P5 AND MUCOL

Tristan du Pree
Nikhef Staff Meeting
6th February 2024

WHAT IS P5?

Exploring the Quantum Universe

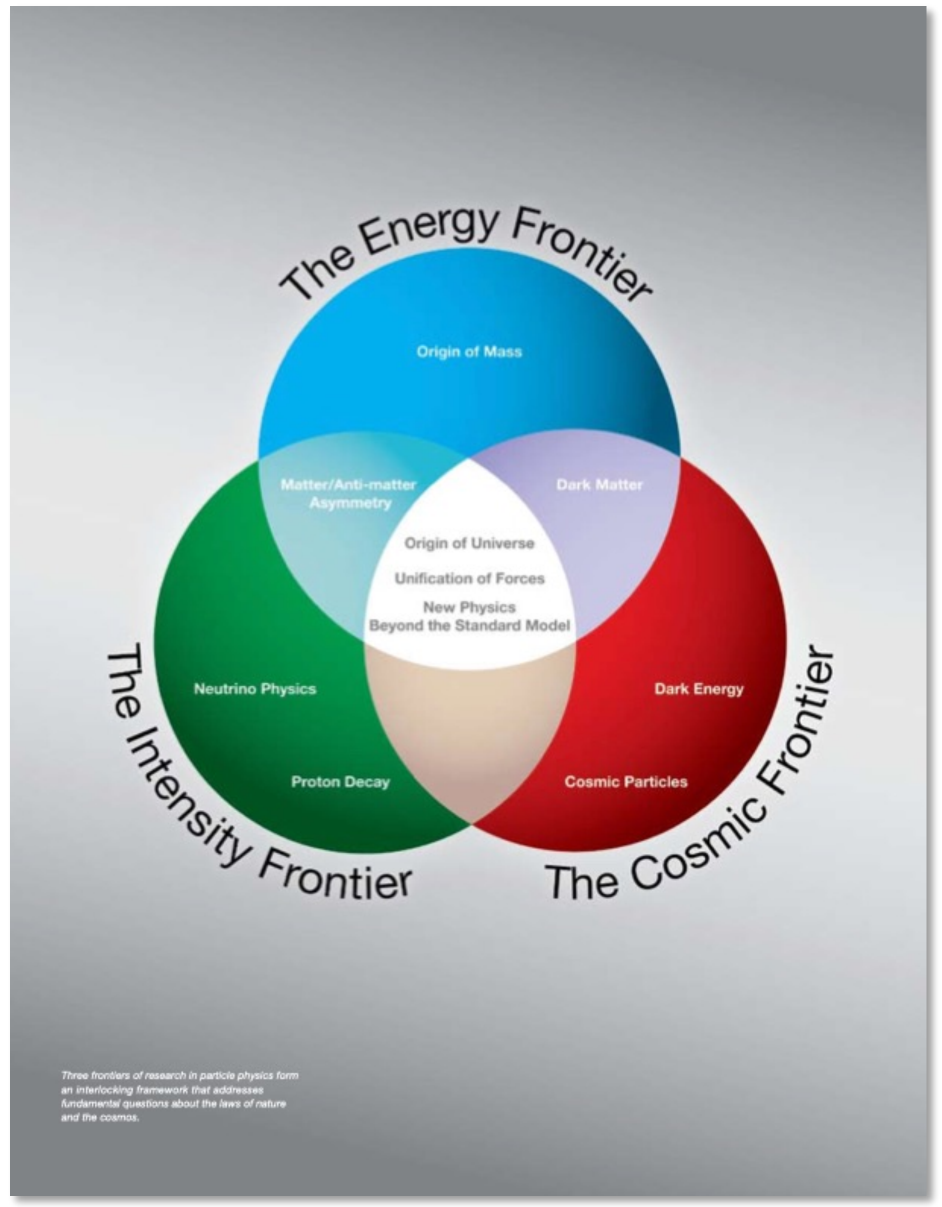
Procedure:

- Particle Physics Project Priotorization Panel
  - Subpanel of HEPAP, which advises DOE and NSF

Previous reports:

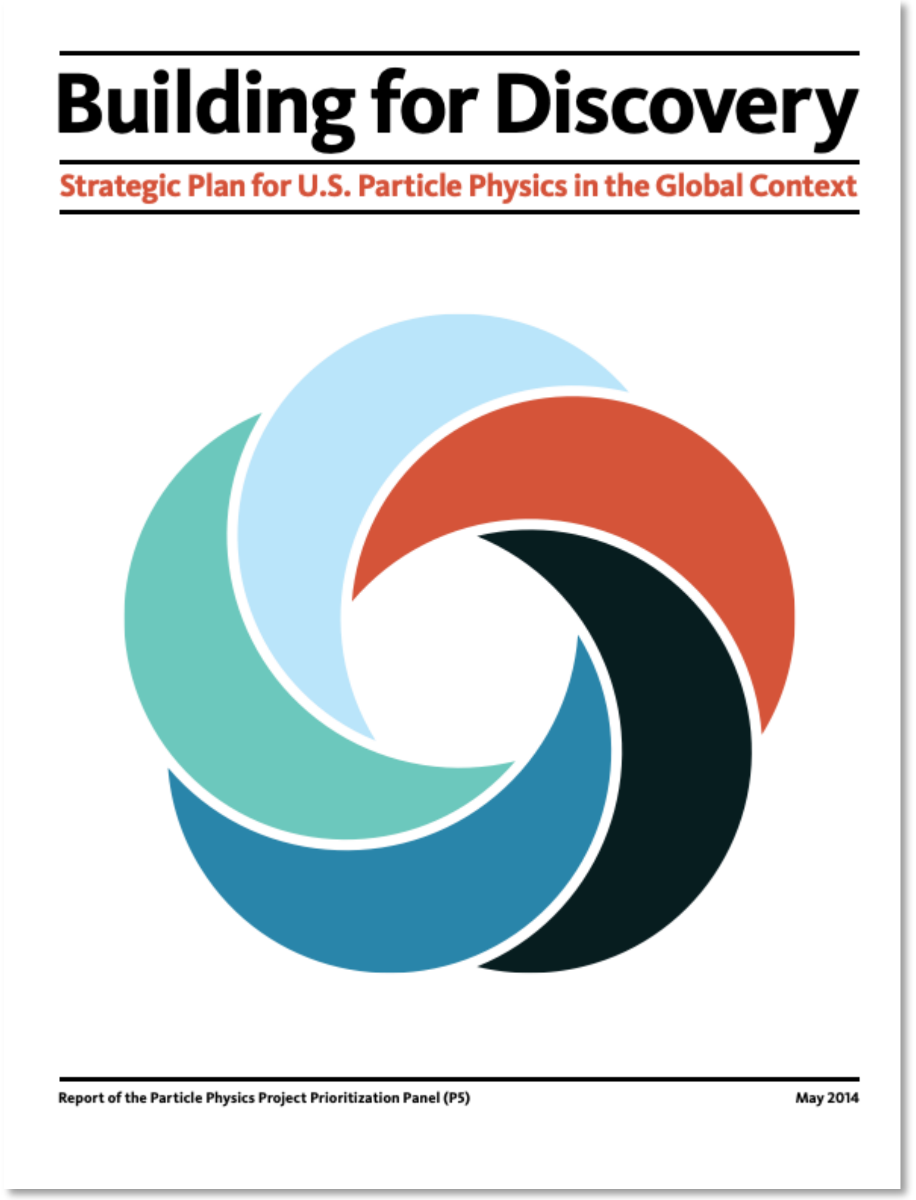
- 2008 & 2014
  - A.o. recommended DUNE
    & increased US HEP budget

2008



Three frontiers of research in particle physics form an interlocking framework that addresses fundamental questions about the laws of nature and the cosmos.

2014



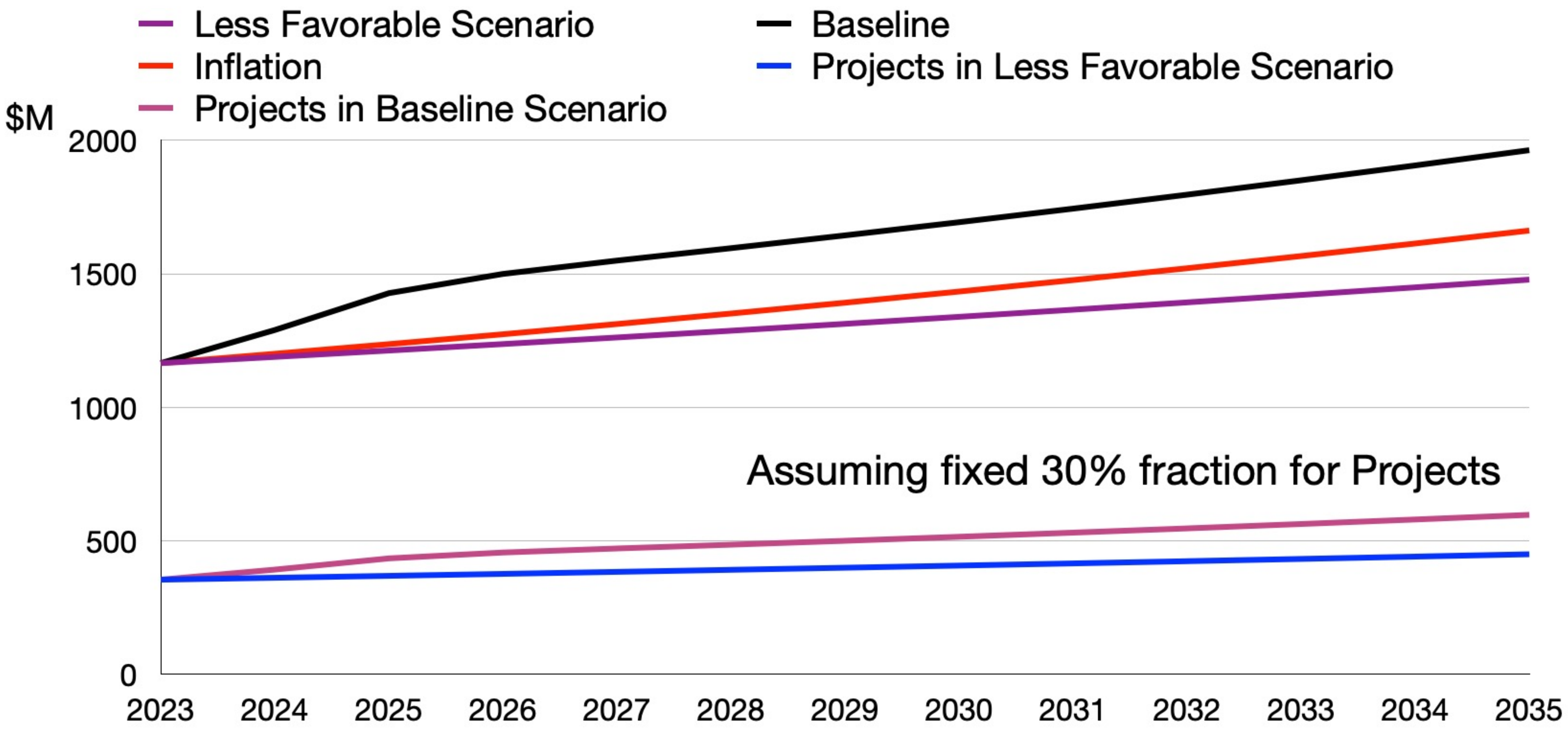
Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

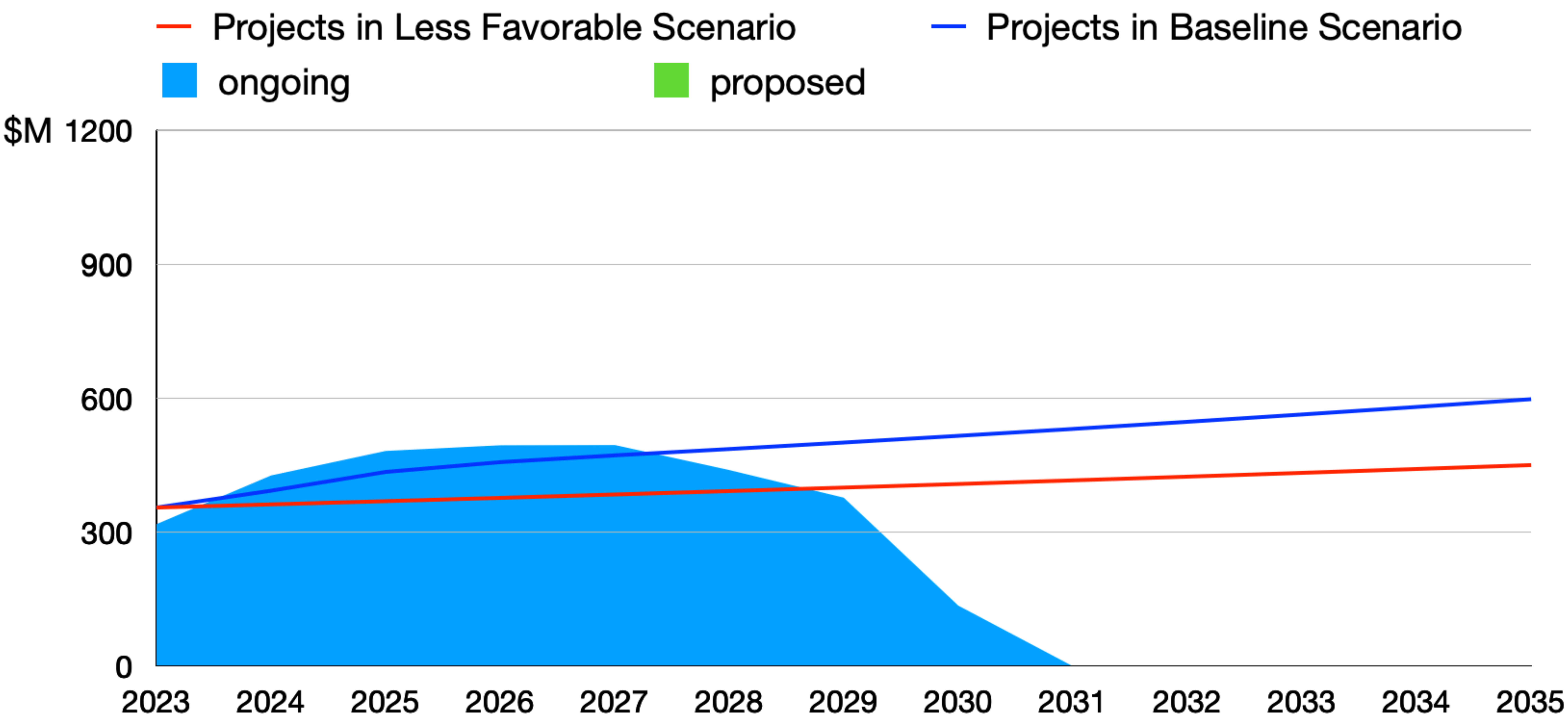
Report of the Particle Physics Project Prioritization Panel (P5)

May 2014

P5 – BUDGET SCENARIOS

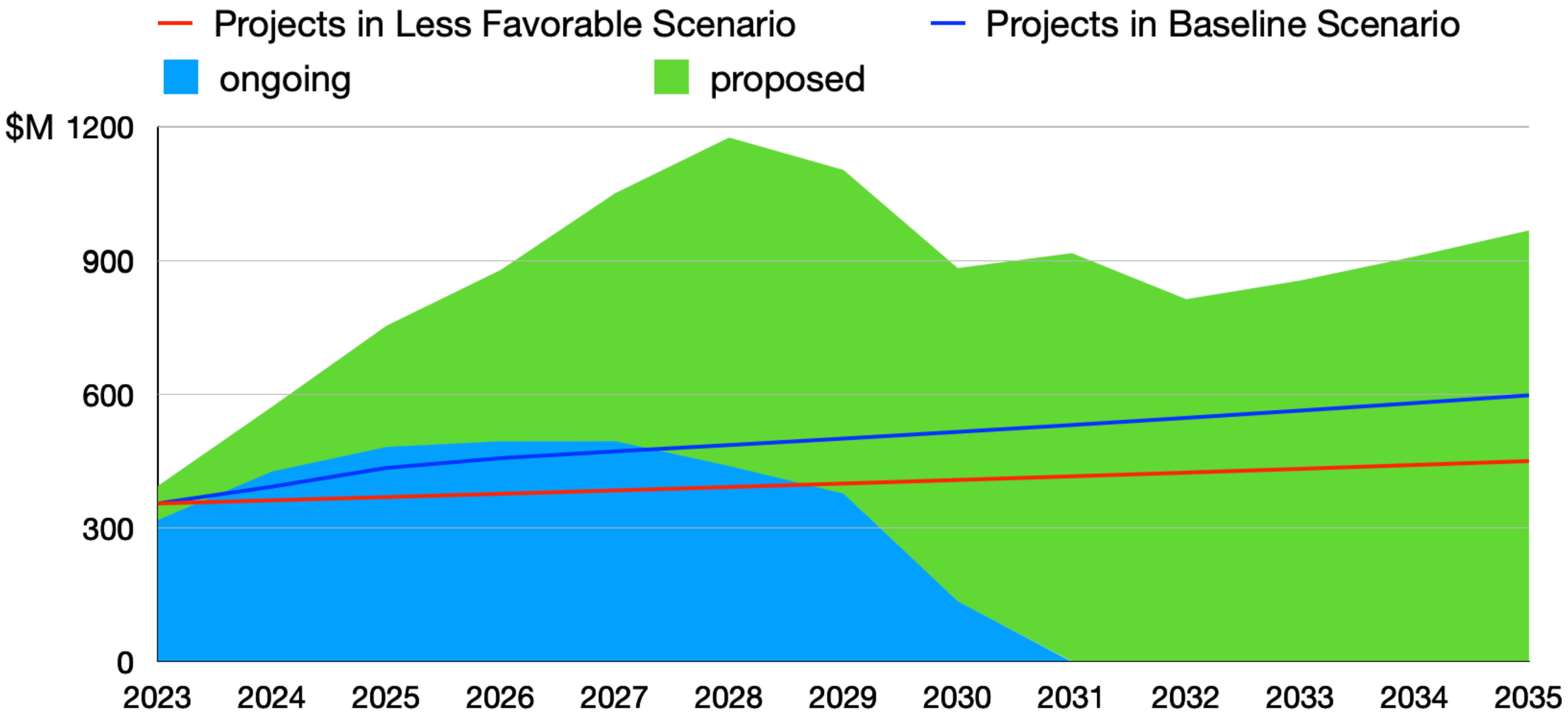


P5 – BUDGET



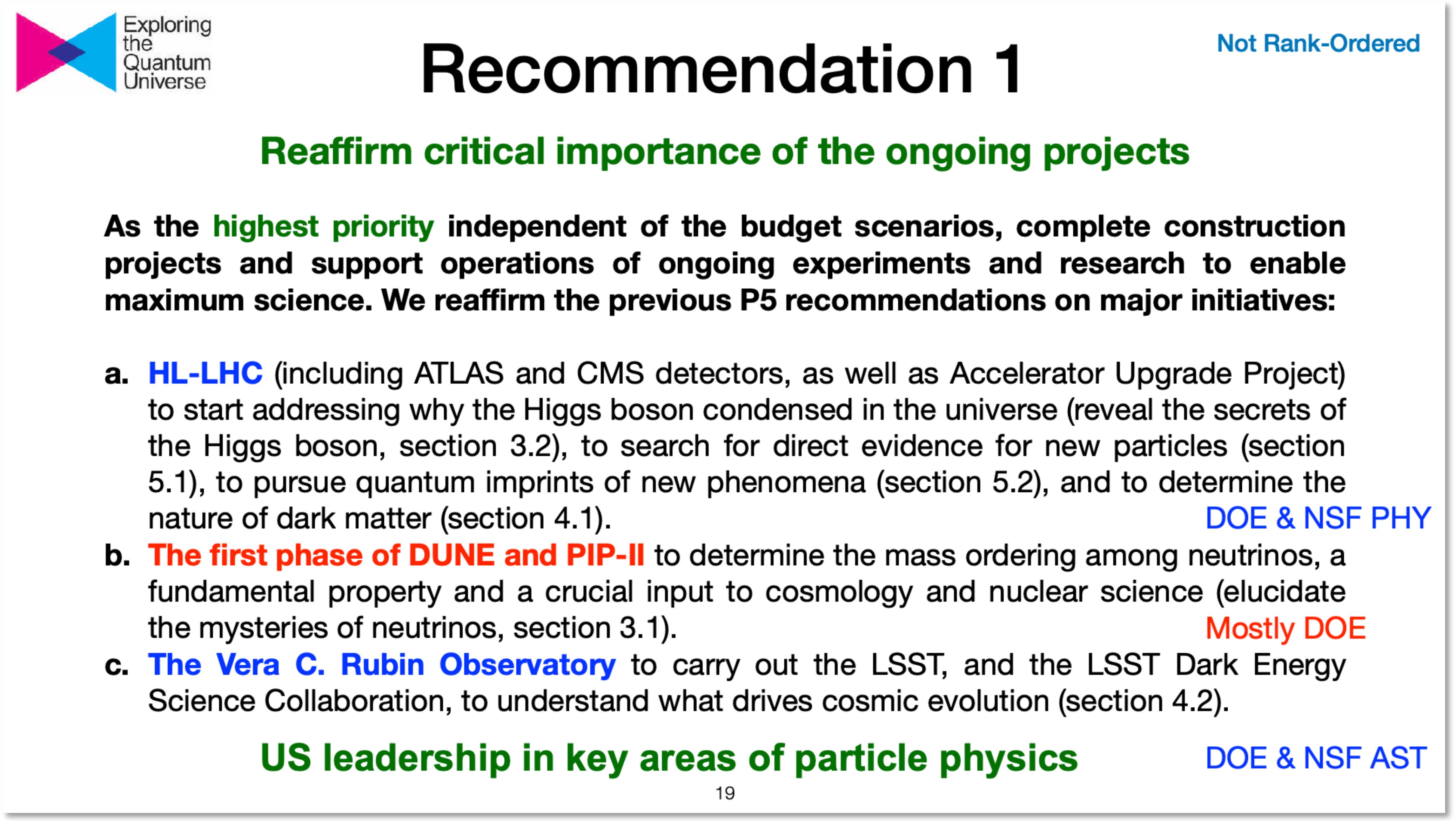
Projects in Less Favorable Scenario
Projects in Baseline Scenario
ongoing
proposed
$M
1200
900
600
300
0
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035

P5 – BUDGET PRIORITIES



RECOMMENDATION 1

Reaffirm ongoing projects



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Recommendation 1

Reaffirm critical importance of the ongoing projects

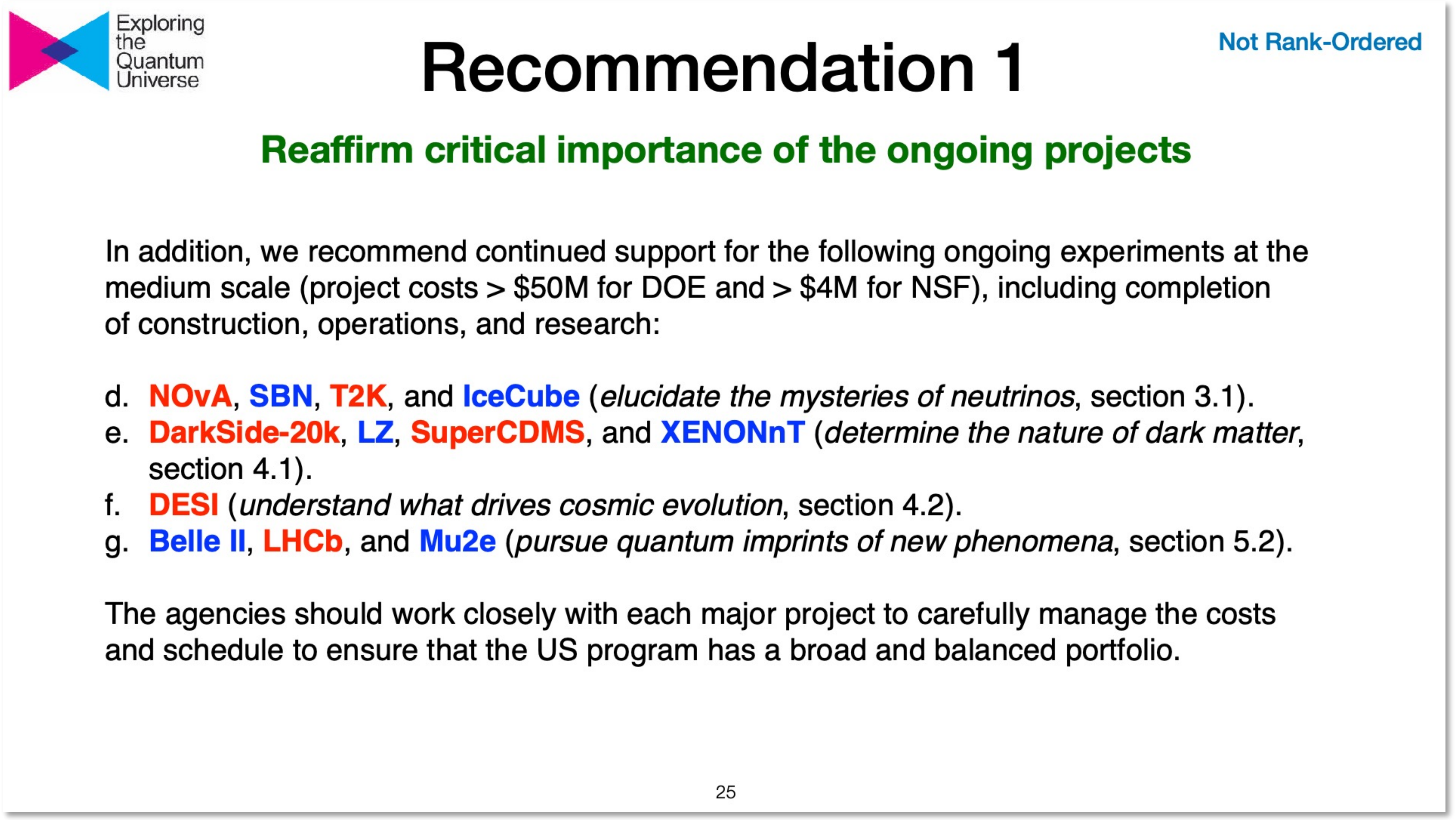
As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We reaffirm the previous P5 recommendations on major initiatives:

a. **HL-LHC** (including ATLAS and CMS detectors, as well as Accelerator Upgrade Project) to start addressing why the Higgs boson condensed in the universe (reveal the secrets of the Higgs boson, section 3.2), to search for direct evidence for new particles (section 5.1), to pursue quantum imprints of new phenomena (section 5.2), and to determine the nature of dark matter (section 4.1). DOE & NSF PHY

b. **The first phase of DUNE and PIP-II** to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1). Mostly DOE

c. **The Vera C. Rubin Observatory** to carry out the LSST, and the LSST Dark Energy Science Collaboration, to understand what drives cosmic evolution (section 4.2).

US leadership in key areas of particle physics DOE & NSF AST



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Recommendation 1

Reaffirm critical importance of the ongoing projects

In addition, we recommend continued support for the following ongoing experiments at the medium scale (project costs > $50M for DOE and > $4M for NSF), including completion of construction, operations, and research:

d. **NOvA**, **SBN**, **T2K**, and **IceCube** (*elucidate the mysteries of neutrinos*, section 3.1).

e. **DarkSide-20k**, **LZ**, **SuperCDMS**, and **XENONnT** (*determine the nature of dark matter*, section 4.1).

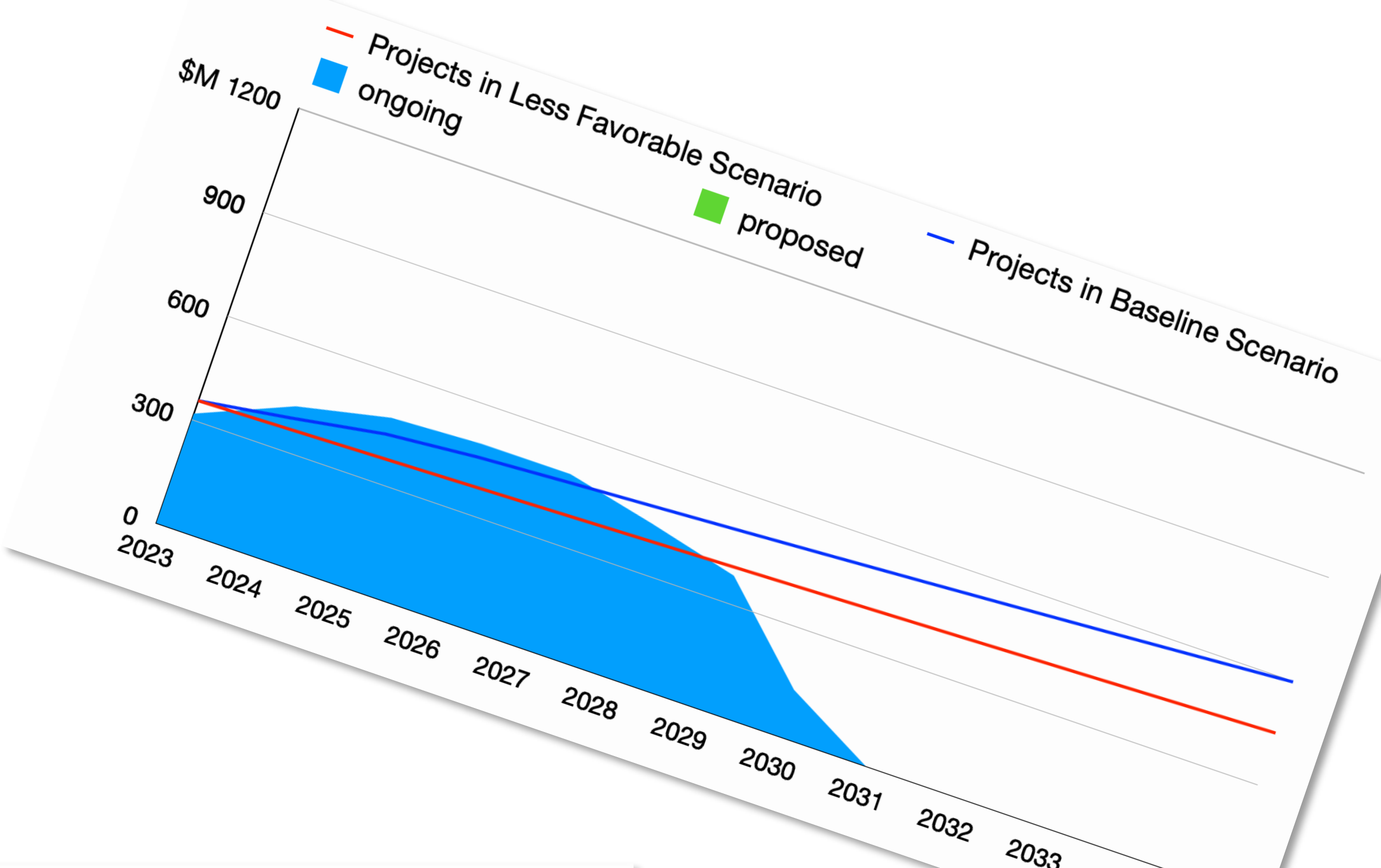
f. **DESI** (*understand what drives cosmic evolution*, section 4.2).

g. **Belle II**, **LHCb**, and **Mu2e** (*pursue quantum imprints of new phenomena*, section 5.2).

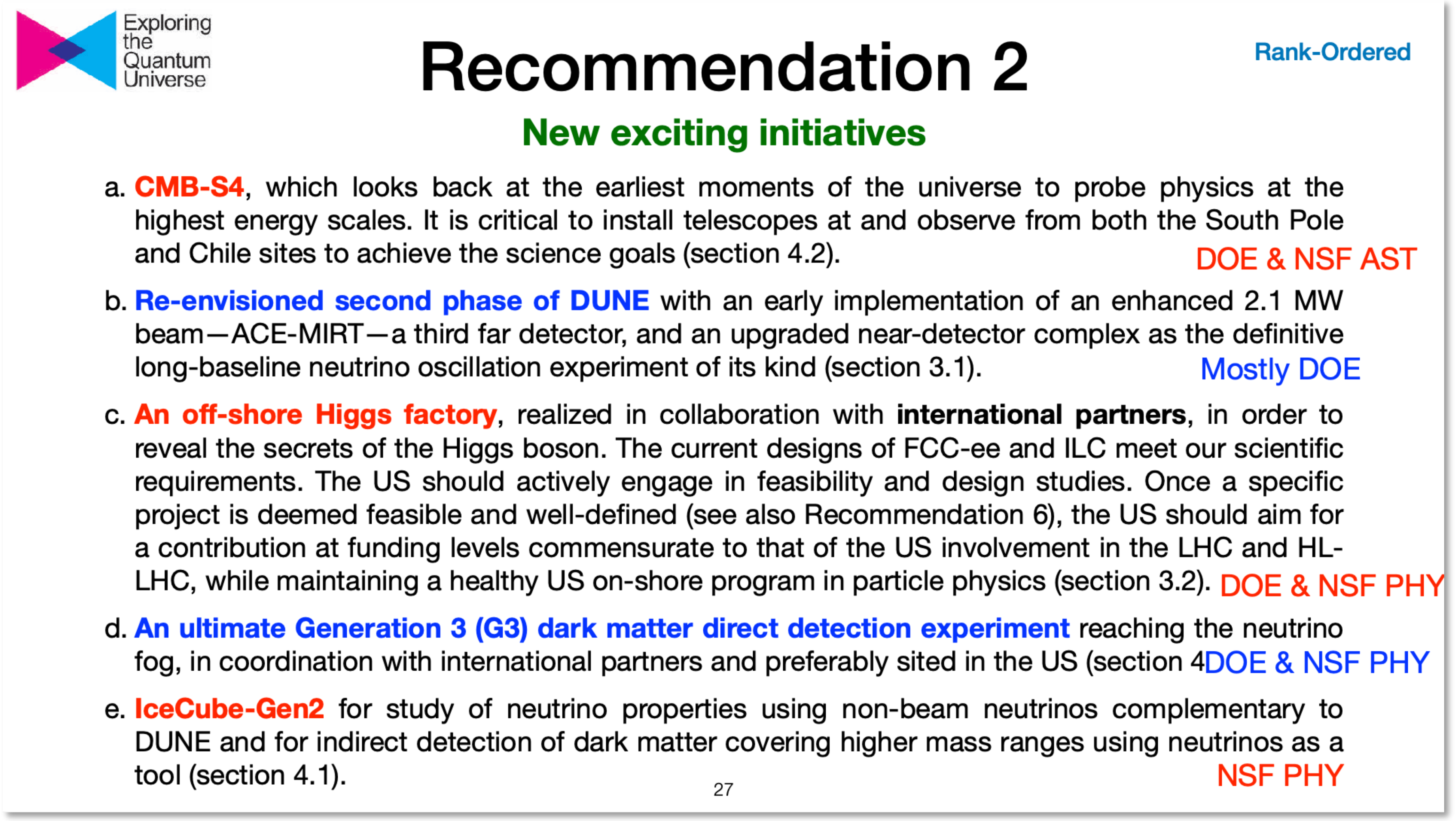
The agencies should work closely with each major project to carefully manage the costs and schedule to ensure that the US program has a broad and balanced portfolio.

- A.o. HL-LHC (ATLAS+CMS), DUNE, XENONnT, LHCb

RECOMMENDATION 2



New exciting initiatives (and hard choices)



Exploring the Quantum Universe

Recommendation 2

Rank-Ordered

New exciting initiatives

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).
DOE & NSF AST

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).
Mostly DOE

c. **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).
DOE & NSF PHY

d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4
DOE & NSF PHY

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).
NSF PHY

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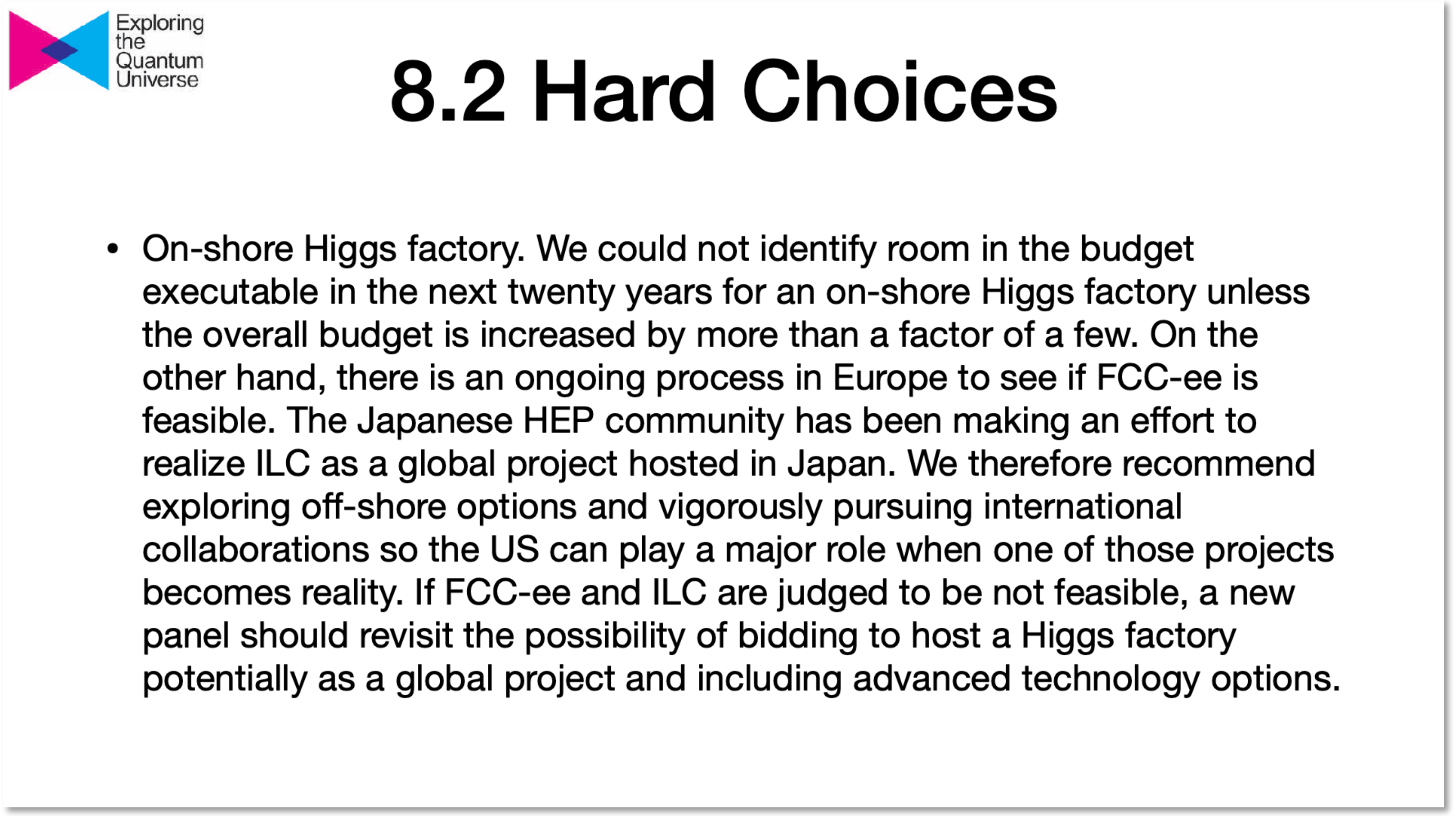


Exploring the Quantum Universe

8.2 Hard Choices

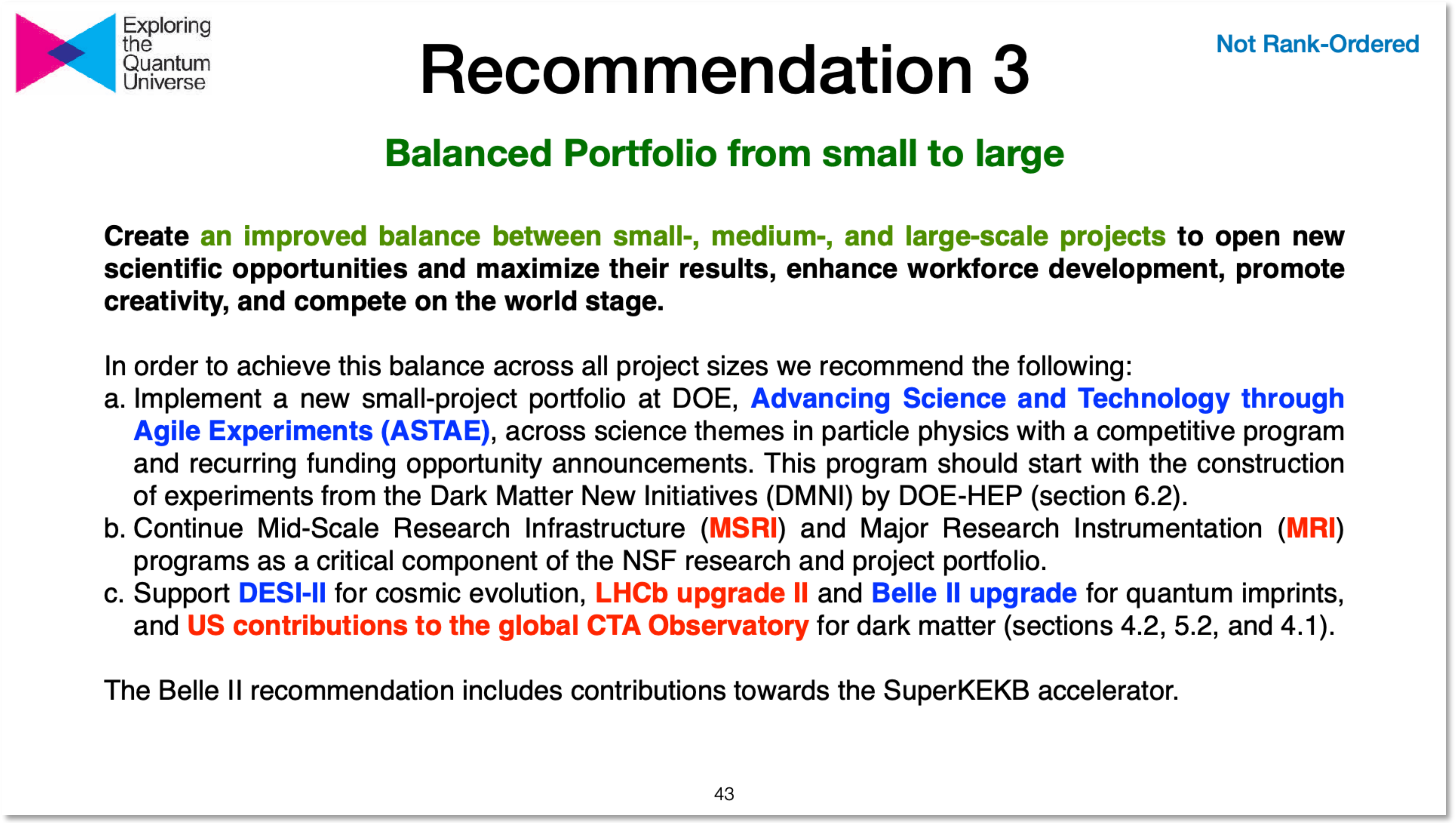
- On-shore Higgs factory. We could not identify room in the budget executable in the next twenty years for an on-shore Higgs factory unless the overall budget is increased by more than a factor of a few. On the other hand, there is an ongoing process in Europe to see if FCC-ee is feasible. The Japanese HEP community has been making an effort to realize ILC as a global project hosted in Japan. We therefore recommend exploring off-shore options and vigorously pursuing international collaborations so the US can play a major role when one of those projects becomes reality. If FCC-ee and ILC are judged to be not feasible, a new panel should revisit the possibility of bidding to host a Higgs factory potentially as a global project and including advanced technology options.

➢ Next-generation Neutrinos/DarkMatter

➢ An “Off-shore” Higgs factory (ILC/FCC)

RECOMMENDATION 3+5

Balanced portfolio (small/medium/large-scale)



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Recommendation 3

Balanced Portfolio from small to large

Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

In order to achieve this balance across all project sizes we recommend the following:

a. Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (**MSRI**) and Major Research Instrumentation (**MRI**) programs as a critical component of the NSF research and project portfolio.

c. Support **DESI-II** for cosmic evolution, **LHCb upgrade II** and **Belle II upgrade** for quantum imprints, and **US contributions to the global CTA Observatory** for dark matter (sections 4.2, 5.2, and 4.1).

The Belle II recommendation includes contributions towards the SuperKEKB accelerator.

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Recommendation 5

Diversity, Inclusion, Equity, Relevance to society

The following workforce initiatives are detailed in section 7:

a. All projects, workshops, conferences, and collaborations must incorporate ethics agreements that detail expectations for professional conduct and establish mechanisms for **transparent reporting, response, and training**. These mechanisms should be supported by laboratory and funding agency infrastructure. The efficacy and coverage of this infrastructure should be reviewed by a HEPAP subpanel.

b. Funding agencies should continue to support programs that **broaden engagement** in particle physics, including strategic academic partnership programs, **traineeship programs, and programs in support of dependent care and accessibility**. A systematic review of these programs should be used to identify and **remove barriers**.

c. Comprehensive **work-climate studies** should be conducted with the support of funding agencies. Large collaborations and national laboratories should consistently undertake such studies so that issues can be identified, addressed, and monitored. Professional associations should spearhead field-wide work-climate investigations to ensure that the unique experiences of individuals engaged in smaller collaborations and university settings are effectively captured.

d. Funding agencies should strategically increase support for **research scientists, research hardware and software engineers, technicians, and other professionals** at universities.

e. A plan for **dissemination of scientific results to the public** should be included in the proposed operations and research budgets of experiments. The funding agencies should include funding for the dissemination of results to the public in operation and research budgets.

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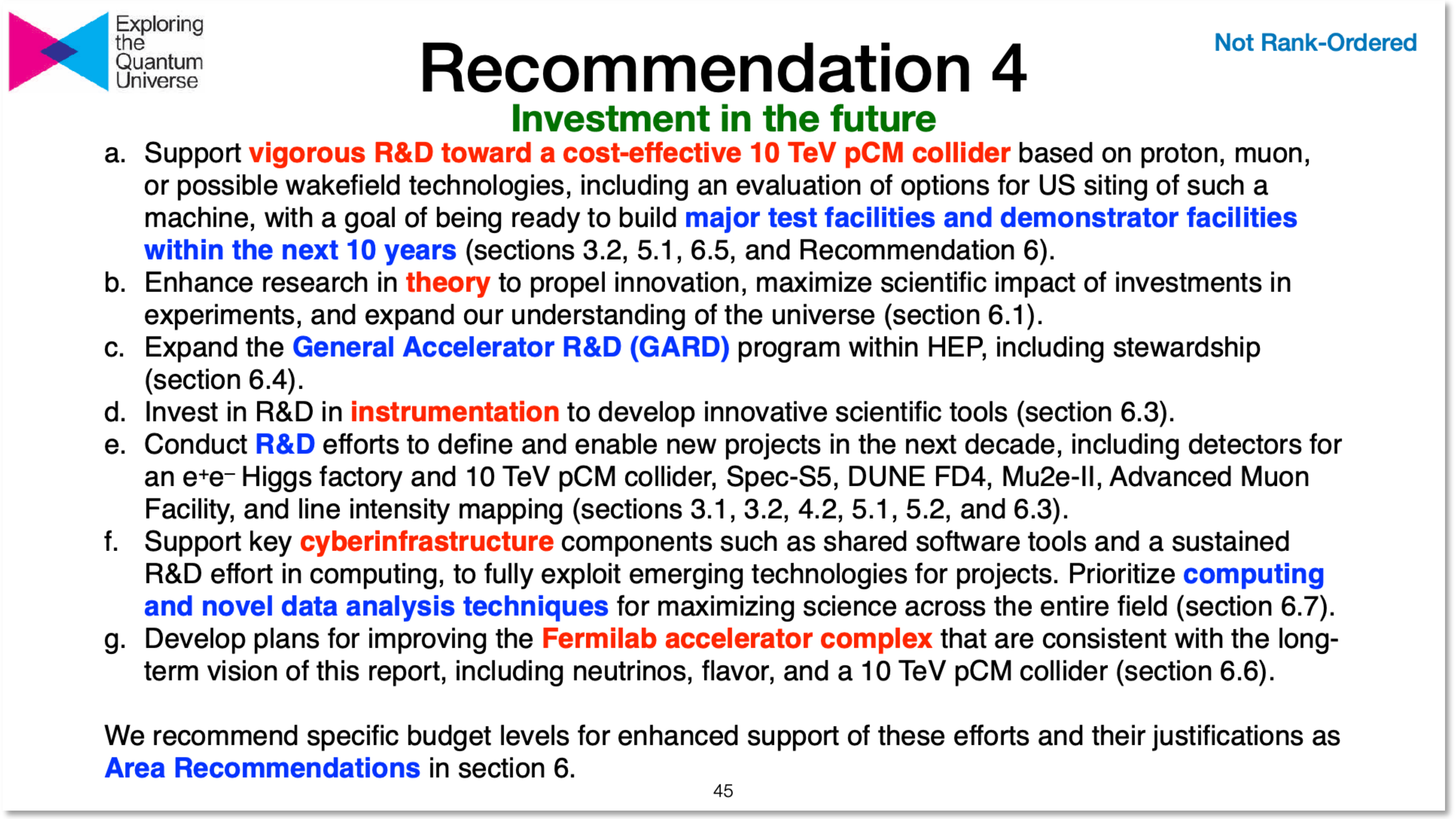
- ➢ Diversity, inclusion, and relevance to society

RECOMMENDATIONS 4+6

Investments in future (theory, cyber, instrumentation)



Exploring the Quantum Universe

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Recommendation 4

Investment in the future

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).
b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).
c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).
e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).
f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).
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).

We recommend specific budget levels for enhanced support of these efforts and their justifications as **Area Recommendations** in section 6.

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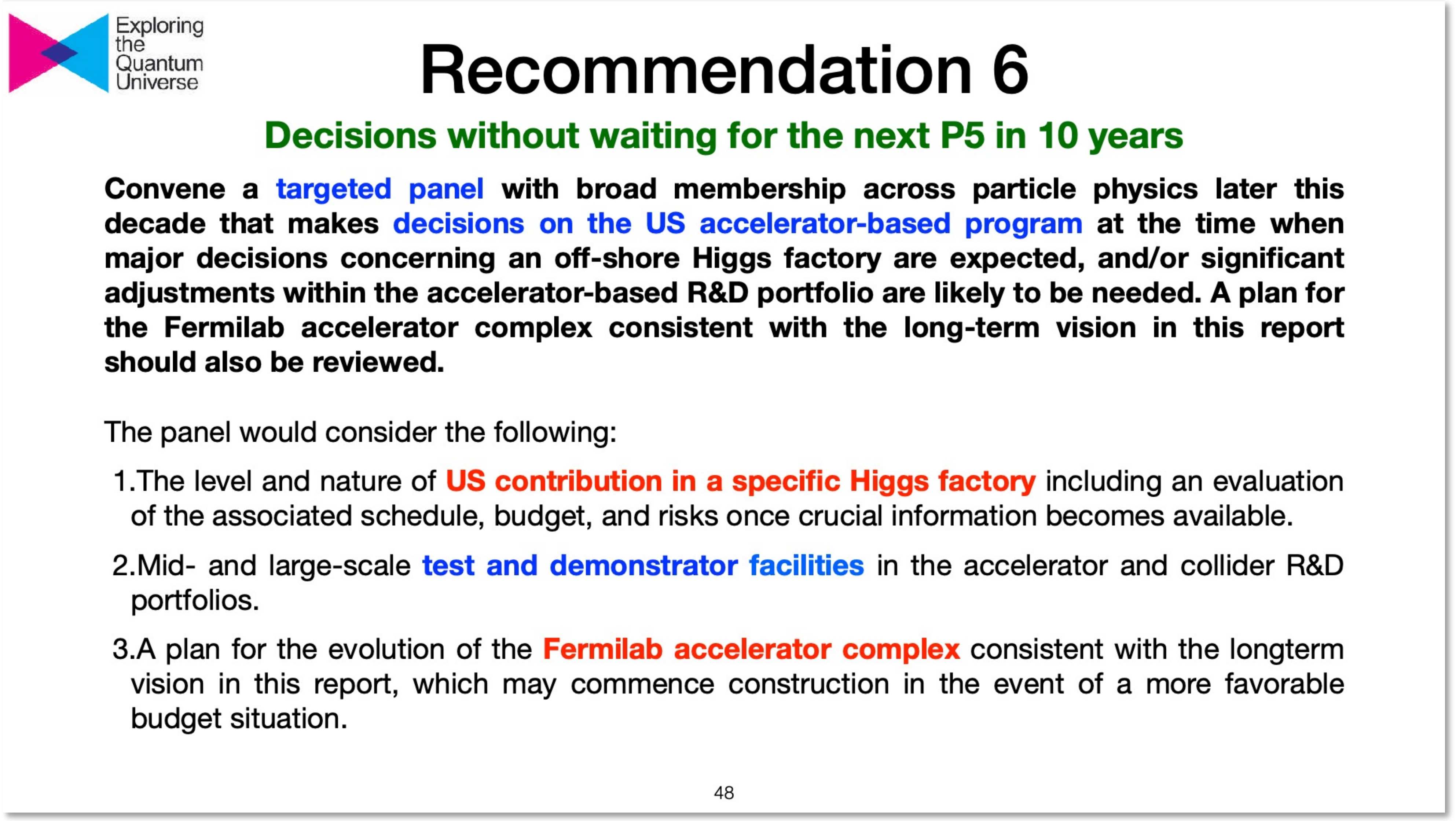

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Recommendation 6

Decisions without waiting for the next P5 in 10 years

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 longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

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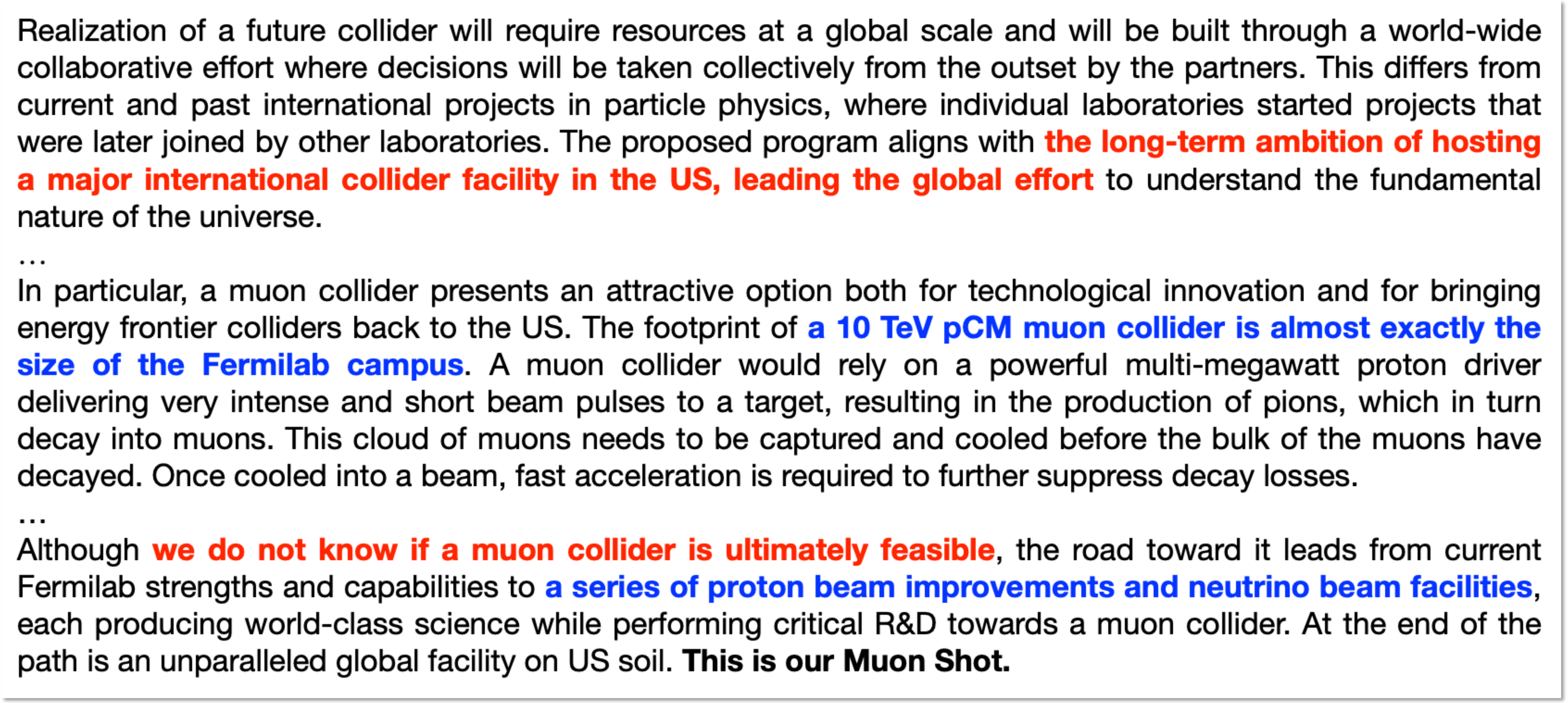
➢ General accelerator and collider R&D

THE MUON SHOT



Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, 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**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

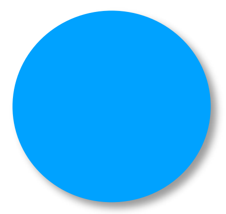
COLLIDER OPTIONS

e^+e^-

- ✅ Precision physics
- ❌ Energy limited

COLLIDER OPTIONS

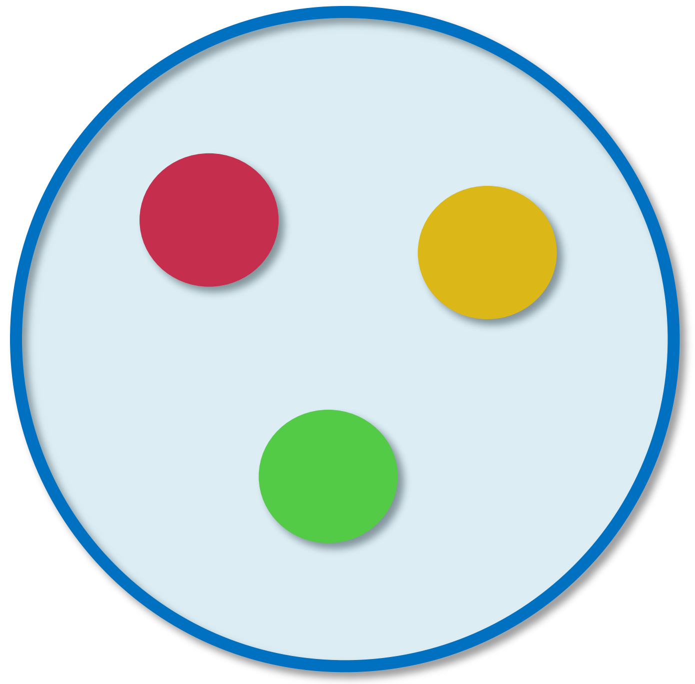
e^+e^-



✅ Precision physics

❌ Energy limited

pp



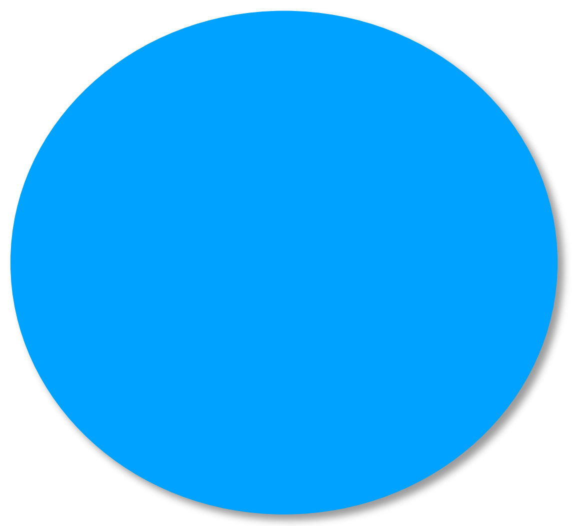
✅ Higher energy

❌ Messy & suboptimal

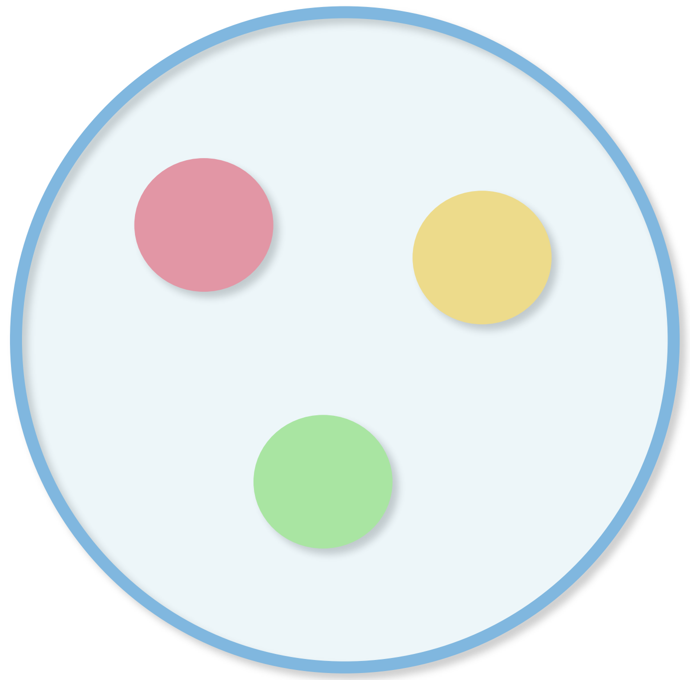
THE BEST OF BOTH WORLDS!

$\mu^+\mu^-$

m_e = 0.5 MeV



m_μ = 106 MeV



m_p = 938 MeV

✅ Precision physics

✅ And high energy

MAIN CHALLENGE

So, what's the catch?

- Finite lifetime
  - τ_μ = 2μs

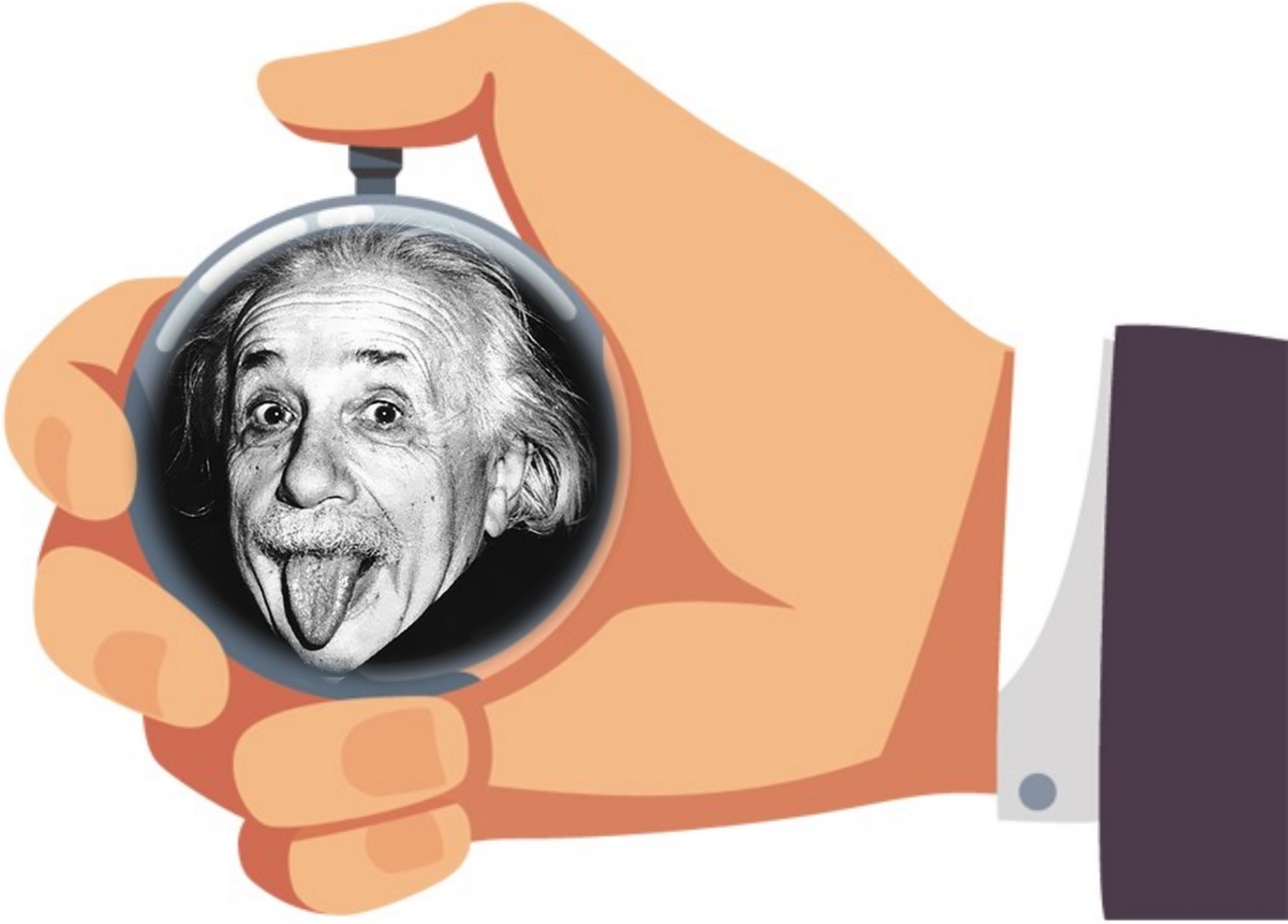
MAIN CHALLENGE

The main challenge:

- Finite lifetime
  - $\tau_\mu = 2\mu s$

Example: 5 TeV muon

- $\gamma = 50{,}000$
  - $\gamma\tau_\mu \sim 0.1s$
- $\gamma c\tau_\mu = 3x10^7 m$
  - 1000 x LHC!

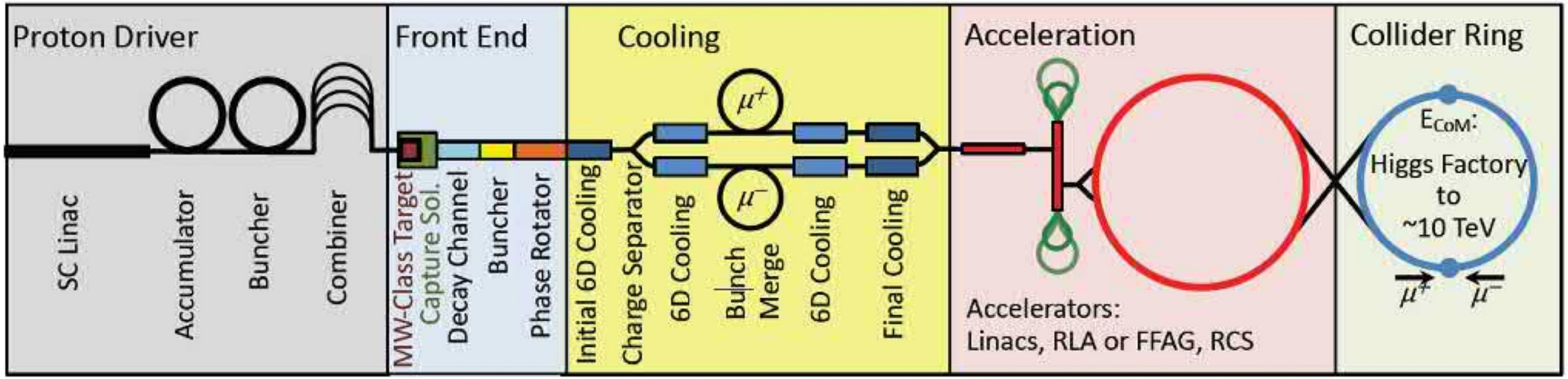


“Een echte muoncollider-fysicus kan niet zonder gamma”

MUON COLLIDER SCHEME

In 0.1s 😅

Approach: p → π → μ → cool → accelerate → collide



More details in the upcoming Topical Lectures on Future Particle Colliders, 20-22 March 2024 at Nikhef

MUON COLLIDER BENEFITS

High energy

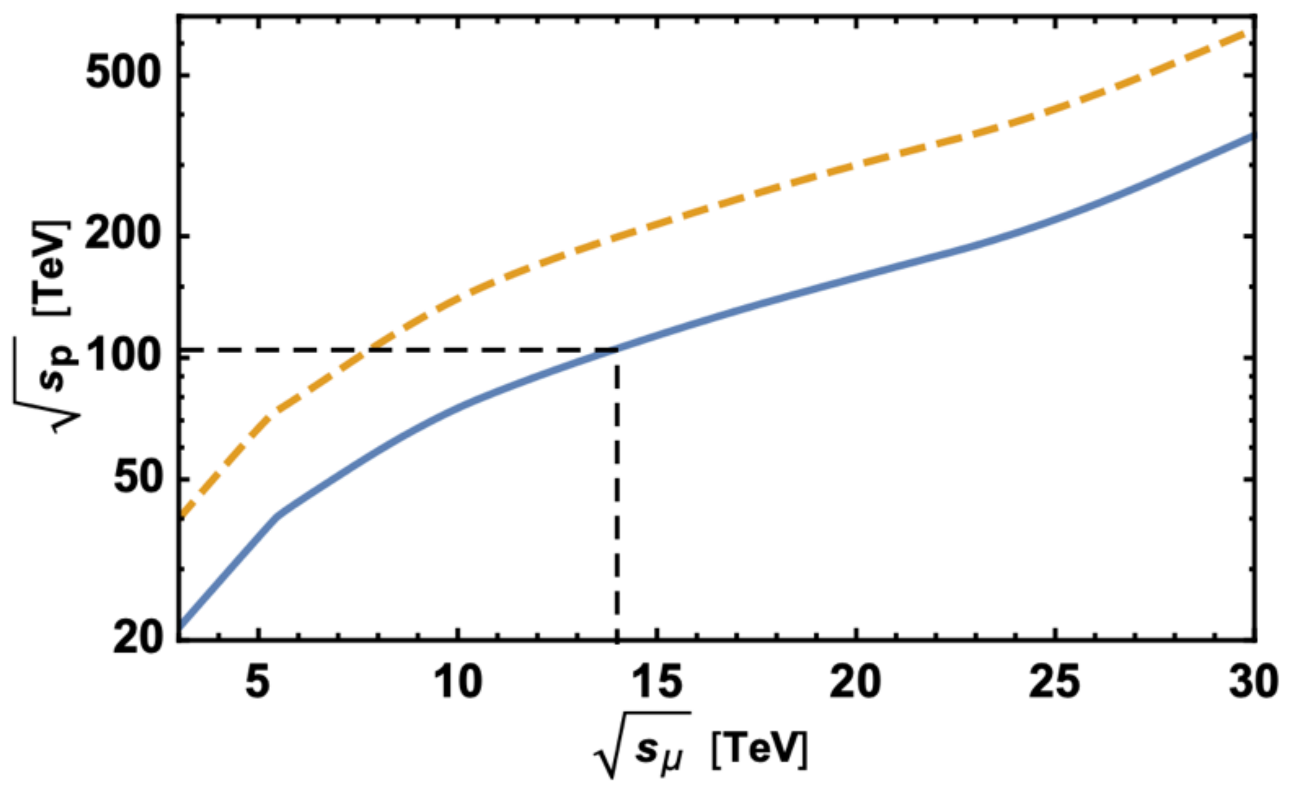
- Discovery machine
- Higgs self-coupling
  - Like FCC-hh

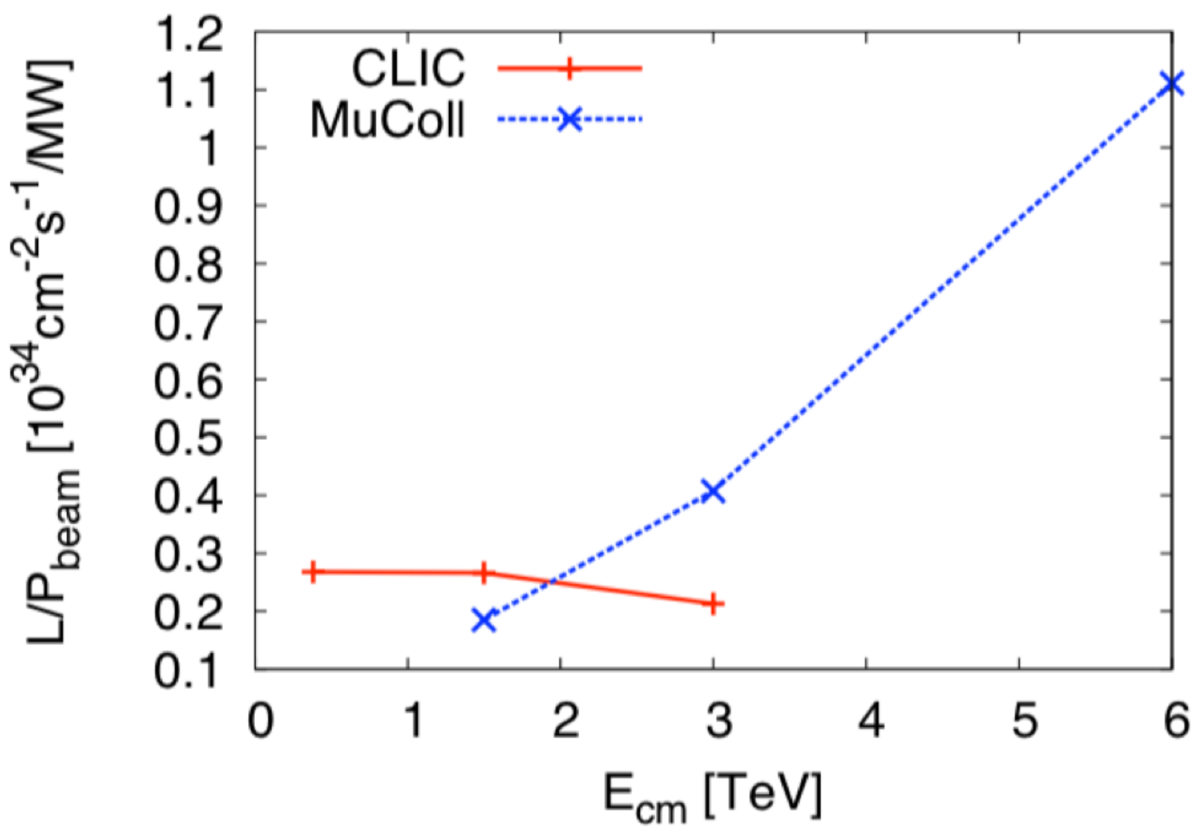
Precision physics

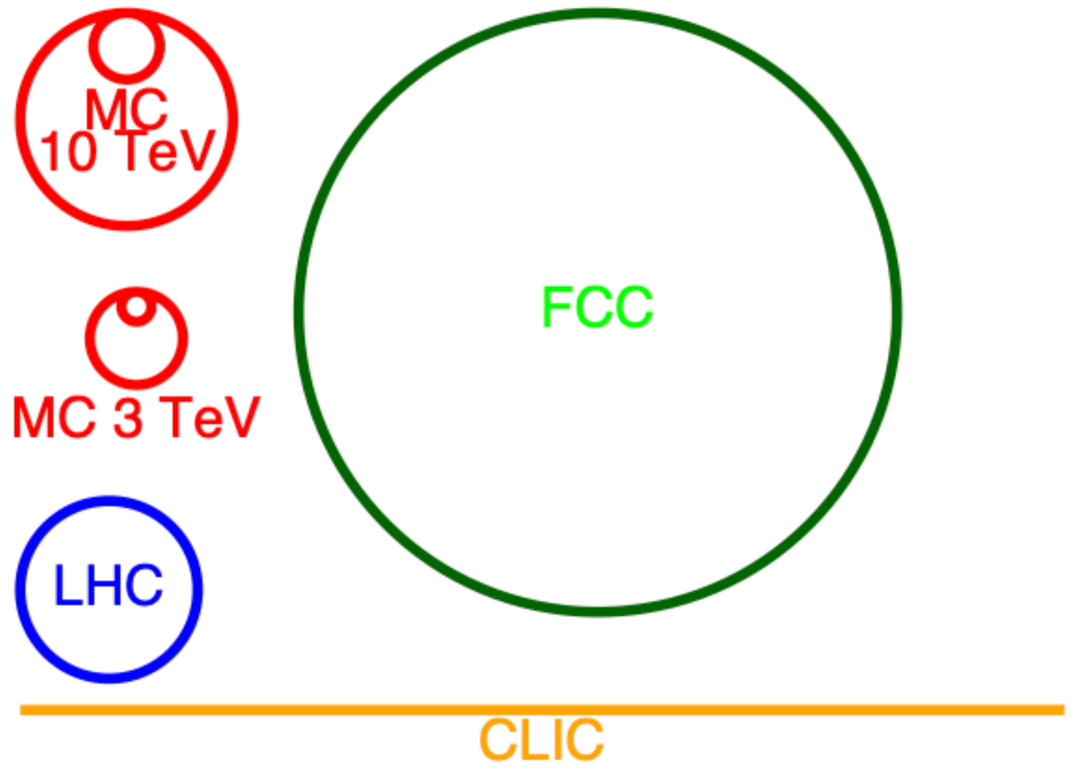
- Luminority frontier
- Higgs factory
  - Like FCC-ee

Compact & efficient

- √s=10 TeV:
  10-30km
  - Like LHC







➢ And in the meantime we will do a lot of accelerator+detector R&D

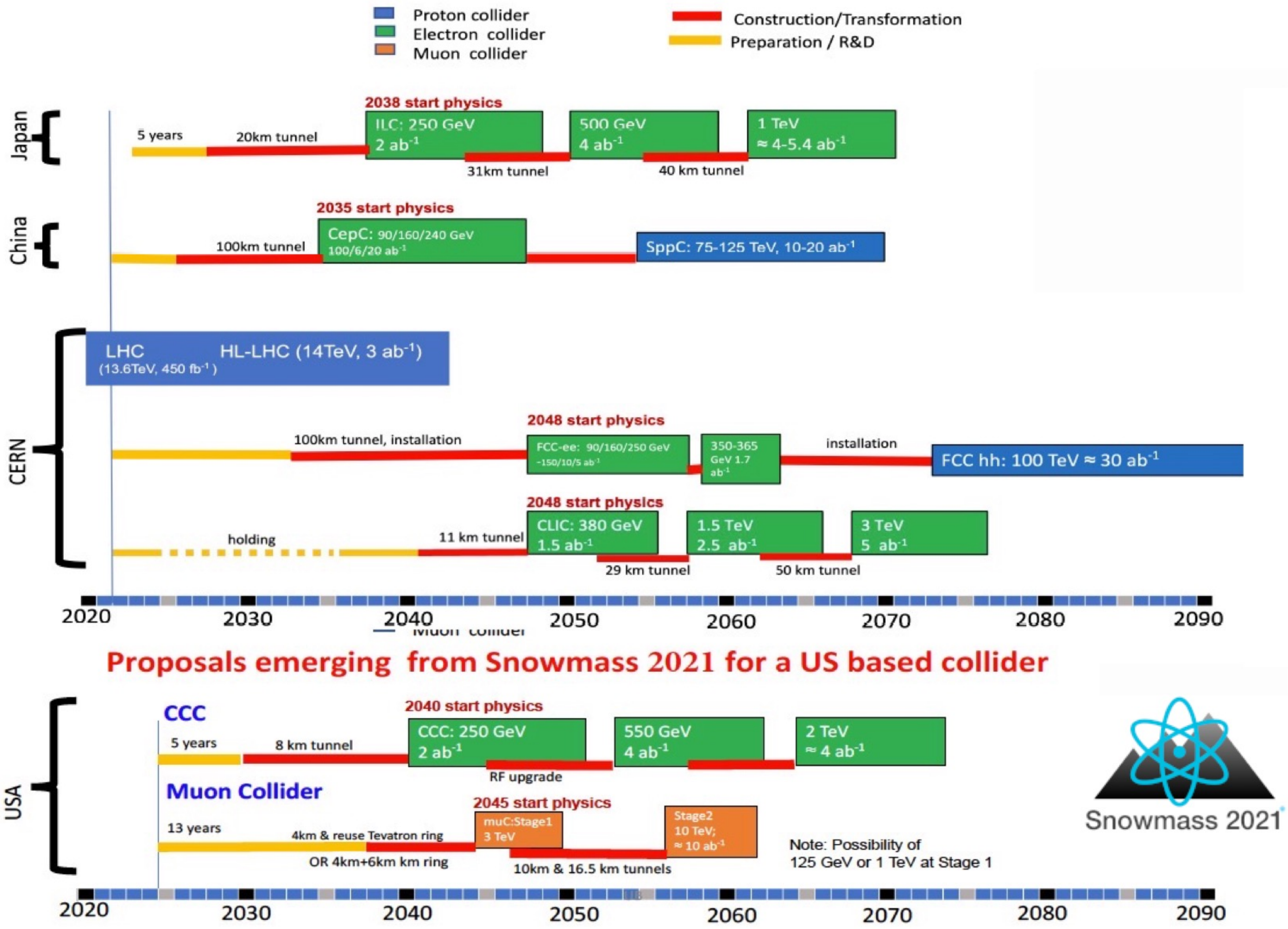
CERN’s future

- HL-LHC
- + CLIC?
- + FCC?
- + MuCol?

TIMELINES

MuCol start in 2045?

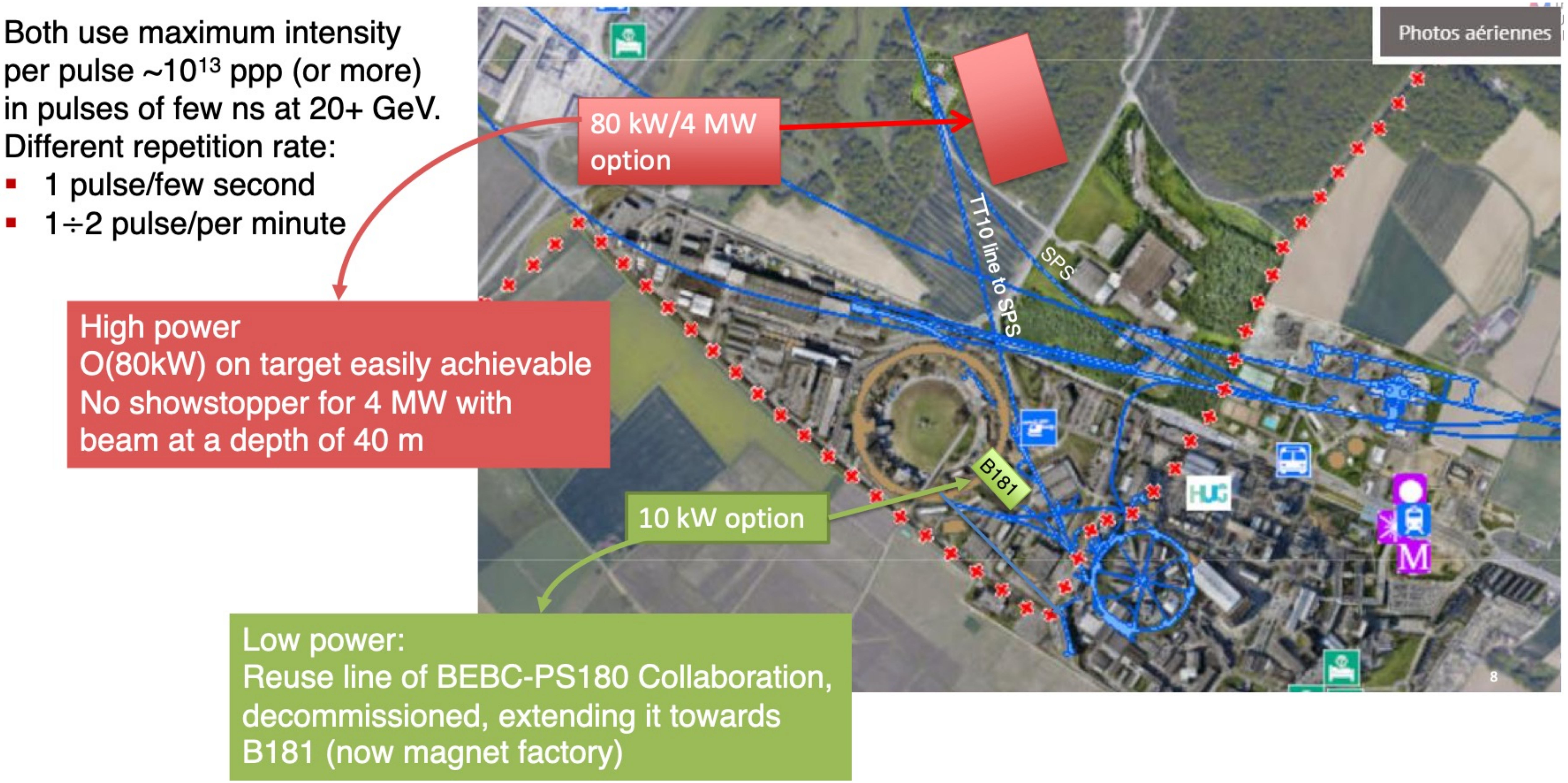
- Driven by technology
  - Timeline similar to other projects



PLANS FOR A DEMONSTRATOR

D.Lucchesi, for the IMCC – 17 Oct 2023 at CERN

At CERN site?



Both use maximum intensity per pulse ~10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
Different repetition rate:

- 1 pulse/few second
- 1÷2 pulse/per minute

80 kW/4 MW option

High power
O(80kW) on target easily achievable
No showstopper for 4 MW with beam at a depth of 40 m

10 kW option

Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now magnet factory)

MUON COLLIDER

Many advantages

- Physics: Precision & Discovery
- Technology: Accelerator R&D
- Practicalities: Footprint & Cost
- Outreach: It’s New & Exciting!

Netherlands involvement

- Mice (F.Filthaut) & UTwente (Magnets)

Now: Let’s study physics, detector, accelerator

The New York Times

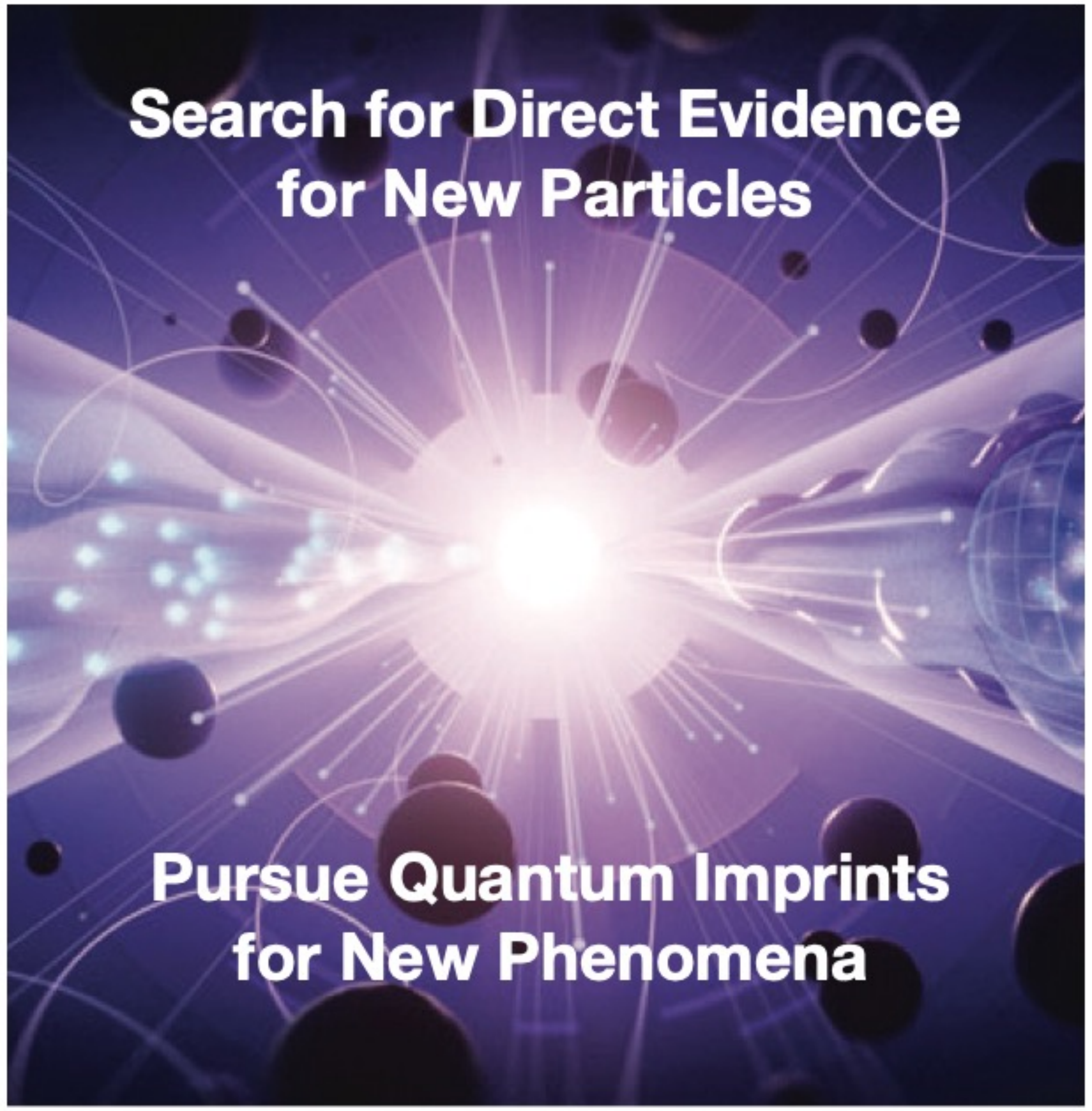
Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

Explore the Quantum Universe

Reveal the Secrets of the Higgs Boson

Elucidate the Mysteries of Neutrinos



Search for Direct Evidence for New Particles

Pursue Quantum Imprints for New Phenomena

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

BACKUP

Poster design
by R. Taylor

International
MUON Collider
Collaboration

MuCol

Funded by
the European Union

CERN

iFAST

Supported by MUST (MUon collider STrategy network), part of I.FAST EU Project

IMCC and MuCol
Annual Meeting 2024

12-15 March 2024, CERN

Scientific Program Committee - Chairs: L. Bottura & C. Carli (CERN). Members: M. Casarsa (INFN), A. Chance (CEA), R.Franqueira Ximenes (CERN), S. Gilardoni (CERN), D. Giove (INFN), A. Grudiev (CERN), S. Jindariani (FNAL), A.Lechner (CERN), R. Losito (CERN), D. Lucchesi (INFN), E. Metral (CERN), N. Milas (ESS), M. Palmer (BNL), N. Pastrone (INFN), L. Quettier (CEA), C. Rogers (STFC), D. Schulte (CERN), A. Wulzer (IFAE/ICREA), A. Yamamoto (CERN).

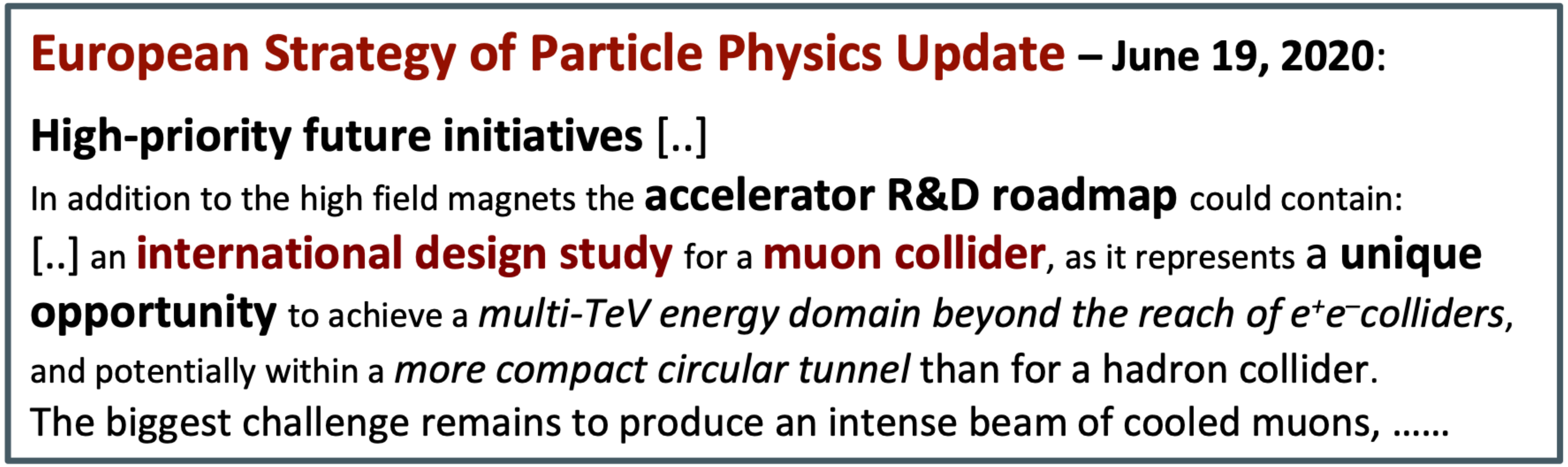
CERN Organising Committee : D. Schulte (Project Leader), A. Augier, M. Lancellotti.

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

Info & Registration

indico.cern.ch/event/1325963/

ESPPU



European Strategy of Particle Physics Update – June 19, 2020:

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, ……

Accelerator R&D Roadmap Plan

Accelerator R&D Roadmap

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

~70 Meu/5 years

The panel has identified
a development path that
can address the major challenges and deliver a
3 TeV muon collider by 2045

Site

MDI

Accelerator

Collider

High Field dipoles
Solenoids

RF Cavities
SC e NC

Cooling cell
Demonstrator

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

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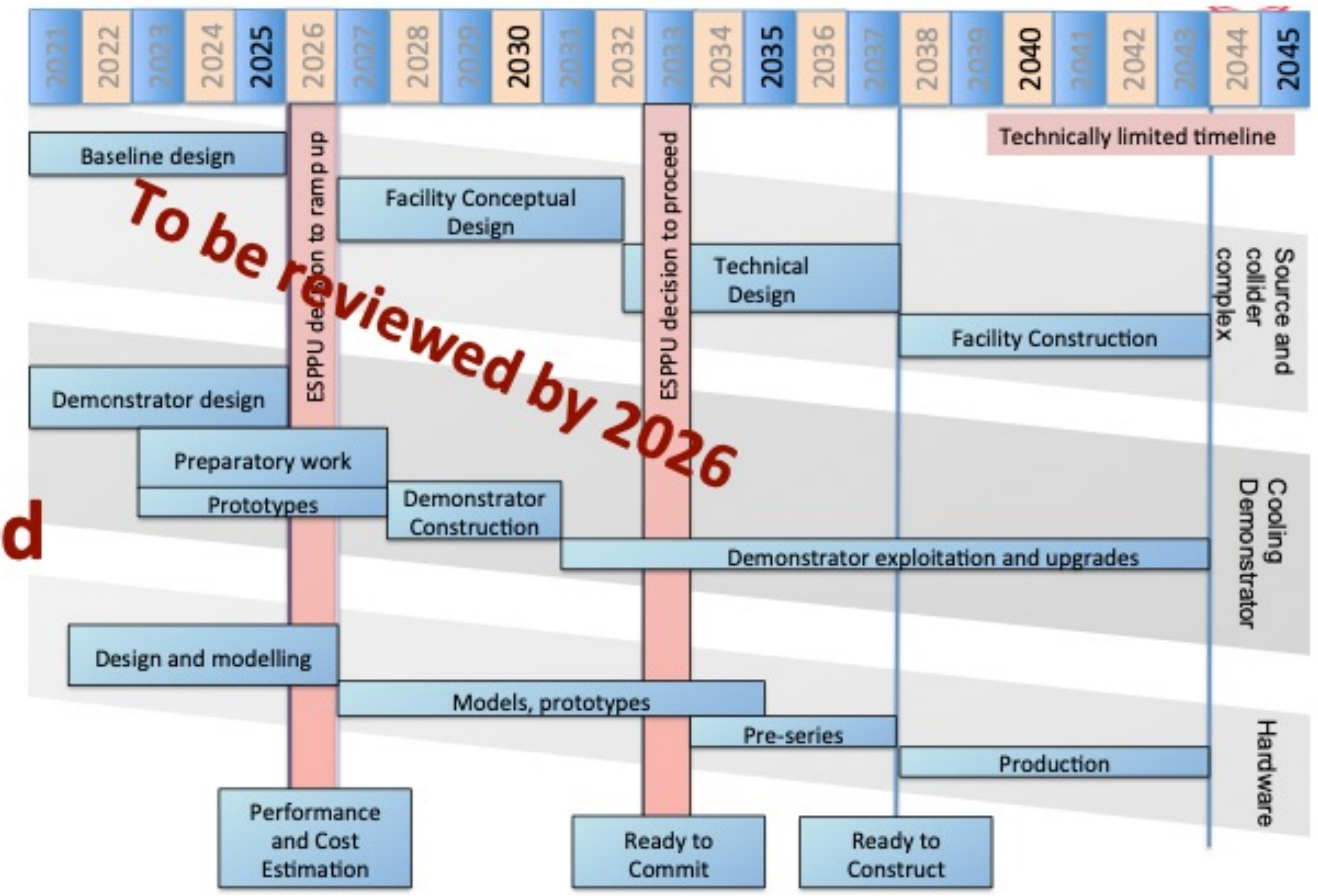
Implementation Considerations



To be reviewed by 2026

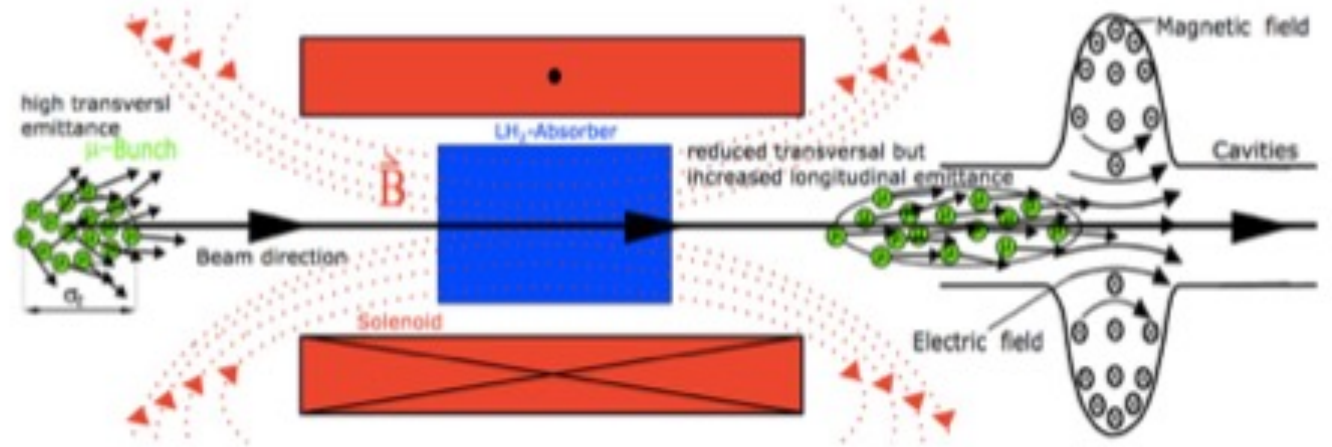
GOAL:
Identifying shortest possible **timeline** – **Technically limited**

- On the critical path
  - Muon cooling technologies and integration
  - Magnet technology

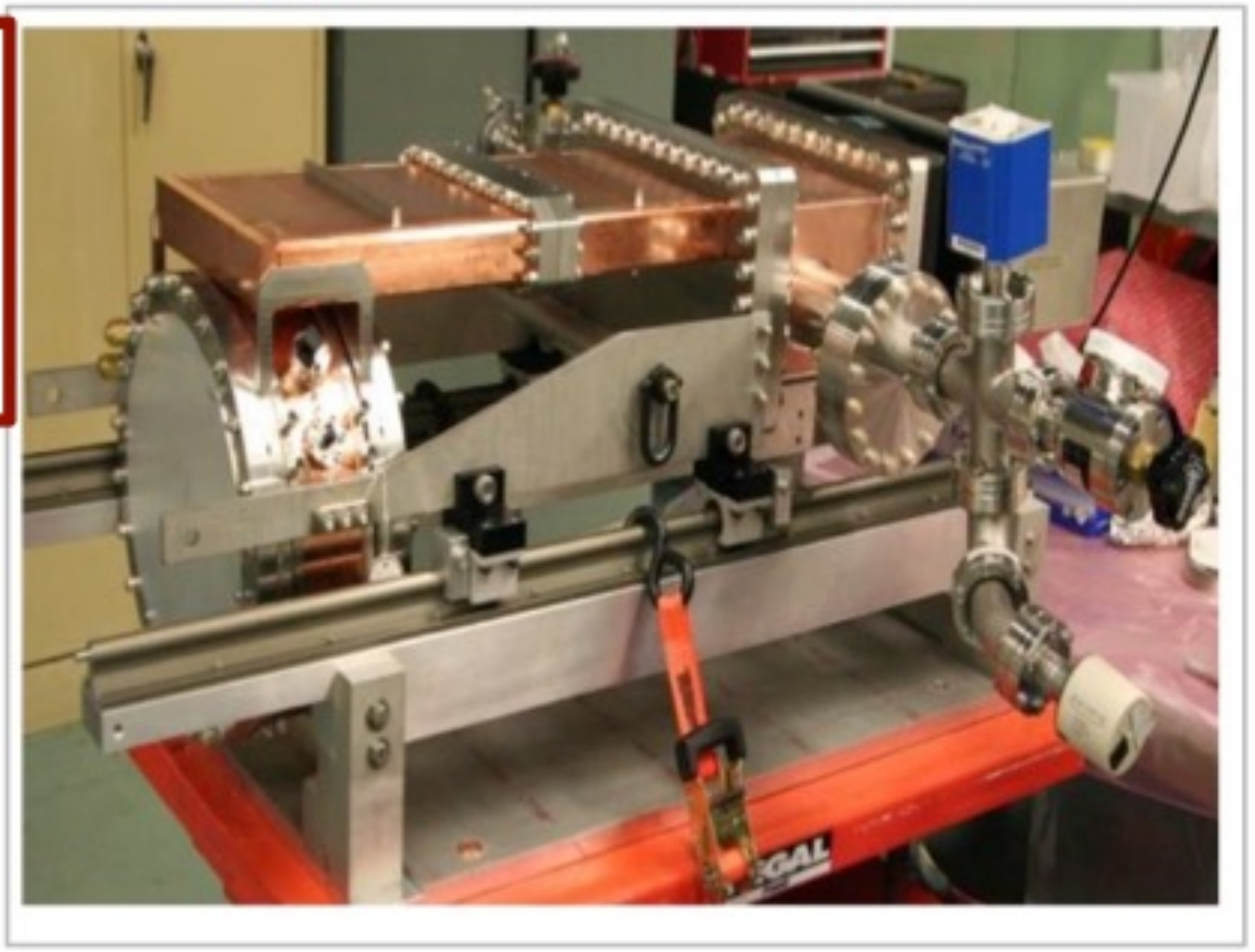
- Detector technologies R&D is essential and require dedicated effort to finalize experiment design @ 10 TeV

- Technology appears to be ready before 2040
  - Provided funding is being made available
  - Initial stage to start physics before 2050 appears feasible
  - Baseline design before next ESPPU would lead to CDR phase

Ionizing Cooling Cell design and integration

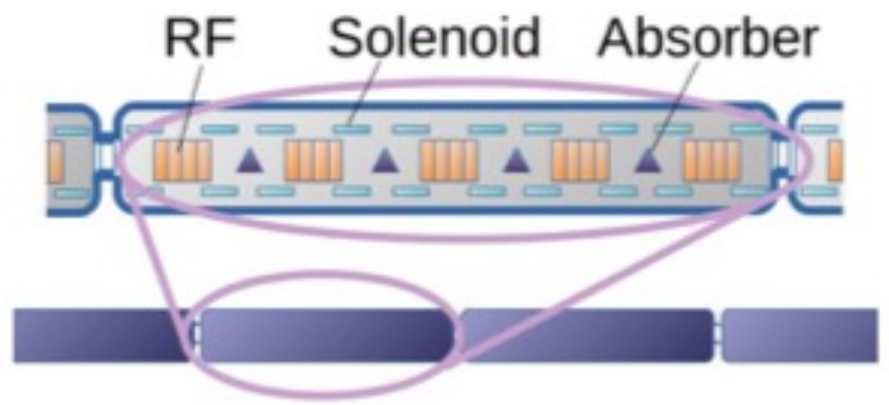


MuCool @ FNAL
demonstrated cavity
with >50 MV/m in 5 T solenoid

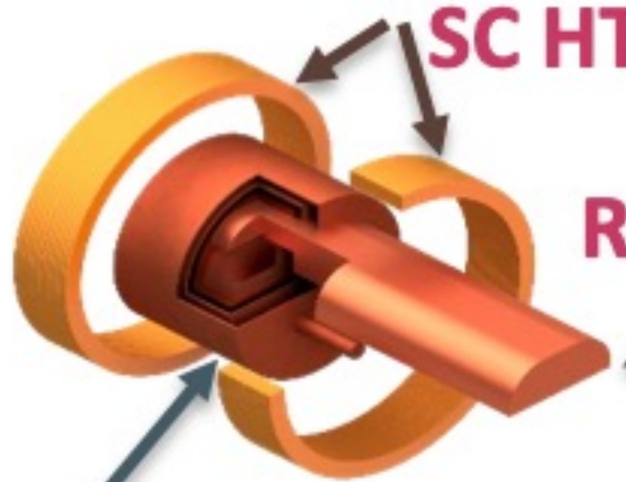


Technology requirements:

- Large bore solenoidal magnets
- High-gradients NC-RF in a multi-T fields
- Absorbers with large muon intensities
- Integration: Solenoids coupled to each other, high power RF & absorbers, instrumentation, cooling, vacuum, alignment, …



Bare coils and RF cavity

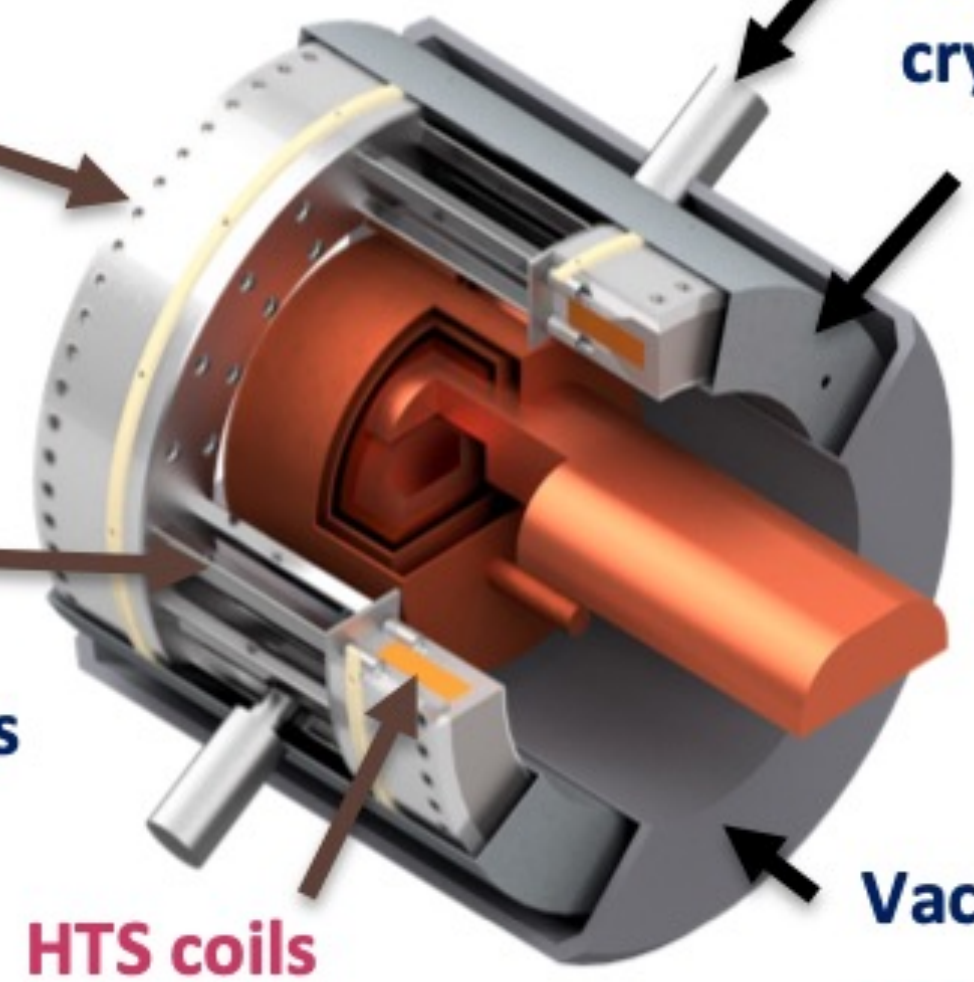


SC HTS coils

RF Wave guide

Pillbox test cavity

with cryostat



Two stage cryocooler

Thermal shield

Coil support structure

Tie rods for repulsion and compression forces

HTS coils

Vacuum vessel

Need some infrastructure early:

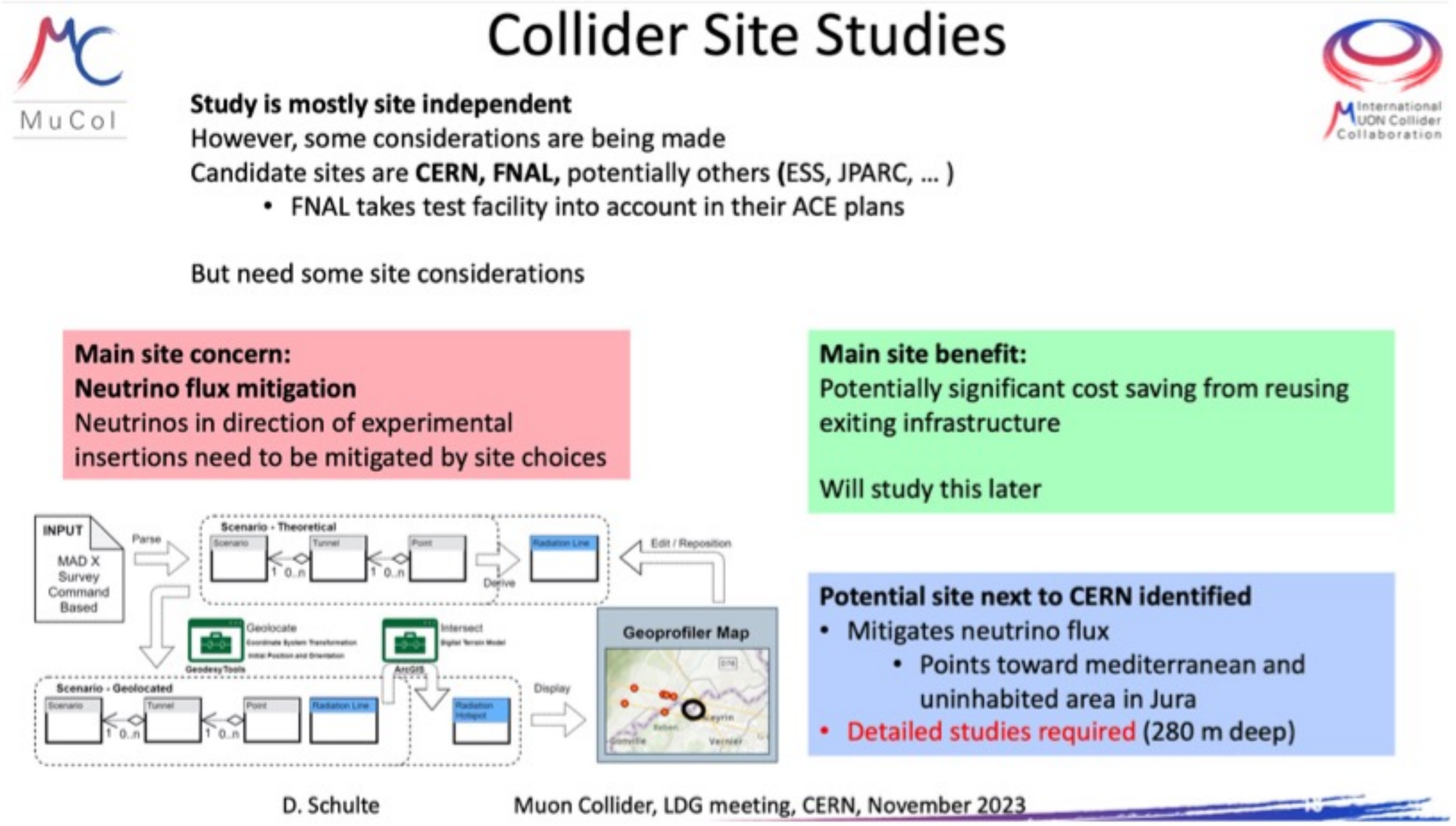
- to test RF cavities in magnetic field

➔ discussion on facilities at STFC, INFN, CEA, …

Which facility and where?

- **Focus on two energy ranges:**

3 TeV technology ready for construction in 10-20 years
10+ TeV with more advanced technology



Collider Site Studies

Study is mostly site independent
However, some considerations are being made
Candidate sites are **CERN, FNAL,** potentially others (ESS, JPARC, …)
- FNAL takes test facility into account in their ACE plans

But need some site considerations

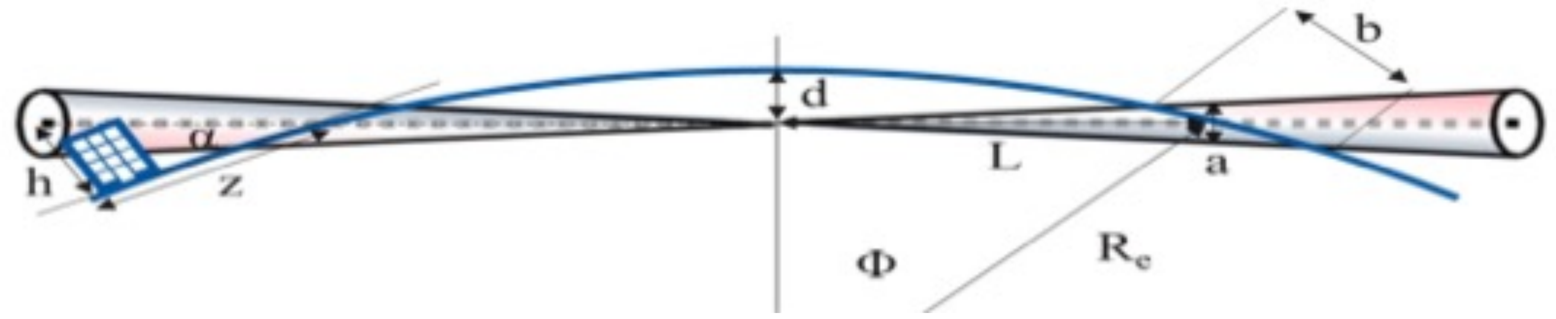
Main site concern:
Neutrino flux mitigation
Neutrinos in direction of experimental insertions need to be mitigated by site choices

Main site benefit:
Potentially significant cost saving from reusing exiting infrastructure

Will study this later

Potential site next to CERN identified
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

D. Schulte Muon Collider, LDG meeting, CERN, November 2023



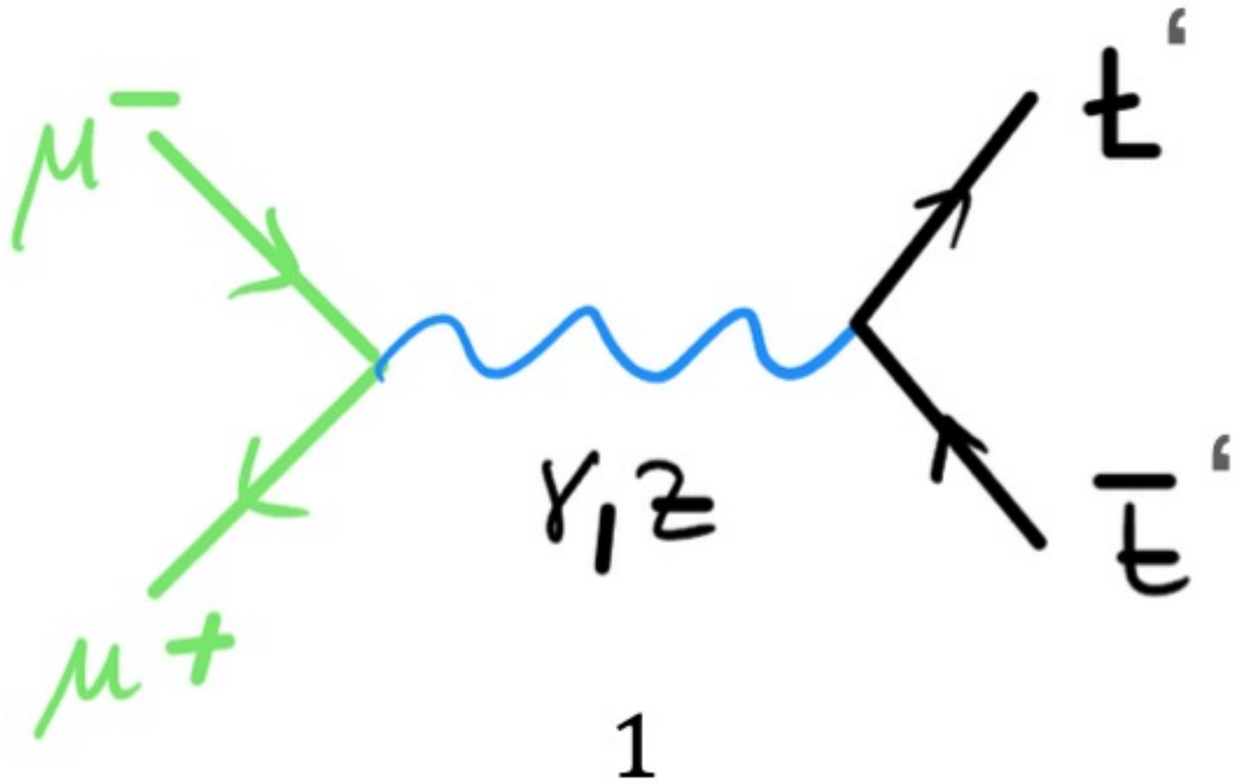
Staging optimization is linked to:

- **HTS Magnet technology maturity**
- **Physics motivated energy choice**
- **Tunnel ring use/re-use**
- **Luminosity goal**
- **Performance/Power consumption**

Physic processes: two colliders in one

F. Maltoni
"Physics Overview" Annual Meeting IMCC

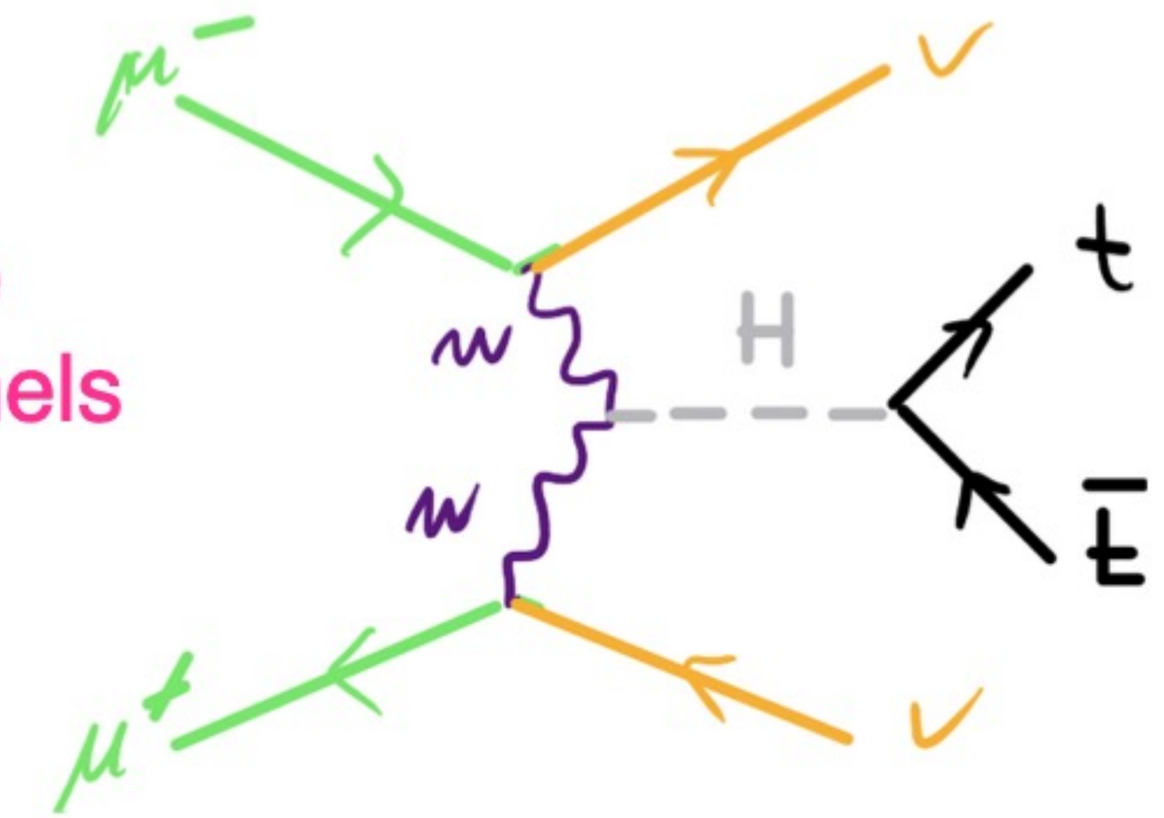
Multi-TeV muon collider opens a completely new regime :



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)

Different physics can be probed in the two channels



$$\sigma \sim \frac{1}{M^2}\log^n\frac{s}{M}$$

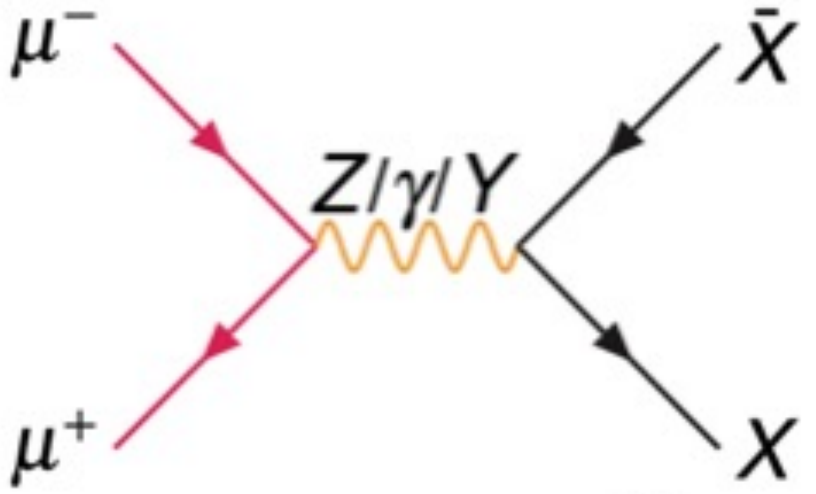
Standard Model coupling measurements
Discovery light and weakly interacting particles

Muon Colliders, 1901.06150
The muon Smasher's guide, *Rept.Prog.Phys.* 85 (2022) 8, 084201 2103.14043
Muon Collider Forum Report, 2209.01318
Towards a Muon Collider, *Eur.Phys.J.C* 83 (2023) 9, 864, 2303.08533

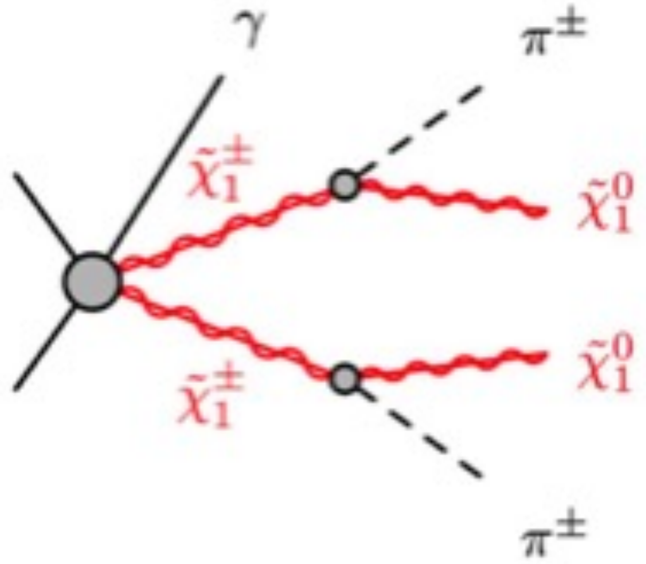
Direct BSM reach

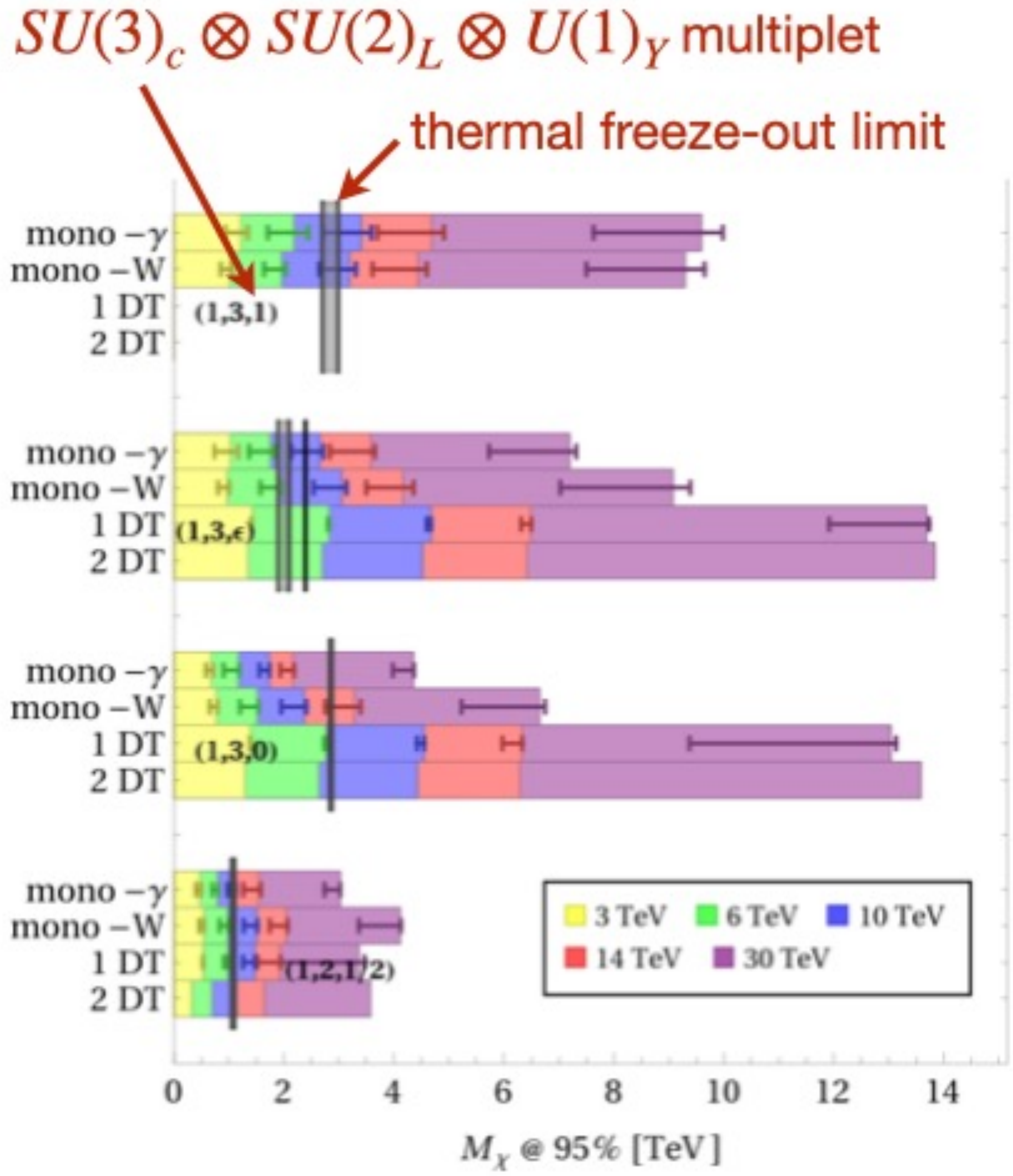
F.Filthaut @ Veldhoven

Benefit of having high E_{CM} is most clear in the case of pair production of new particles: access to particles with mass $m_X \lesssim E_{\mathrm{CM}}/2$



- "straightforward" if X decay yields multiple visible decay products
- more detailed studies have been carried out to assess sensitivity to e.g. displaced tracks (as relevant in compressed SUSY WIMP DM scenarios)





$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ multiplet

thermal freeze-out limit

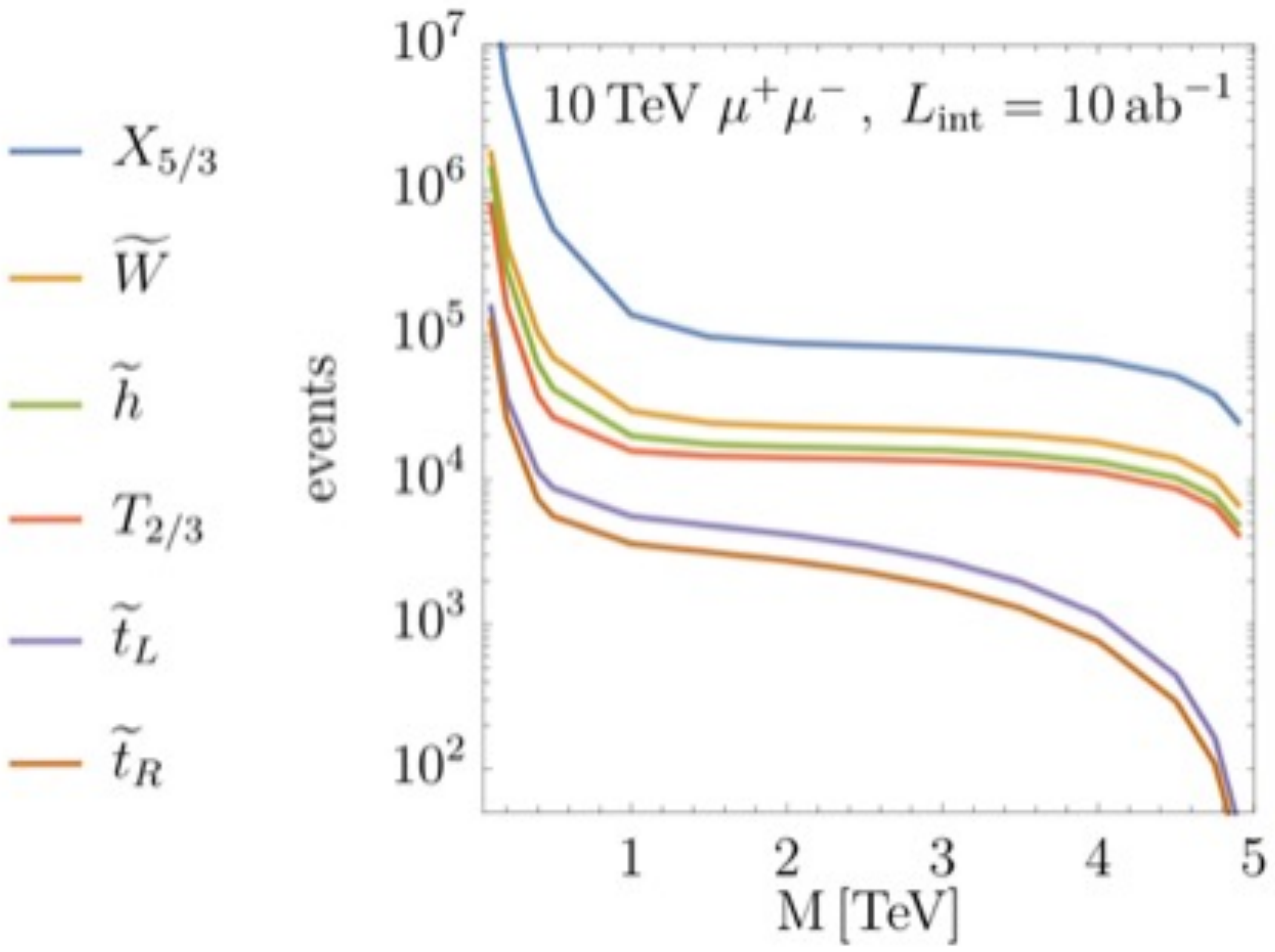
(from EPJC 2023)

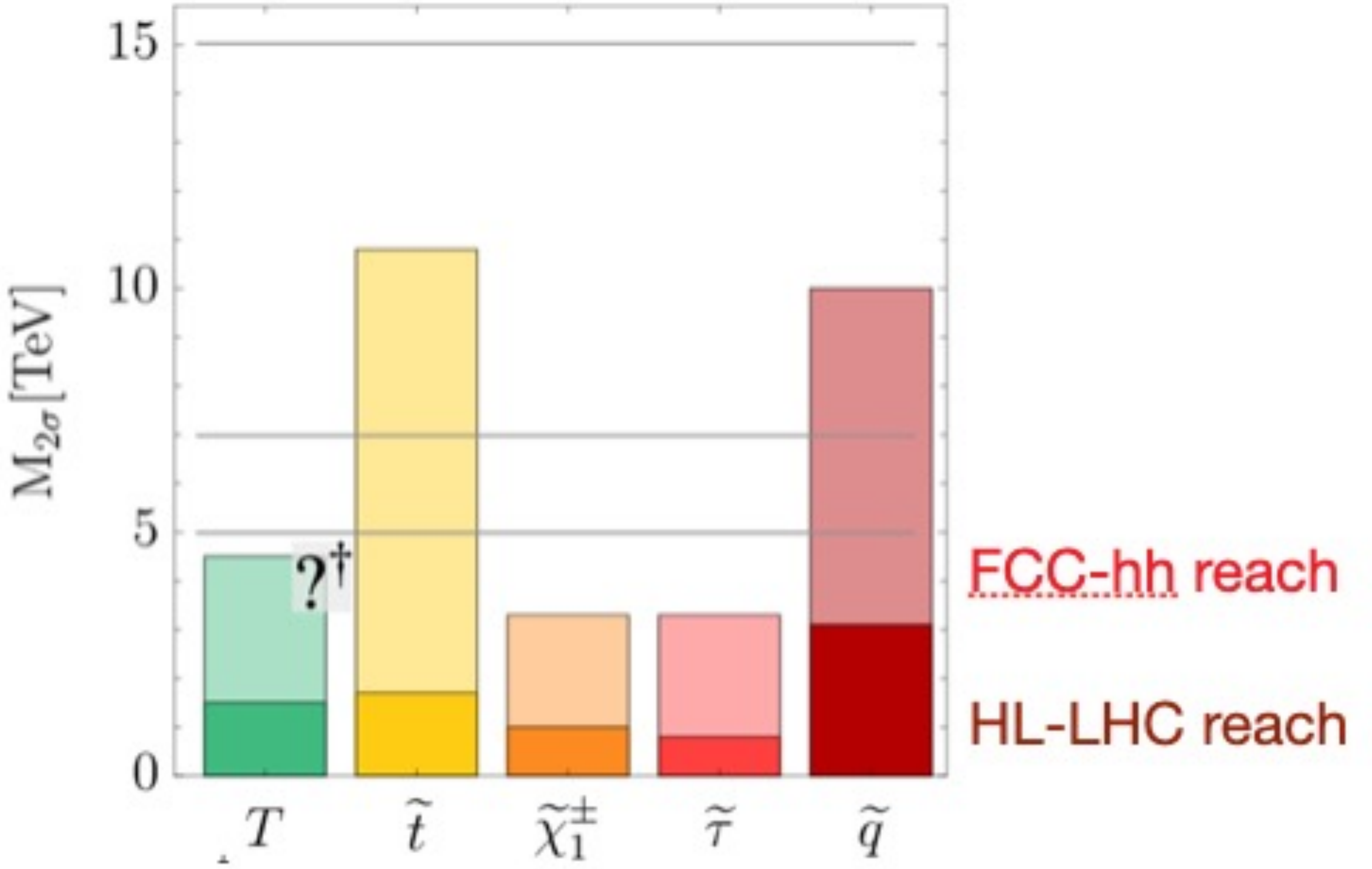
Direct BSM reach

F.Filthaut @ Veldhoven

Absent clear evidence for specific BSM physics scenarios, study benchmark pair production of BSM particles

- production through gauge couplings relatively model-independent; mass reach for multiple production processes ($T, \chi_1^\pm, \tilde{\tau}$) may exceed that of a 100 TeV FCC-hh
- clearly conclusions change if new particles have strong couplings

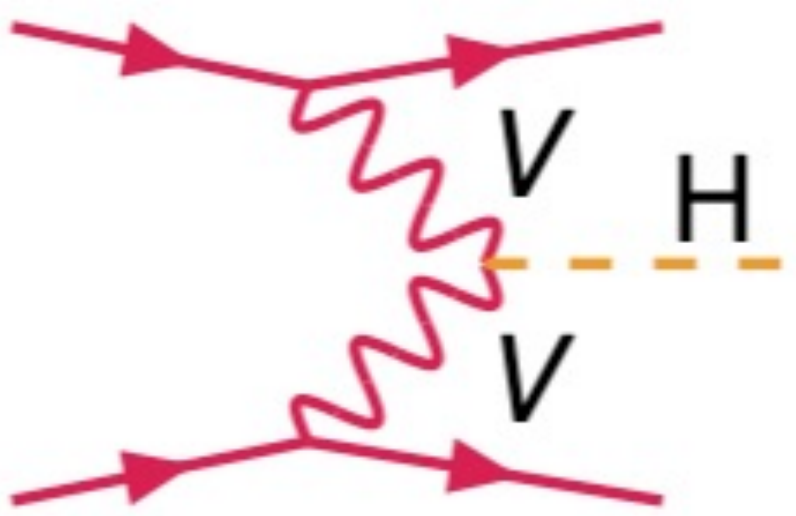




(Single-)Higgs Physics

F.Filthaut @ Veldhoven

Despite the muons' elementary nature, the Higgs production cross section is dominated by much lower energy scales: VBF ($V = W, Z$)



- expect ~ 10^7 single-H events in 10 ab^{-1} of 10 TeV data
- interpretation in terms of coupling constants:

$$\frac{\sigma_{i\to H}\cdot \mathrm{BR}_{H\to f}}{\sigma^{\mathrm{SM}}_{i\to H}\cdot \mathrm{BR}^{\mathrm{SM}}_{H\to f}} = \frac{\kappa_i^2\kappa_f^2}{\kappa_H^2},$$

$$\kappa_H^2 = \sum_f \kappa_f^2 \mathrm{BR}^{\mathrm{SM}}(H\to f)$$

precision comparable to that obtainable with (other) Higgs factories

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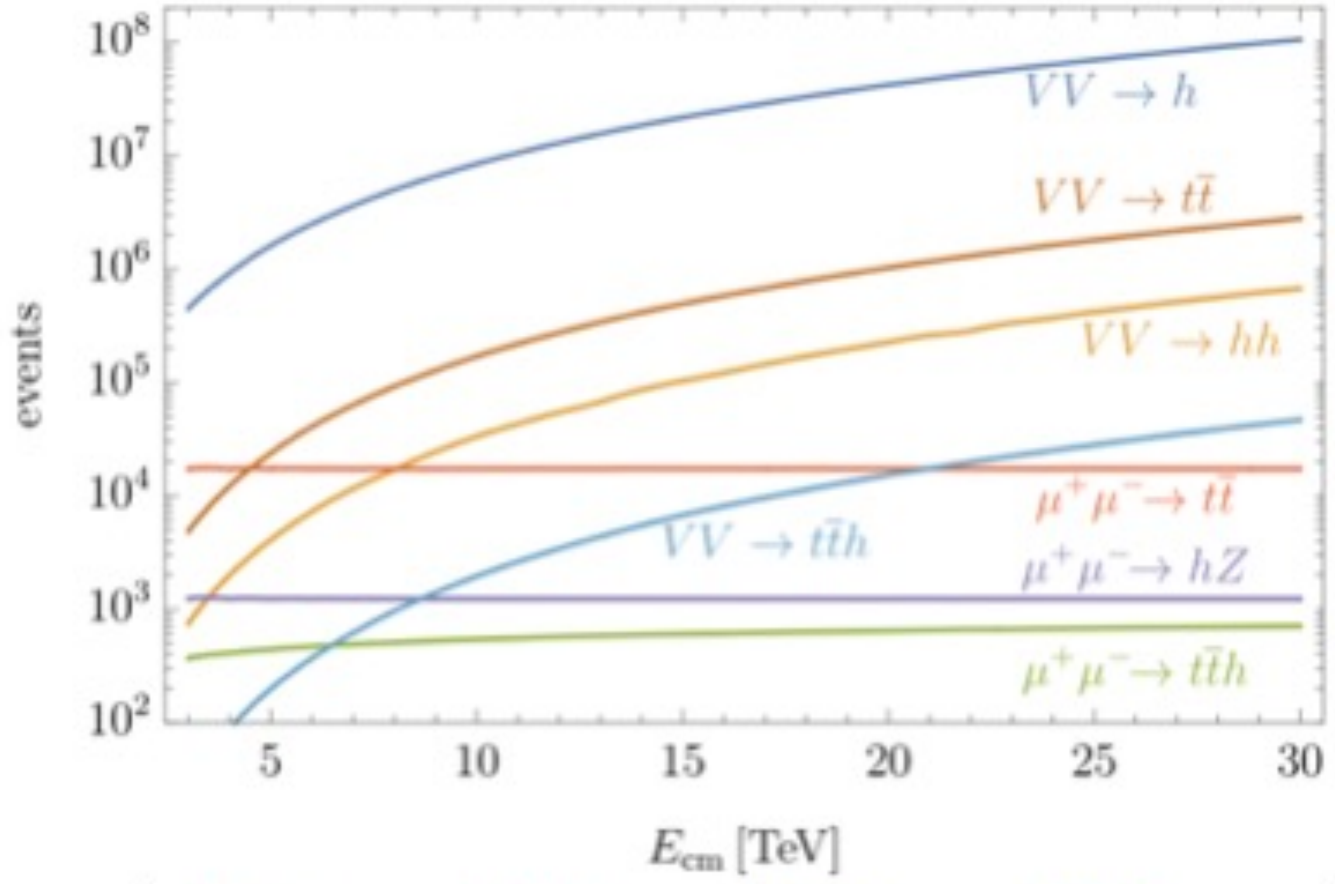
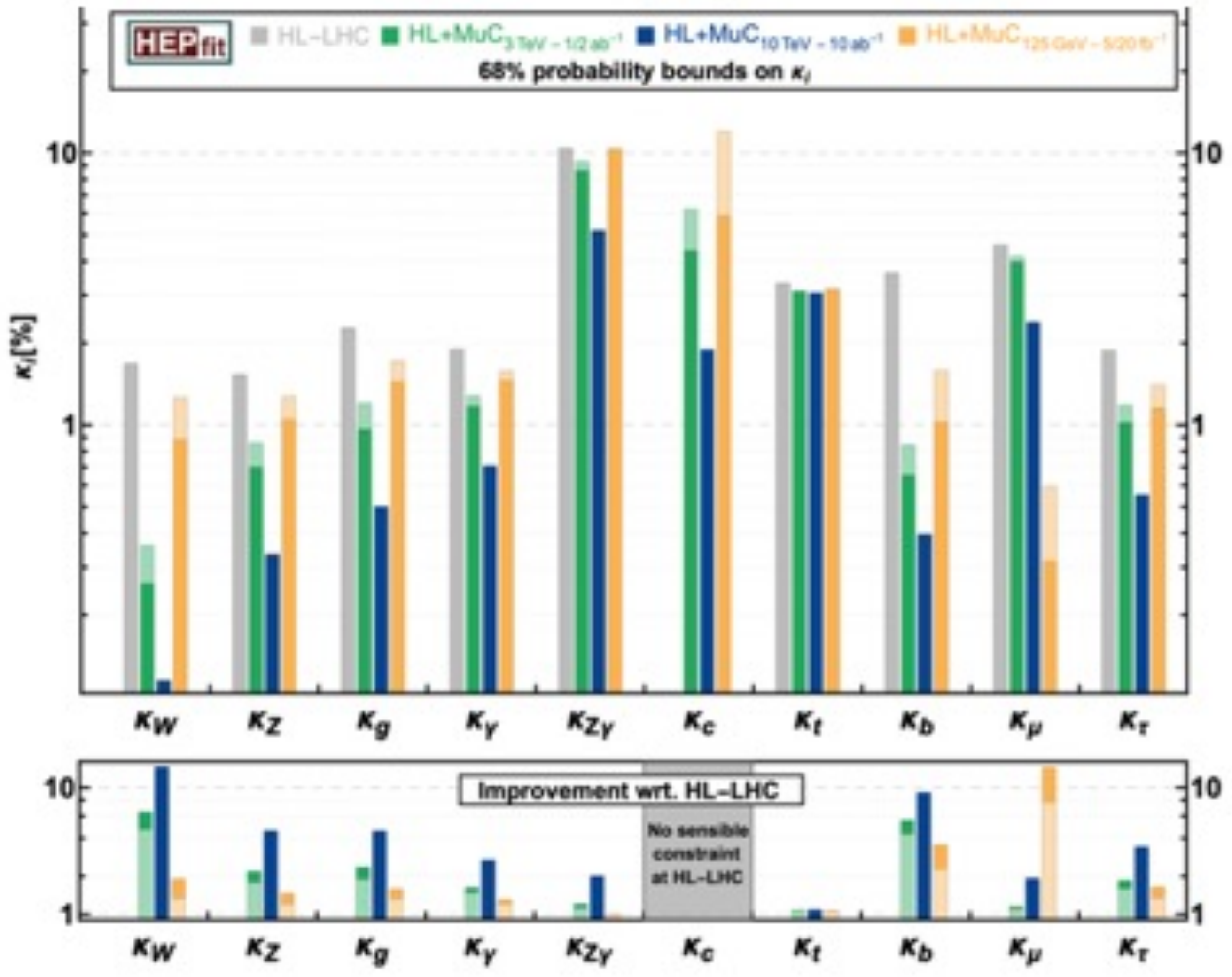




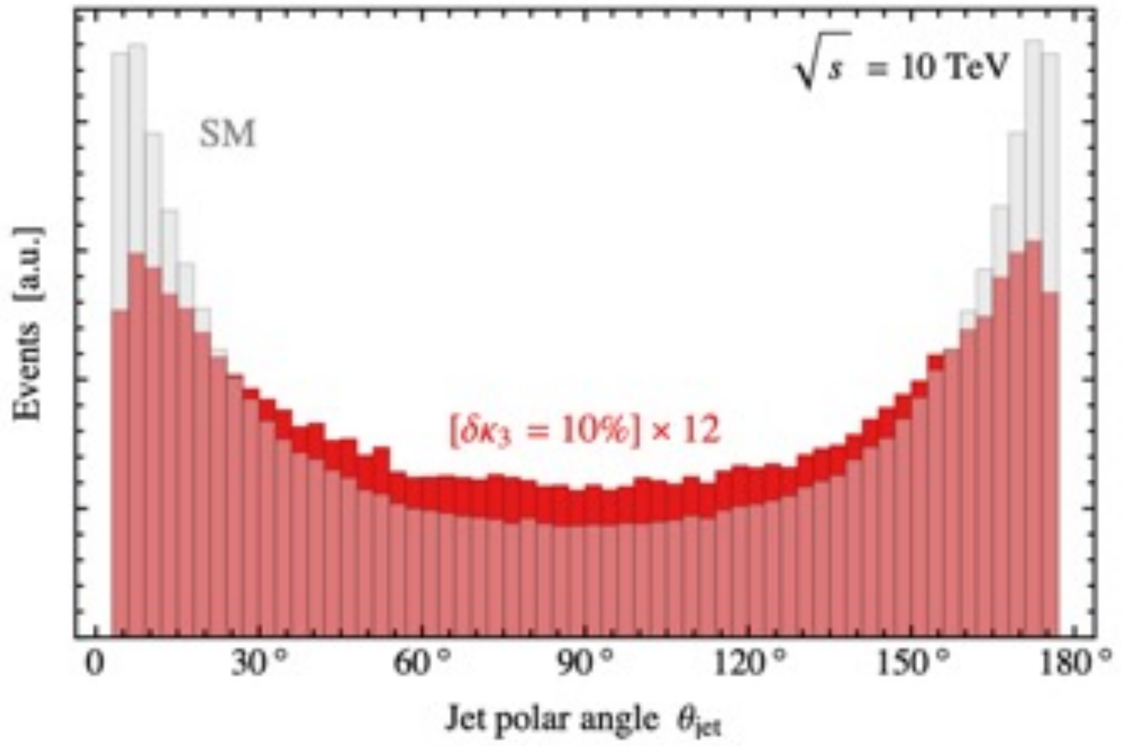
Higgs self-couplings

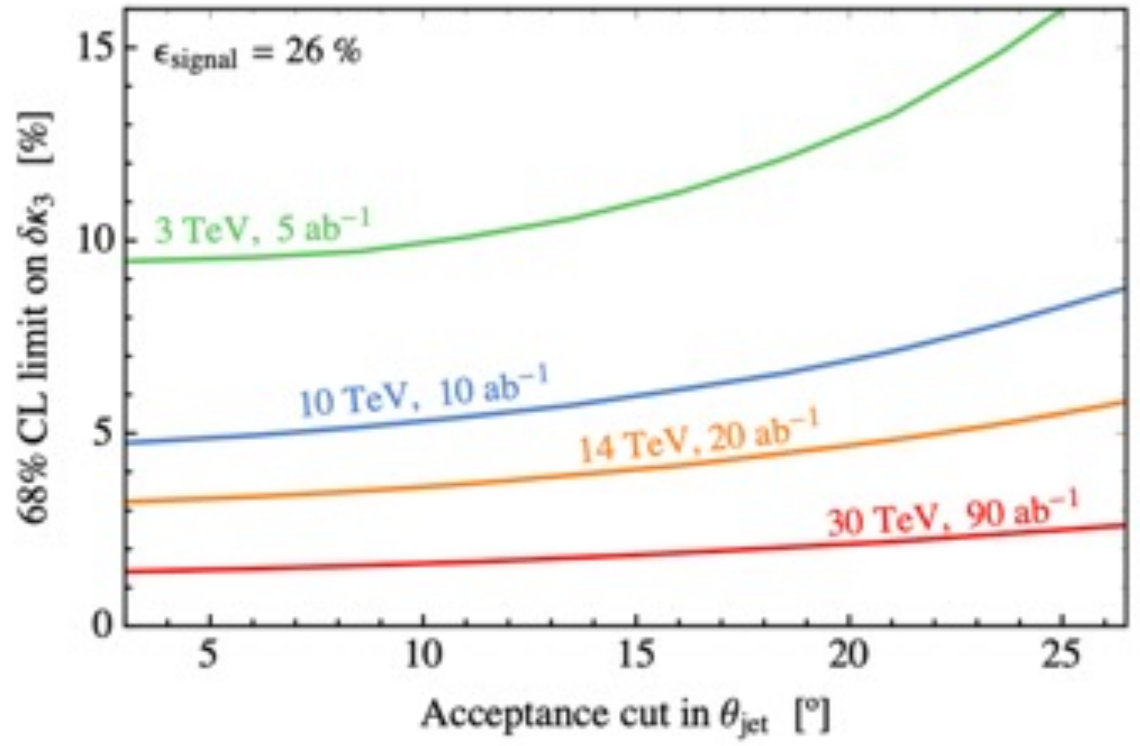
F.Filthaut @ Veldhoven

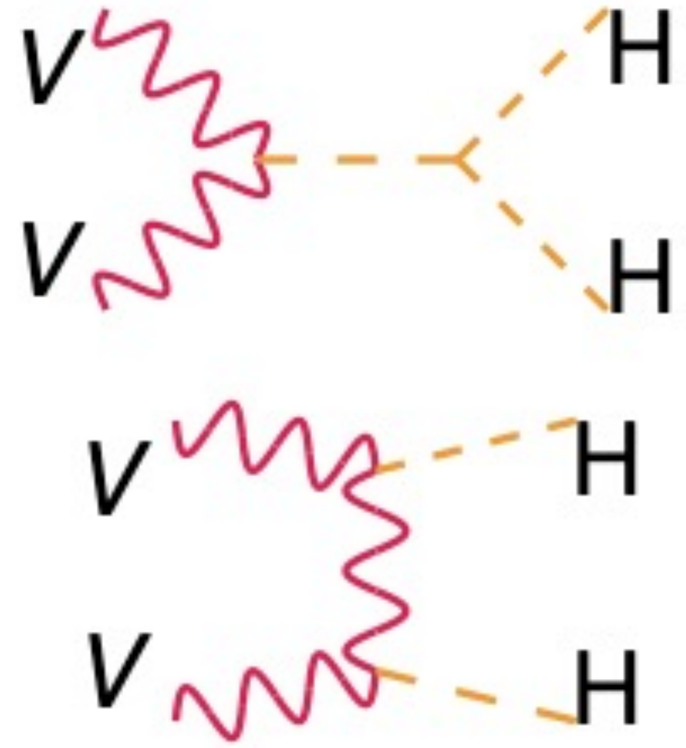
10 ab^{-1} of 10 TeV data ➠ also ~ 3·10^4 VBF-produced HH events expected according to SM: wealth of data to study the Higgs potential

$$V = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v}(1 + \delta\kappa_3) H^3 + \frac{m_H^2}{8v^2}(1 + \delta\kappa_4) H^4$$

- in tree level EFT formulation: $\delta\kappa_3 = v^2(C_6 - \frac{3}{3} C_H)$ (coefficients of $\mathcal{O}_6$, $\mathcal{O}_H$ operators): $\mathcal{O}_6 = -\frac{m_H^2}{2v^2}(\Phi^\dagger\Phi - v^2/2)^2$, $\mathcal{O}_H = \frac{1}{2}(\partial_\mu(\Phi^\dagger\Phi))^2$







Expect ~ 5% uncertainty on $\delta\kappa_3$, somewhat dependent on angular acceptance

- lift degeneracy between C_6, C_H by considering high-m_{HH} tail specifically ($\mathcal{O}_H$ sensitive to compositeness)

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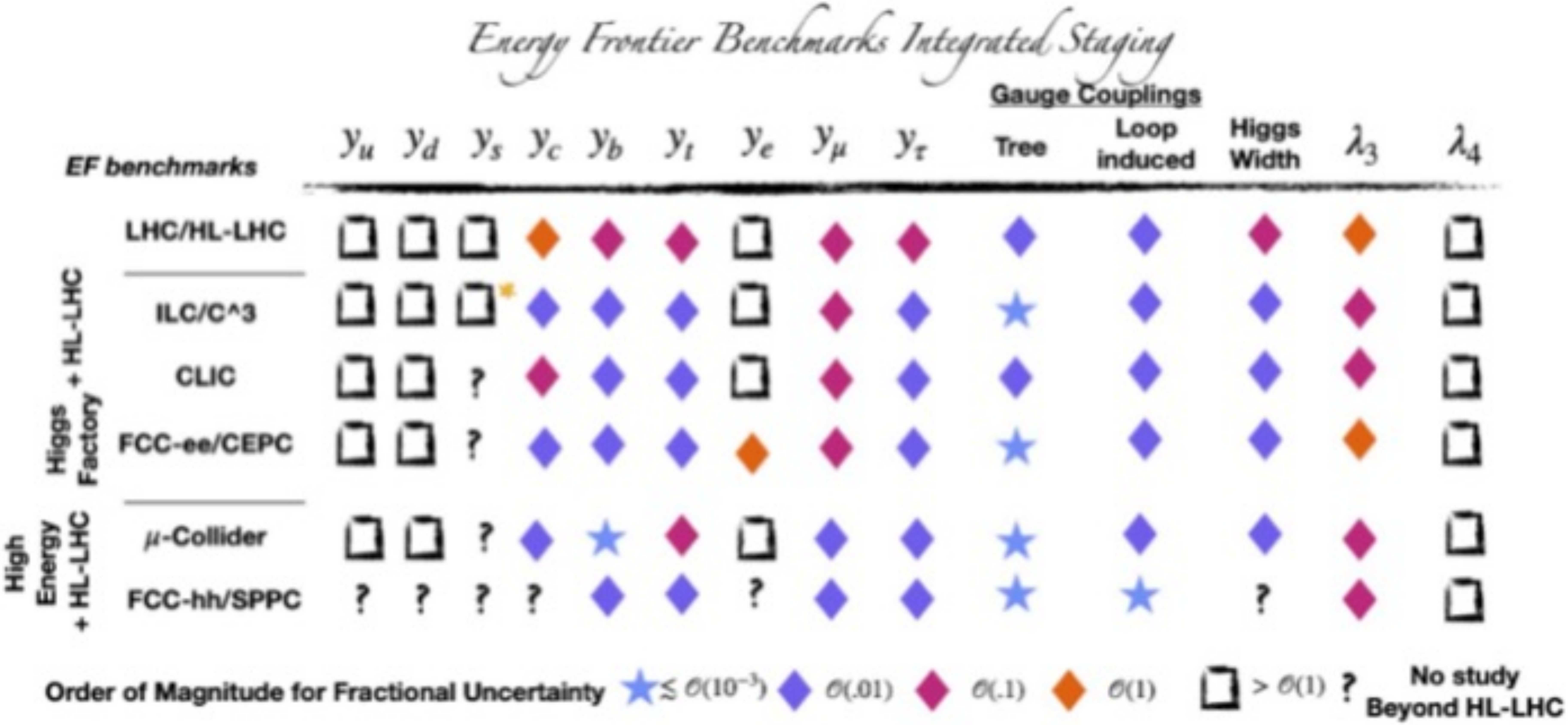


Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings Tree	Gauge Couplings Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	☐	☐	☐	🔶	♦	♦	☐	♦	♦	🔷	🔷	♦	🔶	☐
Higgs Factory + HL-LHC	ILC/C^3	☐	☐	☐*	🔷	🔷	🔷	☐	♦	🔷	★	🔷	🔷	♦	☐
	CLIC	☐	☐	?	♦	🔷	🔷	☐	♦	🔷	🔷	🔷	🔷	♦	☐
	FCC-ee/CEPC	☐	☐	?	🔷	🔷	🔷	🔶	♦	🔷	★	🔷	🔷	🔶	☐
High Energy + HL-LHC	μ-Collider	☐	☐	?	🔷	★	♦	☐	🔷	🔷	★	🔷	🔷	♦	☐
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	♦	☐

Order of Magnitude for Fractional Uncertainty ★ $\leq \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ♦ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$? No study Beyond HL-LHC

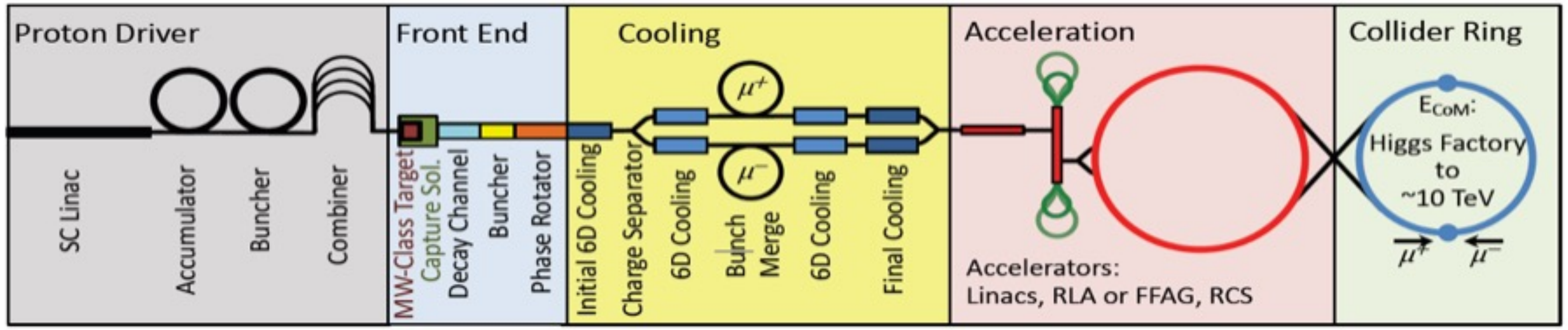
Challenge: $\mu^{\pm}$ production

F.Filthaut @ Veldhoven

$\tau_\mu \approx 2.2\,\mu$s ➠ need a high muon production rate

Baseline: production from $\pi^{\pm} \rightarrow \mu^{\pm}\nu_\mu(\bar{\nu}_\mu)$, with $\pi^{\pm}$ produced in proton-nucleus collisions

- premium on high-power (2—4 MW) target (Hg jet) and efficient capture of $\pi^{\pm}$ ($B \lesssim$ 20 T solenoid) to produce ~ 10^{11} μ / s



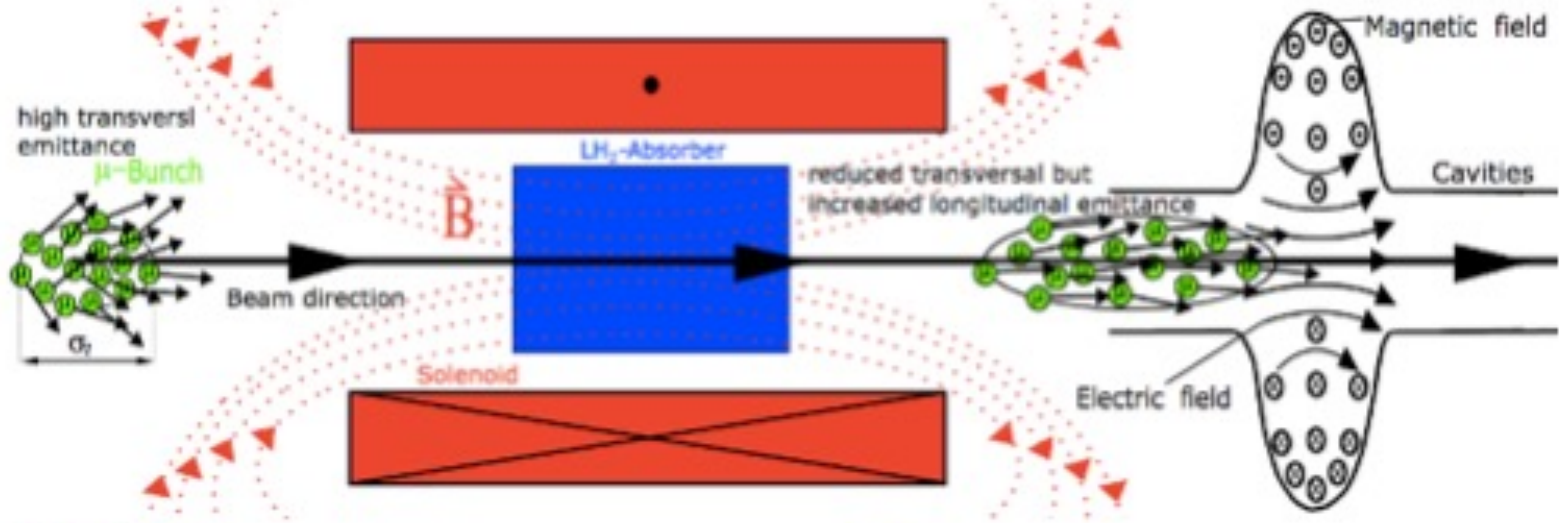
- alternative Low-EMittance Muon Accelerator (LEMMA) scheme:
  start with ~ 45 GeV e^+ beam impinging on e^- at rest ➠
  threshold for $e^+e^- \rightarrow \mu^+\mu^-$ production (fully collimated in lab system)
- limitation: e^+ production $\mathcal{O}(10^{15}$/s)

Challenge: $\mu^{\pm}$ cooling

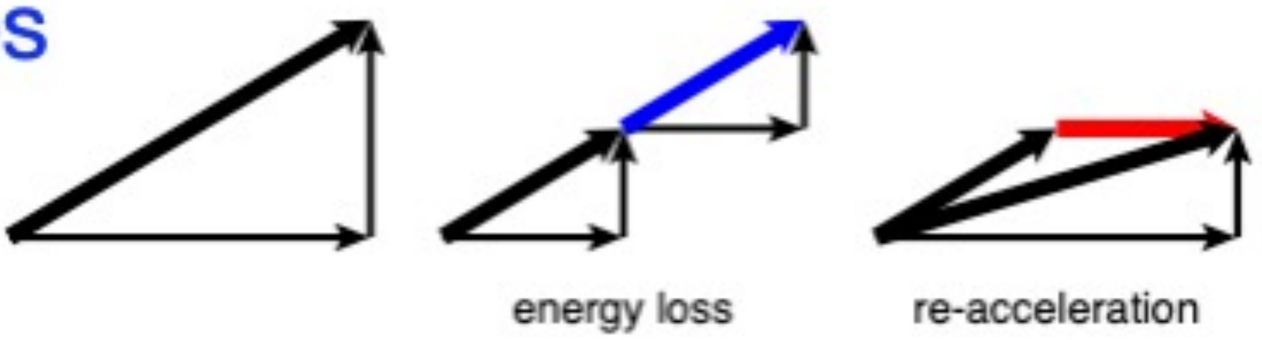
F.Filthaut @ Veldhoven

In the baseline production scenario, rapid cooling is needed before acceleration is possible: ionisation cooling

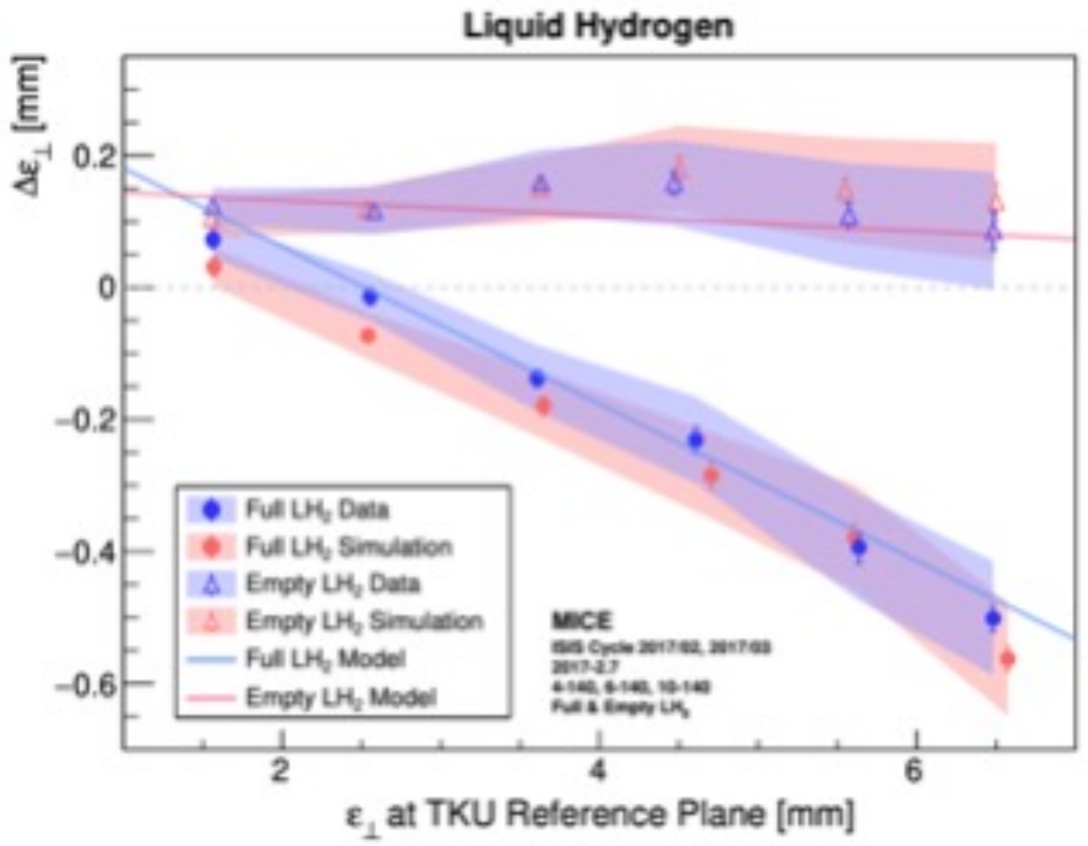
- minimise multiple Coulomb scattering by having E loss occur in low-Z material: LH_2
- all in a strong solenoidal field



Physics of E loss by charged particles in matter is well understood, but technical challenges are significant



- demonstration (w/o RF re-acceleration): MICE, Nature 578 (2020) 53
  - more quantitative emittance evaluation: arXiv:2310.05669

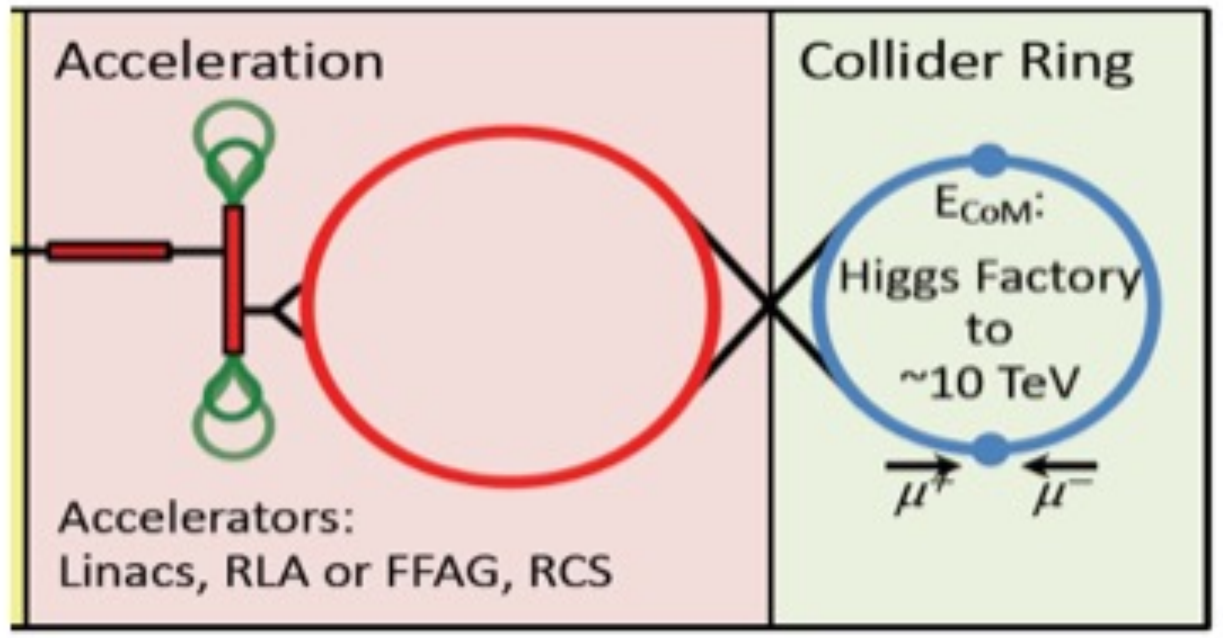


Challenges: acceleration, ν radiation

F.Filthaut @ Veldhoven

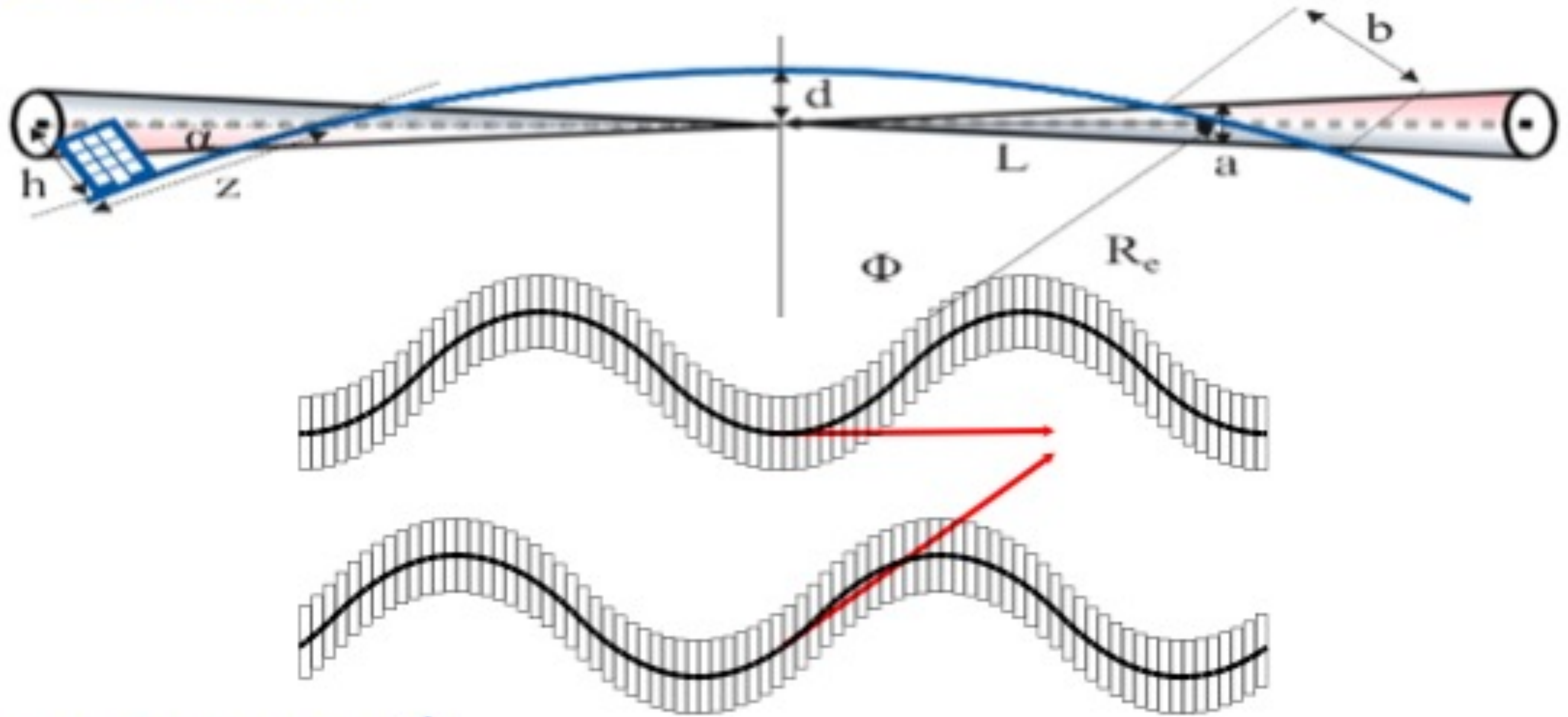
Short τ_μ also means that acceleration needs to be done very rapidly (perhaps 100 μs) ➠ cost efficiency: combination of recirculating linacs + rapid-cycling synchrotron

- different CM energies require different RCS



$\nu - N$ interaction cross section $\propto E_\nu$ ➠ ν radiation from the collider is a concern

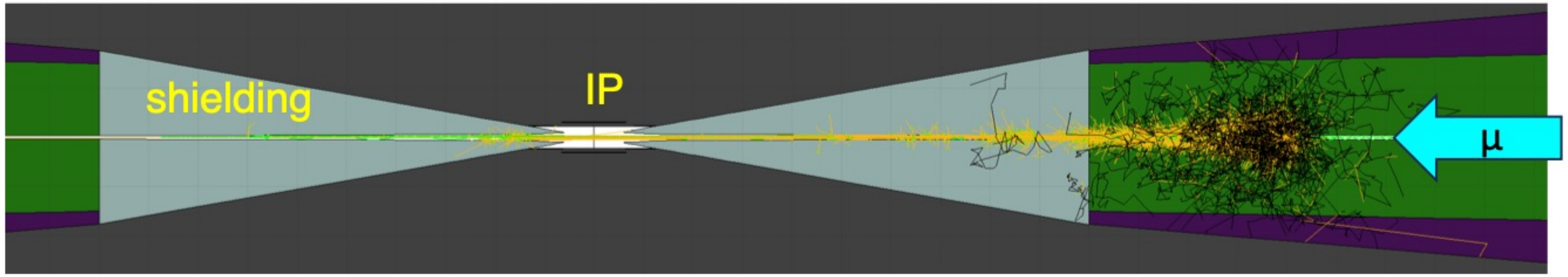
- plan: time-dependent deformation of the μ trajectory to spread radiation over a larger area
  - at 5 TeV beam energy, it may be necessary to place beam line components on movers



Also need to shield magnets from decay $e^\pm$

Beam background sources in the detector region

- ✗ Muon decay along the ring, $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$: dominant process at all center-of-mass energies
  - ✱ photons from synchrotron radiation ofμ energetic electrons in collider magnetic field
  - ✱ electromagnetic showers from electrons and photons
  - ✱ hadronic component from photonuclear interaction with materials
  - ✱ Bethe-Heitler muon, $\gamma + A \rightarrow A' + \mu^+\mu^-$
- ✗ Incoherent e^-e^+ production, $\mu^+\mu^- \rightarrow \mu^+\mu^-e^+e^-$: important at high $\sqrt{s}$
  - ✱ small transverse momentum $e^-e^+ \Longrightarrow$ trapped by detector magnetic field
- ✗ Beam halo: level of acceptable losses to be defined, not an issue now



Single muon decay tracks

$N_\mu^\pm \sim 2x10^{12}$/bunch

F. Collamati et al. 2021 JINST 16 P11009

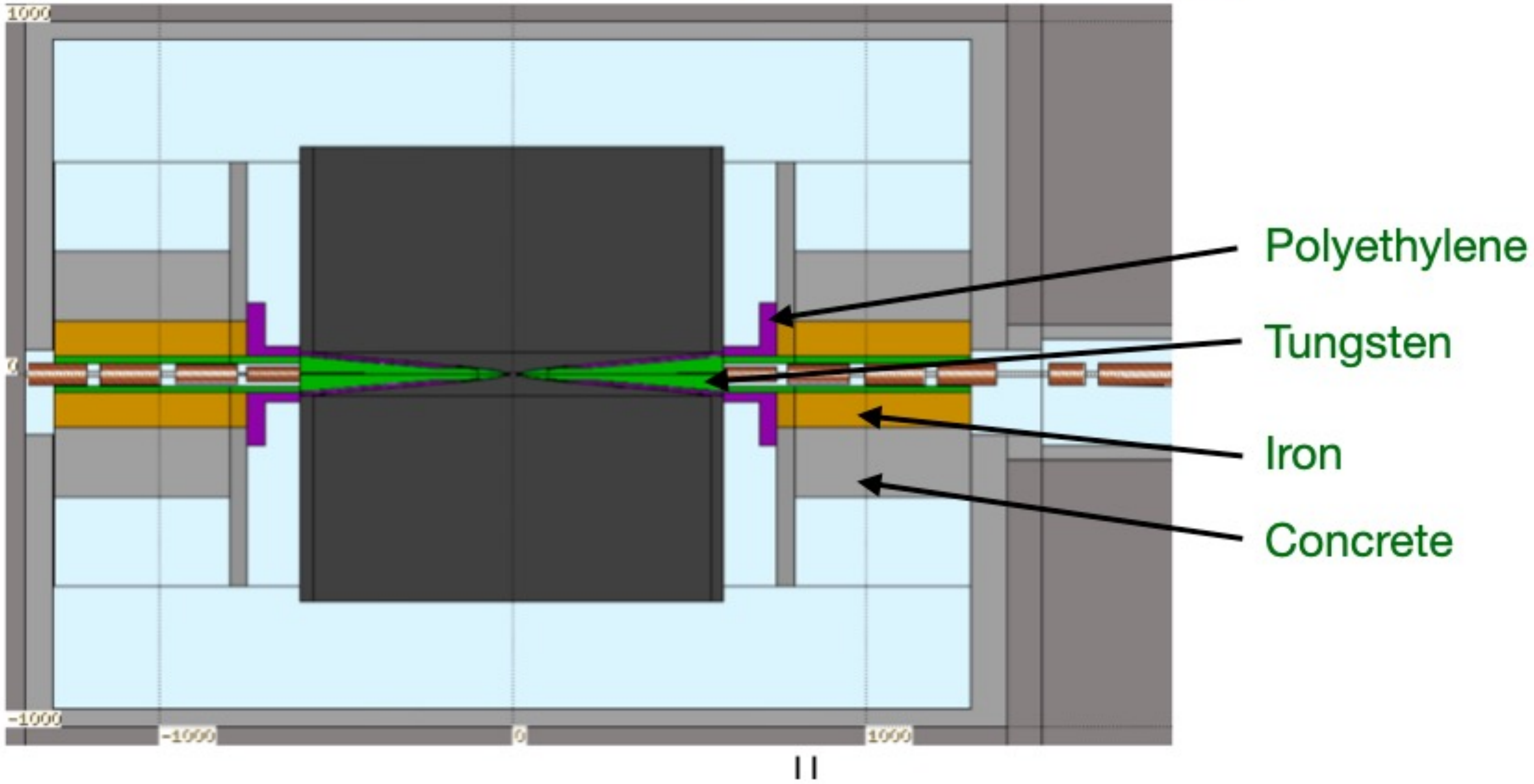
Beam-induced background

F.Filthaut @ Veldhoven

For 5 TeV μ: $\gamma = 2.4\ 10^4$ ➠ decay length in lab frame is ~ $1.6\ 10^7$ m.

With $2\ 10^{12}\ \mu$ / bunch: ~ $10^5\ \mu$ decays / m: challenging background!

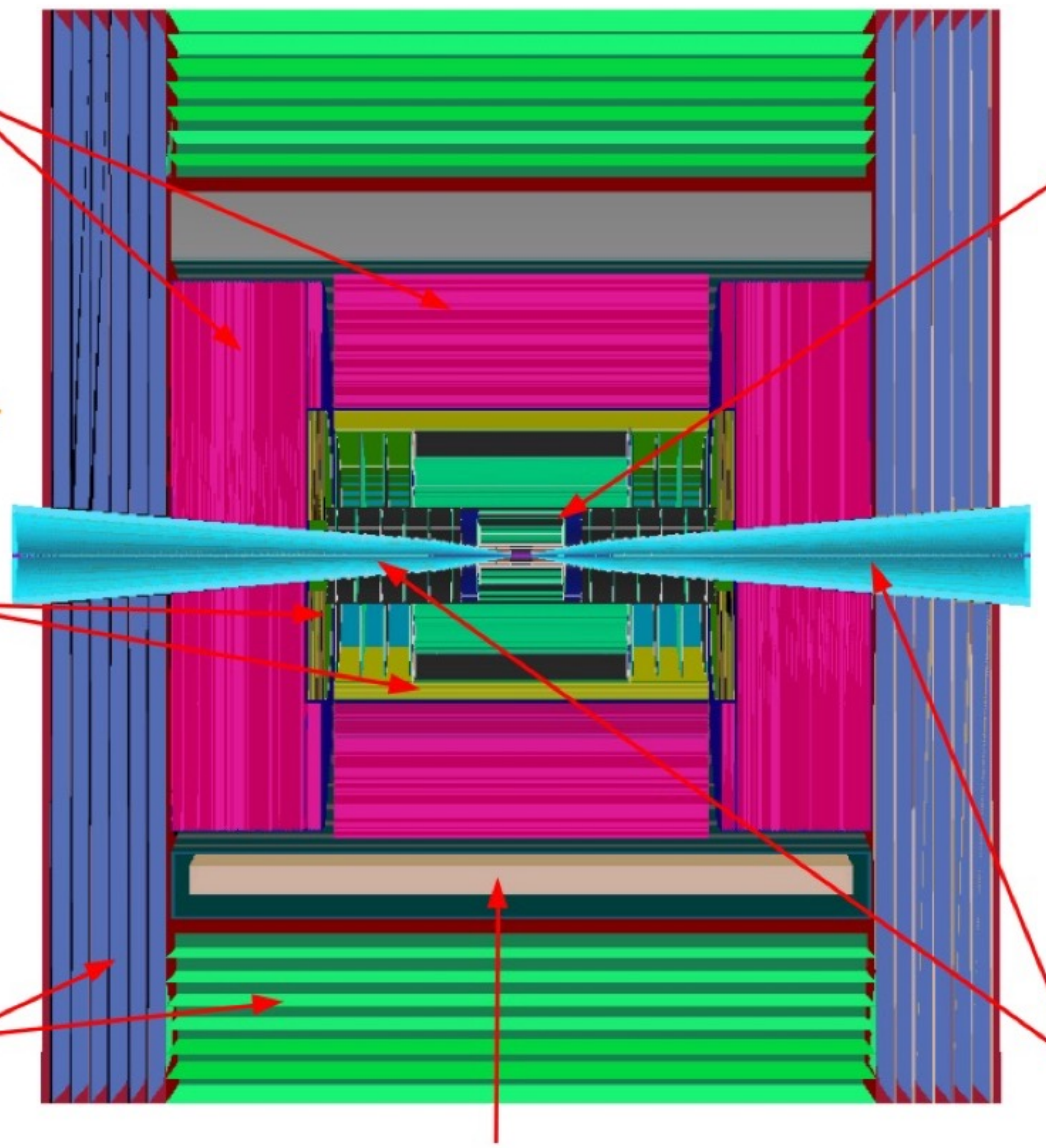
- direct decay $e^{\pm}$ but also secondary particles from interactions with upstream accelerator elements ➠ shielding is an important consideration
- in particular, tungsten nozzle limiting acceptance in θ, likely by 10°



First detector concept at $\sqrt{S} = 3$ TeV based on CLIC's detector concept

CLICdp-Note-2017-001

- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to adapt to available beam-induced background



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

superconducting solenoid (3.57T)

tracking system

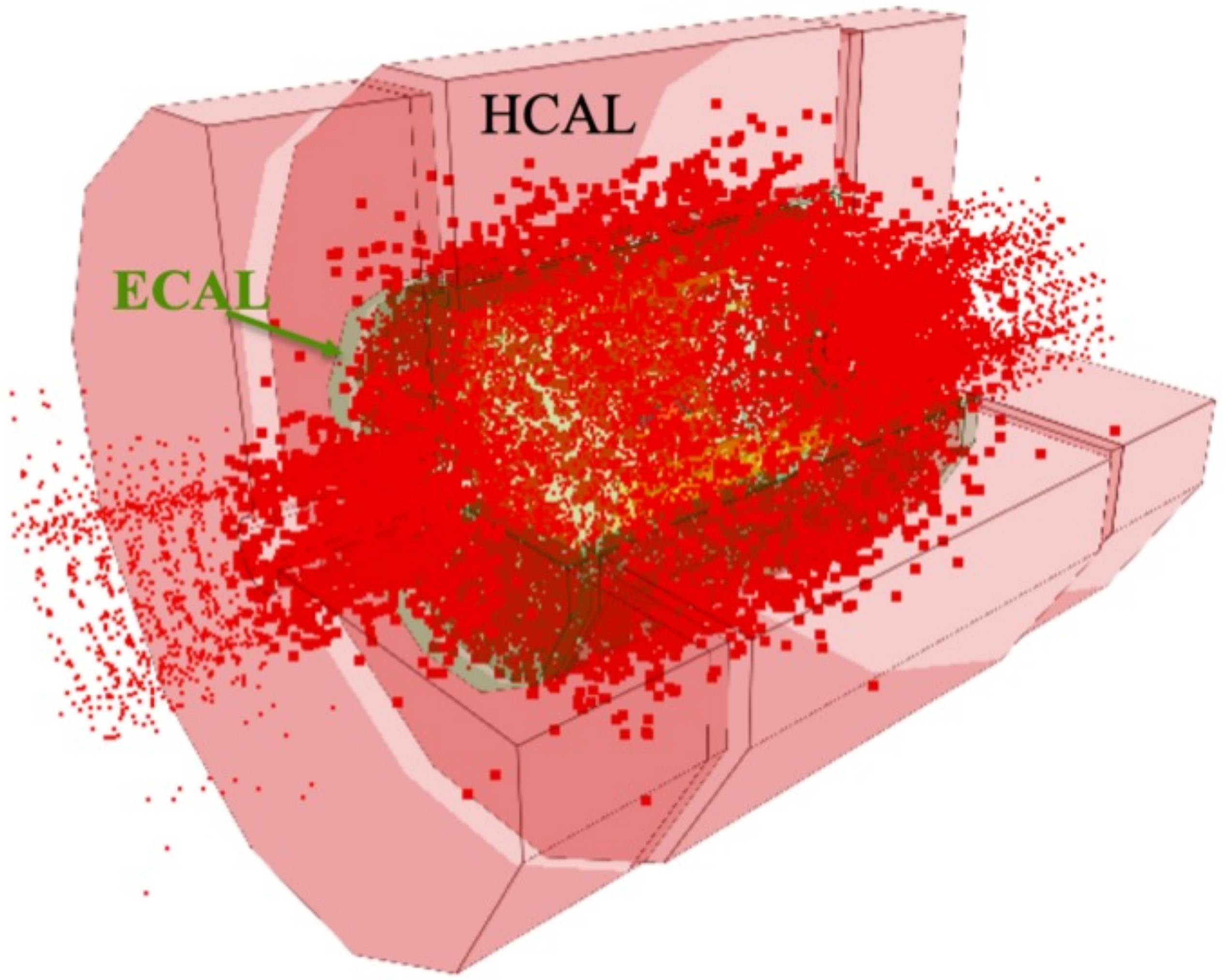
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

ILCSoft is the simulation and reconstruction framework, forked from CLIC's software.
Transition to key4hep in progress, timeline depending on person power.
Tutorial made in July 2023.

Calorimeter system: full detector & BIB simulation

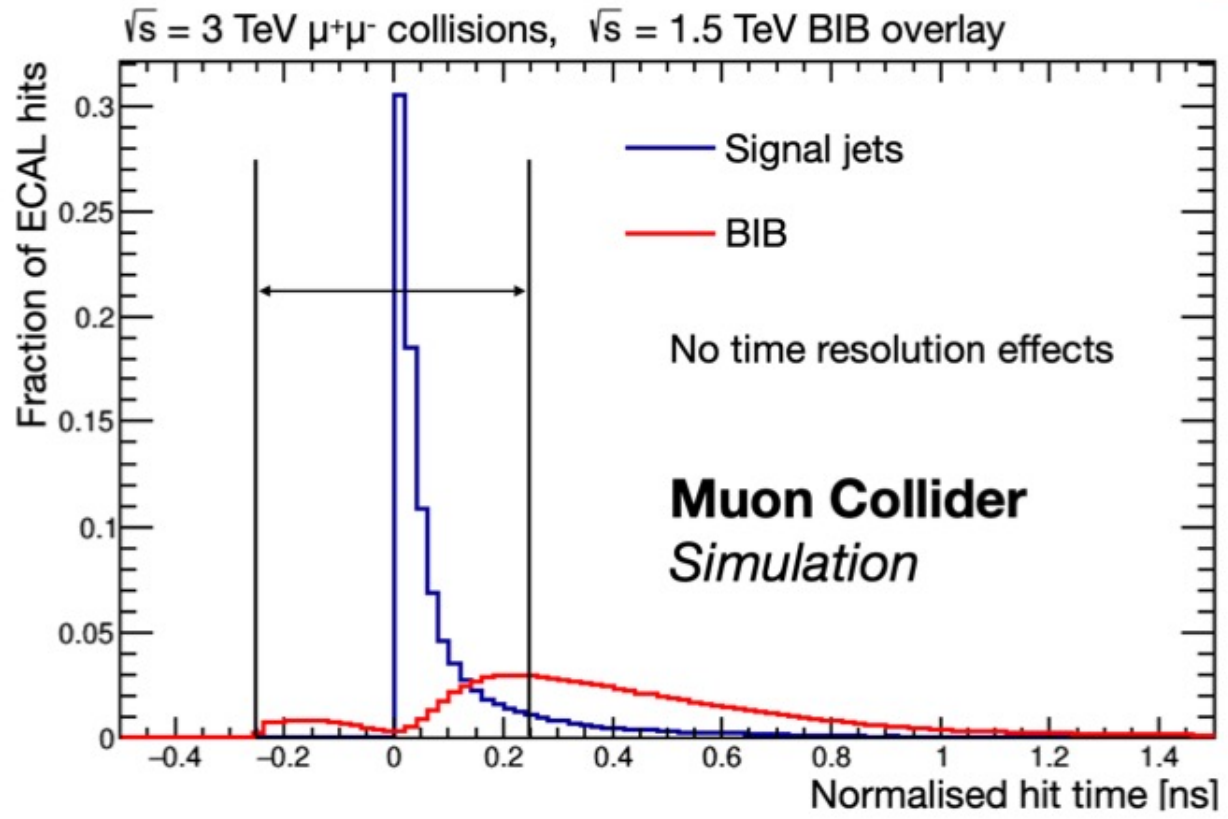


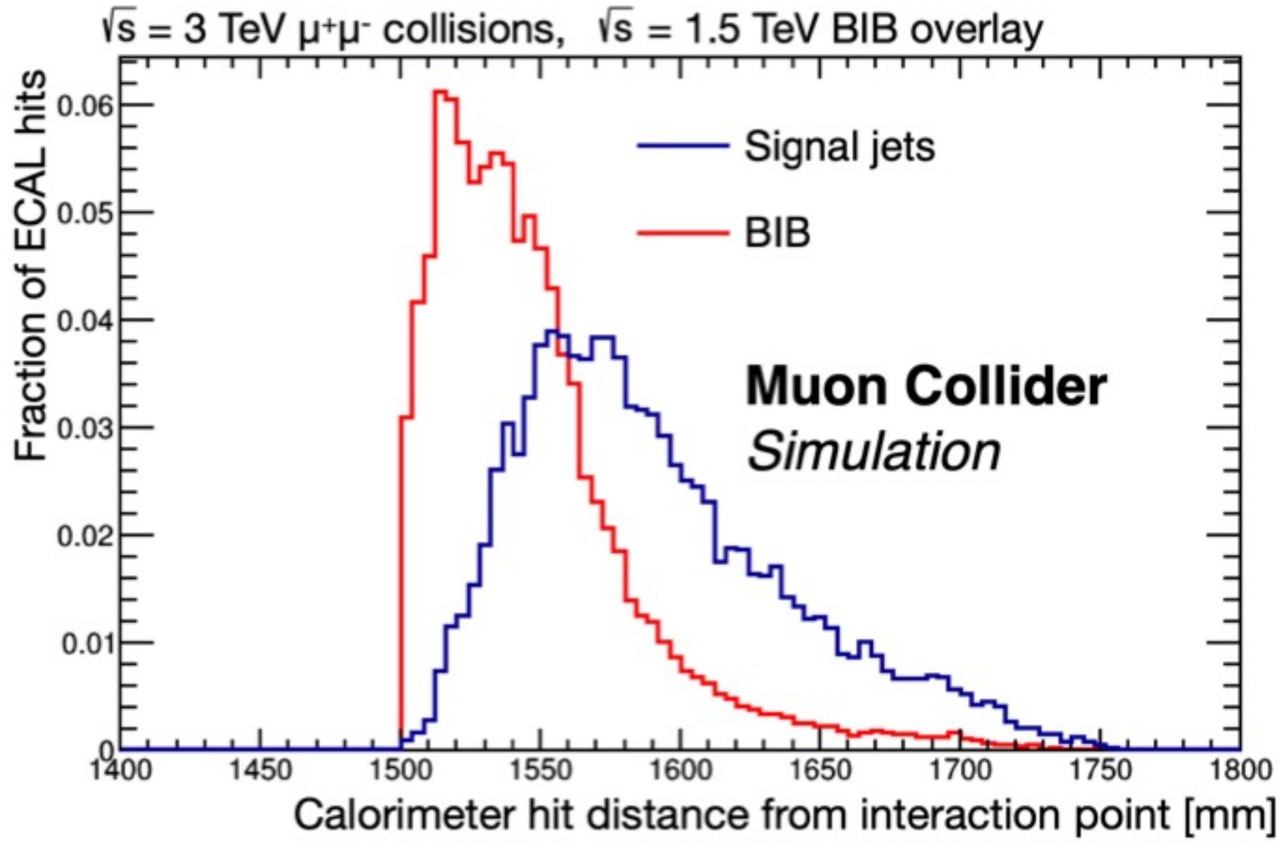
ECAL surface flux: 300 particle/cm^2

- 96% photons, 4% neutrons
- $E_{\gamma}^{Ave.} \sim 1.7$ MeV

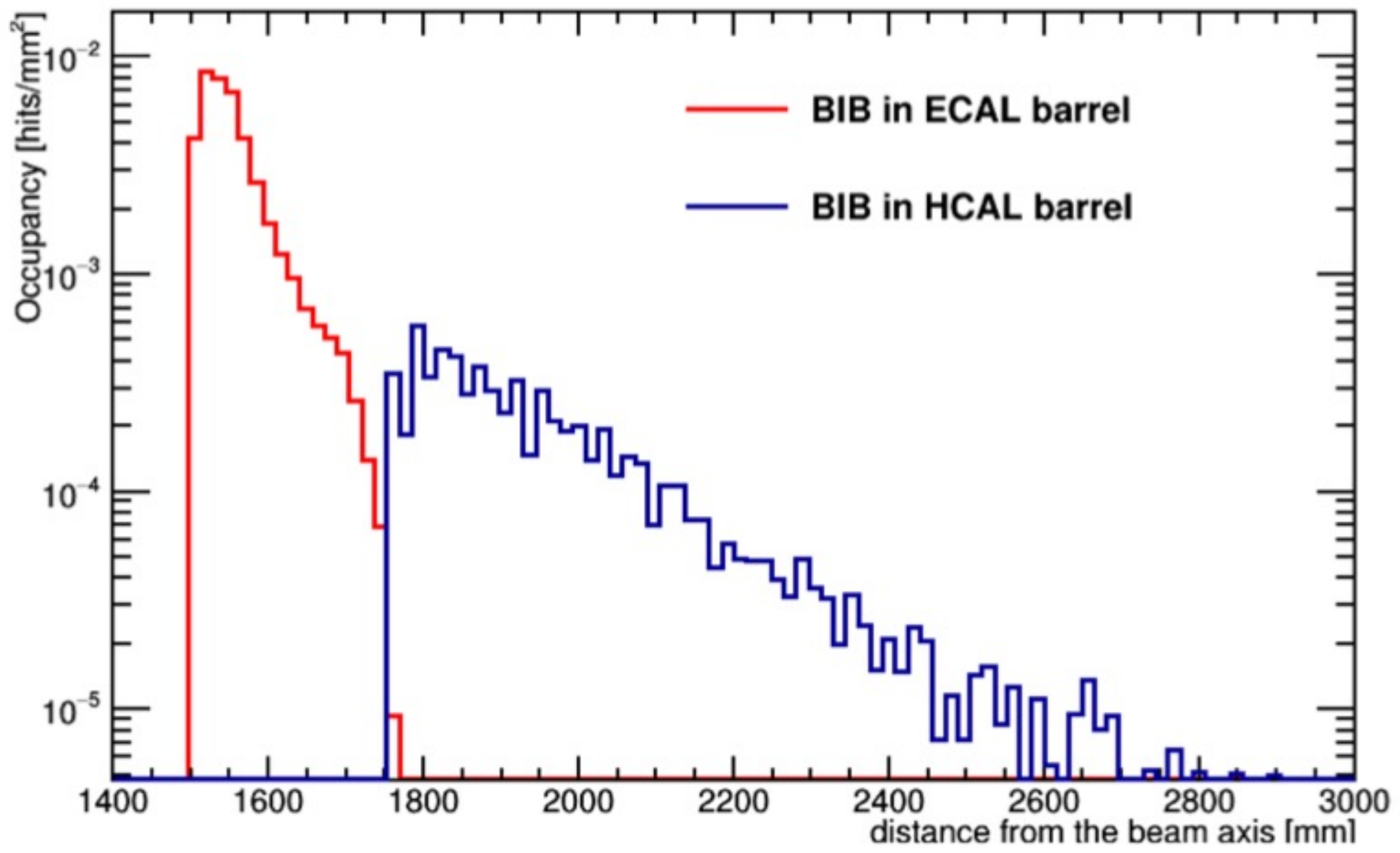
Calorimeter requirements

- time-of-arrival: resolution ~100 ps to reject out-of-time particles.
- Longitudinal segmentation: different profile signal vs. BIB.
- High granularity: to separate BIB particles from signal to avoid overlaps in the same cell





Occupancy: ECAL > 10 times HCAL



Engaged in DRD6 with dedicated ECAL R&D: **Crilin**

Module: 5 layers of PbF2 crystals (10x10x40 mm^3) Cerenkov light detected with SiPMs

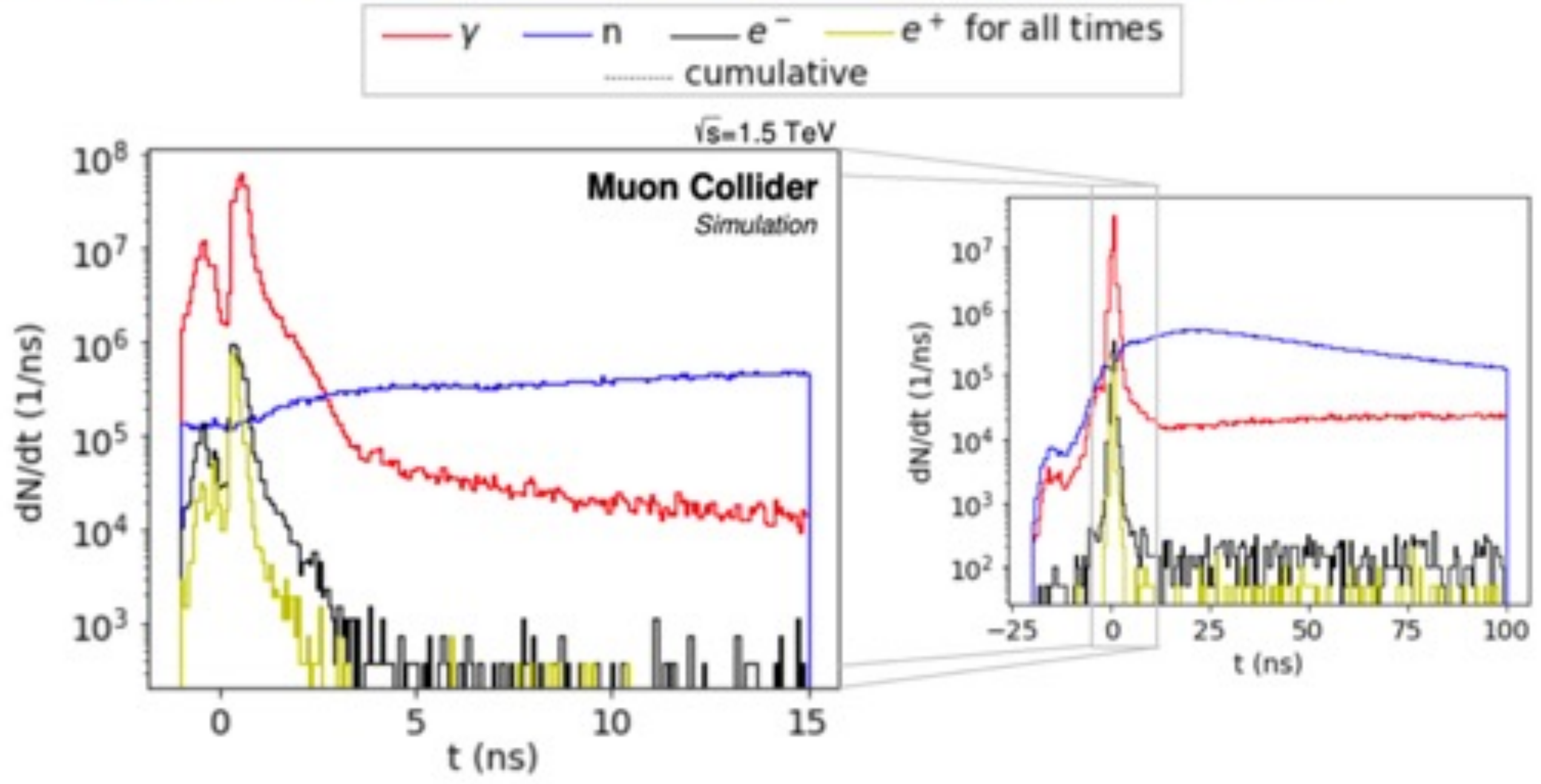
Dedicated HCAL proposal in progress.

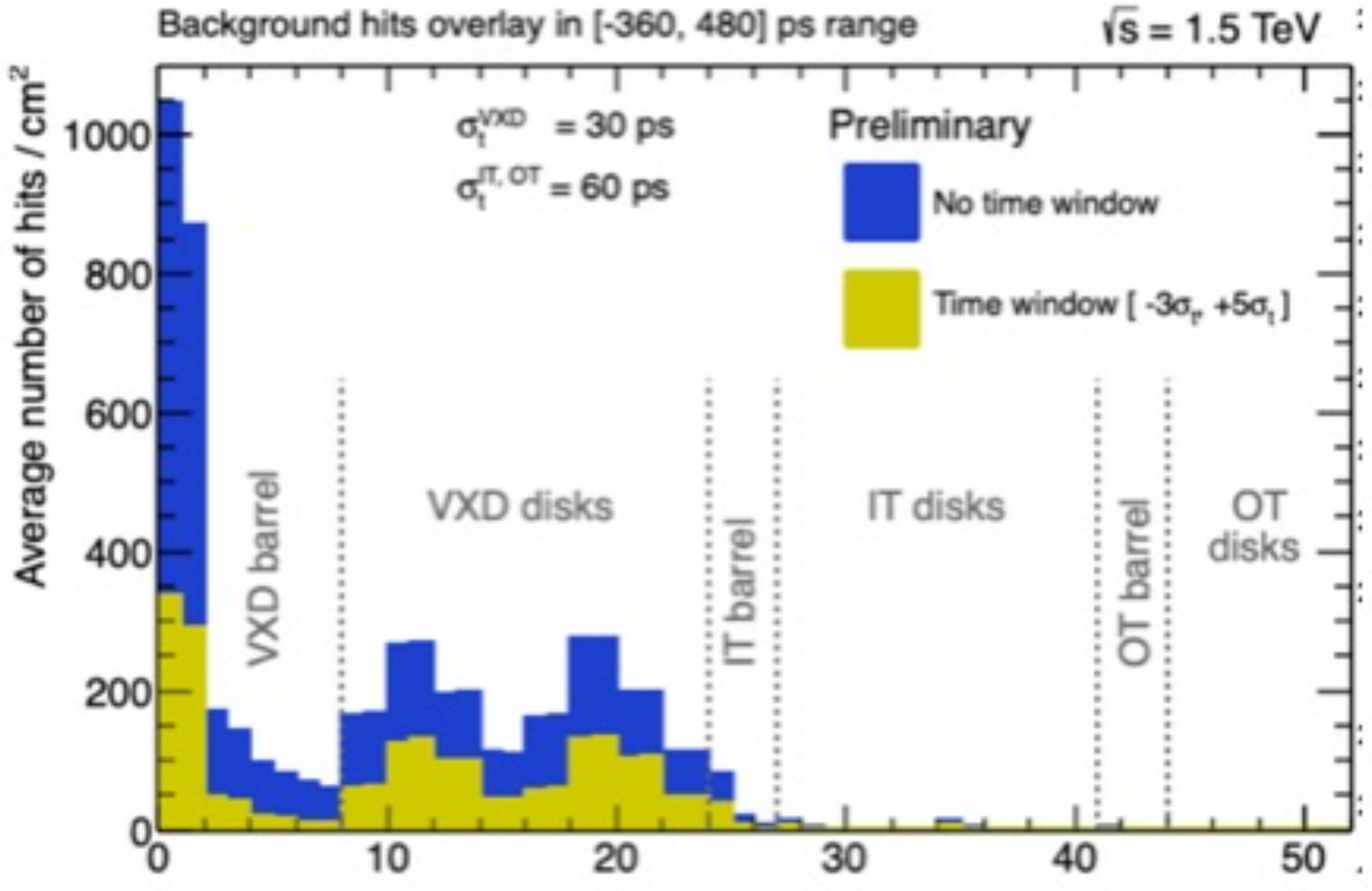
Tracking & vertex detectors

F.Filthaut @ Veldhoven

Beam-induced background remaining after shielding is still a problem

- fine granularity to reduce occupancy
- precise timing (30 ps for vertexing, 60 ps for tracking assumed)
  - challenge for the vertex detector, especially for small pixel size ($25\ \mu m \times 25\ \mu m$)
  - need for “4D tracking”





13

Magnet Roadmap *presented to November 2023 LDG*

Consensus of experts (review panel):

- Anticipate technology to be **mature in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
- This corresponds to 3 TeV design
- Could build 10 TeV with reduced luminosity performance
  - Can recover some but not all luminosity later

The Muon Collider: a superconducting technology driver for science and society

Still under discussion:

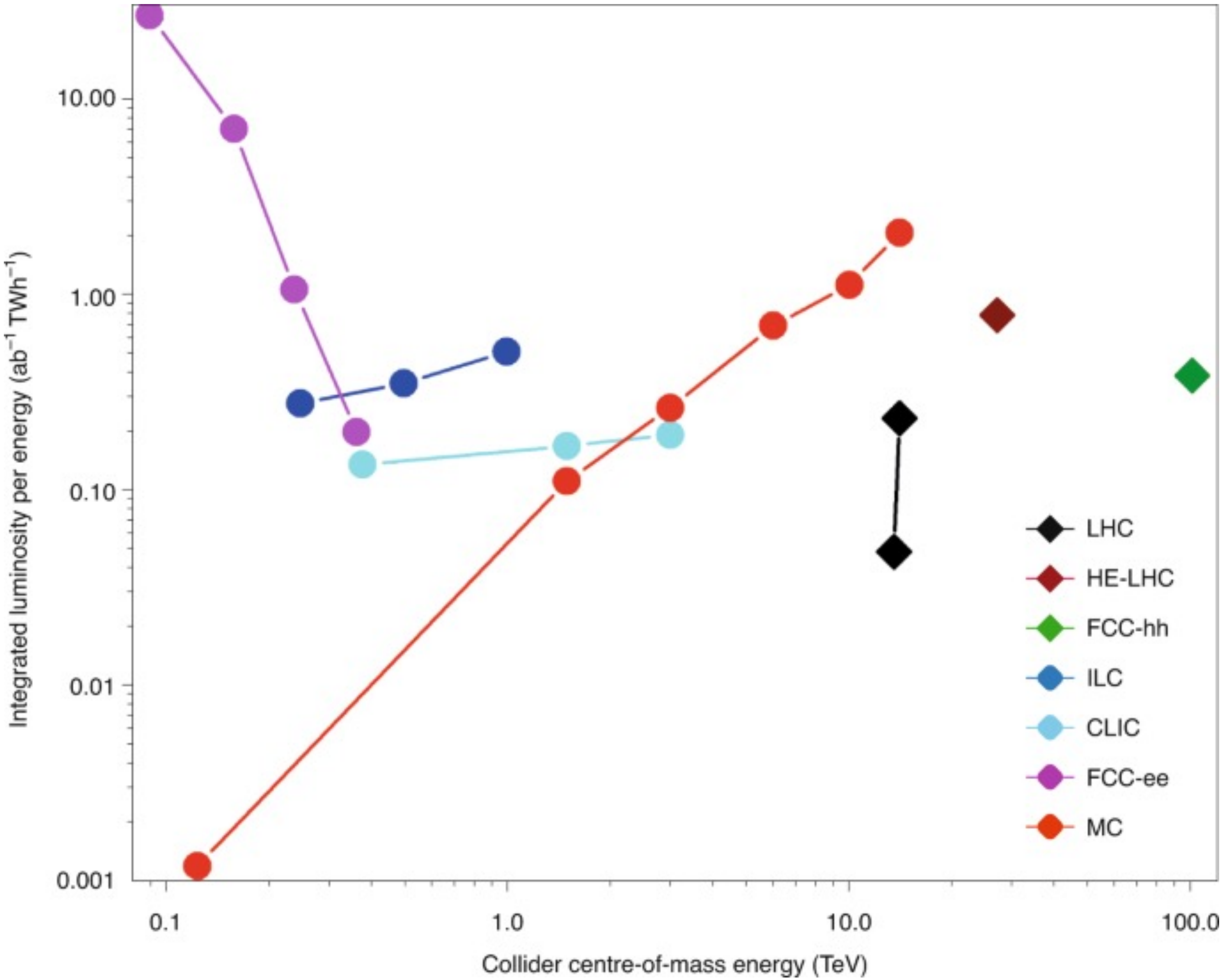
- Timescale for HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**

STRATEGY:

- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

LUMI


Integrated luminosity per energy (ab^{-1} TWh^{-1})
10.00
1.00
0.10
0.01
0.001
0.1
1.0
10.0
100.0
Collider centre-of-mass energy (TeV)
LHC
HE-LHC
FCC-hh
ILC
CLIC
FCC-ee
MC

COSTS (1)

125-600 GeV

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

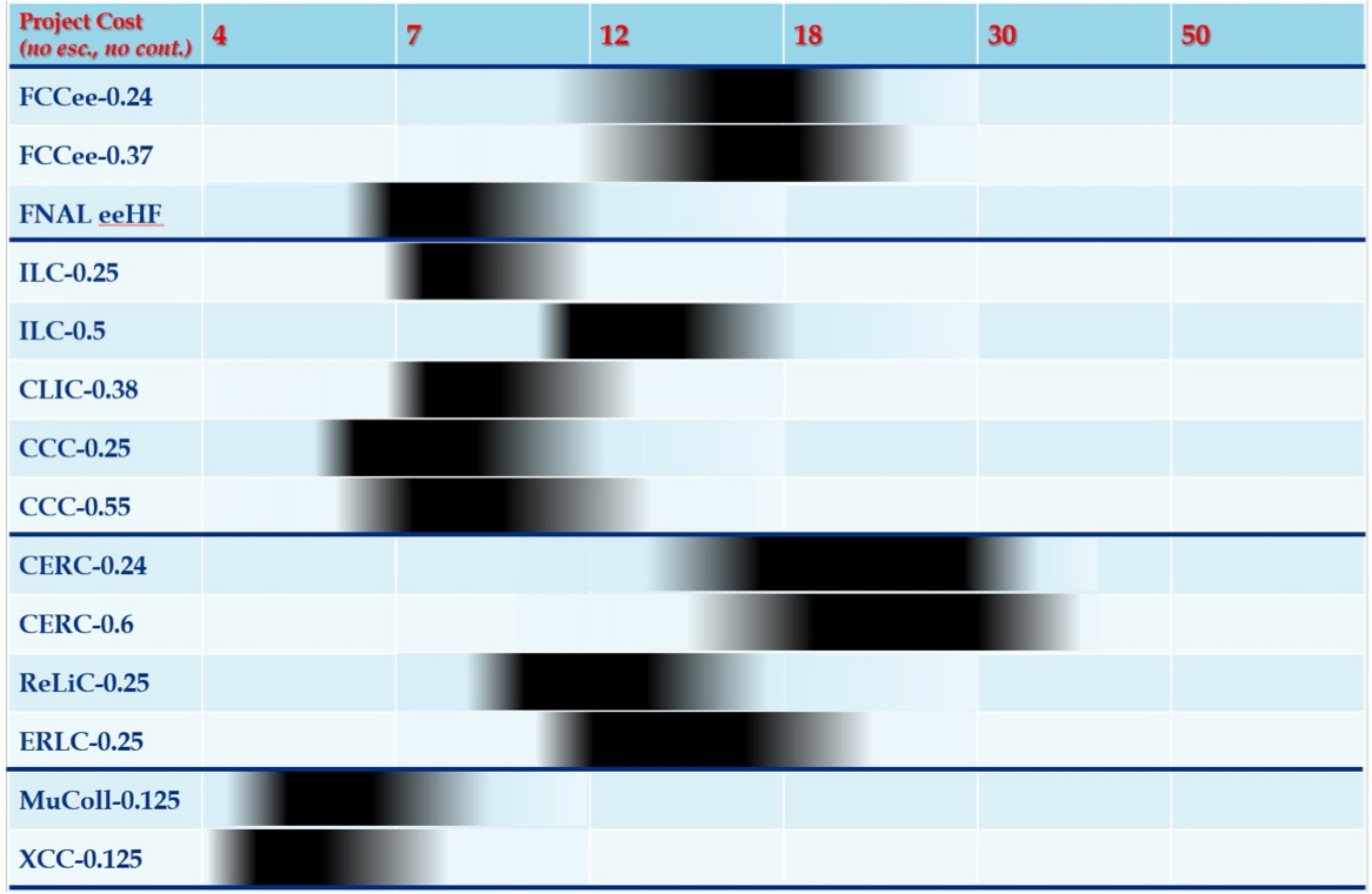


Figure 8. The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (2)

1-10 TeV

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

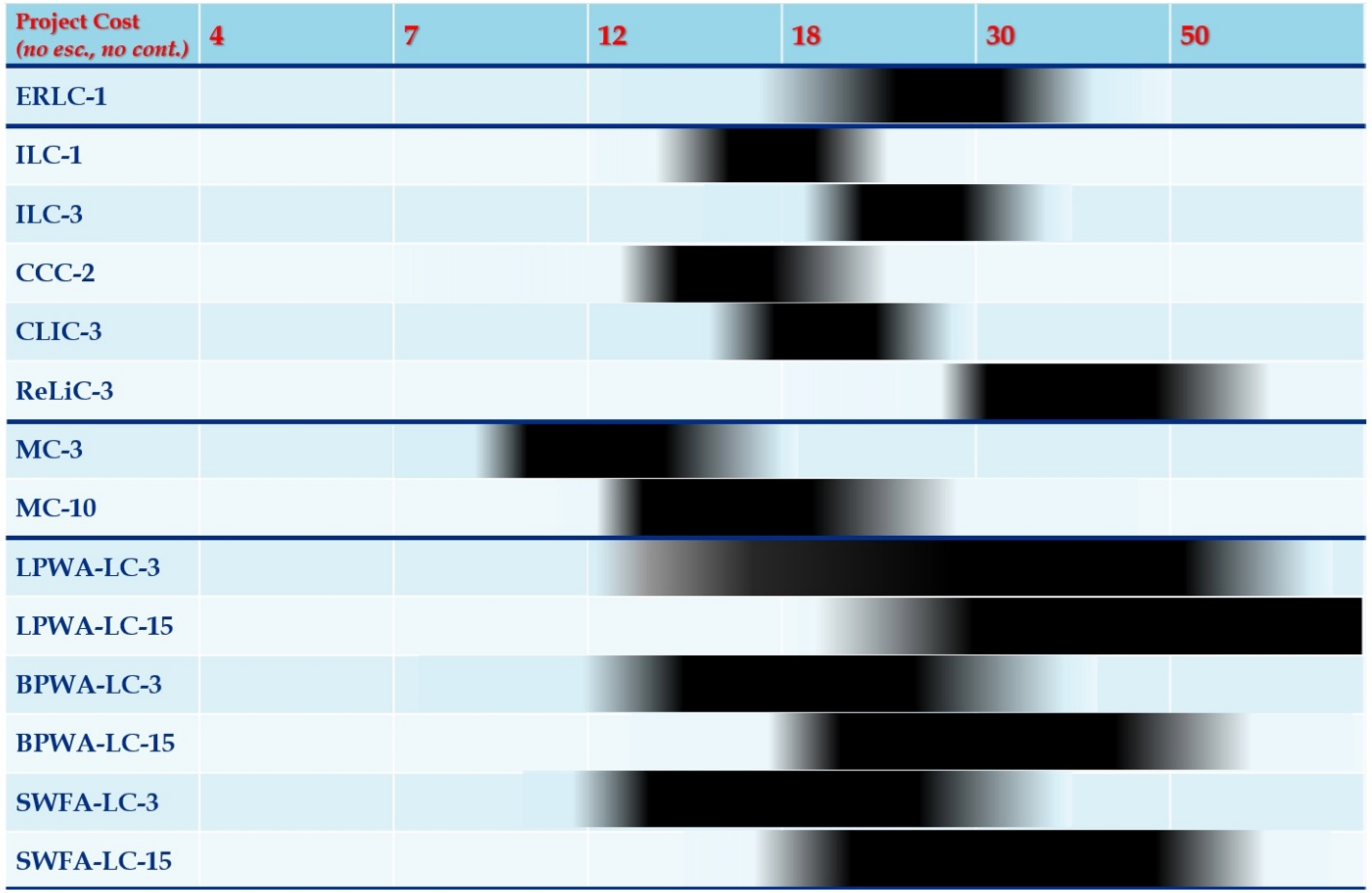


Figure 9. The ITF cost model for the multi-TeV lepton collider proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

COSTS (3)

Other

Snowmass 21 - https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018/pdf

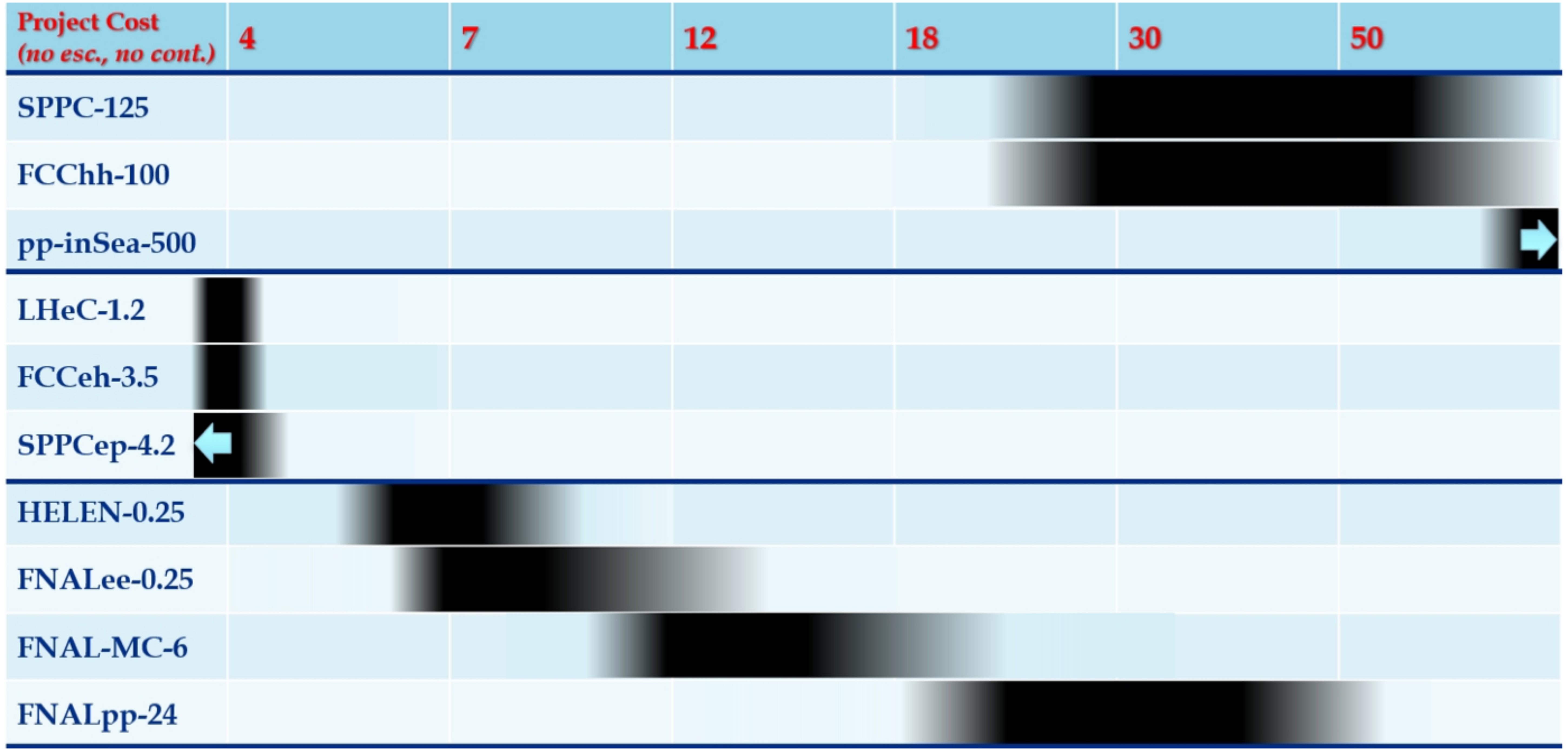


Figure 10. The ITF cost model for the energy frontier hadron collider, electron-proton colliders (incremental cost from hadron collider only) and for the proposed Fermilab site-filler colliders. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends are the cost estimate range for each machine. Right-arrow for the 500 TeV "Collider-in-the-Sea" indicates higher than 80 B$ cost. Left-arrow for the electron-proton "SPPC-CEPC" collider concept indicates smaller than 4 B$ cost.