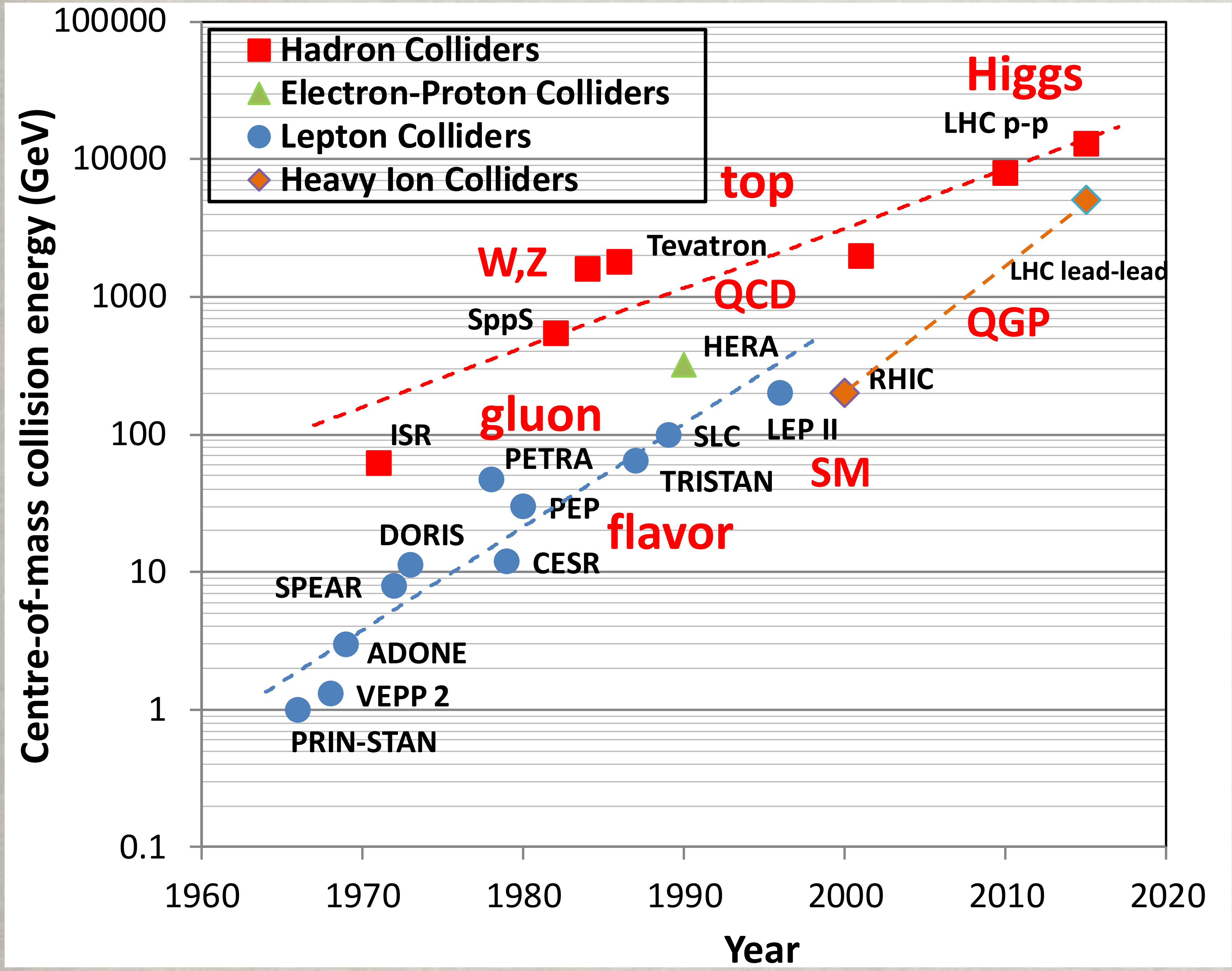
Aspects of
Future Colliders

Tao Han
University of Pittsburgh

PPC 2022 @ Washington University
June 10, 2022


- HL – LHC Leads the Way
- Future Collider Agora & Physics Reach
- Fermilab Site Fillers

Colliders:
Primary Tools at the Energy Frontier

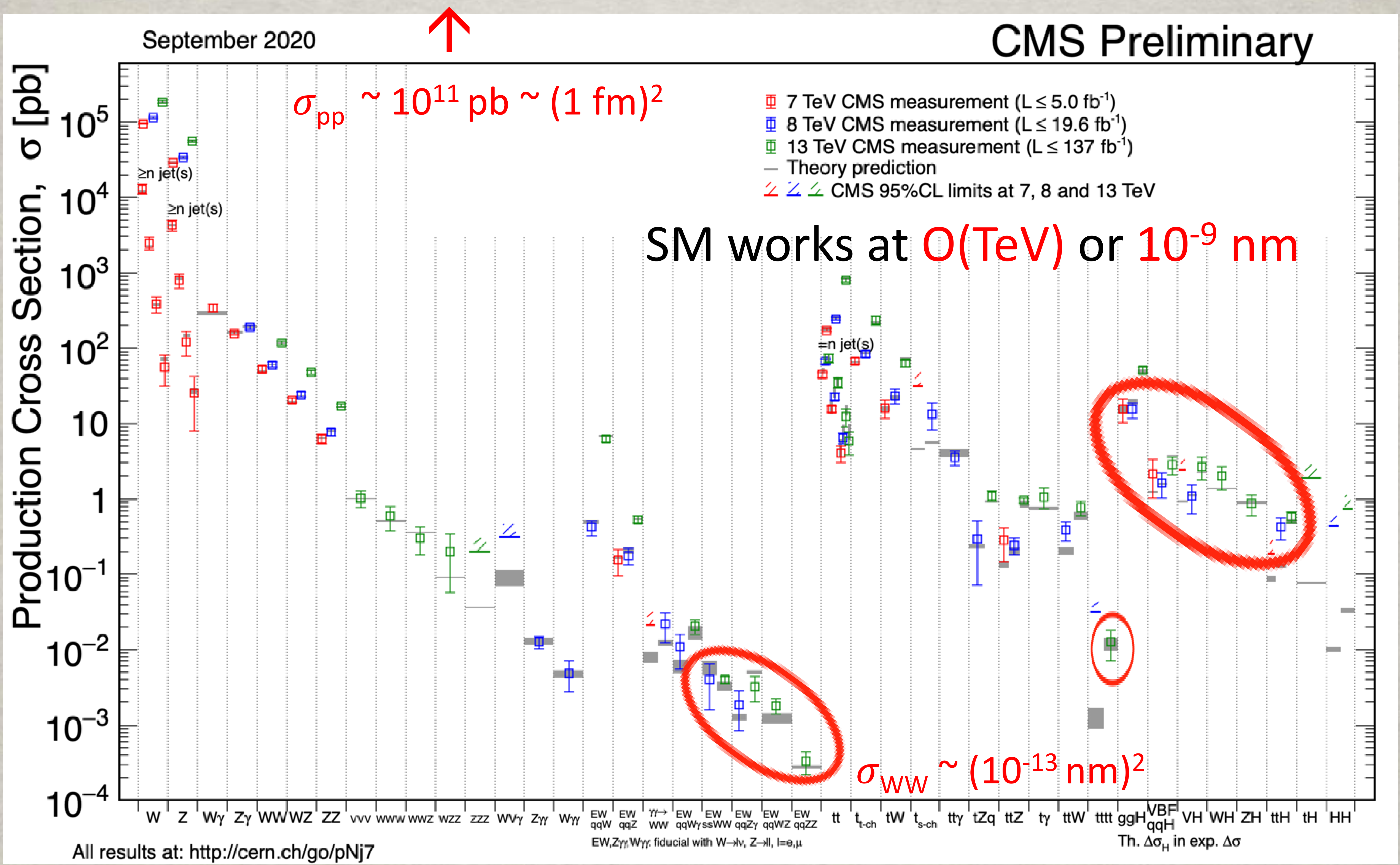


Frank Zimmermann, Lepton-Photon Conf. 2022

- EWSB: Higgs & extension
- Particle DM: WIMP & beyond
- Neutrino masses: Majorana & CPv
- Flavor & CPv Scale & symmetry
- BSM …

→ Complementarity to Astro-physics & Cosmology

LHC Rocks!



LHC: The energy frontier & precision frontier!

High-Luminosity LHC

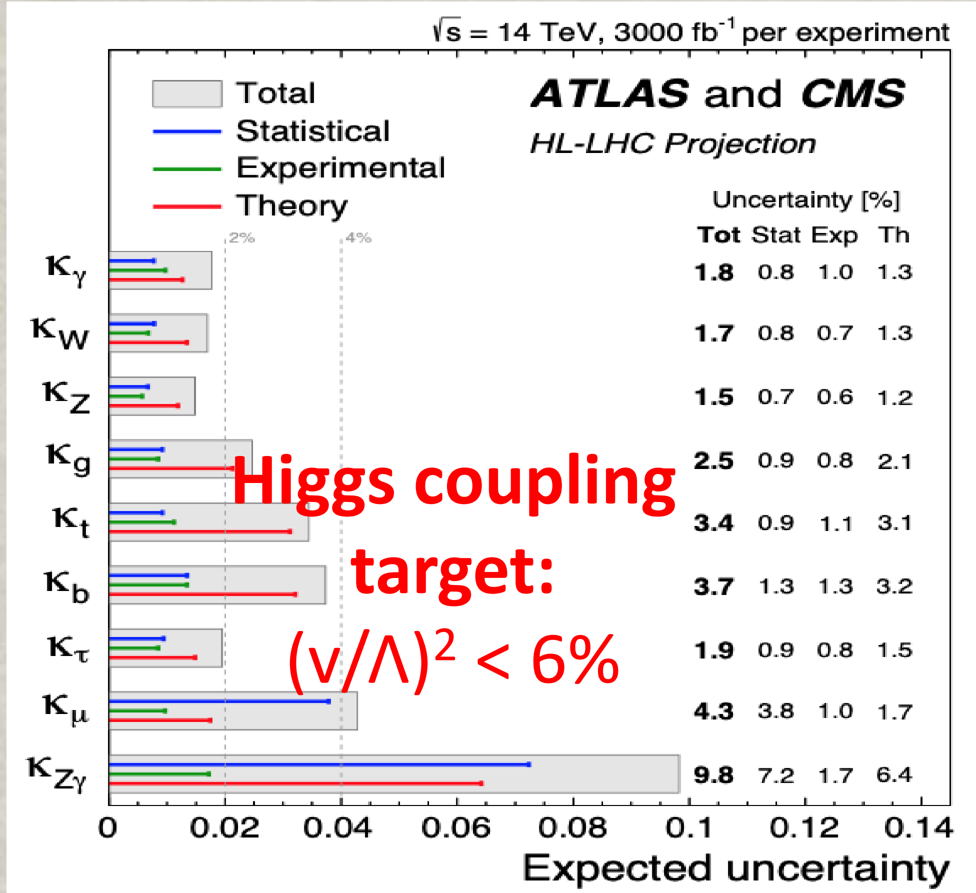
HL-LHC

- Fully approved in 2016, technology available, construction well underway!

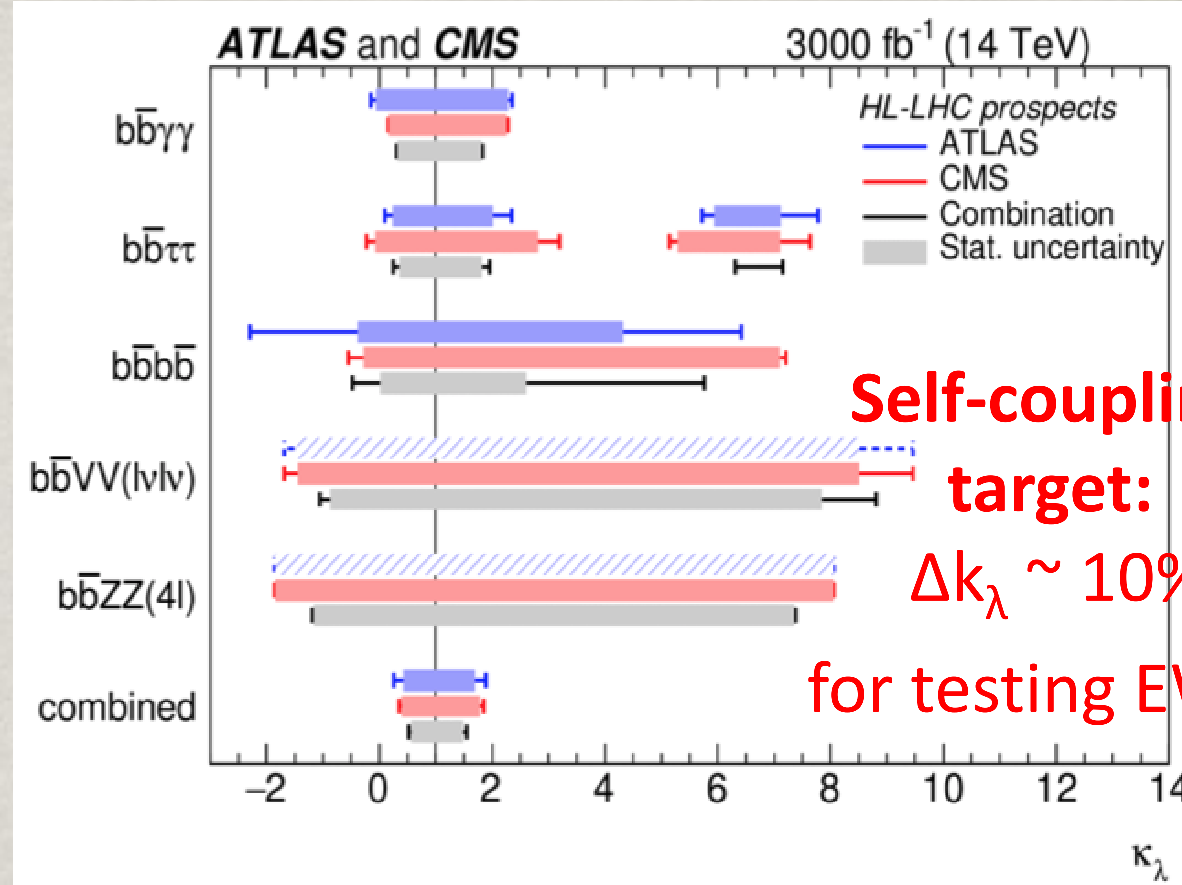
- Run 3 started: beams in April 22, 2022
- Stable beam collisions detected by ATLAS/CMS

--- more excitement to come!

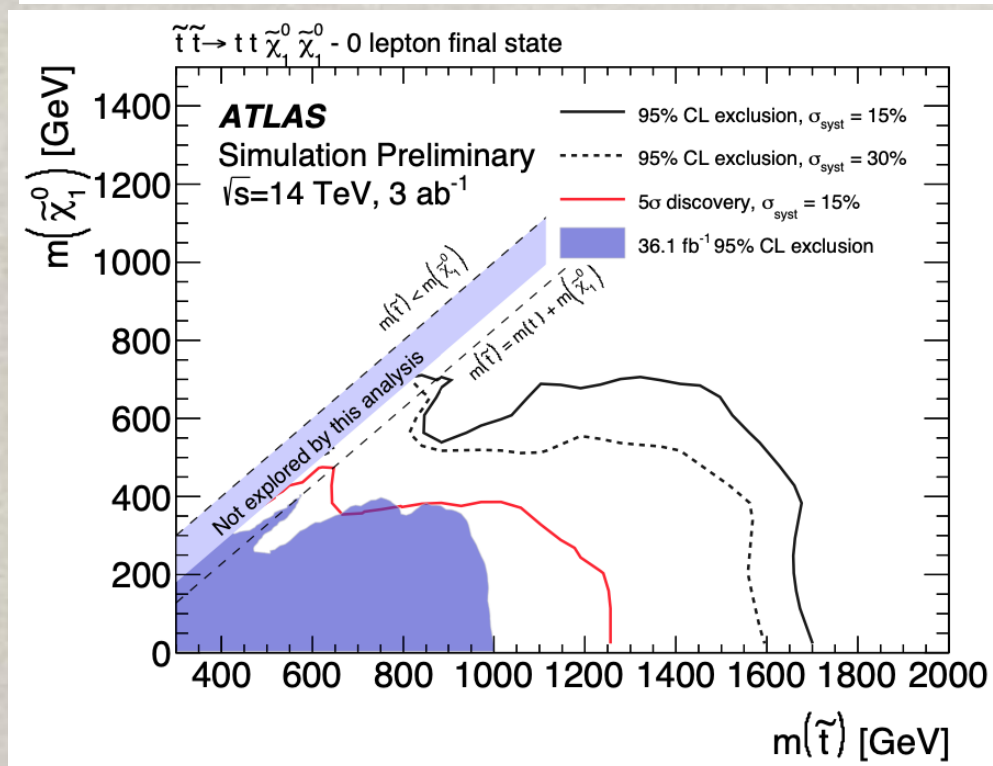
Sample physics reach projection @ HL-LHC

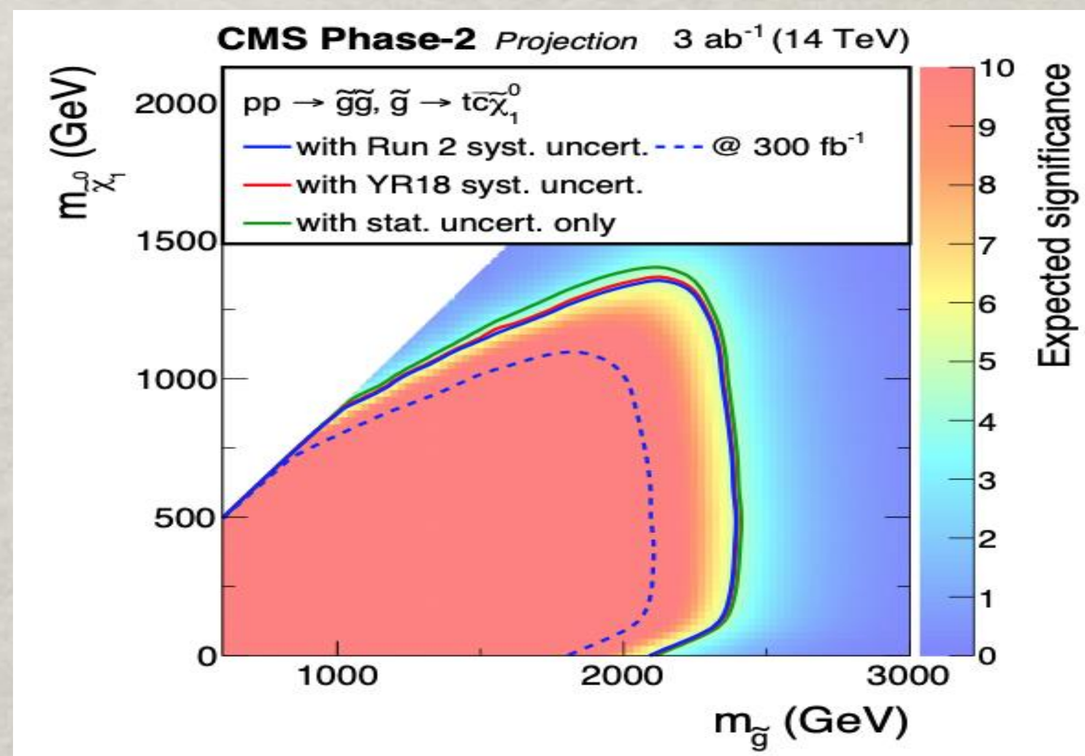


Higgs coupling target: $(v/\Lambda)^2 < 6\%$



Self-coupling target: $\Delta k_\lambda \sim 10\%$ for testing EWPT





and plus much more …

HL-LHC: arXiv:1812.07831;
Christian Ohm, Lepton-Photon Conf. 2022

Beyond the LHC:
Challenges for accelerator technology

- Reduce synchrotron radiation
- Strong bending magnetic field
- Increase accelerating gradient
- Rare beam particle production e^+, muon …
- Costs, sustainability / power consumption

Snowmass 2021

DPF Community Planning Exercise
https://snowmass21.org

- Accelerator Frontier → Implementation Task Force
- Energy Frontier/Neutrino Frontier → Physics goals

PLEASE join the community effort: July 17-26

http://seattlesnowmass2021.net/registration

Early-bird deadline next Monday June 13th(midnight)!

Future Colliders Agora

8 Higgs/EW factories:

Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

17 HE Colliders:

Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV

Future Colliders under Discussions*

Higgs factories

High energy frontier

Snowmass 2021 Energy Frontier Collider Study Scenarios

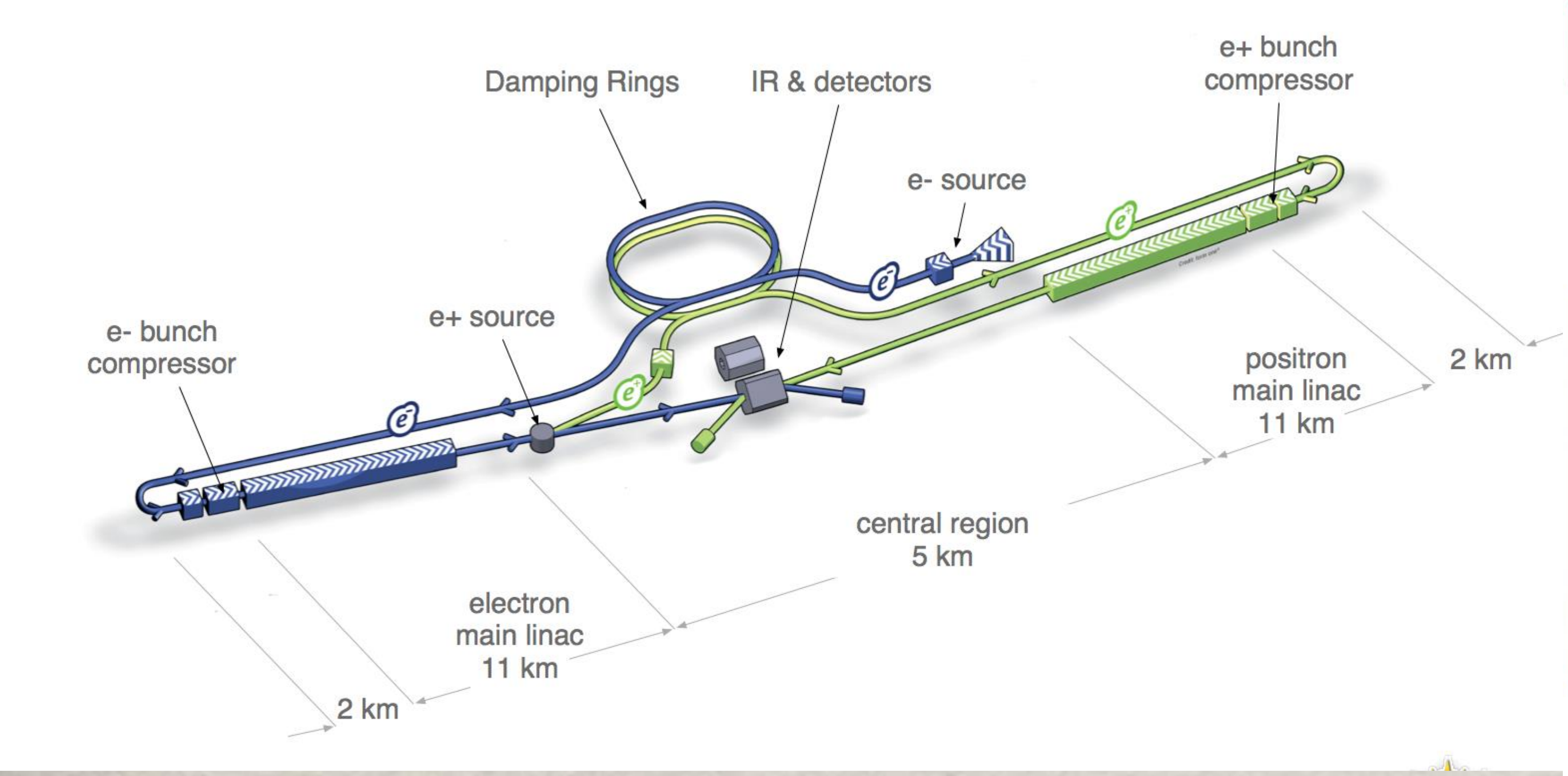
Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
		1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		2 M_{top}		1.5
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

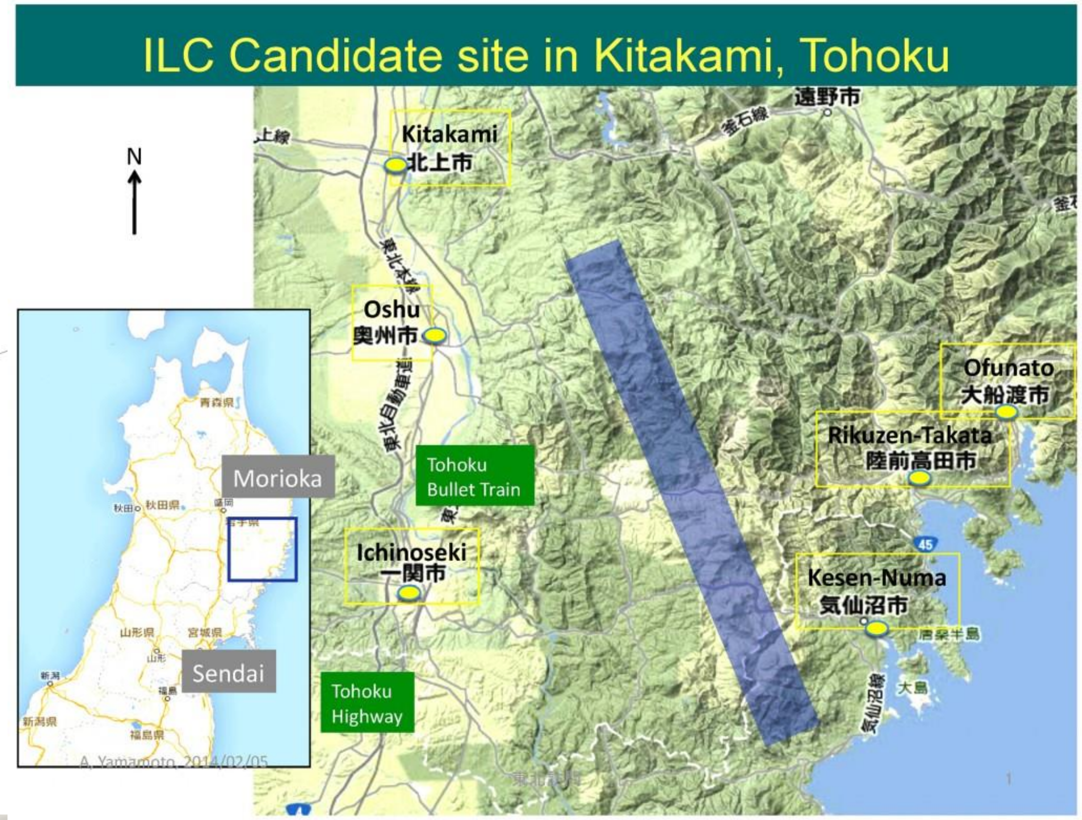
* Snowmass Energy Frontier: https://snowmass21.org

ILC (International Linear Collider) as a Higgs Factory & beyond

Under serious consideration in Japan; Pre-lab proposed

https://arxiv.org/abs/1901.09829, 2106.00602



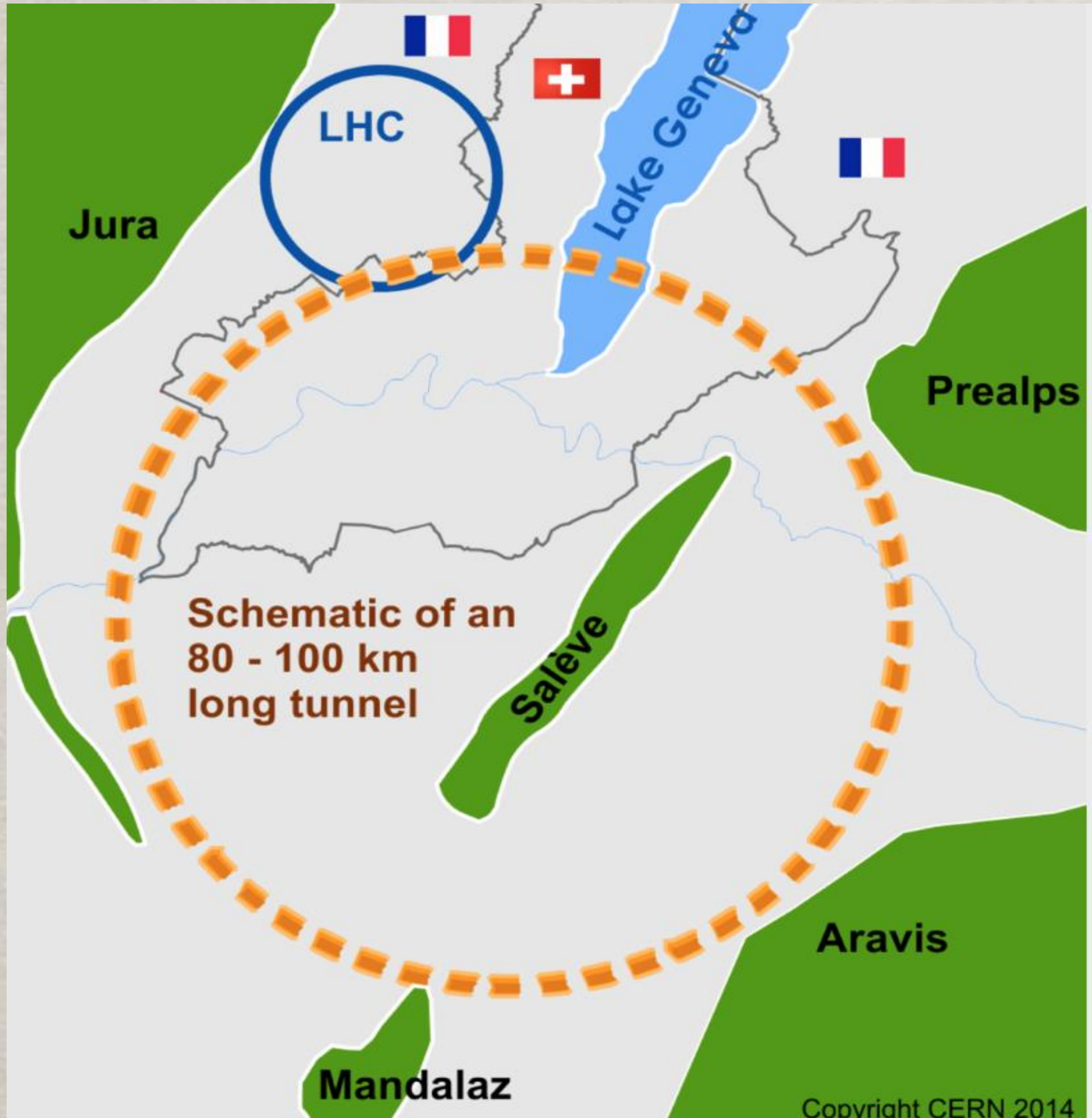


Ecm = 250 GeV / 2 ab^{-1} /yr: a Higgs factory

= 500 GeV / 4 ab^{-1} /yr: a top-quark factory

= 1000 GeV / 8 ab^{-1} /yr: new particle threshold

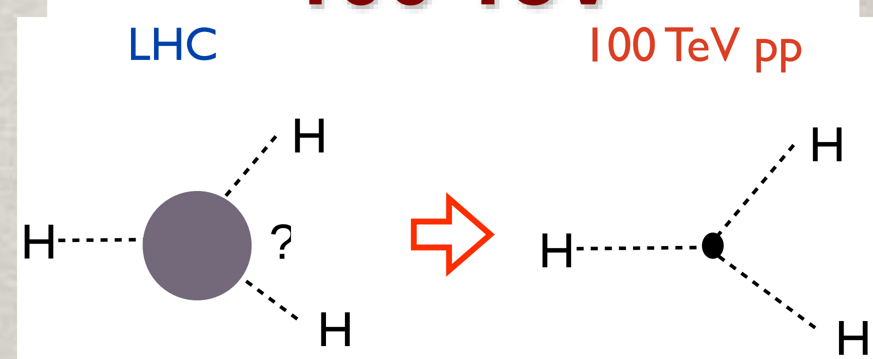
Future Circular Collider (FCC): CERN
CEPC/SppC: China



FCC-ee
80/100 km
90 - 400 GeV

10^{12} Z; 10^{6} Higgs bosons;
10^{6} top quark pairs

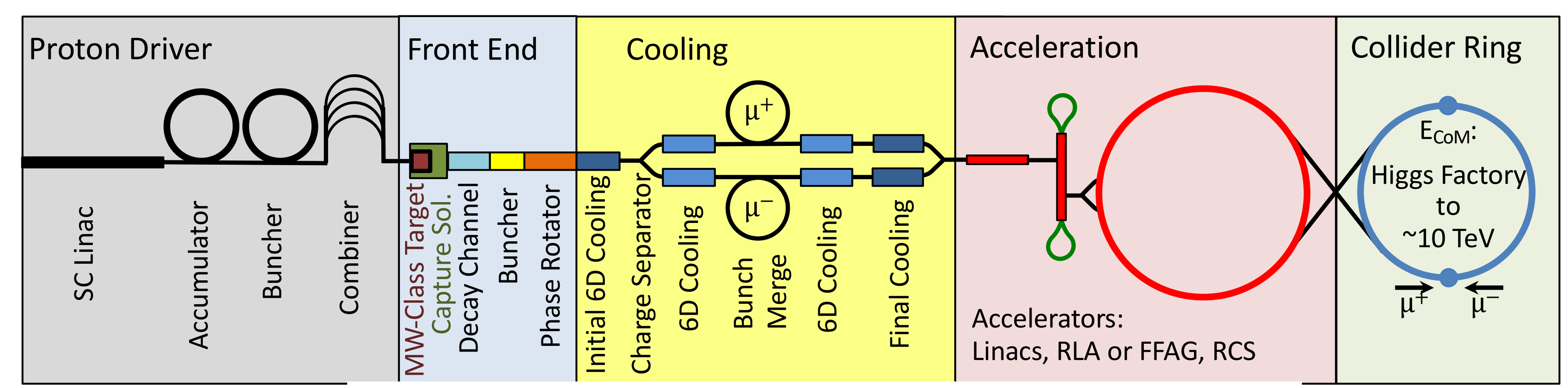
FCC-hh
80 /100 km, 16/20T
100 TeV



Open new energy frontier!

https://arxiv.org/abs/1607.01831, https://arxiv.org/abs/1606.00947;
Arkani-Hamed, TH, Mangano, LT Wang, Phys. Rept. 1511.06495.

Recent technological breakthroughs:

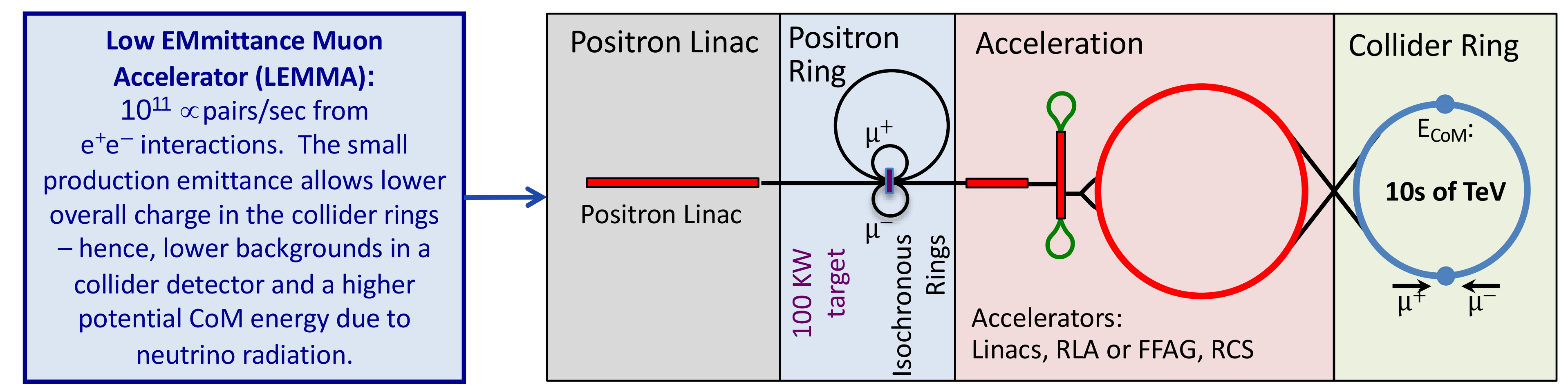


Proton-Driver:

Muon **A**ccelerator **P**rogram
map.fnal.gov

New results on μ cooling by **MICE** collaboration
Nature 508(2020)53

LEMMA: e^+e^- (at rest) → $\mu^+\mu^-$ (at threshold)



Low **EM**ittance **M**uon **A**ccelerator
web.infn.it/LEMMA

J.P. Delahauge et al., arXiv:1901.06150

Muon Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$
$L \sim 4\ \text{fb}^{-1}/\text{yr}$
$\Delta E_{cm} \sim 5$ MeV

(Current Snowmass 2021 point)

Parameter	Units	Higgs
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.008
Beam Energy Spread	%	0.004
Higgs Production/10^7 sec		13'500
Circumference	km	0.3

- Multi-TeV colliders: Lumi-scaling scheme: $\sigma\, L \sim$ const.

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

$1\ \text{ab}^{-1}$ /yr

The representative choices:

E_{cm} = 3, 6, 10, 14, 30 TeV; L = 1, 4, 10, 20, 90 ab^{-1}

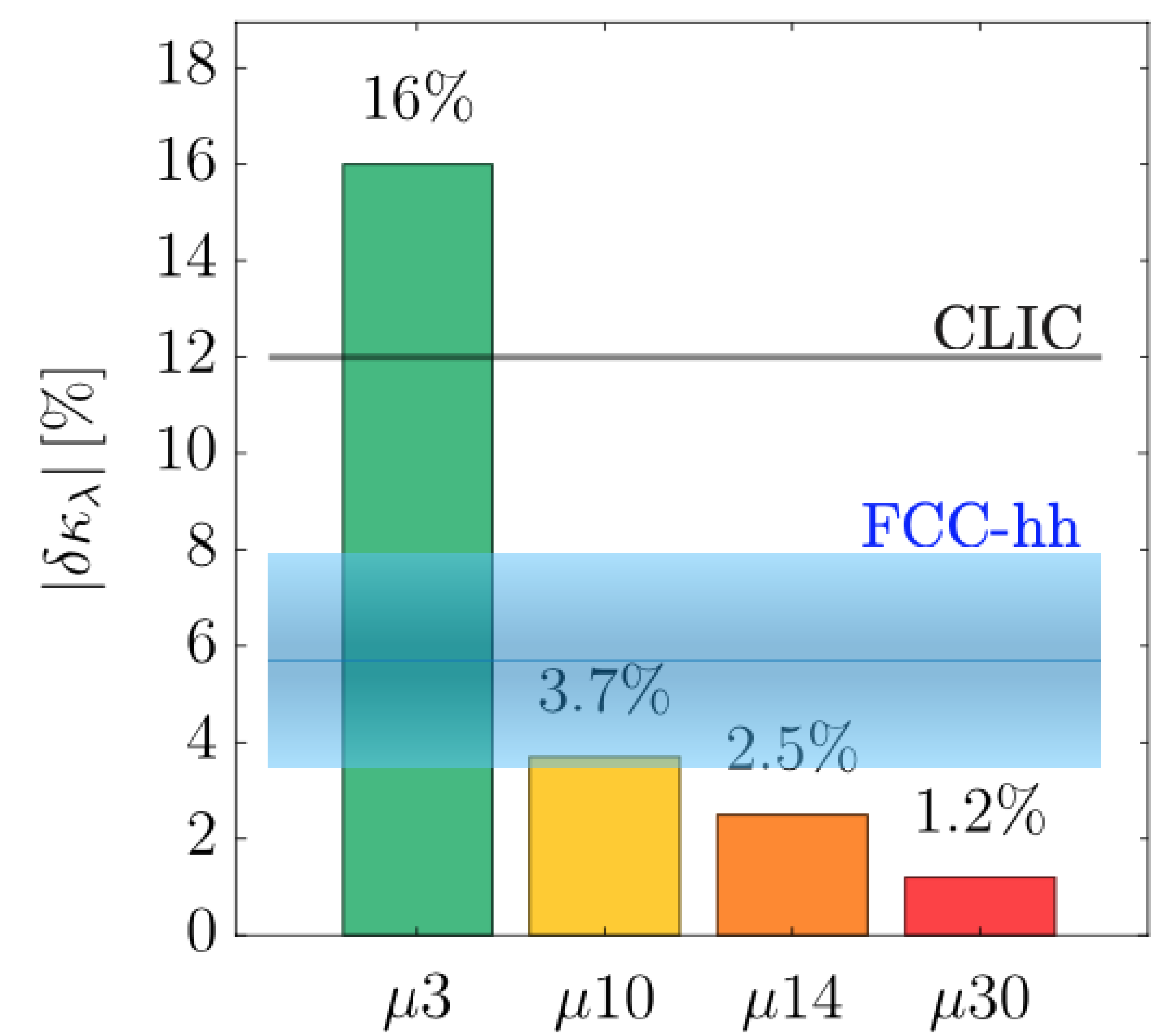
International Muon Collider Collaboration
https://muoncollider.web.cern.ch

European Strategy, arXiv:1910.11775; arXiv:1901.06150; arXiv:2007.15684.
TH, Ma, Xie, arXiv:2007.14300, The Muon Smasher's Guide, arxiv:2103.14043.

Physics Reach (very selective)
Precision Higgs physics

	HL-LHC	muC: 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
$\kappa_{Z\gamma}$	10	7.2	7.1
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
κ_t^*	3.3	3.1	3.1

* No input used for μ collider

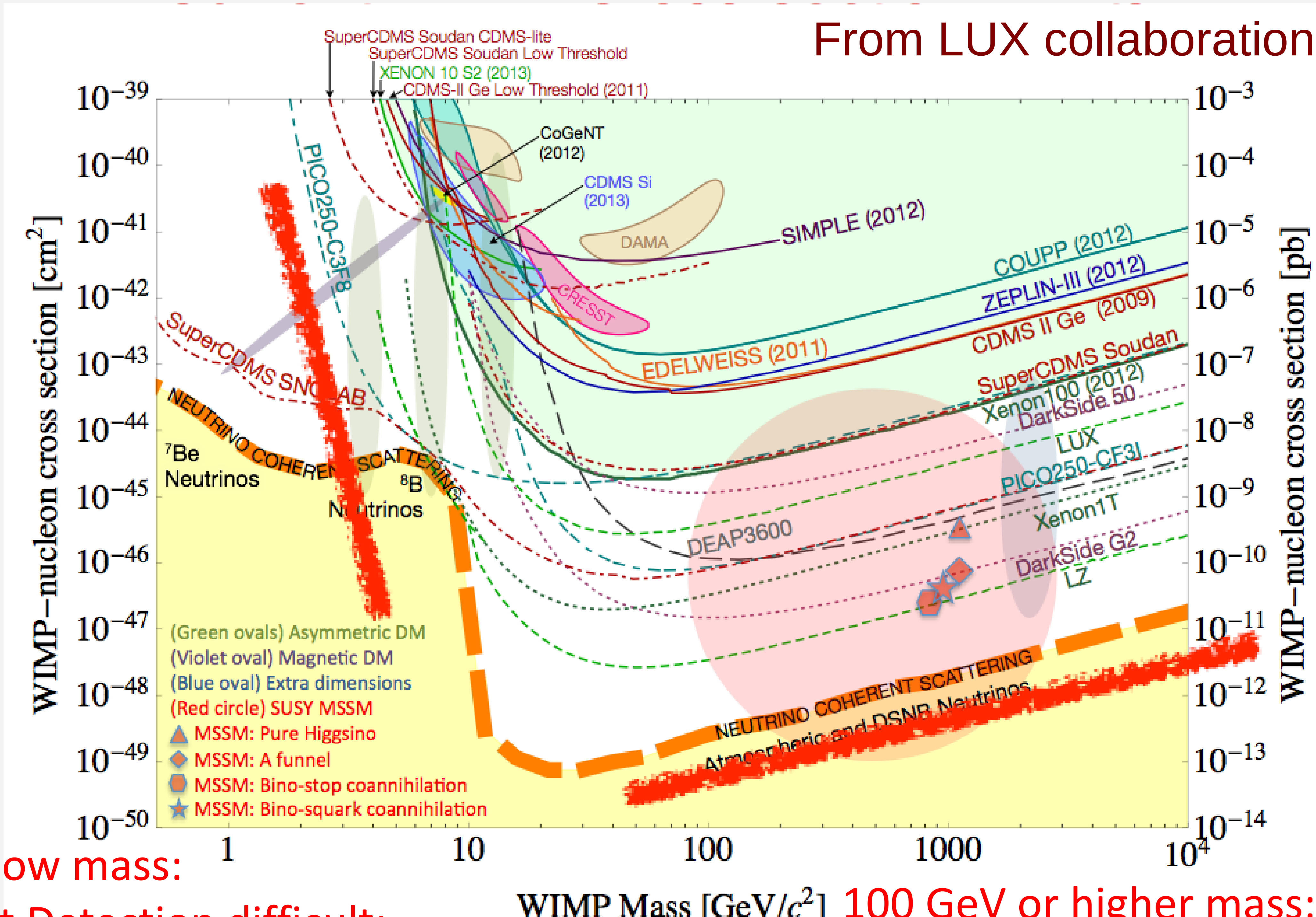


If SM tested at Δk_λ < O(10%),

then EW underwent a cross-over transition.

C. Aime et al., Muon Collider Physics Summary: arXiv:2203.07256

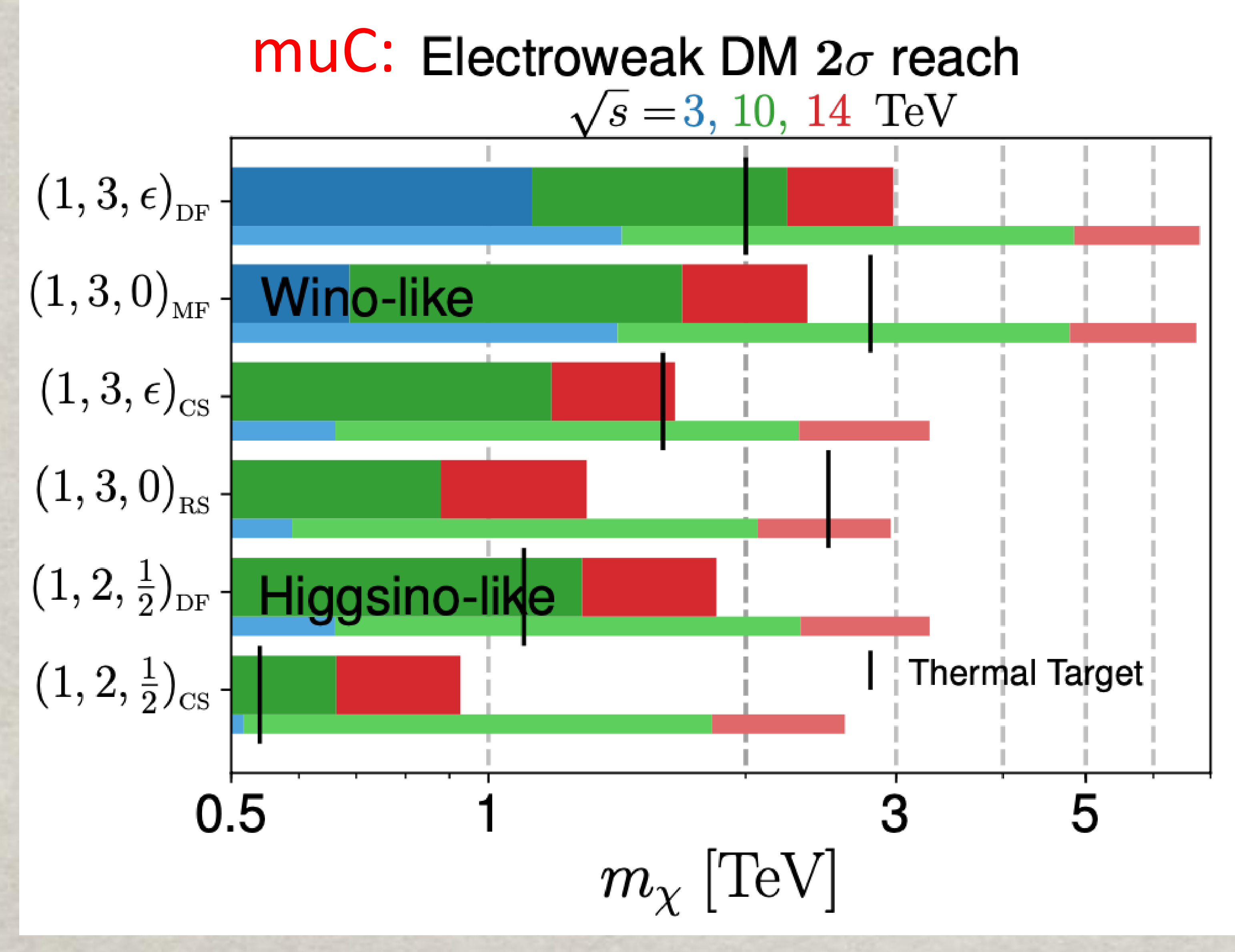
DM Searches



GeV low mass:
Direct Detection difficult;
Collider complementary

100 GeV or higher mass:
HE Colliders extend threshold

The mass reach for minimal WIMP DM @ muC



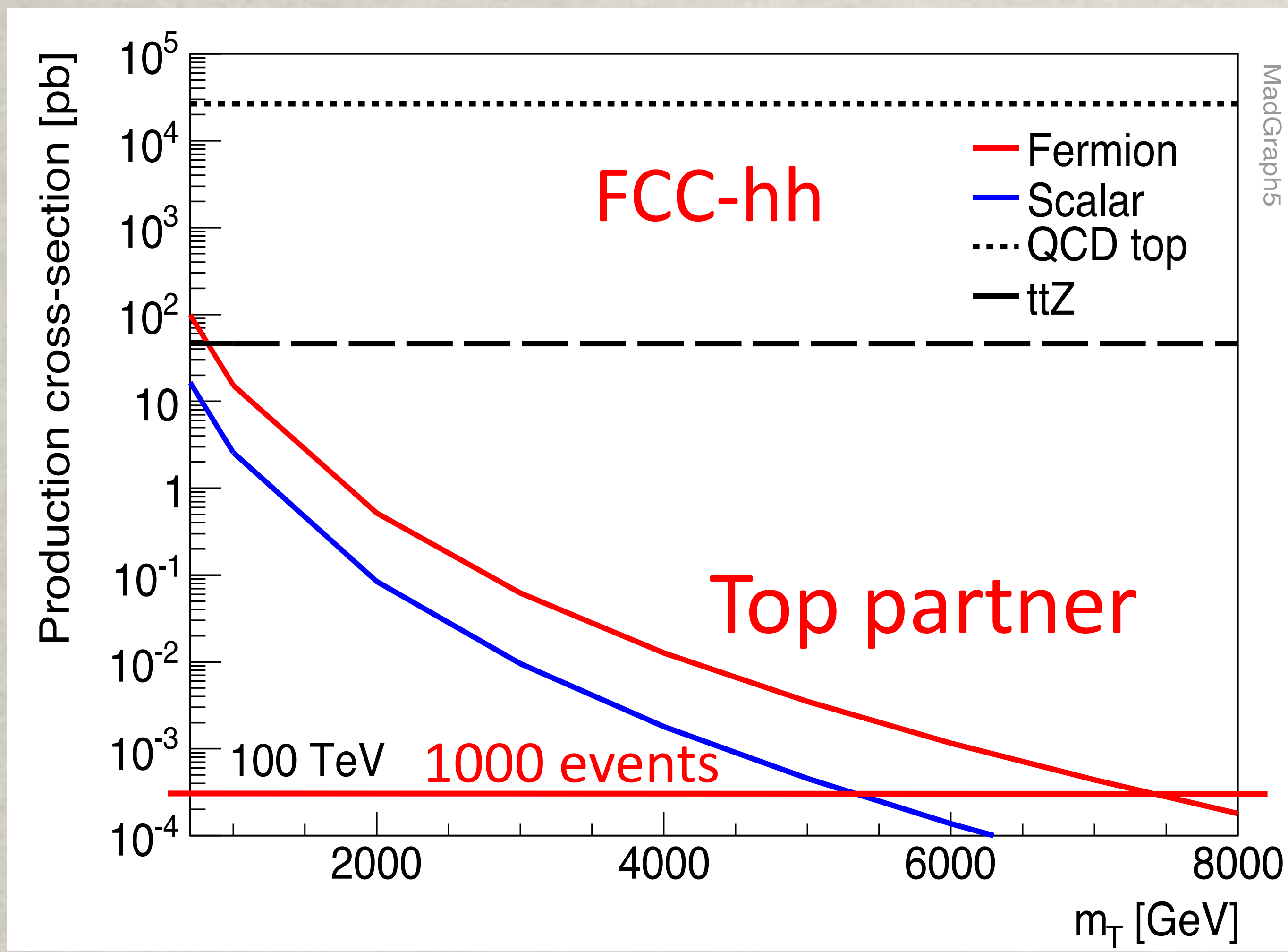
Mass bound by thermal relic:

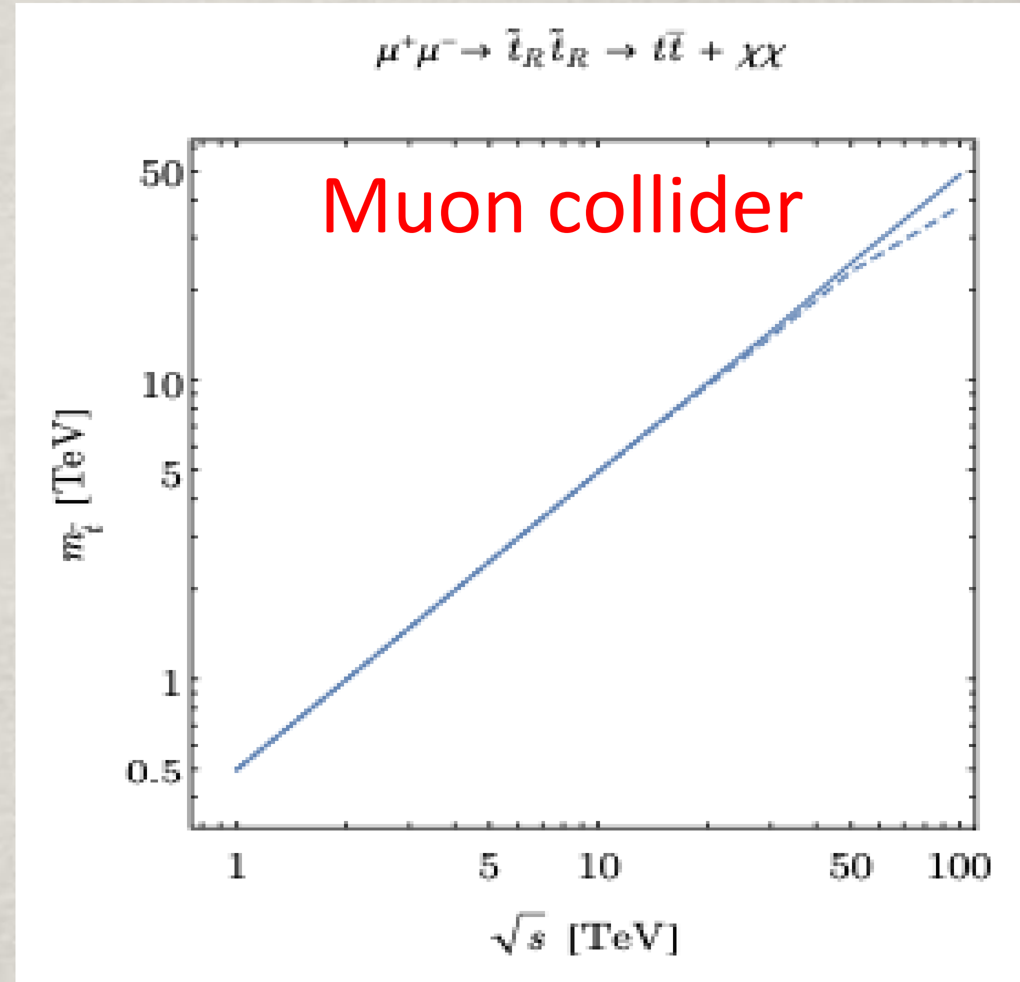
$$M_{DM} < 1.8 \text{ TeV} \left(\frac{g_{\text{eff}}^2}{0.3}\right)$$

- A 14-TeV muC fully covers the thermal target M ~ 3 TeV
- More advantageous than hadron colliders i.e. FCC-hh

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

Pushing the "Naturalness" limit





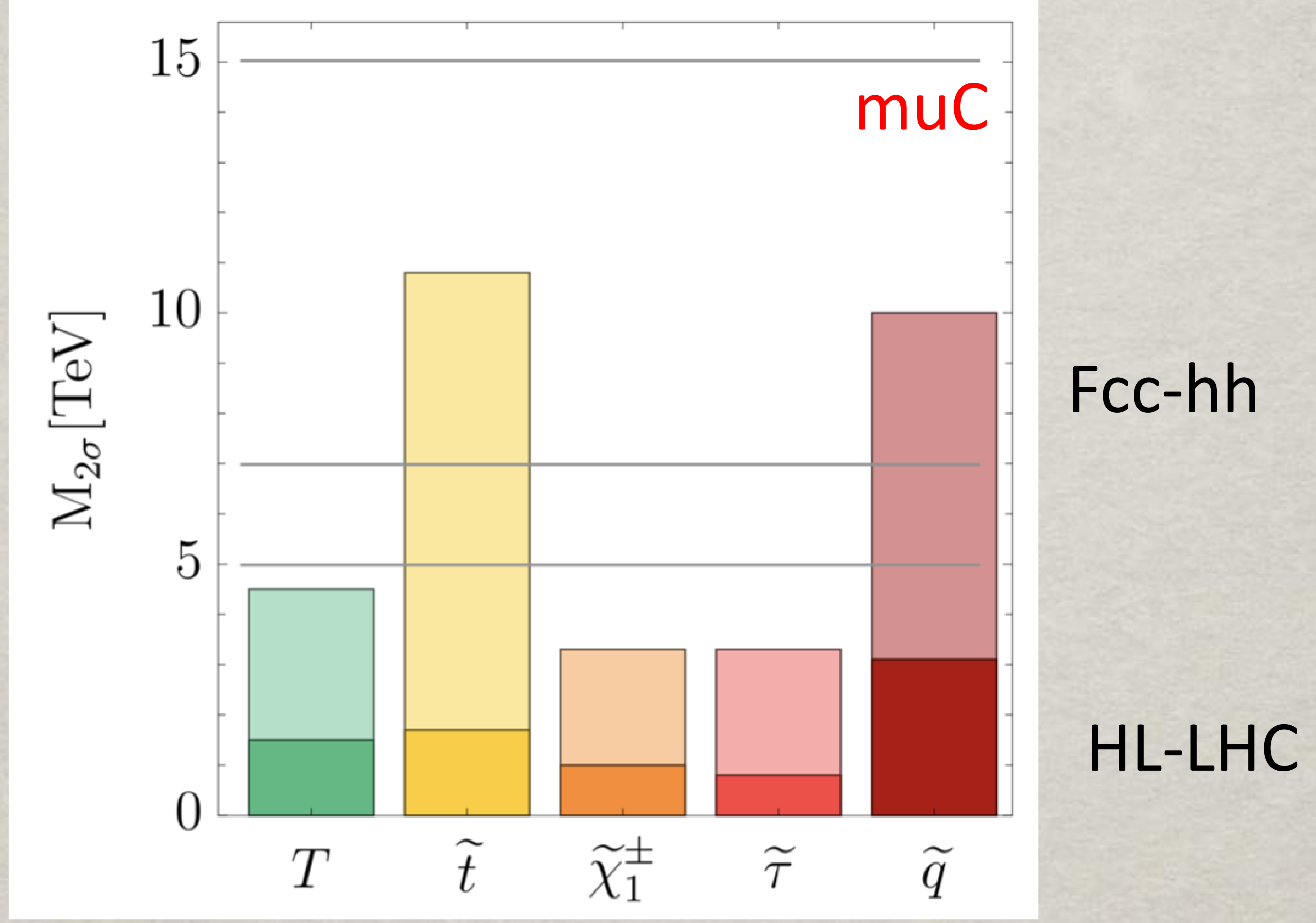
Top quark partners searches:

The 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!

FCC: Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495;
muC: The Muon Smasher's Guide, https://arxiv.org/abs/2103.14043

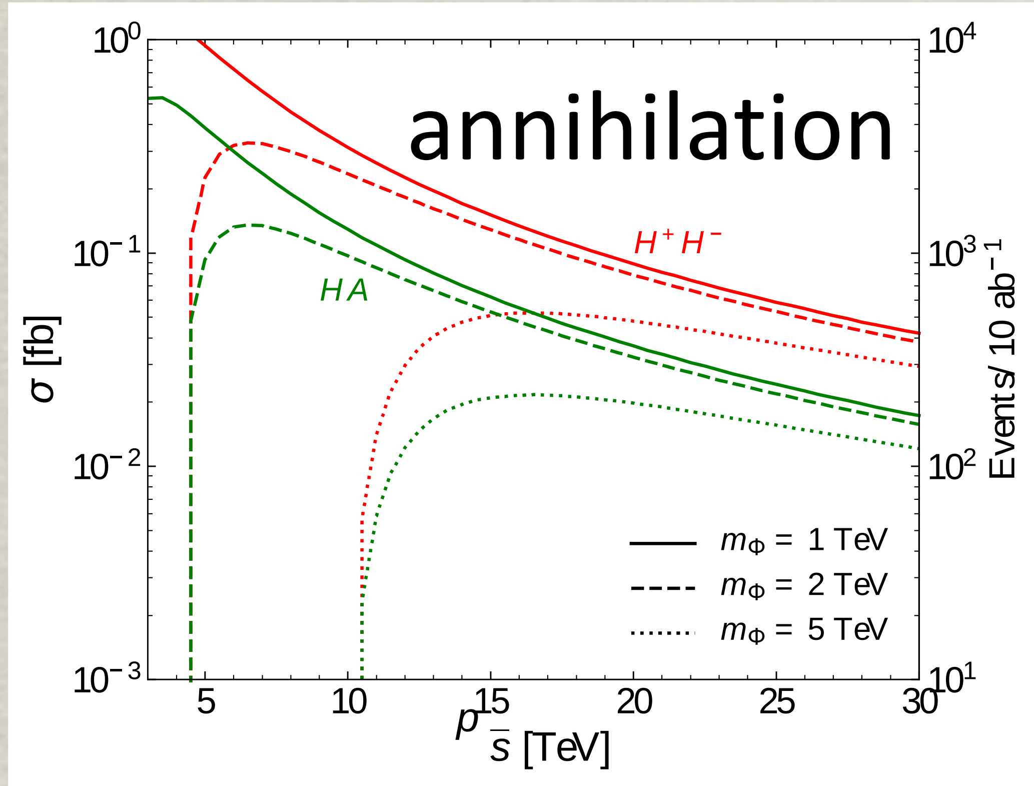
New Particle Searches

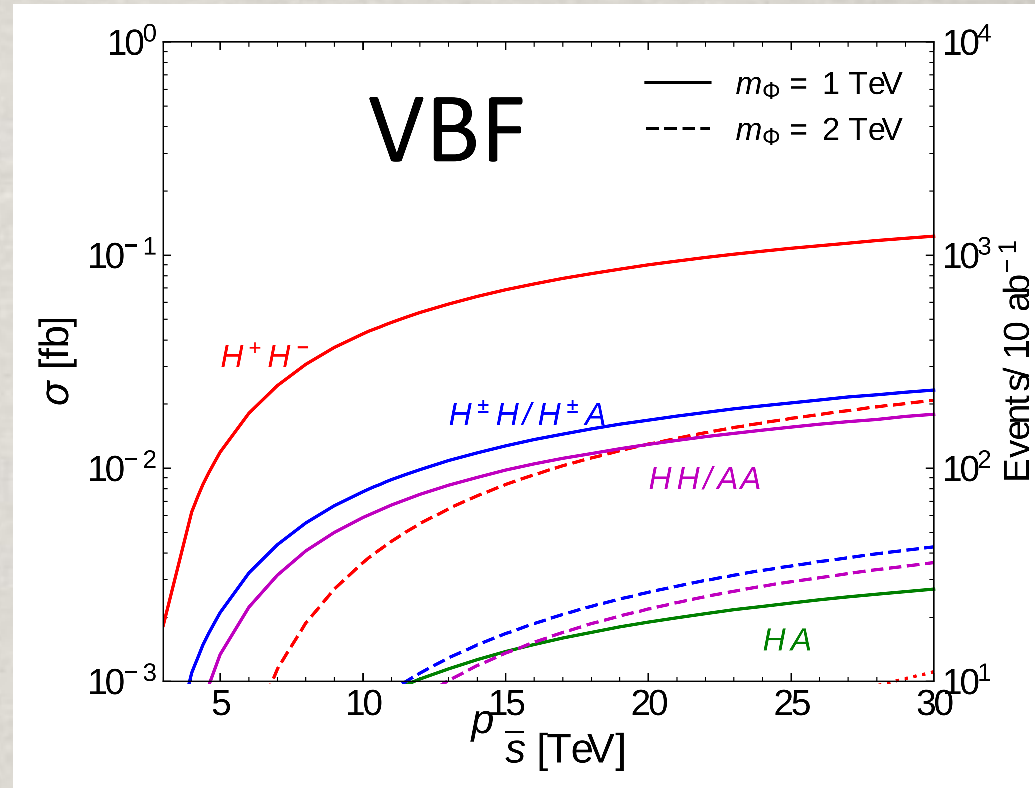


- $F_{cc\text{-}hh}$ vs HL-LHC: 6x reach, which is comparable to a 10-TeV muC

C. Aime et al., Muon Collider Physics Summary: arXiv:2203.07256

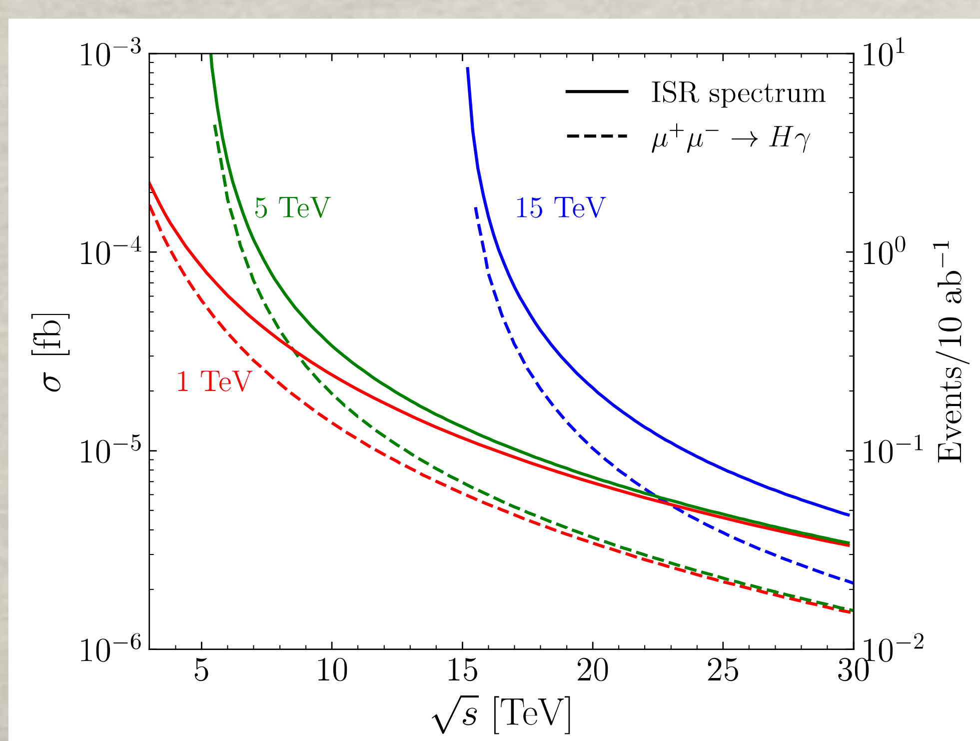
e.g.: Heavy Higgs Boson Production @ muC

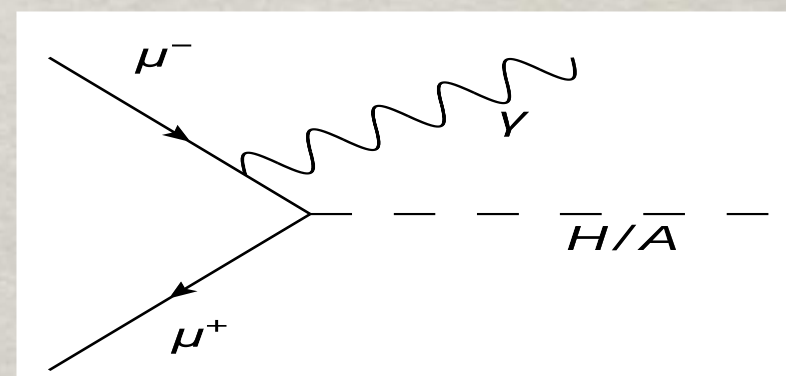




Discovery up to threshold $M_H \sim E_{cm}/2$

Radiative returns:





Discovery extended to $M_H \sim E_{cm}$

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386;
TH, Z. Liu et al., arXiv:1408.5912.

Recast: Future Colliders Agora

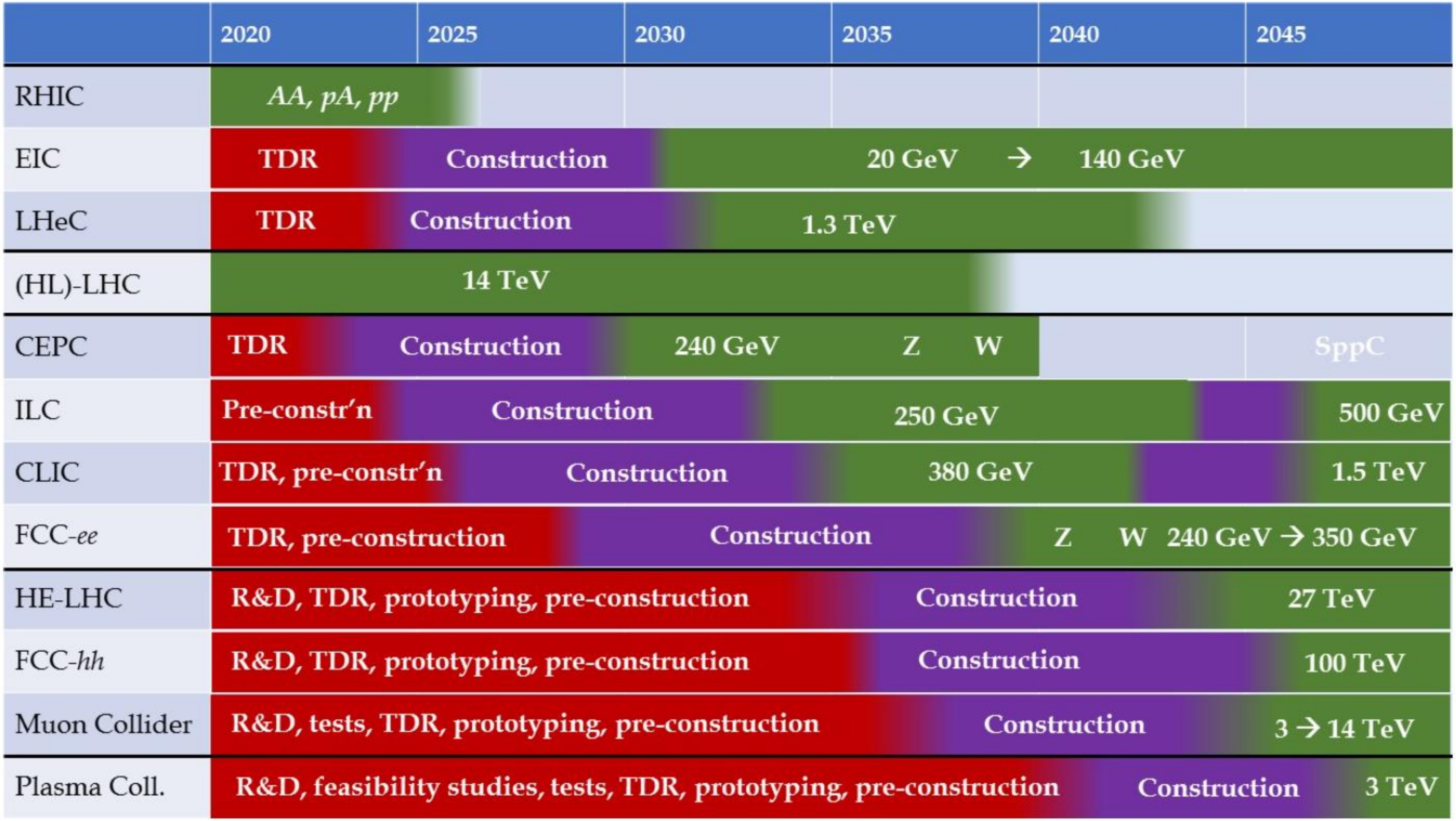
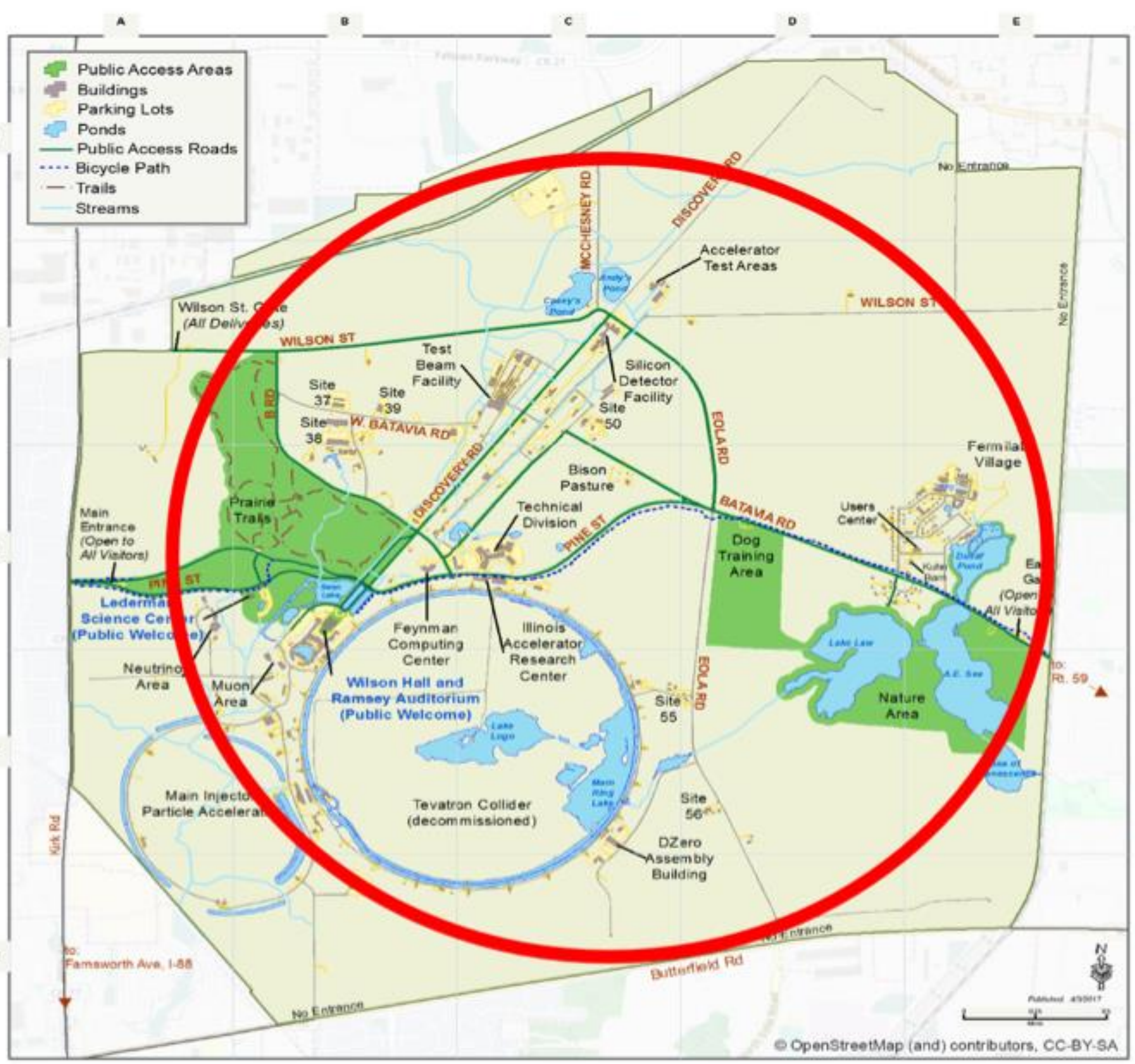


FIG. 42. Approximate technically limited timelines of future large colliding beam facilities.

V. Shiltsev & F. Zimmermann: arXiv:2003.09084

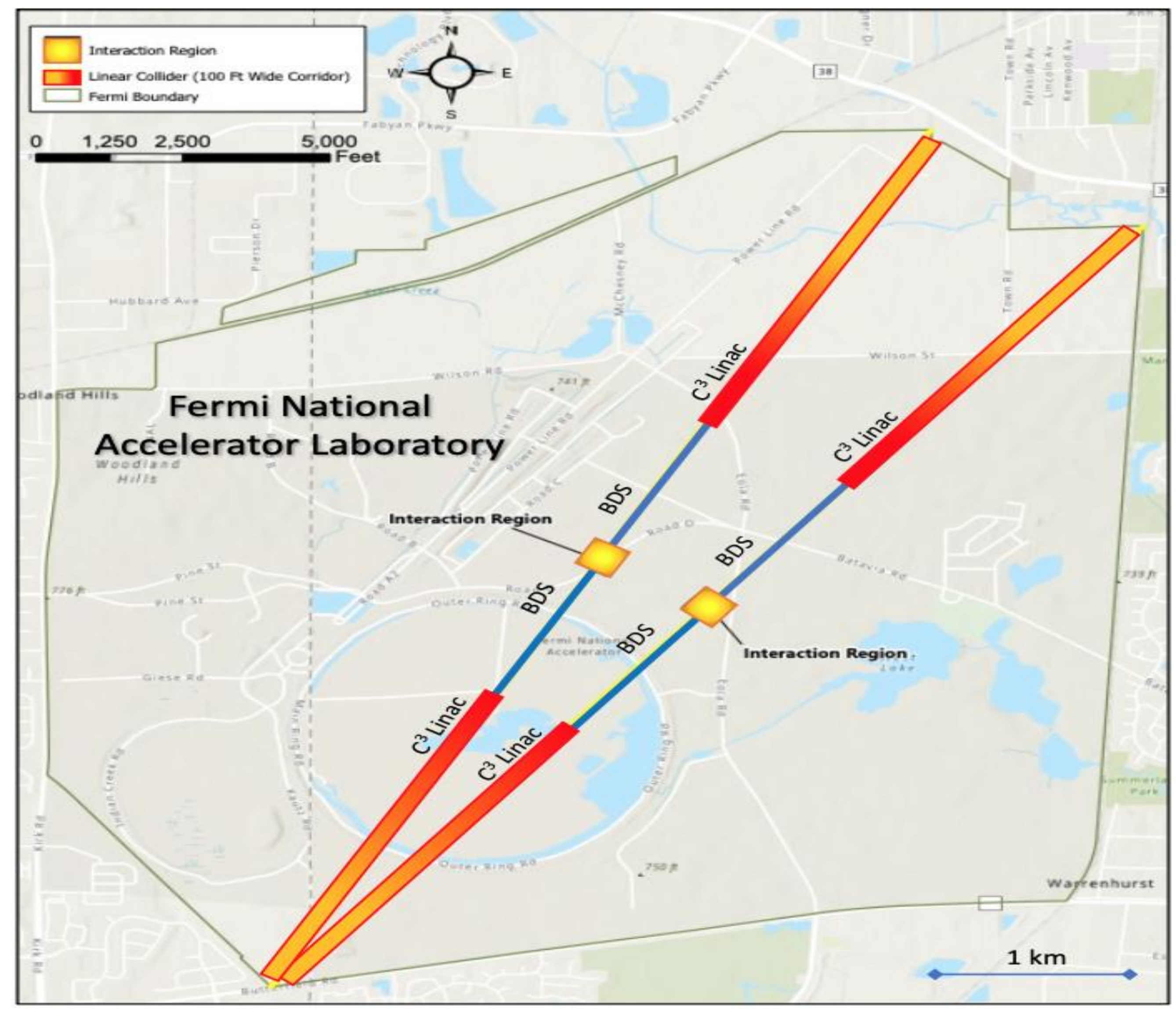
Fermilab Site Fillers

Circumference ~16 km



1. e+e- Site Filler, √s = 90-240 GeV
2. Muon Collider, √s = 0.126 – 8 (10) TeV
3. pp Site Filler Collider, √s = 24-28 TeV

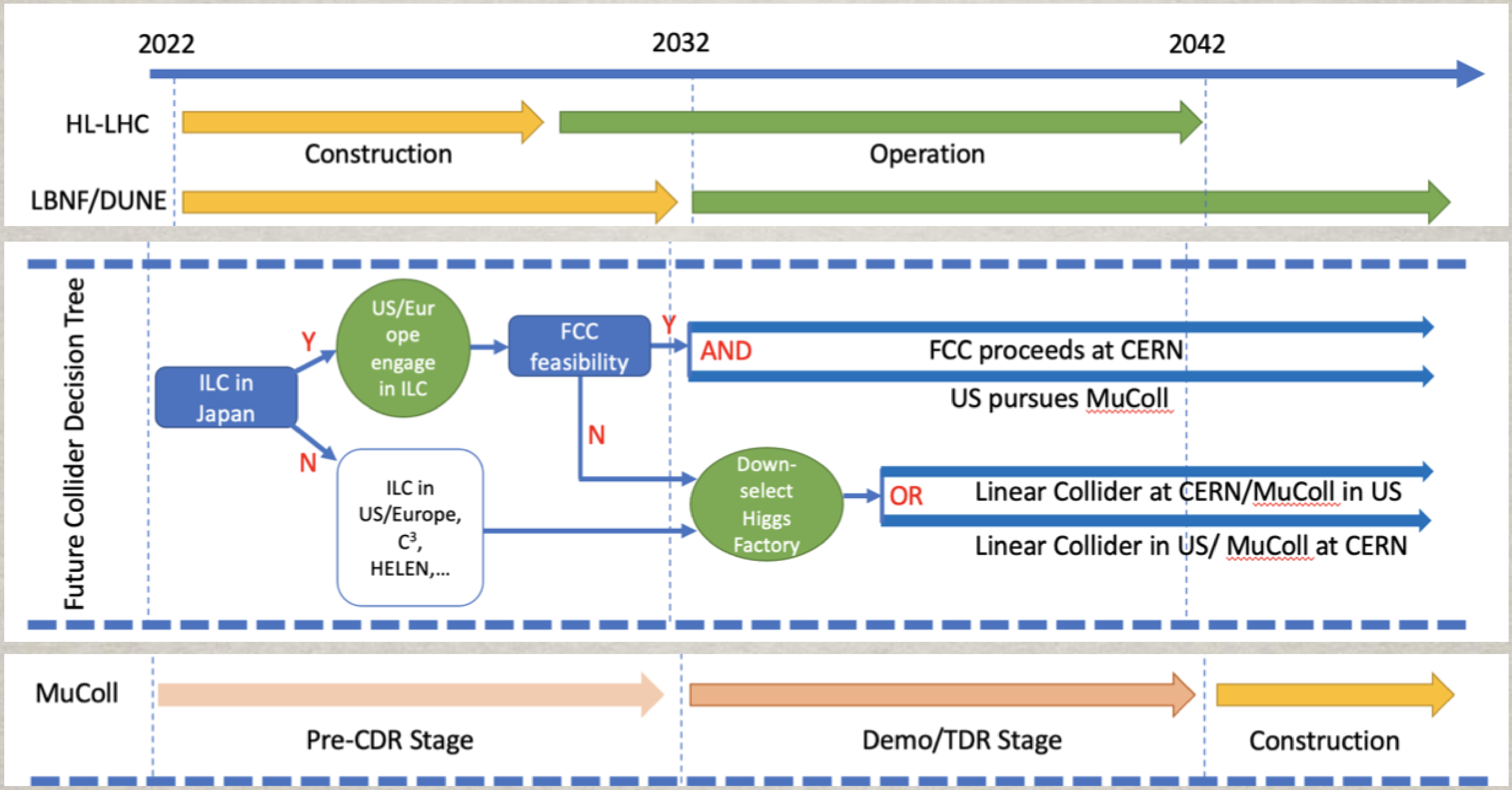
Linear ~7 km



1. C³ (Cool Copper Cavity) e+e- Collider, √s = 90 – 500 GeV
2. NC RF (CLIC-Klystron) e+e- Collider, √s = 90 – 500 GeV
3. SRF-Travelling Wave e+e- Linear Collider, √s = 90 – 250 GeV

P. Bhat et al., Snowmass White paper: arXiv:2203.08088

Future Collider "Decision Tree"



C. Aime et al., Muon Collider Physics Summary: arXiv:2203.07256
V. Shiltsev & F. Zimmermann: arXiv:2003.09084

Summary

- Colliders: indispensable to explore the energy frontier; complementary to other frontiers: flavor, neutrino, DM.
- LHC leads the way: $\lambda_{HHH} \sim 50\%$; $M_{NP} \sim O(1\text{ TeV})$
- Higgs factory:

  Near future: ILC (240 GeV – 1 TeV)

  Future Lepton collider $g \sim 1\%$; $\lambda_{HHH} < 10\%$; $Br_{inv.} \sim 2\%$; $\Gamma_{tot} < 6\%$
- Future Fcc-hh: new physics reach

  6x LHC reach: 10 – 30 TeV → fine-tune $< 10^{-4}$

  WIPM DM mass ~ 1 – 5 TeV; $\lambda_{HHH} < 10\%$
- HE muon collider: $\lambda_{HHH} < 5\%$; $M_{NP} \sim E_{cm}/2 - E_{cm}$.

Much R&D needed, future colliders needed!

Future is bright!