Particle Physics Questions and Opportunities at the FCC-ee

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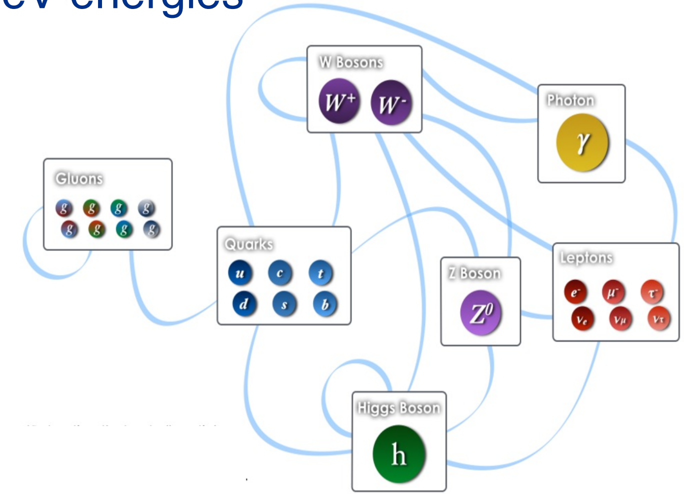
Fermilab/UChicago
MIT, March 25, 2024

Outline

- Knowns and unknowns of the HEP landscape now
- What may be happening in our field in the next two decades
- Opportunities for the FCC-ee to advance our understanding of the field

The Particle Physics Landscape

- The Standard Model 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 -

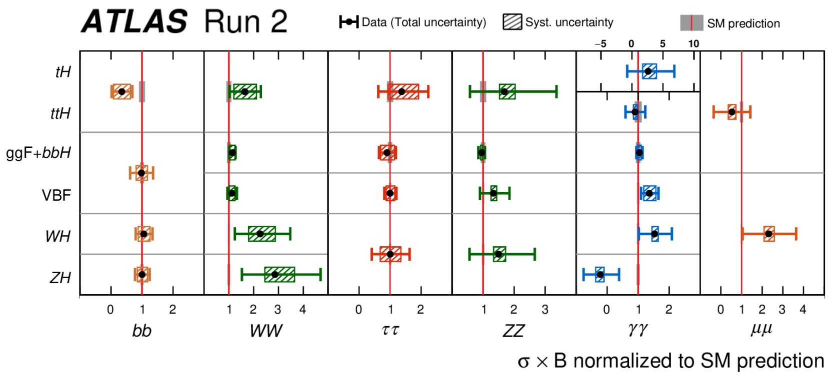
Mysteries of Particle Physics unanswered in the Standard Model

- 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?

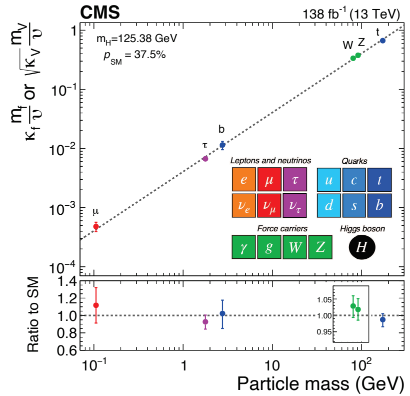
The SM is silent about all the above BUT,
The powerful global HEP experimental program already underway could provide decisive clues to help us decipher many of these mysteries in the next two decades

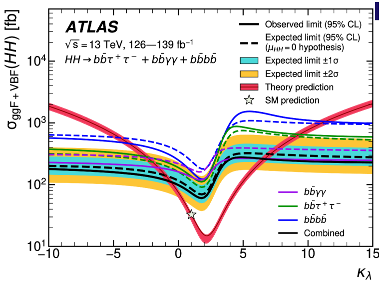
The Great Success of the Higgs boson at the LHC

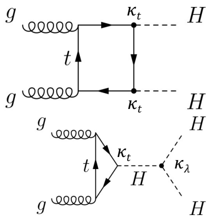
- Its discovery and subsequent study of its properties at the LHC has provided *a first portrait* of the electroweak symmetry breaking mechanism



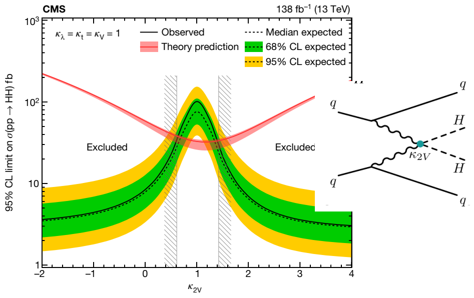
The LHC favors a SM-like Higgs boson



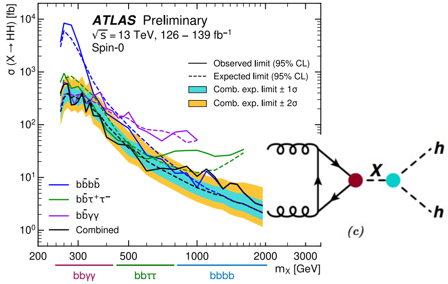




+ higher order EFT operators



di-Higgs production being probed at LHC



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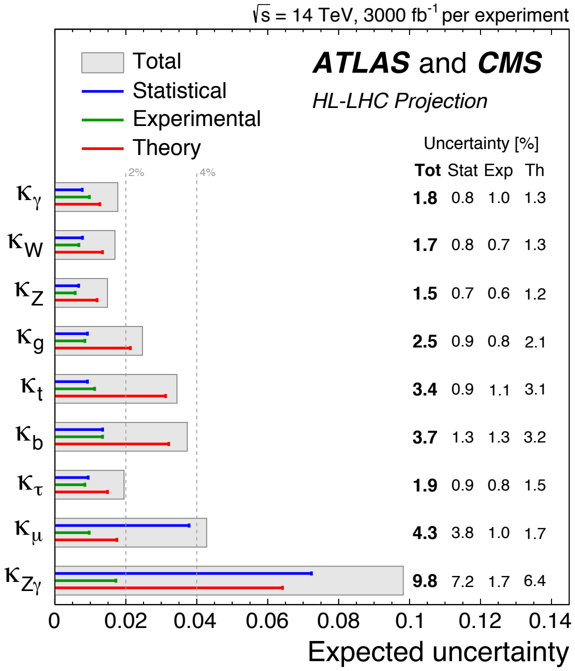
Precision Higgs measurements at the HL-LHC:



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

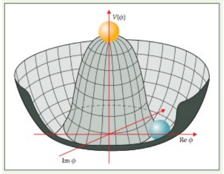
The Higgs sector open questions

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

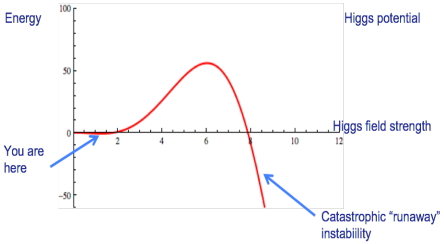
- With m_H = 125 GeV, its mass maximally allow us explore its interactions with SM particles
- The Higgs field can give mass to all known matter particles, but calls for an explanation of the mass hierarchies
- It hints at but does not explain Baryogenesis, Dark Matter/Sector portals, and possibly Inflation

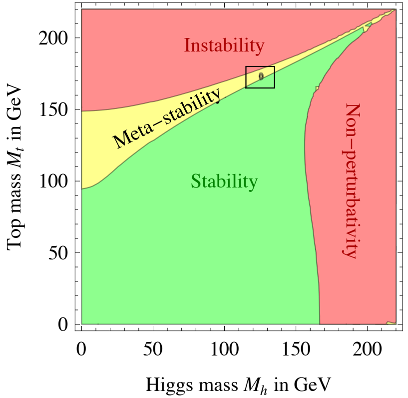
- In the SM, the Higgs potential is fixed by hand to give EWSB

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



- The SM Higgs potential is unstable
  – catastrophic runaway at some point

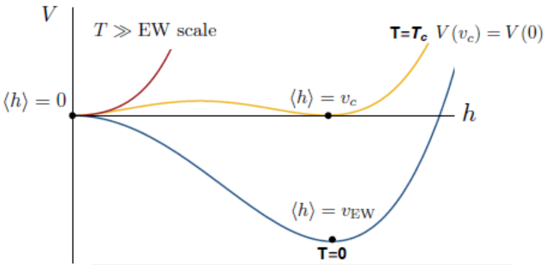




- Scalar's masses are associated with quadratic divergences

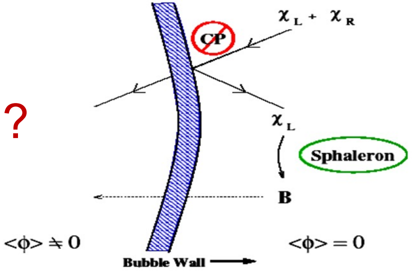
More scalars beyond the Higgs boson, motivated by many puzzles

- Can help explain 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

Entering a new era in exploring the Dark Sector

Standard Model → Portal → Dark Sector

Portal can be the Higgs boson itself or New Messengers: e.g. Dark photon, Dark Higgs, Heavy Neutral Leptons, Axion-like particles, whose dynamics is not fixed by SM dynamics

→ New Forces and New Symmetries

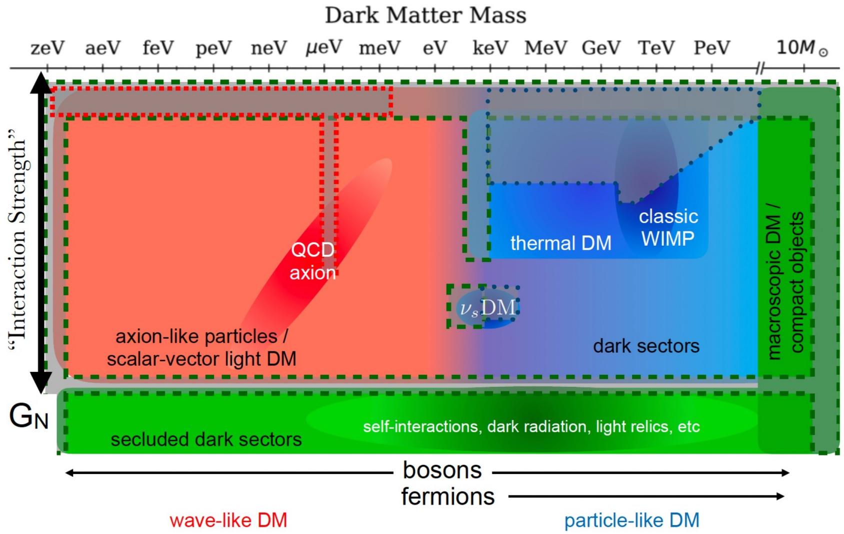
→ Multiple new dark sector states, incl. DM

Interesting, distinctive phenomenology

Long-Lived Particles

Feebly interacting particles (FIP's)

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

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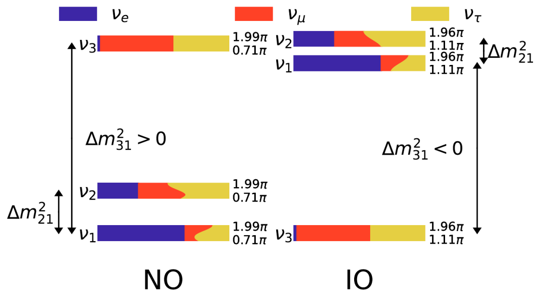
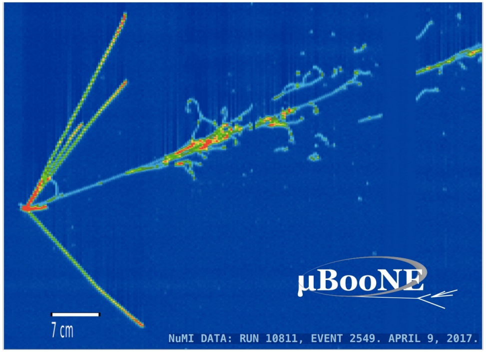
Neutrinos at many energy scales



- The origin of the tiny neutrino masses and of neutrino mixings is a 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

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



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HEP 2045

what will/could be the landscape by 2045

Higgs/EWSB in the light of HL-LHC

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

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

Neutrinos, Charged Lepton and Quark Flavor

A powerful global program with potential for many surprises

- 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, Mu2e discovery of CLFV? Muon or electron EDMs?
- 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 or nearly so, next-generation spectroscopic survey will be in operation: discoveries about early universe physics, dark energy, dark matter?

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

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
$\sim 10^{12}$ 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

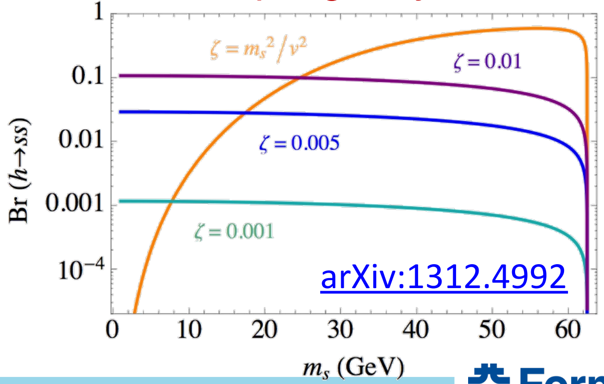
This assumes no-flavor violation couplings, but flavor violating channels should be explored

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 !



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Examples Scenarios for Higgs Exotic Decays

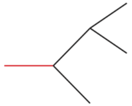
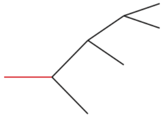
Higgs portals to new physics with suppressed SM couplings/ dark sector mediators

Portals	Couplings
Scalar (dark Higgs)	$(\kappa \mathbf{S} + \lambda_{\mathbf{SH}} \mathbf{S}^2)\lvert\mathbf{H}\rvert^2$
Fermion (sterile neutrino; SUSY neutralino)	$\mathbf{y_N NHL}; \quad \frac{\kappa}{\mathbf{M}}(\mathbf{NN} + \mathbf{N}^\dagger\mathbf{N}^\dagger)\lvert\mathbf{H}\rvert^2$
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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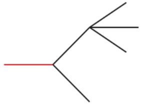
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

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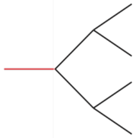
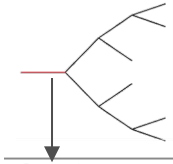
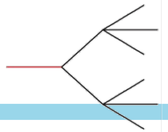
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

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

Higgs exotic decays: a rich variety of possibilities

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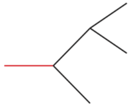
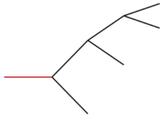
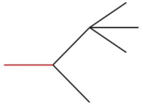
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

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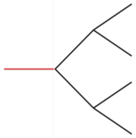
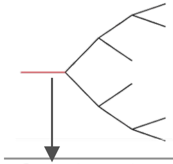
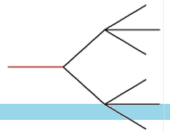
$h \to 2 \to 4$  	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

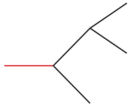
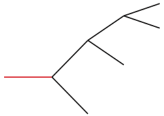
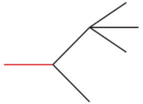
LHC's strength

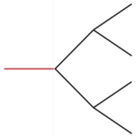
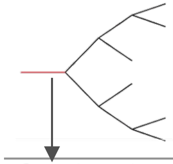
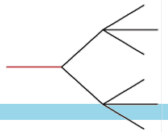
HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

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

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 $\mathcal{F}_i$
$h \to 2$	$h \to \not\!\!E_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not\!\!E_T$ $h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$ $h \to (\mu^+\mu^-) + \not\!\!E_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not\!\!E_T$ $h \to jj + \not\!\!E_T$ $h \to \tau^+\tau^- + \not\!\!E_T$ $h \to \gamma\gamma + \not\!\!E_T$ $h \to \ell^+\ell^- + \not\!\!E_T$

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

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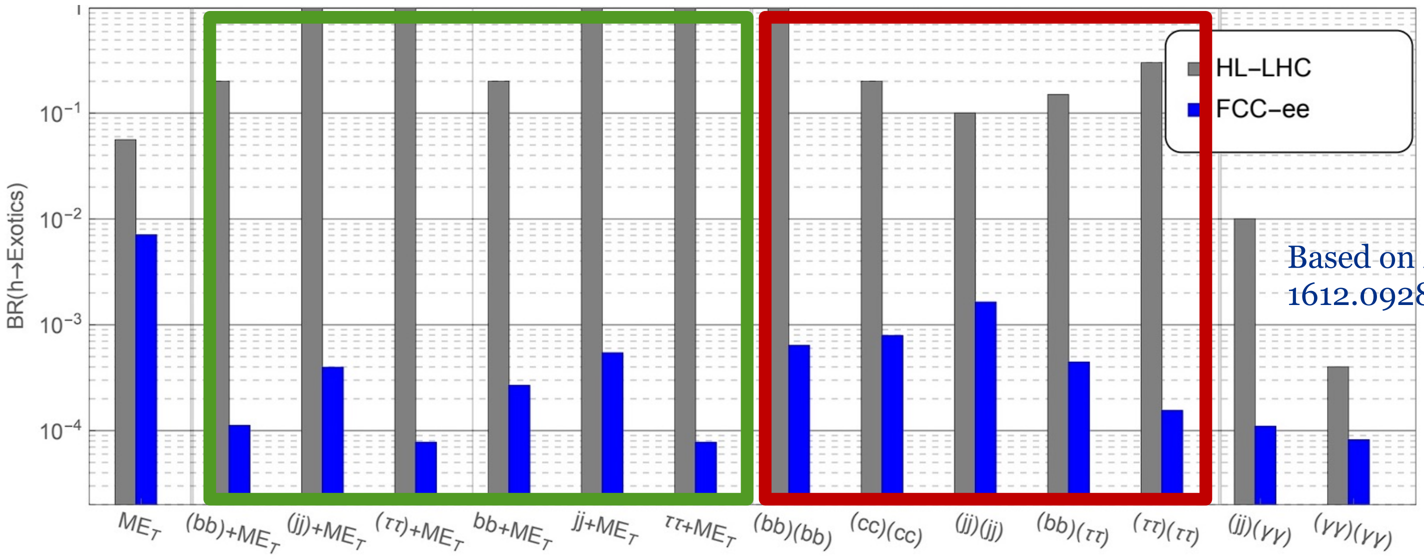
HL-LHC and FCC-ee coverage in selected Higgs Exotic Decay BRs

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

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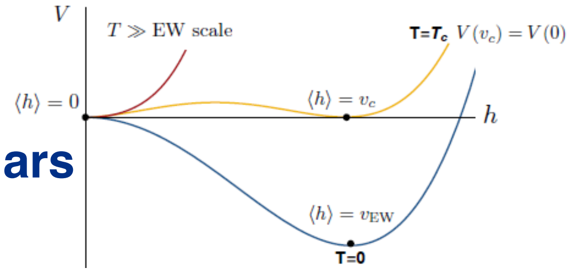
Higgs-Scalar Portal and the EW Phase Transition (EWPT):

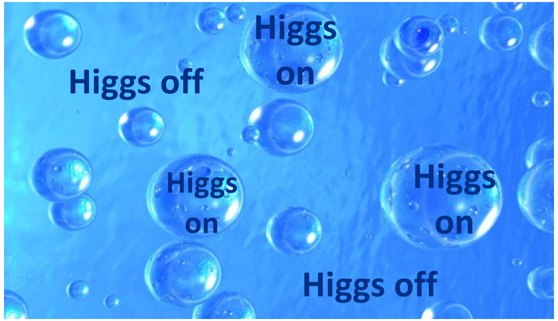
- A strong first order EWPT necessary for EW Baryogenesis → $\mathbf{v(T_c)/T_c \geq 1}$
- The SM Higgs sector is not enough (Higgs boson is too heavy)



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

Phenomenology of SM plus Singlet models

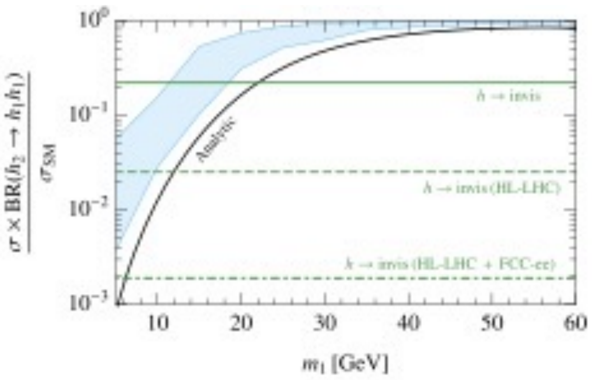
- Z_2-symmetric (at T=0) scenario: **Invisible Decays**

➢ Requires sizeable $s^2 |H|^2$ coupling for a 2-step strongly 1st order EWPT, [(0,0)→(0,v_S) →(v,0)], that calls for a careful treatment of perturbativity

➢ **No S-H mixing – S is stable** (invisible decays)

} BR(H)$_{inv}$ bounds (Missing E_T)

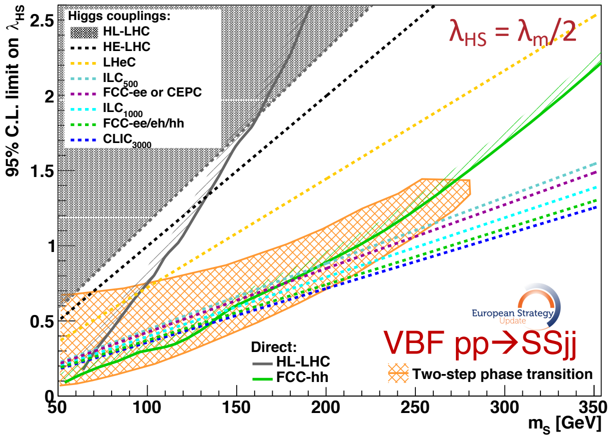
Low mass singlet: $m_s < m_h/2$



Current bounds imply m_S < 20 GeV

Kozaczuk, Ramsey-Musolf, Shelton '19

$m_s > m_h/2$



Scenarios for EW baryogenesis based on EW symmetry non-restoration can also be tested via Higgs invisible decays M.C, Krause, Z. Liu, Y Wang'21

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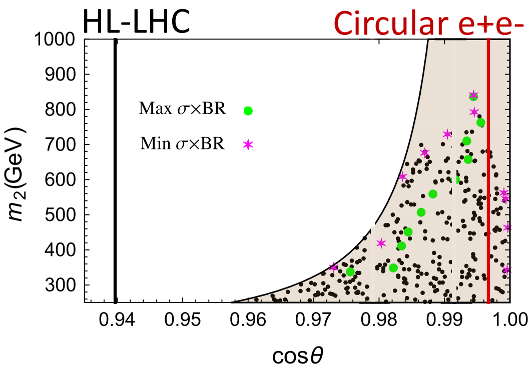
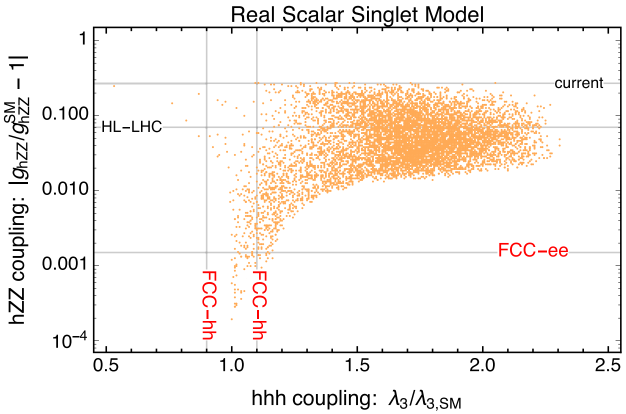
Higgs Phenomenology in Singlet models with mixing

Mixing between doublet and singlet states implies reduction in Higgs signal strengths compared to SM Higgs boson; equivalently one can observed deviations in HZZ coupling and Higgs self coupling





Higgs Exotic Decays: H→ SS

- If singlet sufficiently light ➔ **BR (H→SS)** open
- Sizeable $s^2 |H|^2$ coupling needed for a strongly 1st order EWPT ➔ BR (H→SS) to be bounded from below

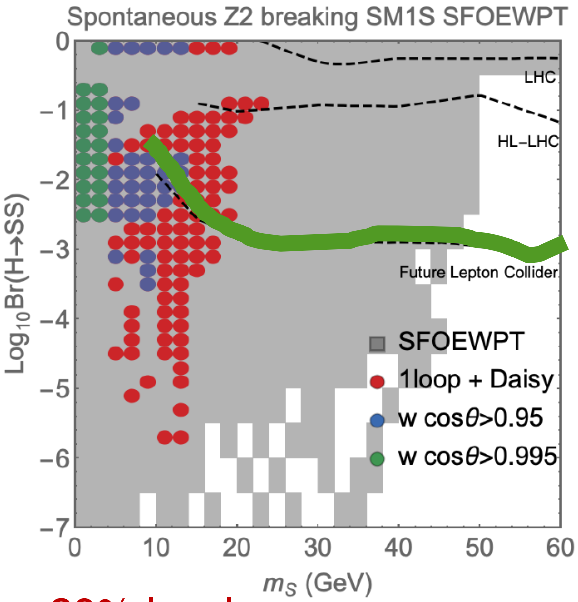
➔ exotic Higgs decays are a potent probe of Singlet extensions with viable EW Baryogenesis

Specifics of Higgs exotic decays depend on Z_2 symmetry breaking mechanism

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



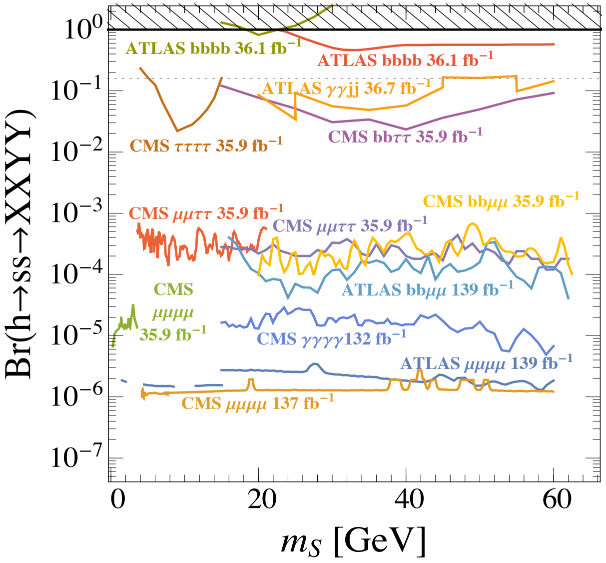
Higgs trilinear coupling receives variations at most at the 20% level, hence contributions to di-Higgs production only detectable at FCC-hh. Model parameter first probed at FCC-ee through mixing

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

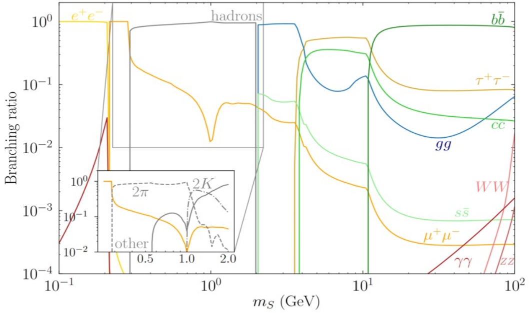
Considering LHC current bounds on exotic H decays:

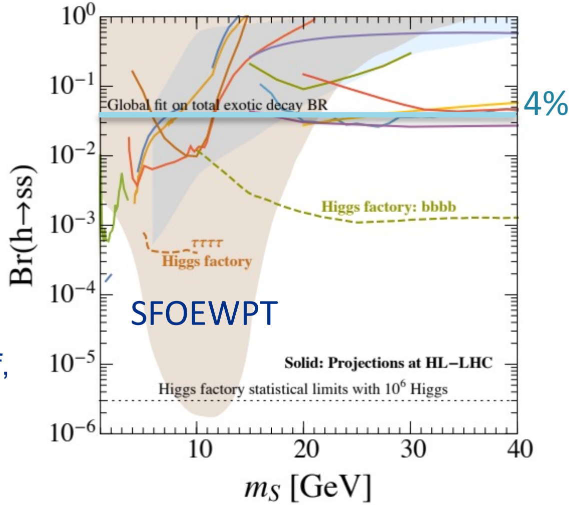


Besides the 4b's final state, the rest involves at least a pair of EW states

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





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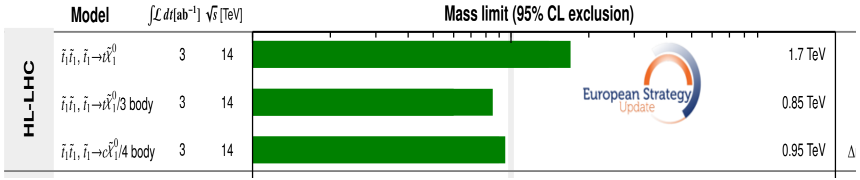
What is behind the EWSB mechanism?

➢ **Radiative breaking**: is the EW phase transition a quantum phase transition ?

e.g. Supersymmetry, provides dynamical radiative EWSB mainly governed by the mass difference between top-quarks and it super-partners

Current LHC program has a long way ahead in the search for SUSY

- Colored SUSY particles, squarks & gluinos, have the highest σ's at hadron colliders.
- Given the Higgs mass value, simplest SUSY models imply stops should be in the TeV range



Top-squark projections: R-parity conserving SUSY, prompt searches. 5σ discovery is 5–10% lower for each process

- FCC-hh will have reach in the 10 TeV range -

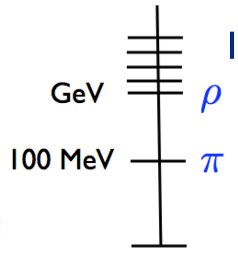
FCC-ee has potential in exotic H/Z decays searching for singlet-like scalars in extended SUSY scenarios and

possible exploration of current hints of mild (2σ) excesses at LHC in the compressed electroweakino region with $m_{\chi02} \sim 150$ GeV and $\Delta m_{(\chi02-\chi01)} \sim 20 - 25$ GeV

What is behind the EWSB mechanism?

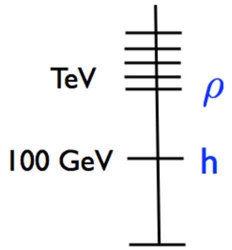
➢ Composite Higgs

It emerges as bound state of a new strongly interacting composite sector characterized by a strong coupling $g_* \gg g_{\rm SM}$ and a confinement scale m_* (like $\Lambda_{\rm QCD}$ but much higher)

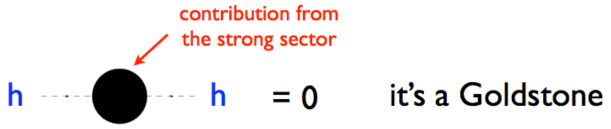


Inspired by pions in QCD

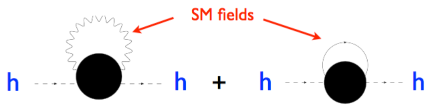
Higgs as a PNGB



Higgs is light because is a kind of pion of a new strongly interacting confining Composite Sector



Mass protected by the global symmetries



Mass generated at one loop: explicit breaking of global symmetry due to SM couplings

Many new physics models allow for composite Higgs Boson/s

Agashe et. al, hep-ph/0412089; Carena et. al, arXiv:0701055; Giudice et. al, arXiv:0703164; Reviews: Panico and Wulzer, arXiv:1506.01961; Cacciapaglia et. al, arXiv:2002.04914

The global symmetry breaking vev is $f = \dfrac{m_*}{g_*}$

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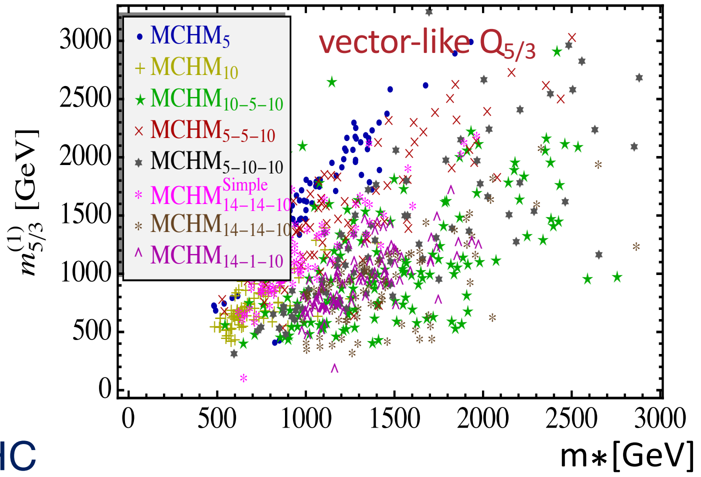
Composite Higgs Models

m_* controls the masses of new vector-like fermion and gauge boson resonances

$1/m_*$ is a measure of the "size" of the composite Higgs

New heavy states content and masses are model specific: depend on global symmetry pattern and fermion embedding

M.C., Da Rold, Ponton'14



LHC bounds → $m_* > 1.4$ TeV

CHMs generic predictions

- One/more of the lightest heavy fermions could be seen at LHC
  - Predictions and interpretations will be model dependent
  - Discovery of such particles may point towards Composite Higgs, but how to learn more?
- Higgs has variations of its couplings to SM particles through elementary + composite sector mixing and sees the new strong force directly via modified self-interactions

dimension 6 operator $\mathcal{O}_\phi \sim \frac{1}{f^2}\frac{1}{2}\left(\partial_\mu |H|^2\right)^2$

D. Liu et. al, arXiv:1603:03064
de Blas et. al, arXiv:1905.03764

- Other EW deviations scale like $1/m_*^2$

e.g. dimension 6 operator $\mathcal{O}_\mathcal{W} \sim \frac{1}{m_*^2}\frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) D^\mu W^a_{\mu\nu}$

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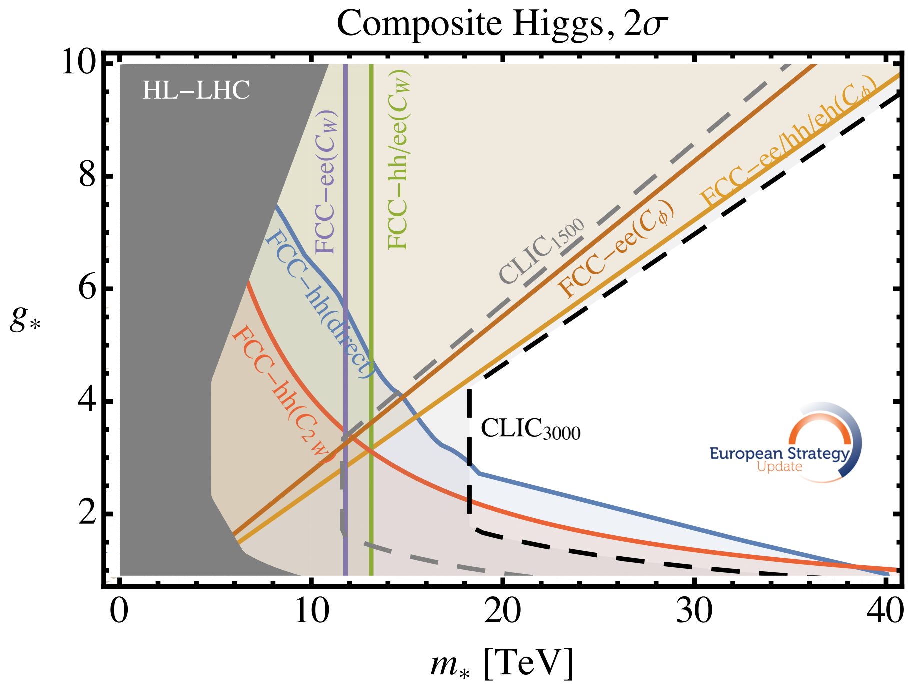
FCC-ee sensitivity to Composite Higgs

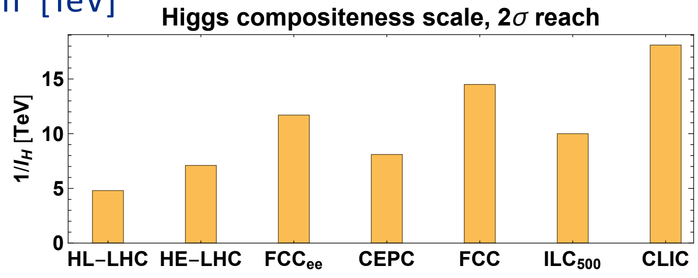
From probes of operators in the EFTCH



FCC-ee sensitive to $f \lesssim 5$ TeV via modified Higgs self-interactions

FCC-ee sensitive to $m_* \lesssim 12$ TeV via other EW modifications

m*[TeV]



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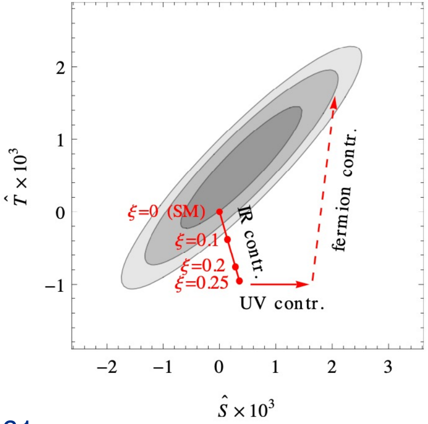
FCC-ee Tera-Z confronting Composite Higgs

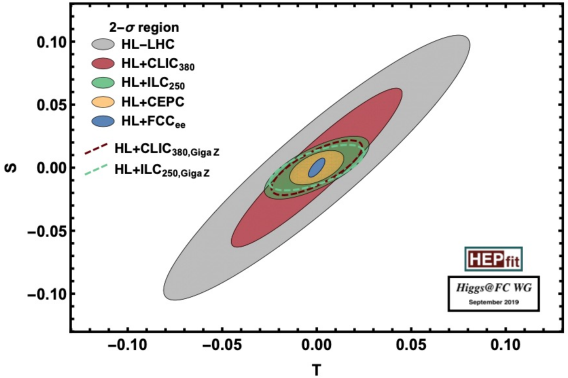
- V(h) depends on the chosen global symmetry and on the fermion embedding
- Higgs couplings to W/Z determined by the global symmetries/gauge groups involved
- Higgs couplings to SM fermions depend on fermion embedding on those gauge groups
- Composite Higgs models generically imply significant contributions to the EW oblique parameters; main effects through modified Higgs couplings
- Full contributions are highly model dependent, but FCC-ee Tera-Z will provide some very strong constraints

After EWSB → $\xi = v/f$



C. Grojean et. al, arXiv:1306.4655

G. Panico and A. Wulzer, arXiv:1506.01961



arXiv:1905.0376

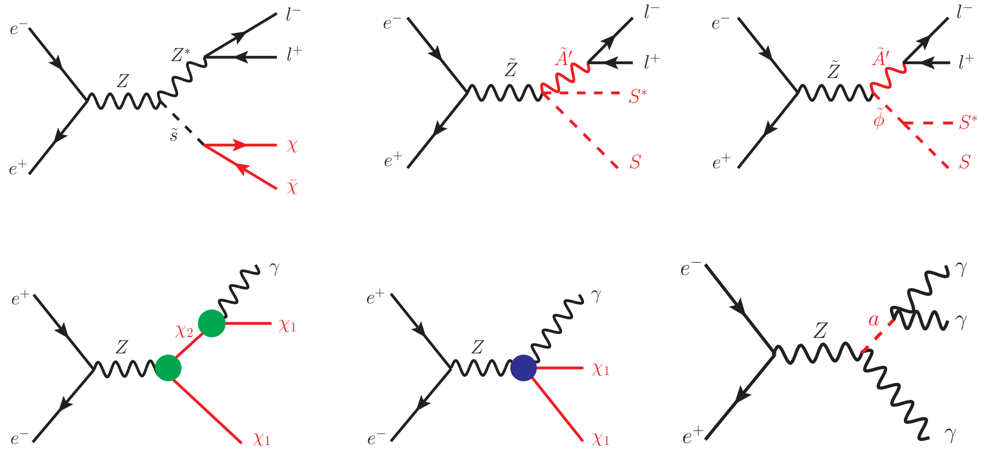
FCC-ee handles to exposing the Dark Sector

Special strength in exploring the existence of a light sector with feeble interactions to the SM and the possible DM candidate/s

- Already discussed possible impact on Higgs exotic decays
- Of similar importance are the many opportunities to search for new particles in Z rare decays

Z boson Exotic Decays exposing the Dark/Feeble Sector

- Fermionic DM in Higgs –scalar portals
- scalar DM in vector portals
- Inelastic Fermionic DM in vector portals
- Magnetic and electric dipole operators with inelastic fermionic DM
- Axion Like-Particles



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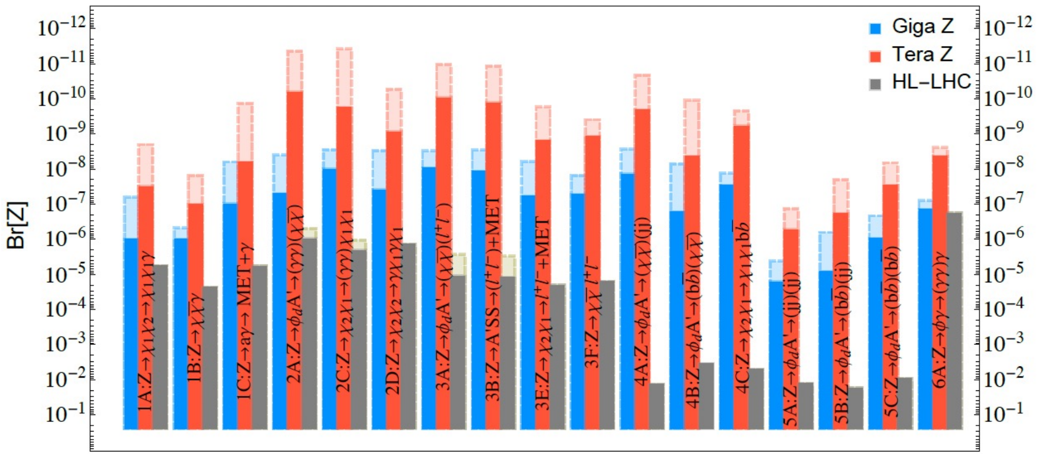
Z boson Exotic Decays exposing the Dark Sector

- TERA Z reach to Dark Sectors

exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}}aB_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_{\mu}B_{\nu}\partial_{\rho}B_{\sigma}$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A', \phi_d \to (\gamma\gamma), A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A, \phi_H \to (\gamma\gamma), \phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1, \chi_2 \to \chi_1\phi, \phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2, \chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A', A' \to (\ell^+\ell^-), \phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1, \chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal



Searches can provide unique probes for DM scenarios at future Z-factory, especially when missing energy and/or hadronic objects appears in the final states

J. Liu, LT. Wang, XP. Wang, W. Xue, arXive:1712.07237

Feebly Interacting/Long-Lived Particles: ALPS at FCC-ee

- ALPs: light, gauge-singlet pseudoscalars, with derivative couplings to SM

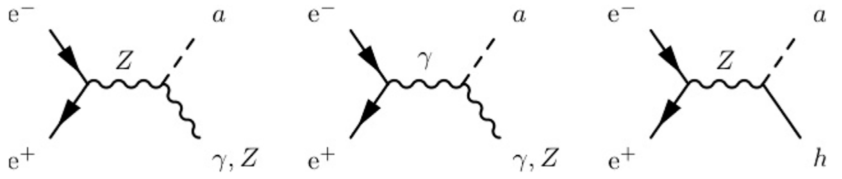
$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \sum_\psi \frac{c_{ff}}{2}\frac{\partial^\mu a}{f}\bar\psi\gamma_\mu\gamma_5\psi + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde G^{\mu\nu,a} + c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde F^{\mu\nu} + c_{\gamma Z}\frac{\alpha}{2\pi s_w c_w}\frac{a}{f}F_{\mu\nu}\tilde Z^{\mu\nu} + c_{ZZ}\frac{\alpha}{4\pi s_w^2 c_w^2}\frac{a}{f}Z_{\mu\nu}\tilde Z^{\mu\nu} + c_{WW}\frac{\alpha}{2\pi s_w^2}\frac{a}{f}W^+_{\mu\nu}\tilde W^{-\mu\nu}$$

+ Higgs portal: $\frac{c_{ah}}{f^2}(\partial_\mu a)(\partial^\mu a)H^\dagger H + \frac{c_{Zh}}{f^3}(\partial^\mu a)\left(H^\dagger iD_\mu H + \text{h.c.}\right)H^\dagger H$

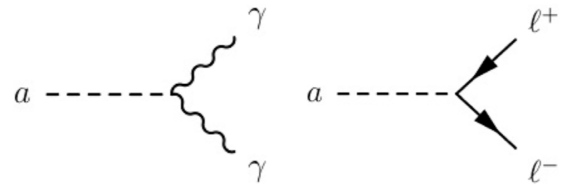
- ALPS many opportunities: address strong CP problem; provide a non-thermal DM candidate; can be portals to a dark sector and much more
- ALPS can couple to all SM particles with varying strength for a wide mass range

At FCC-ee, besides production in H/Z decays: Z → γa; h → Za; h → aa;

Thanks to clean environment they can also be searched for in γ/H/Z associated production



With decays:



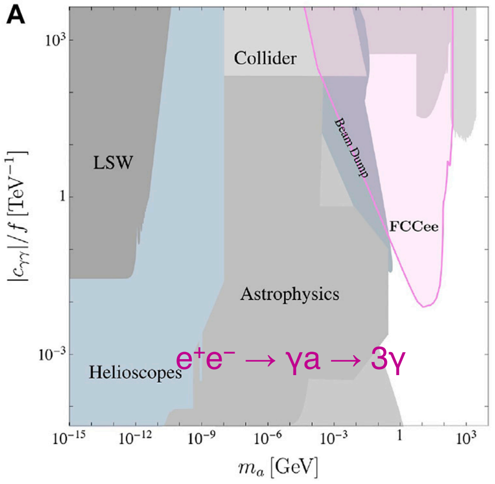
They can be searched for masses and decay lengths not explored elsewhere

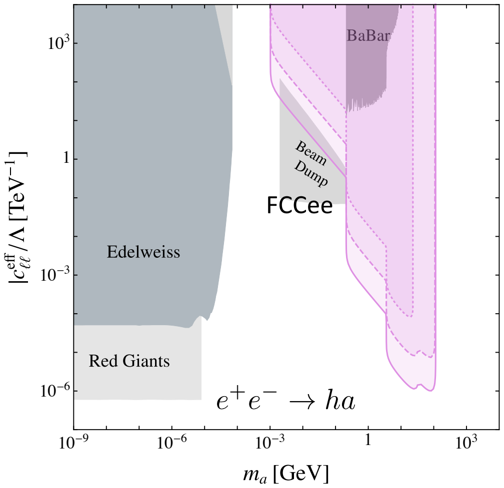
Fermilab

ALPS Discovery Potential at the FCC-ee

- Variety of signatures inside the detector, depending on life-time:

If very long-lived, ALPS are detected as missing momentum; if somewhat shorter lifetime they can be detected in decays to gauge bosons, leptons and quarks





Projected sensitivity regions with runs at the Z-pole and at the ZH maximum, respectively

Searches sensitive to ALPS' decay lengths of up to 1.5 m

For long-lived ALPs reach may be significantly improved with a dedicated far detector (decay lengths of up to100 m)

(left) $e^+e^- \to \gamma a \to 3\gamma$, Br($a \to \gamma\gamma$) =1 and assuming c_{WW}=0 that implies $c_{\gamma Z} = - s_w^2\, c_{\gamma\gamma}$

(right) $e^+e^- \to ha \to bb\, l^+l^-$, Br($a \to l^+l^-$) =1 with c_{hz}= 0.72(0.1)(0.015)Λ/TeV for solid (dashed) (dotted) contours.

Sensitivity based on 4 expected signal events

Bauer, Heiles, Neubert,Thamm arXive: 1808.10323

Fermilab

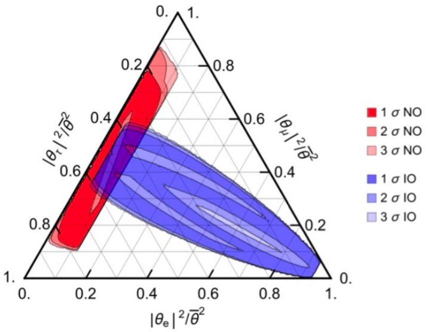
Feebly interacting/long-lived Particles: Heavy Neutral Leptons

HNL and a low scale seesaw at FCC-ee

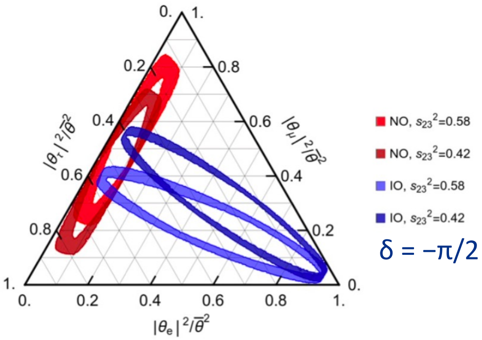
$$\mathbf{y_N NHL}; \qquad \theta_e = \frac{y_{N\nu_e}}{\sqrt{2}}\frac{v}{M_N} \qquad \theta_\mu = \frac{y_{N\nu_\mu}}{\sqrt{2}}\frac{v}{M_N} \qquad \theta_\tau = \frac{y_{N\nu_\tau}}{\sqrt{2}}\frac{v}{M_N} \qquad |\theta|^2 = |\theta_e|^2 + |\theta_\mu|^2 + |\theta_\tau|^2$$

- The thetas measure the strength of the active-sterile mixing
- Their relative contributions to $|\theta|^2$ are constrained by neutrino oscillation experiments

Allowed range for the relative magnitude of the HNL couplings to individual SM flavors with $N_{sterile} = 2$



Relative flavor mixings consistent with current neutrino oscillation data



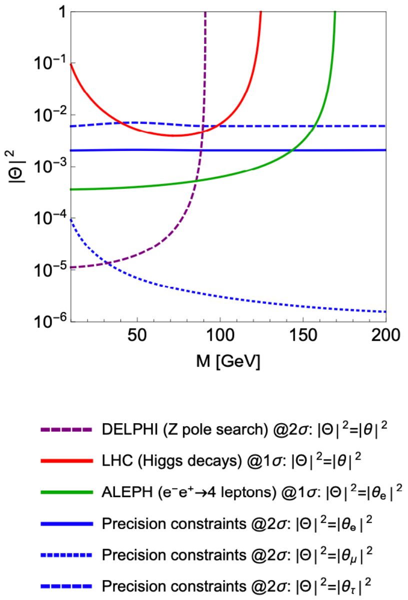
$\delta = -\pi/2$

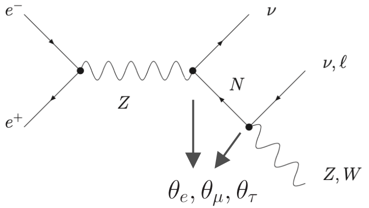
Projected 90% CL contours for the relative mixings after 14 years of data taking at DUNE

In a variety of "symmetry-protected seesaw" scenarios (e.g. nuMSM, inverse seesaw, linear seesaw), FCC-ee programme, if it can see a HNL signal, could also measure these ratios

Abdullahi et. al, hep-ph/2203.08039

Present Constraints on low scale seesaw

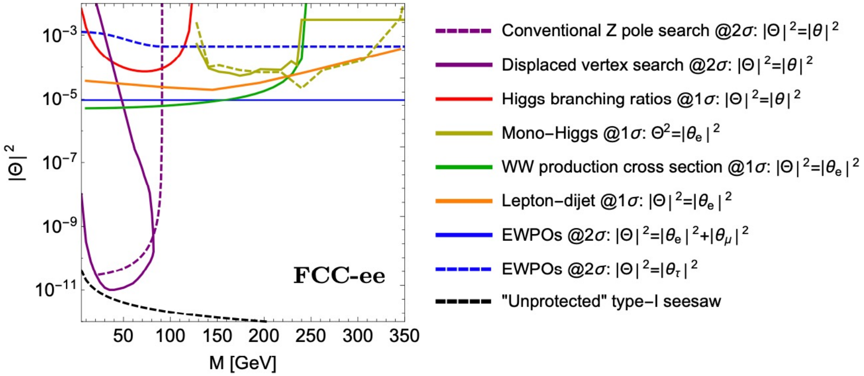




- EWP tests are sensitive to the thetas over a broad range of HNL masses, e.g. the Fermi constant extracted from muon decays now has a contribution $|\theta_e|^2 + |\theta_\mu|^2$
- NuTEV strongly constrains $|\theta_\mu|^2$
- Strong limits from DELPHI direct search at the Z pole for $Z \to \bar{\nu}\, N$

FCC-ee reach for low scale seesaw

- EWP tests constraints for masses up to O(1000 TeV)

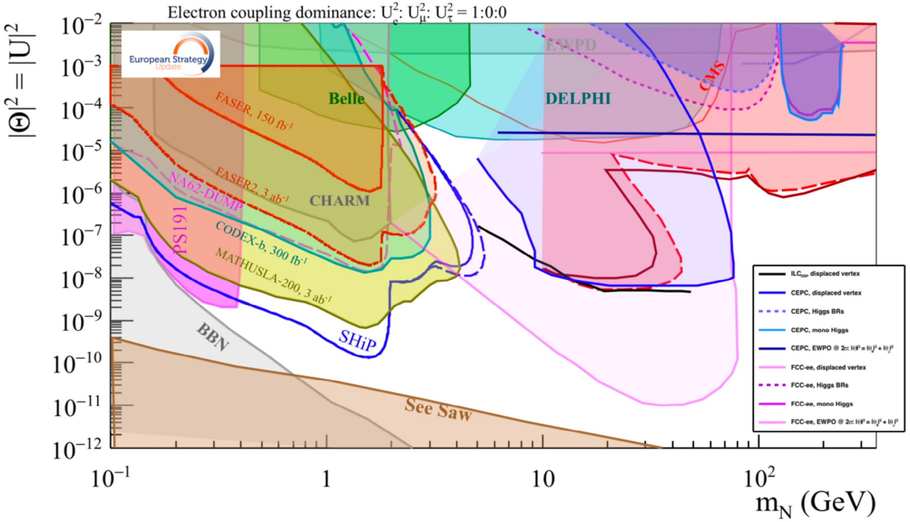


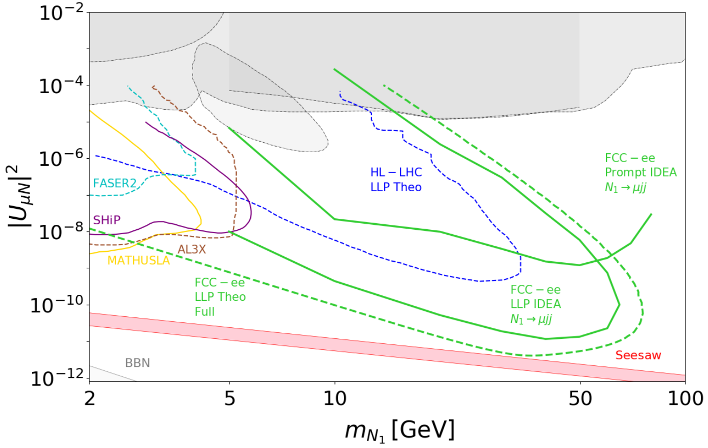
- Below the Z-pole, direct searches, with & without displaced vertices, are sensitive almost all the way down to the naive ”unprotected” seesaw values

Antusch et. al, arXiv:1502.05915; arXiv:1612.02728

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

Outlook

- 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 strengths of FCC-ee are essential for exploring the dynamics behind the Higgs sector and the possible existence of portals and scenarios for a dark sector.
- The precision and reach of FCC-ee holds the possibility to make direct contact between collider physics and other parts of the HEP experimental program, including neutrino oscillations, dark matter and cosmic exploration, and flavor probes.
- We should be as ambitious as possible in designing the detectors/experiments for FCC-ee, both for discovery of new phenomena and for characterization of what we could see soon.
- Fcc-ee will be a strong precursor to FCC-hh