«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
1963–2023
60th ANNIVERSARY OF ACTIVITIES

Particle Physics: where we are now, what may come next

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Outline

- Knowns and unknowns of the HEP landscape now
- What may be happening in our field in the next two decades

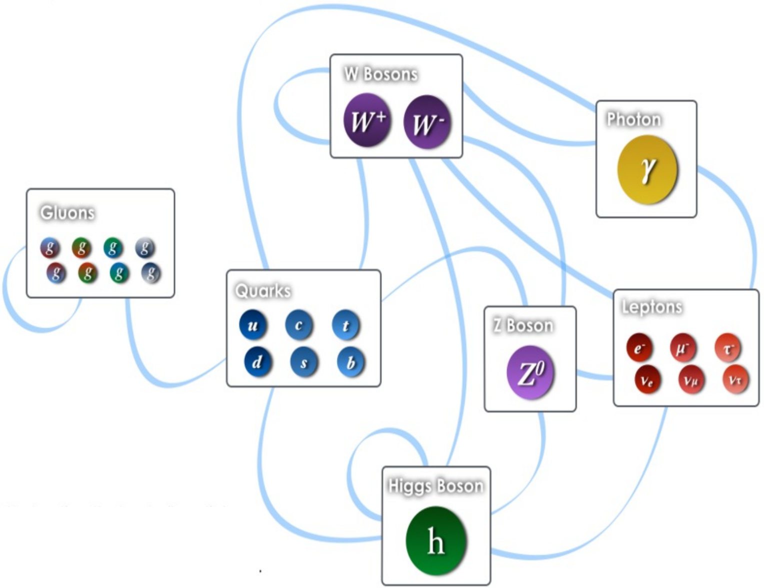
  - Opportunities to advance our understanding of the field -

Particle Physics: A Discovery Science

Its mission is to understand the most fundamental layers of reality and the laws by which its constituents interact

The Standard Model (SM) landscape:

- The SM describes the right degrees of freedom for quarks and leptons, and for the particles that carry the forces among them.
- It uncovers nature's most fundamental symmetries governing those interactions at high accuracy up to several TeV energies



- **Many particle physics topics are NOT described by the SM**
  - they were not meant to be - not even neutrino masses -

Consensus particle theorist's view of the road ahead: @LHC start in 2009

Consensus particle theorist's view of the road ahead: @LHC and elsewhere

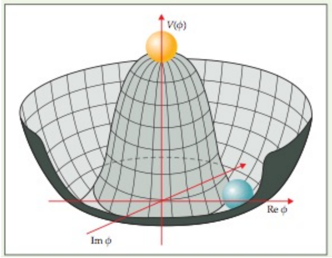
Mysteries of Particle Physics unanswered in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
- What is the history of the Electroweak Phase Transition?
- The reason for the Hierarchy in Fermion Masses and their Flavor Structure
- The Nature of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- What is the nature of Dark Energy?
- What are the quantum properties of Gravity and the quantum origins of Spacetime?
- What caused Cosmic Inflation after the Big Bang?

The SM is silent about all the above BUT,
The powerful global HEP experimental program already underway could provide decisive clues to help us decipher many of these mysteries in the next two decades

The Higgs Boson: The Idea of the Higgs Mechanism

What turned the Higgs field on? How did it happen?



$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

- The Higgs field potential describes the energetics of turning on the Higgs field to a certain (complex) value
- Because of the symmetry there are degenerate vacua
- Because of the infinite degrees of freedom in Quantum Field Theory, once one of the degenerate ground states is chosen it is hard to transition to another

Electroweak Symmetry Breaking (EWSB) $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

Apply condensed matter ideas to particle physics

Now the quantum vacuum is the "medium"

"The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention" **-- Peter Higgs, 1964**

The Brout-Englert-Higgs Mechanism and the Higgs Boson

- A scalar field with self-interactions causes Electroweak Symmetry Breaking in the vacuum and gives mass to the gauge bosons of the broken symmetry

- The Higgs boson also appears in the theory

The Mass Mechanism for quarks and leptons
(Weinberg and Salam)

- The symmetry of the theory gives different charges to nature's left- and right–handed fermions: they are chiral
  The SM is a $SU(2)_L \times U(1)_Y$ chiral gauge theory

- A massive fermion combines the left- and right-handed pieces but it is not possible to do it directly since they have different charges:

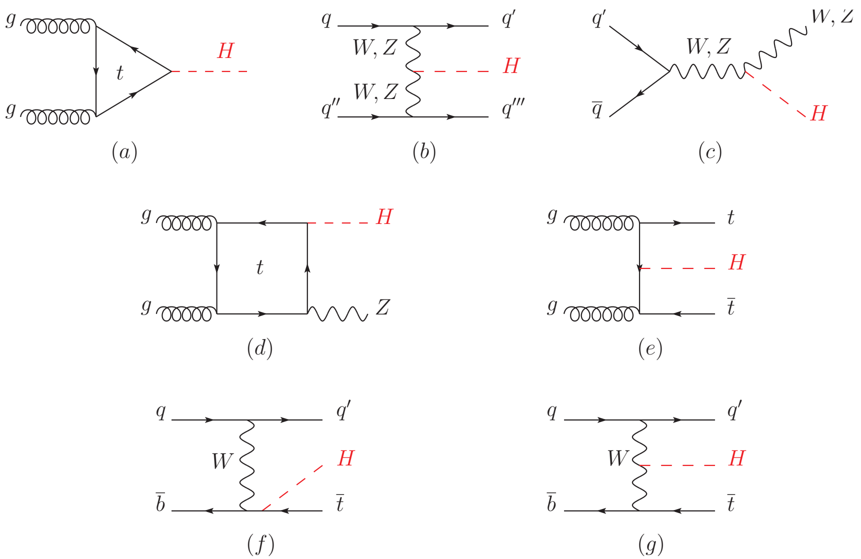
The fermionic Yukawa interaction $\mathcal{L}_{Yukawa} = -y_u(H\bar{u}_L u_R + H^\dagger \bar{u}_R u_L)$
allows the Higgs field to connect left- and right-handed fields and generates mass through EWSB

The Higgs boson at the LHC

The Higgs boson existence makes the SM by itself self consistent up to very high energies

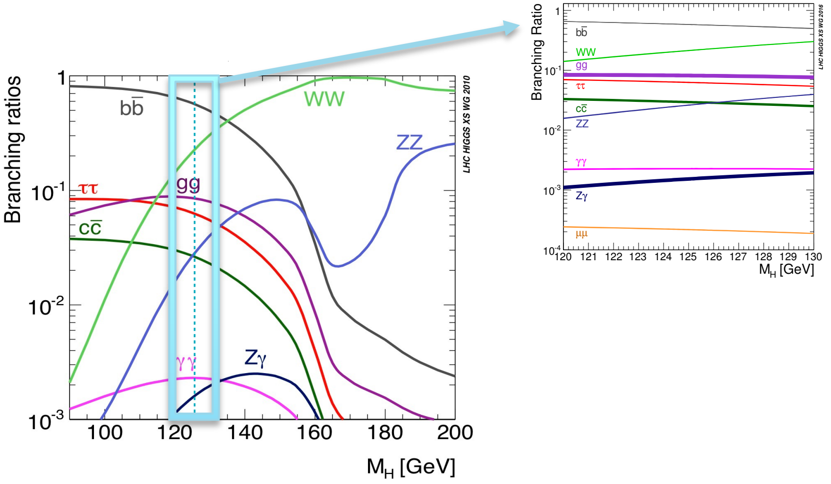
❖ With m_H = 125 GeV, its mass maximally allow us explore its interactions with SM particles

Higgs Production Channels and Decay Branching Ratios



MC, Grojean, Kado, Sharma

https://pdg.lbl.gov/2022/reviews/rpp2022-rev-higgs-boson.pdf



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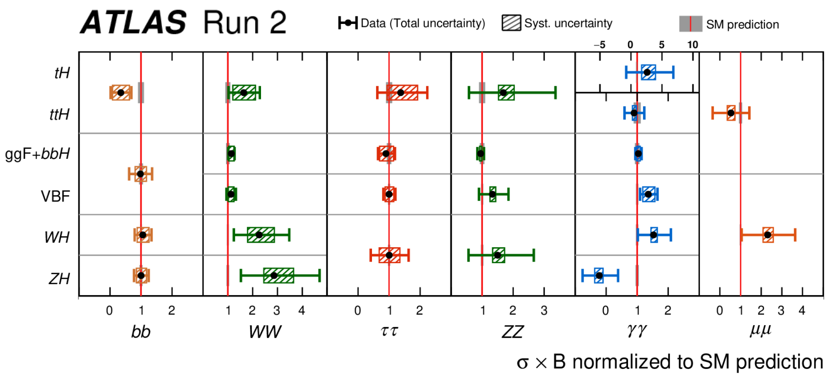
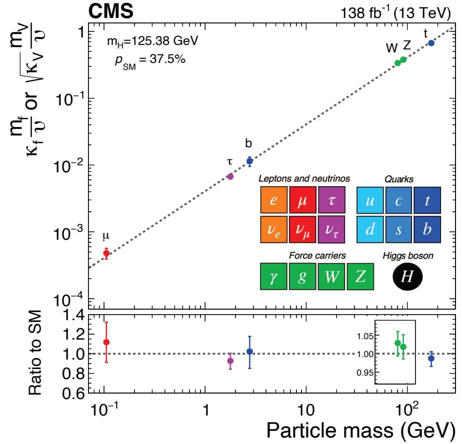
The Great Success of the Higgs boson at the LHC

- Its discovery and subsequent study of its properties at the LHC has provided *a first portrait* of the electroweak symmetry breaking mechanism

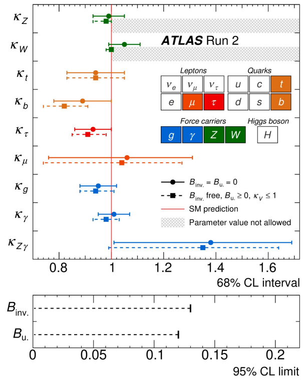


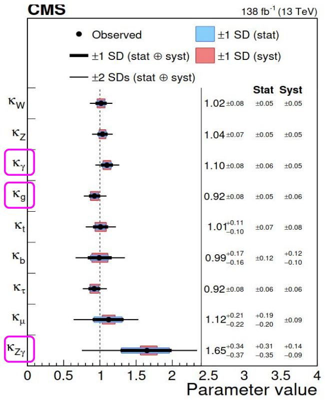
The LHC favors a SM-like Higgs boson

Correlations between masses and couplings consistent with SM



$$g_{hf\bar{f}} = \frac{m_f}{v}, \qquad g_{hVV} = \frac{m_V^2}{v}$$





Departures from SM predictions of the order of several to few tens of percent allowed at this point

$$\kappa_i = \frac{g_{hii}}{g_{hin}^{SM}}$$

Nature 607, no.7917, (2022); [arXiv:2207.00092]; [arXiv:2207.00043]

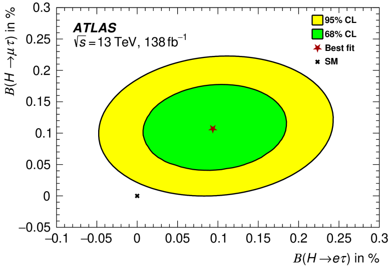
Starting to get info on the 2nd gen. couplings

The Great Success of the Higgs boson at the LHC

Explor: Do all fermions get their masses from the same Higgs field? What about lighter fermion couplings? Do Higgs couplings conserve flavor/CP?

Possible flavor violation in Higgs decays (?)

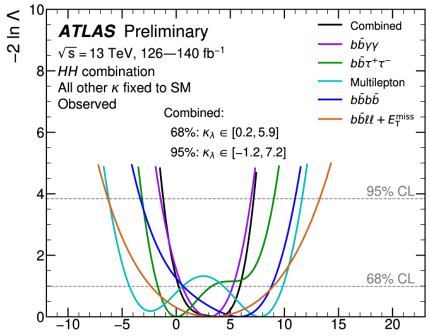
Departures from flavor conserving couplings can be correlated with effects in flavor violating couplings



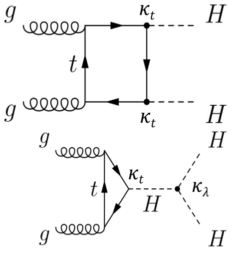
No hint from CMS, though:

$$BR(H \to \tau\mu, e) < 0.15\%$$

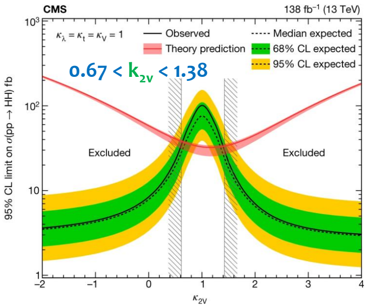
Di-Higgs production being probed at LHC

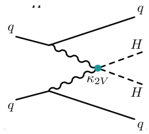


ATLAS-CONF-2024-006

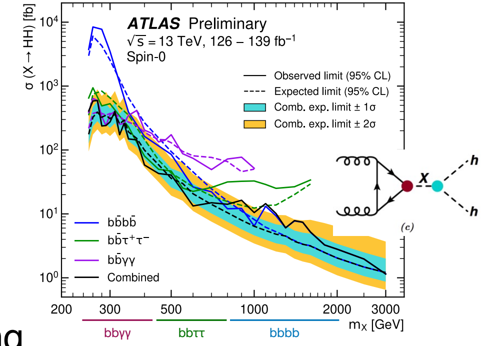


+ higher order EFT operators





$k_{2V} \neq 0$
Existence of VVHH coupling

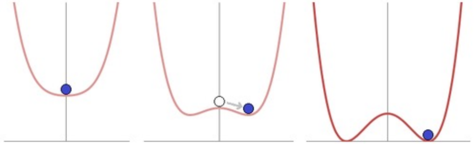


The Higgs sector open questions

❖ In the SM, the Higgs potential is fixed by hand to give EWSB

There is no explanation for how the Higgs mass parameter and self-coupling are determined

$$\mathbf{V(H) = -m^2|H|^2 + \lambda|H|^4}$$



- What is behind the EWSB mechanism?

  Radiative Breaking (like in Supersymmetry) or Compositeness

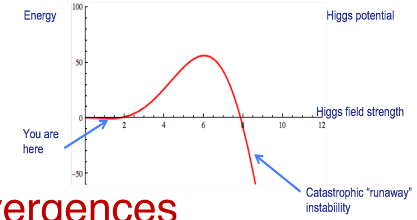
- What was the history of the electroweak phase transition?

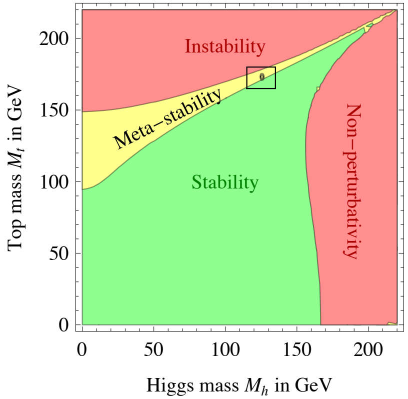
  We need to understand its dynamics

- The SM Higgs potential is unstable

  – catastrophic runaway at some point

- Scalar's masses are associated with quadratic divergences

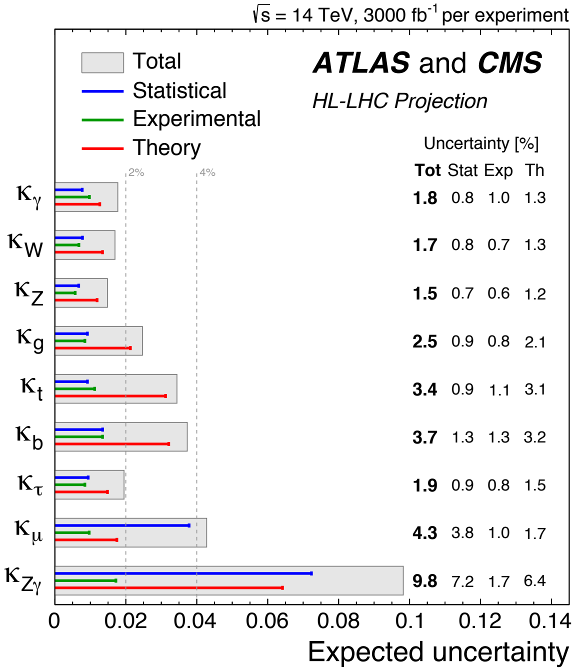




❖ The Higgs field can give mass to all known matter particles, but calls for an explanation of the mass hierarchies

❖ It hints at but does not explain Baryogenesis, Dark Matter/Sector portals, and possibly Inflation

Precision Higgs measurements at the HL-LHC: (circa 2040)



With 30 times more data at slightly higher energies

A powerful tool to explore new physics needed to explain many particle physics topics

This could include other Higgs bosons, new particles, new forces, and connections with invisible sectors

HL-LHC (3 ab^{-1} @ 14TeV):

Expected ~ 2-4% precision for most Higgs couplings

Higgs self-coupling only at 50% accuracy

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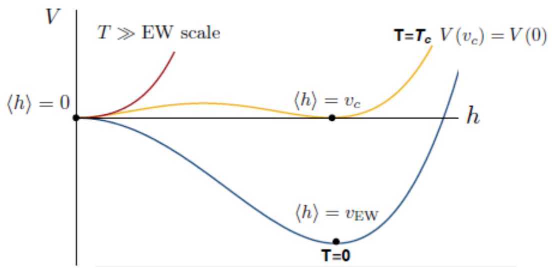
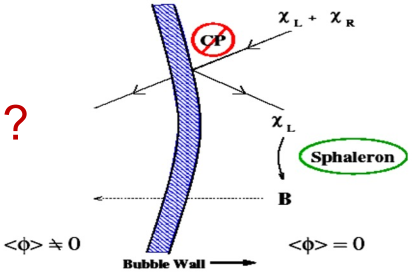
More scalars beyond the Higgs boson, motivated by many puzzles

- Can play a role in the dynamics of the Higgs potential – hence EWSB -
- Can help stabilize the SM Higgs potential
- Can be portals for Dark Matter
- Can play a role in generating light fermion masses



- Provide a strong first order EW phase transition
- Provide new sources of CP violation

} Electroweak Baryogenesis ?



- Additional scalars, although associated to quadratic divergences - as the Higgs itself- can also connect with quartic divergences and explanations of Dark Energy and Inflation

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CP violation: questions and opportunities

❖ The SM is build based on symmetries **$SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ ➔ $SU(3)_c$ x $U(1)_{em}$**

What about CP Symmetry?

- In the weak sector, direct CP violation is naturally built in the quark mixing matrix and observed in K, D and B meson decays

CPV in the quark sector is not sufficient to explain baryogenesis
CPV can be present in the lepton sector, to be proved at DUNE and may be elsewhere, can help explain leptogenesis

- In strong interactions, there is no signal of CP violation, BUT there is no reason to impose this symmetry in QCD

Strong CP Problem: the experimental upper limit on the neutron EDM implies that Θ_{QCD} should be extremely small, why?

Postulate a pseudoscalar light particle- QCD Axion, also a good DM candidate

Symmetries and Neutrinos:

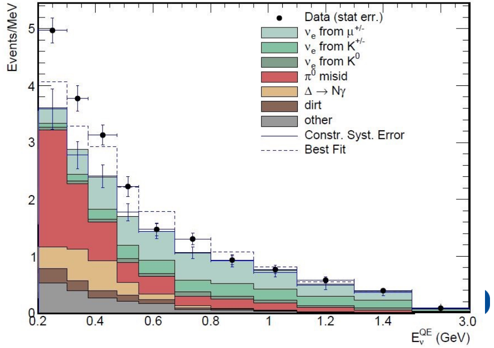
❖ The SM is build based on symmetries: What if the gauge symmetries and the fermion content get unified? One could expect:

- Gauge coupling unification modulo effects from heavier stuff
- Proton decay
- 3-Neutrino see-saw mass generation with possibility of leptogenesis

❖ Neutrinos are also suggesting opportunities beyond their mass generation:

- Neutrinos, being weakly interacting neutral fermions, can mix with steriles with many possible origins, e.g., the dark matter
- Possible exotic properties of neutrinos less constrained than other SM particles
- Can provide a window to new physics at very high energies

In fact, there are currently several puzzling neutrinos anomalies, in particular the MiniBooNE low energy excess, following on LSND results -

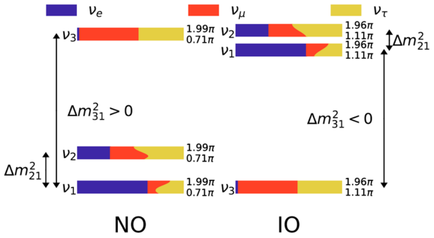


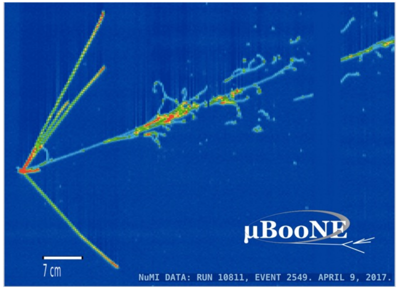
Neutrinos at many energy scales

- The origin of the tiny neutrino masses and of neutrino mixings is great mystery
- The dominant paradigm for explaining neutrino masses requires the existence of new heavy electroweak singlet leptons

But the energy scale of these heavy neutral leptons is not specified

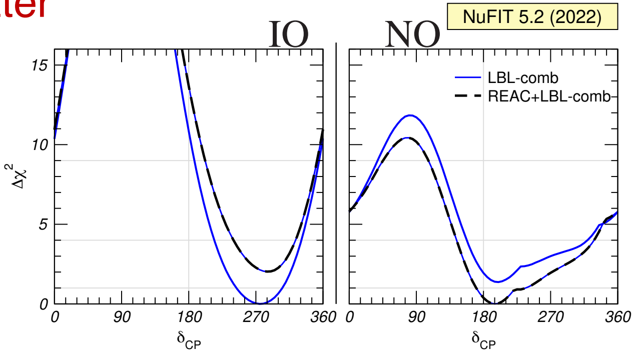
- Heavy neutral leptons more generally could be connected to other mysteries, e.g. can be portals to the dark sector
- Neutrino CP violation could be the origin of the matter antimatter asymmetry; Low-scale leptogenesis is a viable possibility





T2K and NoVa working towards the question of CP-violation, entangled with the question of mass ordering.

in NO: b.f δCP ~ 195◦ ⇒ CPC allowed at 0.6 σ
in IO: b.f δCP ~ 270◦ ⇒ CPC disfavored at 3 σ



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Lepton flavor opportunities

In the quark sector no compelling evidence for flavor effects beyond CKM

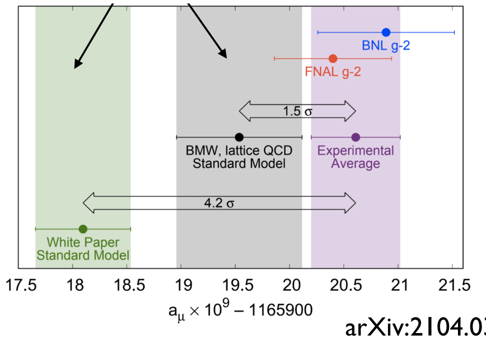
What about LFV in the charged lepton sector?

Could be new particles that couple differently to electrons/muons/taus

- new gauge bosons, new scalars, leptoquarks - new type of particles appearing in extended symmetries of nature- or squarks in special types of supersymmetry

Have we already seen such effects?

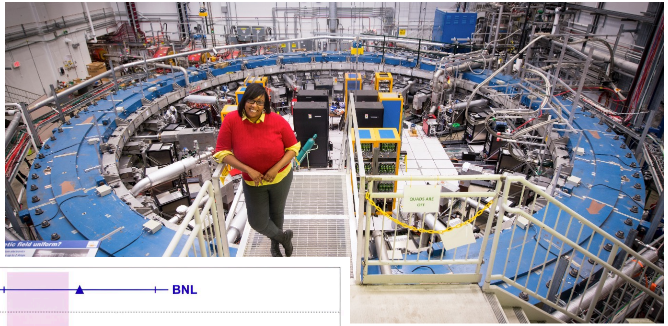
- The muon g-2 anomaly :

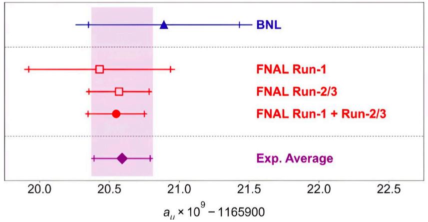


arXiv:2104.03281

4.2 (5.1) standard deviation from SM expectation

Lattice theory calculations under scrutiny





arXiv:2308.06320

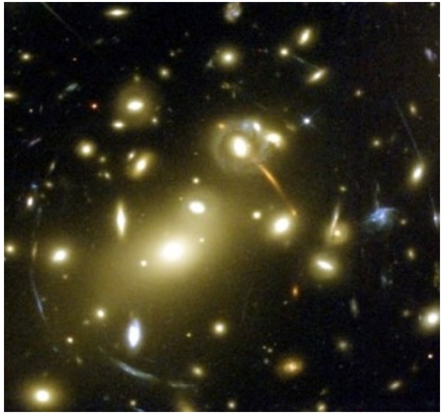
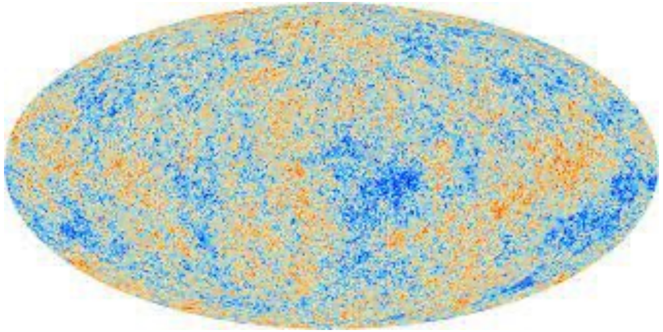
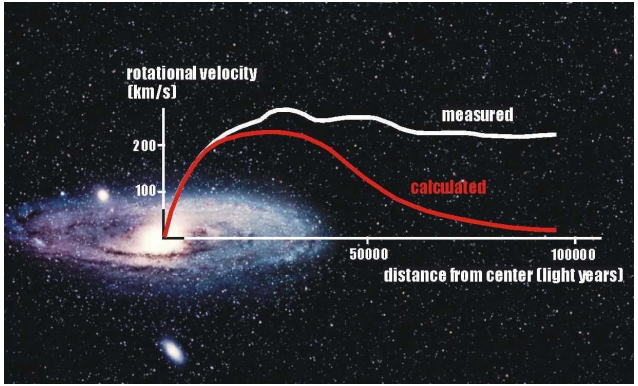
Mu2e Fermilab experiment will provide a huge jump in sensitivity to some possible effects

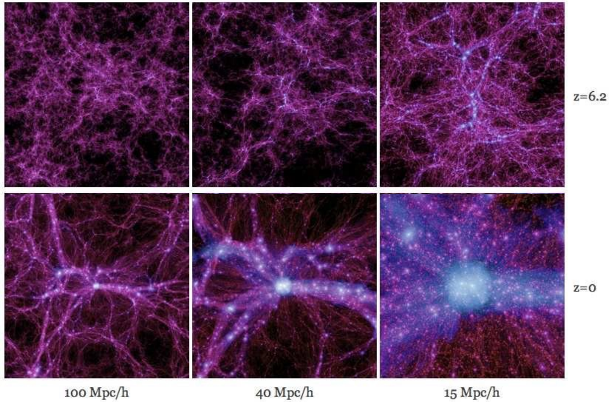
What do we know about Dark Matter ?

- very little -

- Couples gravitationally
- It is the most abundant form of matter

We have evidence from many scales at many times

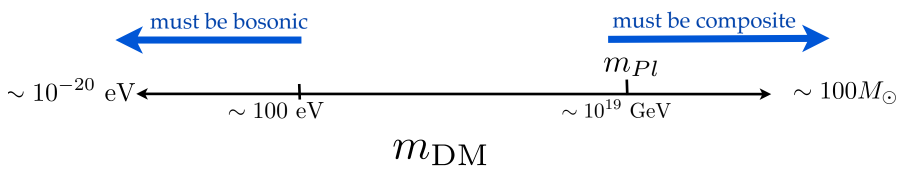




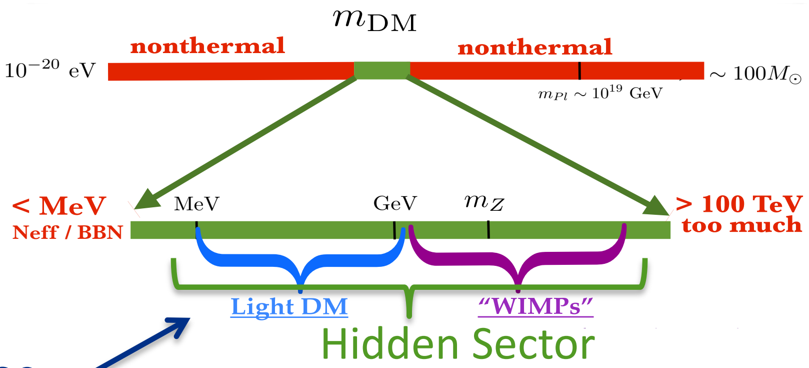


What do we know about Dark Matter ?

- very little -

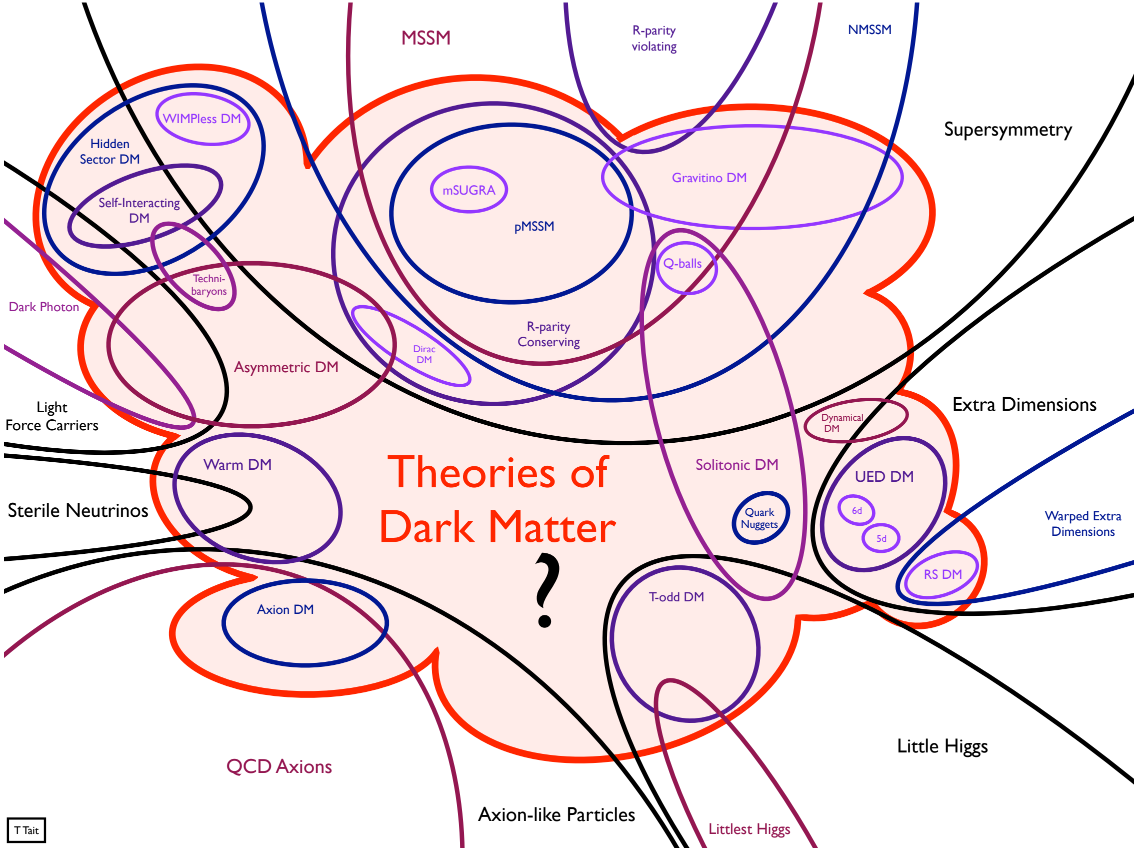
- Couples gravitationally
- It is the most abundant form of matter
- It can be part of a larger invisible/dark sector with new dark forces
- It must be made of something different that all the particles we know, it can be made of particles or compact objects, or better described as wavelike disturbances
- Its mass can be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses





Folding in assumptions about early Universe cosmology can provide some guidance

Beyond the SM theories with DM Candidates

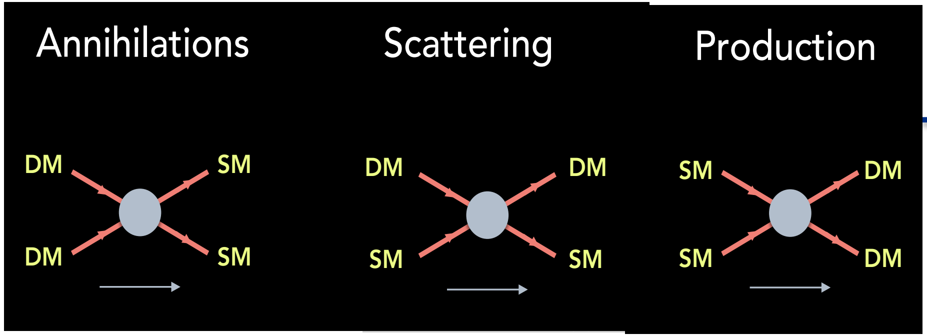


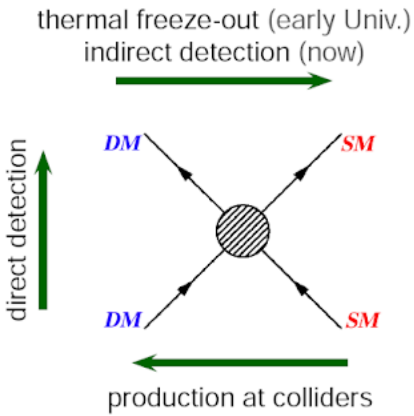
Some of them embedded in theories proposed to solve other problems

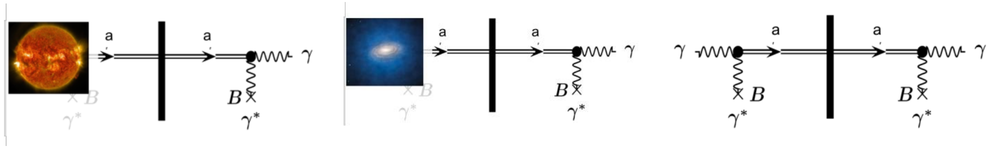
Entering a new era in the search for Dark Matter:

through important advancements in cosmological, astrophysical and terrestrial probes

Small-Scale Structure needs to be better understood







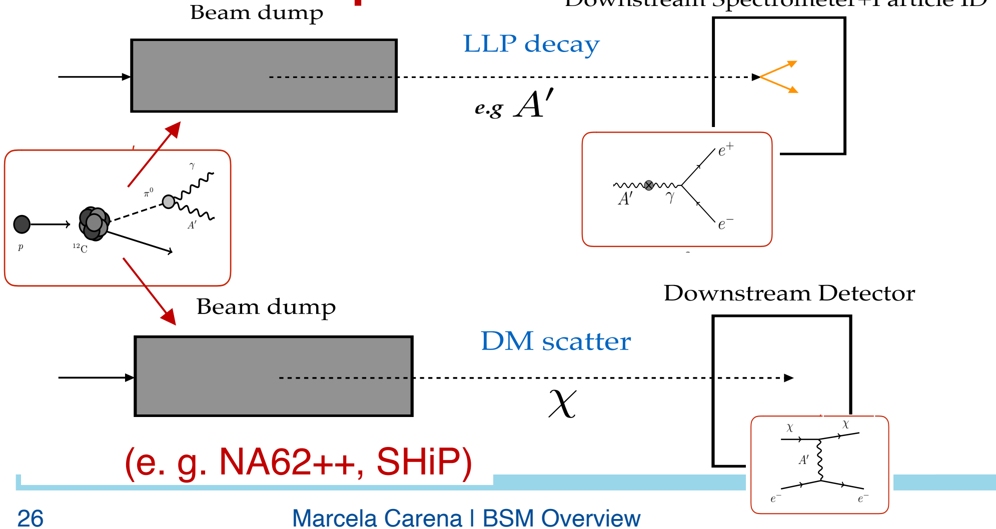
Axions from the Sun, the galactic Halo or created at the lab, can resonantly convert to a detectable photon

Entering a new era in exploring the Dark Sector:

Portals can be the Higgs itself or Feeble Interacting Particles (FIPs):
Dark photon, Dark Higgs, Heavy Neutral Leptons, Axion-like particles, Millicharged particles

Accelerator based searches for MeV-GeV dark matter with lepton or proton beams

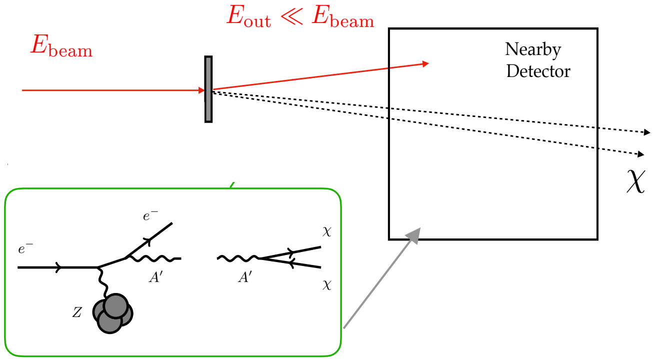
Beam dump



(e. g. NA62++, SHiP)

Fixed target: Missing Energy/Momentum

The electron or muon beam is the signal



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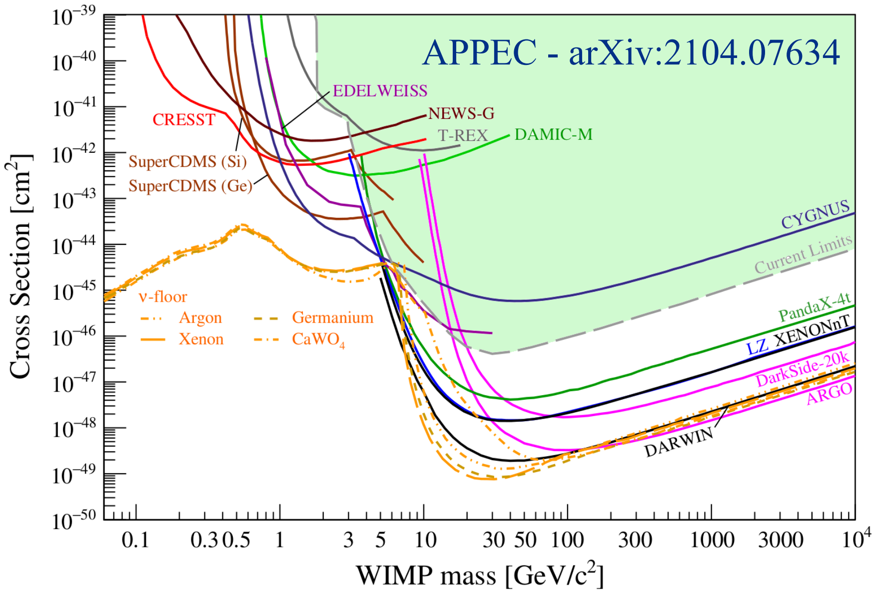
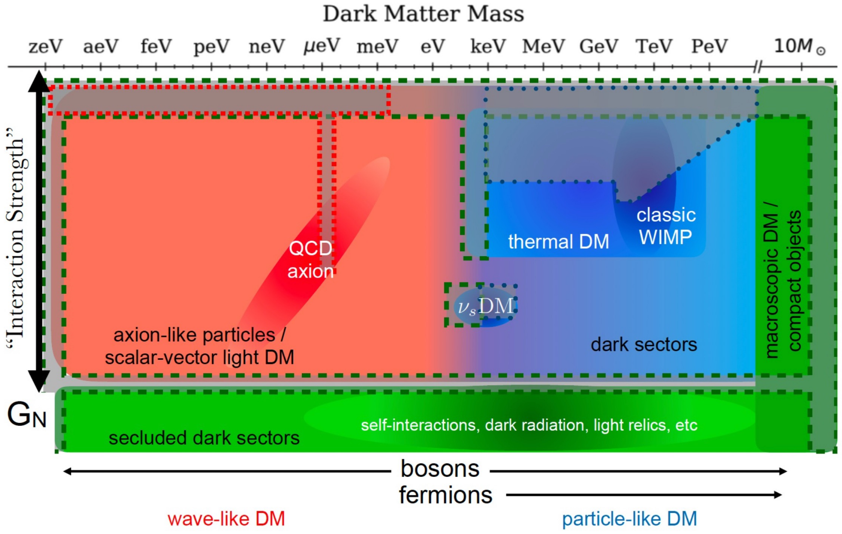
WIMP Direct Detection Searches



neutrino floor:" both ν-N and ν-e backgrounds

Marching down to the Neutrino Floor

Need a broad program for discovery and characterization of the dark sector, and to understand how it connects to the other unknowns of HEP

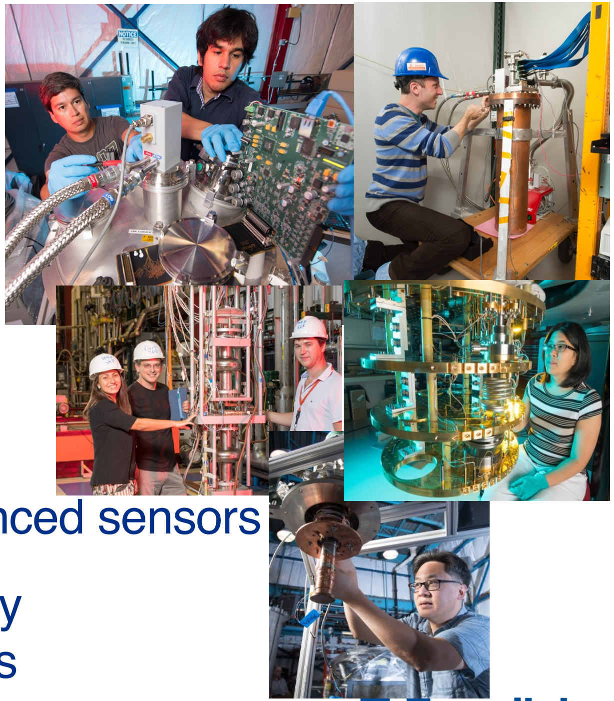


Snowmass Cosmic Frontier Report, arXiv:2211.09978

Many model specific searches of DM production at accelerator base exp. (LHC/beam dump/etc)

Dark Matter Outlook

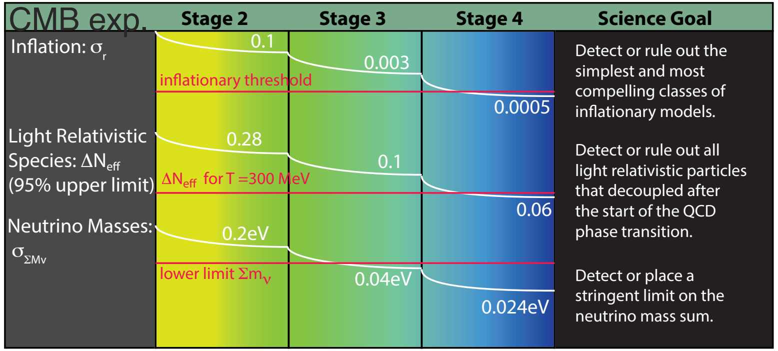
- Challenging experimental program since we are trying to detect particles in a mass range that spans 90 orders of magnitude; we don’t know how they interact - other than gravitationally - and we don’t know how many kinds there are or whether they are accompanied by other dark sector particles
- The current dark matter program is just scratching the surface of the much broader program that we may need
- If we are lucky and get direct detection or accelerator production of dark matter, we will want to move aggressively to experiments for further characterization of the dark sector
- In all scenarios we will need to develop much more advanced sensors
- Next generation lab experiments can be complemented by new/better results from telescopes or space-based probes

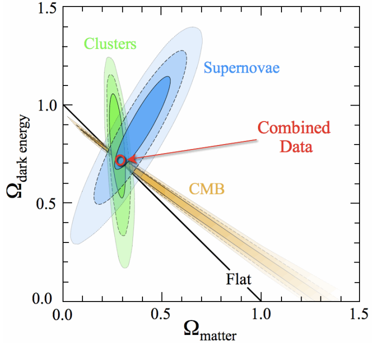


Cosmological probes

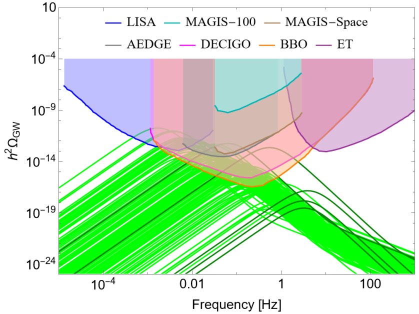
- CMB observations provide the most direct access to inflation, and inform us about neutrino mass, N_{eff} (light relics), dark energy and the Hubble constant
- Cosmic surveys study dark energy/modify gravity, dark matter (gravitational and non-gravitational interactions), neutrinos and inflation through various probes of the geometry, expansion history and structure of the universe. They also tell us where to look for indirect dark matter signals
- Gravity Waves are a probe of phase transitions (e.g inflationary and electroweak) and dark matter

Snowmass Cosmic Frontier arXiv:2203.07638





GW from PT form dark CPV for EWBG



M.C., Y.Y Li, Ou and Wang, JHEP 02 (2023) 139

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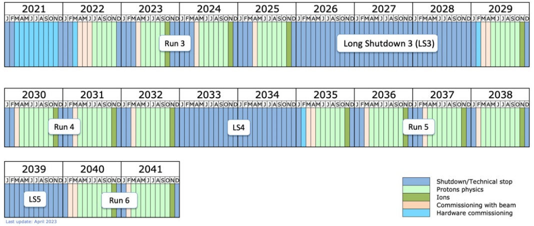
HEP: what may be happing through the next 2 decades

Higgs/EWSB landscape in the light of HL-LHC



It will have been running with upgraded detectors
-- there are proposals to add new detectors --

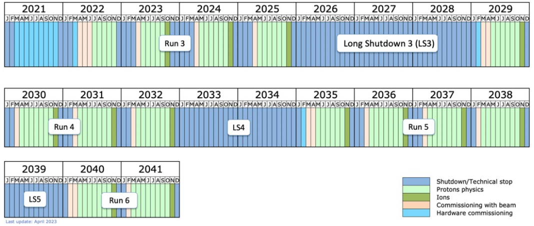
Many discoveries or “evidence for” possible by the time of the mature HL-LHC dataset

- Higgs cousins of many types with many possible implications
- Higgs portal/s to the dark sector
- Feebly-interacting particles, long-lived particles, MET signatures
- New heavy fermions, heavy gauge bosons, superpartners
- Evidence that Higgs boson is composite
- Higgs flavor violation, Higgs flavor anomalies, Higgs CP violation
- And more

The items on the discovery list are all very challenging,
so no surprise that they have not been discovered yet

Fermilab

Higgs/EWSB landscape in the light of HL-LHC



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Future Colliders : CEPC? ILC, CLIC ? FCCee, FCChh ? Muon Collider ?
They will mostly probe new physics indirectly

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Neutrinos, Charged Lepton and Quark Flavor

A powerful global program with potential for many surprises

- SBN results will make a definite statement about the MiniBooNE anomaly and its possible BSM interpretations – a variety of discoveries possible
- Mass ordering may be known at 5 sigma from global fits including NOvA, T2K, KM3NeT, JUNO, but only if no tension in the combined data; CP violation will still be uncertain
- DUNE, HyperK, and other neutrino expt. mature results, could discover CP violation, anomalies in oscillation physics, light and boosted dark matter, heavy neutral leptons, ...
- Muon g-2 unambiguous endgame:
  - The experimental value already is in solid grounds and will be even more precise; J-PARC muon g-2/EDM experiment will have an independent measurement
  - The theory prediction will not be in doubt
  - if confirmed, it will require new particles and/or forces
  - Other experiments, e.g. LHC, beam dump (NA62, run1 of SHIP), and missing momentum exp., Belle2, CMB-S4, will narrow the posibilities

Neutrinos, Charged Lepton and Quark Flavor

A powerful global program with potential for many surprises

Mu2e will be running and could have an emerging discovery of lepton flavor violation

Muon or electron EDMs may yield surprises...

Mature B physics results from BELLE II, LHCb, ATLAS/CMS, etc: discoveries and/or anomalies?

Lattice and perturbative QCD accuracy at the sub-percent level for all SM predictions

Dark Sector and Cosmic

- G2 and G3 direct dark matter searches will be done, could have discovered one or more kinds of DM particles
- A full and varied slate of dark matter new initiatives for light DM completed: any discovery?
- Fixed target accelerator-based experiments completed: did we discover anything?
- Confirmed indirect DM signals?
- Rubin/LSST will be completed, CMB-S4 completed (Chile site only?) or nearly so, next-generation spectroscopic survey will be in operation ➔ could yield discoveries/evidence for
  - Primordial B-modes; energy scale and other features of cosmic inflation
  - Dark energy is dynamical
  - Dark matter properties (e.g. self-interaction)
  - Source of the current Hubble tension
  - Neutrino masses
  - Better measurement of N_{eff}

In every discovery scenario we will need new collider experiments to fill out the whole story!

Some observations

- The ongoing broad HEP program, centered on elucidating fundamental mysteries of our universe and profiting from the rapid technology advancements to explore revolutionary ideas, will provide an exciting scientific environment in 2045 - at the dawn of the FCC-ee era.
- The HEP program should include new directions that expand the intellectual boundaries, both to maximize discoveries and make the science connections we will need to make sense out of discoveries
- With so much discovery potential in the coming decade, we should be planning for success, being ambitious, but realistic about timescales,
- An exciting field with multiple Noble Prize worthy discoveries can provide the momentum to launch new initiatives

Extra: FCC-ee Opportunities for BSM physics

FCC-ee Unique Opportunities for Precision and **Exploration**

ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \to H_{125}$]

TeraZ will provide
~10^{12} b pairs and 1.7 10^{11} τ pairs

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Higgs Measurements: an exploration tool at FCC-ee

- LHC and future HL-LHC measurements will confirm SM expectations at the 2-4 % level for couplings to gauge bosons, 3rd gen. fermions plus 2nd gen. charged leptons
- FCC-ee programme:

-- can measure Higgs production inclusively as a recoil in e+e-→ HZ, yielding an absolute measurement of the HZZ coupling and a model independent extraction of Γ_H

Coupling	HL-LHC	linear colliders (250 or 380 GeV)	circular colliders (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.73	0.43 / 0.33
κ_Z[%]	1.3*	0.29	0.17 / 0.14
κ_g[%]	2*	1.4	0.90 / 0.77
κ_γ [%]	1.6*	1.4	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10	10 / 10
κ_c [%]	–	2.0	1.3 / 1.1
κ_t [%]	3.2*	3.1	3.1 / 3.1
κ_b [%]	2.5*	1.1	0.64 / 0.56
κ_μ [%]	4.4*	4.2	3.9 / 3.7
κ_τ [%]	1.6*	1.1	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.26	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.8	1.0 / 0.88

With σ_{HZ} and Γ_H known, FCC-ee programme aims at measuring Higgs couplings (in non-rare decays) at percent to sub-percent level

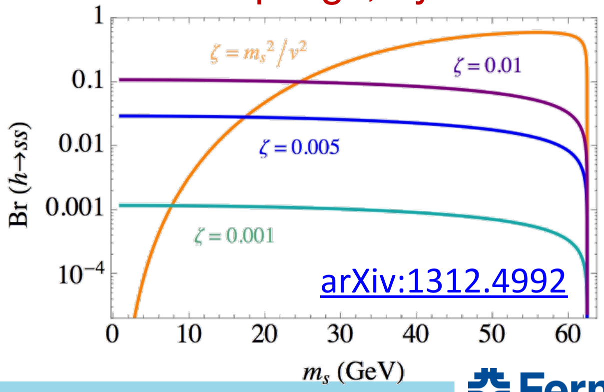
Higgs rare/exotic decays bounded below the 1% level

This assumes no-flavor violation couplings, but flavor violating channels should be explored

Higgs Exotic Decays

- Outstanding discovery opportunity for light new particles that may be directly tied to mysteries in particle physics intimately connected to the Higgs sector
  - EW symmetry breaking process and its thermal history [enabling EW Baryogenesis]
  - Stability of the EW scale relative to the Planck scale, dynamics of EWSB
  - Portals to Dark Sectors or Dark Matter candidates
  - Strong CP-problem and light axion-like particles
- Also, Higgs properties are propitious to enable Higgs rare decays
  - All its SM decays are accidentally suppressed by small Yukawa couplings, by multibody phase space, or by loop factors.
  - As a result, its decay width is tiny ➔ $\Gamma_H \sim 4$ MeV
  - small couplings to BSM could have sizable BRs

$$L = \frac{\zeta}{2} s^2 |H|^2$$



can give BR(h→ss) ~ O(10%) for ζ *as small as* 0.01 !

Examples Scenarios for Higgs Exotic Decays

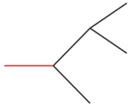
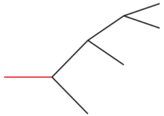
Higgs portals to new physics with suppressed SM couplings/ dark sector mediators

Portals	Couplings
Scalar (dark Higgs)	$(\kappa \mathbf{S} + \lambda_{\mathbf{SH}} \mathbf{S^2}) \lvert \mathbf{H} \rvert^2$
Fermion (sterile neutrino; SUSY neutralino)	$\mathbf{y_N N H L}; \quad \frac{\kappa}{\mathbf{M}} (\mathbf{NN} + \mathbf{N^\dagger N^\dagger}) \lvert \mathbf{H} \rvert^2$
Vector (dark Z, dark photon)	$\frac{\epsilon}{\mathbf{2} \cos \theta_{\mathbf{W}}} \mathbf{B}_{\mu\nu} \mathbf{Z}_{\mathbf{D}}^{\mu\nu}$ (Higgs exotic decay through Z-Z_D mixing)
pseudoscalar (axion-like particles)	$\frac{c_{ah}}{f^2} (\partial_\mu a)(\partial^\mu a) H^\dagger H + \frac{c_{Zh}}{f^3} (\partial^\mu a)\left(H^\dagger iD_\mu H + \text{h.c.}\right) H^\dagger H$

- One can also have some combinations of the above, e.g in 2HDM's or SUSY + scalars
- Beyond considering new particles with prompt decays also studies for long-lived new particles (displaced or invisible decays) are to be explored

Higgs Exotic Decays: a rich variety of possibilities

- Focus on 2-body Higgs decays to BSM particles with subsequent decays to BSM or SM particles
- These processes are well-motivated by SM + Scalar singlets, 2HDMs (+ Scalar), SUSY models, gauge SM extensions (e.g. dark photons), SM + Fermion/s (e.g. Heavy Neutral leptons), etc.

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
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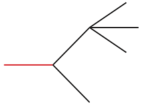
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
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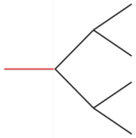	$h \to (b\bar{b})(\tau^+\tau^-)$
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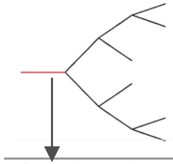	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
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	$h \to (\gamma\gamma)(\gamma\gamma)$
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$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
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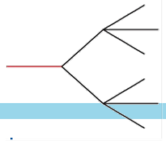	$h \to \ell^+\ell^- + \not{E}_T + X$

Z. Liu et al. arXiv:1312.4992 ; arXiv:1612.09284

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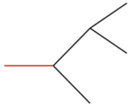	$h \to (b\bar{b}) + \not{E}_T$
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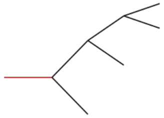	$h \to (jj) + \not{E}_T$
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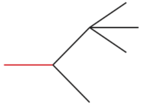	$h \to jj + \not{E}_T$
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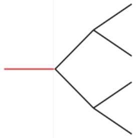	$h \to (b\bar{b})(\tau^+\tau^-)$
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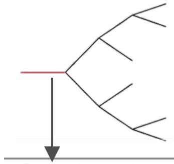	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
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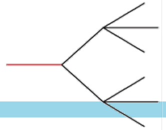	$h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

Z. Liu et al. arXiv:1312.4992 ; arXiv:1612.09284

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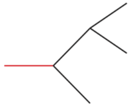
$h \to 2 \to 3$ 	$h \to \gamma + \not\!\!E_T$
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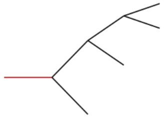
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not\!\!E_T$
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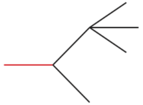
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not\!\!E_T$
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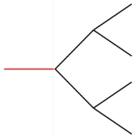
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
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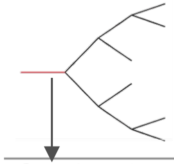	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
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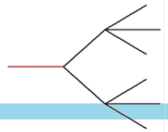
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not\!\!E_T$
	$h \to \ell^+\ell^- + \not\!\!E_T + X$

LHC's strength

HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

All the rest: challenging at the LHC due to missing energy and/or hadronic background

(HL-)LHC will provide valuable first-hand information on these challenging channels

FCC-ee will have great opportunities to cover these searches

Z. Liu et al. arXiv:1312.4992 ; arXiv:1612.09284

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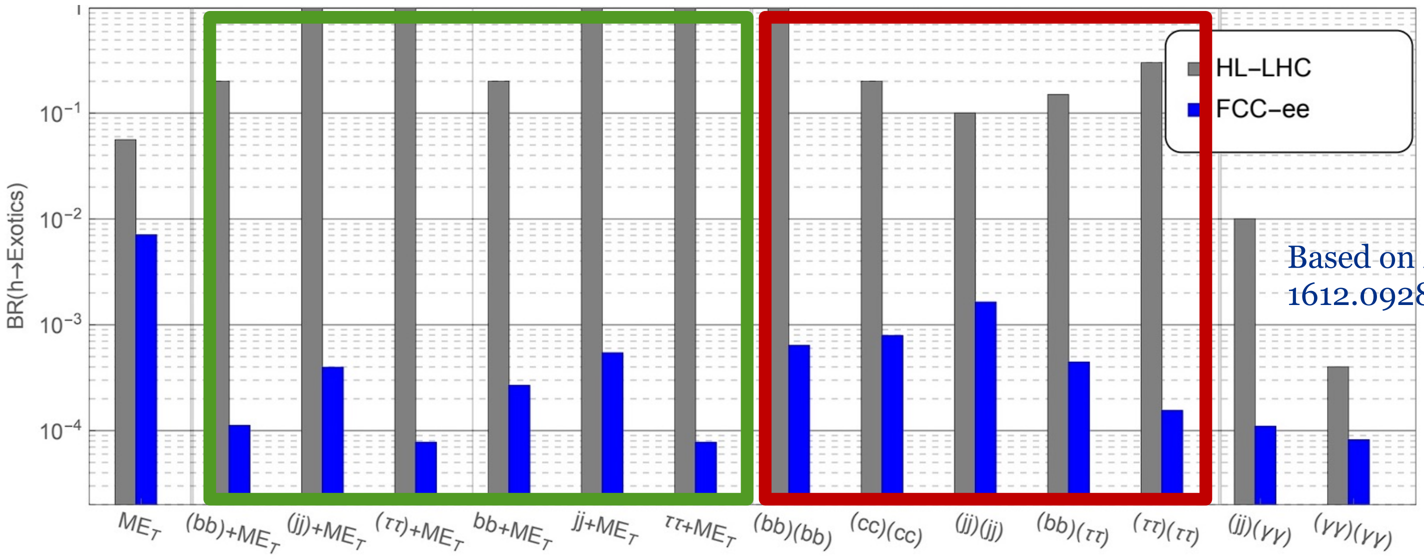
HL-LHC and FCC-ee coverage in selected Higgs Exotic Decay BRs

95% C.L. upper limit limit on BR(H → exotics)



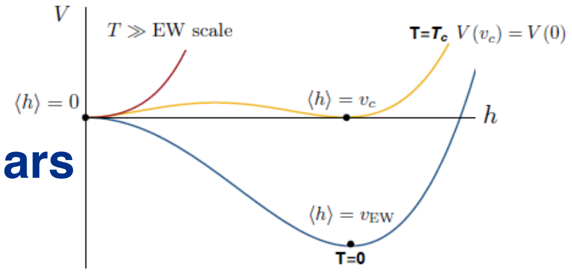
Based on Zhang, Liu, Wang, 1612.09284, with updates

HL-LHC: from various studies and projections available in the literature
FCC—ee are from arXiv:1612.09284 and $ee \to ZH$ (except for the first channel, $h \to inv$)

Missing E_T , e.g. in SUSY/DM models yields about 2-4 orders of magnitude improvement
H → 4 f, e.g. in extended Higgs sectors and/or Higgs portals yields about 2-3 orders of magnitude improvement

Higgs-Scalar Portal and the EW Phase Transition (EWPT):

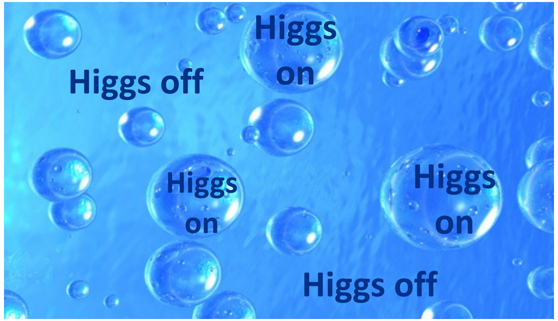
- A strong first order EWPT necessary for EW Baryogenesis → $\mathbf{v(T_c)/T_c \geq 1}$
- The SM Higgs sector is not enough (Higgs boson is too heavy)



Electroweak Baryogenesis needs New Physics/New Scalars

- **Simplest extensions involve singlet scalars**

To enable a strong first-order EWPT, the singlet should induce a sufficiently large deformation to the early universe scalar potential, hence, should have significant couplings to the Higgs



- **Many other SM extensions, e.g.**

2HDMs
Models with Dark CP violation and gauged lepton/baryon number
Models of EW non-restauration, with multiple singlets and possibly with an inert doublet)
Supersymmetric models with singlets (MSSM ruled out by Higgs precision)
Models with heavy Fermions, etc.

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Enhancing the EWPT strength through a Singlet Scalar

Scalar couples to the Higgs and affects the tree level potential

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \ + V_0^{\text{explicit}}(h,s)$$

We have separated out terms that explicitly break the Z_2 symmetry: $s \to -s$

Possible scenarios:

- Explicit Z_2 breaking → $V_0^{explicit}(h,s) = a_1 h^2 s + b_1 s + b_3 s^3$
- Z_2 - preserving (at T=0) → $\langle (h,s) \rangle = (v_{\text{EW}}, 0)$
- Spontaneously Z_2 breaking → $\langle (h,s) \rangle = (v_{\text{EW}}, w_{\text{EW}})$

The last case follows naturally in scenarios where, e.g., the singlet is the Higgs-like boson of a complex scalar in the dark sector that spontaneously breaks a dark gauge symmetry

To determine phase transition pattern requires finite temperature potential

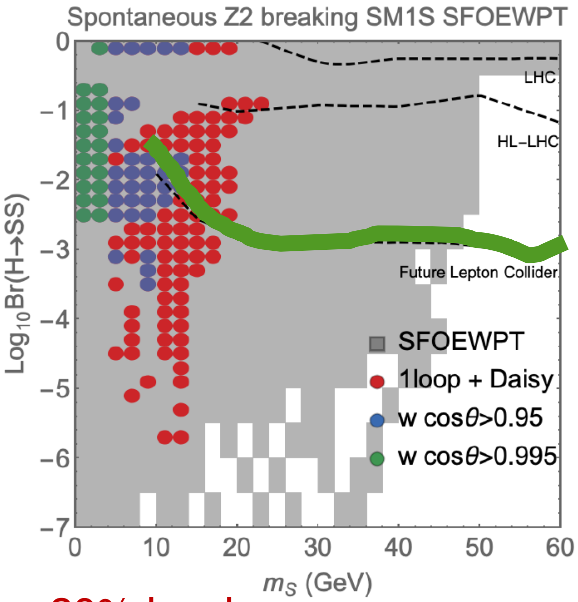
$$V(h,s,T) = V_0(h,s) + V_{\text{CW}}(h,s;T) + V_T(h,s,T)$$

Precision calculations of the full potential is an area of intense theoretical activity

Higgs Exotic Decays into Singlets - Spontaneous Z_2 Breaking Case-

Follows naturally in scenarios where the singlet is the Higgs-like boson of a complex scalar in the dark sector that spontaneously breaks a dark gauge symmetry

- A firm prediction of a light scalar
- Higgs decays into a pair of light scalars
- Higgs exotic decays complements the Higgs precision program
- Higgs exotic decays requires further studies of **merged jets** for lighter singlet masses
- Also possible to have long-lived Higgs exotic decays in certain parameter space



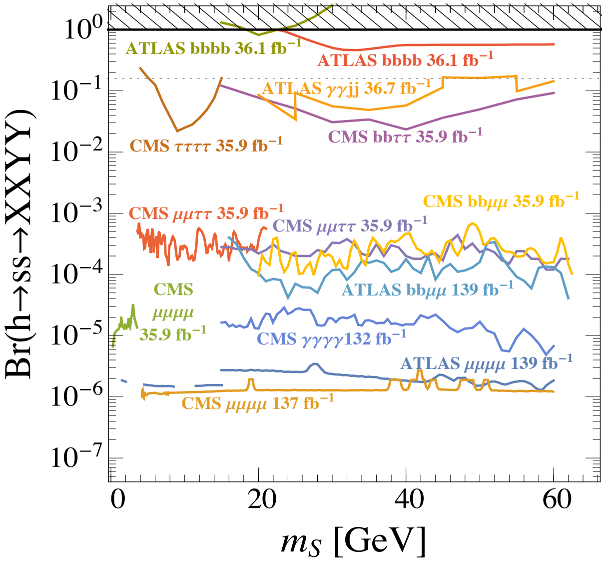
Higgs trilinear coupling receives variations at most at the 20% level, hence contributions to di-Higgs production only detectable at FCC-hh. Model parameter first probed at FCC-ee through mixing

MC, Liu, Wang, **1911.10206**

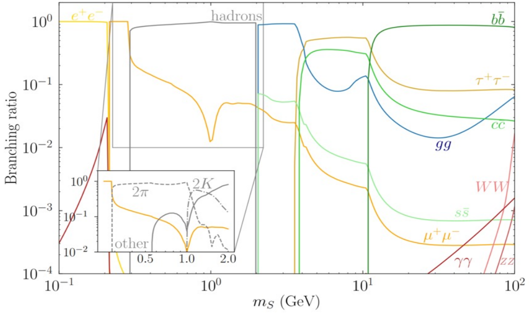
Exotic Higgs decays as a potent probe of viable EW Baryogenesis

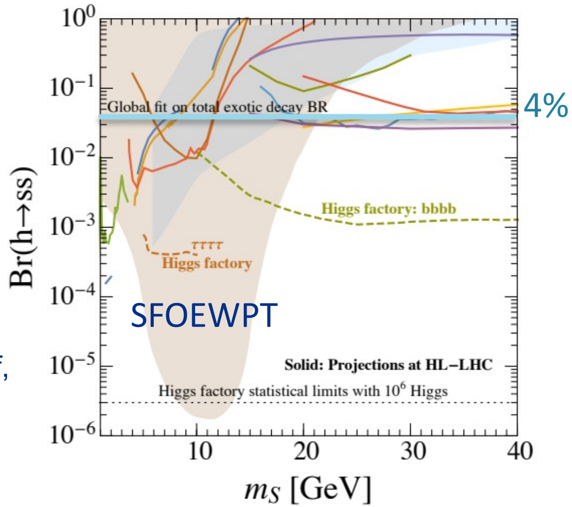
H→ SS can lead to many final states with S inheriting Higgs-like hierarchical BR's, mediated through mixing

Considering LHC current bounds on exotic H decays:



Bounds on Br(h → ss) from Br(h → ss → XXYY) and updated for HL-LHC projections



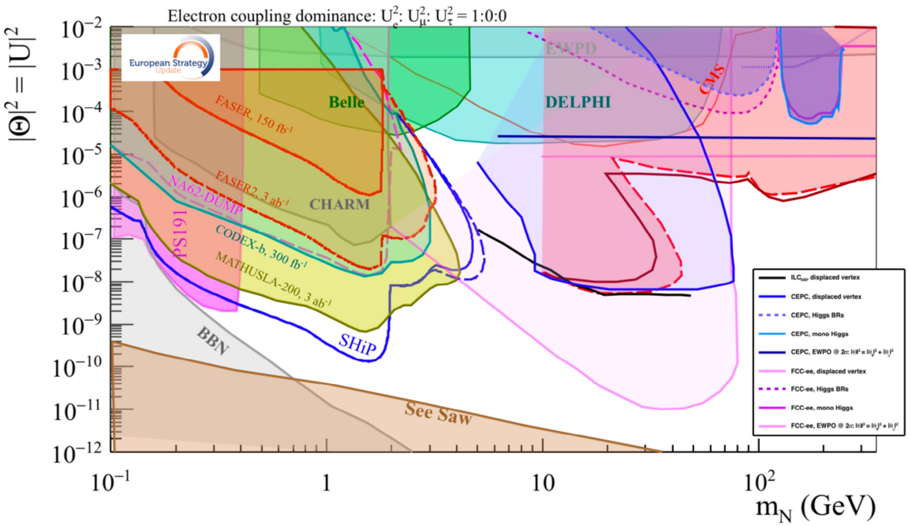


MC, Kozaczuk, Liu, Ou, Ramsey-Musolf, Shelton, Wang, Xie, 2203.08206

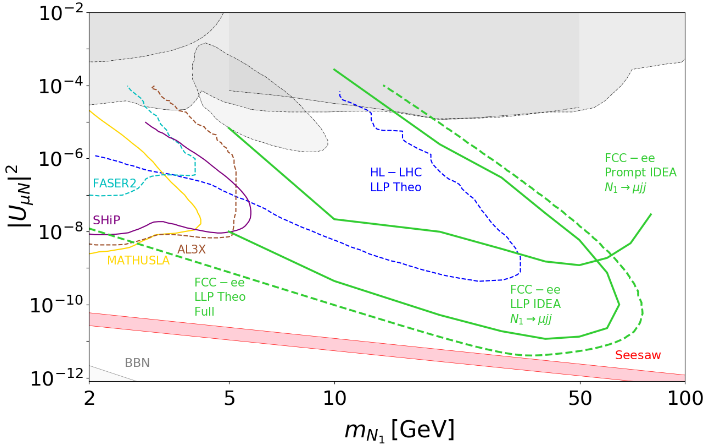
Besides the 4b's final state, the rest involves at least a pair of EW states

FCC-ee reach for low scale seesaw

- Same information combined with other experiments



Verhaaren et. al, hep-ph/2203.05502



FCC-ee with SHiP cover most of the allowed parameter space below the Z pole

favorable case: $|\theta|^2 \simeq |\theta_e|^2$

New analysis:

HNL decays inside FCC-ee detector with a displacement larger than 0.4mm (the search has been carried out for the first time with MC simulations in the μvjj final state, and seems to confirm the theoretical estimates we had before. This analysis can now be used for detector requirementd

Grojean talk: 7th FCC Physics Workshop, Annecy 2024

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