Future Colliders

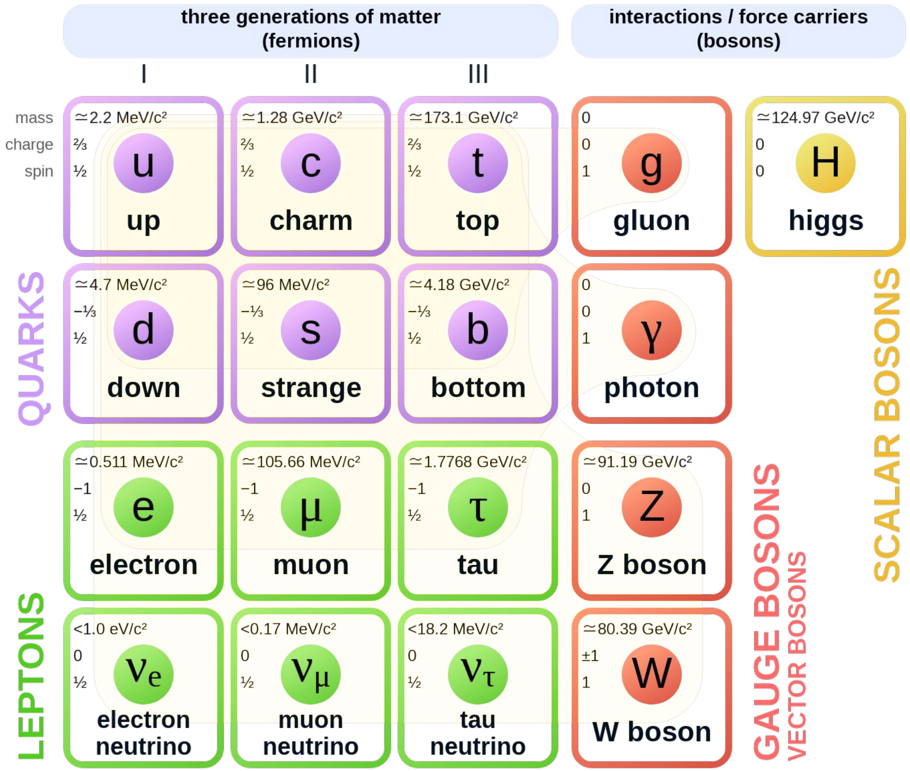
Simone Pagan Griso (LBNL)

290e Seminar

Berkeley, Jan 25th 2023

Prelude

Within the last century we have built an impressive synthesis of the fundamental physics at the (smallest and) largest scales.



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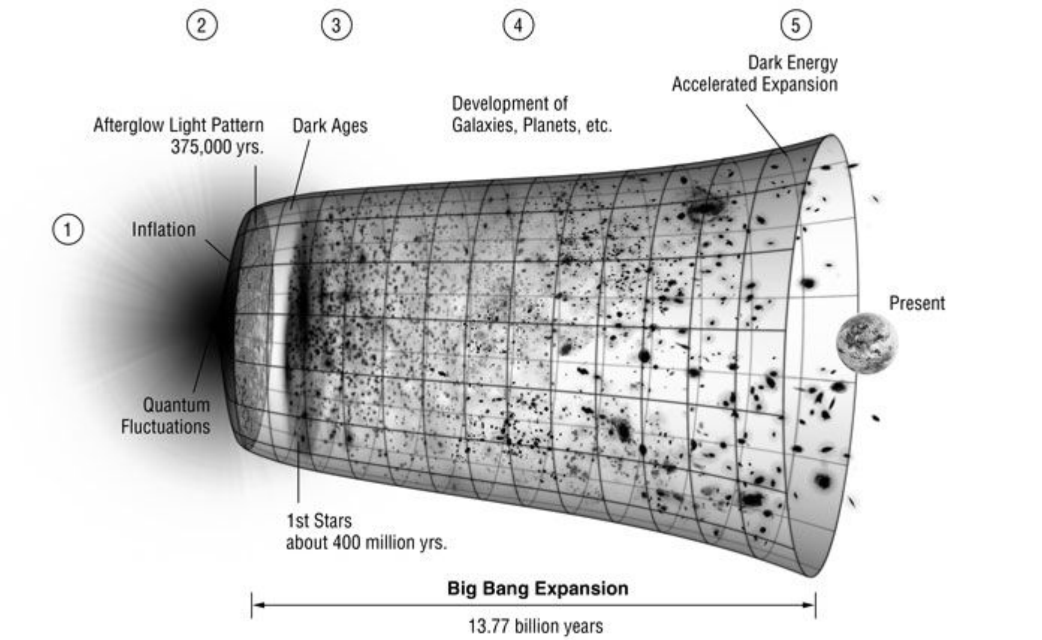


Adapter from source: NASA/ LAMBDA Archive / WMAP Science Team

We all work to ensure that the next century will be even more exciting!

A Vision for the Future of Particle Physics

The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") process is a Science study for the entire HEP community to build a vision for the future of particle physics in the U.S. and its international partners.

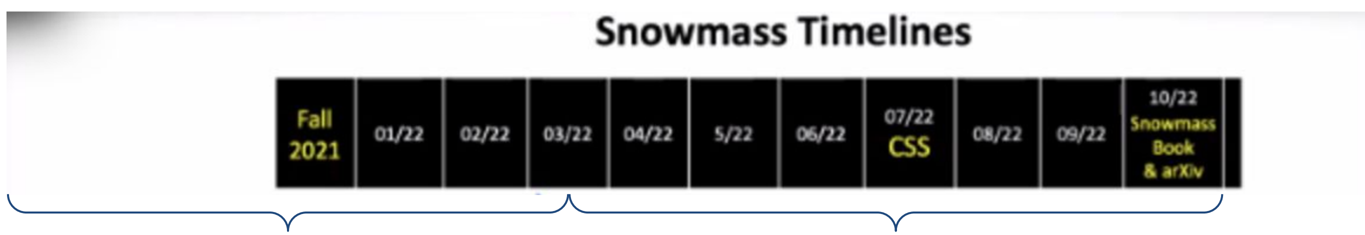
- Once every ~10 years

Work divided in 10 frontiers and several dedicated cross-frontiers groups

Energy Frontier Report, arXiv:2211.11084
Accelerator Frontier Report, arXiv:2209.14136
Implementation Taskforce Report, arXiv:2208.06030
… and many more (see https://snowmass21.org)

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 Frontier

Snowmass effort started in April 2020



Community Input

Report Preparation

The P5 Panel

Snowmass reports are the input to the Particle Physics Project Prioritization Panel (aka P5):

- In charge of formulating a 10-year plan (20-year vision) within funding constraints
- Panel members just appointed
- Expect report by the end of 2023

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Snowmass 2013 and the 2014 P5 Panel

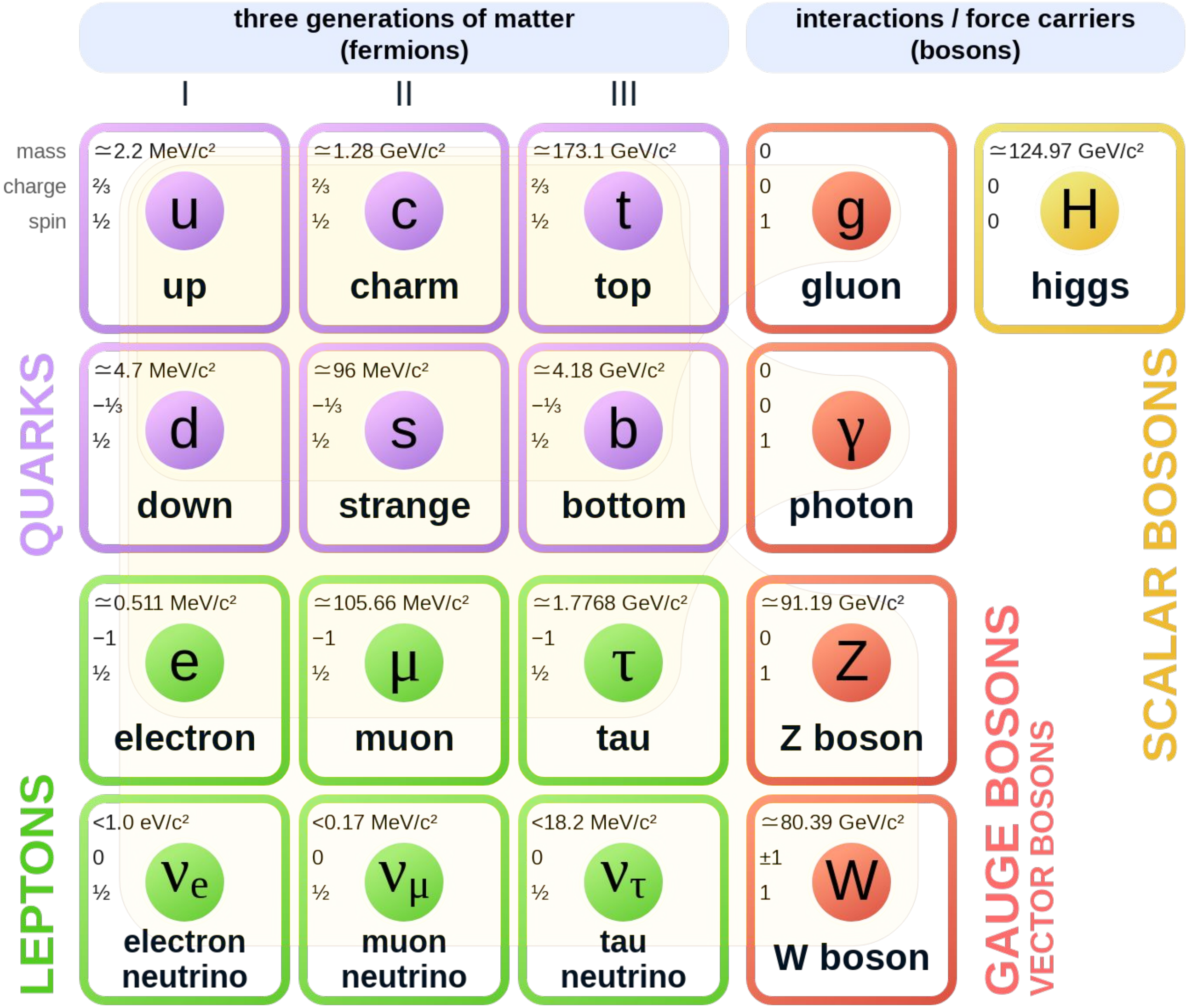
2014 P5 Drivers

- **Higgs boson as tool for discovery**
- **Physics of Neutrino mass**
- **Identify new physics of dark matter**
- **Dark Energy and Inflation**
- **Explore the unknown**

Full text is here.

Building the Standard Model

Colliders at the Energy Frontier have been instrumental in understanding the building blocks of the Standard Model (SM) of Particle Physics



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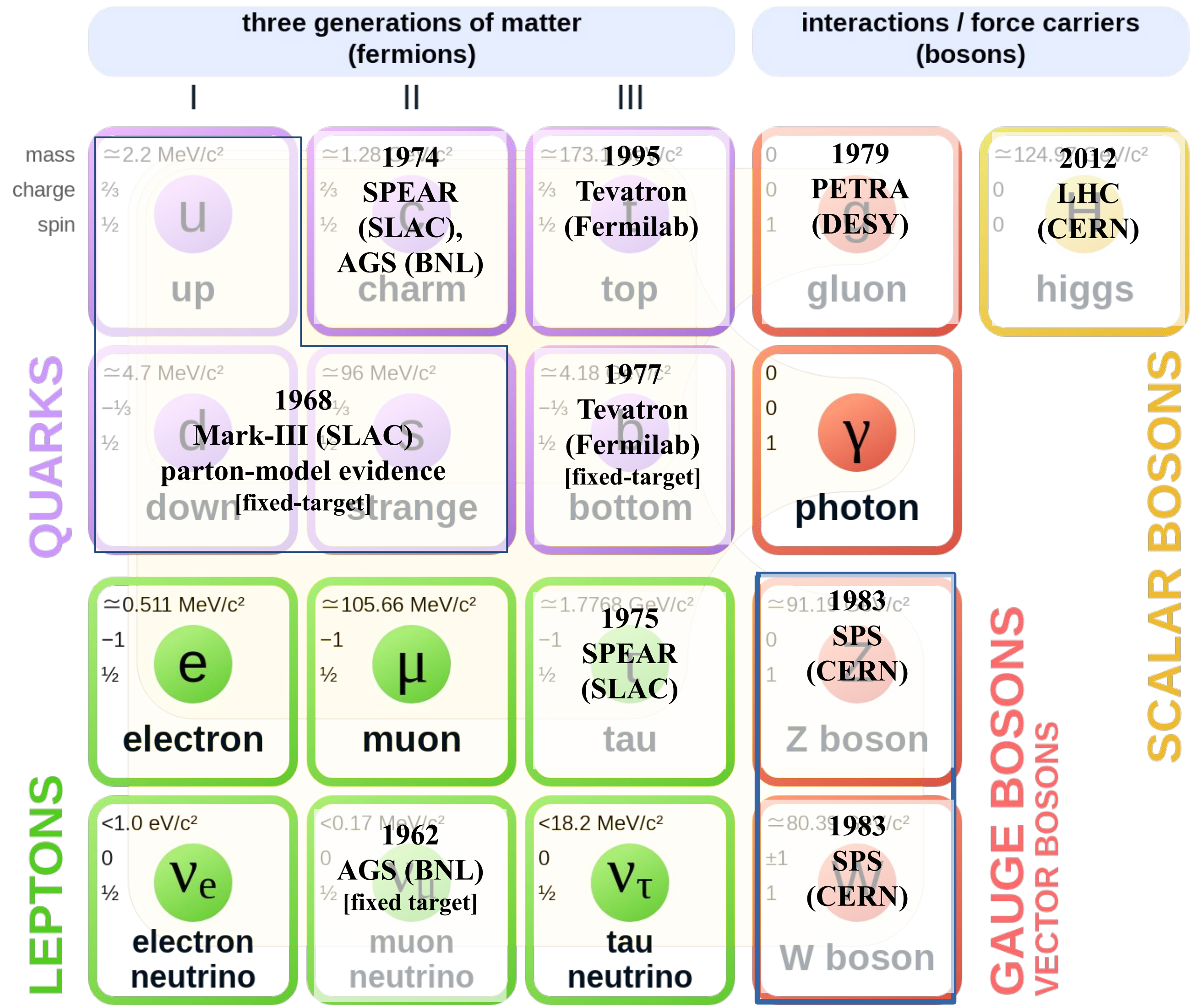

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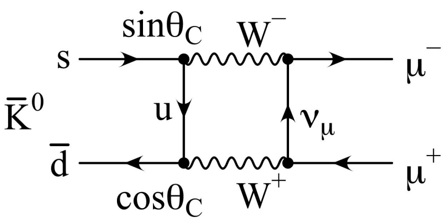
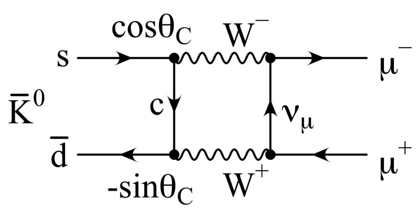
Keys to success: Theory <-> Experiments

Experimental breakthroughs and Theoretical advancements have both contributed to this success

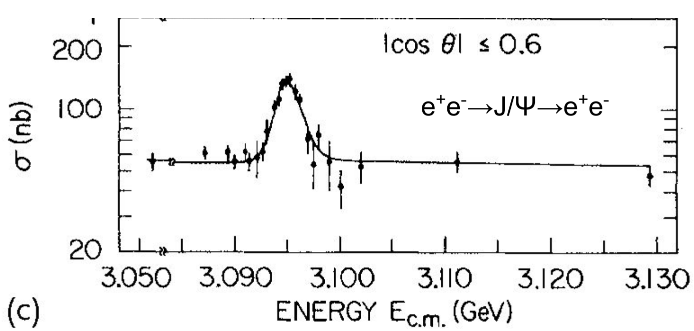
Prediction of charm quark

Predicted to explain suppression of FCNC:
$BR(K^0 \rightarrow \mu\mu) \sim 10^{-8}$





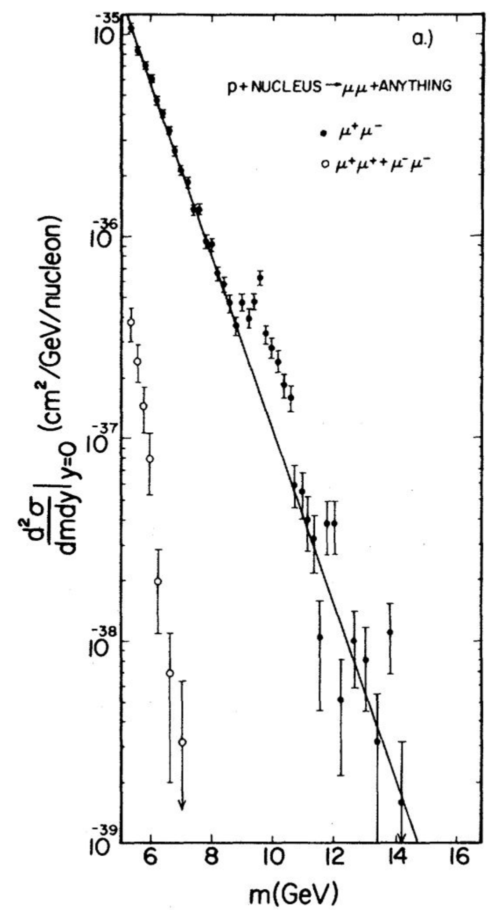
Then discovered through direct production of J/Ψ



PRL 33, 1406 PRL 33, 1404 (1974)

Discovery of bottom quark

No obvious reason for a 3rd generation, still..

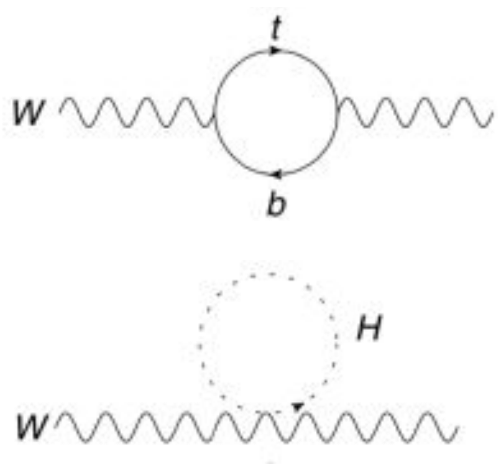


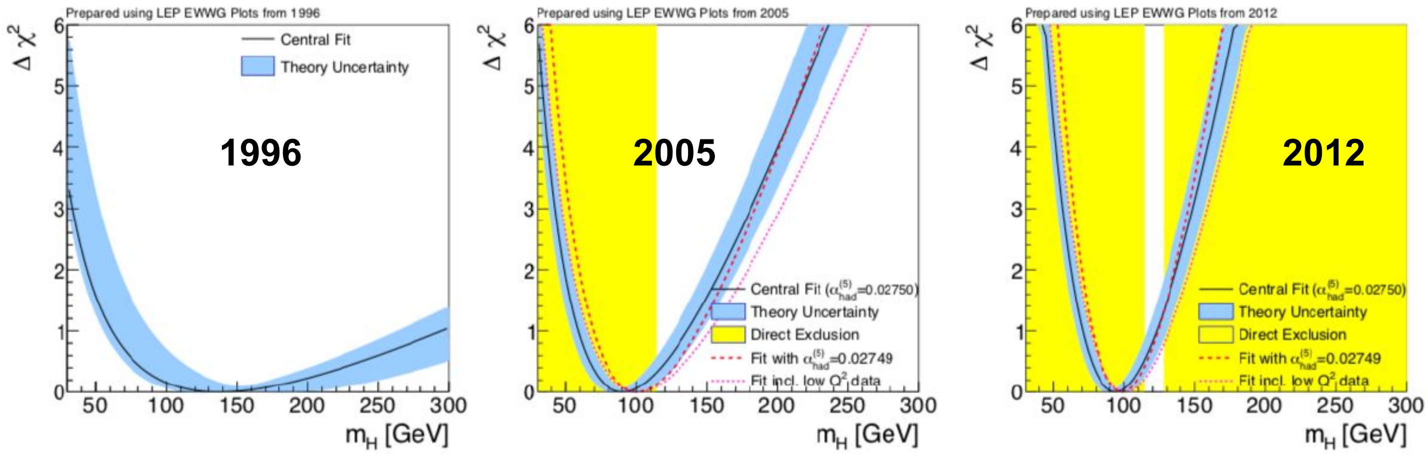
Bottom quark discovery through production of Upsilon meson

Phys. Rev. Lett. 39, 252 (1977)

Keys to success: Precision measurements <-> Direct searches

Precision measurements can stress-test the Standard Model
and ultimately point towards the energy scale we need for a discovery





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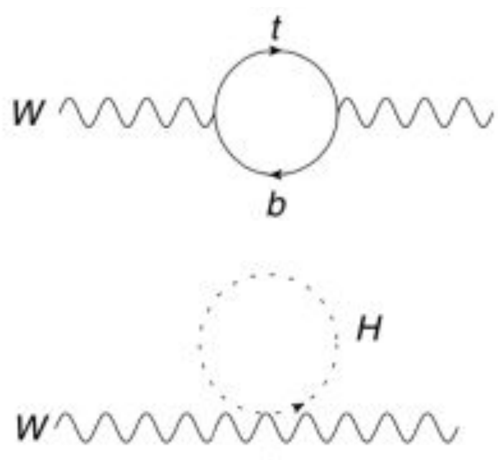
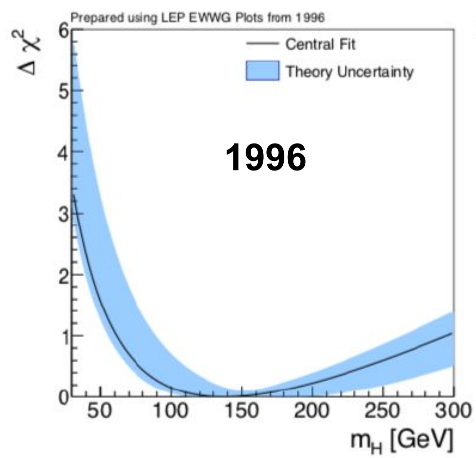
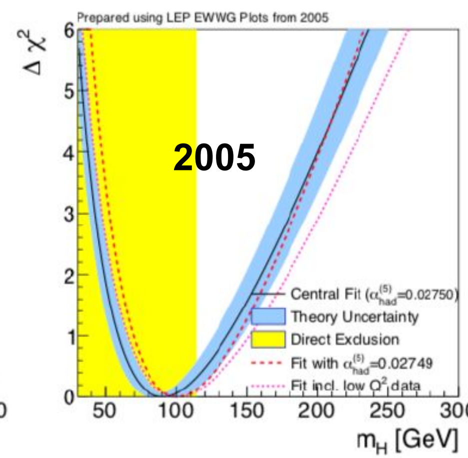
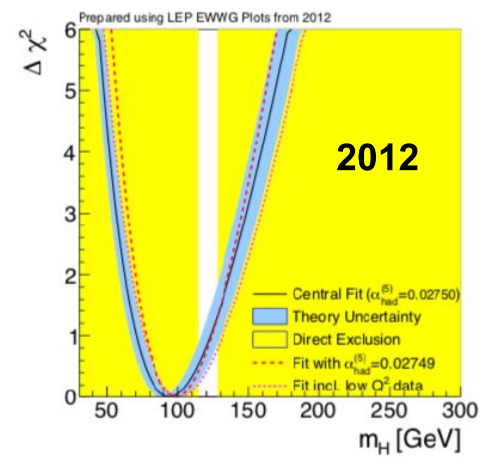
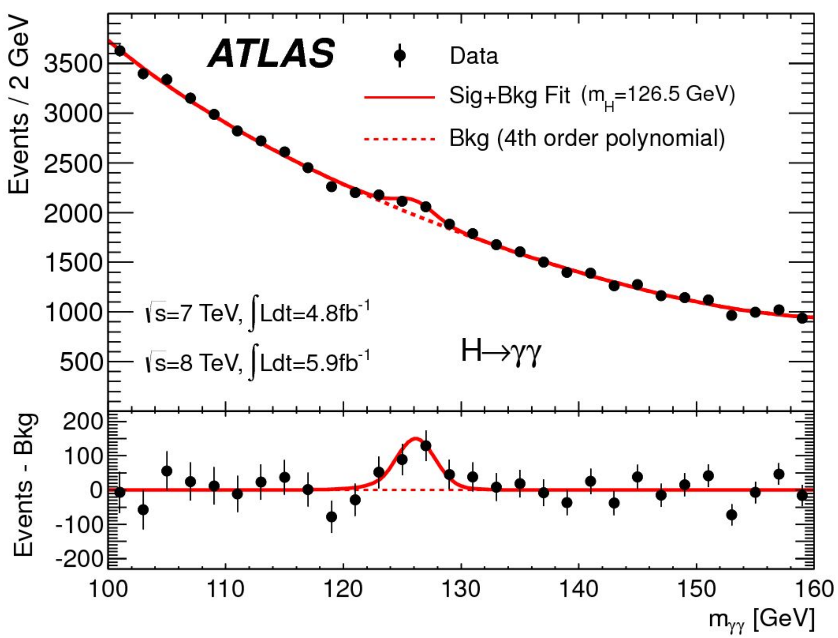




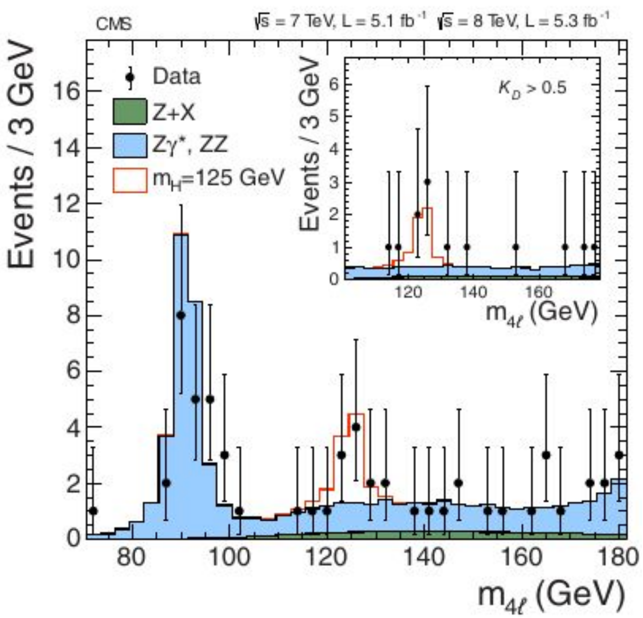




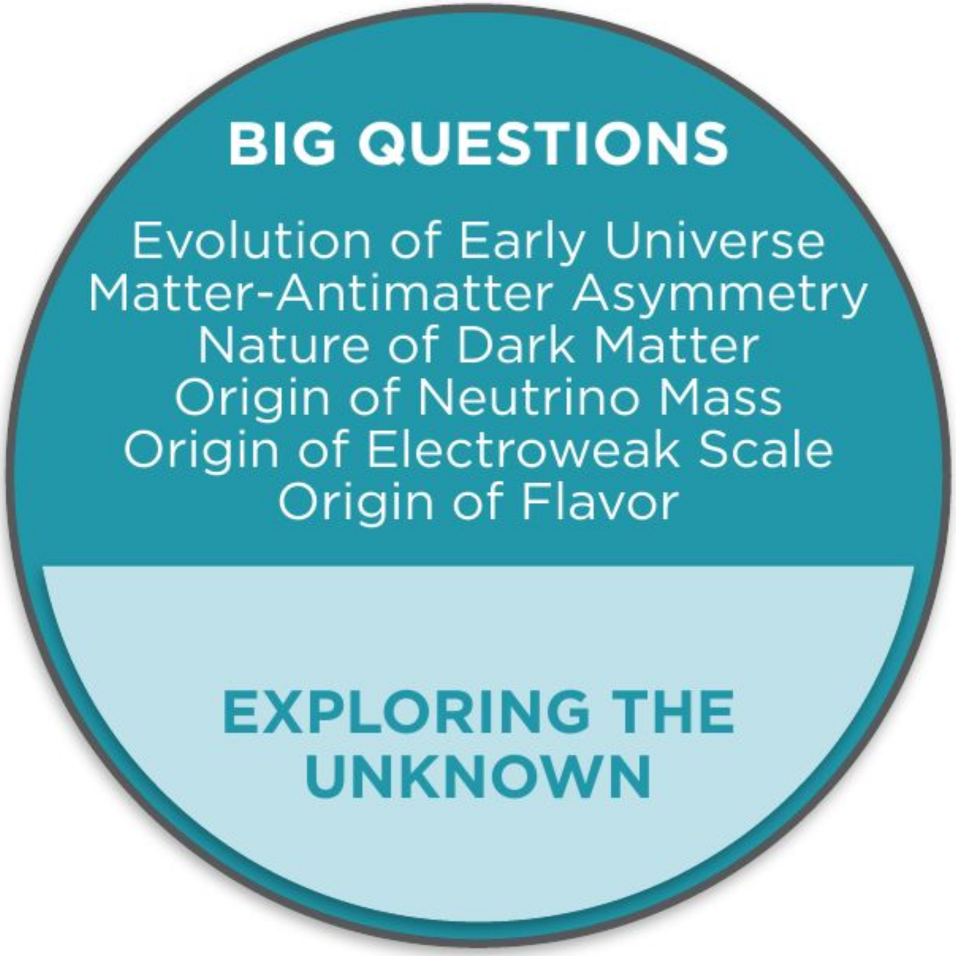


July 2012

PLB 716 (2012) 1, PLB 716 (2012) 30



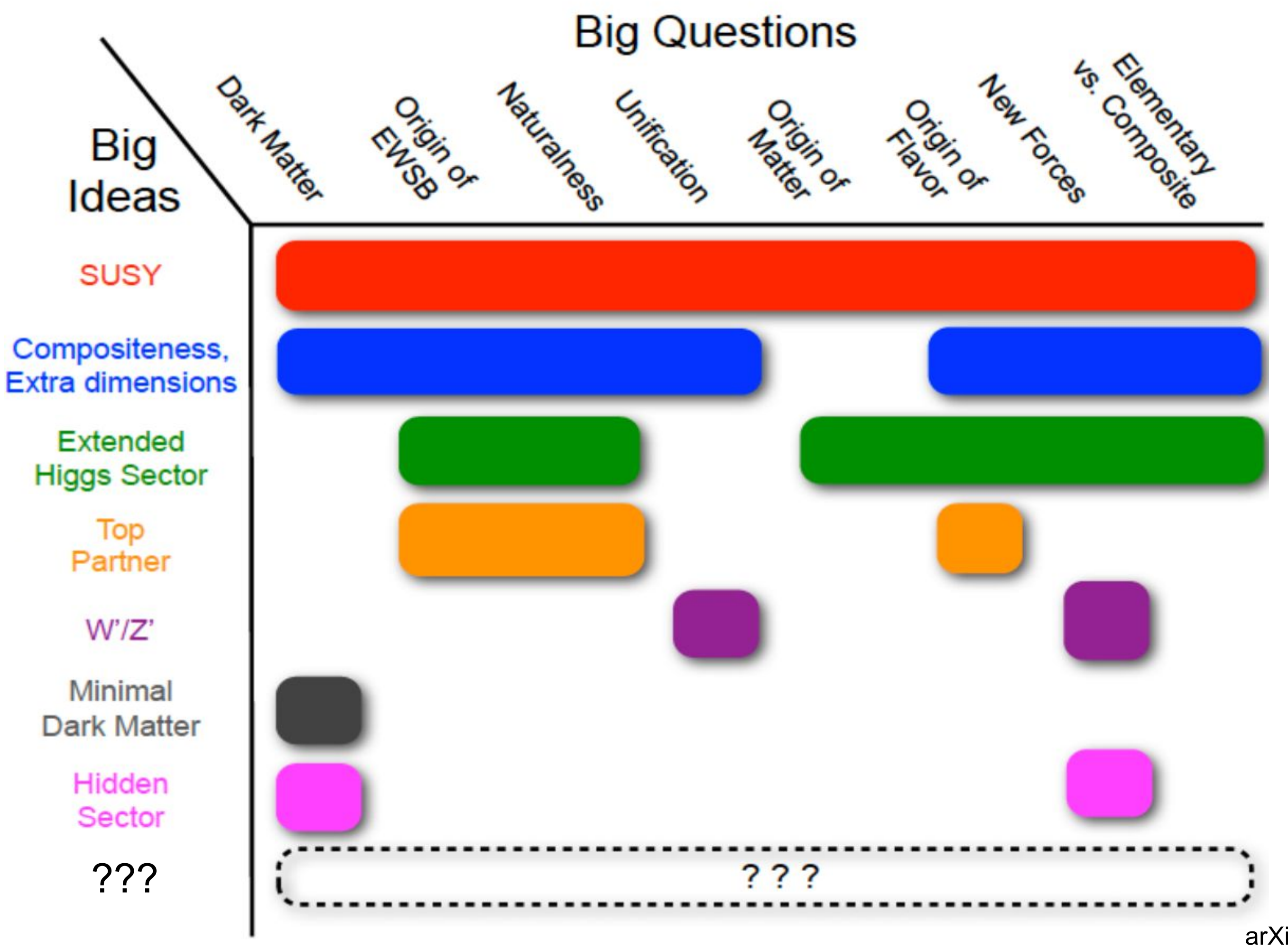
The (current) Standard Model is not enough!



Content: Snowmass EF Report
Alternative design by T. Holmes

The (current) Standard Model is not enough!

Plenty of extensions of the Standard Model have the potential of addressing these questions, including the ones we haven't thought of yet

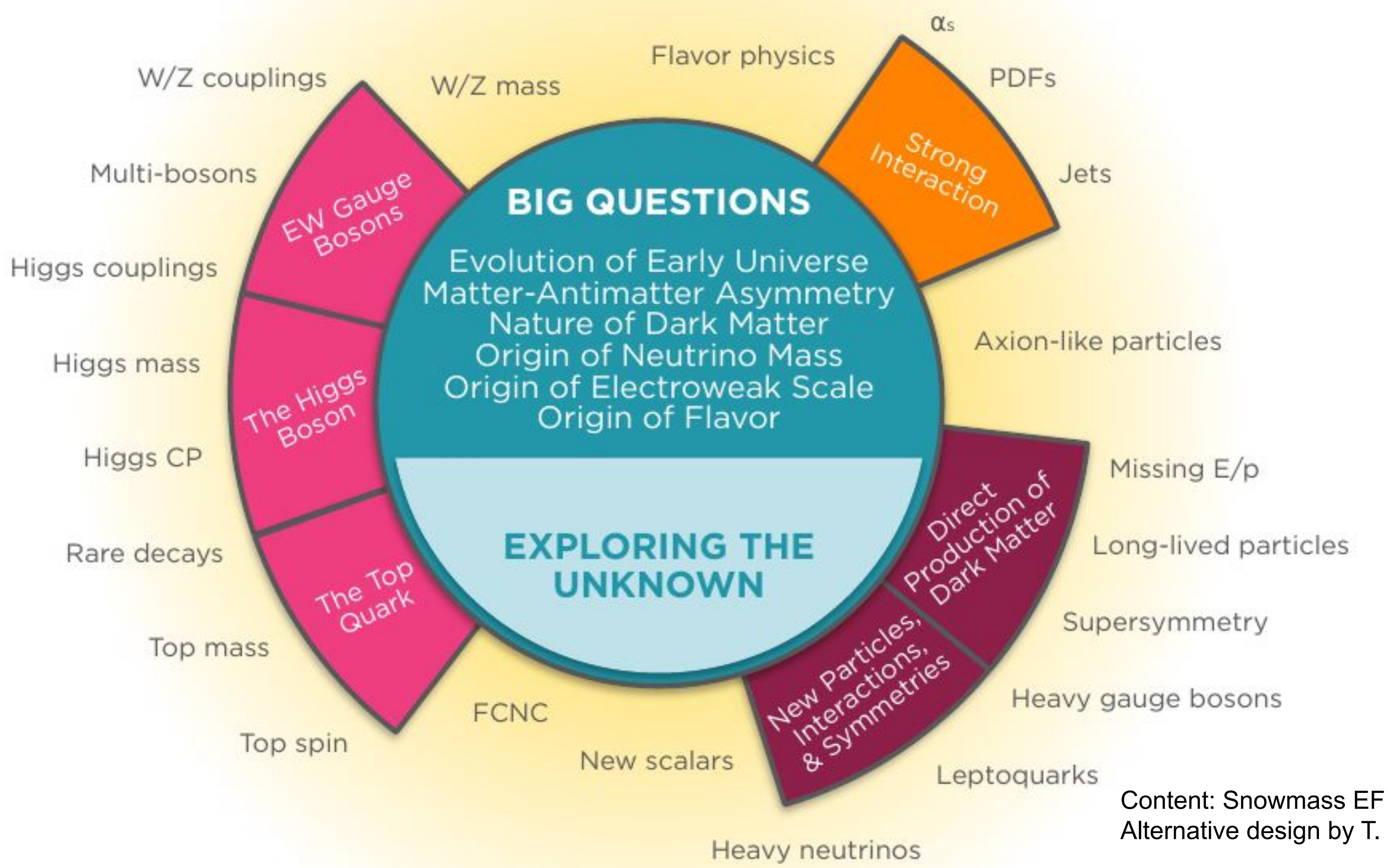


arXiv:1311.0299

Most pointing to higher energy scales where new particles will manifest

Probes and Signatures of new physics at colliders

With such an exciting and vast landscape of possibilities,
the **breadth of the experimental program** is of paramount importance



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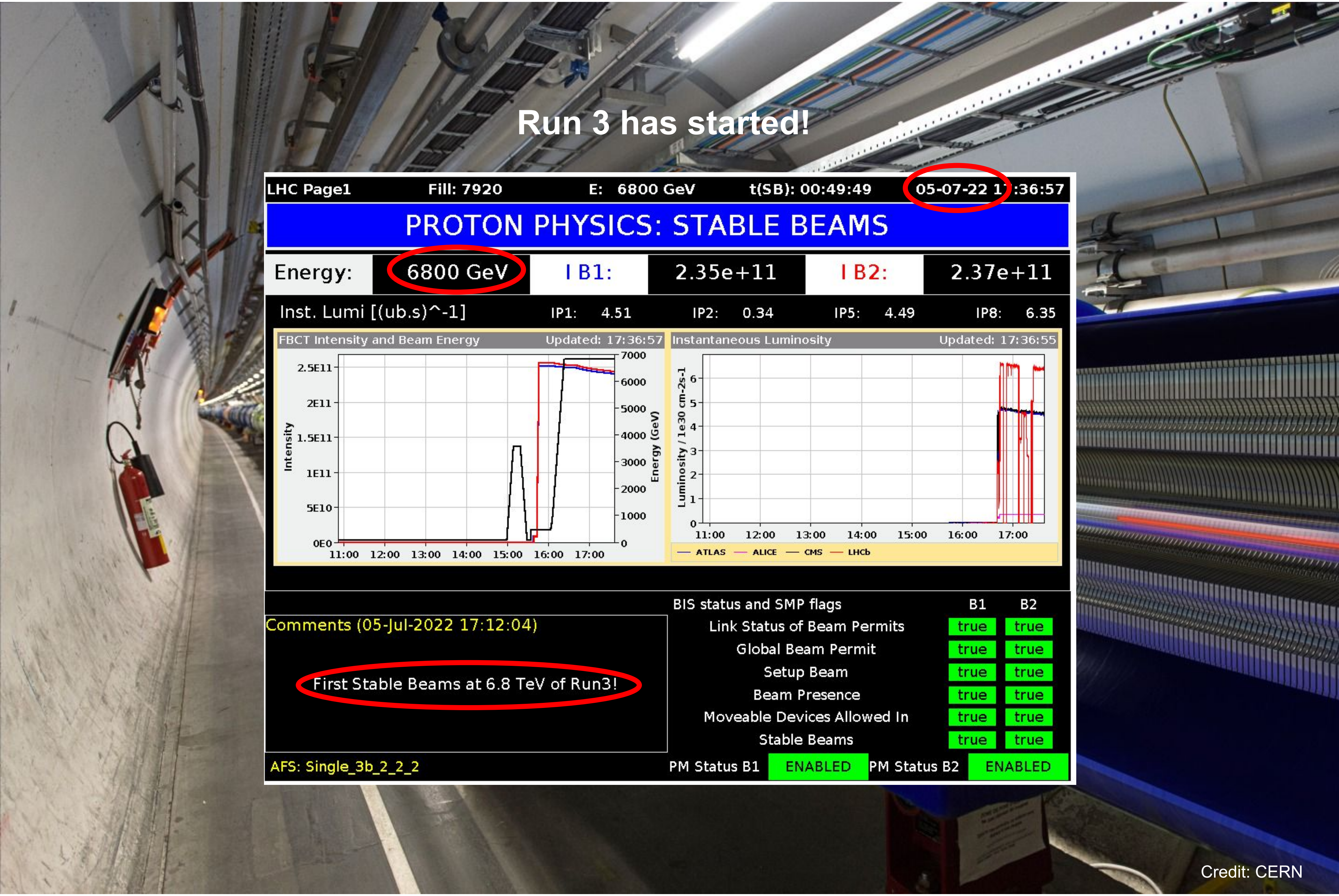
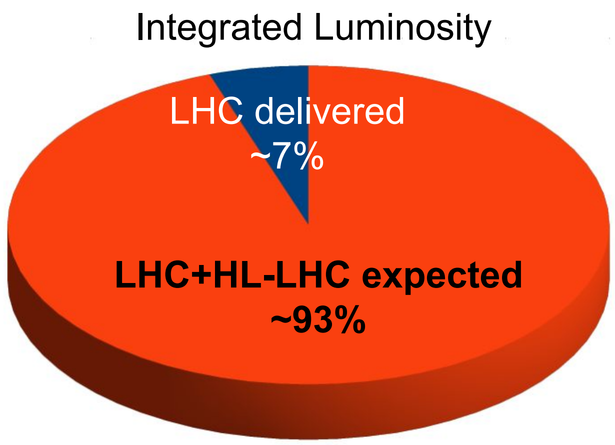
Colliders offer the unique ability to probe, with a single experimental setup, all sectors of the SM and its extensions

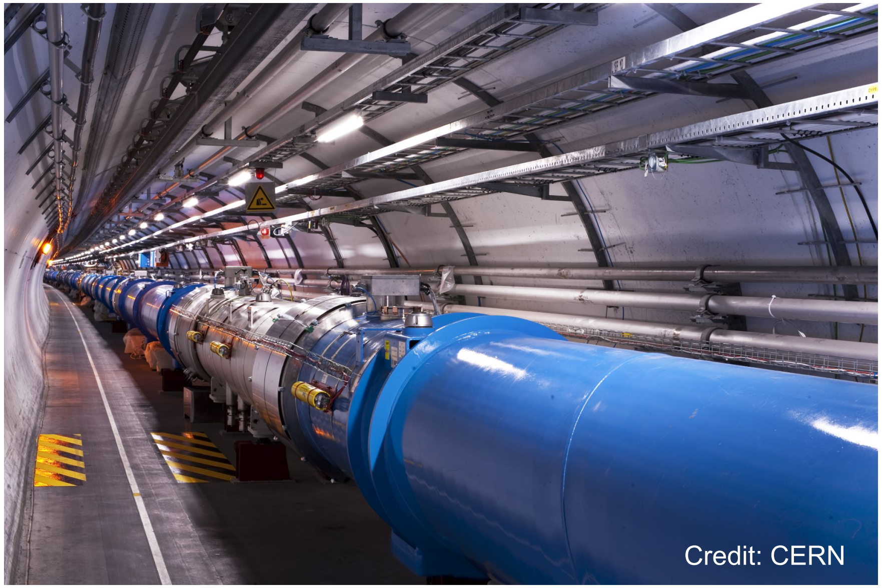
The Large Hadron Collider



HL-LHC: our upcoming Energy-Frontier Collider

Operation: 2029 to ~2040



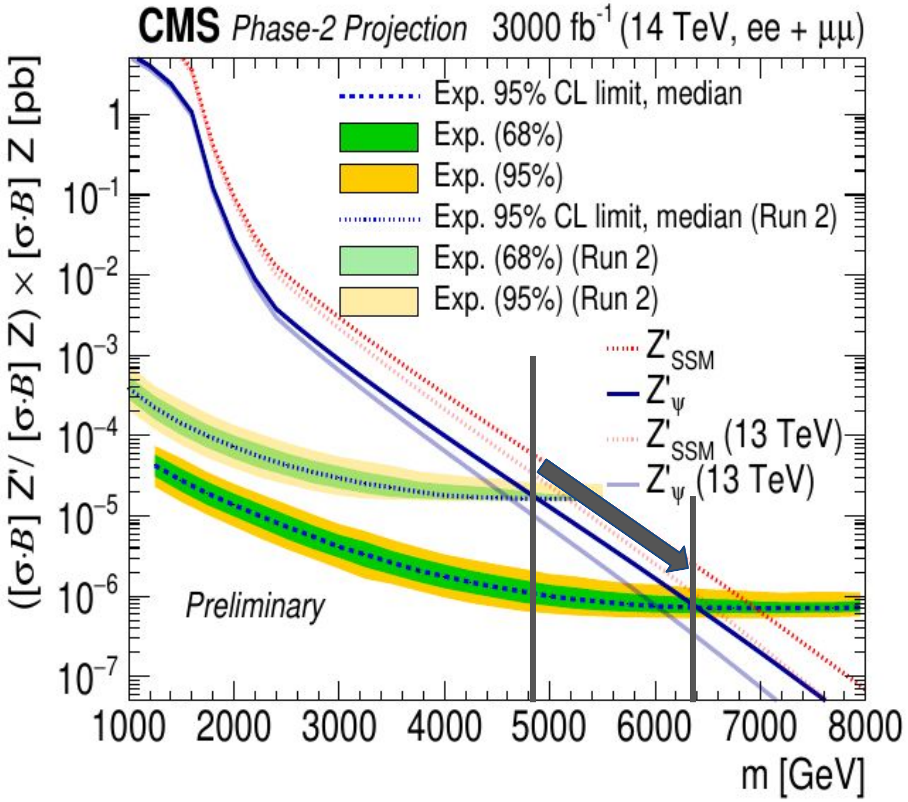


@CERN

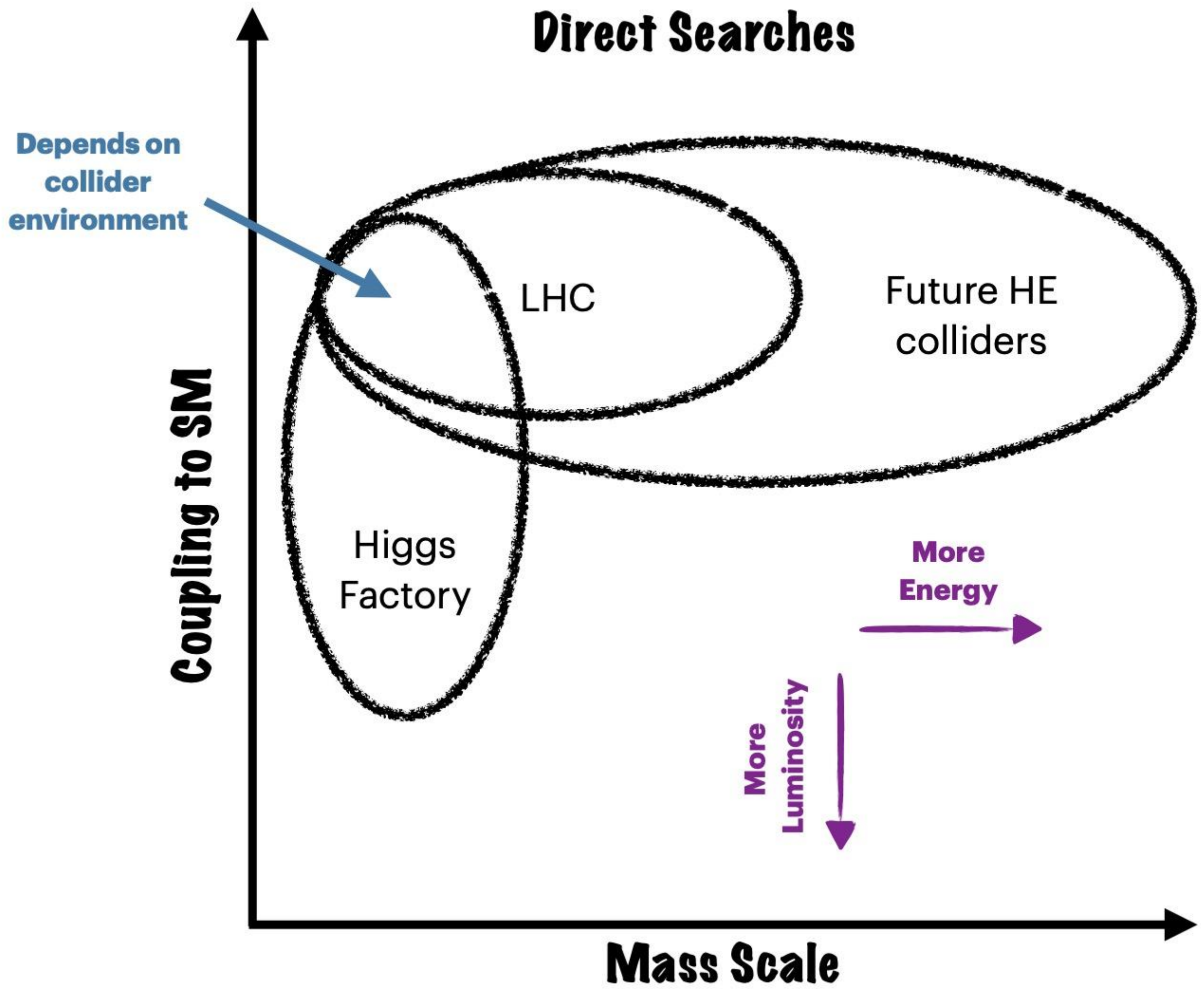
Only a fraction of the p-p center-of-mass energy is transferred through the hard-scattering interaction

=> Large integrated luminosity allows access to higher energy scales as well

And more: new auxiliary experiments at HL-LHC can further boost its discovery potential!



Beyond HL-LHC



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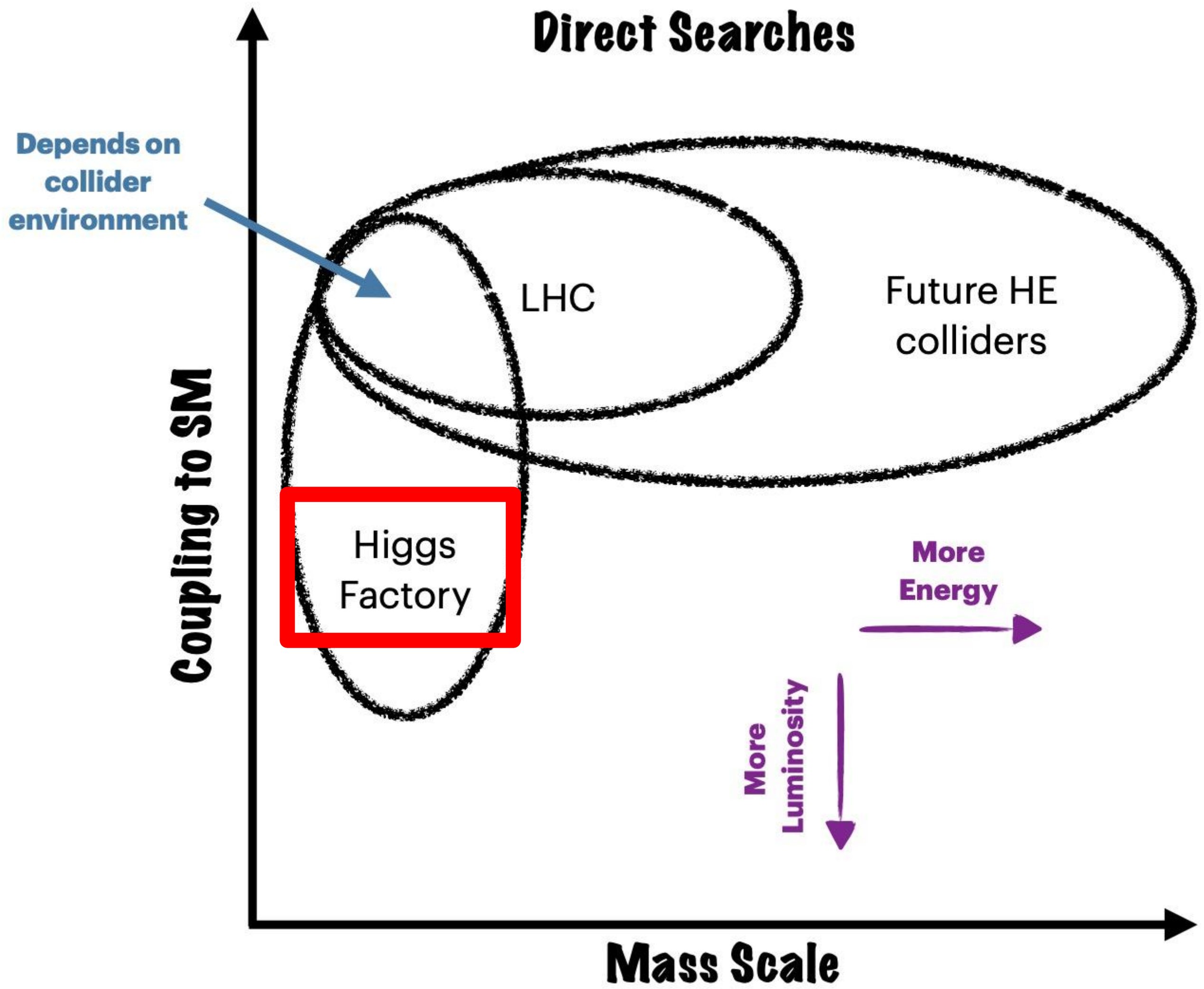
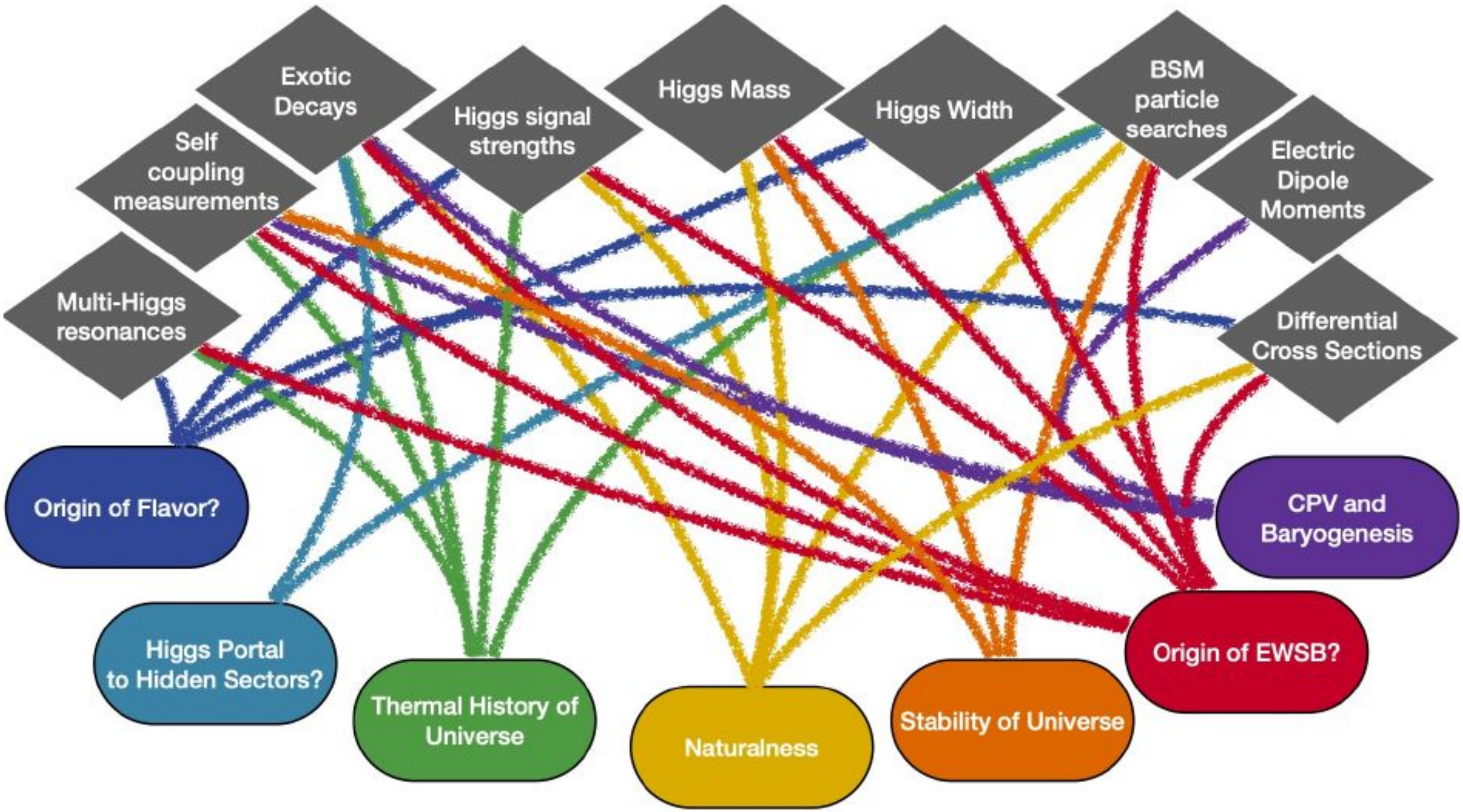


Higgs is everywhere

Higgs properties are connected to many of the fundamental questions we want answers for

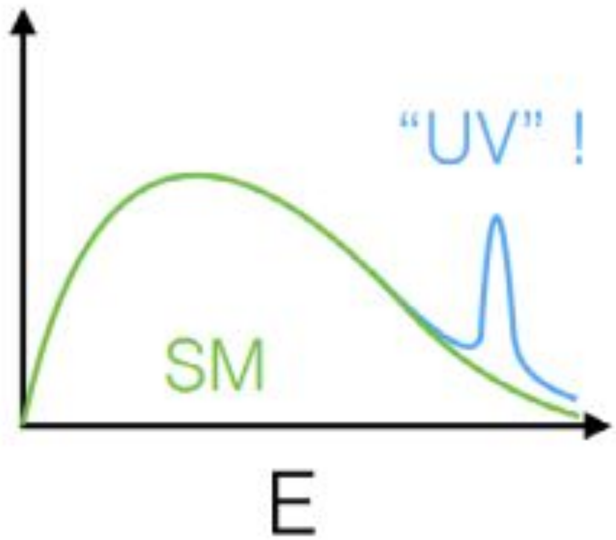


Higgs Factories: target

Primarily aim to study in great depth the Higgs sector of the Standard Model

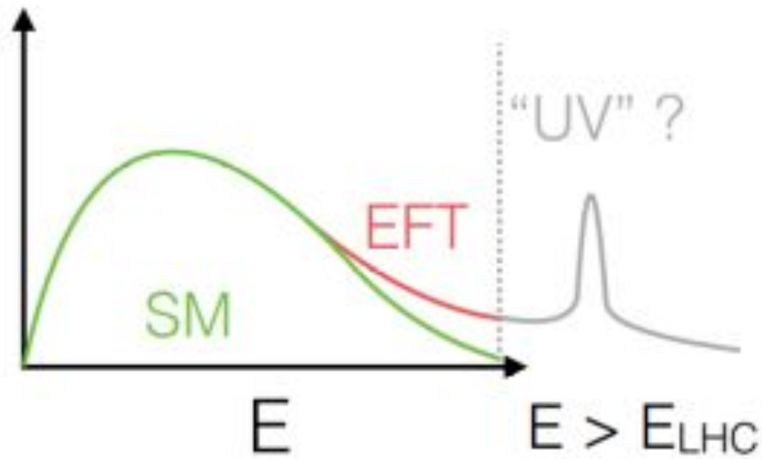
Two key areas:

- Direct search of new "light" states
- Precision measurements



E.g. by measuring Higgs properties with a precision $\delta\eta_{SM}$

$$\delta\eta_{\mathrm{SM}} \sim g^2_{\mathrm{BSM}} \frac{v^2}{M^2}$$
$$\sim 5\% \cdot \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$



Need to reach precision on Higgs couplings < 1% to probe multi-TeV scales.

Higgs Factories: options

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	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		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

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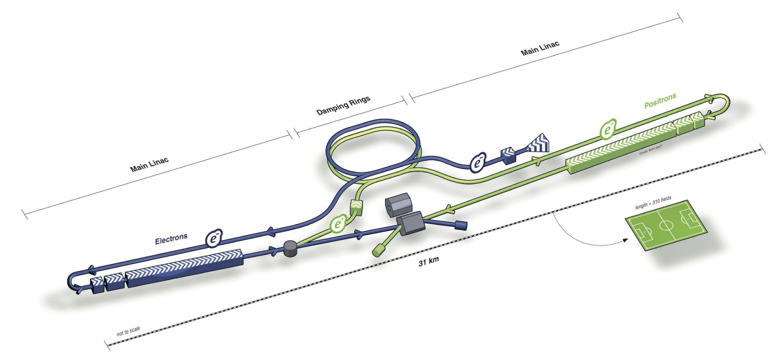
μ-collider	$\mu\mu$	125 GeV		0.02

Linear Colliders

- Lepton-Lepton collision provides a very clean environment for precision measurements.
- Large accelerating gradients.
- Extend to upgrade in Energy.
- Only 1 interaction point.



ILC. Proposed site: Kitakami highland (Japan)

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		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

Circular Colliders

- Lepton-Lepton collision provides a very clean environment for precision measurements.
- Higher luminosity than linear colliders
- More difficult to upgrade Energy.
- Multiple interaction points.

FCC-ee @ CERN
CEPC @ China (site tbd)

New (light) states

Higgs potentially couples to all known particles that have a mass.

- Can potentially be sensitive to new light states

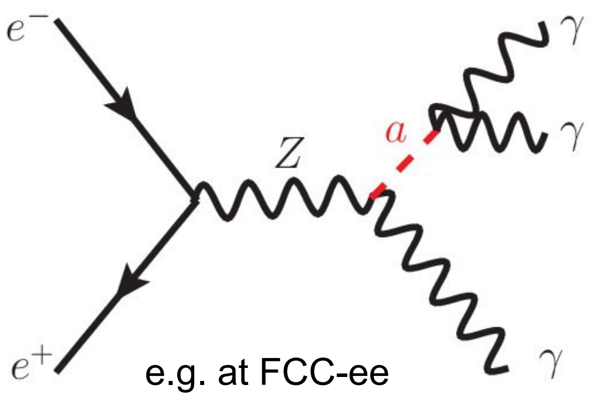
In general Higgs factories can probe new particles with m ~ $s^{1/2}/2$ extensively.

- Small physics backgrounds (a bit more on this later)
- Lower radiation environment allows to push on detector accuracy

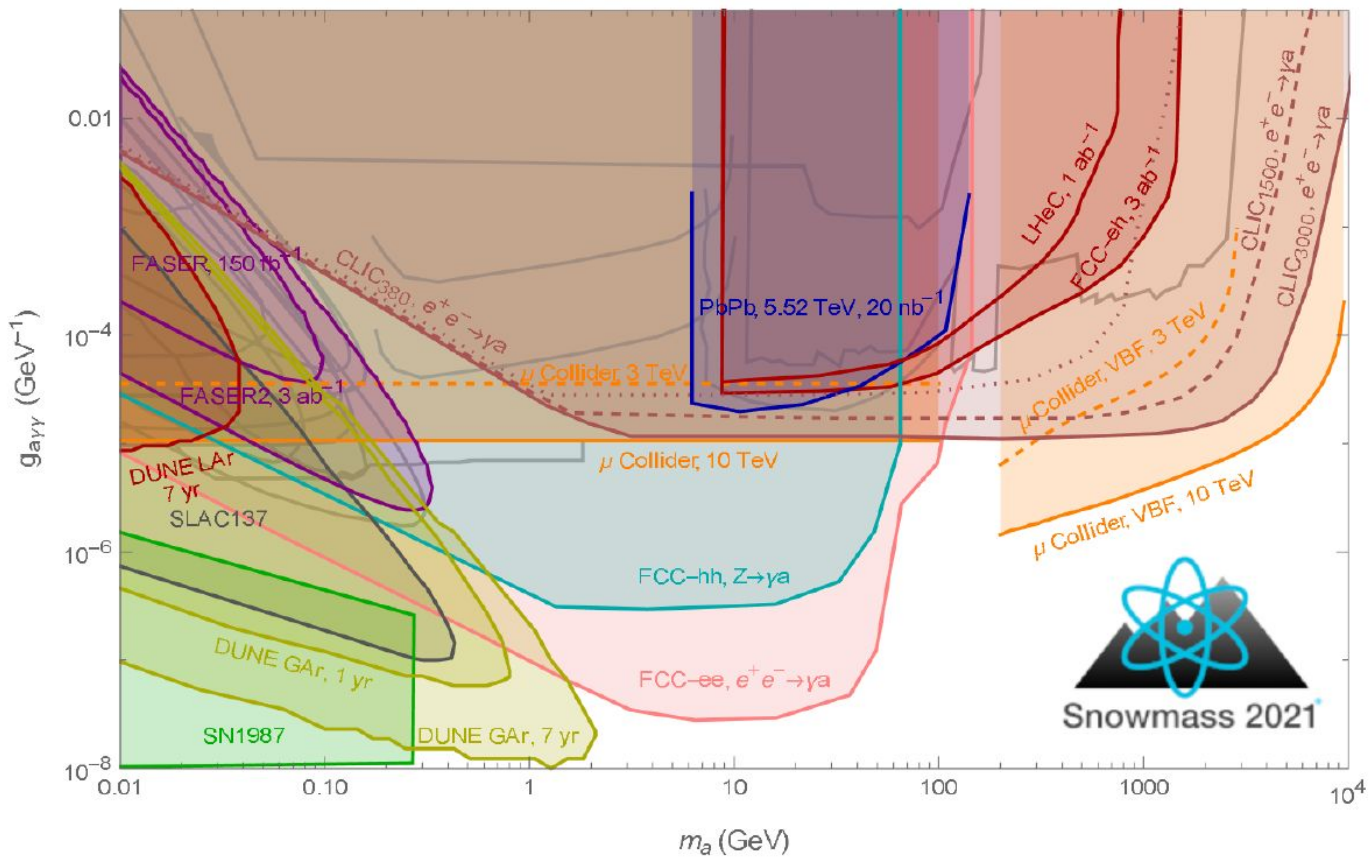
Example:

Axion-like Particle (a)

- Extension of axions, postulated to explain why no CP violation in the strong force

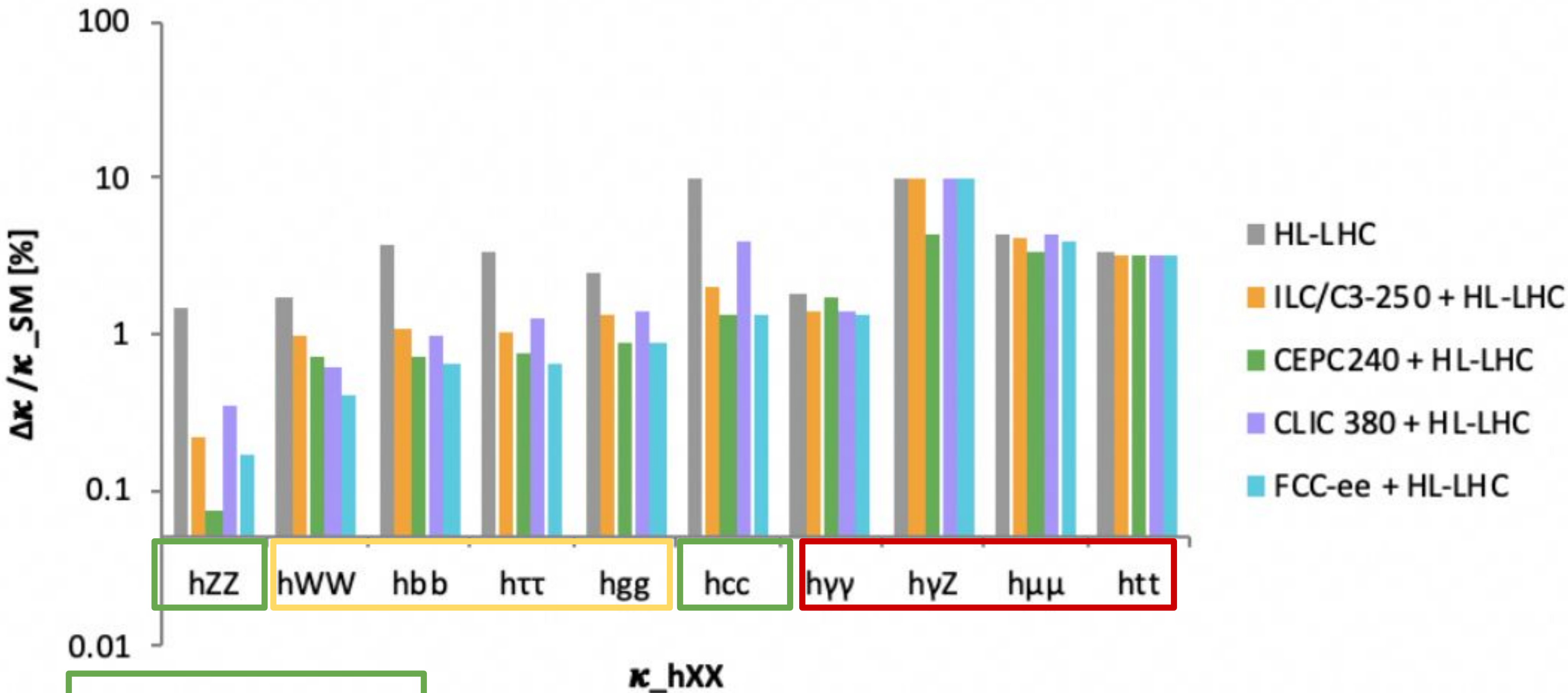


e.g. at FCC-ee



Precision measurements

Reminder: aim to measure them at sub-percent accuracy.
Target met for most, although for top-quark, γγ, Zγ and μμ marginal improvement.

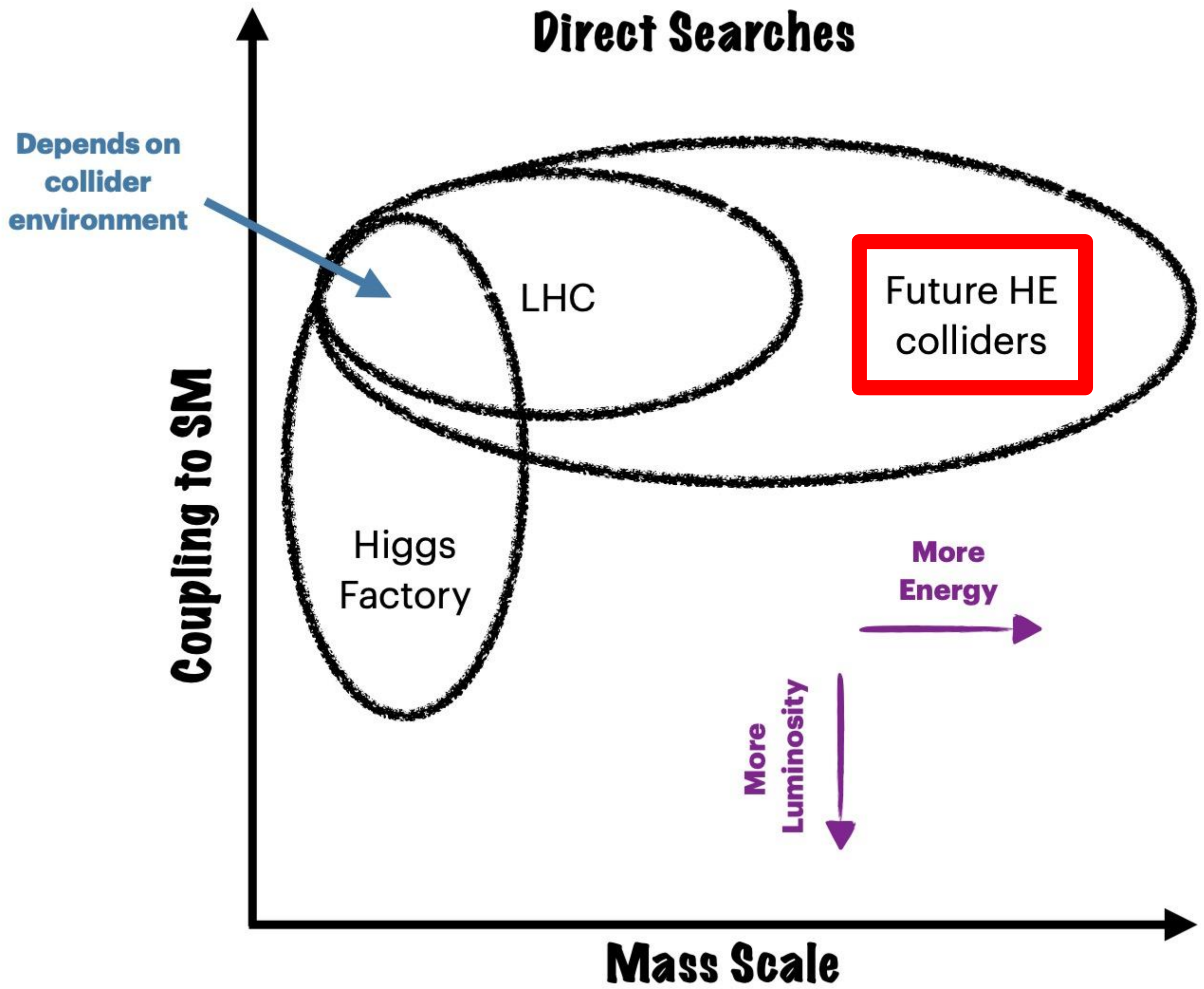


~ x10 improvement

x[1-10] improvement

marginal improvement

Beyond HL-LHC



How to reach even higher center-of-mass energy?

| pp | e^+e^- | $\mu^+\mu^-$ |

multi-TeV lepton-hadron colliders also considered, not discussed here

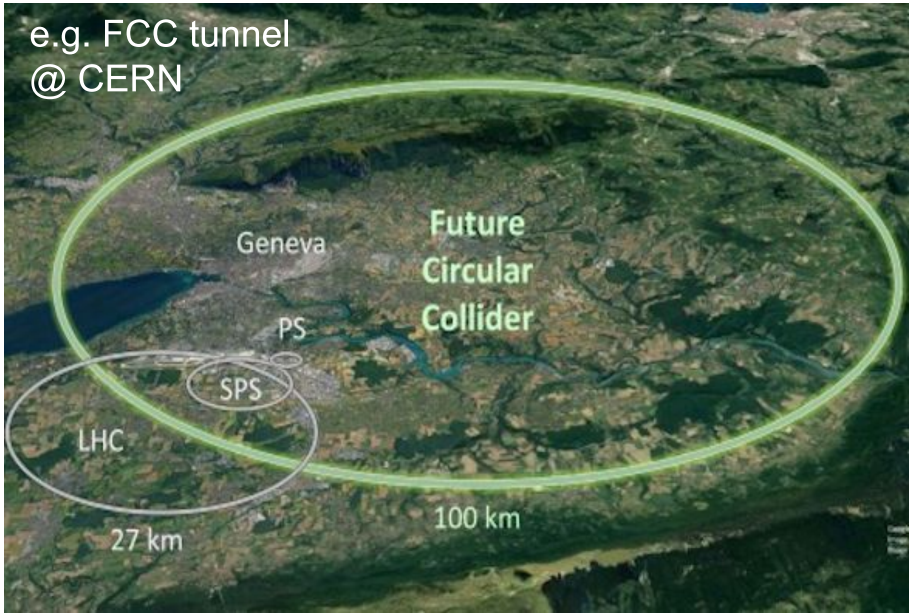
How to reach higher center-of-mass energy?

pp | e^+e^- | $\mu^+\mu^-$

- Large collider ring, stronger magnets
  - re-use FCC-ee/SpeC tunnel

$$p \propto qB\rho$$

- Need large statistics (luminosity) to sample highest energy scales



	FCC-hh	SppC
Center-of-mass [TeV]	100	75 (125-150)
Circumference [km]	91	100
Luminosity [/ab/yr] / IP	3	~1

How to reach higher center-of-mass energy?

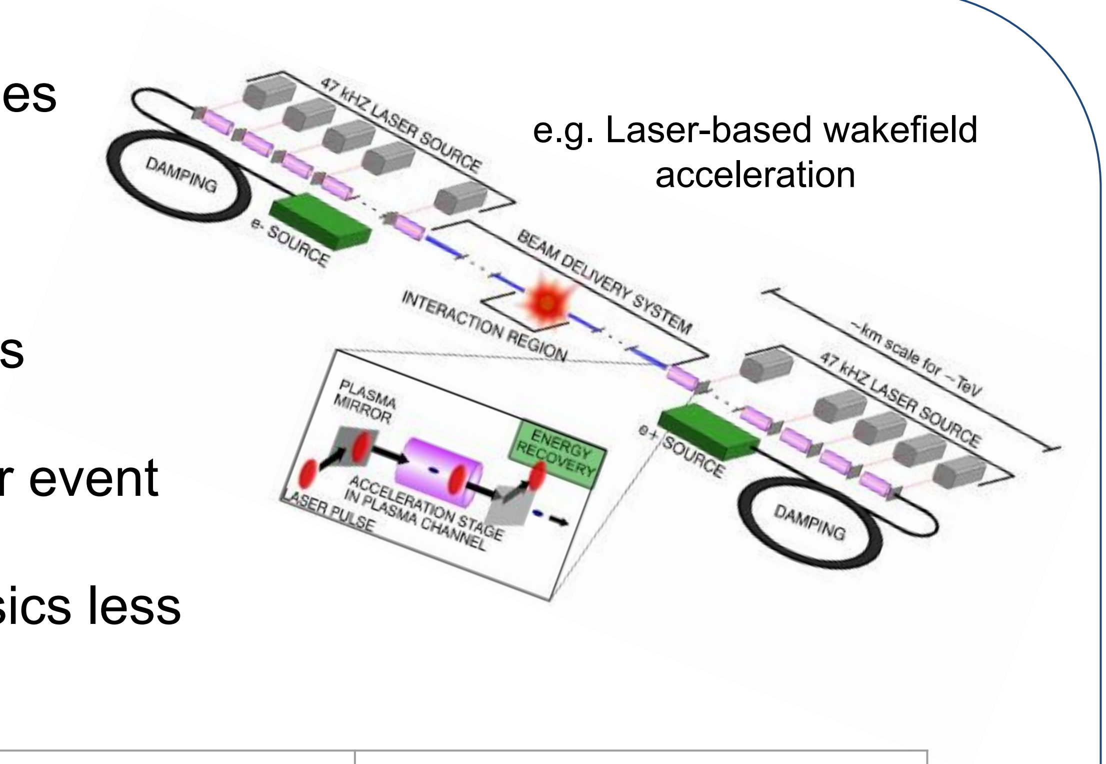
pp | e^+e^- | $\mu^+\mu^-$

- Large synchrotron radiation implies linear accelerator

$$P_{\text{loss}} \propto q^2\gamma^4$$

- Need large acceleration gradients

- Low physics backgrounds, easier event reconstruction
- γγ technically preferred, but physics less studied



e.g. Laser-based wakefield acceleration

	ILC/CLIC/CCC	Wakefield Accelerators
Center-of-mass [TeV]	3	15
Length [km]	27-59	1.3 - 18
Luminosity [/ab/yr]	0.6	~1.3

How to reach higher center-of-mass energy?

pp

e^+e^-

$\mu^+\mu^-$

- Large community interest during Snowmass
  - ~40 EF contributed papers
  - > 60 early-career authors in forum report

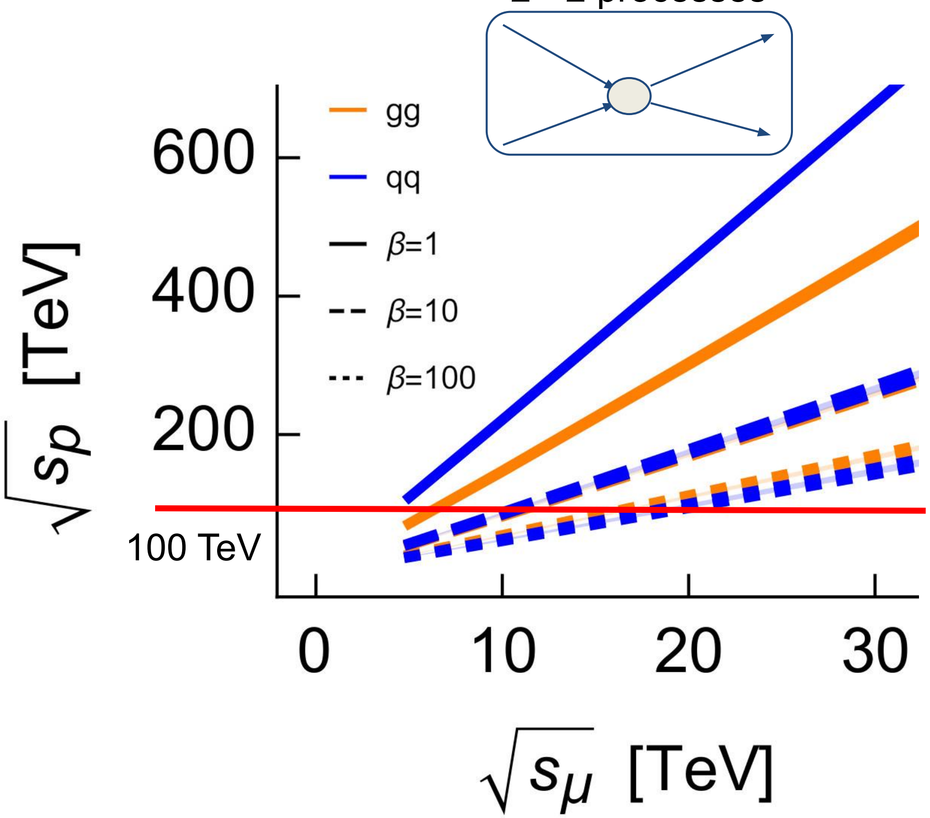
- Expect large beam-induced background (τ_0^{μ}~2μs)
- Low physics backgrounds
- In principle scalable to even higher energies

	MuC-3	MuC-10
Center-of-mass [TeV]	3	10 (14)
Circumference [km]	4.5	10
Luminosity [/ab/yr]	0.2	2

Lepton vs Hadron colliders: expected signals

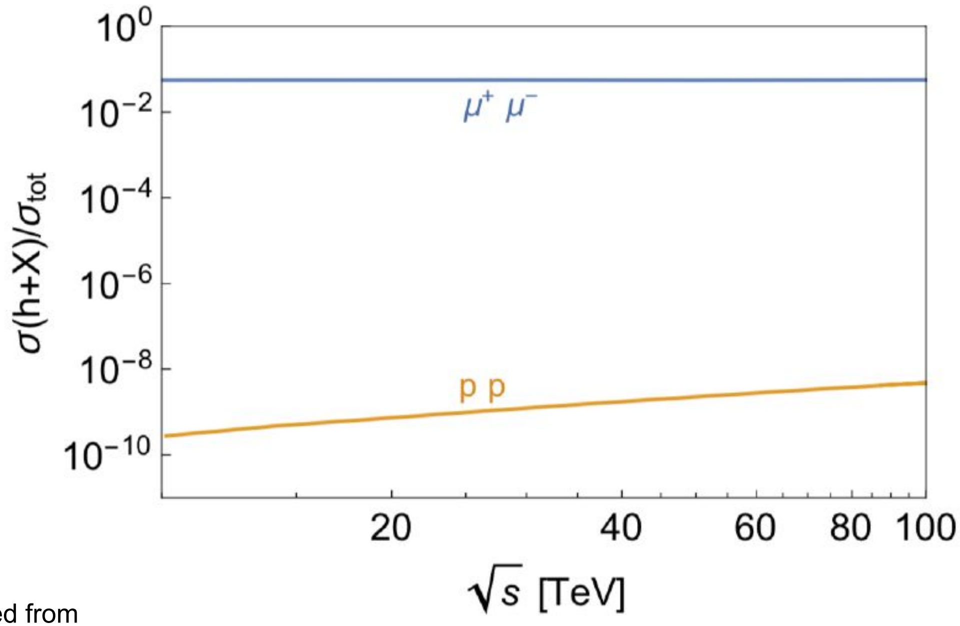
Protons: involve scattering of constituents (partons)
Leptons: full center-of-mass energy available in collisions*

Signals



Backgrounds

e.g. Higgs over total production x-section



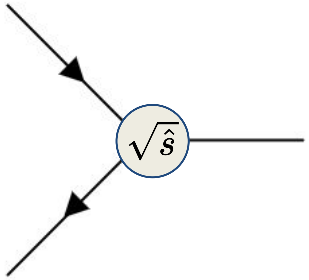
Adapted from arXiv:2103.14043

Practically, a lot of details that depend on the specific process, hence the need for a broad set of studies

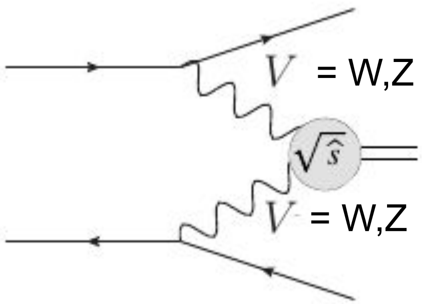
Not a “simple” jump in Energy

Moving to ~10 TeV parton/lepton energy scale has qualitative new features

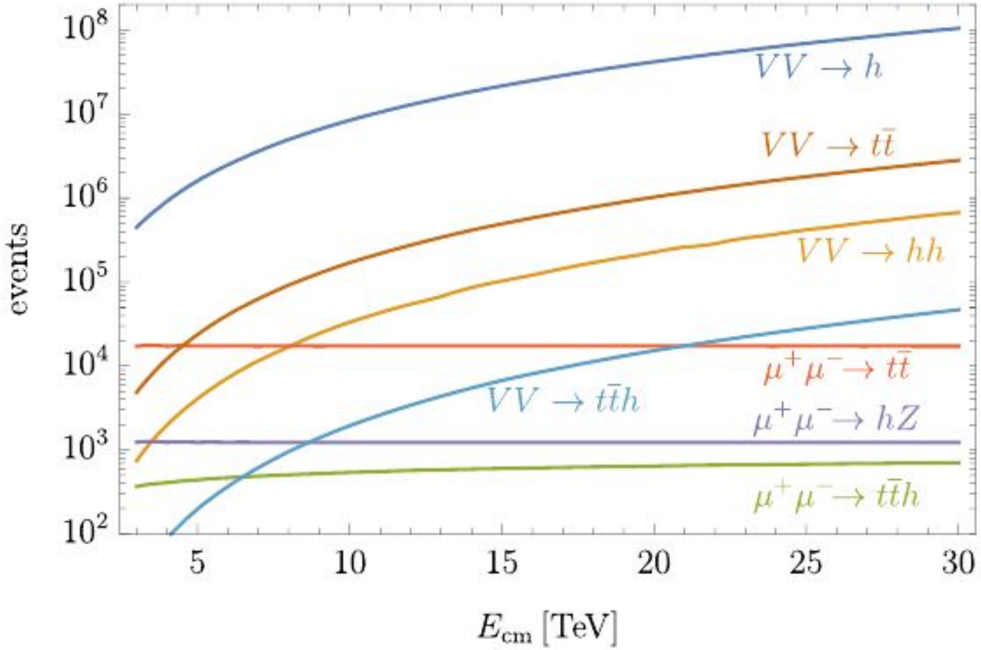
Just 1/100s examples: **new dominant production mechanisms**



$$\sigma \sim 1/\hat{s}$$



$$\sigma \sim \log \hat{s}$$



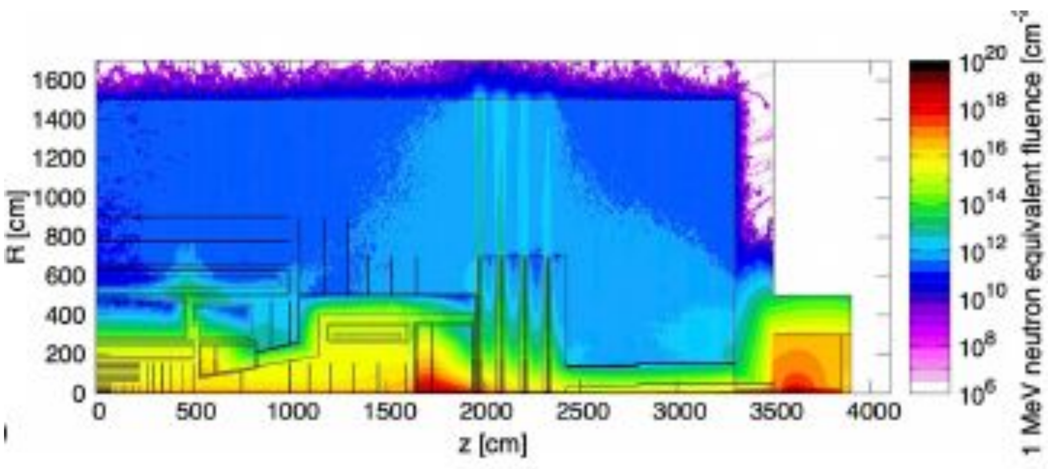
Not a “simple” jump in Energy

Moving to ~10 TeV parton/lepton energy scale has qualitative new features

Just 2/100s examples: **detectors**

New technology to develop detectors able to extract the full physics potential

Radiation Hardness



Adapted from: Eur. Phys. J. ST 228 (2019) 4, 755

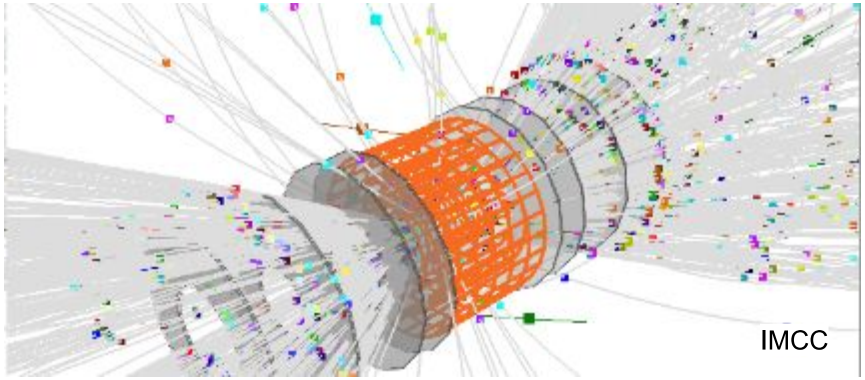
More than x10 than HL-LHC at FCC-hh

- requires robust R&D

Event Reconstruction

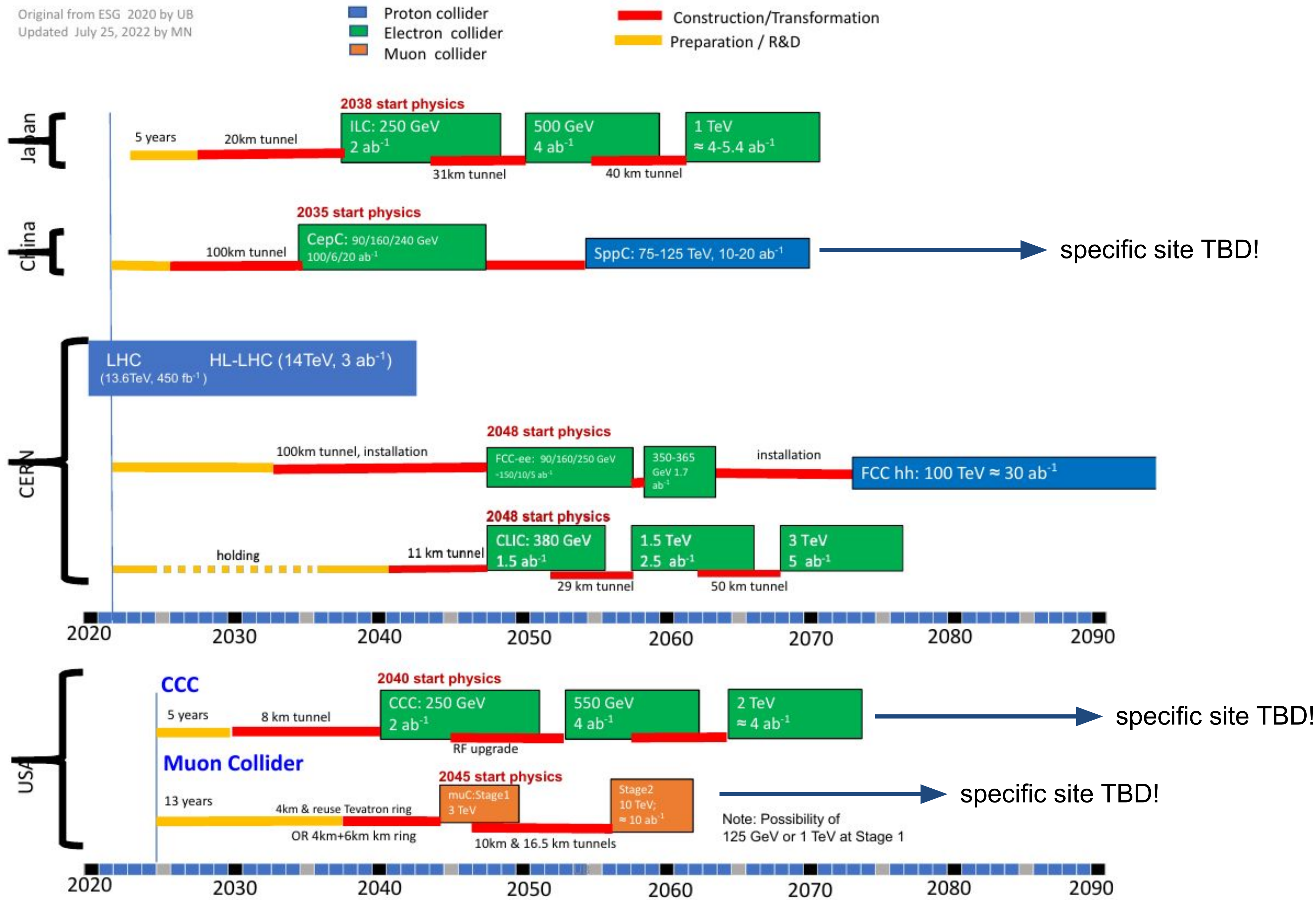
Unprecedented complexity:

- innovative algorithms / detectors’ layouts
- O(10)ps timing information



NEW Proved feasibility of full event reconstruction in a muon collider detector with detailed simulations

How (When) do we get there? Proposed timelines



Physics Beyond the Standard Model

These colliders have enormous potential to answer fundamental questions!

Group our guide to physics beyond the SM in three categories

1. Observed phenomena lacking a fundamental explanation (in backup)

- Dark Matter
- Matter-Antimatter asymmetry in the Universe
- Origin of neutrinos masses
- …

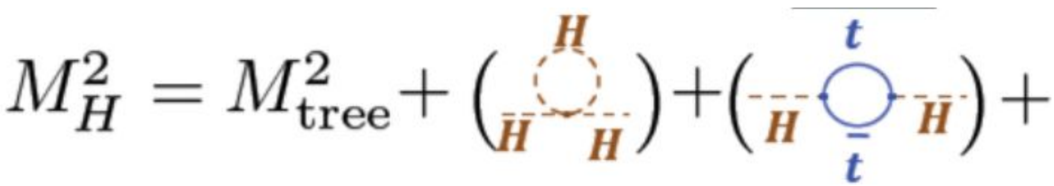
2. Guiding theoretical principles

- Natural energy scale "cut-offs"
- Flavor structure of the SM
- …

3. Unexpected new phenomena (in backup)

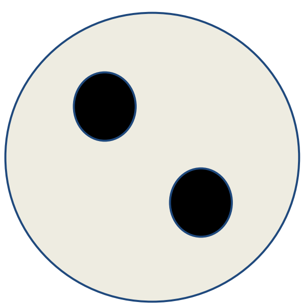
- Historically have opened roads to revolutionary discoveries

Solutions to the hierarchy problem

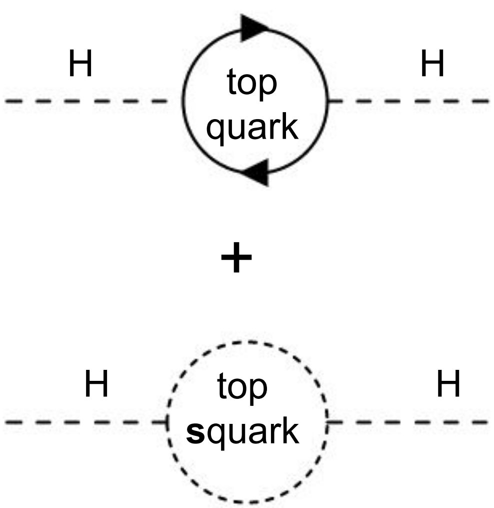


The unique scalar nature of the Higgs boson suggests new physics
Testing the ≲ 10 TeV regime provides very strong tests of this arguments
(other options are also possible)

<u>Compositness</u>



<u>New "symmetries"</u>



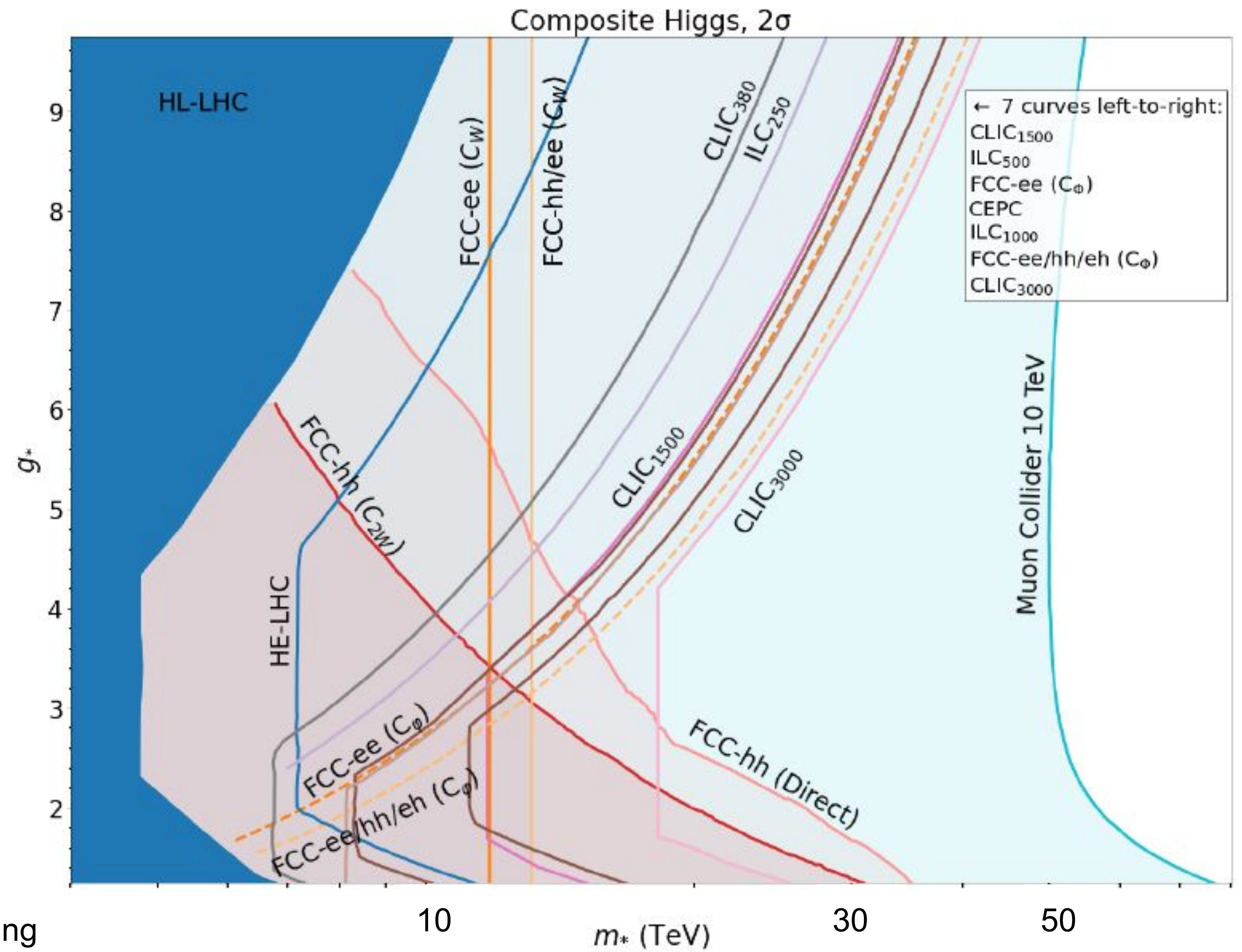
≅ 0

Higgs compositness

New constituents and inevitable a new "strong force" to bind them together

- Visible effects from direct searches as well as precision measurements
- Evaluated through sensitivity of effective Wilson coefficients

Unitarity limit ~4π



Expect a strong coupling

Supersymmetry

Long-sought for very good reasons

- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

Large model-parameters space and vast phenomenology

Simplified classes of signatures

Full models with additional assumptions

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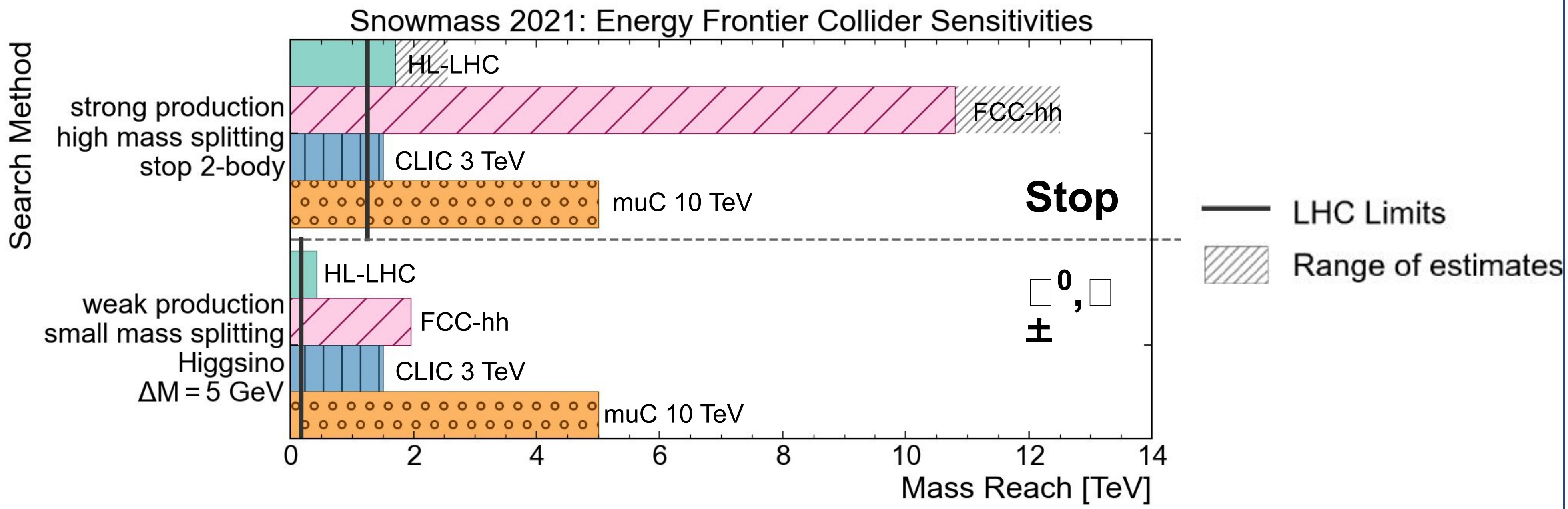


Multi-TeV colliders extend the reach to the ~10 TeV scale!

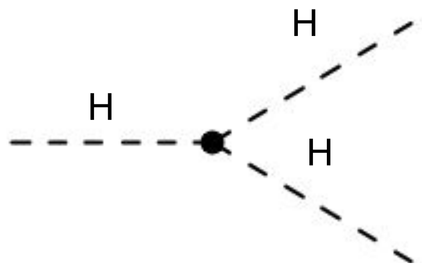
High Energy <-> High Luminosity <-> High Precision

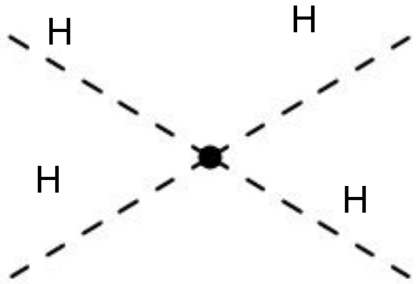
HE machines, with appropriate detector, are also precision measurement devices!

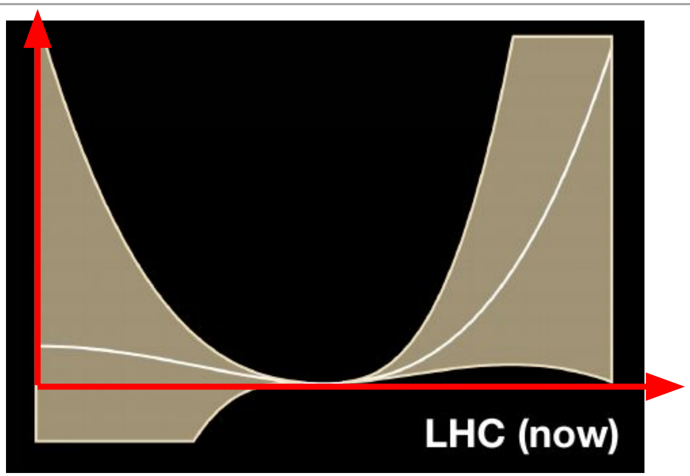
	H factories	l^+l^- @ 3 TeV	l^+l^- @ 10 TeV	pp @ 100 TeV
# Higgs bosons	$\sim 10^6$	$\sim 5\cdot 10^6$	10^7	$\sim 10^{10}$

Obviously an over-simplification, control of systematics and physics background play very important roles!

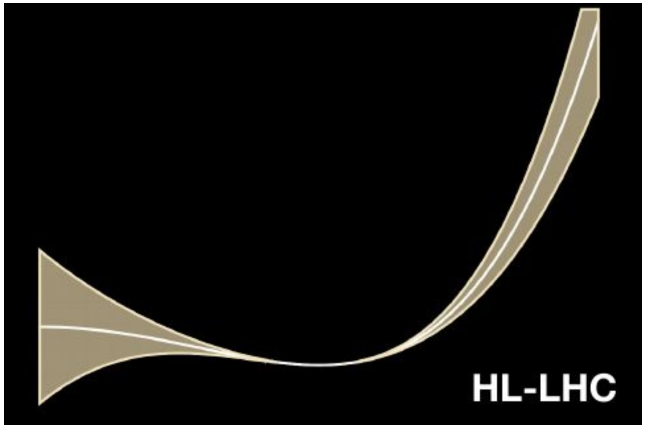
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

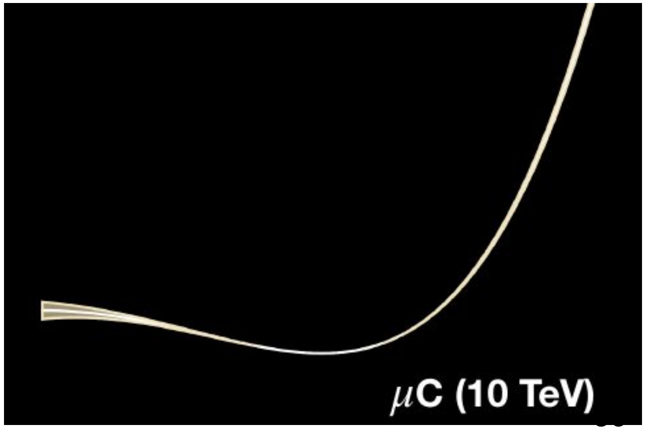






Credit:
R. Petrossian-Byrne,
N. Craig

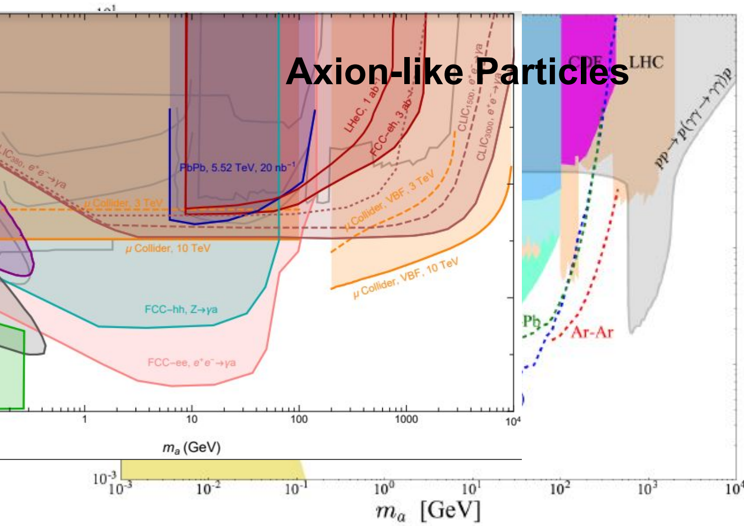


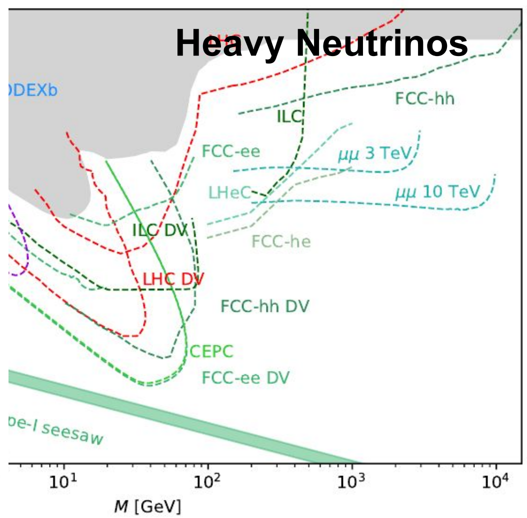


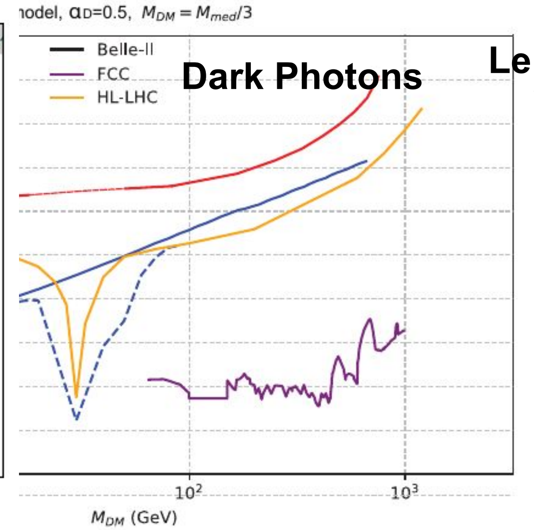
Extremely rare process:
only multi-TeV colliders can probe it accurately

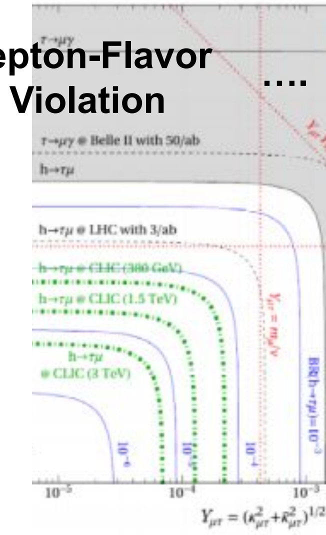
… and much MUCH more!

Vast program addressing the fundamental questions outlined and much more!

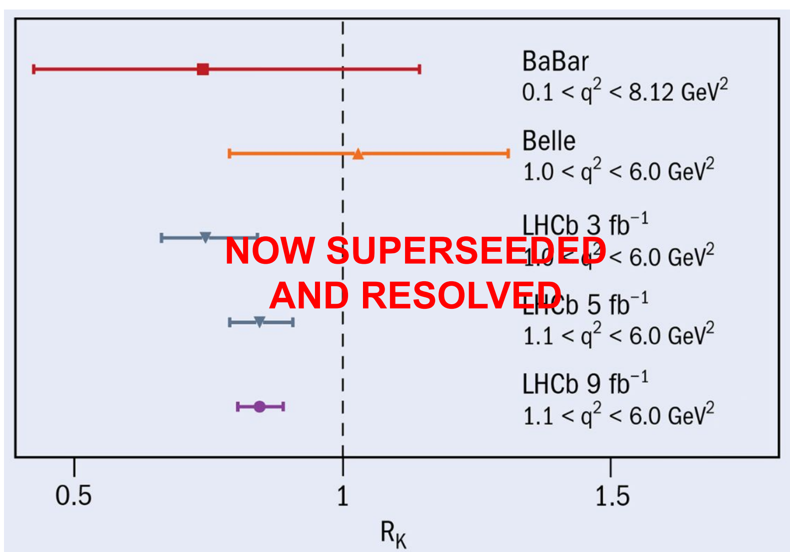




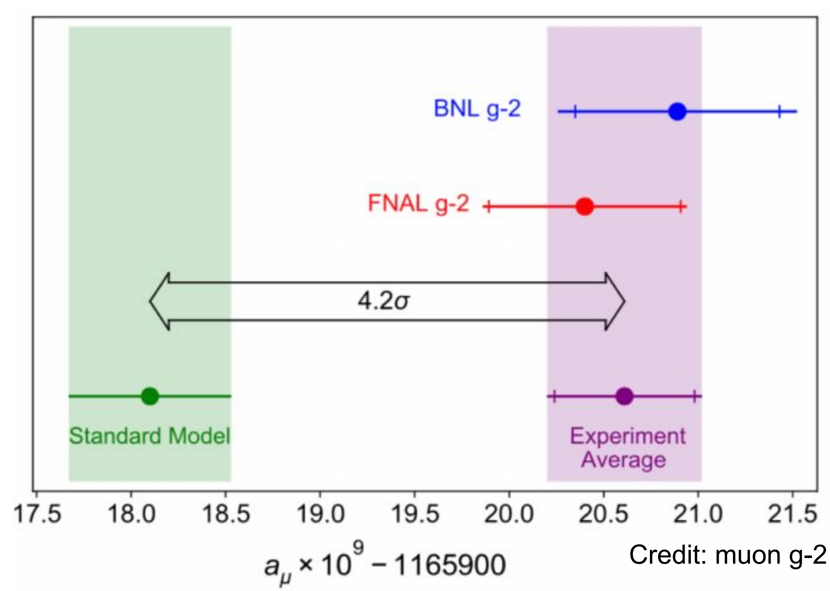




… and ability to react to signals found in low-energy experiments



Credit: LHCb, CERN Courier



Credit: muon g-2 collab.

Concluding: The Energy Frontier Vision

Three main thrusts emerging from the Snowmass Energy Frontier report:

1) "The EF supports continued strong US participation in the success of the **LHC, and the HL-LHC**"

2) "The EF supports a fast start for construction of an **e+ e− Higgs factory** (linear or circular),"

3) "and a significant **R&D program for multi-TeV colliders** (hadron and muon)."

"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."

The P5 process has just started and will define guidelines for the research directions in the next decade.

BACKUP

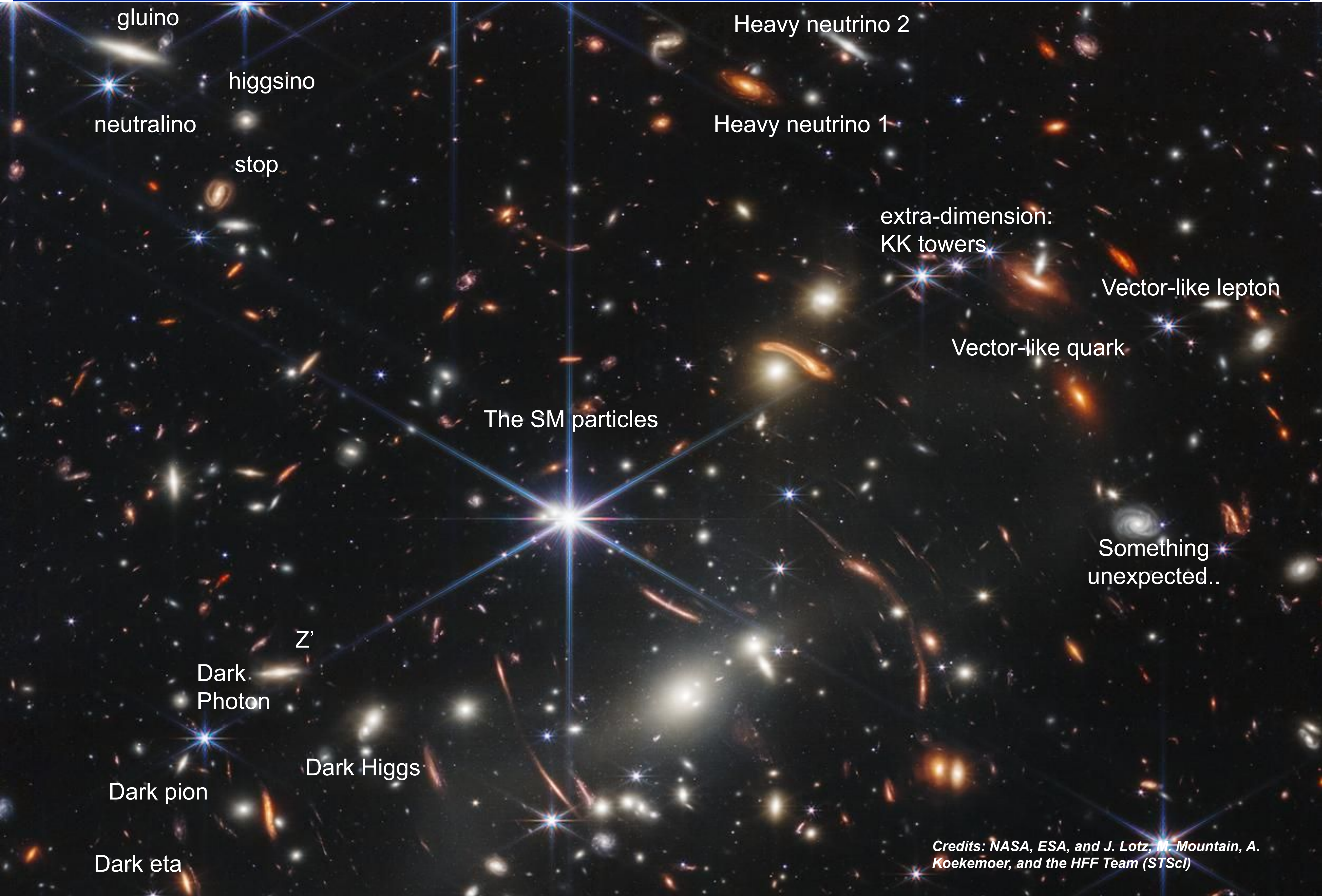
Snowmass collider options evaluated by a panel of experts to ensure homogeneous metrics.

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

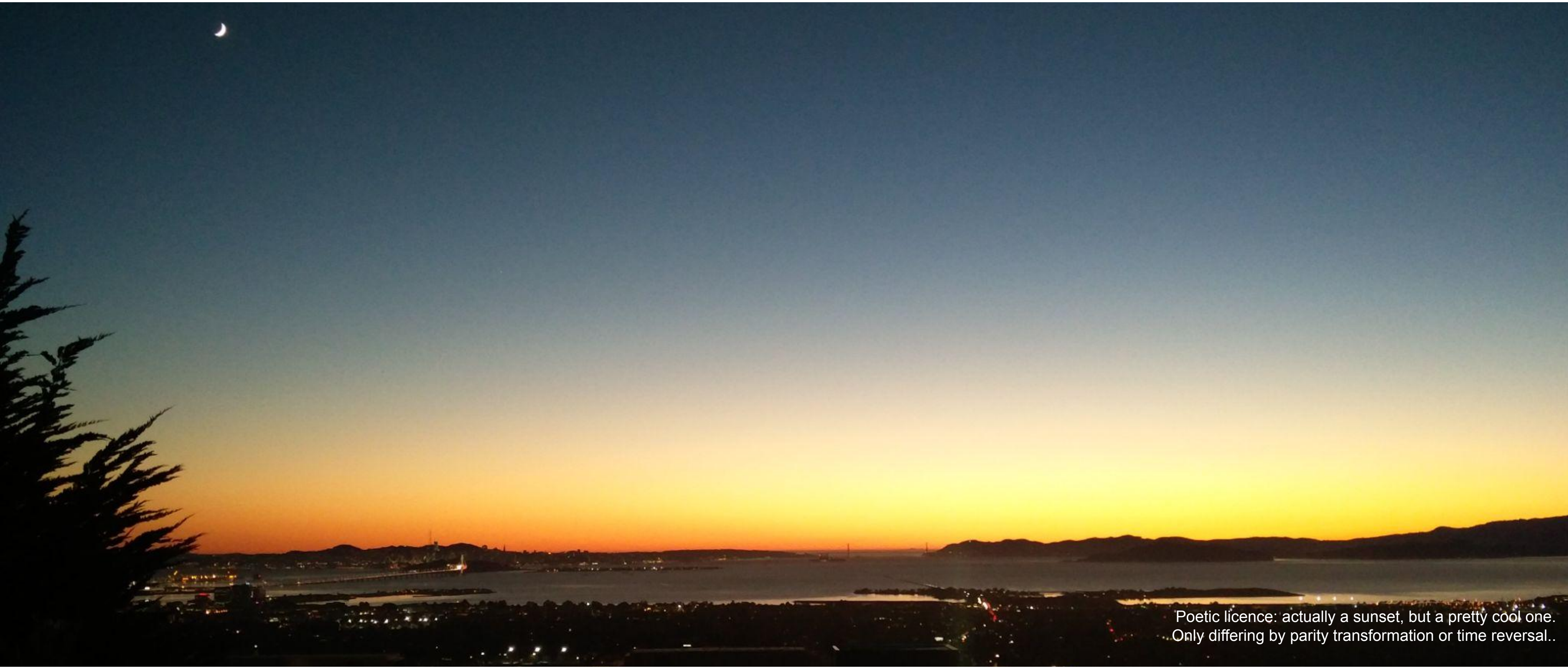
	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	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

V. Shiltsev, MC Physics and Detector Workshop

The night sky



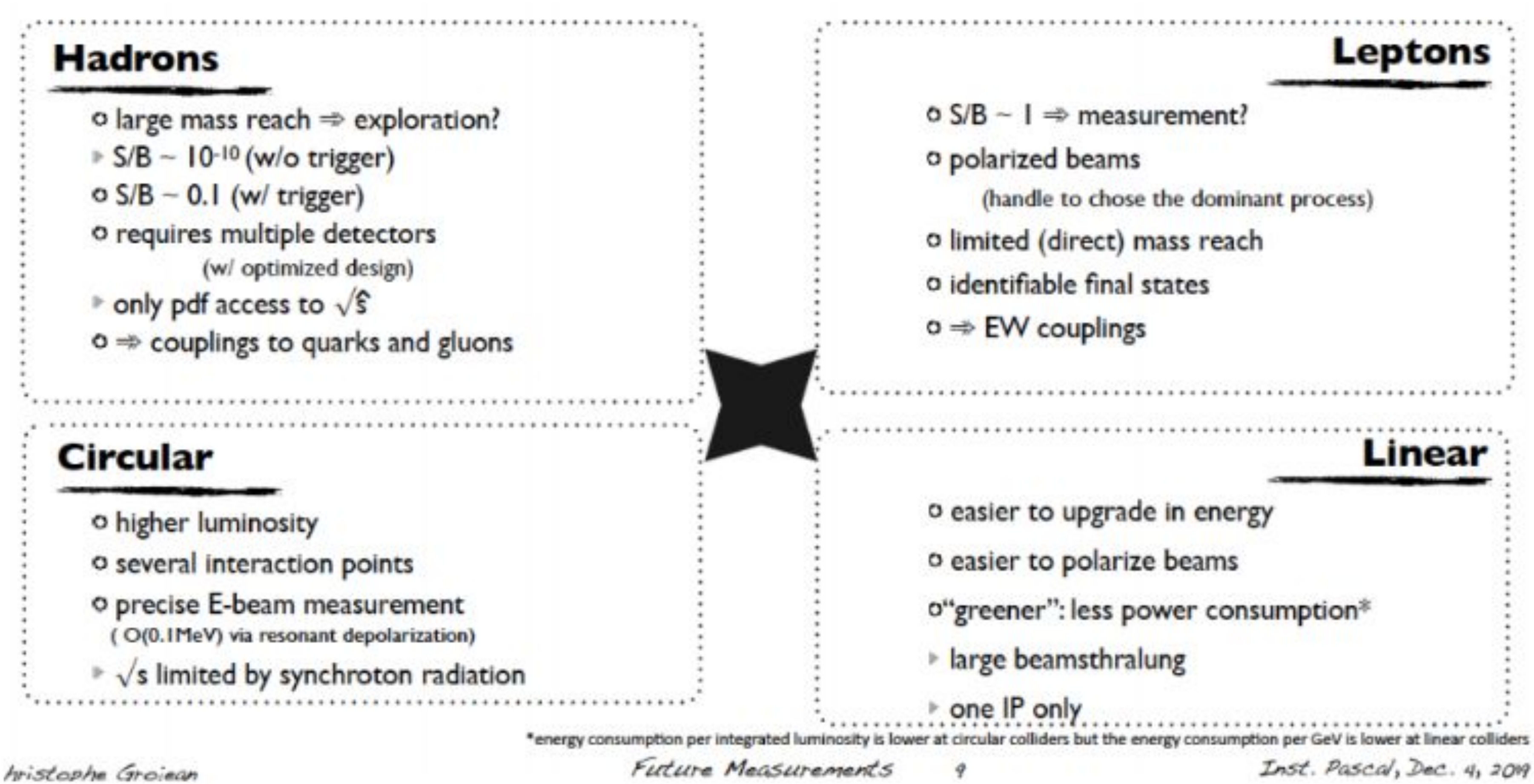
When the morning comes …



When the morning (end of Snowmass) comes, it is important we find the resources to develop the tools that get us to those “stars” in the most effective way.

The Energy Frontier advocates for wide-range and strong R&D activities in Accelerator, Computing, Instrumentation, Theory and their intersections to ensure a robust program that will **enable multi-TeV colliders to become a reality**, and that is flexible enough to adapt to what we will (or will not) find along the way.

Not all collider options are equal



- Need balance physics reach with e.g.
  - effort, technology, sustainability required to achieve them
  - and ...

Keys to success: Precision measurements <-> Direct searches

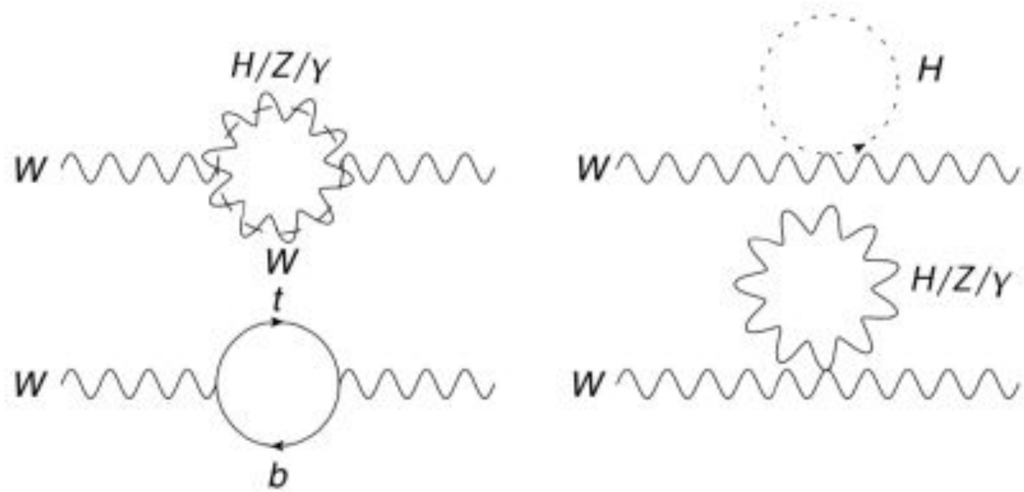
Precision measurements can stress-test the Standard Model
and ultimately point towards the energy scale we need for a discovery

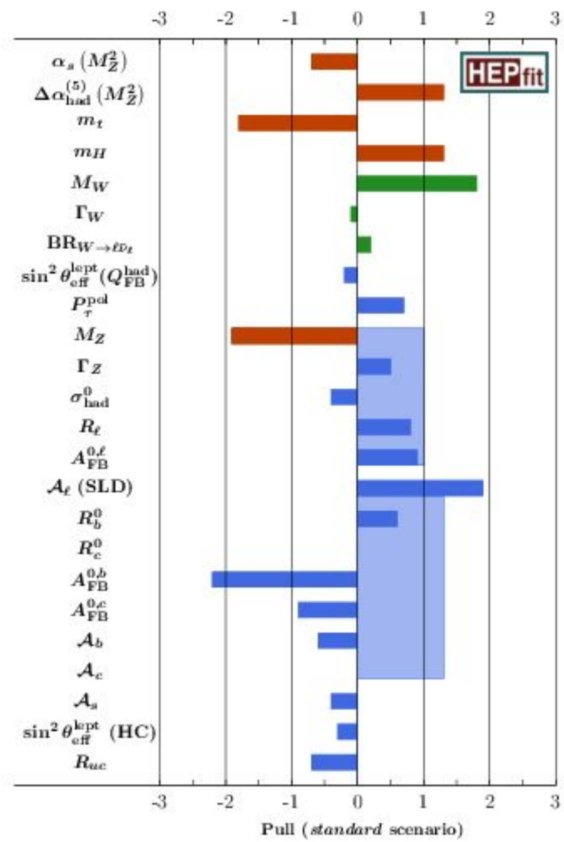
Electroweak precision observables

Precision measurements of electroweak observables can over-constrain Standard Model parameters

- electroweak unification parameters link different observables
- sensitivity to virtual corrections if accuracy is high enough

e.g. sensitivity of W mass corrections to top and Higgs masses





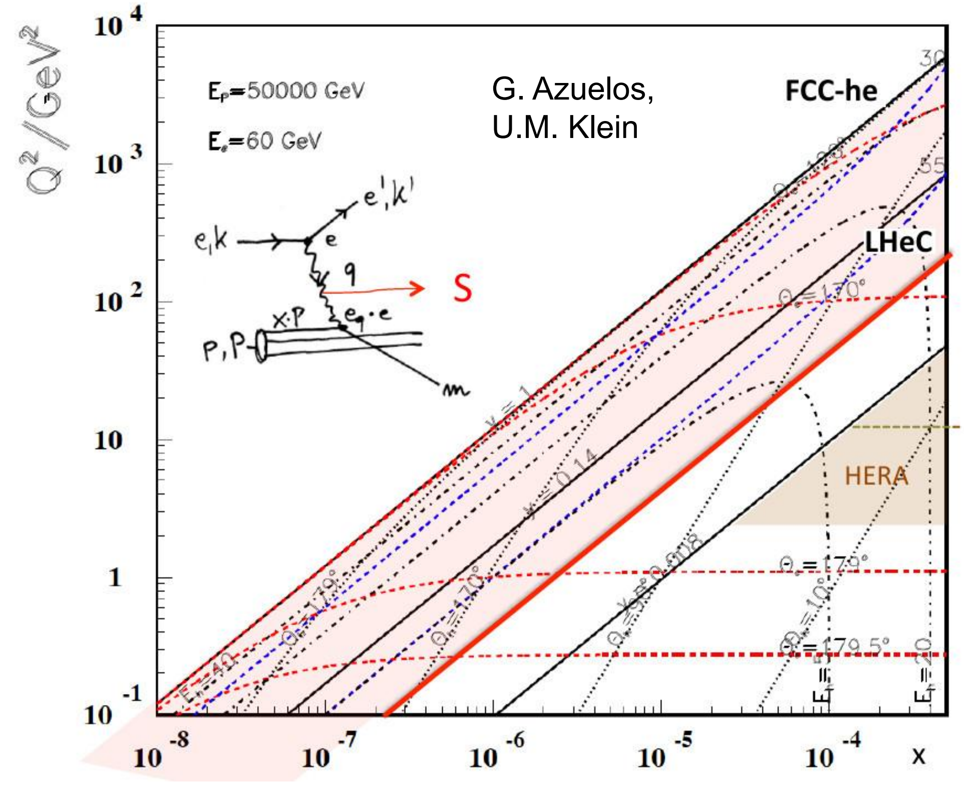
arXiv:2112.07274,
arXiv:2204.04204

Lepton-Hadron colliders

Proposals for electron-hadron (and muon-hadron) colliders as well!

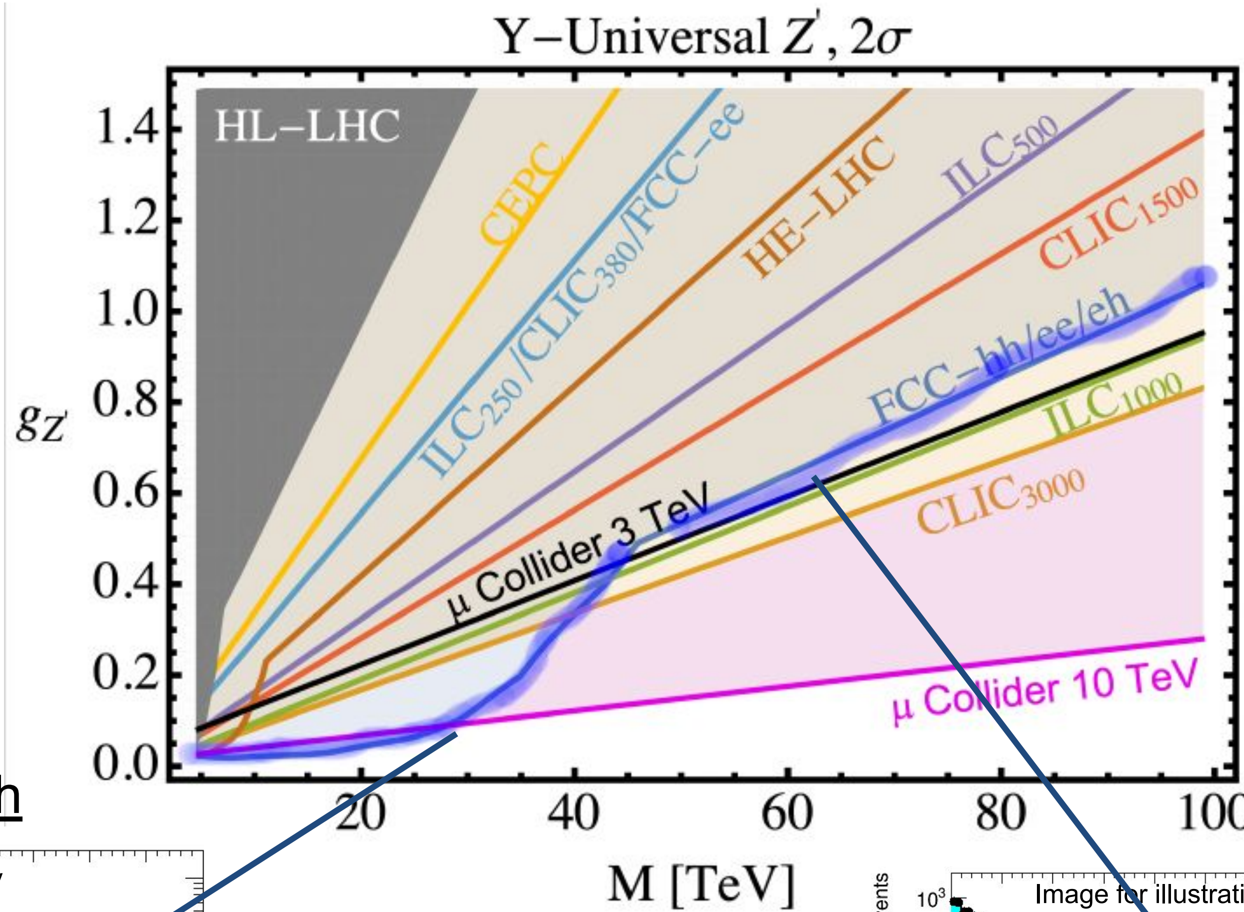
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2

- And synergy with the Electron-Ion collider (EIC) at BNL
- Improved measurements of proton parton distribution function
  - fundamental for precision measurements at hadron colliders!
- Direct discovery potential as well!

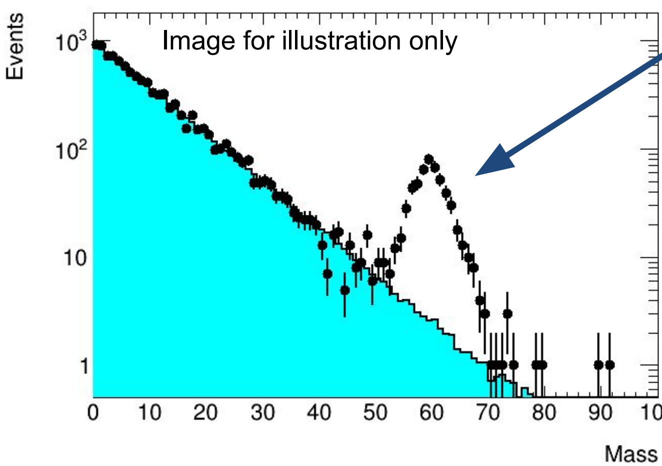


Exploring the unknown: new forces

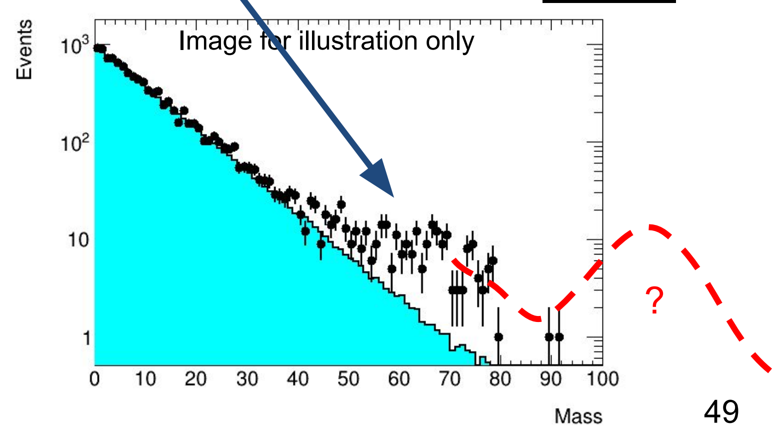
Probe mediator of new forces to the tens of TeV range!



Direct reach



Indirect reach



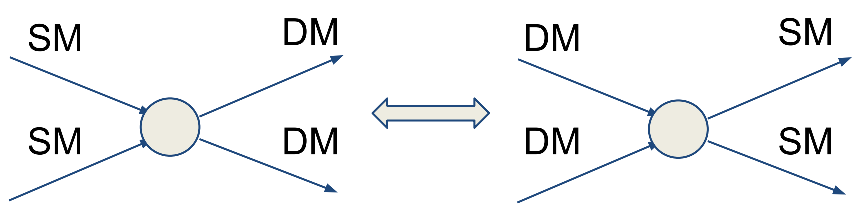
Dark Matter at Colliders

Aim to create Dark Matter in laboratory and study its properties in detail

- very complementary to searches in the cosmic frontier!
- WIMP, Mediator searches, Beyond-WIMP

<u>Example: WIMP in minimal models</u>

- Non-baryonic matter, no EM interactions observed (dark), ~84% of matter
- Evolution of dark matter density regulated by production/annihilation processes

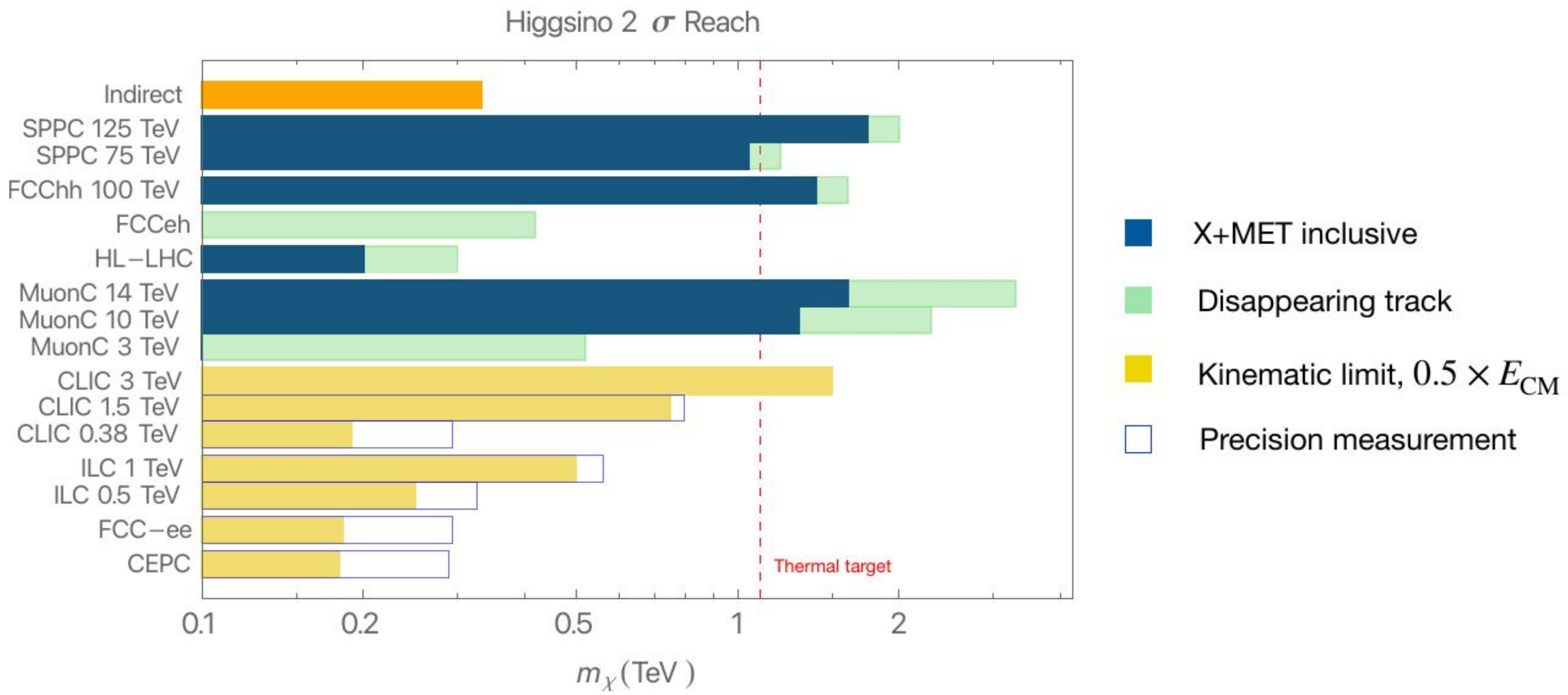


$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}$$

Typical EWK cross-section from unrelated quantities

- In a minimal weakly-interactive model, DM is part of a EWK multiplet
  - Fixing its structure allows to compute rates
  - Comparing with observed density can derive a target DM particle mass

A statement on the WIMP paradigm at colliders



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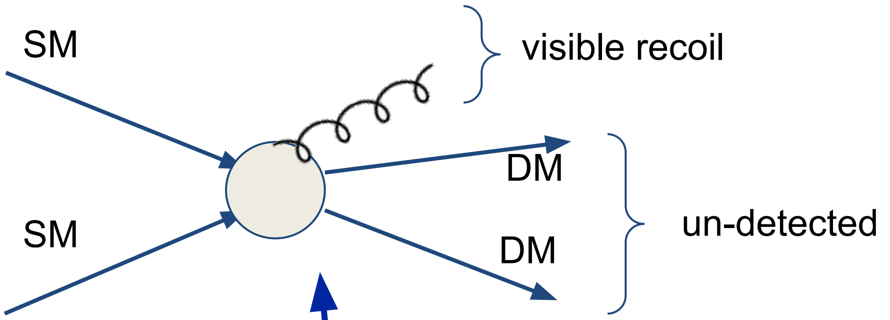

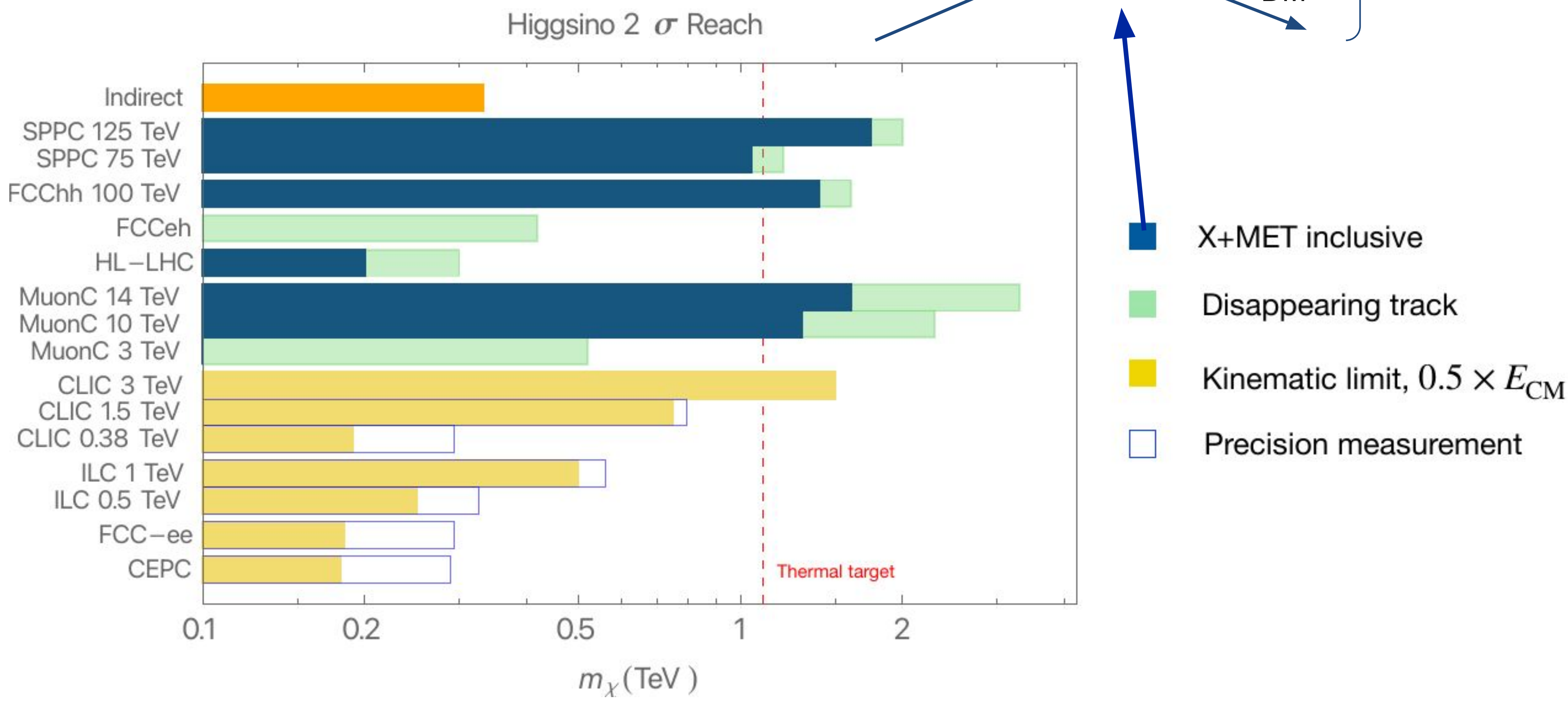

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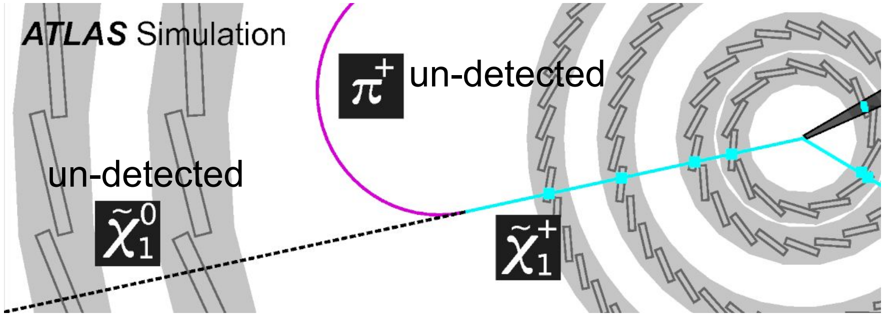

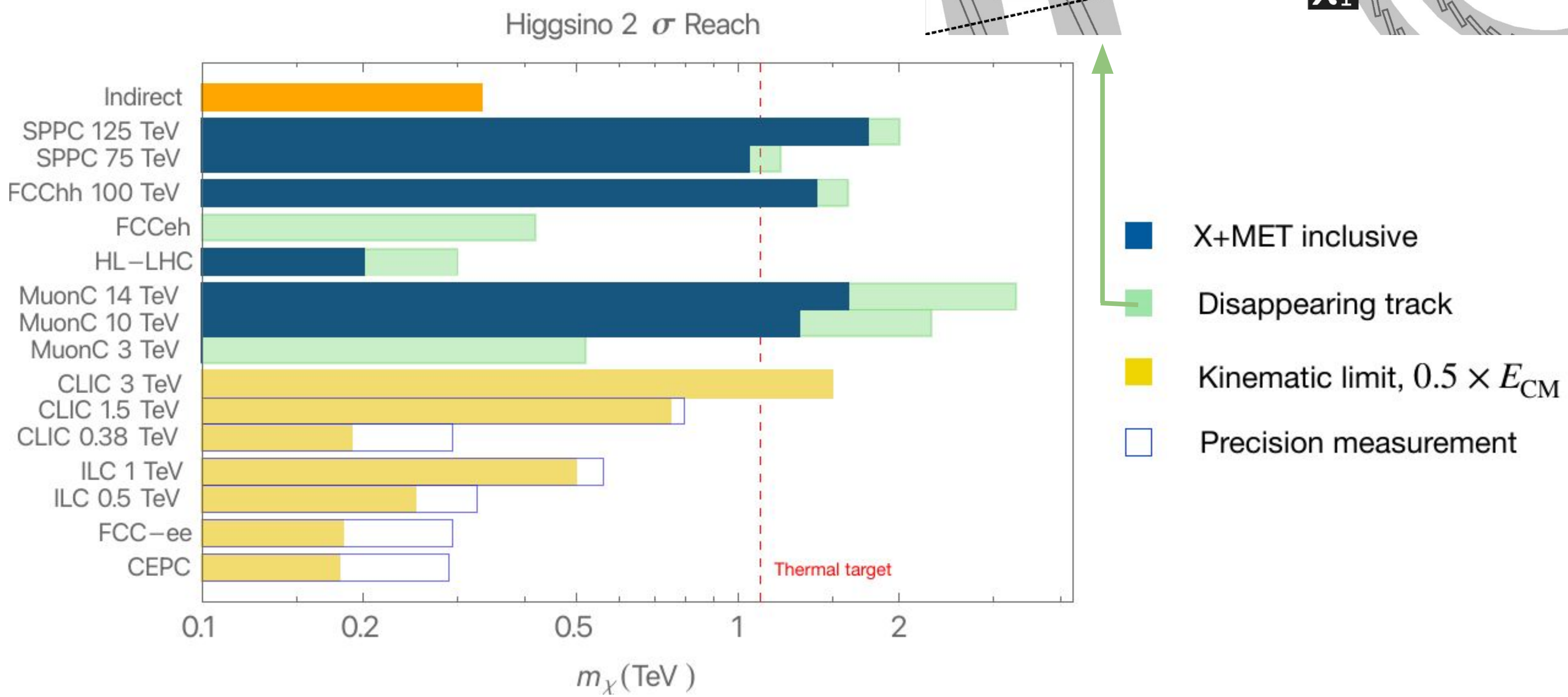

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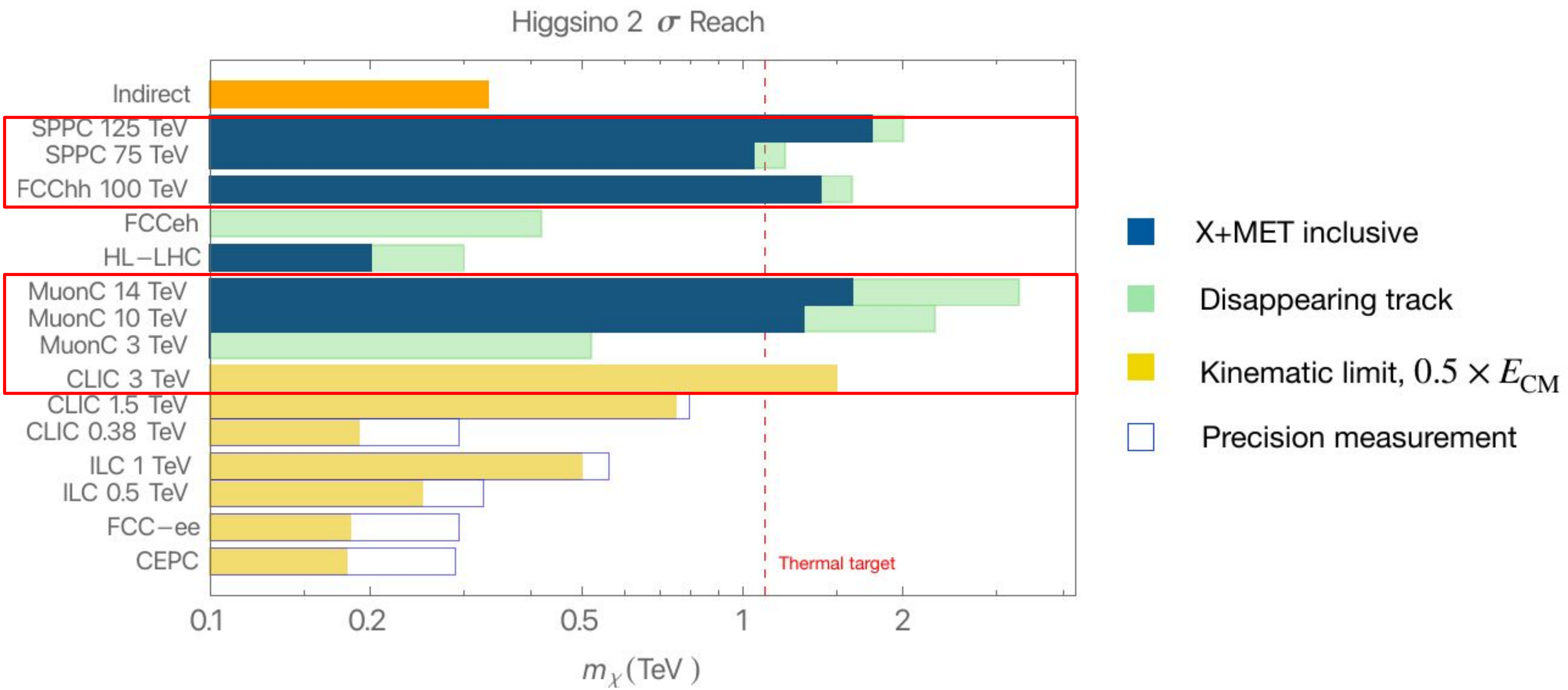
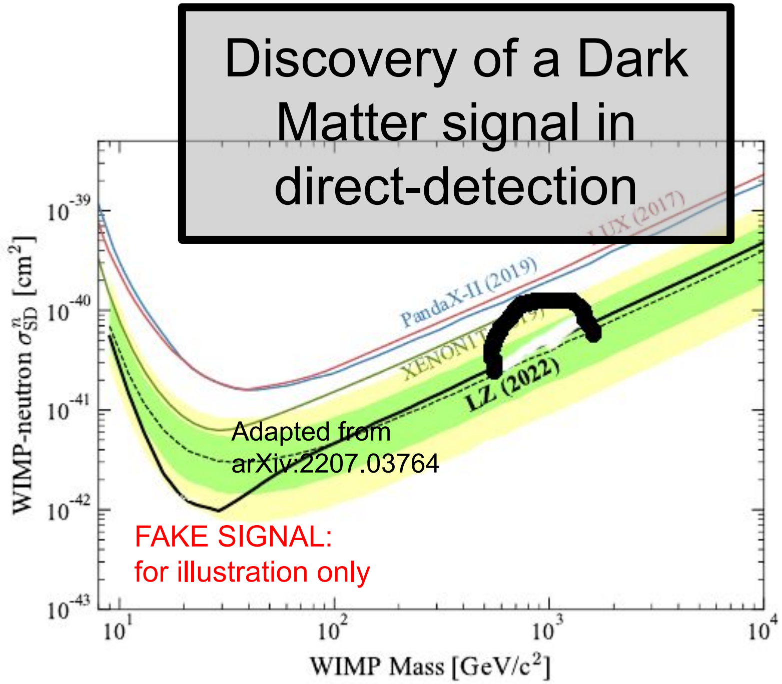


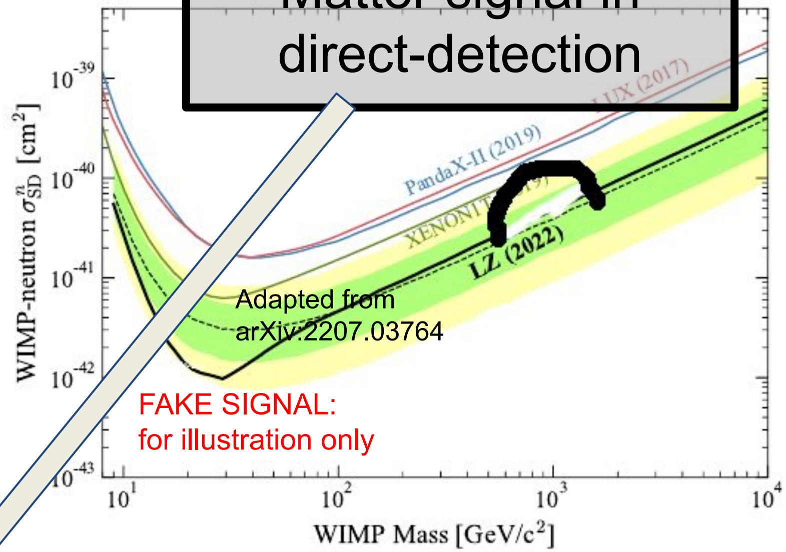
Need multi-TeV colliders to arrive to this natural target

[I have] A dream… and the importance of flexibility!

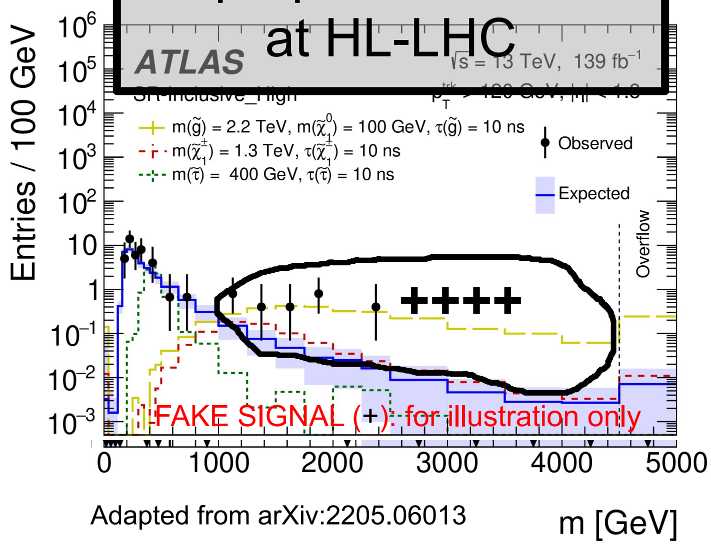


[I have] A dream… and the importance of flexibility!

Discovery of a Dark Matter signal in direct-detection



Its properties studied at HL-LHC



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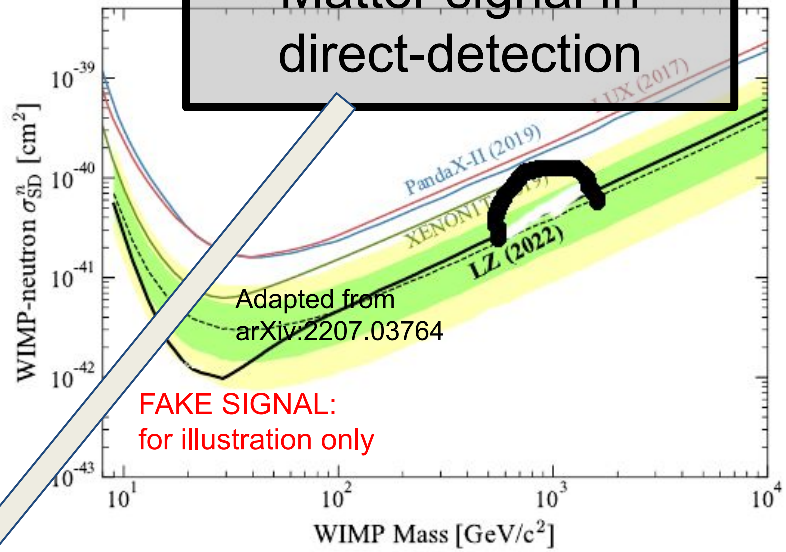

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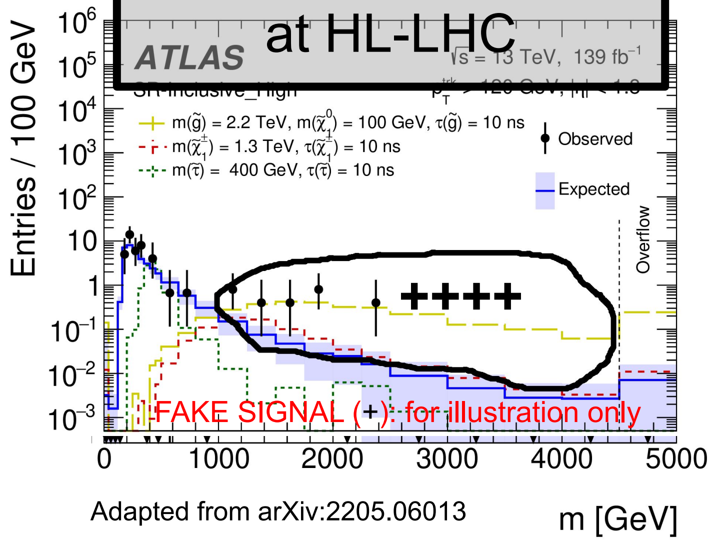
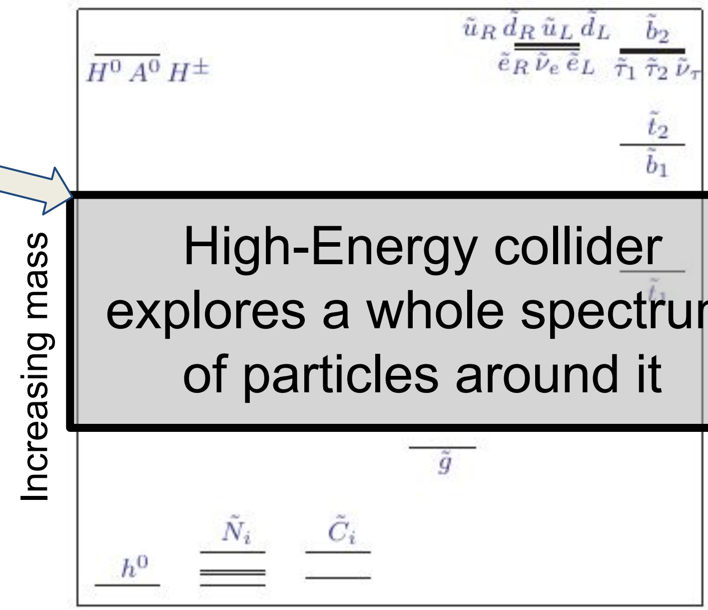


Adapted from arXiv:2205.06013

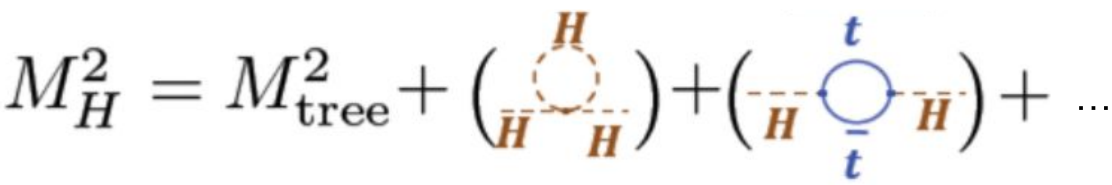
High-Energy collider explores a whole spectrum of particles around it



hep-ph/9709356

Example: Naturalness

- The Higgs boson is the only fundamental scalar we found so far
- Intrinsic "unstable" mass corrections from virtual contributions

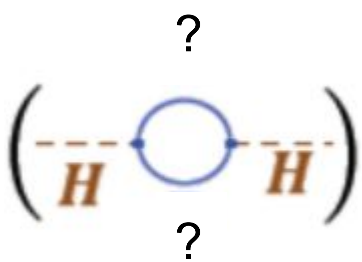


$\Delta M_H \sim \Lambda^2$

Hierarchy problem

$\Lambda \rightarrow$ scale where new physics enters

- Connected to: "Why the EWK scale is so much lower than e.g. Planck scale?"
- Additional contribution that (partially) cancel the divergency is needed



$M_? \sim 0.1 – 10$ TeV

- The better the cancellation, the higher the need for additional energy scale is pushed on, it is therefore "natural" to expect some contribution near the EWK scale
- **Multi-TeV colliders** are needed to elucidate the hierarchy between EWK and Planck scales observed

Supersymmetry

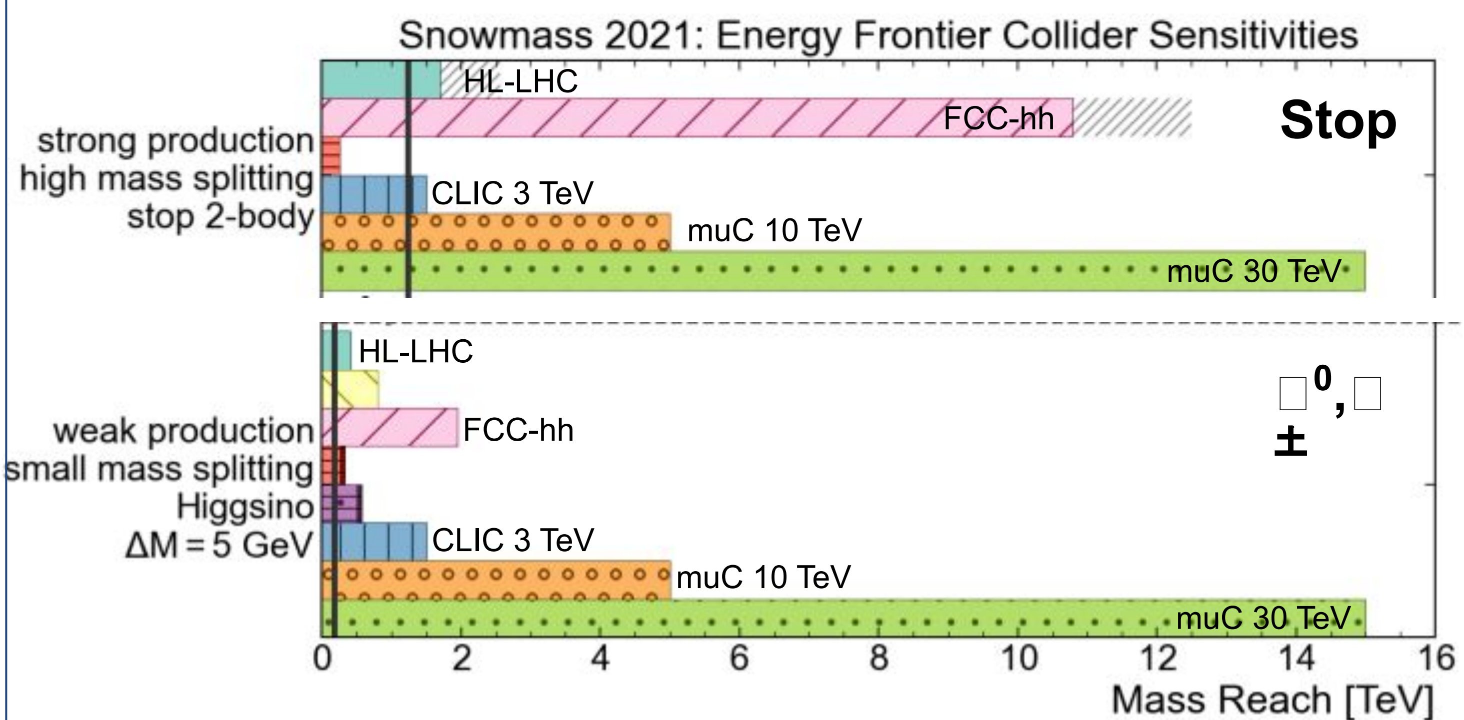
Long-sought for very good reasons

- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)

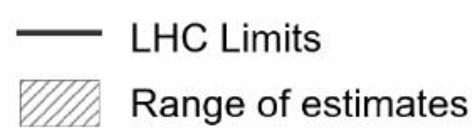
Large model-parameters space and vast phenomenology

Simplified classes of signatures

Full models with additional assumptions (in backup)



Multi-TeV colliders extend the reach to the ~10 TeV scale!



Supersymmetry

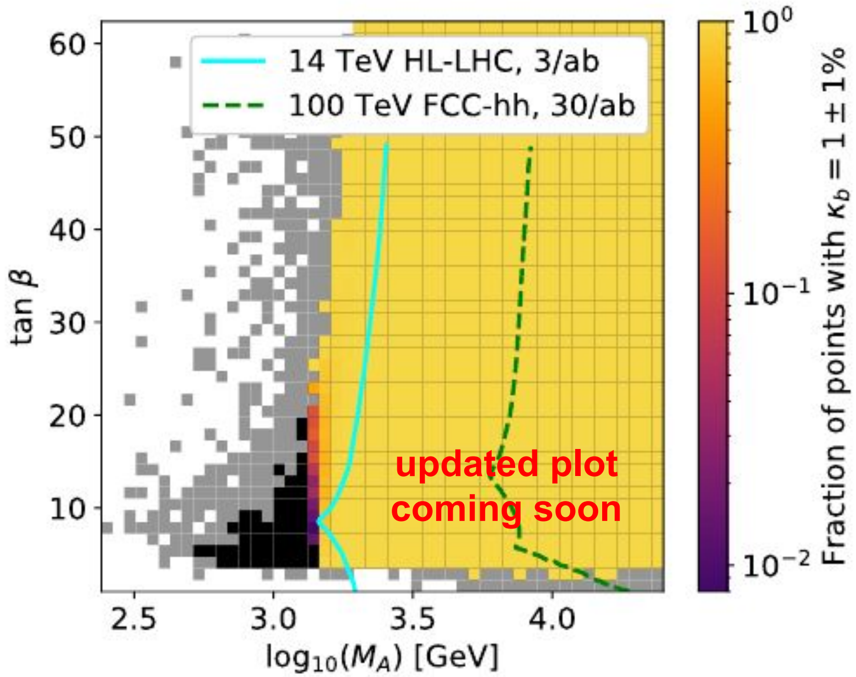
Long-sought for very good reasons

- alleviate hierarchy problem
- can provide a natural Dark Matter candidate
- fundamental in extensions that unify all forces (including gravity)
- …

Large model-parameters space and vast phenomenology

Full models with additional assumptions:

pMSSM -> Minimal Supersymmetric model + external constraints + simplifying assumptions

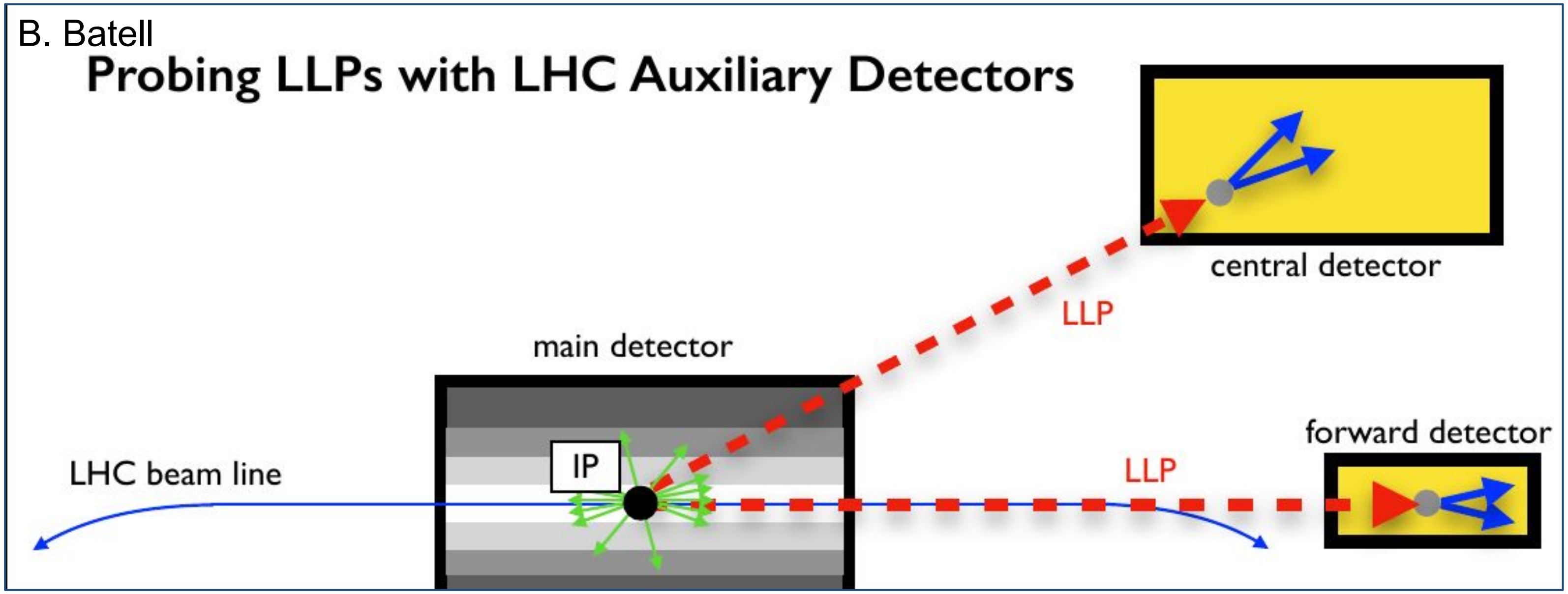


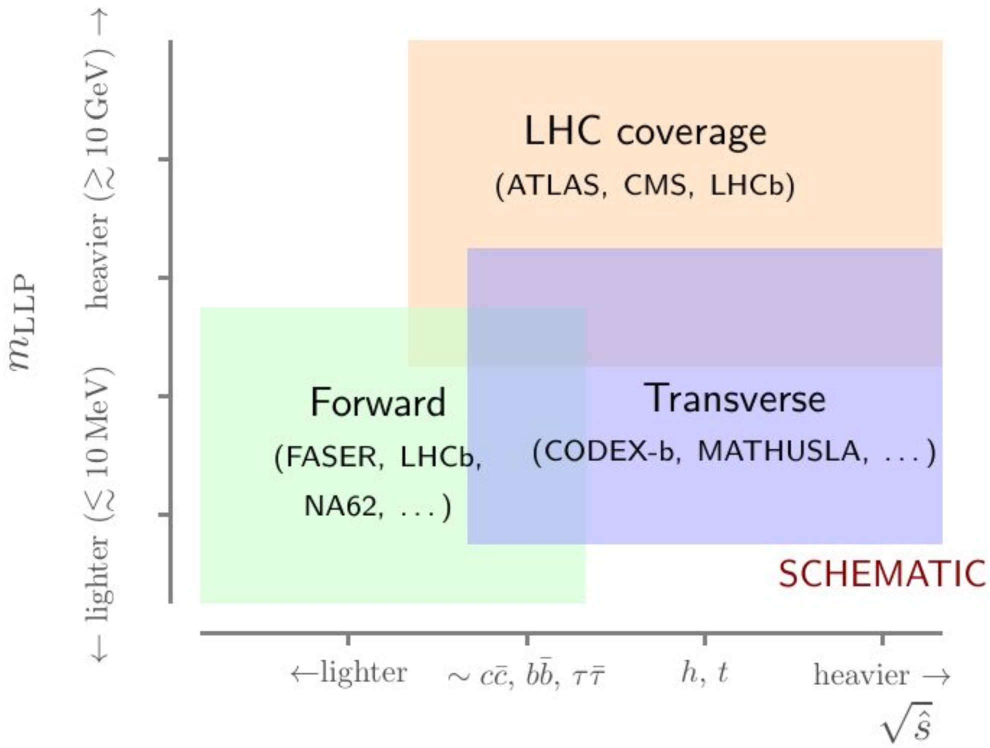
Hypothetical scenario:

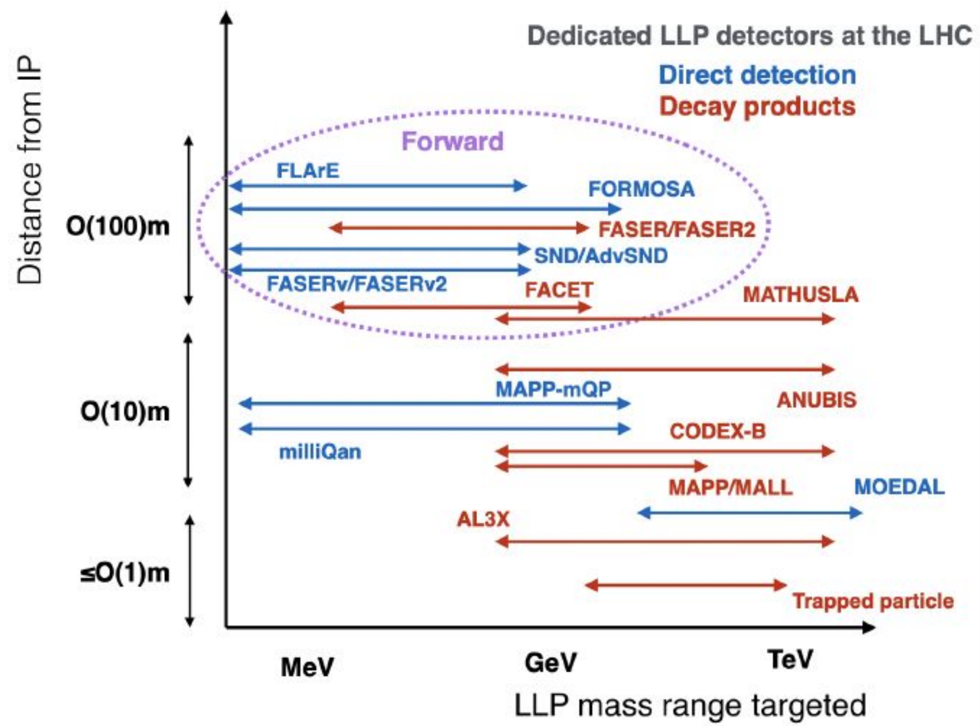
- Colored points: allowed parameter space after future precision measurements of H-bb (@1%) coupling.
- Solid lines: direct searches of an heavy Higgs

Multi-TeV colliders needed to extend reach beyond HL-LHC!

Auxiliary Experiments at the HL-LHC

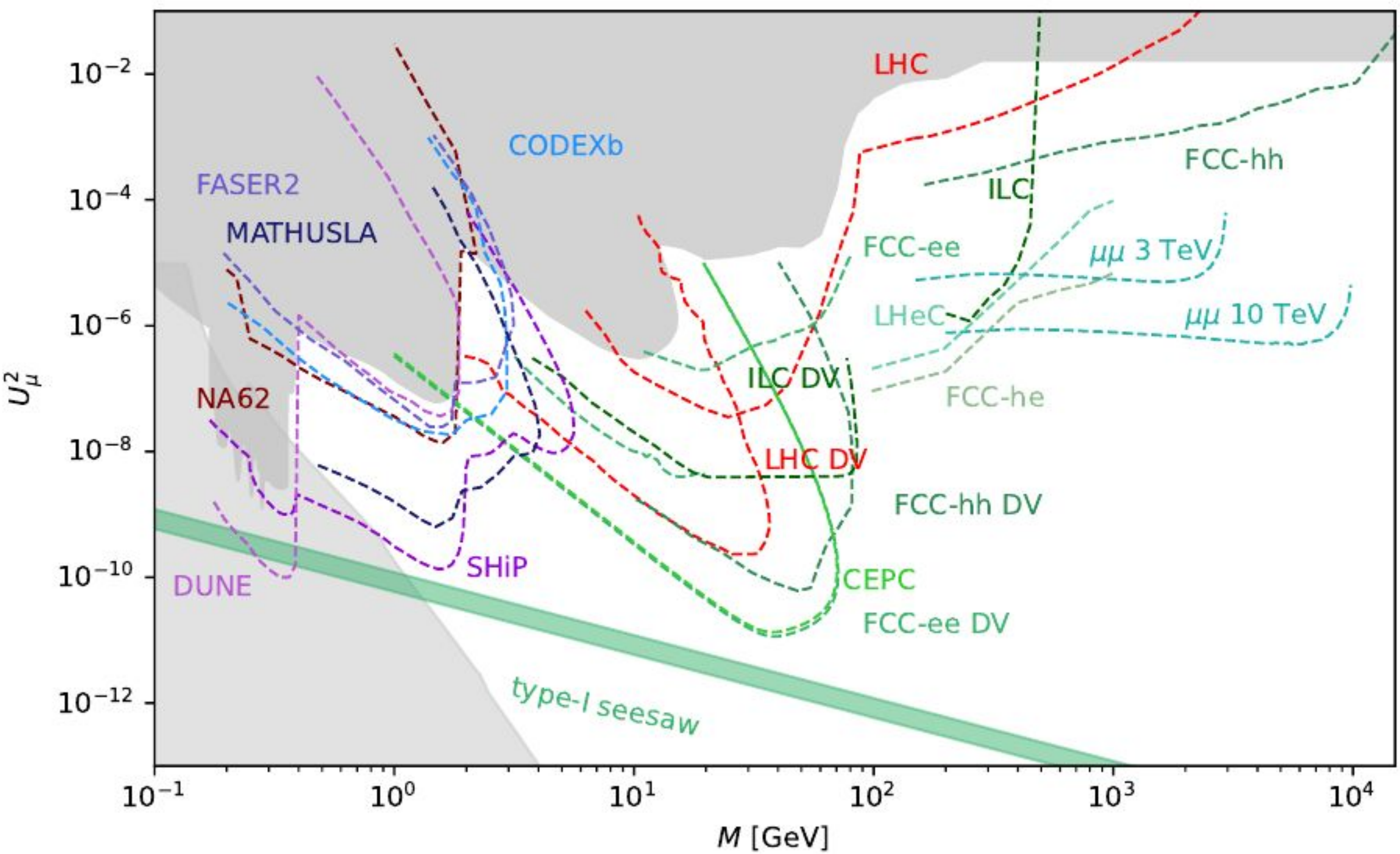




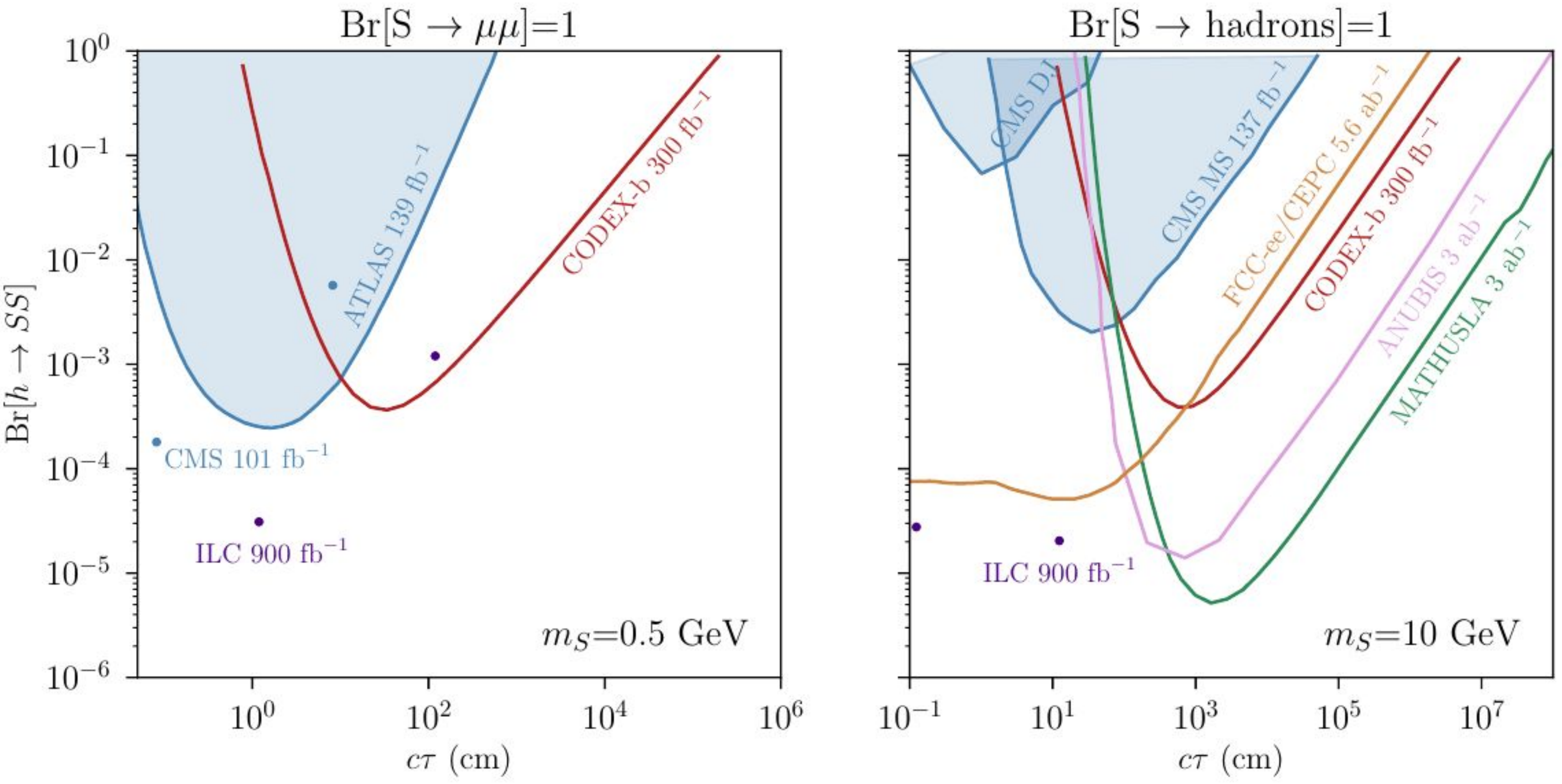


HL-LHC auxiliary experiments: Heavy Neutral Leptons

Just one example out of many – strong synergy with Rare-Processes Frontier



HL-LHC auxiliary experiments: Higgs Portal



The Energy Frontier Vision

Resource needs and plan for the five year period starting 2025:

1. Prioritize HL-LHC physics program, including far-forward experiments,
2. Establish a targeted e^+e^- Higgs Factory detector R&D program for US participation in a global collider,
3. Develop an initial design for a first stage Tev-scale Muon Collider in the US, with pre-CDR document at the end of this period,
4. Support critical detector R&D towards EF multi-TeV Colliders.

Resource needs and plan for the five year period starting 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of a e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation and deliver CDR for a first stage TeV-scale muon collider.

Resource needs and plan after 2035:

1. Evaluate continuing HL-LHC physics program to the conclusion of archival measurements,
2. Begin and support the physics program of the Higgs Factories,
3. Demonstrate readiness to construct and deliver TDR for a first-stage TeV-scale muon collider,
4. Ramp up funding support for detector R&D for EF multi-TeV Colliders.