



Snowmass'21 Accelerator Frontier

Planning for Future

Steve Gourlay (LBNL)

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Vladimir Shiltsev (Fermilab)

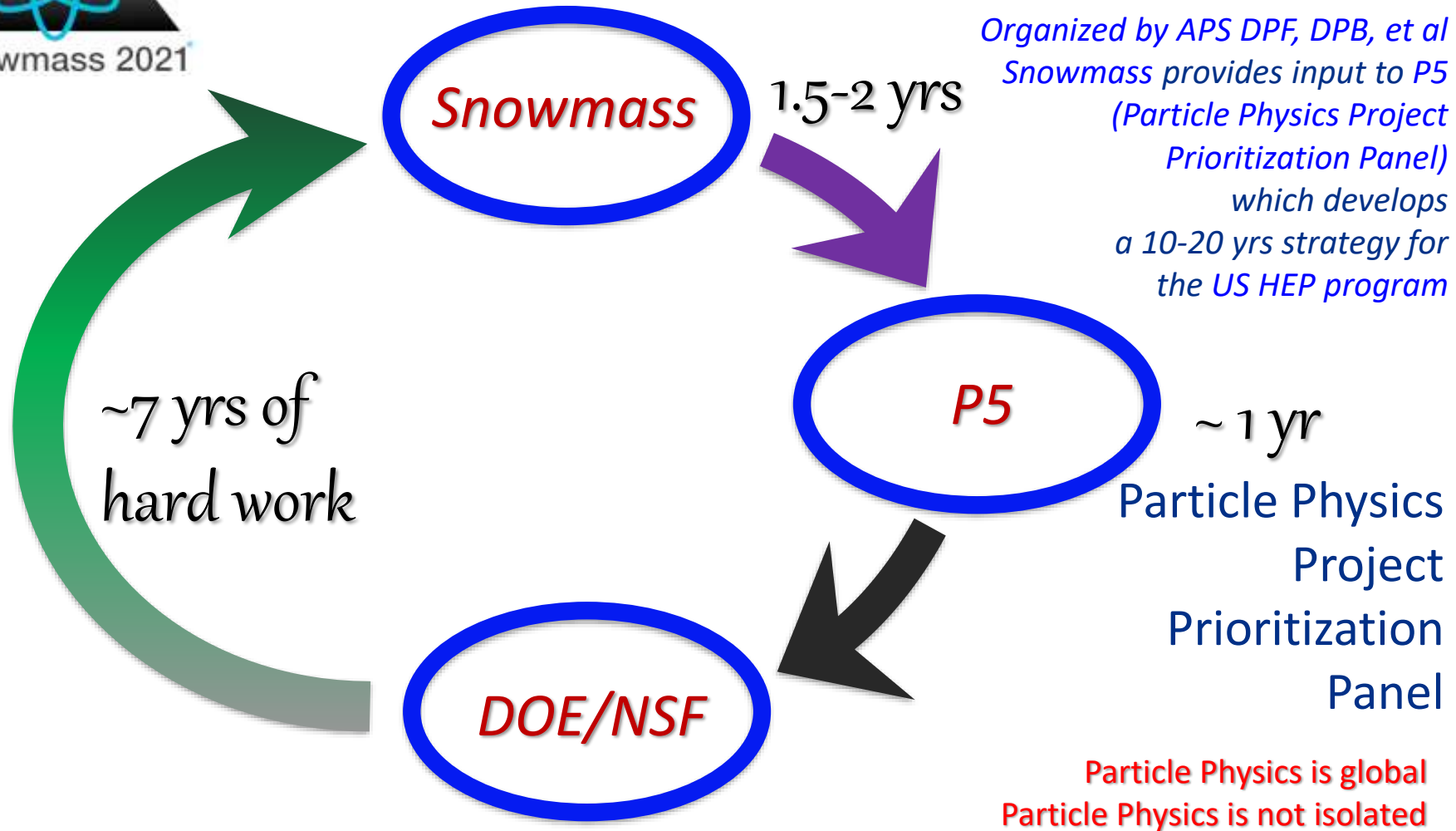
ICTS "Horizons'2022", Nov. 17, 2022



ICTS

INTERNATIONAL
CENTRE *for*
THEORETICAL
SCIENCES

Snowmass'21 *"a particle physics community study"*



<https://www.snowmass21.org/>

Snowmass'21 Accelerator Frontier Conveners



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Focus:

- Understand the most important questions for the field of *Accelerator Science and Technology*
- Identify promising opportunities and tools to address them
- Consider a mix of large, mid, and small scale accelerators as well as R&D
- **Provide information to P5 to help develop a strategy for US HEP**

Accelerator Frontier Topical Groups

– see *snowmass21.org*

- AF1: Beam Physics and Accelerator Education
- AF2: Accelerators for Neutrinos
- AF3: Accelerators for EW/Higgs
- AF4: Multi-TeV Colliders
- AF5: Accelerators for PBC and Rare Processes
- AF6: Advanced Accelerator Concepts
- AF7: Accelerator Technology R&D
 - RF
 - Magnets
 - Targets & Sources

**Among 30 Topical Group Conveners – 9 International
(DESY, CERN, INFN, ESRF, IHEP/Beijing, Orsay)**

Goals of the AF Topical Groups

- Each AF Working group will address the overall questions:
 1. What accelerators & tools needed to advance the physics?
 2. What is currently available (state of the art) around the world?
 3. What new accelerator facilities could be available on the next decade
(or next-next decade)?
 4. What is the readiness and needed R&D to enable these future opportunities?
 5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facility?
- The last two are hard questions with big impact on strategy development → created **Implementation Task Force** to develop metrics for guidance (see below)

Snowmass AF: Inputs and Discussions

- ❖ >500 People Took Part in the AF discussions:
 - ❖ ~25% early career scientists and engineers
 - ❖ >70 attended “final” meeting in Seattle in July’22
- ❖ 63 Topical Workshops & Meetings, 8 Cross-Frontier **Agoras**:
 - ❖ 5 on all types of colliders: ee, linear/circular, mumu, pp, advanced
 - ❖ 3 on experiments and accelerators for rare processes physics
- ❖ Special cross-Frontier Groups (e.g., AF-EF-TF-IF-NF):
 - ❖ eeCollider Forum, Muon Collider Forum, Implementation Task Force
 - ❖ 2.4MW design group FNAL, Nat’l Future Collider R&D Program proposal
- ❖ Summarized in Many Reports/Documents:
 - ❖ 257 Letters of Interest, 121 White Papers
 - ❖ Reports of the Implementation Task Force, ee- and Muon Collider Fora
 - ❖ 9 AF Topical Group summary reports
 - ❖ Accelerator Frontier Summary Report (today’s topic)

AF Report: Executive Summary

arxiv:2209.14136

“Intro”:

- Since last P5, this Snowmass’21 process

“Future Facilities”:

- TBD by P5 – accelerator/people need to be part of P5; ITF analysis can greatly help
- *Multi-MW FNAL complex upgrade* will be priority for NF in 2030 (AccFrontier is ready)
- Many opportunities for Rare Processes (AF ready), incl. *PAR* and utilize what we have
- Several Higgs/EW factories are feasible: *FCCee, C3 and HELEN* to be explored
- $O(10 \text{ TeV/parton})$ needed for >2040’s, *muon colliders* to be explored/ pre-CDR by 2030
- Need an *Integrated Future Colliders R&D program* in OHEP to provide design reports by next Snowmass/P5’2030 and engage internationally (FCC, ILC, IMCC)

Accelerator Frontier

S. Gourlay, T. Raubenheimer, V. Shiltsev

G. Arduini, B. Amman, C. Barthelemy, M. Bai, S. Belovestnyy, S. Bernabeu, P. Blot, A. Brusa-Geslin, J. Caldeira, C. Gelsner, G. Hoffmann, M. Hogg, E. Huang, D. Li, S. Lind, R. Miller, P. Monetti, E. Nard, M. Palmer, N. Paudyal, F. Pedersoli, E. Preghz, Q. Qin, J. Power, T. Ruan, G. Saldá, D. Sestini, V. E. Sosa, J. Tang, A. Vasiliev, B. Wiser, F. Zimmermann, A.V. Zolotarev, R. Zou

For over half a century, high-energy accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity frontier research in high energy physics (HEP) continuously drive the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more green efficient. Despite these past efforts, the increasing size, cost and demands required for modern and future accelerator-based HEP projects arguably distinguish them as the most challenging scientific research endeavors. In the meantime, the international accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals.

Major developments since the last Snowmass/HEPAP P5 strategic planning exercise in 2013-2014 include start of the PIP-II proton beam construction for the LBNL/DUNE neutrino program in the US; emergence of the FCC/CEPC projects for Higgs/EW physics research at CERN and in China, respectively; a significant reduction of activity related to linear collider projects (ILC in Japan and CLIC at CERN); and, paradoxically, the end of the Muon Accelerator Program in the US and creation of the International Muon Collider Collaboration (IMCC) in Europe. The last decade saw several notable planning advancements, including the US DOE GARD Roadmap, European Strategy for Particle Physics and the Accelerator R&D Roadmap, EuPRAXIA, etc.

In addition, since the last Snowmass meeting that took place in 2013 was shortly after the confirmation of the Higgs, the goals for the Energy Frontier have changed as a result of the LHC measurements. While a Higgs/EW factory at 250 to 300 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or few TeV e^+e^- collider has diminished. Instead, the community is focused on a 90-TeV (parton e^+e^-) discovery collider that would follow the Higgs/EW Factory. This is an important change that will refocus some of the accelerator R&D program.

The technical maturity of proposed facilities ranges from show-ready to those that are still largely conceptual. Over 100 contributed papers have been submitted to the Accelerator Frontier of the US particle physics decadal community planning exercise, Snowmass2021. These papers cover a broad spectrum of topics: beam physics and accelerator education, accelerators for neutrinos, colliders for Electroweak/Higgs studies and multi-TeV energies, accelerators for Higgs factory colliders and rare processes, advanced accelerator concepts, and accelerator technology for Radio Frequency cavities (RF), magnets, targets, and sources.

Future facilities: The accelerator community in the US and globally has a broad range of accelerator technologies and expertise that will be needed to design and construct any of the near-term HEP accelerator projects. P5 will need to prioritize what option(s) should be developed. Planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process. Accelerator experts can contribute to the US and international projects under consideration by providing top-down metrics for expected cost-scales and technology/maturity evaluations, following the ITF findings.

Among possible actively discussed future facilities options are:

- A multi-MW beam power upgrade of the Fermilab proton accelerator complex that seems to be the highest priority for the neutrino program in the 2030s; corresponding accelerator technology and beam physics studies are needed to identify the most cost- and power-efficient solution that could be timely implemented leading to breakthrough results of the DUNE neutrino program;
- Several beam facilities for atom and Dark Matter (DM) searches are shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAR (a 1 GeV, 100 kW PIP-II Accelerator Ring); in general, we should efficiently utilize existing and upcoming facilities to explore dedicated or parallel opportunities for rare process measurements - examples are the SLAC SSF electron line, MWs of proton beam power potentially available after construction of the PIP-II SSF line, options of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC, etc.
- In the area of future colliders - several approaches are identified as both promising and potentially feasible, and call for further exploration and support: in the Higgs/EW sector - there is growing support for the FCC at CERN and proposals of somewhat more advanced linear colliders in the US or elsewhere, such as C^3 and HELEN;
- At the energy frontier, the discovery machines such as $O(30 \text{ TeV } e^+e^-)$ mass colliders have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these projects could be explored technically and documented in pre-CDR level reports by the end of this decade.

The US HEP accelerator R&D portfolio presently contains no collider-specific steps. This creates a gap in our knowledge-base and accelerator/technology capabilities. It also limits our national reputation for a leadership role in particle physics in that the US cannot lead or even contribute to proposals for accelerator-based HEP facilities. To address the gap, the community has proposed that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) to carry-out technology R&D and accelerator design for future collider concepts. This program would aim to create synergistic engagement in projects proposed abroad (e.g., FCC, ILC, IMCC). It would support the development of design reports on collider options by the time of the next Snowmass and P5 (2029-2030), particularly for options that can feasibly be hosted in the US, and to create R&D plans for the decade past 2030. Without such a program there may be few accelerator-based proposals for a future P5 to evaluate.

#1 Accelerators for Neutrinos and Rare Processes

Accelerators for ν 's: 2020s – PIP-II constr./commiss.

What's in plan for 2030s?



France



India



Italy



Poland



United Kingdom



United States

Cryoplant Building

0.8 GeV PIP-II Linac Status (webcam Nov 2022)

PIP-II Injector Test



HWR CM



SSR1 CM Prototype



Multi-MW ν -Beams for DUNE

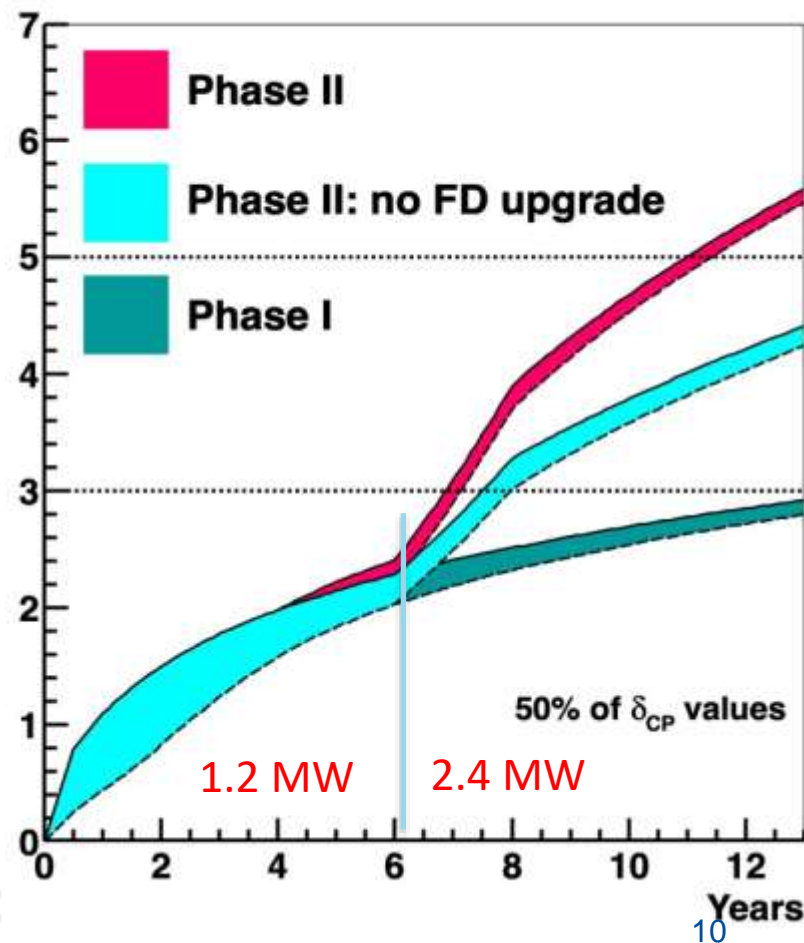
LBNF/DUNE Project –

Phase I:

- By 2032: **1.2 MW proton beam** (120 GeV, MI) on target + near ν -detector + 20 kton LAr ν -detector in Lead, SD
- Expected rate of “physics” outcome – up to $\sim 3\sigma$ in δ_{CP} , in the first 6 years (also Δm^2_{32} , $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$)
- To get to $\sim 5\sigma$ will take too long, plus – competitor experiment *Hyper-K* in Japan (30 GeV J-PARC p beam)

Proposed LBNF/DUNE Phase II :

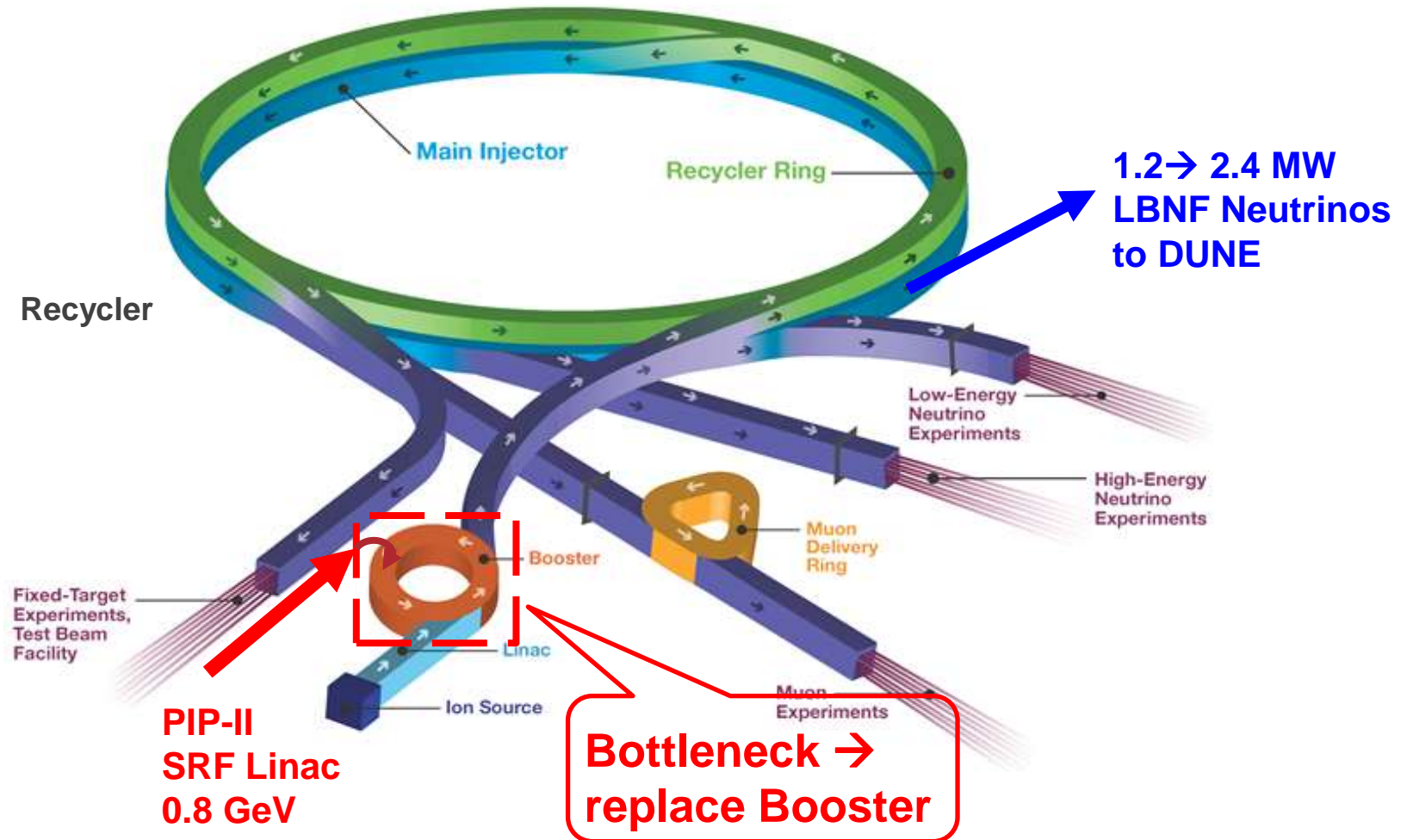
- By 2038: **~ 2.4 MW proton beam** + new near ν -detector + extra 20 kton LAr ν -detector
- Expected to get to $\sim 5\sigma$ in δ_{CP} in the following 6 years



<https://arxiv.org/abs/2203.06100>

2.4 MW Upgrade Challenge

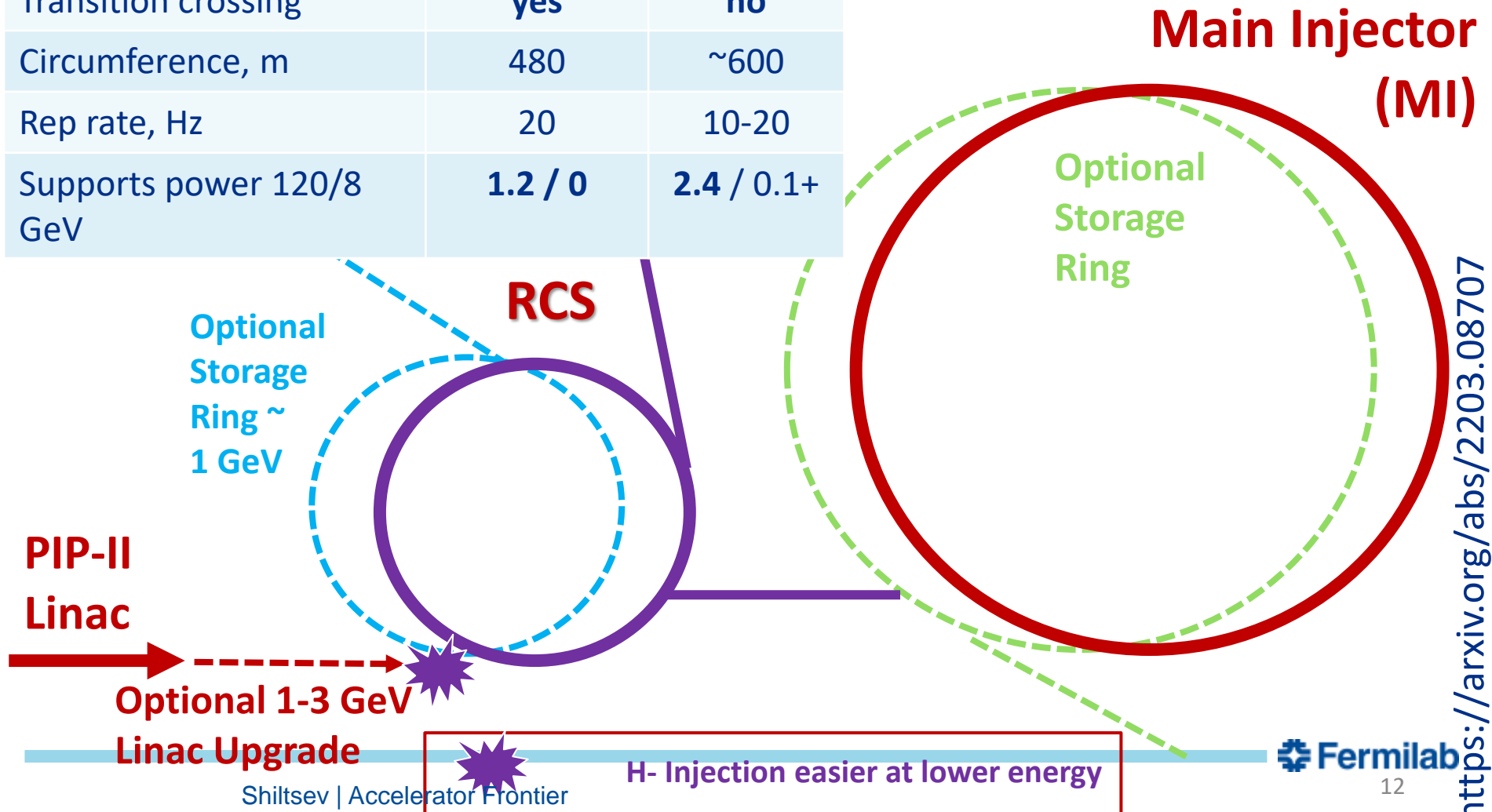
Fermilab Accelerator Complex



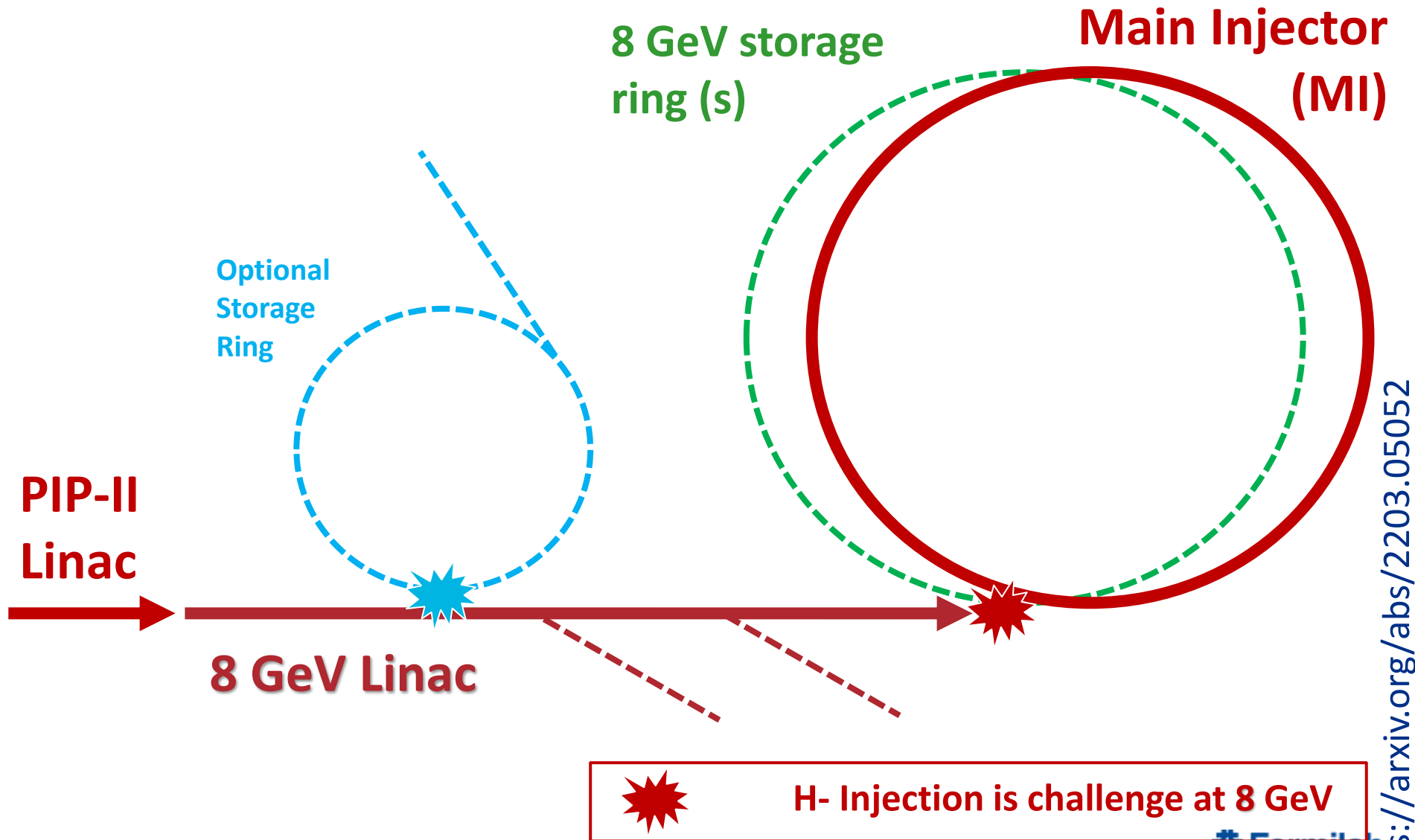
Booster prevents x2 PIP-II power: injection energy and transition-crossing limits

2.4 MW: Rapid-Cycling Synchrotron (RCS) Option

	8 GeV Booster	8 GeV RCS
Injection energy, GeV	0.8	1-3
Transition crossing	yes	no
Circumference, m	480	~600
Rep rate, Hz	20	10-20
Supports power 120/8 GeV	1.2 / 0	2.4 / 0.1+

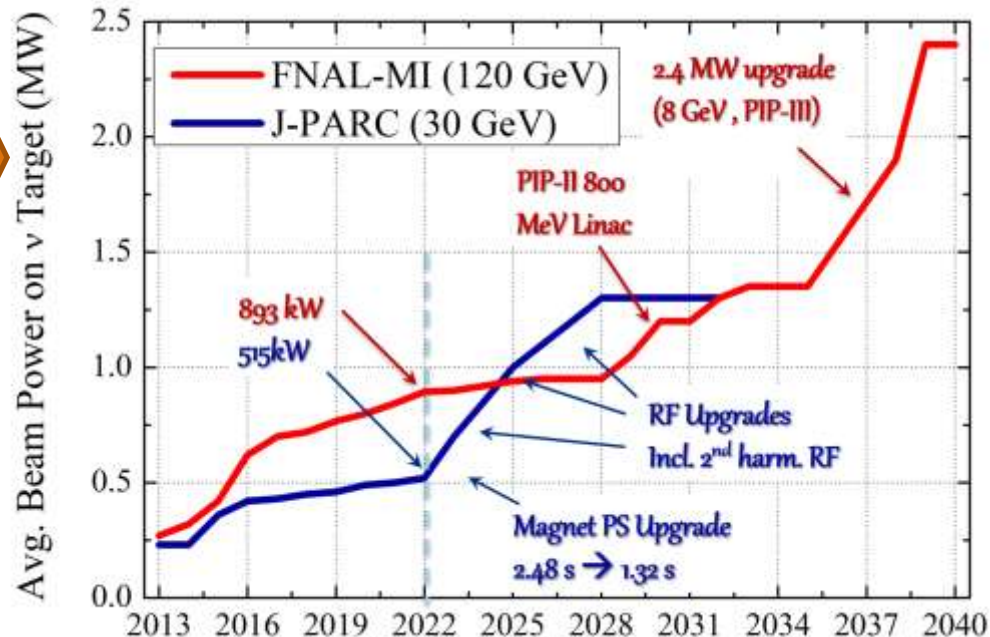


Path to 2.4 MW: 8 GeV Linac Option



2.4 MW Upgrade: Challenges

- ❖ Competition with Hyper-K / J-PARC
- ❖ Short timeline, design Q:
 - ❖ Other spigots ($\mu 2e$ -II, DM and RPF, MuCollider)
- ❖ Cost challenge
- ❖ The rest of the complex
 - ❖ Main Injector RF upgrade
 - ❖ 2.4 MW target R&D
- ❖ Performance risk (beam losses):
 - ❖ Instabilities
 - ❖ Injection, collimation
 - ❖ Space-charge effects
 - ❖ IOTA-ring p R&D



Nov.17, 2022

NUMI horn 0 space-charge dominated

State of Large-Scale Facilities

- LBNF / DUNE Phase 1 will continue until early 2030's
- At that point, US could pursue LBNF Phase 2 or Energy Frontier
 - Multiple global options exist for Higgs factories that could be constructed: (ILC, FCC-ee, CEPC, CLIC)
 - Interest in mid-TeV colliders has declined but 10+ TeV is important
 - Environmental efficiency (carbon footprint) is increasingly important
 - LBNF Phase 2 would provide infrastructure for strong Muon Collider R&D program
 - Technology development is providing potential improvements, e.g. C^3 , HELEN, High Q_0 SRF, High η RF, ... but need accelerator designs
- European and Asian milestones will impact US choices
- Technology and physics R&D is progressing and will provide options for accelerators in future decades

*#2 Colliders: Higgs/EW
Factories and Energy Frontier
(≥ 10 TeV cme parton)*

Implementation Task Force

<https://arxiv.org/abs/2208.06030>

- The Accelerator Frontier **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider projects:
 - Higgs/EW factories
 - Lepton colliders with 3 TeV cme
 - Lepton and hh colliders 10+ TeV cme parton
 - FNAL site-fillers and eh colliders
- ITF addressed (four subgroups):
 - Physics reach (impact), beam parameters
 - Size, complexity, power, environment
 - Technical risk, readiness, and R&D required
 - Cost and schedule



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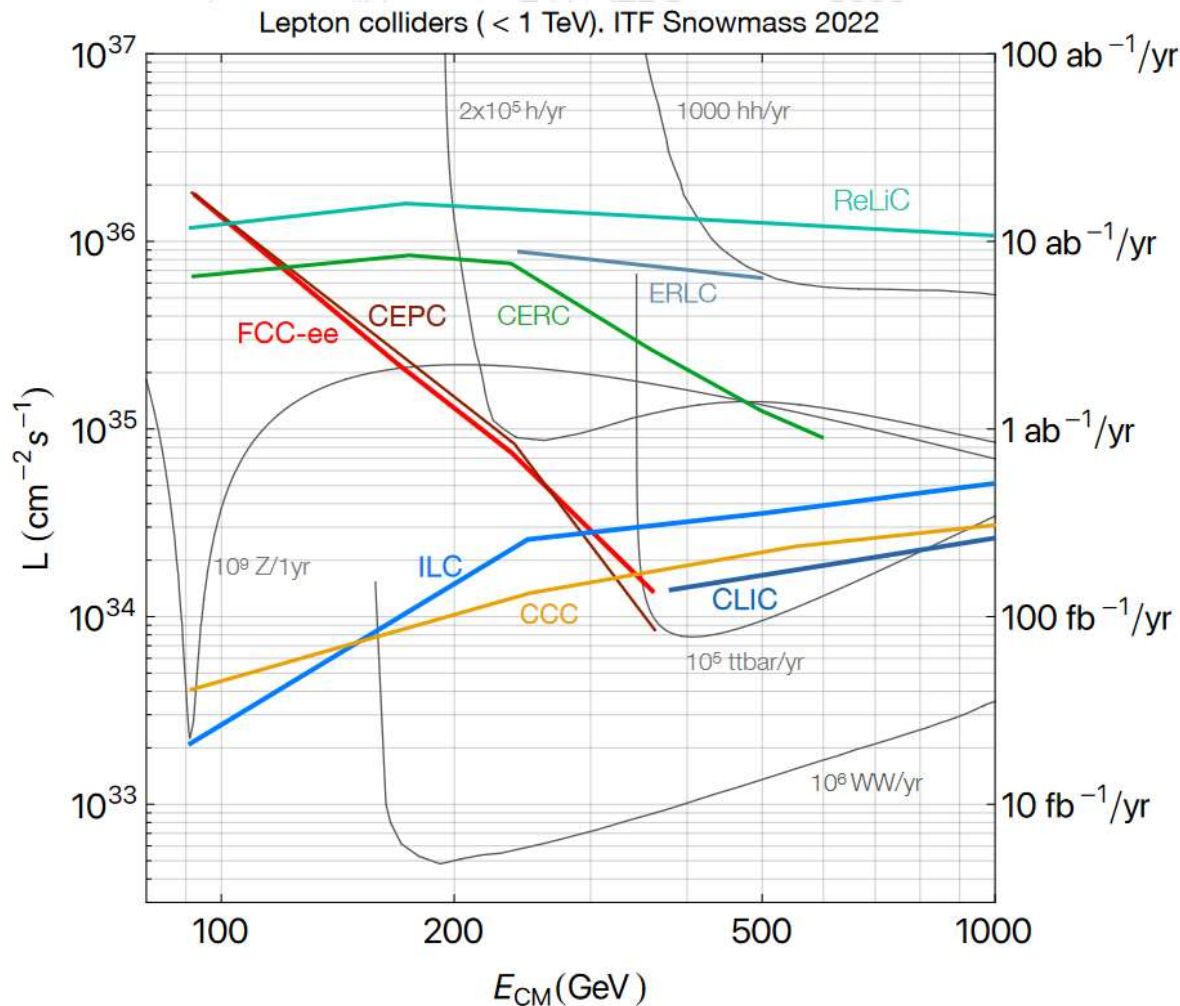


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ITF on Collider Physics: Higgs/EW

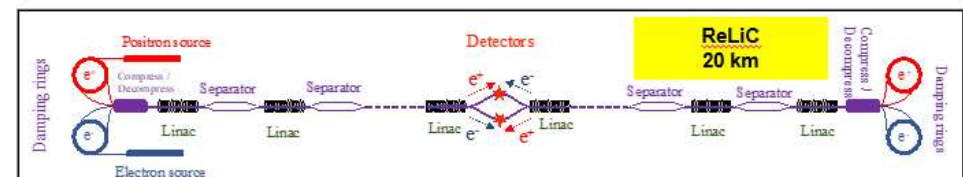
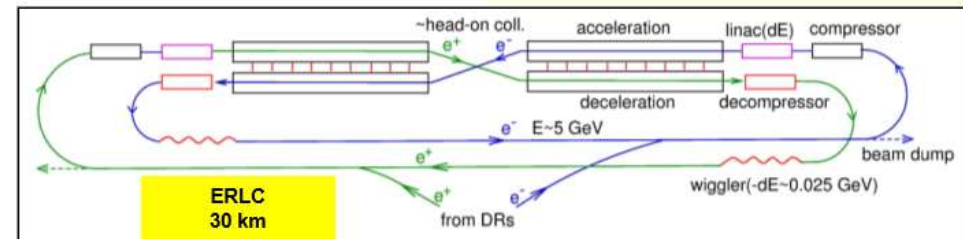
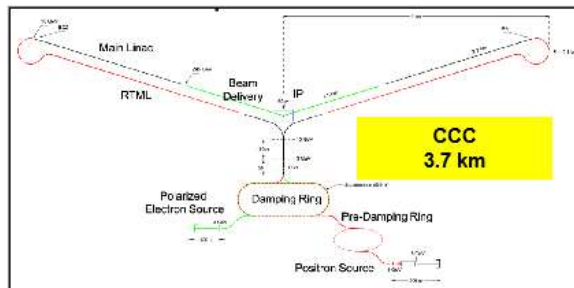
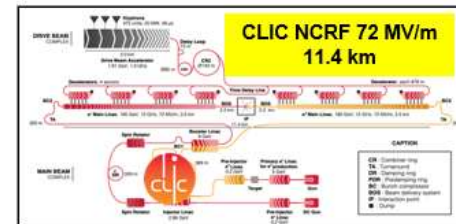
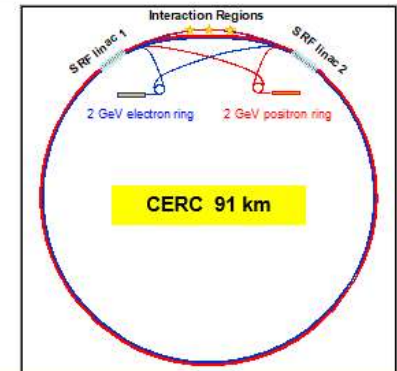
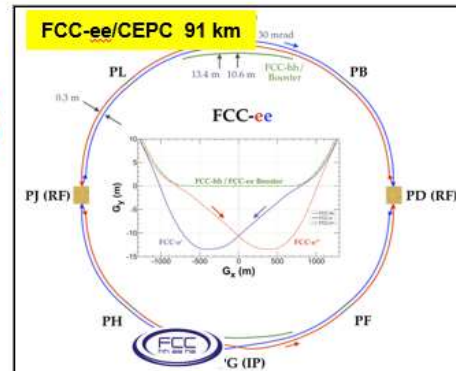


Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10Ms). Also shown are lines corresponding to yearly production rates of important processes.

Proposals – Higgs/EW Physics

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





HELEN

A map of the Fermi National Accelerator Laboratory (Fermilab) complex. The main area is outlined in green and labeled "Fermi National Accelerator Laboratory". A blue line representing the "TW SRF Linac" runs vertically through the center. A yellow square at the top of this line is labeled "Interaction Region". Two labels "BDS" (Beam Delivery System) are placed along the linac, one above and one below the interaction region. The map includes surrounding roads, green spaces, and water bodies. A scale bar at the bottom right indicates "1 km". The Google logo is visible at the bottom center.

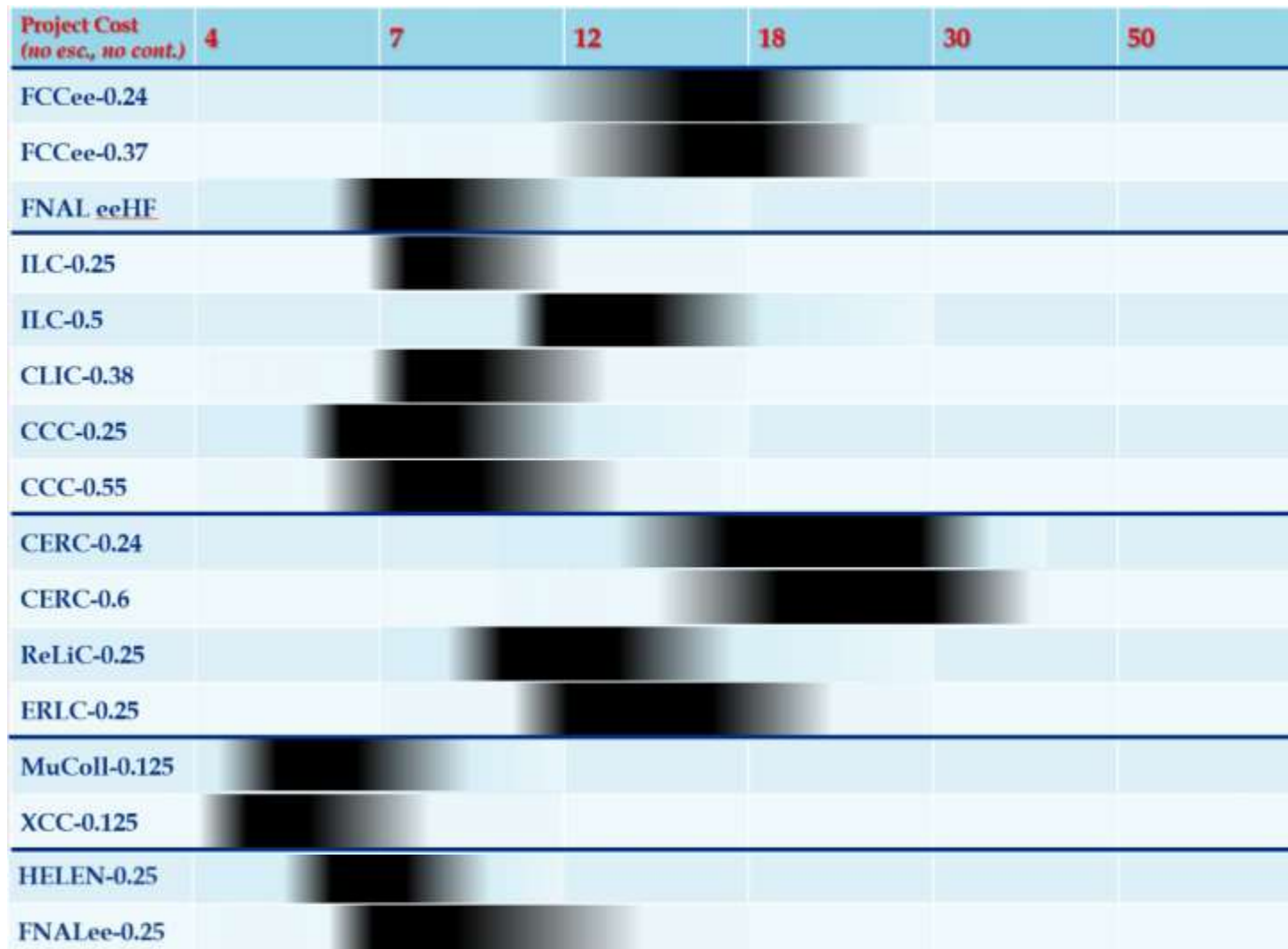


Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, [arXiv:2208.06030](https://arxiv.org/abs/2208.06030)

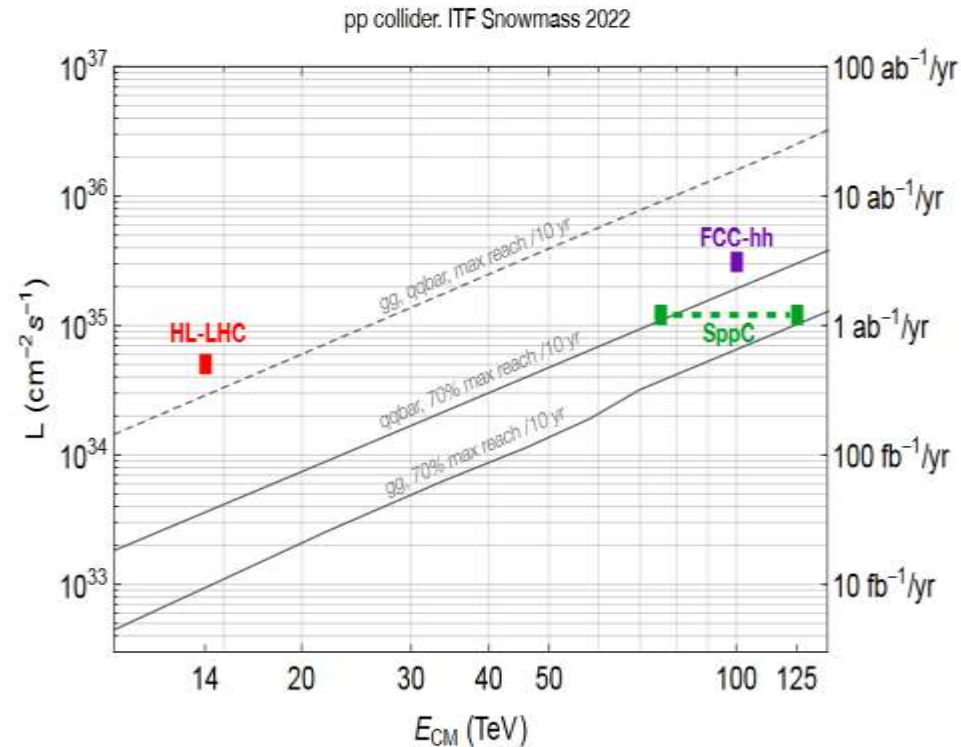
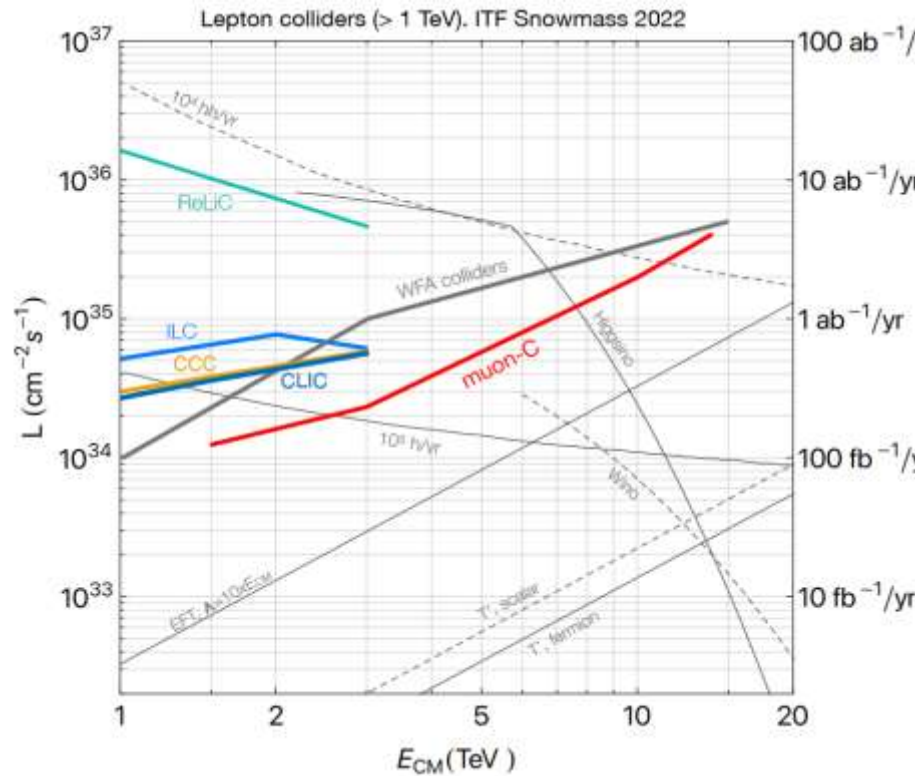
		CME (TeV)	Lumi per IP@ Higgs (10 ³⁴)	Years, pre- project R&D	Years to 1 st Physics	Cost Range (2021 B\$)	Electric Power (MW)
Circular e^+e^-	FCCee (4 IPs)	0.24	7.7	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear e^+e^-	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C ³	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s-chan	XCC- $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
	$\mu\mu$ -Higgs	0.13	0.01	>10 ²¹	19-24	4-7	200

Higgs Factories Costs: Nuances



30-parameter ITF cost model. 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.

ITF on Collider Physics: Energy Frontier

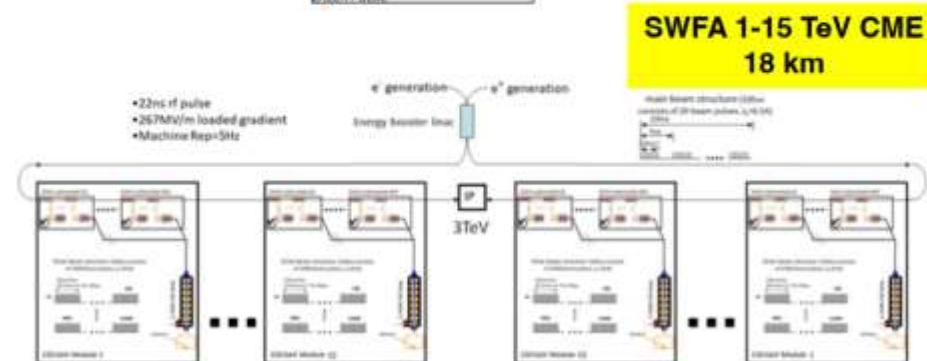
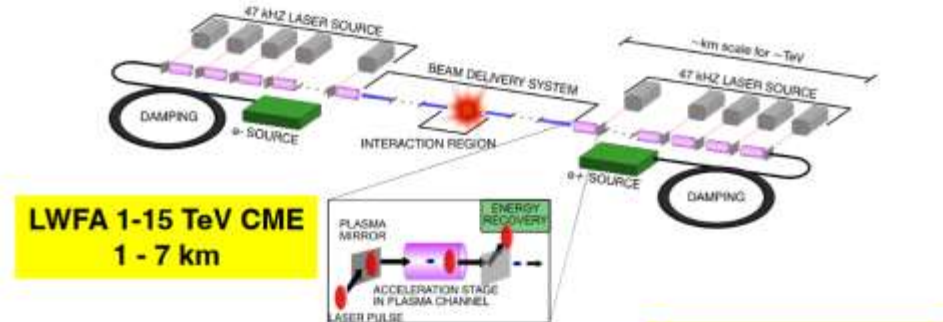
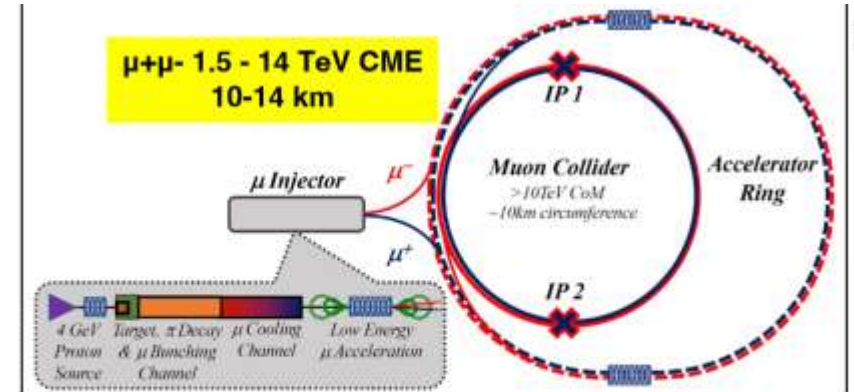
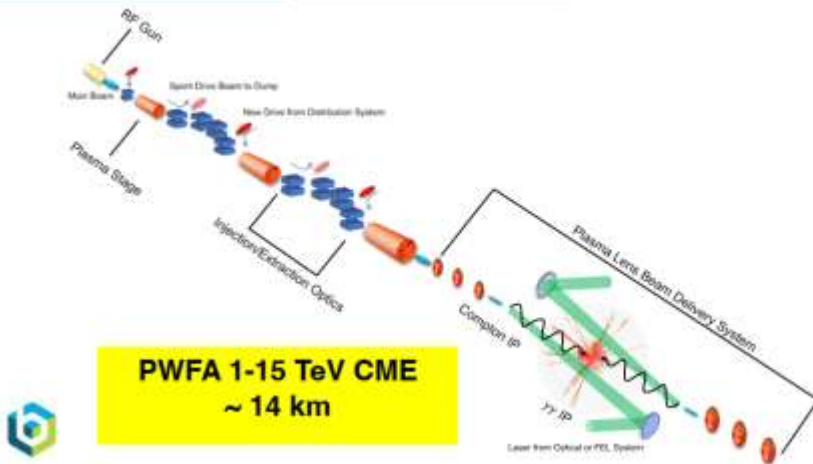


Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10Ms). For lepton colliders: shown are the luminosity requirement for 5σ discoveries of the benchmark DM scenarios Higgsino and Wino. For hadron colliders: shown are the luminosity requirements with two possible initial states gg and qq : 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

Proposals – Multi-TeV Lepton Colliders

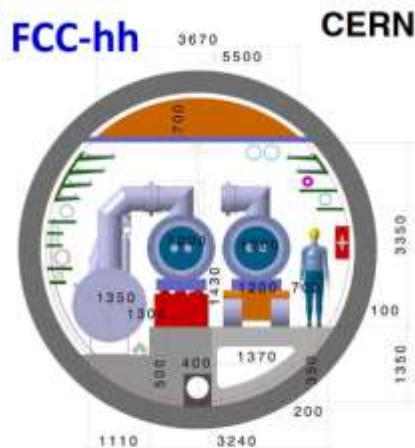
High energy lepton collider concepts(8)

Name	CM energy range
High Energy ILC	e^+e^- , $\sqrt{s} = 1 - 3$ TeV
High Energy CLIC	e^+e^- , $\sqrt{s} = 1.5 - 3$ TeV
High Energy CCC	e^+e^- , $\sqrt{s} = 1 - 3$ TeV
High Energy ReLIC	e^+e^- , $\sqrt{s} = 1 - 3$ TeV
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

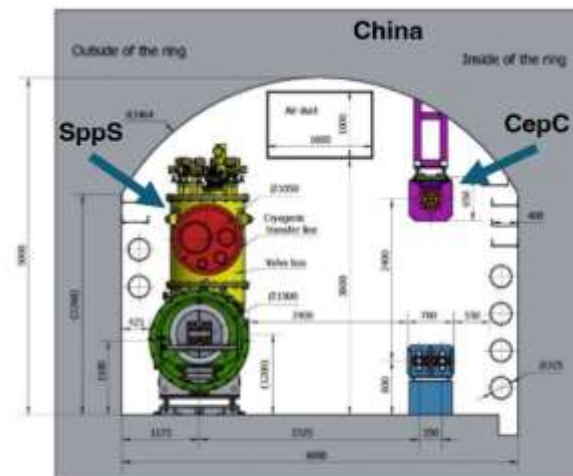


Proposals – Multi-TeV *hh* and *eh* colliders

Name	CM energy range
FCC-hh	$pp, \sqrt{s} = 100 \text{ TeV}$
SPPC	$pp, \sqrt{s} = 75 - 125 \text{ TeV}$
Collider-in-Sea	$pp, \sqrt{s} = 500 \text{ TeV}$
LHeC	$ep, \sqrt{s} = 1.2 \text{ TeV}$
FCC-eh	$ep, \sqrt{s} = 3.5 \text{ TeV}$
CEPC-SPPC-ep	$ep, \sqrt{s} = 5.5 \text{ TeV}$



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



SPPC 125 TeV, 20 T magnets, 110 km

ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10 ³⁴)	Years, pre- project R&D	Years to 1 st Physics	Cost Range (2021 B\$)	Electric Power (MW)
FCCEE-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10 ²⁷	>25	>80	»1000

Luminosity per Power

Circular *ee*

ERL based *ee*

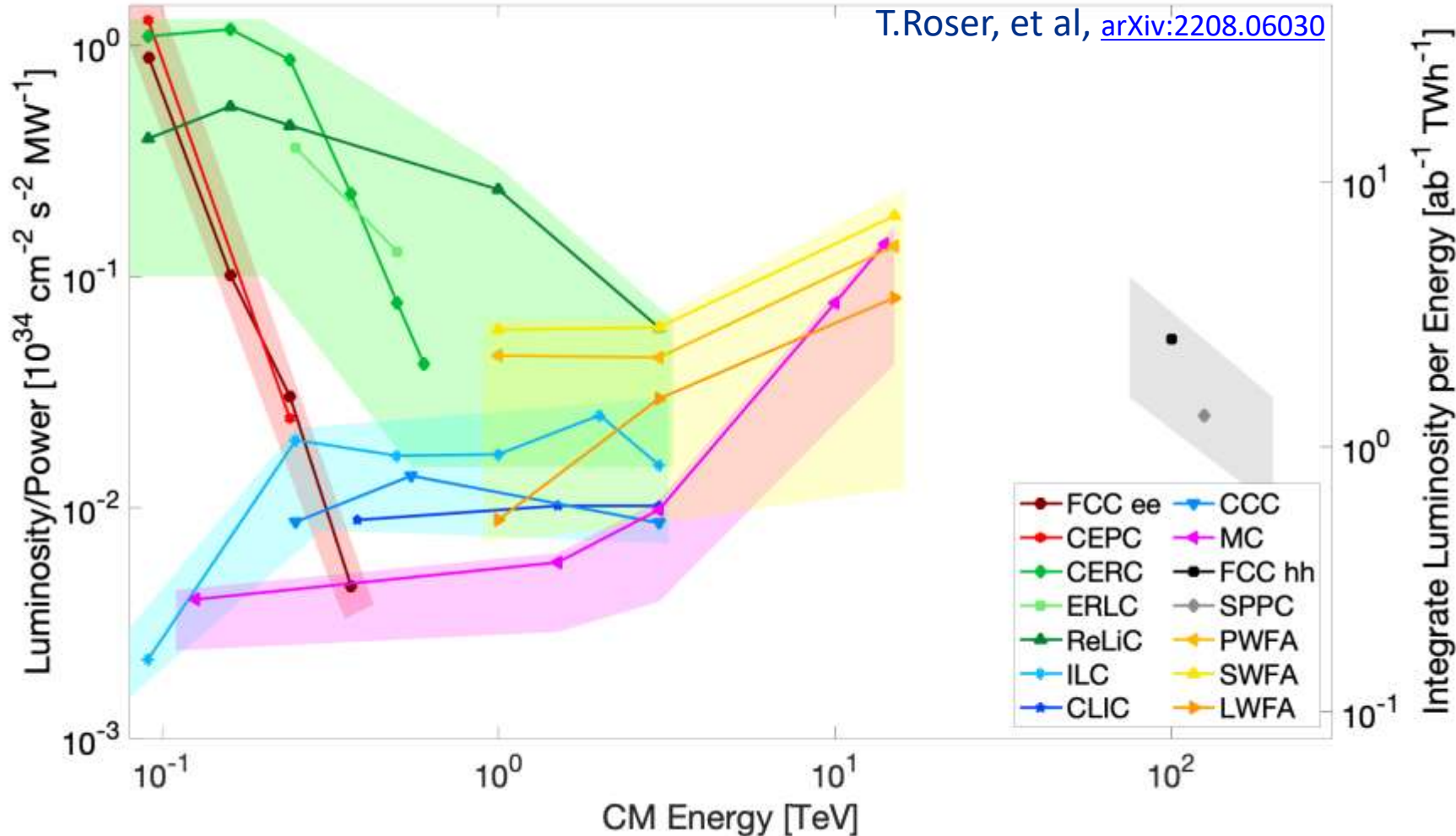
Linear *ee*

Muon coll

Wakefield

Hadron *pp*

T.Roser, et al, [arXiv:2208.06030](https://arxiv.org/abs/2208.06030)

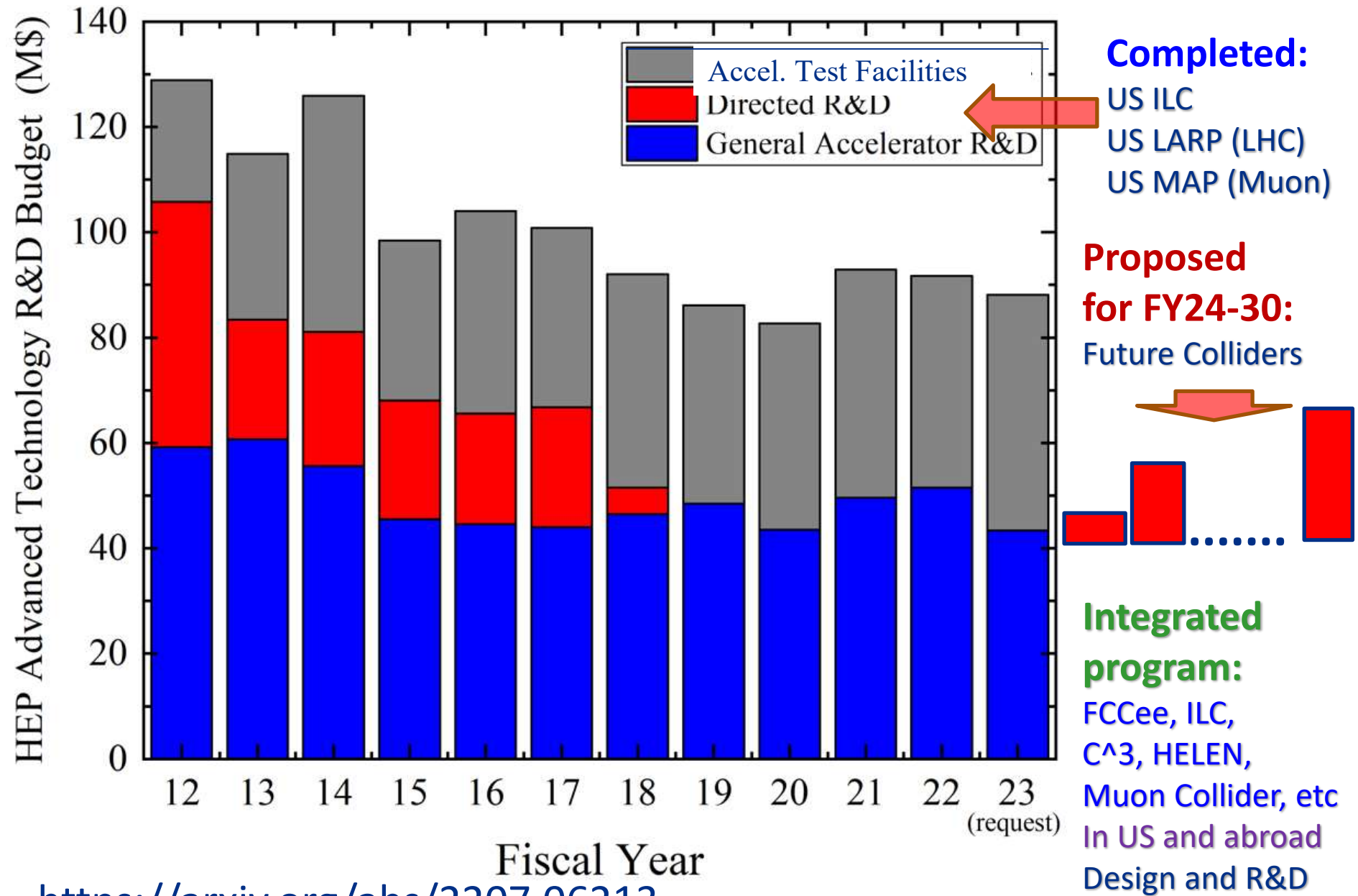


Luminosity is per IP, Integrated luminosity assumes $1e7$ seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

AF Messages for Large-Scale Facilities

- Options for the next US engagement include Intensity or Energy frontier
- We need **an integrated future collider R&D program** (a focused R&D program in OHEP) to engage in the design and to coordinate the development of next generation collider projects such as: *ILC, CLIC, FCCee, CCC/HELEN, multi-TeV Muon Collider*.
- We have and need to keep **an active R&D program** in labs and universities aimed at general accelerator R&D that is critical in developing technologies and options for future HEP accelerators (but does not develop accelerator proposals).

Future Colliders R&D Program - Initiative



Accelerator R&D for HEP: Next Decade

Multi-MW targets:

- 2.4 MW for PIP-III
- 4-8 MW for muon collider

Magnets for colliders and RCSs:

- 16T dipoles
- 40T solenoids
- 1000 T/s fast cycling ones
- ...coordinated with US MDP

Accelerator & Beam Physics

- High intensity/brightness beams acceleration and control
- High performance computer modeling and AI/ML approaches
- Design integration and optimization, incl energy efficiency

Wakefields:

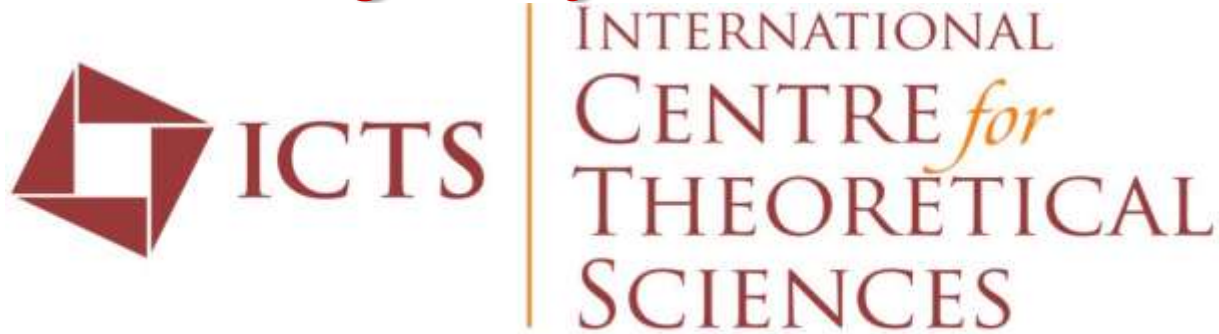
- collider quality beams
- efficient drivers and staging
- close coordination with Int'l (Euro Roadmap, EUPRAXIA,..)

SC/NC RF:

- 70-120 MV/m C³
- 70 MV/m TW SRF
- new materials, high Q_0
- efficient RF sources



Thanks for your attention!



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- AF Report is at [arxiv:2209.14136](https://arxiv.org/abs/2209.14136), tons of material (all reports, etc) available at:
<https://snowmass21.org/accelerator/>