FERMILAB-SLIDES-23-326-PPD

The Future of the Energy Frontier

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Why and how

A new era

“Higgs Factories”

“Discovery” Machines

Summary and outlook

WHY?

- **A ~ century of discoveries**

  1919 proton, 1927 beta decay spectrum, 1932 neutron, 1932 positron, 1936 muon, 1947 kaon, 1947 pion, 1955 antiproton, 1956 electron neutrino, 1962 muon neutrino, 1968 partons, 1974 charm quark, 1977 b quark, 1977 tau, 1979 gluon, 1983 W and Z, 1995 top quark, 1998 neutrino oscillations, 2000 tau neutrino, 2000 quark-gluon plasma, 2012 Higgs boson.

- **Fundamental questions open to date**
  - **Why the Electroweak Symmetry breaking occurs?**
  - **What is the origin of the matter vs. antimatter asymmetry?**
  - **What is dark matter?**
  - **What is the origin of neutrino's mass?**
  - **What is the origin of flavor?**
  - **…**
- **Opportunity for groundbreaking discoveries**

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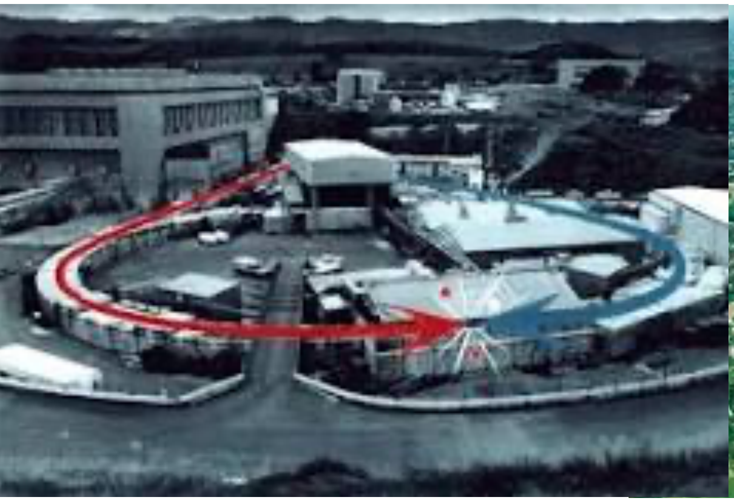
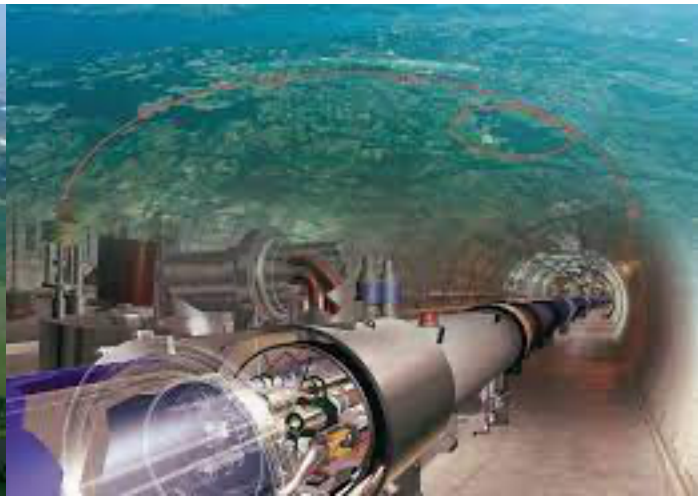
ENERGY FRONTIER

- **A ~ century of discoveries**

  *1919 proton, 1927 beta decay spectrum, 1932 neutron, 1932 positron, 1936 muon, 1947 kaon, 1947 pion, 1955 antiproton, 1956 electron neutrino, 1962 muon neutrino, 1968 partons, **1974 charm quark**, 1977 b quark, **1977 tau**, **1979 gluon**, **1983 W and Z bosons**, **1995 top quark**, 1998 neutrino oscillations, 2000 tau neutrino, **2000 quark-gluon plasma**, **2012 Higgs boson***

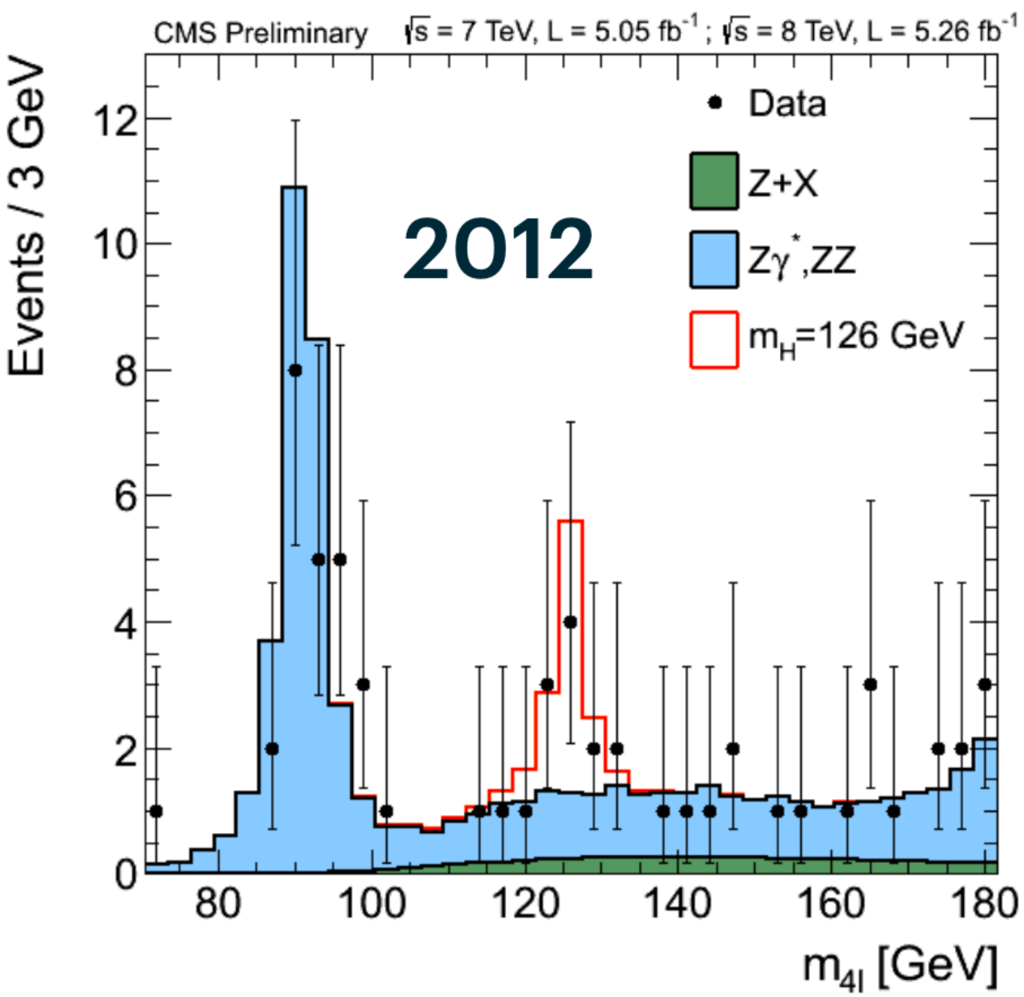


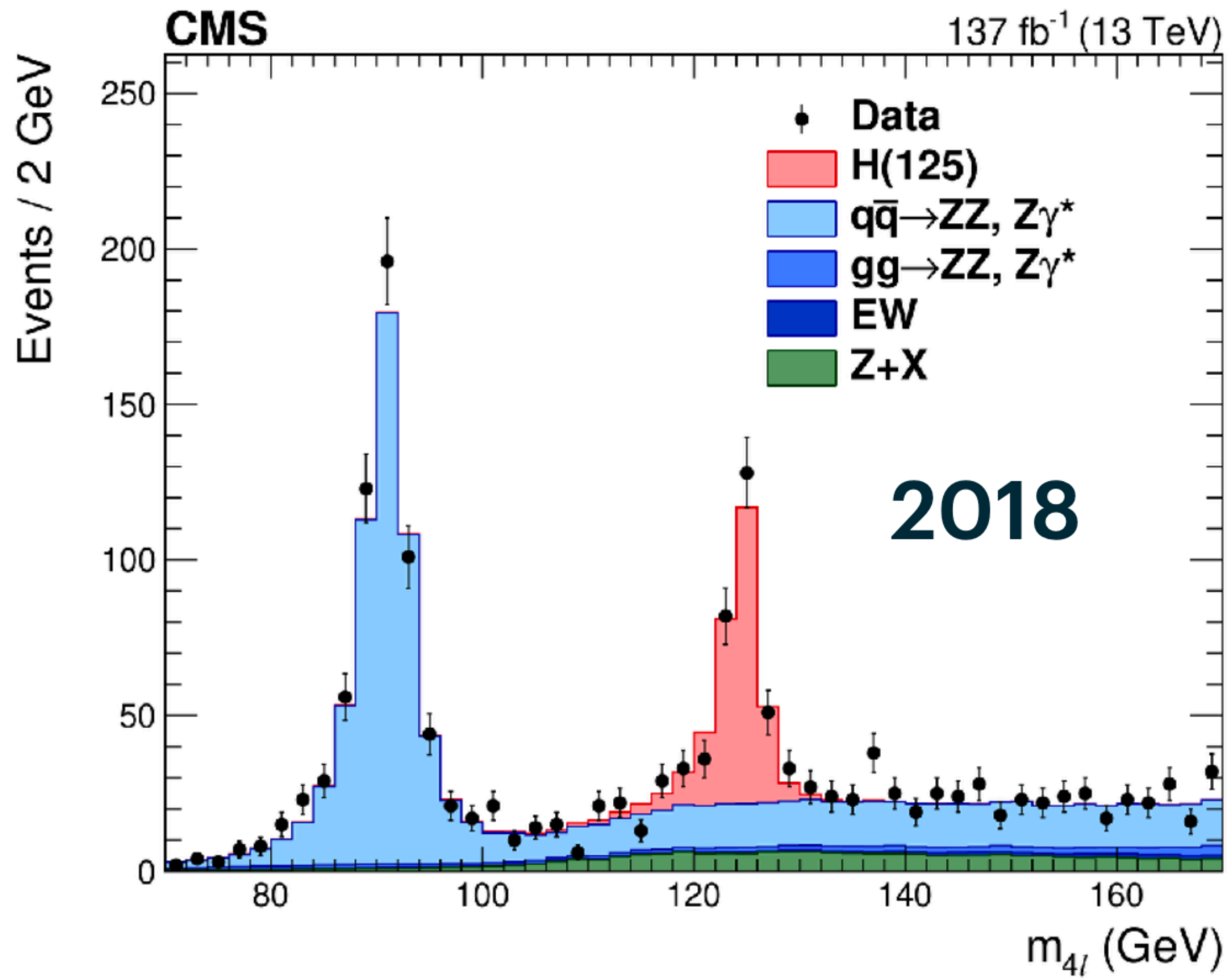


- **Colliders as essential probes to decode Nature at its most fundamental level**
  - **Exploring ~ all sectors of the SM and the Unknown @ one experimental complex**

A NEW ERA

- **Past discoveries inform the path forward ("data driven")**





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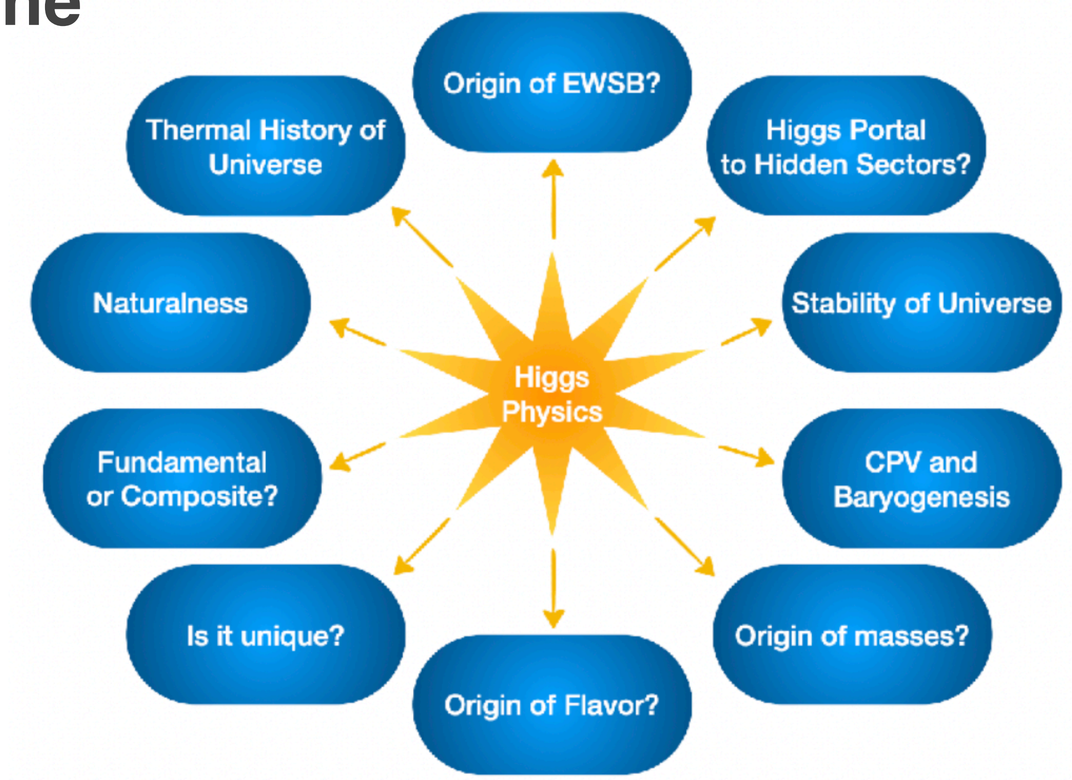
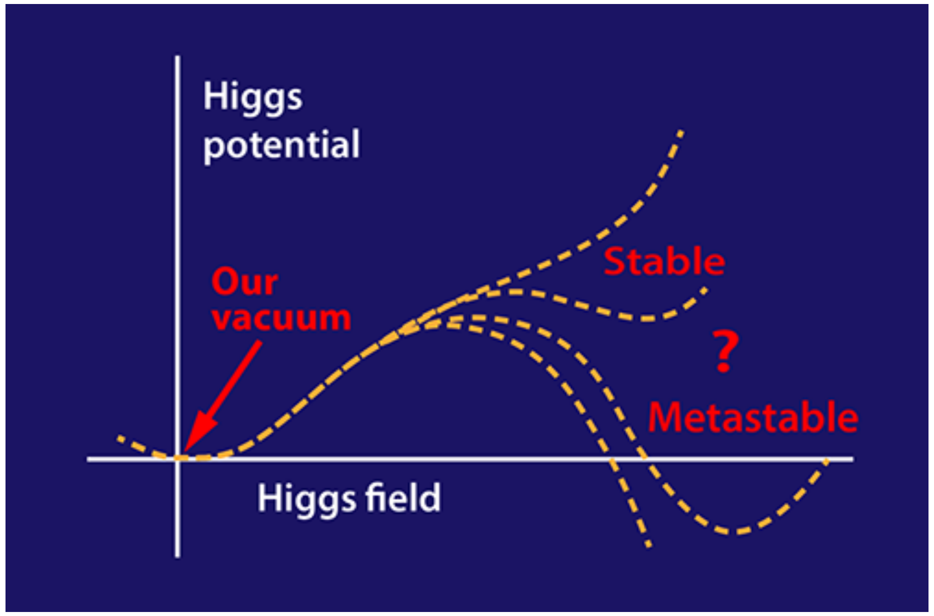
THE HIGGS BOSON AS A WINDOW TO NEW PHYSICS

- The Higgs boson is our probe to understand the Universe
  - Its matter content
  - Its origin
  - Its evolution …
- A precision measurement of the Higgs boson properties challenge the limits and the consistency of the SM and directly probe for the existence of new particles
  - Mass
  - Couplings (including to invisible particles)
  - Self couplings
  - Other states….





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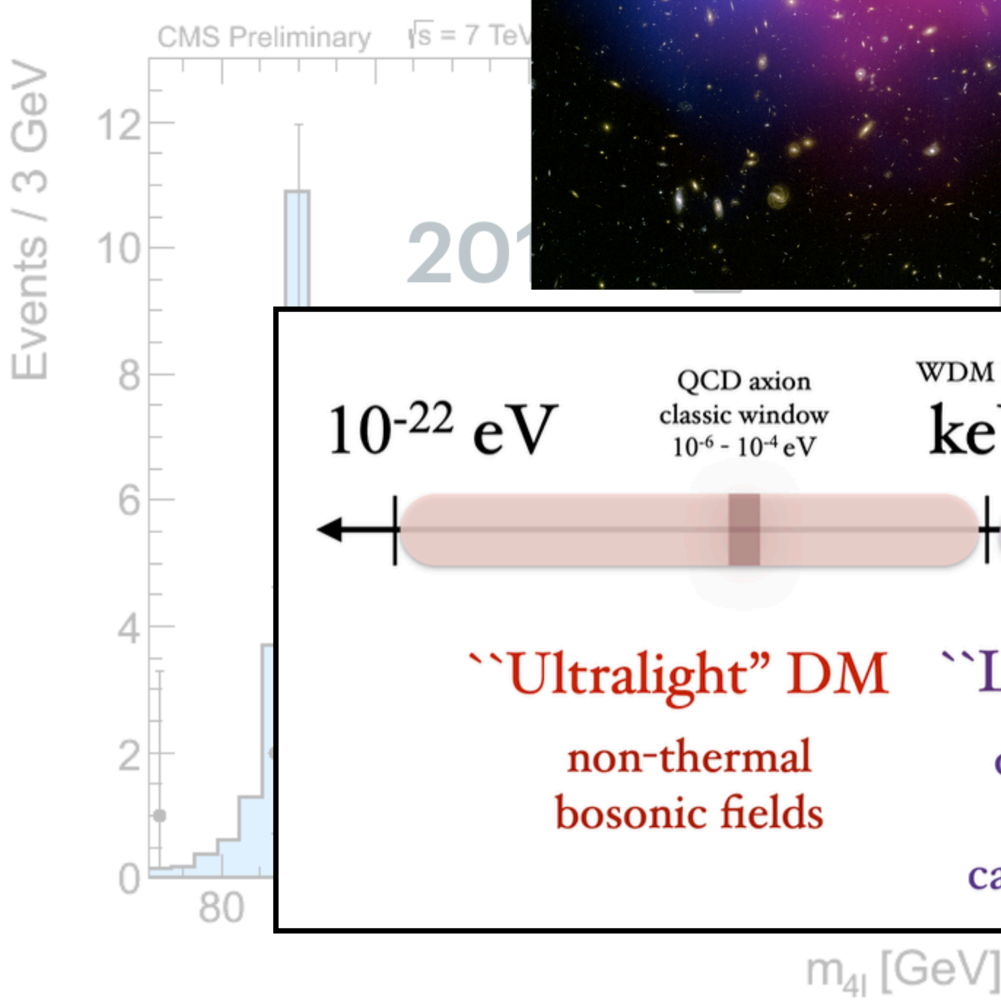
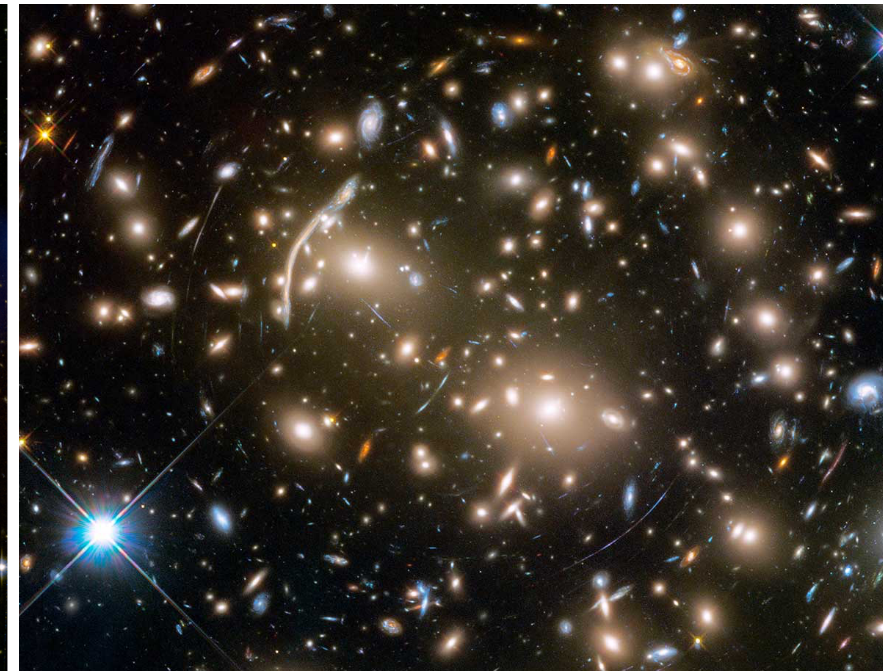
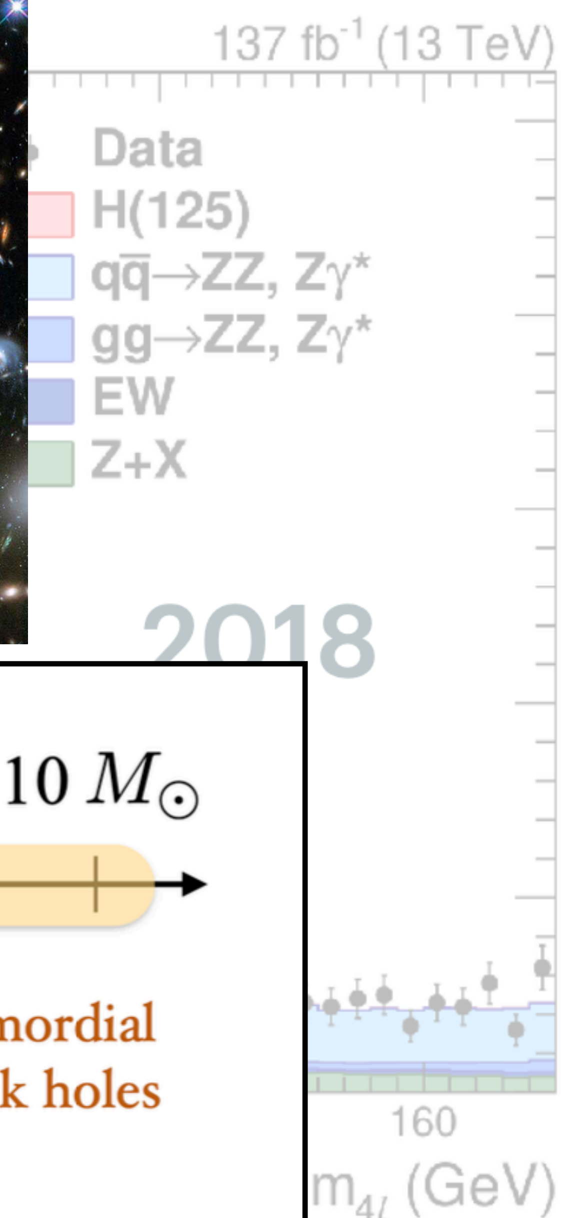
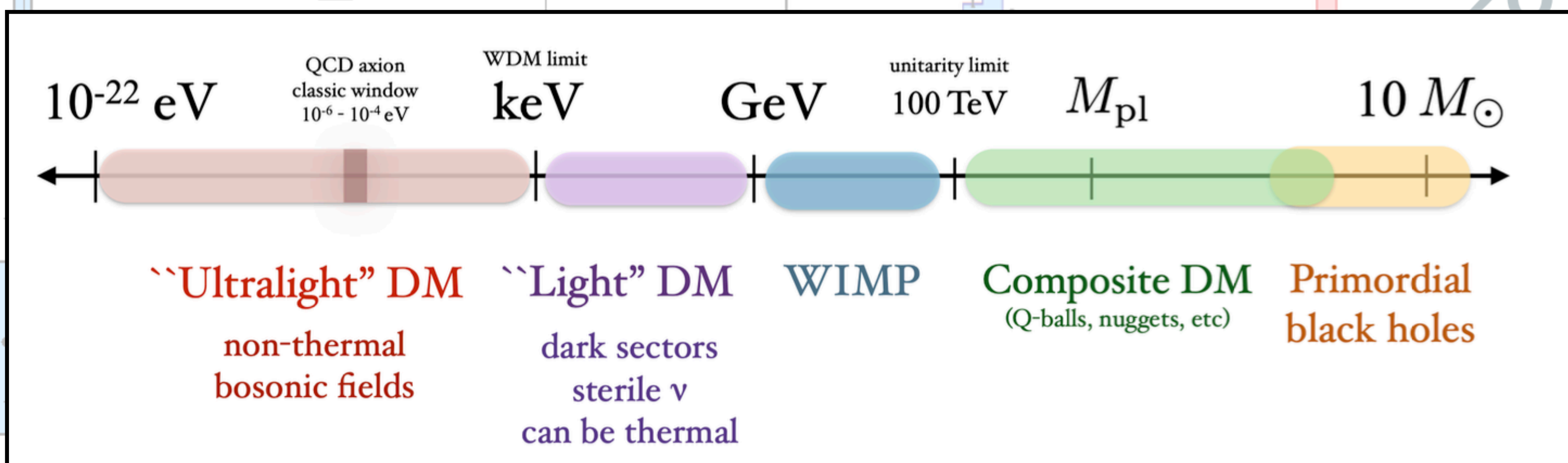
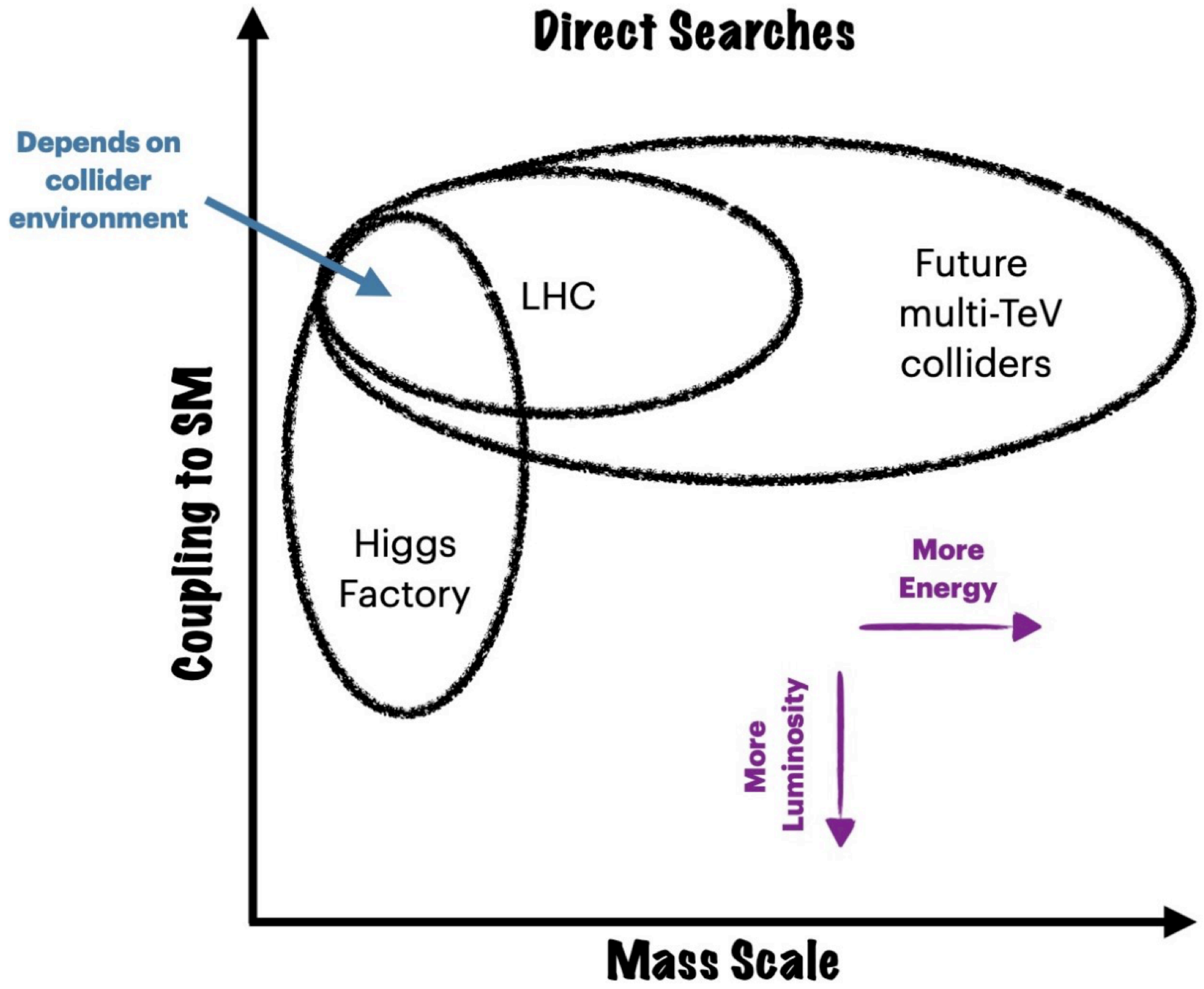








THE VISION FOR FUTURE COLLIDERS



“HIGGS FACTORIES”

PRECISION MACHINES

with potential for direct

discoveries at low scales

SNOWMASS VIEW: HIGGS FACTORIES

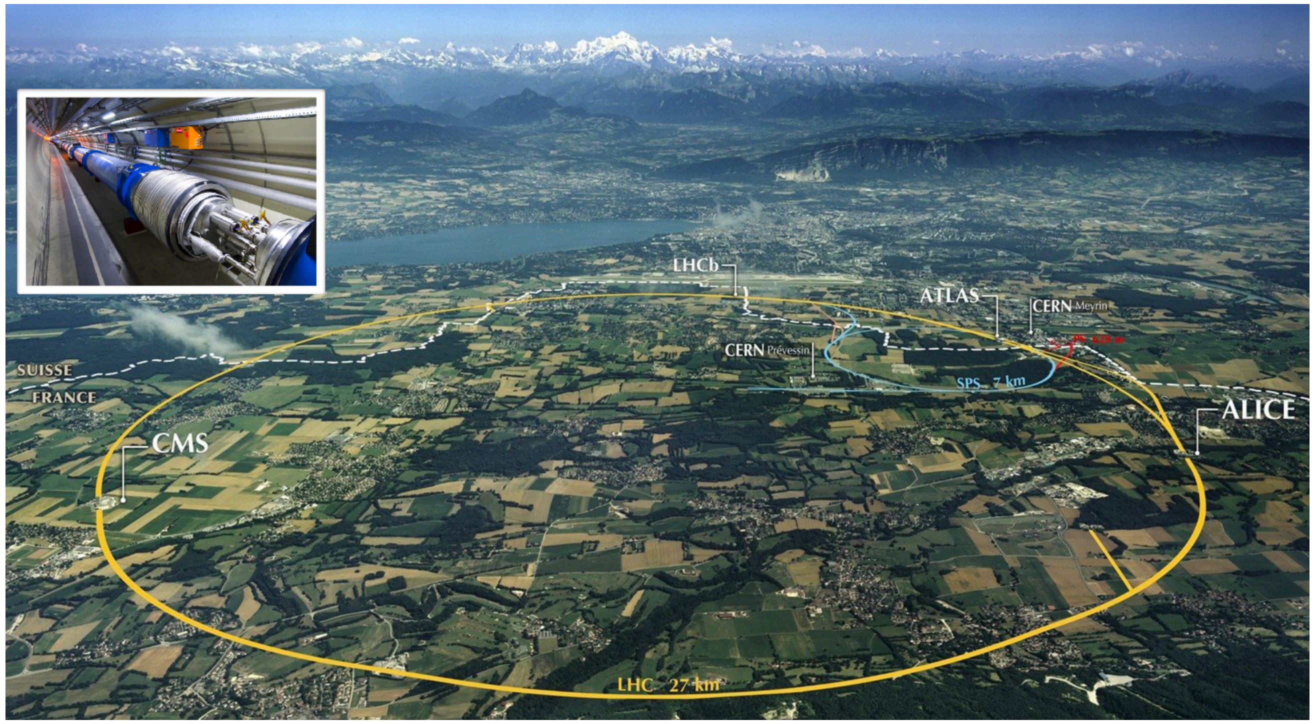
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500* GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

Assume the same physics reach for ILC and newly proposed C^3

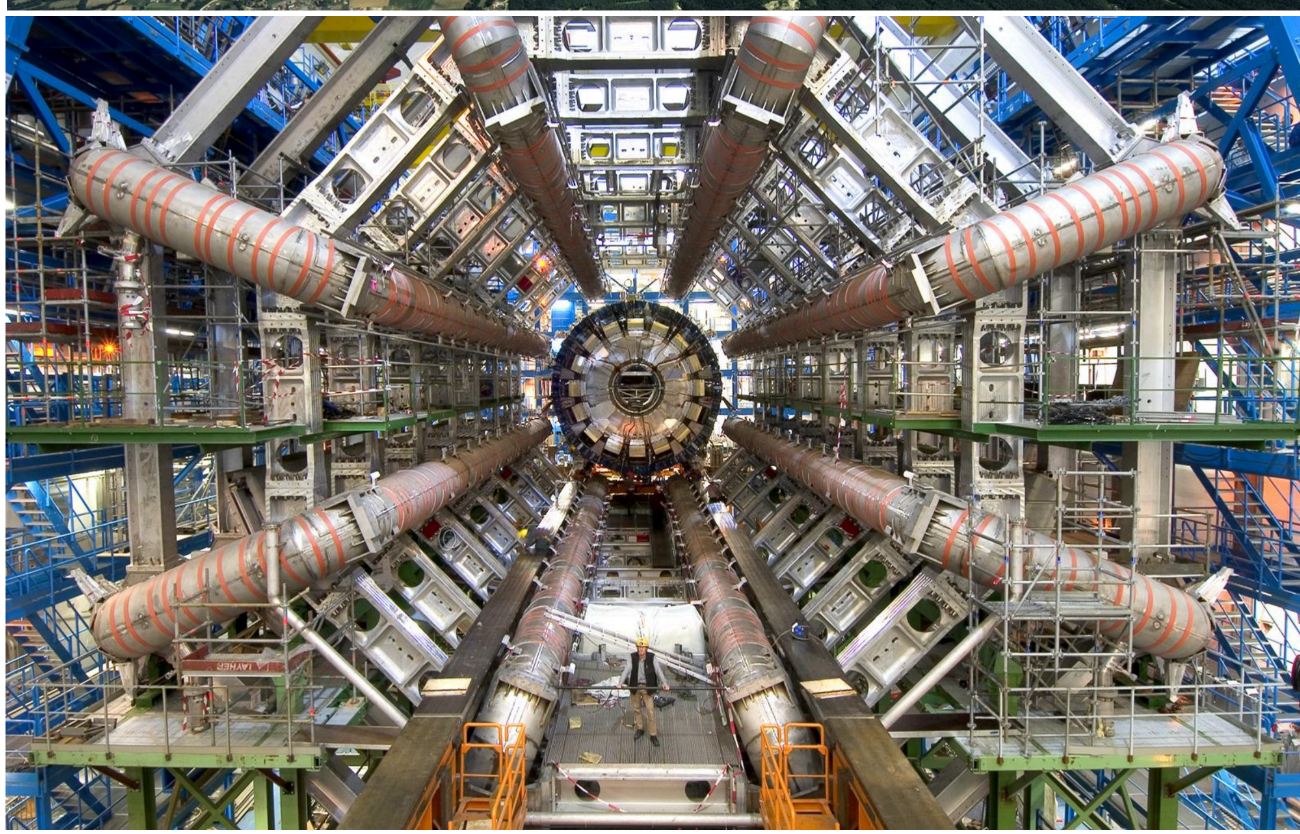
Polarization not in baseline design for C^3

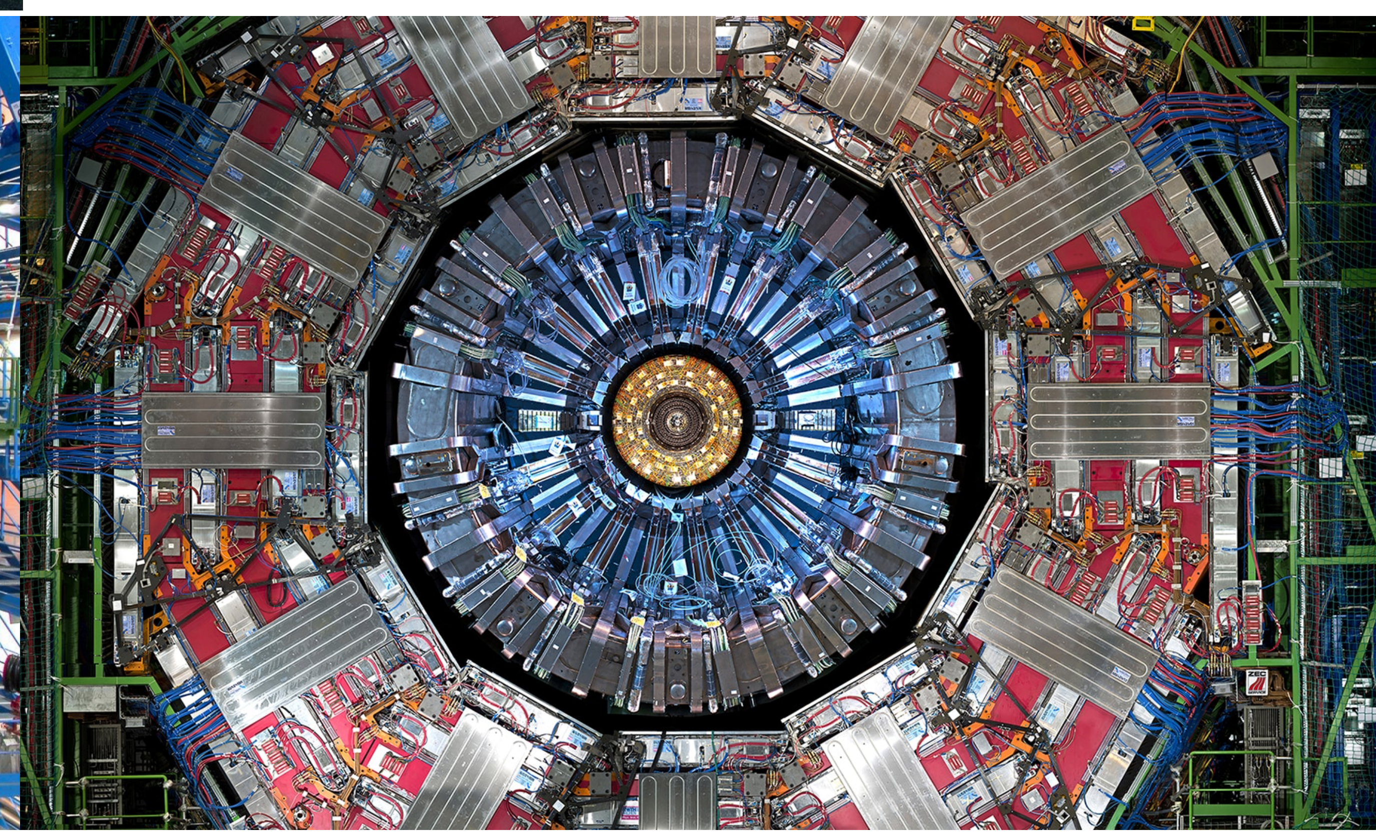
Other technological solutions (including HELEN) summarized in https://arxiv.org/pdf/2209.14136.pdf

THE LARGE HADRON COLLIDER



- Data taking started in 2009
- Run 3 is on-going
- The High Luminosity LHC will operate till ~2040
  - 95% of data remains to be collected!





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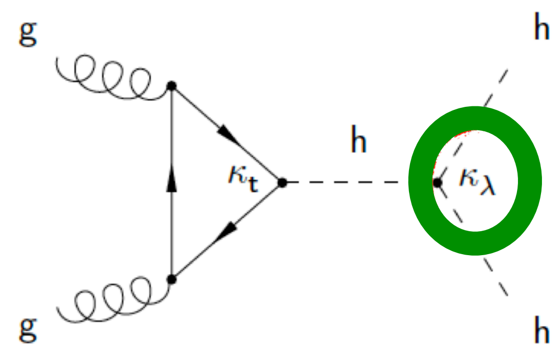
THE HIGGS BOSON TODAY

- **Mass** **± 140 MeV**
- **(Indirect) width** **@ 75%**
- **Couplings to top, bottom, gauge bosons** **O(5-10)%**
- **Coupling to 1st generation and 2nd generation quarks** **n/a**
- **Coupling to electrons** **n/a**
- **Self coupling** **n/a**
- **BR to invisible** **< 15%**

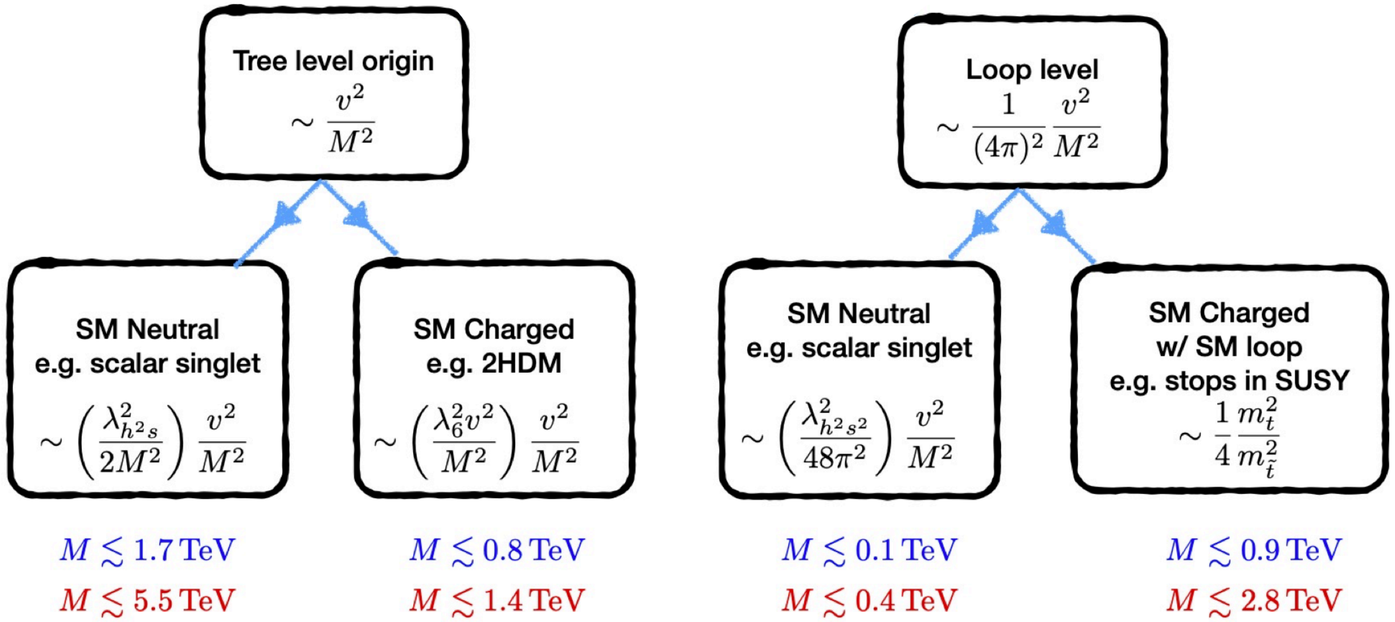
$$V(h) \equiv \frac{1}{2} m_h^2 h^2 + \frac{\lambda_3}{3!} h^3 + \frac{\lambda_4}{4!} h^4 + \cdots$$



What is our target?

2209.07510

$\delta\eta_{SM}$ $\sim 1\%$ $\sim .1\%$

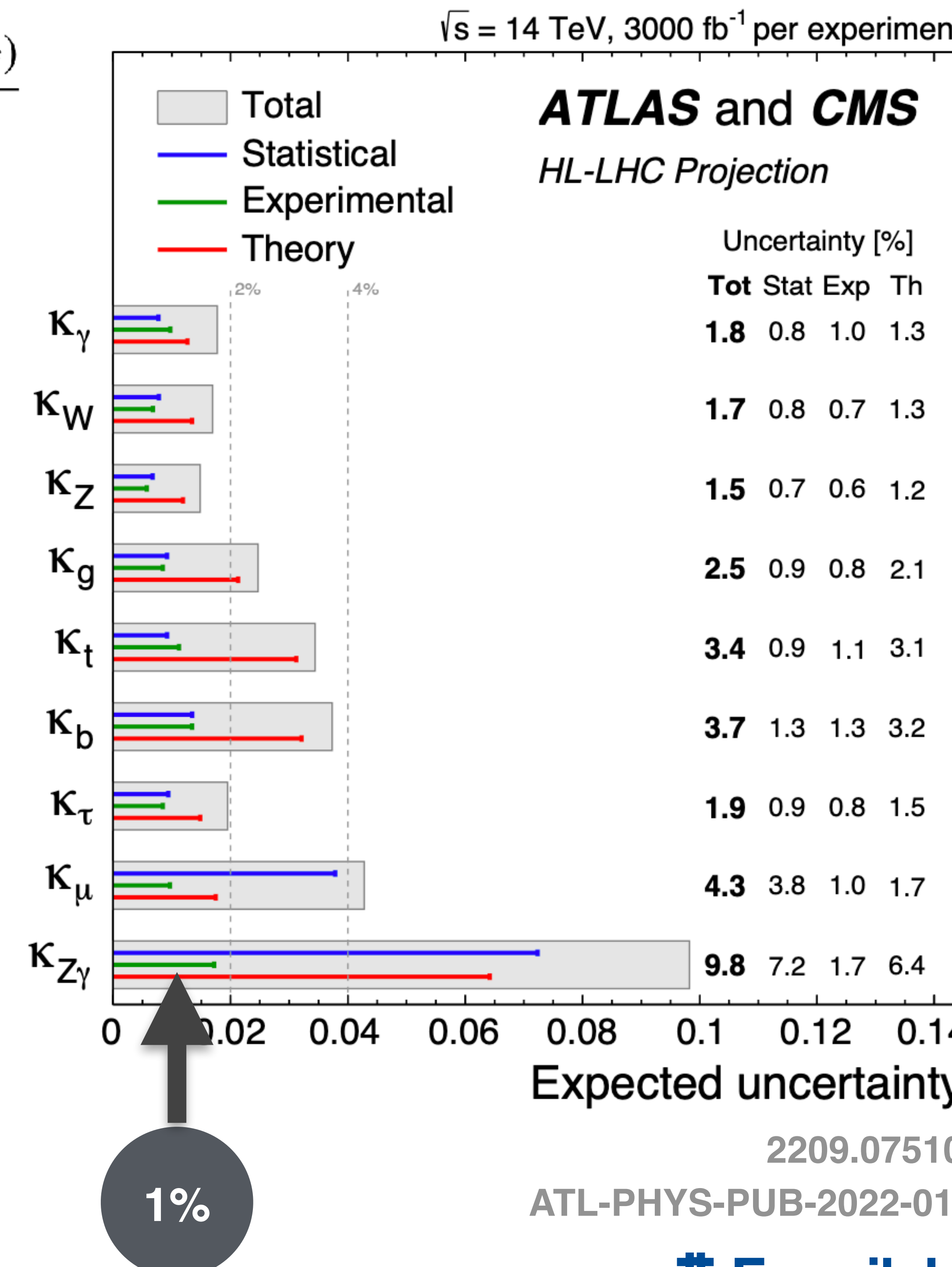


THE HIGGS BOSON IN THE 2040'

By the end of the HL-LHC, 170M Higgs bosons per experiment (and 120k HH)

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

- Mass ± 30 MeV
- (Indirect) width @ 17%
- Couplings ~ %
  - Couplings to u, d, and s quarks n/a
  - κ_c < 1.75 at the 95% CL
  - Couplings to electrons n/a
- BR into invisible < 2.5 %
- Trilinear coupling λ_3 @ 50%
- Quartic coupling λ_4 n/a



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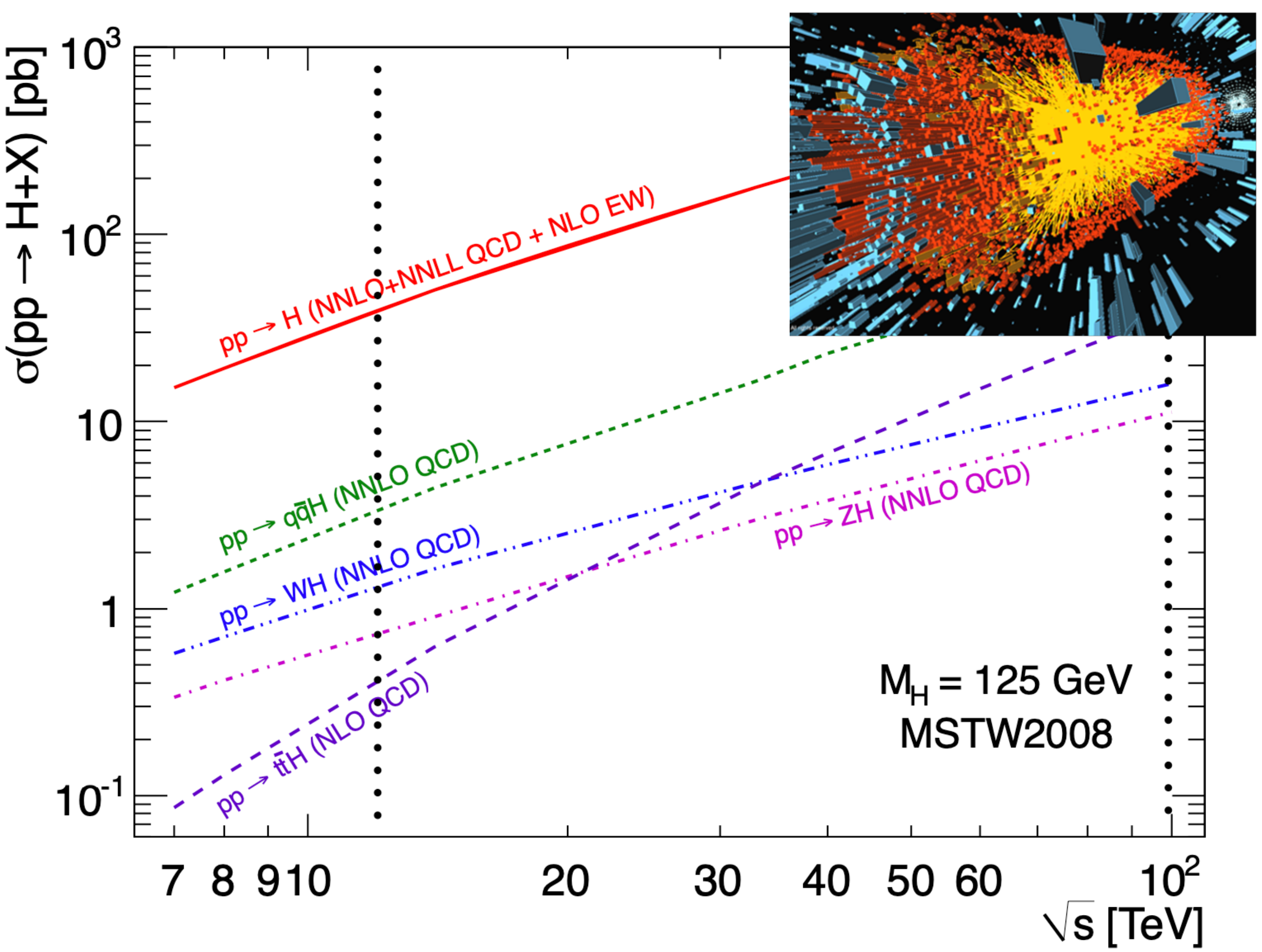
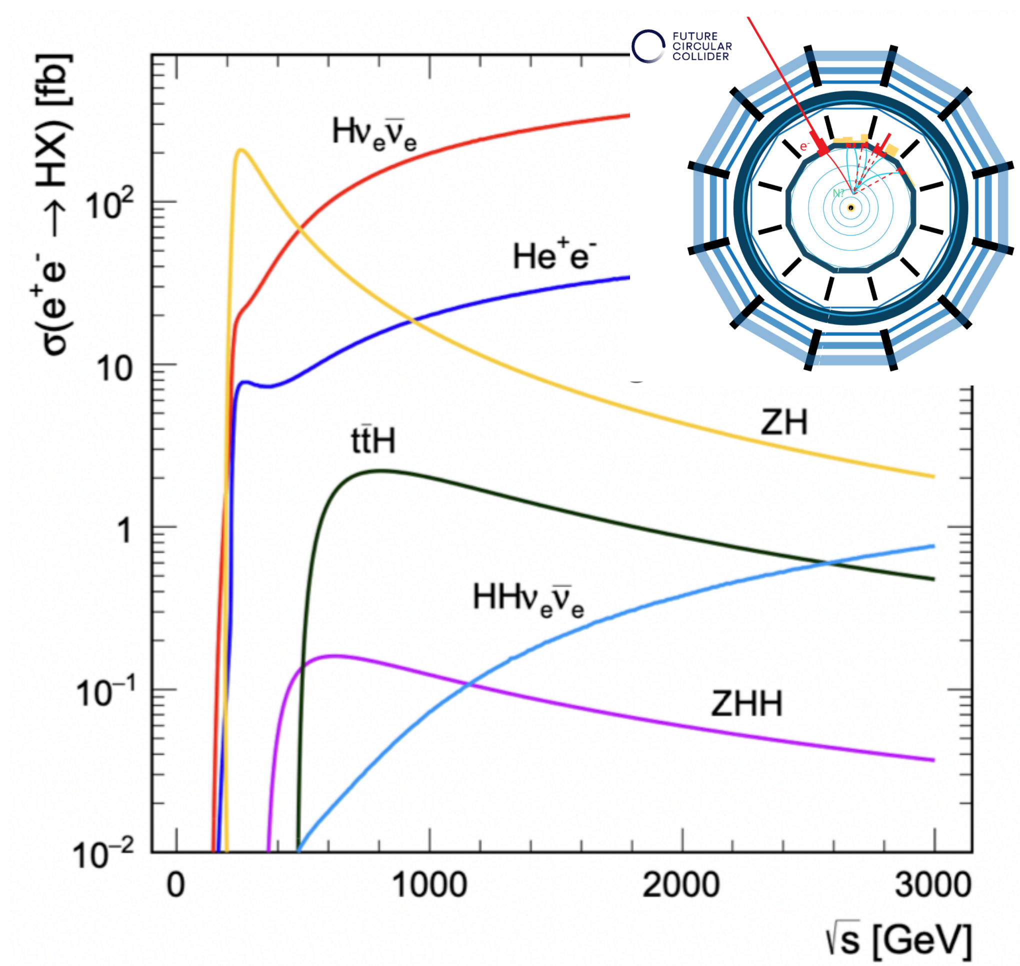
FROM PROTON TO ELECTRON MACHINES

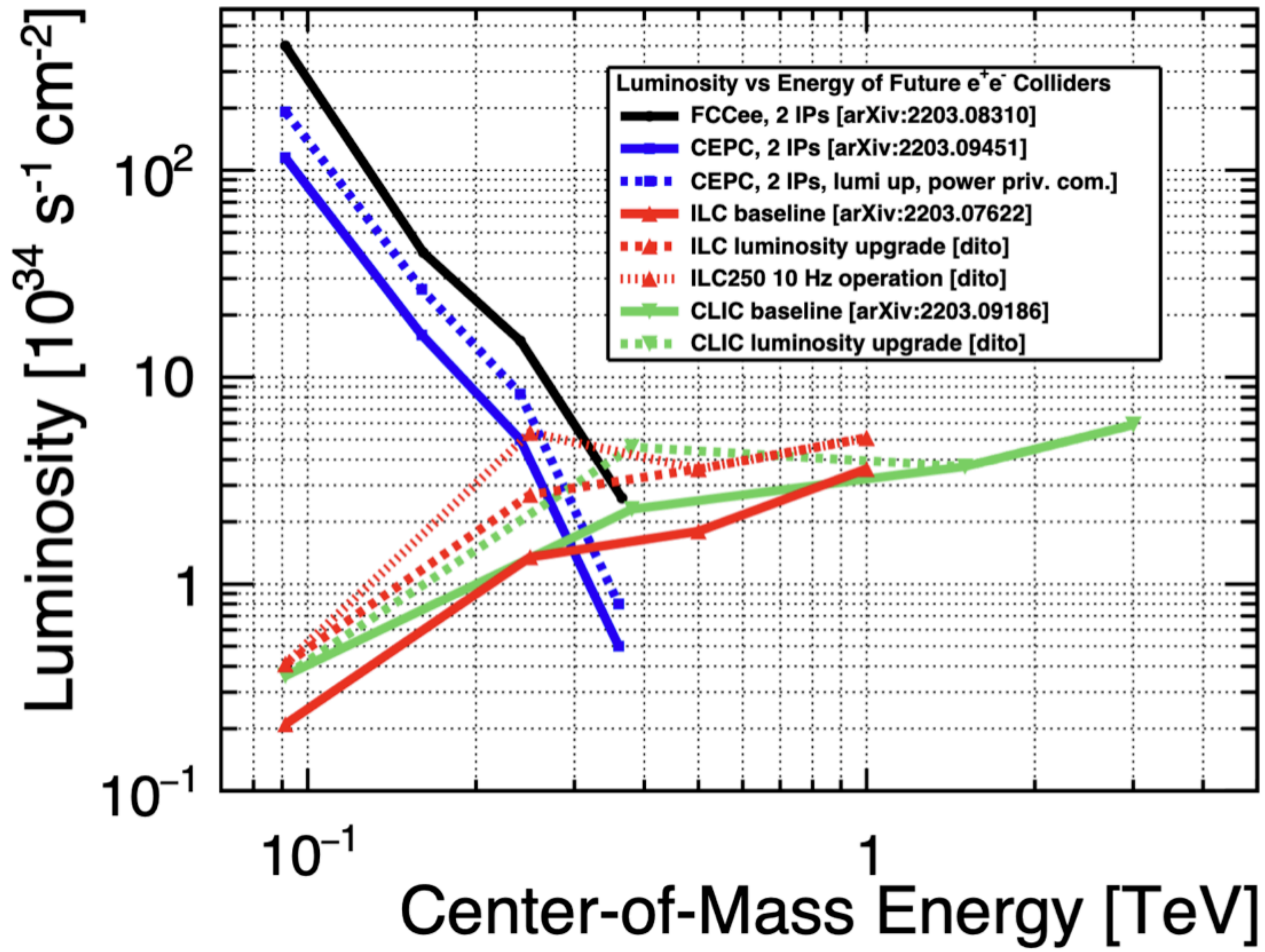
- LHC & HL-LHC
  - High cross-section ~ 60 pb
  - Very low S/B
  - Challenging environment

- 1st stage e^+e^- Higgs factory - O(250 GeV)
  - Low cross-section ~ 0.001 w.r.t LHC
  - S/B ~ 1
  - Clean environment
  - Well defined initial state (and polarization)





LINEAR VS CIRCULAR ELECTRON MACHINES



	Circular	Linear
Beam Polarization	Transverse	Longitudinal
Interaction Points	2 to 4	Push/pull for 2 detectors
Energy Upgrade	pp, eh, AA	Increase of √s

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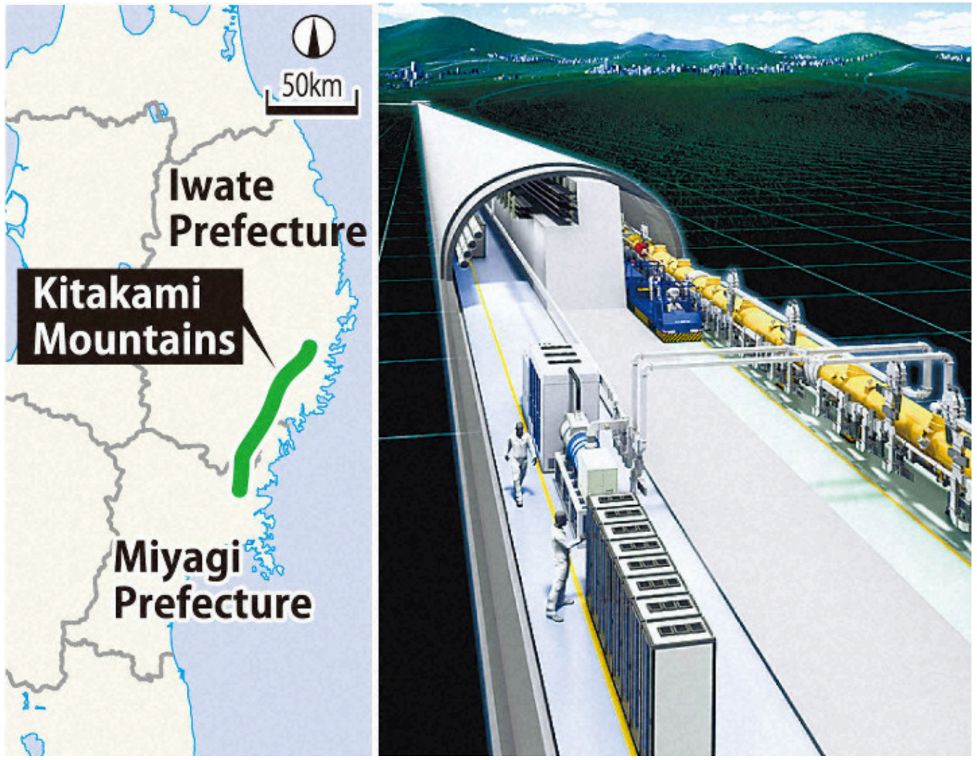
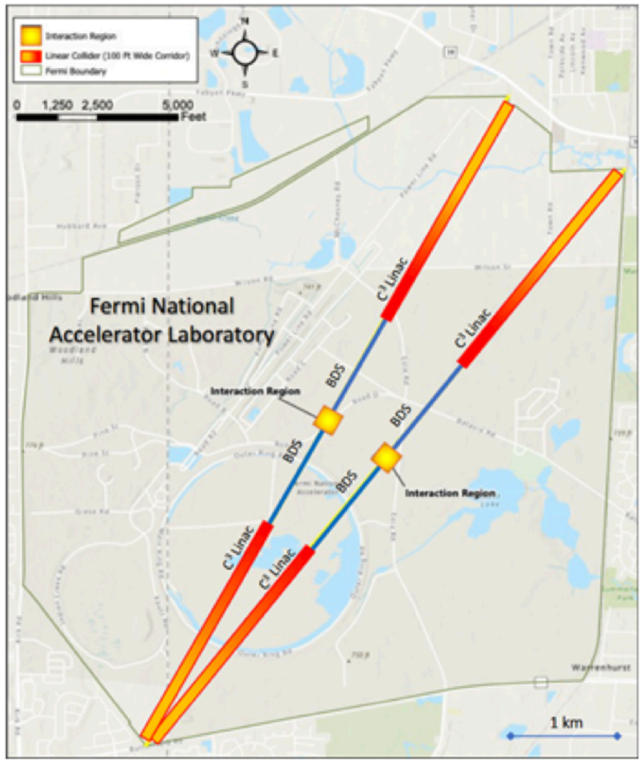
LINEAR COLLIDERS: SRF TECHNOLOGY

- International Linear Collider
  - SRF cavities, 1.3 MHz, 31.5 to 35 MV/m gradient
    - Up to 50 MV/m already demonstrated!
  - ~21 Km footprint
  - “Shovel” ready
    - TDR in 2013
    - Mature technology, already in use in European XFEL, LCLS-II / LCLS-II-HE
- Newly proposed HELEN: 1.3 GHz traveling wave SRF at 70 MV/m gradient
  - Cost and AC power savings, ~7.5 km footprint, could be upgraded either to higher luminosity or to higher energy



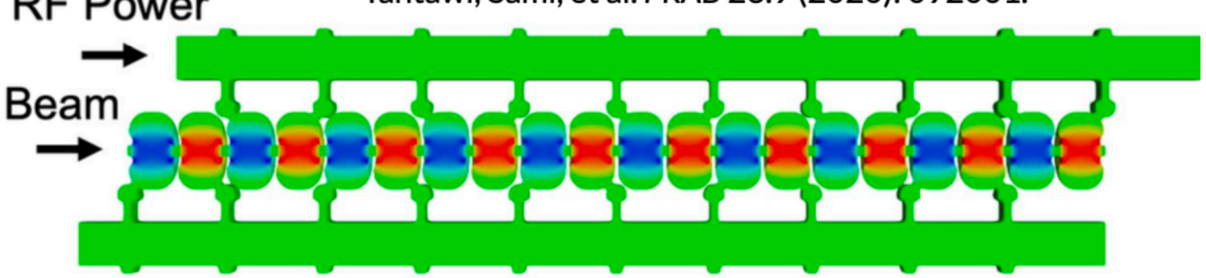


LINEAR COLLIDERS: RF TECHNOLOGY

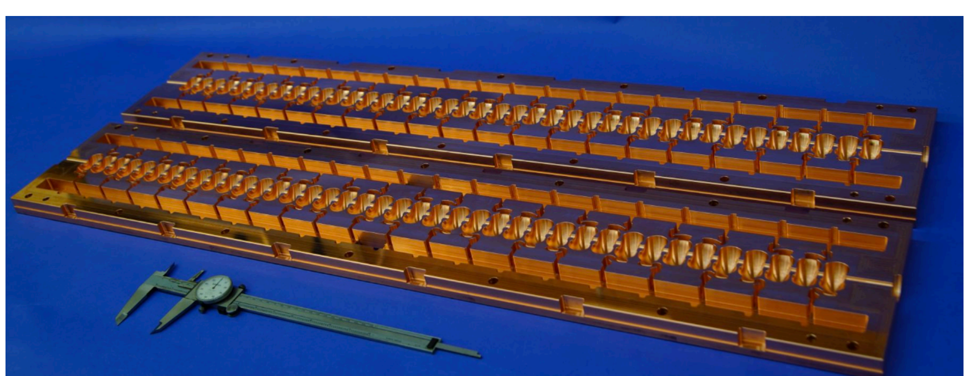
- Cool Copper Collider or C^3
  - Power is distributed to each cavity from common RF manifold
  - 5.7 GHz 70 MV/m cool copper RF at 77K
  - 8 Km footprint

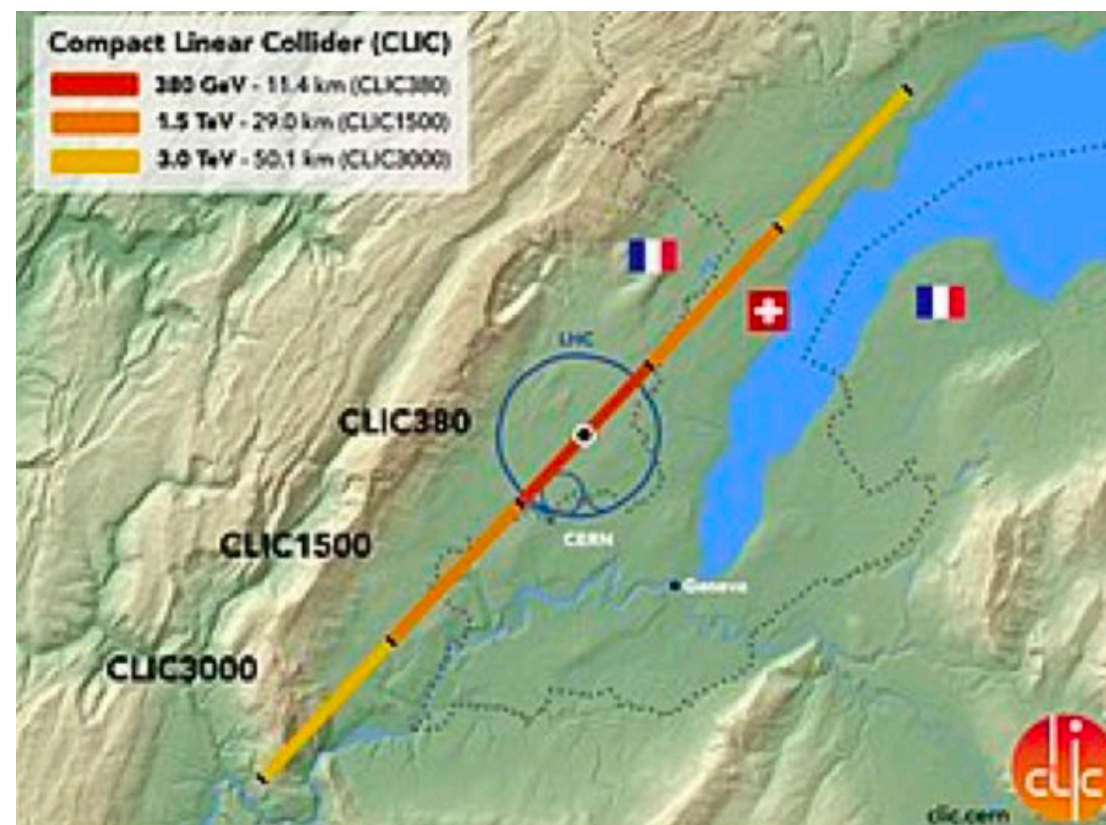
- Compact Linear Collider - CLIC
  - Novel two-beam accelerating technique
  - 72 MV/m, room temperature operations
  - First phase 11km (@ CERN)
  - CDR in 2012, recent updates

Tantawi, Sami, et al. *PRAB* 23.9 (2020): 092001.



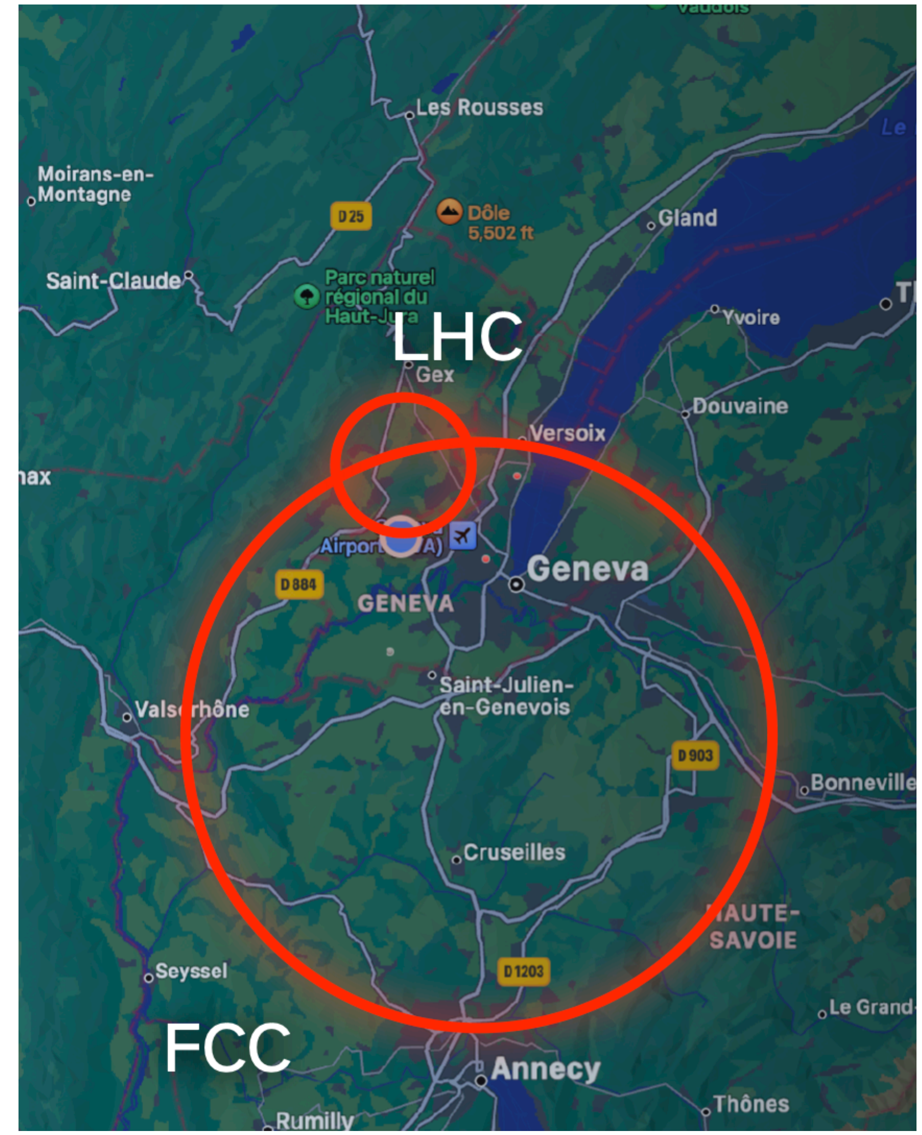
Electric field magnitude for equal power from RF manifold





CIRCULAR COLLIDERS

- **Future Circular Collider: FCC-ee**
  - **Double ring e^+e^-**
  - **Based on 60 years of experience**
    - **400-800MHz, SRF cavities**
    - **Key concepts demonstrated at previous colliders**
    - **Few remaining challenges!**
  - **Total length 91km, at CERN**
  - **CDR in 2018, tunnel feasibility report expected in 2025**



Courtesy of L.L.Lee

CEPC
- **Double ring e+e-, design similar to the FCC-ee**
- **Infrastructure will support SPPC (and possibly ep)**
- **CDR in 2018, feasibility report expected in 2023**
- **China**

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FROM THE LHC TO THE HIGGS FACTORIES

	Today	*@ HL-LHC*	*@ e^+e^- Higgs Factories*
Mass	10^{-3}	10^{-4}	10^{-5}
Coupling to 3rd generation	10%	1%	Range of 0.1%
Coupling to 2nd generation	10% (muons)	1% (muons) 50% (charm)	Improvement by 10x and probing H→ss
Coupling to 1st generation	?	?	~2σ with dedicated run
Coupling to Gauge Bosons	10%	1%	Range of 0.1%
Branching ratio to invisible	< 10%	< 1%	< 0.1%
Trilinear coupling	?	50%	30%

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"PRECISION" AS A TOOL FOR DISCOVERIES

What is our target?

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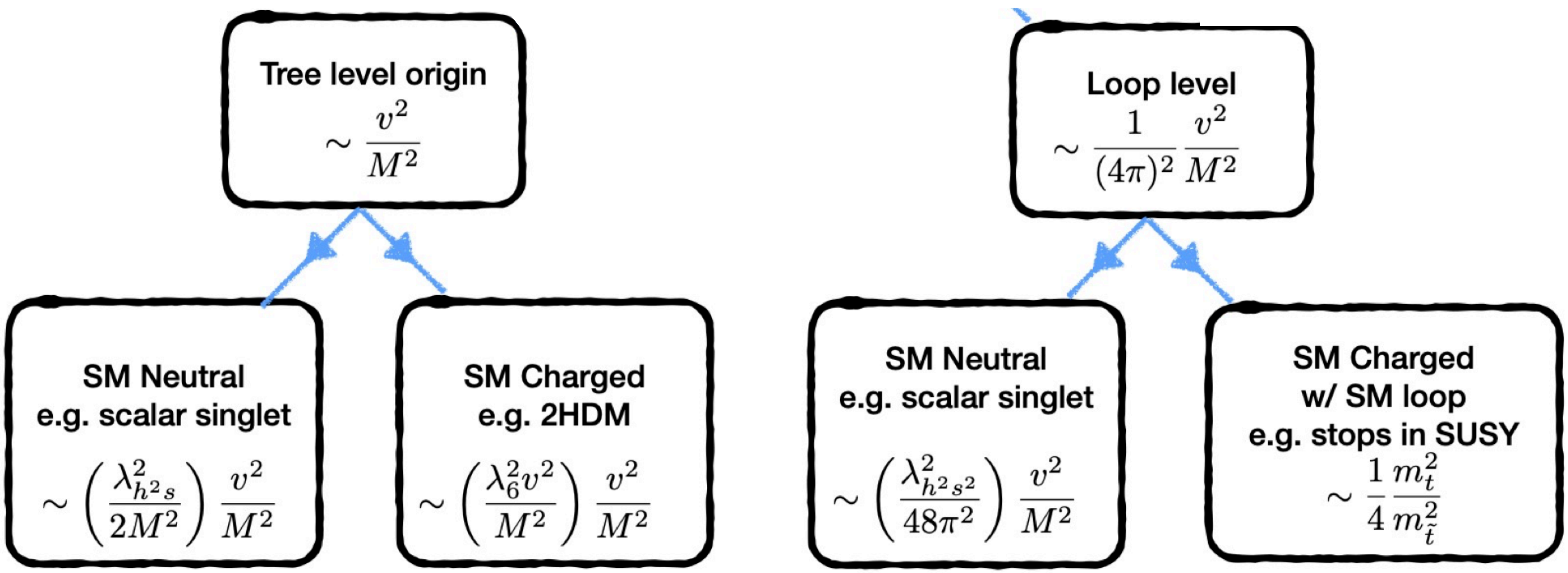
$\delta\eta_{SM}$ $\sim 1\%$ / $\sim .1\%$



SM Neutral (tree)	SM Charged (tree)	SM Neutral (loop)	SM Charged (loop)
$M \lesssim 1.7\,\mathrm{TeV}$	$M \lesssim 0.8\,\mathrm{TeV}$	$M \lesssim 0.1\,\mathrm{TeV}$	$M \lesssim 0.9\,\mathrm{TeV}$
$M \lesssim 5.5\,\mathrm{TeV}$	$M \lesssim 1.4\,\mathrm{TeV}$	$M \lesssim 0.4\,\mathrm{TeV}$	$M \lesssim 2.8\,\mathrm{TeV}$

MULTI-TEV COLLIDERS

MACHINES FOR DIRECT DISCOVERIES AT HIGH SCALE

with potential for precision program

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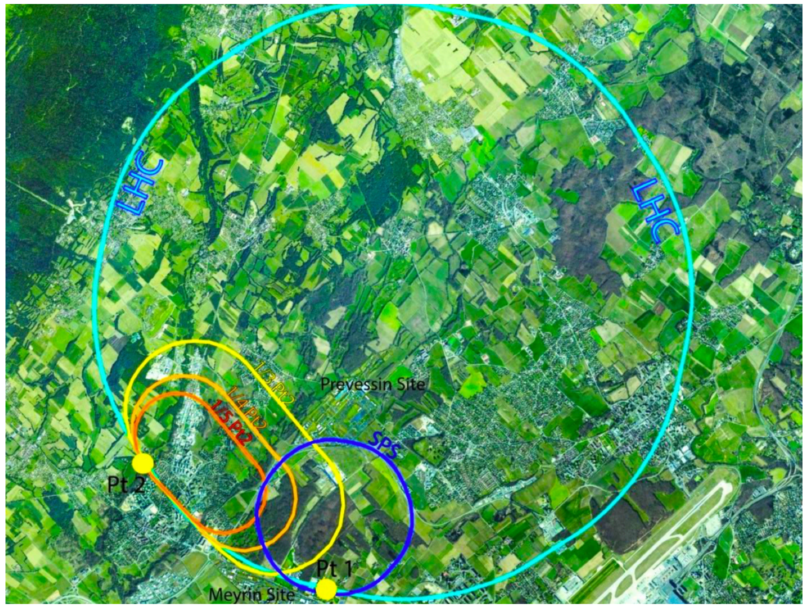
SNOWMASS VIEW: MULTI TEV COLLIDERS

Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	±80/0	2.5
		3.0	±80/0	5
μ-collider	$\mu\mu$	3		1
		10		10

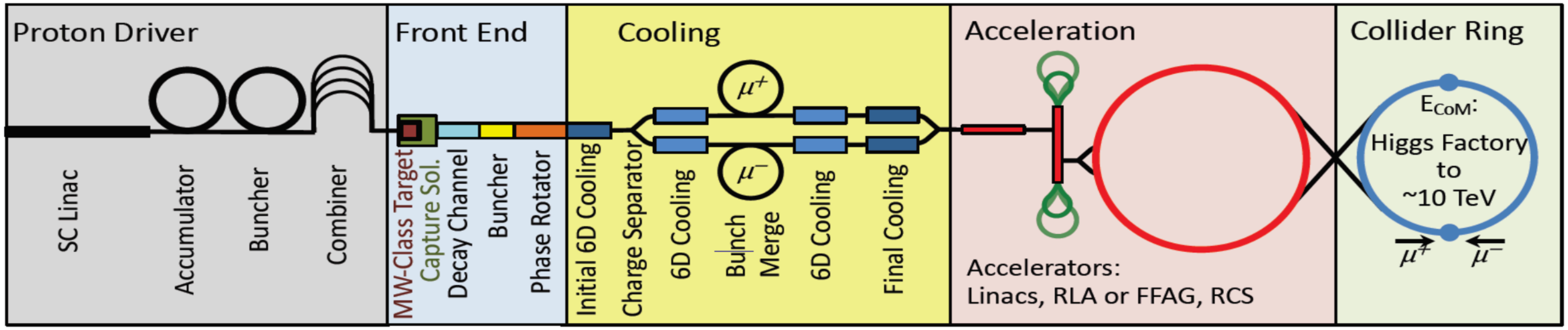
- Future Circulare Collider: FCC-hh
  - Re-uses the FCC-ee infrastructure
  - R&D for high field magnets (16T)
  - CDR in 2018
  - Hosts electron recovery Linac: eh
    - 60 GeV electron beam
    - ERL components can be relocated from HL-LHC, well proven concepts

SPPC

- Same collider tunnel as CEPC
- 2-ring collider fed by injector chain of 4 accelerators
- R&D for high field magnets (target 20T)
- CDR in 2019



SNOWMASS VIEW: MUON COLLIDER



Short, intense proton bunch

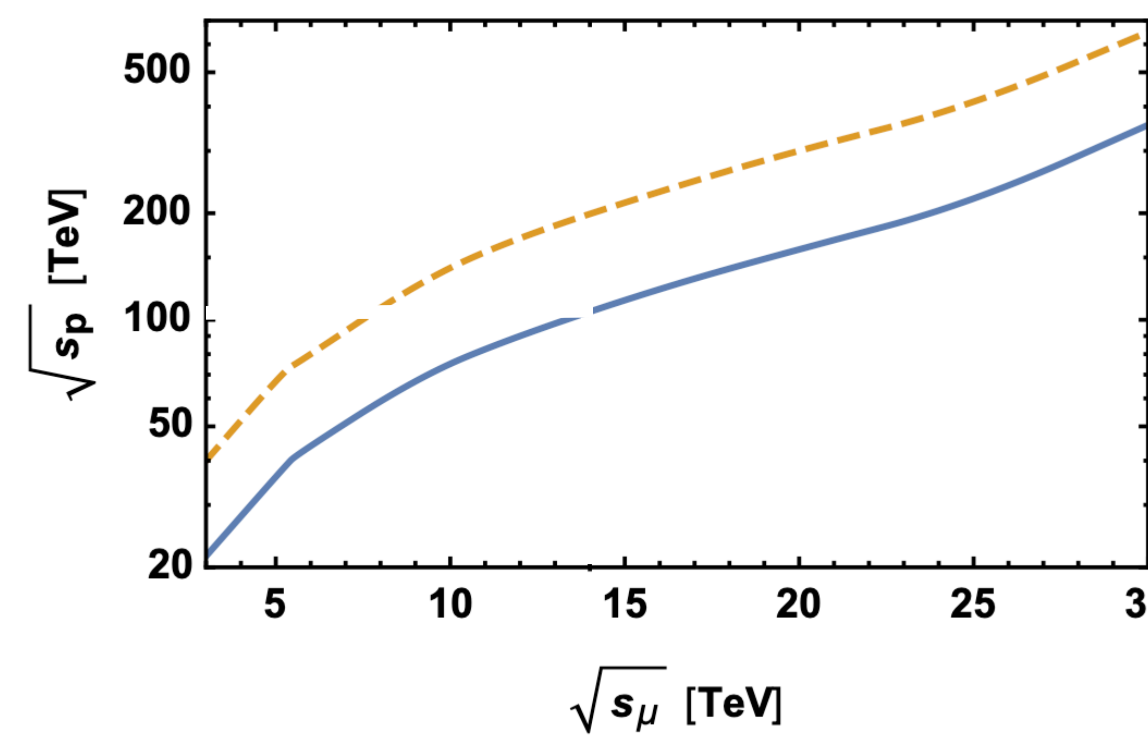
Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Protons produce pions which decay into muons
muons are captured

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B\rangle$	T	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63



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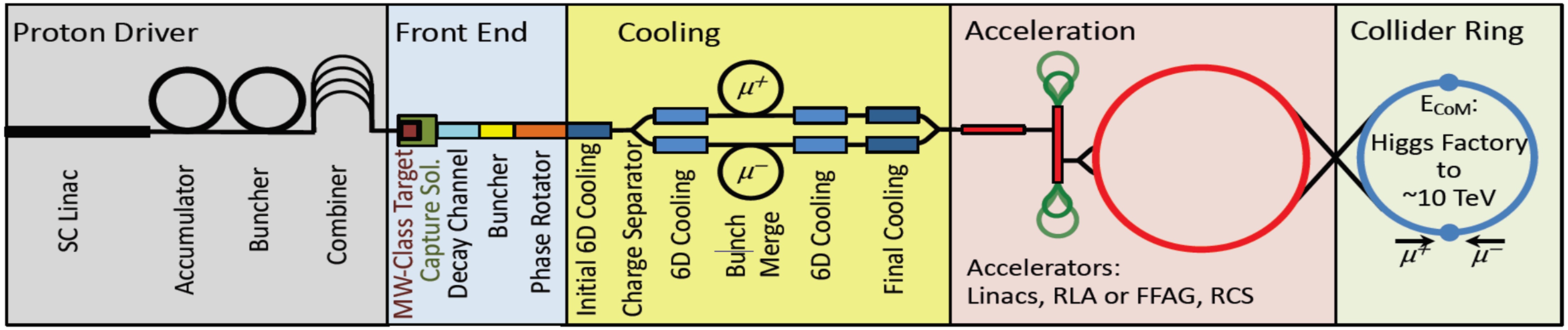

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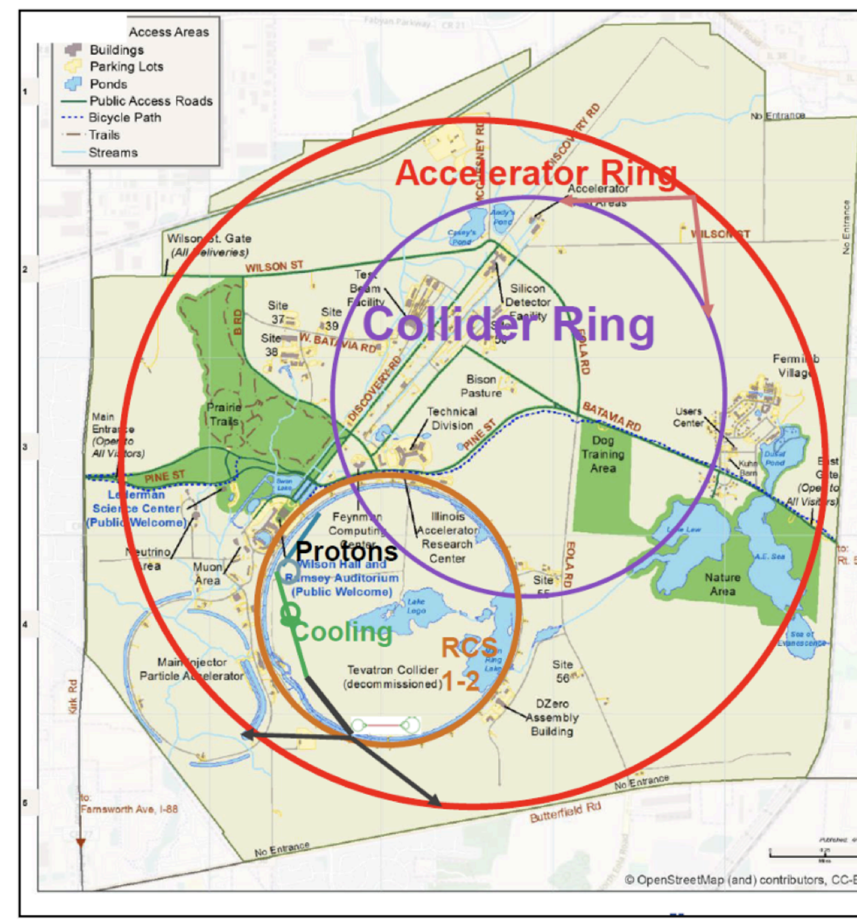

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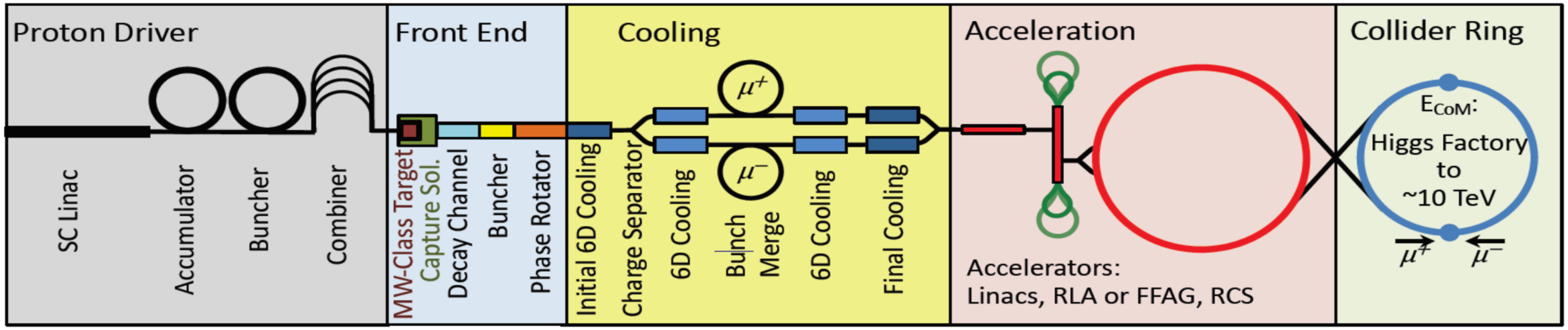
SNOWMASS VIEW: MUON COLLIDER



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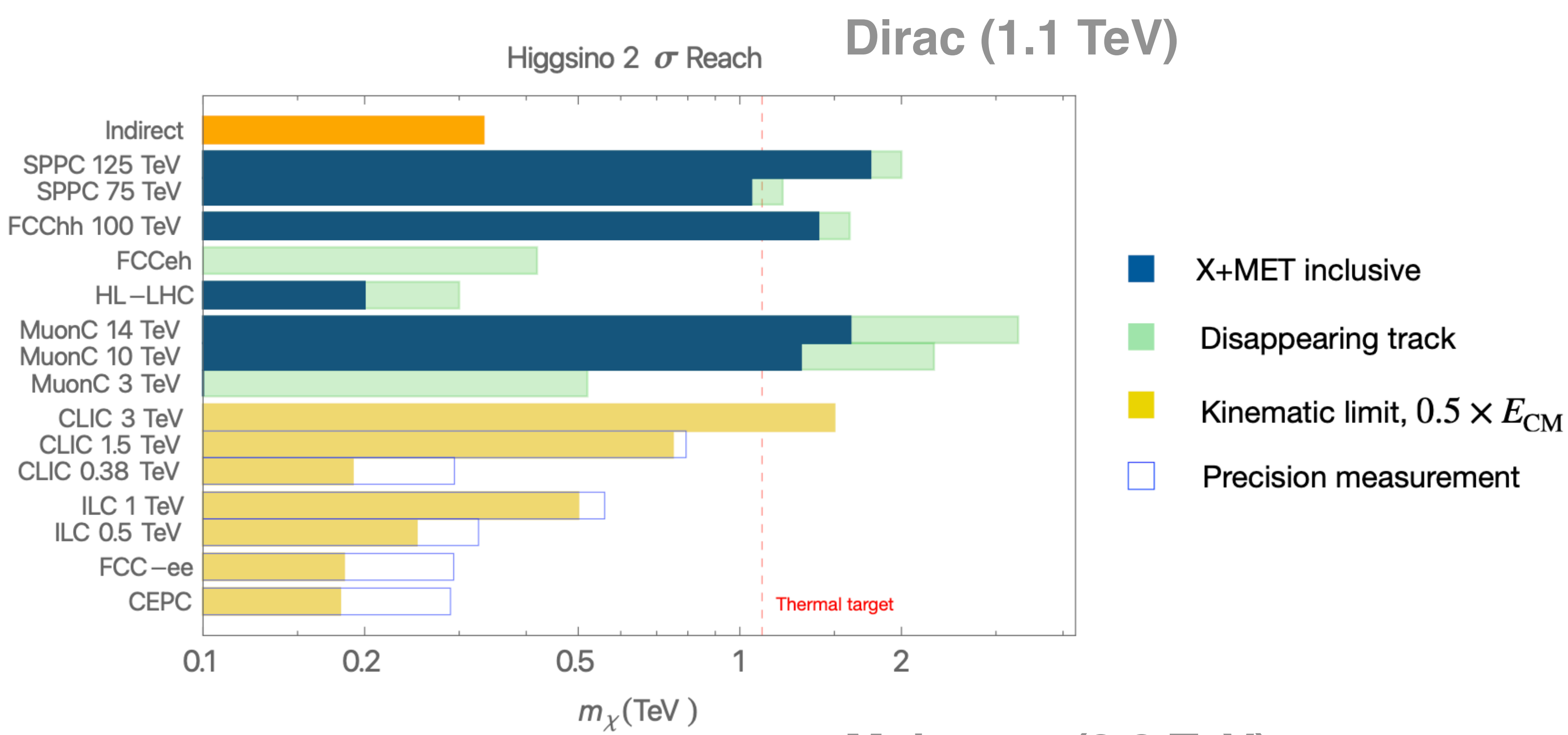
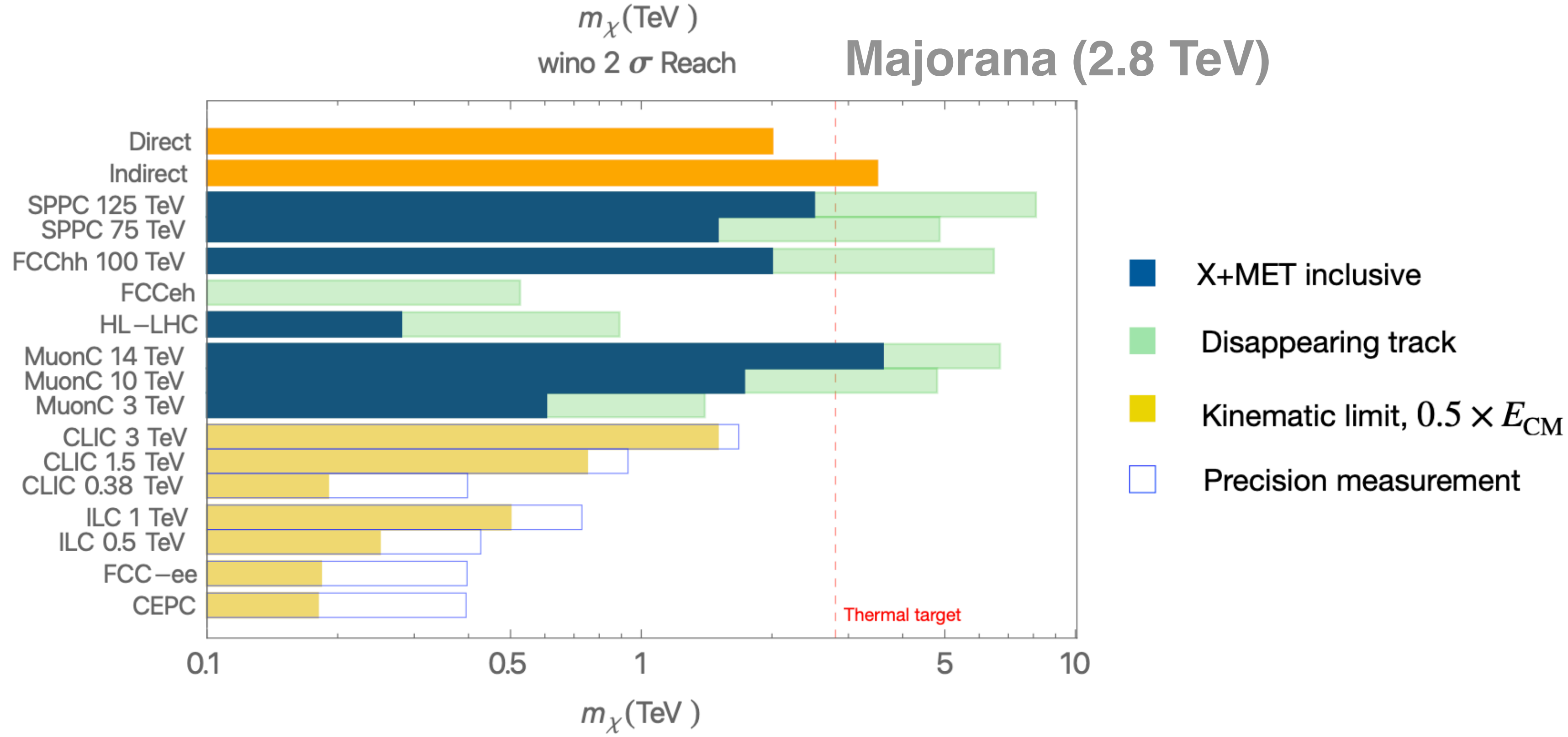
- **Significant R&D is required to demonstrate MuC elements (Cooling, Fast ramping magnets, Target, Neutrino Flux, Beam Induced Background,…)**
  - **Renewed interest in the U.S. and Europe**
  - **Formal collaboration formed**

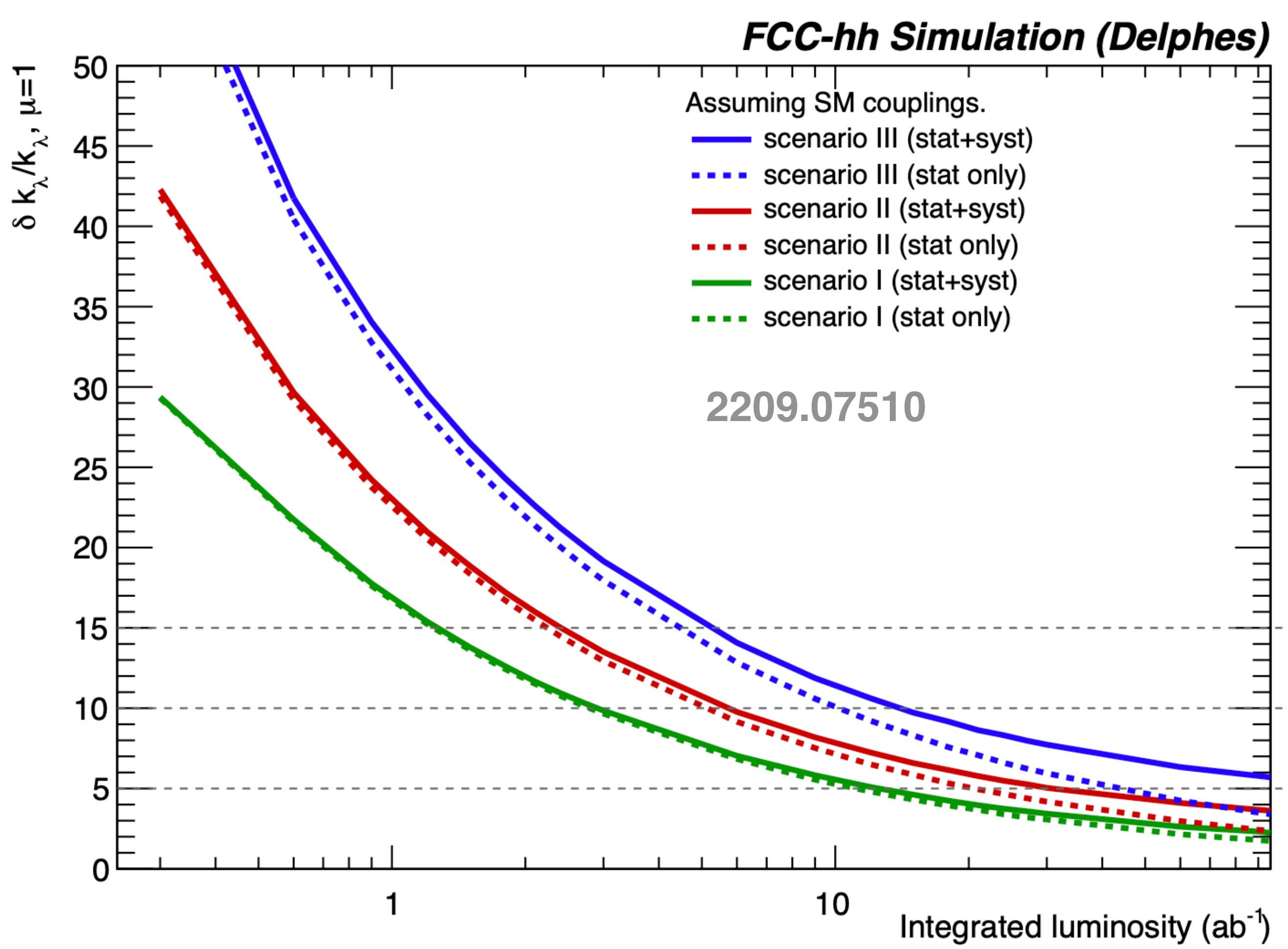
“CLOSING THE WINDOW ON WIMP DARK MATTER”



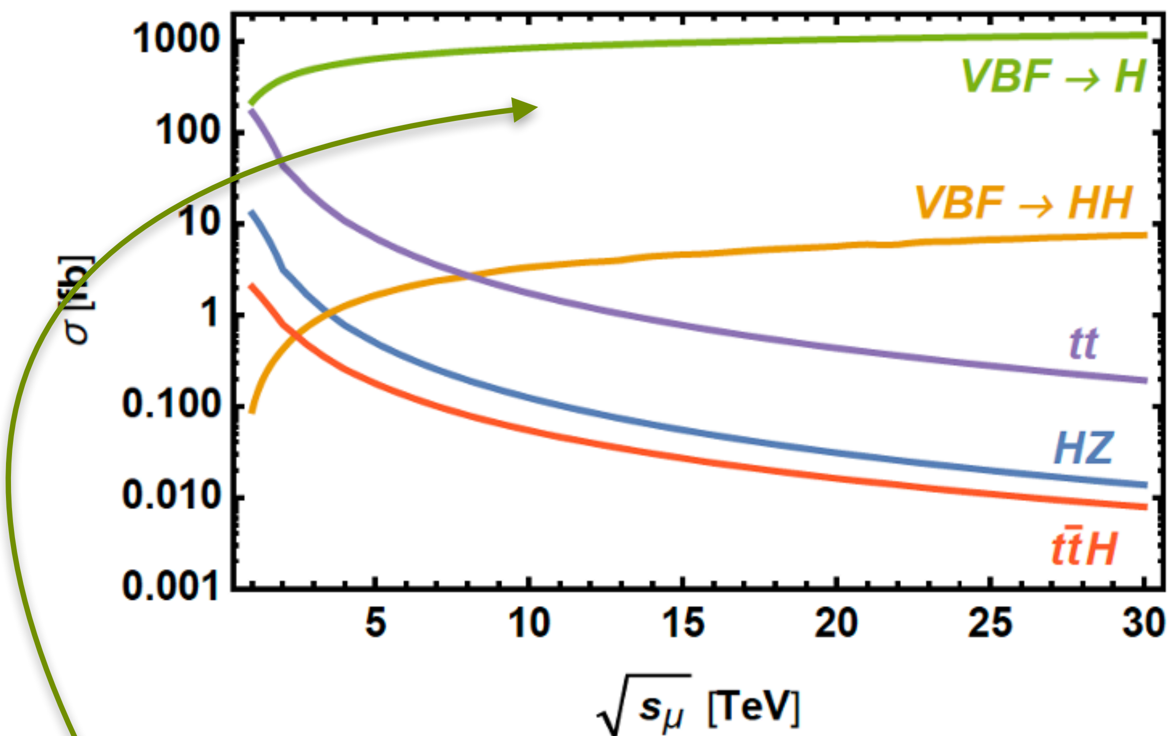


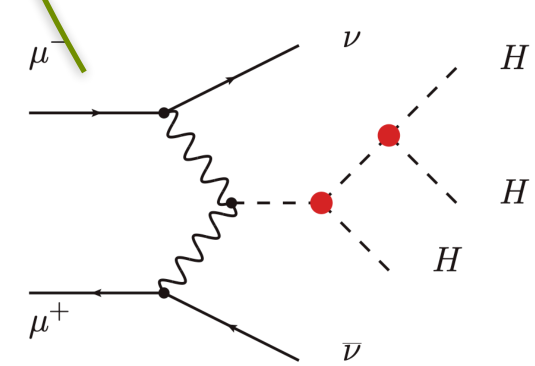
HIGGS PHYSICS AT FUTURE MULTI-TEV COLLIDERS

- **At FCC-hh/SPPC**
  - **Factor 40 in cross section w.r.t LHC, 10x luminosity ➜ x400 in event yields and x20 in precision**



- **At 10 TeV Muon Collider**





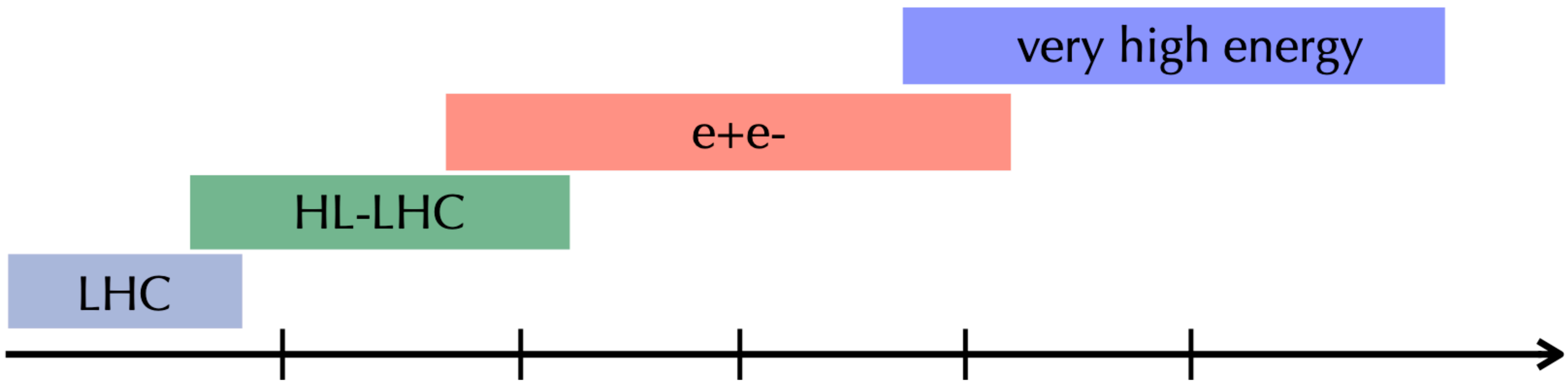
Trilinear coupling

- **3 TeV - 15-30%**
- **10 TeV - 4%**

- *Quartic coupling*
  - *@ 2σ FCC-hh/SPPC (33/ab)*
  - *50% at Muon Collider (14 TeV, 33/ab)*

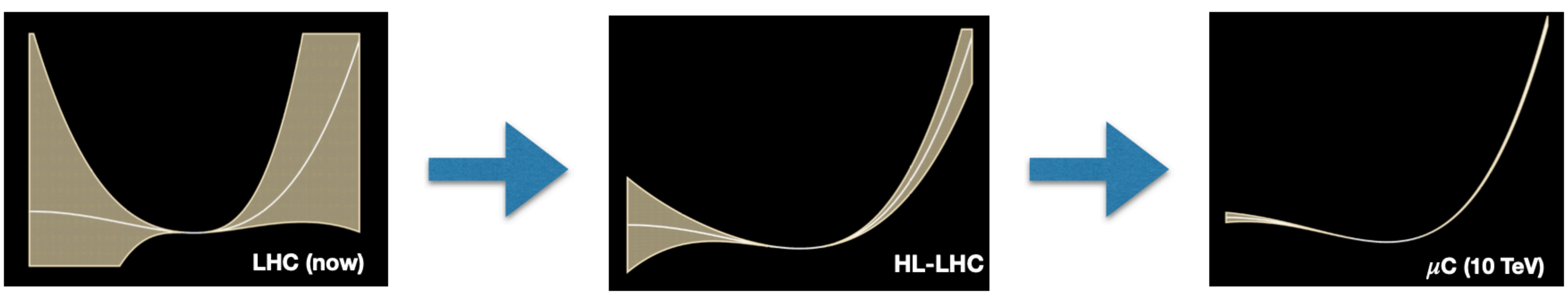
2004.03505

ULTIMATE PRECISION IN HIGGS PHYSICS



H couplings to:	**O(10)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

Courtesy of C. Vernieri



Or pp (100TeV)

Courtesy of N. Craig

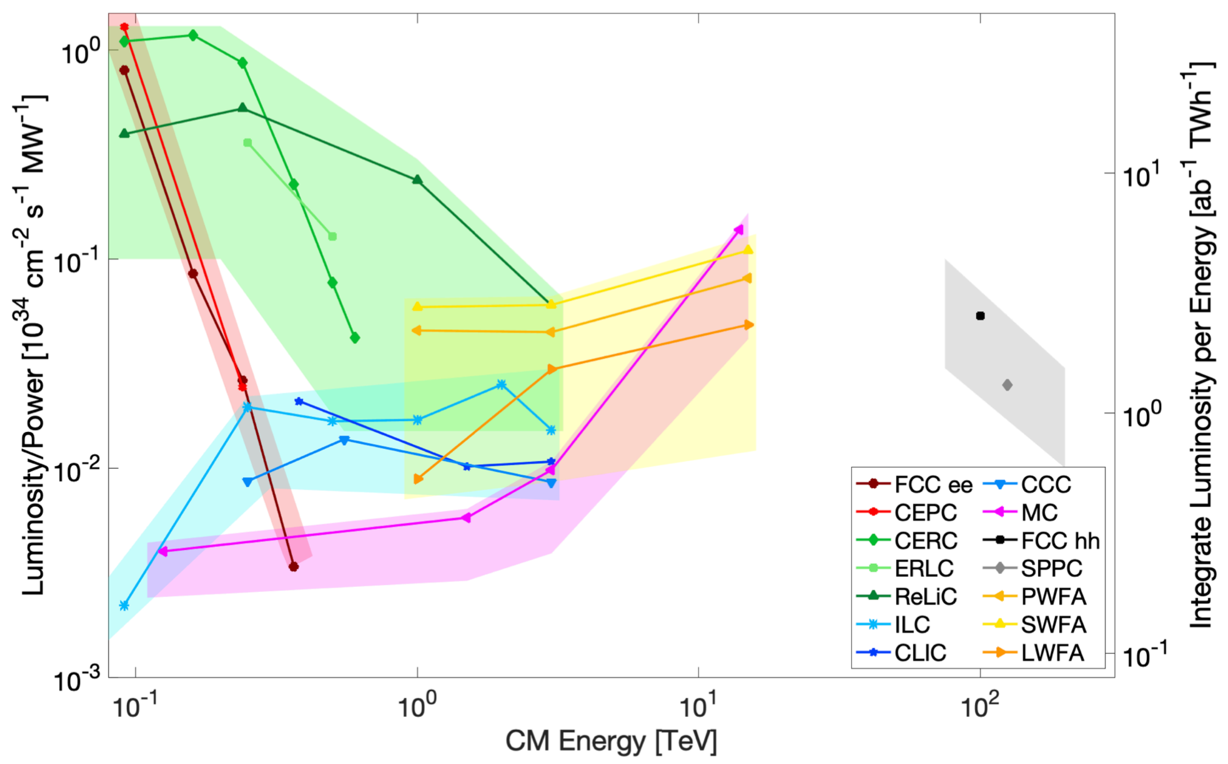
SUMMARY AND OUTLOOK

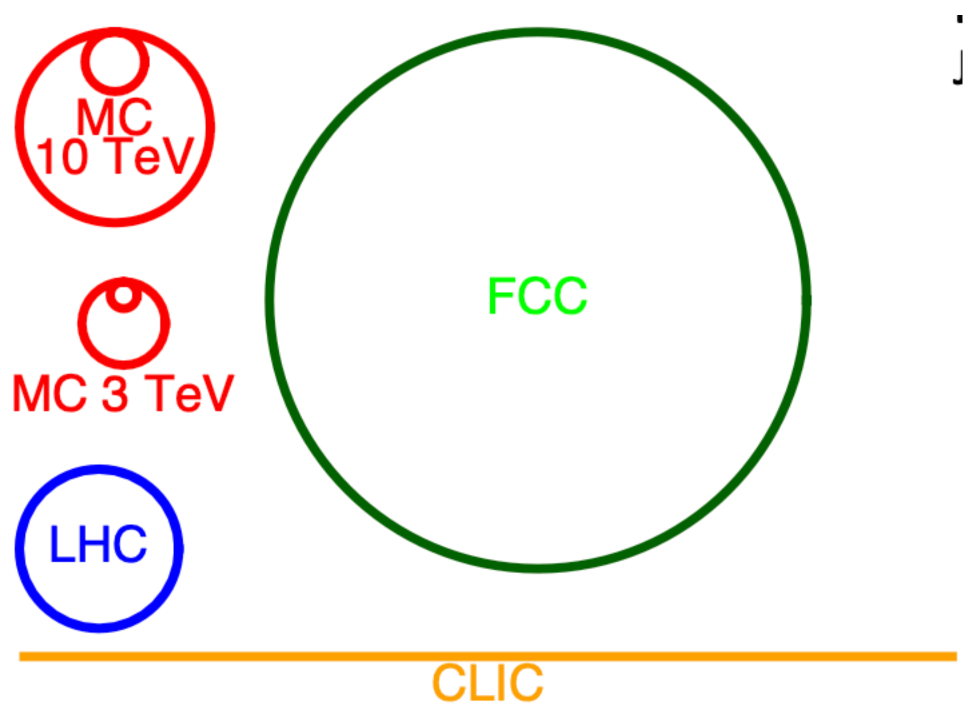
- Colliders do offer unparalleled opportunities for discoveries that can revolutionize our understanding of the Universe.
- By 2040, the LHC will have delivered the largest high-energy pp dataset ever collected!
- Beyond the HL-LHC, an integrated future colliders program consisting of an e+e- Higgs factory followed by an energy-frontier collider to explore the ~10 TeV scale promises to be the most far-reaching strategy for collider physics that foreseeable technologies can enable.
- Different solutions are being explored by the community, each one requiring cutting-edge R&D in accelerator and detectors.

VERY EXCITING TIMES for COLLIDER PHYSICS!

ADDITIONAL MATERIAL

“TAKE HOME” MESSAGE IN 1 SLIDE





COLLIDER IMPLEMENTATION TASK FORCE (I)

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	$<$12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	$\sim$400
High Energy CLIC	3 (1.5-3)	5.9	3-5	19-24	18-30	$\sim$550
High Energy CCC	3 (1-3)	6.0	3-5	19-24	12-18	$\sim$700

2208.06030

COLLIDER IMPLEMENTATION TASK FORCE (II)

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPS	125 (75-125)	13 (26)	>10	>25	30-80	~400

2208.06030

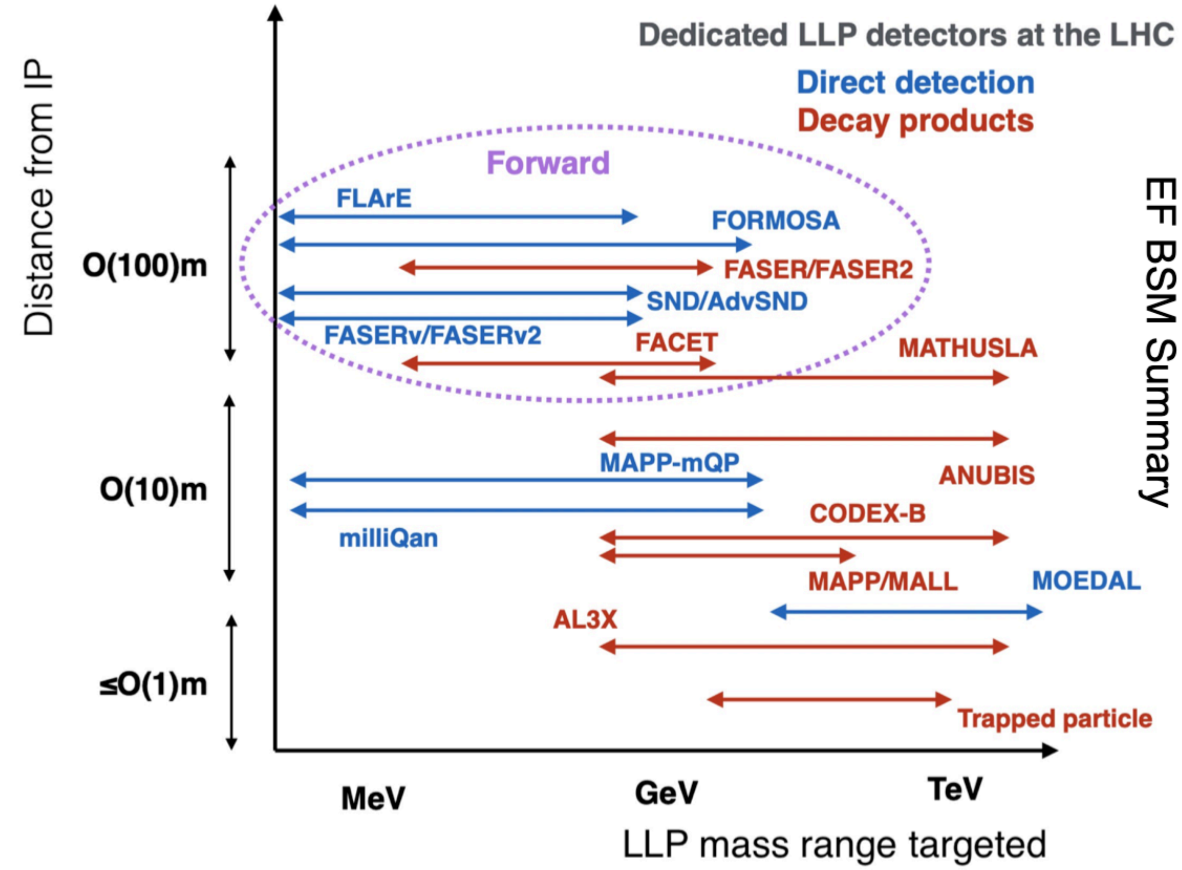
SNOWMASS EF SUMMARY AND PLAN

	LHC	Higgs Factory	Multi TeV Colliders
2025-2030	Prioritize LHC and aux. experiments	Establish a targeted e^+e^- Higgs factory detector R&D program.	1. Develop an initial design for a first stage TeV-scale Muon Collider in the US. 2. Support critical detector R&D towards EF multi-TeV colliders.
2030-2035	Continue strong support for the HL-LHC physics program.	Support construction of an e^+e^- Higgs factory.	1. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.
After 2035	Continuing support of the HL-LHC physics program to the conclusion of archival measurements.	Support completing construction and establishing the physics program of the Higgs factory.	1. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider. 2. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

"The US EF community has also expressed **renewed interest and ambition to bring back energy-frontier collider physics to the US** soil while maintaining its international collaborative partnerships and obligations."

OTHER FACILITIES AT COLLIDERS

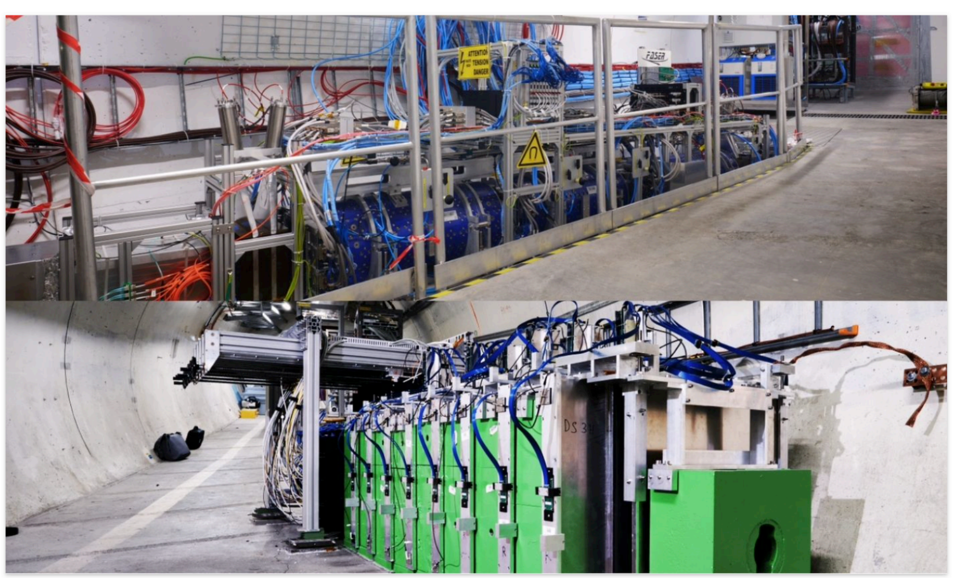
- Auxiliary experiments complementing and thus allowing to fully exploit the capabilities of the collider complex
  - Electron-proton/ion colliders, beam dump experiments, new facilities for charged lepton flavor violations, etc.



New LHC experiments enter uncharted territory

The first observation of collider neutrinos by FASER and SND at the LHC paves the way for exploring new physics scenarios

22 MARCH, 2023 | By Kristiane Bernhard-Novotny & Chetna Krishna



FASER (top) and SND@LHC (bottom) detectors

- Yielding sensitivity to dark photons, milli-charged particles, exotic Higgs decays, dark scalars, HNLs, ALPs, LLPs, DM, neutralinos, ...

Fermilab

FCC-EE: BEYOND THE HIGGS

2209.08078

- Circular colliders pushing the frontier on EW precision
  - *e.g.* FCC-ee at Z-pole, 5x10[12] Z_{ee} ~ LEP x 10[5] (with E_{CM} < 100 keV)

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

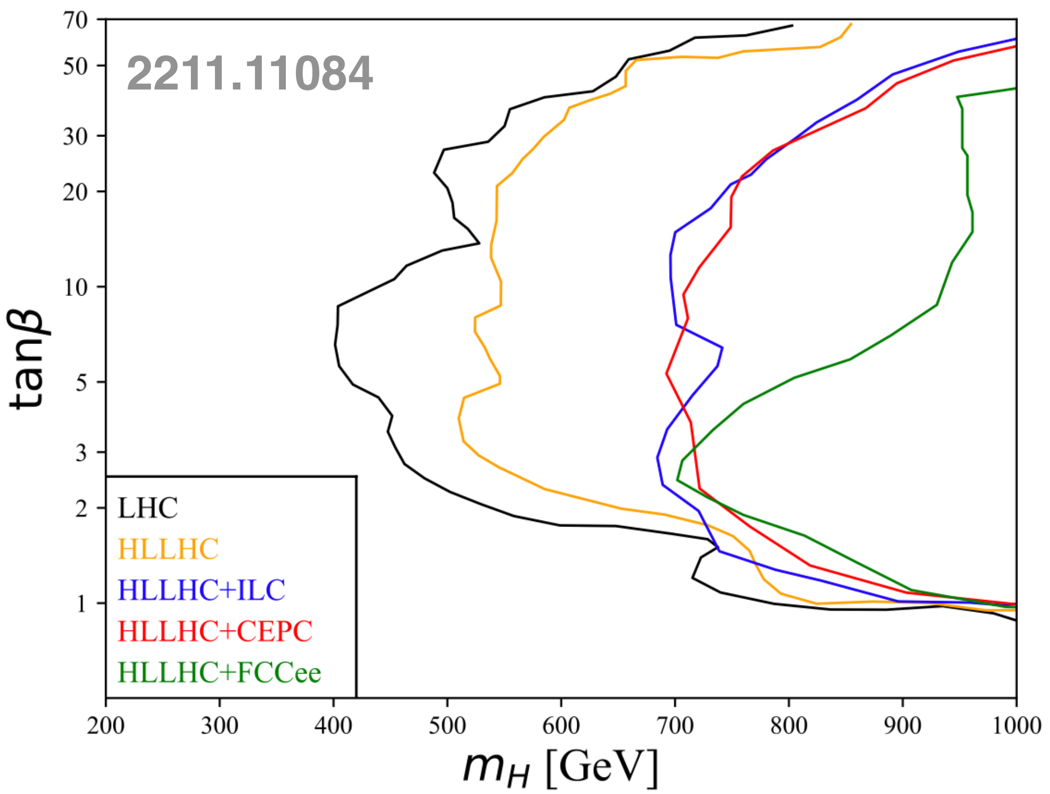
- **Flavor physics with ~10[12] bb, cc** (CKM, CP violation in neutral B mesons,…)
- **Tau physics program with ~2x10[11] $\tau\tau$** (lepton universality, …)
- **QCD at the Z** (coupling, fragmentation….)
- ***and much more***

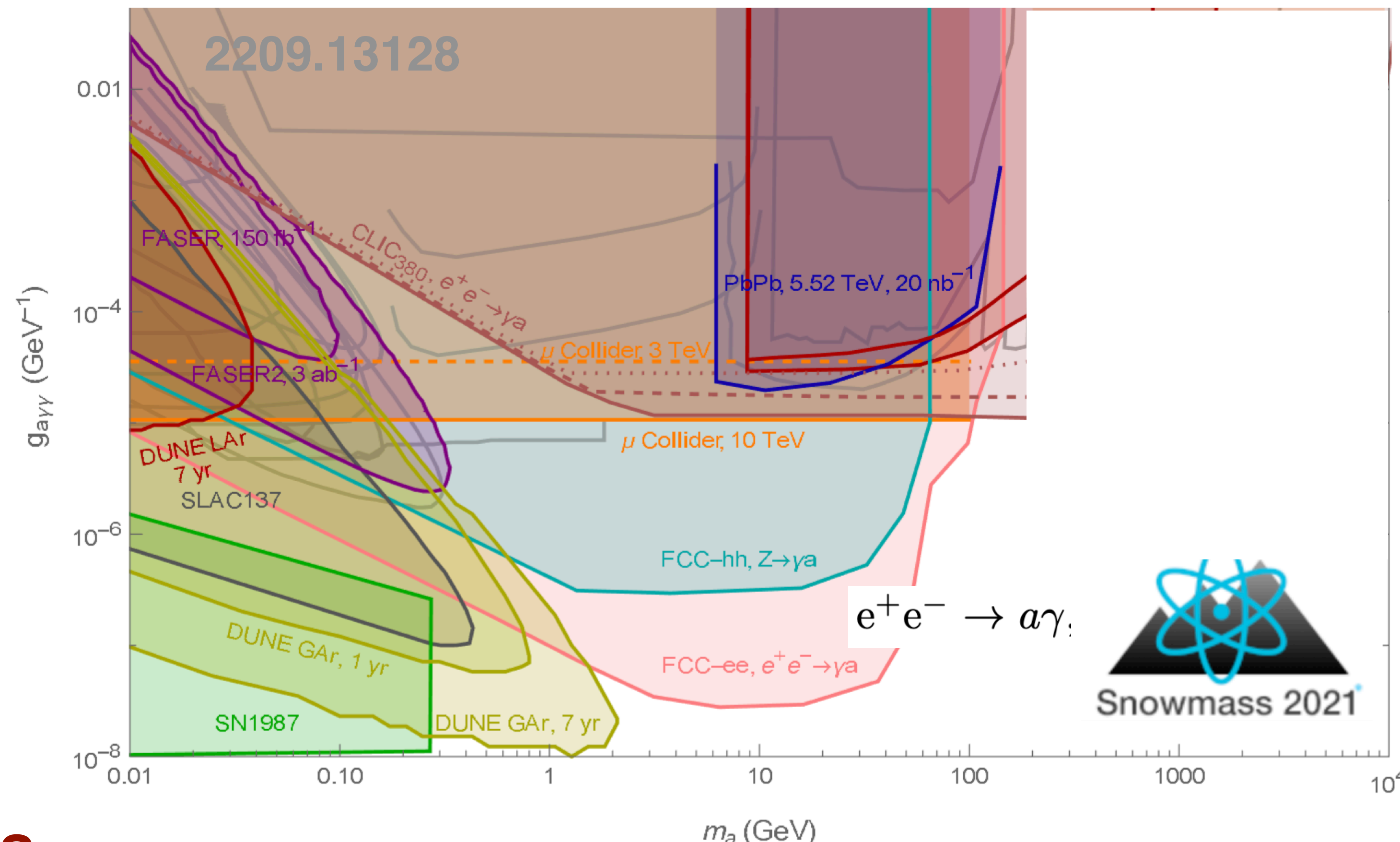
Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\rm had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

FCC-EE: BEYOND THE SM

2209.13128

- **Additional Higgs bosons**
  - ***e.g.* Higgs Doublet Model, simplest extension after scalar singlets to the Higgs sector, allowing additional Higgs bosons**
- **Dark Sectors**
  - **axion-like particles, extensions of QCD axion models proposed to solve the strong CP problem**





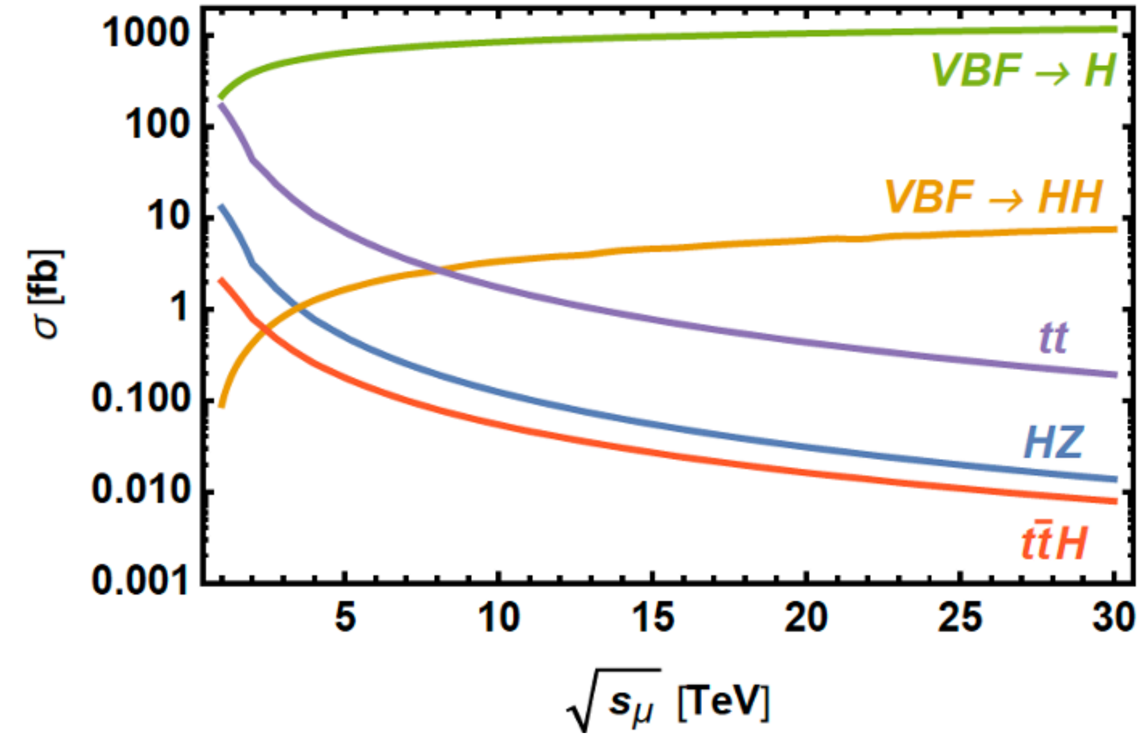
from **Higgs precision measurements**

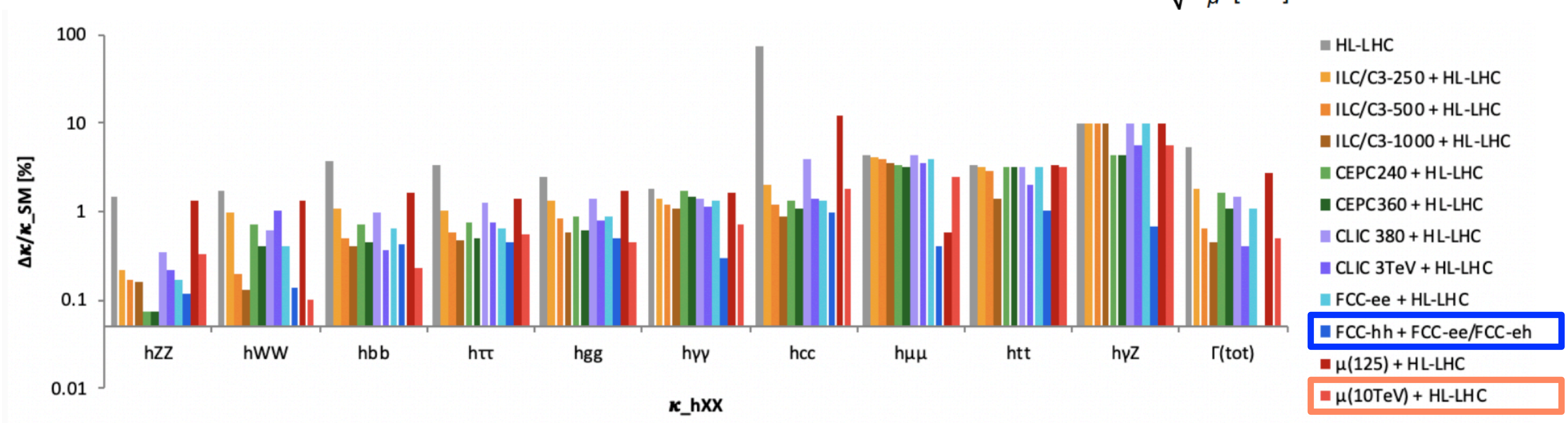
HIGGS BOSON AT FUTURE MULTI-TEV COLLIDERS

- **At FCC-hh/SPPC**
  - **Factor 10-50 in cross section w.r.t LHC, 10x luminosity ➜ 20 Billion Higgs Bosons (!)**

	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55

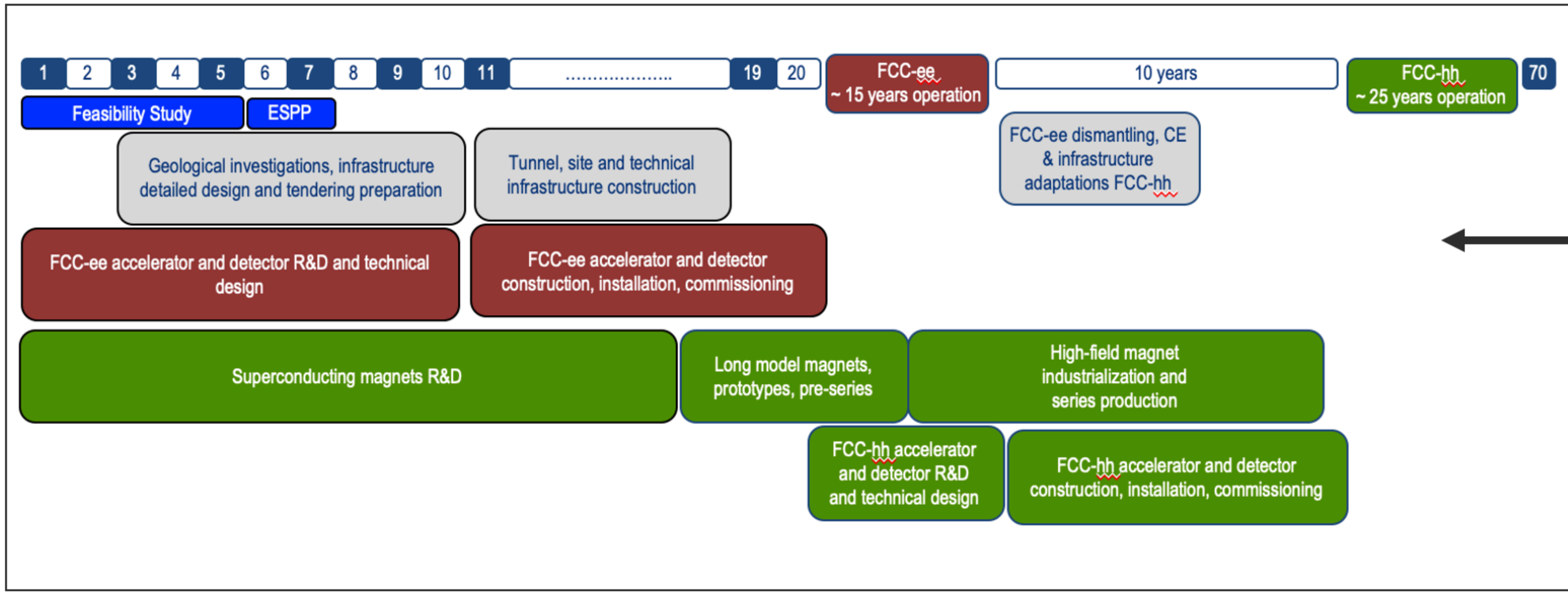
- **At 10 TeV Muon Collider**





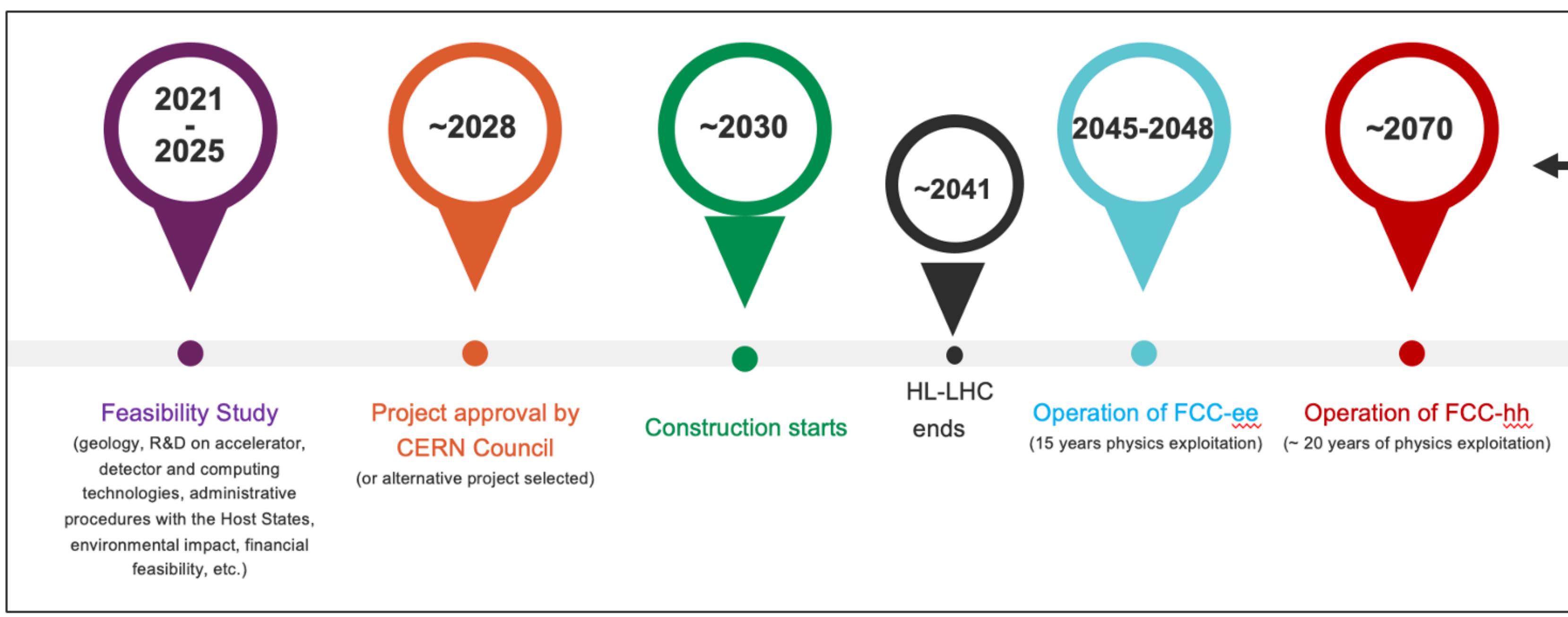
Fermilab

FCC timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

Technical schedule:
FCC-ee could start operation **in 2040 or earlier**

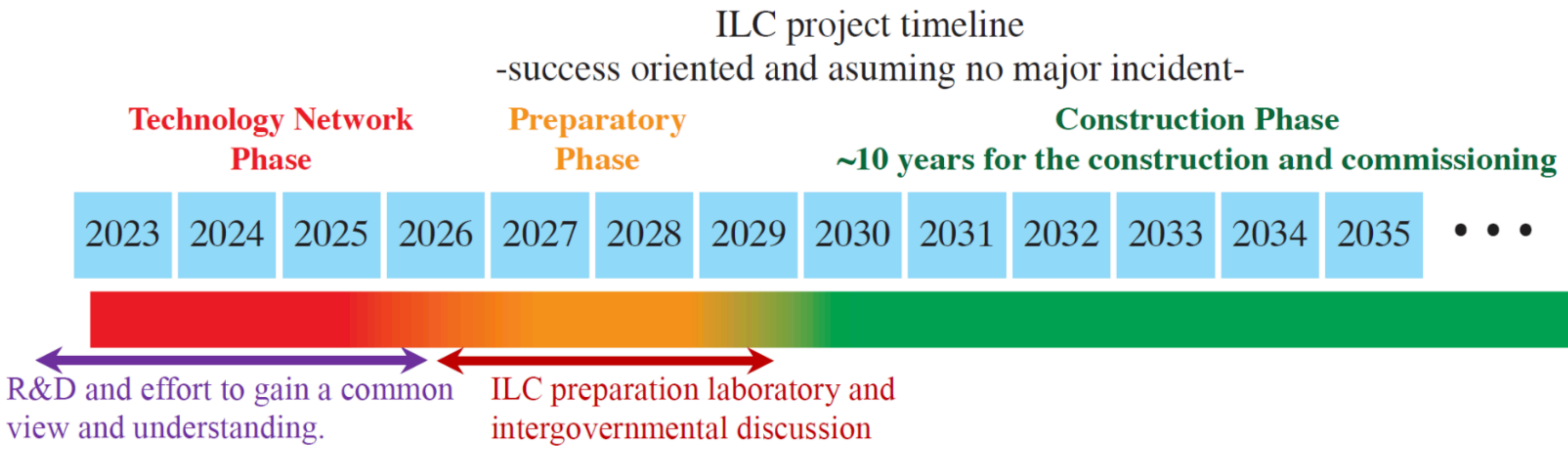


Realistic schedule takes into account:
- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

F. Gianotti

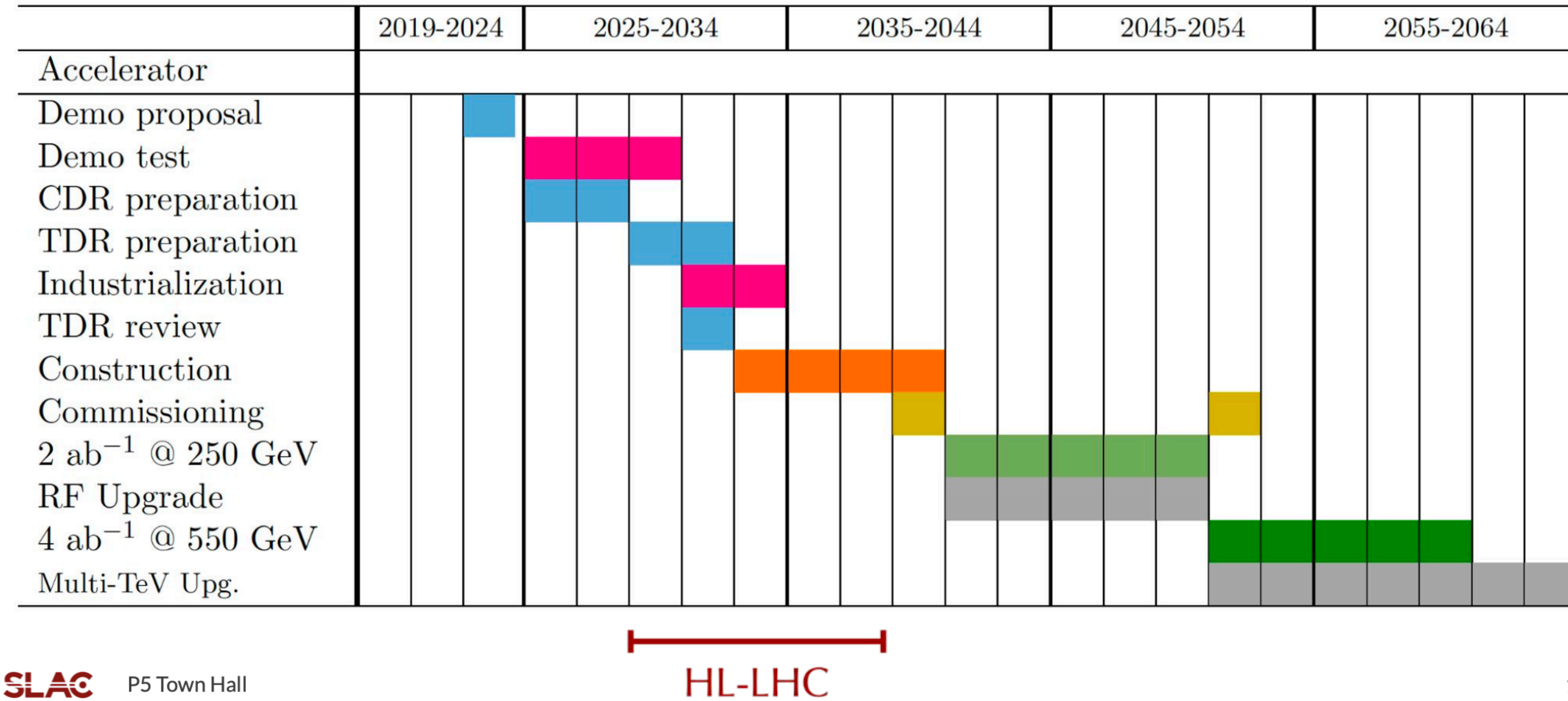
ILC TIME LINE



Technical Timeline for 250/550 GeV CoM

Technically limited timeline developed through the Snowmass process

Energy upgrade in parallel to operation with installation of additional RF power sources



Muon Collider Timeline

MuCol

Muon collider important in the long term

- Even after potential FCC-hh

But also **plan B as next project in Europe** and maybe **plan A in US** and elsewhere

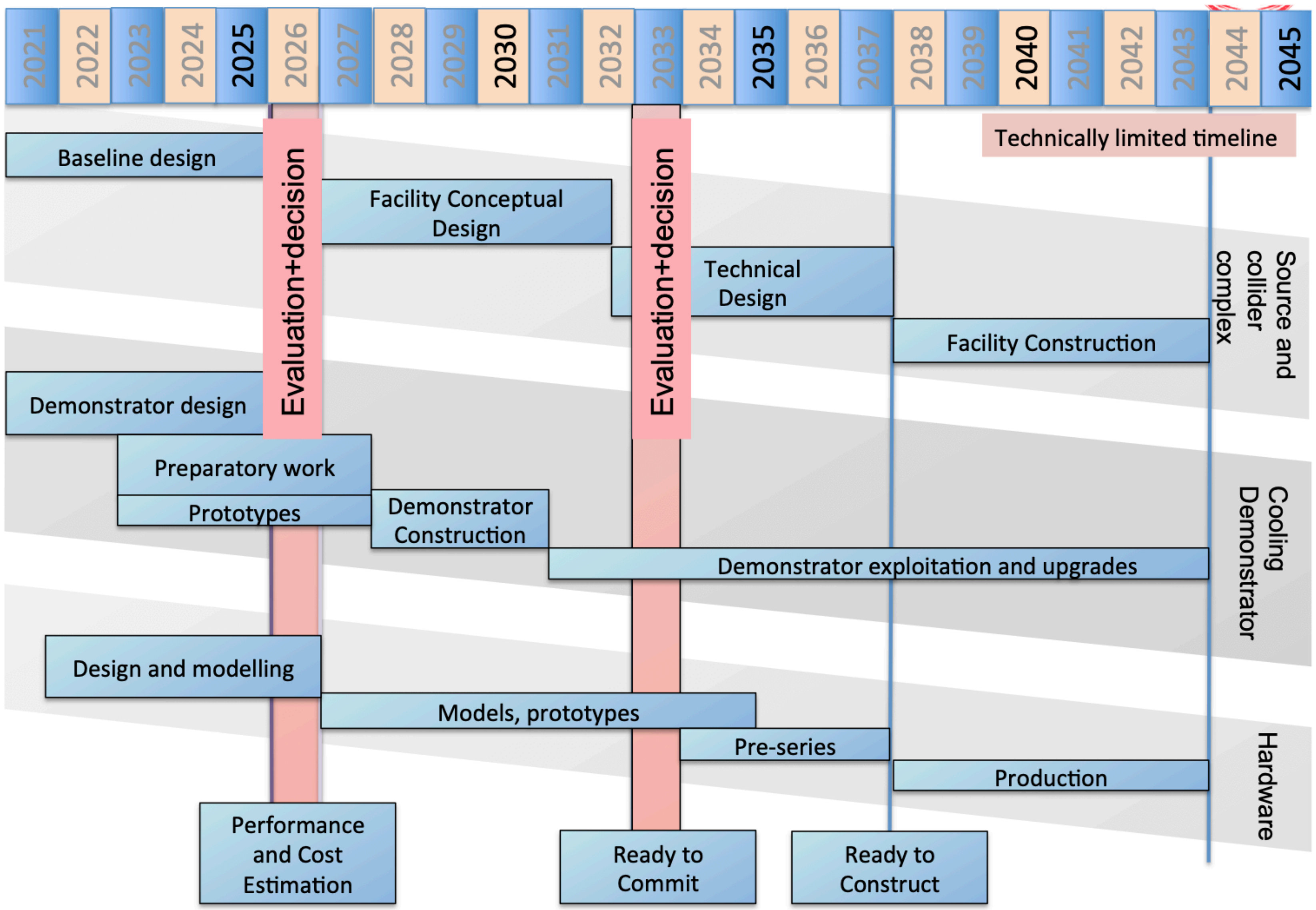
Fast track option if require next as project after HL-LHC:

- Lower energy initial option, e.g. 3 TeV
- Upgrade to 10 TeV later
  - Little extra cost

Subject to funding

Technically limited timeline

To be reviewed considering progress, funding and decisions



FCNC

probes of FCNC interactions beyond the SM through processes such as Z/γq → t production or t → Hq decay (q = u, c).

Table 1. The 95% C.L. expected exclusion limits on the branching fractions for integrated luminosities of 30 ab^{-1} and 3 ab^{-1} in comparison with present experimental limits and estimation for the HL-LHC.

Detector	$\mathcal{B}(t \to u\gamma)$	$\mathcal{B}(t \to c\gamma)$	Ref.
CMS (19.8 fb^{-1}, 8 TeV)	13×10^{-5}	170×10^{-5}	[15]
CMS Phase-2 (300 fb^{-1}, 14 TeV)	2.1×10^{-5}	15×10^{-5}	[16]
CMS Phase-2 (3 ab^{-1}, 14 TeV)	0.9×10^{-5}	7.4×10^{-5}	[16]
FCC-hh (3 ab^{-1}, 100 TeV)	9.8×10^{-7}	12.9×10^{-7}	
FCC-hh (30 ab^{-1}, 100 TeV)	1.8×10^{-7}	2.4×10^{-7}	
Detector	$\mathcal{B}(t \to uH)$	$\mathcal{B}(t \to cH)$	Ref.
CMS (36.1 fb^{-1}, 13 TeV)	4.7×10^{-3}	4.7×10^{-3}	[17]
ATLAS (36.1 fb^{-1}, 13 TeV)	1.9×10^{-3}	1.6×10^{-3}	[18]
FCC-hh (3 ab^{-1}, 100 TeV)	8.4×10^{-5}	7.7×10^{-5}	
FCC-hh (30 ab^{-1}, 100 TeV)	4.8×10^{-5}	4.3×10^{-5}	