The 2020-2023 US HEP Planning Process: from Snowmass to P5

Accelerator Frontier Aspects

CERN ABP Seminar, Dec. 14, 2023

BE Auditorium (**6/2-024**)

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Stephen Gourlay, Tor Raubenheimer
(Snowmass'21 AF Conveners)

Abstract

Snowmass is a particle physics community study that takes place in the US every 7-9 years, e.g., the previous one was in 2013. The Snowmass'21 study (the name is historical, originally held in Snowmass, Colorado) took place in 2020-22. It was organized by the American Physical Society Divisions (DPF, DPB, DNP, DAP, DGRAV) and strived to define the most important questions for the field and to identify promising opportunities to address them, to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. The P5, Particle Physics Project Prioritization Panel, chaired by H. Murayama (UC Berkeley), has taken the scientific input from Snowmass'21 to develop a strategic plan by the Fall of 2023 for U.S. particle physics that can be executed over a 10-year timescale in the context of a 20-year global vision for the field. We will discuss major recommendations of the Snowmass Accelerator Frontier.

Special Thanks to CERN !

Active Participants in the Snowmass'21 "Accelerator Frontier":

(topical group conveners)

Gianluigi Arduini
Susan Izquierdo Bermudez
Mike Lamont
Frank Zimmermann

(speakers/fora/ITF)

Michael Benedikt
Daniel Schulte
Steinar Stapnes
Philippe Lebrun (ITF)
Elias Metral (ABP Roadmap), et al.

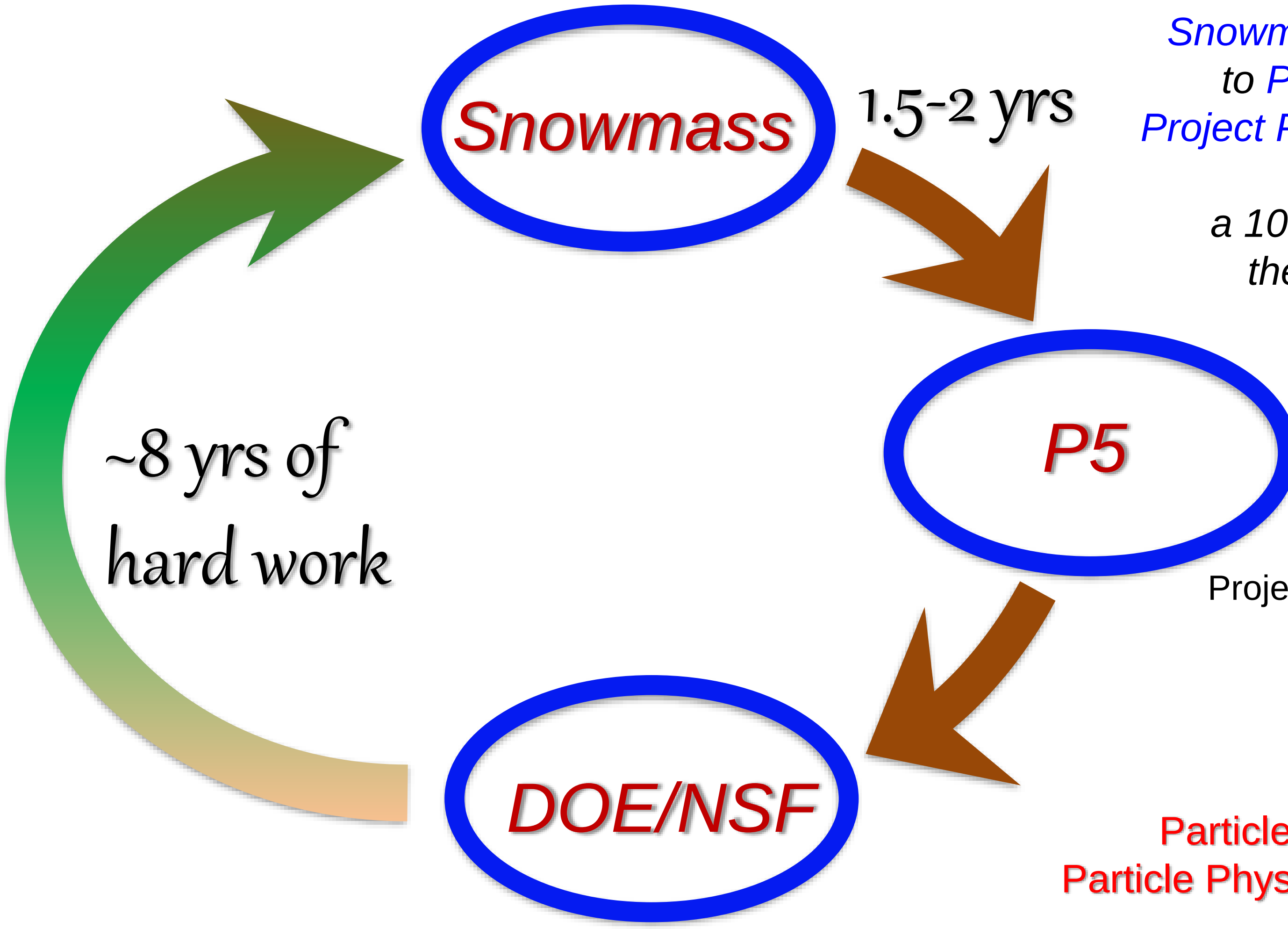
(P5 member)

Amalia Ballarino

+ many contributors (Letters of Interest, White Papers, summary reports, publications, etc)

What is *Snowmass* :

"Snowmass is a particle physics community study"



Snowmass provides input to P5 (Particle Physics Project Prioritization Panel) which develops a 10-20 yrs strategy for the US HEP program

Particle Physics Project Prioritization Panel

Particle Physics is global
Particle Physics is not isolated

https://www.snowmass21.org/

Snowmass 2021

Previous *Snowmass/P5* (2013/14)

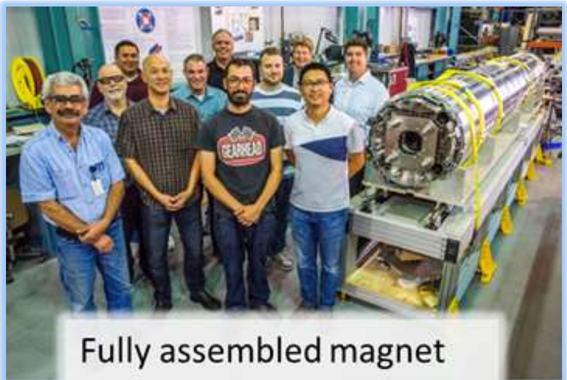
- Major accelerator-related recommendations:
  - Contribute to LHC and HL-LHC — done, in process
  - Engage in the ILC in Japan, contribute if it goes — unclear
  - Build >1 MW proton source PIP-II for ν LBNF/DUNE — in process
  - Provide beams for g-2 and mu2e experiments — done, in process
  - Reassess Muon Accelerator Program and MICE — done

- A follow-up 2015 Accelerator R&D subpanel recommended several thrusts :
  - Beam Physics (incl. IOTA and PIP-III) — in process
  - Sources and Targets (incl. multi-MW) — in process
  - RF (high-Q, high-G, low cost) — in process
  - Magnets and materials (16 T, low cost) — in process
  - Advanced acceleration (towards wakefield colliders) — in process

Few Examples – Facilities/Programs

(under construction) AUP LHC Nb_3Sn IR quads for HI-LHC

CD-3 project
be ready LS3
FNAL
BNL
LBNL


Fully assembled magnet

(construction started) PIP-II 800 MeV proton SRF linac @FNAL

Goal: 1.2MW for LBNF/DUNE
Beam to Booster in 2029
30% Int'l contrib.

(completed) ILC@Fermilab 1st 1.3GHz full CM with beam

FAST facility
ILC type beam
31.5MeV/m
255 MeV/CM
= *G*, Q_0 specs

(ongoing) muon beams for g-2 and mu2e experiments

FNAL
8 GeV *p*'s → target → μ's
Run-3 (2023) major muon *g-2* result

Few Examples – Accelerator R&D

Snowmass 2021

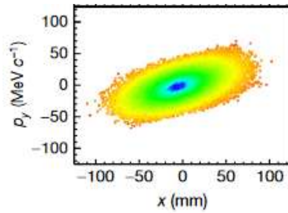
Record 14.5T Dipole (at FNAL, part of the US MDP)

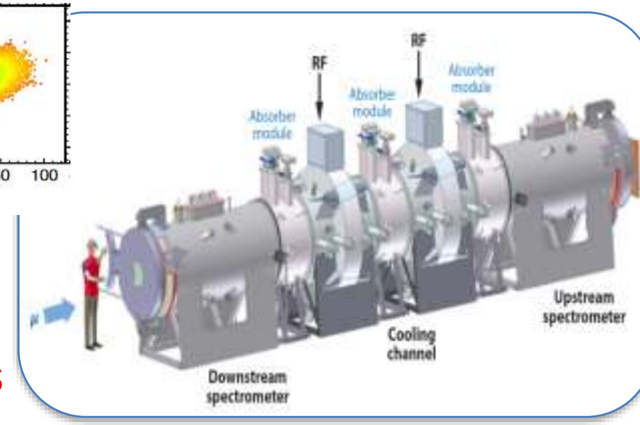
Nb3Sn conductor

Stress control

U.S. MAGNET DEVELOPMENT PROGRAM

MAP/MICE: Ionization cooling of muons (140 MeV/*c*, RAL, UK)





MICE

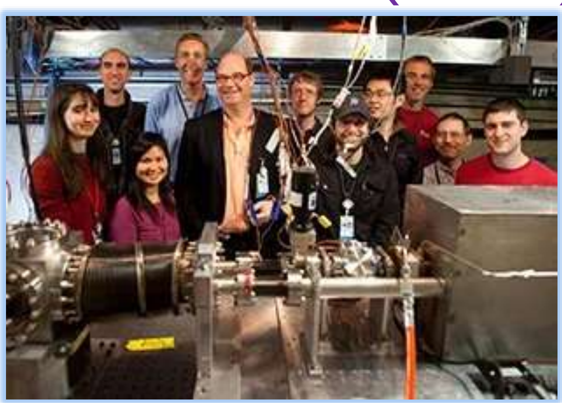
~10% in one pass

FACET-II User facility (SLAC)

BELLA: PWFA records (LBNL)

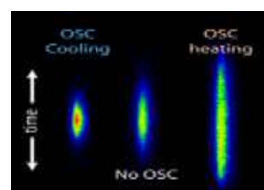
Unique beam
10 GeV
1 nC
1x1x1 μm

8 GeV/0.2m
staging p.o.p
5+0.1 GeV



IOTA Ring/Optical Stochastic cooling *e*- (100 MeV, FNAL)

soon – experiments with *p*'s



THz bandwidth

Snowmass'2021

- Started in 2020→ ~1 yr COVID delay → finish 2022:
  - Community of ~3000 people, incl. international
  - Snowmass *CSS Workshop* in Seattle (July'22) ~1400 people
  - Final report to P5, that starts early '23 (Final report Dec 7, 2023)
- **10 "Frontiers": Energy, Theory, Cosmic, … Accelerator**

Accelerator Frontier – Key Questions:

1. What is 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 R&D would 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 facilities?

Accelerator Frontier Conveners

Steve Gourlay
(LBNL/FNAL)

Tor Raubenheimer
(SLAC)

Vladimir Shiltsev
(FNAL)

Topical Group		Topical Group co-Conveners			
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bai (SLAC)	S. Lund (MSU)	
AF02	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)	
AF03	Accelerators for EW/Higgs	F. Zimmermann (CERN)	Q. Qin (ESRF)	G.Hoffstaetter (Cornell) A.Faus-Golfe (IN2P3)	
AF04	Multi-TeV Colliders	M. Palmer (BNL)	A. Valishev (FNAL)	N. Pastrone (INFN) J.Tang (IHEP)	
AF05	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	Richard Milner (MIT)	
AF06	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)	R. Assmann (DESY)
AF07	Accelerator Technology R&D				
	Sub-Group RF	E. Nanni (LBNL)	H.Weise (DESY)	S. Belomestnykh (FNAL)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	Frederique Pellemoine (FNAL)	

Snowmass Activities: pre-Seattle

Snowmass 2021

Proponents' Inputs	Letters-Of-Interest 257	White Papers 114
AF1: Beam Physics, Education & General	61	24
AF2: Accelerators for Neutrinos	18	9
AF3: Accelerators for EW/Higgs	32	11
AF4: Multi-TeV Colliders	56	10
AF5: Accelerators for PBC and Rare Proc.	37	7
AF6: Advanced Accelerator Concepts	71	10
AF7: Accelerator Technology R&D	137	43

PLUS:

- > 30 Topical Workshops
- 8 Cross-Frontier ***Agoras***
  - All types of colliders: ee, linear/circular, mumu, pp, advanced
  - Experiments and acceleratosr for rare processes physics
- Special cross-Frontier Groups (e.g., AF-EF-TF)
  - eeCollider Forum, Muon Collider Forum, Implementation Task Force

Accelerator Frontier Summary

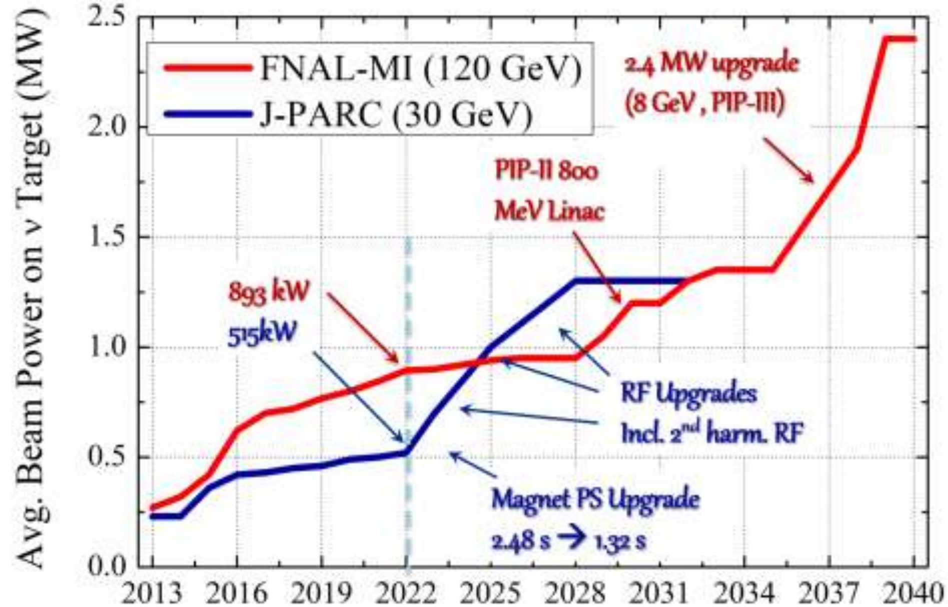
- *Draft Report* → finalized in Seattle → *Final Report*
- AF Topical Group, ITF and Fora Summaries
- Below, only few topics will be briefly covered:
  - Accelerators for Neutrinos
  - Accelerators for Rare Processes/DM Searches
  - Future Colliders
  - Key Accelerator R&D
- For each - key "messages" (vision):
  - Proposed directions ("what")
  - Timeline ("when") – e.g., by 2030, after 2030
  - Challenges ("what's needed")

1. Multi-MW ν Beams for DUNE

Snowmass 2021

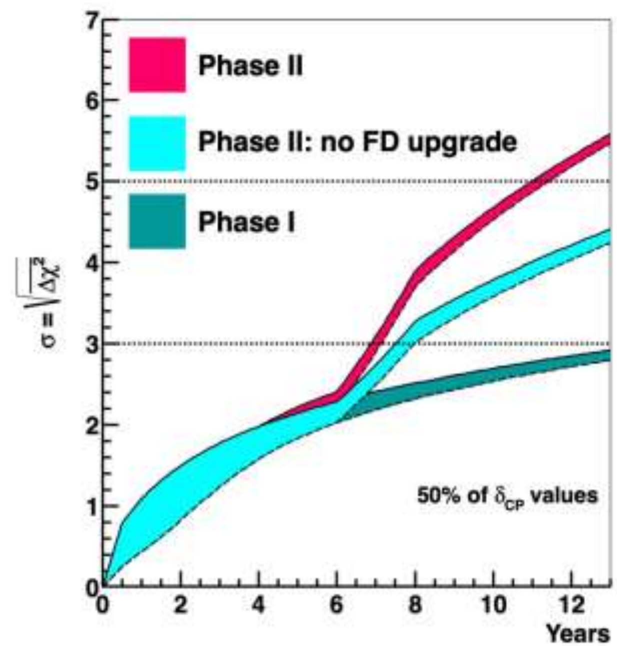
LBNF/DUNE Project – Phase I :

- By 2032: **1.2 MW** proton beam (120 GeV) 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 get too long, plus – competitor experiment Hyper-K in Japan



Proposed Plan - LBNF/DUNE Phase II :

- By 2038: ~2.4 MW proton beam (120 GeV) on target + new near ν-detector + extra 20 kton Lar ν-detector
- Expected to get to ~5σ in δ_{CP} in the following 6 years
- Accelerator options proposed/under active study now:
  - (understand max performance and limits with PIP-II linac)
  - New 8 GeV RCS [two options] with/w.o. new 1-3 GeV linac upgrade
  - New 8 GeV linac with or without new 8 GeV accumulator ring
  - In any case – need upgrade of MI RF power and new m-MW targets
  - See S.Nagaitsev talk earlier today
  - Fermilab has formed a special design group



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2. >20 Proposed Experiments For Rare Processes

(most via Snowmass Whitepapers)

DM searches, Axion searches, CLFV experiments, muons, light mesons, beam dump experiments… calls for corresponding beam facilities @ FNAL, SLAC, Jlab

Experiment	Experiment type	Primary beam particle	Beam Energy [GeV]	Beam power [kW]	Beam time structure
Proton Storage Ring: EDM and Axion Searches	Precision tests, Dark Matter	proton	0.7 GeV/c beam momentum	1e11 polarized protons per fill	Fill the ring every 1000s
Physics with Muonium	Precision tests	proton (producing surface muons)	0.8 GeV	1e13pml POT per second	CW
Nucleon Electromagnetic Form Factors from Lepton Scattering	Neutrino	electron or proton (producing muons)	0.85 GeV to 2 GeV	1 nA to 10 microA for electrons 10^7 to 10^8 per second for muons	A continuous or pulsed structure (ideally with a duty factor of 1% or larger) should be sufficient
Rare Decays of Light Mesons (REDTOP)	Precision tests	proton	1.8-2.2 GeV (Run I), 0.8-0.92 (Run II), 1.7 (Run III)	0.03-0.05 (Run I), 200 (Runs II and III)	CW, slow extraction for Run I
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	proton	0.8-2	1,000	quasi-continuous
CLFV with Muon Decays	CLFV	proton	Not critical 0.8 to a few GeV	100 or more	continuous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better
Mu2e II	CLFV	proton	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	0.8 to 1.5 GeV	100 or more	<O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^(-5) or better duty factor
PRISM-like Charged Lepton Flavor Violation	CLFV	proton	1-3 GeV	up to 2 MW	15ns pulses at a rep rate of about 1 kHz
Electron Missing Momentum (LDMX)	Dark Sector	electron	~3 GeV to ~20 GeV	O(1 electron per RF bucket at 53 MHz)	CW-ish
Electron Beam Dumps	Dark Sector	electron	few GeV	10^(20) electrons on target over the experiment al runtime	Pulsed beam (duty factor not specified)
Proton Irradiation Facility	R&D	proton	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)
SBN	Neutrino	proton	8	32	20Hz
Mu2e	CLFV	proton	8	8	<10^(-10) extinction
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec
Muon beam dump	Dark Sector	proton (producing muons)	3 GeV muons	3e14 muons in total on target for the whole run	CW
Muon Collider R&D and Neutrino Factory	R&D	proton	5 - 30GeV	1e12 to 1e13 protons per bunch	10 - 50 Hz rep rate and bunch length 1-3 ns
Muon Missing Momentum	Dark Sector	proton (producing muons)	few 10s of GeV	10^(10) muons per experimental runtime	Pulsed beam (duty factor not specified)
High Energy Proton Fixed Target	Dark Sector, Neutrino	proton	O(100 GeV)	1e12 POT/s therefore ~20 kW	CW via resonant extraction. "If we could up the duty factor that would be even better"(?)
Test-Beam Facility	R&D	proton	120, lower energies would also be beneficial	10 to 100 kHz on the testing apparatus	Pulsed beam (duty factor not specified)
Tau Neutrinos	Neutrino	proton	120	1200 or higher	MI time structure

Electron beams:
~ GeV to multi-GeV

Proton beams:

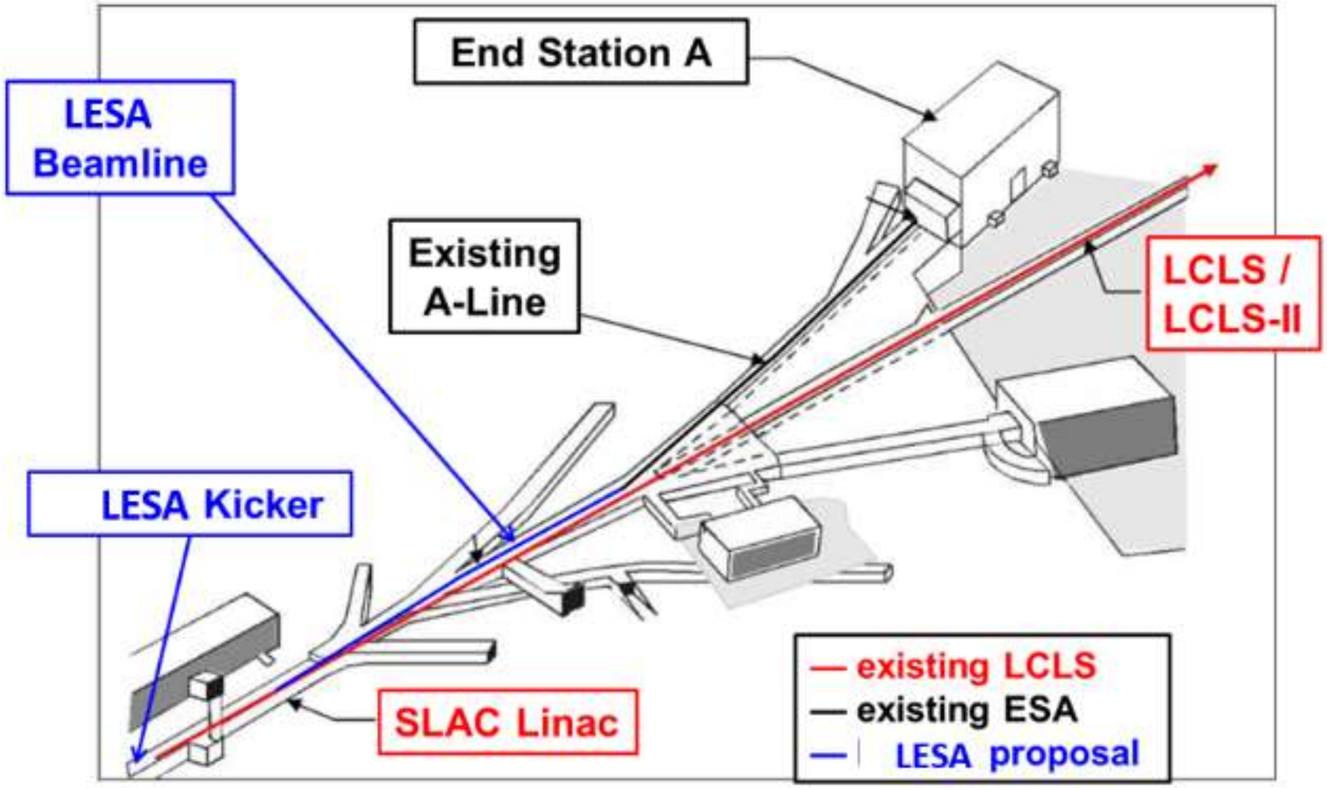
~2 GeV CW-capable beam

~2 GeV pulsed beam from storage ring ~1MW

~8 GeV pulsed beam ~1MW

120 GeV Slow extraction or LBNF beam

Started LESA Beamline for LDMX @ SLAC



Features:

- SLAC electron SRF linac *E*=4-8 GeV
- Low intensity, almost CW beamline, 1-500 *e-/us*
- Beam dump and LDMX experiment
- CD-process started

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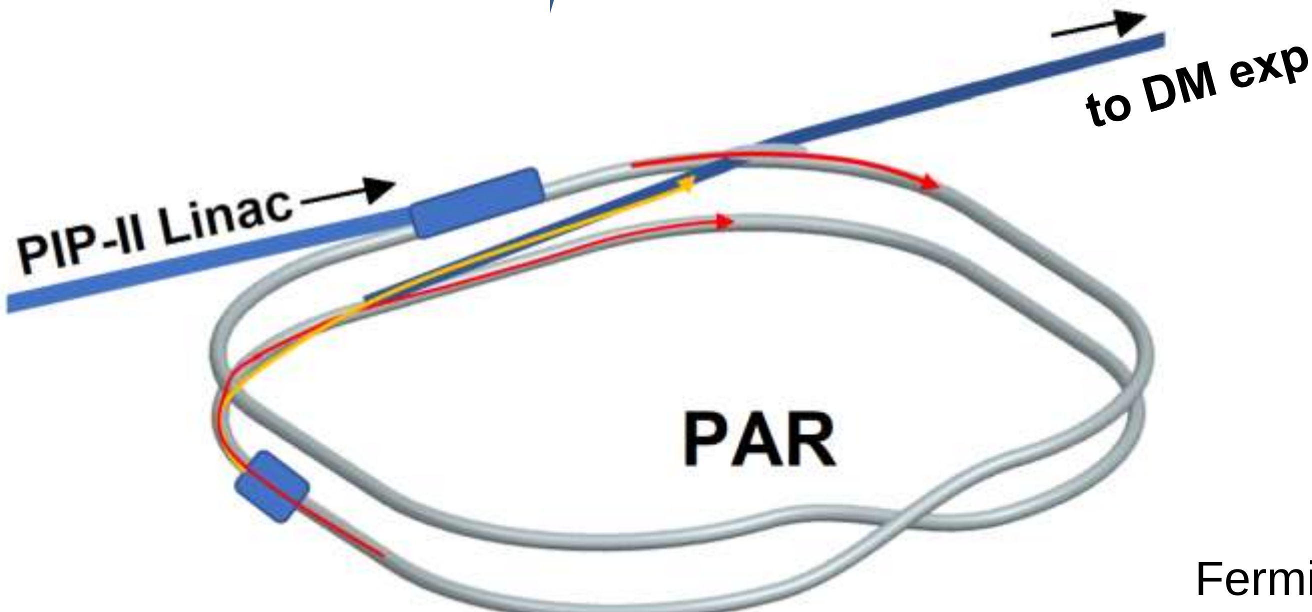
Proposed PIP-II Accumulator Ring (PAR)



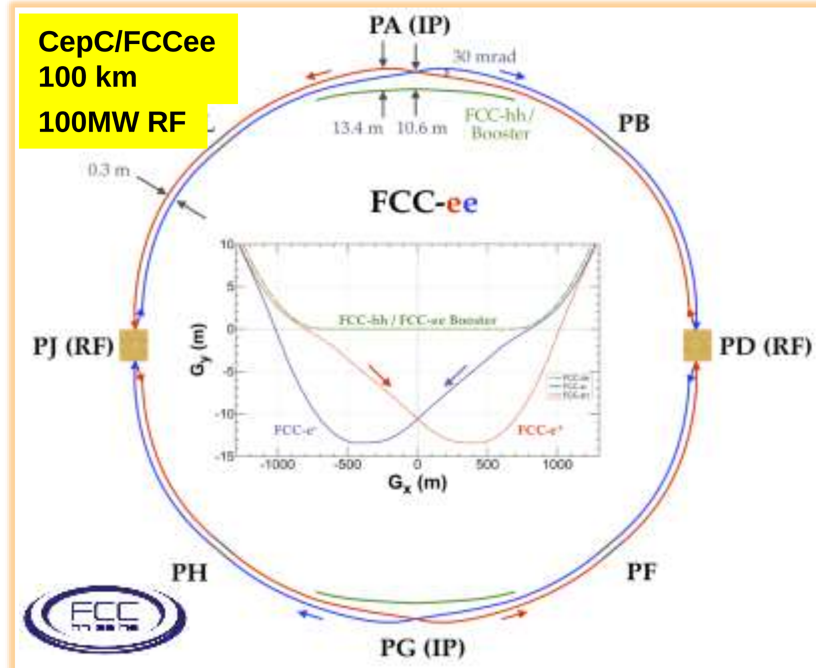
Fermilab

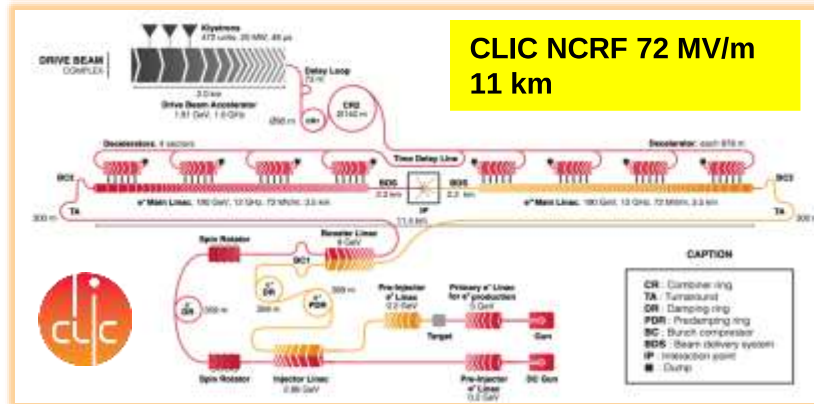
Snowmass white papers PAR, PIP2-BD

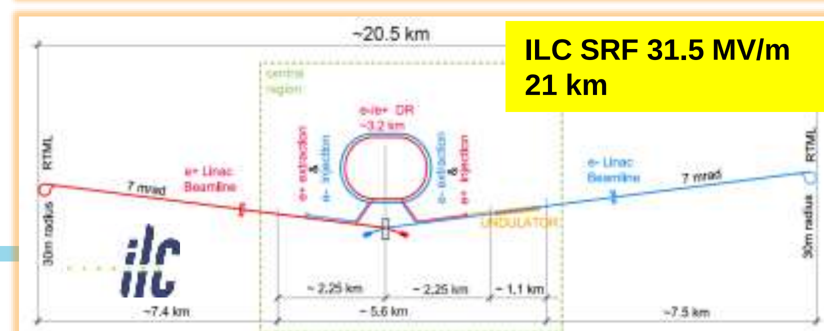
Features:
- Fixed *E*=0.8-1.0 GeV proton storage ring
- *C*=480m in the form of a *folded figure 8*
- Power 100 kW for Dark Sector program, 100Hz
- There is also compact version *C*=120 m

Future Collider Proposals: 8 Higgs/EW factories

Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

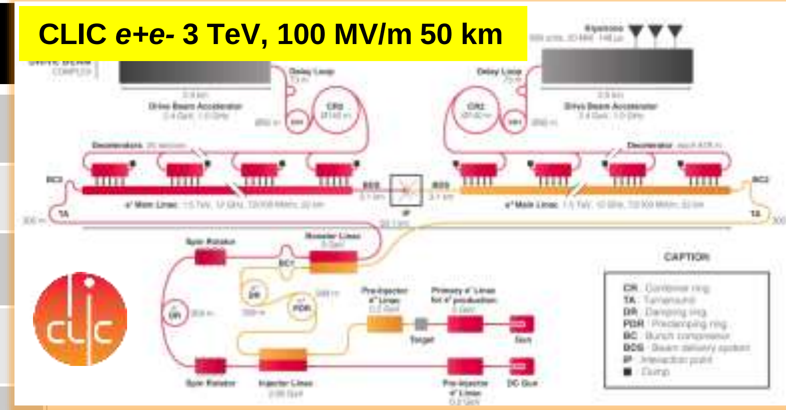


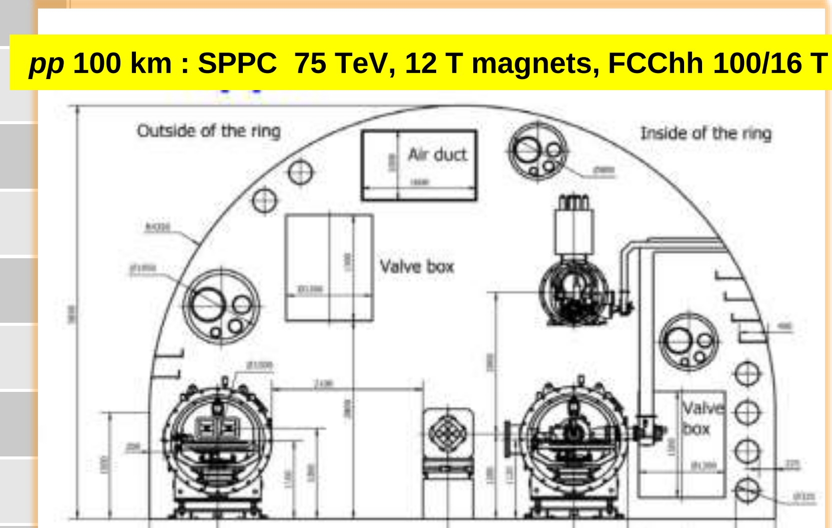


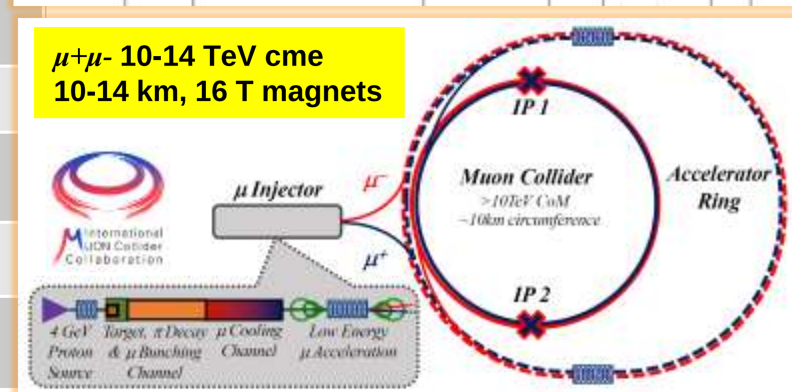


17 (!) High Energy Collider Concepts/Proposals

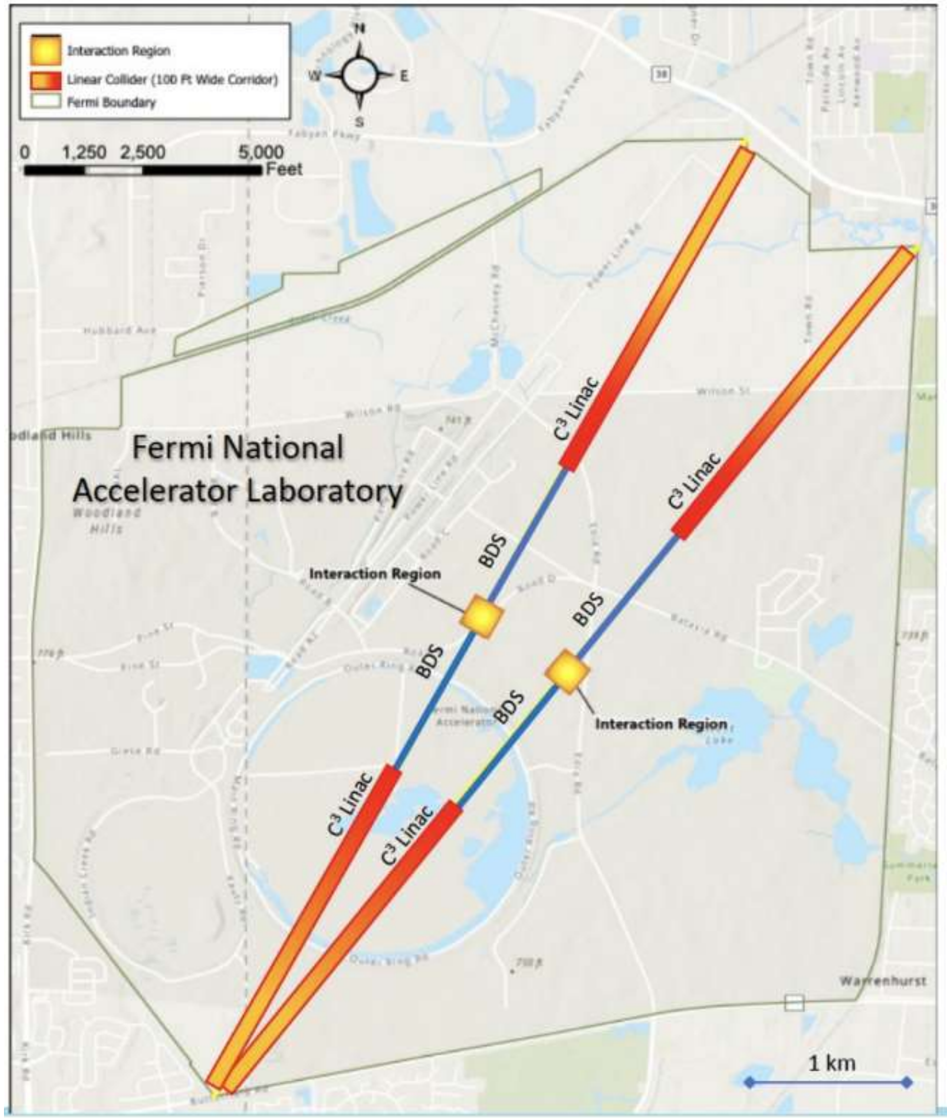
Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV







(New!) LC-Higgs Factories on FNAL Site

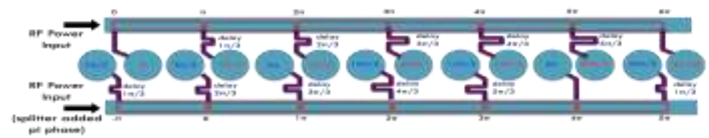


Must fit ~7 km incl BDS

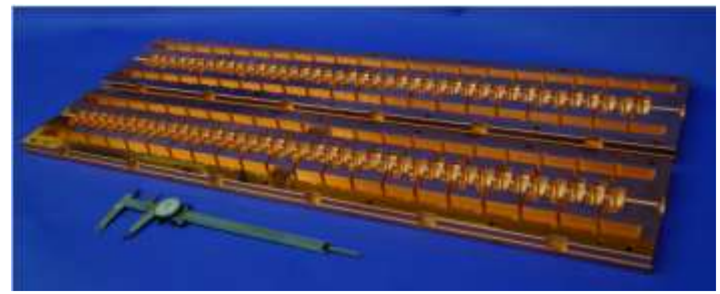
Requires gradients of at least 72MV/m

Compact → lower cost (wrt ILC/CLIC)

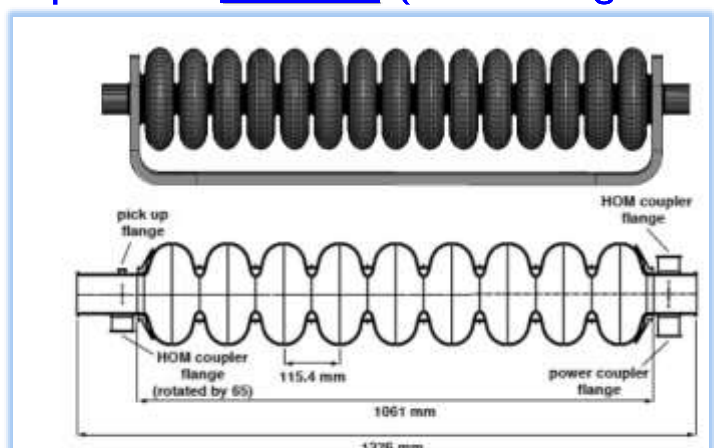
Option 1: Cool Copper Collider (C^3)



5.7GHz
77K



Option 1: ***HELEN*** (Travelling Wave ILC)



1.3GHz
2 K

FNAL Citing – *O*(10 TeV) Muon Collider

Snowmass 2021

- First design concept of up to 10 TeV collider developed
- Operation at 125 GeV, 1 and 3 TeV can be envisioned as intermediate stages
- Capitalize on existing facilities and expertise:
  - PIP-II and upgrades,

Muon Colliders Forum:

a) aim for 10 TeV cme
b) DOE support+join IMCC (CERN-led Int'l Muon Collider Collaboration)
c) Carry out R&D and deliver pre-CDR ca 2030

Implementation Task Force

- The Accelerator Implementation Task Force (ITF) is charged with developing metrics and processes to facilitate a comparison between collider projects.
- 10 int'l experts, 2 *Snowmass Young's*, 3 liaisons to Energy & Theory Frontiers
- ITF addressed (four subgroups):
  - Physics reach (impact), beam parameters
  - Size, complexity, power, environment
  - Technical risk, technical readiness, validation and R&D required
  - Cost and schedule


Thomas Roser (BNL, Chair)


Philippe Lebrun (CERN)


Steve Gourlay (LBNL)


Tor Raubenheimer (SLAC)


Katsunobu Oide (KEK)


Jim Strait (FNAL)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REPORT

JINST **18** P05018 (2023)


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ITF Report

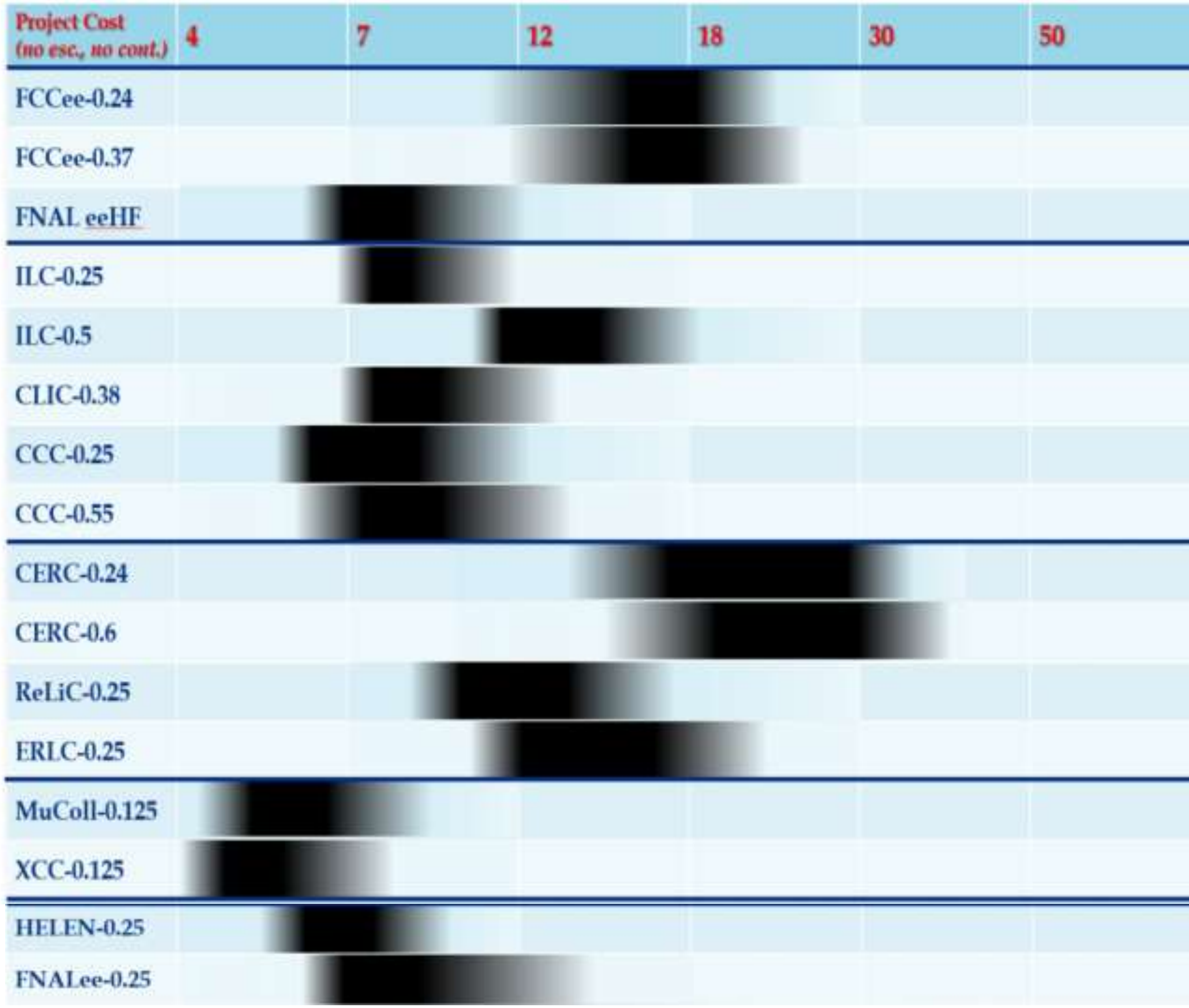
T.Roser, et al, *JINST* **18** P05018 (2023)

Higgs factory summary 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]
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

Cost Estimates for Higgs Factories

- 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.



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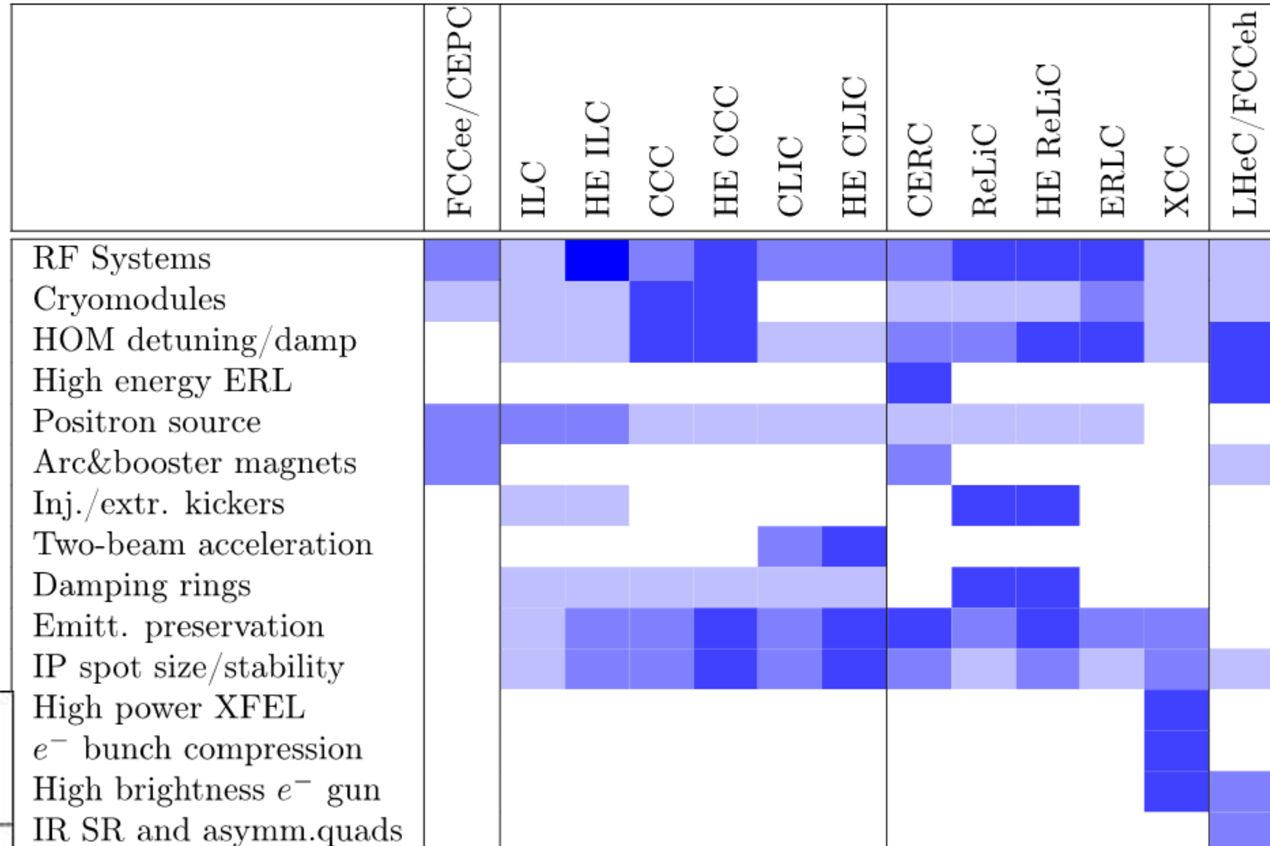
ITF Technical Risk Registry

- 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.



Proposal Name (c.m.e. in TeV)	Collider Design Status	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

ITF Table 14: "Design Status": I - TDR complete, II - CDR complete, III - substantial documentation; IV - limited documentation and parameter table; V - parameter table. Overall risk tier category ranging from Tier 1 (lower overall technical risk) to Tier 4 (multiple technologies that require further R&D).

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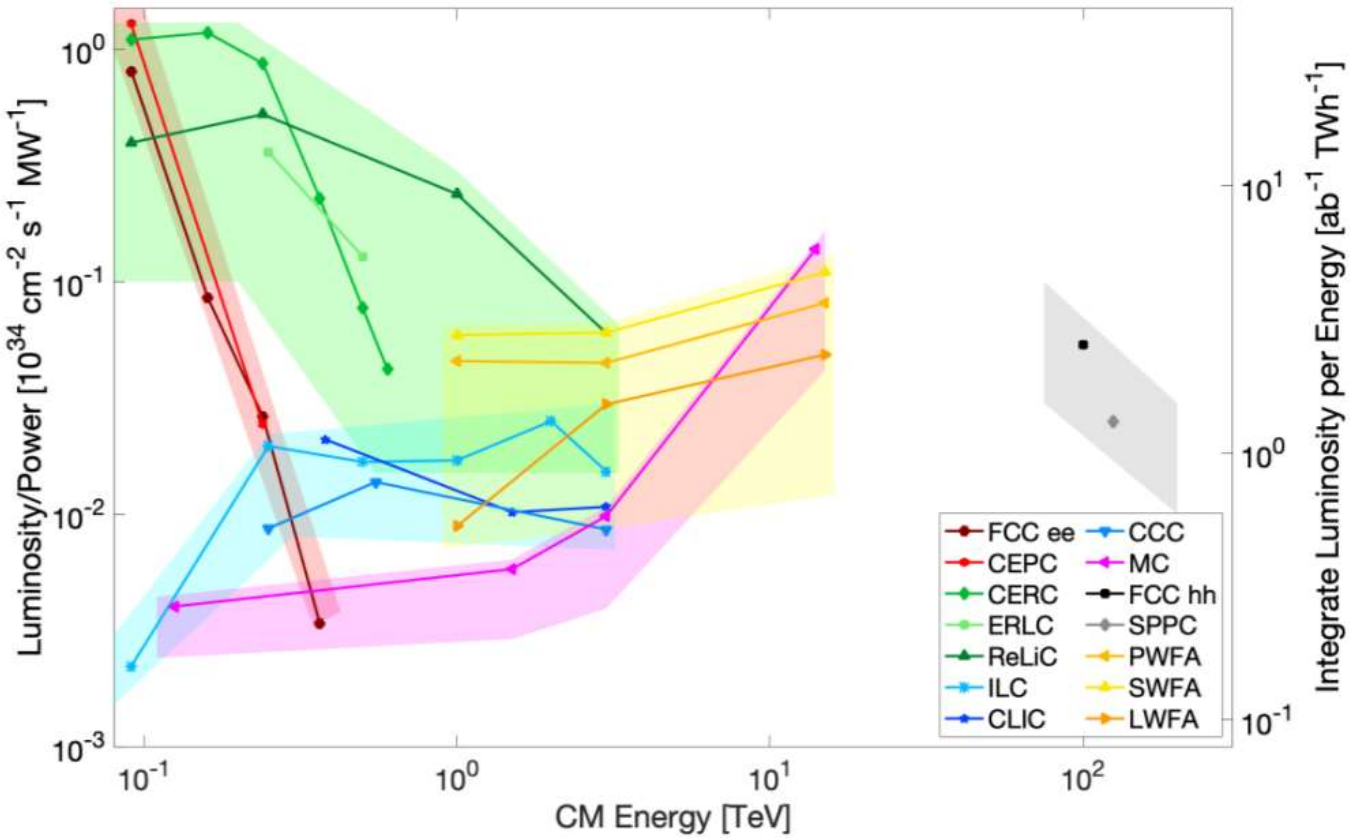
Luminosity per Power

Circular *ee*	ERL based *ee*	Linear *ee*	Muon coll	Wakefield	Hadron *pp*

- 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.



Once again: luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.

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ITF Report: 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	280
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
MC-Higgs	0.13	0.01	>10	19-24	4-7	~200
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-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

Future Colliders R&D Program - Initiative

Snowmass 2021

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

June 30, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat[1,†], S. Belomestnykh[1,5], D. Denisov[3], S. Gourlay[6], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[4], M.A. Palmer[3], T. Raubenheimer[4], V. Shiltsev[1], A. Valishev[1], F. Zimmermann[7]

We propose that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) and charge the program

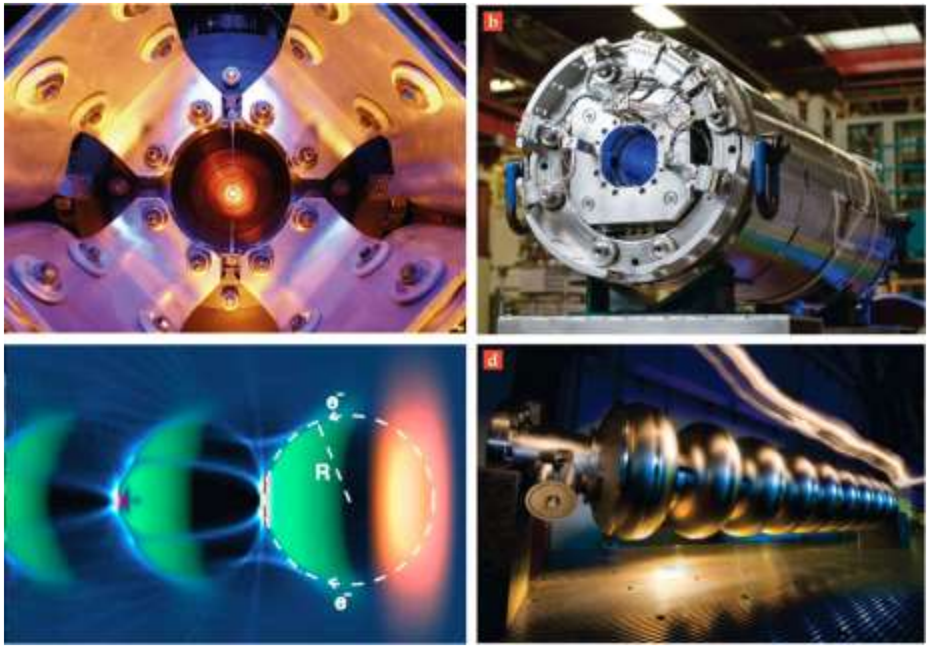
- to carry-out technology R&D and accelerator design for future collider concepts,
- to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, CLIC, IMCC),
- to develop design reports on collider options, by the time of the next Snowmass and P5 (2029–2030), particularly for options that are feasible to be hosted in the U.S.,
- to develop R&D plans for the decade beyond 2030.

Multi-MW targets:

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

Magnets for colliders and RCSs:

- 16T dipoles
- 30T solenoids
- 1000 T/s fast cycling ones coordinate with US MDP



Advanced:

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

SC/NC RF:

- 72-120 MV/m C^3
- 72 MV/m TW SRF
- new materials, high Q_0
- efficient power sources

Post-"Snowmass", NAS EPP and P5:

https://snowmass21.org/accelerator/start

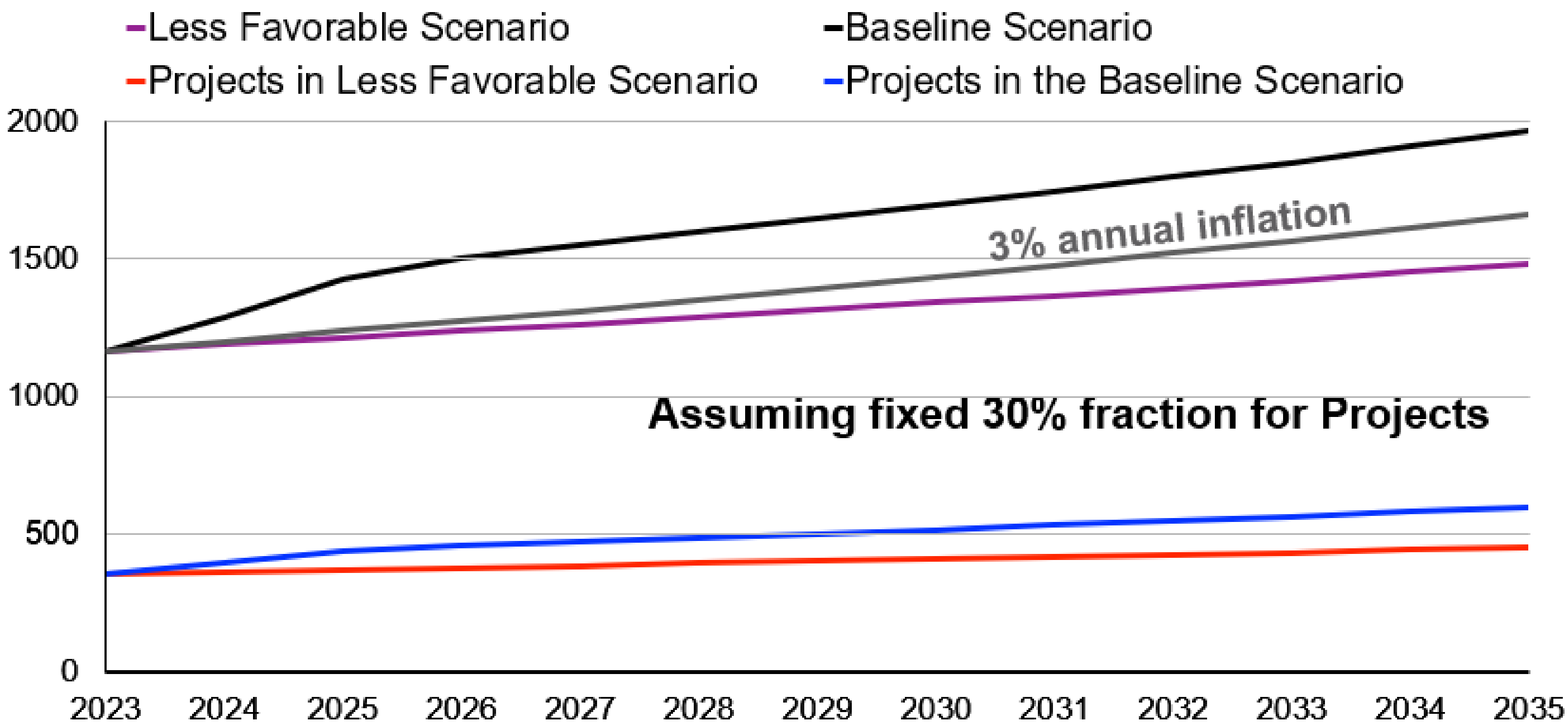
- All Snowmass Report published
  - Incl. Accelerator Frontier/ITF/e+e- and MuC TFs
  - 20 AF peer-reviewed papers in JINST
- HEPAP *Int'l Benchmarking Panel* (Nov 2, 2023)
- **P5 committee (H.Murayama, next slides):**
  - Many collaborative activities: FCC, MuCol, C3, ILC, …
  - 4 Town Hall meetings, Report released Dec. 7, 2023
- Parallel effort @ ***National Academy of Sciences***:
  - *Elementary Particle Physics 2024: Progress and Promise*
  - M.Spiropulu, M.Turner (Co-Chairs), F.Gianotti, YK Kim, et al
  - Identify the fundamental questions in particle physics, experimental and theor. tools, research directions
  - Unlike P5, the Committee will not prioritize projects nor consider budget as part of its deliberations

P5 Report (Dec 7, 2023)

https://www.usparticlephysics.org/2023-p5-report/

Budget Scenarios

P5



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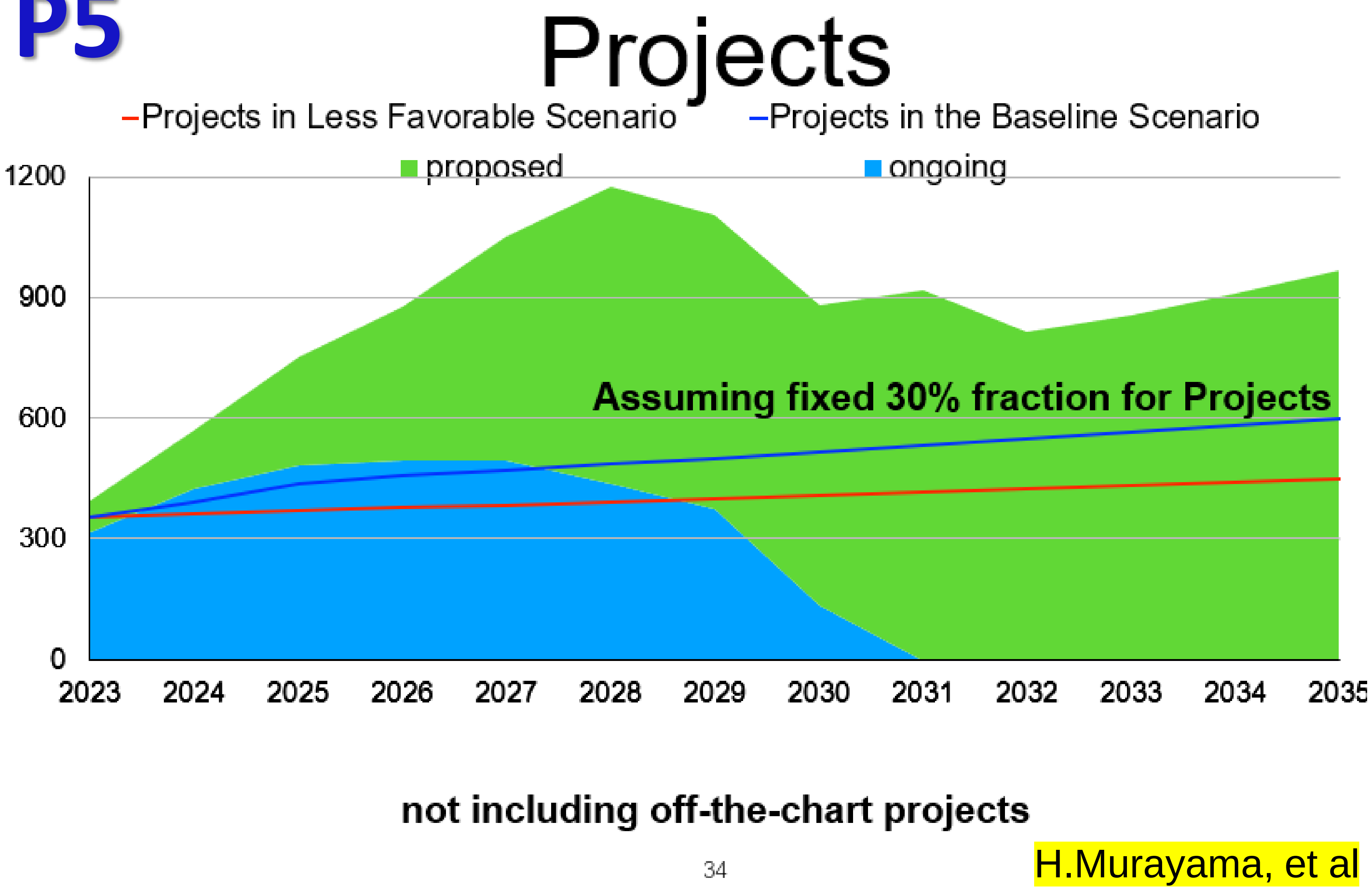
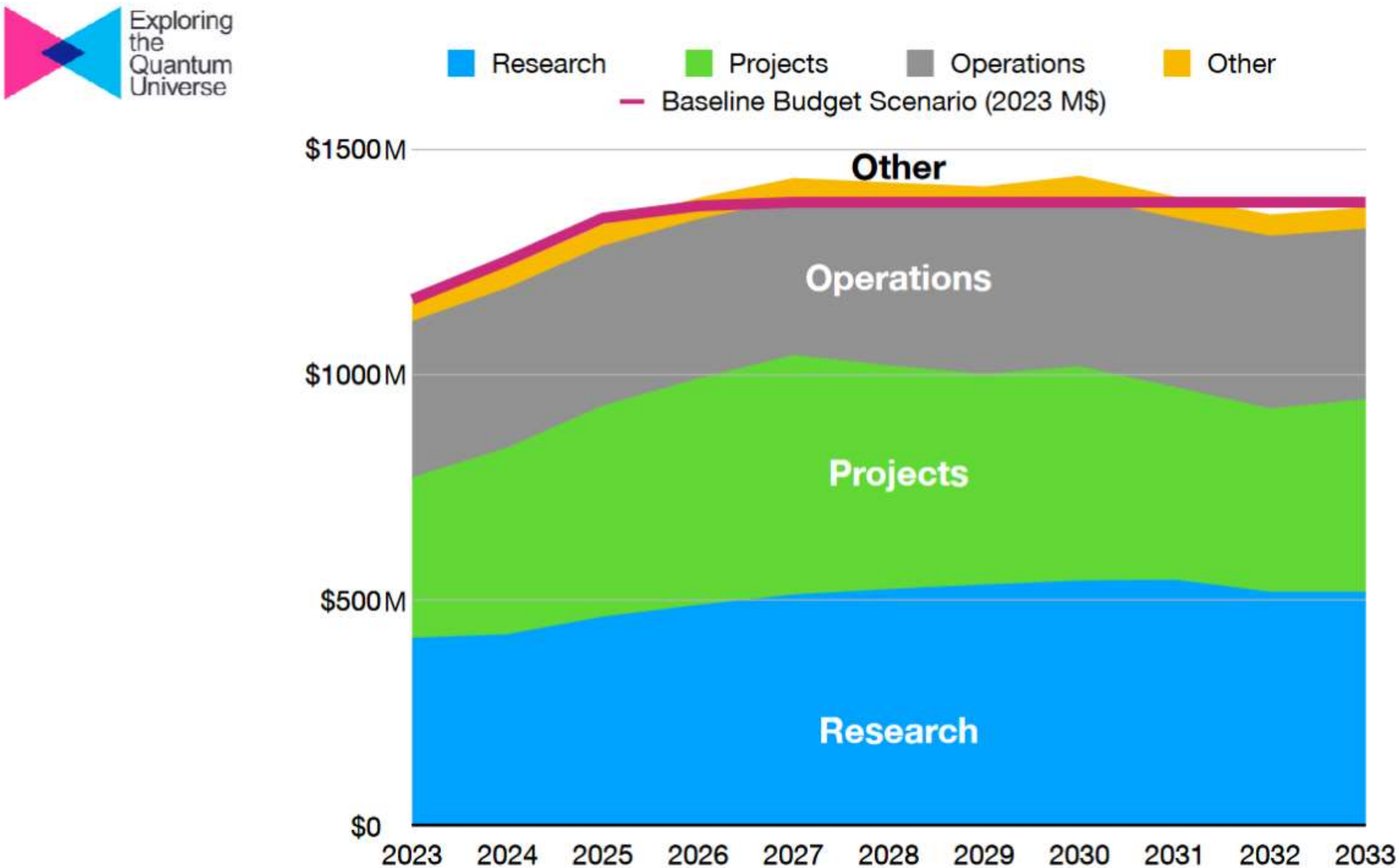
H.Murayama, et al

P5



H.Murayama, et al

P5 Outlook (Dec 7, 2023)



Not in the Report

H.Murayama, et al

rmilab

P5 Recommendations (of relevance to AF):
In the baseline scenario

- Recommendation 1 (out of 6): Highest priority
  - HL-LHC
  - First Phase of LBNF/DUNE and PIP-II
  - Vera C. Rubin Observatory
- Recommendation 2: Portfolio of major projects
  – (in order)…#3 "… An **off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2)

P5 Recommendations (of relevance to AF):
In the baseline scenario

- Recommendation 3: (Belle II upgrade among others)
  - …contributions towards the SuperKEKB accelerator.

- Recommendation 4: R&D Programs ["… - theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider."]
  - **a.** Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
  - **c.** Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
  - **g.** Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

P5 Recommendations (of relevance to AF):
In baseline scenario

- Recommendation 6: "Targeted Panel"

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

- **The panel would consider the following:**
  - 1.The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
  - 2.Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
  - 3.A plan for the evolution of the **Fermilab accelerator complex** consistent with the long term the longterm vision in this report, which may commence construction in the event of a more favorable budget situation

P5 Recommendations (of relevance to AF): In baseline scenario

- Among 20 "Area Recommendations":

General Accelerator R&D

8. **Increase annual funding to the General Accelerator R&D program by $10M per year** in 2023 dollars to ensure US leadership in key areas.

9. Support generic accelerator R&D with the construction of small scale test facilities. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.

Collider R&D

10. To enable targeted R&D before specific collider projects are established in the US, an investment in **collider detector R&D funding at the level of $20M per year** and **collider accelerator R&D at the level of $35M per year** in 2023 dollars is warranted.

12. Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with **defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex** within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.

- … other notable messages:
  - The **GARD** program is critical in supporting a broad range of AS&T for DOE SC
  - [there is] …The long-term ambition of hosting a major international collider facility in the US
  - A muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus.
  - …Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities… At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.** **[p.23]**

P5 Comments (of relevance to AF):

Exploring the Quantum Universe

2.5 International and Inter-Agency Partnerships

In the case of the Higgs factory, crucial decisions must be made in consultation with potential international partners. The FCC-ee feasibility study is expected to be completed by 2025 and will be followed by a European Strategy Group update and a CERN council decision on the 2028 timescale. The ILC design is technically ready and awaiting a formulation as a global project. **A dedicated panel should review the plan for a specific Higgs factory once it is deemed feasible and well-defined;** evaluate the schedule, budget and risks of US participation; and give recommendations to the US funding agencies later this decade (Recommendation 6). When a clear choice for a specific Higgs factory emerges, US efforts will focus on that project, and R&D related to other Higgs factory projects would ramp down.

Parallel to the R&D for a Higgs factory, **the US R&D effort should develop a 10 TeV pCM collider (design and technology)**, such as a muon collider, a proton collider, or possibly an electron-positron collider based on wakefield technology. The US should participate in the International Muon Collider Collaboration (IMCC) and take a leading role in defining a reference design. We note that there are many synergies between muon and proton colliders, especially in the area of development of high-field magnets. R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating **demonstrator facilities within a 10-year timescale** (Recommendation 6).

Area Recommendation 20: HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at developing a sustainability strategy for particle physics.

Thanks for your attention!

- Thanks to Frank, Elias and Yannis for inviting me
- Special thanks to
  - My co-conveners S.Gourlay and T.Raubenheimer
  - Accelerator Frontier Topical Group conveners and liaisons to EF, NF and TF
  - Tor R. and M.Palmer for insights on the P5 Report

Snowmass 2021

Back up slides

Additional Input – From DOE Office of Science:

“…to all SC federal advisory committees (incl HEPAP) on December 1, 2023 to provide input to an SC wide facility prioritization”

>100M$

2003
Similar
20-Years
Outlook

Ranked by:
Science Readiness

Priority	Program	Facility	Outcome
1	FES	ITER	Under construction
2	ASCR	UltraScale Scientific Computing Capability	Become ExaScale
3	HEP	Joint Dark Energy Mission	ESA built the Euclid mission and NASA is building the Nancy Grace Roman Telescope
3	BES	Linac coherent Light Source	Built and operating
3	BER	Protein Production and Tags	Part of the Bioenergy Research Centers
3	NP	Rare Isotope Accelerator	Built and operating as FRIB
7	BER	Characterization and Imagining	Part of the Bioenergy Research Centers
7	NP	CEBAF Upgrade	Built and operating
7	ASCR	ESNet Upgrade	Built and operating
7	ASCR	NERSC upgrade	Built and operating
7	BES	Transmission Electron Achromatic Microscope	Built and operating
12	HEP	BTeV	Canceled
13	HEP	Linear Collider	Never built
14	BER	Analysis and Modeling of Celluar Systems	Part of the Bioenergy Research Centers
14	BES	SNS 2.4 MW Upgrade	Under development
14	BES	SNS Second target Station	Under development
14	BER	Whole Proteome Analysis	Part of the Bioenergy Research Centers
18	NP/HEP	Double Beta Decay Underground Detector	Under development
18	FES	Next-Step Spherical Torus	Not built
18	NP	RHIC II	A simpler upgrade was done that still acieved the goal.
21	BES	National Synchrotron Light Source Upgrade	Built and operating
21	HEP	Super Neutrino Beam	Became LBNF/DUNE
23	BES	Advanced Light Source Upgrade	Under construction
23	BES	Advanced Photon Source Upgrade	Under construction
23	NP	eRHIC	Became EIC
23	FES	Fusion energy Contingency	Not built
23	BES	HFIR Second Cold Source and Guide Hall	Built and operating
23	FES	Integrated Beam Experiment	Not built

DOE HEP Facilities TBC (HEPAP , Dec 7, 2023):

- Accelerator Complex Enhancement Main Injector + Target (ACE-MI+T)
  - Will double up MI beam power to 2.1MW

near-term

mid-term

- Advanced Accelerator Test Facilities:
  - Plasma wakefield (10-20M$/yr now → increase?)

- Future Energy Frontier Collider
  - HEP envisions as a contribution to an offshore collider
  - An on-shore collider is probably outside 10yr frame
- Accelerator Complex Enhancement Booster Replacement (ACE-BR)

longer-term

From the ITF Report Draft: Tables 1-3, 5

Snowmass 2021

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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
MC-Higgs	0.13	0.01	>10	19-24	4-7	~200
CLIC-3	3	5.9	3-5	19-24	18-30	~550
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MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560

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

Fermilab site-fillers

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	~110
e^+e^- Circular Higgs Factory at FNAL	0.24 (0.09-0.24)	1.2	3-5	13-18	7-12	~200

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