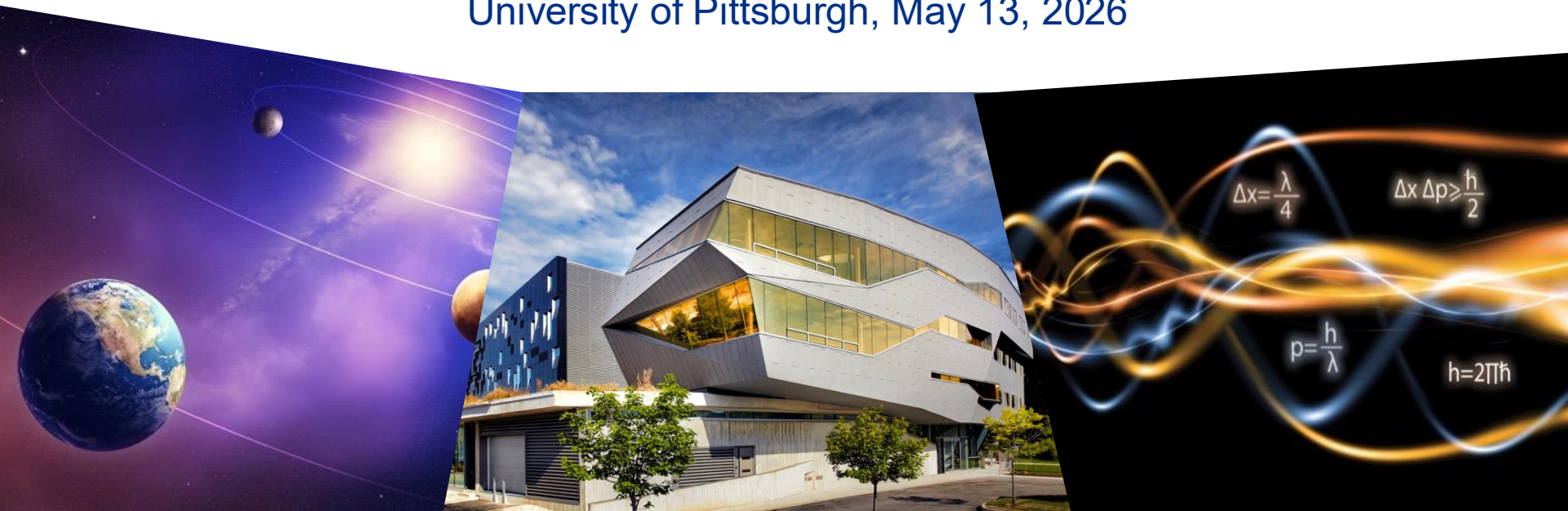


Pathways to Discoveries in Particle Physics

Marcela Carena

Perimeter Institute/UChicago/Fermilab

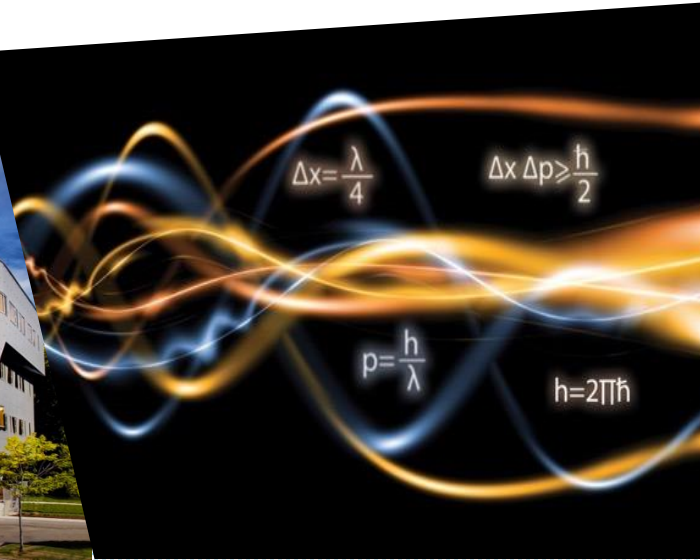
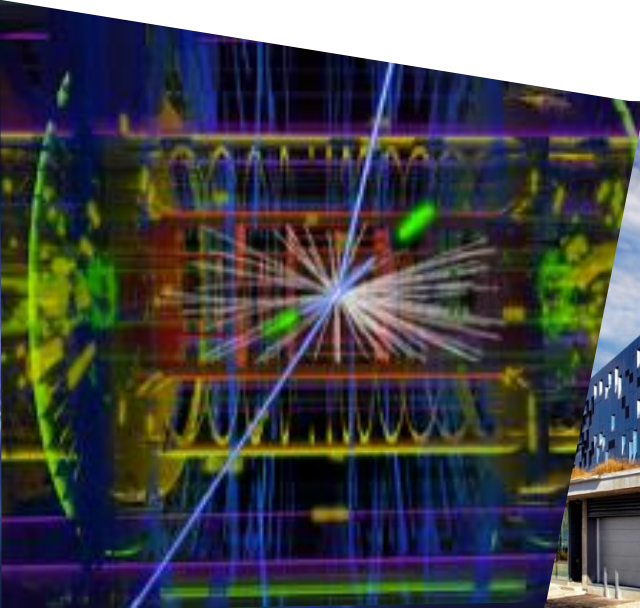
Phenomenology 2026 Symposium
University of Pittsburgh, May 13, 2026



Outline

- Many pathways
- What may be happening in our field in the next 15 years
- Opportunities for the FCC-ee to advance our understanding of the field

Particle Physics: the road ahead



$$\Delta x = \frac{\lambda}{4}$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$p = \frac{h}{\lambda}$$

$$h = 2\pi\hbar$$

Supersymmetry
Extra Dimensions
Strong Dynamics

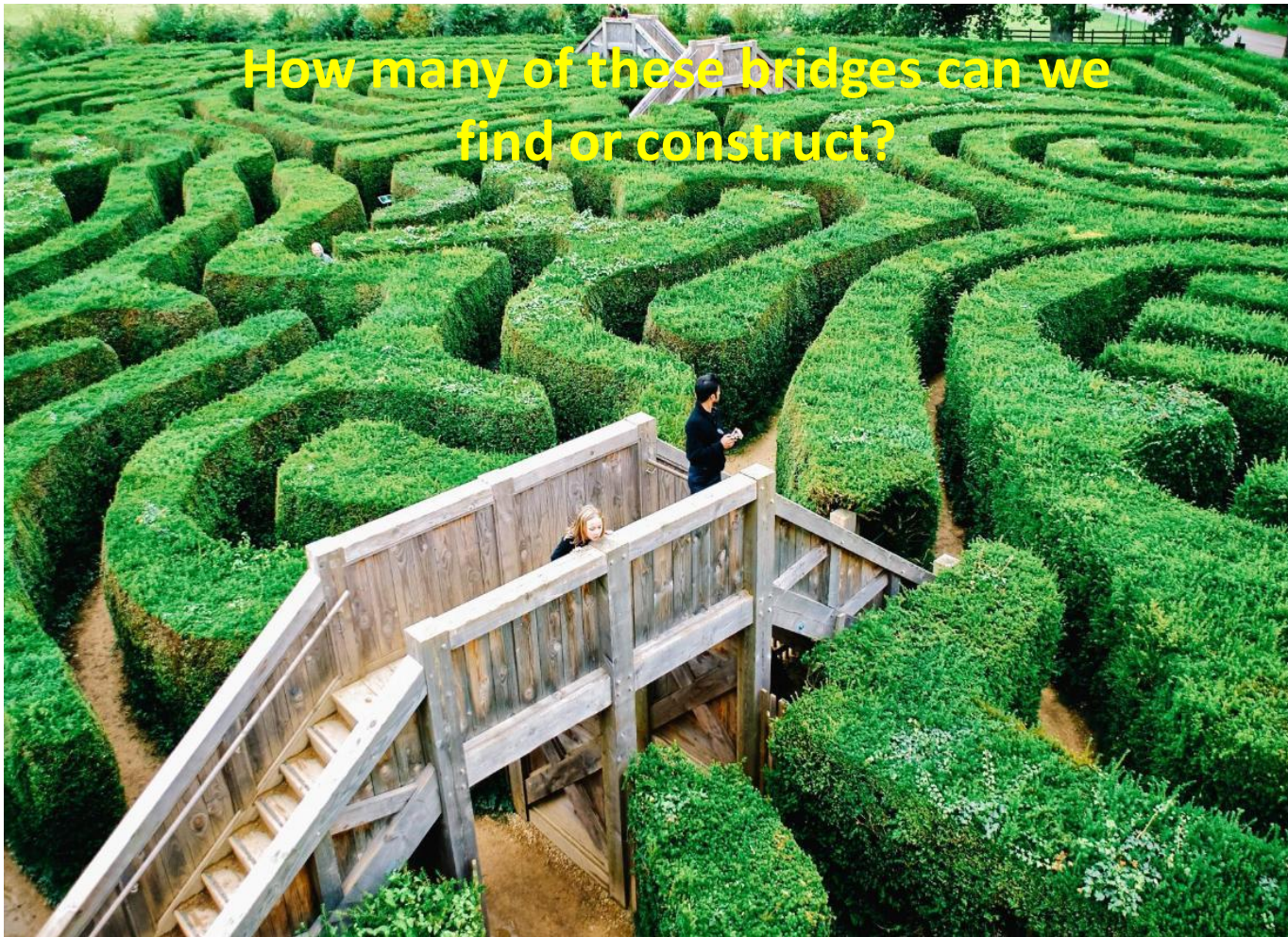
Higgs Boson
Dark Matter
New Forces

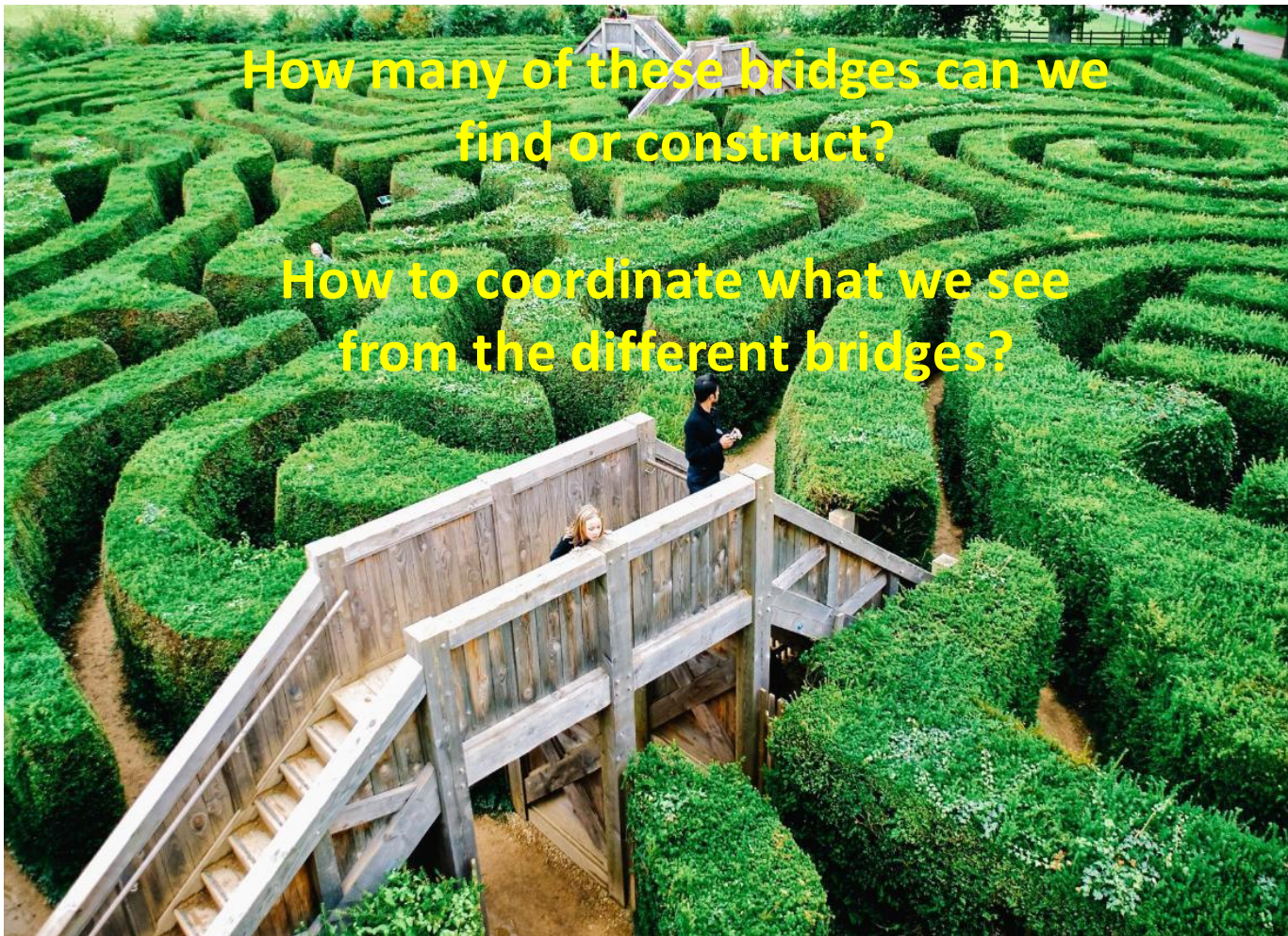
Consensus particle physicist's view of the
road ahead: @LHC start in 2009



**Consensus particle physicist's view
of the road ahead: 2026**

How many of these bridges can we find or construct?





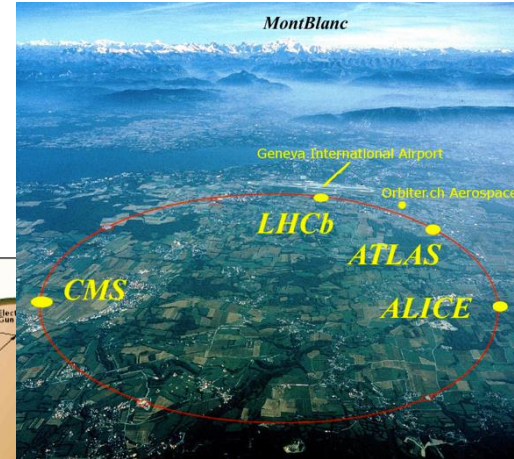
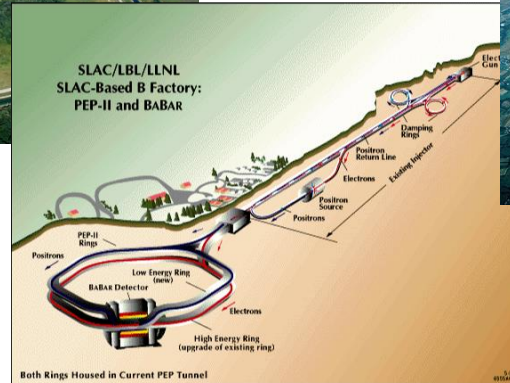
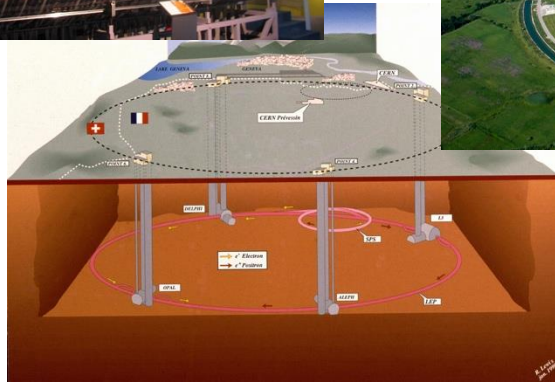
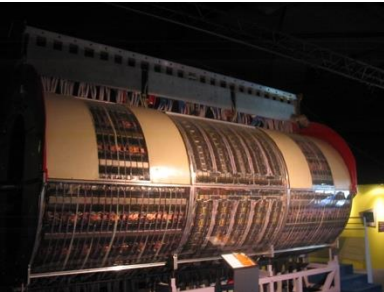
How many of these bridges can we find or construct?

How to coordinate what we see from the different bridges?

Big Colliders for Big Science

Since the 1980s particle colliders have been our biggest and most important bridges.

They enable many discoveries! with the HL-LHC the latest and greatest



Big Science in particle physics is not just colliders anymore

During the same period, new pathways started to be explored aggressively

Many successes in **neutrinos, particle astrophysics, and cosmology** have led to bigger and bigger bridges in these other pathways:

- Neutrinos (JUNO, HyperK, DUNE etc) is a >\$5B program
- Cosmic (Rubin/LSST, DESI, Simons, etc) is a >\$1B program
- Direct DM detection future plans (XLZD, PandaX-30t, DarkSide-20k, multiple axion searches) could be a >\$0.5B program
- Particle pheno theory has scaled and broadened too: > \$2B per decade program

HEP 2041

what will/could be the landscape by 2041



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

- JUNO, HyperK, DUNE, and other neutrino expt. mature results, will determine the mass hierarchy and could discover CP violation, anomalies in oscillation physics, light and boosted dark matter, heavy neutral leptons, ...
- Detection of neutrinoless double beta decay
- Mu2e discovery of CLFV
- Mature B physics results from BELLE II, LHCb, ATLAS/CMS, etc: discoveries and/or unresolved anomalies?
- Confirmed detection of an EDM?

Dark Sector and Cosmic

- Broad program of direct dark matter searches will be done, could have discovered one or more kinds of DM particles
- More clues on DM properties from Rubin/LSST, Simons, etc
- Did accelerator-based experiments including HL-LHC see evidence of new feebly-interacting particles?
- Confirmed indirect DM signals?
- Confirmed that dark energy is dynamical?
- Non-BSM sources of the Hubble tension ruled out: points to new forces or particles

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

European Strategy for Particle Physics: FCC-ee



Remit of the European Strategy Group (ESG)

- In June 2024, the CERN Council established and approved the **remit of the European Strategy Group**

"The aim of the Strategy update should be to develop a **visionary and concrete plan** that greatly advances human knowledge in fundamental physics through the **realisation of the next flagship project at CERN**. This plan should attract and value **international collaboration** and should **allow Europe to continue to play a leading role in the field.**"
- The ESG should take into consideration:
 - The **input of the particle physics community**;
 - The **status of implementation of the 2020 Strategy update**;
 - The **accomplishments over recent years**, including the results from the LHC and other experiments and facilities worldwide, the progress in the construction of the High-Luminosity LHC, the outcome of the Future Circular Collider Feasibility Study, and recent technological developments in accelerator, detector and computing;
 - **The international landscape of the field**
- **The Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive.**



Timeline for the update of the European Strategy for Particle Physics

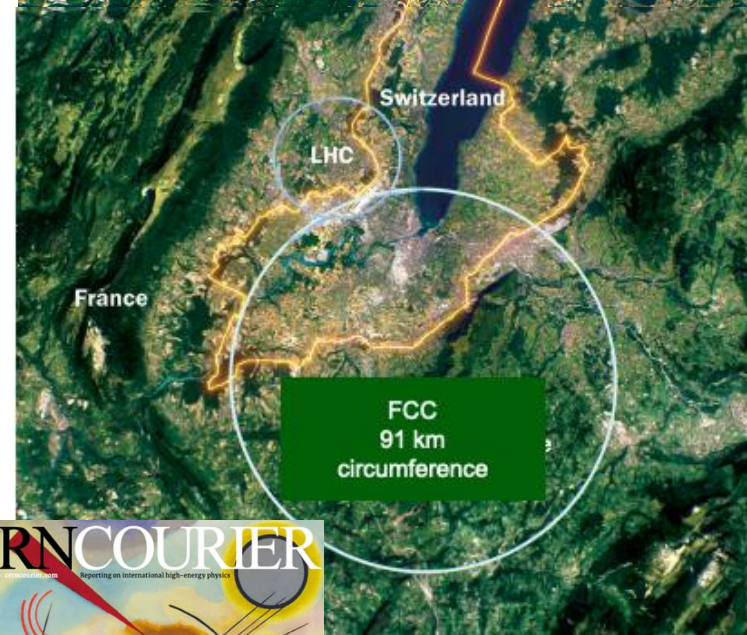


ESPP web page: <https://europeanstrategyupdate.web.cern.ch/>

European Strategy Plan A and Plan B

“The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN,” explains strategy secretary Karl Jakobs of the University of Freiburg.

“A descoped FCC-ee is the preferred alternative option. Descoping scenarios include removing the top-quark run, constructing two rather than four interaction regions and experiments, and decreasing the RF-system power.”





ESG recommendation for alternative option(s) for next flagship collider at CERN

A descoped FCC-ee is the preferred alternative option for the next flagship collider at CERN.

Descoped/staged FCC-ee:

- ❑ no top run
- ❑ 30 MW beam power instead of 50 MW
- ❑ 2 caverns/experiments instead of 4

→ -1.26 BCHF. Physics objectives impacted

→ -0.35 BCHF. Inst. Lumi. reduction (60%)

→ -0.80 BCHF. Inst. Lumi. reduction (61%)

} Total reduction ~36.5%



Construction cost: 12.85 BCHF instead of 15.28 BCHF

“Although this would have a significant impact on the breadth of the physics programme and the precision achieved, the descoped FCC-ee would still provide a very strong physics programme and a viable path towards high energies, compared to the alternative collider options. Should additional resources become available, these descoping scenarios would be reversible.”

“Several other alternative options, listed here in alphabetical order, were also assessed. They offer substantially reduced precision physics programmes and would not be competitive with a collider like the FCC-ee. Moreover, in themselves, they currently lack a viable path towards energies of 10 TeV. At this stage, without knowing the reasons for which the FCC-ee would not be feasible, the other alternative options are not ranked.”

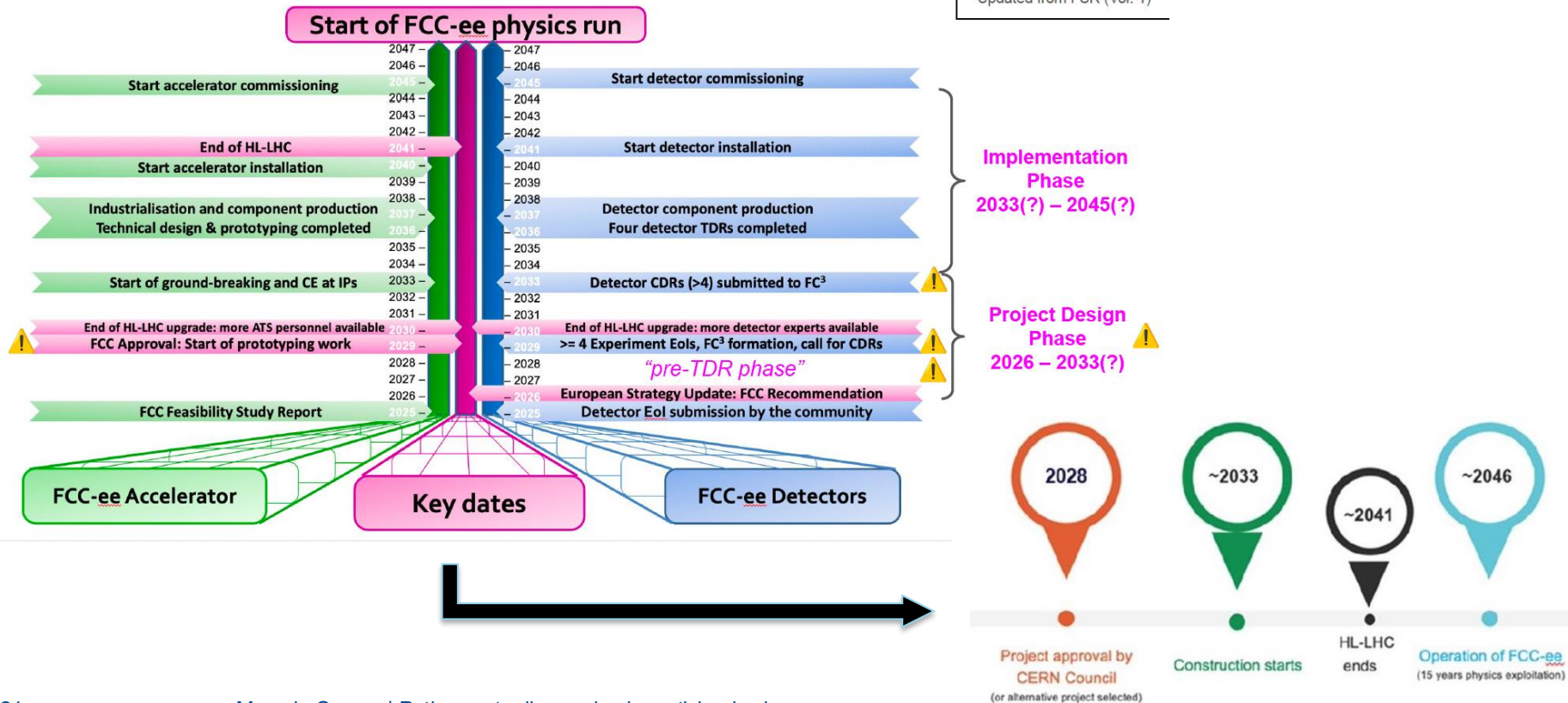
F. Gianotti, [16 Dec 2025](#)

FCC-ee final approval (2028) and start of physics run (~2047)



Updated key dates (tbc)

Updated from FSR (Vol. 1)



Momentum growing for FCC-ee

Private donors pledge 860 million euros for CERN's Future Circular Collider

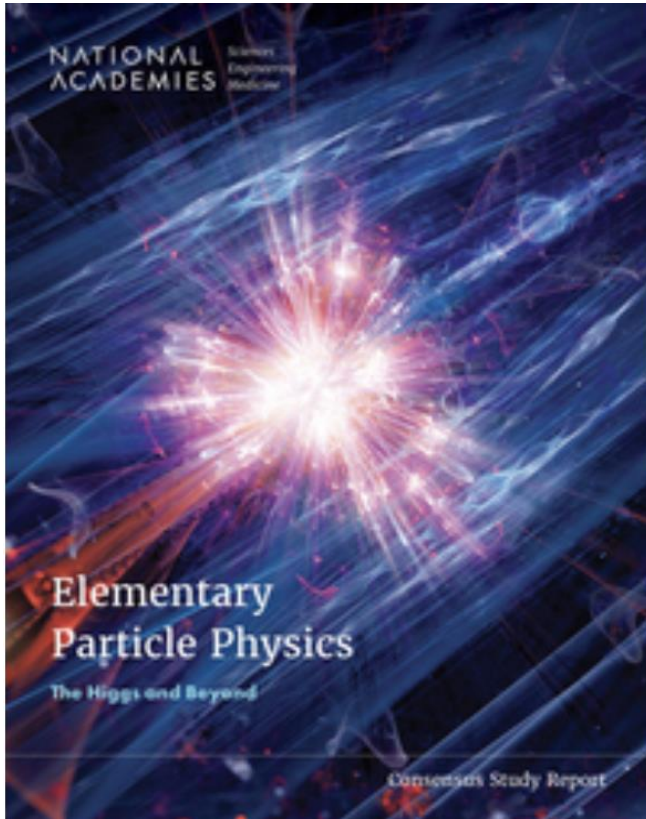
A consortium of private donors (individuals and philanthropic foundations) have agreed to support the proposed Future Circular Collider at CERN

18 DECEMBER, 2025

French President Emmanuel Macron spoke at CERN in Nov 2023 of France's ambitions to remain in "first place" during a visit to the world's most powerful particle accelerator on the Franco-Swiss border, where a successor, even more powerful, is being studied.



What about the U.S.?



2025 National Academy study:

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national **muon collider research and development** program to enable the construction of a demonstrator of the key new technologies and their integration.

Recommendation 2: The United States should participate in the international **Future Circular Collider** Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.

Physics opportunities at FCC-ee



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

Higgs factory

m_H, σ, Γ_H
self-coupling
 $H \rightarrow bb, cc, ss, gg$
 $H \rightarrow \text{inv}$
 $ee \rightarrow H$
 $H \rightarrow bs, ..$

Top factory

$m_{\text{top}}, \Gamma_{\text{top}}, ttZ, \text{FCNCs}$

Flavor

“boosted” B/D/ τ factory:

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

$B_c \rightarrow \tau \nu$
 $B_s \rightarrow D_s K/\pi$
 $B_s \rightarrow K^* \tau \tau$
 $B \rightarrow K^* \nu \nu$
 $B_s \rightarrow \phi \nu \nu \dots$

QCD - EWK

most precise SM test

$m_Z, \Gamma_Z, \Gamma_{\text{inv}}$
 $\sin^2\theta_W, R_Z^Z, R_b, R_c$
 $A_{\text{FB}}^{b,c}, \tau \text{ pol.}$
 $\alpha_S,$
 m_W, Γ_W

BSM

feebly interacting particles

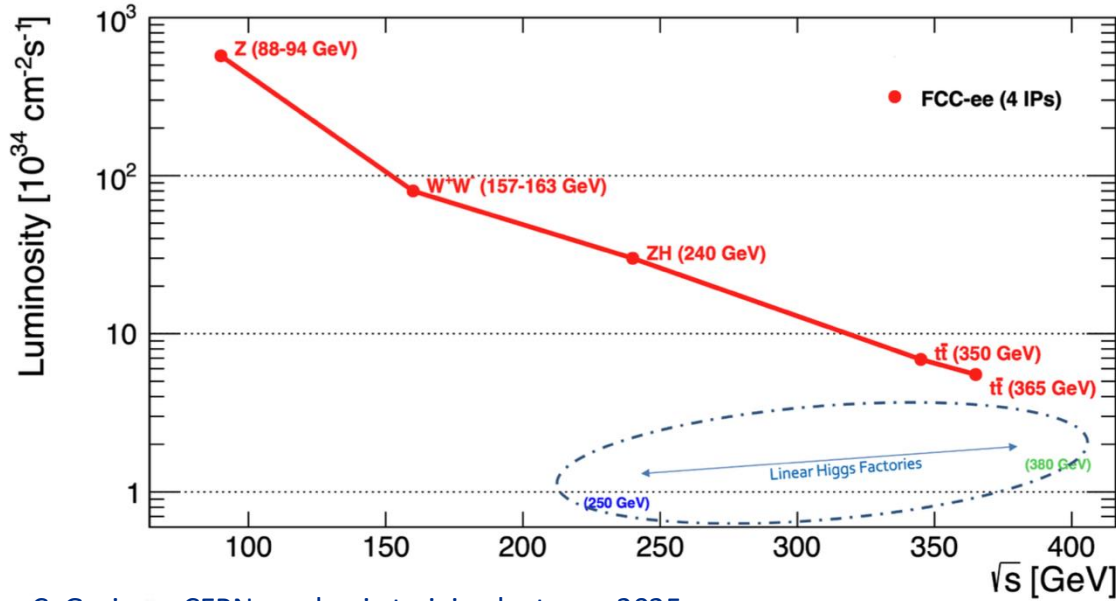
Heavy Neutral Leptons
(HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

FCC-ee will have amazing capabilities:



C. Grojean, CERN academic training lectures, 2025

In various running modes, FCC-ee produces:

10^5 Z's per second

10^4 W's per hour

1500 Higgs per day

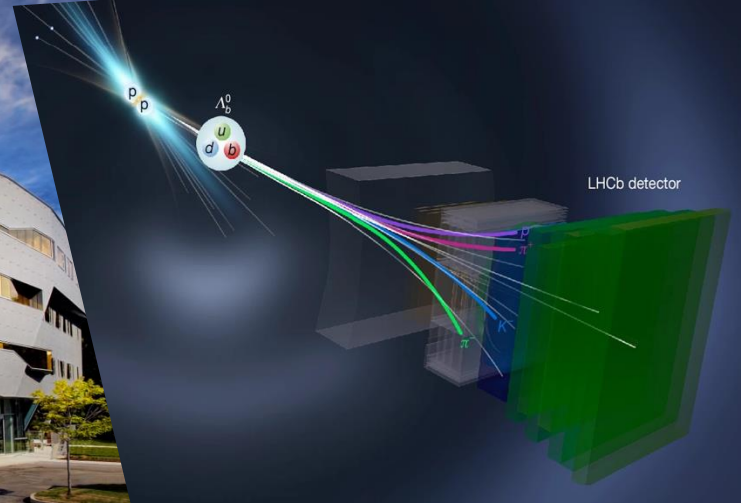
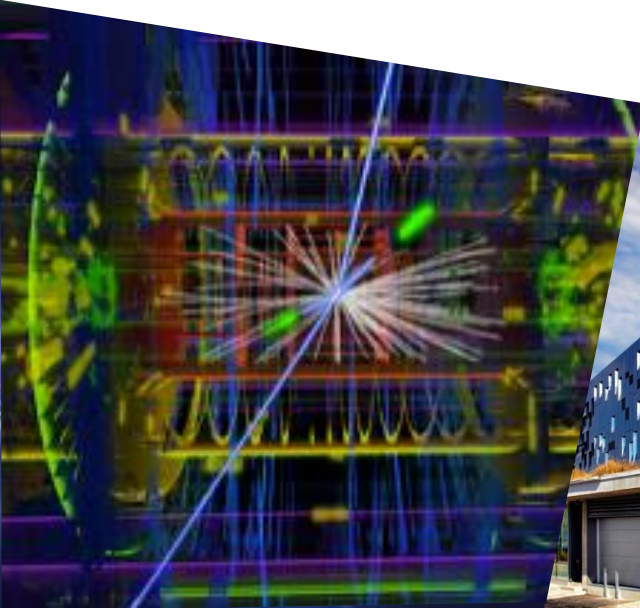
1500 tops per day

in each of 4 detectors

TeraZ will provide $\sim 10^{12}$ b pairs
and $1.7 \cdot 10^{11}$ τ pairs

[s-channel H $\sqrt{s} = 125$ GeV 5? years ~ 5000 $e^+e^- \rightarrow H_{125}$]

Some examples of Higgs opportunities at FCC-ee



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 $e^+e^- \rightarrow HZ$, yielding an absolute measurement of the HZZ coupling and a model independent extraction of Γ_H **(1.3% precision)**

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		
$\kappa_{\tau\nu}$ [%]	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

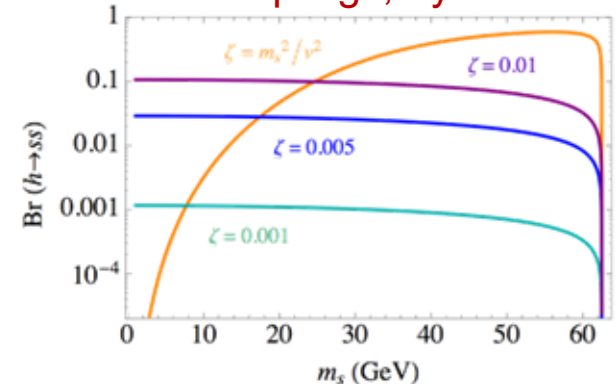
This assumes no-flavor violation couplings, but flavor violating channels should be explored

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 $\rightarrow \Gamma_H \sim 4 \text{ MeV}$
 - small couplings to BSM could have sizable BRs

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

can give $\text{BR}(h \rightarrow ss) \sim \mathcal{O}(10\%)$ for ζ as small as 0.01 !



Examples Scenarios for Higgs Exotic Decays

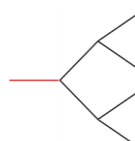
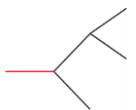
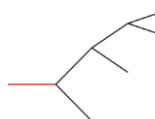
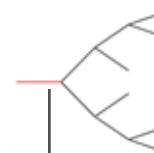
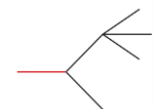
Higgs portals to new physics with suppressed SM couplings/ dark sector mediators

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

- 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	Decay Topologies	Decay mode \mathcal{F}_i
$h \rightarrow 2$	$h \rightarrow \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4$	$h \rightarrow (b\bar{b})(b\bar{b})$
$h \rightarrow 2 \rightarrow 3$	$h \rightarrow \gamma + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\tau^+\tau^-)$
	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (b\bar{b})(\mu^+\mu^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (jj)(\gamma\gamma)$
			$h \rightarrow (jj)(\mu^+\mu^-)$
$h \rightarrow 2 \rightarrow 3 \rightarrow 4$	$h \rightarrow (b\bar{b}) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$		
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
			$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$

Z. Liu et al. [arXiv:1312.4992](https://arxiv.org/abs/1312.4992) ; [arXiv:1612.09284](https://arxiv.org/abs/1612.09284)

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	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$		

LHC's strength

HL-LHC has large number of Higgs produced and great sensitivity to exotic decays into leptons and photons

Z. Liu et al. [arXiv:1312.4992](https://arxiv.org/abs/1312.4992) ; [arXiv:1612.09284](https://arxiv.org/abs/1612.09284)

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	$h \rightarrow (jj) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (jj)(jj)$
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	$h \rightarrow (\tau^+\tau^-) + \cancel{E}_T$		$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \rightarrow (\gamma\gamma) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
	$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T$		$h \rightarrow (\gamma\gamma)(\mu^+\mu^-)$
	$h \rightarrow (\mu^+\mu^-) + \cancel{E}_T$		$h \rightarrow \gamma\gamma + \cancel{E}_T$
$h \rightarrow 2 \rightarrow (1+3)$	$h \rightarrow b\bar{b} + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 4 \rightarrow 6$	$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + \cancel{E}_T$
	$h \rightarrow jj + \cancel{E}_T$		$h \rightarrow (\ell^+\ell^-) + \cancel{E}_T + X$
	$h \rightarrow \tau^+\tau^- + \cancel{E}_T$		$h \rightarrow \ell^+\ell^-\ell^+\ell^- + \cancel{E}_T$
	$h \rightarrow \gamma\gamma + \cancel{E}_T$		$h \rightarrow \ell^+\ell^- + \cancel{E}_T + X$
	$h \rightarrow \ell^+\ell^- + \cancel{E}_T$	$h \rightarrow 2 \rightarrow 6$	

LHC's strength

HL-LHC has large number of Higgs produced and great sensitivity to exotic decays into leptons and photons

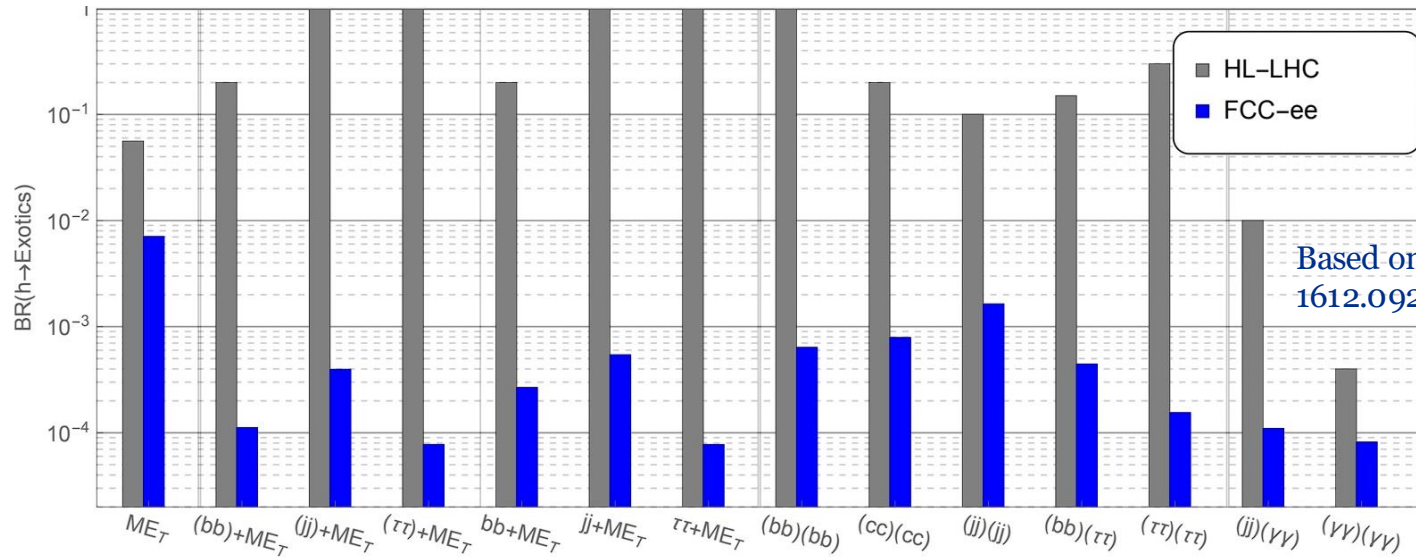
All the rest: challenging at the LHC due to missing energy and/or hadronic background

FCC-ee will have great opportunities to cover these searches

Z. Liu et al. [arXiv:1312.4992](https://arxiv.org/abs/1312.4992) ; [arXiv:1612.09284](https://arxiv.org/abs/1612.09284)

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

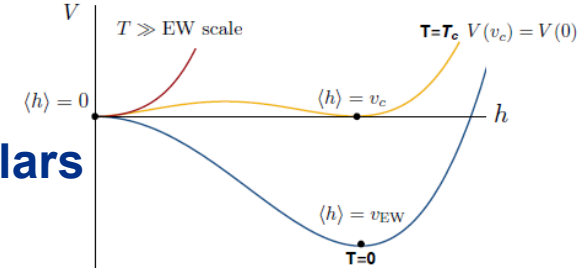
FCC—ee are from arXiv:1612.09284 and $ee \rightarrow ZH$ (except for the first channel, $h \rightarrow inv$)

Missing E_T , e.g. in SUSY/DM models yields about 2-4 orders of magnitude improvement

$H \rightarrow 4 f$, 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 $\rightarrow v(T_c)/T_c \geq 1$
- 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.**

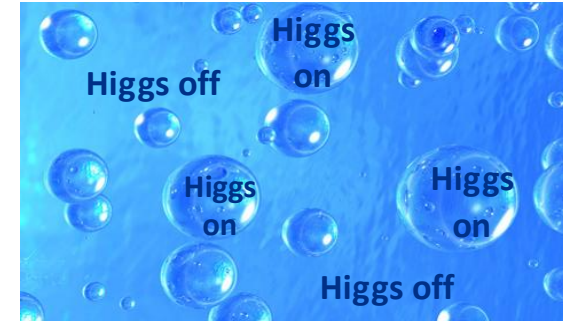
2HDMs

Models with Dark CP violation and gauged lepton/baryon number

Models of EW non-restoration, with multiple singlets and possibly with an inert doublet)

Supersymmetric models with singlets (MSSM ruled out by Higgs precision)

Models with heavy Fermions, etc.



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: $s \rightarrow -s$

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

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

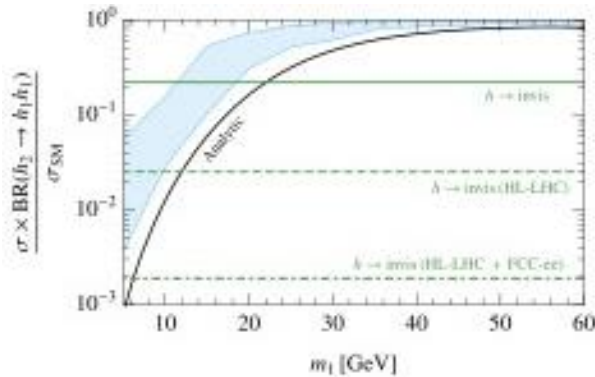
FCC prospects to determine the EWSB thermal history

- Z₂-symmetric (at T=0) scenario: Invisible Decays**

- Requires sizeable $s^2 |H|^2$ coupling for a 2-step strongly 1st order EWPT, $[(0,0) \rightarrow (0, v_S) \rightarrow (v, 0)]$, that calls for a careful treatment of perturbativity
- No S-H mixing – S is stable** (invisible decays)

BR(H)_{inv} bounds
(Missing E_T) or
pp → VSS (AP)
pp → SSjj (VBF)
Universal shift in
coupling via σ(ZH)

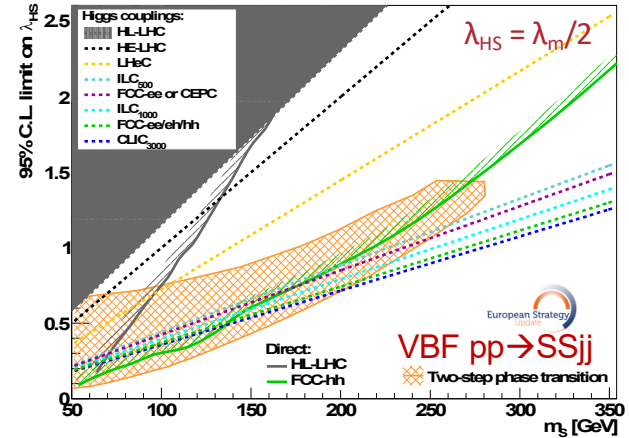
Low mass singlet: $m_s < m_{h/2}$



Current bounds
imply $m_s < 20$ GeV

Kozaczuk, Ramsey-Musolf, Shelton '19

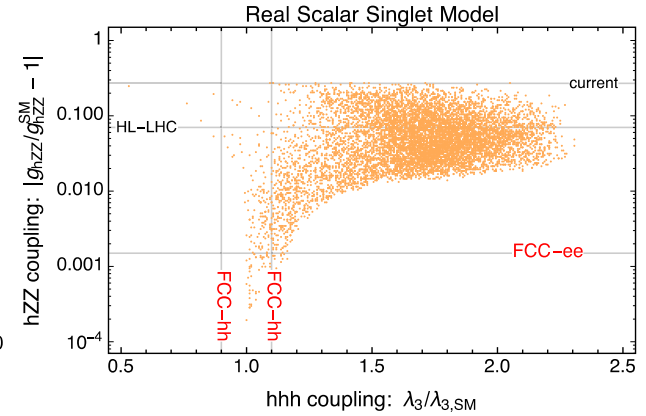
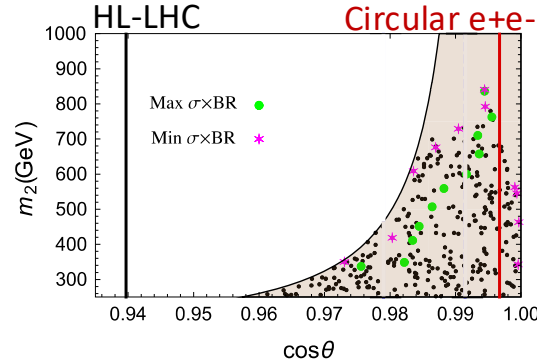
$m_s > m_{h/2}$



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

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 observe deviations in HZZ coupling and Higgs self coupling



Higgs Exotic Decays: $H \rightarrow SS$

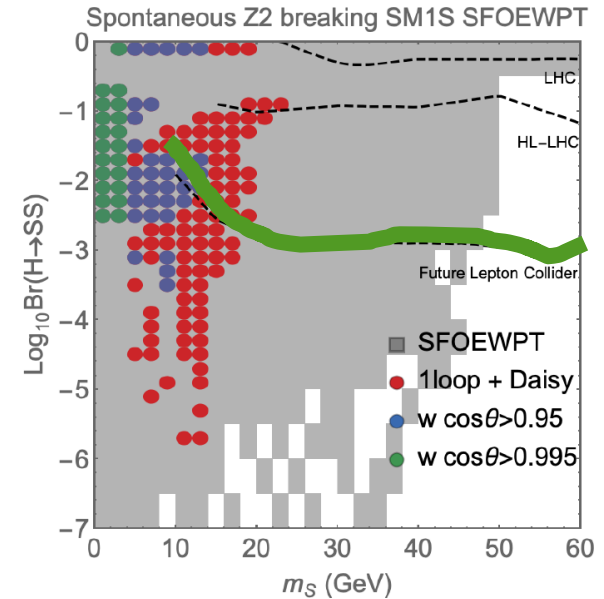
- If singlet sufficiently light \rightarrow **BR ($H \rightarrow SS$)** open
- Sizeable $s^2 |H|^2$ coupling needed for a strongly 1st order EWPT \rightarrow BR ($H \rightarrow SS$) to be bounded from below
- \rightarrow exotic Higgs decays are a potent probe of Singlet extensions with viable EW Baryogenesis

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

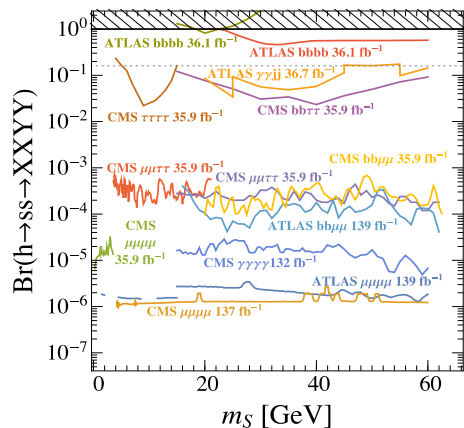


Higgs trilinear coupling receives variations at most at the 20% level, hence contributions to di-Higgs production only detectable at FCC-hh. Model parameter first probed at FCC-ee through mixing

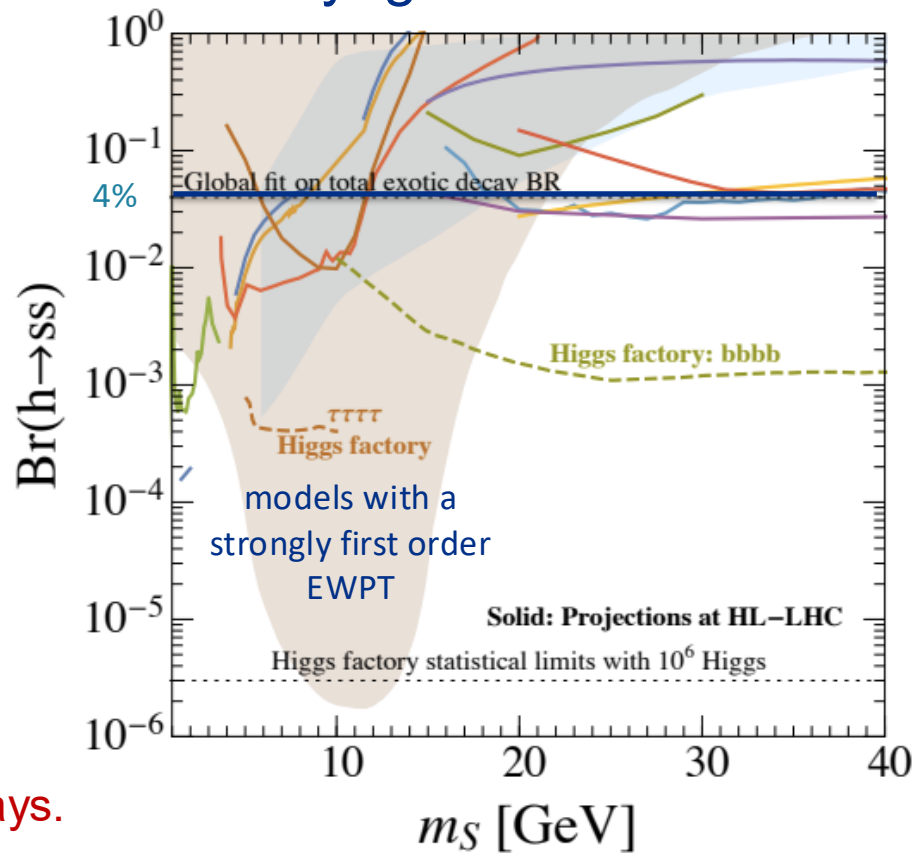
MC, Liu, Wang, [1911.10206](https://arxiv.org/abs/1911.10206)

Exotic Higgs decays as a probe of viable EW Baryogenesis

$H \rightarrow ss$ can lead to many final states with s inheriting Higgs-like hierarchical BR's, mediated through mixing



Bounds on $\text{Br}(h \rightarrow ss)$ from $\text{Br}(h \rightarrow ss \rightarrow \text{XXYY})$ and updated for HL-LHC projections



Given the clean environment with low background at lepton colliders \rightarrow there is ample scope for future studies in exotic decays.

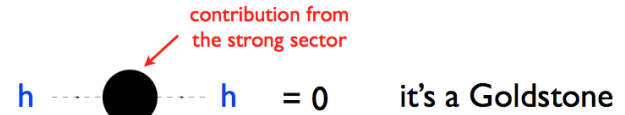
What is behind the EWSB mechanism?

➤ Composite Higgs

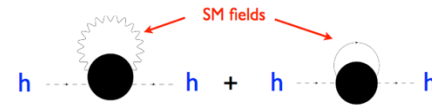
It emerges as bound state of a new strongly interacting composite sector characterized by a strong coupling $g_* \gg g_{\text{SM}}$ and a confinement scale m_* (like Λ_{QCD} but much higher)



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



Mass protected by the global symmetries



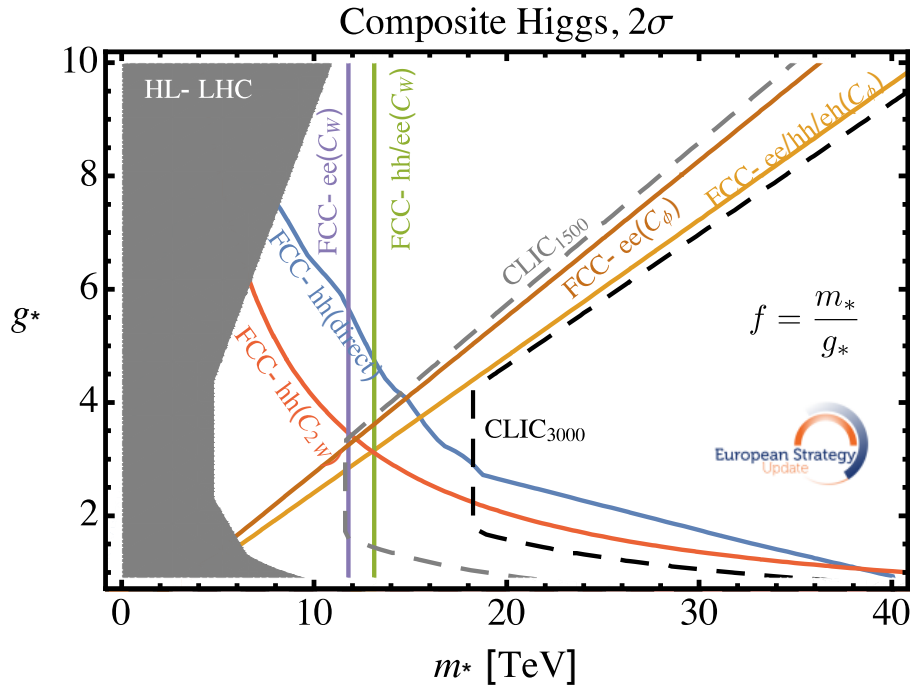
Mass generated at one loop: explicit breaking of global symmetry due to SM couplings

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

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

FCC-ee sensitivity to Composite Higgs

From probes of operators in the EFTCH



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

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

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

$$\mathcal{O}_W \sim \frac{1}{m_*^2} \frac{ig}{2} \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right) D^\mu W_{\mu\nu}^a$$

Dim. 6
Ops.

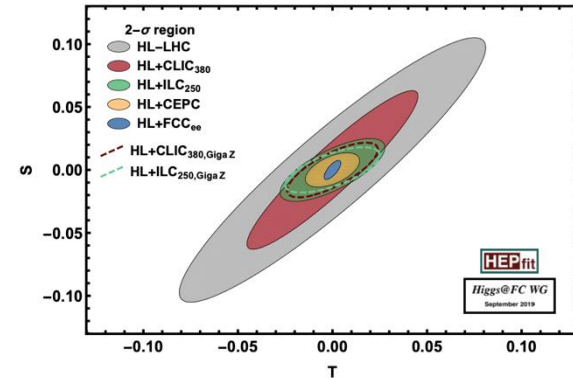
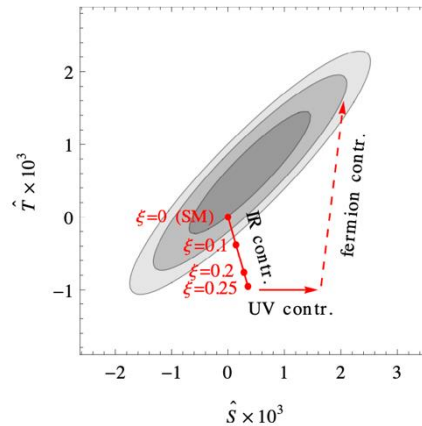
FCC-ee sensitive to $f \gtrsim 5$ TeV via modified Higgs self-interactions

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

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 $\rightarrow \xi = v/f$



arXiv:1905.0376

C. Grojean et. al, arXiv:1306.4655

G. Panico and A. Wulzer, arXiv:1506.01961

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

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

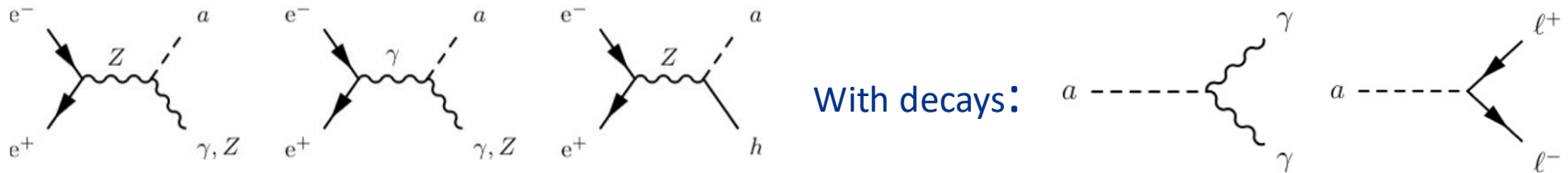
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \sum_\psi \frac{c_{ff}}{2} \frac{\partial^\mu a}{f} \bar{\psi} \gamma_\mu \gamma_5 \psi + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{\gamma\gamma} \frac{\alpha}{4\pi}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

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

- 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: $Z \rightarrow \gamma a$; $h \rightarrow Z a$; $h \rightarrow a a$;

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

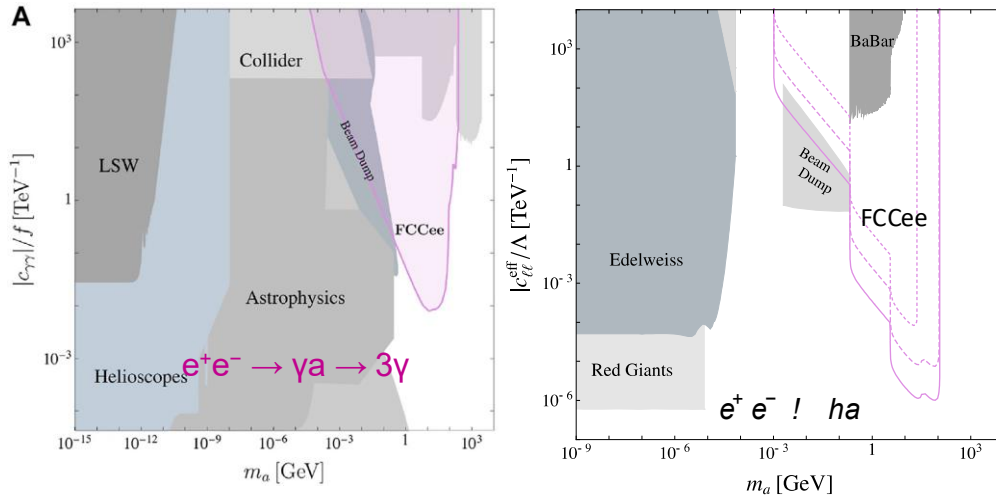


They can be searched for masses and decay lengths not explored elsewhere

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 (ECAL)

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

(right) $e^+e^- \rightarrow h a \rightarrow b\bar{b} l^+l^-$, $\text{Br}(a \rightarrow l^+l^-) = 1$ with $c_{hz} = 0.72(0.1)(0.015)\Lambda/\text{TeV}$ for solid (dashed) (dotted) contours.

Sensitivity based on 4 expected signal events

Bauer, Heiles, Neubert, Thamm arXiv: 1808.10323

Quantum information at FCC-ee

Thinking about particle physics in the language of quantum information may yield new fundamental insights and pave the way for new physics discoveries

- There is a fascinating relationship between entanglement and symmetry, seen for example:
 - in the Higgs sector (MC, Low, Wagner arXiv 2307:08112, +et al. arXiv 2505.00873),
 - SM fermion flavor mixing (Thaler and Trifinopoulos, arXiv:2410:23343).
- Using spin or flavor quantum numbers to define qubits, lots of recent work on how to extract quantum information from collider data (talk by Fabio Maltoni)
- Measuring entanglement, concurrence, discord, trace distance, magic, etc at FCC-ee will give a different window into the BSM physics.

e.g. see arXiv:2504:00086

Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics

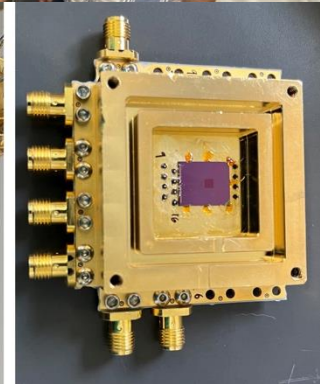
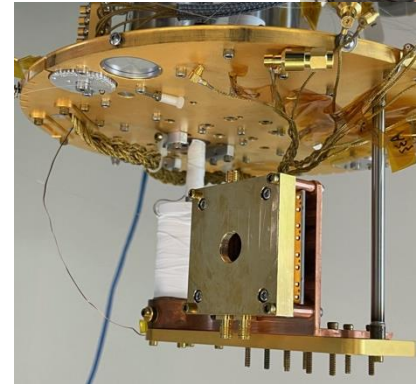
Quantum information at FCC-ee

- If we want to optimize the quantum information potential of FCC-ee, we should push for longitudinally polarized beams: useful but not in the baseline

e.g. see arXiv:2602:02719, Tao Han et al. and talk by Youle Su

- And if there are 4 detectors at FCC-ee, one of them should be **QUOD: the QUantum Optimized Detector**
- We also need more R&D towards adapting quantum sensor technology to collider detectors

Superconducting nanowire single photon detectors (SNSPDs) repurposed and scaled up as charged particle detectors in the CERN test beam



AI in the FCC era

- Dramatic changes are coming to how we do theory and experiment
- The AI landscape is changing so fast that any specific predictions we make, may look naive and obsolete in a year or two
- For example, agentic AI only became available less than two years ago, but is already being applied aggressively by particle physicists (talk by Konstantin Matchev)



The FERMIACC: Agents for Particle Theory

Agentic Diagrammatica: Towards Autonomous Symbolic Computation in High Energy Physics

HEPTAPOD: Orchestrating High Energy Physics Workflows Towards Autonomous Agency



Outlook

- The broad HEP program is pursuing many pathways, profiting from rapid technology advancements in AI and quantum.
- **FCC-ee is the bridge we can develop now** to explore the dynamics behind the Higgs sector and provides many opportunities for BSM discoveries.
- FCC-ee will connect to many other pathways for other HEP discoveries related to neutrinos, dark matter, cosmic, and flavor probes.
- We should be as ambitious as possible in designing the detectors/experiments for FCC-ee
- A successful FCC-ee paves the road for FCC-hh and gives momentum to a muon collider.



The maze has paths. Let's build the bridges to find them.



Extras

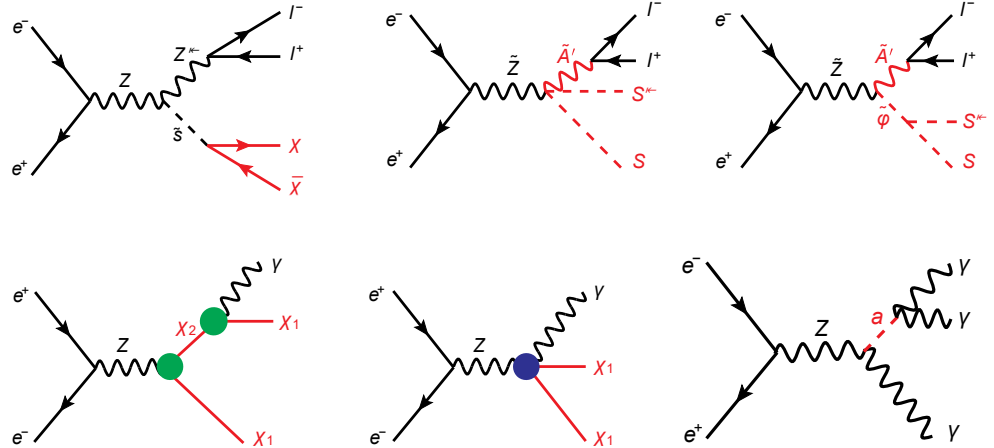
FCC-ee handles to exposing the Dark Sector

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

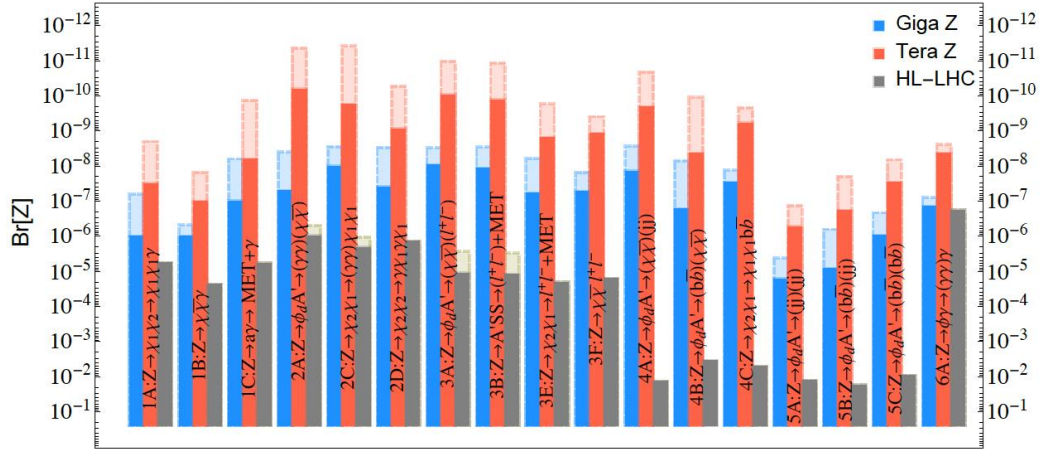
- Fermionic DM in Higgs –scalar portals
- scalar DM in vector portals
- Inelastic Fermionic DM in vector portals
- Magnetic and electric dipole operators with inelastic fermionic DM
- Axion Like-Particles



Z boson Exotic Decays exposing the Dark Sector

- TERA Z reach to Dark Sectors

exotic decays	topologies	n_{res}	models
$Z \rightarrow \tilde{E} + \gamma$	$Z \rightarrow \chi_1 \chi_2, \chi_2 \rightarrow \chi_1 \gamma$	0	1A: $\frac{1}{\Lambda_{1A}} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 B_{\mu\nu}$ (MIDM)
	$Z \rightarrow \chi \bar{\chi} \gamma$	0	1B: $\frac{1}{\Lambda_{1B}} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu}$ (RayDM)
	$Z \rightarrow a \gamma \rightarrow (\tilde{E}) \gamma$	1	1C: $\frac{1}{4\Lambda_{1C}} a B_{\mu\nu} \tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \rightarrow A' \gamma \rightarrow (\bar{\chi} \chi) \gamma$	1	1D: $e^{\mu\nu\rho\sigma} A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \rightarrow \tilde{E} + \gamma \gamma$	$Z \rightarrow \phi_d A', \phi_d \rightarrow (\gamma \gamma), A' \rightarrow (\bar{\chi} \chi)$	2	2A: Vector portal
	$Z \rightarrow \phi_H \phi_A, \phi_H \rightarrow (\gamma \gamma), \phi_A \rightarrow (\bar{\chi} \chi)$	2	2B: 2HDM extension
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \phi, \phi \rightarrow (\gamma \gamma)$	1	2C: Inelastic DM
	$Z \rightarrow \chi_2 \chi_2, \chi_2 \rightarrow \gamma \chi_1$	0	2D: MIDM
$Z \rightarrow \tilde{E} + \ell^+ \ell^-$	$Z \rightarrow \phi_d A', A' \rightarrow (\ell^+ \ell^-), \phi_d \rightarrow (\bar{\chi} \chi)$	2	3A: Vector portal
	$Z \rightarrow A' S S \rightarrow (\ell \ell) S S$	1	3B: Vector portal
	$Z \rightarrow \phi(Z/\gamma^*) \rightarrow \phi \ell^+ \ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \rightarrow \chi_2 \chi_1 \rightarrow \chi_1 A' \chi_1 \rightarrow (\ell^+ \ell^-) \tilde{E}$	1	3D: Vector portal and Inelastic DM
	$Z \rightarrow \chi_2 \chi_1, \chi_2 \rightarrow \chi_1 \ell^+ \ell^-$	0	3E: MIDM, SUSY
	$Z \rightarrow \bar{\chi} \chi \ell^+ \ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \rightarrow \tilde{E} + J J$	$Z \rightarrow \phi_d A' \rightarrow (\bar{\chi} \chi)(j j)$	2	4A: Vector portal
	$Z \rightarrow \phi_d A' \rightarrow (b \bar{b})(\bar{\chi} \chi)$	2	4B: Vector portal + Higgs portal
	$Z \rightarrow \chi_2 \chi_1 \rightarrow b \bar{b} \chi_1 + \chi_1 \rightarrow b \bar{b} \tilde{E}$	0	4C: MIDM
$Z \rightarrow (J J)(J J)$	$Z \rightarrow \phi_d A', \phi_d \rightarrow j j, A' \rightarrow j j$	2	5A: Vector portal + Higgs portal
	$Z \rightarrow \phi_d A', \phi_d \rightarrow b \bar{b}, A' \rightarrow j j$	2	5B: vector portal + Higgs portal
	$Z \rightarrow \phi_d A', \phi_d \rightarrow b \bar{b}, A' \rightarrow b \bar{b}$	2	5C: vector portal + Higgs portal
$Z \rightarrow \gamma \gamma \gamma$	$Z \rightarrow \phi \gamma \rightarrow (\gamma \gamma) \gamma$	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,
arXiv:1712.07237

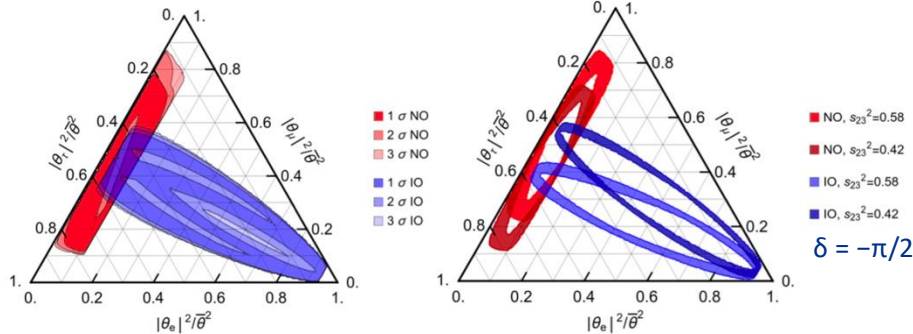
Feebly interacting/long-lived Particles: Heavy Neutral Leptons

HNL and a low scale seesaw at FCC-ee

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

- 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 $N_{\text{sterile}} = 2$



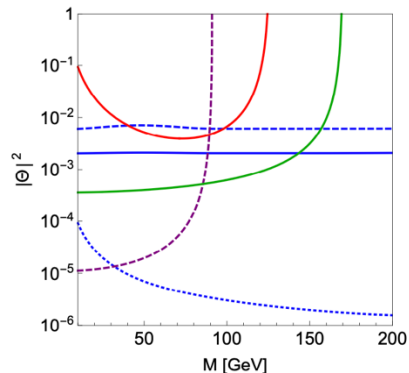
Relative flavor mixings consistent with current neutrino oscillation data

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

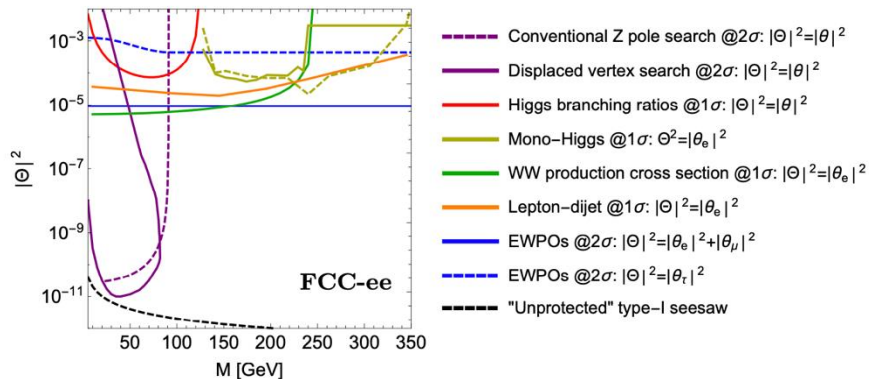
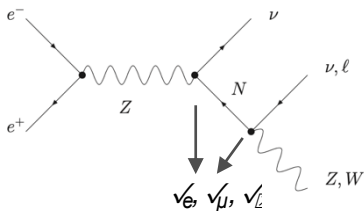


- EWP tests are sensitive to the thetas over a broad range of HNL masses, e.g. the Fermi constant extracted from muon decays now has a contribution $|\theta_e|^2 + |\theta_\mu|^2$
- NuTeV strongly constrains $|\theta_\mu|^2$
- Strong limits from DELPHI direct search at the Z pole for $Z \rightarrow \bar{\nu}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

FCC-ee reach for low scale seesaw

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

- DELPHI (Z pole search) @2 σ : $|\Theta|^2 = |\theta|^2$
- LHC (Higgs decays) @1 σ : $|\Theta|^2 = |\theta|^2$
- ALEPH ($e^+e^- \rightarrow 4$ leptons) @1 σ : $|\Theta|^2 = |\theta_e|^2$
- Precision constraints @2 σ : $|\Theta|^2 = |\theta_e|^2$
- ... Precision constraints @2 σ : $|\Theta|^2 = |\theta_\mu|^2$
- ... Precision constraints @2 σ : $|\Theta|^2 = |\theta_\tau|^2$

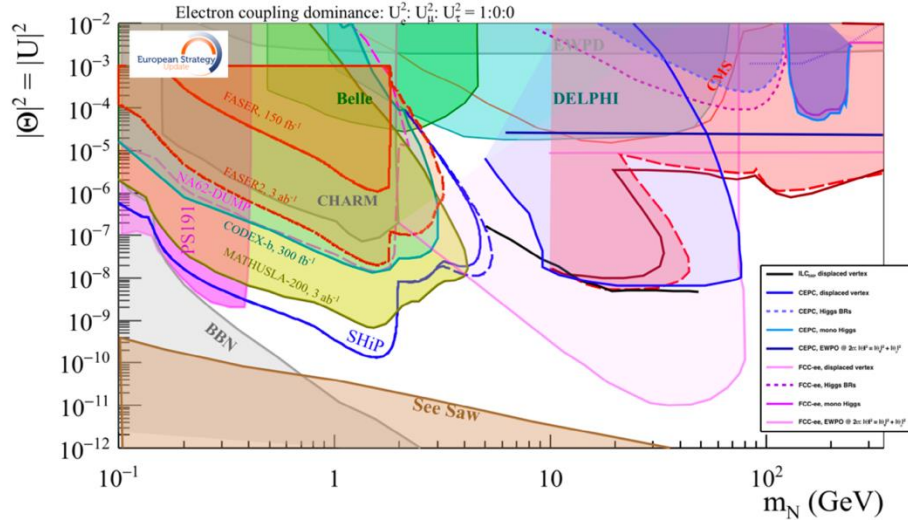


- Below the Z-pole, direct searches, with & without displaced vertices, are sensitive almost all the way down to the naive "unprotected" seesaw values

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

FCC-ee reach for low scale seesaw

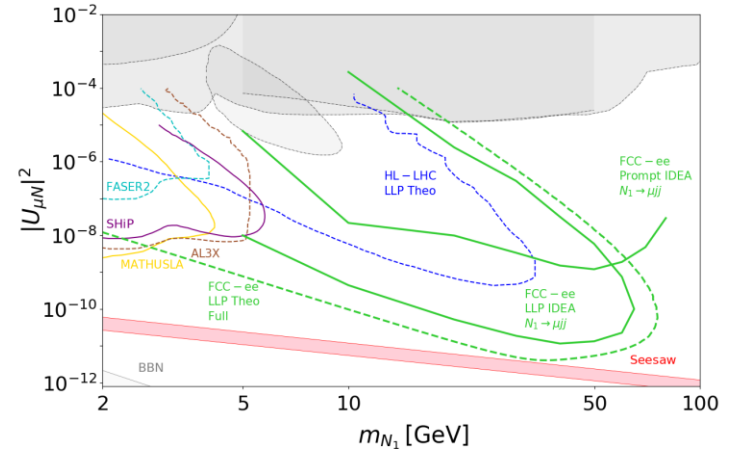
- Same information combined with other experiments



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 $\mu\nu jj$ final state, and seems to confirm the theoretical estimates we had before. This analysis can now be used for detector requirements

Grojean talk: 7th FCC Physics Workshop, Annecy 2024

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

CHMs generic predictions

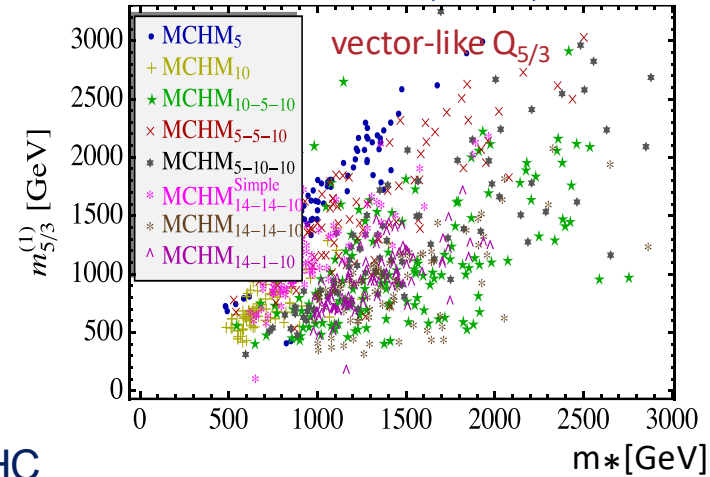
- One/more of the lightest heavy fermions could be seen at LHC
 - Predictions and interpretations will be model dependent
 - Discovery of such particles may point towards Composite Higgs, but how to learn more?
- Higgs has variations of its couplings to SM particles through elementary + composite sector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

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

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

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

M.C., Da Rold, Ponton'14



LHC bounds $\rightarrow m_* > 1.4 \text{ TeV}$

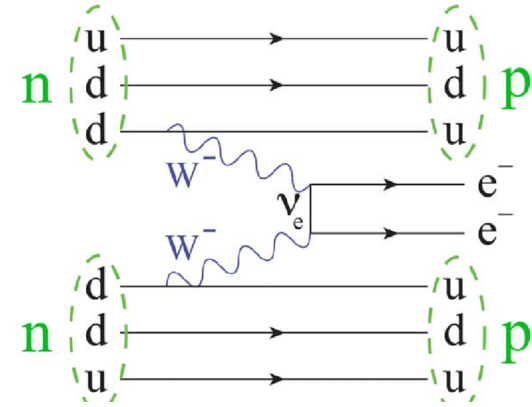
D. Liu et. al, arXiv:1603:03064
de Blas et. al, arXiv:1905.03764

Neutrinoless double beta decay: Majorana phases and CP violation

Neutrinoless double beta decay ($0\nu\beta\beta$) is a lepton number violating process that, if observed, shows neutrinos are Majorana

The half-life for $0\nu\beta\beta$ is proportional to square of the “effective Majorana mass” $m_{\beta\beta}$

$$m_{\beta\beta} = \left| m_1 \cos^2 \theta_{12} \cos^2 \theta_{13} + m_2 e^{2i\lambda_2} \sin^2 \theta_{12} \cos^2 \theta_{13} + m_3 e^{2i(\lambda_3 - \delta)} \sin^2 \theta_{13} \right|$$



Venktesh Singh

- Here δ is the Dirac phase, and λ_2 , λ_3 are the two additional Majorana phases
- The inverted mass hierarchy is the most favorable case for the experiments; in this case

$$m_{\beta\beta}^{\text{inv}} \simeq \cos^2 \theta_{13} \left[(m_1 \cos^2 \theta_{12})^2 + (m_2 \sin^2 \theta_{12})^2 + 2 \cos(2\lambda_2) m_1 \cos^2 \theta_{12} m_2 \sin^2 \theta_{12} \right]^{1/2}$$

- So experiments may be sensitive to the value of one of the Majorana phases

Axion Searches

- Various experimental constraints restrict f_a to the range $10^9 - 10^{12}$ GeV
- The axion mass is then fixed: $m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$
- An axion can convert to two photons, with a coupling that is somewhat model dependent

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a/N} \left(\frac{E}{N} - 1.92 \right)$$

- Axion direct dark matter searches use resonant cavities inside magnets, trying to detect an axion converting to a single photon in the cavity
- Many other kinds of experiments and astrophysical observations have more general sensitivity to axions

