Future Colliders for HEP

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CEPC Workshop
October 24, 2022

Snowmass 2021

DPF Community Planning Exercise

The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It 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. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them.

Snowmass frontiers:

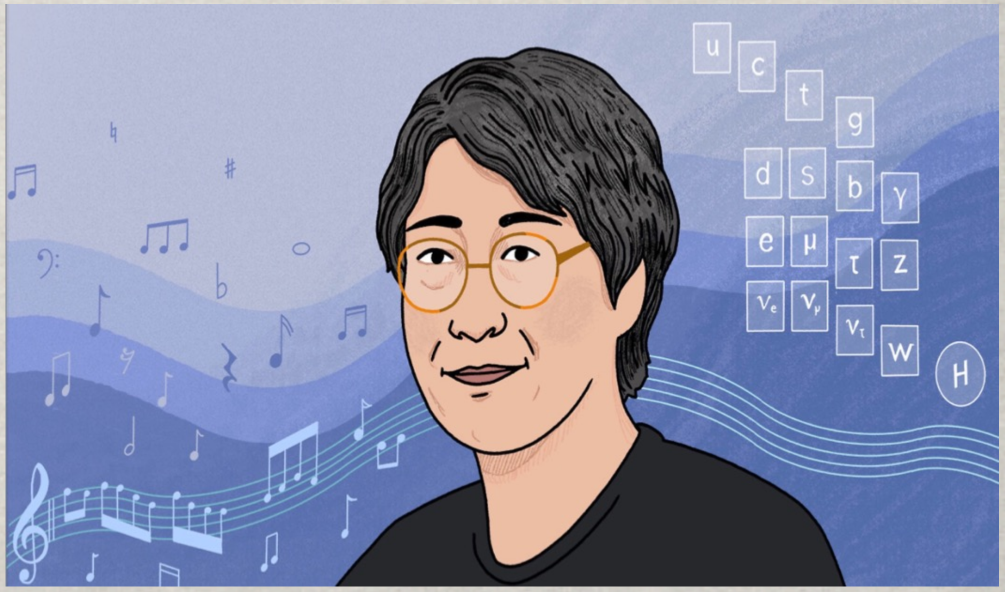
- Energy Frontier
- Neutrino Physics Frontier
- Rare Processes and Precision
- Cosmic Frontier
- Theory Frontier
- Accelerator Frontier
- Instrumentation Frontier
- Computational Frontier
- Underground Facilities
- Community Engagement
- Snowmass Liaisons

and Snowmass Early Career

https://snowmass21.org

With this year-long study, the Snowmass output will provide inputs for the prioritization of the research directions of the field in the decade to come: the "P5" process (Particle Physics Project Prioritization Panel).

The P5 chair: Prof. Hitoshi Murayama



The Beginning of a new era

The underlying landscape is becoming visible

The peak is fundamentally connected to the unseen mountain range

The failure of minimal extensions to the Standard Model implies a much richer sector to explore.

With all the new experiments ready to push deeper into every frontier, we all feel the excitement of being poised for an explosion of new data and answers to the questions posed a decade ago.

BSM as the guide for the future

We are not shooting in the dark.

Let's move away from "The SM is incomplete" and "we need to search everywhere"

Instead, we might say

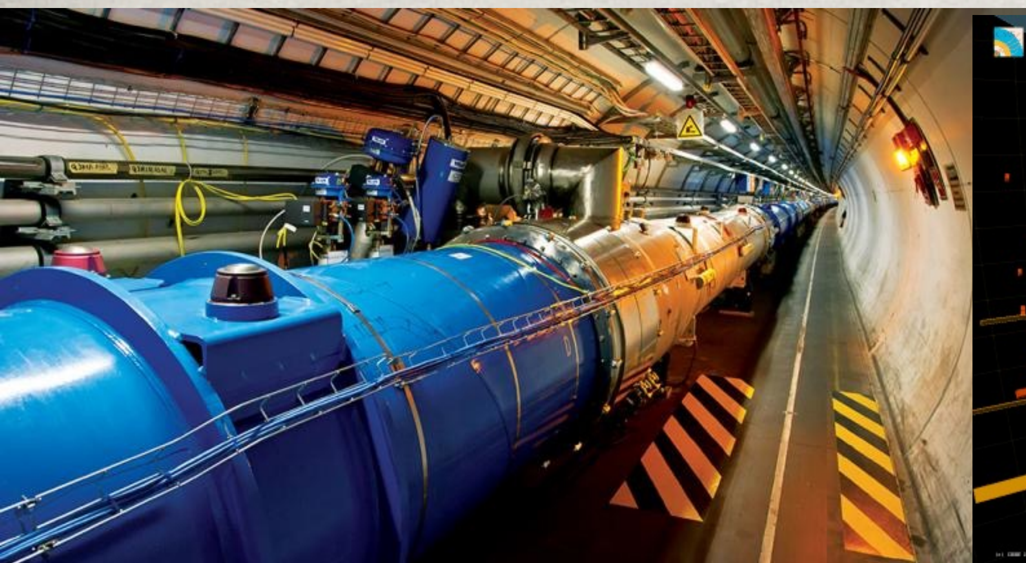
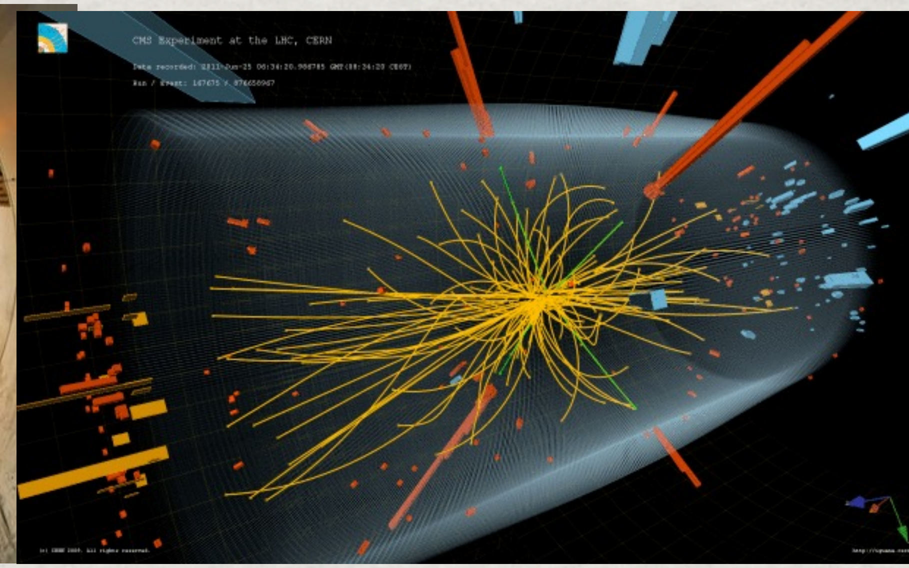
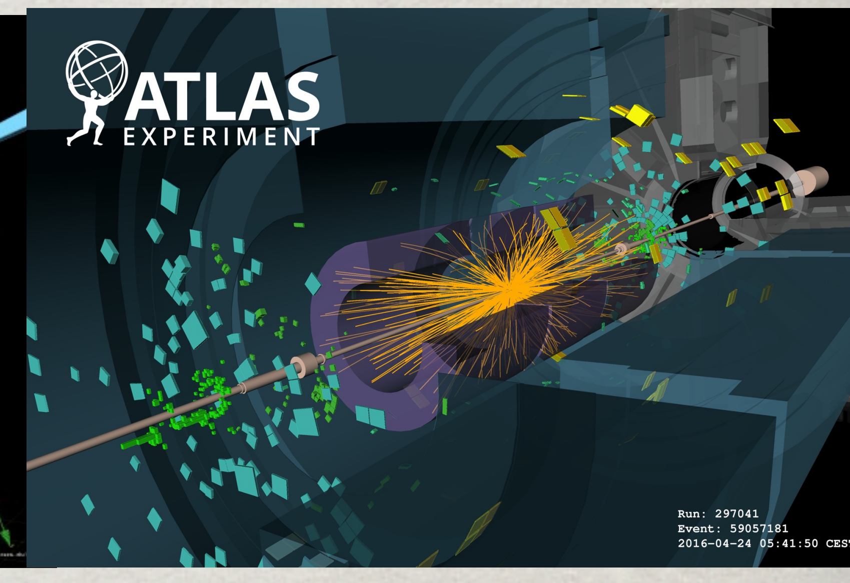
We have made the following discoveries, which will enlarge our model of the Universe once we figure out how it fits into what we already know.

(1) Dark matter exists and its gravitational interactions are being mapped by a host of cosmic probes
(2) Neutrinos interact with both gravity and the weak force, and we are measuring their interactions and flavor properties and narrowing down their masses.
(3) Our Universe has an anti-matter deficit, is accelerating, and is filled with ancient thermal radiation, and we have new tools to measure matter, energy and space-time at all epochs

We have seen many examples in this summer study of how these are all connected.
For example: Exploring the Dark Sector has the potential to address the hierarchy problem, neutrino masses, baryon asymmetry, and even strong CP. Signatures will show up in all the frontiers.
Cosmic probes and GW are an orthogonal approach to some of the same questions tying the accelerating Universe and large scale structure to fundamental questions in particular physics

This type of message, coupled with specific ***benchmark paths*** is most compelling (a la T.Slatyer's talk)

LHC will continue at the energy frontier

- Already ~ O(140 fb^{-1}) @ ATLAS/CMS
- Run 3 up-coming: 300 fb^{-1}
- HL-LHC: 3000 fb^{-1}

  → lead the energy/precision frontier!

Further searches at the LHC will be limited by

- Backgrounds
- Systematics
- New physics threshold

Snowmass'21 Accelerator Frontier Conveners

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

Vladimir Shiltsev (FNAL)

Topical Group		Topical Group co-Conveners			
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bai (SLAC)	S. Lund (MSU)	
AF02	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)	
AF03	Accelerators for EW/Higgs	F. Zimmermann (CERN)	Q. Qin (ESRF)	G.Hoffstaetter (Cornell) A.Faus-Golfe (IN2P3)	
AF04	Multi-TeV Colliders	M. Palmer (BNL)	A. Valishev (FNAL)	N. Pastrone (INFN) J.Tang (IHEP)	
AF05	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	Richard Milner (MIT)	
AF06	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)	R. Assmann (DESY)
AF07	Accelerator Technology R&D				
	Sub-Group RF	E. Nanni (LBNL)	H.Weise (DESY)	S. Belomestnykh (FNAL)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	Frederique Pellemoine (FNAL)	

Implementation Task Force

https://arxiv.org/abs/2208.06030

- The Accelerator Frontier **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider projects:
  - Higgs/EW factories (focus of slides below)
  - Lepton colliders with 3 TeV cme
  - Lepton and hh colliders 10+ TeV cme
  - FNAL site-fillers and eh colliders
- ITF addressed (four subgroups):
  - ➢ Physics reach (impact), beam parameters
  - ➢ Size, complexity, power, environment
  - ➢ Technical risk, readiness, and R&D required
  - ➢ Cost and schedule


Thomas Roser (BNL, Chair)


Philippe Lebrun (CERN)


Steve Gourlay (LBNL)


Tor Raubenheimer (SLAC)


Katsunobu Oide (KEK)


Jim Strait (FNAL)


Vladimir Shiltsev (FNAL)


Reinhard Brinkmann (DESY)


John Seeman (SLAC)

Future Colliders under Discussions*

Snowmass 2021 Energy Frontier Collider Study Scenarios

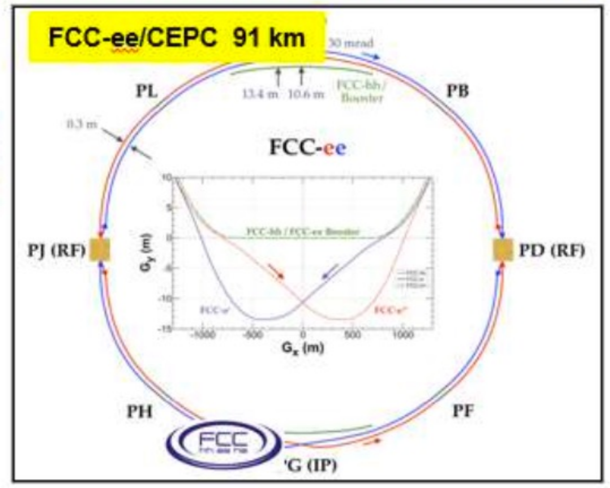
Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z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

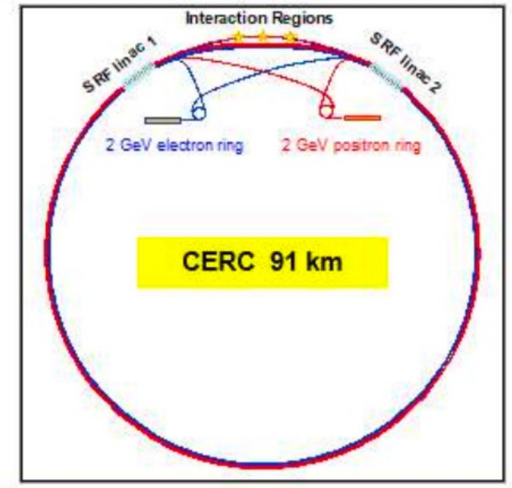
* Snowmass Energy Frontier: https://snowmass21.org

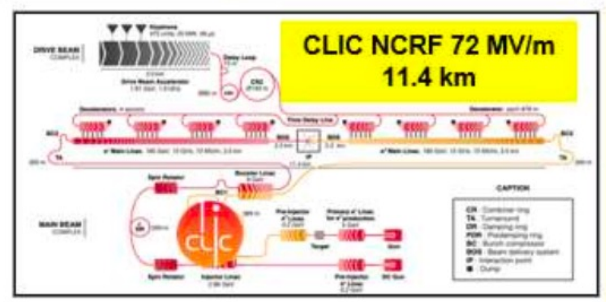
Proposals – Higgs/EW Physics

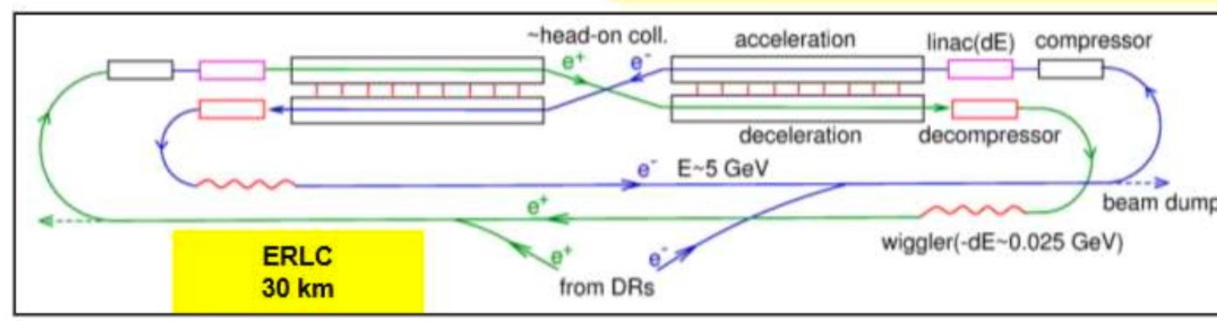
Higgs factory concepts (10)

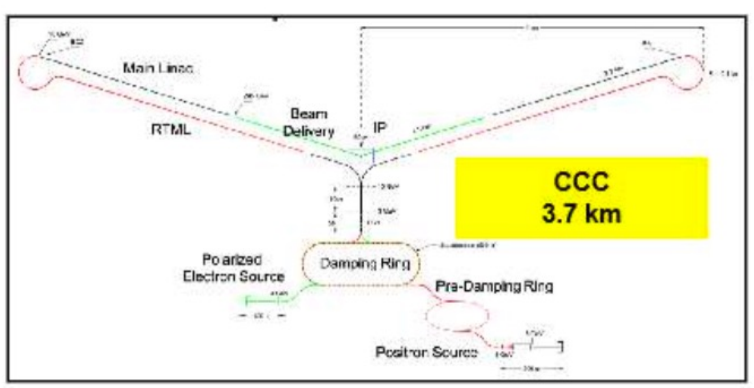
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 1$ TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee ($\gamma\gamma$),$\sqrt{s} = 0.125 - 0.14$ TeV
MC (Higgs factory)	μ+μ−, $\sqrt{s} = 0.13$ TeV

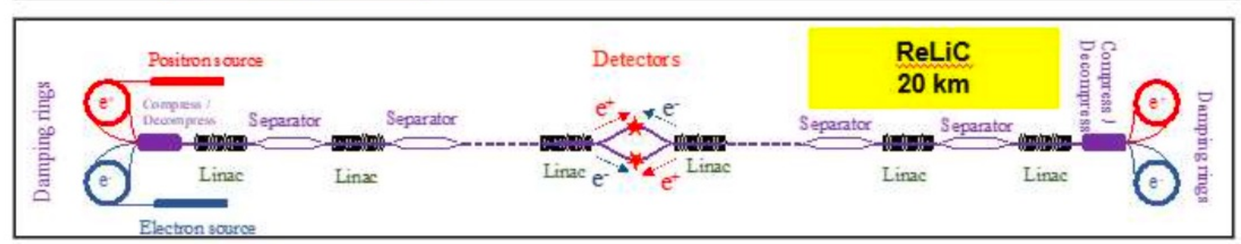








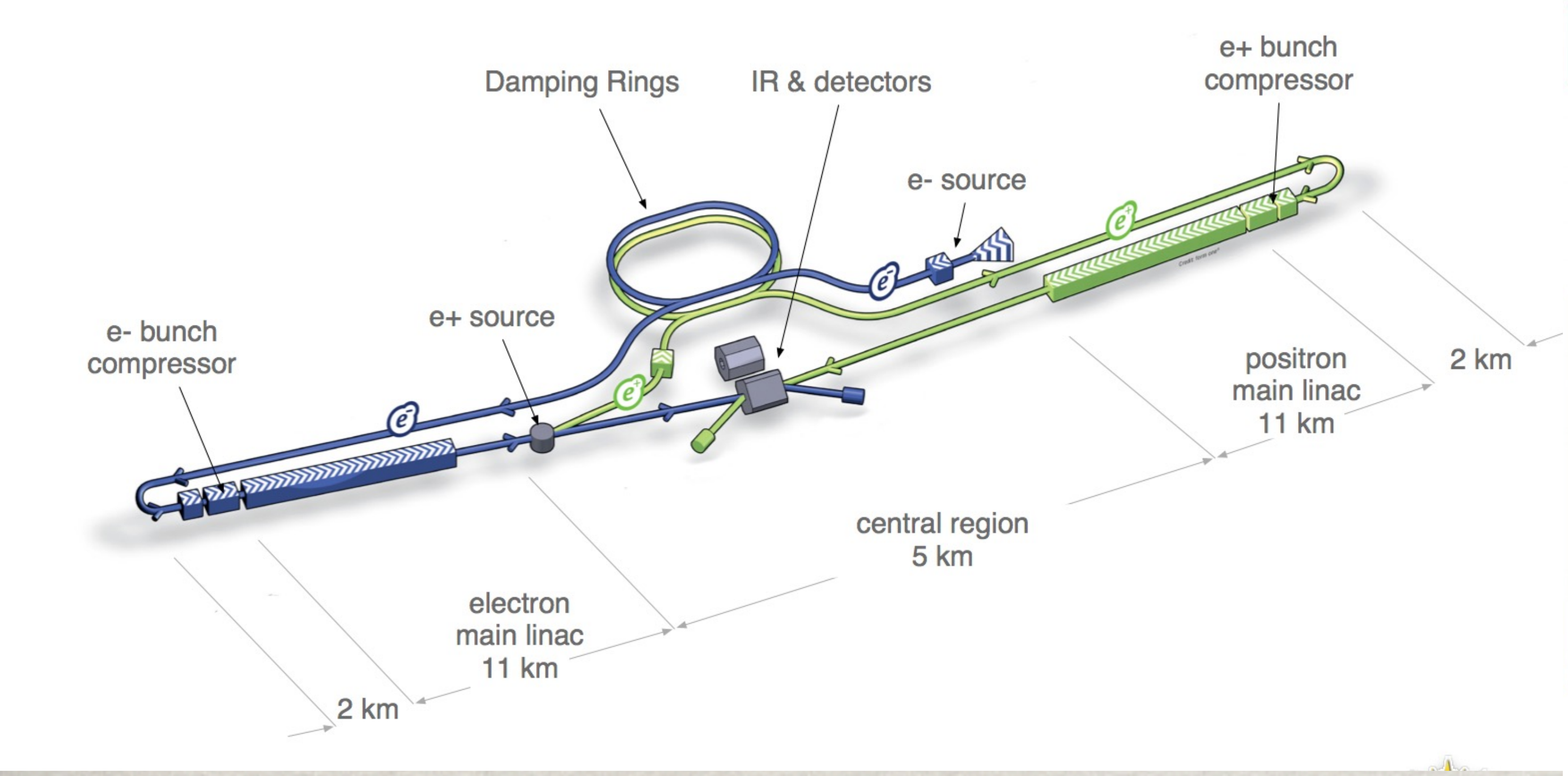


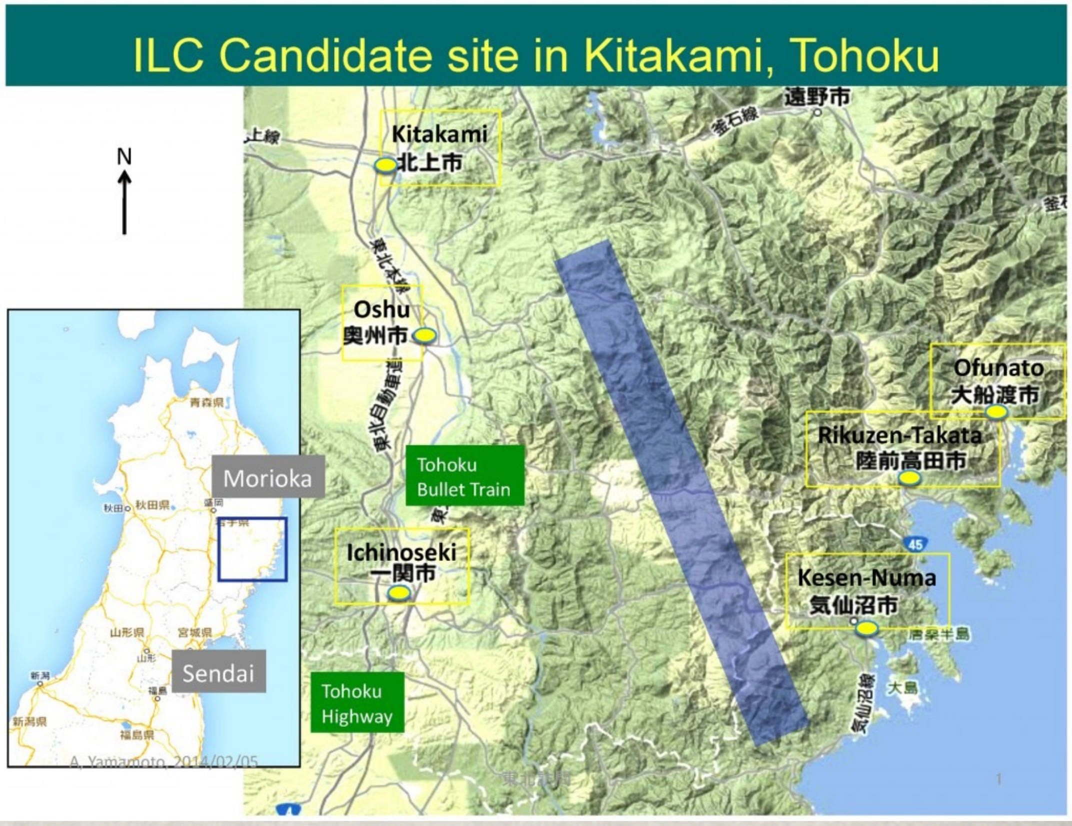


ILC (International Linear Collider) as a Higgs Factory & beyond

Under serious consideration in Japan

https://arxiv.org/abs/1901.09829



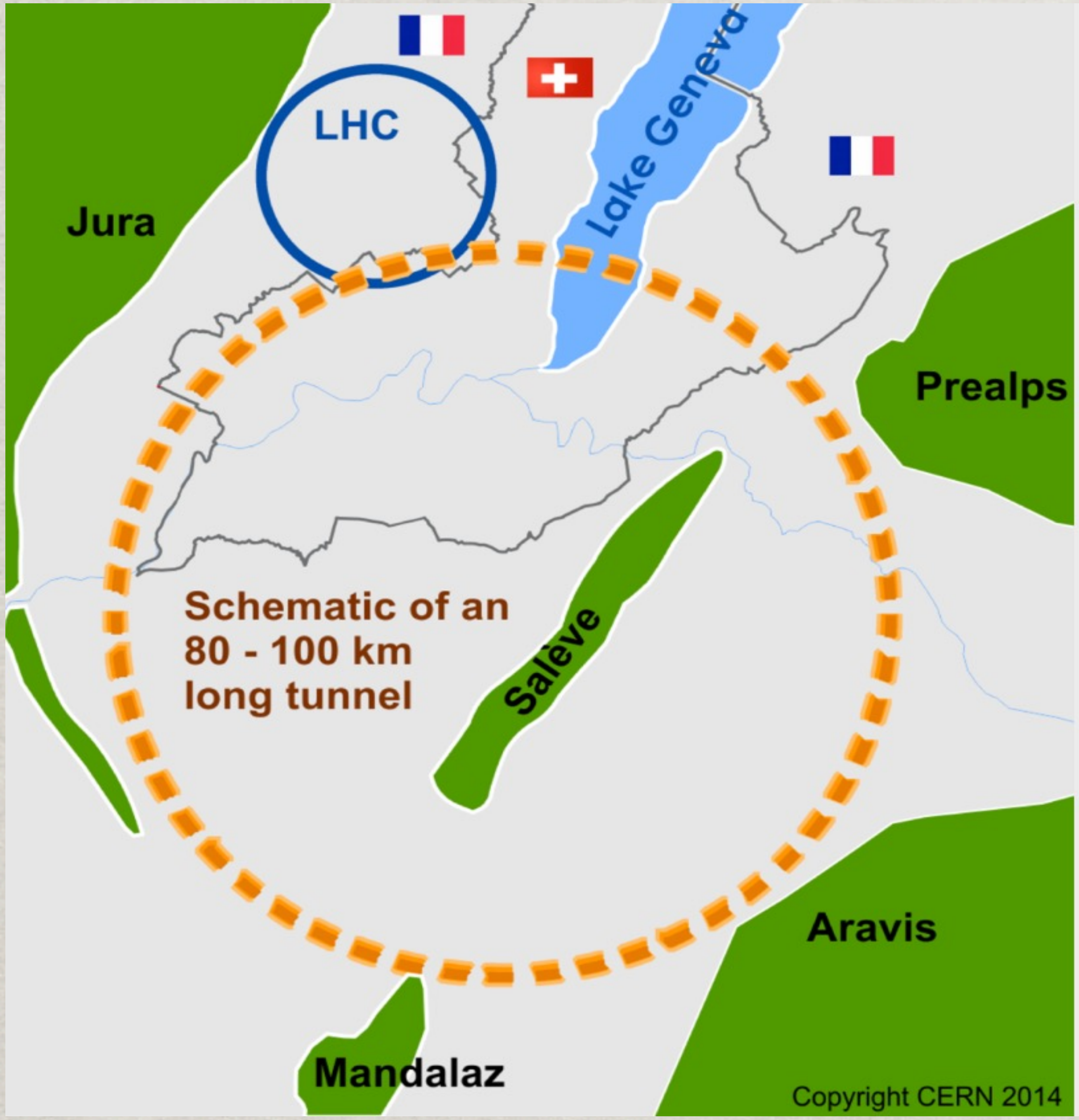


Ecm = 250 GeV / 2 ab^{-1} /yr: a Higgs factory

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

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

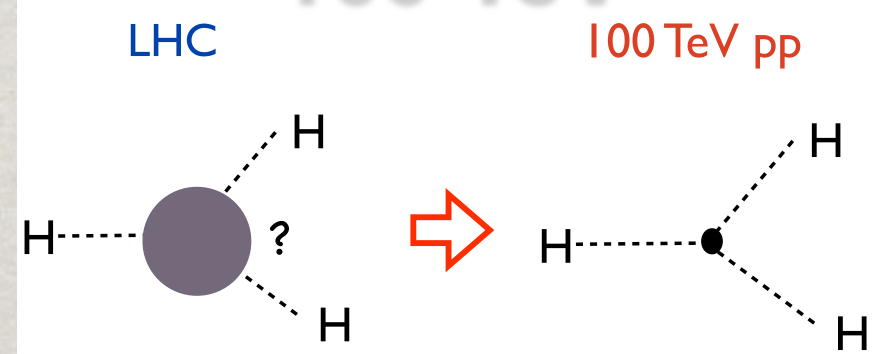
FCC (future circular collider): CERN



FCC-ee
80/100 km
90 - 400 GeV

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

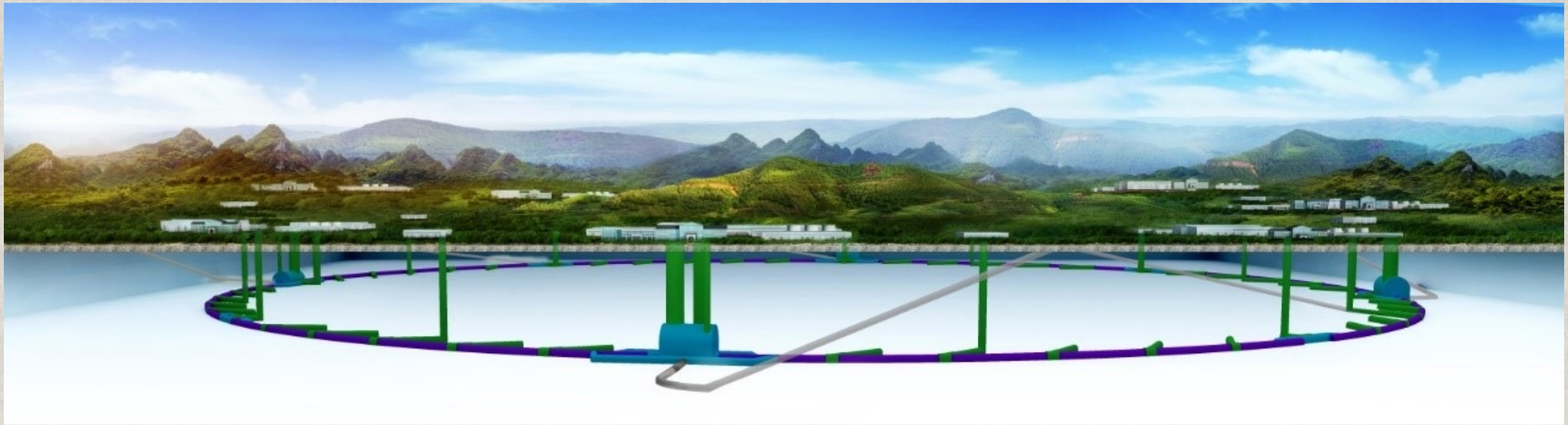
FCC-hh
80 /100 km, 16/20T
100 TeV



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.

CEPC (Circular e^-e^+) / SppC (Super pp), China



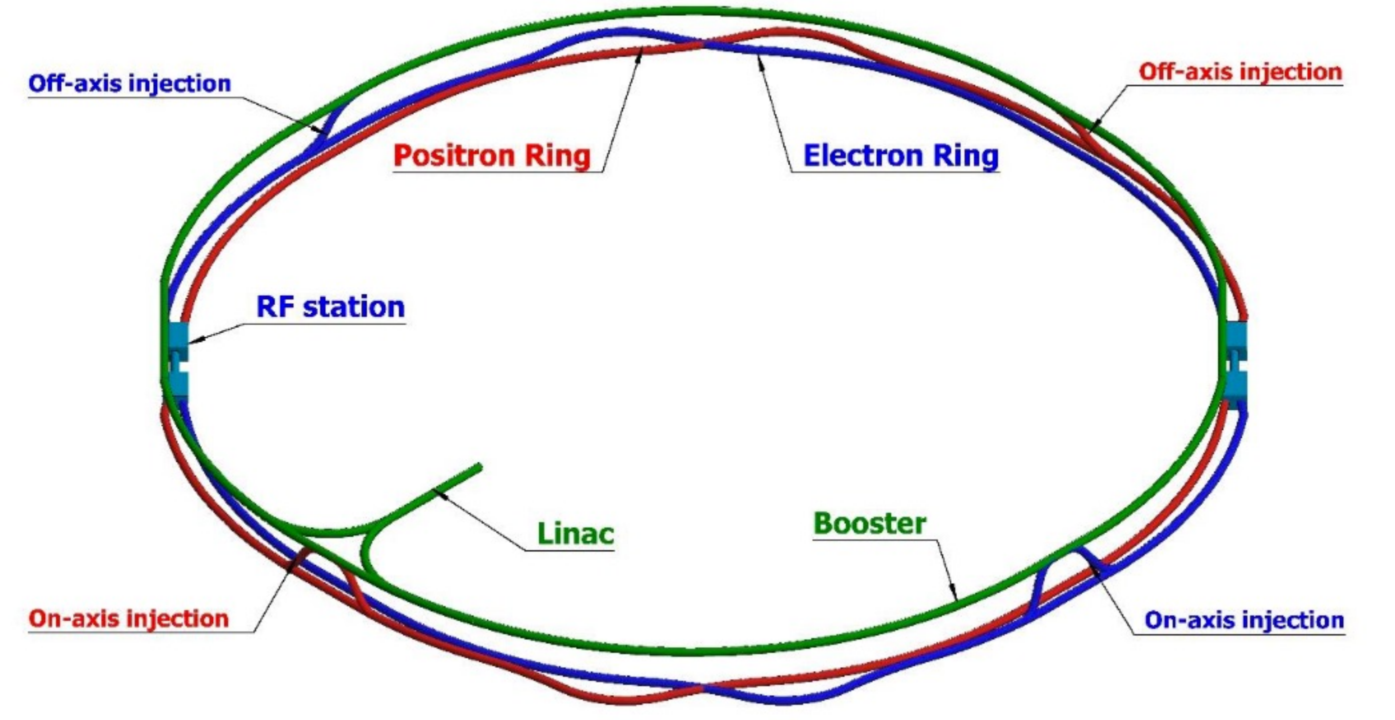


Figure 2.2: CEPC layout

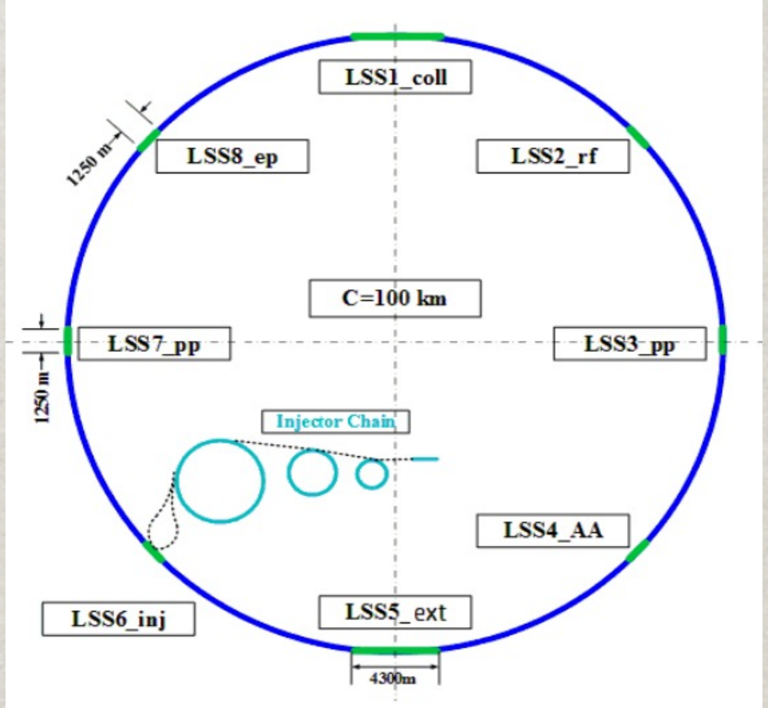
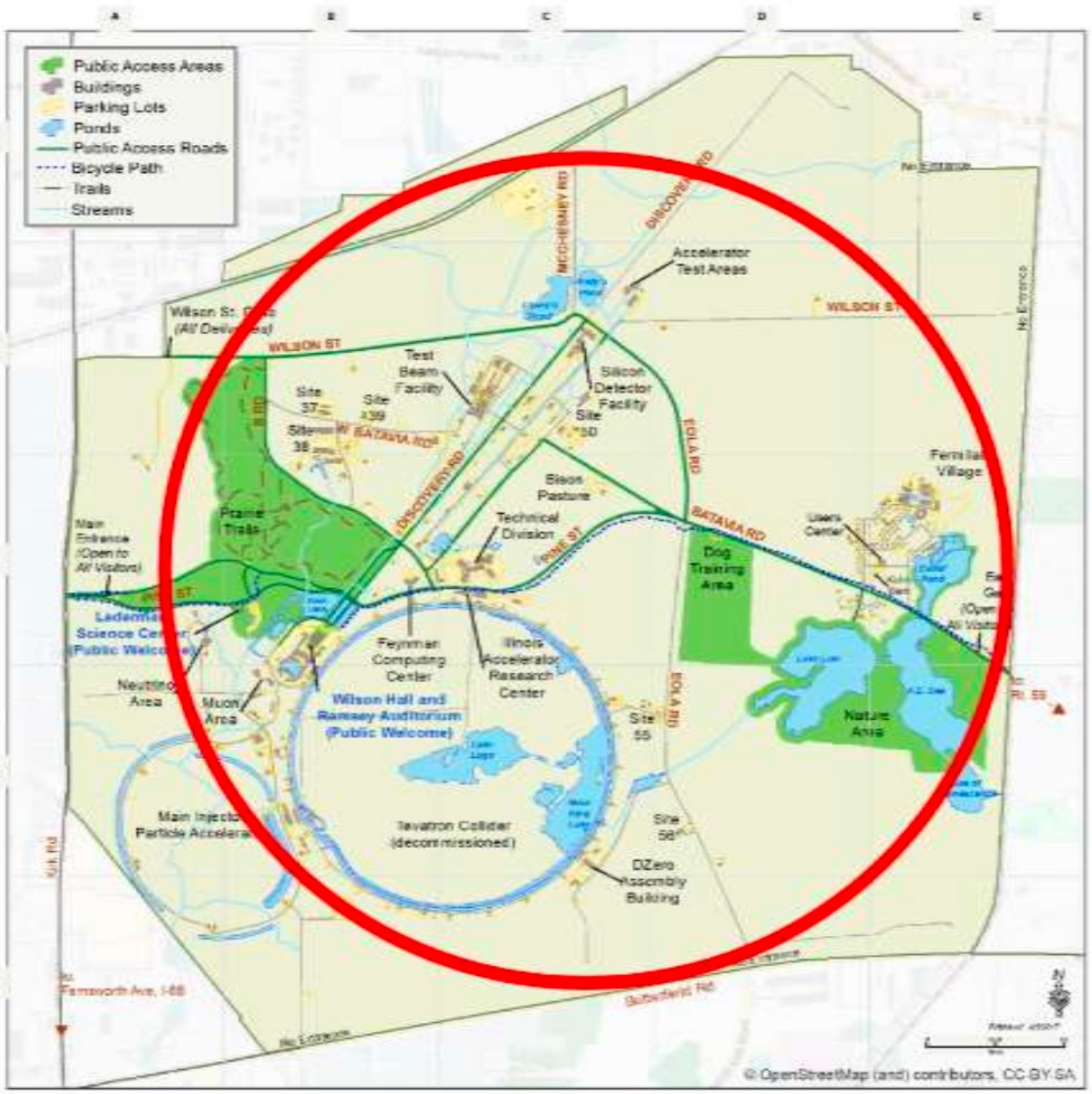


Figure 8.1.1: SPPC accelerator complex

Similar physics goals to FCC-ee, FCC-hh !

https://arxiv.org/abs/1811.10545

250 GeV cme Fermilab Site-Fillers



16-km collider e+e- ring

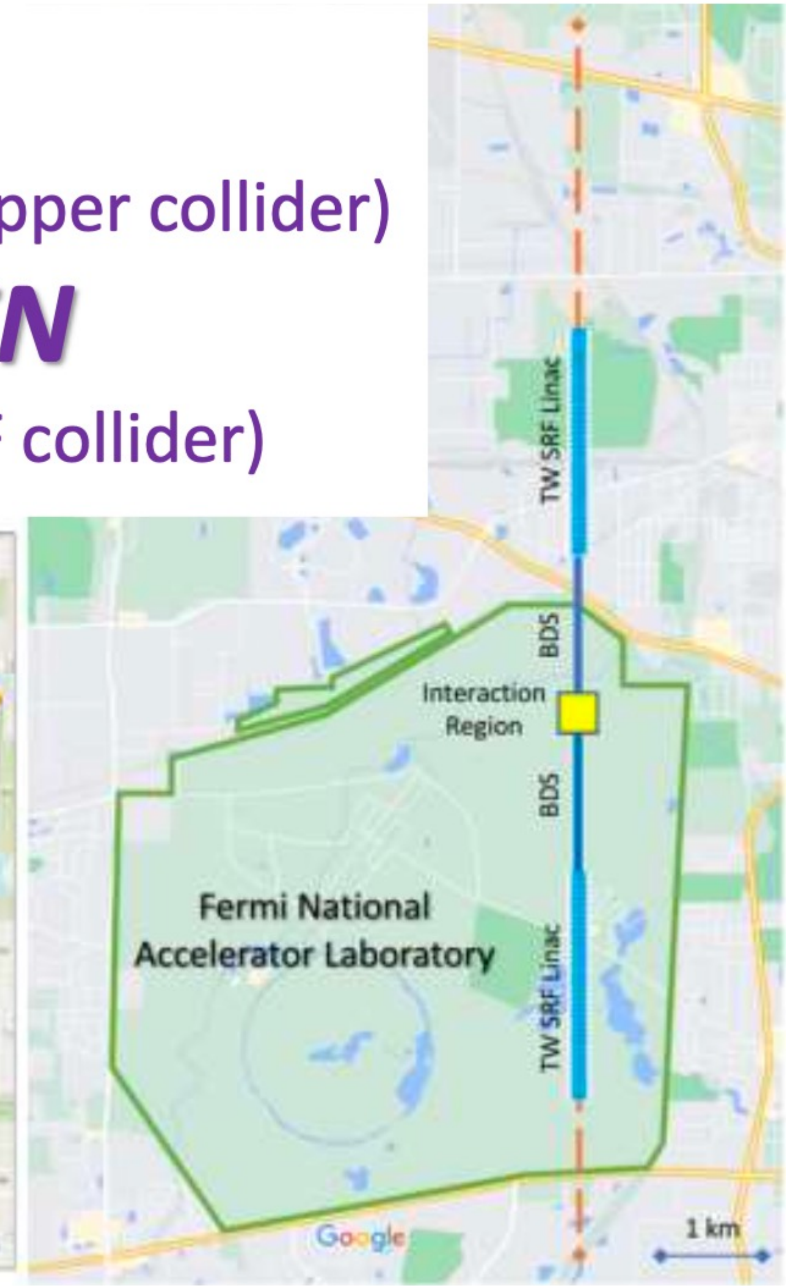
https://arxiv.org/abs/2203.08088

CCC

(cool copper collider)

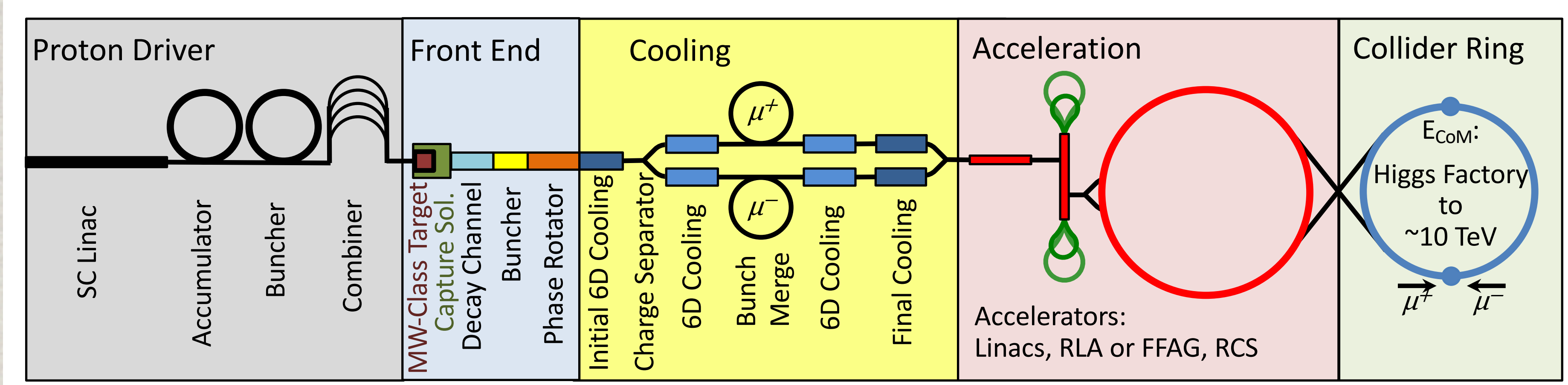
HELEN

(TW SRF collider)



cool- or *SC-RF* e+e- linear colliders
7-km for 250 GeV, 12-km 0.5+ TeV

Recent technological breakthroughs:

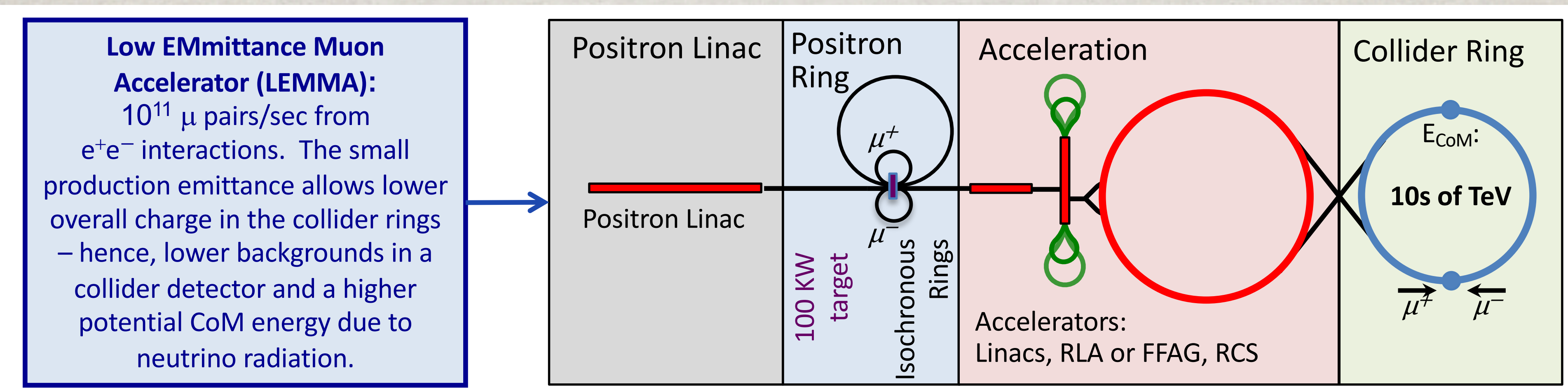


Proton-Driver:

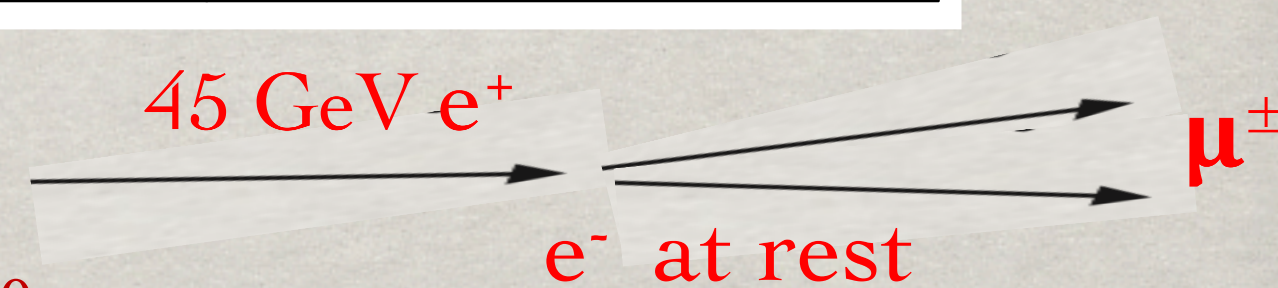
Muon Accelerator Program
map.fnal.gov

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

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



Low EMittance Muon Accelerator
web.infn.it/LEMMA



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

Implementation Task Force on Higgs Factories

Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

		CME (TeV)	Lumi per IP@ Higgs (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
Circular *e+e-*	FCCee (4 IPs)	0.24	7.7	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear *e+e-*	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C^3	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s-chan	XCC-$\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
	$\mu\mu$-Higgs	0.13	0.01	>10	19-24	4-7	200

ITF's Look Beyond Higgs Factories

ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	$O(300)$
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Why muon colliders?

- (Snowmass Energy Frontier) HEP aspires 10+ TeV cme/parton
- Muon Collider is a viable option for the HEP future:
  - Combines discovery reach and precision physics
  - *x7* energy reach vs *pp* – eg 14 TeV *μμ* = 100 TeV pp
  - *μ*'s do not radiate when bent → acceleration in rings:
    - *Smaller(est) footprint* – 10-15 km vs 50-100 km
    - *(Best) power efficiency* – *Lumi/Power* grows with energy
    - *Low(est) cost* – due to compactness and power efficiency
- (ITF) 3-10 TeV Muon Collider can be designed in ~10-15 yrs and built in 20-25 yrs from now:
  - *Past studies in the US and UK (+now in CERN) – big advance*
  - *No insurmountable obstacles identified*
  - *But challenging technologies and design require R&D*

International Muon Collider Collaboration

https://muoncollider.web.cern.ch

Fermilab on site:

Site filler Accelerator

- **Largest**

Radius is ~2.65 km

- **~16.5 km Circumference**
  - **~2/3 LHC**

~RCS accelerator

If B_{ave}= 3 T → E_{μ}= 2.4 TeV

(B_{max} = 8T, B_{pulse} =±2T)

Doubled ?

B_{ave}= 6.3 T → E_{μ}= 5 TeV

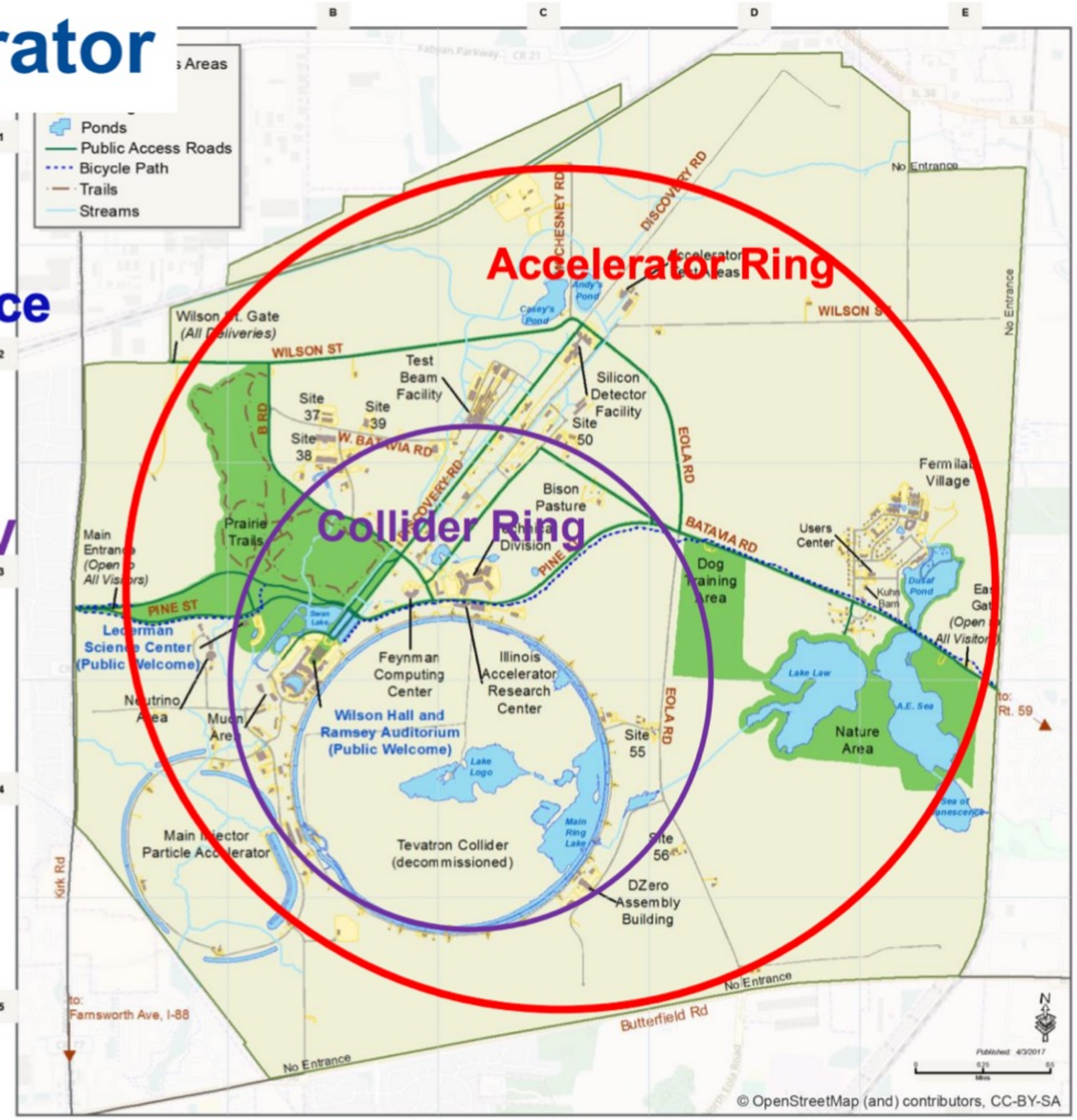
(B_{max} = 16T, B_{pulse} =±4T)

10 TeV collider

Collider Ring ~10 km

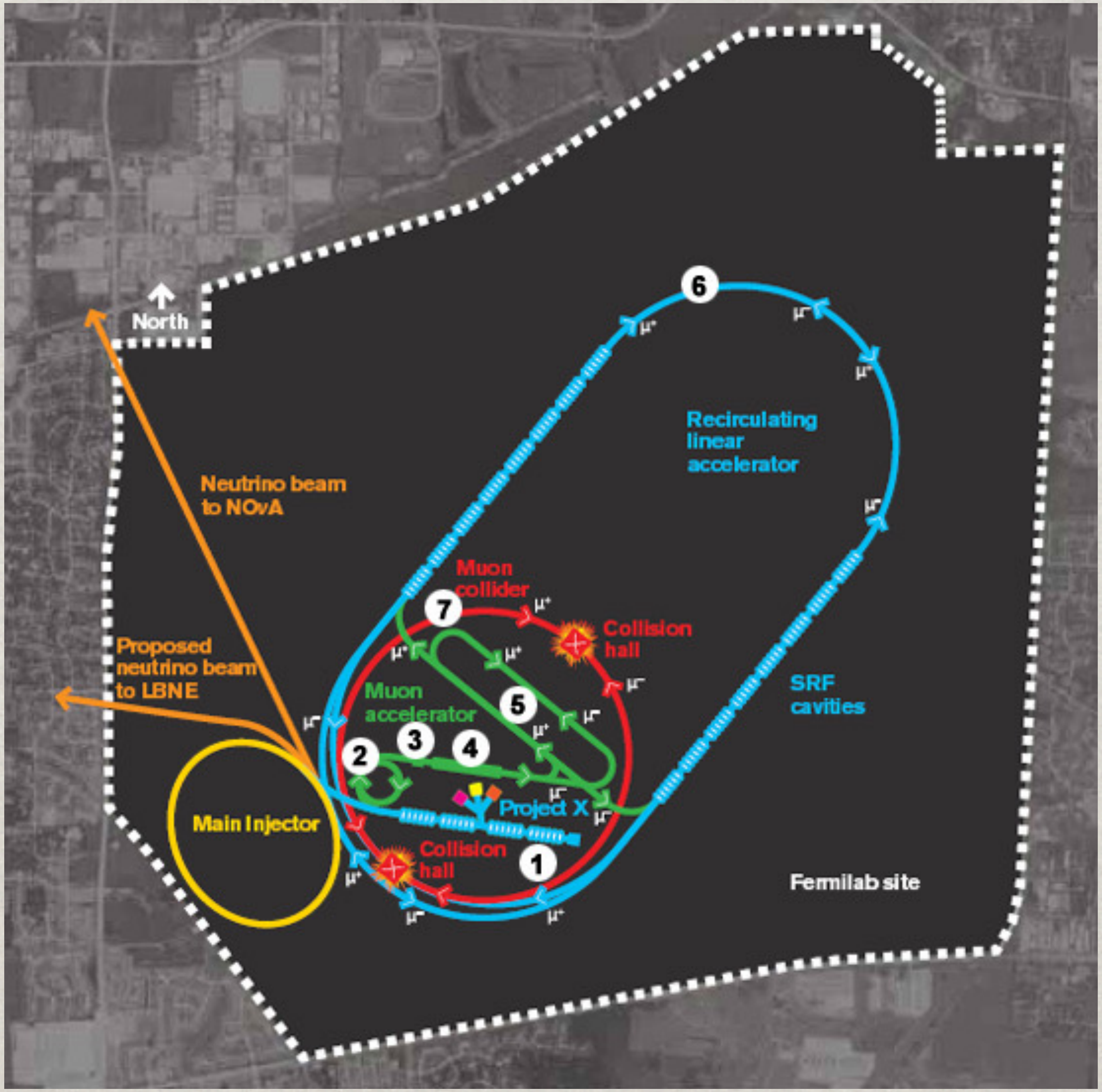
B_{ave} = 10 T

τ_{μ} = 0.104 s



Daniel Schulte; Mark Palmer; Katsuya Yonehara talk, March 2022

Muon collider on FNAL site: It may reach ~ m_h – 10 TeV



(Curtesy of Pushpa Bhat)

Snowmass Day: https://indico.fnal.gov/event/50538

Accelerator Frontier Recommendation (to P5)

On Colliders: We need an integrated future collider R&D program to engage in the design and to coordinate the development of the next generation collider projects:

- to address in an integrated fashion the technical challenges of promising future collider concepts, that are not covered by the existing *General Accelerator R&D* (GARD) program.
- to enable synergistic U.S. engagement in ongoing global efforts (e.g., FCC, ILC, IMCC)
- to develop collider concepts and proposals for options feasible to be hosted in the U.S. (e.g., CCC, HELEN, Muon Collider, etc)

Physics Potential @ Future Colliders

Precision Higgs Physics: $(v/\Lambda)^2 < 6\%$

ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

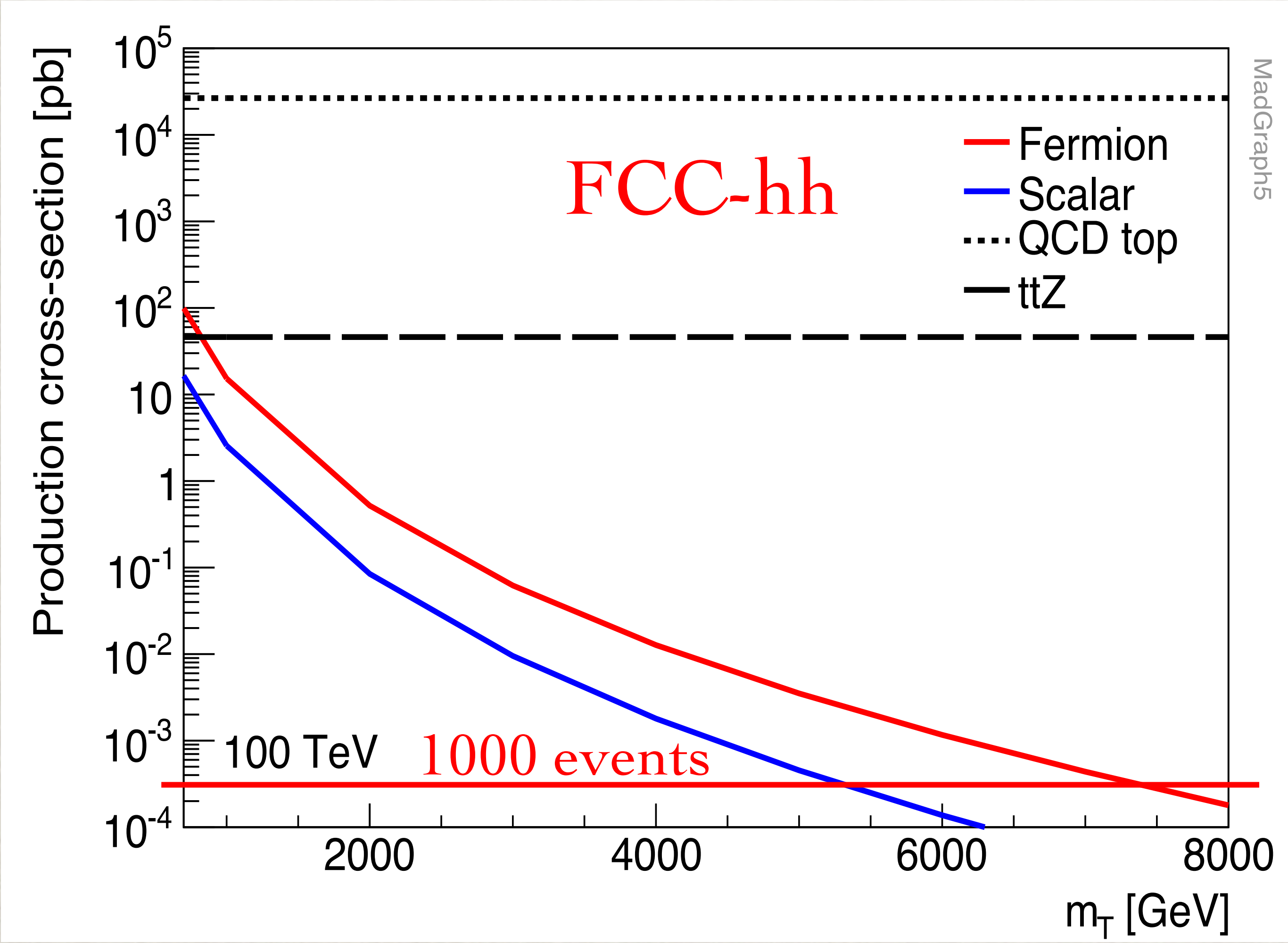
- Model-independent measurement:
  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV, $\Delta k_{W,Z} < 1\%$
  (HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)
- Higgs Factory: **10^6** Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

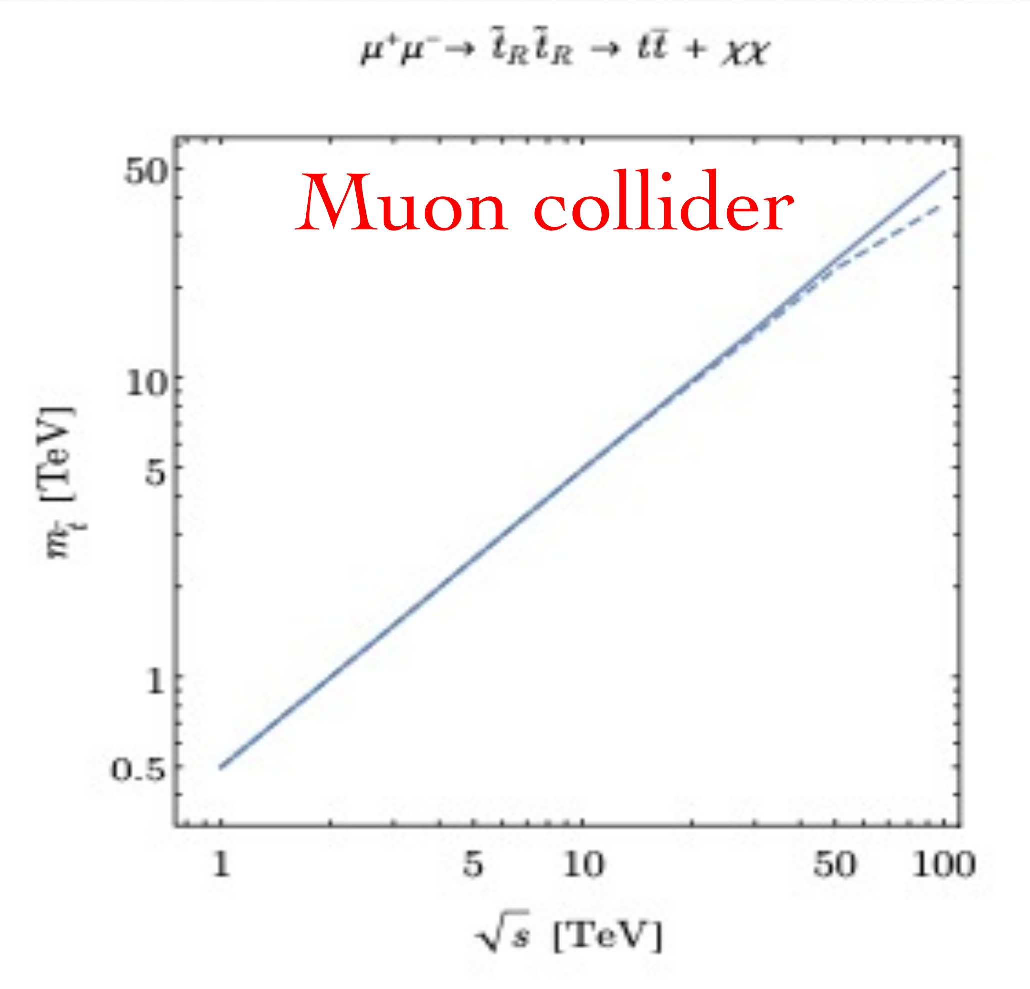
- FCC-hh / SPPC:
  $\Delta k_{HHH} \sim 5\%$
- 14 TeV muon collider:
  $\Delta k_{HHH} \sim 3\%$, $\Delta k_{W,Z} < 0.5\%$, $Y_\mu \sim 1\%$

Critically important to test the EW phase transition!

ILC: arXiv:1710.07621; TLEP Report: 1308.6176;
FCC: Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495;
muC: TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204.

Pushing the "Naturalness" limit





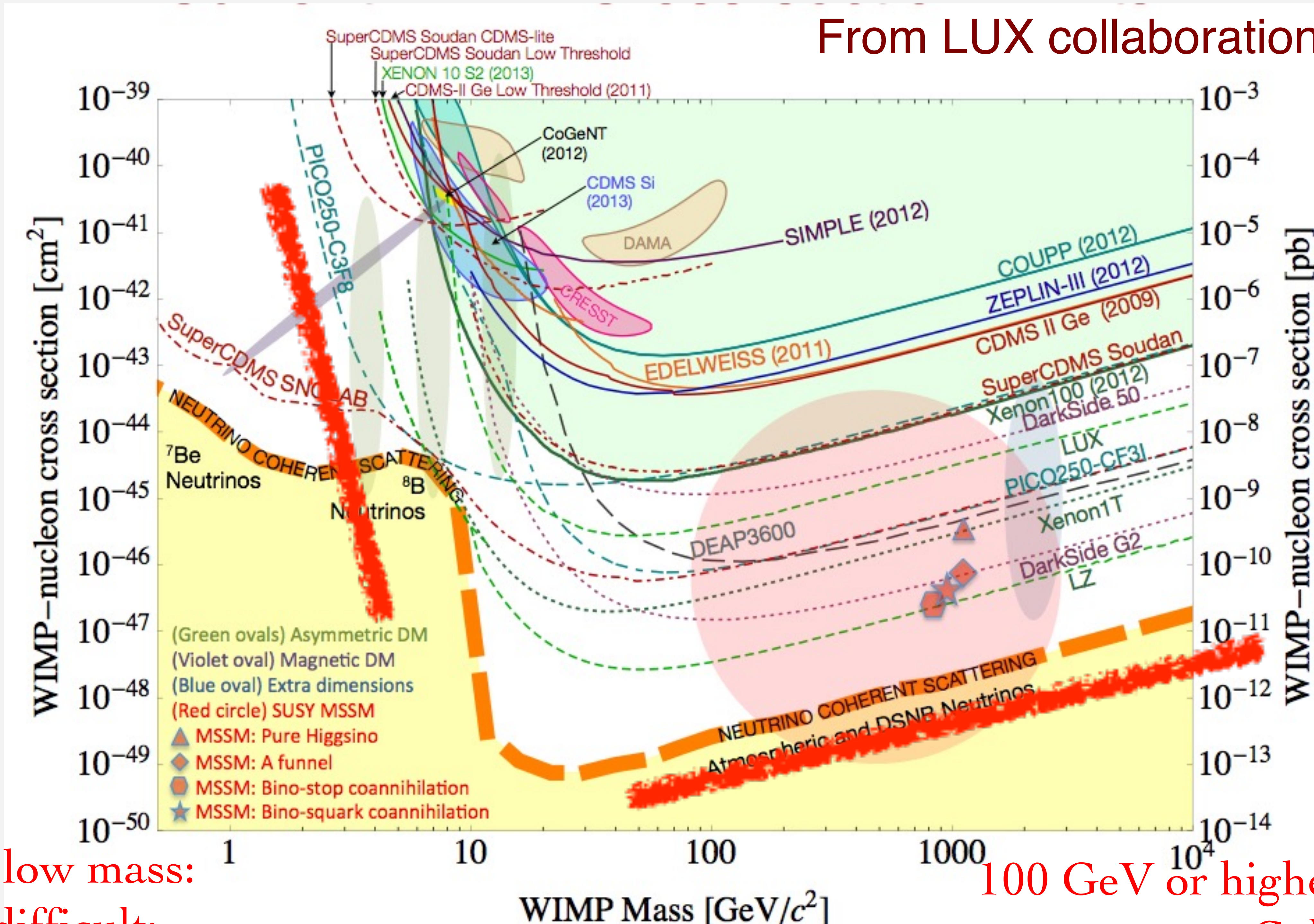
Top quark partners searches:

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

DM Searches

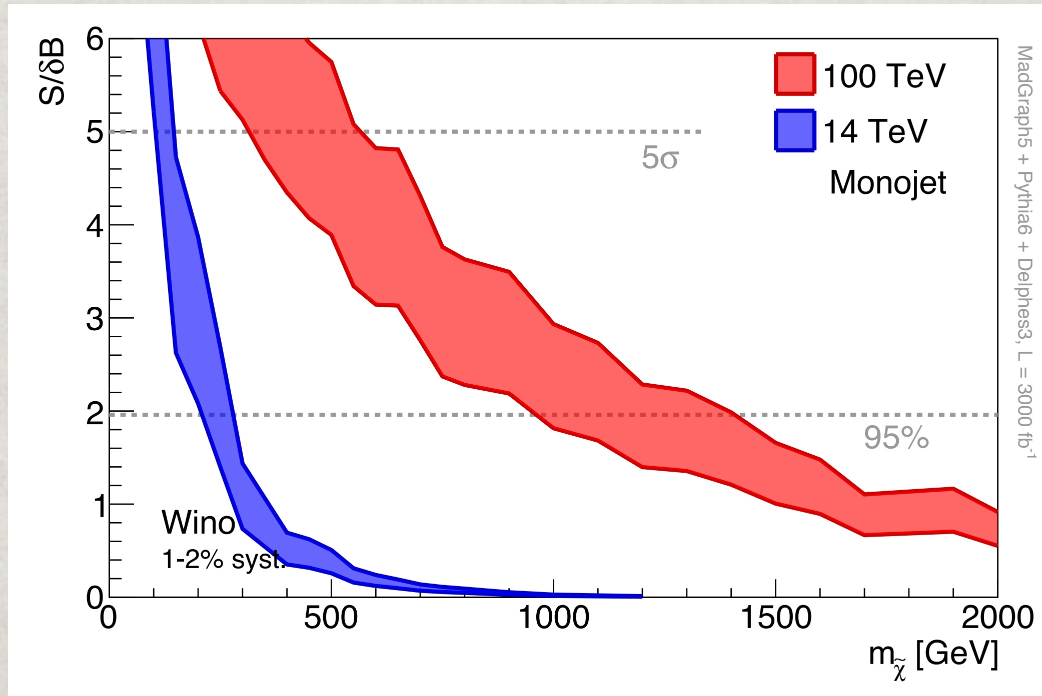


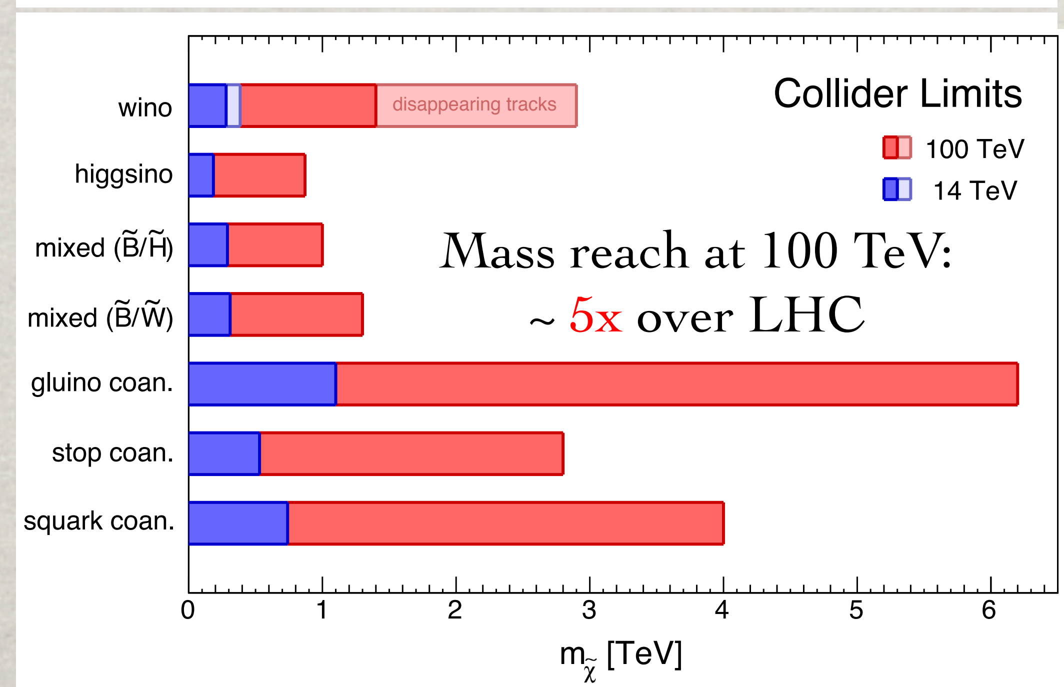
GeV low mass:
DD difficult;
Collider complementary

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

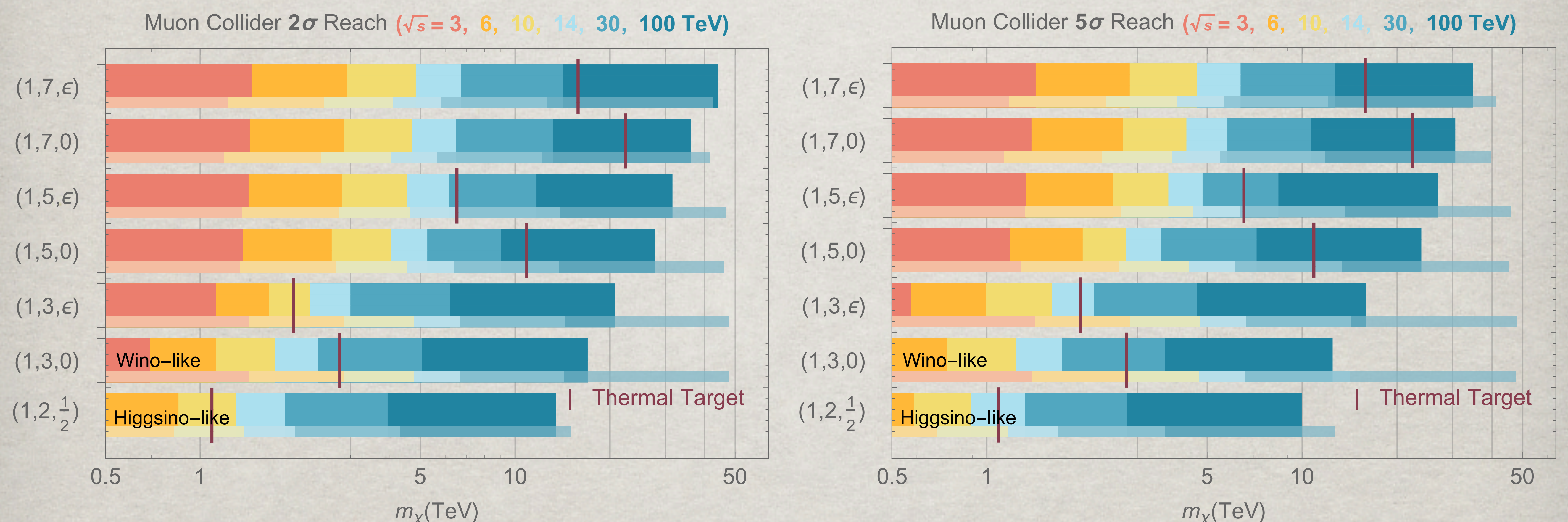
WIMP DM:
mass bounded by the thermal relic

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





The mass reach for minimal WIMP DM: Model-independent EW multiplets @ muC



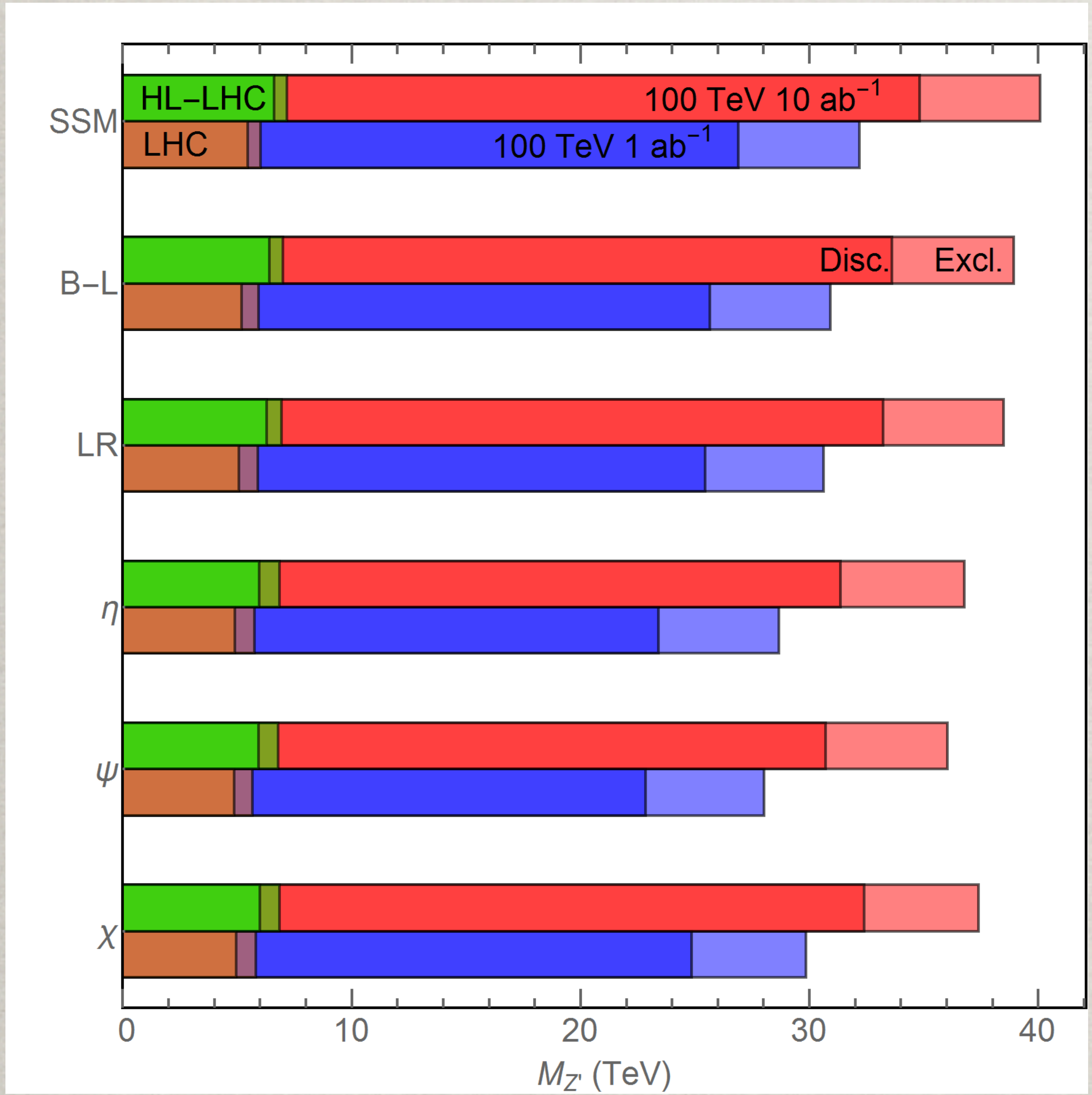
E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

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

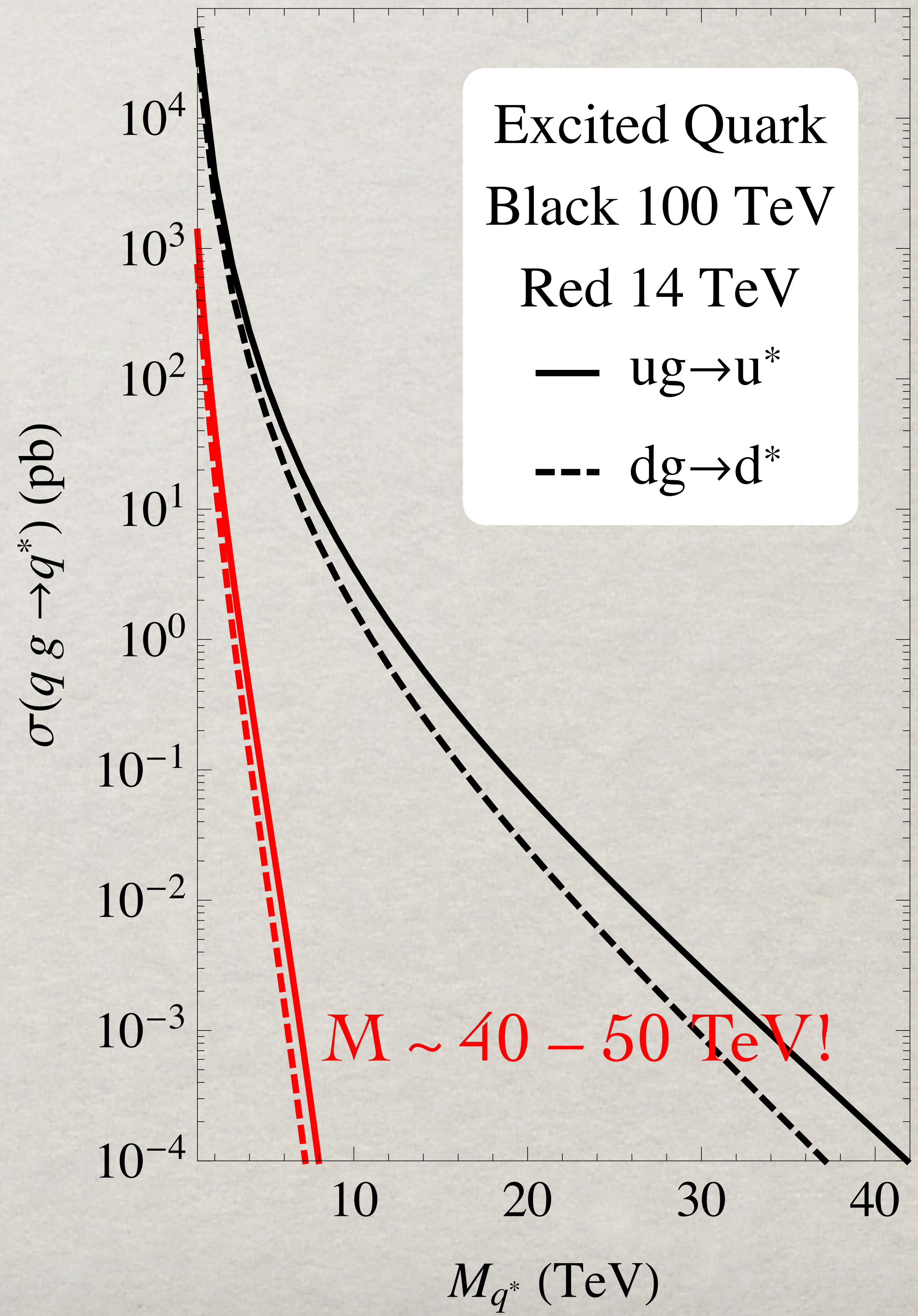
New Particle Searches

Electroweak Resonances: Z',W'



~ 6x over LHC

Colored Resonances:



Several Useful References:

1. Overview of accelerators – V.Shiltsev, Physics Today **73**, 4, 32 (2020).
2. RMP colliders – V.Shiltsev, F.Zimmermann, Rev.Mod.Phys. **93**, 015006 (2021).
3. Ultimate limits of colliders – V.Shiltsev, Proc. IPAC'21, WEPAB017 (2021).
4. Snowmass Accelerator Frontier report – arxiv:2209.14136
5. ITF Report – T.Roser, V.Shiltsev, et al, arXiv:2208.06030
6. *αβγ* cost model – V.Shiltsev, JINST **9** T07002 (2014).
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