The Physics case for
Energy Frontier Discovery Machines

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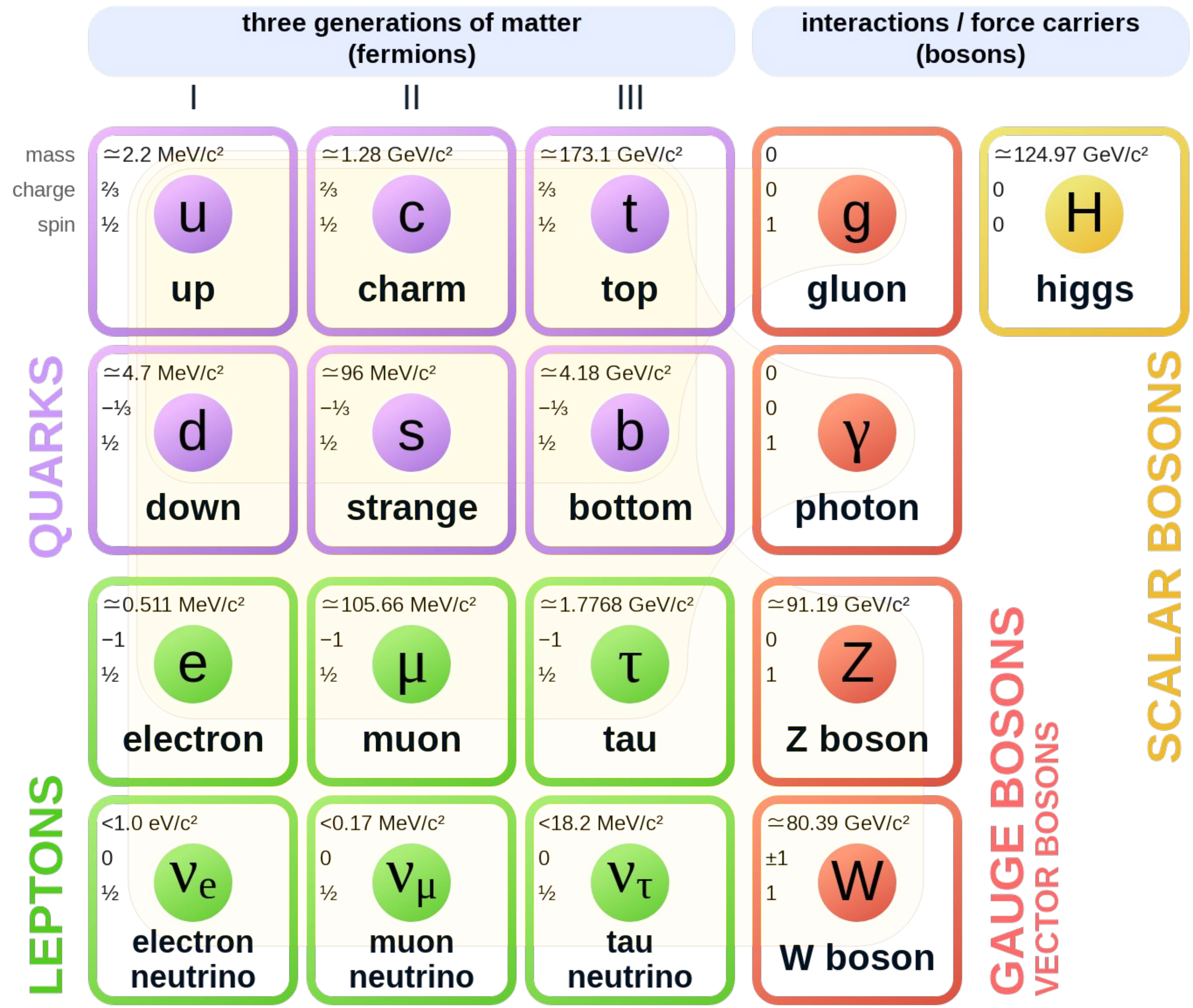
BERKELEY LAB
Lawrence Berkeley National Laboratory

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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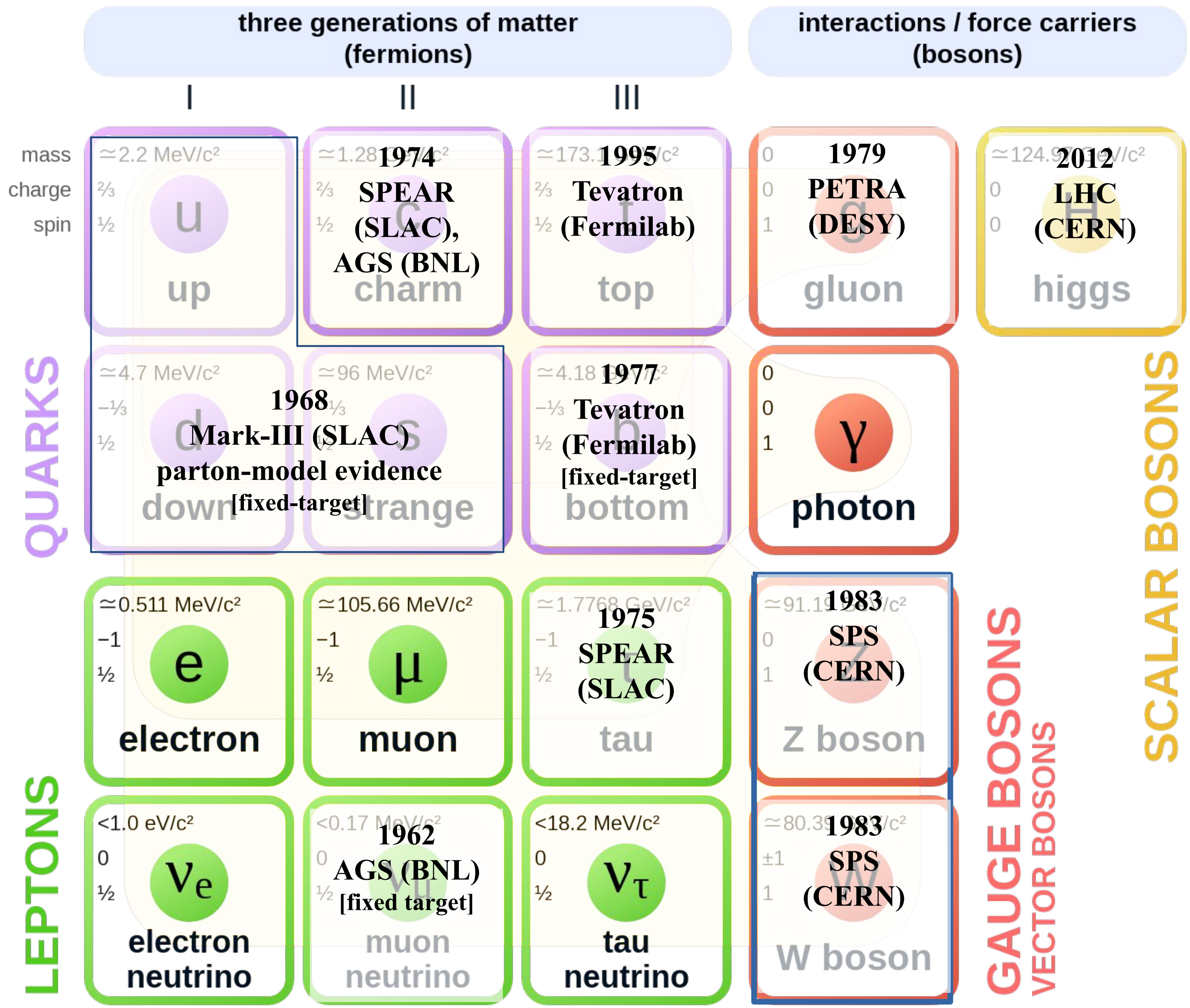

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Keys to success

Theory ⟺ Experiment

Direct ⟺ Indirect

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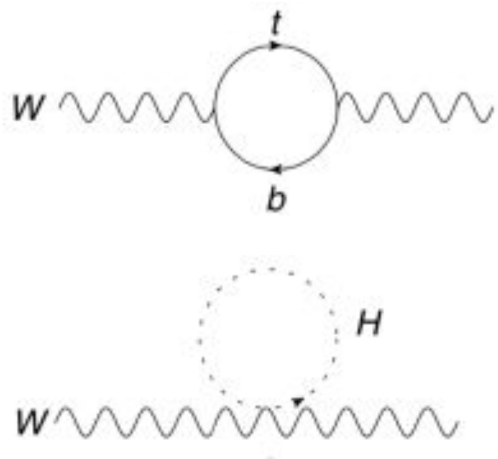
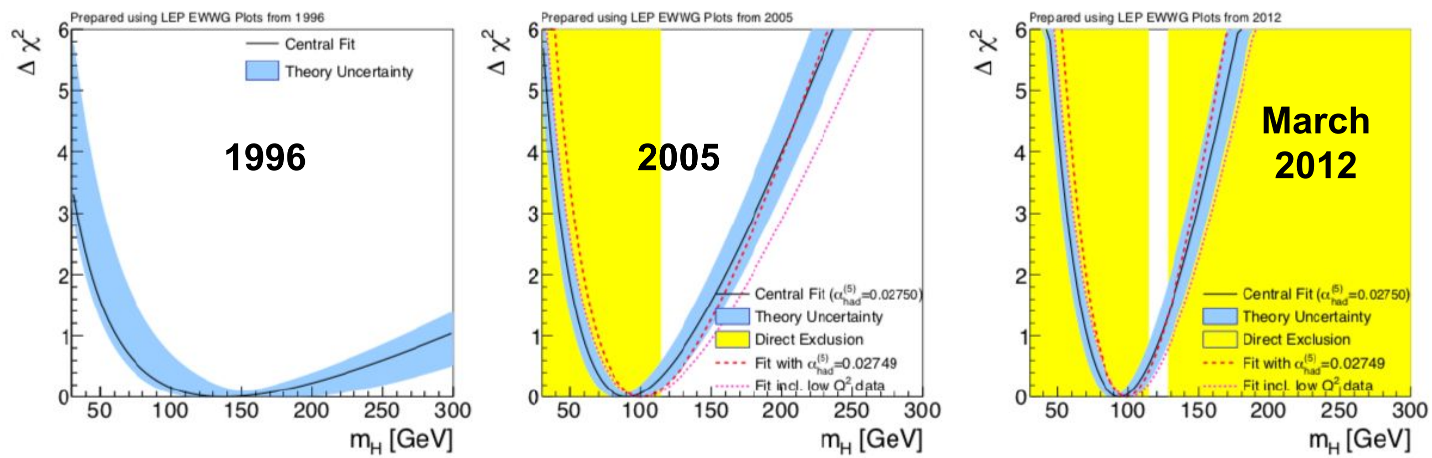


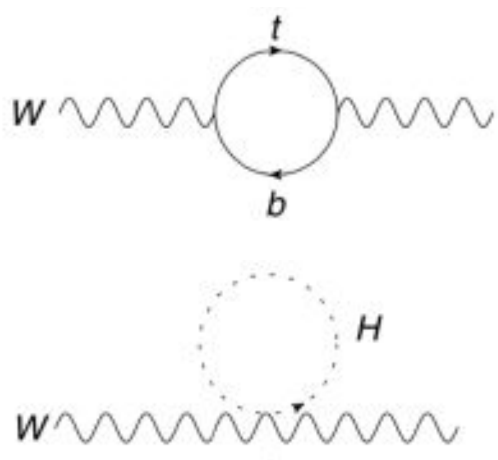
LEP EWK Working Group, 1996 - 2012

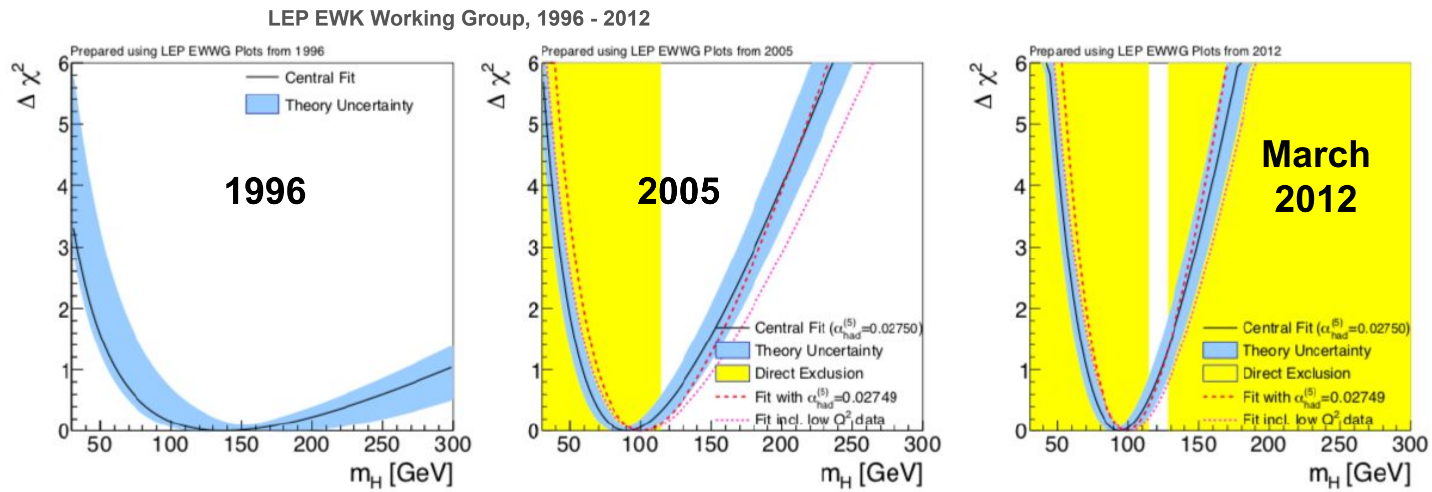


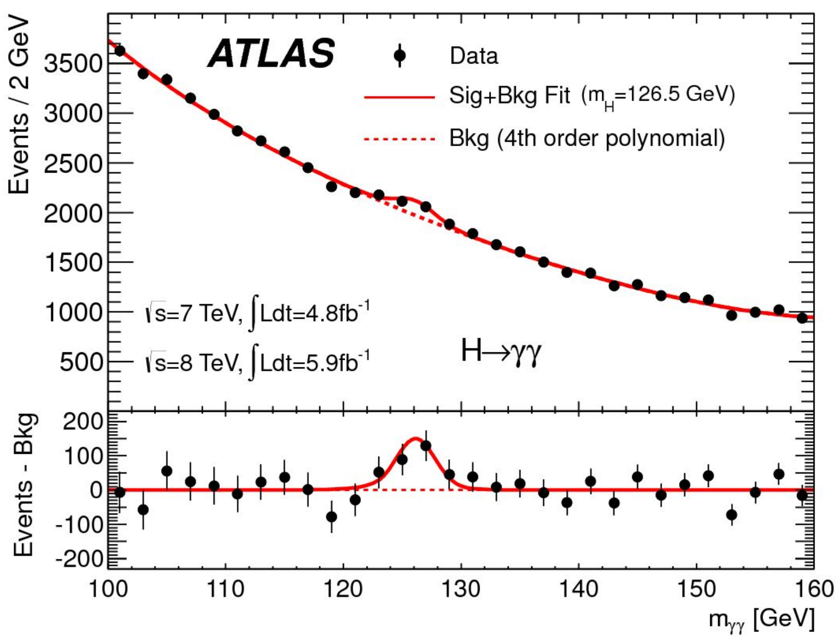
Keys to success

Theory ⟺ Experiment

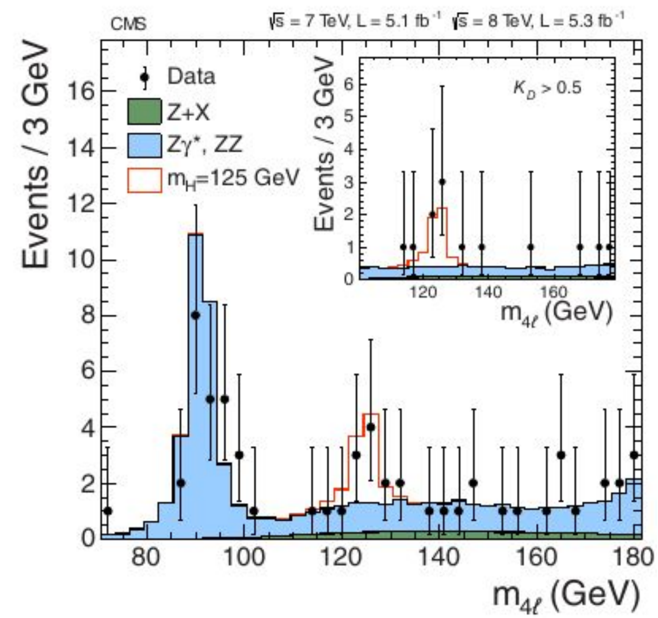
Direct ⟺ Indirect







July
2012



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

The (current) Standard Model is not enough!

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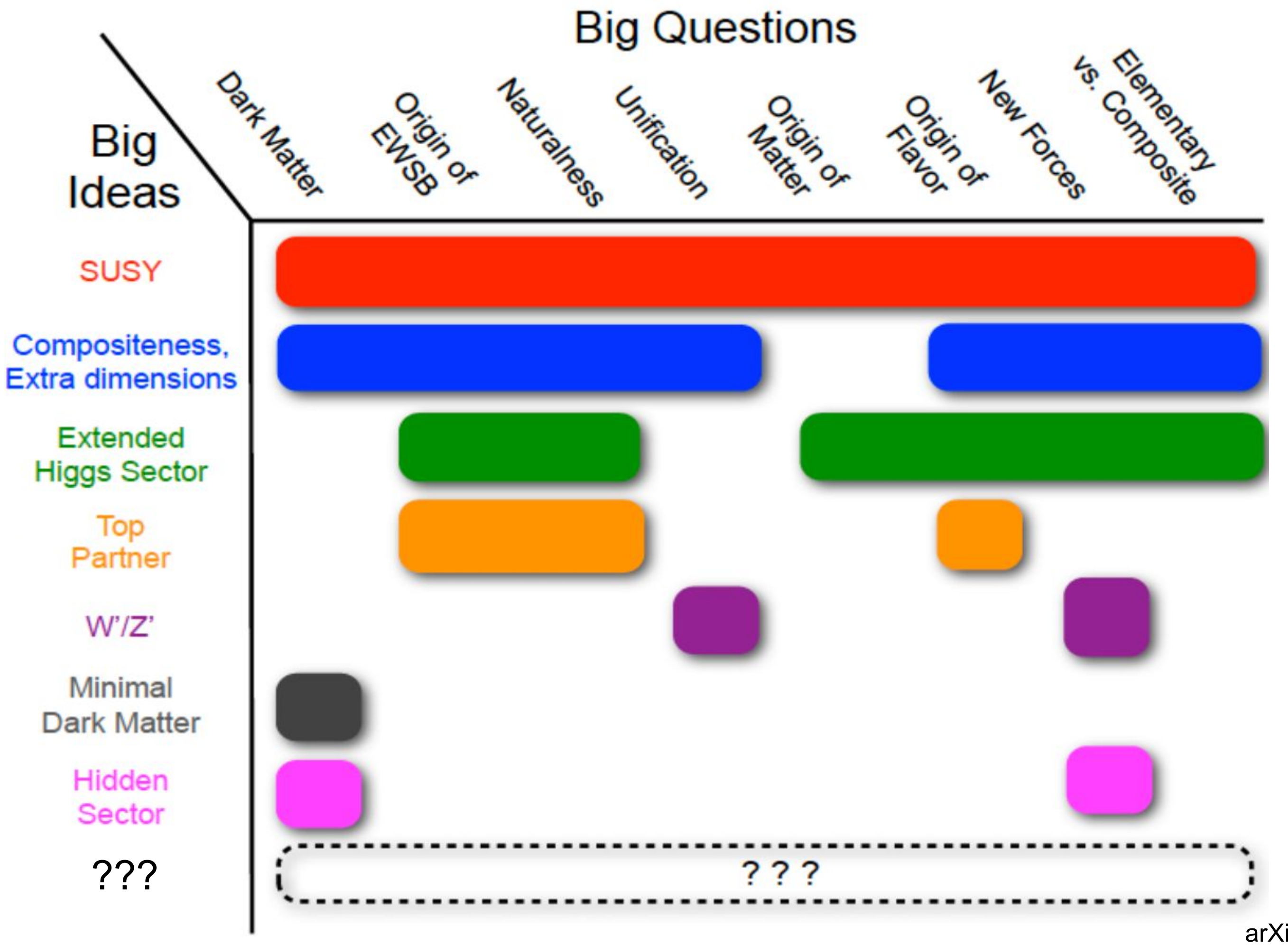
Plenty of extensions of the Standard Model have the potential of addressing these questions, including the ones we haven't thought of yet

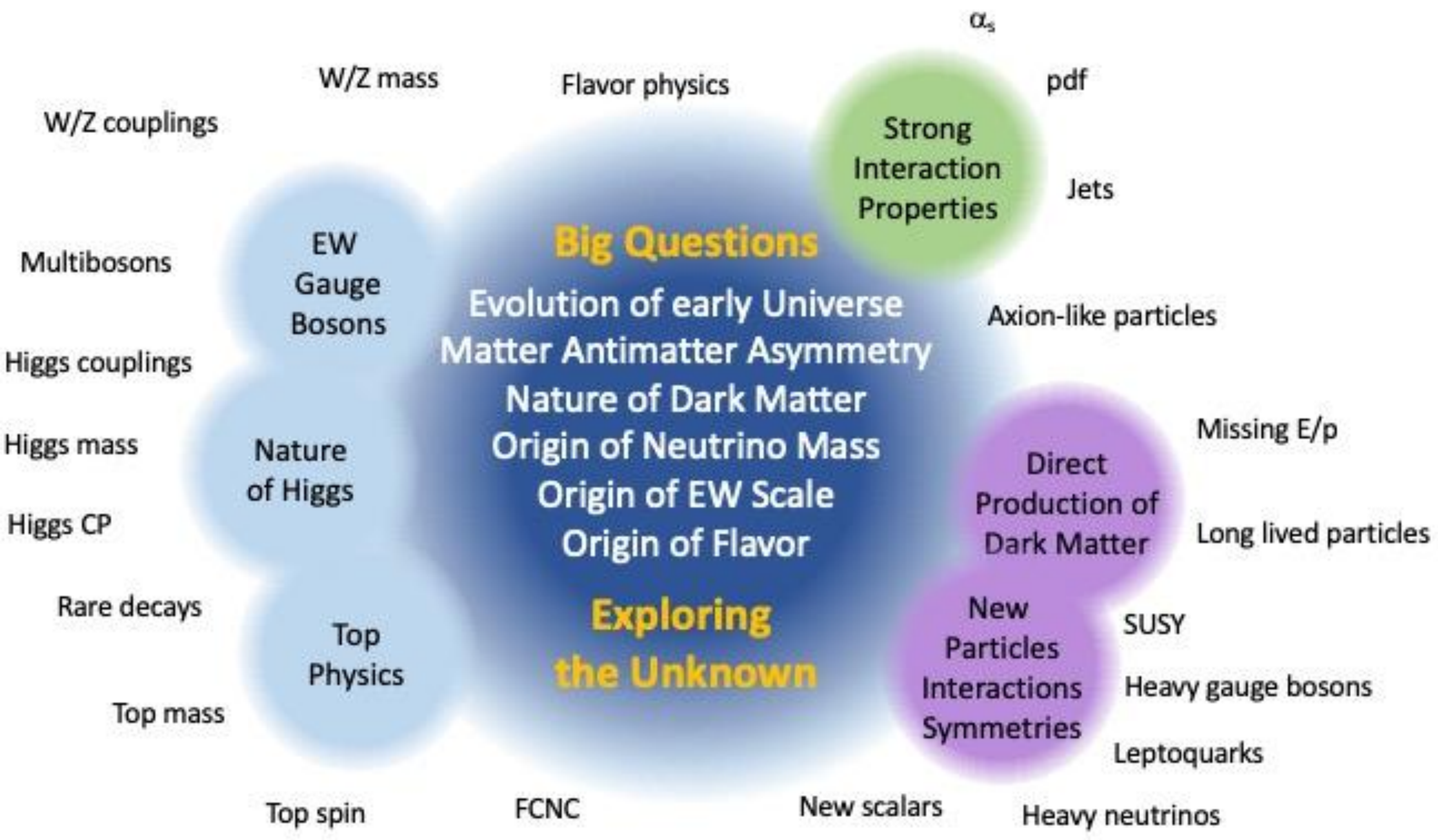


arXiv:1311.0299

Most pointing to higher energy scales where new particles will manifest

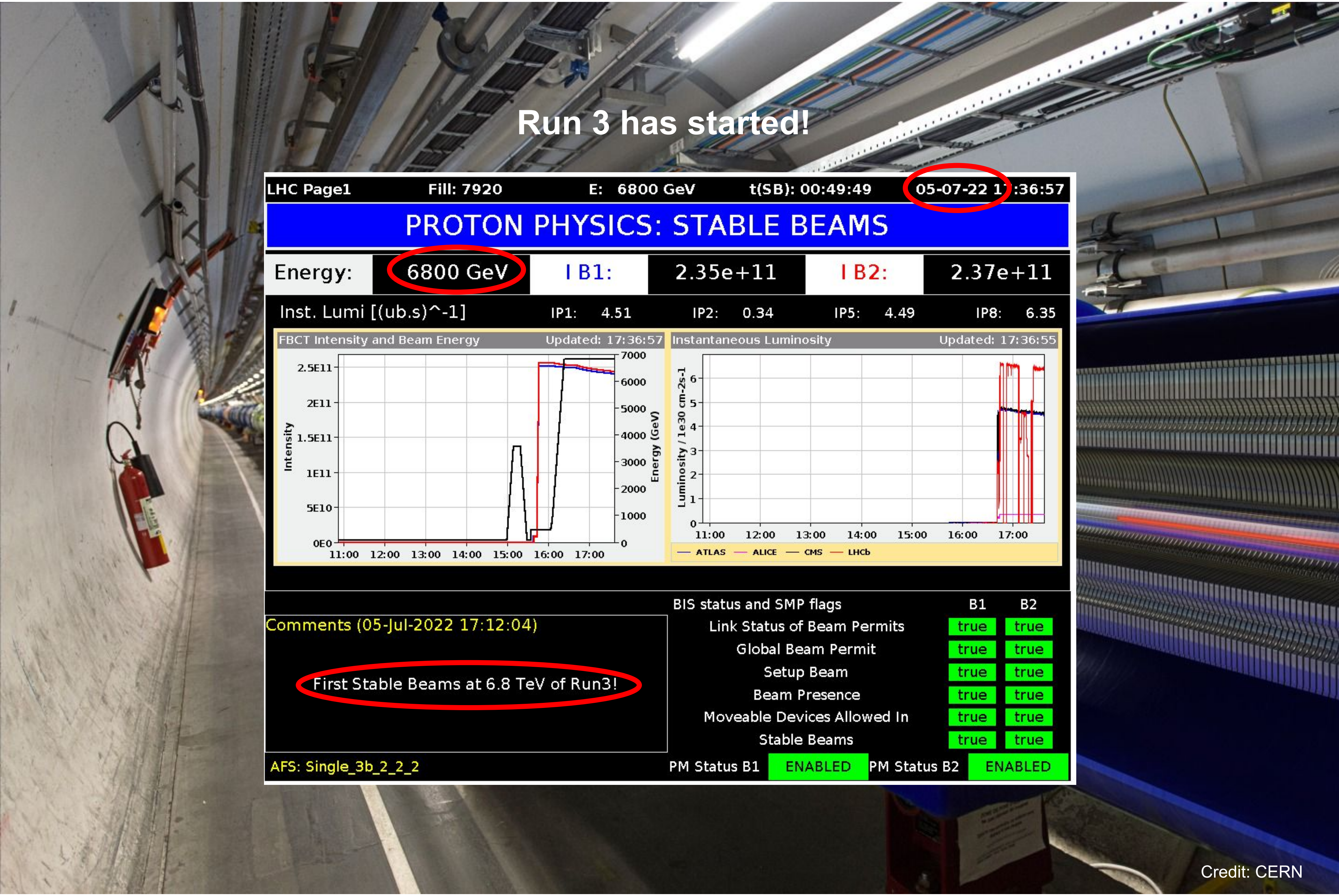
Probes and Signatures of new physics at colliders

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

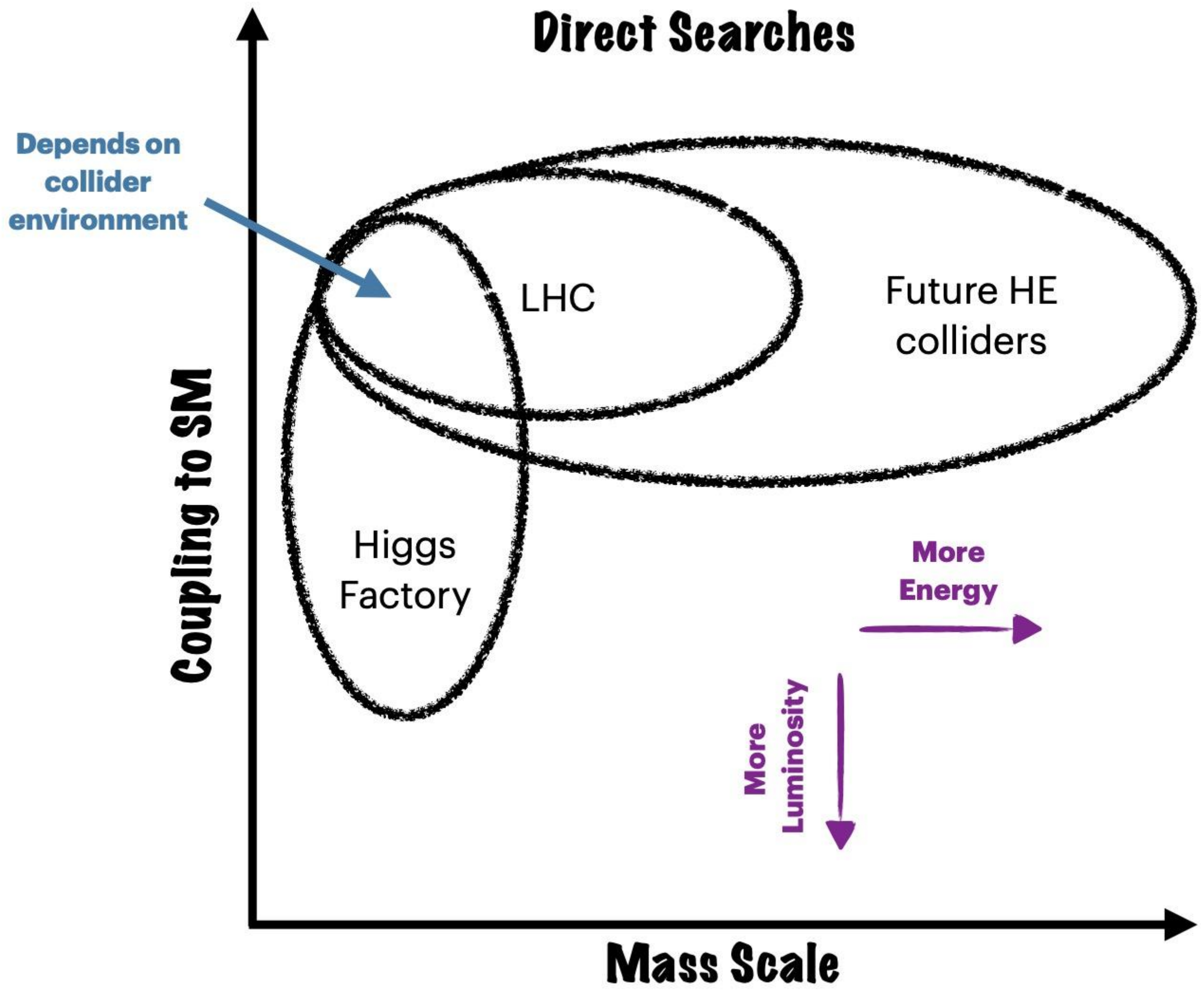


Colliders offer the unique ability to probe, with a single experimental setup,
all sectors of the SM and its extensions

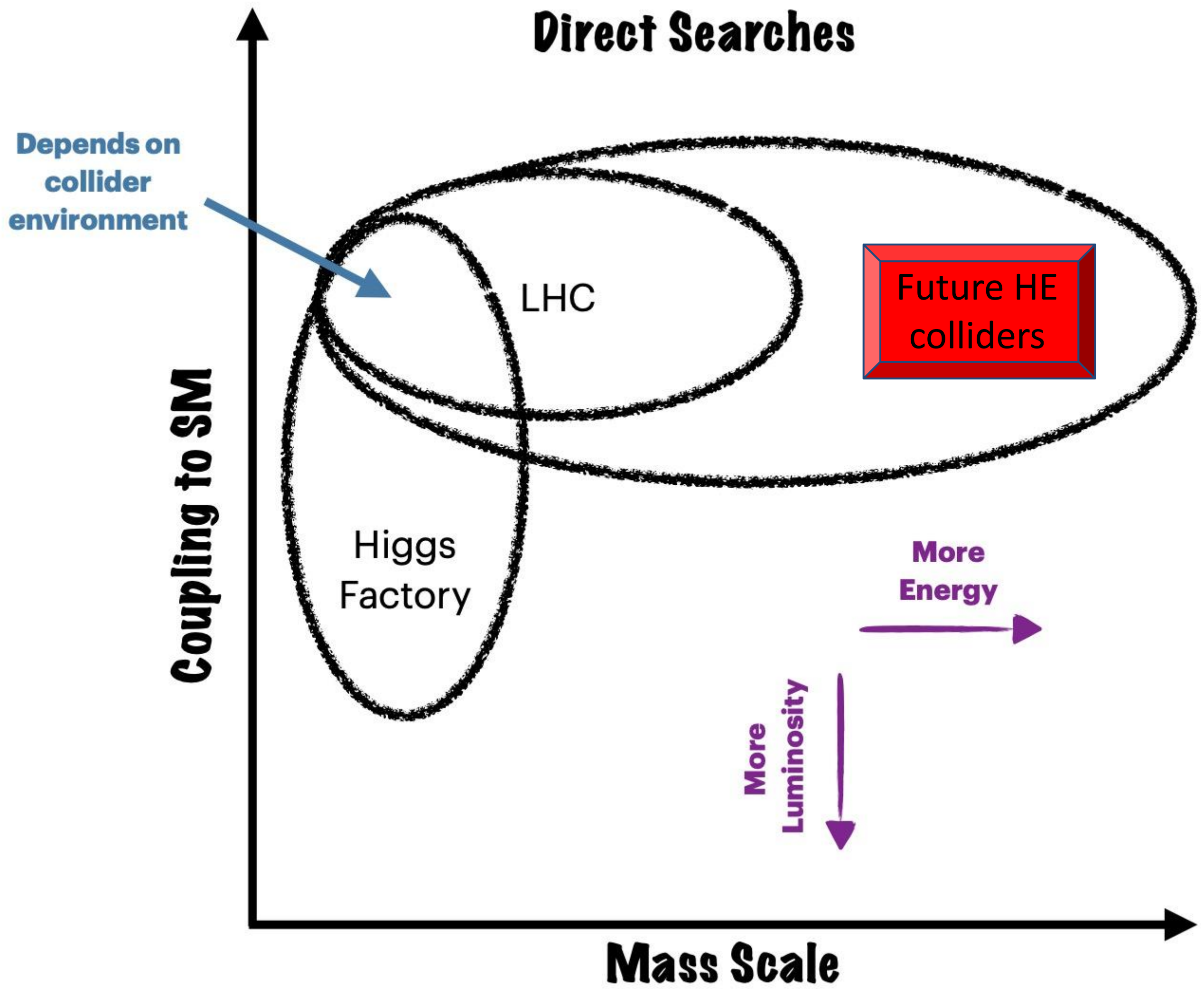
The Large Hadron Collider



Beyond LHC


Direct Searches
Depends on
collider
environment
LHC
Future HE
colliders
Higgs
Factory
More
Energy
More
Luminosity
Coupling to SM
Mass Scale

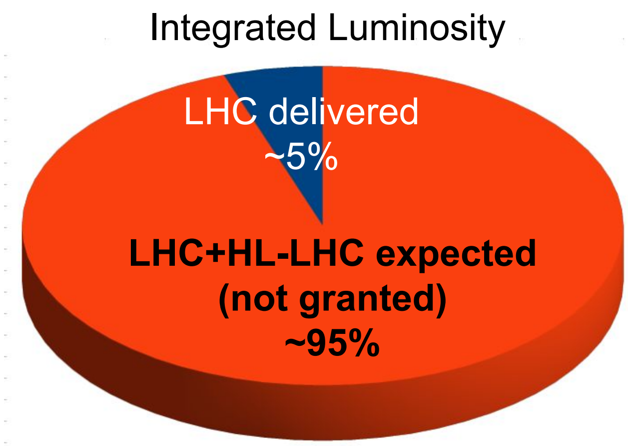
Beyond LHC

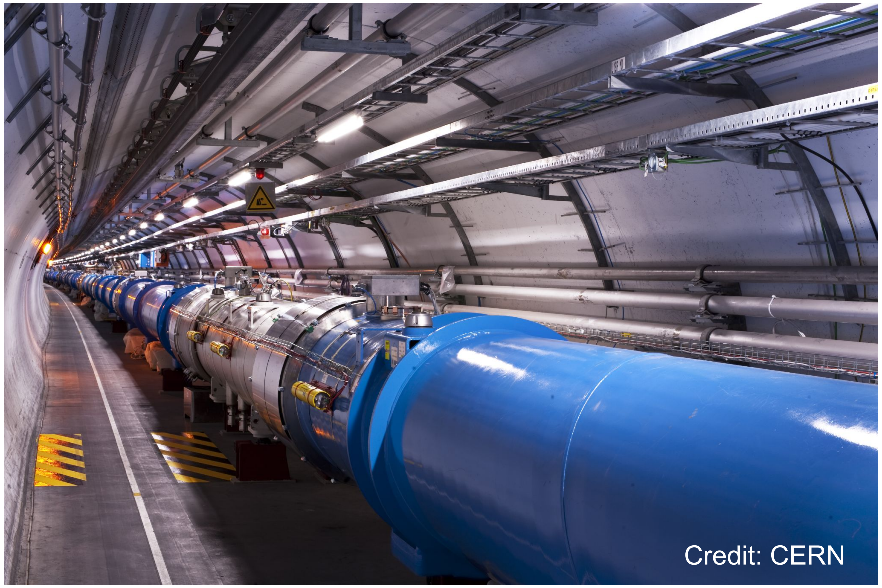


Direct Searches
Depends on collider environment
LHC
Future HE colliders
Higgs Factory
More Energy
More Luminosity
Coupling to SM
Mass Scale

HL-LHC: our upcoming Energy-Frontier Collider

Operation: 2029 to ~2040



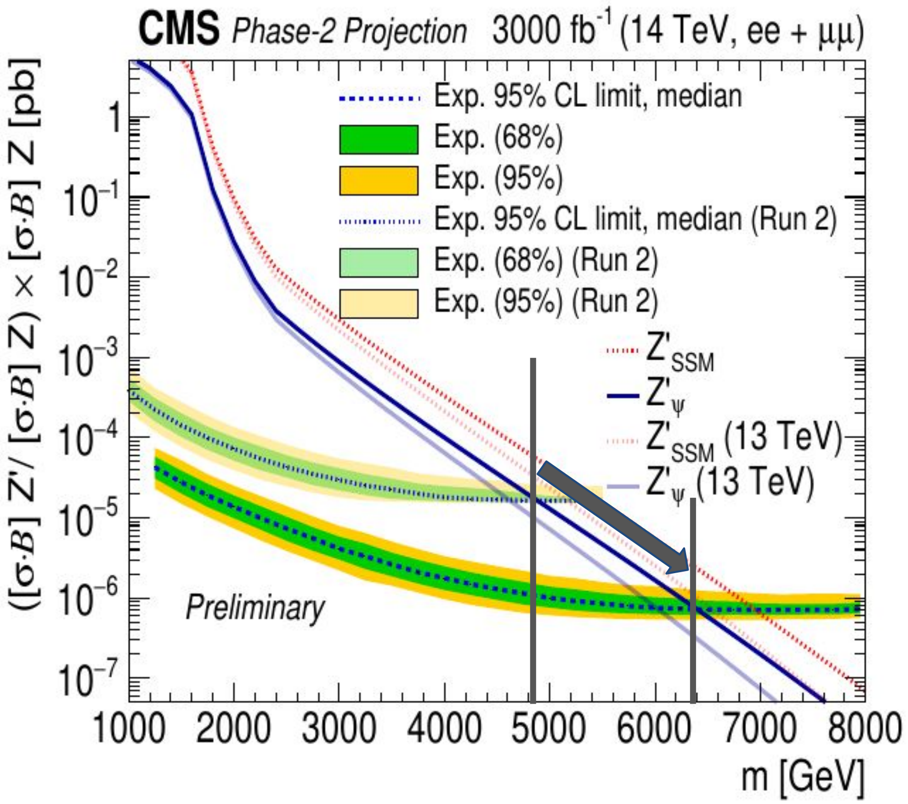


@CERN

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!



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

pp

e^+e^-

$\mu^+\mu^-$

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

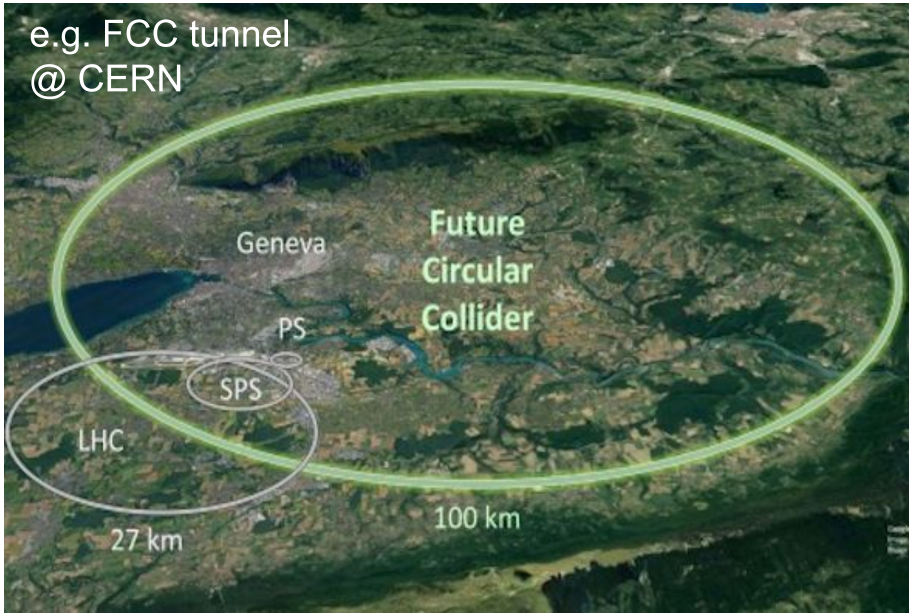
How to reach higher center-of-mass energy?

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?

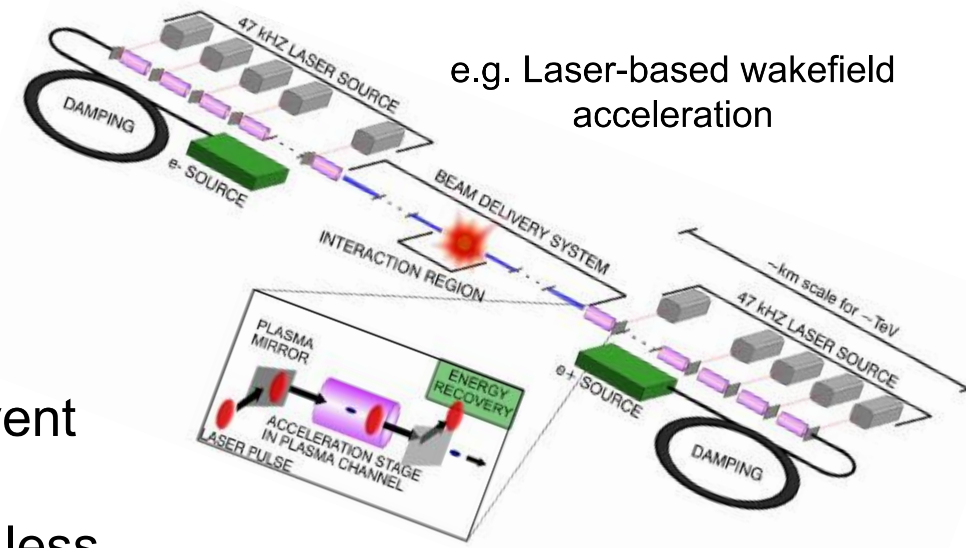
pp | e^+e^- | $\mu^+\mu^-$

- 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

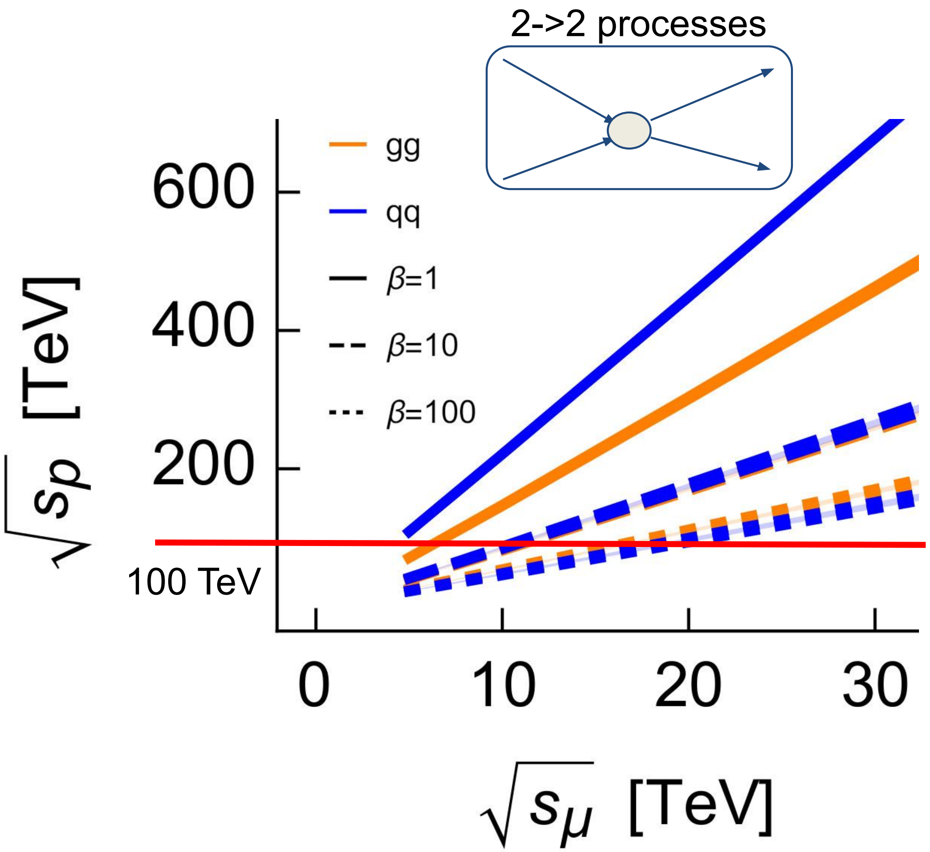
- Expect large beam-induced background (τ_0^{μ}~2μs)
- Low physics backgrounds
- In principle scalable to even higher energies

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

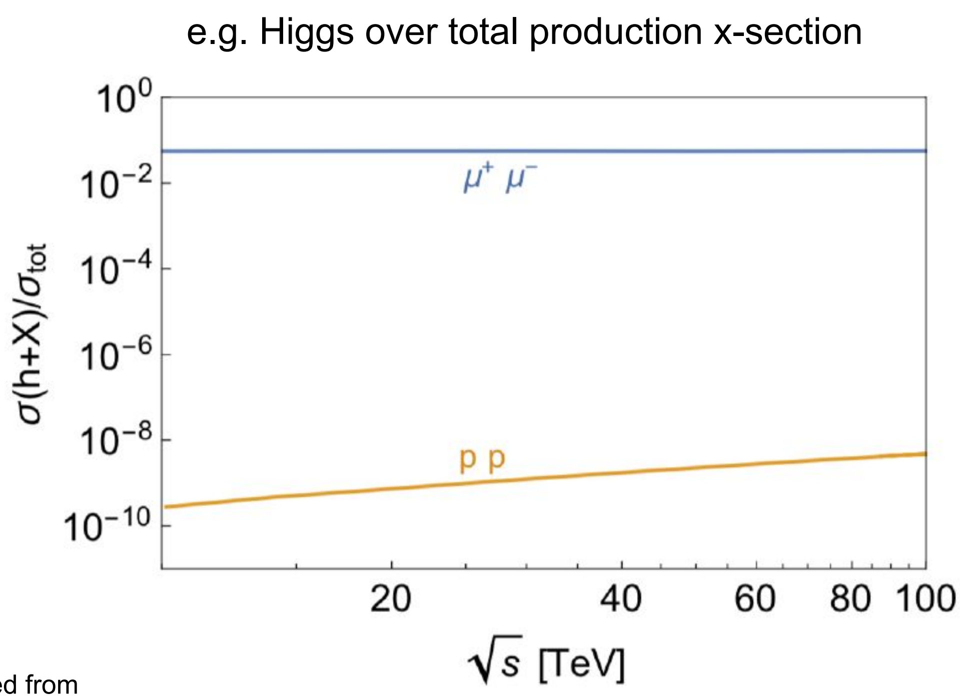
Lepton vs Hadron colliders: expected signals

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

Signals



Backgrounds



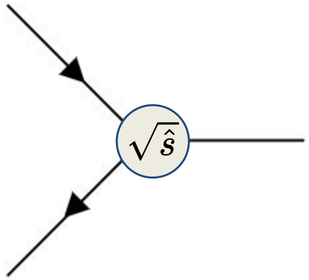
Adapted from arXiv:2103.14043

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

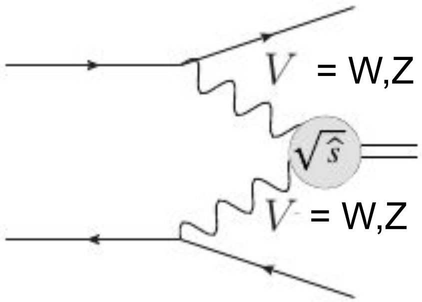
Not a “simple” jump in Energy

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

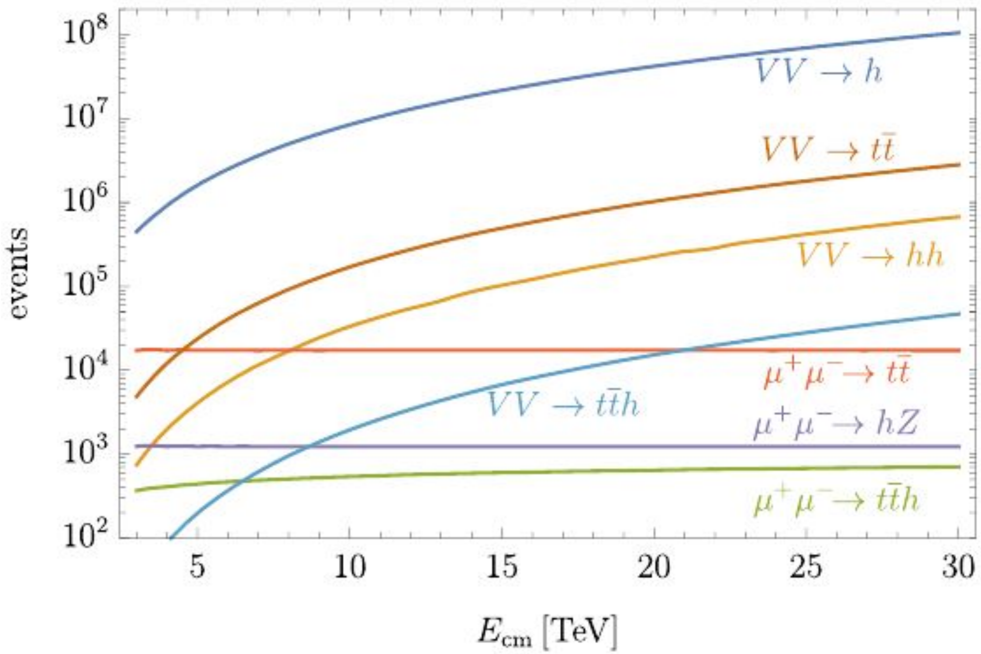
Just 1/100s examples: **new dominant production mechanisms**



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



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



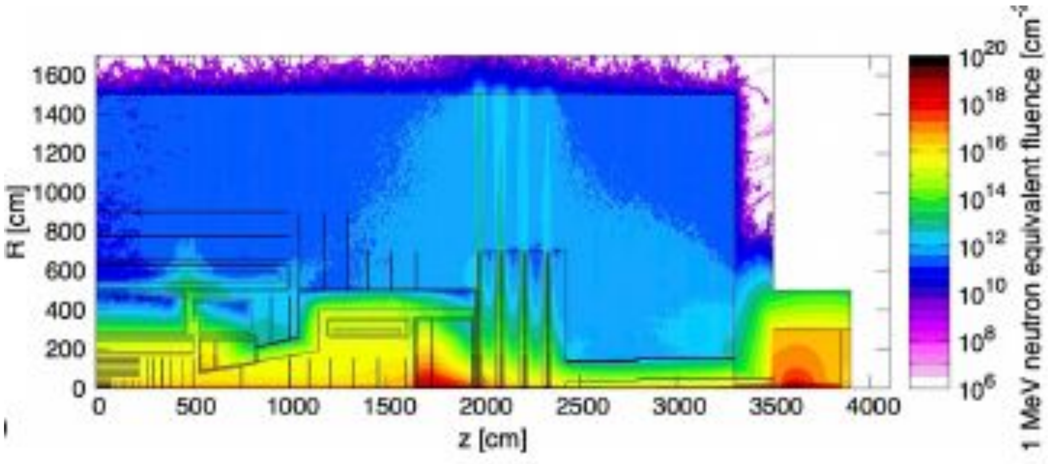
Not a "simple" jump in Energy

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

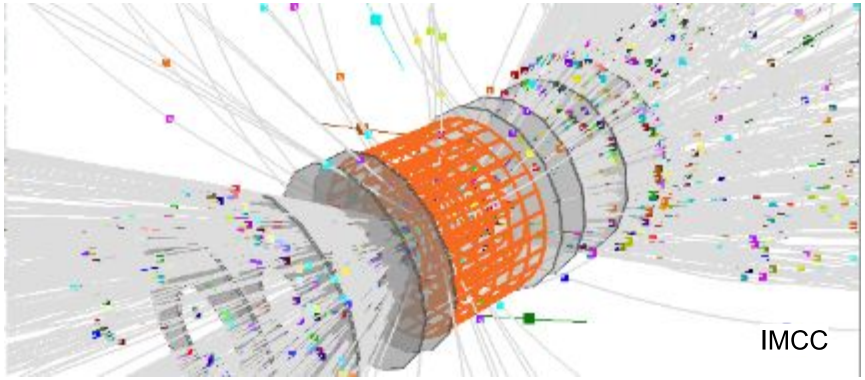
More than x10 than HL-LHC at FCC-hh

- 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?

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
Muon Collider	10 (1.5-14)	20	>10	>25
LWFA - LC - $\gamma\gamma$ (Laser-driven)	15 (1-15)	50	>10	>25
PWFA - LC - $\gamma\gamma$ (Beam-driven)	15 (1-15)	50	>10	>25
Structure WFA - LC - $\gamma\gamma$ (Beam-driven)	15 (1-15)	50	>10	>25
FCC-hh	100	30	>10	>25
SPPS	125 (75-125)	13	>10	>25

from Snowmass AF Implementation Taskforce

- None of these colliders is happening tomorrow
- Critical to address as quickly as possible the key R&D challenges

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

- 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

- Historically have opened roads to revolutionary discoveries

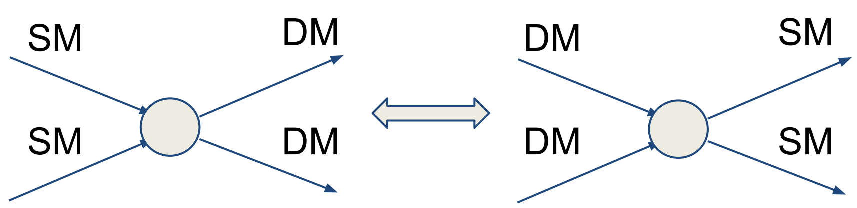
Dark Matter at Colliders

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

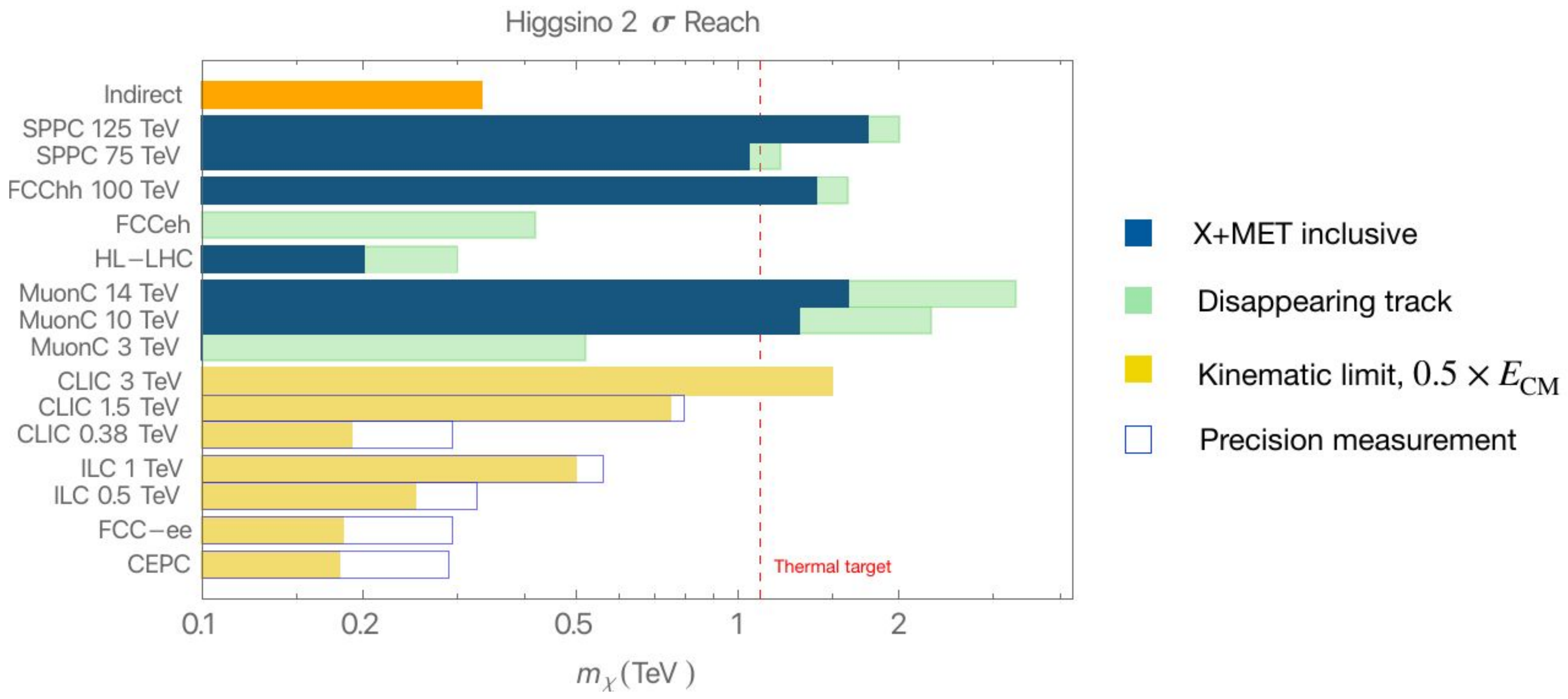


$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\,\mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}$$

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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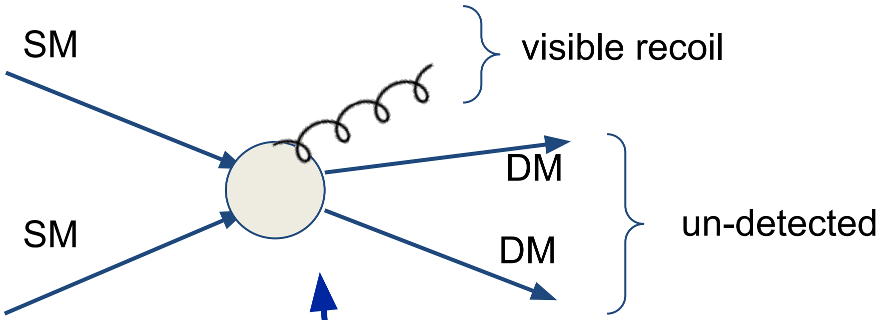

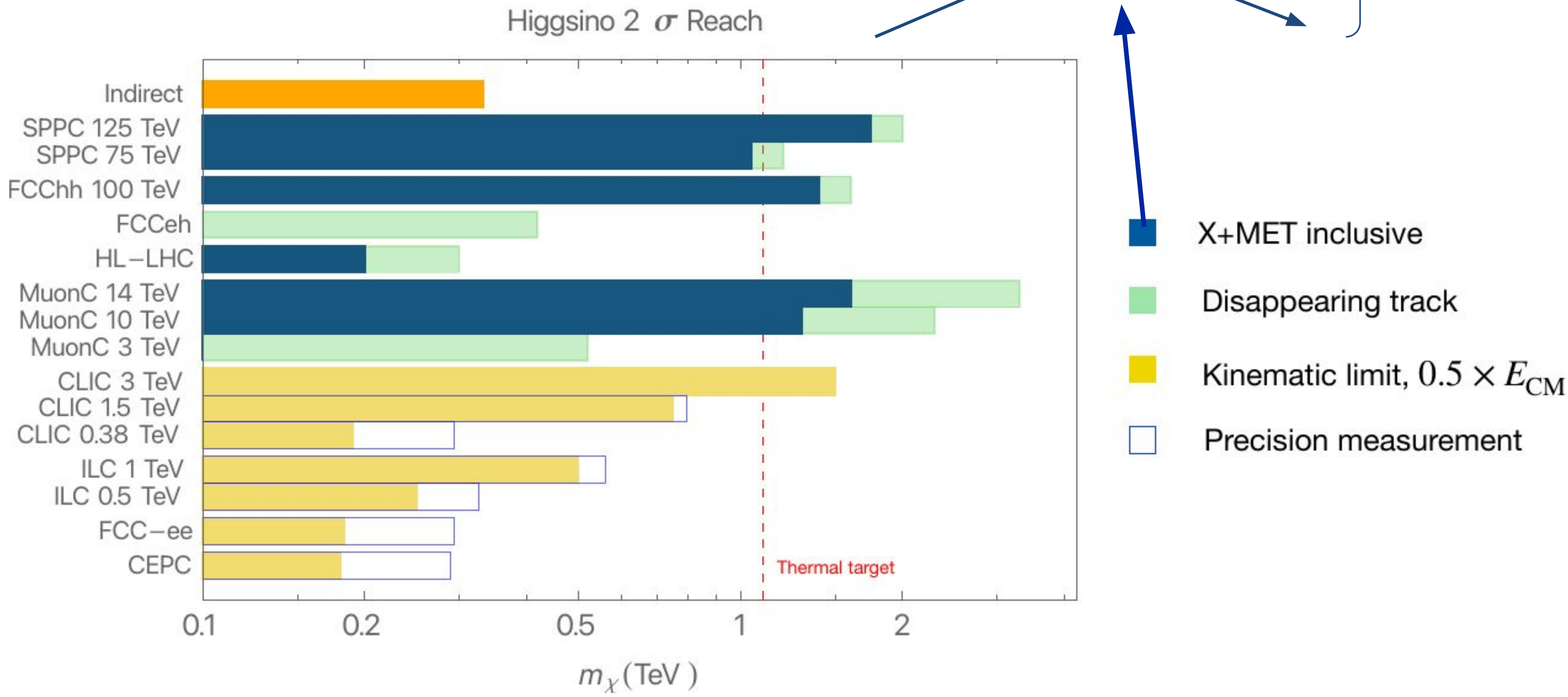

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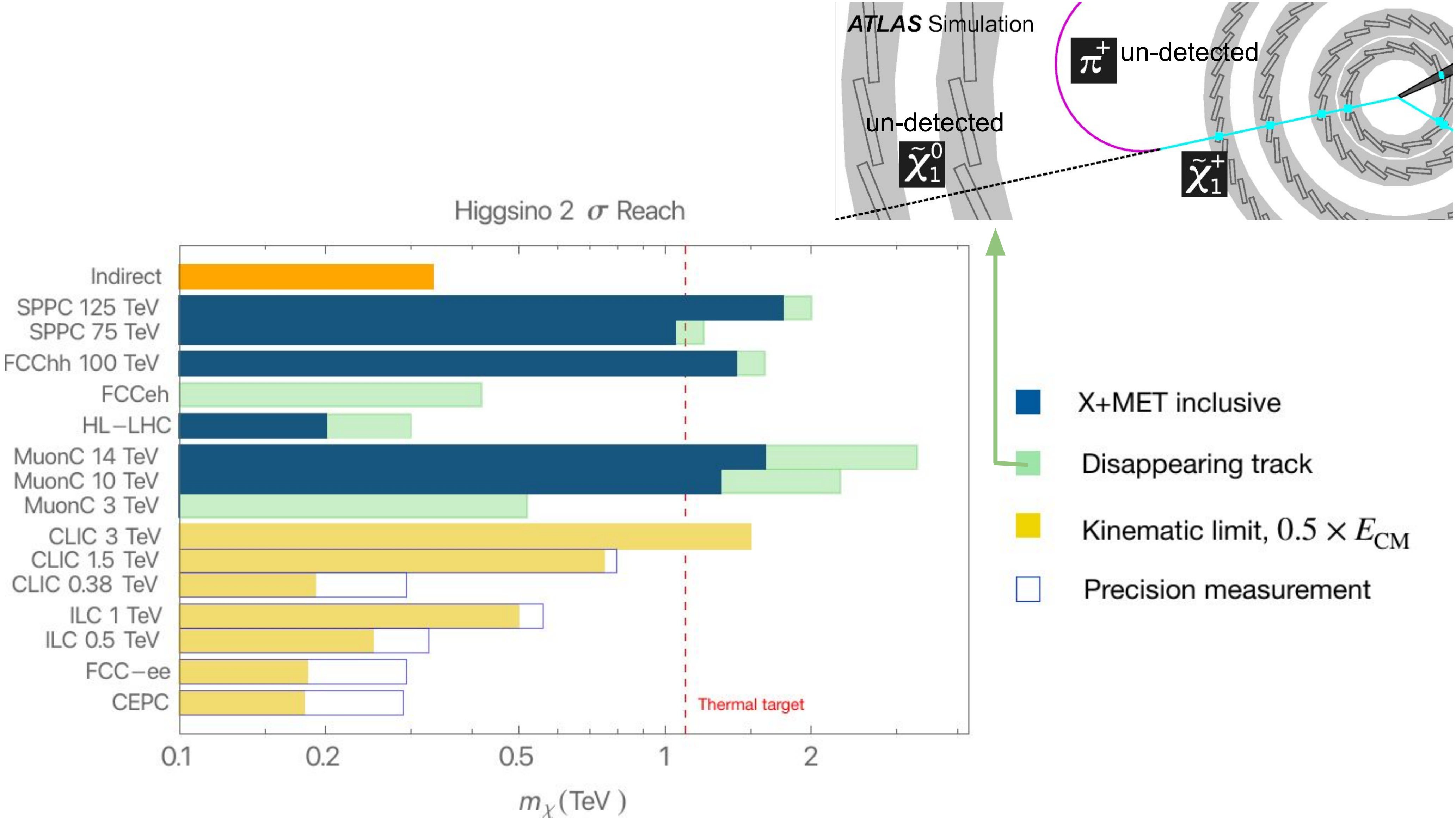

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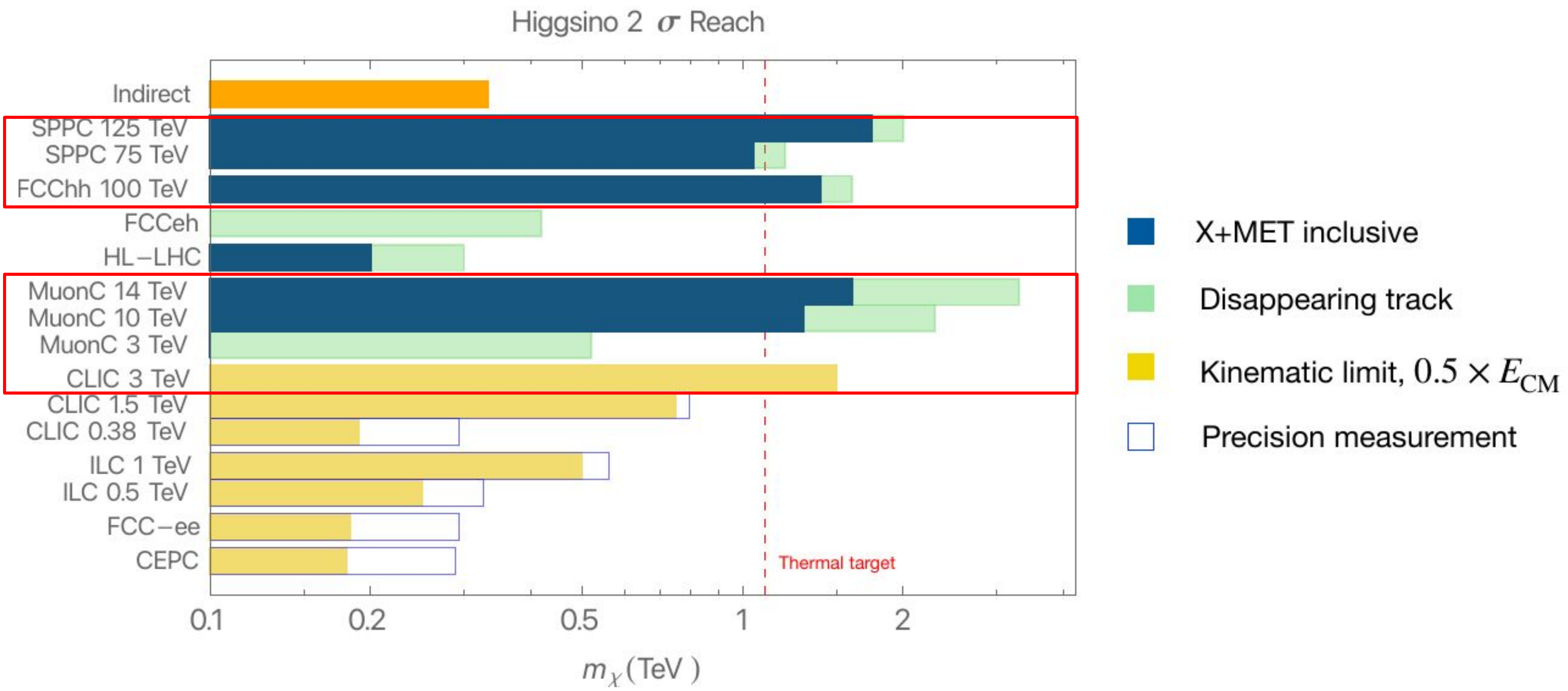
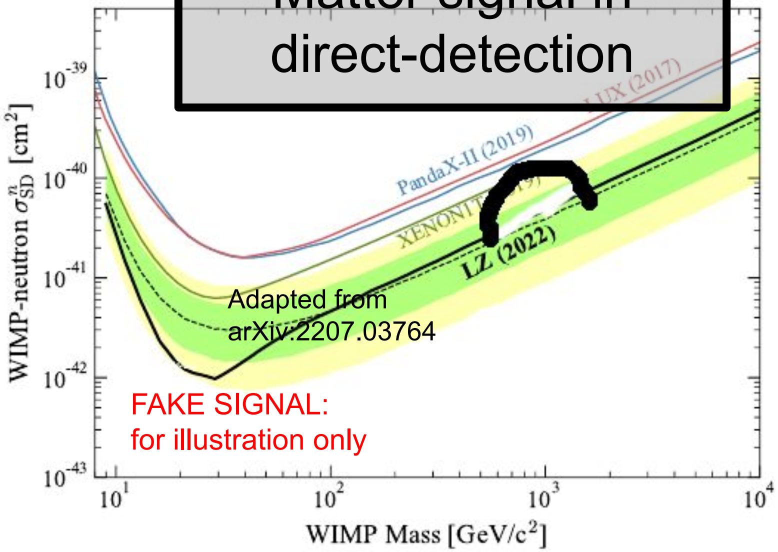


Need multi-TeV colliders to arrive to this natural target

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

Discovery of a Dark Matter signal in direct-detection



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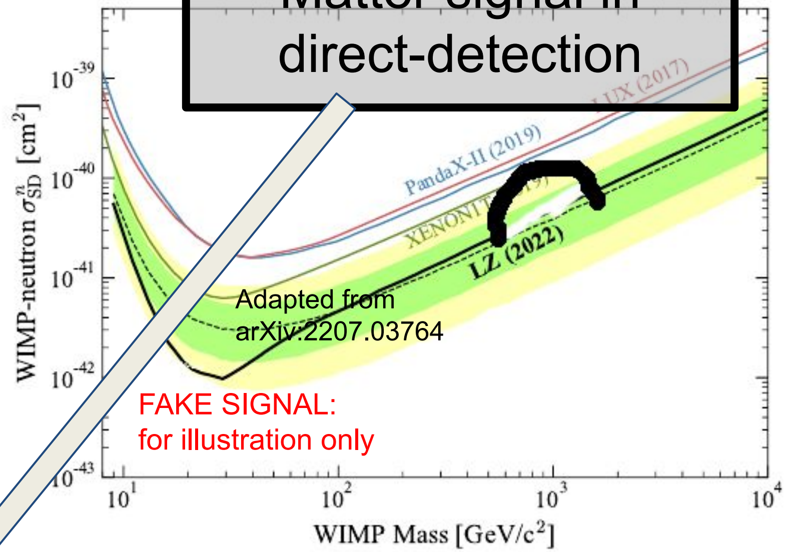
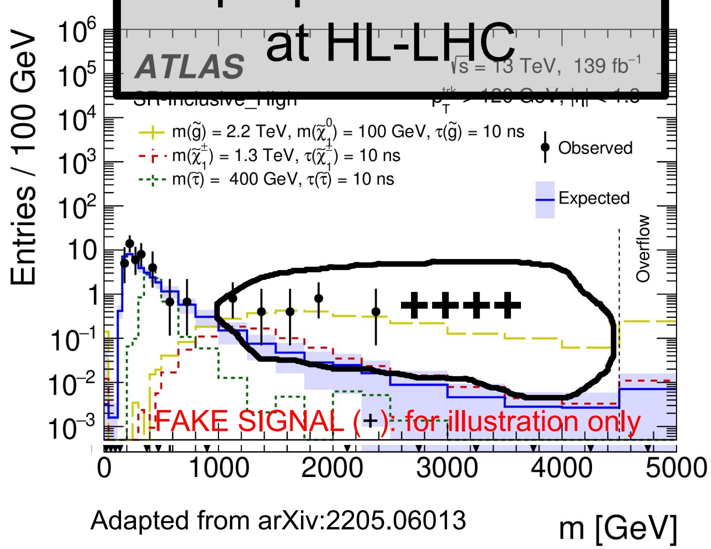


Its properties studied at HL-LHC



Adapted from arXiv:2205.06013

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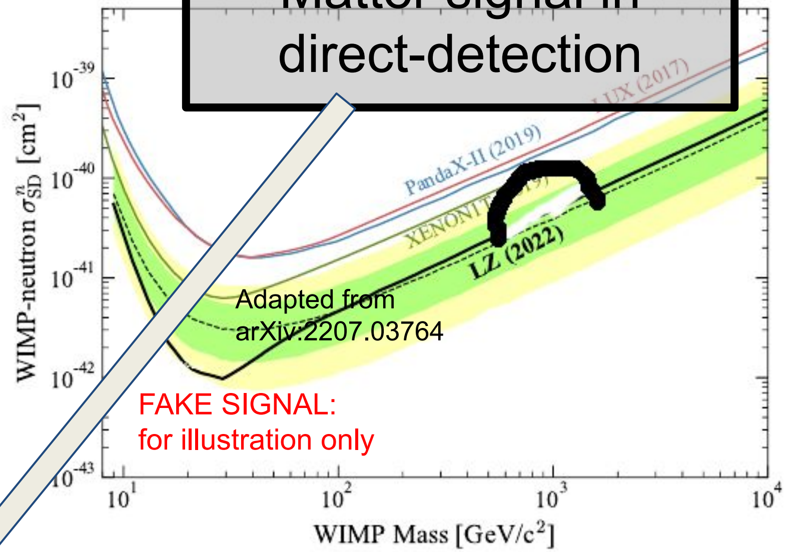

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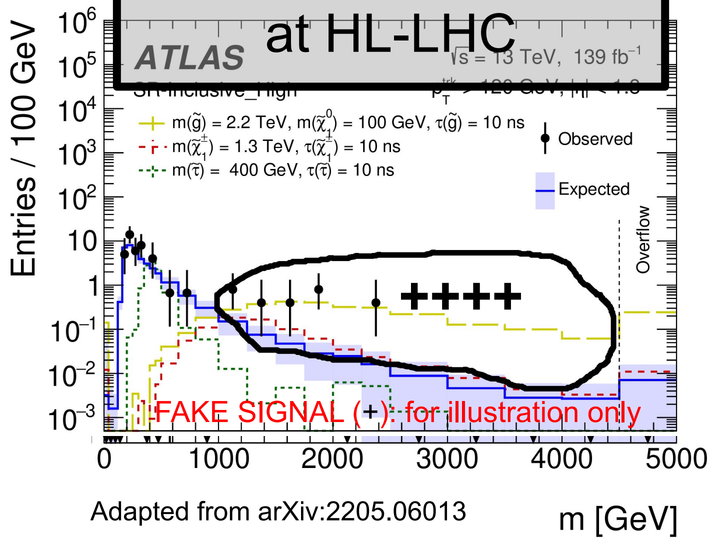
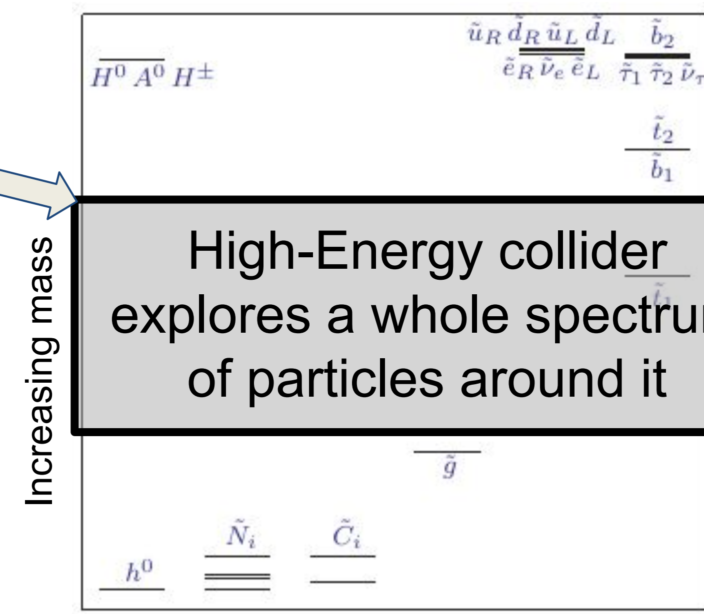
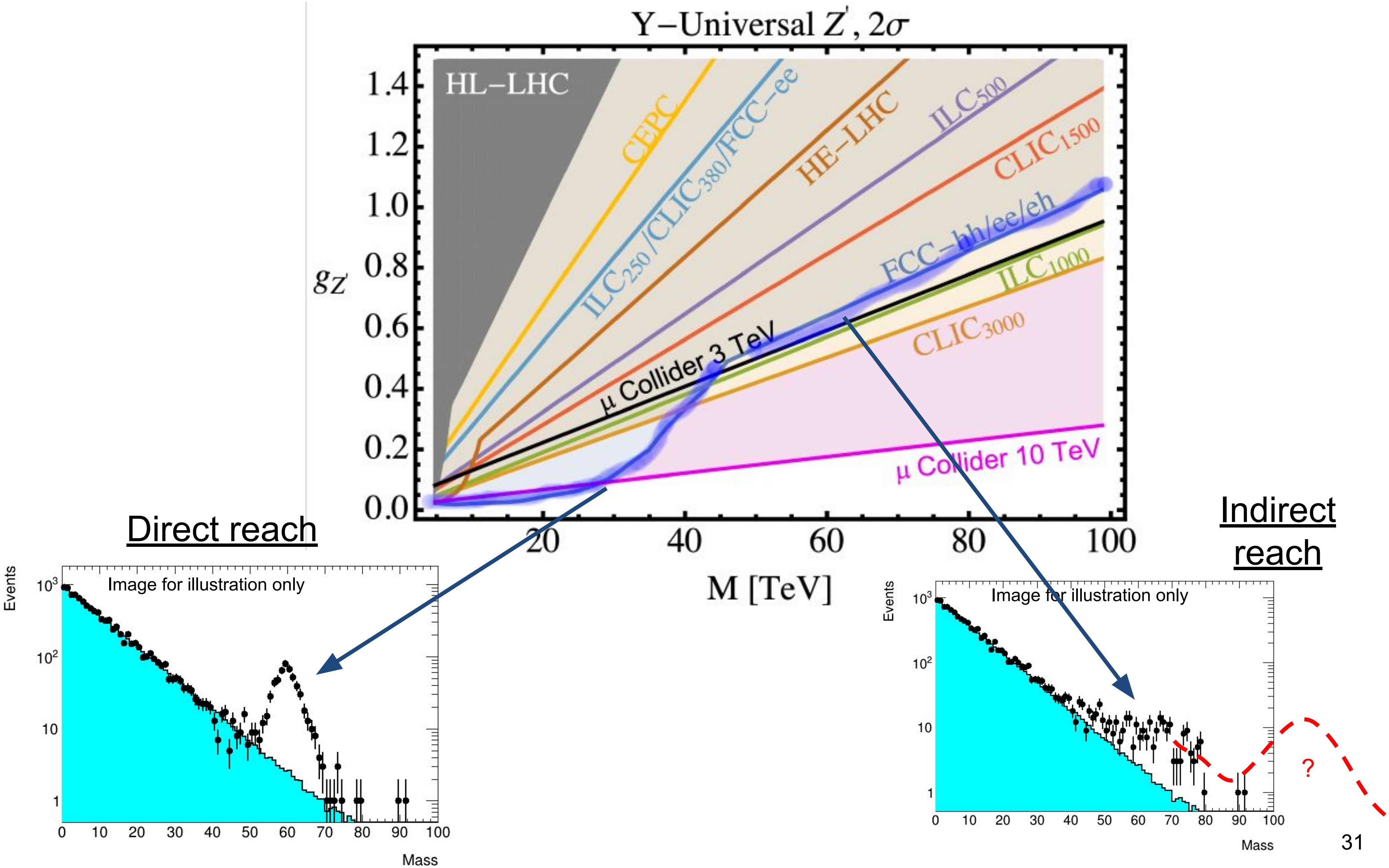


High-Energy collider explores a whole spectrum of particles around it



Exploring the unknown: new forces

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

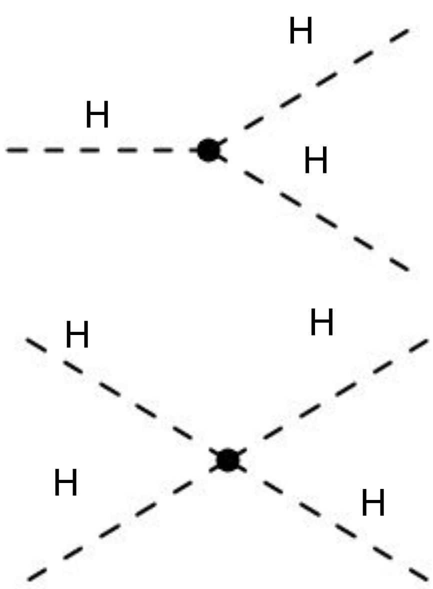


High Energy <-> High Luminosity <-> High Precision

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	~10^6	~$5 \cdot 10^6$	10^7	~10^{10}

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

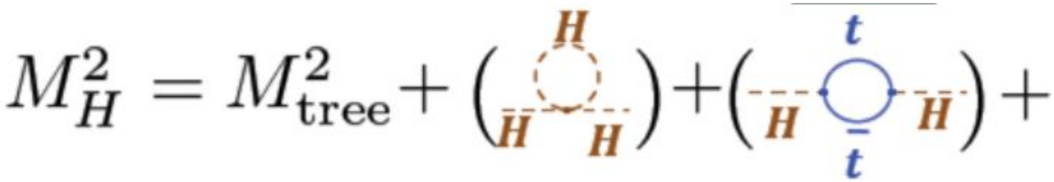


collider	Indirect-h_{SM}	$h_{SM}h_{SM}$	combined
HL-LHC [27]	100-200%	50%	50%
$\text{ILC}_{250}/\text{C}^3$-250 [20, 17]	49%	–	49%
$\text{ILC}_{500}/\text{C}^3$-550 [20, 17]	38%	20%	20%
$\text{ILC}_{100}/\text{C}^3$-1000 [20, 17]	36%	10%	10%
CLIC_{380} [22]	50%	–	50%
CLIC_{1500} [22]	49%	36%	29%
CLIC_{3000} [22]	49%	9%	9%
FCC-ee [23]	33%	–	33%
FCC-ee (4 IPs) [23]	24%	–	24%
FCC-hh [28]	-	2.9-5.5%	2.9-5.5%
μ(3 TeV) [26]	-	15-30%	15-30%
μ(10 TeV) [26]	-	4%	4%

3-5%

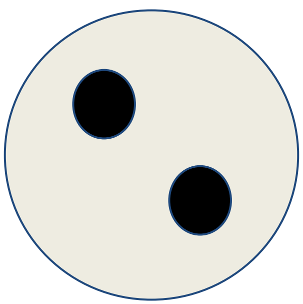
Extremely rare process:
only multi-TeV colliders can probe it accurately

Solutions to the hierarchy problem

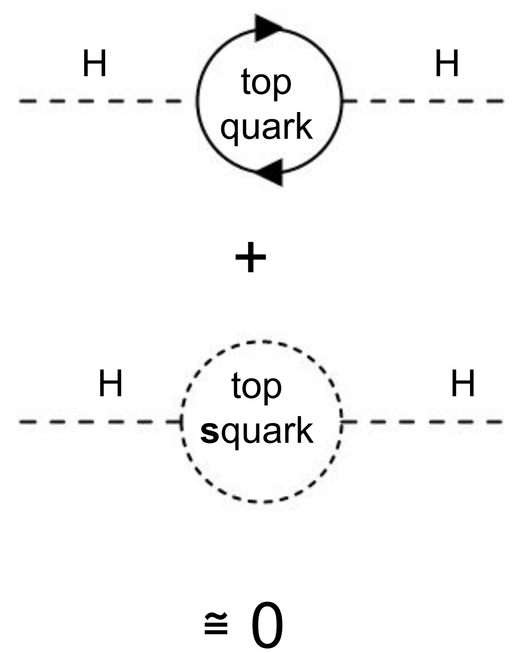


The unique scalar nature of the Higgs boson suggests new physics
Testing the ≲ 10 TeV regime provides very strong tests of this arguments
(other options are also possible)

Compositeness



New "symmetries"

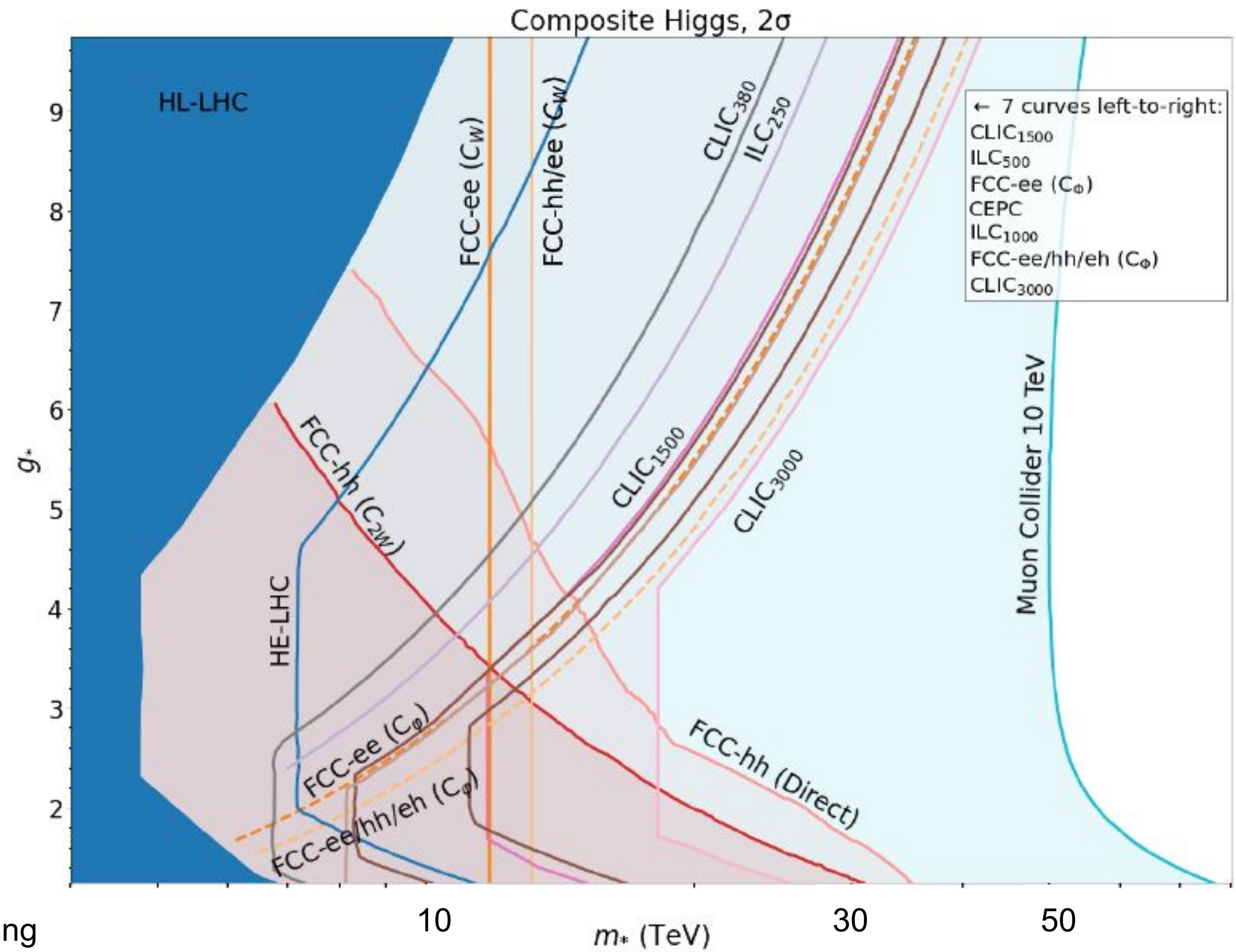


Higgs compositness

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

Supersymmetry

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- alleviate hierarchy problem
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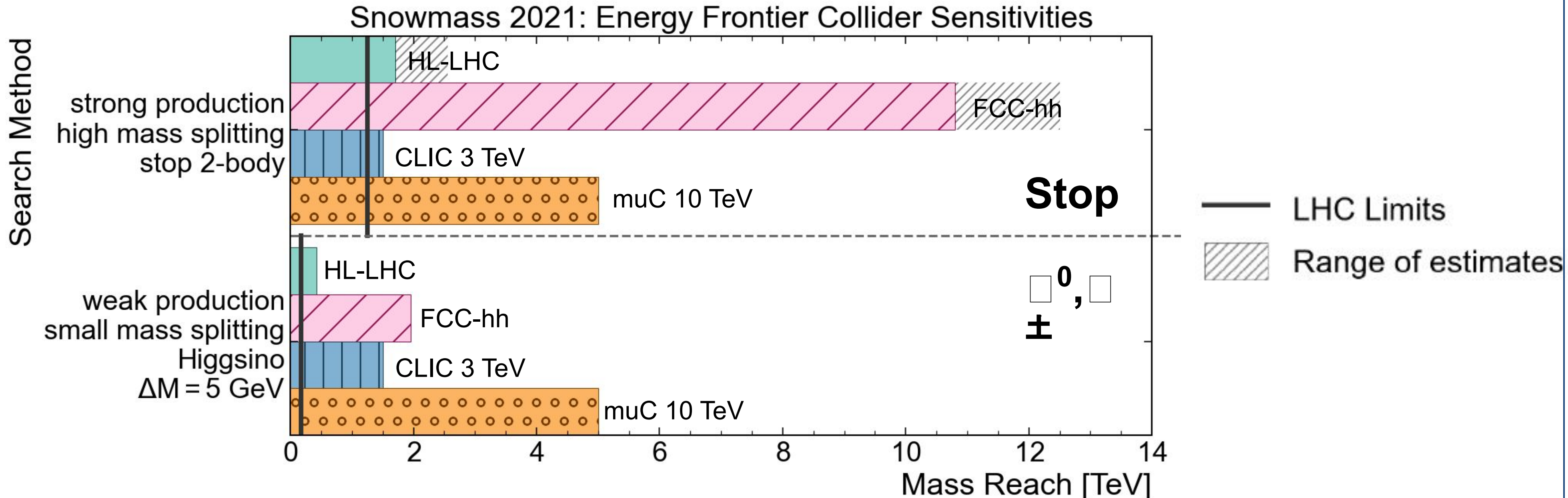
Large model-parameters space and vast phenomenology

Simplified classes of signatures

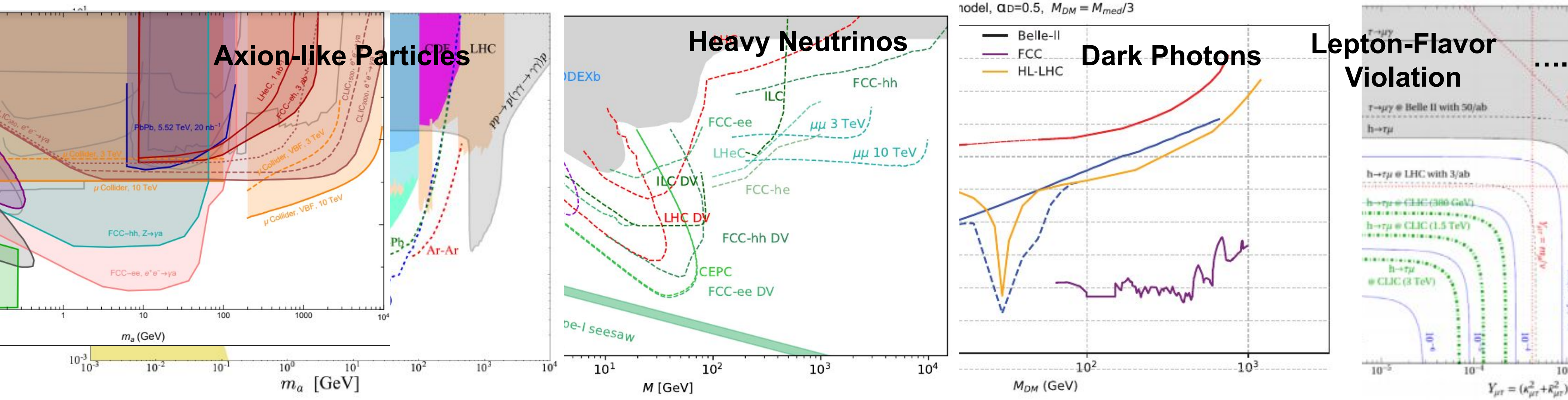
Full models with additional assumptions (in backup)



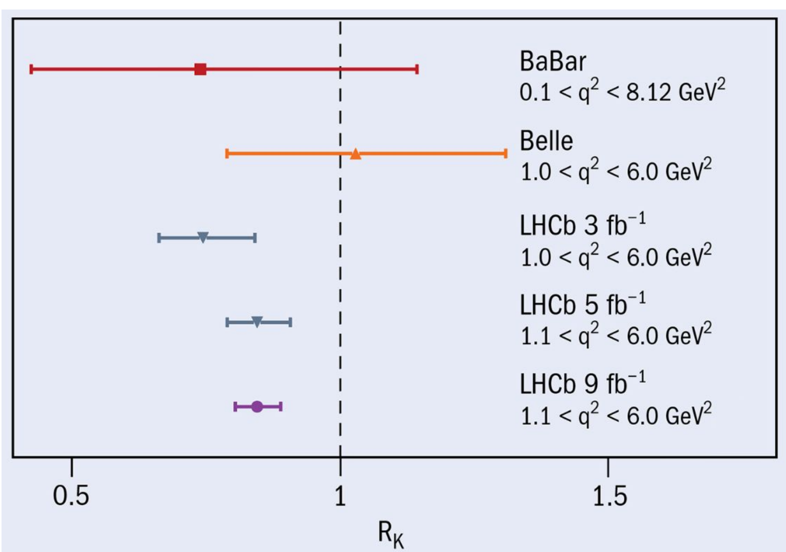
Multi-TeV colliders extend the reach to the ~10 TeV scale!

… and much MUCH more!

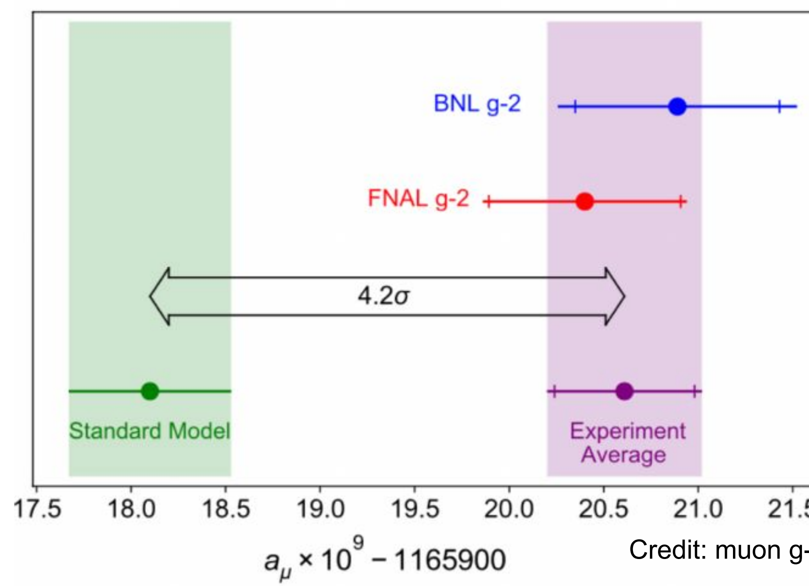
Vast program addressing the fundamental questions outlined and much more!



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

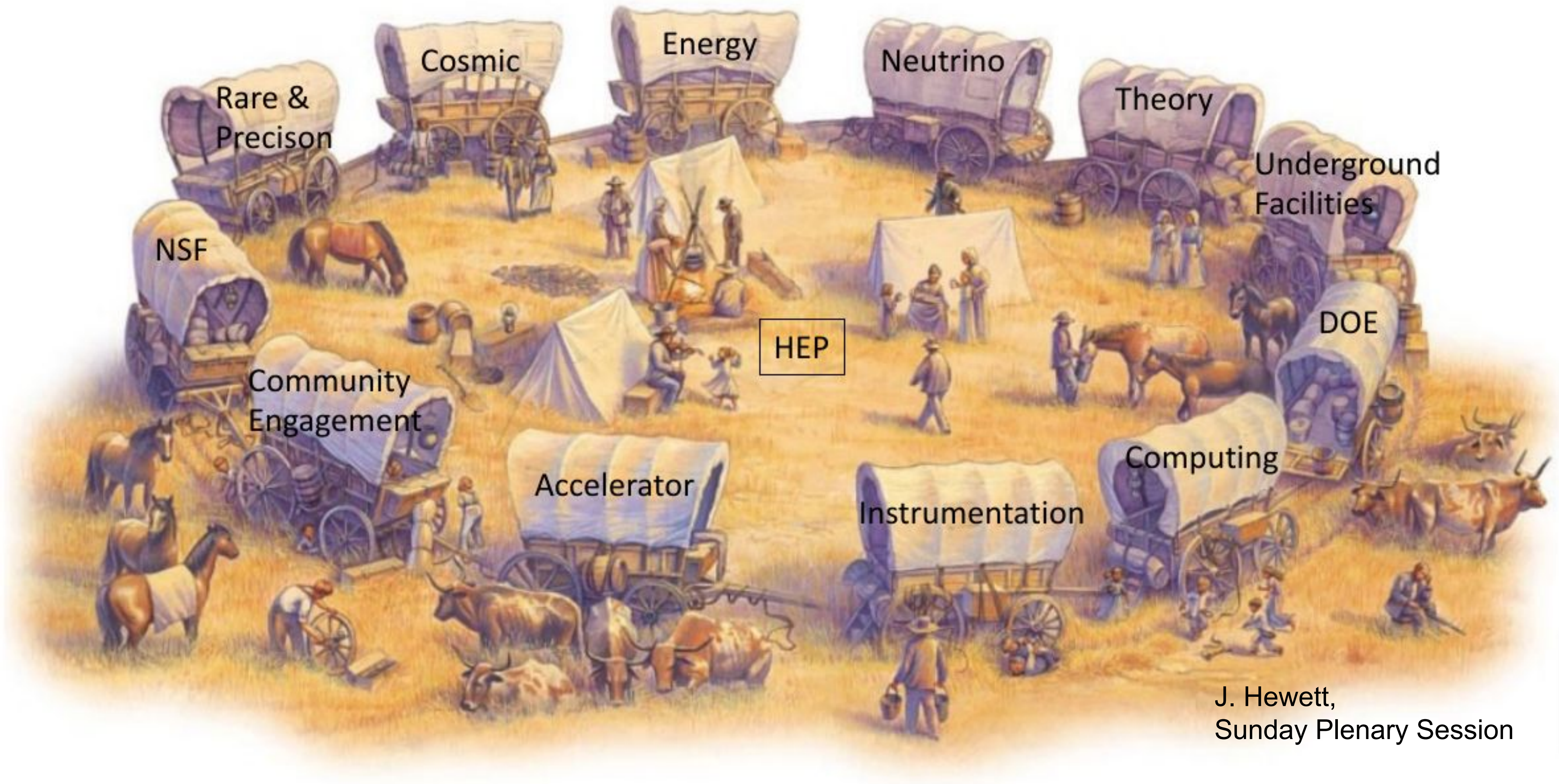


Credit: LHCb, CERN Courier



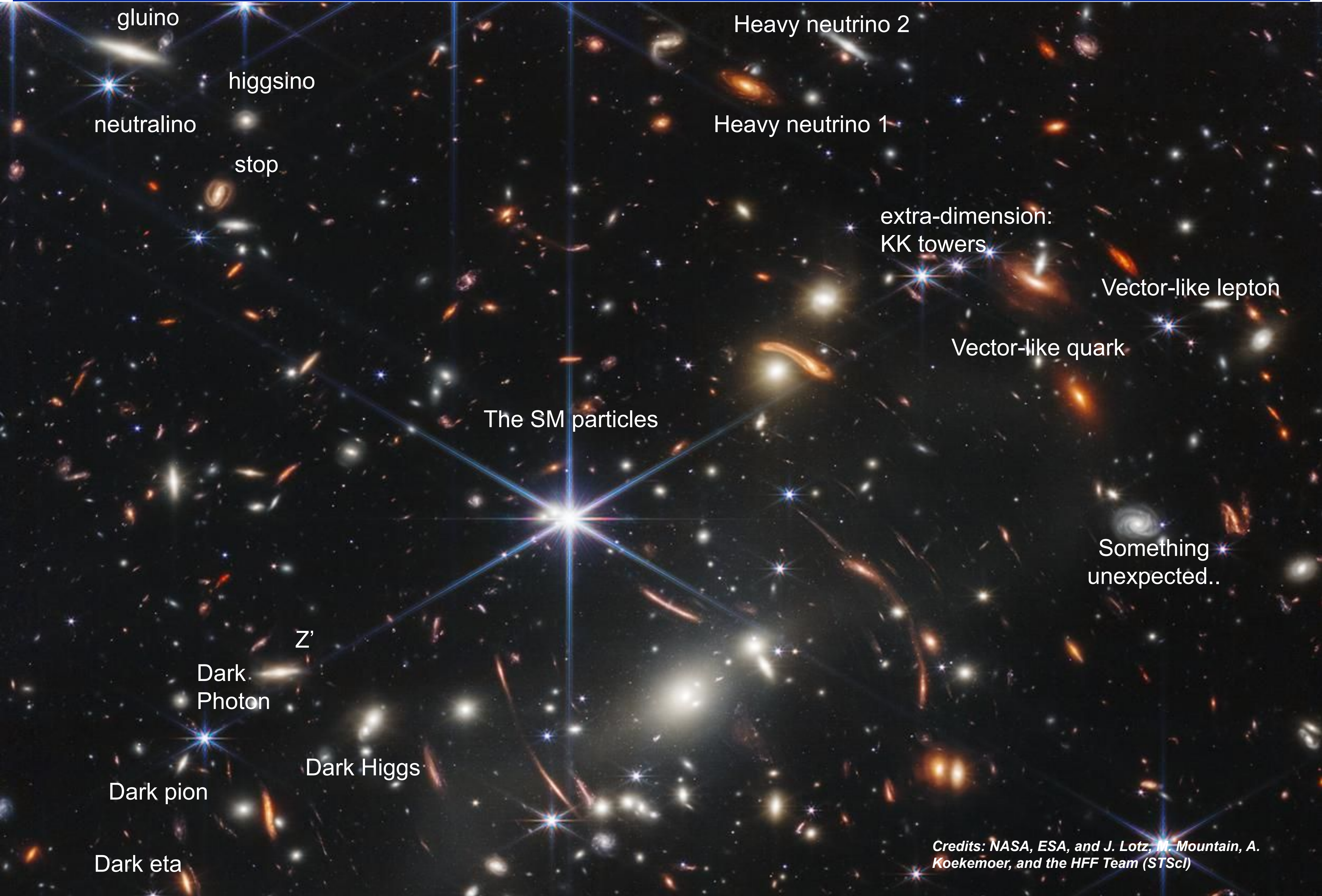
Credit: muon g-2 collab.

Concluding…

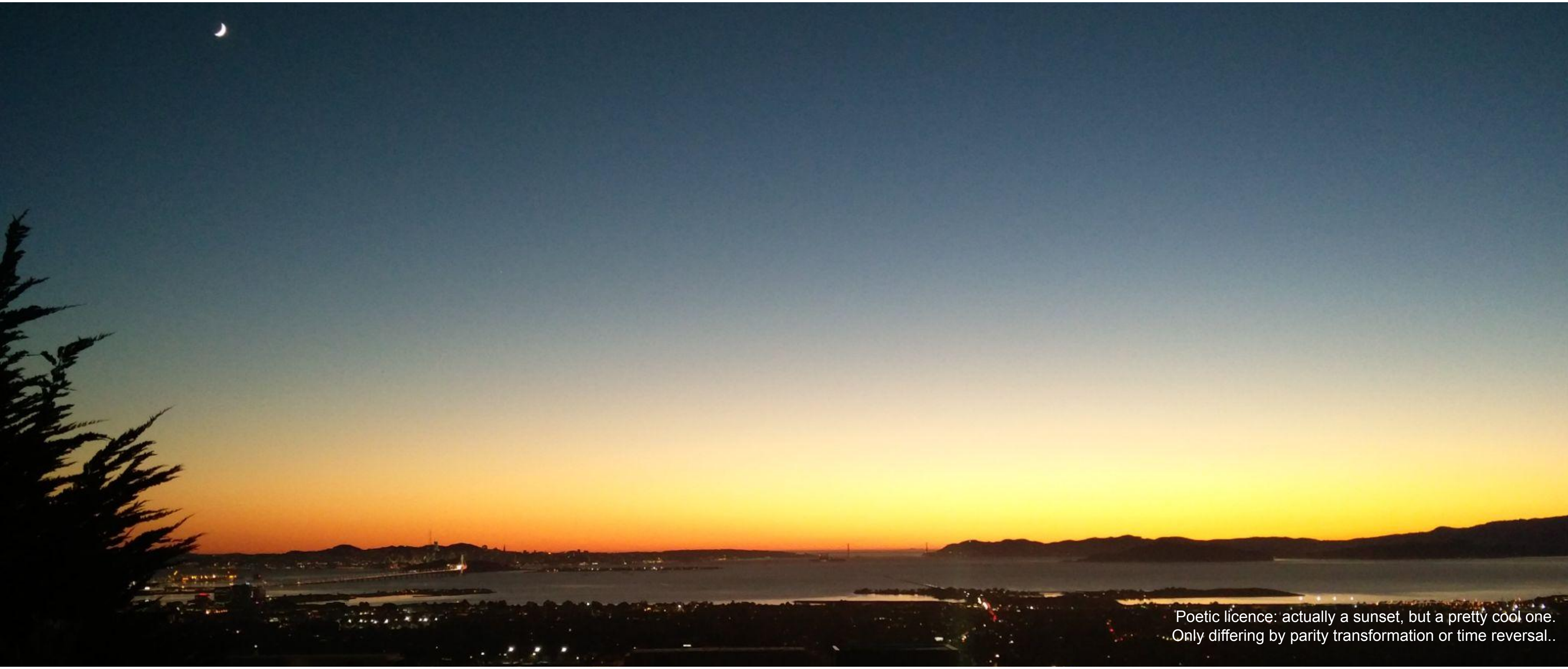


J. Hewett,
Sunday Plenary Session

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.

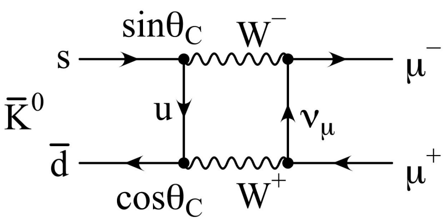
BACKUP

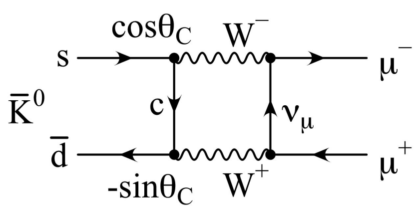
Keys to success: Theory <-> Experiments

Experimental breakthroughs and Theoretical advancements have both contributed to this success

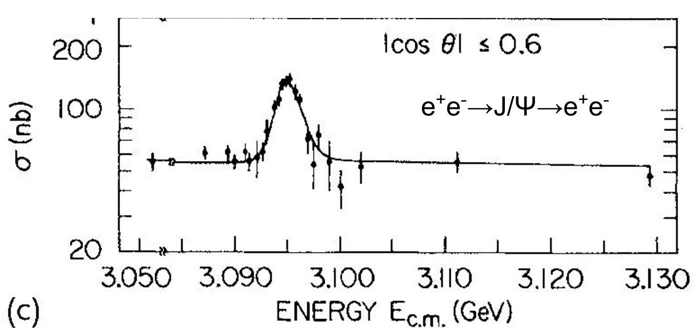
Prediction of charm quark

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





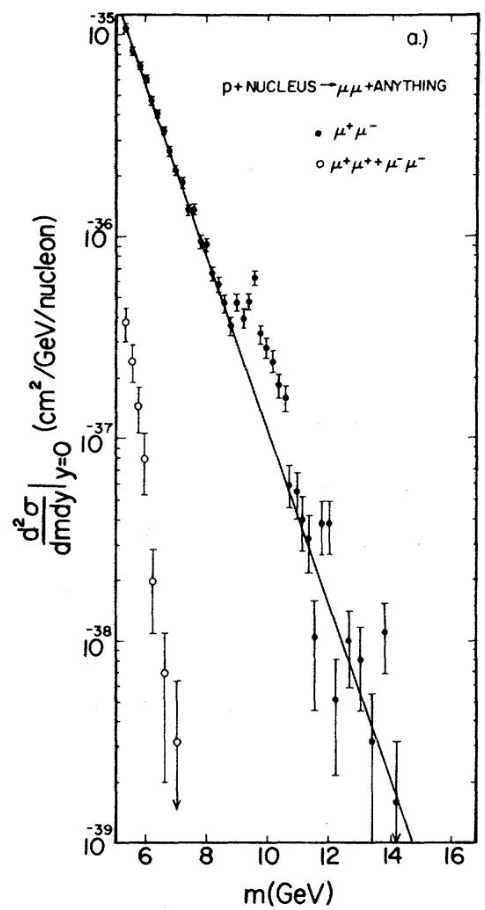
Then discovered through direct production of J/Ψ



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

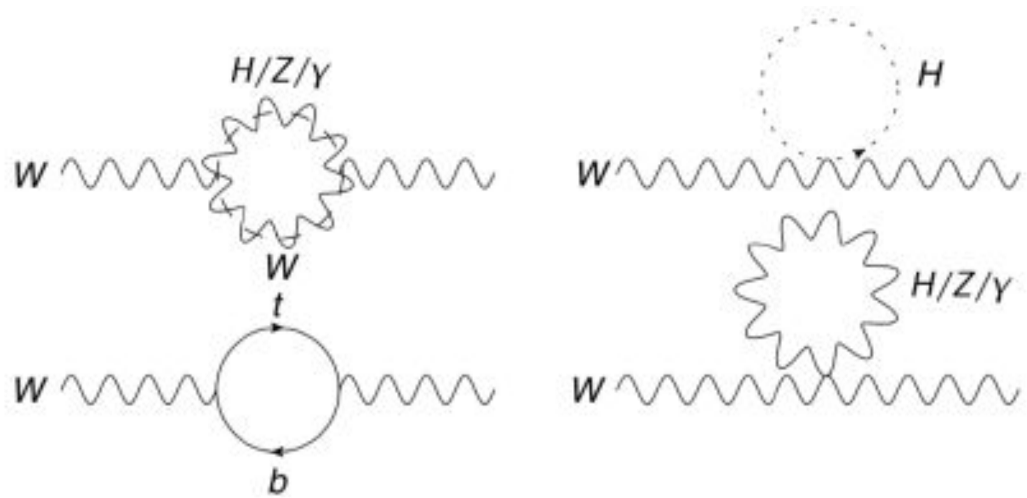
Precision measurements can stress-test the Standard Model
and ultimately point towards the energy scale we need for a discovery

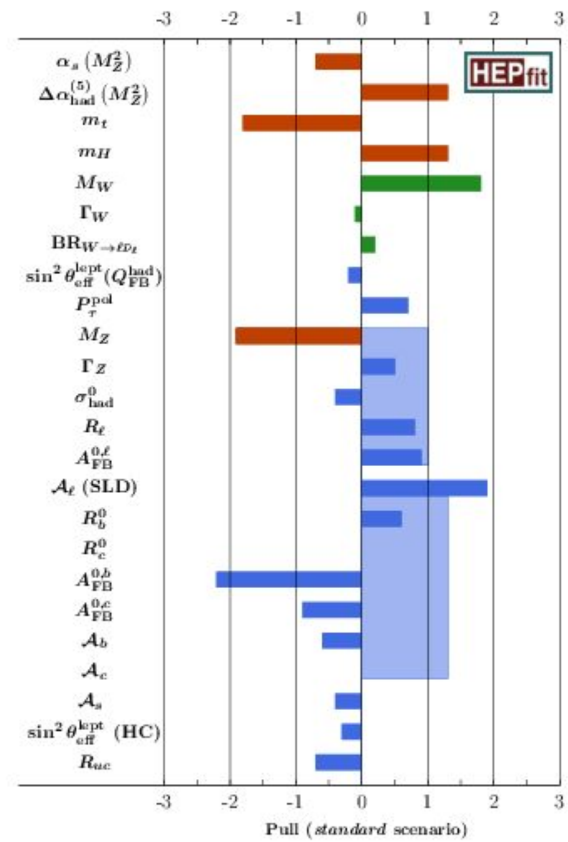
Electroweak precision observables

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





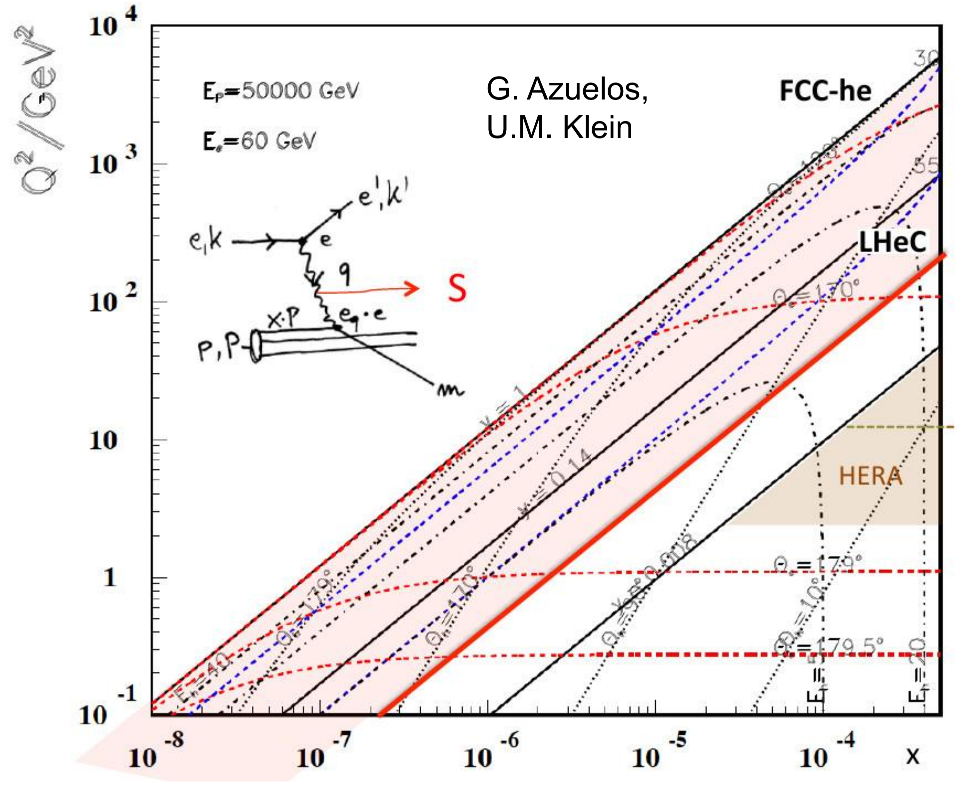
arXiv:2112.07274,
arXiv:2204.04204

Lepton-Hadron colliders

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

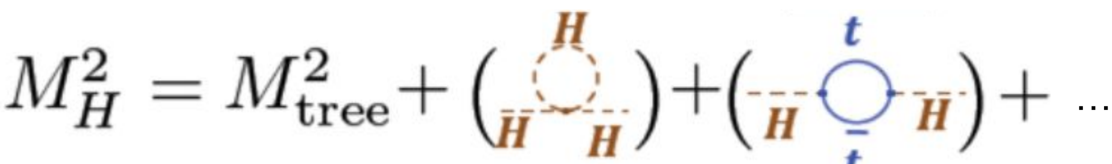
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2

- 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!



Example: Naturalness

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

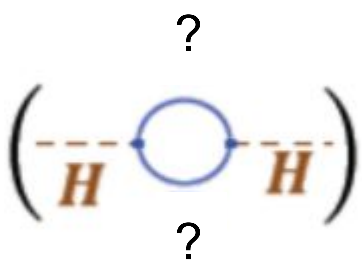


$\Delta M_H \sim \Lambda^2$

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



$M_?$ ~ 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

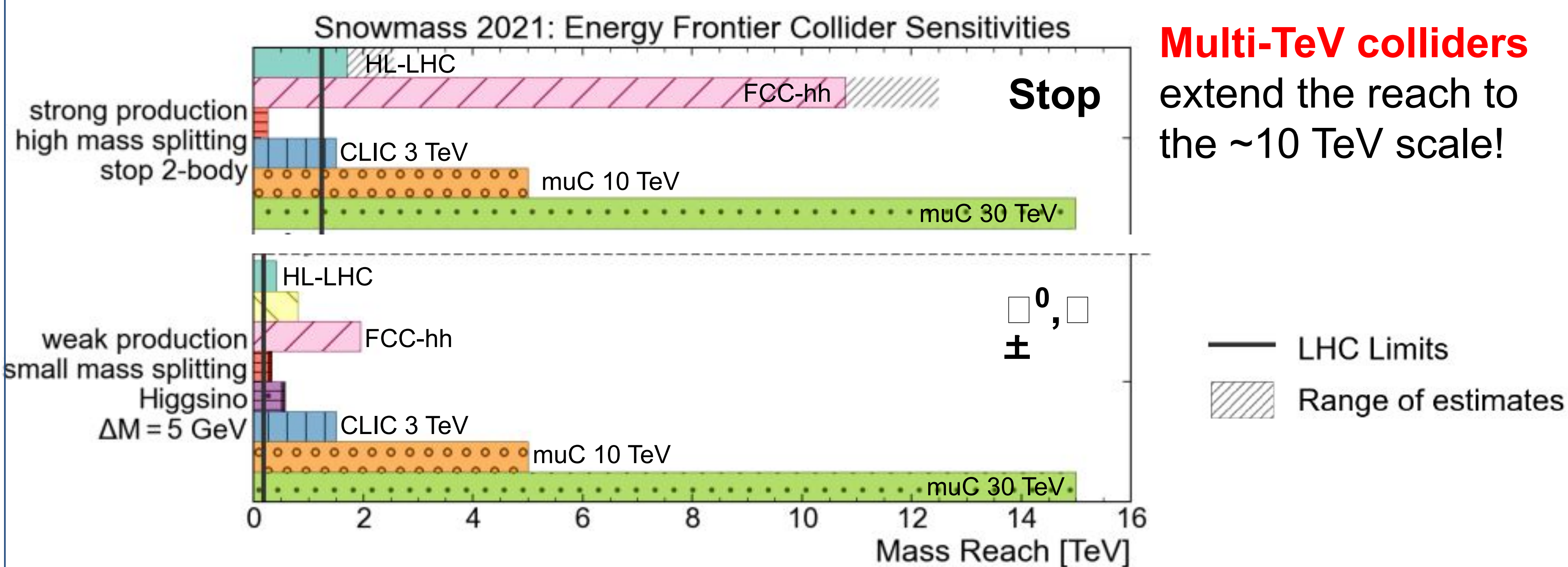
Supersymmetry

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

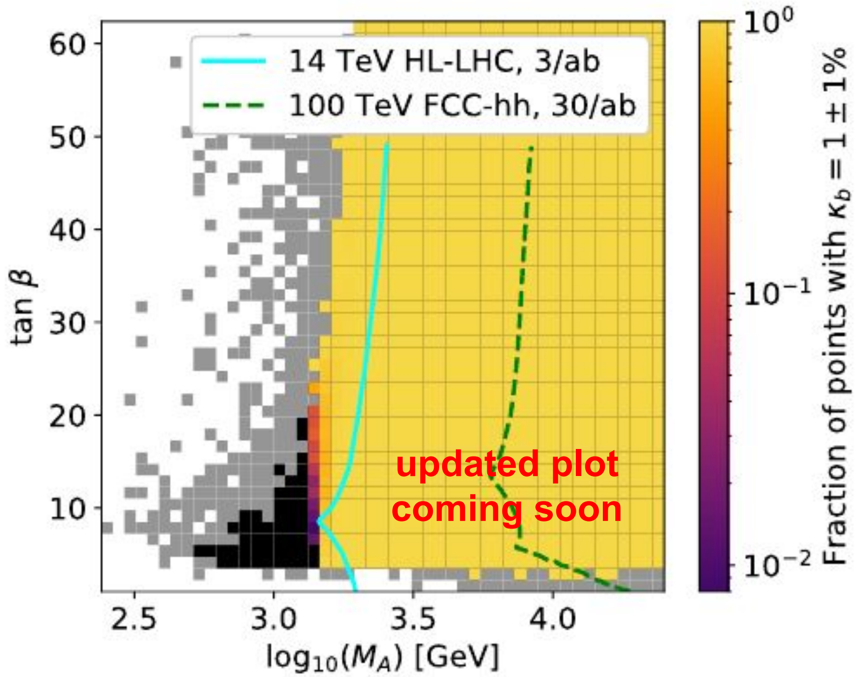
Long-sought for very good reasons

- 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

<u>Full models with additional assumptions:</u>

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

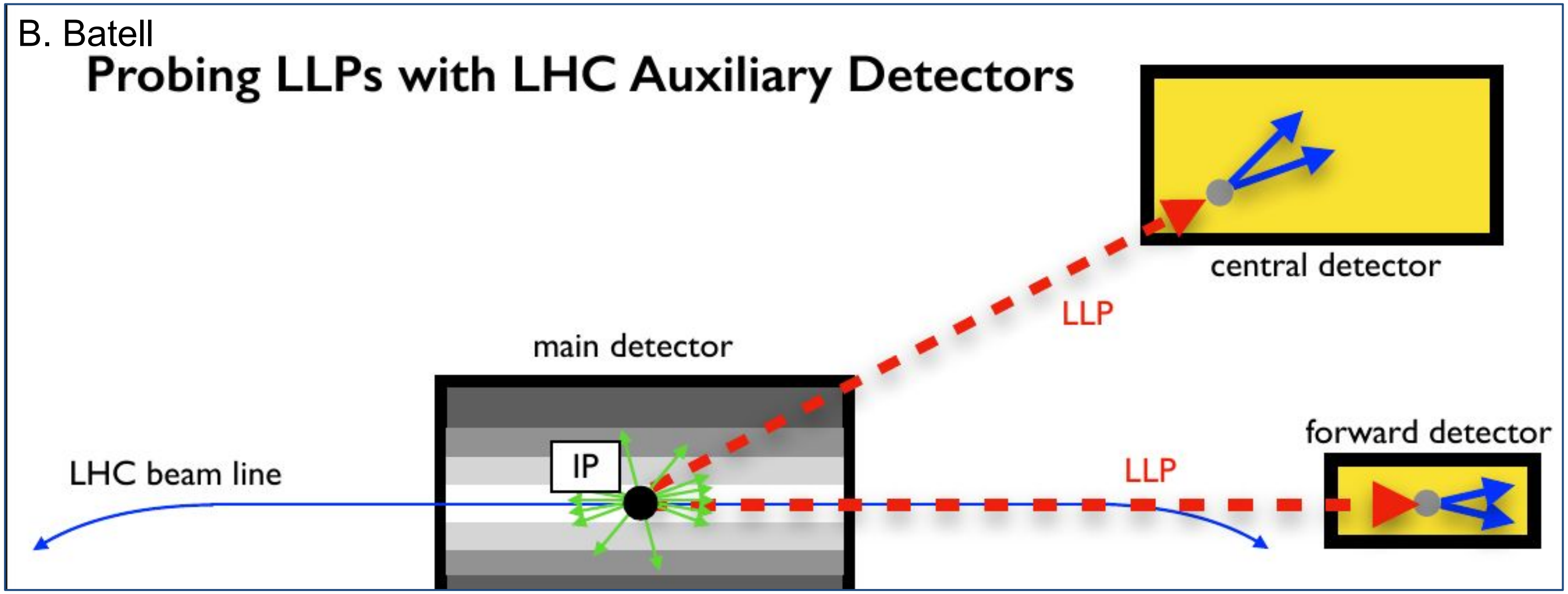


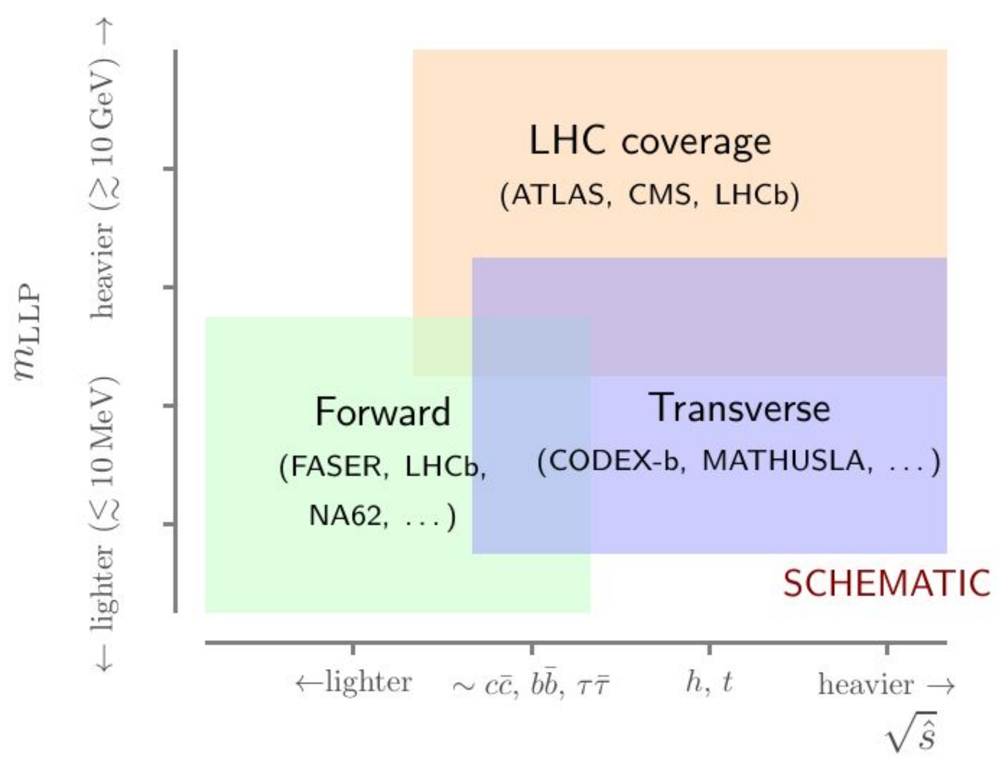
Hypothetical scenario:

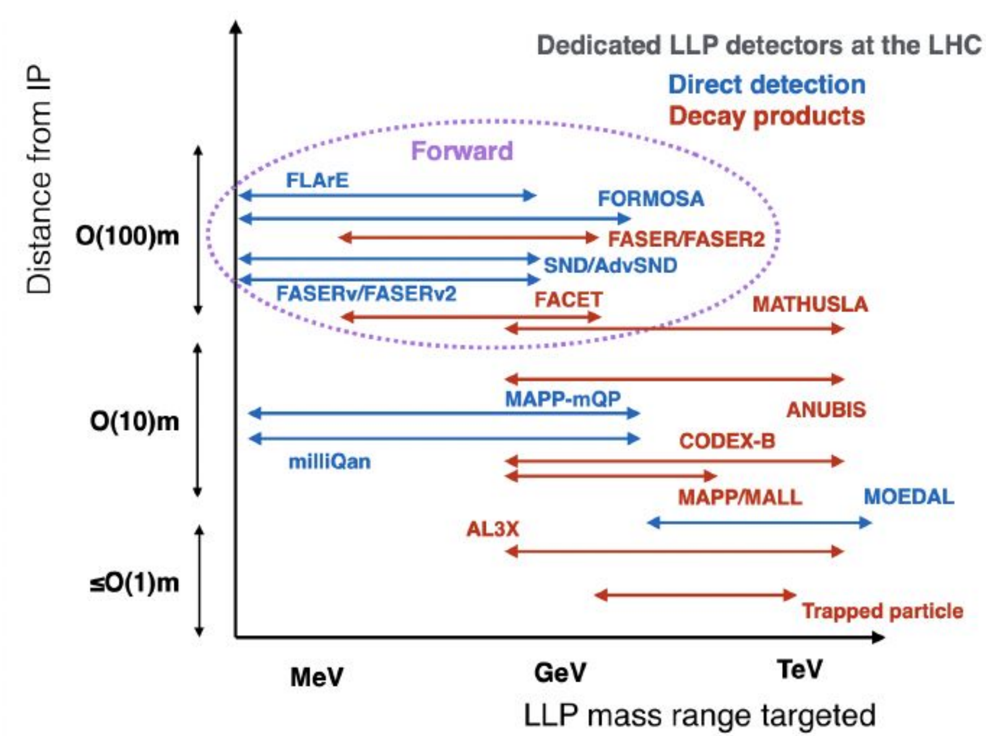
- Colored points: allowed parameter space after future precision measurements of H-bb (@1%) coupling.
- Solid lines: direct searches of an heavy Higgs

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

Auxiliary Experiments at the HL-LHC

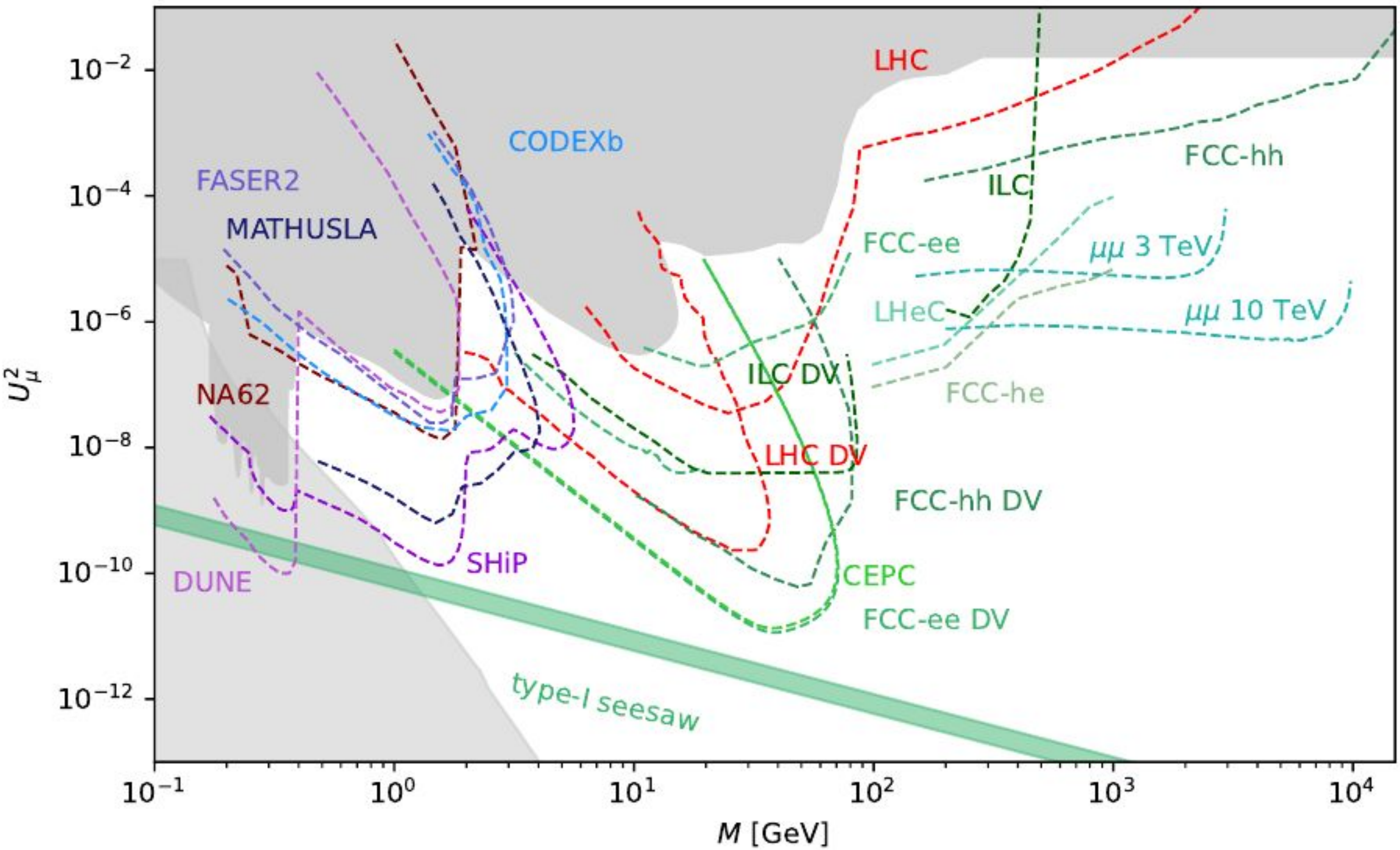




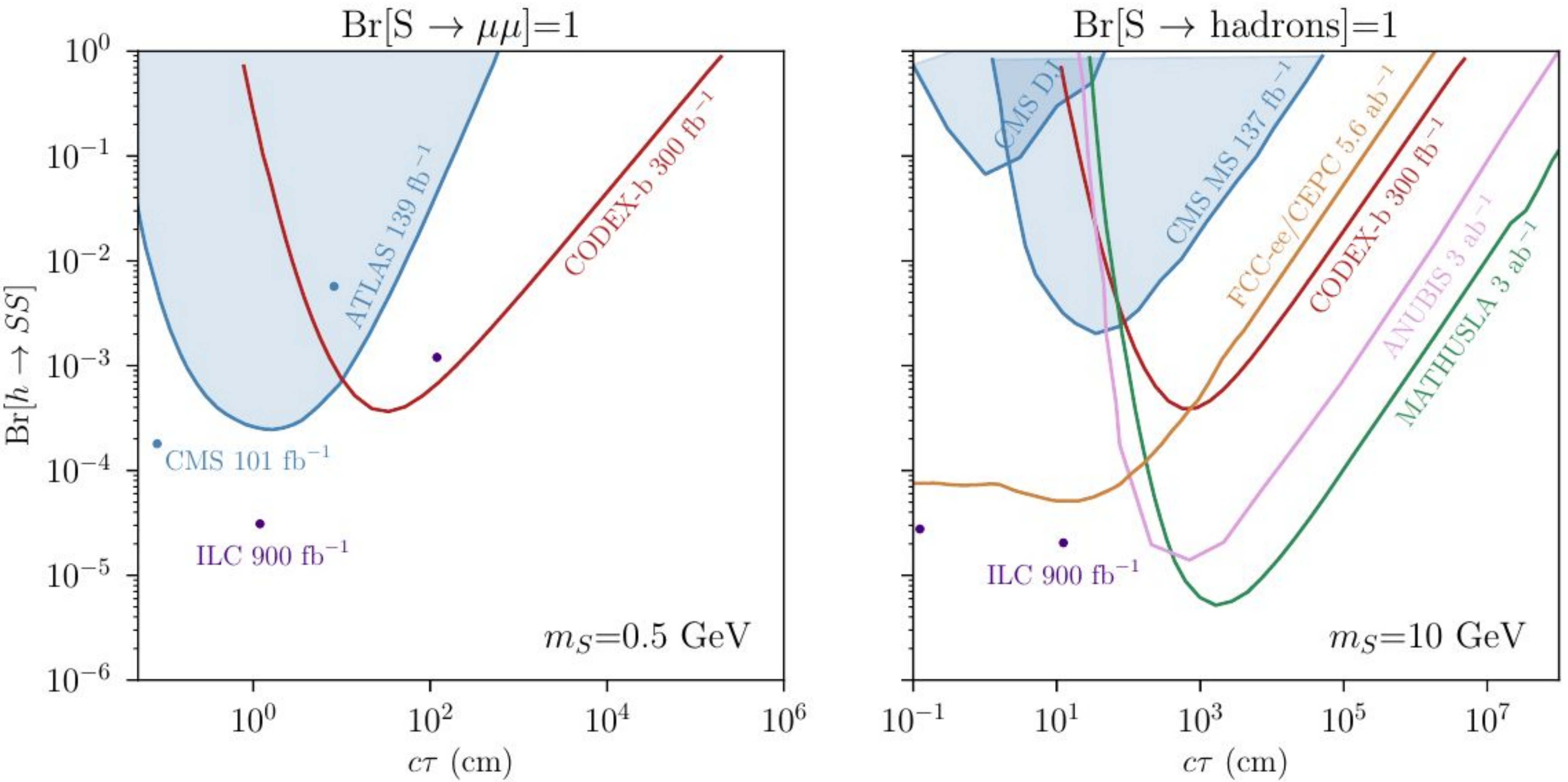


HL-LHC auxiliary experiments: Heavy Neutral Leptons

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.