Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Snowmass 2021

Snowmass'21 Accelerator Frontier

Planning for Future

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

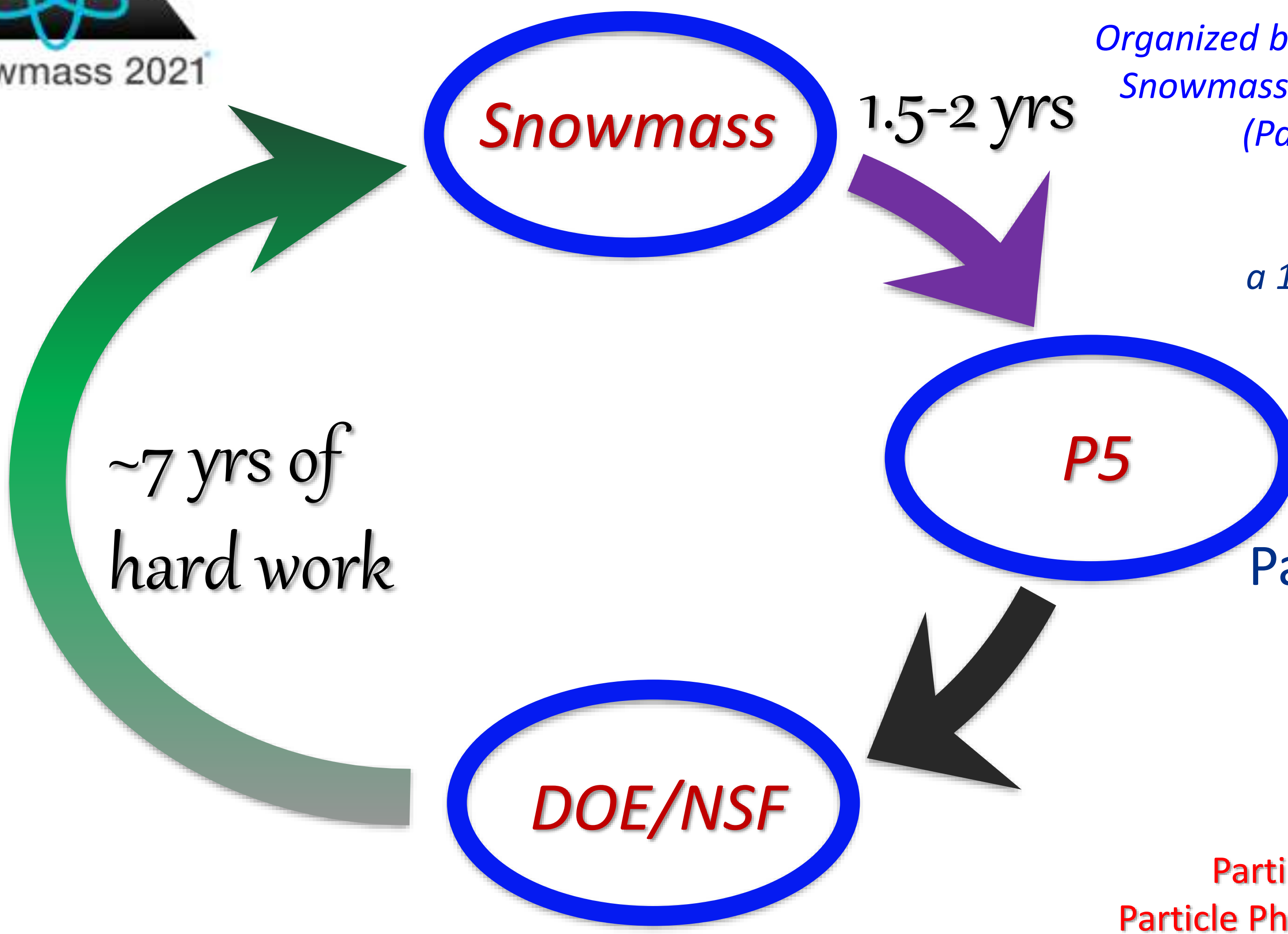
Vladimir Shiltsev (Fermilab)

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

ICTS | INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

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

Snowmass 2021



Organized by APS DPF, DPB, et al
Snowmass provides input to P5
(Particle Physics Project
Prioritization Panel)
which develops
a 10-20 yrs strategy for
the US HEP program

~ 1 yr

Particle Physics Project Prioritization Panel

Particle Physics is global
Particle Physics is not isolated

https://www.snowmass21.org/

Snowmass'21 Accelerator Frontier Conveners

Steve Gourlay
(LBNL)

Tor Raubenheimer
(SLAC)

Vladimir Shiltsev
(FNAL)

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/Bejing, 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 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

#1 Accelerators for Neutrinos and Rare Processes

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

PIP-II Injector Test

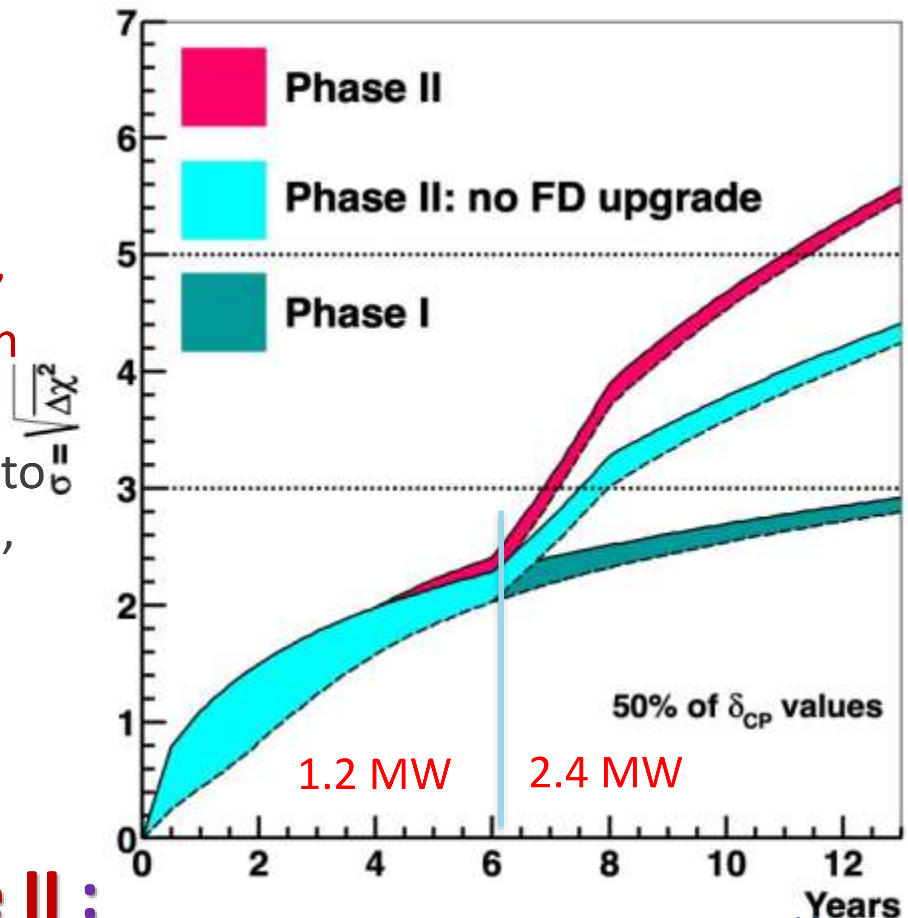
HWR CM

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 ~3σ in δ_{CP}, in the first 6 years (also Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$)
- To get to ~5σ will take too long, plus – competitor experiment *Hyper-K* in Japan (30 GeV J-PARC *p* beam)

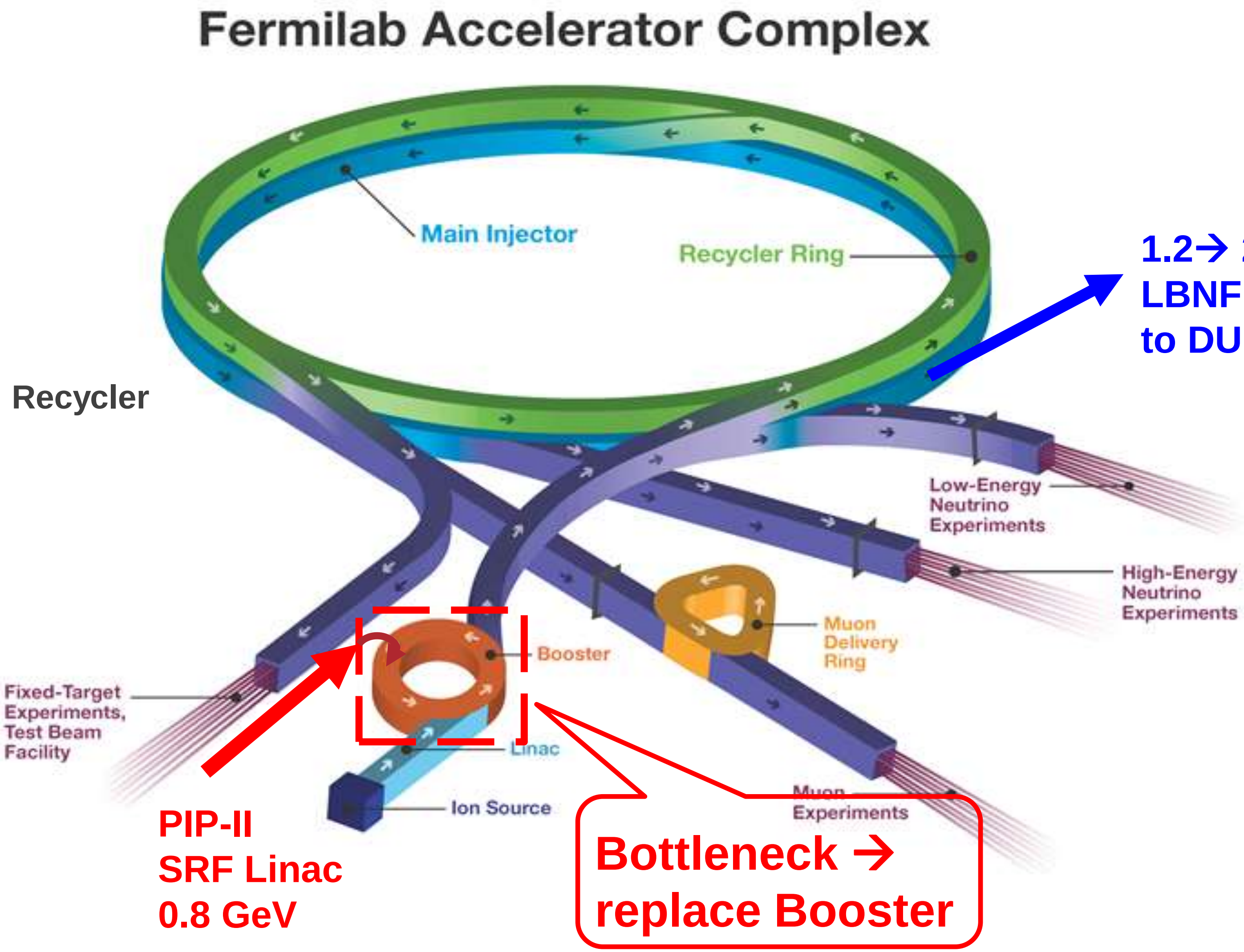


https://arxiv.org/abs/2203.06100

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 ~5σ in δ_{CP} in the following 6 years

2.4 MW Upgrade Challenge

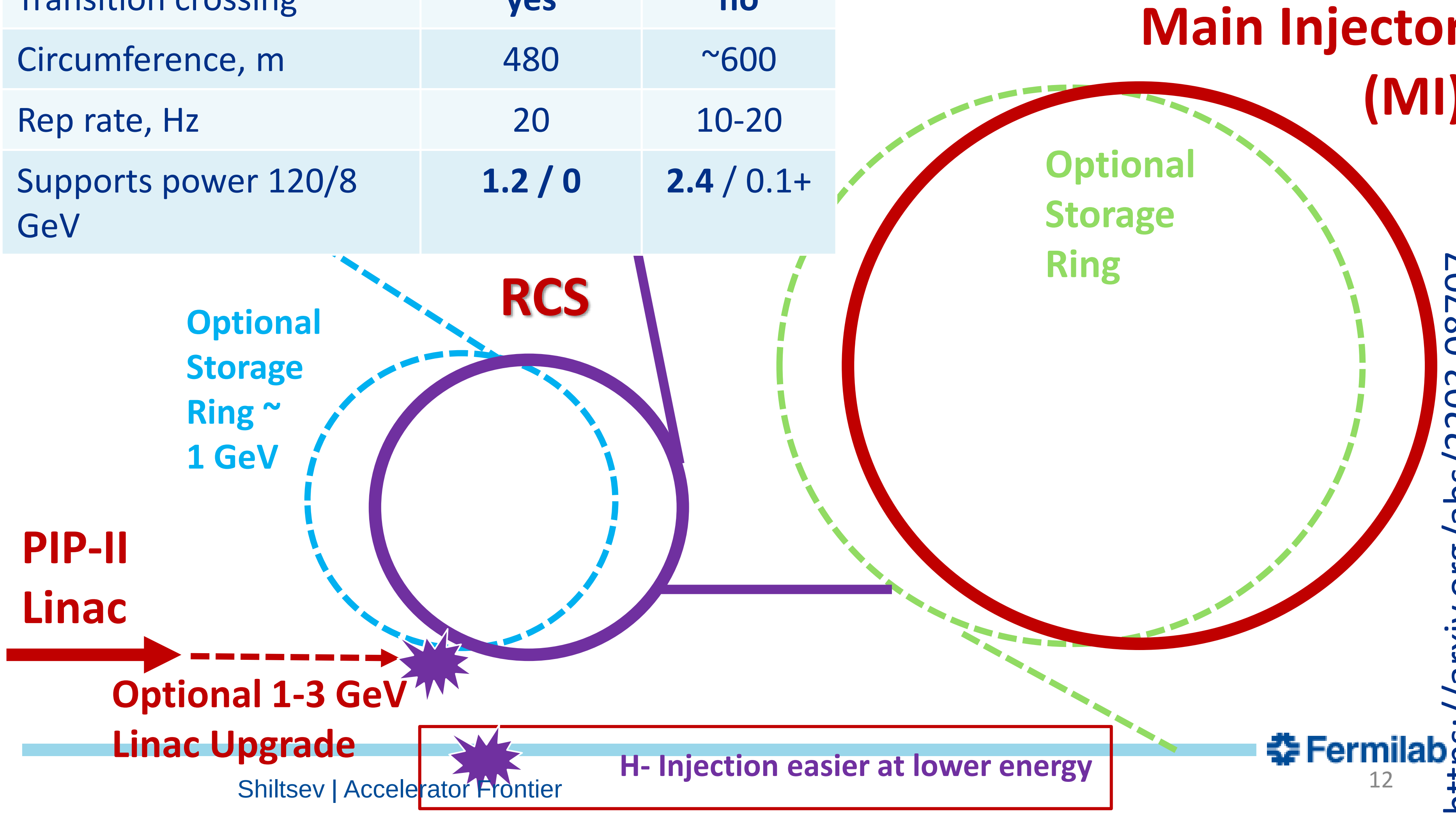


https://arxiv.org/abs/2203.08276

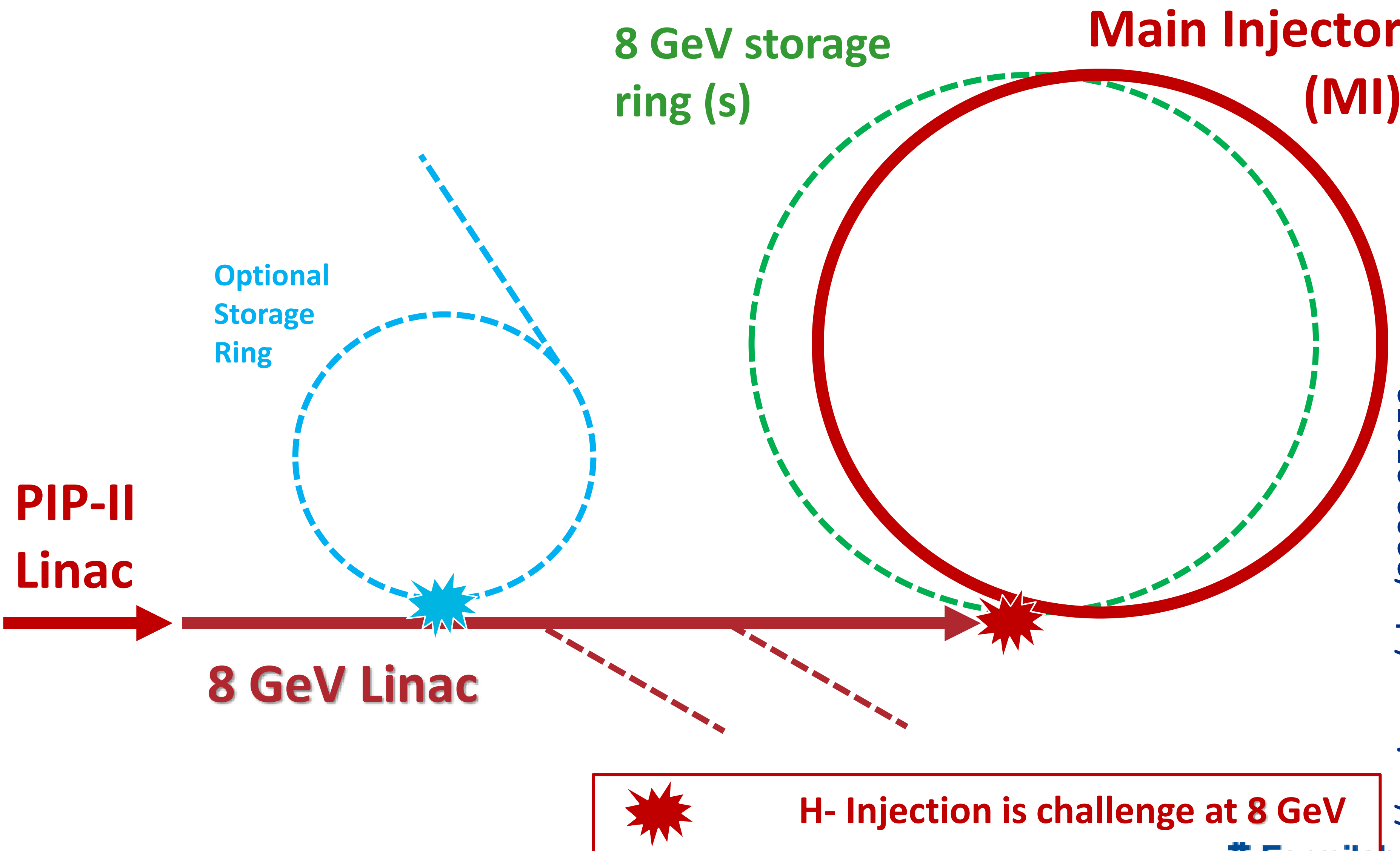
Booster prevents x2 PIP-II power: injection energy and transition-crossing limits

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+

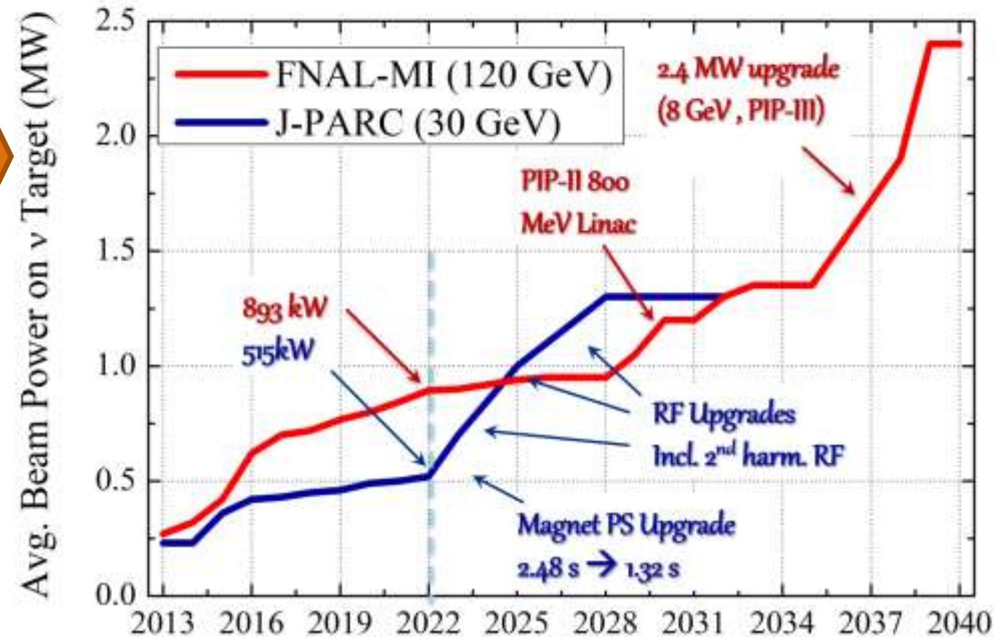


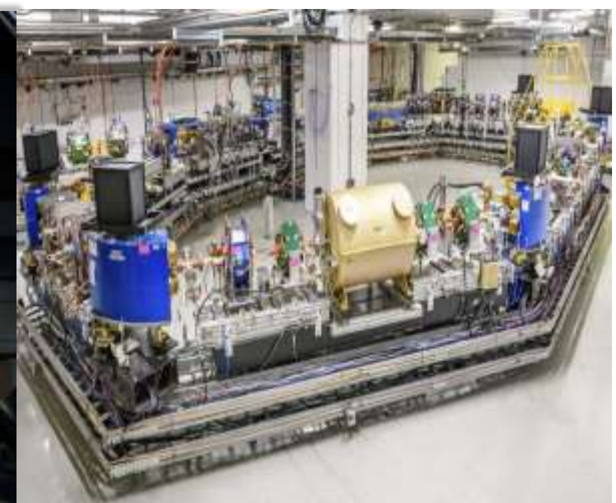
Path to 2.4 MW: 8 GeV Linac Option



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





NUMI horn 0.9MW

Space-charge dominate

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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Katsunobu Oide (KEK)


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REPORT


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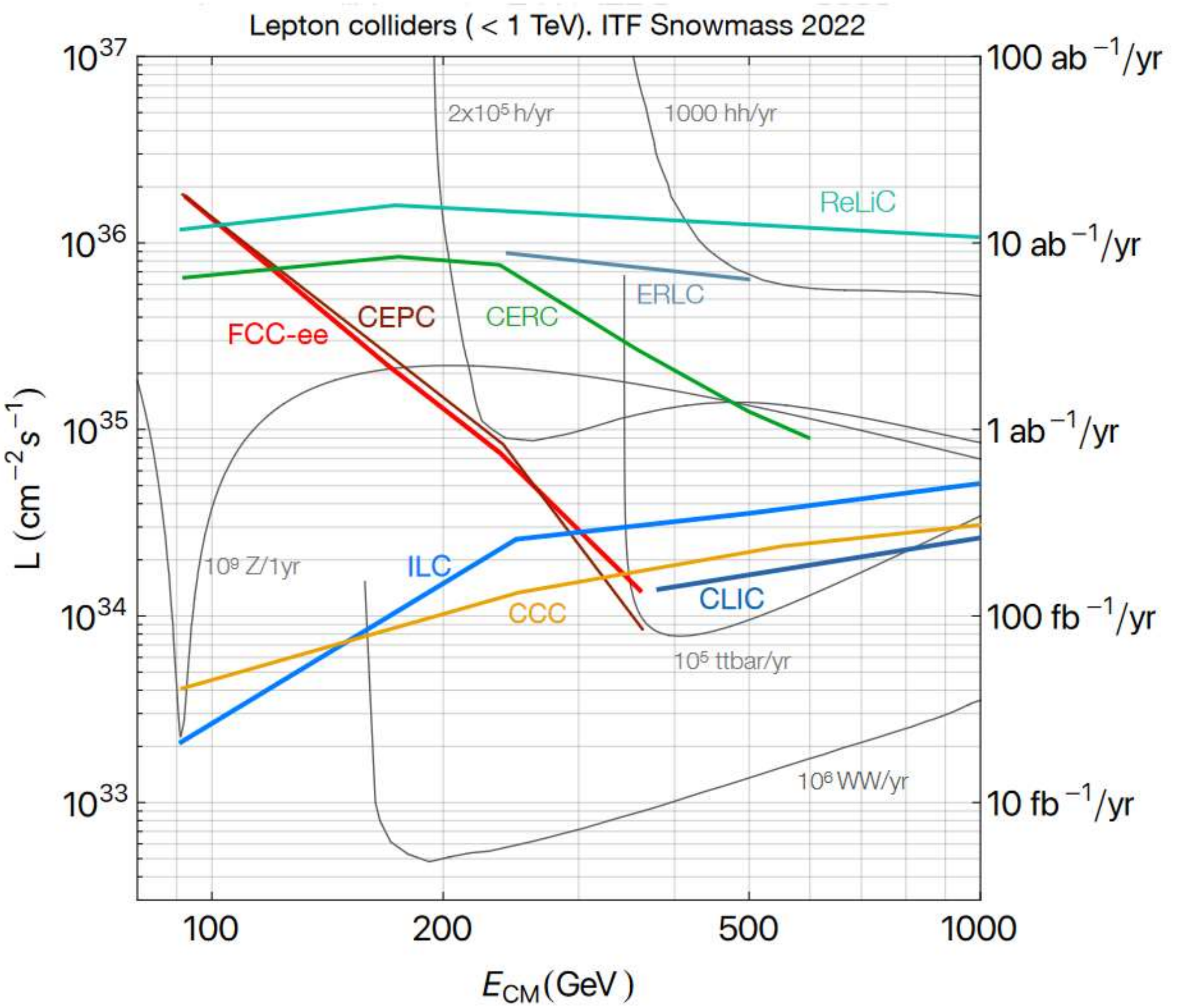
[1] Below I mostly follow T.Roser presentation in Seattle

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.

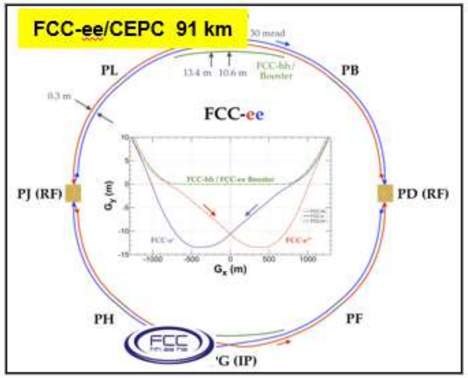
Snowmass 2021

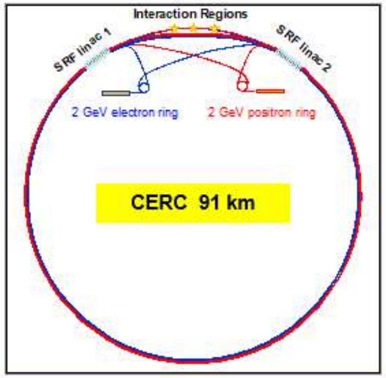
Proposals – Higgs/EW Physics

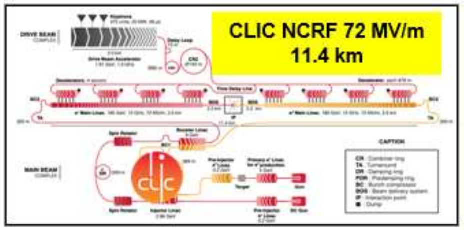
6

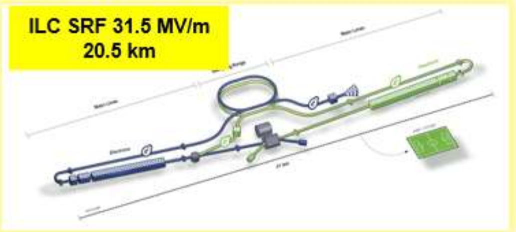
Higgs factory concepts (10)

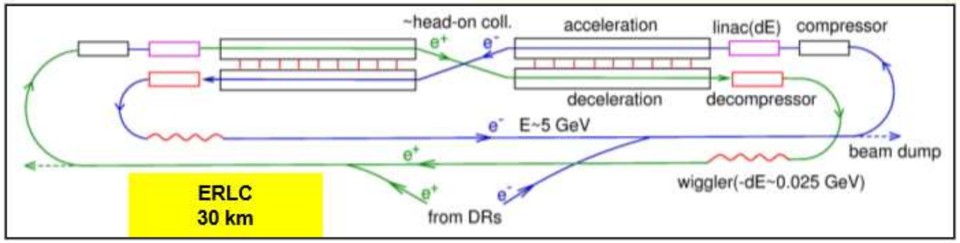
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ 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

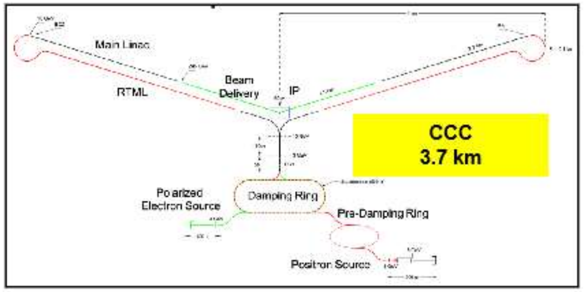


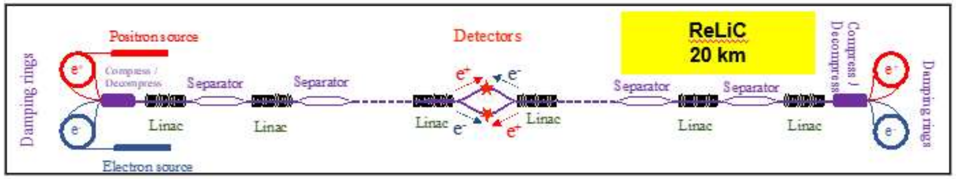






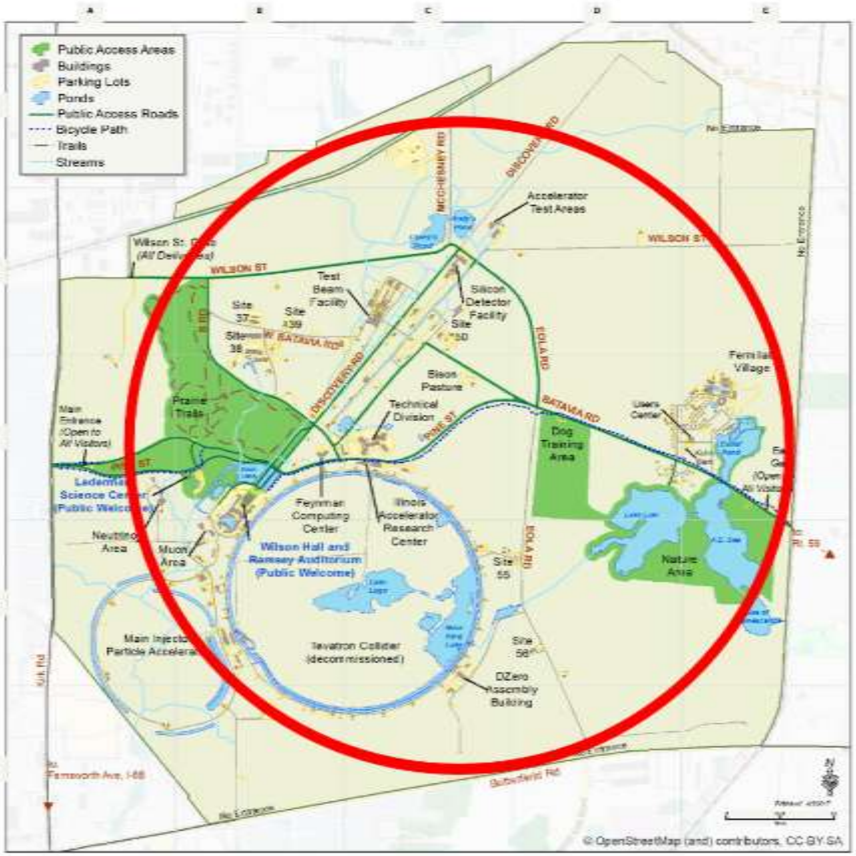






Fermilab

250 GeV cme Fermilab Site-Fillers



16-km collider e+e- ring

https://arxiv.org/abs/2203.08088

CCC

(cool copper collider)

HELEN

(TW SRF collider)

cool- or *SC-RF* e+e- linear colliders
7-km for 250 GeV, 12-km 0.5+ TeV

https://arxiv.org/abs/2203.08211
https://arxiv.org/abs/2110.15800

Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

		CME (TeV)	Lumi per IP@ Higgs (10^34)	Years, pre-project R&D	Years to 1st 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-γγ	0.125	0.1	5-10	19-24	4-7	90
	μμ-Higgs	0.13	0.01	>10	19-24	4-7	200

Higgs Factories Costs: Nuances

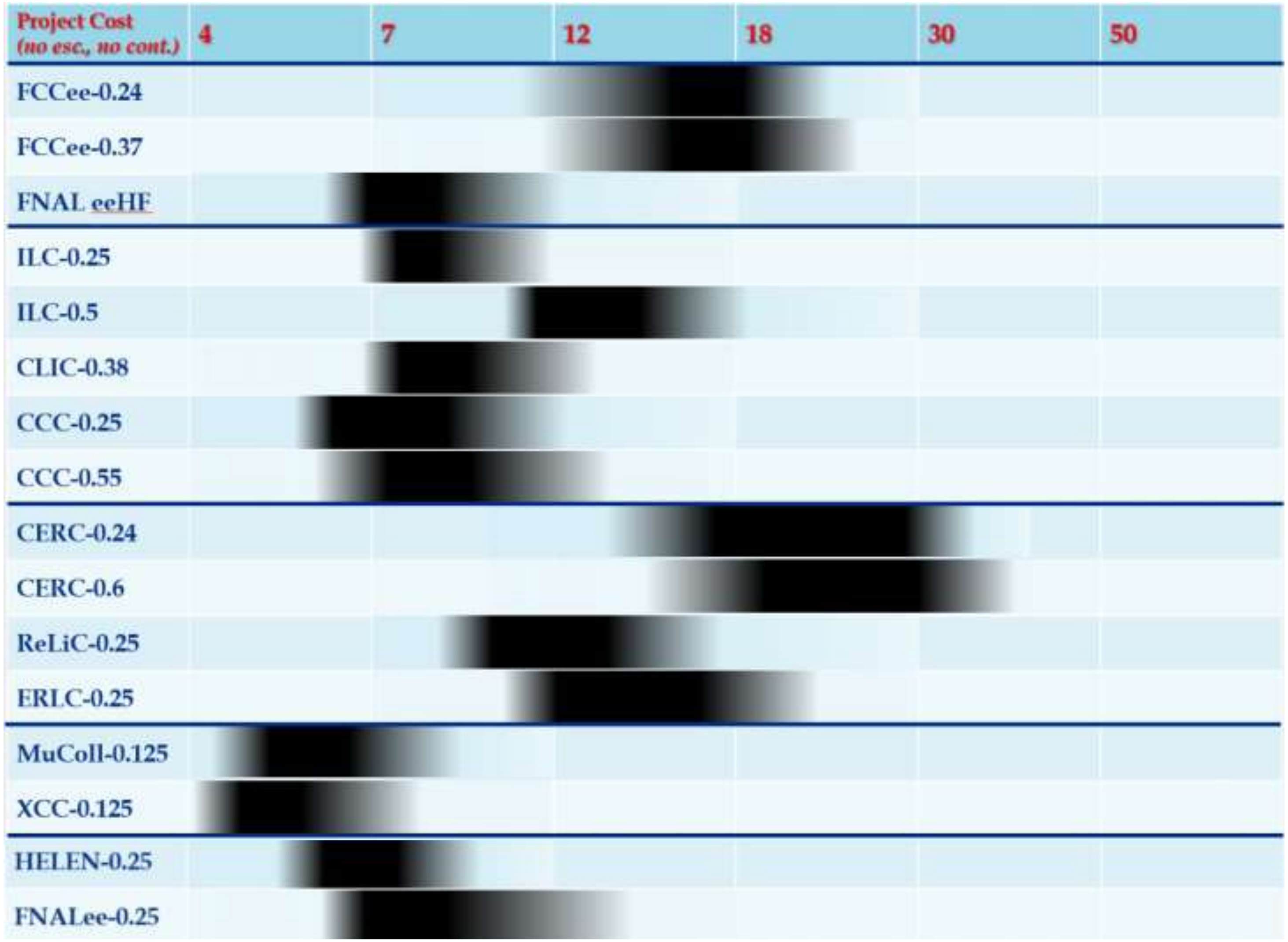
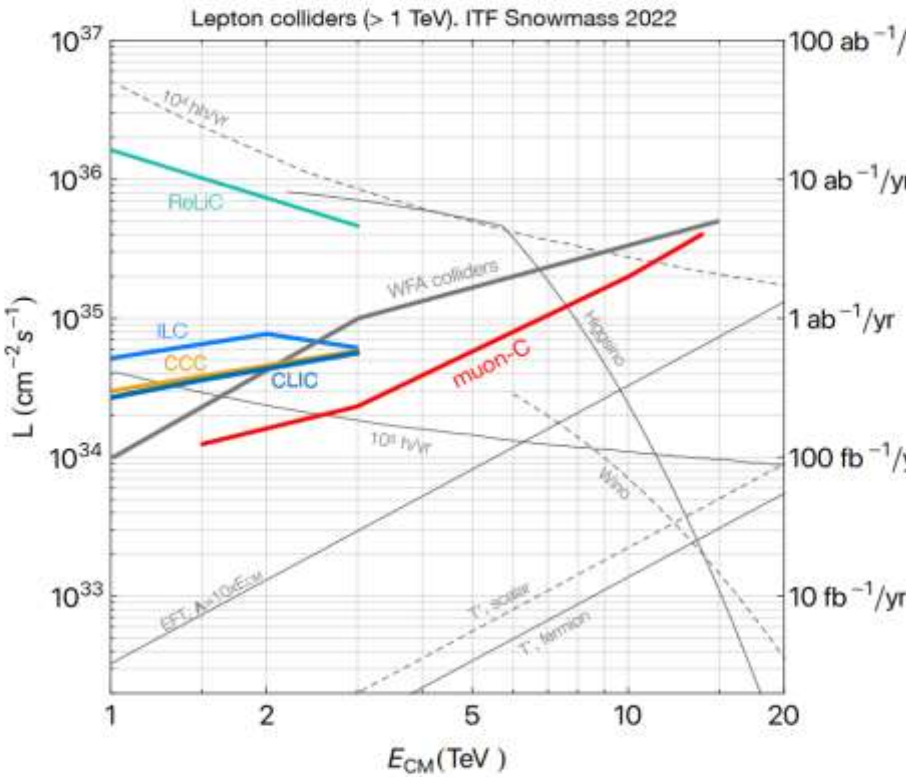
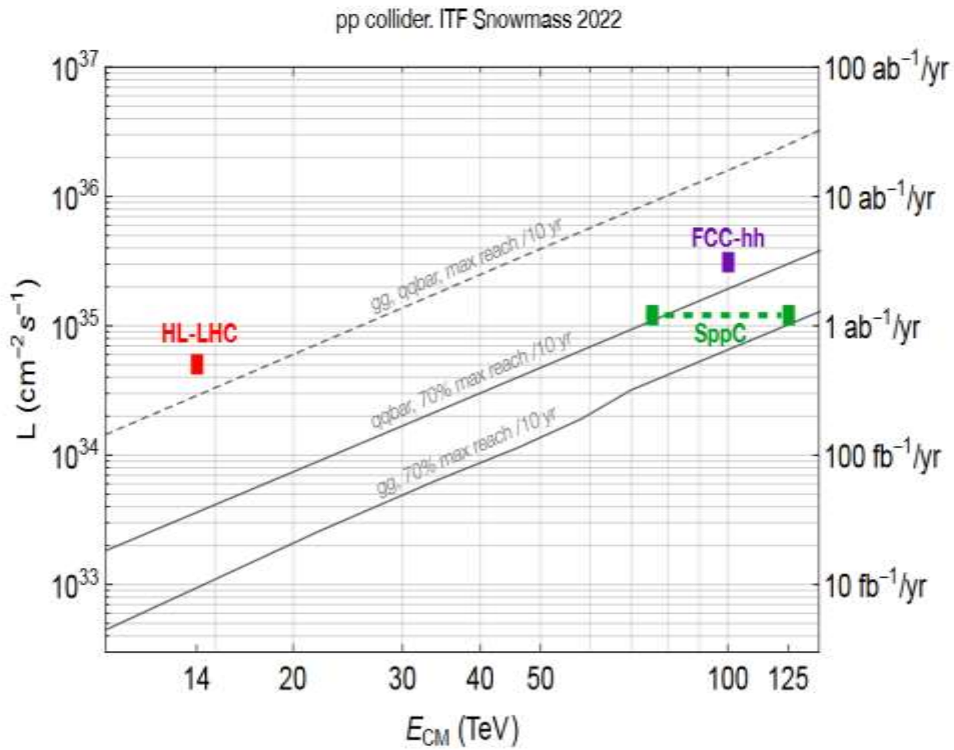


Fig.8 - ITF Report – T.Roser, et al, arXiv:2208.06030

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



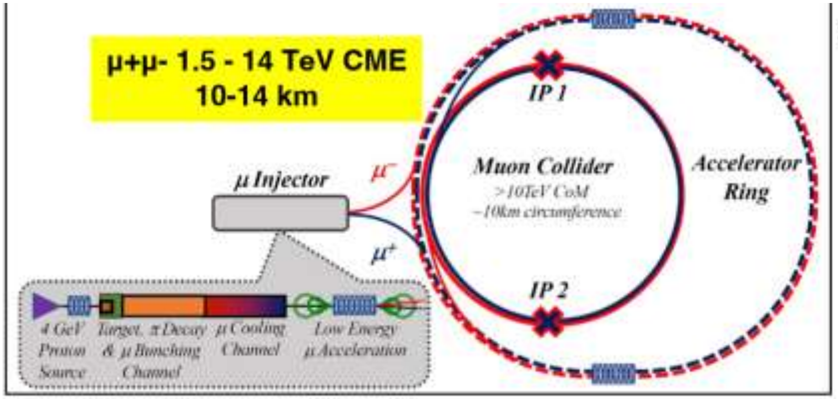


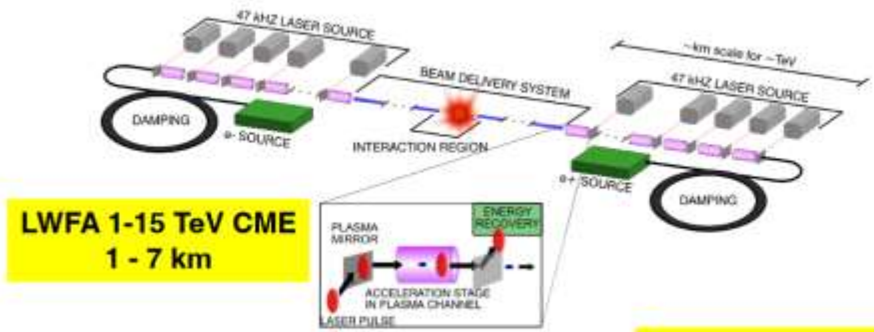
Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10Ms). For lepton colliders: shown are the luminosity requirement for 5σ discoveries of the benchmark DM scenarios Higgsino and Wino. For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

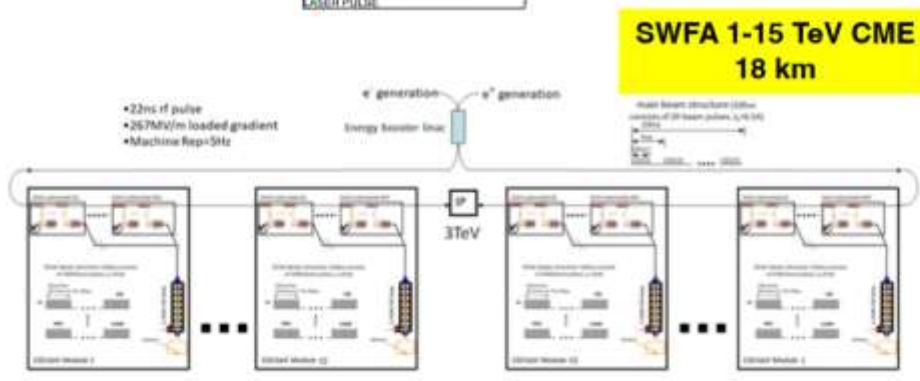
Proposals – Multi-TeV Lepton Colliders

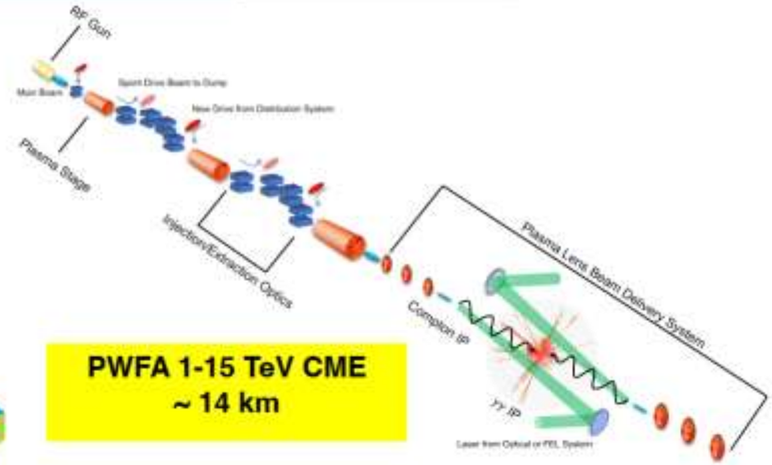
High energy lepton collider concepts(8)

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







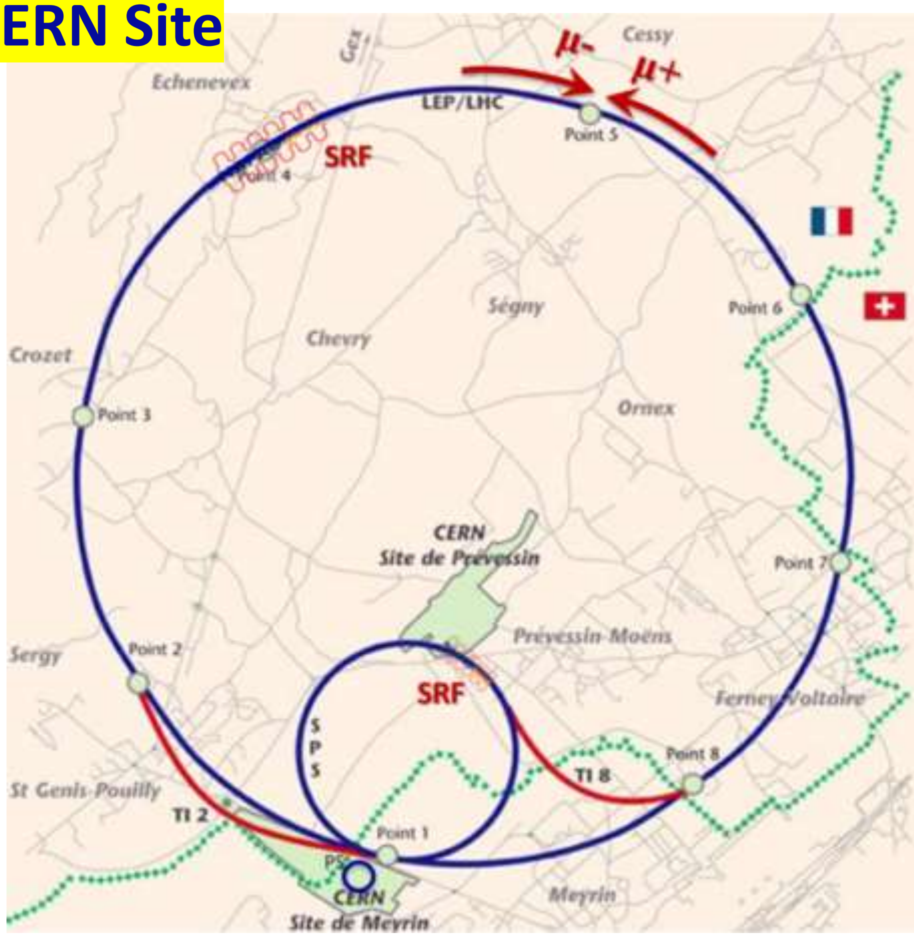


Big Advantage : Re-Use of Infrastructure

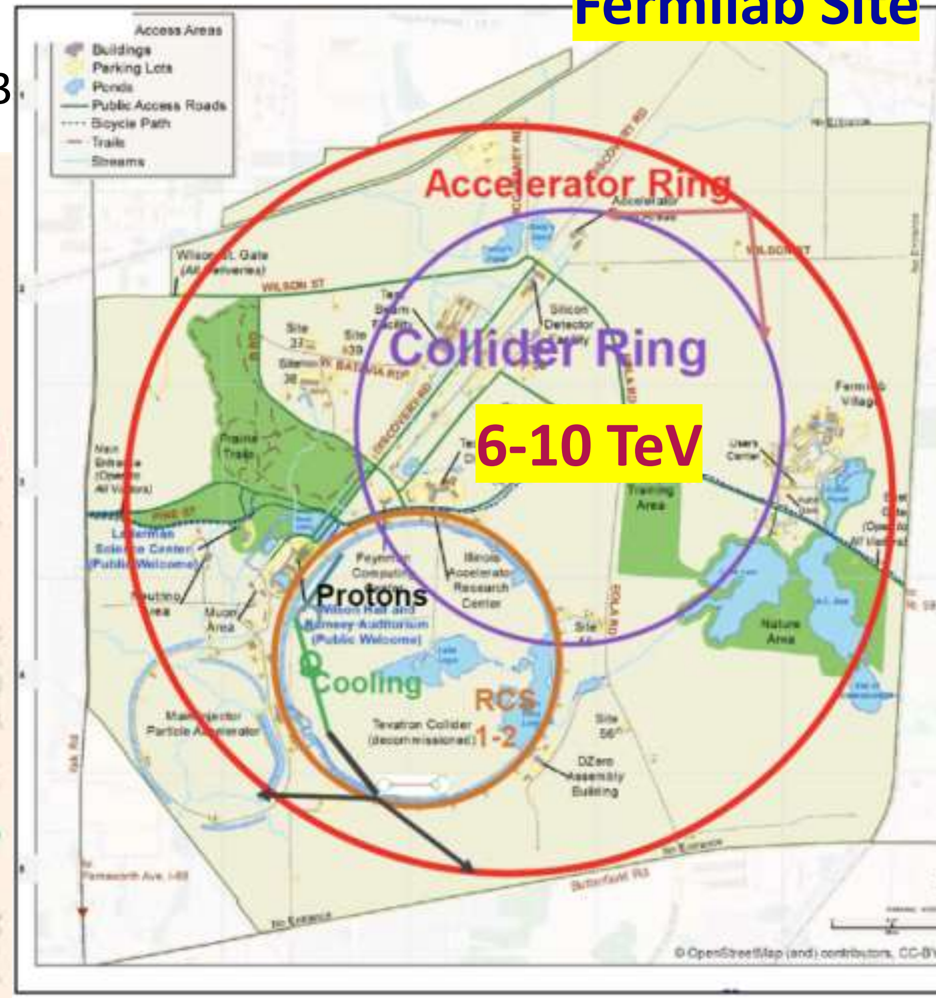
Pulsed 14 TeV MC in LHC Tunnel

D. Neuffer and V. Shiltsev 2018 *JINST* **13** T10003

CERN Site



Fermilab Site



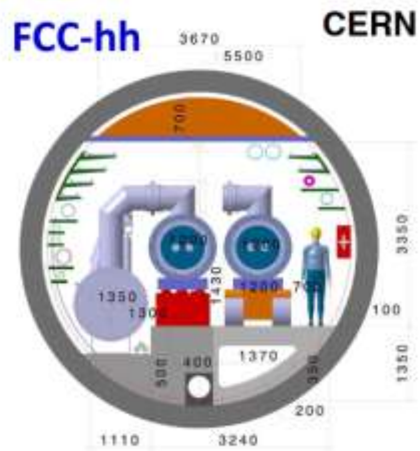
6-10 TeV FNAL Muon Collider

P. Bhat, et al, arXiv: 2203.08088

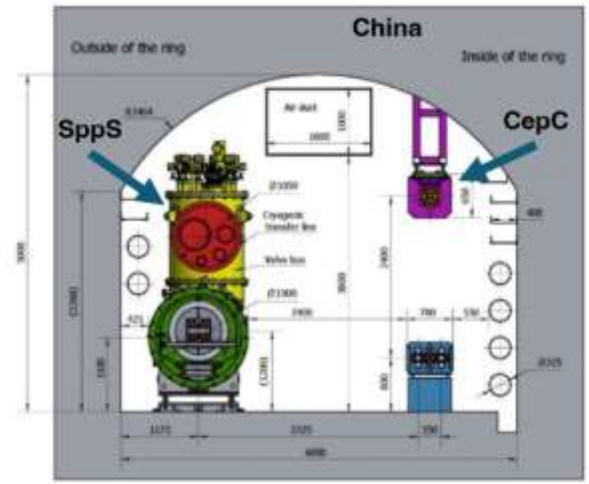
Also: staging is possible – eg 3 or 6 TeV

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

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



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



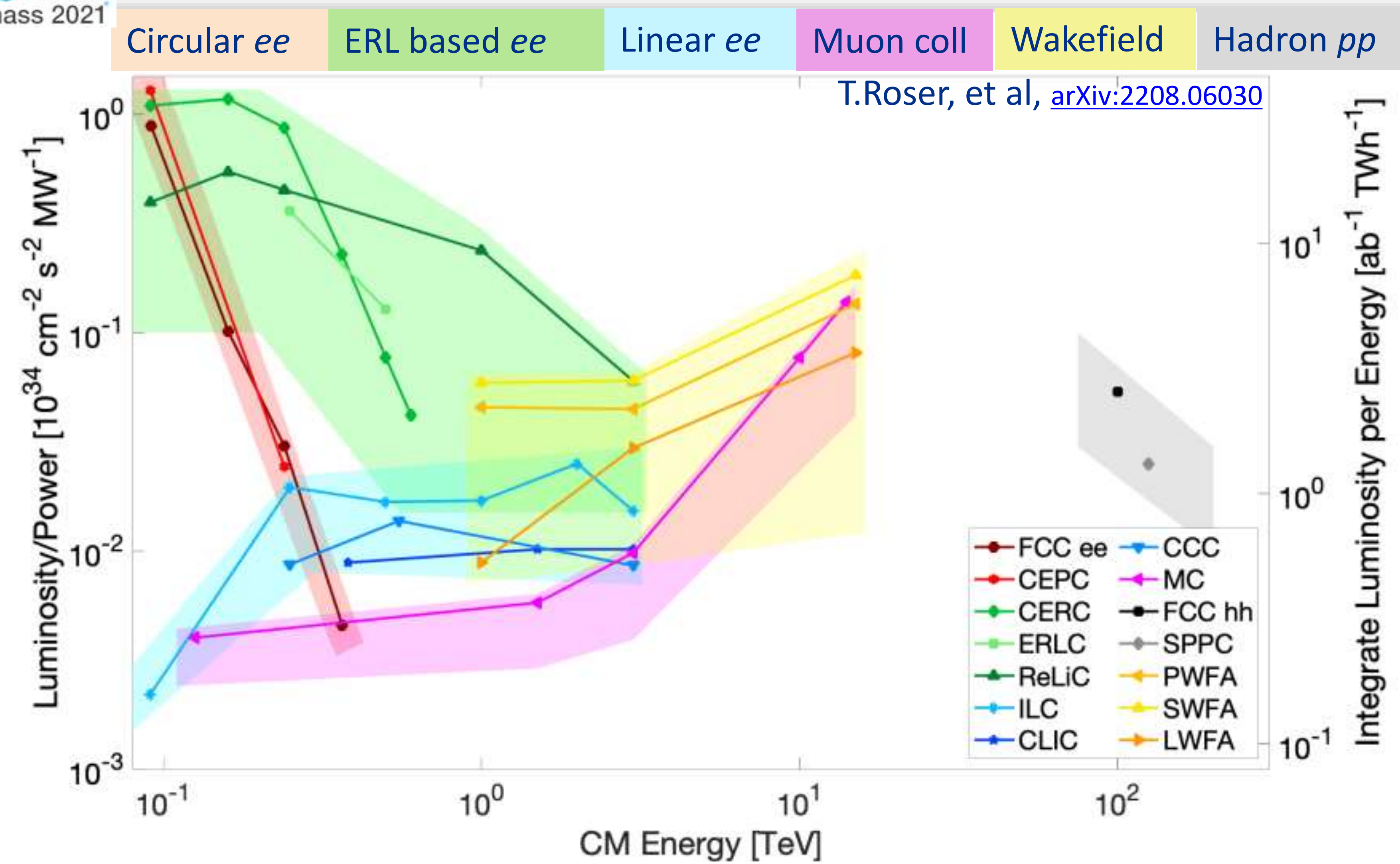
SPPC 125 TeV, 20 T magnets, 110 km

ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st 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	>25	>80	»1000

ITF Report – T.Roser, et al, arXiv:2208.06030

Luminosity per Power

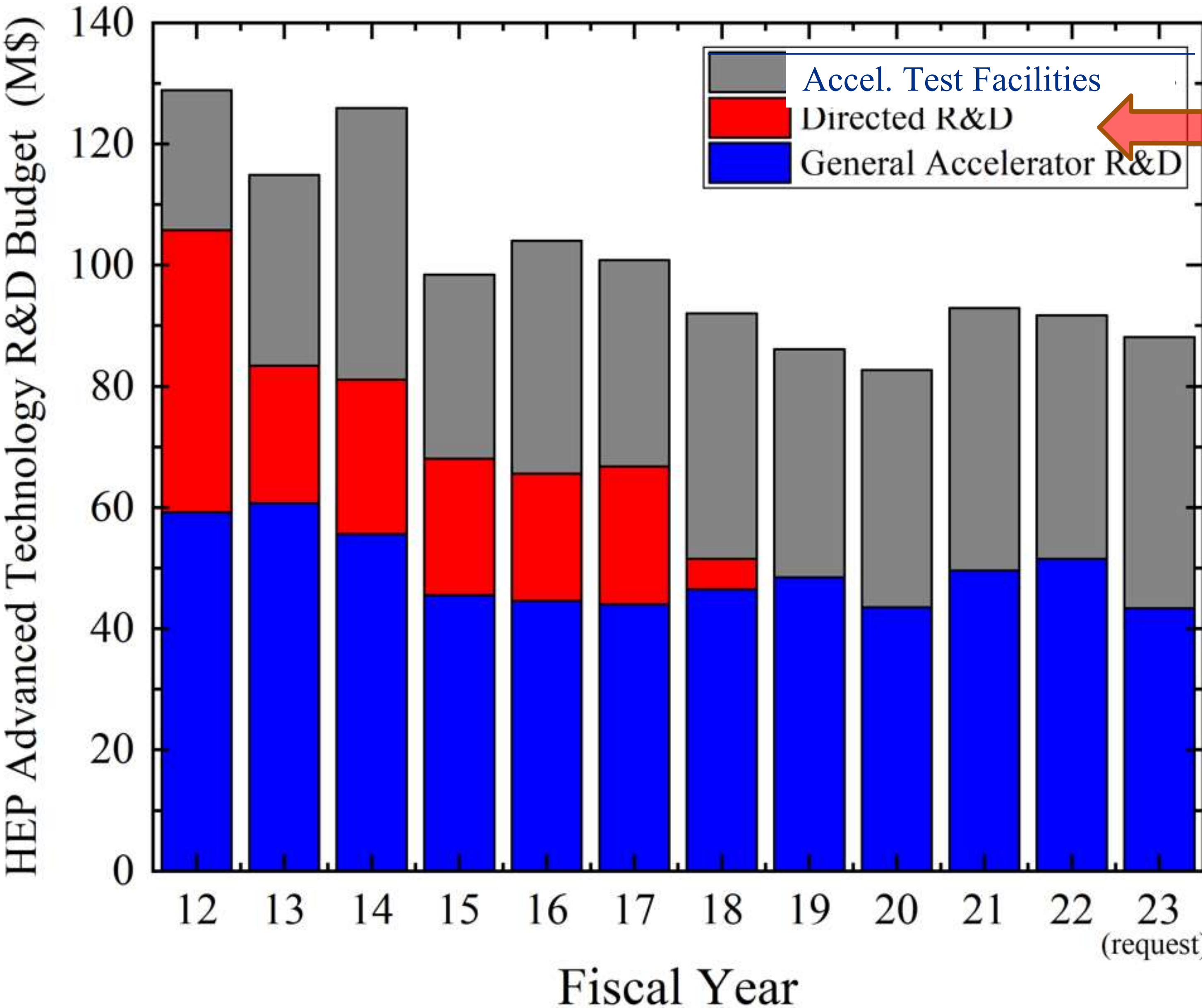


Luminosity is per IP, Integrated luminosity assumes 1e7 seconds/yr. *Luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.* Color bands reflect approximate uncertainty for different collider concepts.

AF Messages for Large-Scale Facilities

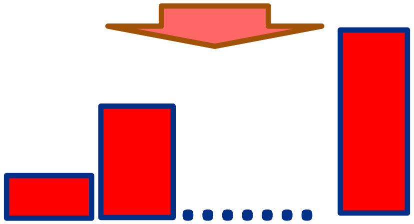
- Options for the next US engagement include Intensity or Energy frontier
- We need an integrated future collider R&D program (a focused R&D program in OHEP) to engage in the design and to coordinate the development of next generation collider projects such as*: ILC, CLIC, FCCee, CCC/HELEN, multi-TeV 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



Completed:
US ILC
US LARP (LHC)
US MAP (Muon)

Proposed for FY24-30:
Future Colliders



Integrated program:
FCCee, ILC,
C^3, HELEN,
Muon Collider, etc
In US and abroad
Design and R&D

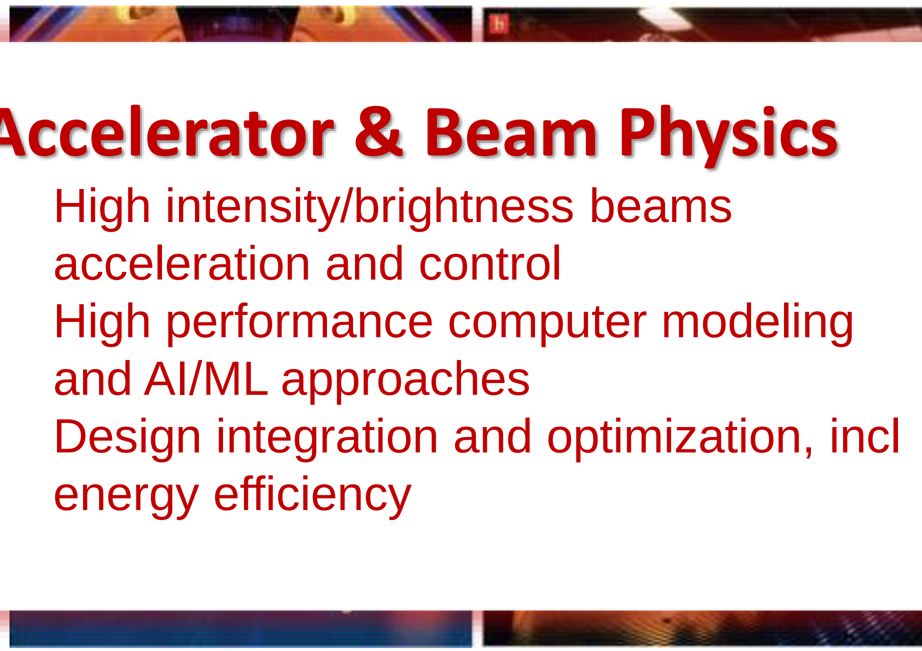
https://arxiv.org/abs/2207.06213

Accelerator R&D for HEP: Next Decade

Multi-MW targets:
- **2.4 MW for PIP-III**
- 4-8 MW for **muon collide**

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 C^3
- 70 MV/m TW SRF
- new materials, high Q_0
- efficient RF sources

AF Summry report available at https://arxiv.org/abs/2209.14136

Thanks for your attention!

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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

- Special thanks to
  - *AF topical group conveners, liaisons, ITF chair and and fora convers*
  - *Swapan C. for inviting me to present here the Snowmas'21 AF summary*
- AF Report is at arxiv:2209.14136, tons of material (all reports, etc) available at:

https://snowmass21.org/accelerator/