ICHEP 2022 BOLOGNA

ICHEP 2022 XLI International Conference on High Energy Physics Bologna (Italy)

6 13 07 2022

Plans for future energy frontier accelerators to drive particle physics discoveries

Nadia Pastrone INFN TORINO

Snowmass 2021

On behalf of the ***Snowmass Multi-TeV Colliders Topical Group - AF4***

Mark ***PALMER****, Brookhaven National Laboratory – U.S.A.*

Nadia ***PASTRONE****, Istituto Nazionale di Fisica Nucleare – Italy*

Jingyu ***TANG****, Institute of High Energy Physics – China*

Marlene ***TURNER****, Lawrence Berkeley National Laboratory – U.S.A.*

Alexander ***VALISHEV****, Fermilab – U.S.A.*

What kind of large-scale global accelerator project(s) can we envision

undertaking to advance the frontiers in particle and accelerator physics, and to answer the fundamental questions of our field?

Study known phenomena

Search for direct evidence of BSM physics

The type/design of a collider concept directly influences ***what signatures are possible to probe*** *within the foreseeable accelerator parameters, detector technology and physics backgrounds*

Particle Physics Community Planning Exercise

Snowmass 2021

- Snowmass as a **scientific study** provides an opportunity for the **entire particle physics community** to come together 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**, will take this scientific input and develop a **strategic plan 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**

10 Snowmass 2021 Frontiers

two-year process

- Energy ← Muon Collider Forum since 2021; e+e- Colliders Forum since 2022
- Neutrino Physics
- Rare Processes and Precision
- Cosmic
- Theory ←
- Accelerator ←
- Instrumentation
- Computational

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

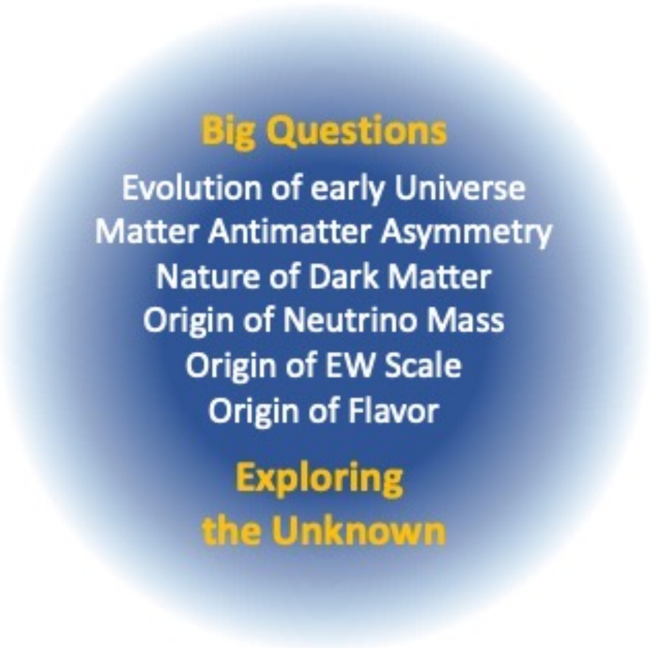
Most important questions for Particle Physics

- Standard Model (SM) of particle physics is confirmed with high precision
- Fundamental questions are still open and unexplained

- A physics program must be envisaged to push the exploration of particle physics to the TeV energy scale and beyond to pursue:

➔ **in-depth precise studies of the SM**

➔ **exploration of physics beyond the SM (BSM) to discover new particles and interactions**



Colliders at the energy frontier are a unique tool for investigation

50 years at the forefront of scientific HEP discoveries!

Physics goals in a nutshell

- Study the Higgs boson
  - precision Higgs-boson measurements (mass, width, couplings)
  - measurements of the shape of the Higgs potential
- QCD and PDF – improved theory precision ➔ HL-LHC and FCChh/SPPC
- BSM searches – energy scale and characteristics not known

➔ **What is the physics potential of each future collider concept?**

➔ **What collider and detector developments are required to deliver the performance able to pursue both precision measurements and discovery searches?**

2020 Update of the European Strategy for Particle Physics

19 June 2020 10.17181/CERN.JSC6.W89E

- Ensure Europe's continued **scientific and technological leadership**
- **Strengthen the unique ecosystem of research centres in Europe**

3 High-priority future initiatives

- **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.
  These compelling goals will require **innovation and cutting-edge technology:**
  - ✓ ramp up R&D on advanced accelerator technologies, in particular **high-field superconducting magnets**, **including high-temperature superconductors**
  - ✓ investigate the **technical and financial feasibility of a future hadron collider at CERN** with a centre-of-mass energy of at least **100 TeV** and **with an electron-positron Higgs and electroweak factory as a possible first stage**
  - ✓ the ILC in Japan would be compatible with this strategy
- The European particle physics community must **intensify accelerator R&D** and sustain it with adequate resources. **A roadmap should prioritise the technology**

Input to EU Strategy of Particle Physics

European Strategy Update

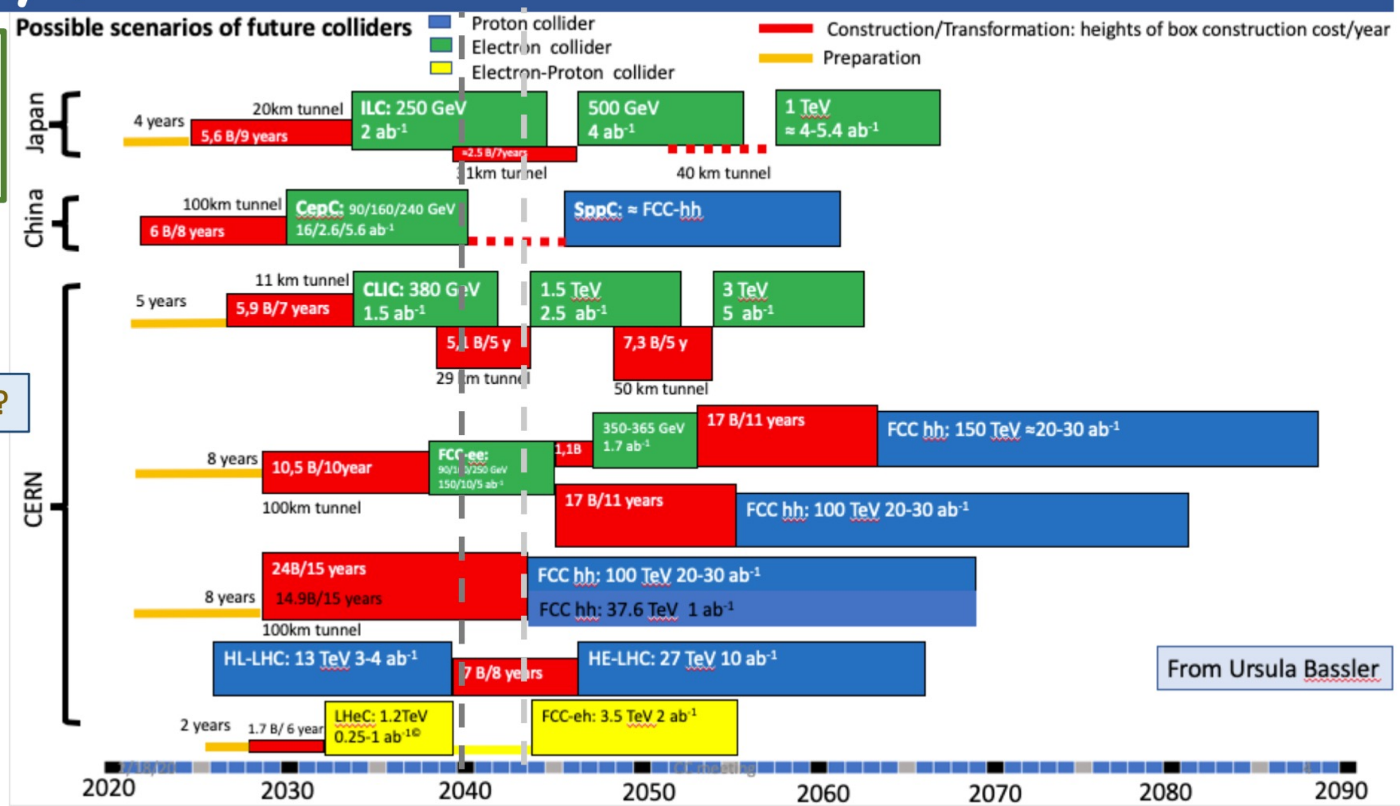
2020 Strategy Update

Halina Abramowicz

High-priority future initiatives

Map of possible future facilities submitted as input to the Strategy Update

Where is the muon collider?



Input Document to EU Strategy Update - Dec 2018:

"Muon Colliders," [arXiv:1901.06150](https://arxiv.org/abs/1901.06150)

by *CERN-WG on Muon Colliders*

J.P. Delahaye et al.

EU Strategy → Accelerator R&D Roadmap

European **Strategy Update – June 19, 2020**:

3 High-priority future initiatives

High-priority future initiatives [..]
In addition to the high field magnets the **accelerator R&D roadmap** could contain:
[..] an **international design study** for a **muon collider**, as it represents
a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of e^+e^-colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

The Roadmap aims at a programme of accelerator R&D to support the design and delivery of future particle accelerators in the next 5-10 years.
The objectives:

- improvement of **magnet** and **radio-frequency acceleration** systems
- investigations of the potential of **laser/plasma acceleration** and **energy-recovery linac** techniques
- development of new concepts for muon beams and **muon colliders**

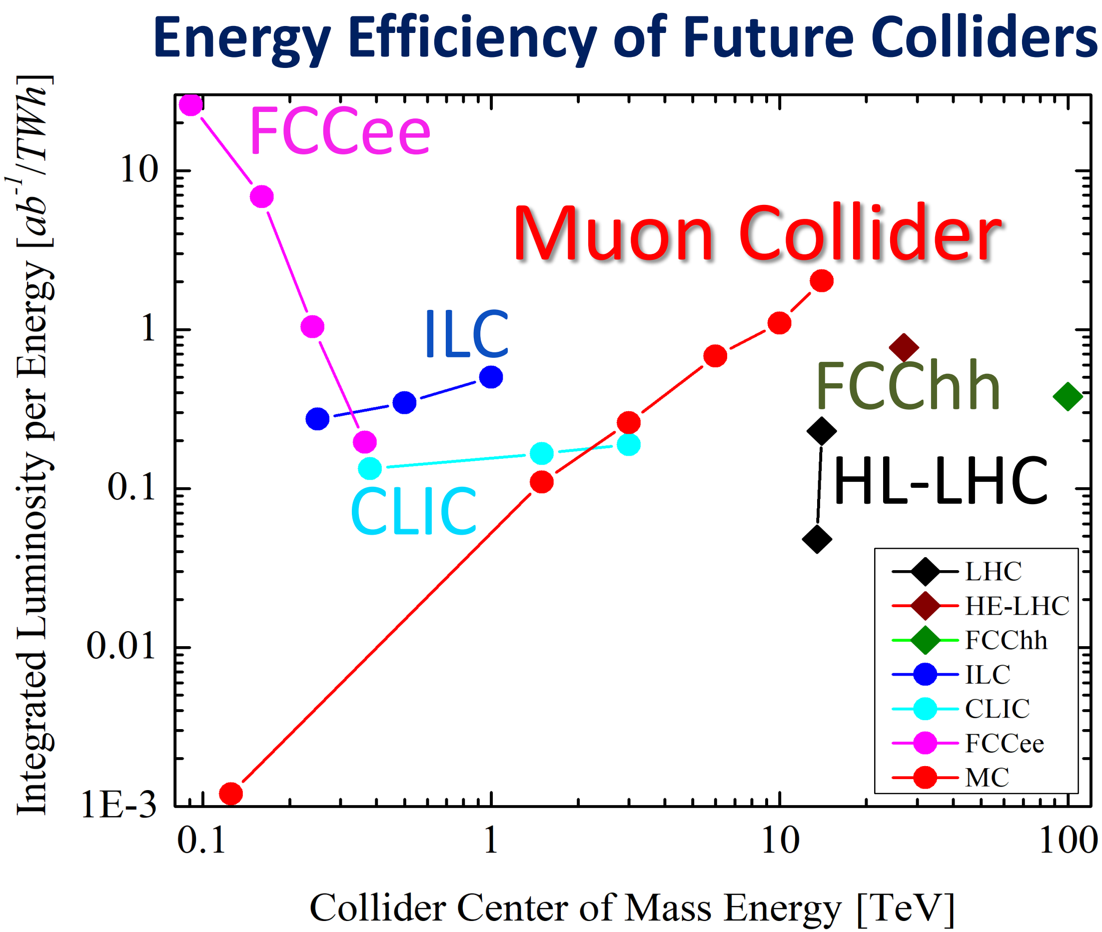
The goals:

- document the collective view of the field for the future R&D
- support subsequent decisions on prioritisation, resourcing and **implementation**

Accelerator R&D Roadmap **Jan '22**

Snowmass Implementation Task Force

- Established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact
- Collider proposals grouped into four categories that address similar physics:
  - **Higgs factory colliders** with a typical center of mass (CM) energy of 250 GeV
  - **High energy lepton colliders** with up to 3 TeV CM energy
  - **Lepton and hadron colliders with 10 TeV or higher** parton CM energy
  - **Lepton-hadron colliders**



Higgs factories - $E_{cm} < 1\,TeV$

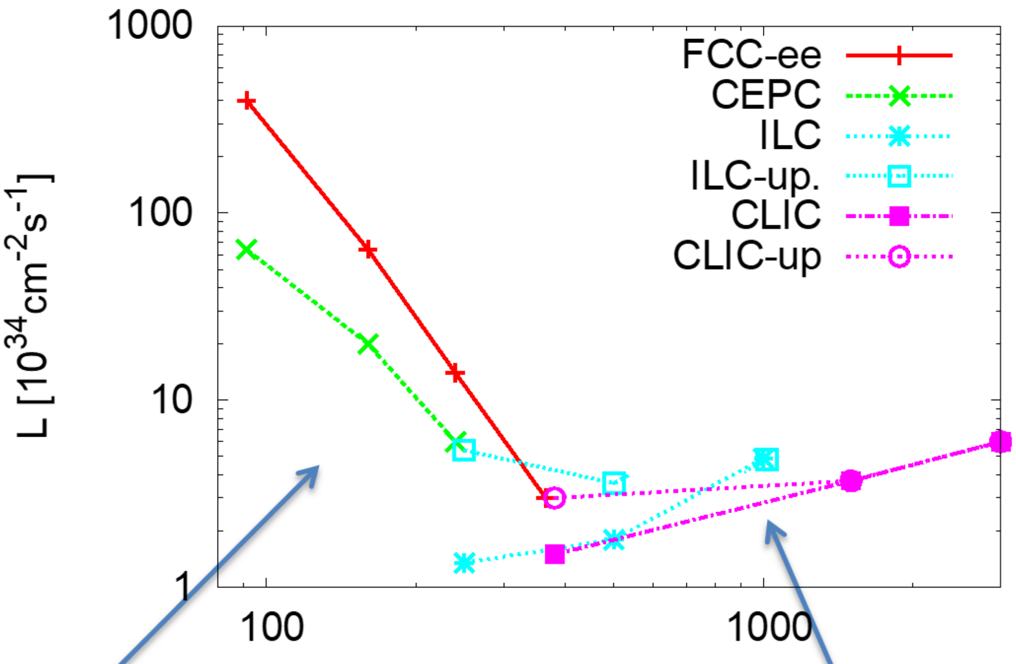
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Parton energy < 1 TeV (HL-LHC)

s-channel production (muon-collider)

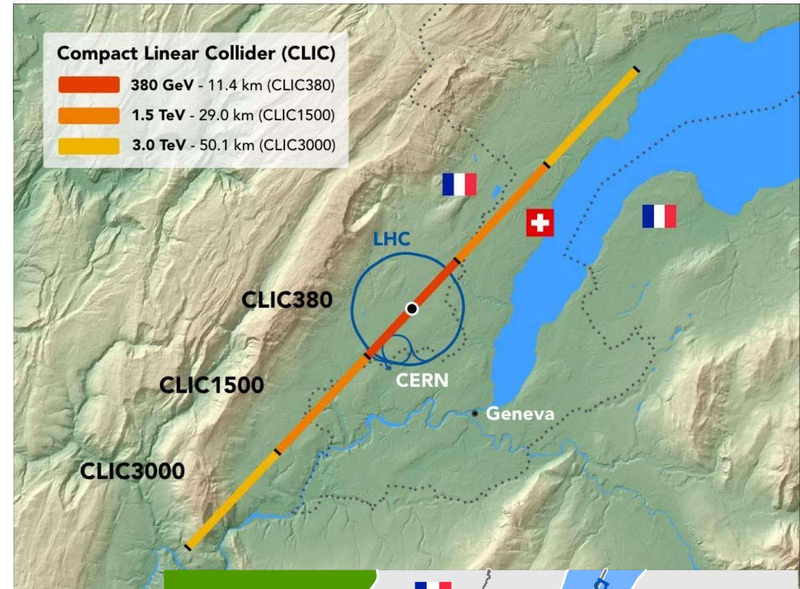
Linear vs Circular lepton e^+e^- collider

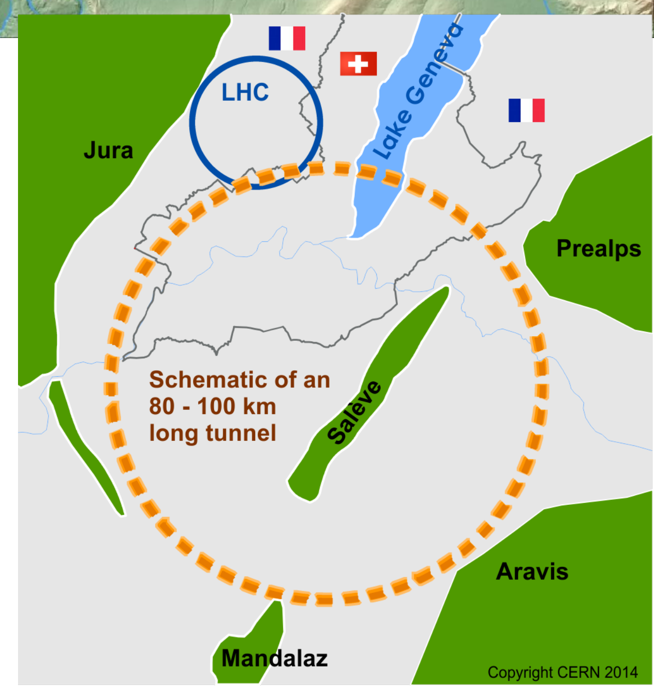
Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF} E_{cm}$





multi-TeV collider concepts

- **Collider scenarios to operate in the 1-100 TeV c.m. energy range (or beyond)**:
  - lepton-lepton:
    - e+e-
    - μ+μ-
  - hadron-hadron
  - lepton- hadron
  - gamma-gamma not discussed here

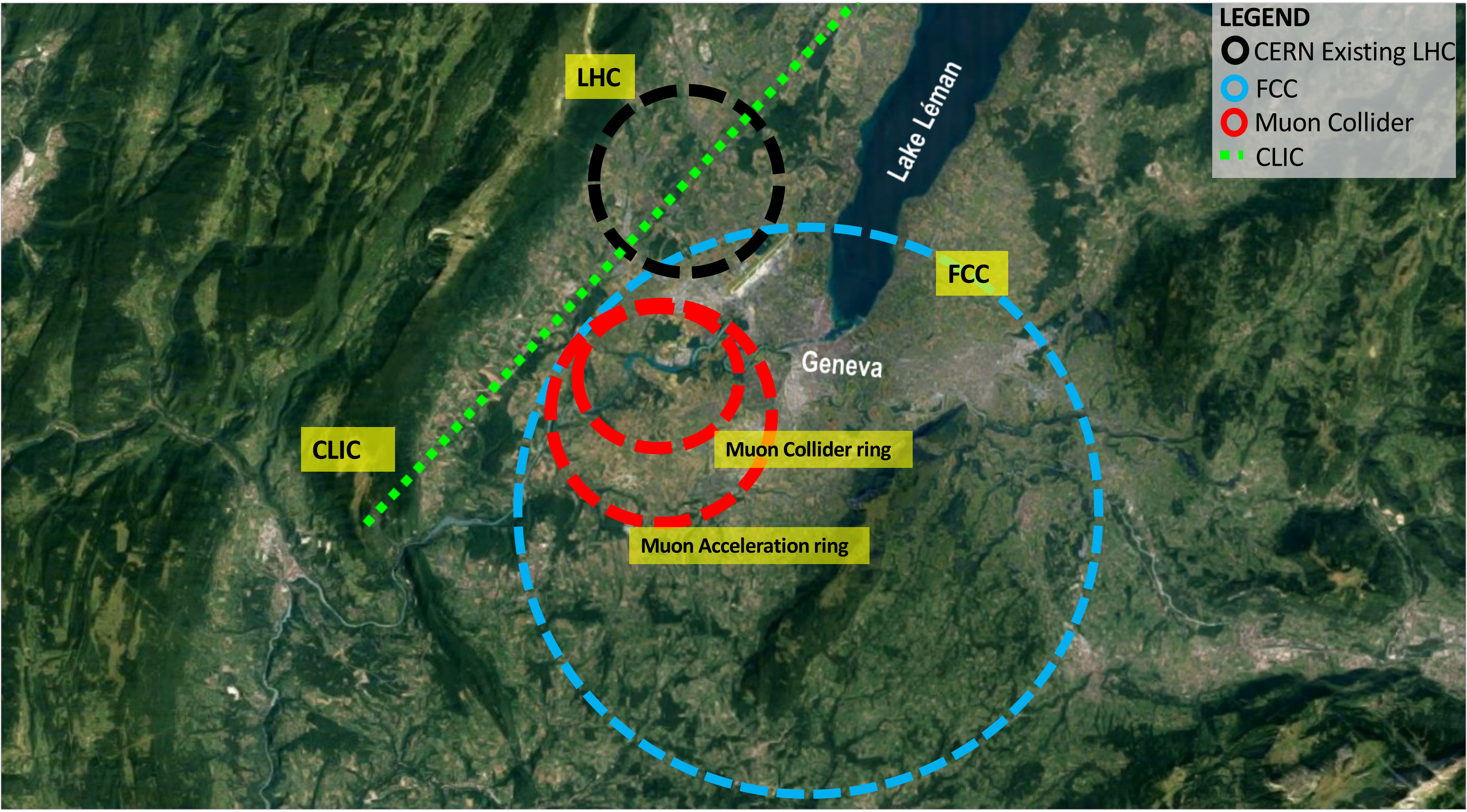
to explore the unknown
at the highest possible energy scale

- **Issues discussed**:
  - the physics reach
  - the level of maturity of the facility concepts
  - the potential machine routes
  - timelines
  - R&D requirements
  - energy efficiency and cost
  - synergies to develop accelerator and detector technologies

Multi-TeV concepts parameters

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh SPPC 125 TeV	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	±80/0	2.5
		3.0 TeV	±80/0	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Footprint of future colliders @ CERN



U.S. possible options

- A US-sited linear e+e− (ILC/CCC) Collider
- Hosting a 10 TeV range muon collider
- Exploring other e+e− collider options to fully utilize the Fermilab site

Muon Collider @ FNAL option

10 TeV collider requires ~16 T dipoles in RCS scenarios With rapid-cycling 2-4 T magnets

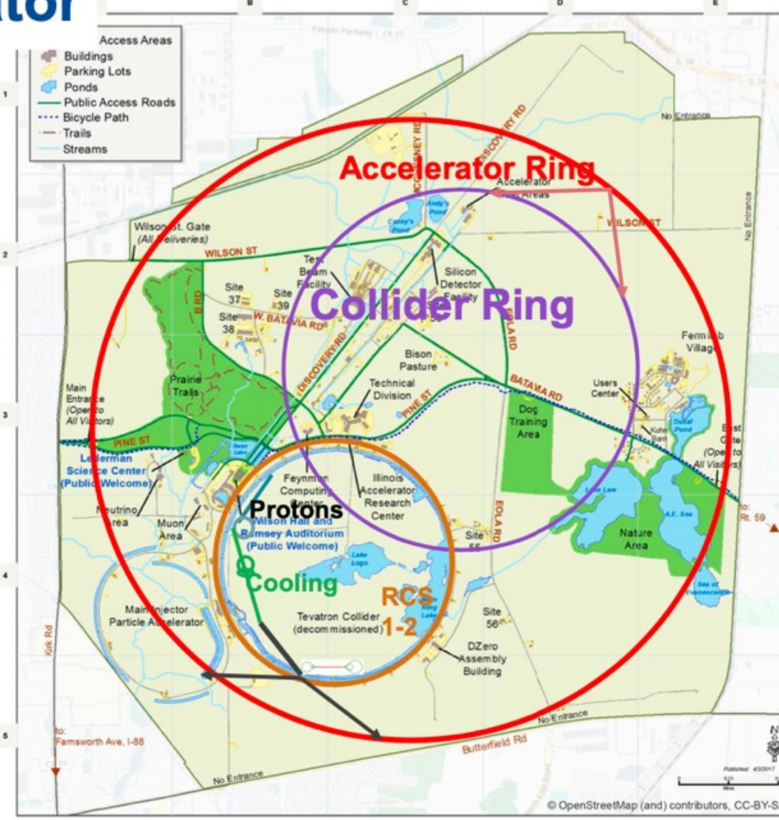
Fermilab has formed a Future Colliders Group, which is actively exploring a site filler option

Site filler Accelerator

- **Proton Source**
  - **PIP-III→target**
- **μ Cooling**
- **Linac + RLA → 65 GeV**
- **RCS 1 and 2 → 1000 GeV**
  - **Tevatron-size**
- **RCS 3 → 5 TeV**
  - **Site filler accelerator**

10 TeV collider

Collider Ring ~10 km



Fermilab

FCChh/SppC vs Muon Collider

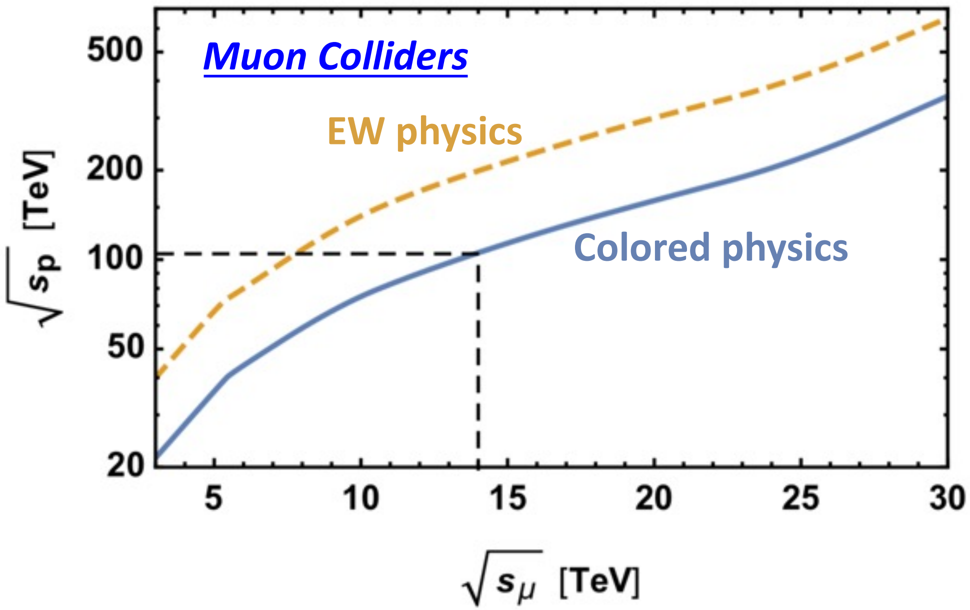
A 100 TeV proton-proton collider (e.g. FCC-hh, SppC) provides an effective energy reach similar to that of a 10-TeV scale muon collider with sufficient integrated luminosity

The 100 TeV hadron collider will have an advantage when it comes to searching for colored states, while the muon collider naturally is stronger for EW states

One of the key measurements from the multi-TeV colliders is the measurement of the Higgs self-coupling measurement to a precision of a few percent, and the possibility of scanning (establishing?) the Higgs potential

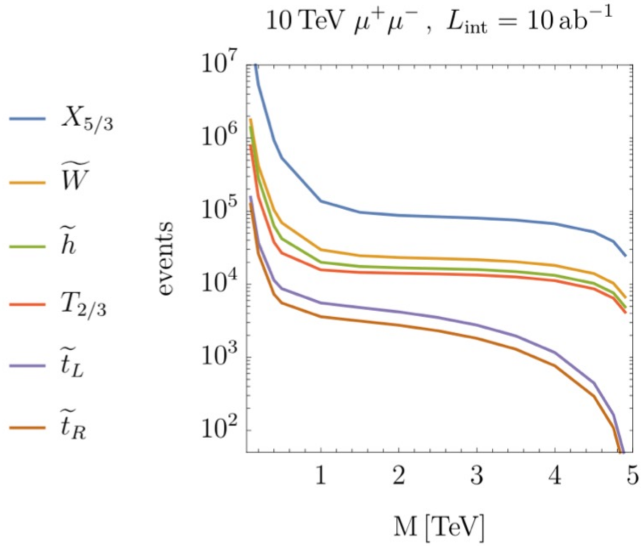
Strong synergy on High Field Magnets R&D and much more!

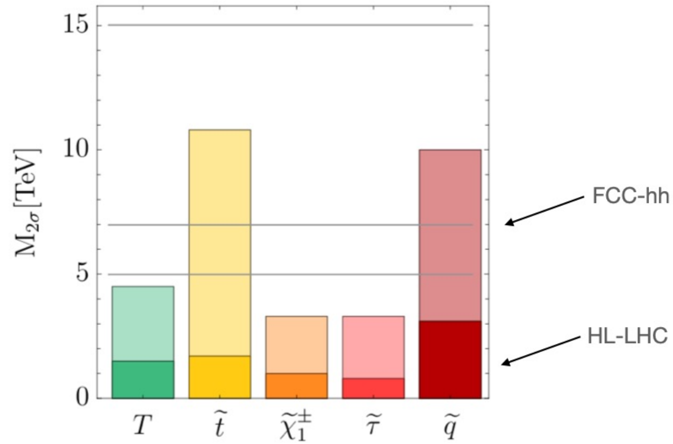
Energy at which $\sigma_{pp} = \sigma_{\mu\mu}$

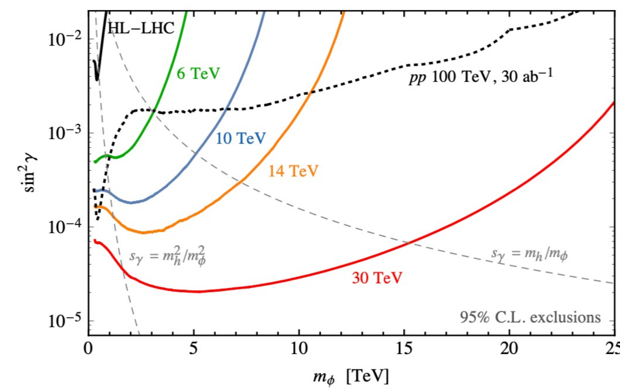


Muon Collider physics reach in a nutshell

arXiv:2203.07256 **Muon Collider Physics Summary**
arXiv:2203.07261 **The physics case of a 3 TeV muon collider stage**







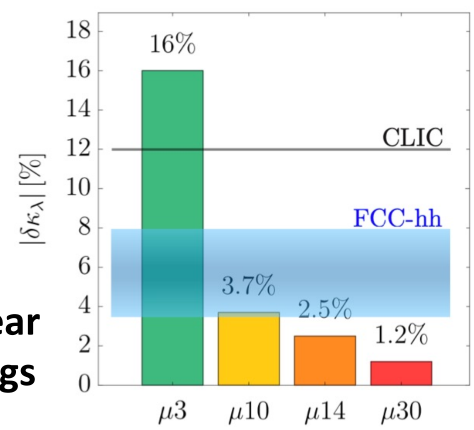
Exclusion contour for a scalar singlet of mass mϕ mixed with the Higgs boson with strength sin γ

Higgs coupling sensitivities k-framework

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

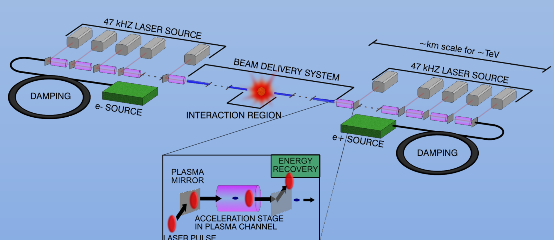
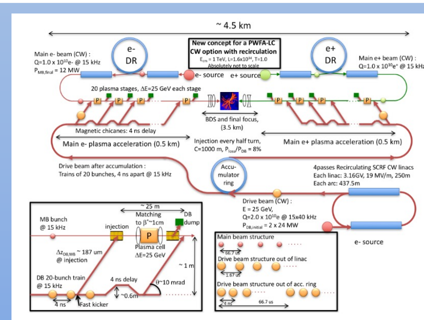
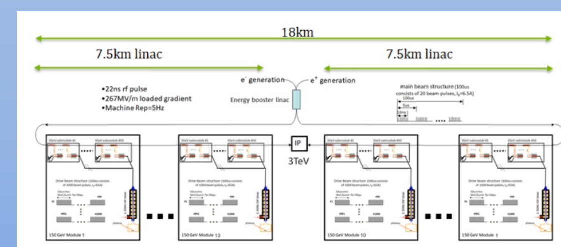
* No input used for μ collider

Higgs trilinear self-couplings



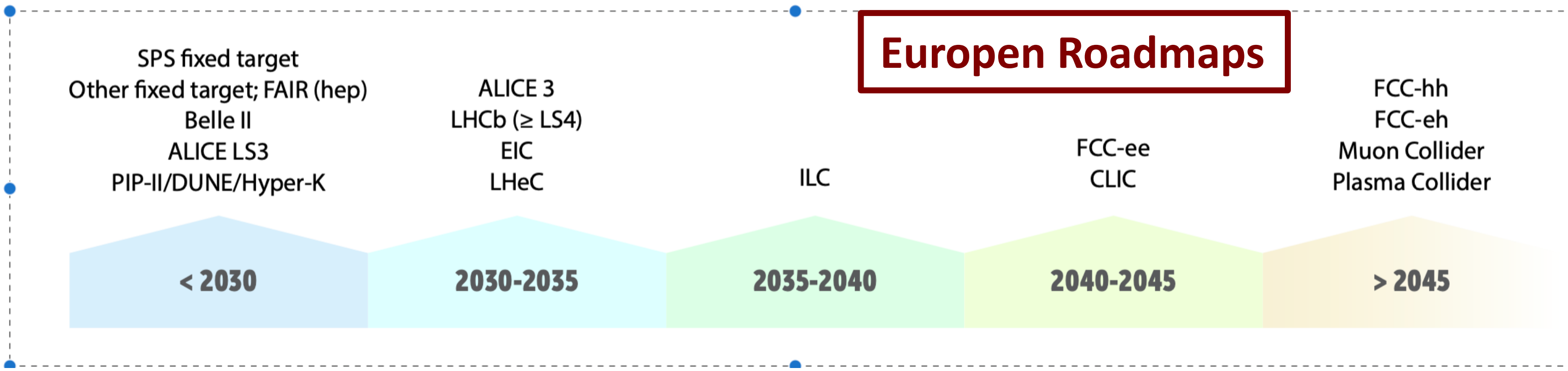
Multi-TeV e+e- Collider Based on Advanced Plasma and Structure Accelerators

- Acceleration goal: ~GV/m average gradients in wakefields ➔ **compact TeV colliders**
- **Three different collider design** based on the energy source: laser pulses (LPA) or electron beams (PWFA, SWFA) and the medium sustaining the wakefields: plasmas (LPA,PWFA) or dielectric based structures (SWFA)
- **All concepts will require extensive R&D efforts**

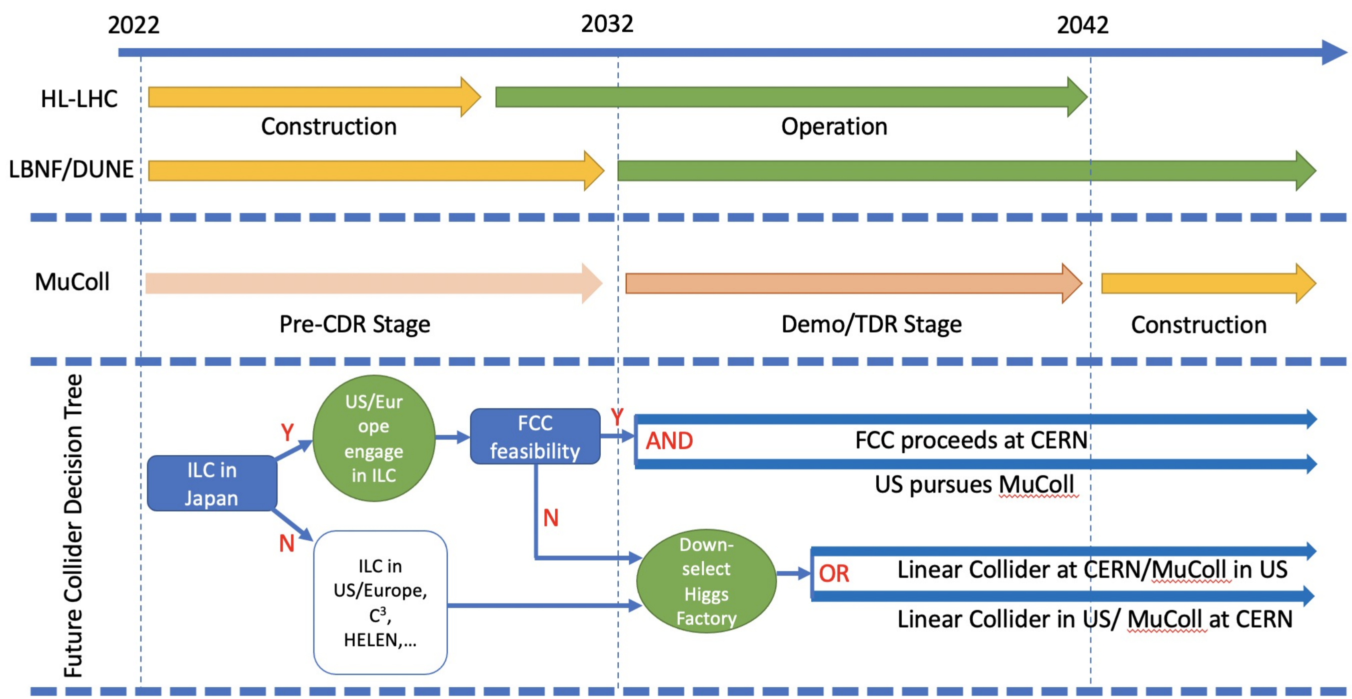
Laser Plasma Accelerator (LPA)	Beam-Driven Plasma Wakefield Accelerator (PWFA)	Beam-Driven Structure Wakefield Accelerator (SWFA)
		

ANA technology	PWFA	PWFA	PWFA	SWFA	SWFA	SWFA	LPA	LPA	LPA
Center-of-mass energy [TeV]	1	3	15	1	3	15	1	3	15
Beam energy [TeV]	0.5	1.5	7.5	0.5	1.5	7.5	0.5	1.5	7.5
Geo. Luminosity [10^{34} cm^{-2} s^{-1}]	1	10	50	1	10	50	1	10	50
Particles/bunch [10^9]	5.0	5.0	5.0	3.1	3.1	3.1	1.2	1.2	7.5
Single beam power [MW]	1.7	16.8	15.5	2.8	27.0	24.8	4.5	13.5	10.3
RMS bunch length [μm]	5	5	5	40	40	40	8.5	8.5	2.2
Repetition rate [kHz]	4.2	14	2.6	11	36	6.6	47	47	1.1
Facility site power (to main) [MW]	22.4	224	206	16.9	166	152	113	338	344

Timeline considerations



Snowmass



Concept Maturity Evaluation - multi-TeV Colliders

Design Maturity	Maturity Criteria #1 (Design Maturity)	Maturity Criteria #2 (R&D Maturity)
0	No end-to-end design concept prepared	Concept proposed, but no systematic design requirements and/or parameters available.
1	No end-to-end design concept prepared	Concept proposed, proof-of-principle R&D underway
2	**End-to-end preliminary design concept** under development	Ongoing R&D to address **fundamental physics/technical issues.**
3	**End-to-end preliminary design concept** available	**Sub-system operating parameters established** based on preliminary design concepts **for novel/critical sub-systems**
4	**End-to-end integrated design concept** under development	**Preliminary design concepts with operating parameters** established **for all sub-systems.** Sub-system design R&D underway.
5	**End-to-end integrated design concept** available. Enables **end-to-end performance evaluation.**	**Sub-system preliminary designs** exist. **Sub-system design R&D** continues.
6	**End-to-end performance evaluation** complete. **Reference** (pre-CDR level) **Design Report** under development.	**Sub-system performance risk assessment** complete.
7	**Reference Design** available. **Sub-system parameters** and **high potential alternatives** documented.	**Sub-system detailed design** and **performance R&D** for highest risk sub-systems underway.
8	**Conceptual Design Report** in preparation.	**Sub-system specifications** with **validated operating parameters** established. **High risk sub-system R&D** underway.
9	**Conceptual Design Report** and **detailed cost estimate** avaialable.	**High risk sub-system R&D** ongoing. **Risk mitigation strategy for sub-system performance** established.
10	Ready for **Construction Proposal**. Detailed Engineering Design being developed.	**Performance Optimization R&D** underway.

Concept Maturity Evaluation

Design Maturity	Maturity Criteria #1 (Design Maturity)	Maturity Criteria #2 (R&D Maturity)
0	No end-to-end design concept prepared	Concept proposed, but no systematic design requirements and/or parameters available.
1	No end-to-end design concept prepared	Concept proposed, proof-of-principle R&D underway
2	**End-to-end preliminary design concept** under development	Ongoing R&D to address **fundamental physics/technical issues.**
3	**End-to-end preliminary design concept** available	**Sub-system operating parameters established** based on preliminary design concepts **for novel/critical sub-systems**
4	**End-to-end integrated design concept** under development	**Preliminary design concepts with operating parameters** established **for all sub-systems.** Sub-system design R&D underway.
5	**End-to-end integrated design concept** available. Enables **end-to-end performance evaluation**.	**Sub-system preliminary designs** exist. **Sub-system design R&D** continues.
6	**End-to-end performance evaluation** complete. **Reference** (pre-CDR level) **Design Report** under development.	**Sub-system performance risk assessment** complete.
7	**Reference Design** available. **Sub-system parameters** and **high potential alternatives** documented.	**Sub-system detailed design** and **performance R&D** for highest risk sub-systems underway.
8	**Conceptupal Design Report** in preparation.	**Sub-system specifications** with **validated operating parameters** established. **High risk sub-system R&D** underway.
9	**Conceptual Design Report** and **detailed cost estimate** availalable.	**High risk sub-system R&D** ongoing. **Risk mitigation strategy for sub-system performance** established.
10	Ready for **Construction Proposal**. Detailed Engineering Design being developed.	**Performance Optimization R&D** underway.

Collider-in-Sea	**WFA** **MuCollider** **MuIC** **1-TeV Class ILC (Nb3Sn)** **SppC** **Multi-TeV ILC (Nb3Sn)** **TeV-Class CCC** **1-TeV Class ILC (Nb)**	**FCC-eh** **FCC-hh** **CLIC**
Low maturity conceptual development. Proof-of-principle R&D required. Concepts not ready for facility consideration.	Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding for basic R&D required. Availability of "generic" accelerator test facility access often necessary.	Efforts would benefit from directed R&D funding to mature collider concepts. Availability of test facilities to demonstrate a broad range of technology concepts required. Some large-ticket demonstrators are generally required before a detailed reference design can be completed.	Funding approach typically transition to "project-style" efforts with significant dedicated investment required.

Conclusions

- Strong collaboration across frontiers: Accelerator, Energy and Theory
- A huge amount of work submitted in arXiv (whitepapers) before Community Meeting in Seattle later in July

- EF/AF shared outlook:
  - exploit HL-LHC: Higgs physics and searches
  - e+e− Higgs factory: Higgs boson couplings, precision EW measurements
    ➔ **possible essentially with current accelerator/detector technologies**
- longer term collider that probes the multi-TeV energy scale:
  ** hadron or muon colliders ➔ **limited by technological readiness**
  ** plasma wakefield or structure advanced acceleration measurements
  ➔ **require substantial accelerator R&D**

- A strong program on Accelerator and Detector R&D both in Europe and U.S.A. is mandatory to train new generation and maintain know-how to face such complex future collider projects

Thanks for the attention!