Colliders for the Future of High Energy Physics

Julia Gonski

4 October 2023

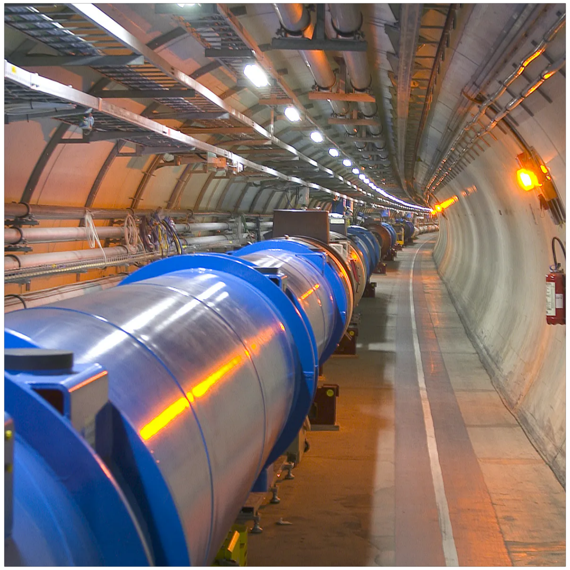
Brookhaven Forum

Outline

- Motivation for future colliders
- Strategic planning processes (US & Europe)
- Options:
  - e^+e^- Higgs factories
  - Multi-TeV colliders
- Synergies (R&D programs, detectors)
- Future & next steps

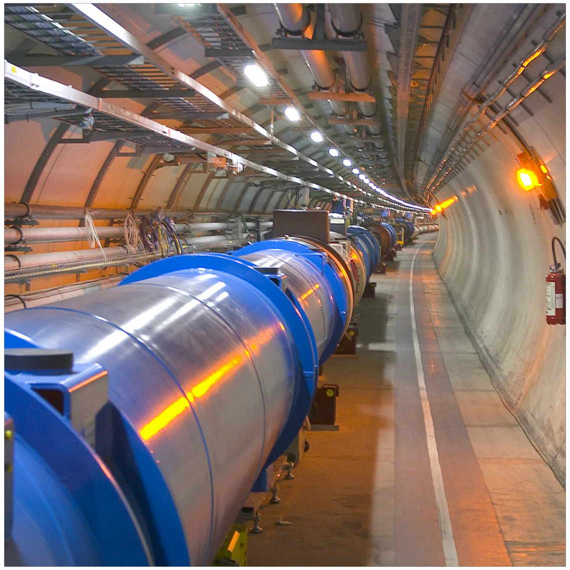
Motivation

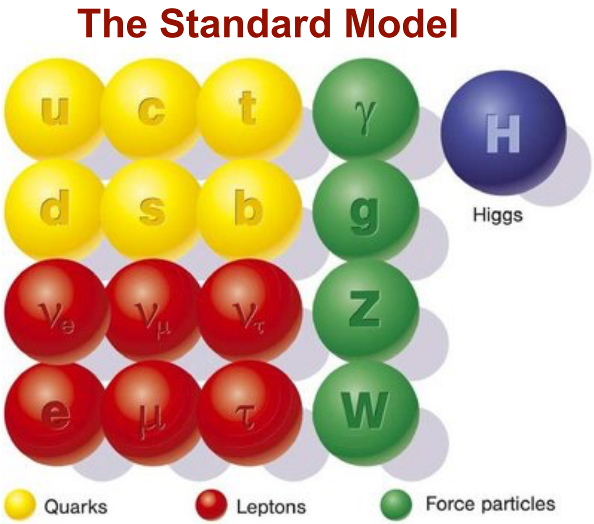
High Energy Accelerator



Motivation

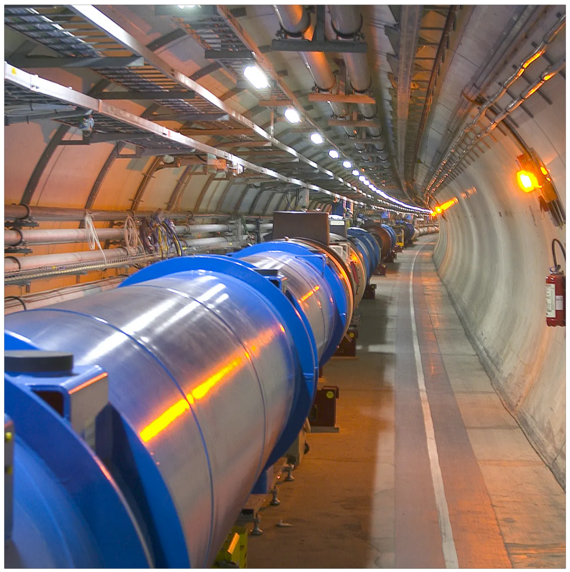
High Energy Accelerator → **Physics Results**





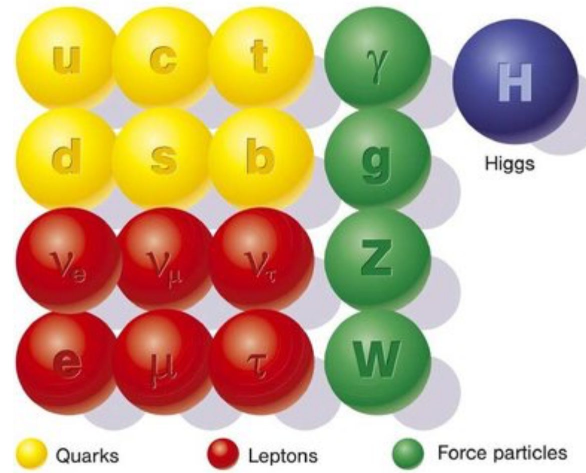
Motivation

High Energy Accelerator

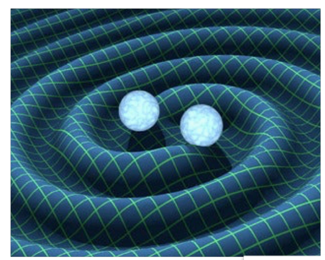


Physics Results

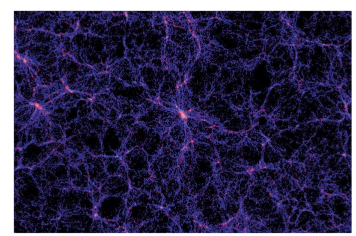
The Standard Model



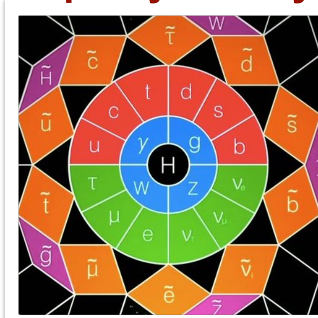
Gravity?



Dark Matter?



Supersymmetry?

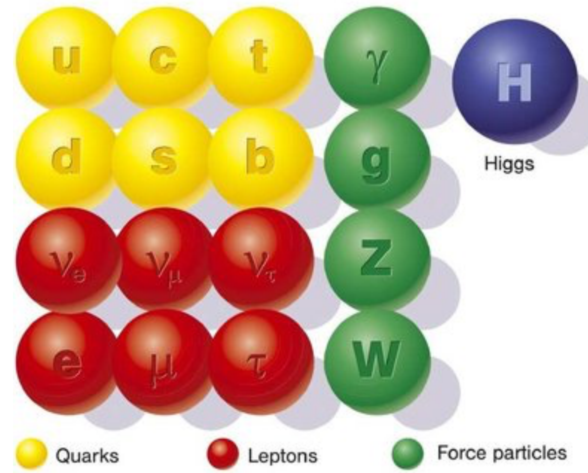


Motivation

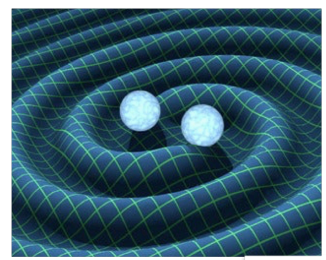
High Energy Accelerator

Physics Results

The Standard Model



Gravity?



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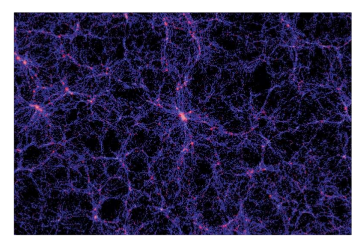
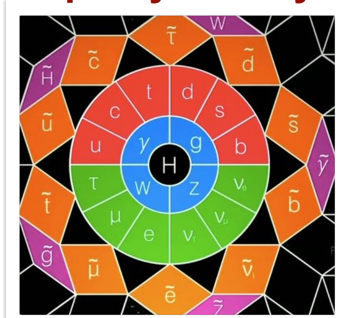


Supersymmetry?

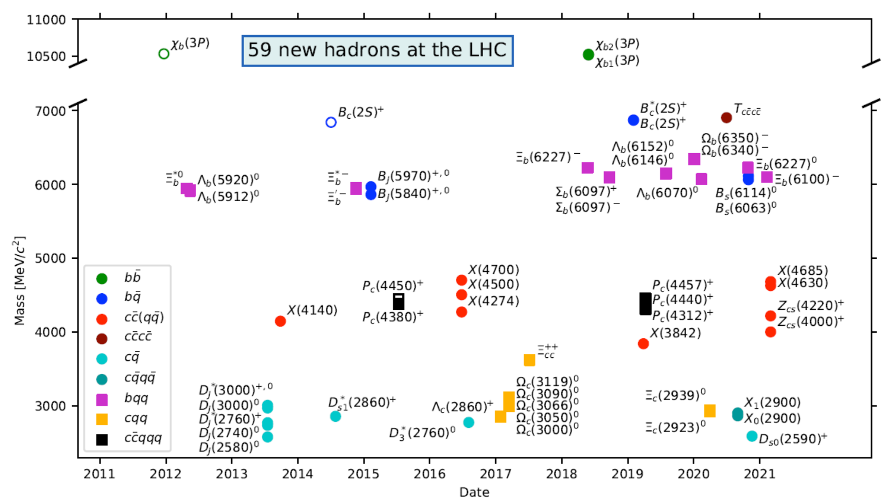


Motivation

Goal: understand the fundamental universe!

Successes of the LHC

- 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)
    - New in 2023: 0.09% precision on mass measurement, observation of H→Zɣ (0.15% BR)
- Observed > 50 new hadrons
- Progress in flavor physics from LHCb: first observation of CP violation in charm processes, best measurement of CKM angle ɣ
- New technologies: accelerator, detector, computational, medical, etc.

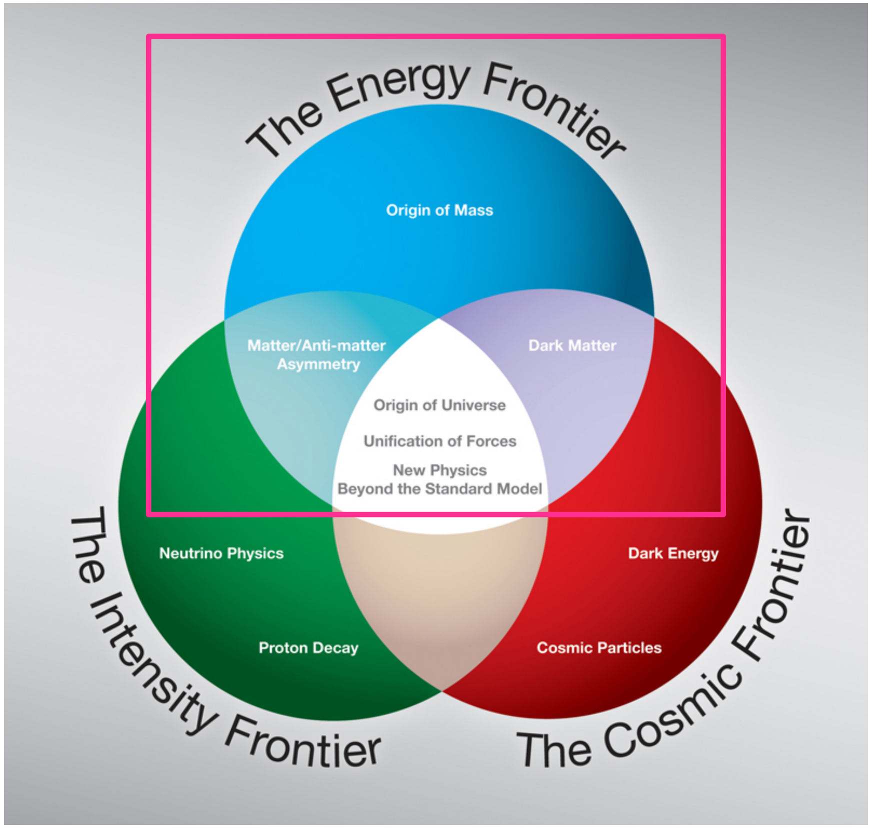


Work Still To Do

➡ Colliders are unique tools!

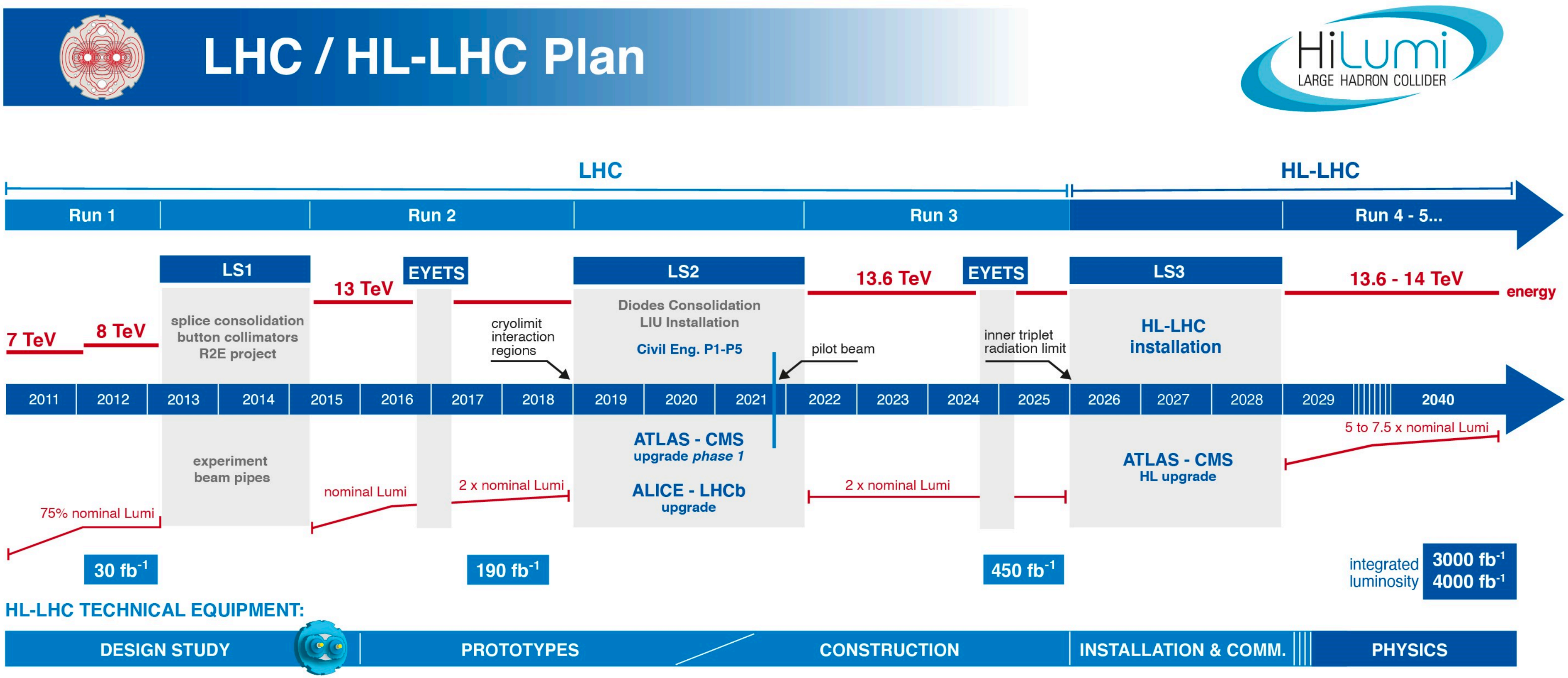
1. Directly probe the **energy** frontier: high-resolution detection of high center-of-mass energy collisions
2. Only way to directly study the **Higgs**: key role as a compass for BSM physics
3. Singular detection opportunity to constrain key **BSM** models, eg. long-lived particles, dark QCD, etc.

DOE Office of Science HEP Frontiers

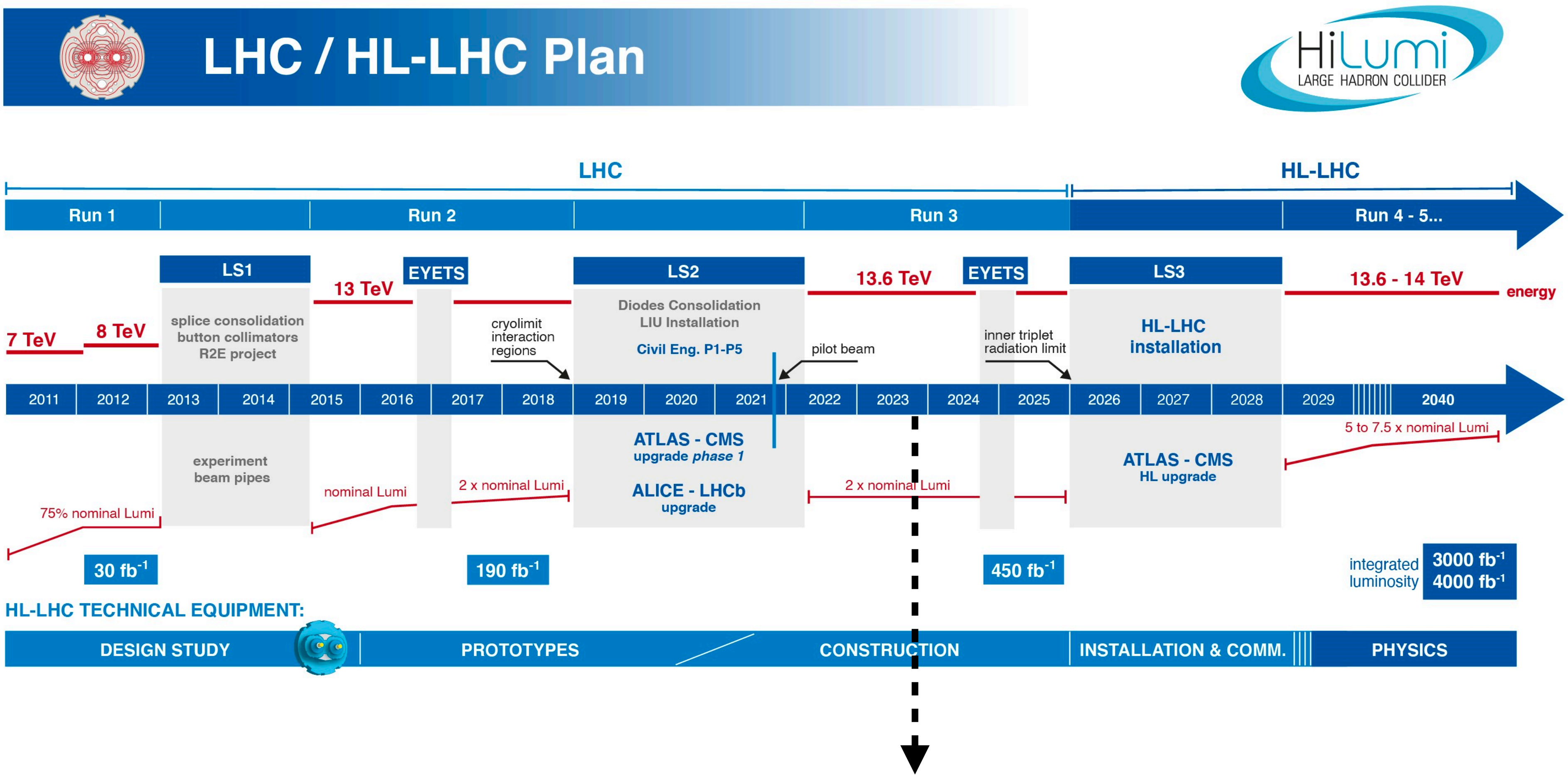


➡ To keep understanding the fundamental universe, the field of high energy collider physics can't end with the LHC!

LHC Timeline

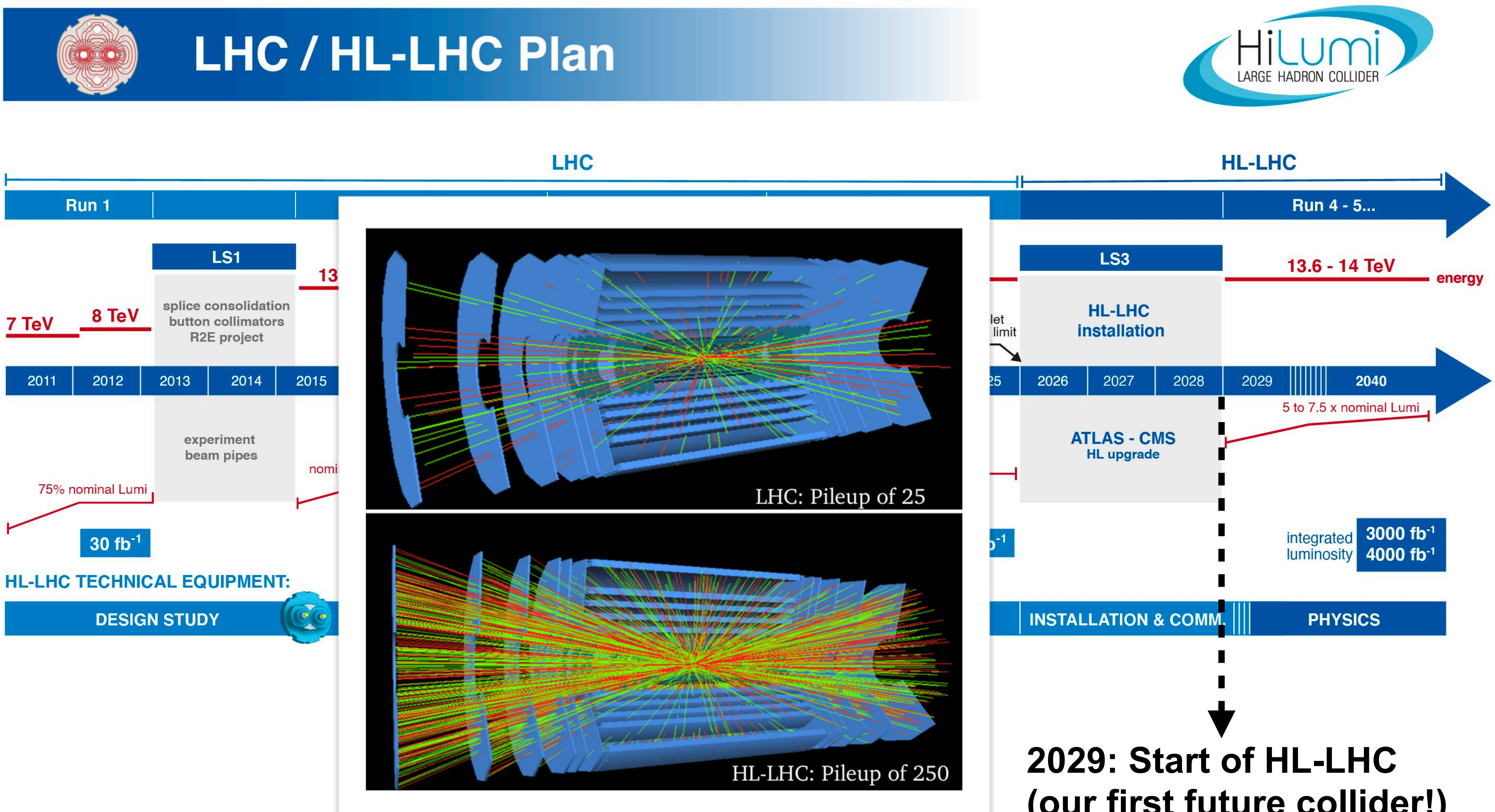


LHC Timeline



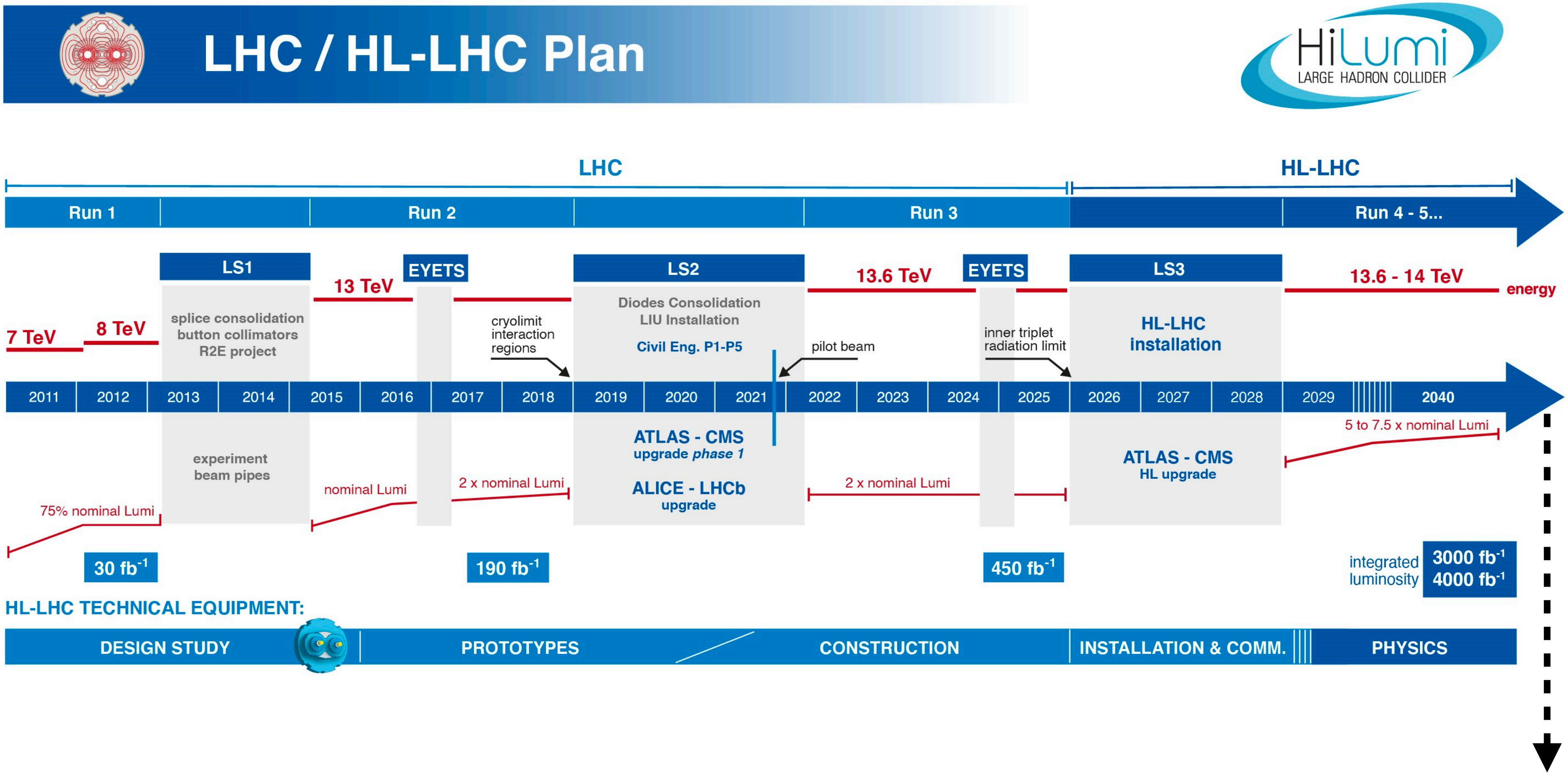
2023: today

LHC Timeline



2029: Start of HL-LHC (our first future collider!)

LHC Timeline



2040: end of LHC data/physics

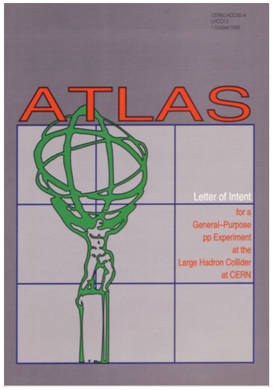
A Brief History…

1992 LHC Committee (LHCC) formed; ATLAS & CMS submit letters of intent to construct detectors

1996 ATLAS & CMS technical proposals are approved

1997 ATLAS & CMS construction begins

2008 LHC begins operation

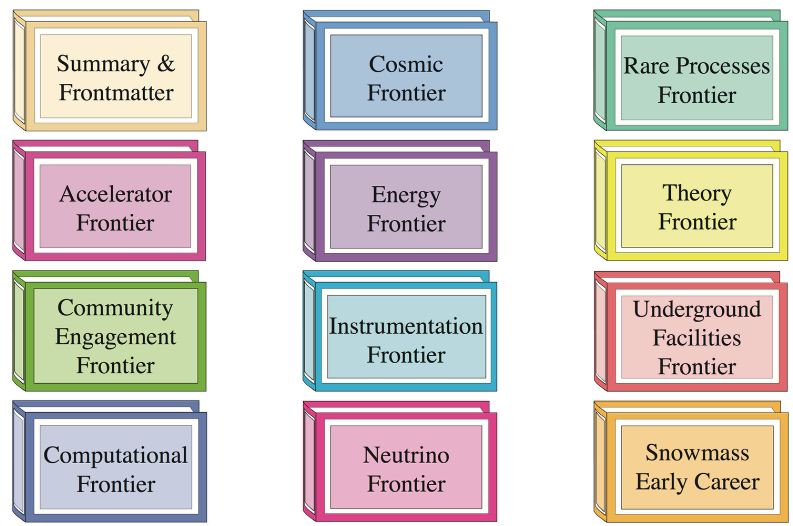


- ➡ It takes > **15 years** to go from detector concept to data-taking
- ➡ To be ready for a collider running shortly after 2040, we need to start preparing **now!**

Snowmass

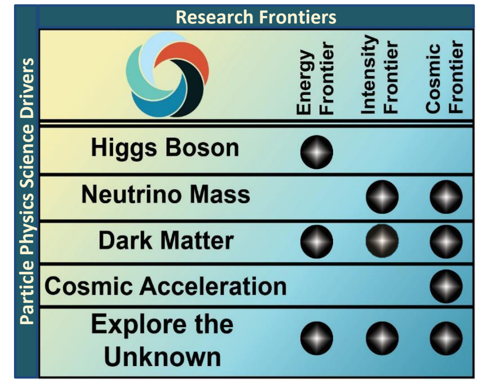
- **Snowmass** [2021-22]: U.S. HEP community effort to express opinions on physics drivers & future experimental facilities
  - Organized into 12 frontiers, which organize white papers and write reports for Snowmass Book
  - Community Summer Study at the University of Washington, Seattle [July 17-27, 2022]
- Preceded by European Committee for Future Accelerators (ECFA) "European Strategy" update in 2020

Snowmass 2021



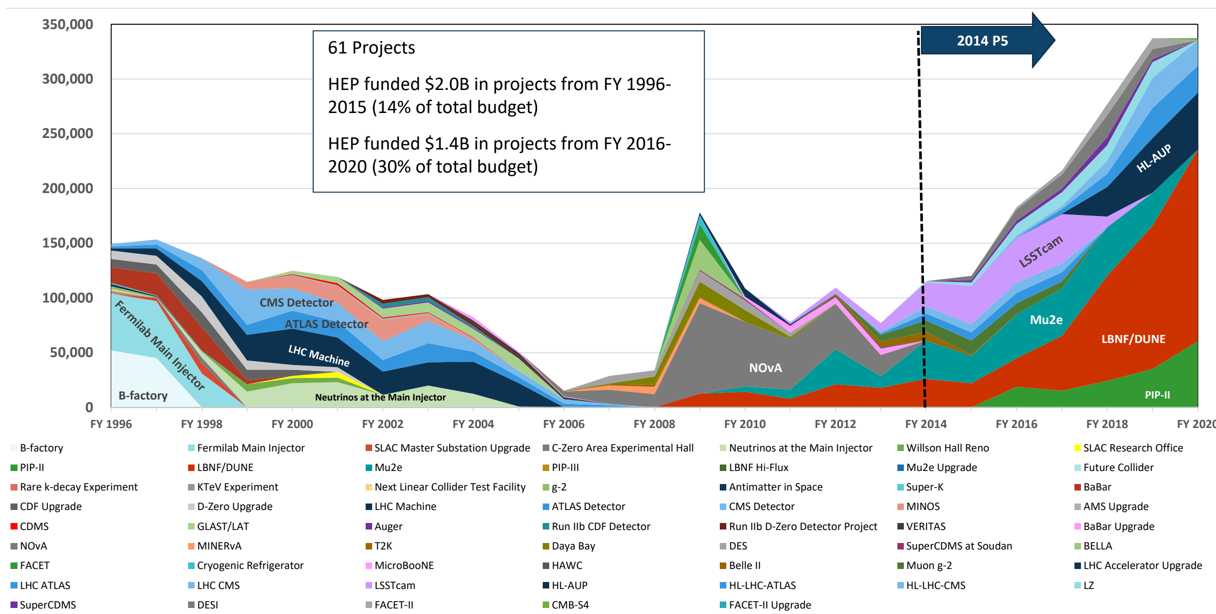
P5

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



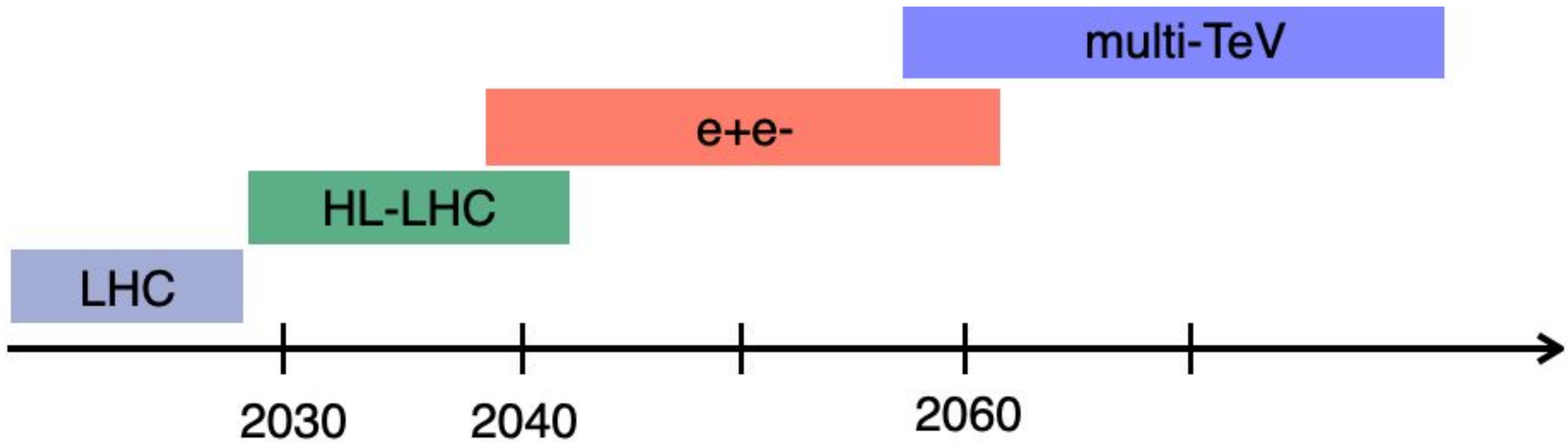
- **2023**: conducted a series of Town Hall meetings to collect more community input [LBNL, Fermilab/Argonne, Brookhaven, SLAC]

➡*Report expected in October 2023: rollout and community endorsement plans under discussion*



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**”



H couplings to: **O(10)%** **O(0.1-1)%** **O(1)‰** 2211.11084

Snowmass Energy Frontier Vision

1. “Fa
2. “Si
3. “Re ... ntier col

H couplin ... 11.11084

Example proposals:

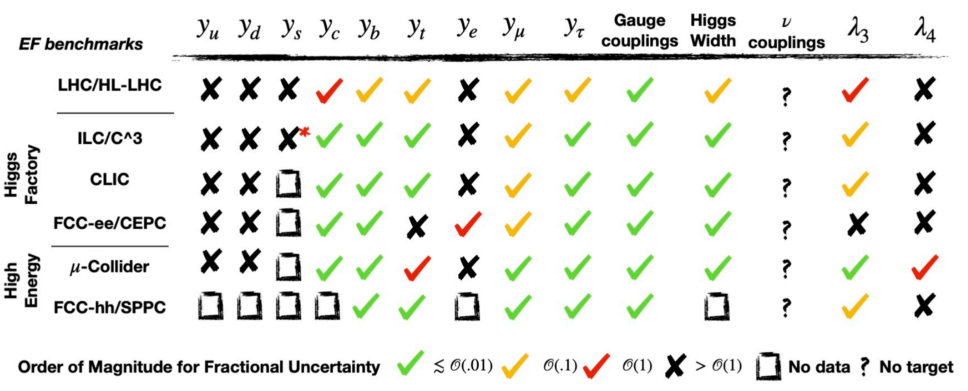
1. Estimated cost
2. Year for start of physics
3. Primary unknowns

❗ **Caveat: a very high-level overview**

See Collider Implementation Task Force report for more details

e+e- Higgs Factories

- Precision study of the Higgs boson and its properties: connected to many fundamental questions in HEP
- Leptons are point-like particles: well-defined initial state, clean experimental environment
- Planned runs at varying energies to enhance Z (~90 GeV), H (~240 GeV), top (~365 GeV) production



[ref]

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	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge couplings	Higgs Width	ν couplings	λ_3	λ_4
	LHC/HL-LHC	✗	✗	✗	✓ (red)	✓ (yellow)	✓ (yellow)	✗	✓ (yellow)	✓ (yellow)	✓ (green)	✓ (yellow)	?	✓ (red)	✗
Higgs Factory	ILC/C^3	✗	✗	✗*	✓ (green)	✓ (green)	✓ (green)	✗	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✓ (yellow)	✗
Higgs Factory	CLIC	✗	✗	□	✓ (green)	✓ (green)	✓ (green)	✗	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✓ (yellow)	✗
Higgs Factory	FCC-ee/CEPC	✗	✗	□	✓ (green)	✓ (green)	✗	✓ (red)	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✗	✗
High Energy	μ-Collider	✗	✗	□	✓ (green)	✓ (green)	✓ (red)	✗	✓ (green)	✓ (green)	✓ (green)	✓ (green)	?	✓ (green)	✓ (red)
High Energy	FCC-hh/SPPC	□	□	□	□	✓ (green)	✓ (green)	□	✓ (green)	✓ (green)	✓ (green)	□	?	✓ (yellow)	✗

Order of Magnitude for Fractional Uncertainty: ✓ (green) $\lesssim \mathcal{O}(.01)$; ✓ (yellow) $\mathcal{O}(.1)$; ✓ (red) $\mathcal{O}(1)$; ✗ $> \mathcal{O}(1)$; □ No data; ? No target

[ref]

Linear

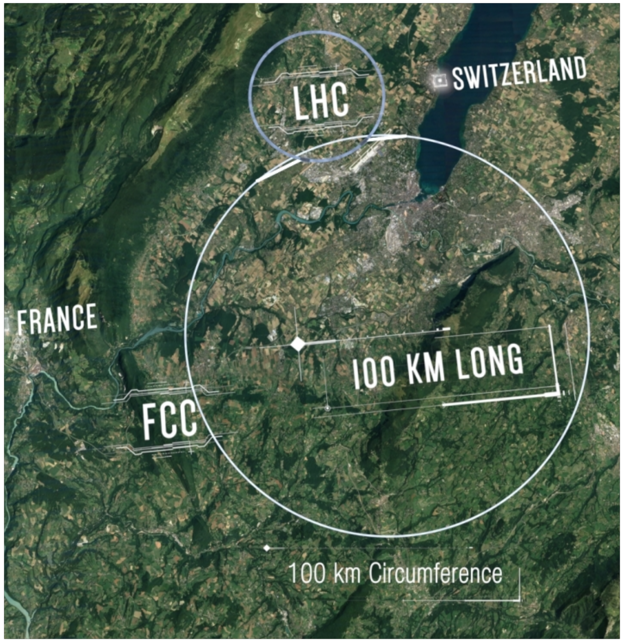
- **Pros**: easily change collision energy, shorter tunnels, longitudinal polarization
- **Cons**: lower luminosity (dump >99.9999% of the beam power)
- **Examples**: Compact LInear Collider (CLIC), **Cool Copper Collider (C^3)**, International Linear Collider (ILC)

Circular

- **Pros**: higher luminosity < 250 GeV; multiple interaction points
- **Cons**: lumi drops with energy; radiate away the beam power
- **Examples**: Chinese Electron Positron Collider (CEPC), **Future Circular Collider (FCC-ee)**, muon collider (μC)

Future Circular Collider (ee)

- From ESP2020 Update: “An **electron-positron Higgs factory** is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate 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) (CDR [2018])
- ~~Primary unknown~~ Established technology; demonstrator available via SuperKEKB, 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]

C³ (Cool Copper Collider)

- Make use of “normal-conducting” RF cavities for a more compact design than superconducting options
  - Normal conductive liquid N2 temperature X-band Cu RF cavities, 70 MeV/m (inherits from CLIC R&D)
  - 8 km footprint for 250/550 GeV CoM; 7 km footprint possible (fits on Fermilab site)
- **Estimated start of physics**: 2040 (technically limited)
- **Cost:** $7-12 B
- **Primary unknown:** demonstrate fully engineered cryomodule & cryogenic flow
  - ~5 year/50 m scale/$120 M demonstrator facility *(compatible with FCC-ee injector selection timeline)*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RESEARCH NEWS

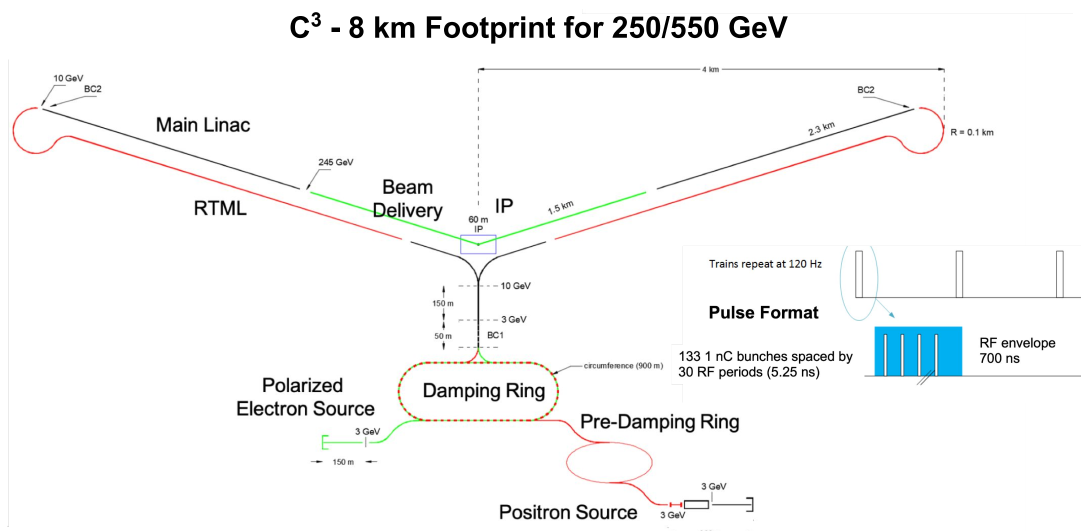
A “Retro” Collider Design for a Higgs Factory

October 6, 2022 • *Physics* 15, 155

The Cool Copper Collider is a new proposal for a Higgs-producing linear collider that would be more compact than other collider designs.

Emilio Nanni/SLAC

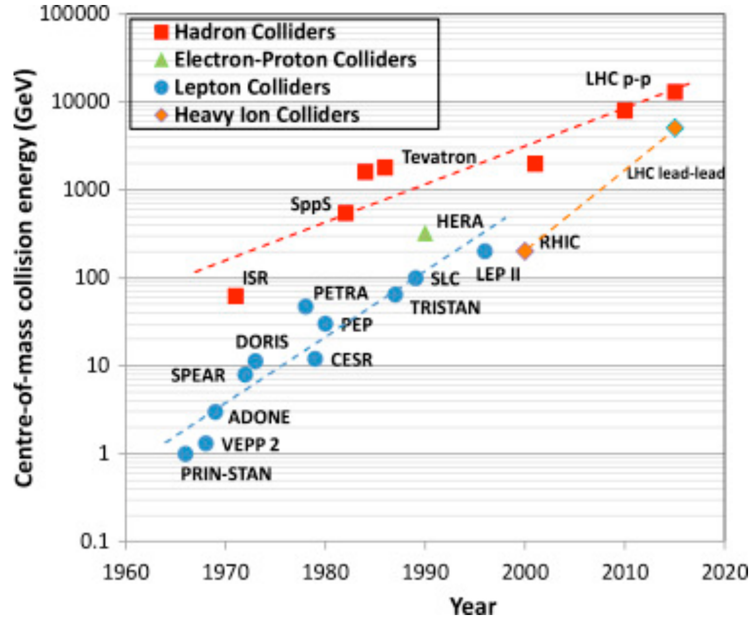
A prototype version of the Cool Copper Collider. The photo shows the central region where the particle beams would pass.



[E. Nanni, C. Vernieri]

Multi-TeV Options

❖ Highest direct discovery potential to never-before-recorded energies (up to ~40 TeV)



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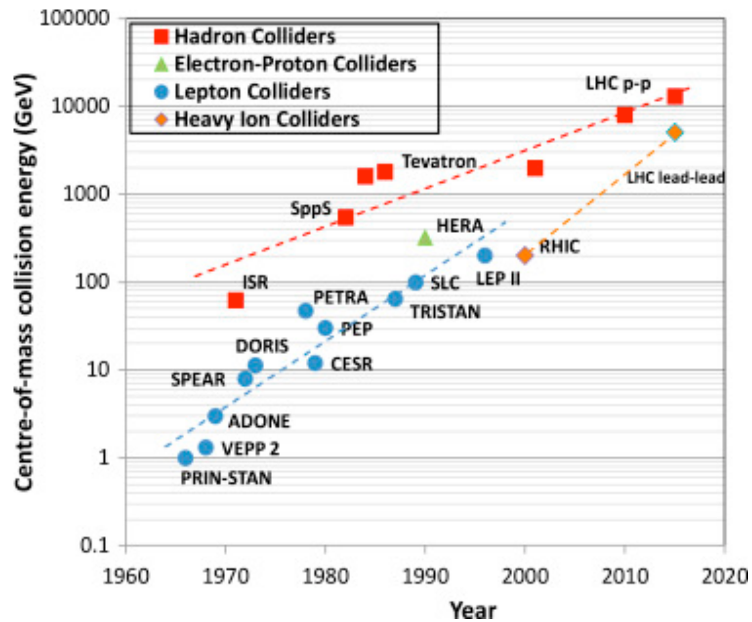


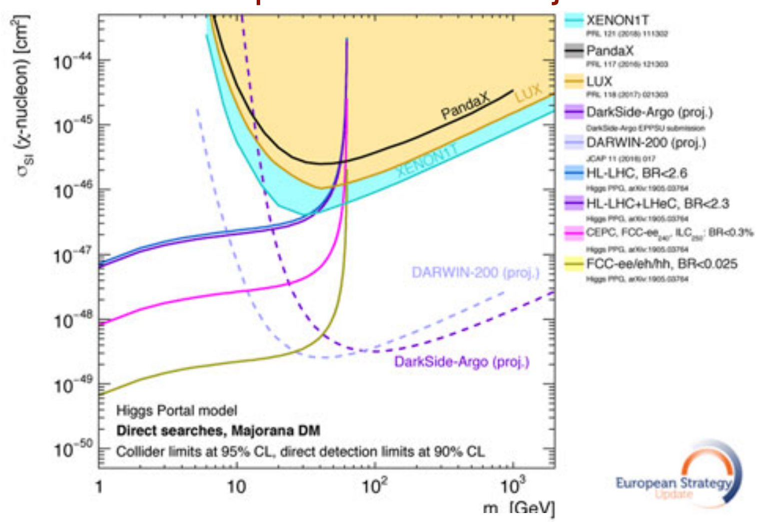
Hadron	Muon
• **Pros**: well-established technology • **Cons**: large construction/power footprint, high pileup/ backgrounds	• **Pros**: similar CoM energy reach for much smaller footprint/budget • **Cons**: unknowns/technical hurdles

Future Circular Collider (hh)

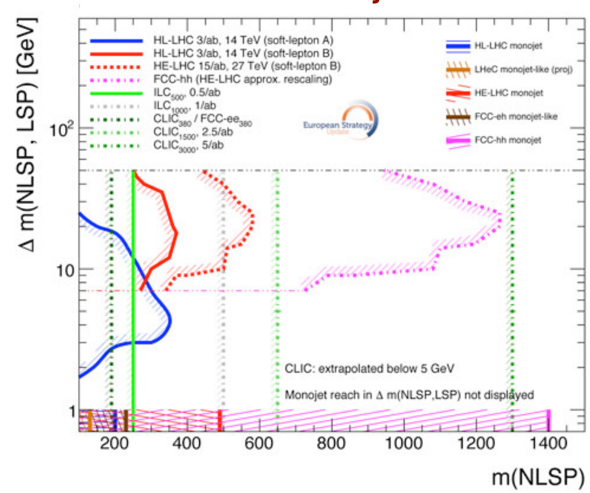
- **Estimated start of physics**: 2070
- **Cost**: 17 BCHF additional for FCC-hh (CDR [2018])
- **Primary unknowns**:
  - Very high-field superconducting magnets: 14 - 20 T
  - Stored beam energy: 8 GJ →machine protection
  - High energy consumption: 4 TWh/year

➡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



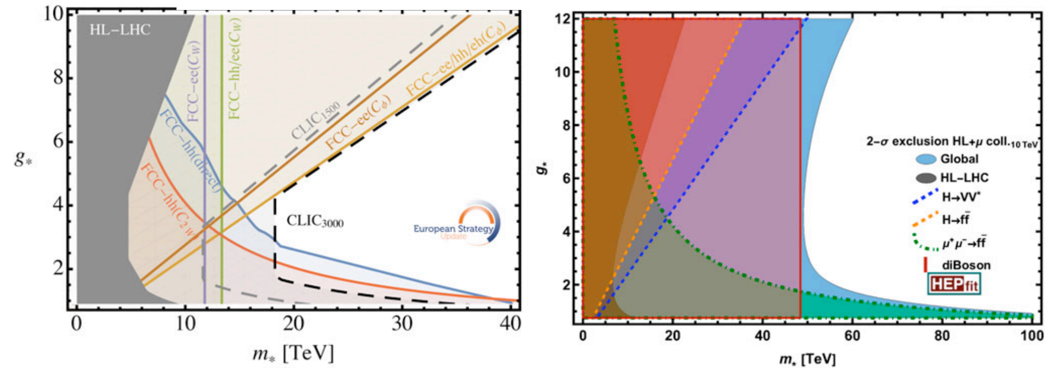
[2306.12897]

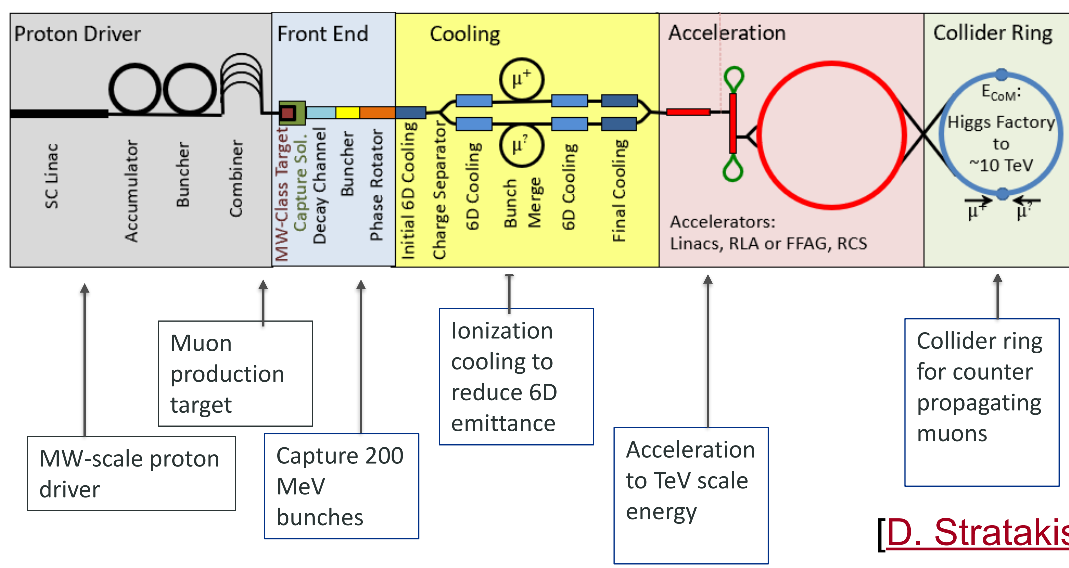
Muon Collider (μC)

- 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 & detector backgrounds

- **Estimated start of physics**: 2045 (technically limited schedule)
  - Needs demonstrator (TDR 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)

Composite Higgs Projections, FCC vs. μC





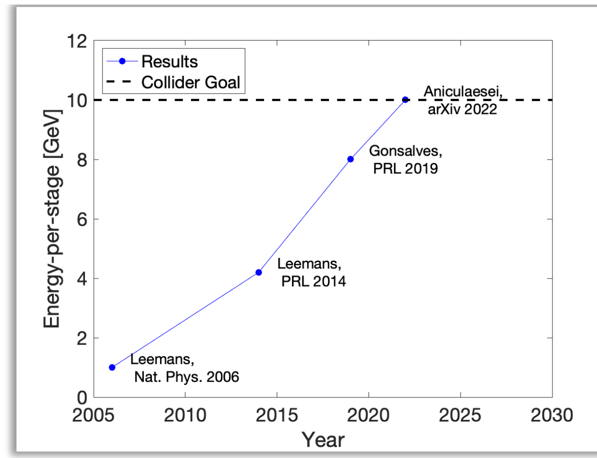
[D. Stratakis]

Future of Accelerators

- 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) and ultra-short bunches (suppress beamstrahlung)
    - Recent performance of single-stage accelerators meeting collider goals
  - High-field superconducting magnets (FCC requirement)
  - Superconducting radio frequency (SRF)

S. Gessner

Laser-Driven Plasma



➡ Current collider technology is not sustainable for long-term!

➡ ***Pressing need for more US-based accelerator R&D 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

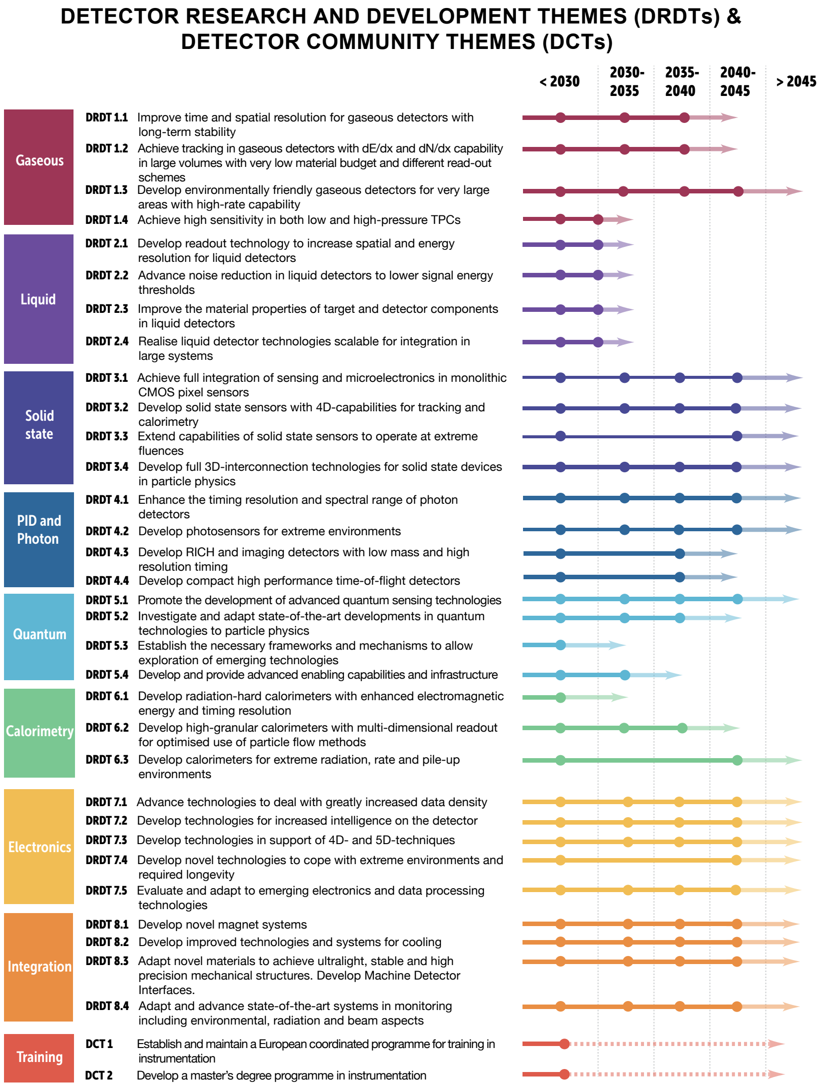

LCLS-II SRF Cavity Processing
Photo credit: Fermilab

Detector R&D

- A priority for the coming decade is to **R&D detector technologies** that can meet the pressing requirements of future collider environments
- Funding requests for detector R&D have been prepared by the e+e- and μC communities

➡ Accelerator-generic detector R&D can facilitate HEP incorporation of the latest & greatest instrumentation

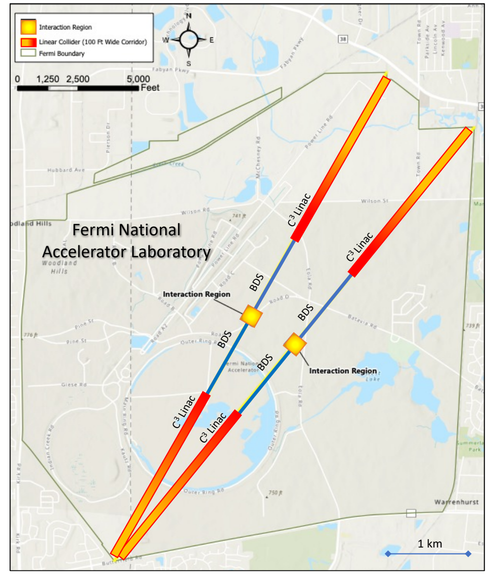
- 4D/5D detectors; precision (O(ps)) timing; quantum sensors; extreme environments (radiation, data density); 3D sensor/readout integration; AI/ML on-detectors



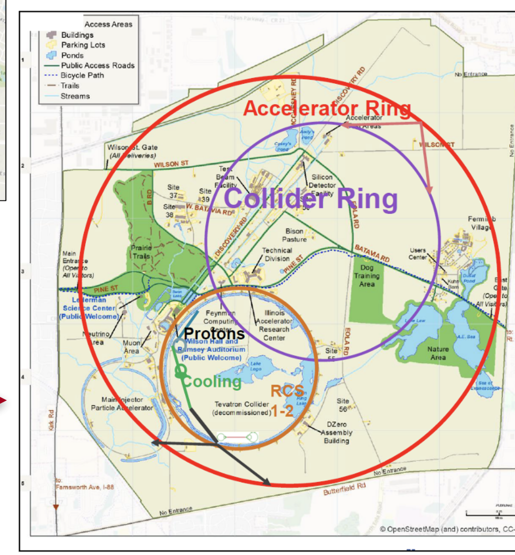
Prospects for US Hosting

SLAC

- Proposed “US National Accelerator R&D Program on Future Colliders” to synergize accelerator & detector R&D for generic future options [2207.06213]
- Some new accelerator concepts have footprints that can fit on Fermilab site
- LBNF/DUNE neutrino program @ Fermilab will continue: requires a unified harmonized path forward across frontiers



C^3 (7km) Options @ Fermilab



μC Options @ Fermilab

[2203.08088]

Looking Forward

Today

P5 Rollout starting now!

Detector R&D collaborations are forming: “Detector R&D” (DRDs) in ECFA and “R&D Collaborations" (RDCs) in CPAD

- Get involved!

2025

FCC Feasibility Study report

2028

Update to European Strategy *(CERN Council FCC endorsement?)*

2030

Demonstrator results from C^3 and/or μC?

2032

DOE CD0 for some machine (to deliver physics by 2040-2045)

2034

Next Snowmass/P5!

Conclusions

SLAC

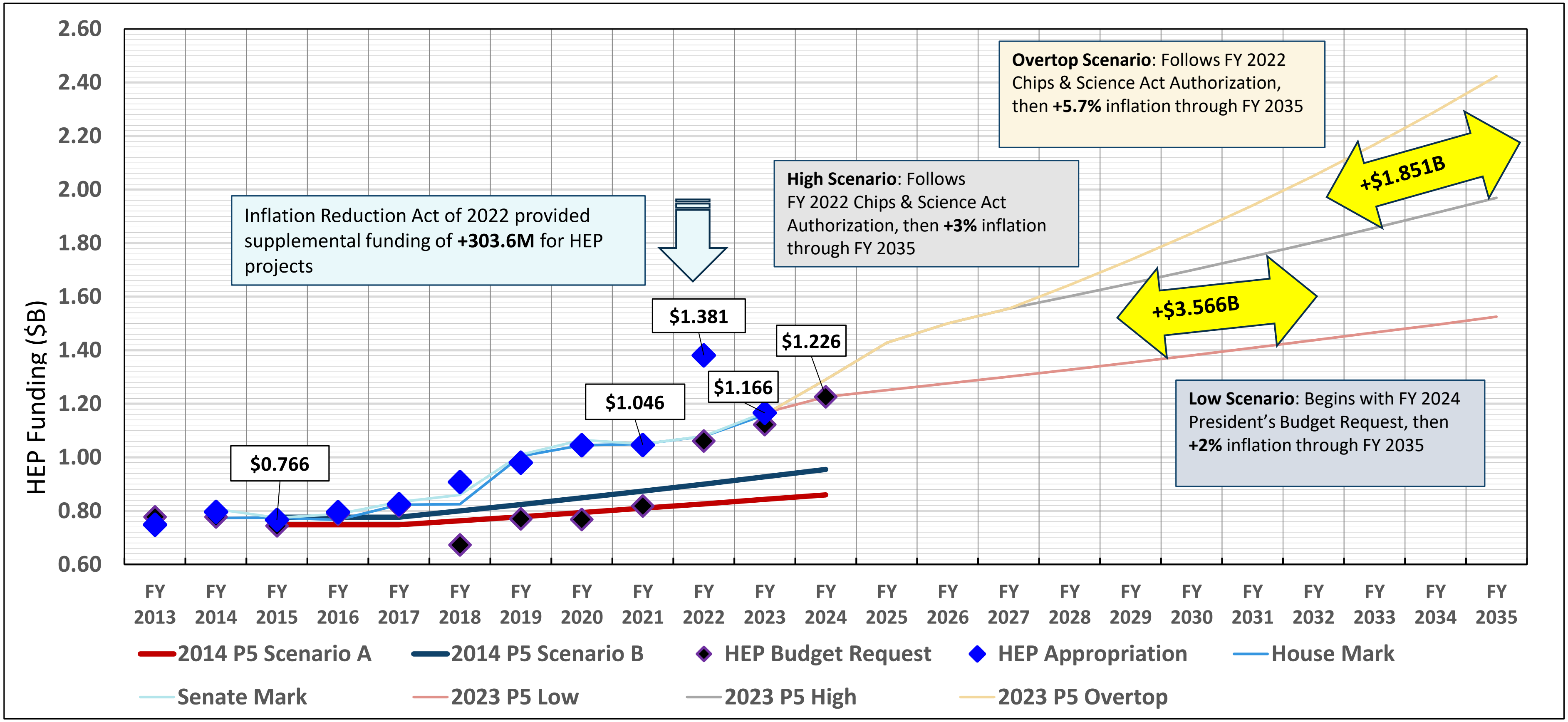
- The LHC was a seminal achievement for HEP, and we need to keep the momentum going!

- 2021-2023 **US Snowmass** and **P5 processes** provide prioritization/ funding recommendations for next 10 years
  - Many exciting proposals for future global collider facilities under consideration

- **Preparation for future colliders has to start now!**
  - 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

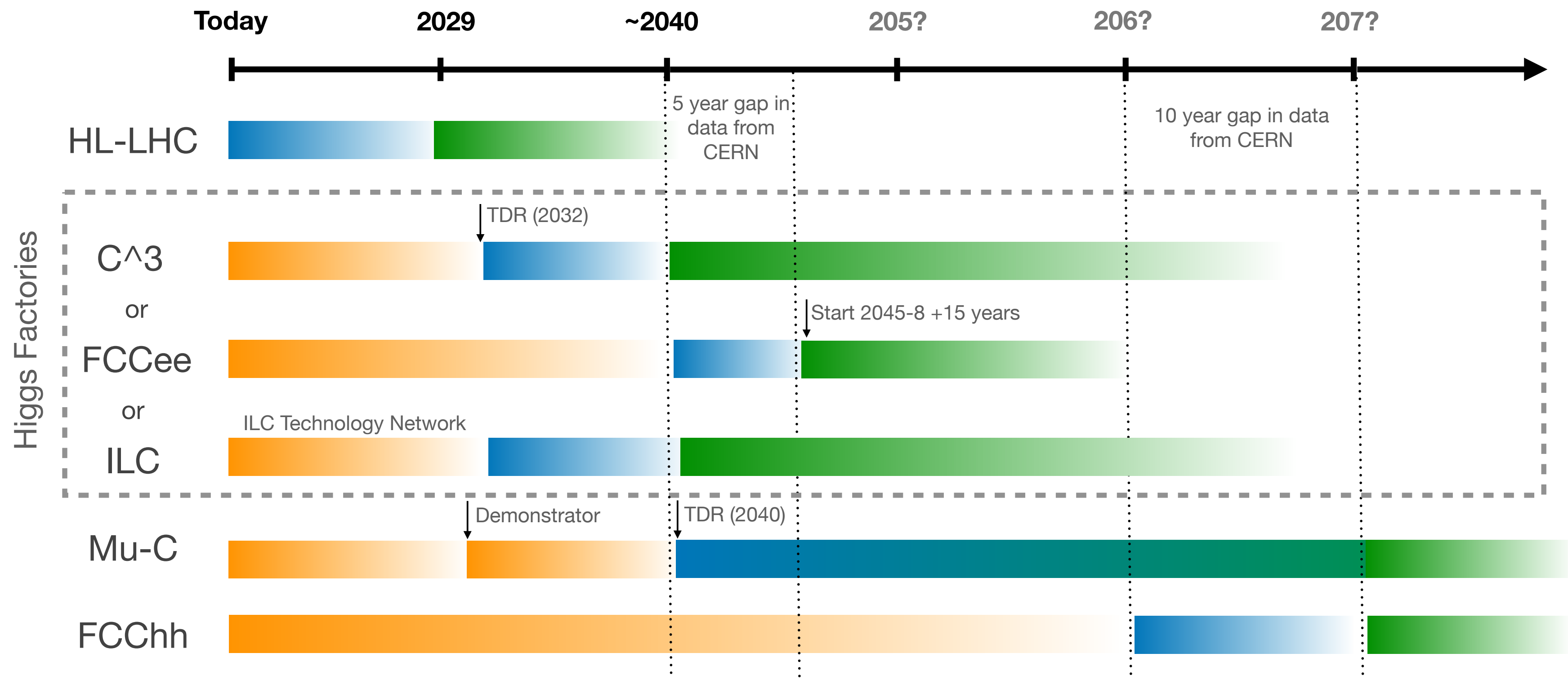
Backup

P5 Budget Scenarios



An Inclusive Timeline

SLAC



- Interleaved accelerator/detector R&D, construction, and physics activity such that 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

R&D
Construction
Physics

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]

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)

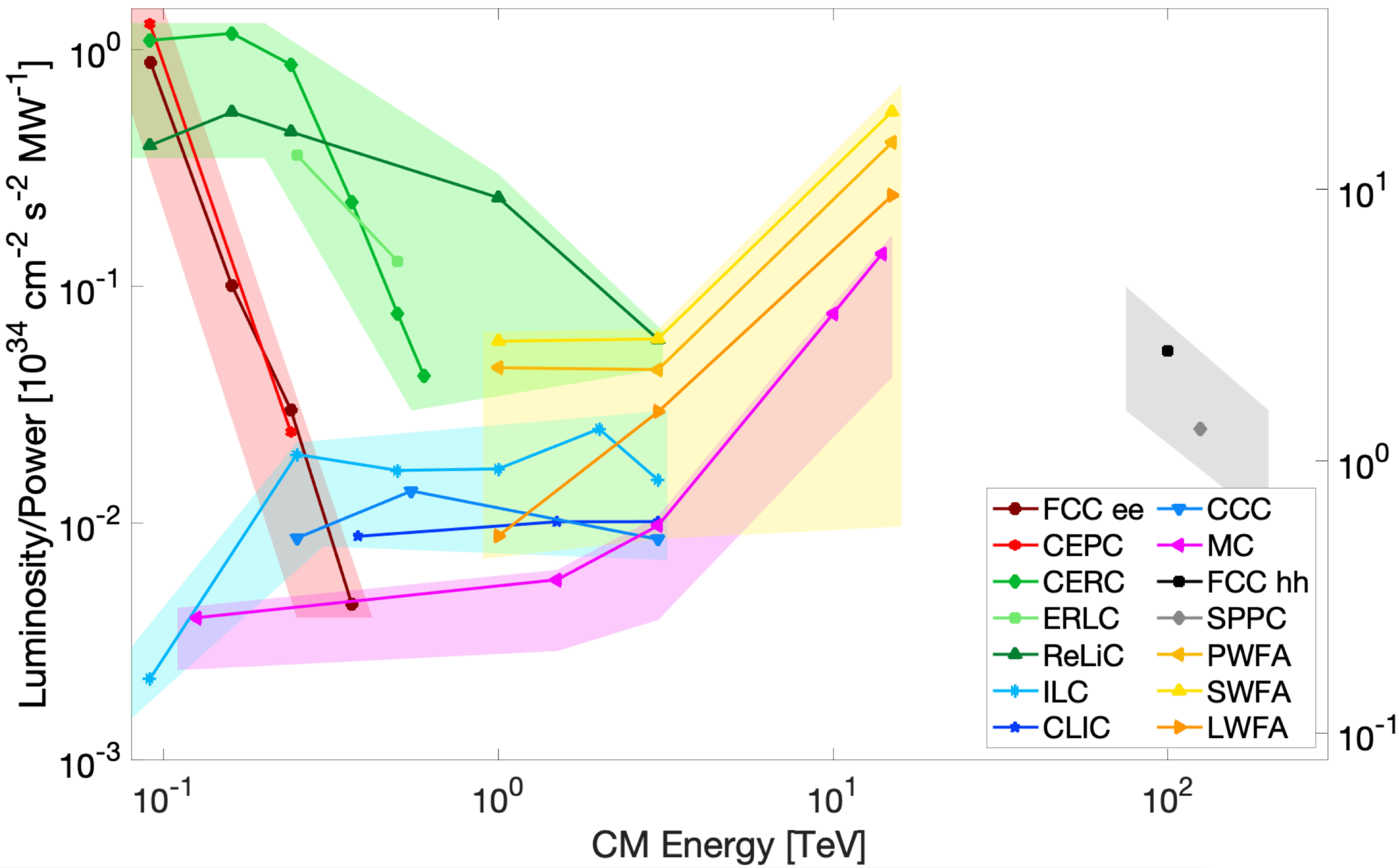
Multi-TeV Colliders

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]

Luminosity vs. Energy

SLAC



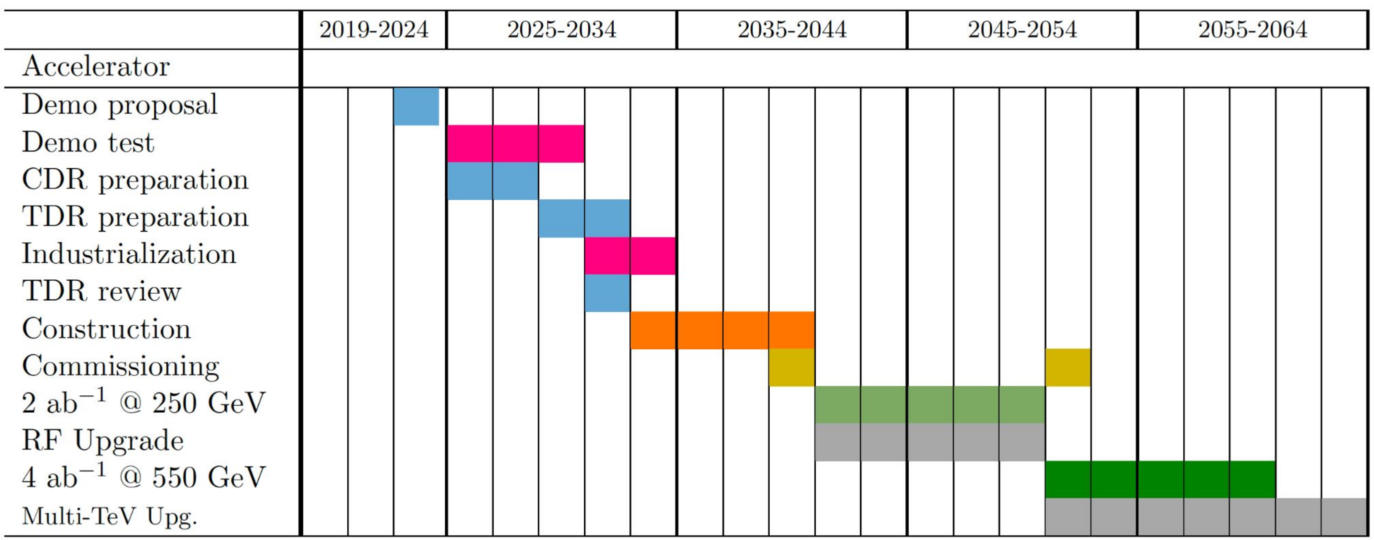
C3 Specs & Timeline

SLAC

C3 Parameters

Collider	C3	C3
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

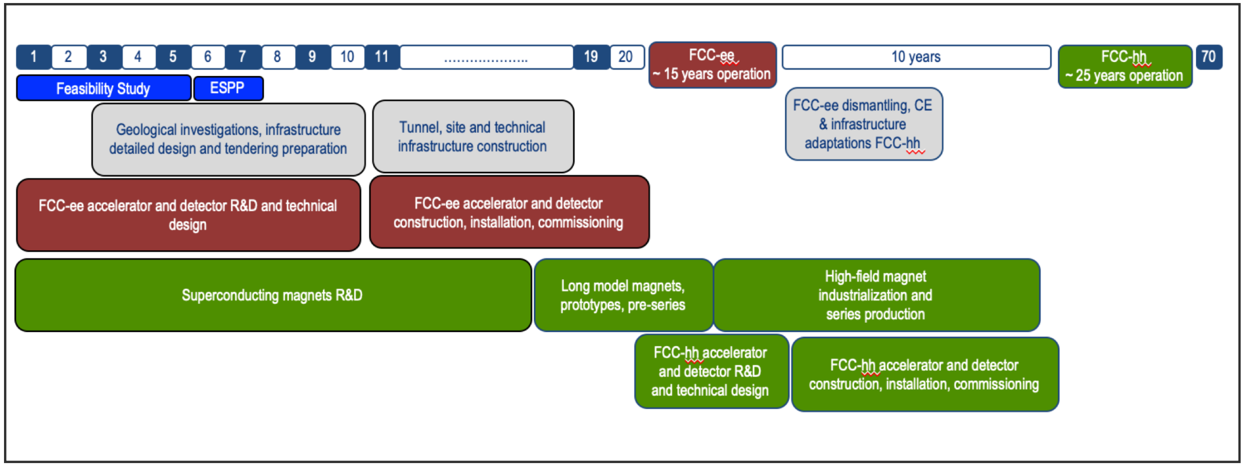
- C3 provides a rapid route to precision Higgs physics with a compact 8 km footprint
    - Higgs physics run by 2040
    - US-hosted facility possible
- C3 time structure is compatible with ILC-like detector design and optimizations ongoing
- C3 upgrade to 550 GeV with only added rf sources
    - Higgs self-coupling and expanded physics reach
- C3 is scalable to multi-TeV
- C3 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]

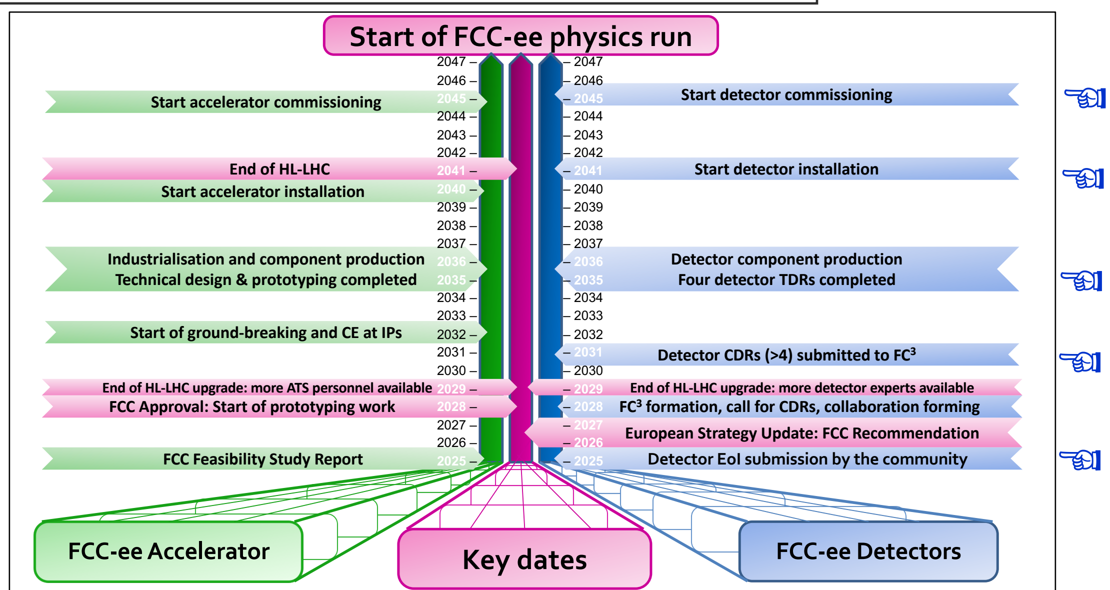
FCC Scheduling & Timeline

SLAC

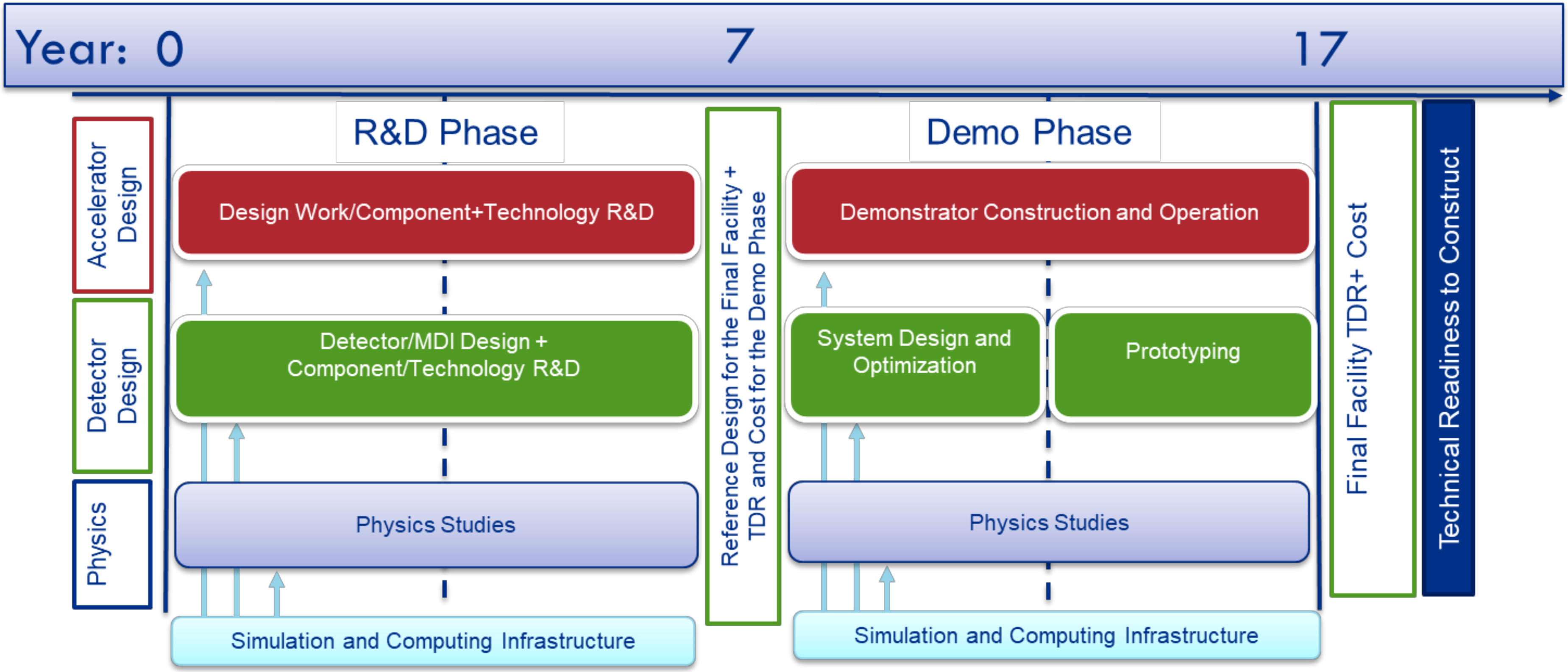


Technical schedule:
FCC-ee could start operation **in 2040 or earlier**

[F. Gianotti]



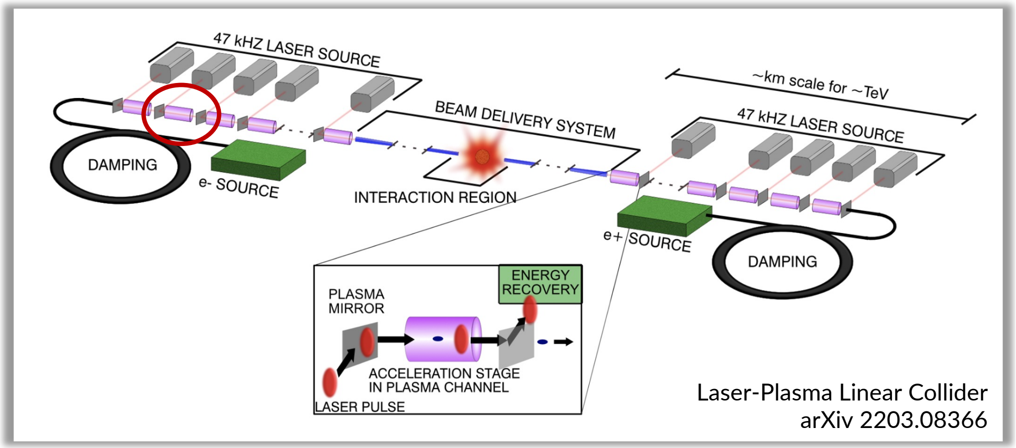
μ-C Scheduling & Timeline



Plasma WakeField Accelerators (PWFA)

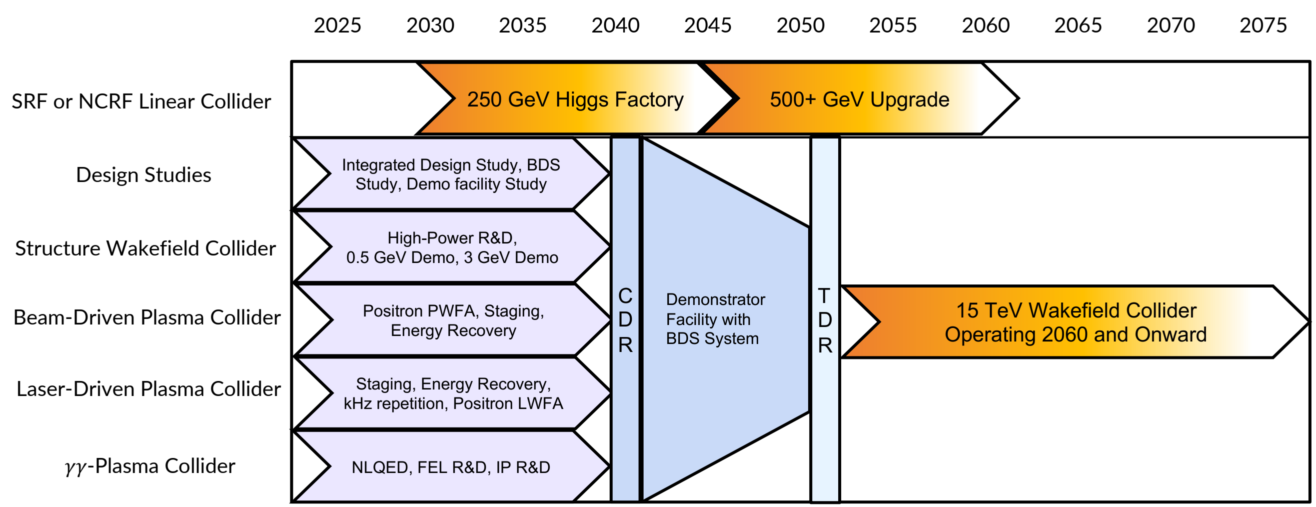
Goals

High-Gradient High-Efficiency Low-Emittance

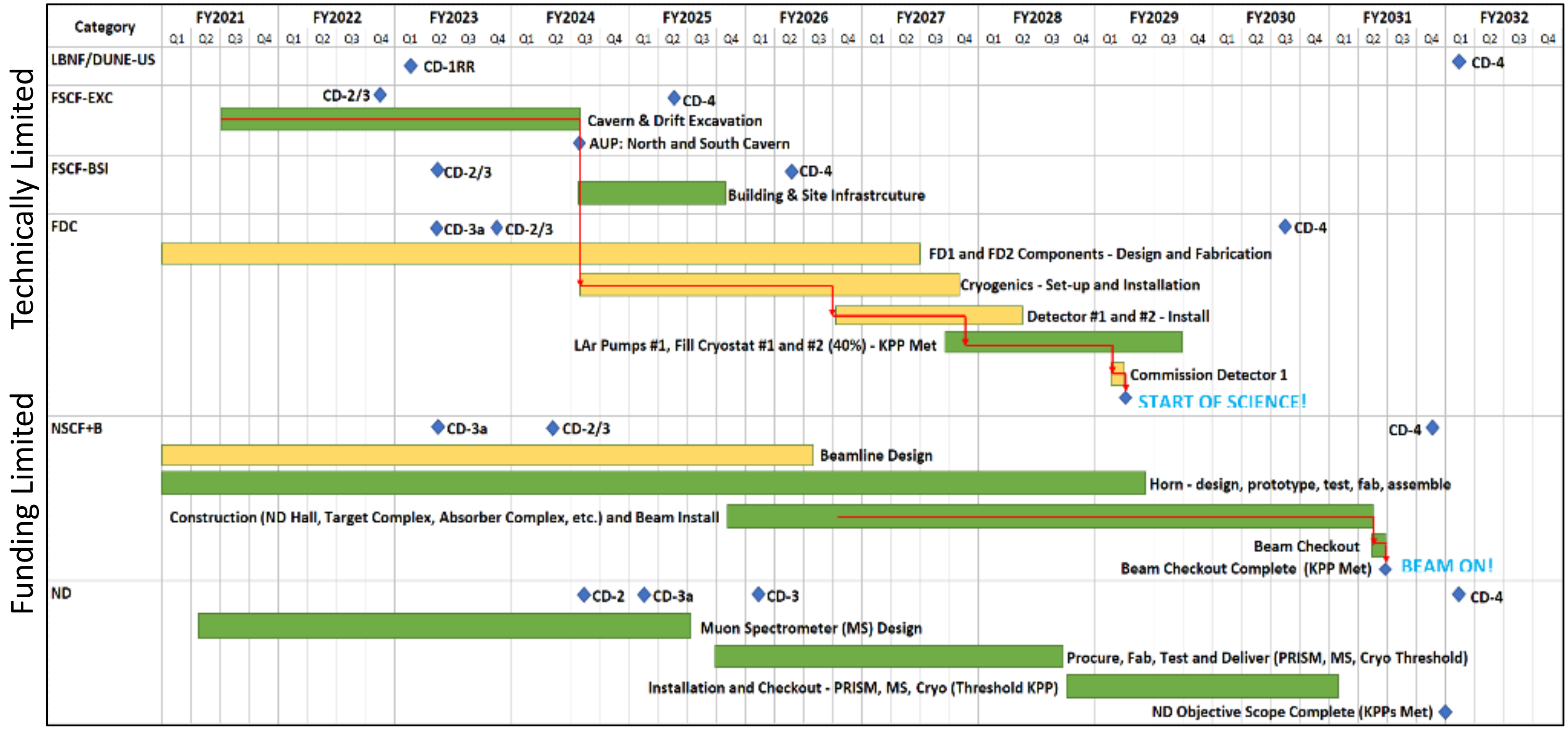


Laser-Plasma Linear Collider
arXiv 2203.08366

S. Gessner



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)

Snowmass EF Summary

2211.11084

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

For the five year period starting in 2030:

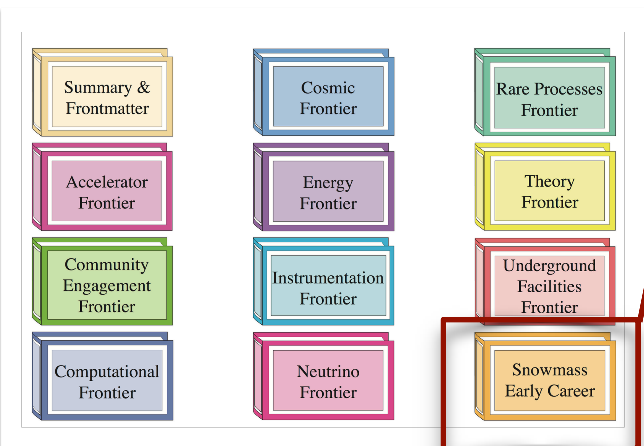
1. Continue strong support for the HL-LHC physics program,
2. Support construction of an e^+e^- Higgs factory,
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

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**



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