US Higgs Factory Planning:
An Early Career Perspective

Julia Gonski

12 June 2024
FCC Week
Early Career Researchers Session

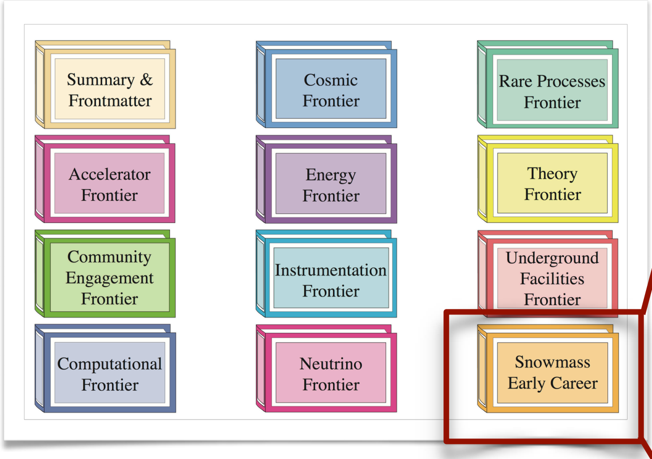
Snowmass

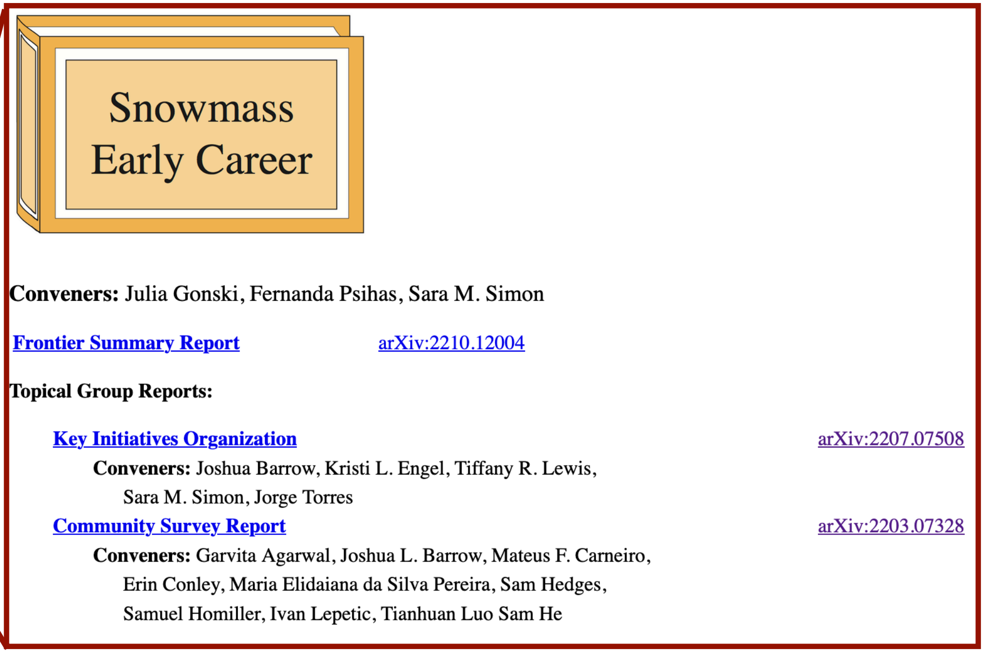
- **Snowmass** [2021-22]: decadal U.S. HEP community effort to express opinions on physics drivers & future experimental facilities
  - Preceded by European Committee for Future Accelerators (ECFA) "European Strategy" update in 2020

Snowmass 2021

Snowmass Early Career

- For the first time in Snowmass history, the Early Career organization has a chapter in the Snowmass Book! [2210.12004]
  - Includes a summary of the SEC survey report and **early career recommendations for P5**
- P5 1.5: ”The panel was especially encouraged by the **active participation of early career members** in the community-driven planning process. They represent the **future of our field** and are essential to the realization of the goals and aspirations detailed in this report.”




Snowmass Early Career

Conveners: Julia Gonski, Fernanda Psihas, Sara M. Simon

Frontier Summary Report arXiv:2210.12004

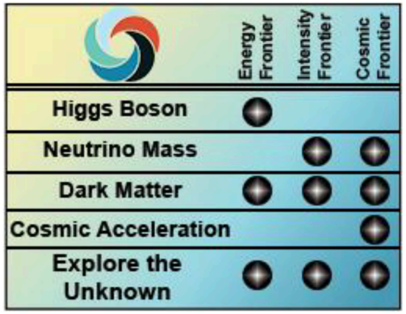
Topical Group Reports:

Key Initiatives Organization arXiv:2207.07508
Conveners: Joshua Barrow, Kristi L. Engel, Tiffany R. Lewis, Sara M. Simon, Jorge Torres

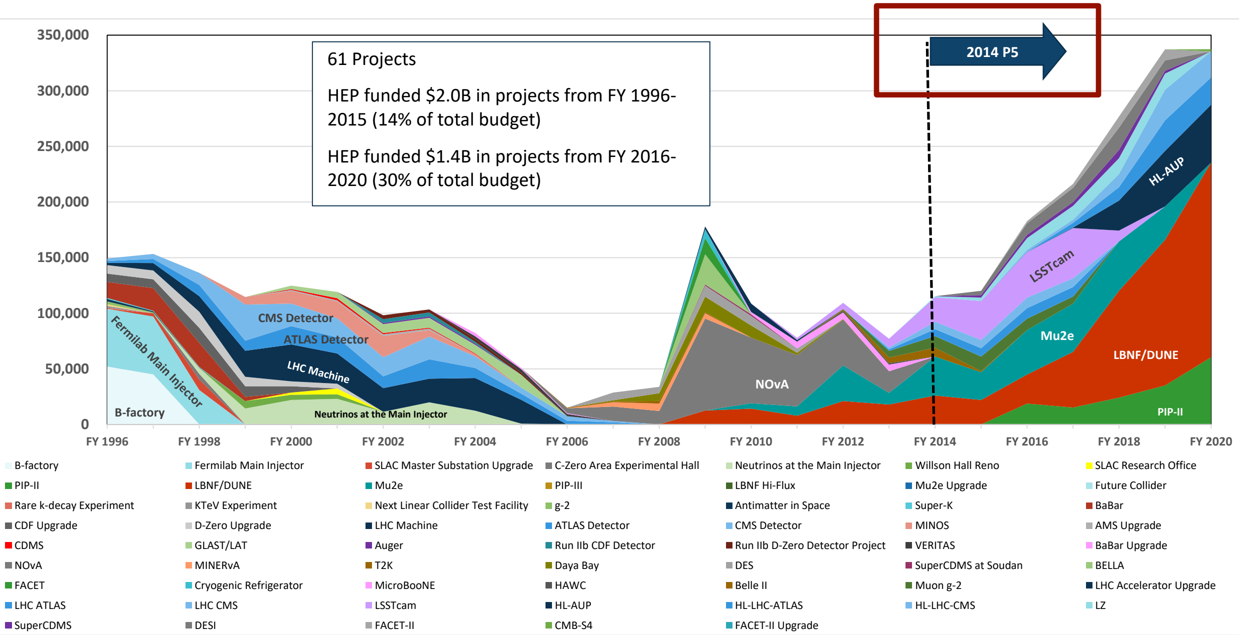
Community Survey Report arXiv:2203.07328
Conveners: Garvita Agarwal, Joshua L. Barrow, Mateus F. Carneiro, Erin Conley, Maria Elidaiana da Silva Pereira, Sam Hedges, Samuel Homiller, Ivan Lepetic, Tianhuan Luo Sam He

P5

- Particle Physics Project Prioritization Panel (P5):
  - Subpanel of High Energy Physics Advisory Panel (DOE)
  - Reviews Snowmass material & lays out priorities for the field for the *next 10 years* within a *20-year context*
- Previous P5 report in 2013 identified 5 science drivers for the field
  - Huge success with funding agencies



	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

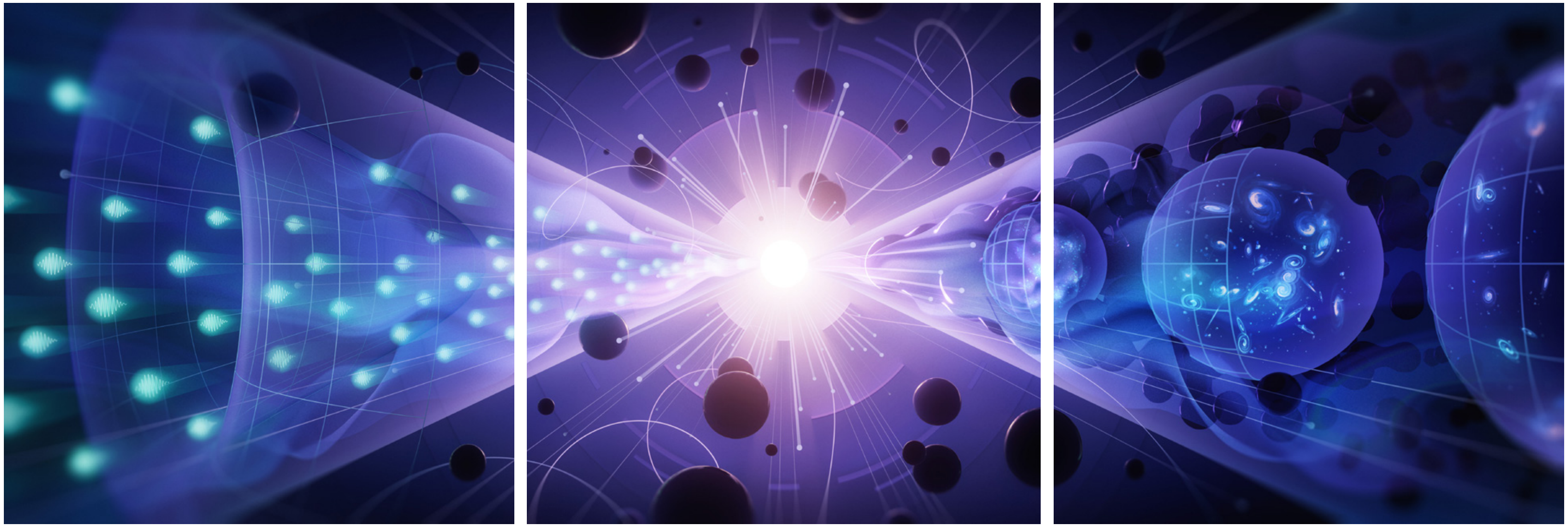


61 Projects

HEP funded $2.0B in projects from FY 1996-2015 (14% of total budget)

HEP funded $1.4B in projects from FY 2016-2020 (30% of total budget)

2023 P5



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

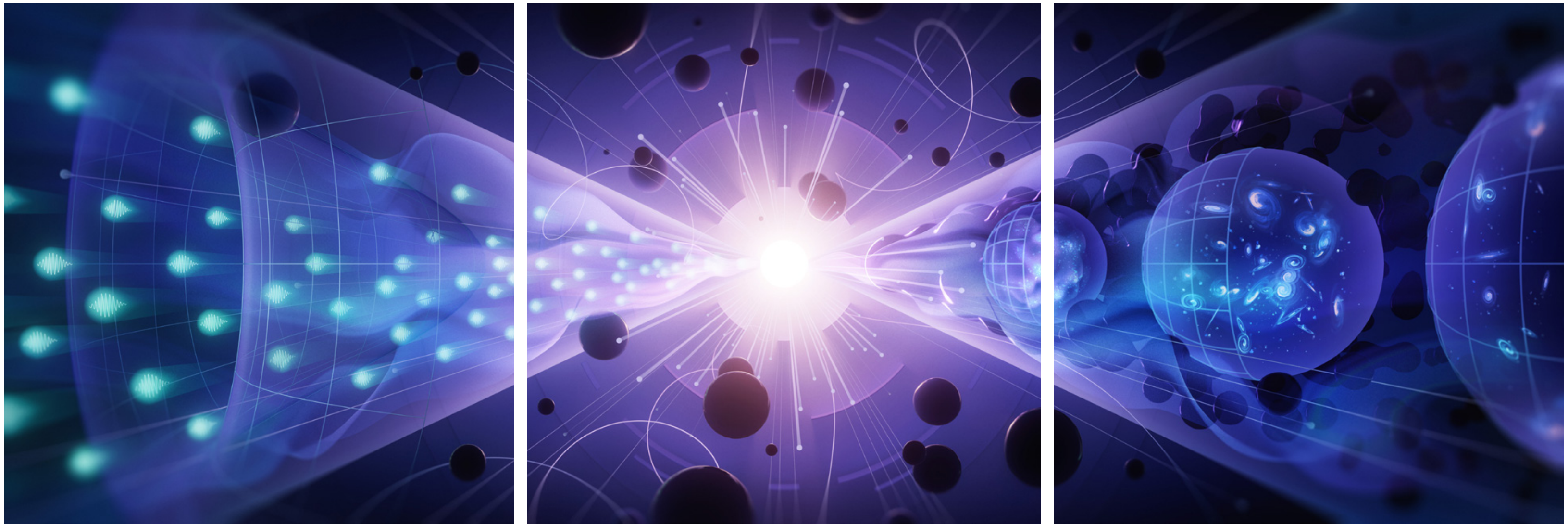
Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

2023 P5



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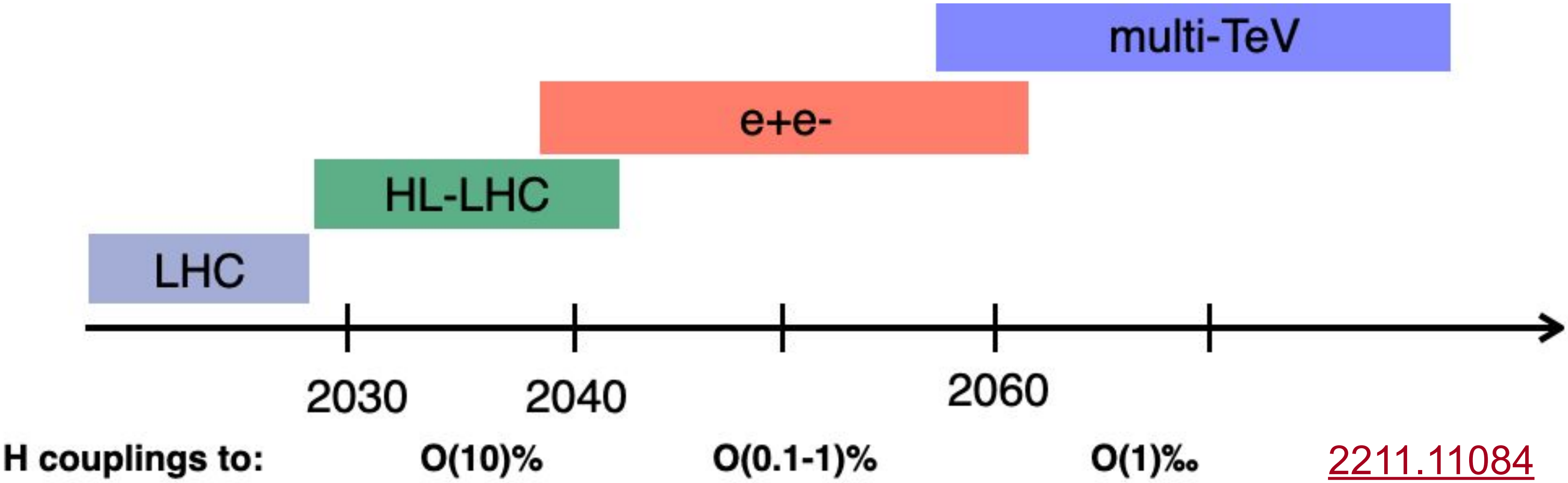
Snowmass Energy Frontier Vision

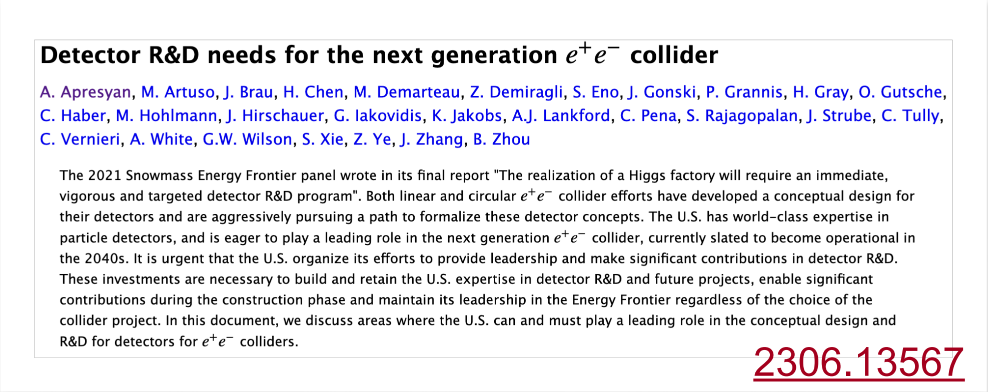
1. "Fast start for construction of an e^+e^- Higgs factory"
2. "Significant R&D program for multi-TeV colliders"
3. "Renewed interest and ambition to bring back energy-frontier collider physics to the **US soil**"



2211.11084

US Higgs Factory Organization

- US Higgs factory "coordination group" to provide budgetary inputs to P5
  - Now formalized as developing **US Higgs Factory Steering Committee** (Monday plenary)



Detector R&D needs for the next generation e^+e^- collider

A. Apresyan, M. Artuso, J. Brau, H. Chen, M. Demarteau, Z. Demiragli, S. Eno, J. Gonski, P. Grannis, H. Gray, O. Gutsche, C. Haber, M. Hohlmann, J. Hirschauer, G. Iakovidis, K. Jakobs, A.J. Lankford, C. Pena, S. Rajagopalan, J. Strube, C. Tully, C. Vernieri, A. White, G.W. Wilson, S. Xie, Z. Ye, J. Zhang, B. Zhou

The 2021 Snowmass Energy Frontier panel wrote in its final report "The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program". Both linear and circular e^+e^- collider efforts have developed a conceptual design for their detectors and are aggressively pursuing a path to formalize these detector concepts. The U.S. has world-class expertise in particle detectors, and is eager to play a leading role in the next generation e^+e^- collider, currently slated to become operational in the 2040s. It is urgent that the U.S. organize its efforts to provide leadership and make significant contributions in detector R&D. These investments are necessary to build and retain the U.S. expertise in detector R&D and future projects, enable significant contributions during the construction phase and maintain its leadership in the Energy Frontier regardless of the choice of the collider project. In this document, we discuss areas where the U.S. can and must play a leading role in the conceptual design and R&D for detectors for e^+e^- colliders.

2306.13567

- Agreement between CERN and US: "Statement aligned with P5: **should FCC-ee receive a "green-light" following the next update of the European Strategy, U.S. intends to collaborate.**" [Rameika]

An Early Career From Here

An Early Career From Here

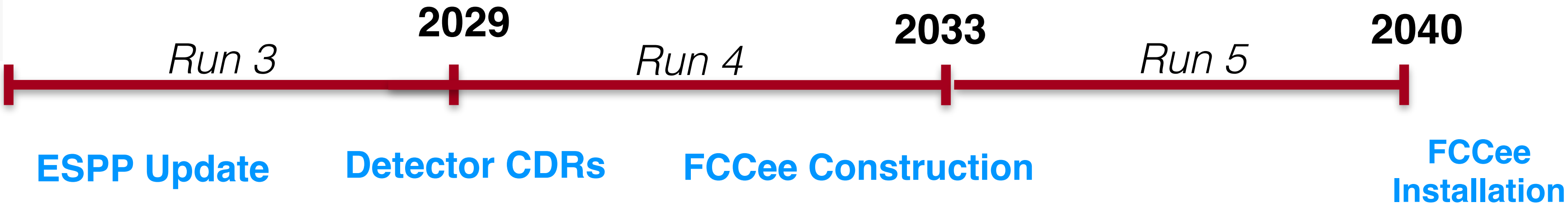
ESPP Update

Detector CDRs

FCCee Construction

FCCee Installation

An Early Career From Here


Run 3

2029

Run 4

2033

Run 5

2040

ESPP Update

Detector CDRs

FCCee Construction

FCCee Installation

PhD

- Physics on Run 3
- Successful installation & commissioning of HL-LHC
- Detector R&D (CPAD), ECFA studies

An Early Career From Here

ESPP Update **Detector CDRs** **FCCee Construction** **FCCee Installation**

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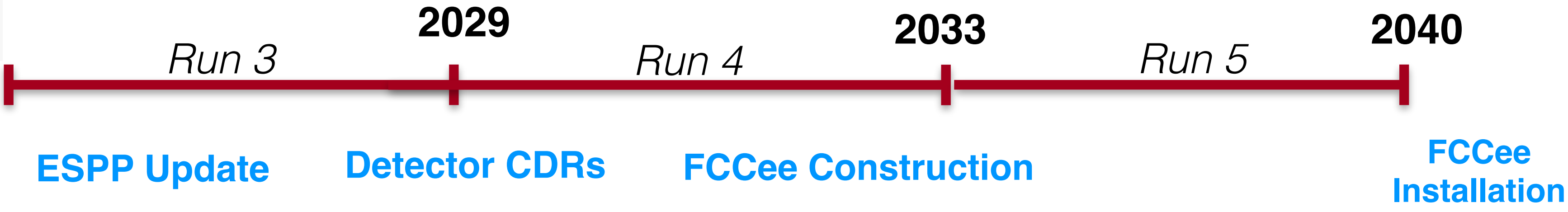
Postdoc

- HL-LHC physics & operations
- Experiment-specific detector prototypes for FCCee

An Early Career From Here



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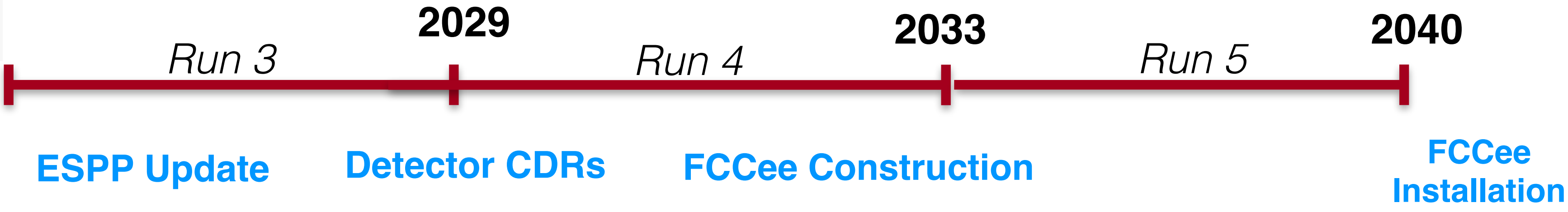
Faculty & Tenure

- Physics on HL-LHC
- Build FCCee detectors
- FCCee experimental leadership/project

An Early Career From Here

LHC EST. 2009 GENEVA SWITZERLAND

FUTURE CIRCULAR COLLIDER



Run 3 **2029** *Run 4* **2033** *Run 5* **2040**

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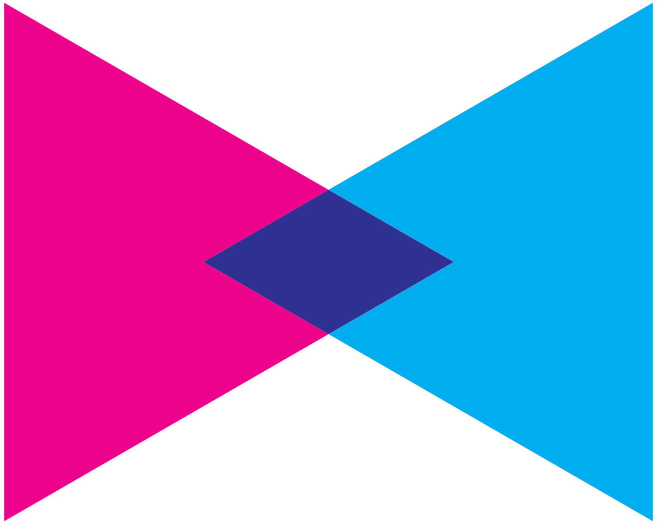
An LHC→FCC career trajectory with lots of physics publications, hardware experience, and leadership opportunities!

Conclusions

- Now is the time to start actively preparing for future colliders
  - Get your physics publications/operations experience from HL-LHC
  - Engage in generic detector & accelerator R&D: pave the way for long-term future of the field
  - As more information becomes available about collider proposals, be ready to capitalize on opportunities
    - Self-nominate for US HFSC positions

- An exciting century of colliders & discoveries ahead!



Backup

Priorities (unordered)

Ongoing (Rec 1)

- **HL-LHC**
- Dune Phase 1
- Vera Rubin/LSST
- Smaller projects: ex. NOvA, IceCube, SuperCDMS, Belle II, LHCb, Mu2e, etc.

Construction (Rec 2)

1. CMB-S4
2. DUNE Phase-II
3. **Off-shore Higgs factory**
4. Gen-3 direct detection DM (preferably US-sited)
5. IceCube-Gen2

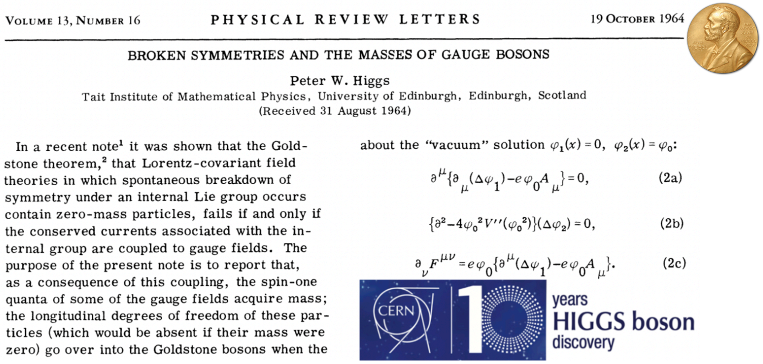
R&D (Rec 4)

- **Cost-effective 10 TeV pCM collider: demonstrator within 10 years**
- Theory
- General Accelerator R&D (GARD)
- Instrumentation for scientific tools
- **Detectors for Higgs factory & 10 TeV pCM**
- Cyberinfrastructure/novel data analysis
- Fermilab accelerator complex

Second Decade of the Higgs Boson

- Higgs boson observation in 2012 by ATLAS & CMS "completes" the Standard Model
  - Measurement of Higgs couplings to bosons (gluons, photons, W/Z) and heaviest fermions (taus, tops, bottoms)
- Higgs has unique connection to remaining BSM questions

➡ P5: "Higgs boson physics can only be studied at high-energy collider experiments"



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

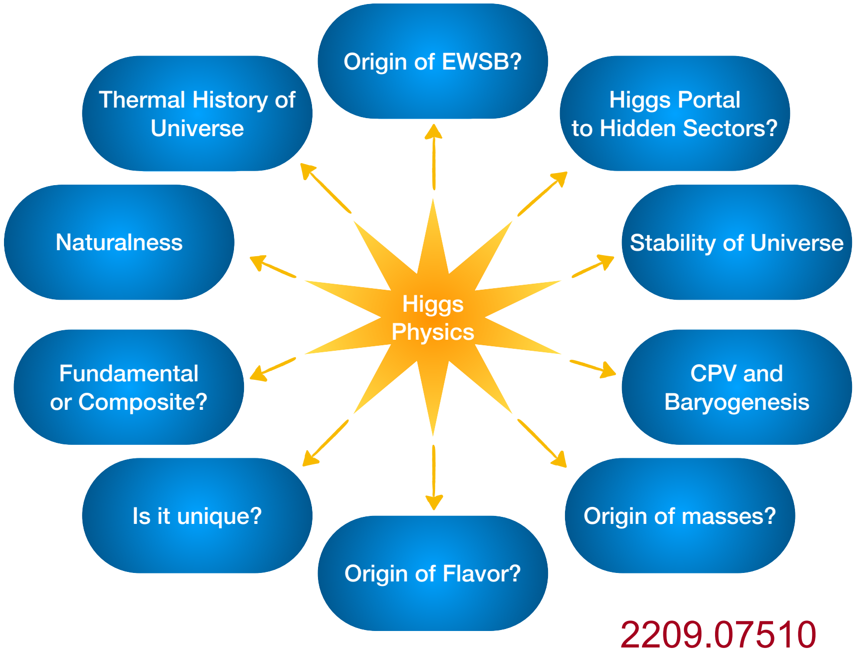
In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental or Composite?

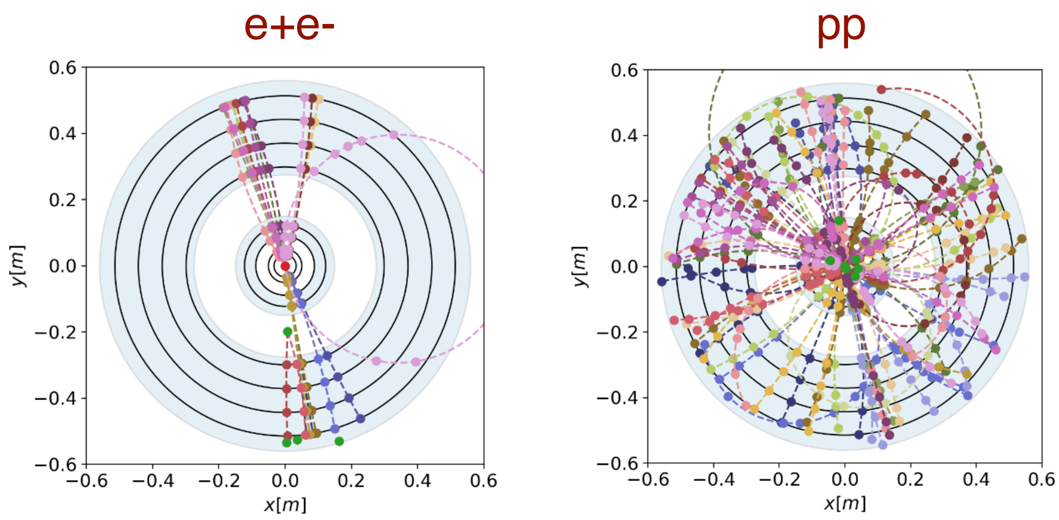
Naturalness

Thermal History of Universe

2209.07510

Why Higgs Factory?

- Electron-positron factory with CoM energy range of 90-350 GeV (scanning Z, WW, H, top production)
- Higgs/precision physics:
  - 10x improvement on Higgs mass/couplings; indirect evidence of new physics through deviations in high-precision measurements
- Beyond the SM searches:
  - Unique sensitivity via clean environment & large luminosities to light, feebly coupled, and/or long-lived particle final states
    - Higgs decay to invisible (ex. dark matter) improved 10x over HL-LHC



(a) $e^+e^- \to \chi_1^+\chi_1^-$

(b) $pp \to \chi_1^+\chi_1^-$

P5 2023 Figure 1: Experiments

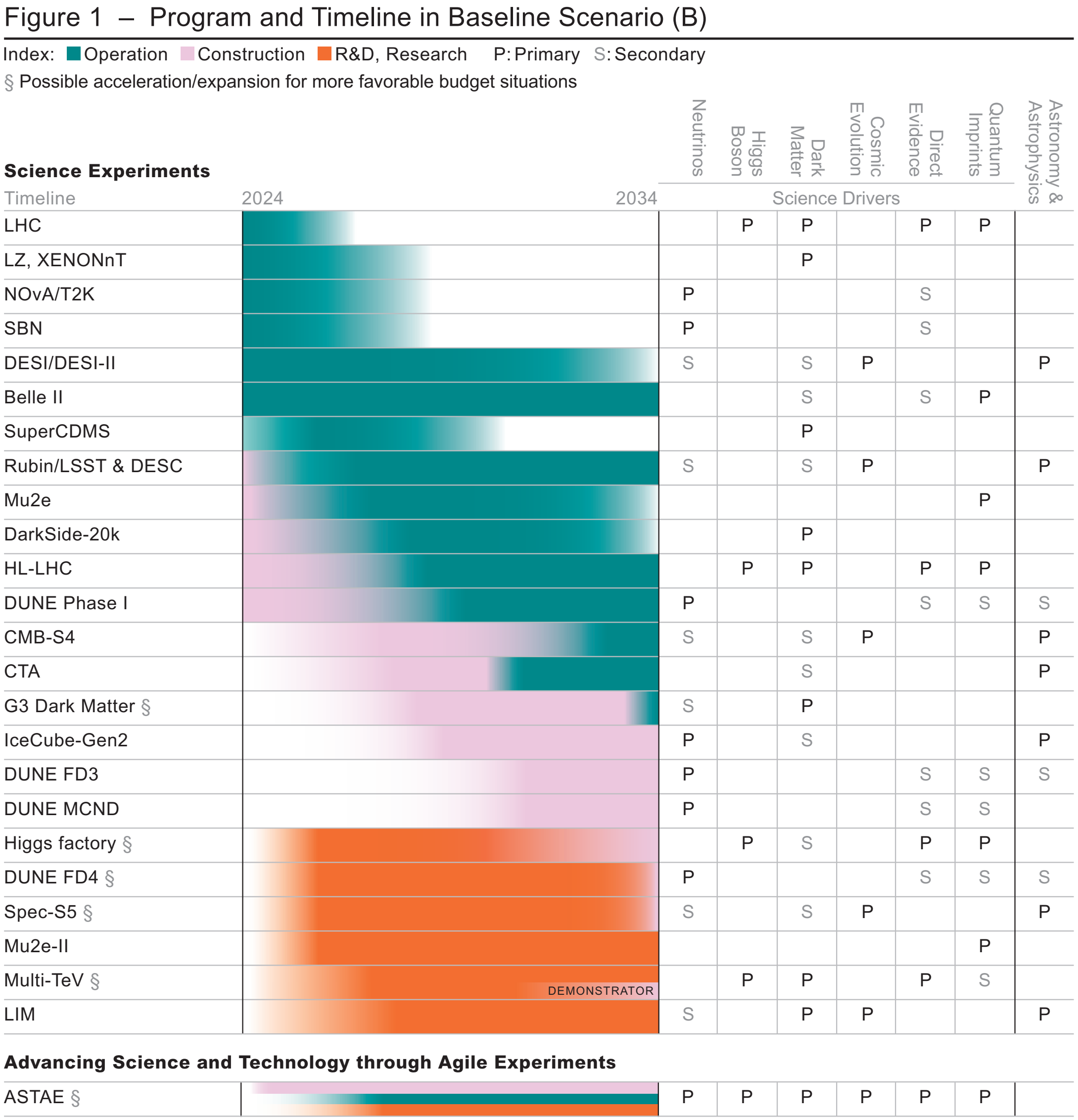


Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: 🟩 Operation ▨ Construction 🟧 R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments

Timeline	2024 – 2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC			P	P		P	P	
LZ, XENONnT				P				
NOvA/T2K		P				S		
SBN		P				S		
DESI/DESI-II		S		S	P			P
Belle II				S		S	P	
SuperCDMS				P				
Rubin/LSST & DESC		S		S	P			P
Mu2e							P	
DarkSide-20k				P				
HL-LHC			P	P		P	P	
DUNE Phase I		P				S	S	S
CMB-S4		S		S	P			P
CTA				S				P
G3 Dark Matter §		S		P				
IceCube-Gen2		P		S				P
DUNE FD3		P				S	S	S
DUNE MCND		P				S	S	
Higgs factory §			P	S		P	P	
DUNE FD4 §		P				S	S	S
Spec-S5 §		S		S	P			P
Mu2e-II							P	
Multi-TeV §	DEMONSTRATOR		P	P		P	S	
LIM		S		P	P			P

Science Drivers

Advancing Science and Technology through Agile Experiments

		Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
ASTAE §		P	P	P	P	P	P	

P5 2023 Figure 1: Initiatives

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: 🟩 Operation 🟪 Construction 🟧 R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Approximate timeline of the recommended program within the baseline scenario. Projects in each category are in chronological order. For IceCube-Gen2 and CTA, we do not have information on budgetary constraints and hence timelines are only technically limited. The primary/secondary driver designation reflects the panel's understanding of a project's focus, not the relative strength of the science cases. Projects that share a driver, whether primary or secondary, generally address that driver in different and complementary ways.

P5 2023 Figure 2: Construction

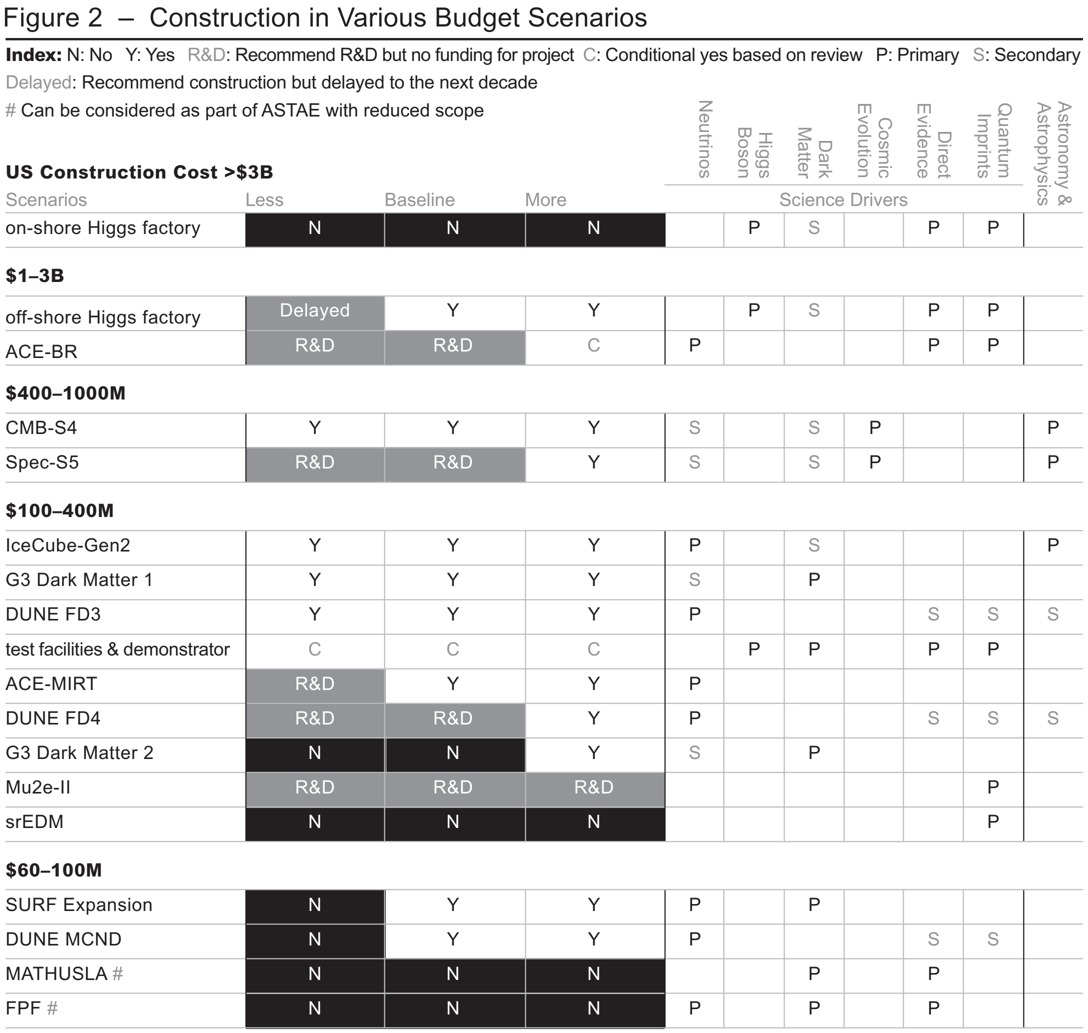


Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

Science Drivers

Medium and large-scale US investments in new construction projects for possible budget scenarios. The projects are ordered in three budget brackets according to the number of "N" entries and then by approximate budget sizes. For the off-shore Higgs factory, test facilities & demonstrators, see Recommendation 6. See the caption of Figure 1 concerning the science drivers, and Section 8 for the rationale behind these choices.

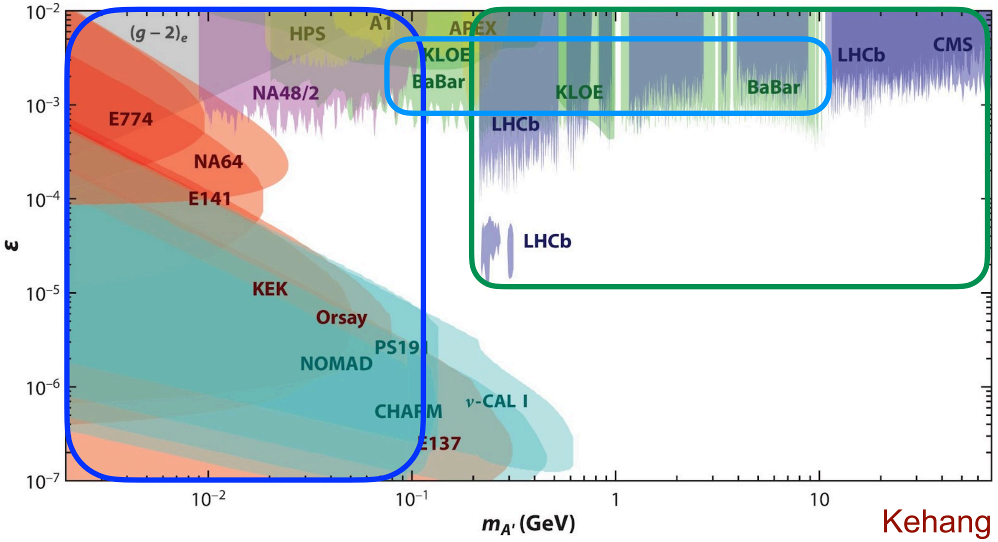
Balanced Program (Rec 3)

- P5 6.2: New small-project portfolio @ DOE “Advancing Science and Technology through Agile Experiments” (ASTAE) [$35 million/year]
- LHC-adjacent experiments and/or proposed Forward Physics Facility (FPF) @ CERN: several decades improvement on LLP benchmarks
- Extracting physics from excess particles at PIP-II or in wakefield demonstrators: new opportunity for beam dump experiments

➡ *Small-scale experiments offer unique physics reach, opportunity for leadership, & invaluable experience with instrumentation*

THE MILLIQAN EXPERIMENT
FASER
SND@ LHC
SHiP Search for Hidden Particles
CODEX−b
MATHUSLA
ANUBIS
FACET
B. Sh

Dark Photon Exclusion



Beam dumps, meson decay, fixed target, …

e+e- colliders & B factories

LHC Experiments

Kehang Bai

AR Graham M, et al. 2021 *Annu. Rev. Nucl. Part. Sci. 71:37–58*

Detector R&D

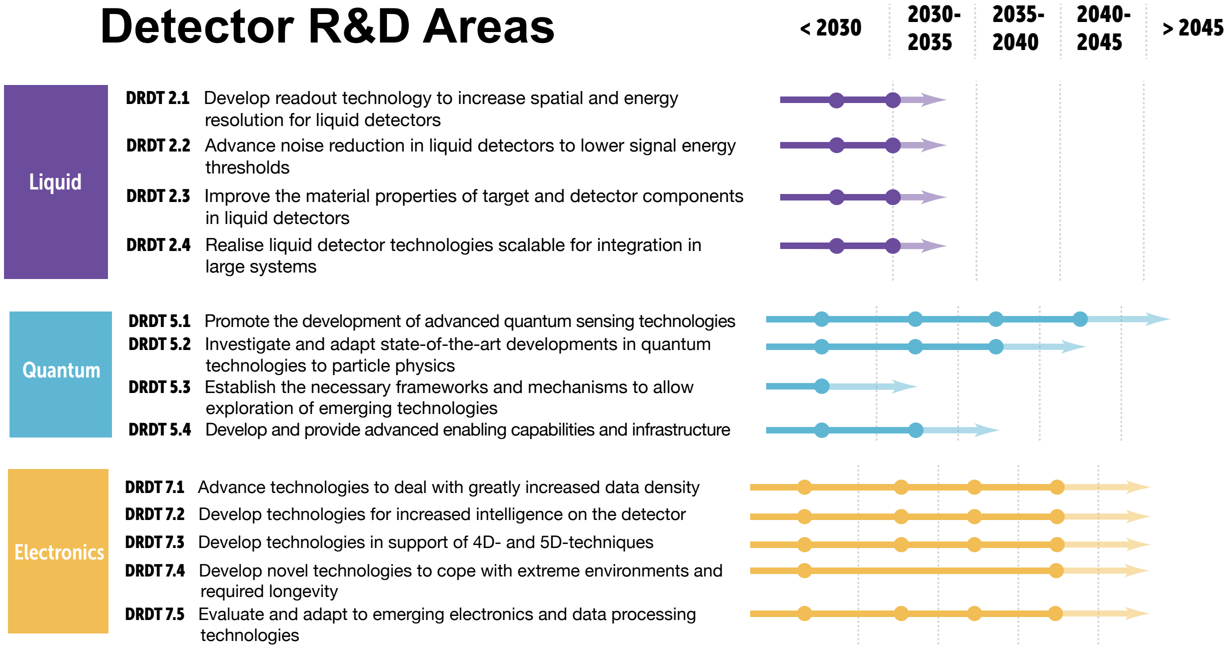
- Need to **R&D detector technologies** that can meet the pressing requirements of future collider environments [$20 million/year]
  - High channel density, high data rate, spatial constraints, high radiation, cryogenic temperatures…
- APS DPF Coordinating Panel on Advanced Detectors (CPAD) organizing R&D Collaborations (RDCs) to coordinate progress on key DOE Basic Research Needs topics: **ongoing now**

➡ Accelerator-generic detector R&D can facilitate the latest & greatest instrumentation for the benefit of all HEP subfields

Next-gen neutrino/LAr TPC detectors

Quantum sensor/ infrastructure for dark matter/computing

“Fast ML” for neutrino/ cosmology experiments & monitoring



Detector R&D Areas

DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors

DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds

DRDT 2.3 Improve the material properties of target and detector components in liquid detectors

DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems

DRDT 5.1 Promote the development of advanced quantum sensing technologies

DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics

DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies

DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure

DRDT 7.1 Advance technologies to deal with greatly increased data density

DRDT 7.2 Develop technologies for increased intelligence on the detector

DRDT 7.3 Develop technologies in support of 4D- and 5D-techniques

DRDT 7.4 Develop novel technologies to cope with extreme environments and required longevity

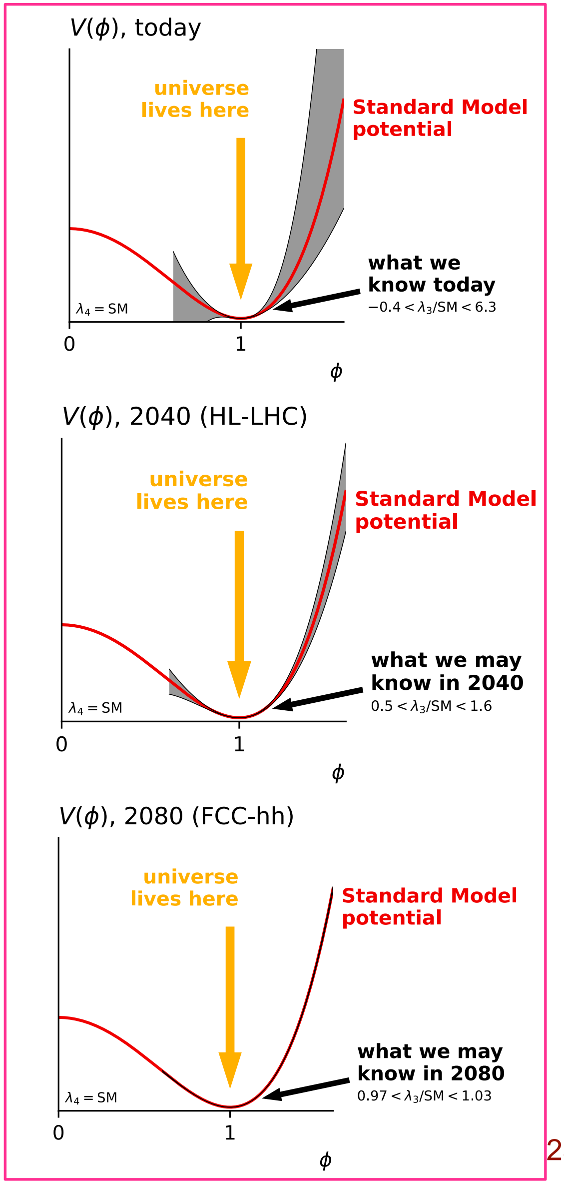
DRDT 7.5 Evaluate and adapt to emerging electronics and data processing technologies

Towards 10 TeV pCM

- Ultimate direct discovery reach of TeV scale phenomena
- Possible with hadron (FCC-hh @ 100 TeV) or muon colliders, but R&D is needed

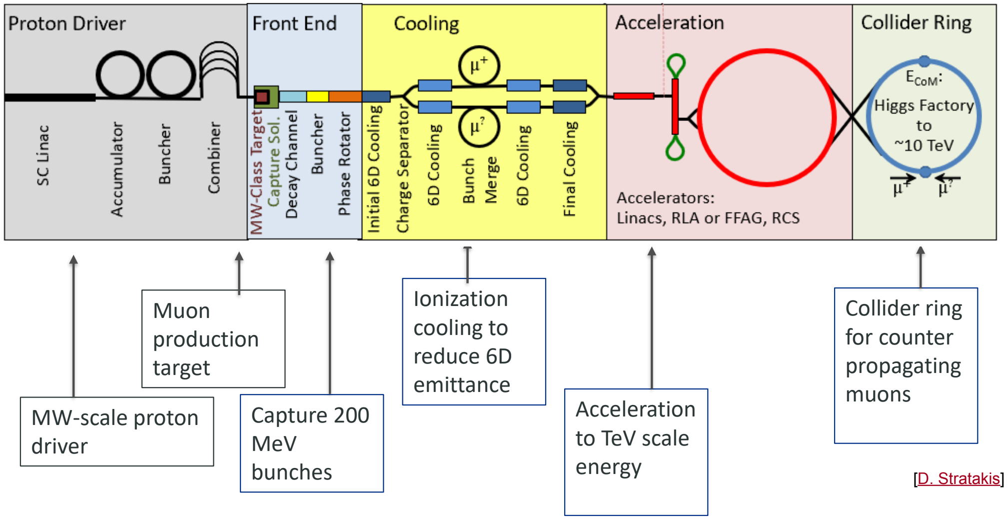
- Higgs physics:
  - Probe the electroweak phase transition; Higgs self coupling measurements to 5% precision

- Direct beyond the SM searches:
  - Direct discovery of the particles responsible for any deviations observed in Higgs factory
  - Dark matter: “reach the thermal WIMP target for minimal WIMP candidates”



Muon Collider

- Best of both worlds: cleanness of leptons, no PDFs as in hadron collider
    - But muons decay! Considerable challenge to accelerate & build detectors
- P5 2.3: “This P5 plan outlines an aggressive R&D program… **for a muon collider test facility by the end of the decade**. This facility would test the feasibility of **developing a muon collider in the following decade**.”
- P5 2.5: “…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 → initiating demonstrator facilities within a 10-year timescale.”



MW-scale proton driver

Muon production target

Capture 200 MeV bunches

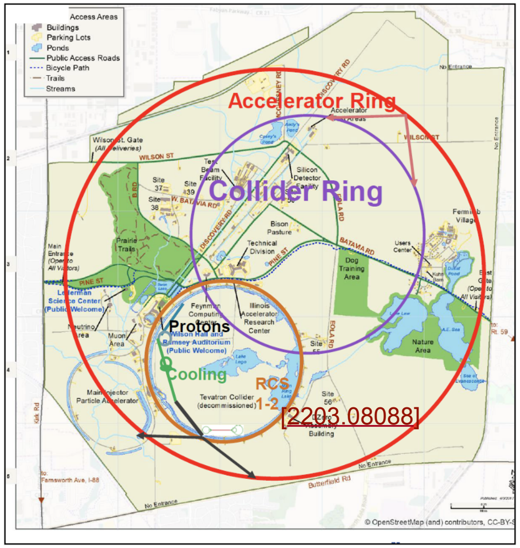
Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

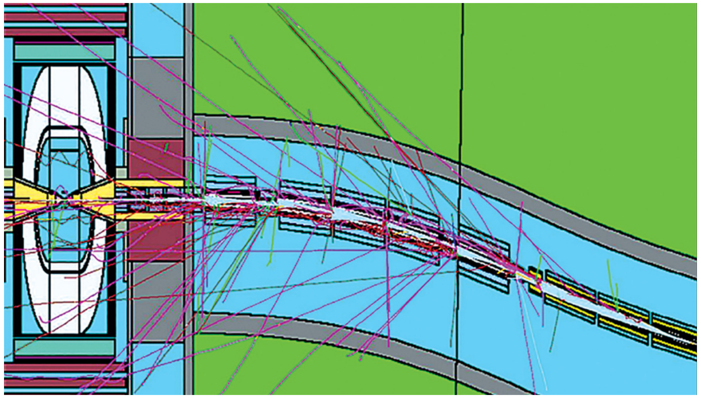
[D. Stratakis]

μC @ Fermilab

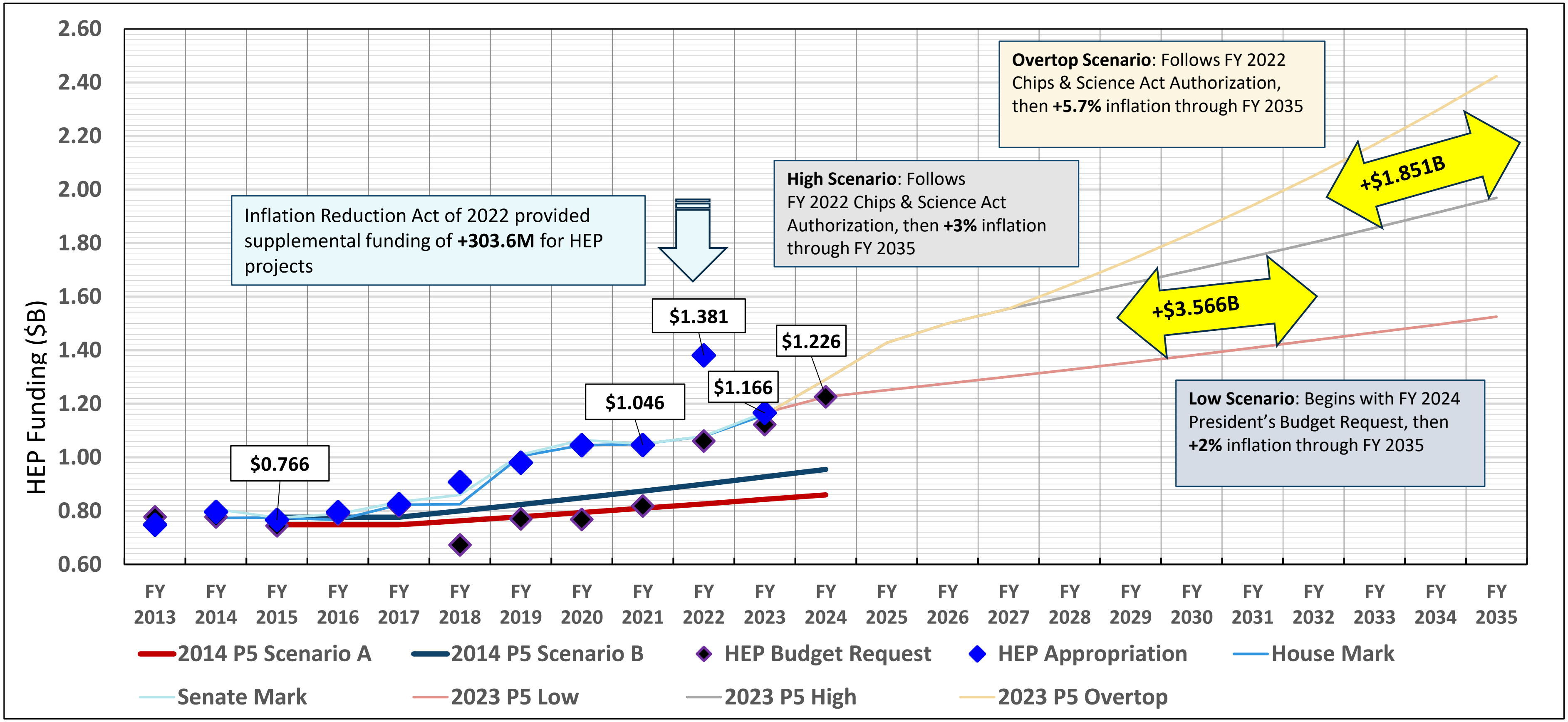


[2203.08088]

μC Beam- Induced Background



P5 Budget Scenarios



Overtop Scenario: Follows FY 2022 Chips & Science Act Authorization, then **+5.7%** inflation through FY 2035

High Scenario: Follows FY 2022 Chips & Science Act Authorization, then **+3%** inflation through FY 2035

Inflation Reduction Act of 2022 provided supplemental funding of **+303.6M** for HEP projects

Low Scenario: Begins with FY 2024 President's Budget Request, then **+2%** inflation through FY 2035

Collider Implementation Task Force Report

- Comprehensive evaluation & comparisons of collider options from Snowmass Accelerator Frontier
- Assessment categories:
  1. Years of pre-project R&D needed (technical risk and maturity)
  2. Years until first physics (technically limited schedule)
  3. Project cost in 2021B$ w/o contingency and escalation (cost)
  4. Total operating electric power consumption in MW (environmental impact)

Higgs Factories

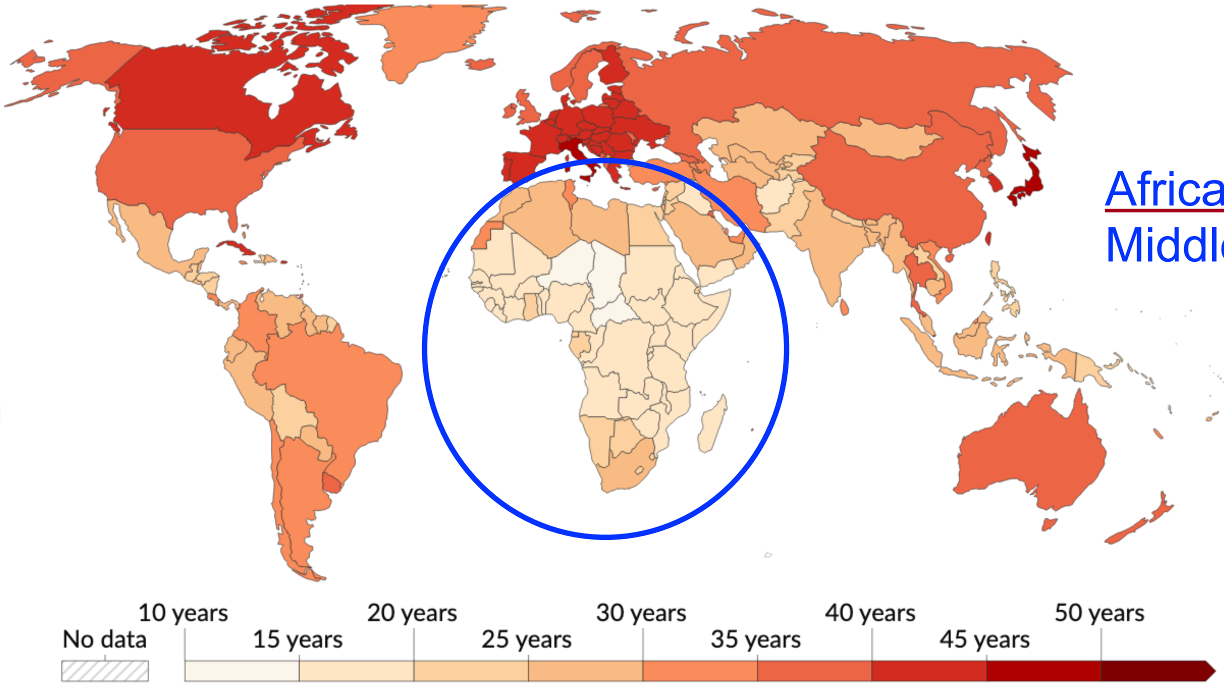
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee^{1,2}	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC^{1,2}	0.24 (0.09-0.37)	8.3 (16.6)	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

[T. Roser]

Global Early Career Pipeline

- In order to fully pursue the bold aspirations of 2023 P5, we need a robust *global* pipeline of early career scientists to take on future collider projects
- Now more than ever, we need to step up outreach to the leading populations/economies of tomorrow

Mean Age of Global Population



Africa & the Middle East

ASFAP
African Strategy for Fundamental and Applied Physics

Collider Implementation Task Force Report

- Comprehensive evaluation & comparisons of collider options from Snowmass Accelerator Frontier
- Assessment categories:
  1. Years of per-project R&D needed (technical risk and maturity)
  2. Years until first physics (technically limited schedule)
  3. Project cost in 2021B$ w/o contingency and escalation (cost)
  4. Total operating electric power consumption in MW (environmental impact)

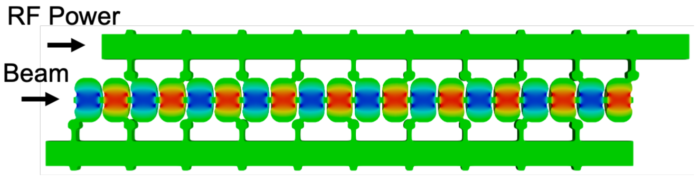
Multi-TeV Colliders

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

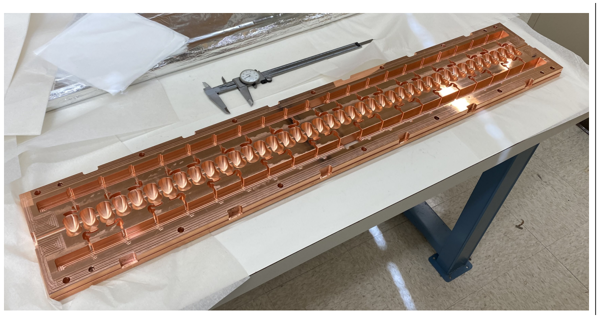
[T. Roser]

C^3 (Cool Copper Collider)

- New concept for linear e+e- collider with “normal-conducting” RF cavities for a more compact design than superconducting options
    - Minimize surface fields, low breakdown at high gradient (70-110 MeV/m)
    - 7 km footprint possible (fits on Fermilab site)
- **Estimated start of physics**: 2040 (technically limited)
- **Cost:** \$7-12 B
- **Primary unknown:** new technology requires demonstrator facility (~5 year/50 m scale/\$120 M)
    - *Compatible with FCC-ee injector selection timeline*

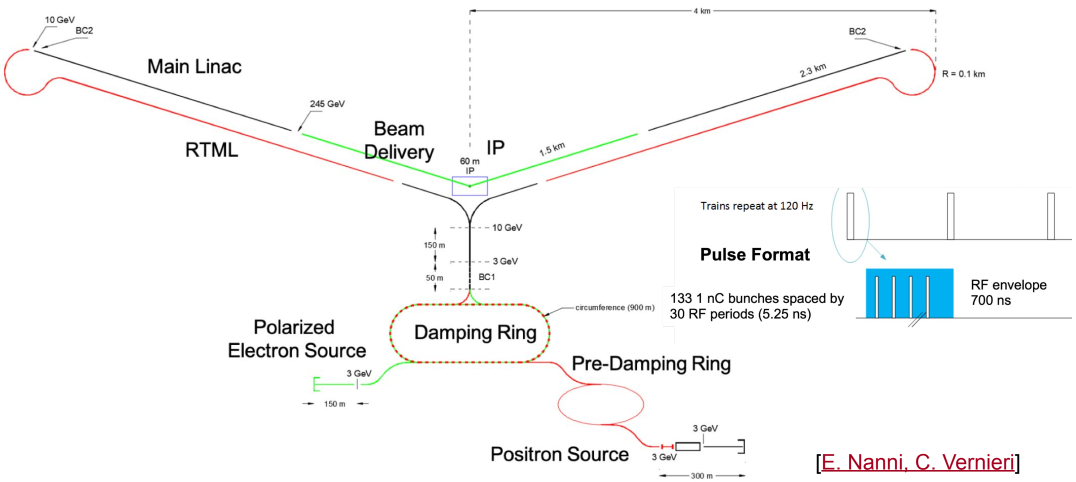


Electric field magnitude for equal power from RF manifold



JINST (2023) P07053, 18(07)

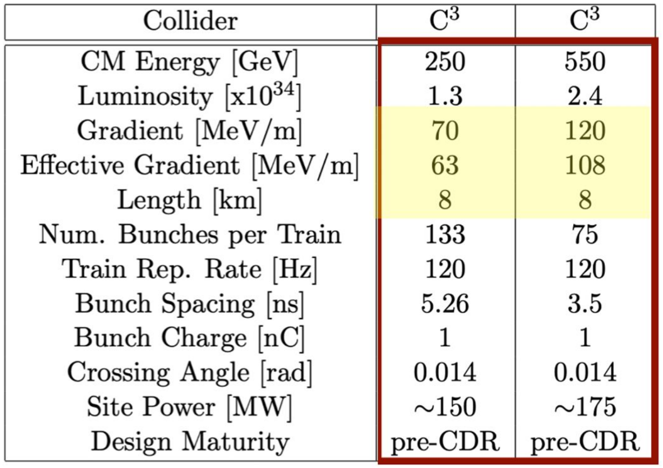
C^3 - 8 km Footprint for 250/550 GeV



[E. Nanni, C. Vernieri]

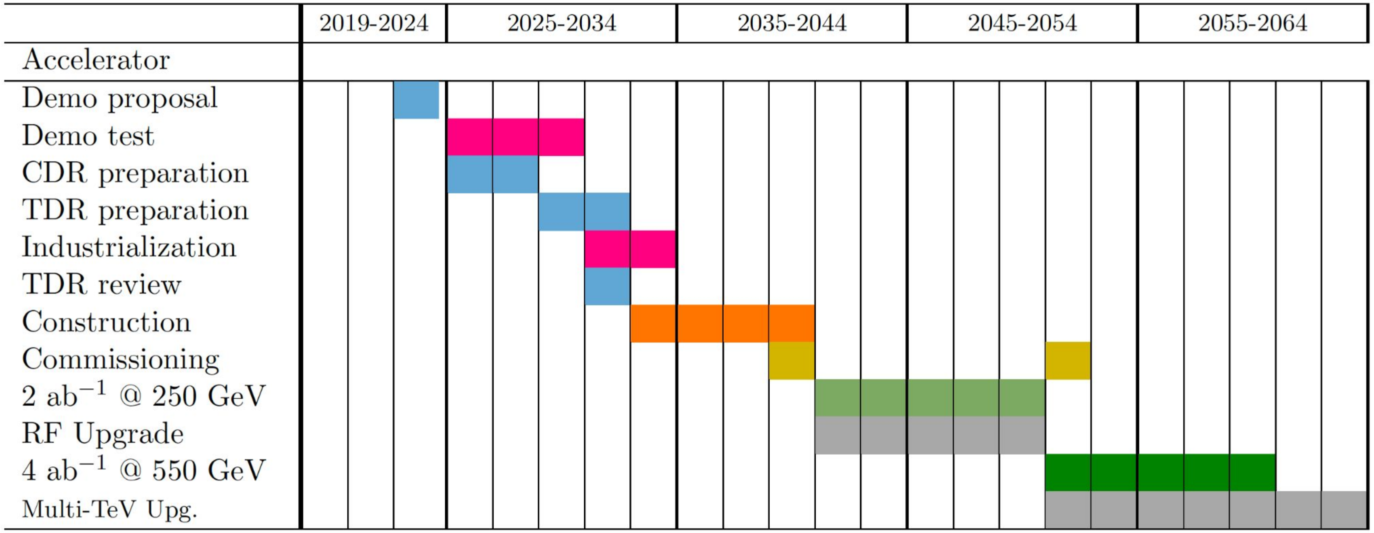
C^3 Specs & Timeline

C^3 Parameters



Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

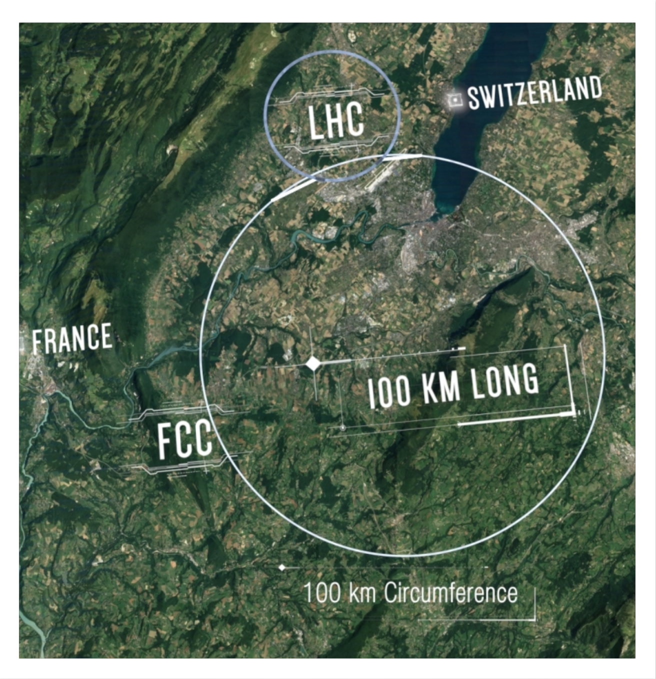
- C^3 provides a rapid route to precision Higgs physics with a compact 8 km footprint
  - Higgs physics run by 2040
  - US-hosted facility possible
- C^3 time structure is compatible with ILC-like detector design and optimizations ongoing
- C^3 upgrade to 550 GeV with only added rf sources
  - Higgs self-coupling and expanded physics reach
- C^3 is scalable to multi-TeV
- C^3 Demo advances technology beyond CDR level
  - 5 year program, followed by completion of TDR and industrialization
  - Three stages with quantitative metrics and milestones for decision points
  - Direct and synergistic contributions to near-term collider concepts



[E. Nanni, C. Vernieri]

Future Circular Collider (ee)

- From European Strategy: “An **electron-positron Higgs factory** is the highest-priority next collider. For the longer term… a **proton-proton collider at the highest achievable energy**.”
    - CERN hosted: take advantage of existing injection system/ infrastructure
- **Estimated start of physics**: 2045
- **Cost**: 12 BCHF for tunnel and FCC-ee (tunnel excavation is large percentage of total cost) (Conceptual Design Report [2018])
- ~~Primary unknown~~ Established technology, but R&D can increase efficiency/reduce cost
    - ❗ FCC-ee @ 250 GeV ≃ 300 MW (~2% of annual electricity consumption in Belgium)



	√s		L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV	Z	182 x 10^{34}	22	2-4 experiments
	160	WW	19.4	2.3	
	240	H	7.3	0.9	**Total ~ 15 years of operation**
	~365	top	1.33	0.16	

LEP statistics in ~few minutes!

[F. Gianotti]

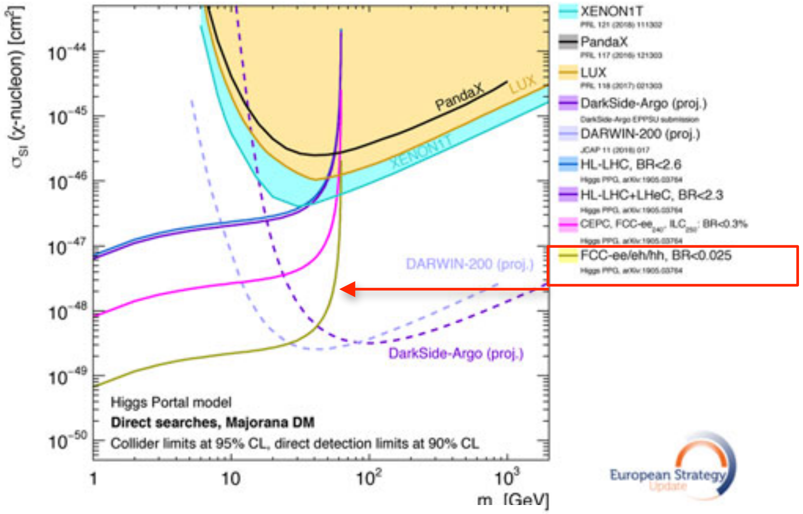
Future Circular Collider (hh)

- Proton-proton synchrotron with √s = 100 TeV
- **Estimated start of physics**: 2070
- **Cost**: 17 BCHF additional for FCC-hh (CDR [2018])
- **Primary unknowns**:
    - Very high-field superconducting magnets: 14 - 20 T
    - Stored beam energy: 8 GJ →machine protection
    - High energy consumption: 4 TWh/year

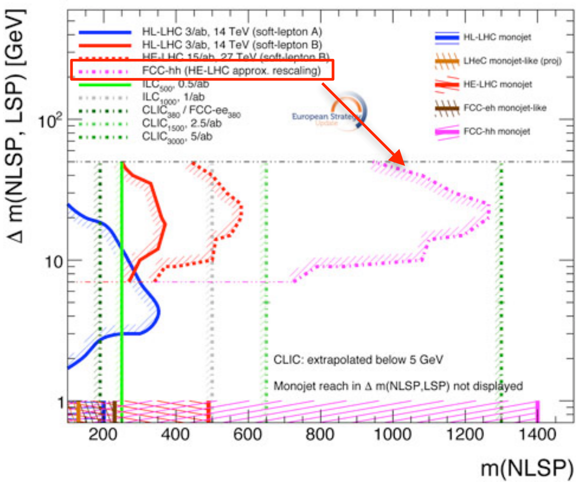
➡FCC Feasibility Study

- Geological, technical, environmental and administrative feasibility of the tunnel and surface areas
- Mid-term review 2023; final results 2025

WIMP Simplified Model Projections

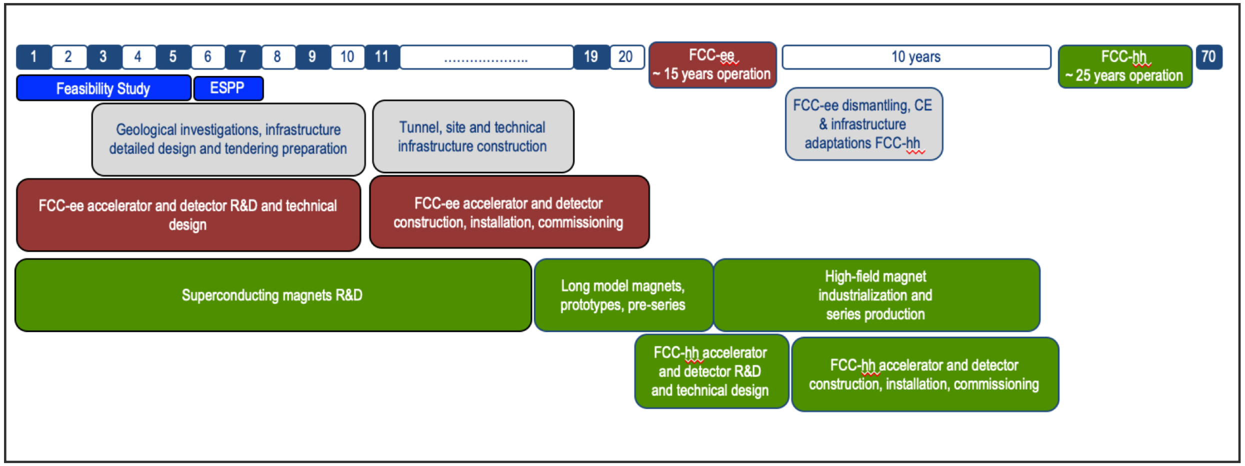


EWK SUSY Projections



[2306.12897]

FCC Scheduling & Timeline


1 2 3 4 5 6 7 8 9 10 11 .... 19 20

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

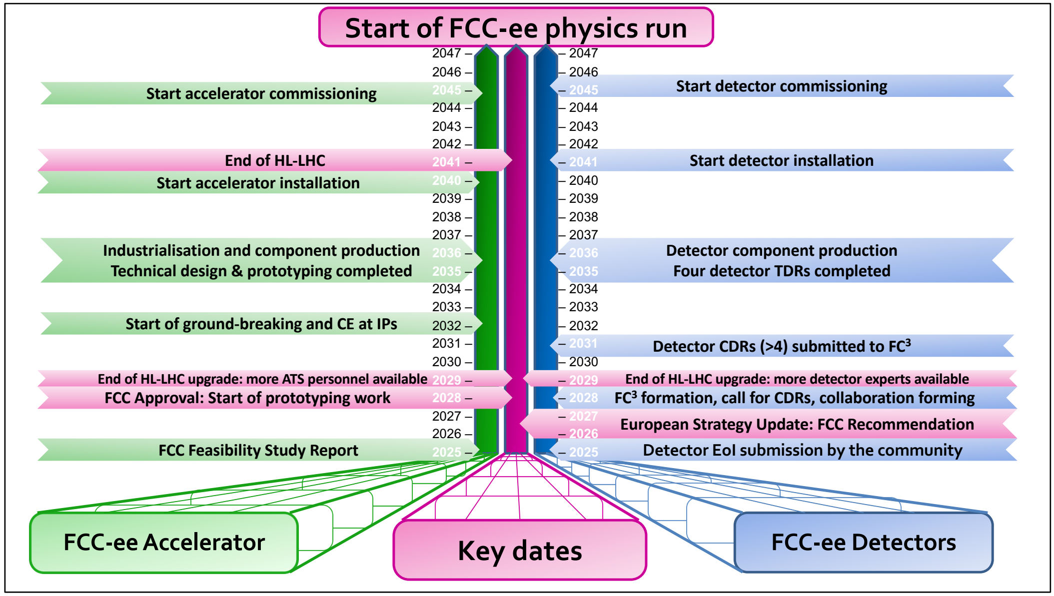
High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

Technical schedule:
FCC-ee could start operation **in 2040 or earlier**

[F. Gianotti]


Start of FCC-ee physics run

2045 Start accelerator commissioning

2041 End of HL-LHC

2040 Start accelerator installation

2036 Industrialisation and component production

2035 Technical design & prototyping completed

2032 Start of ground-breaking and CE at IPs

2029 End of HL-LHC upgrade: more ATS personnel available

2028 FCC Approval: Start of prototyping work

2025 FCC Feasibility Study Report

2045 Start detector commissioning

2041 Start detector installation

2036 Detector component production

2035 Four detector TDRs completed

2031 Detector CDRs (>4) submitted to FC^3

2029 End of HL-LHC upgrade: more detector experts available

2028 FC^3 formation, call for CDRs, collaboration forming

2027–2026 European Strategy Update: FCC Recommendation

2025 Detector EoI submission by the community

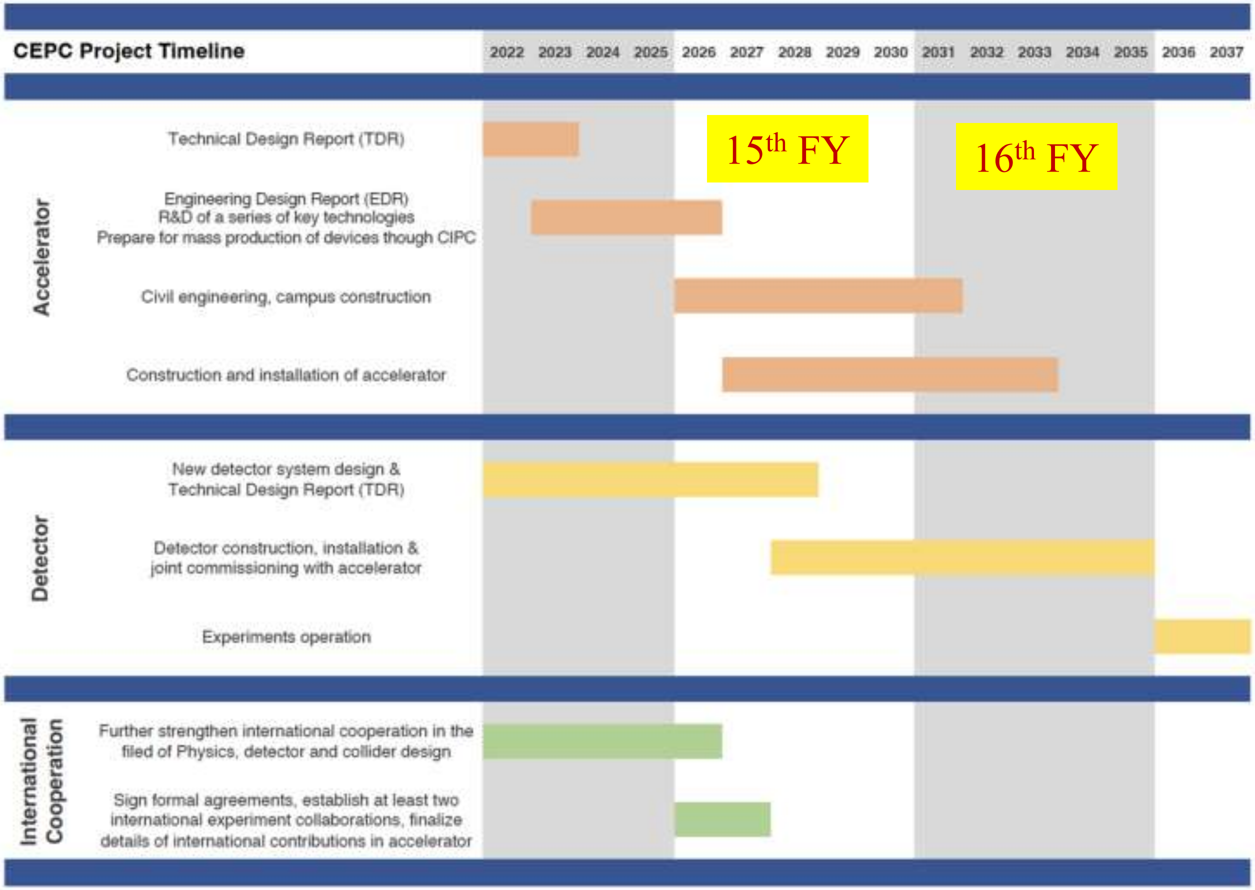
FCC-ee Accelerator

Key dates

FCC-ee Detectors

CEPC/SppC

TDR (2023), EDR(2027), start of construction (2027-8)



15th FY

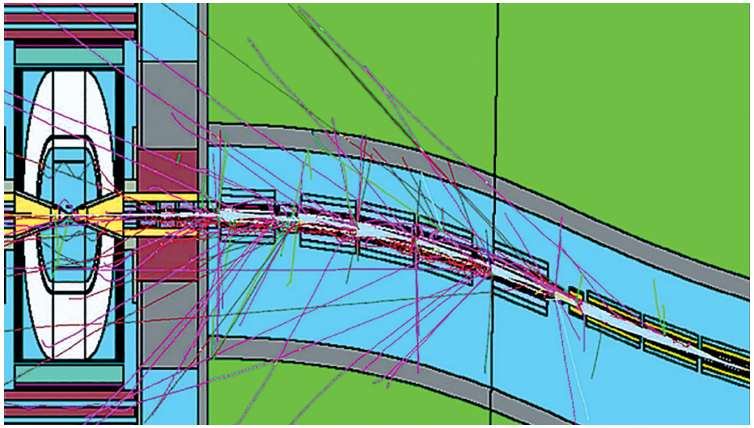
16th FY

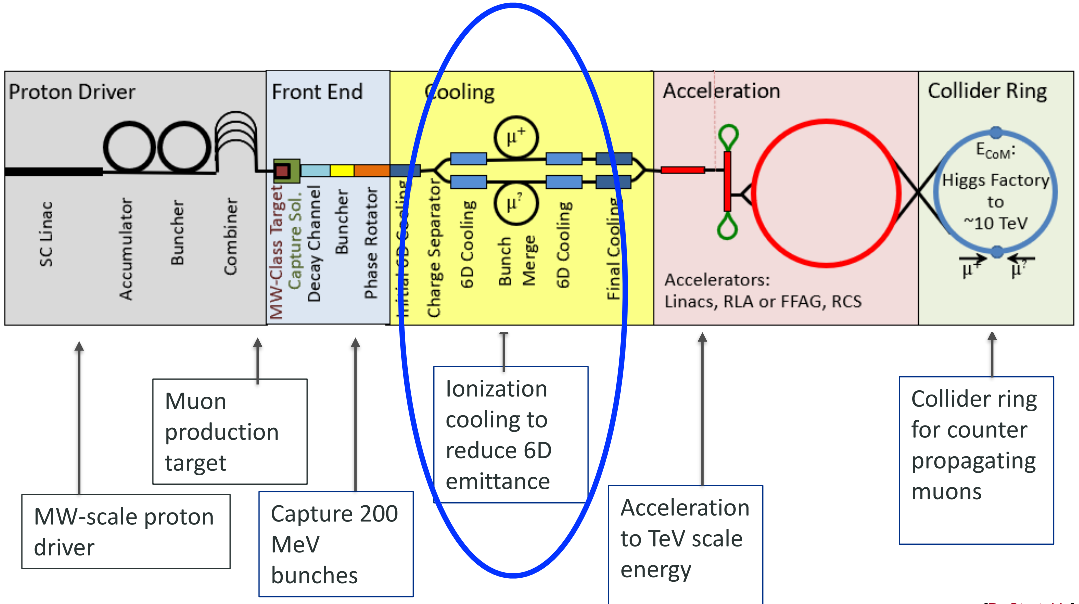
[J. Gao]

Muon Collider (μC)

- Muons are point particles (all energy used in collision) and heavier than electrons (less synchrotron radiation, feasible in circular accelerator)
  - Can provide precision of lepton collider as well as energy reach (10 TeV)
  - *But muons decay!* (τ = 2.2μs) → challenges of accelerating muons & high detector backgrounds
- **Estimated start of physics**: 2045 (technically limited schedule)
  - Needs demonstrator (Technical Design Report in 2030); TDR for final facility in 2040
- **Cost**: $12-18 B
- **Primary unknown:** investment needed to address undemonstrated technologies (eg. muon source and ionization cooling)

μC Beam-Induced Background





MW-scale proton driver

Muon production target

Capture 200 MeV bunches

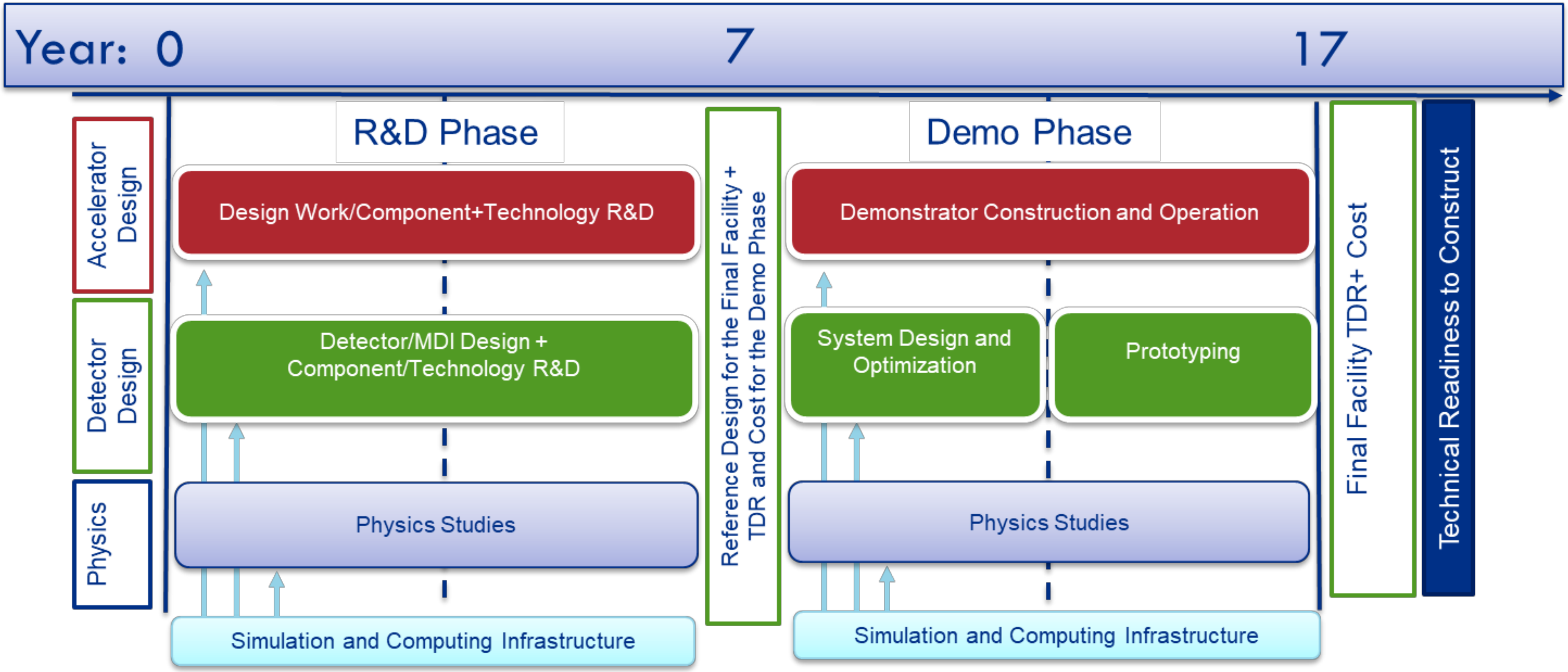
Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

[D. Stratakis]

μ-C Scheduling & Timeline



Year: 0

7

17

Accelerator Design

Detector Design

Physics

R&D Phase

Design Work/Component+Technology R&D

Detector/MDI Design + Component/Technology R&D

Physics Studies

Simulation and Computing Infrastructure

Reference Design for the Final Facility + TDR and Cost for the Demo Phase

Demo Phase

Demonstrator Construction and Operation

System Design and Optimization

Prototyping

Physics Studies

Simulation and Computing Infrastructure

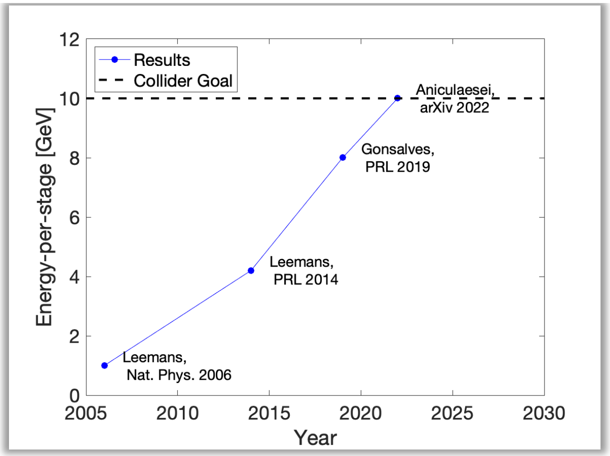
Final Facility TDR+ Cost

Technical Readiness to Construct

Future Accelerator Technology

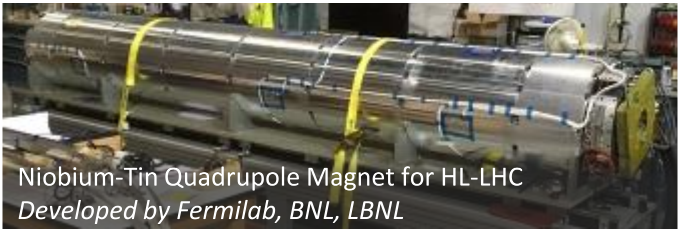
- ➡Current collider technology is not sustainable for long-term
- DOE General Accelerator Research & Development (**GARD**): supports new accelerator concepts & technologies
  - Plasma wakefield accelerators (eg. FACET-II, BELLA): ultra-large gradients (1-100 GeV/m)
    - Recent performance of single-stage accelerators meeting collider goals (right)
  - High-field superconducting magnets (FCC requirement)
  - Superconducting radio frequency (SRF)

S. Gessner


Laser-Driven Plasma

➡*US-based accelerator R&D has exciting potential to enable smaller, cheaper, greener collider options*


Laser-driven Plasma Wakefield Channel *BELLA at LBNL*


Niobium-Tin Quadrupole Magnet for HL-LHC
Developed by Fermilab, BNL, LBNL


LCLS-II SRF Cavity Processing
Photo credit: Fermilab

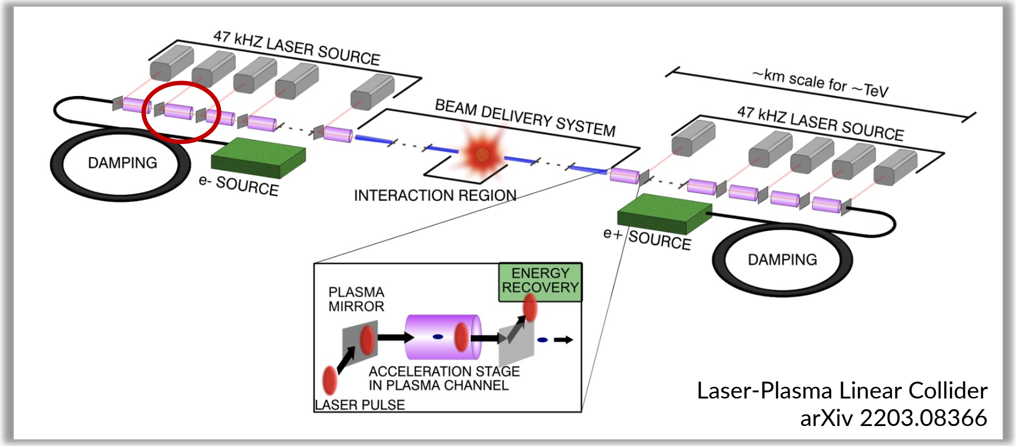
Plasma WakeField Accelerators (PWFA)

Goals

High-Gradient

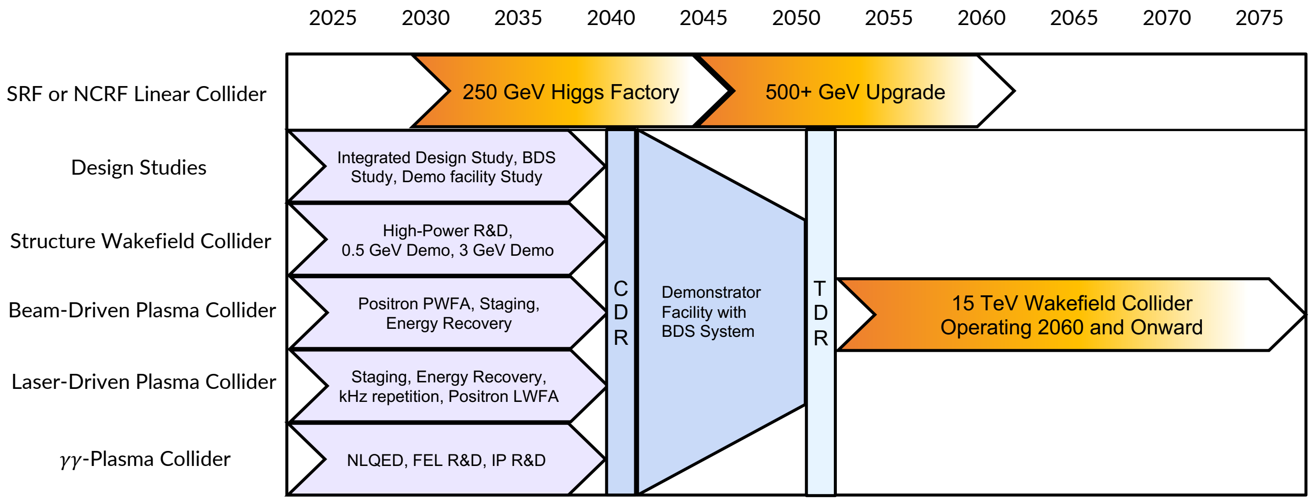
High-Efficiency

Low-Emittance



Laser-Plasma Linear Collider
arXiv 2203.08366

S. Gessner



2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075

SRF or NCRF Linear Collider: 250 GeV Higgs Factory; 500+ GeV Upgrade

Design Studies: Integrated Design Study, BDS Study, Demo facility Study

Structure Wakefield Collider: High-Power R&D, 0.5 GeV Demo, 3 GeV Demo

Beam-Driven Plasma Collider: Positron PWFA, Staging, Energy Recovery

Laser-Driven Plasma Collider: Staging, Energy Recovery, kHz repetition, Positron LWFA

$\gamma\gamma$-Plasma Collider: NLQED, FEL R&D, IP R&D

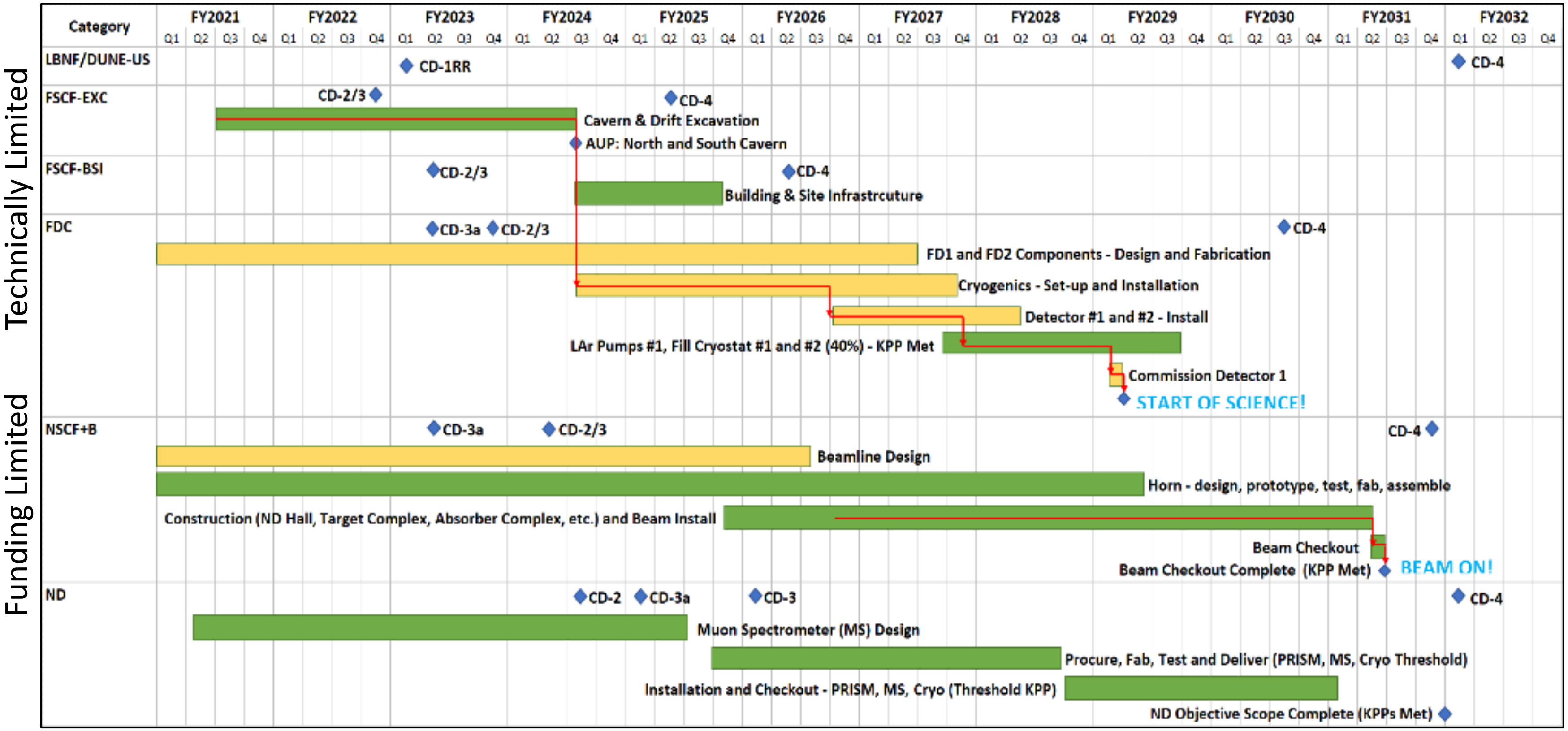
CDR

Demonstrator Facility with BDS System

TDR

15 TeV Wakefield Collider Operating 2060 and Onward

LBNF/DUNE Project Schedule FY21-32

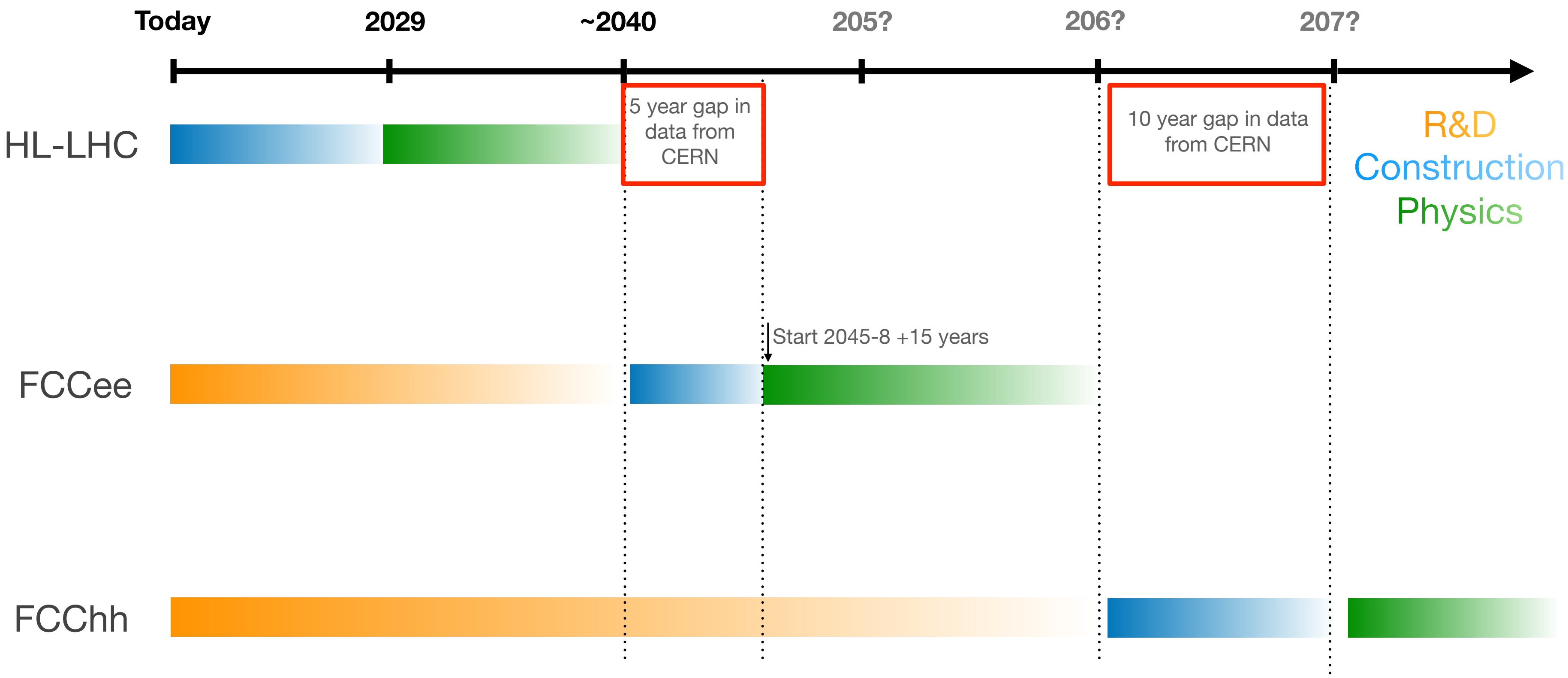


Project CD-4 is defined as Near Detector CD-4 date (last Subproject to finish Early CD4 12/2031 (Dec 2034 late finish at 90% CL)

HEP in Africa

K. Assamagan

An Inclusive Timeline



Today
2029
~2040
205?
206?
207?

HL-LHC
FCCee
FCChh

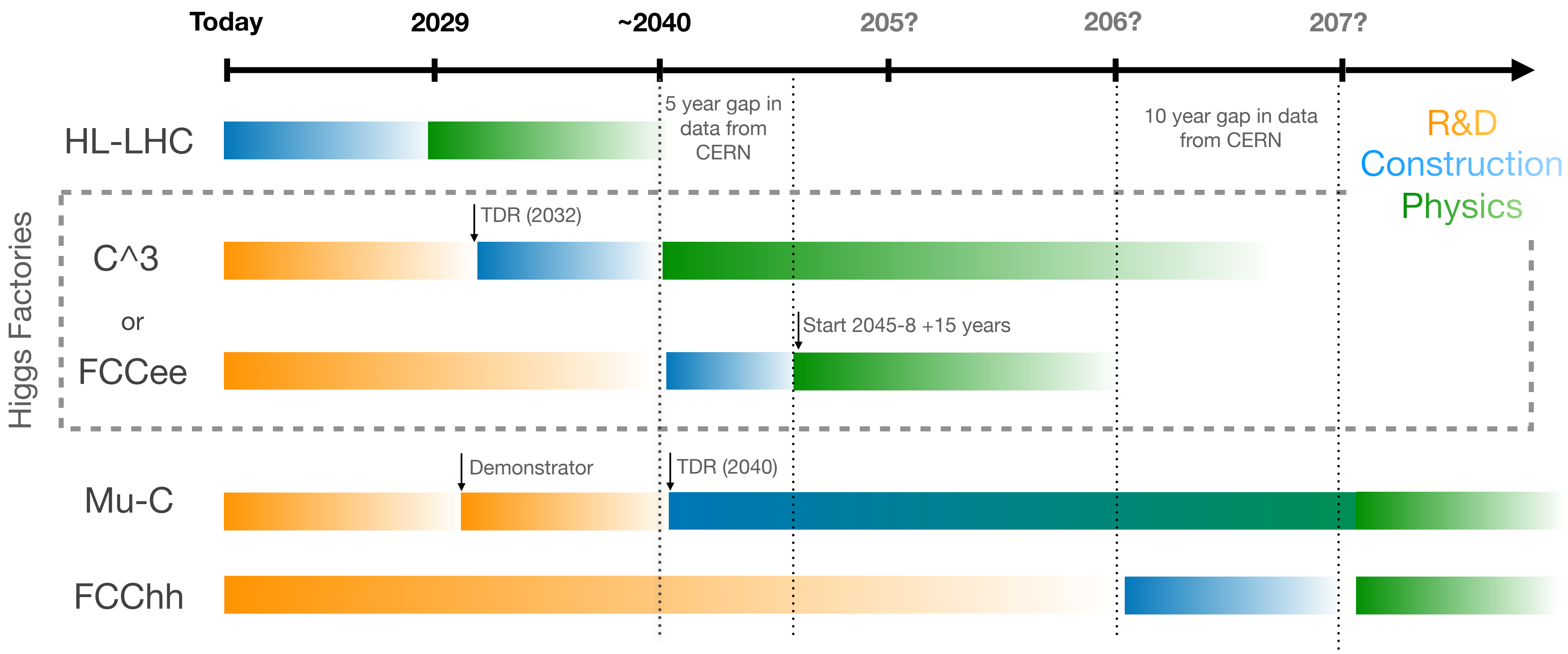
5 year gap in data from CERN

10 year gap in data from CERN

Start 2045-8 +15 years

R&D
Construction
Physics

An Inclusive Timeline



Today

2029

~2040

205?

206?

207?

HL-LHC

5 year gap in data from CERN

10 year gap in data from CERN

R&D

Construction

Physics

Higgs Factories

C^3

TDR (2032)

or

FCCee

Start 2045-8 +15 years

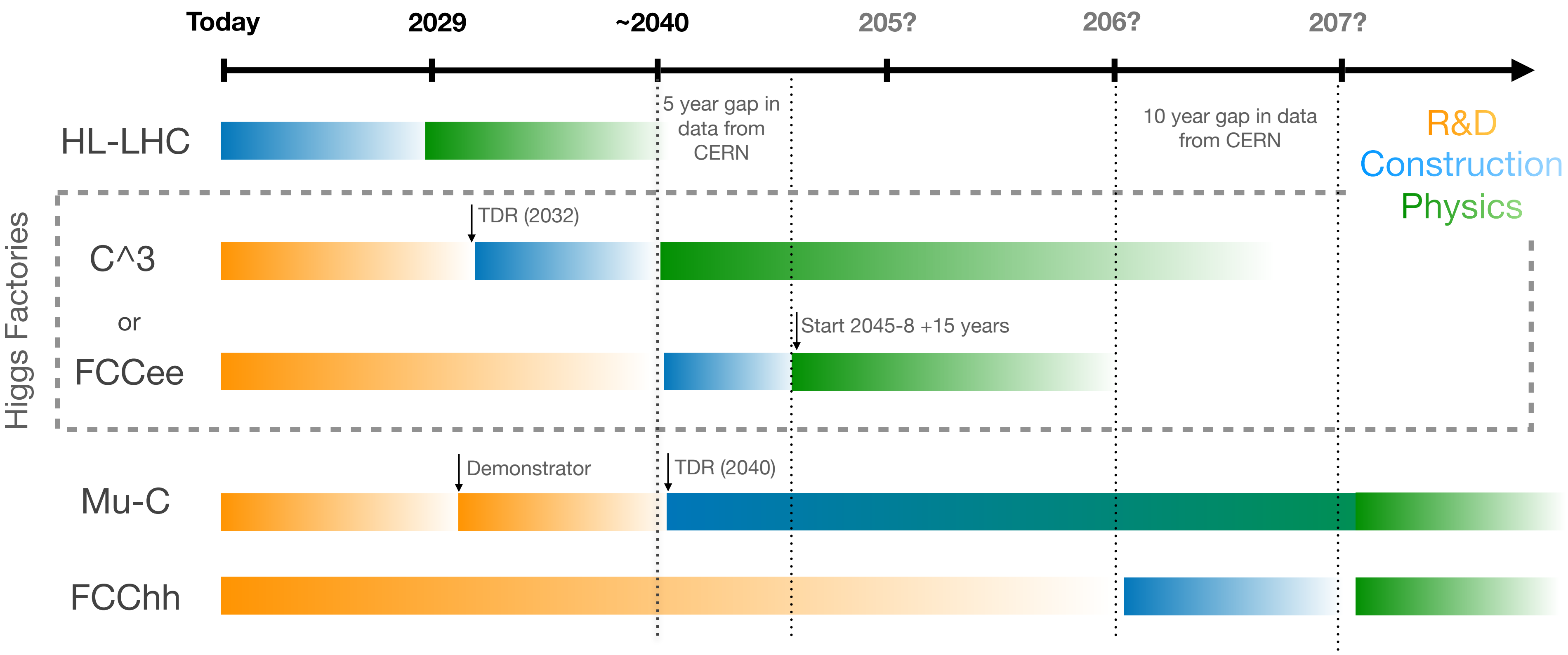
Mu-C

Demonstrator

TDR (2040)

FCChh

An Inclusive Timeline



- Interleaved R&D, construction, and physics so there is *no gap in data across global collider HEP*
- **This is not a flat budget:** leave flexibility for increased lobbying efforts & positive changes in funding expectations

➡ This principle holds for interleaving experiments across frontiers as well!