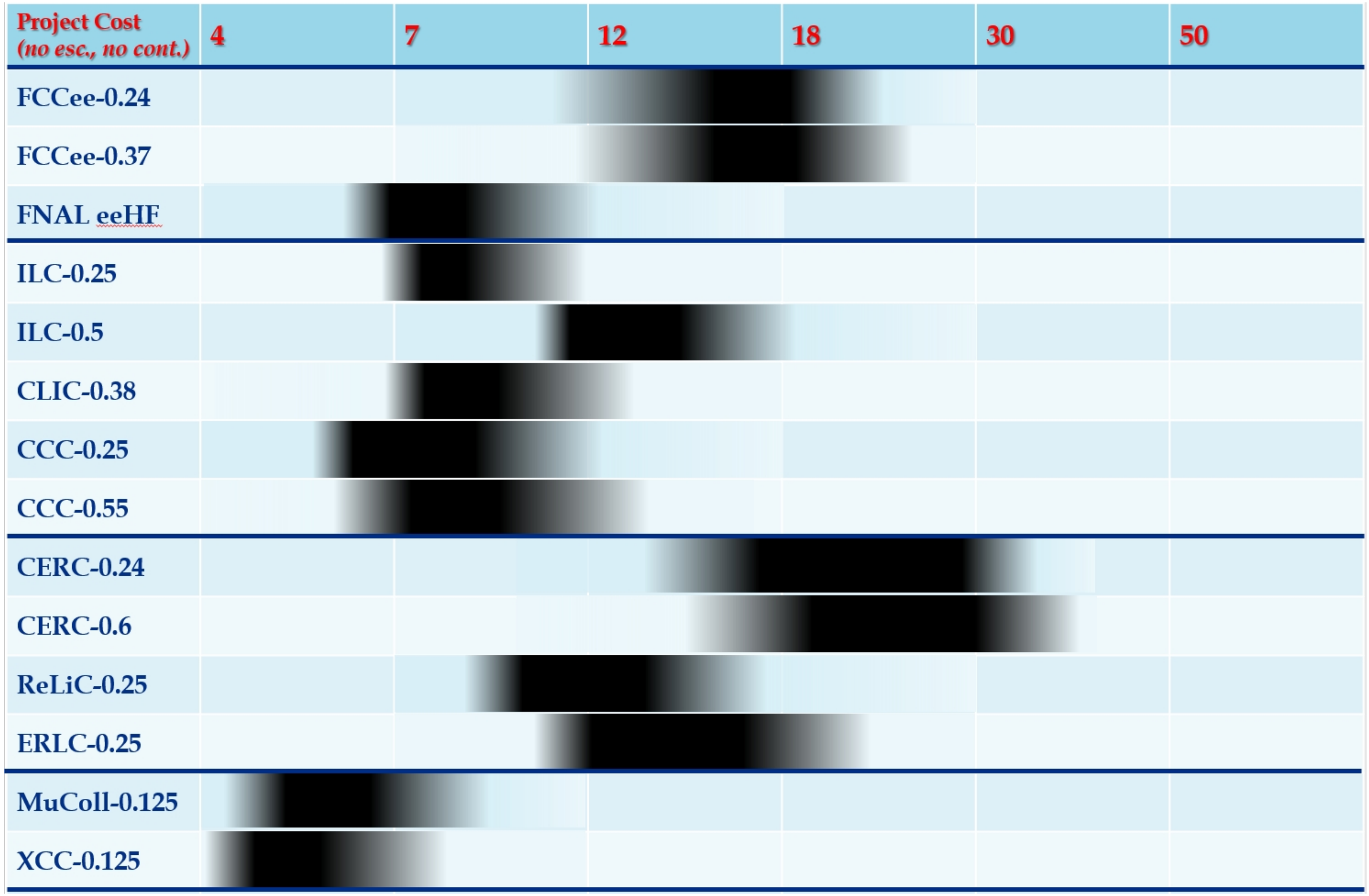
- Estimated costs and cost uncertainties are critical for project preparation and justification to funding agencies and society.
- Costs increase with size of facility but not linearly.
- ITF addressed Total Project Cost (TPC) but without contingency and escalation in 2021B$. This "US accounting" includes costs for all technical components, civil construction and utilities, all associated labor, in-project R&D, design efforts, project management and other overhead, installation and initial commissioning.
- ITF prepared a 30-parameter cost model and benchmarked it against 5 recently completed accelerator projects (XFEL, LHC, Swiss-FEL, NSLS-II, and LCLS-II+HE) with an error of less than 20%.
- The 30 parameters ranged from new and reused accelerators, tunnels, and sources, operating power consumption, length and field of SC and NC magnets, length of vacuum chamber, length and rf voltage of SC and Cu cavities, number of beam dumps, cryomodules, cryo-plants, plasma cells, drive lasers to a 25% addition for design effort and a 30% addition for controls, diagnostics, cables, and installation.

The ITF 30-parameter cost model

- All colliders, except the lepton-hadron colliders, were assumed to be stand-alone projects, since ITF could not assume or decide on a sequence of projects. The lepton-hadron colliders were treated as incremental to an existing hadron-hadron collider. Existing facilities (accelerators, tunnels, utilities) that could be reused were not included in the cost estimate.
- Each collider was divided into "main collider" and "injectors, power drivers, particle sources"
- Costs of existing equipment, either off-the-shelf or from recent project experience, was used. A model of the reduced cost for large quantity series production was used.
- A range of cost estimates for novel technologies (identified for each proposal in the ITF report) was obtained from a high value based on operating test facilities and a low value based on reasonably anticipated advances and cost goals from current trends in similar novel technologies. This is the largest uncertainty in the cost estimates for future colliders.
- Cost reductions from future R&D were not included but could be substantial.
- ITF followed the "Value + Explicit Labor" methodology. "Explicit Labor" is labor not included in industry contracts, typically labor at laboratories. Used 200k$/FTE-year.
- Finally, this cost estimate was also compared to a simpler 3-parameter (length, energy, power consumption) model to get an additional measure of the overall uncertainty.

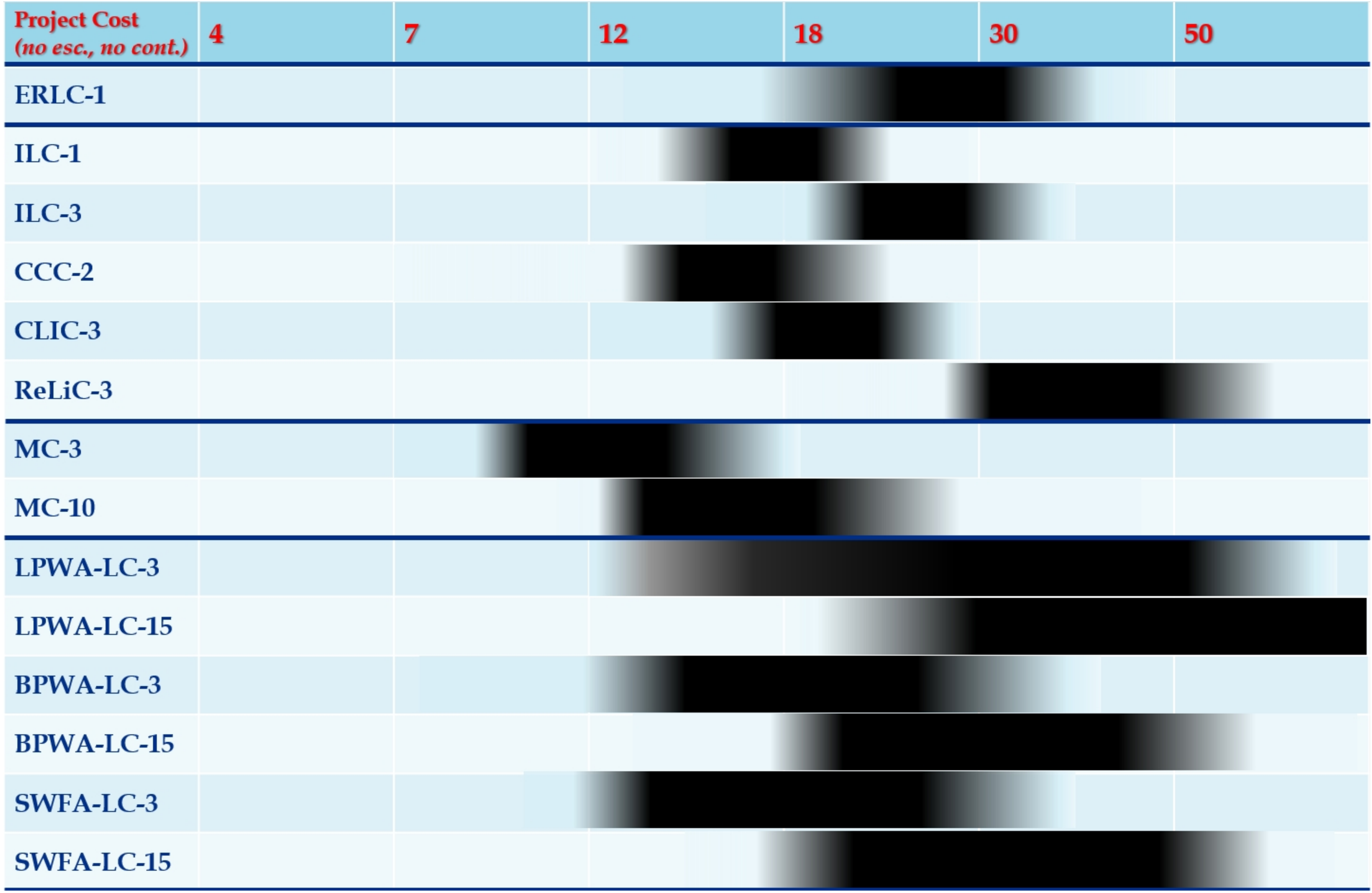
Cost estimates for Higgs factory proposals

- The ITF cost model for the EW/Higgs factory proposals.
- Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation.
- Black horizontal bars with smeared ends indicate the cost estimate range for each machine.



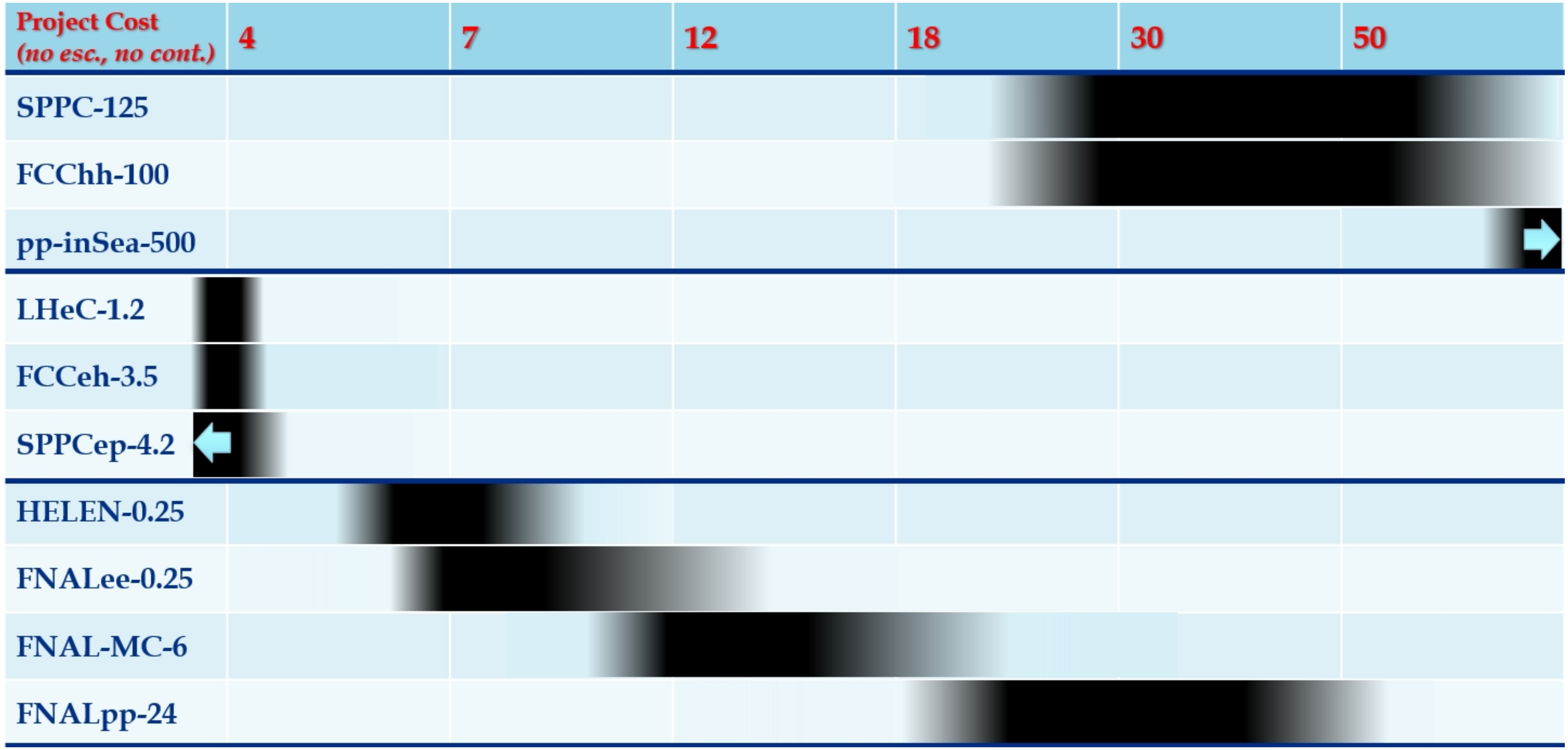
Cost estimates for multi-TeV lepton collider proposals

- The ITF cost model for the multi-TeV lepton collider proposals.
- Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation.
- Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

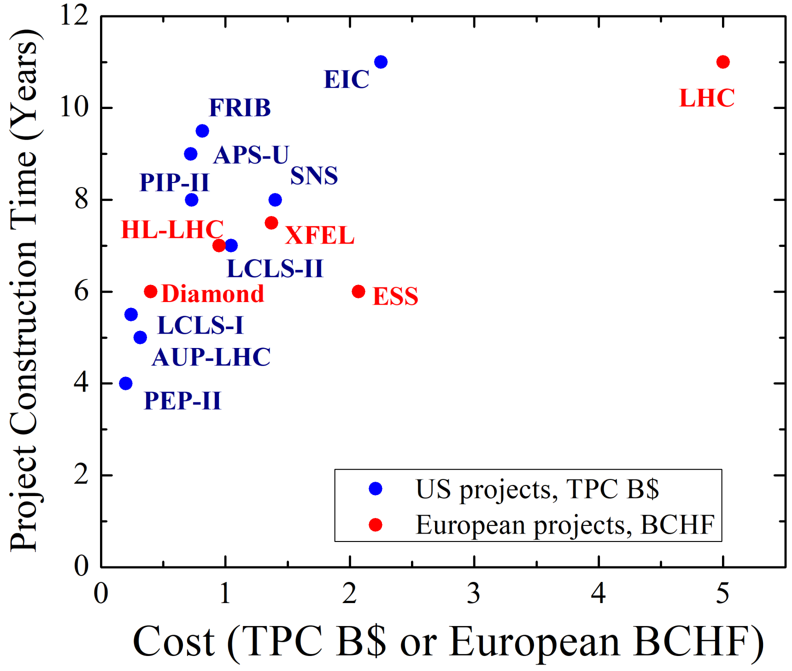


Cost estimates for hadron and lepton-hadron colliders, and FNAL site-filler proposals

- The ITF cost model for the energy frontier hadron collider, electron-proton colliders (incremental cost from hadron collider only) and for the proposed Fermilab site-filler colliders.
- Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation.
- Black horizontal bars with smeared ends are the cost estimate range for each machine.
- Right-arrow for the 500 TeV "Collider-in-the-Sea" indicates higher than 80B$ cost.
- Left-arrow for the electron-proton "SPPC-CEPC" collider concept indicates smaller than 4B$ cost.



Timeline analysis



- Construction time of large projects is determined by
  - Time to establish project and complete pre-project R&D
  - Annual spending rate
  - Availability of experienced staff
  - Pace of civil construction and fabrication of components
  - …
- ITF estimated the timeline of 3 stages: basic design and pre-project R&D; TDR and industrialization; construction period;
- All projects are treated as “stand-alone” (except ep colliders) and timeline starts now or when funding starts to be available. A technically limited construction time was assumed.
- “Years of pre-project R&D” was informed by the technical risk evaluation.
- “Time to first physics” is not just the sum of the 3 stages above since some activities can proceed in parallel.

Timeline of proposals

- Summary of the ITF judgment on collider projects’ R&D duration, design and industrialization, construction, and combined time to first physics.
- The first three columns present these timescales as submitted to the ITF by the project proponents.
- The first group of rows are Higgs and electroweak physics colliders, the second group are energy-frontier lepton colliders, and the third group includes hadron-hadron and lepton-hadron colliders.

Collider Name - c.m.e. (TeV)	Subm’d R&D Durat’n to CDR (yrs)	Subm’d Design to TDR Durat’n (yrs)	Subm’d Project Constrn. Time (yrs)	ITF Judgement Duration Preproject R&D to CDR	ITF Judgement Design & Industr’n Duration to TDR	ITF Judgement Project Constrn. Duration post CD3	ITF Judgement Combined "Time to the First Physics"
ILC-0.25	0	4	9	0-2 yrs	3-5 yrs	7-10 yrs	< 12 yrs
ILC (6x lumi)	10	5	10	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CLIC-0.38	0	6	6	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FCCee-0.36	0	6	8	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CEPC-0.24	6	6	8	0-2 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CCC-0.25	2-3	4-5	6-7	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
FNALee-0.24	tbd	tbd	tbd	3-5 yrs	3-5 yrs	7-10 yrs	13-18 yrs
CERC-0.6	3	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
HELEN-0.25	tbd	tbd	tbd	5-10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
ReLiC-0.25	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
ERLC-0.25	8	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-0.125	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
XCC-0.125	2-3	3-4	3-5	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
SWLC-0.25	8	5	10	5-10 yrs	3-5 yrs	7-10 yrs	19-24 yrs
ILC-1	10	5	5-10	5-10 yrs	3-5 yrs	10-15 yrs	13-18 yrs
ILC-2	10	5	5-10	> 10 yrs	3-5 yrs	10-15 yrs	19-24 yrs
ILC-3	20	5	10	> 10 yrs	3-5 yrs	10-15 yrs	19-24 yrs
CLIC-3	0	6	6	3-5 yrs	3-5 yrs	10-15 yrs	19-24 yrs
CCC-2	2-3	4-5	6-7	3-5 yrs	3-5 yrs	10-15 yrs	19-24 yrs
ReLiC-2	3	5	10	5-10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-1.5	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
MC-3	11	4	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
MC-10	11	4	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
MC-14	11	4	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
PWFA-LC-1	15	tbd	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
PWFA-LC-15	15	tbd	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
LWFA-LC-3	15	tbd	tbd	> 10 yrs	> 10 yrs	10-15 yrs	> 25 yrs
LWFA-LC-15	15	tbd	tbd	> 10 yrs	> 10 yrs	> 16 yrs	> 25 yrs
SWFA-LC-1	tbd	tbd	tbd	> 10 yrs	5-10 yrs	7-10 yrs	19-24 yrs
SWFA-LC-15	tbd	tbd	tbd	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
FCChh-100	2	20	15	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
SPPC-75	15	6	8	> 10 yrs	5-10 yrs	10-15 yrs	> 25 yrs
Coll.-Sea-500	10	6	6	> 10 yrs	5-10 yrs	> 16 yrs	> 25 yrs
CEPC-SPPC	tbd	tbd	tbd	3-5 yrs	3-5 yrs	< 6 yrs	> 25 yrs
LHeC	0	5	5	0-2 yrs	3-5 yrs	< 6 yrs	13-18 yrs
FCC-eh	0	5	5	0-2 yrs	3-5 yrs	< 6 yrs	> 25 yrs

Summary and final comments

- ITF developed metrics to evaluate and compare 24 future collider proposals in physics reach, R&D needs, schedule, cost, and environmental impact and produced summary tables and plots.
- Any of the future collider projects constitute one of, if not, the largest science facility in particle physics. The cost, the required resources and, maybe most importantly, the environmental impact in the form of large electric power consumption will approach or exceed the limit of affordability. **ITF suggests that the planning efforts (Snowmass, P5, EPP-2024) recommend that R&D to reduce the cost and the power consumption of future collider projects is given high priority.**
- Sustainability of scientific facilities is gaining increased importance, especially in Europe. The 2021 European Strategy for Particle Physics – Accelerator R&D Roadmap made the recommendation:
  - “Environmental sustainability should be treated as a primary consideration for future facilities, including those in the near-to-medium future, and the R&D programme should be prioritised accordingly. Objective metrics should be set down to allow appraisal of the impact of future facilities over their entire life cycle, including civil-engineering aspects, and of the resources needed to ensure sustainability.”
- Snowmass, P5, and EPP-2024 should consider a similar recommendation.
- **Personal comment:** The presently ready-to-build collider proposals with their large energy consumption might not be acceptable in today’s world. Taking time to do R&D into more energy efficient technologies (more efficient CW SRF for ERLs, more efficient He refrigerators, much more efficient lasers for LWFA, …) would allow for collider proposals that are much more acceptable in a future with increasing Global Warming. Such R&D might also have important spin-offs for society.

Additional slides

Lepton-hadron colliders summary table

- Main parameters of the lepton-hadron collider proposals.
- For lepton-hadron colliders only, the parameters (years of pre-project R\&D, years to first physics, construction cost and operating electric power) show the increment needed for the conversion of the hadron-hadron collider to a lepton-hadron collider.

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
LHeC	1.2	1	0-2 ?	13-18	<4	~140
FCC-eh	3.5	1	0-2 ?	>25	<4	~140
CEPC-SPPC-ep	5.5	0.37	3-5	>25	<4	~300