Collider Physics:
The Higgs Factory & Beyond

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International Workshop on
New Opportunities for Particle Physics
IHEP, July 18, 2025

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(3). The Energy frontier drives!

10 TeV pCM Energy @ SppC, FCC_{hh} , MuC.
And the race is on …

U.S. Community Summer Study: Snowmass 2021

July 17 – 26, 2022 @ UW – Seattle
http://seattlesnowmass2021.net

Opportunities in HEP for the decade & beyond

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4 Spectroscopic Survey - S5*	Next Gen. Grav. Wave Observatory* Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Snowmass 2021 & the P5 Recommendations

http://seattlesnowmass2021.net

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

Explore the Quantum Universe

P5 report: Recommendation 1

Not Rank-Ordered

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:

Including:

a. HL-LHC (energy frontier)

b. 1st Phase DUNE & PIP-II (LBN neutrino)

c. The Vera Rubin Observatory (dark energy survey)

Recommendation 2

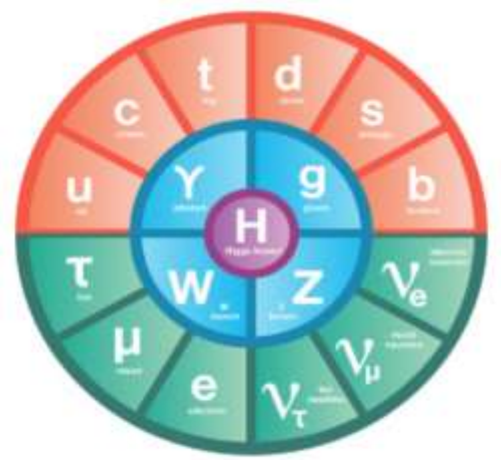
An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

P5 report: Recommendation 4

Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
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).

NAS 2025 Report
Elementary Particle Physics: The Higgs & Beyond
(link …)



Recommendations (8 of them)

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

Recommendation 2: The United States should participate in the international Future Circular Collider Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.

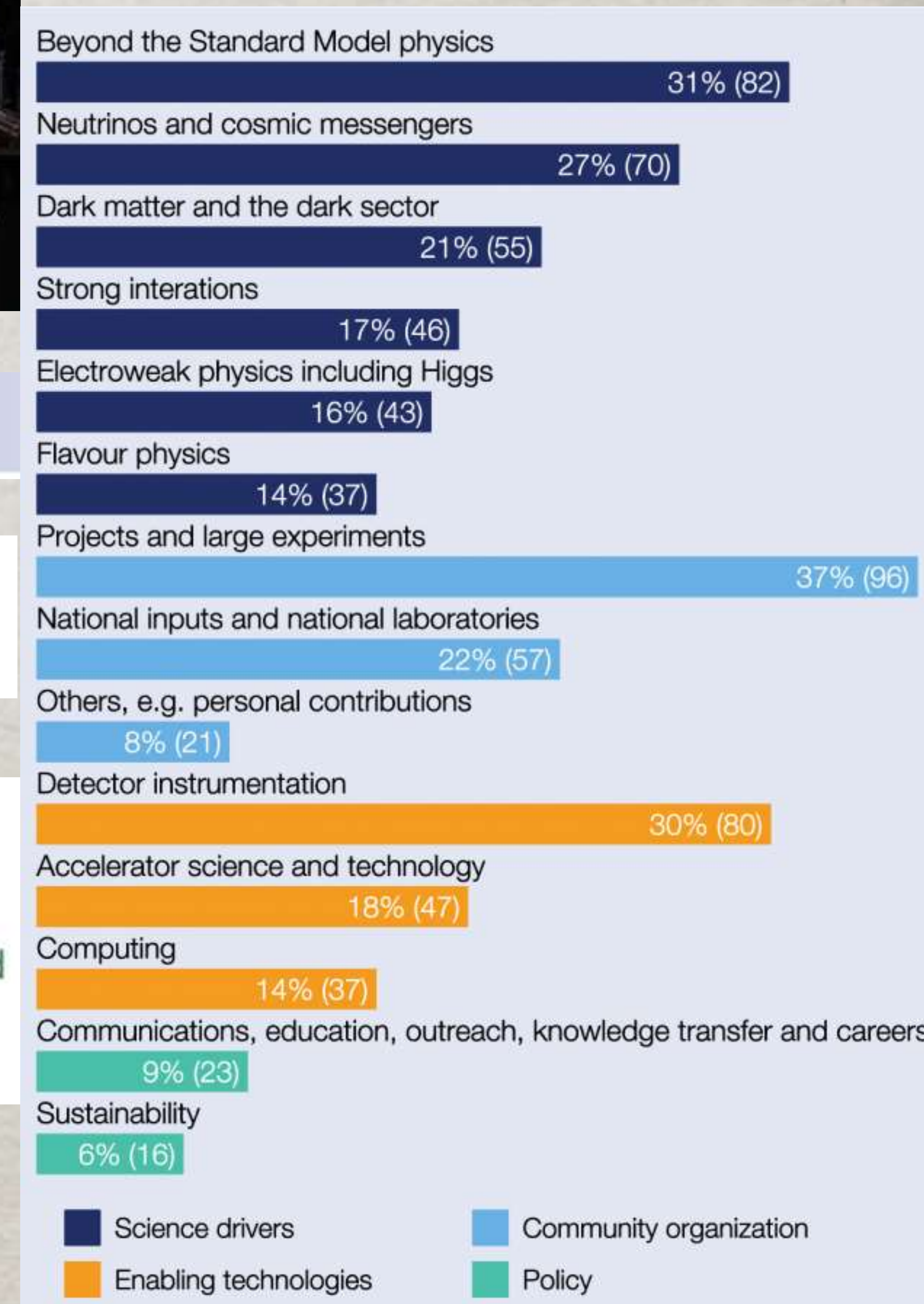
Recommendation 3: The United States should continue to pursue and develop new approaches to questions ranging from neutrino physics and tests of fundamental symmetries to the mysteries of dark matter, dark energy, cosmic inflation, and the excess of matter over antimatter in the universe.

ESPPU

High-priority future initiatives (I): future colliders

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.

Europe, together with its international partners, should 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. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

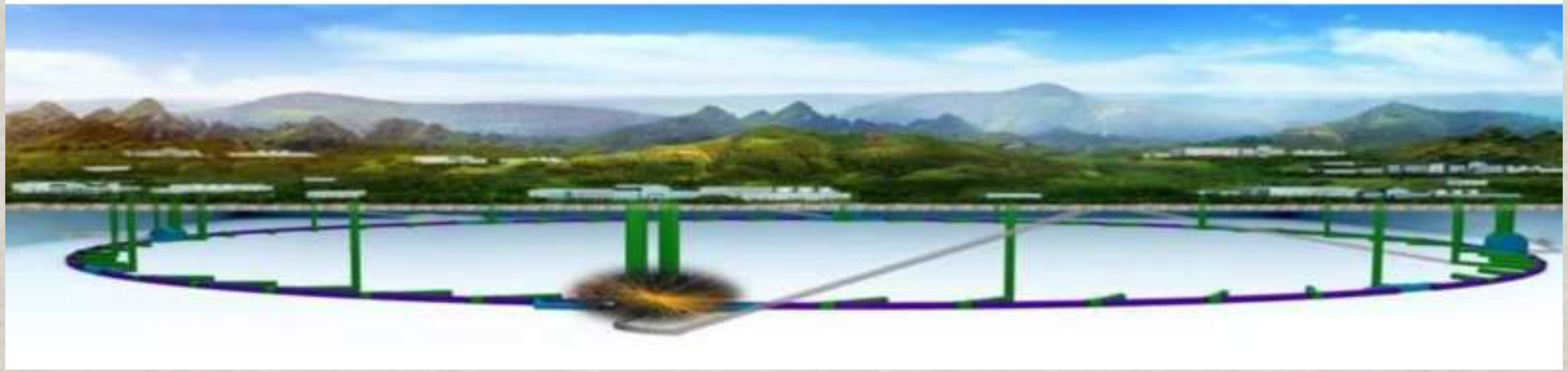


Status of CEPC in China

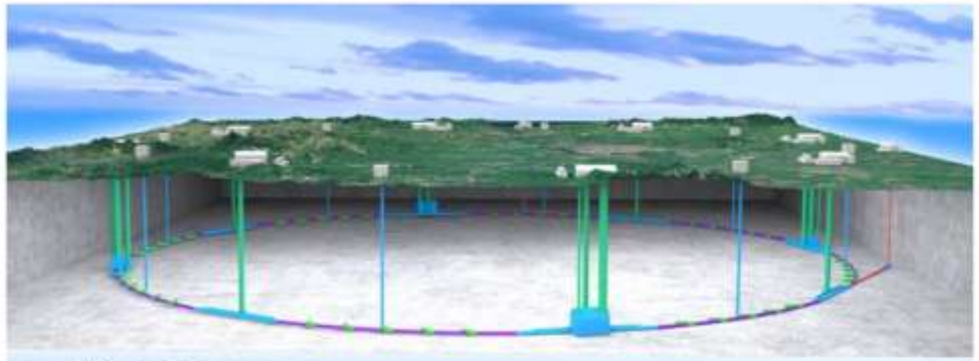
Yifang Wang for the team

Institute of High Energy Physics, Beijing

Venice, June 24, 2025



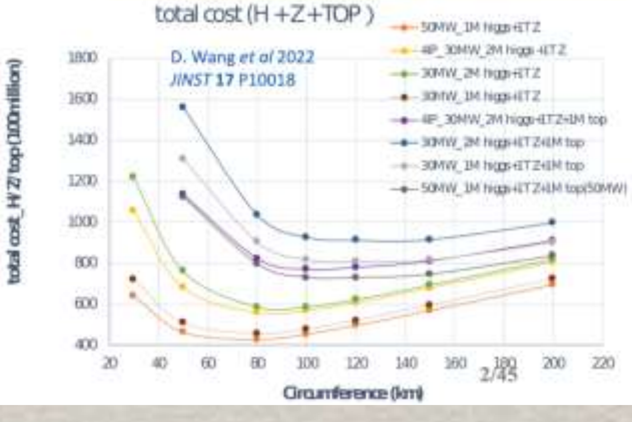
- Since 2005, we were thinking about the next machine after BEPCII/BESIII
- After its discovery, we realized that Higgs is the best portal for new physics and for the future of HEP
- The idea of a Circular e+e- Collider(CEPC) followed by a possible Super proton-proton collider(SPPC) was firstly proposed in Sep. 2012, and reported at Fermilab during the workshop: "Higgs Factories 2012" in Oct. 2012
- It quickly gained momentum in China and in the world



Fermilab-Conf-13-037-APC

arXiv:1302.3318[physics.acc-ph]

Optimum circumference for H/Z/Top



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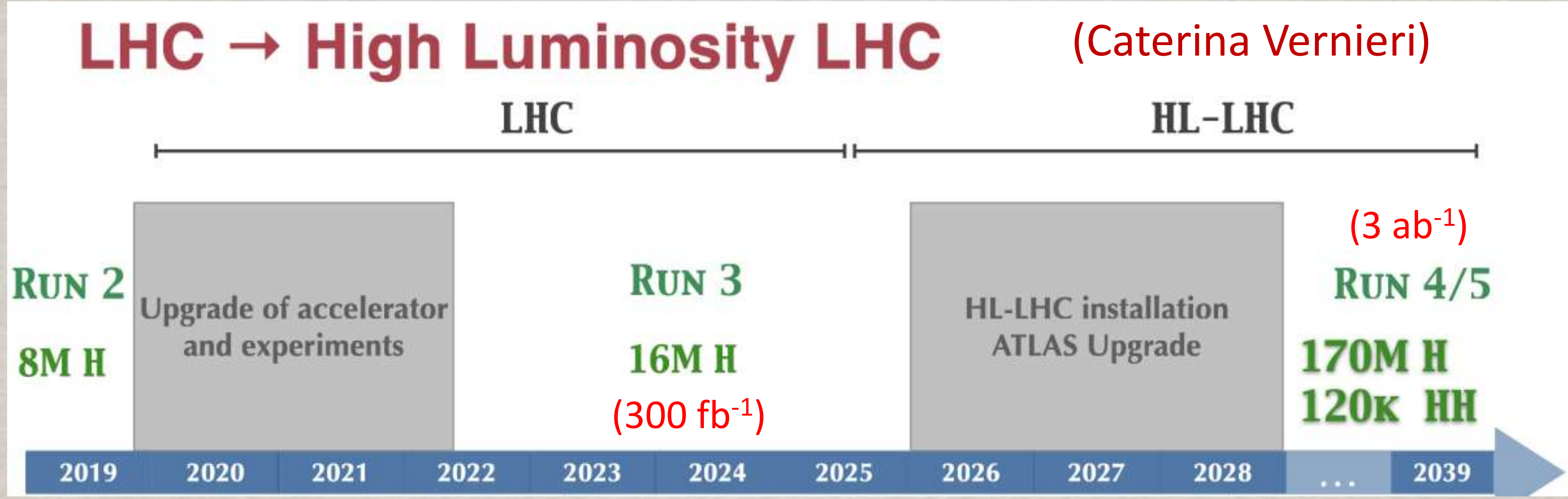
LHC / HL-LHC lead the way:

Energy frontier for the next 15 years!

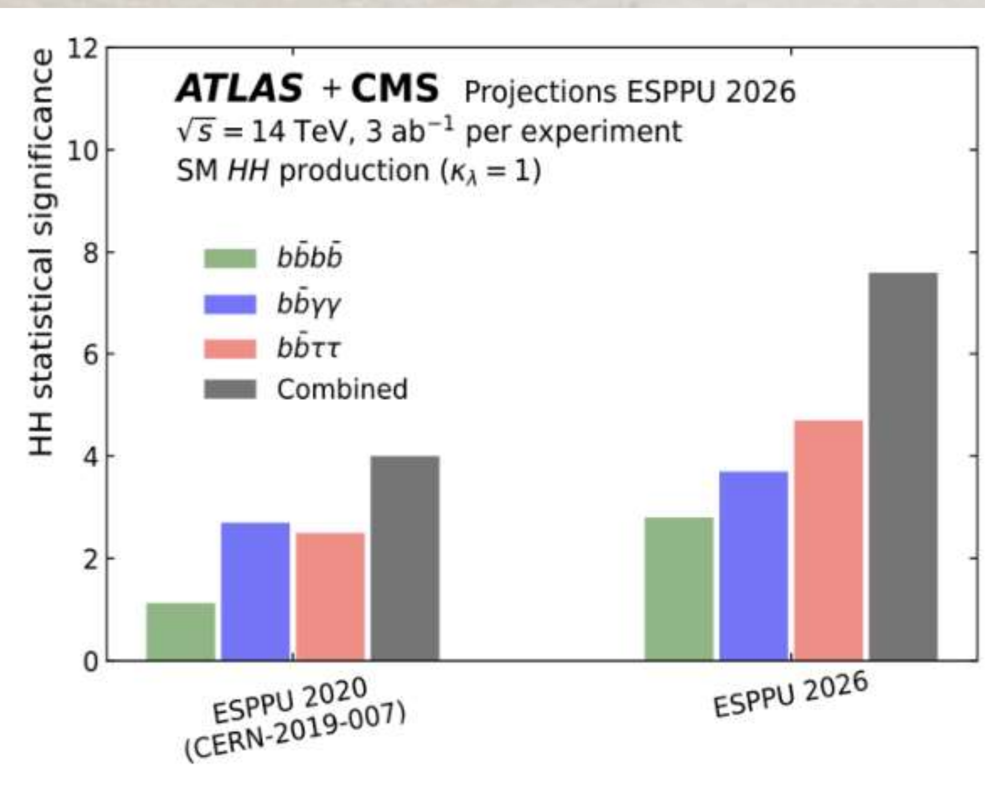


H couplings to:	**O(5-10)%**
H self-coupling to:	**O(50)%**

New physics reach:

M, Λ ~ O(a few TeV)

just above the EW scale!



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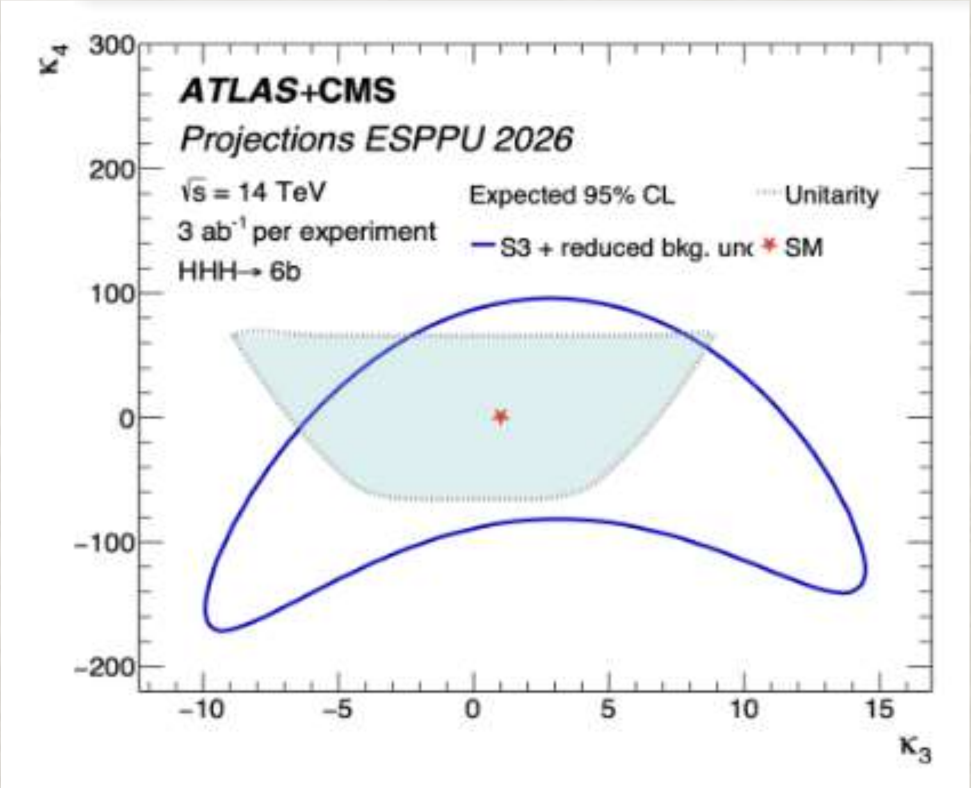
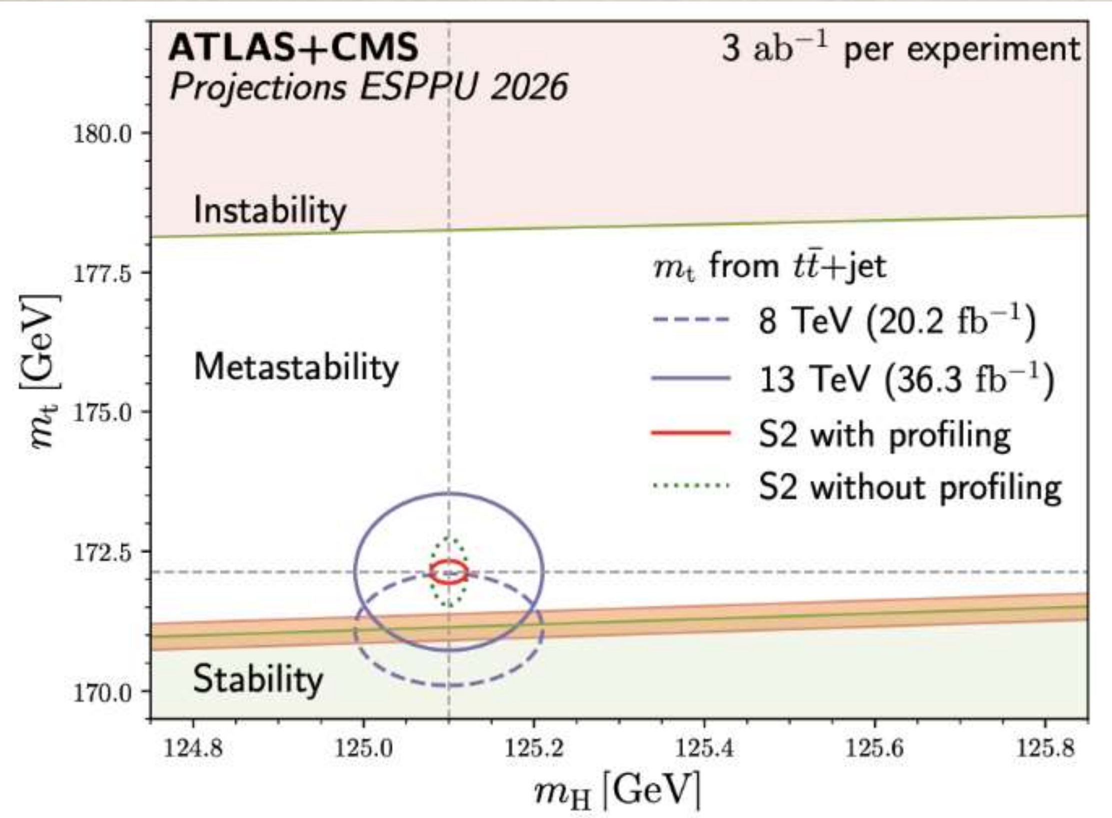
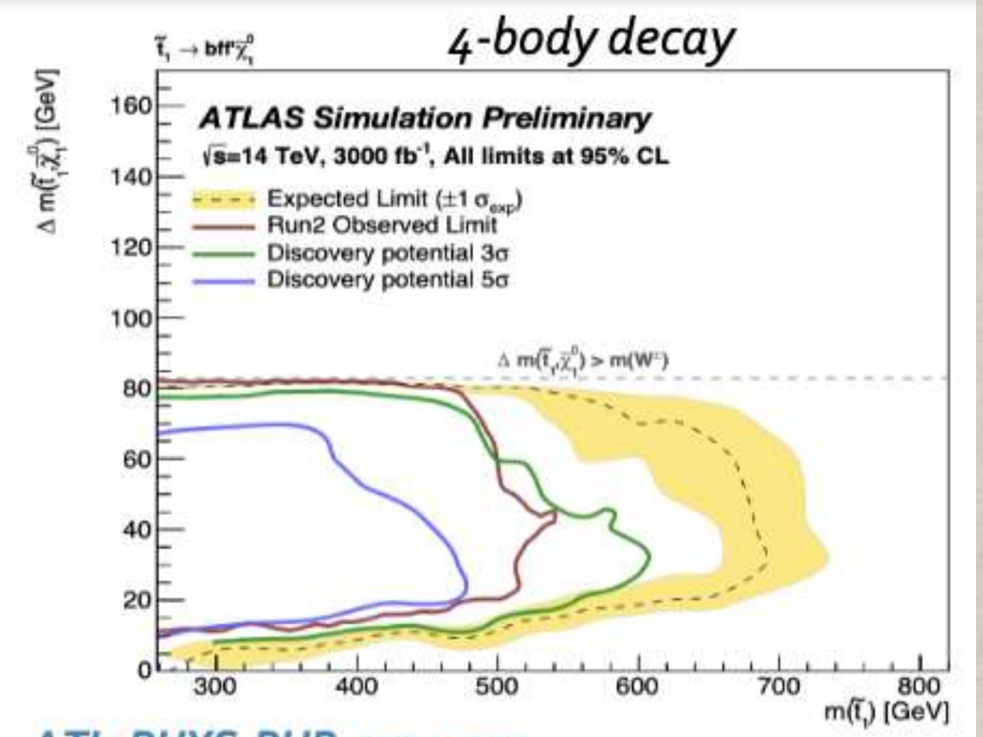
CMS-HIG-25-002







ATL-PHYS-PUB-2024-001

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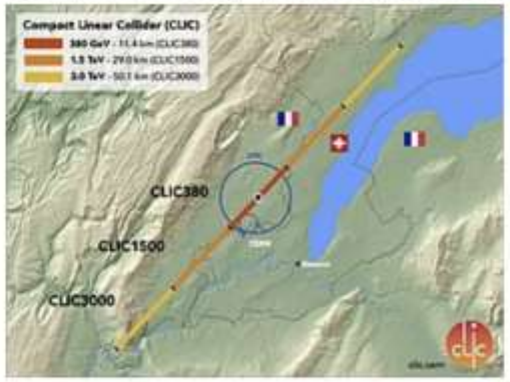
High priority: Higgs Factories

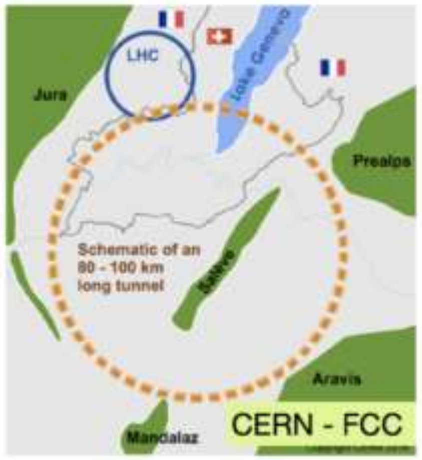
250/500 GeV

CEPC 240 GeV

250/550 GeV
… > TeV

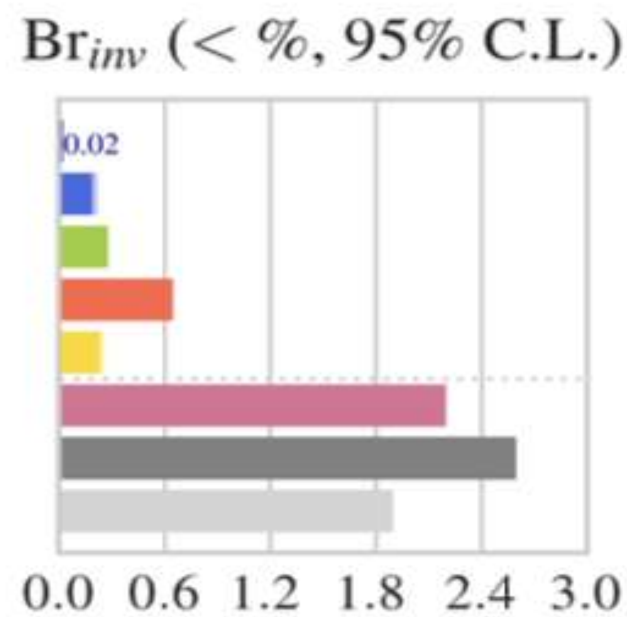
CLIC 380/1500/3000 GeV



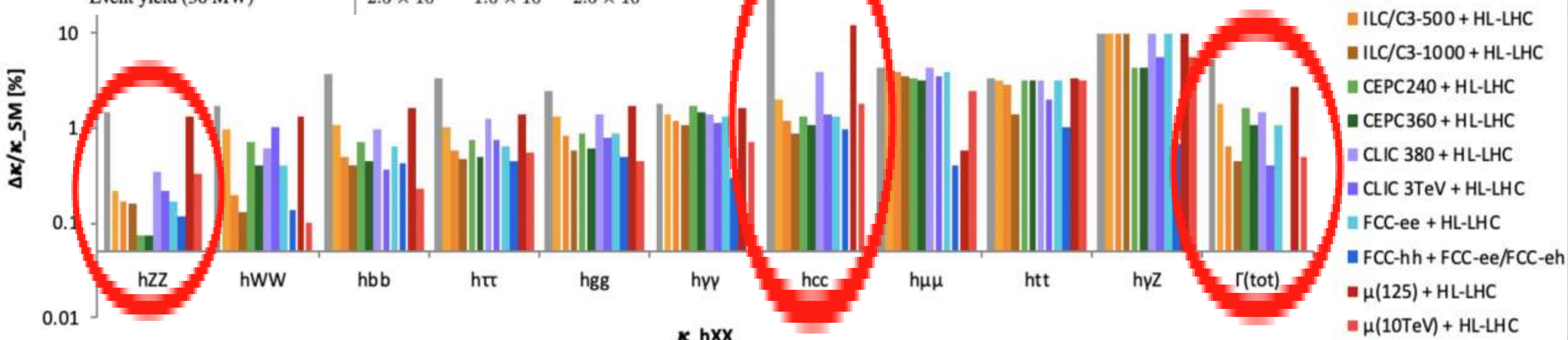


FCC-ee
240/365 GeV

Br_{inv} (< %, 95% C.L.)



Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP ($10^{34}\text{cm}^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}



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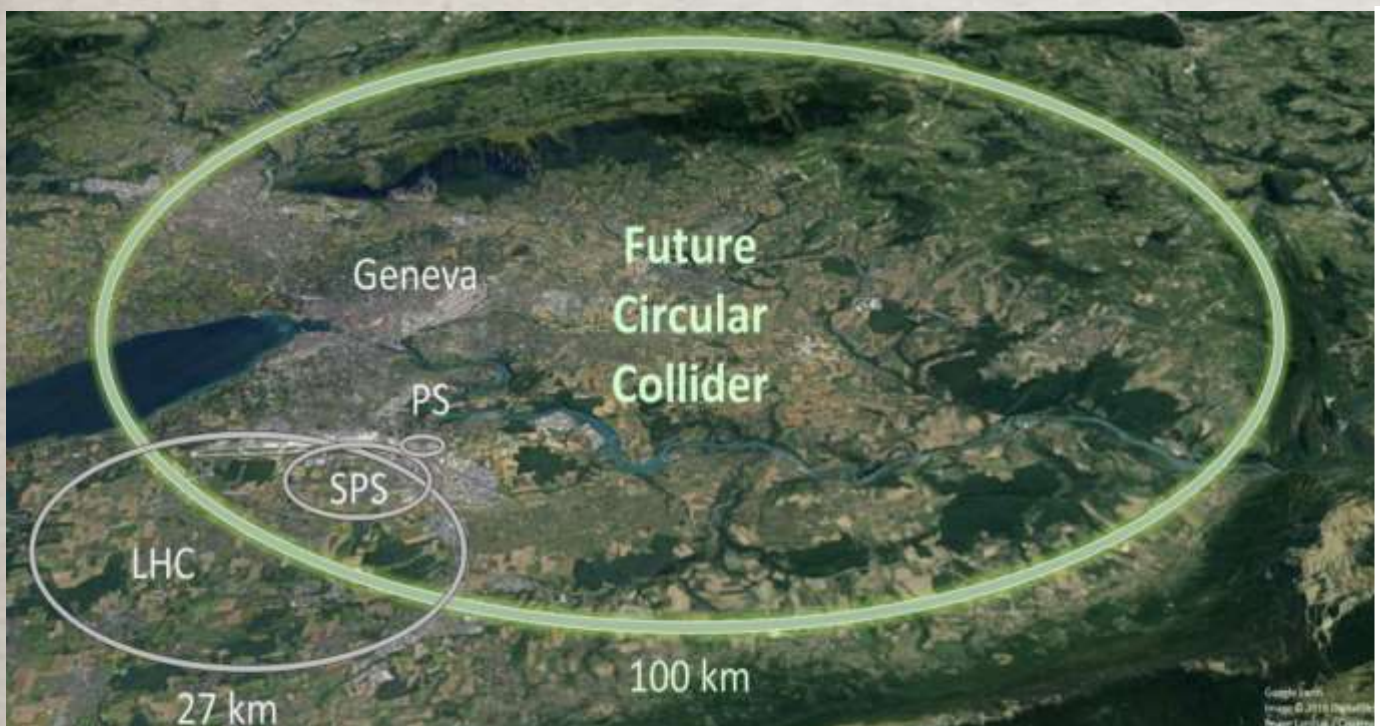
Toward 10 TeV partonic C.M. Energy (pCM)

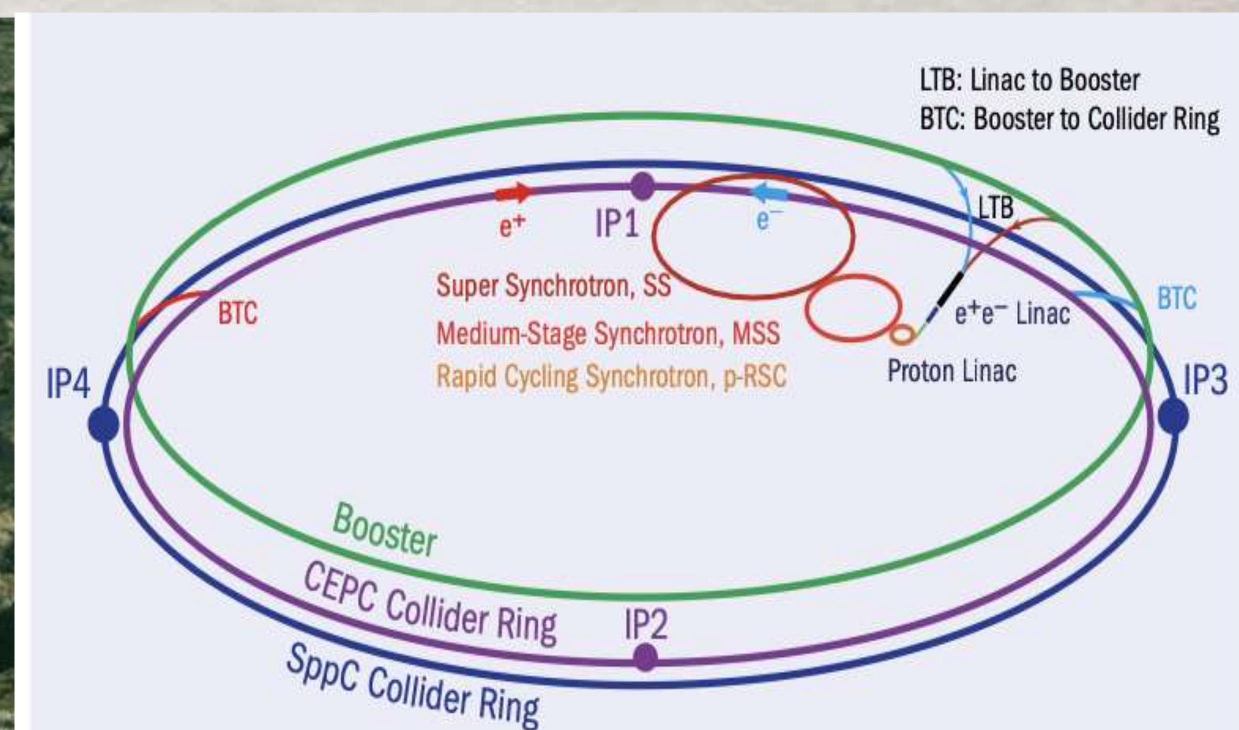
fully explore the Higgs sector/mechanism & beyond

proton+proton @ 100 TeV

FCC-hh @ CERN

SppC in China

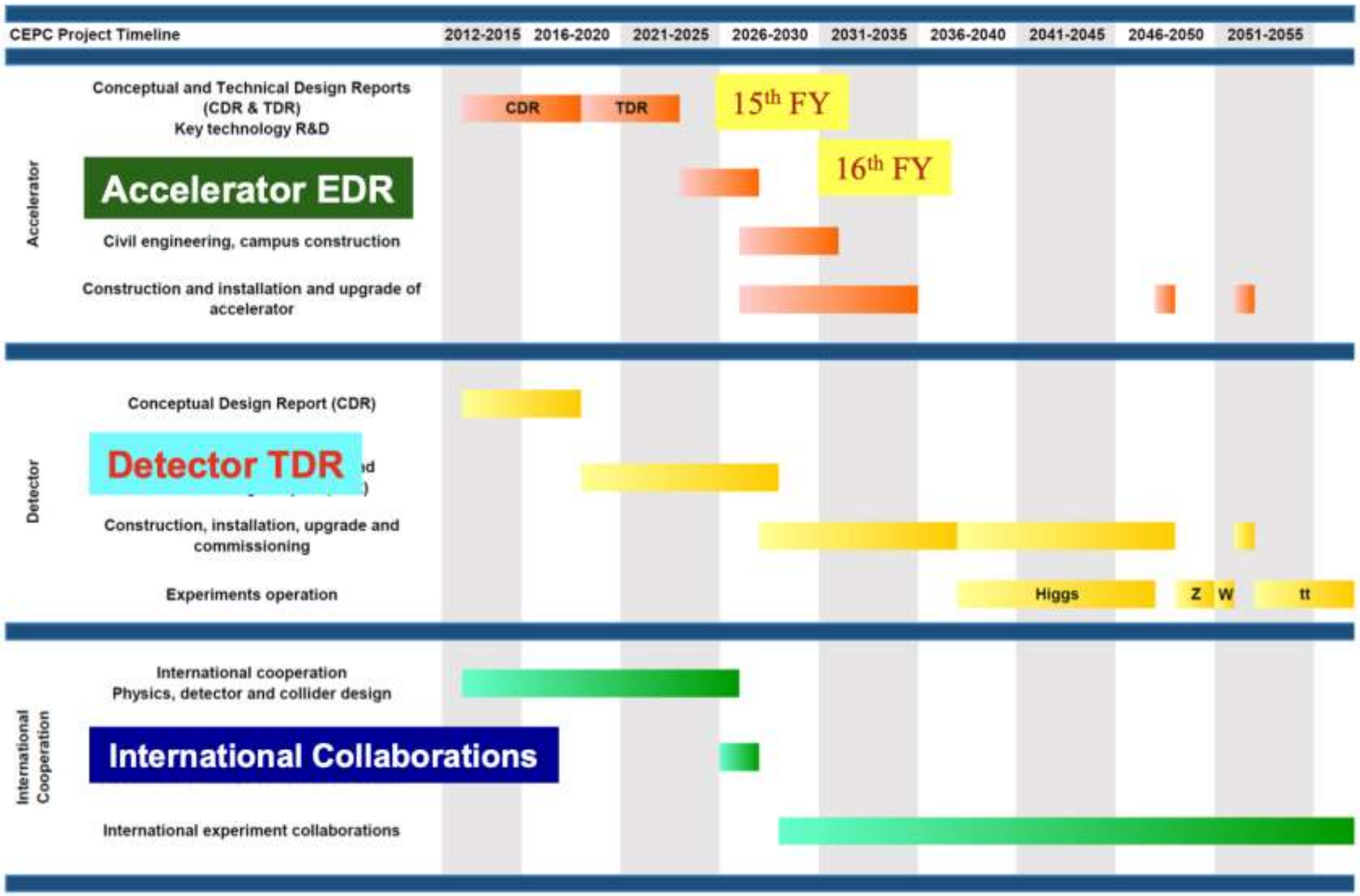




Main parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20.00	T
Physics performance and beam parameters		
Initial luminosity per IP	4.3E+34	$cm^{-2}s^{-1}$
Beta function at initial collision	0.5	m

CEPC Planning and Schedule

TDR (2023), EDR(2027), start of construction (~2027)

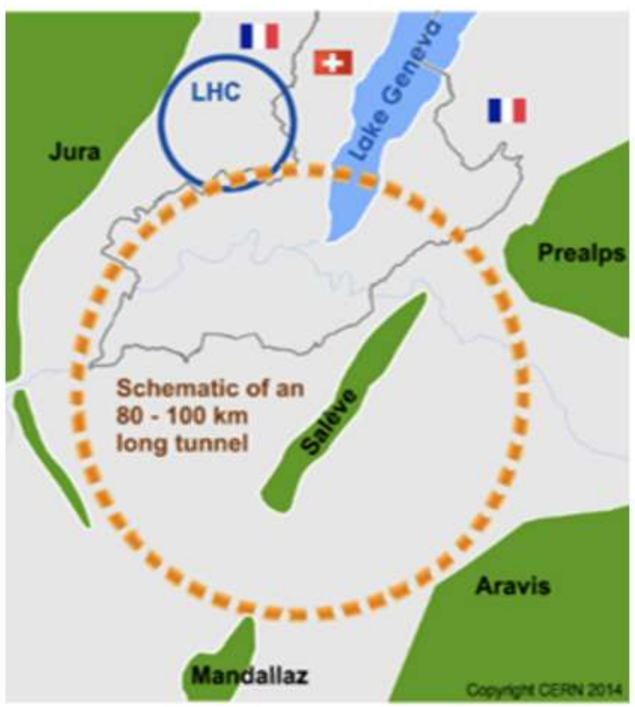


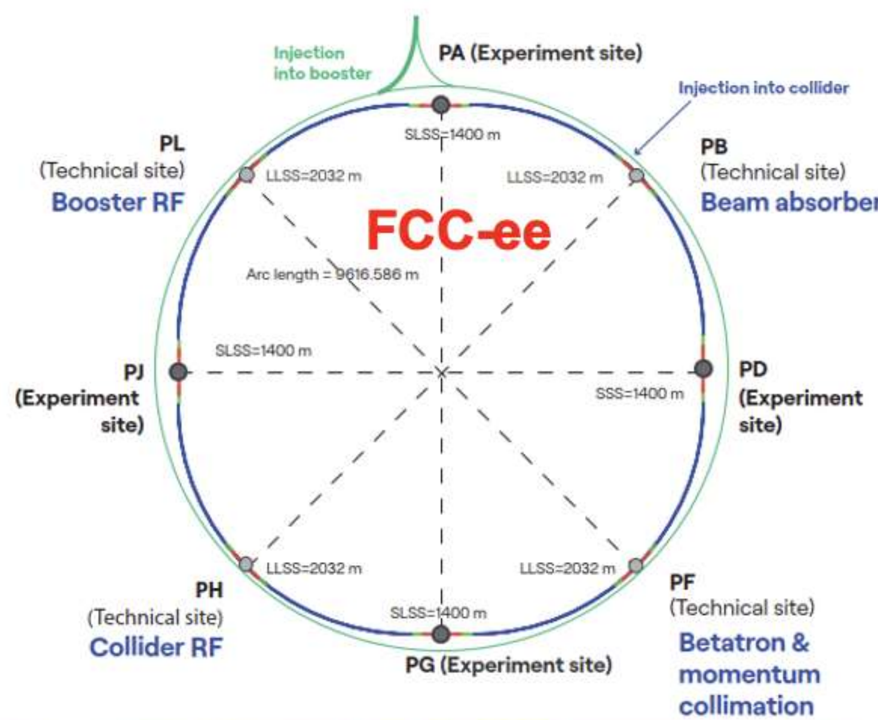
- CEPC plans to submit the proposal to the central government(NDRC) within the "15th five year plan"
- For this purpose, CAS organized studies and reviews
- CEPC was ranked by CAS as the No. 1 for HEP & NP, and No.2 for Basic Science
- We are waiting for the 2nd review by CAS later this year
- Waiting for the "call for proposals" by NDRC by the end of this year

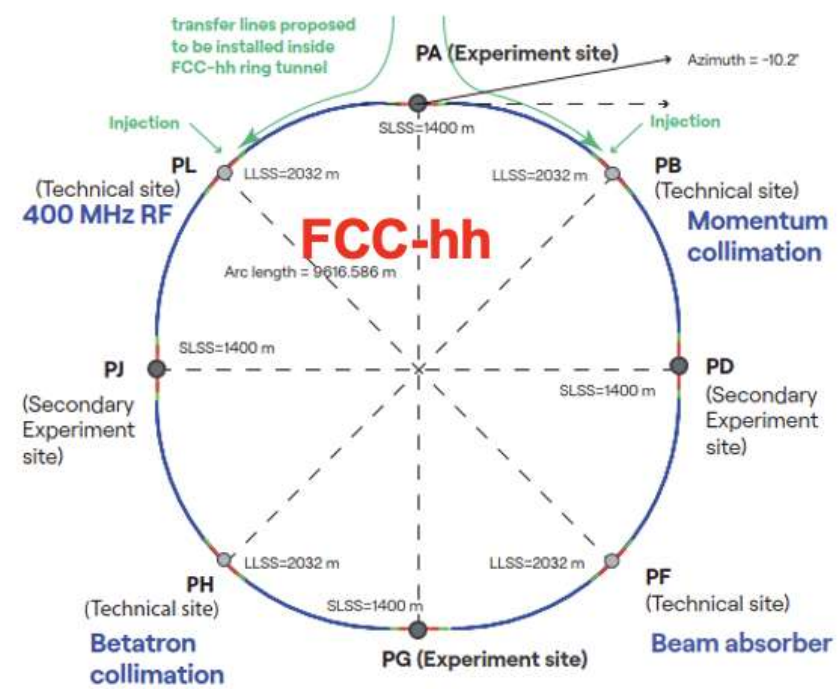
NDRC: National Development and Reform commission

FCC integrated program – scope

- stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within few years of the end of HL-LHC exploitation





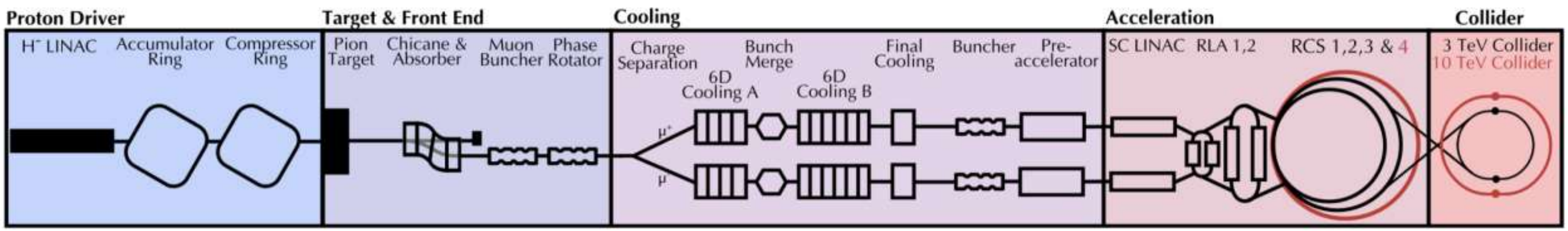


2020 - 2045 | 2046 - 2065 | 2070 - 2100

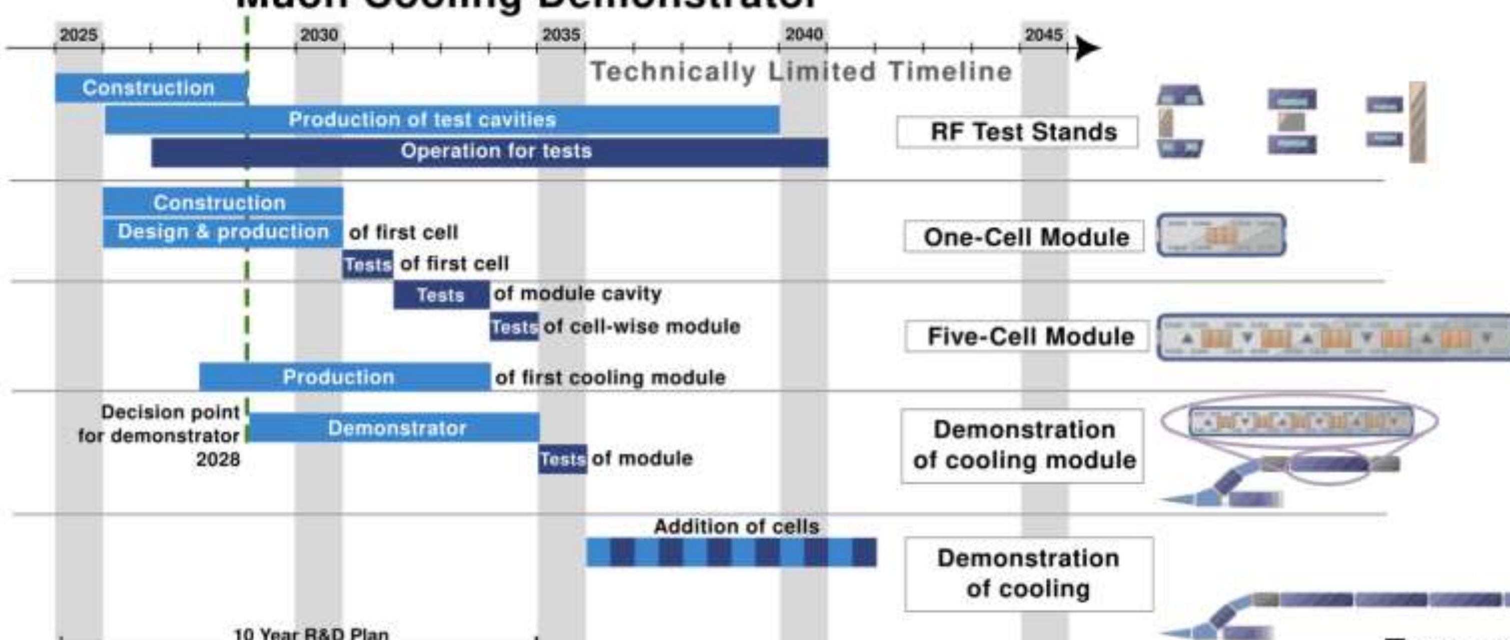
Muon Collider Concept

D. Schulte, Muon Collider, ESPPU Open Symposium, Venice, June 2025

The main challenge is the short muon lifetime $\tau = \gamma \times 2.2\ \mu s$

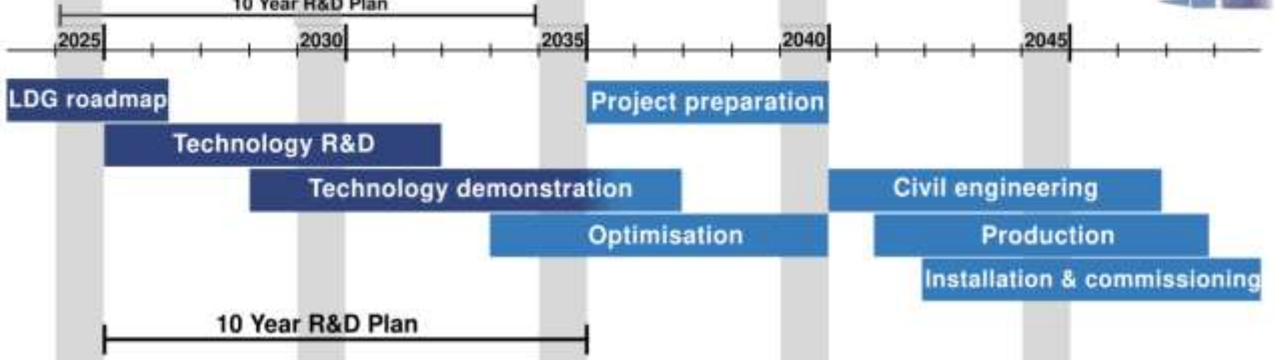


Muon Cooling Demonstrator



Launch RF test stands and first module (700 MHz test stand) right away

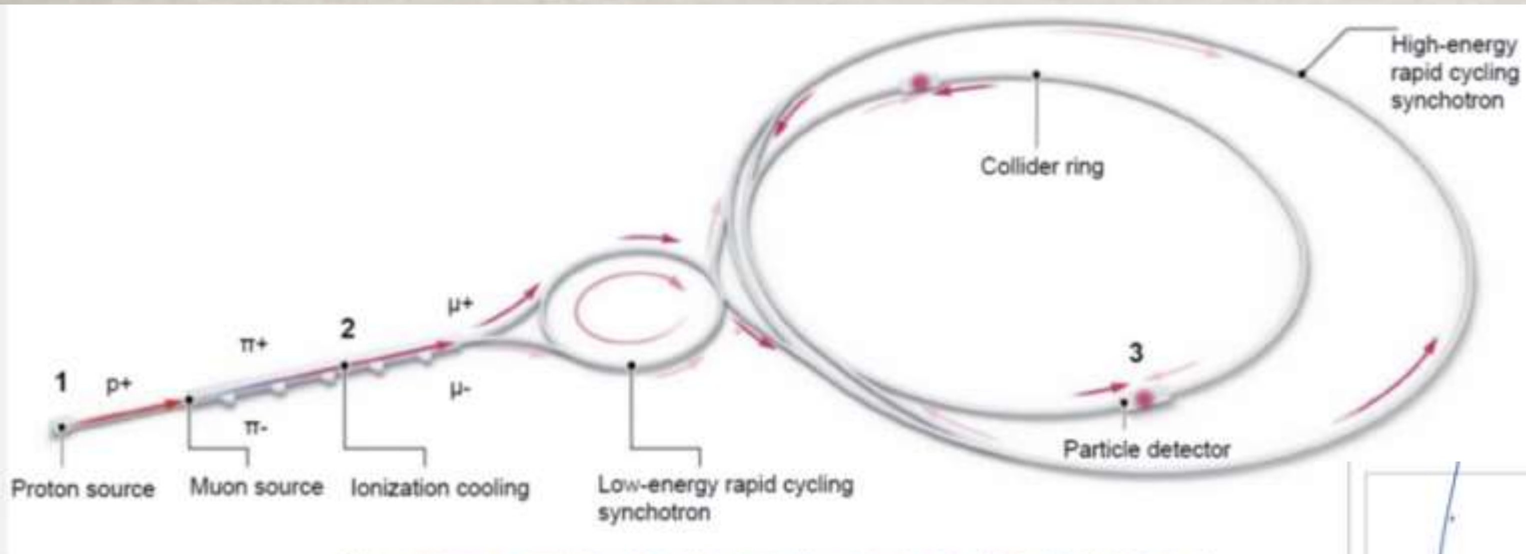
Important decision in 2028 on sharing of effort and demonstrator location

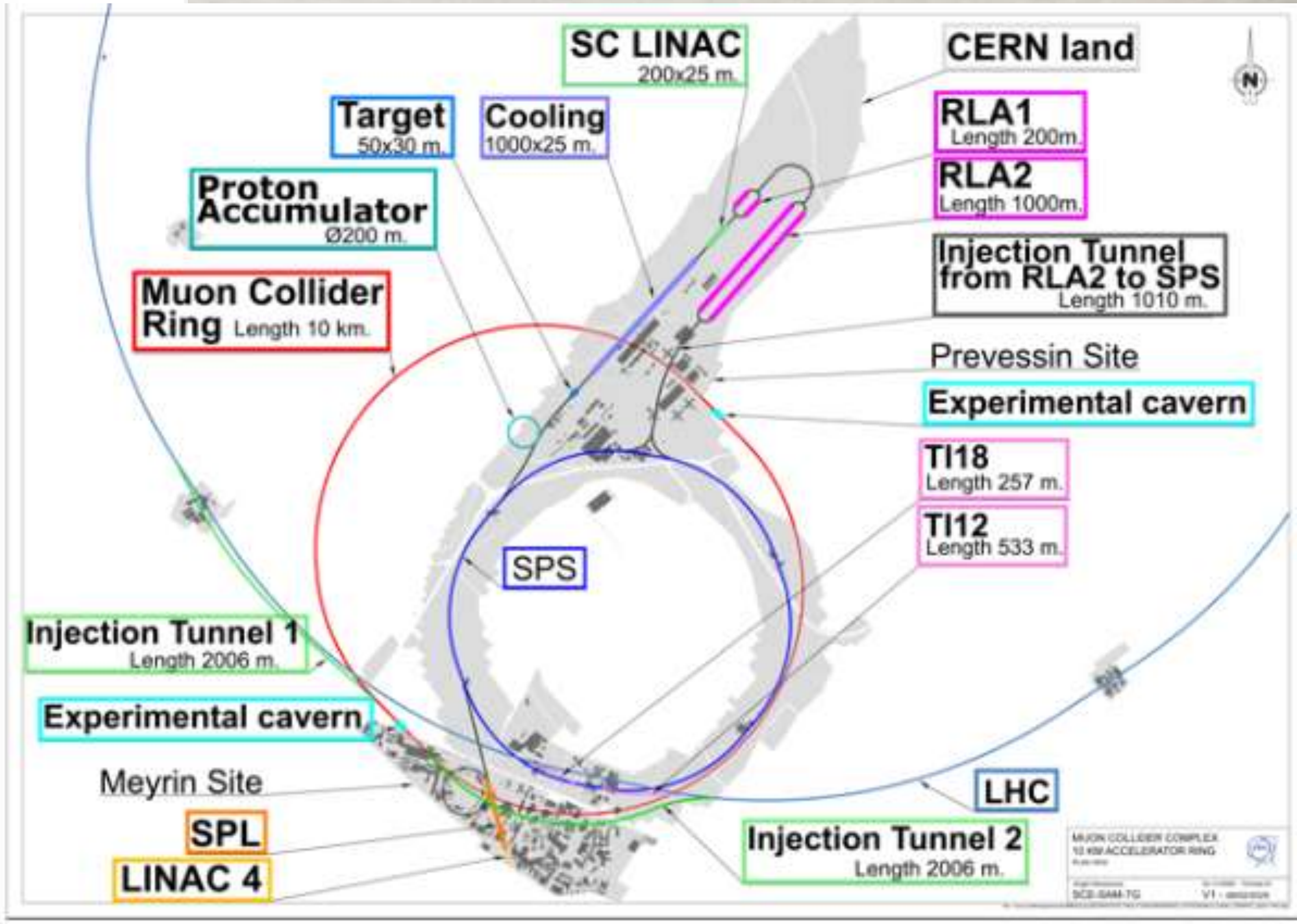


Two promising demonstrator site studies at at CERN

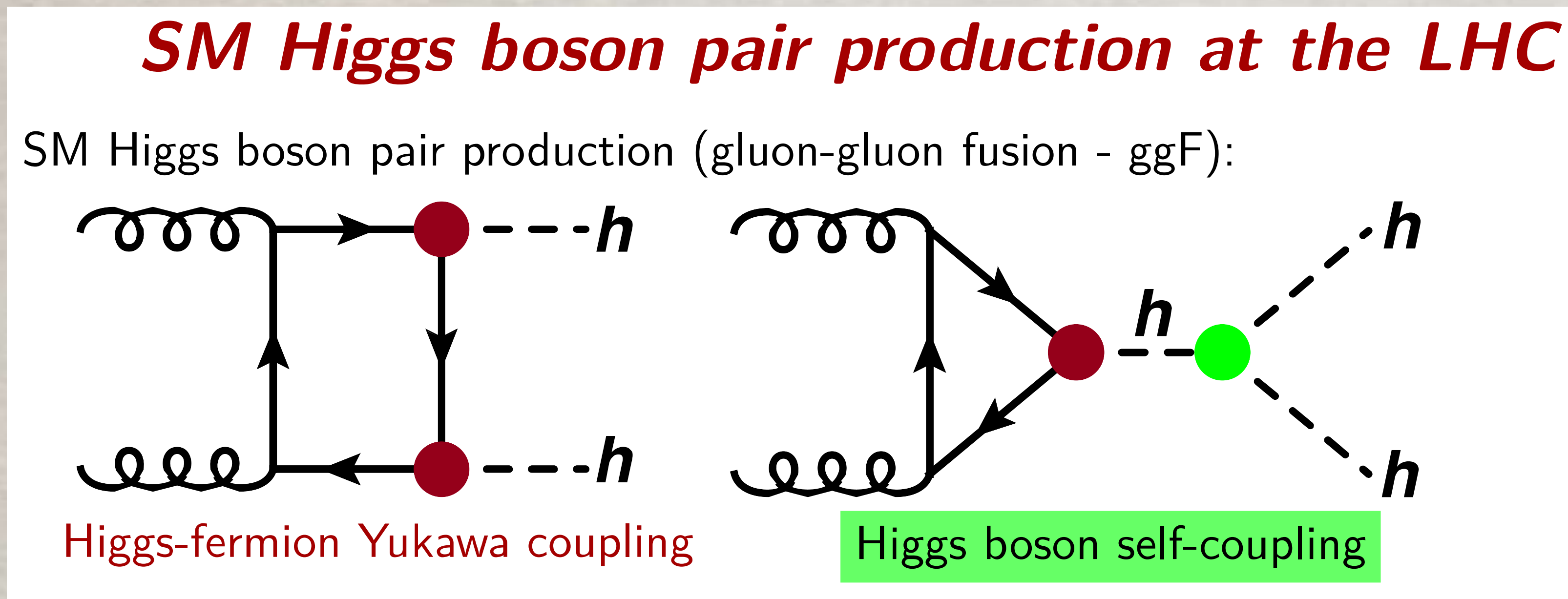
Budget for site Fermilab study approved

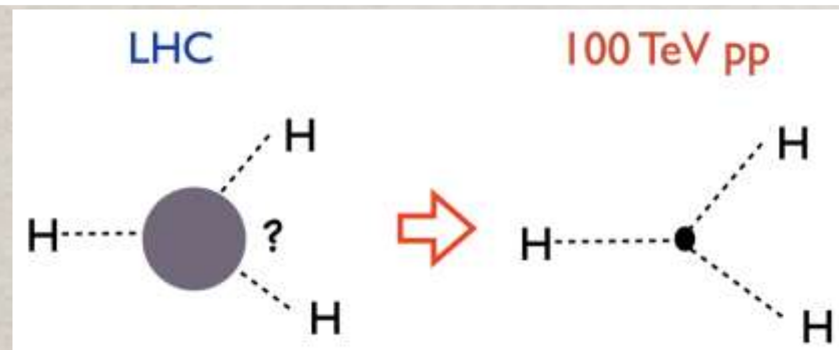
μC Sites at Fermilab and CERN

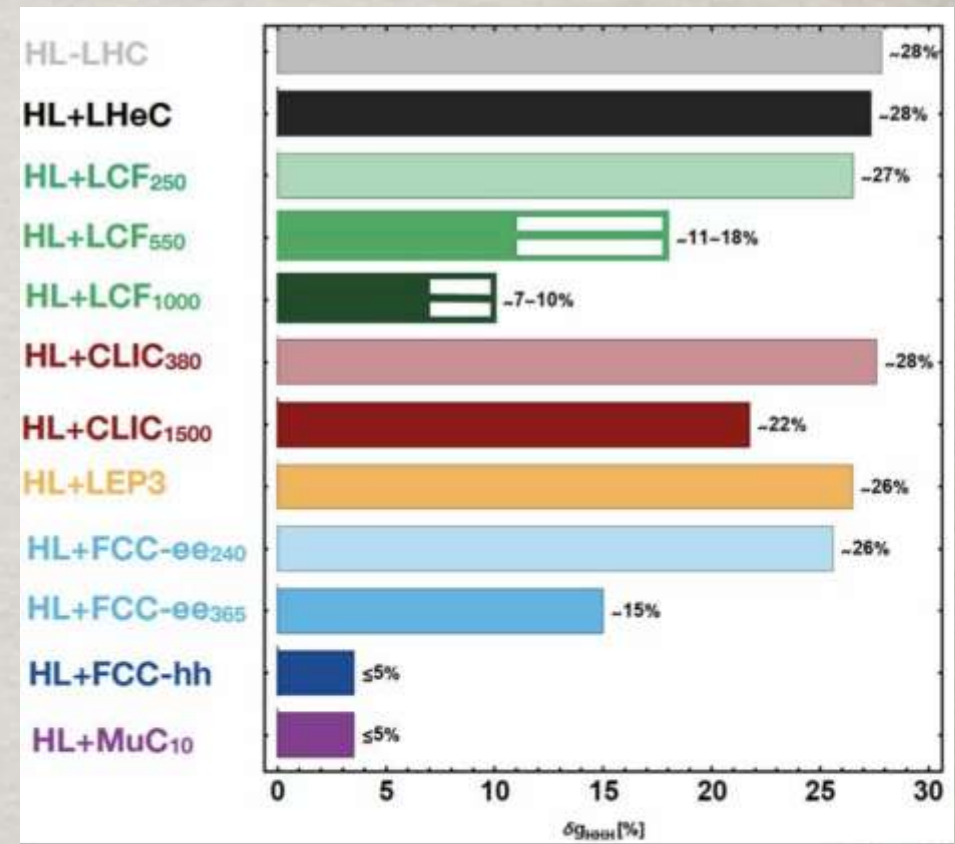




Higgs pair production & triple coupling:







→ hhh dictate EW phase transition & impact on early universe cosmology!

Conclusive test for SM EWPT!

Open a new energy threshold: ~ 10 TeV pCM energies

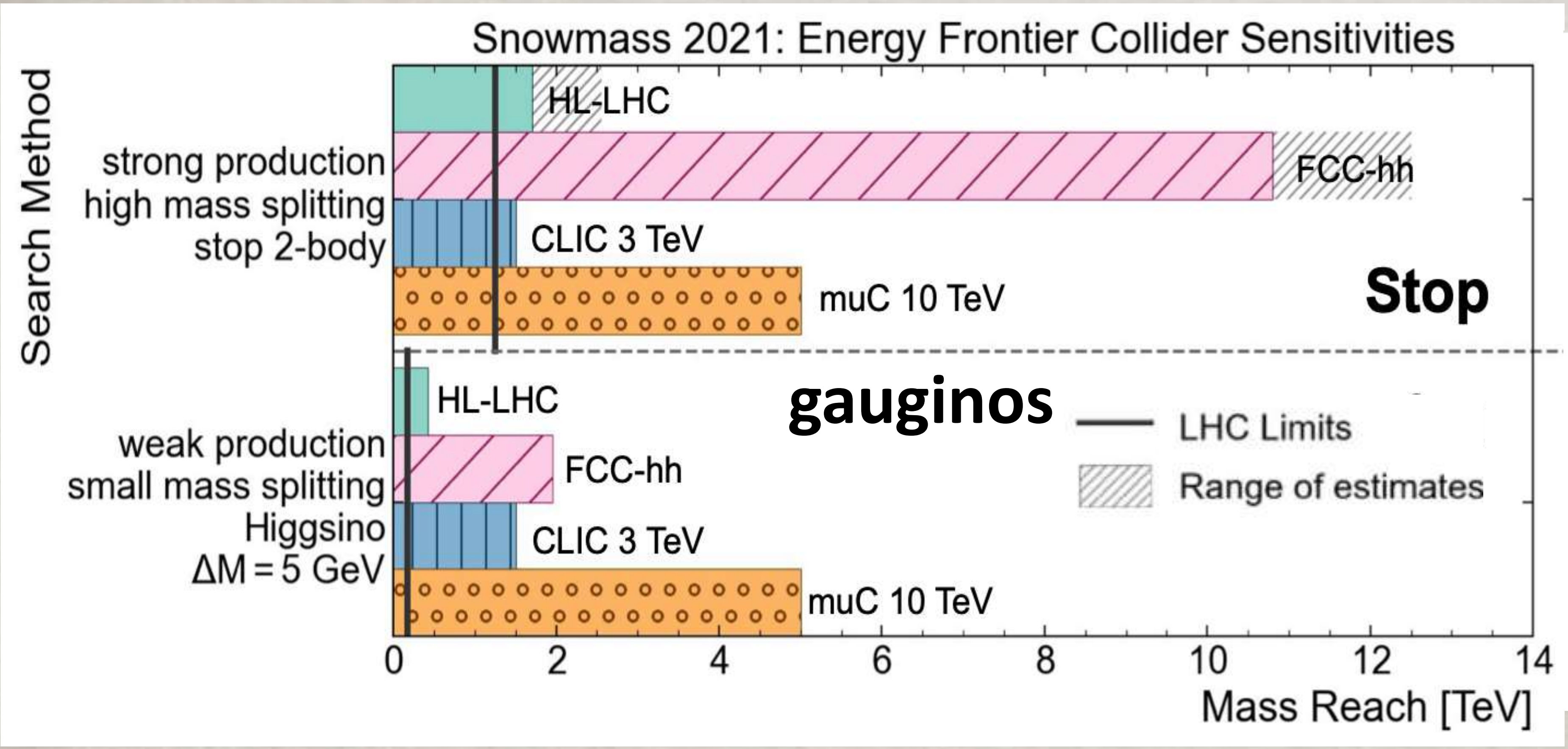
- Direct new heavy state production:
  Higgs H^0A^0, H^+H^-; SUSY particles; quarks / leptons reaching $M > E_{cm}/2$.
- Indirect probe of contact interaction / composite scale.

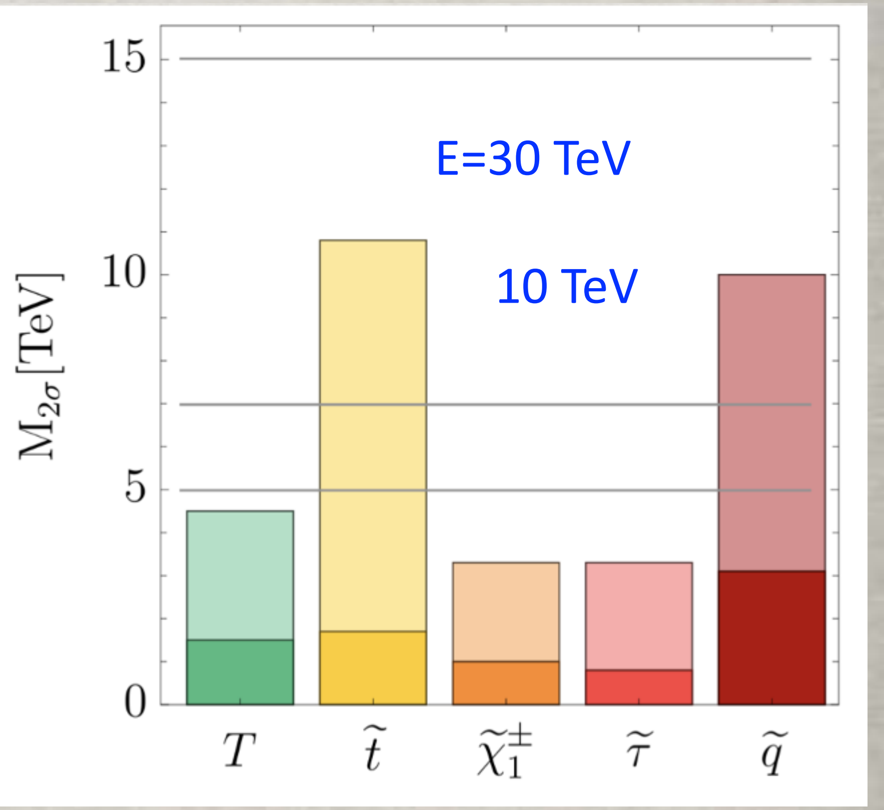
(Strongest) Motivation for Future Colliders

~ 10 TeV pCM energies

Pushing the "Naturalness" limit:

The searches for top quark partners
& gluinos, gauginos, & heavy Higgses …

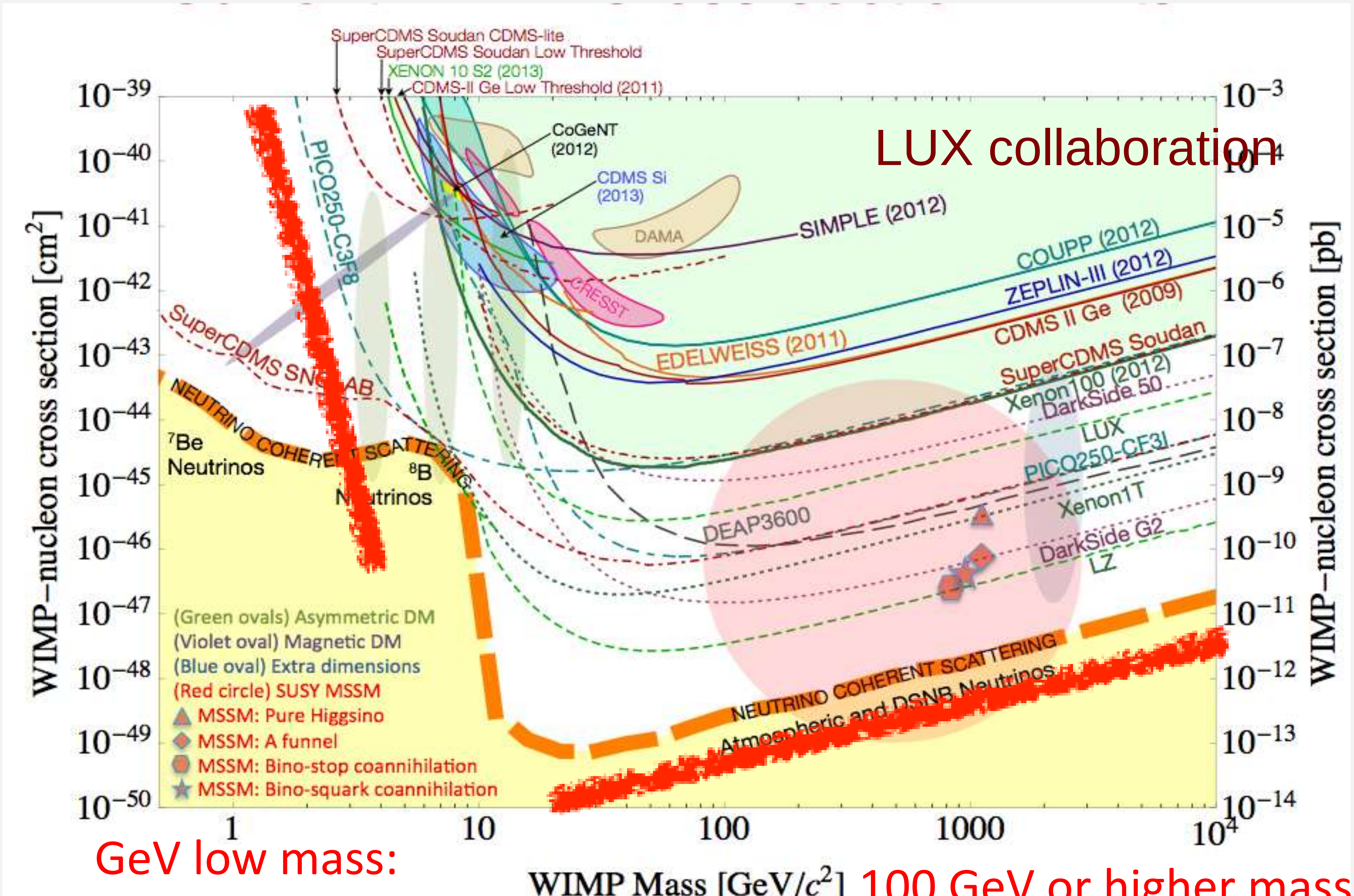




→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1\ \text{TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

Complementarity of DM Direct detection & Colliders



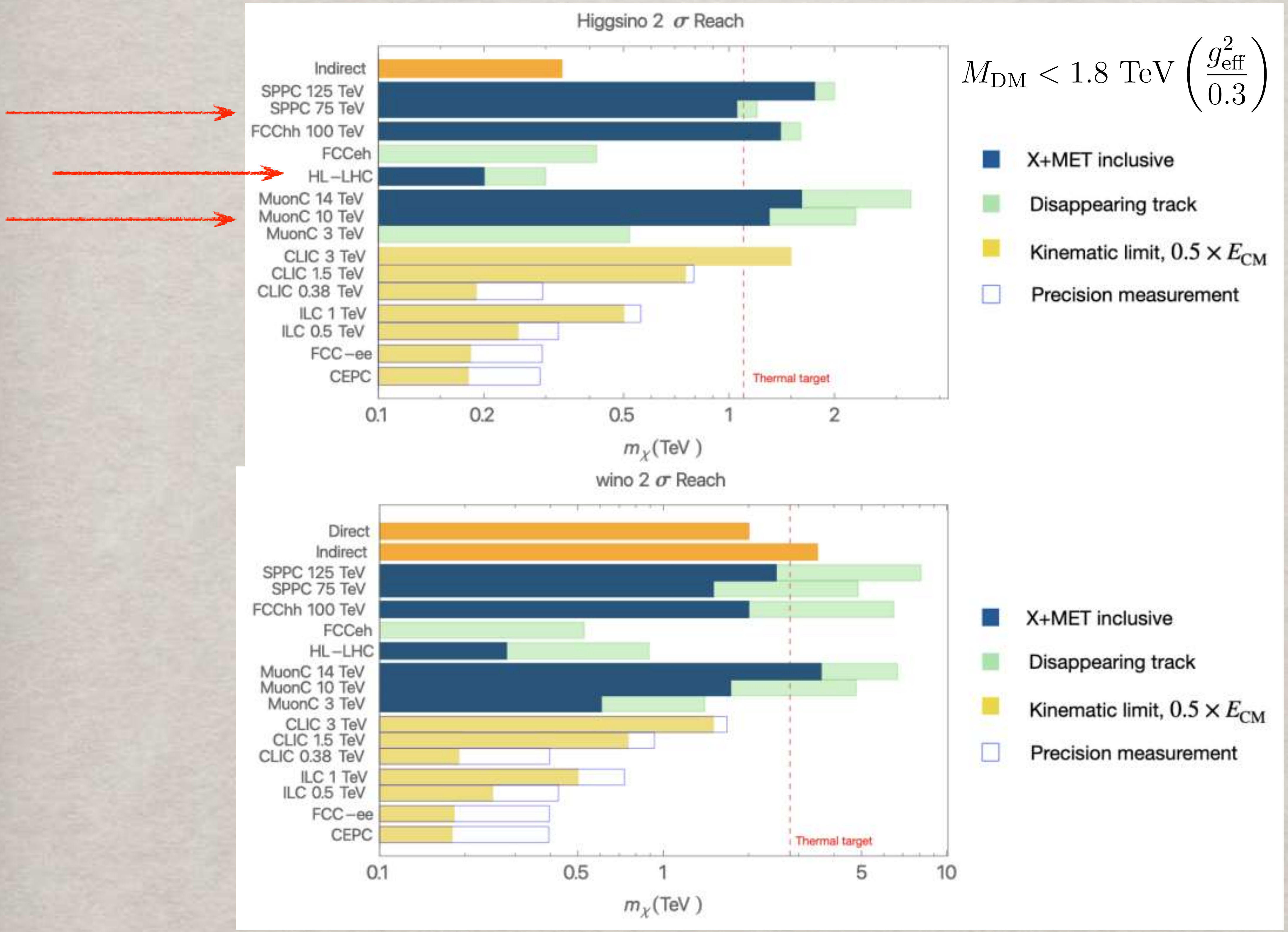
LUX collaboration

GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD + ID + HE Collider

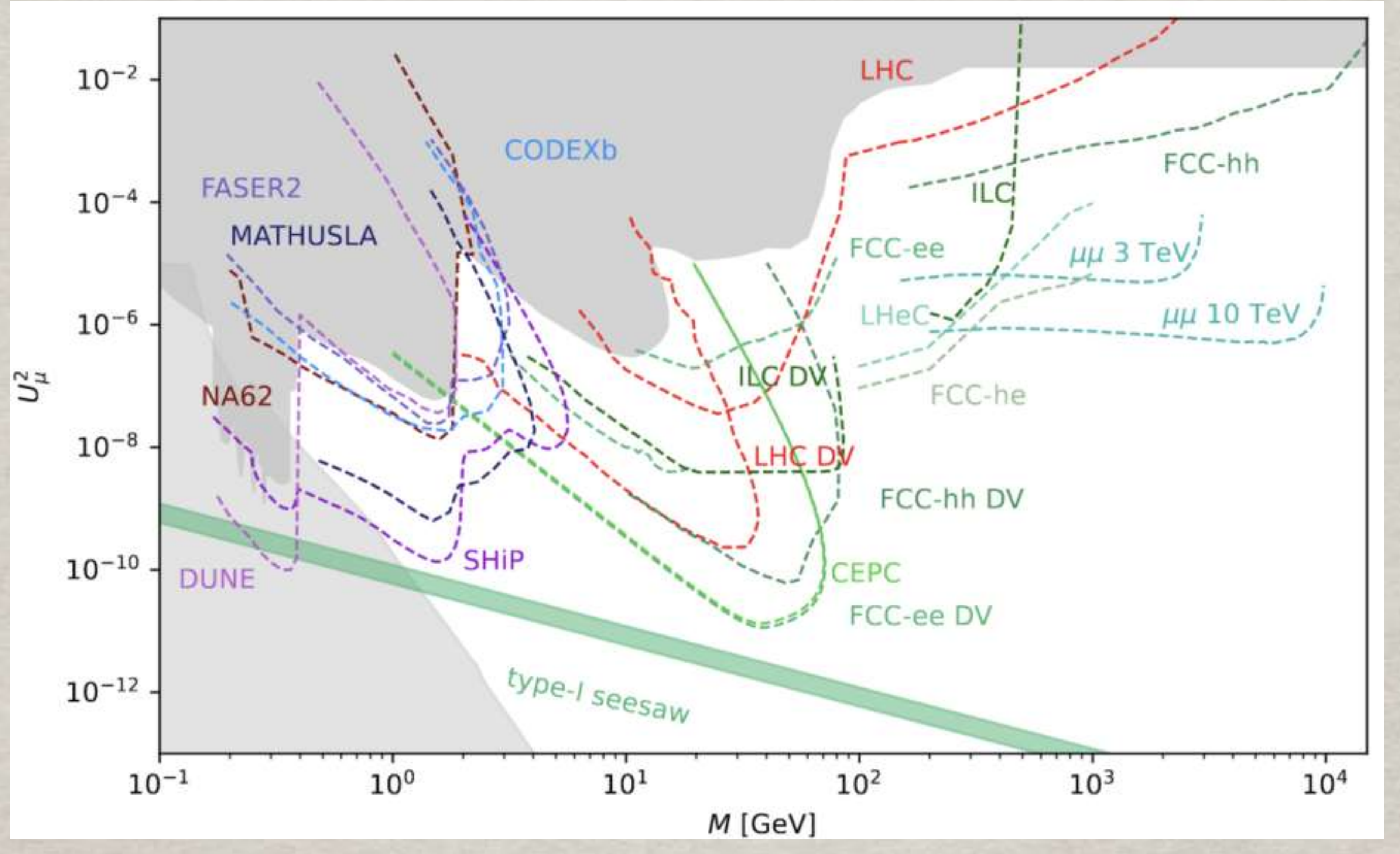
WIMP Dark Matter coverage

Covering the thermal target



TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

Physics example 2: Heavy Neutral Lepton (HNL, N_R, sterile neutrino)



Complementary among a variety of searches.

Questions
that we must find answers

- The nature of the neutrino mass
- The nature of the Dark Matter
- The origin of matter – anti-matter imbalance
- BSM CP violation
- … …

Puzzles

that we may or may not find a solution

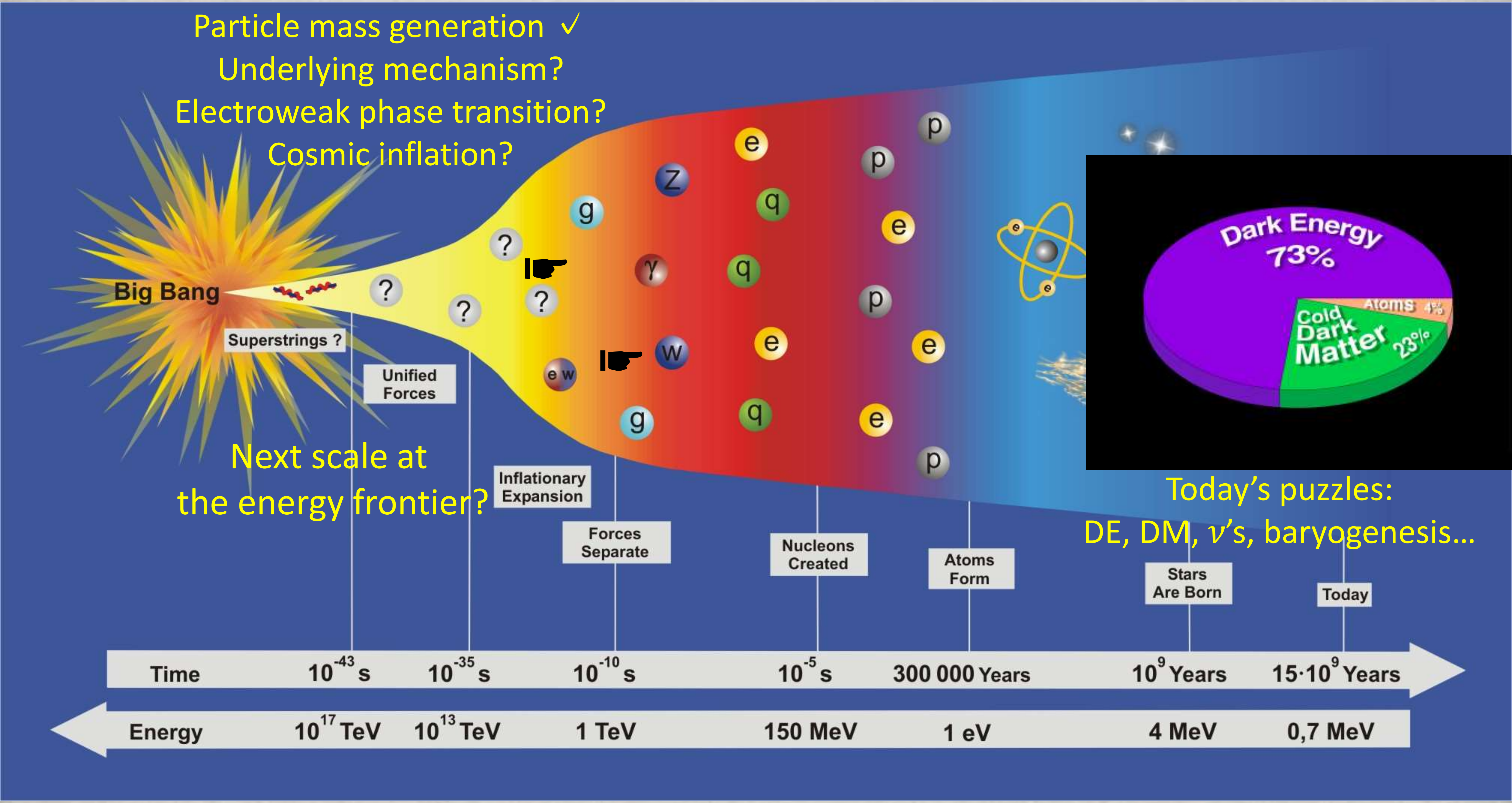
- Nature of the EWSR?
- Flavors: “minimal flavor violation”?
- Mass hierarchy: “Naturalness”?
- New EW dynamics: “Composite”?
- Extended symmetry: SUSY?
- Unified forces: GUTs?
- Quantum gravity? … …

The future of HEP is bright!

A future collider will lead!

Thank You!

A Grand Picture:



The future of HEP is bright!
Exciting journey ahead!