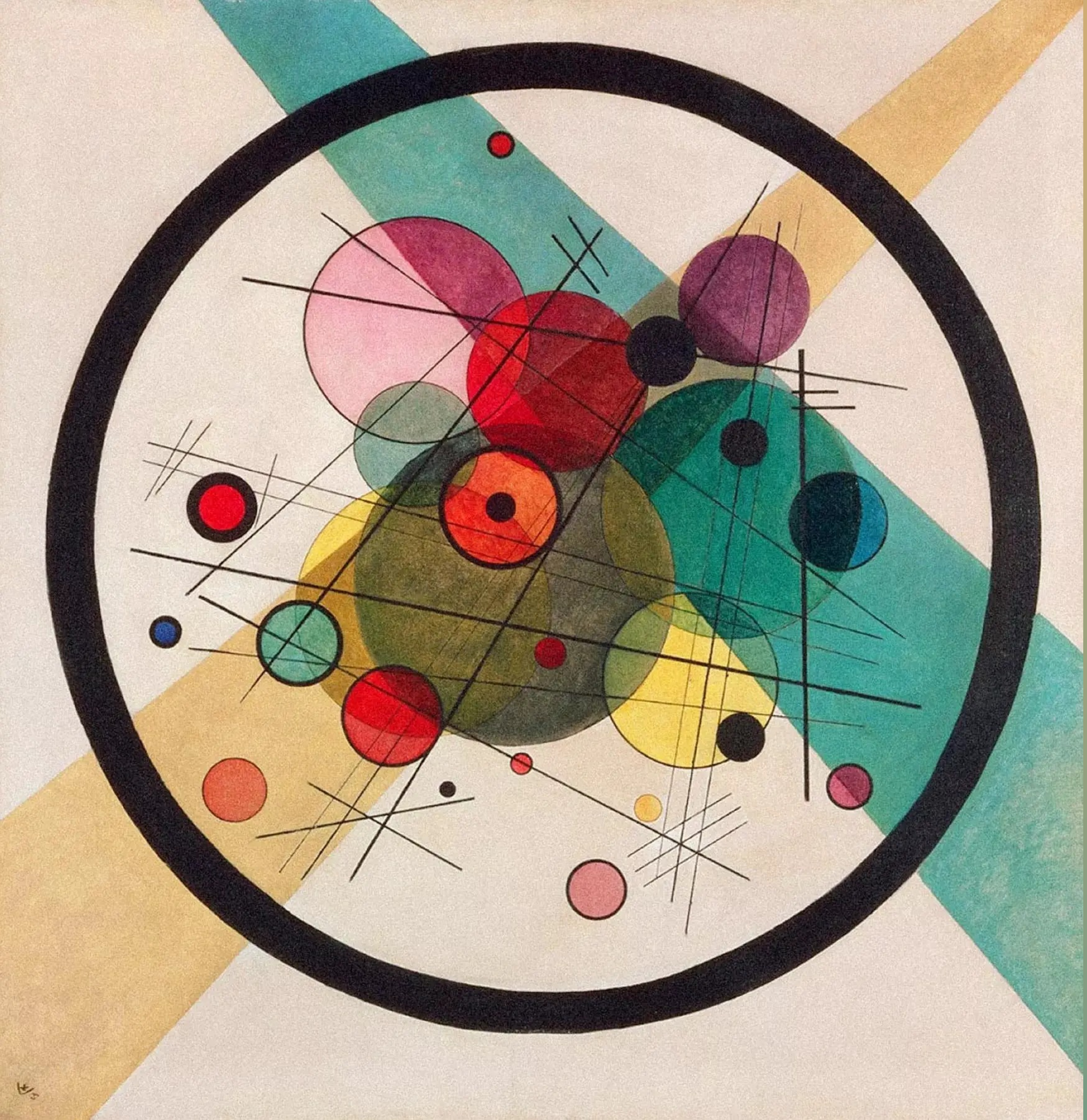


Topical lectures on
Future particle colliders
Theory:

The need for a new collider

March 20, 2024

Juraj Klarić

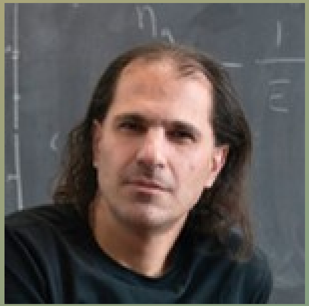
Disclaimers

- In preparing I was inspired by talks by **Matthew McCullough, Cristophe Groejan, Sophie Renner, Gavin Salam…**

- Most of the forecasts focus on the FCC – similar estimates should also hold for the CEPC, the ILC and muon colliders are *very different beasts*
- The list of motivations for future colliders covered here is ***far from exhaustive***
  - apologies if your favorite BSM model was left out
- I am not a BSM model-builder – I primarily work on particle cosmology – my views may be biased

Now that you are aware of my biases, let me ask you about yours!

Why do we need a new collider?



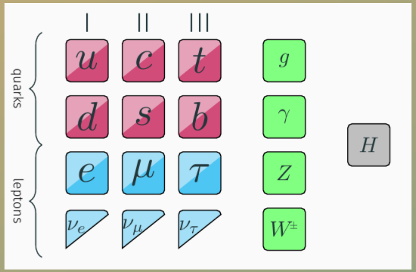
N. Arkani-Hamed

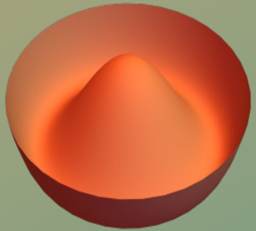
*The biggest bottleneck is:
Is there a big enough group
of young experimentalists who
think devoting twenty,
thirty years of their lives to
studying the hell out of the
Higgs is worth it?*

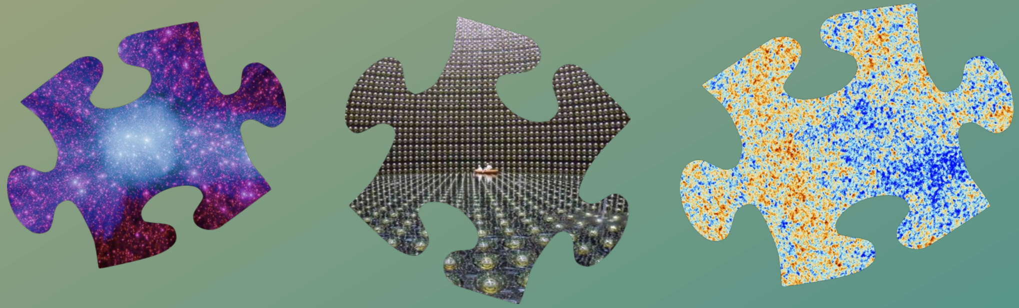
Two main goals

- Test the **Standard Model (SM)**
  - In spite of its immense success, many things remain **untested**
  - We have only seen ***5*** of the ***12 expected Higgs*** couplings!

- Look for **new physics beyond the SM**
  - There are many questions that cannot be answered within the SM framework ***(dark matter, baryogenesis, neutrino masses…)***

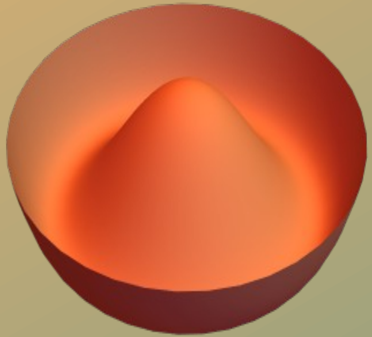






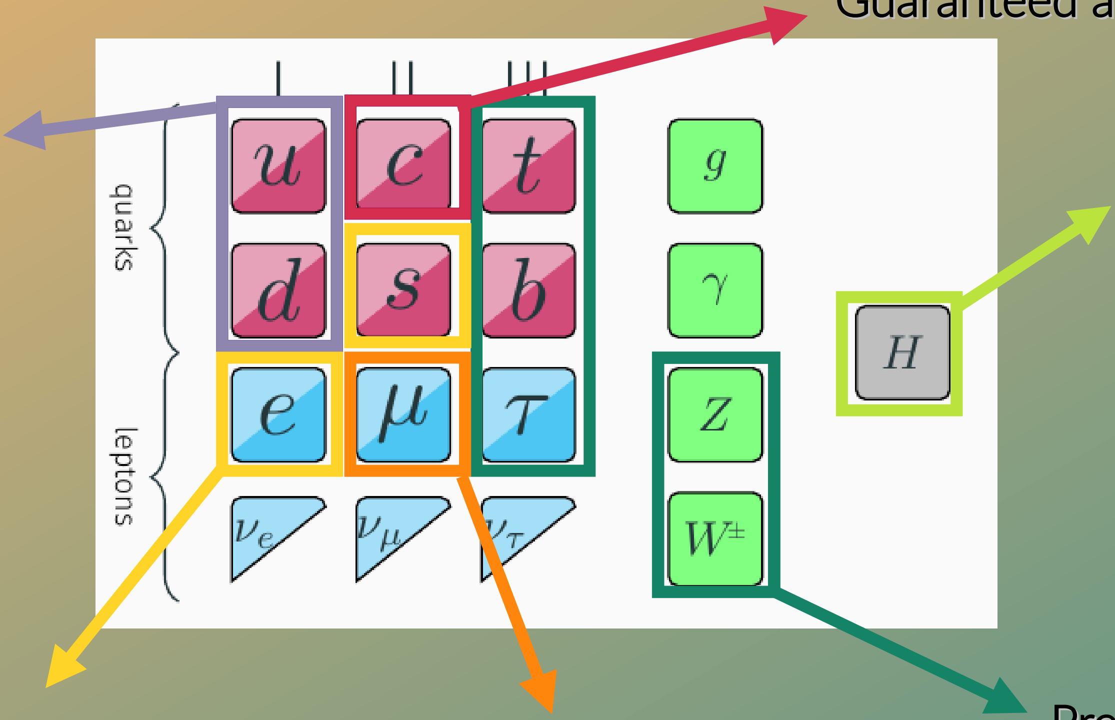
What do we know about the Higgs?

$$\mathscr{L} = yH\psi\bar{\psi} + \mu^2|H|^2 - \lambda|H|^4$$



- 12 years after discovery, still the greatest achievement of the LHC
- Least understood part of the SM
- Only spin-0 particle observed

What does the Higgs interact with?



Guaranteed at FCC-ee

No obvious method, new ideas needed!

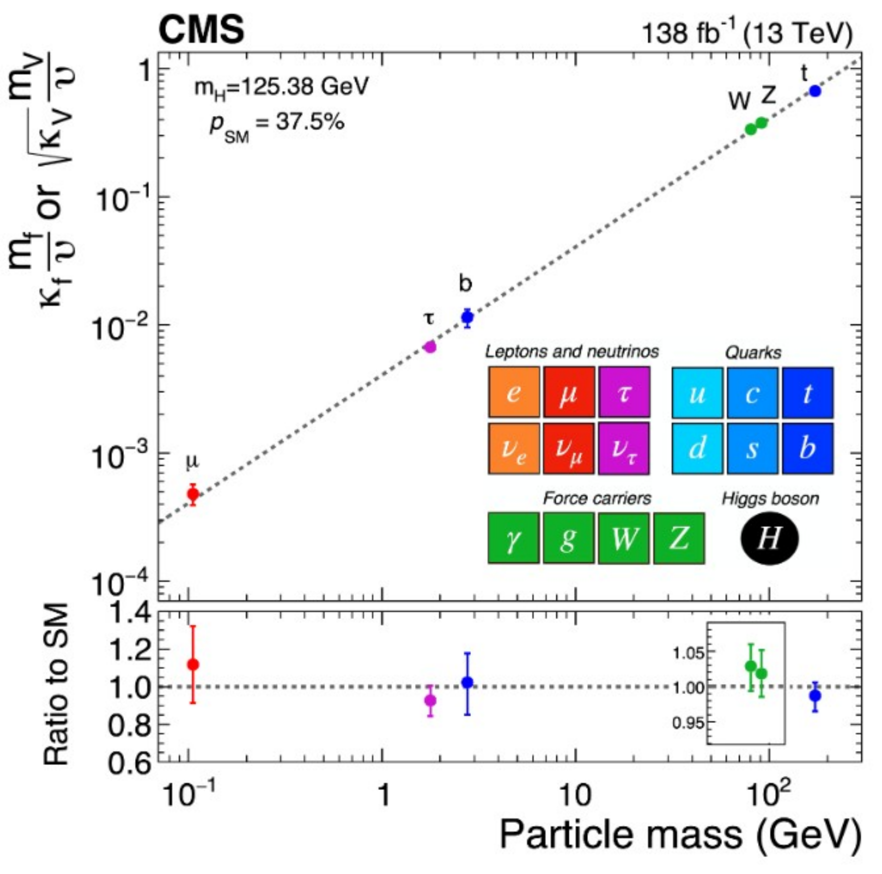
Possible at FCC-hh

Close to measurable at FCC-ee

Expected at the LHC at a 3σ level!

Predicted and measured in direct interactions with H at a 5 σ level!

Measuring the Higgs couplings



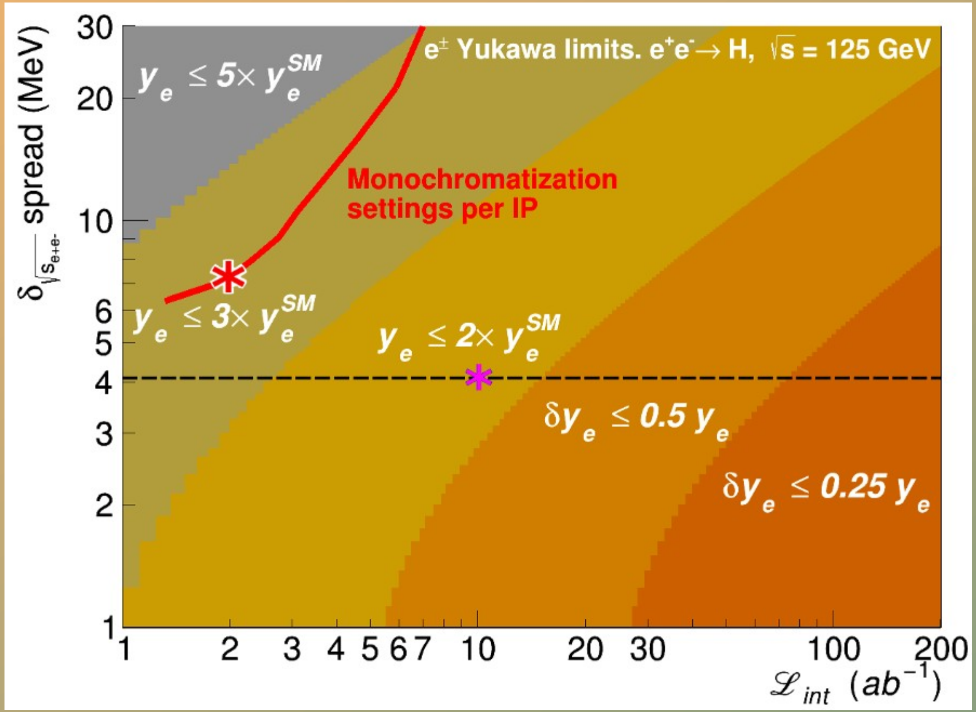
Nat. Phys. 18 (2022) 1329

- So far we have measured couplings to:
  - gauge bosons **W** and **Z**
  - 3rd generation quarks (**t** and **b**)
  - 3rd generation leptons (**τ**)
- LHC on track to see $H \rightarrow \mu\mu$
  - *First couplings beyond the 3rd generation!*
- Next goal:
  - Full 2nd generation:

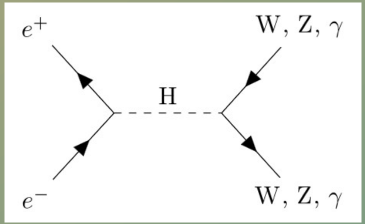
    μ *(LHC),* **c** *(FCC-ee) and* **s***?*

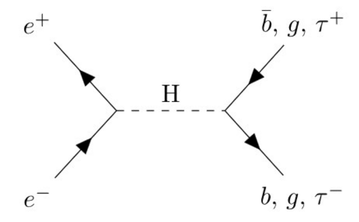
Can we measure the electron Yukawa?

Measuring the electron Yukawa



- At e^+e^- colliders one could directly measure the coupling to electrons
- Resonant production in e^+e^- collisions



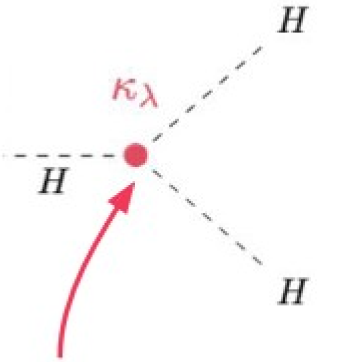


- Only visible after reducing the c.m. energy spread

D. Enterria et. al. 2107.02686

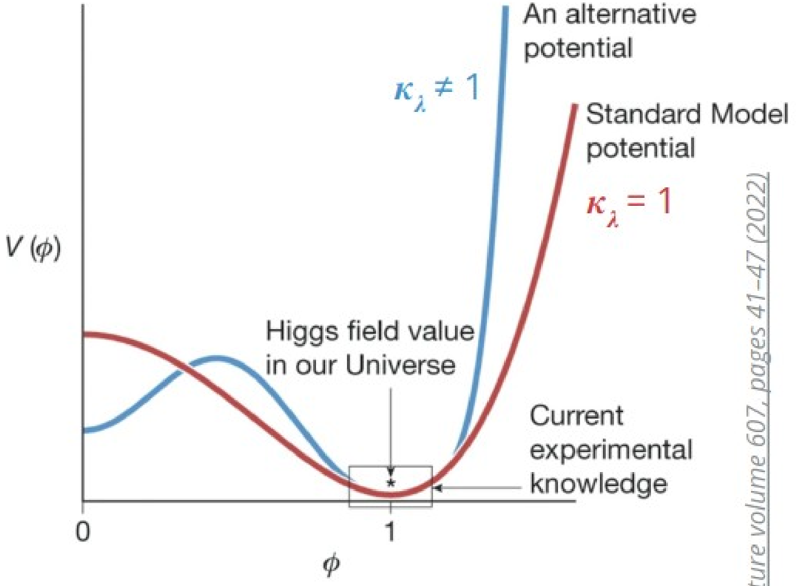
The path to Higgs self-coupling

The Higgs self-coupling



Higgs self-coupling modifier: $\kappa_\lambda = \lambda^{meas}/\lambda^{SM}$

$$V = \frac{m_H^2 v^2}{8}\left(-1 + 4h^2 + 4h^3 + h^4\right)$$

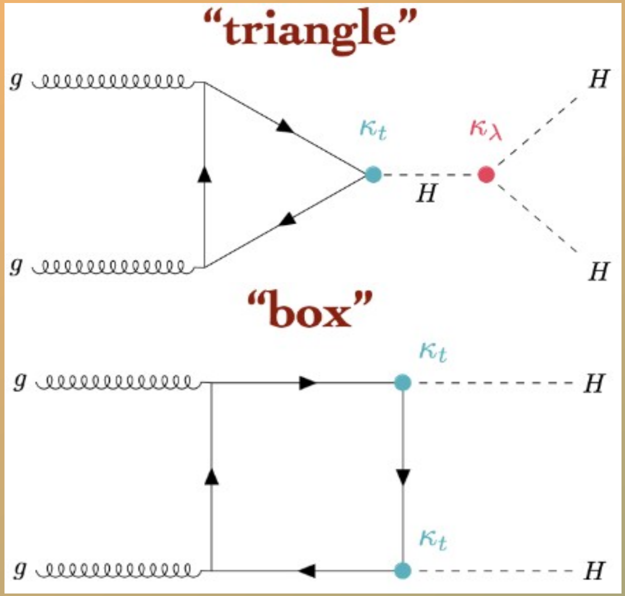


Nature volume 607, pages 41–47 (2022)

$$V(\Phi^+\Phi) = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

From the talk by Angela Taliercio, Birgit Stapf at the 7th FCC Physics Workshop, Annecy

How to measure the H self-coupling?

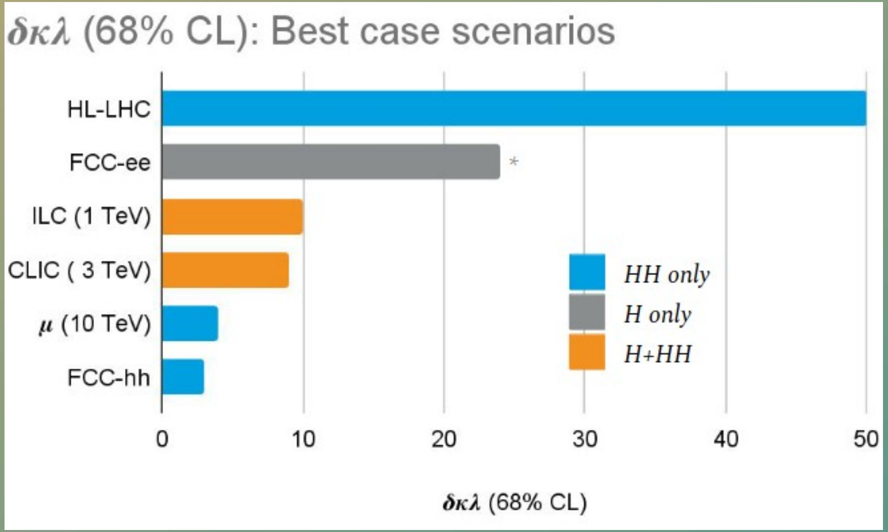


- Interference makes **σ ~ λ**
- Tiny cross section in the SM:
  σ(ggHH) ~ σ(ggH) / 1000
- Very challenging experimentally!

- Currently we only have limits:

$-0.4 < \kappa_\lambda < 6.3$ (*ATLAS-HDBS-2022-03*)

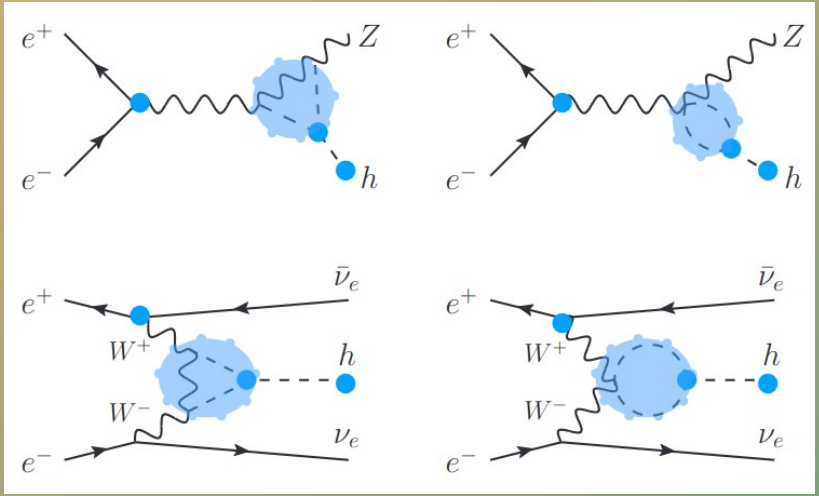
- How about future colliders?



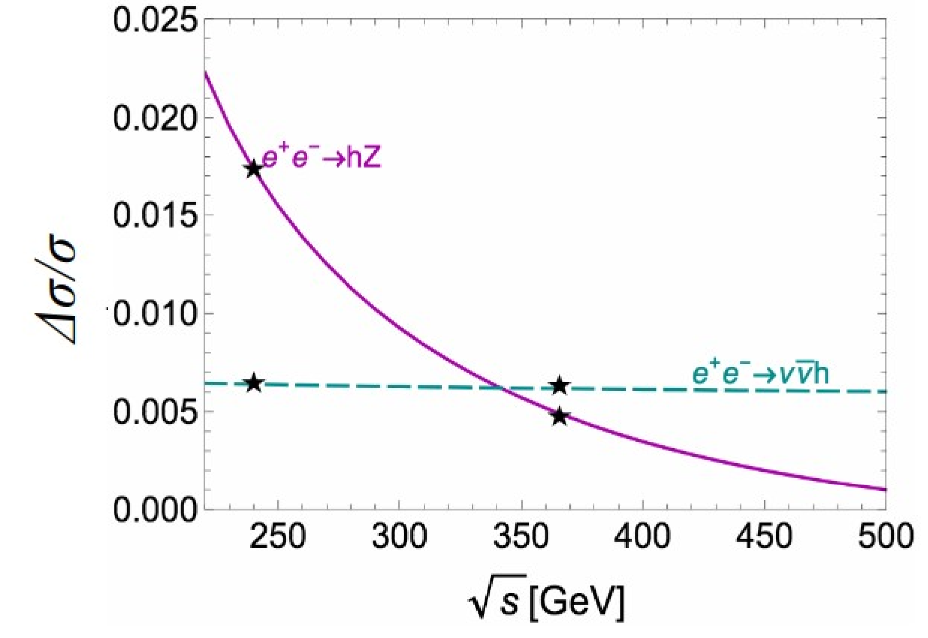
From the talk by Angela Taliercio, Birgit Stapf at the 7th FCC Physics Workshop, Annecy

Indirect Higgs self-coupling at FCCee

- Higgs precision can be sensitive to radiative corrections
- Already single-Higgs observables can lead to self-coupling determination



Di Vita, et al arXiv:1711.03978



- Combination of 240 + 360 GeV runs provides a bound on the h^3 coupling!

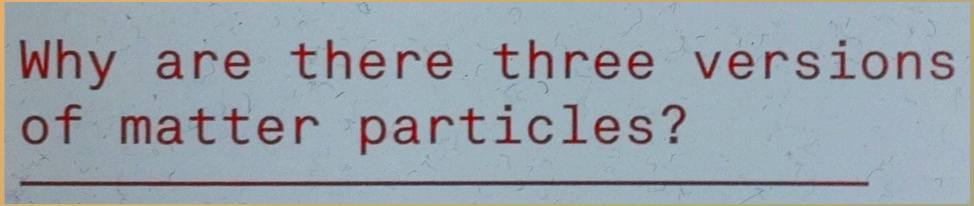
The SM Higgs physics case at future colliders

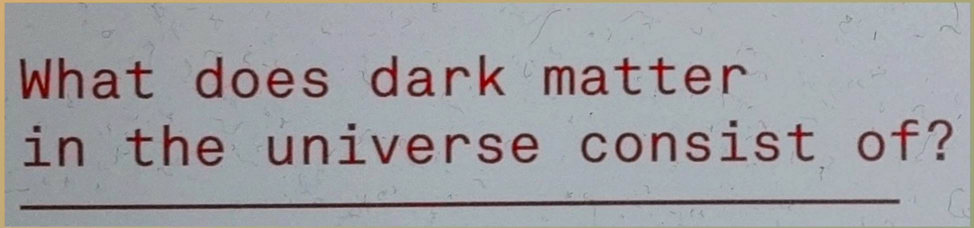
- Expected per-mile level accuracy in couplings
- Sensitive to interactions beyond the reach of the HL-LHC:
  - Charm (perhaps strange) Yukawas
  - Electron Yukawa?
  - Self-couplings: accessible both at e^+e^- and hh colliders
- Determination of the Higgs width to 1% precision

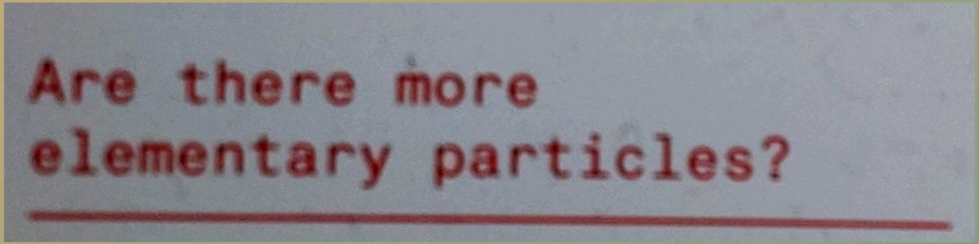
Several "no-lose theorems" in the Higgs sector!

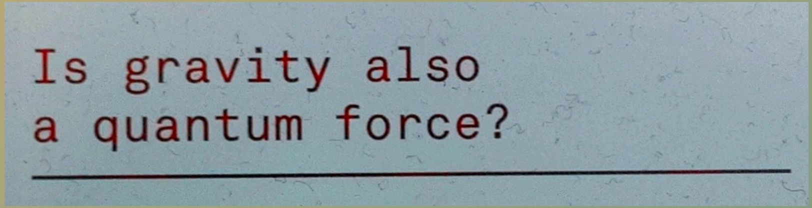
To the SM and beyond!

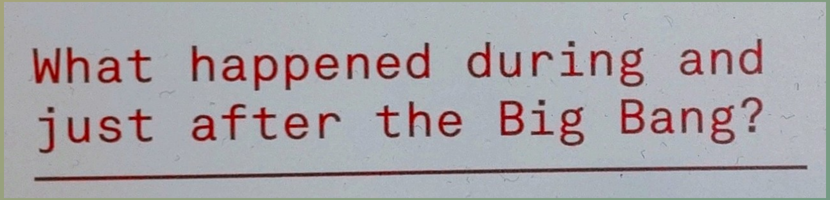
BSM physics is a part of the Nikhef building

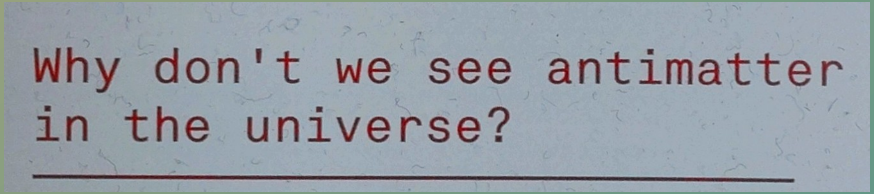

Why are there three versions of matter particles?


What does dark matter in the universe consist of?


Are there more elementary particles?


Is gravity also a quantum force?


What happened during and just after the Big Bang?


Why don't we see antimatter in the universe?

How do neutrinos get their masses?

BSM exploration at future colliders

Higgs physics

- New physics directly coupled to the Higgs
- New physics affecting the Higgs potential

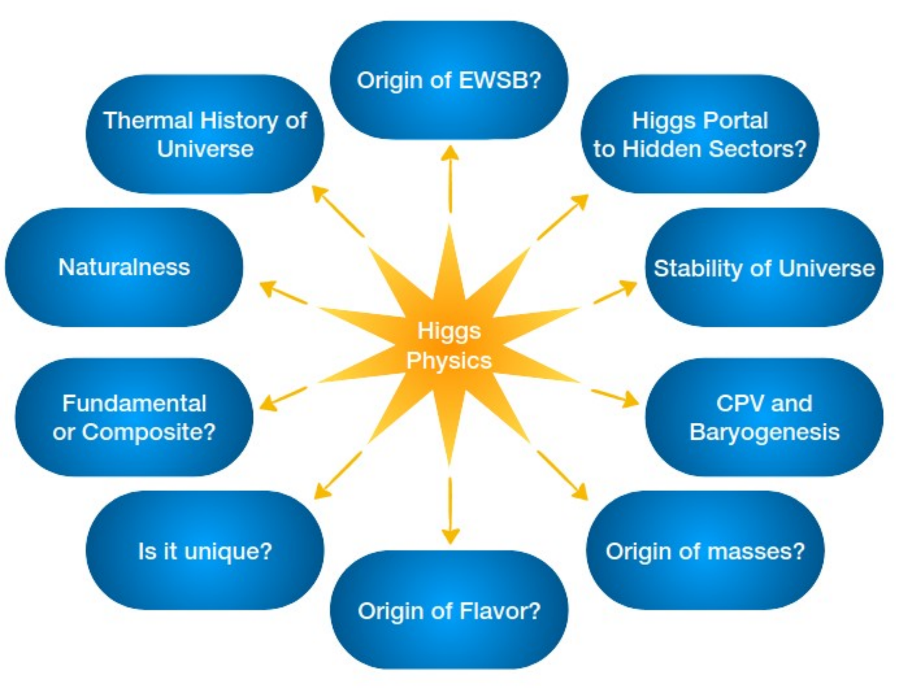
EW and Flavor

- Per-mil accuracy on EW parameters
- B-physics
- τ-physics

Light new physics

- Feebly coupled states that avoid usual searches

Higgs as path to BSM



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

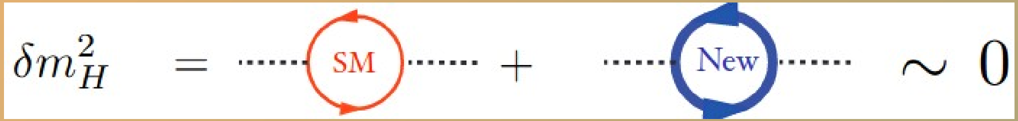
Fundamental or Composite?

Naturalness

Thermal History of Universe

Many of the SM problems are directly connected to the Higgs!

Higgs Naturalness



For e.g. top partners of mass M

$$\delta m_h^2 \sim \frac{N_c y_t^2}{4\pi^2} M^2$$

$$\Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500 \text{ GeV}}\right)^2$$

- Not clear how the Higgs gets it’s mass
- We may expect new physics below the Planck scale
- Why is then $\boldsymbol{M_h \ll M_P}$?
- Large corrections for heavy new physics!
- Several ways out:
  - SUSY
  - Compositness
  - Relaxion…

The great energy desert?

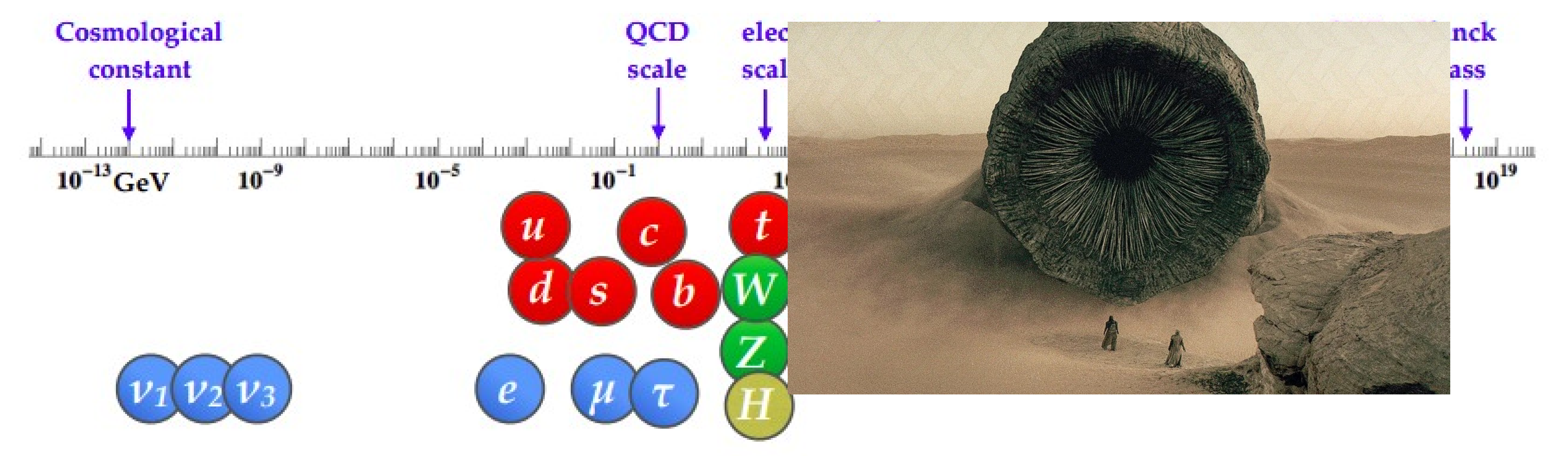
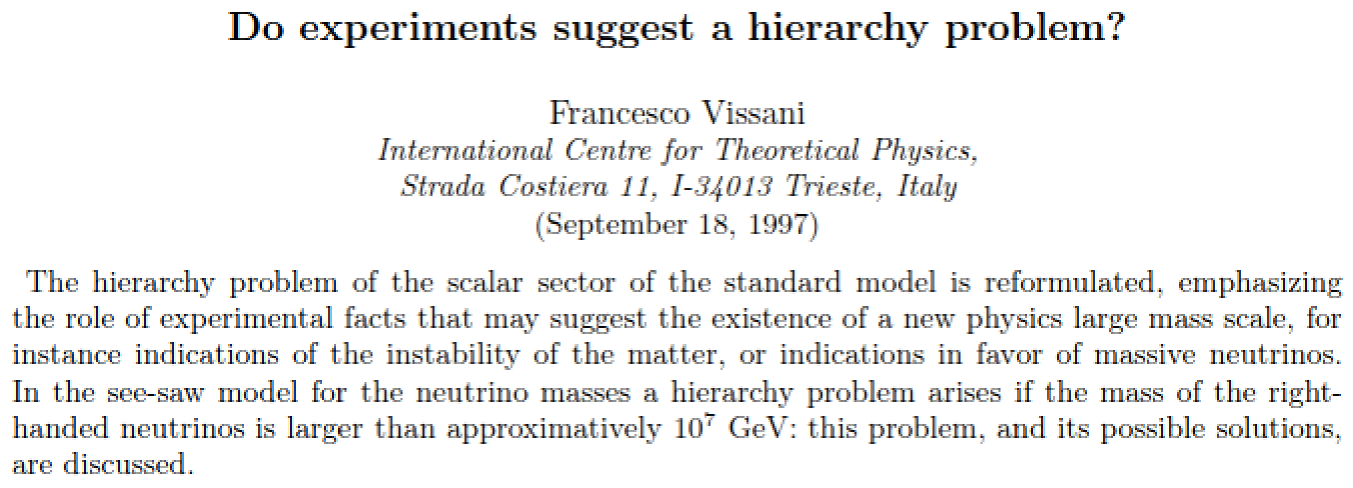


Image credit:
Oz Amram @ Particle Bites

Credit: Warner Bros.

The hierarchy problem and neutrino masses

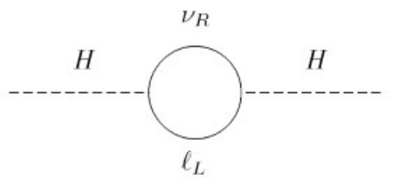


Do experiments suggest a hierarchy problem?

Francesco Vissani
International Centre for Theoretical Physics,
Strada Costiera 11, I-34013 Trieste, Italy
(September 18, 1997)

The hierarchy problem of the scalar sector of the standard model is reformulated, emphasizing the role of experimental facts that may suggest the existence of a new physics large mass scale, for instance indications of the instability of the matter, or indications in favor of massive neutrinos. In the see-saw model for the neutrino masses a hierarchy problem arises if the mass of the right-handed neutrinos is larger than approximatively 10^7 GeV: this problem, and its possible solutions, are discussed.

$$\delta\mu^2 \approx \frac{y_\nu^2}{(2\pi)^2}\, M_R^2\, \log(q/M_R)$$



$$m_\nu(\text{solar}) = 3\times 10^{-3}\ \text{eV}$$

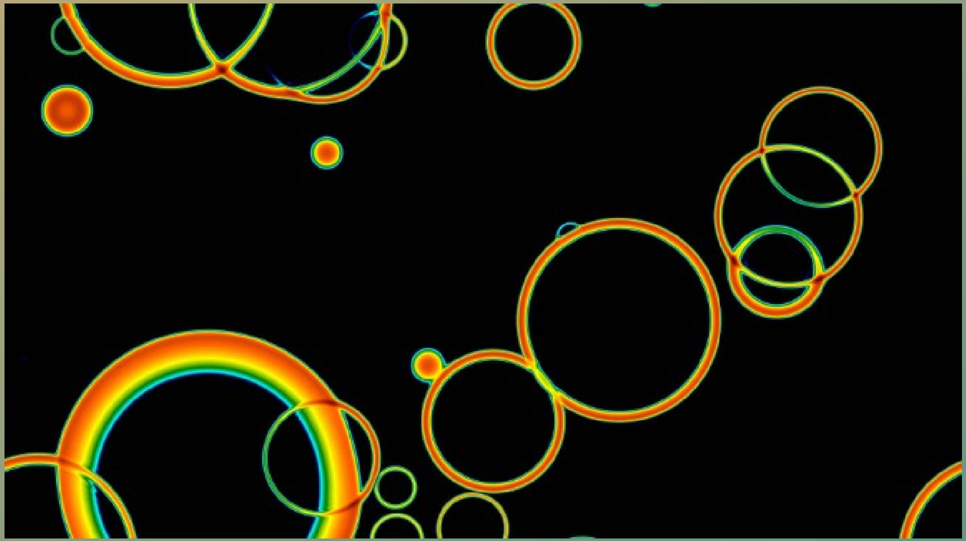
$$M_R \lesssim 7.4\times 10^{7}\ \text{GeV}$$

$$y_\nu \lesssim 8.5\times 10^{-5}$$

In the absence of supersymmetry neutrino masses imply
"light" and ***"feebly coupled"*** *right-handed neutrinos!*

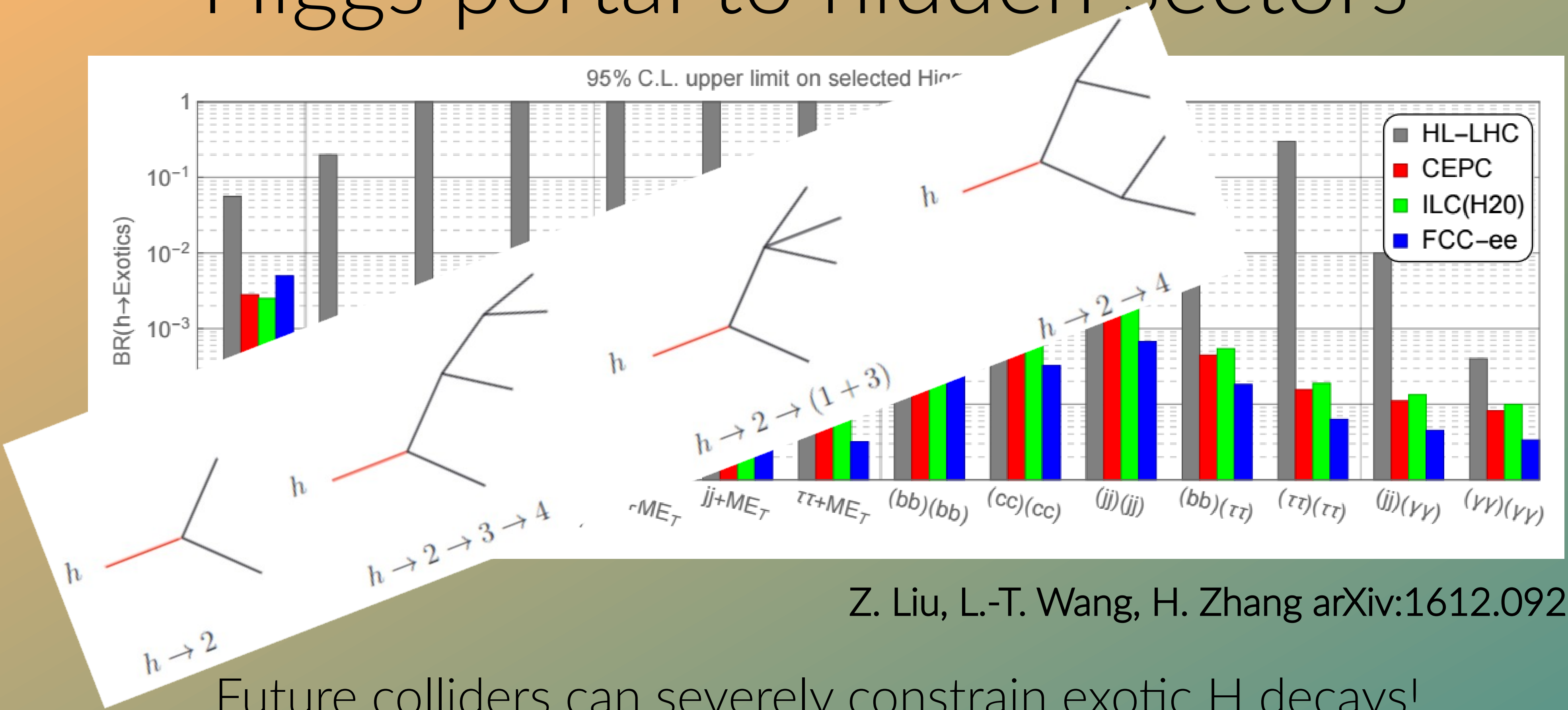
Higgs and the thermal history of the Universe

- In the SM, there are no **first-order phase transitions** (FOPT)
- *Modifications of the Higgs potential* could lead to a FOPT
- Large deviation from equilibrium can lead to **baryogenesis**
- Colliding bubbles of true vacuum – **Gravitational Waves**?
- Potential complementarity between **GW observatories** (LISA) and **future colliders**?



D. Weir 1705.01783

Higgs portal to hidden sectors



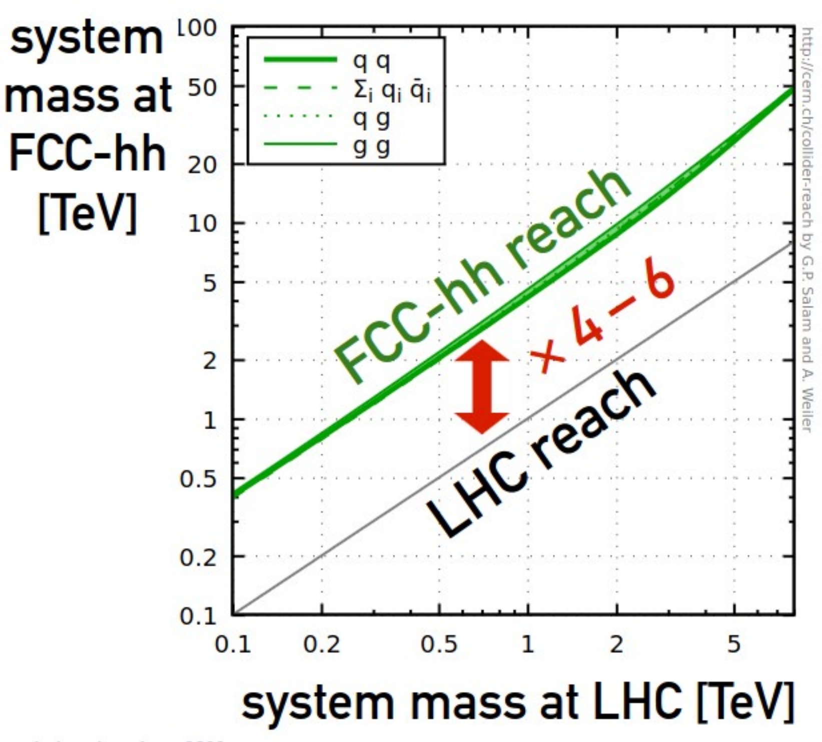
Z. Liu, L.-T. Wang, H. Zhang arXiv:1612.09284

Future colliders can severely constrain exotic H decays!

Direct exploration of higher energies

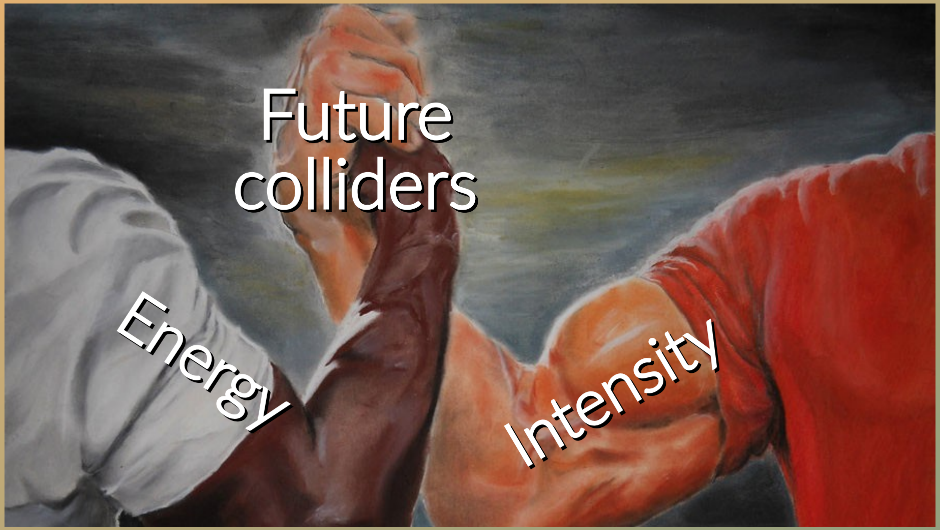
Toy example of **Z’** in the MSSM:

- **LHC**, 13 TeV, 139 fb^{-1}:
  - sensitive to Z’ masses up to **5.1 TeV**
- **FCC-hh**, 100 TeV, 20 ab^{-1}:
  - Sensitive to Z’ masses up to **41 TeV**
- **A factor ~8 improvement!**



Based on the talk by Gavin Salam, FCC Week 2023

Energy or Intensity frontiers?



- Searches for new physics are often separated into intensity or energy experiments
- Future colliders can do both
- Prime example:
  - **Tera-Z @ FCC-ee!**

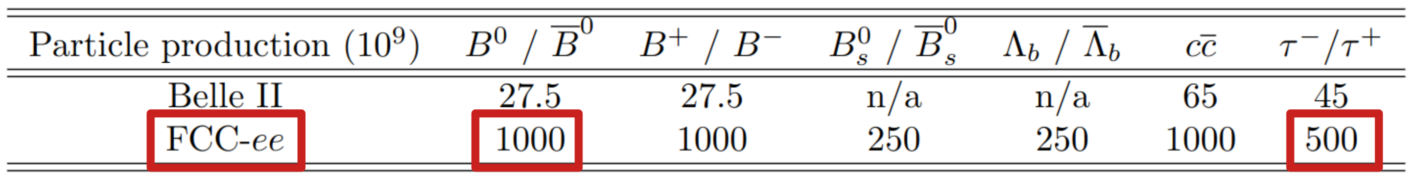
Tera-Z

What would you do with a trillion Z bosons?

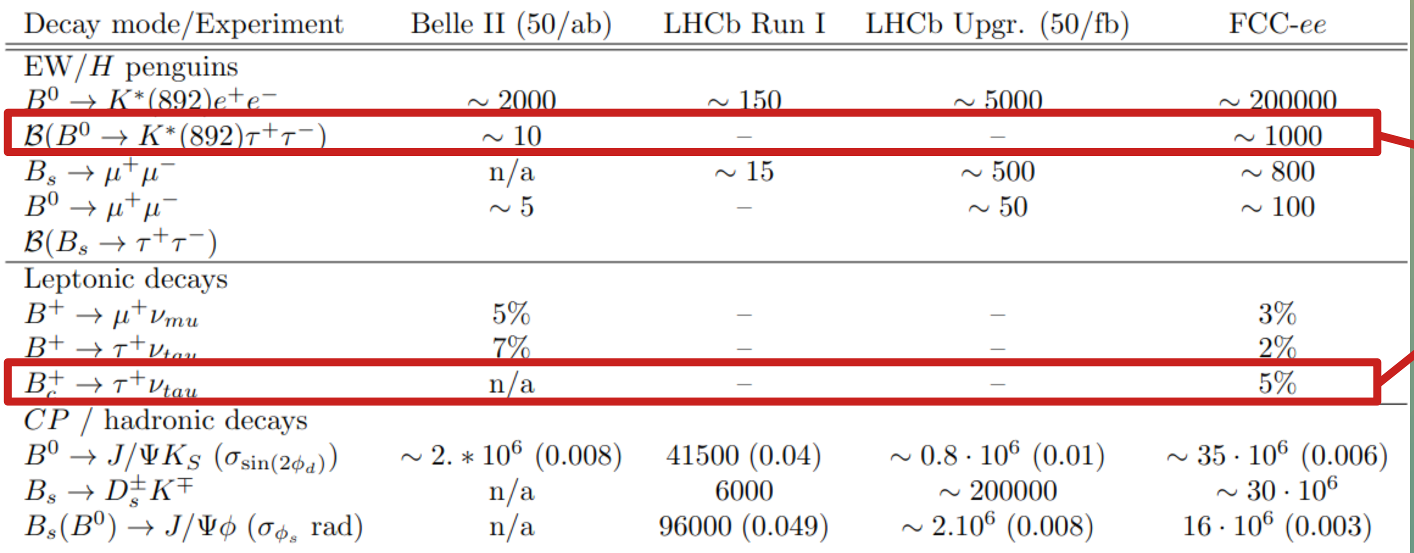
Future Colliders as Flavor Factories

- Tera-Z:
  - expected 10^{12} **bb/cc pairs:**
    - Flavor EWPOs (R_b…)
    - CKM matrix
    - CP violation in neutral B mesons
    - Flavour anomalies
  - $1.7{\cdot}10^{11}$ **ττ pairs:**
    - τ – based EWPOs
    - Lepton universality tests

Flavor physics at future colliders



Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500



Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/*H* penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

Only at future colliders

From the S. Monticelli FCC CDR overview ’19

Tests of lepton flavor universality in tau decays

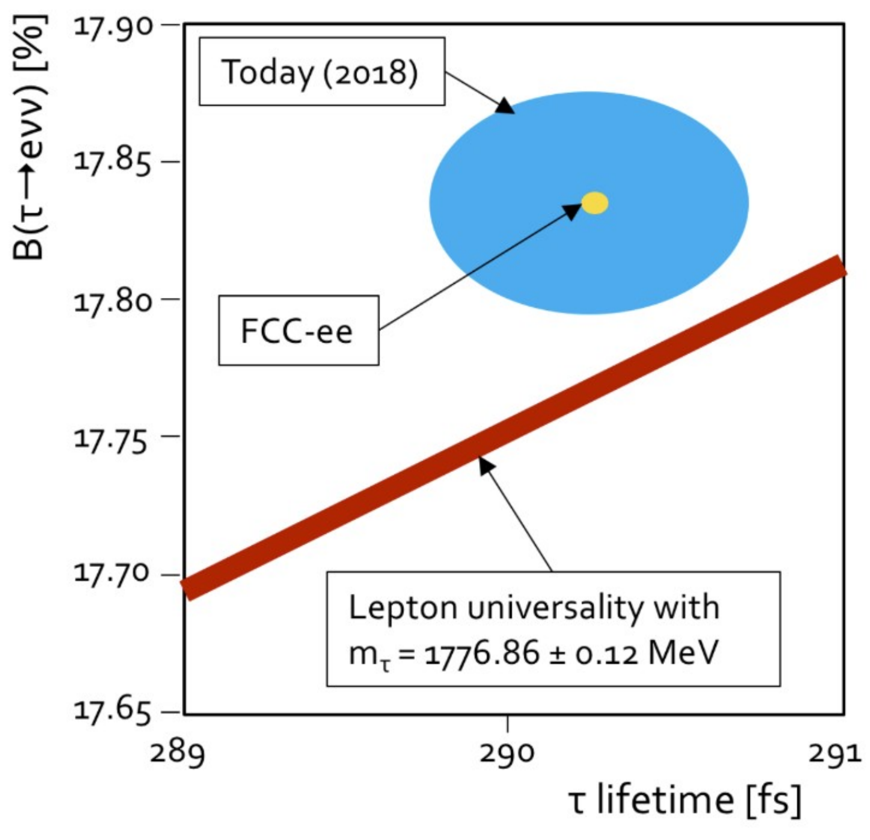
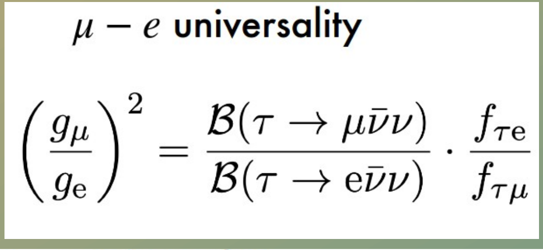


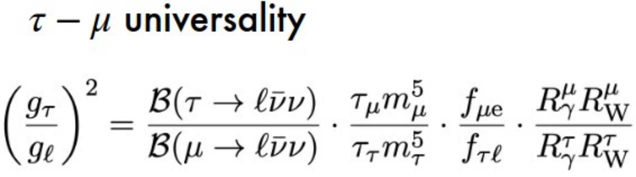
Figure from Dam, 1811.09408

- The FCC-ee can significantly improve improve the uncertainties of LFUV tests



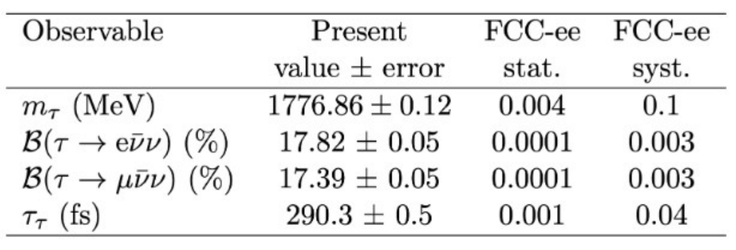
$\mu - e$ **universality**

$$\left(\frac{g_\mu}{g_\mathrm{e}}\right)^2 = \frac{\mathcal{B}(\tau\to\mu\bar\nu\nu)}{\mathcal{B}(\tau\to \mathrm{e}\bar\nu\nu)}\cdot\frac{f_{\tau\mathrm{e}}}{f_{\tau\mu}}$$



$\tau - \mu$ **universality**

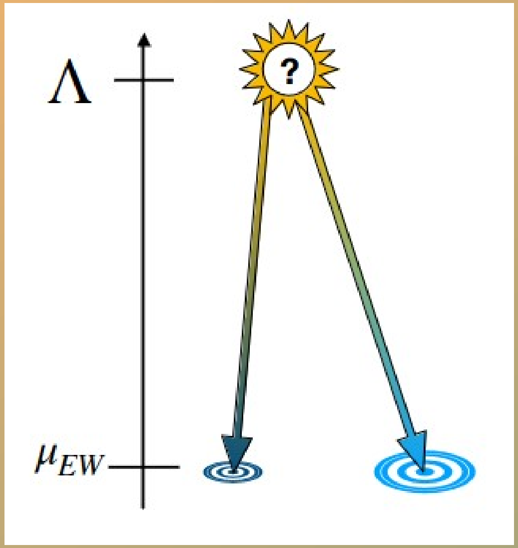
$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\mathcal{B}(\tau\to\ell\bar\nu\nu)}{\mathcal{B}(\mu\to\ell\bar\nu\nu)}\cdot\frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5}\cdot\frac{f_{\mu\mathrm{e}}}{f_{\tau\ell}}\cdot\frac{R^\mu_\gamma R^\mu_\mathrm{W}}{R^\tau_\gamma R^\tau_\mathrm{W}}$$



Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.
m_τ (MeV)	1776.86 ± 0.12	0.004	0.1
$\mathcal{B}(\tau\to \mathrm{e}\bar\nu\nu)$ (%)	17.82 ± 0.05	0.0001	0.003
$\mathcal{B}(\tau\to \mu\bar\nu\nu)$ (%)	17.39 ± 0.05	0.0001	0.003
τ_τ (fs)	290.3 ± 0.5	0.001	0.04

Sophie Renner, FCC Week 2023

The SM Effective Field Theory Interpretation



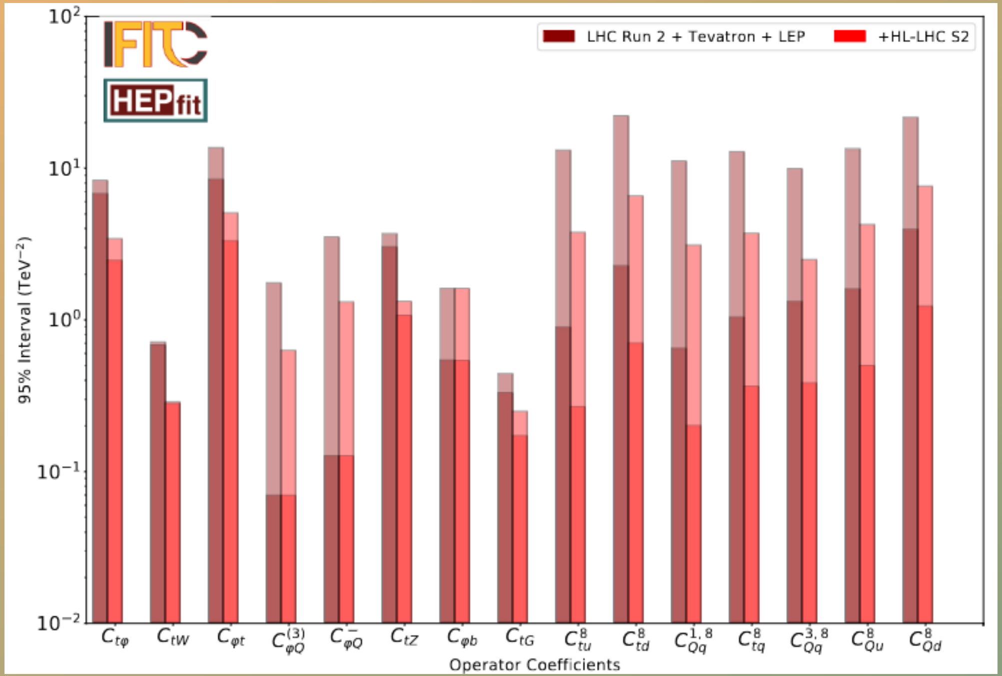
- For high enough BSM scale, new particles are not directly observable
- Instead, we can write down all possible operators built from the SM fields

$$\mathscr{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

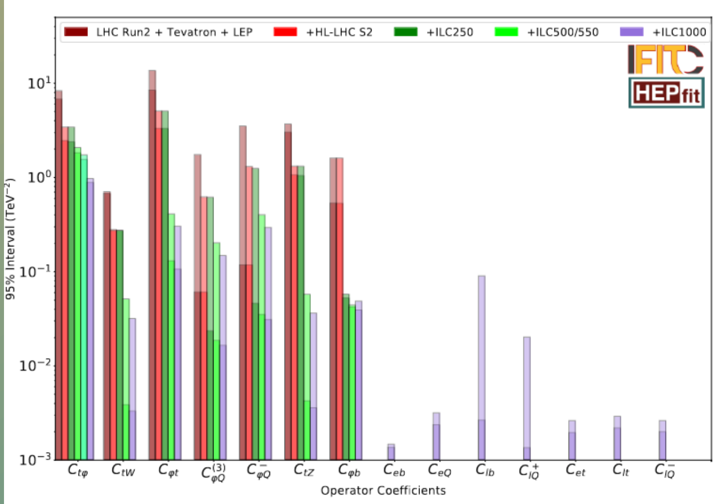
- New physics effects – appear in the **Wilson coefficients**

SMEFT at HL-LHC and ILC

De Blas et. al. 2206.08326



- Even after HL-LHC, some operators only constrained to **below 1 TeV!**
- Orders of magnitude improvement at the ILC



Darker: single parameter fit
Lighter: marginalized fit

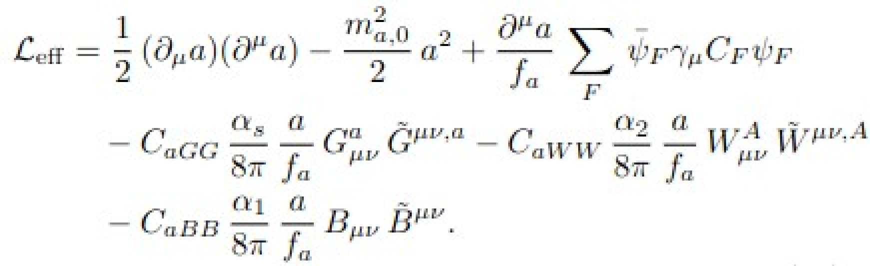
Searches for light and long-lived new physics

Feebly Interacting Particles

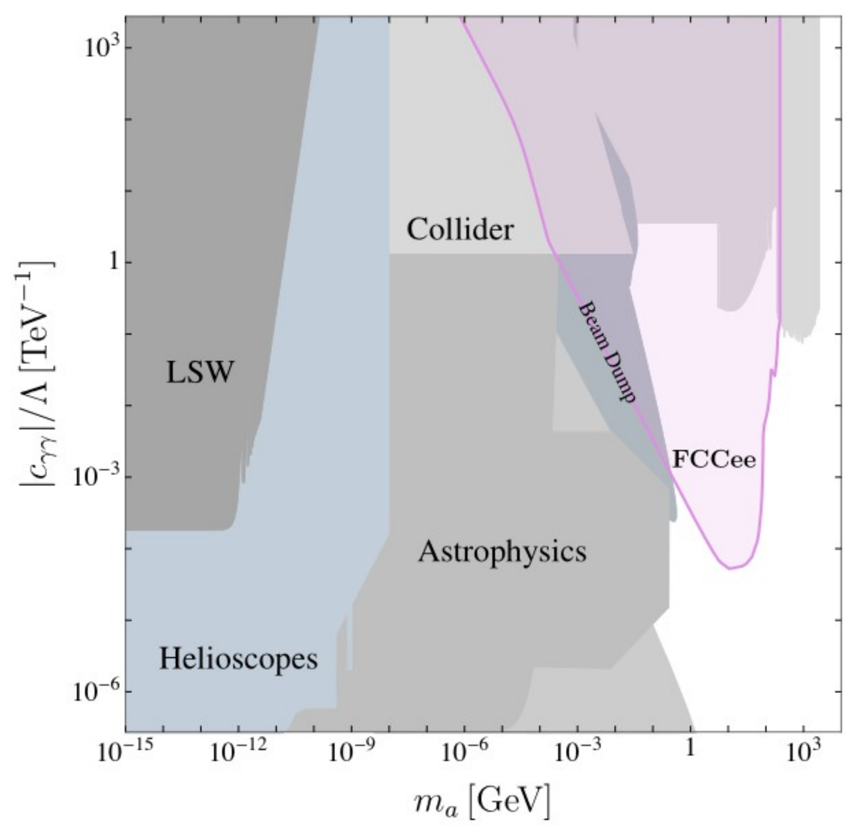
- Particles too light to be described by EFT alone
- Defined by extremely suppressed couplings to the SM
- Conventionally organized into four portals:
  - Vector particles
  - Axions and axion-like particles (**ALPs**)
  - Scalar particles
  - Fermion particles/Heavy Neutral Leptons (**HNLs**)

ALPs at future colliders

- *Pseudoscalar pseudo-Nambu-Goldstone bosons* arising from approximate BSM symmetries broken at some scale $f_a >> v$
- Potential DM candidates
- Coupling to the SM through an effective Lagrangian:

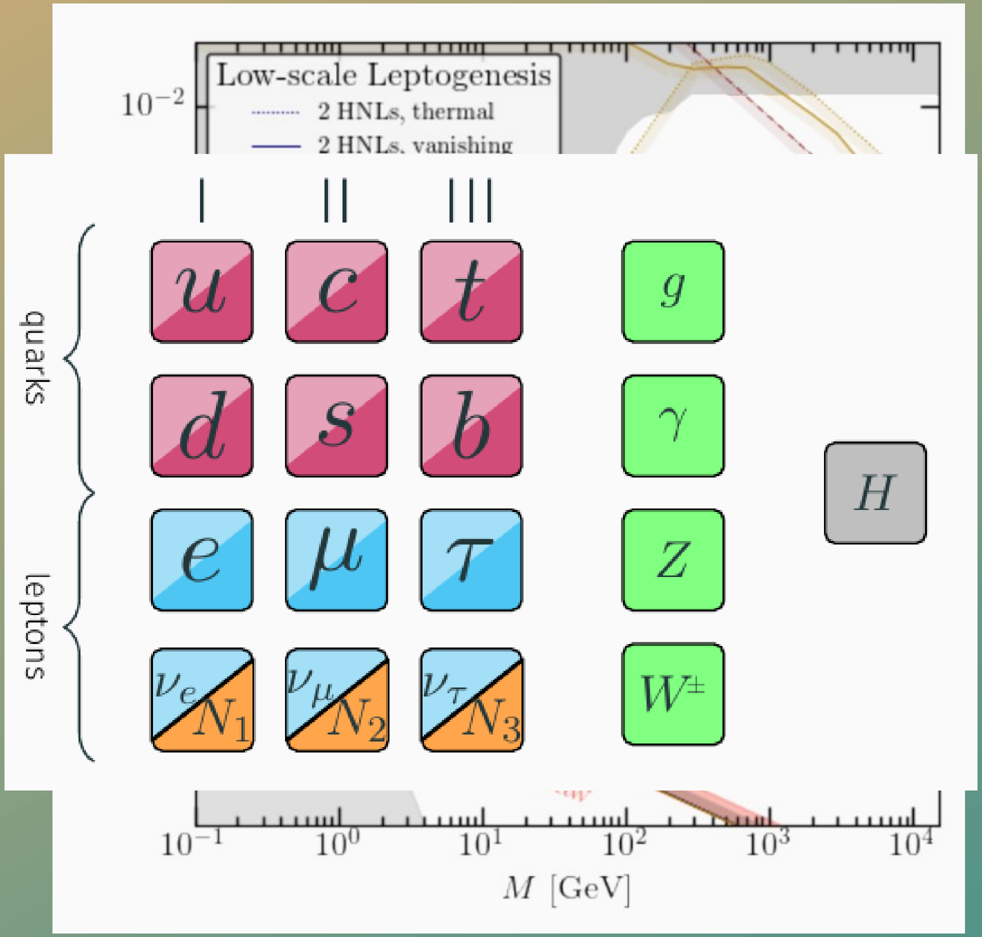


$$\begin{aligned}\mathcal{L}_{\rm eff} = {} & \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f_a}\sum_F \bar\psi_F \gamma_\mu C_F \psi_F \\ & - C_{aGG}\,\frac{\alpha_s}{8\pi}\,\frac{a}{f_a}\,G^a_{\mu\nu}\,\tilde G^{\mu\nu,a} - C_{aWW}\,\frac{\alpha_2}{8\pi}\,\frac{a}{f_a}\,W^A_{\mu\nu}\,\tilde W^{\mu\nu,A} \\ & - C_{aBB}\,\frac{\alpha_1}{8\pi}\,\frac{a}{f_a}\,B_{\mu\nu}\,\tilde B^{\mu\nu}.\end{aligned}$$



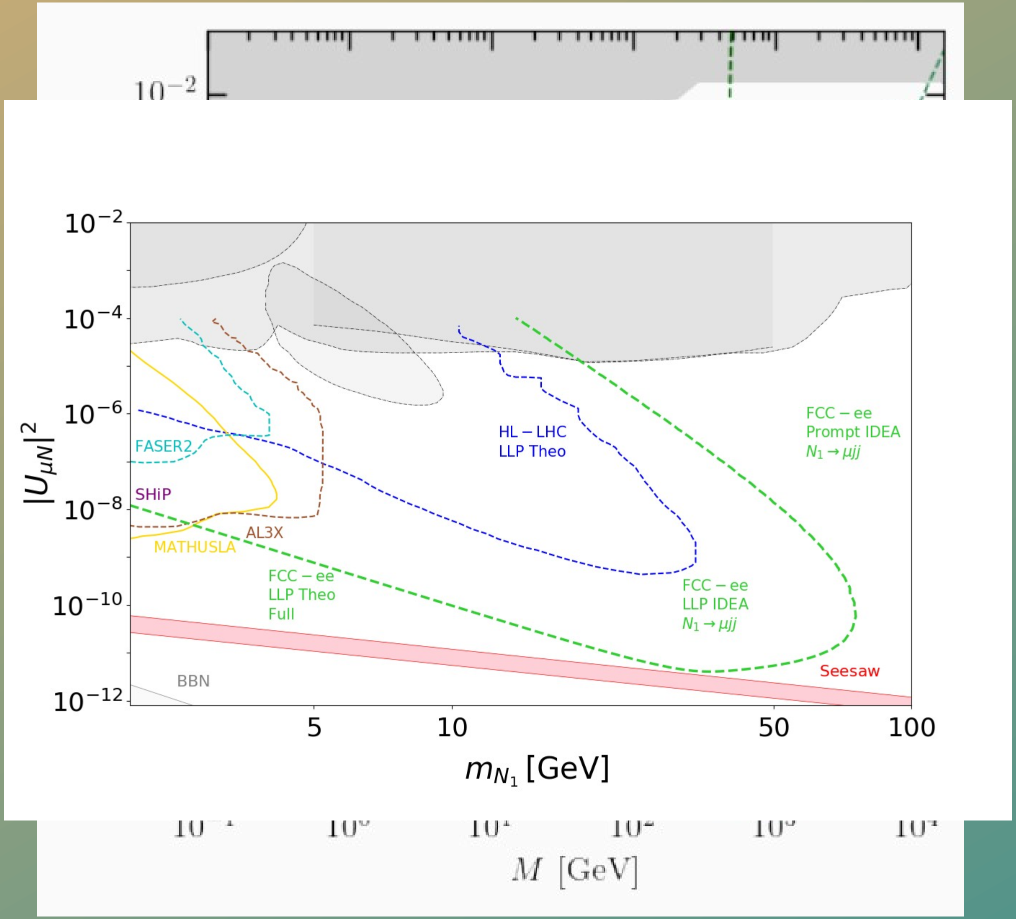
Heavy Neutral Leptons

- Also known as right-handed-neutrinos
- In the νMSM they could simultaneously solve:
  - the baryon asymmetry of the Universe **(BAU)**
  - **Neutrino masses**
  - **Dark matter**
  - All with only 3 new particles!
- All within reach of future colliders!



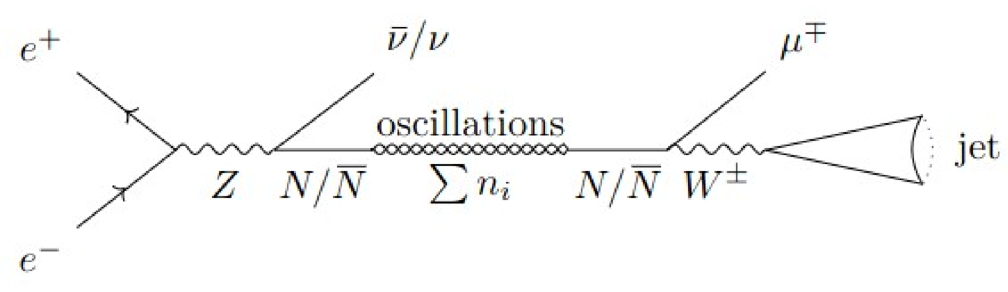
HNLs at future colliders

- Future colliders will be exploring the parameter space of baryogenesis
- The naive seesaw target is tantilisingly close to the reach of FCC-ee
- For masses below m_Z FCC-ee at the Z-pole is most promising
- Larger masses – ILC, hadron colliders, muon colliders…

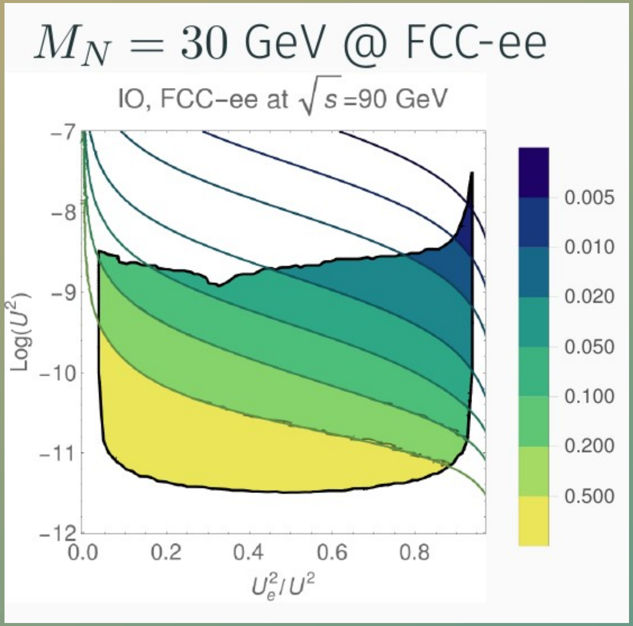


Testing HNL properties at FCC-ee

- Large number of Z-bosons also lead to a substantial number of HNLs
- Sufficient to measure mixing to different flavors to a 0.5% accuracy!
- Very rich phenomenology: Lepton Number Violation, Lepton Flavor Violation, HNL oscillations in colliders etc…



Antusch et. al. 2308.07297



Antusch et. al. 1710.03744

Conclusions

- The Higgs boson offers a guaranteed discovery at future colliders
  - **Self-coupling**, Yukawas: **charm**, *strange*, *electron*
- Significantly higher energies within reach of future colliders
- Both direct and indirect sensitivity to new physics
- Many puzzles within reach, although nothing is guaranteed:
  - Neutrino masses, baryogenesis, dark matter…

Exercise 1: HNLs at the Z-pole

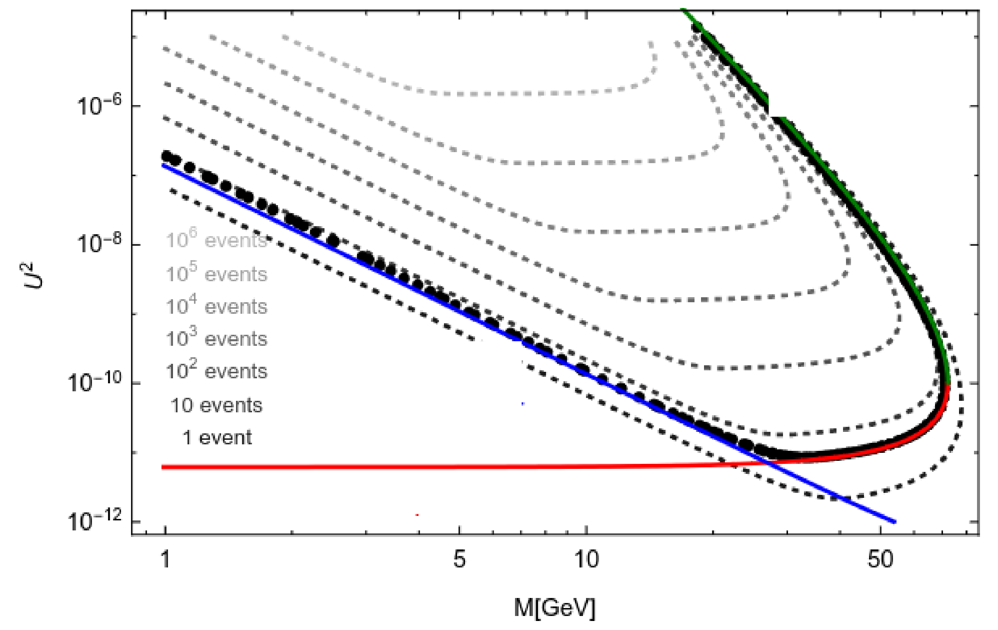


Figure and estimates from M. Drewes 2210.17110

$$\mathrm{BR}(Z \to \nu_\alpha \overline{\nu}_\alpha) = \frac{1}{5}\frac{1}{3}, \quad \beta\gamma = p_N/M,$$

- Consider a HNL with a mixing angle U^2 and a lifetime given by:

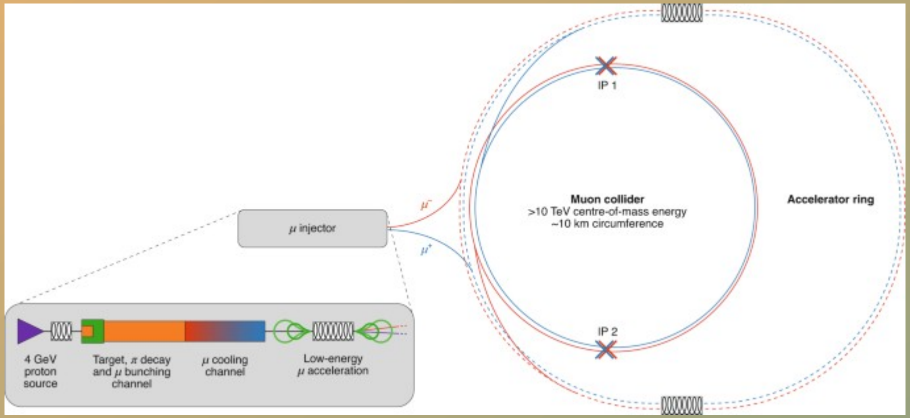
$$\Gamma_N \simeq c_{\mathrm{dec}} \frac{a}{96\pi^3} U^2 M^5 G_F^2$$

- Estimate:
  - The total number of HNLs produced in Z-decays for the Tera-Z scenario with ~ 10^{12} bosons
  - The total number of HNLs leaving a displaced signature inside the detector
  - What gives the limits on HNL detection?

Assume a kinematic suppression factor:

$$\Pi = \left(\frac{2p_N}{m_Z}\right)^2 \left(1 + \frac{(M/m_Z)^2}{2}\right), \quad p_N = \frac{m_Z}{2}\left(1 - (M/m_Z)^2\right)$$

Exercise 2: Muon colliders



- Synchrotron radiation is one of the main bottlenecks for e^+e^- colliders
- Given the estimate of the radiation:

  $$\Delta E_{Synch.} = \frac{4\pi}{3} e^2 \beta^2 \frac{\gamma^4}{R}$$

  compare the energy loss for an electron and muon of the same energy
- Given the muon lifetime $\tau_\mu \approx 2.2 \times 10^{-6} s$ and assuming a synchrotron of a radius R, and N initial muons, compute the number of events for a process with a cross-section σ
- Compute the number of events before all the muons decay
- What is the equivalent number of beam crossings for a stable particle?