BSM physics at future e^+e^- colliders

Paul Cézanne, Le Golfe de Marseille vu de L'Estaque, Musée d'Orsay

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Marseille, France

Juraj Klarić

University of Zagreb

Universiteit van Amsterdam

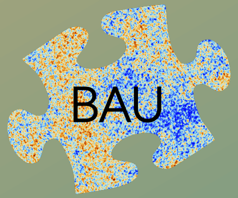
Nikhef

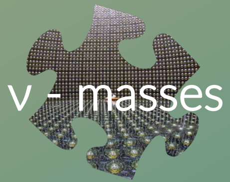
Many open questions

- What is the nature of dark matter?
- Origin of the Baryon asymmetry of the Universe?
- Why is the Higgs so light?
- What is the thermal history of the Universe?
- Why are there multiple generations of fermions?
- What is the solution to the strong CP problem?
- Stability of the EW vacuum?

… and many many more….

- *But each question has multiple proposed solutions!*





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

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The SM Effective Field Theory Interpretation

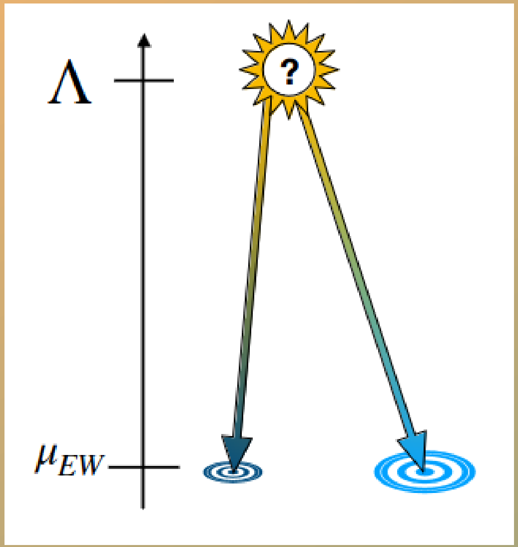

Figure by S. Renner

- 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**

Probing BSM physics in global fits

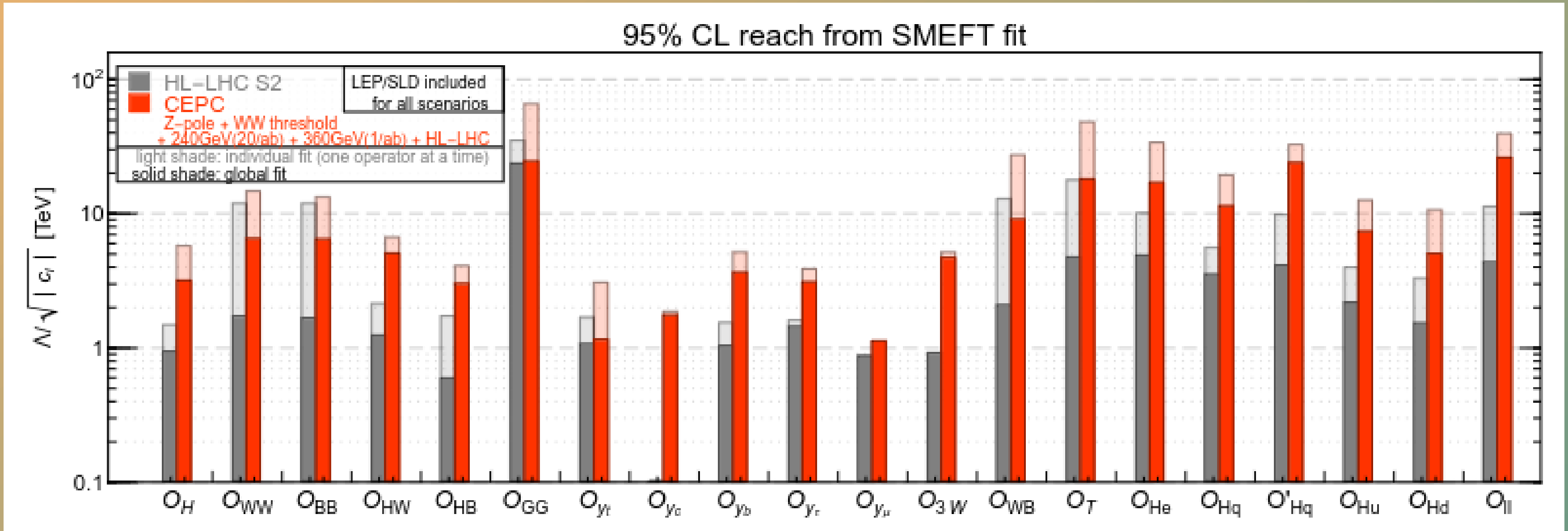

Figure from 2205.0855

Combined CEPC runs can probe physics up to the 10 TeV scale!

See the talk of Z. Liang

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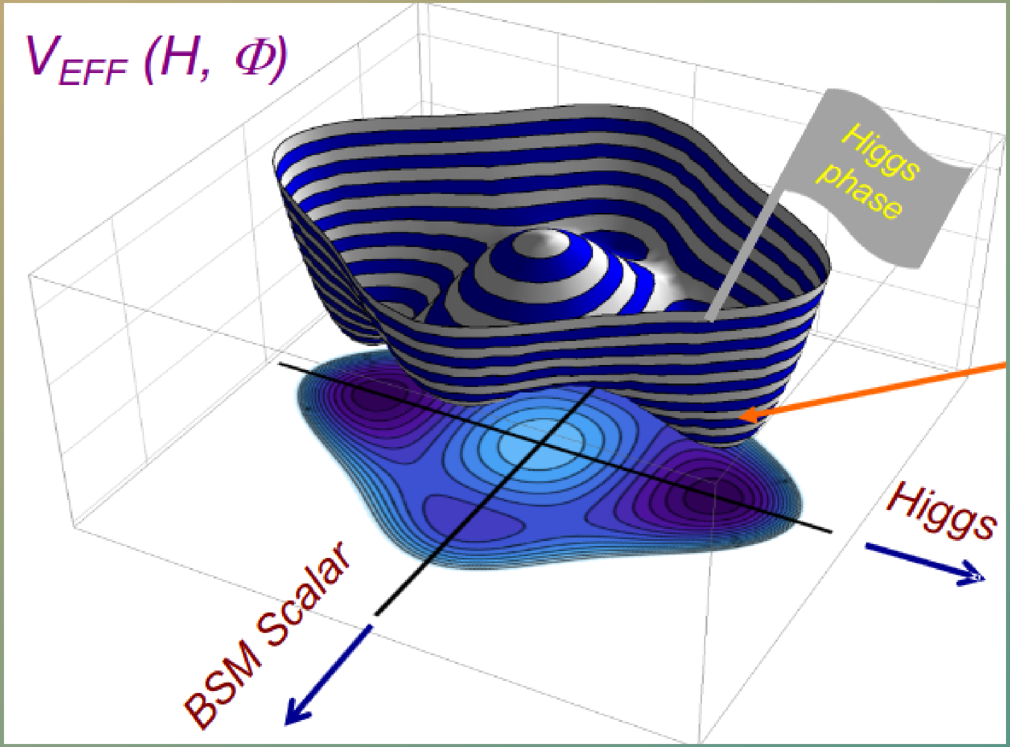
Higgs and the thermal history of the Universe

- 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**?



See talk by M.J. Ramsey -Musolf

BAU

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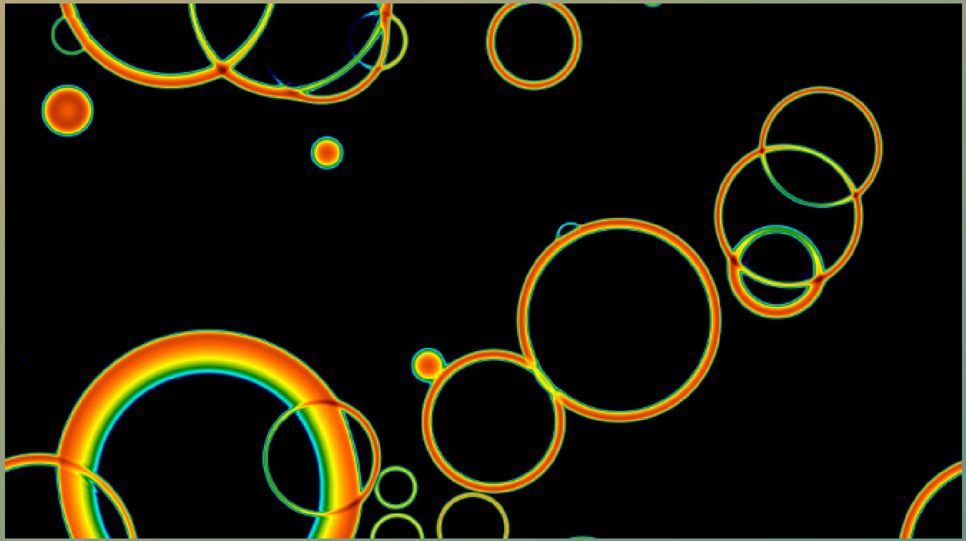
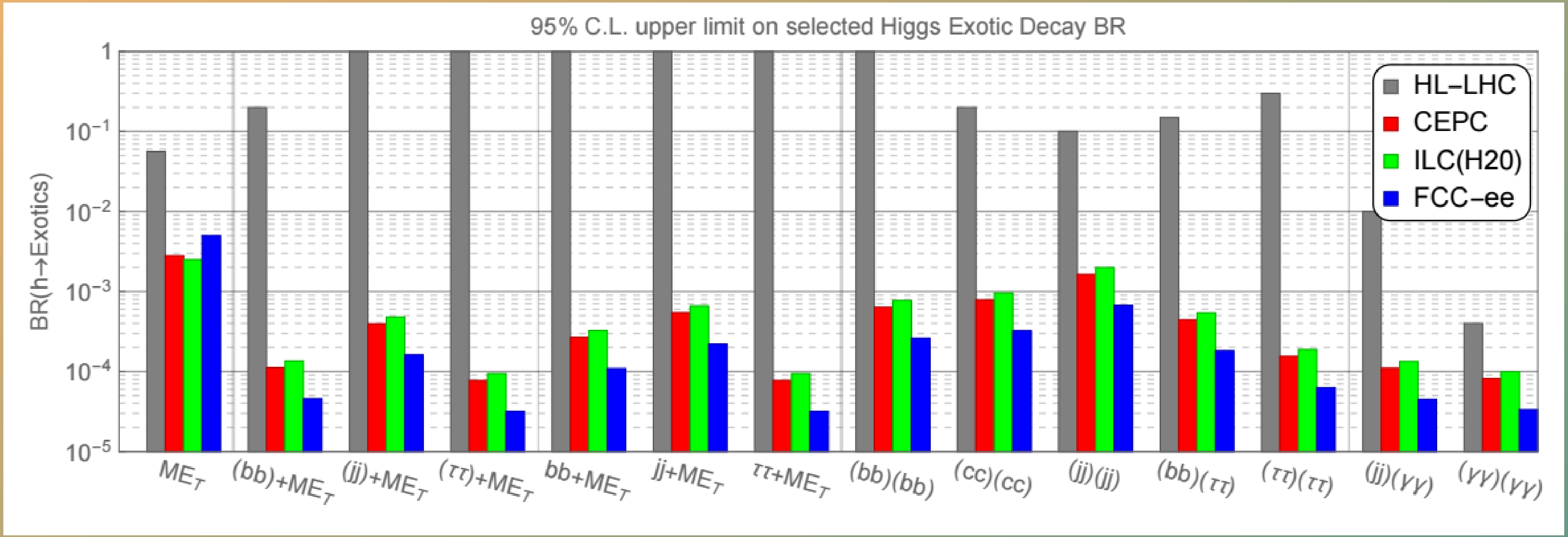


D. Weir 1705.01783

See talk by M.J. Ramsey -Musolf

Higgs portal to hidden sectors



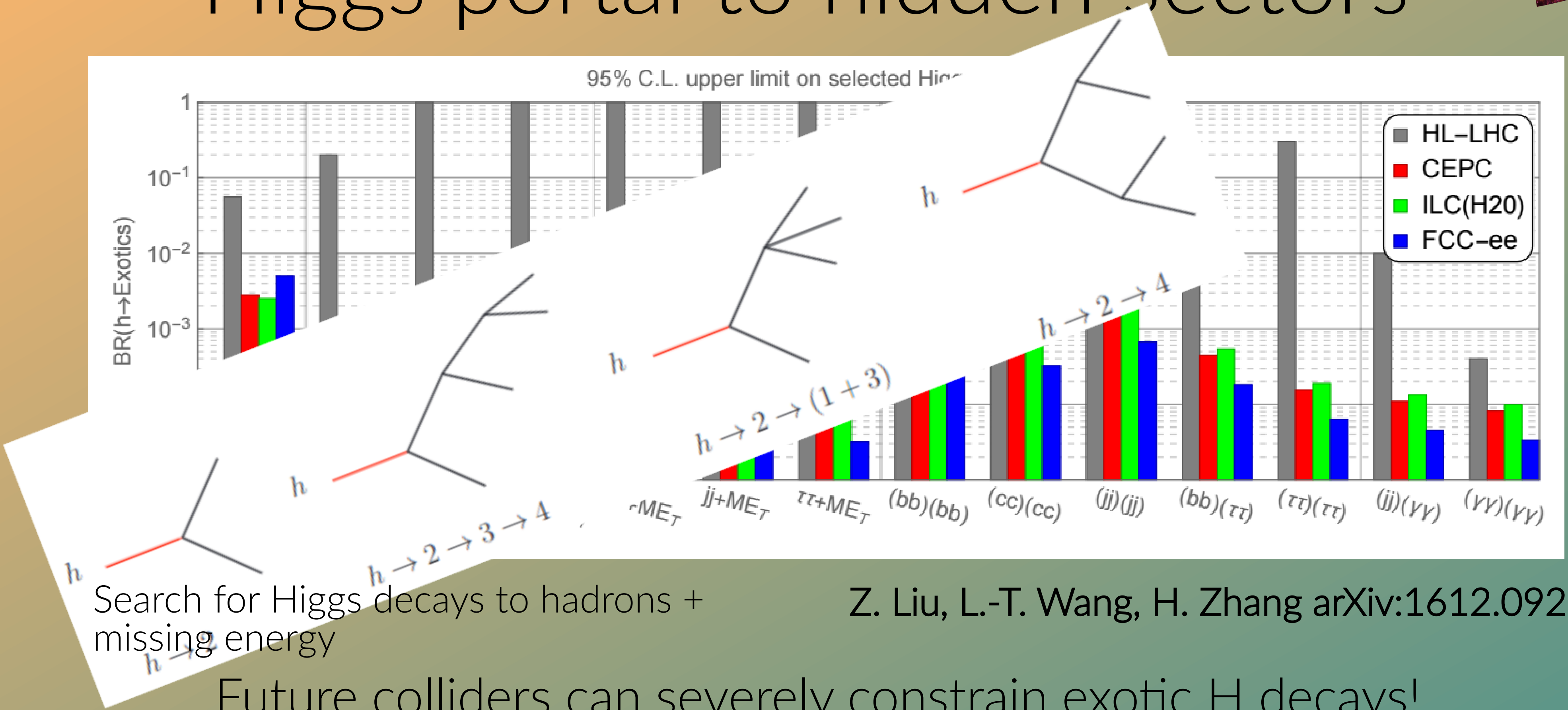
Search for Higgs decays to hadrons + missing energy

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

Future colliders can severely constrain exotic H decays!

Higgs portal to hidden sectors

Dark Matte



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Many more BSM scenarios covered in the talk by Xuai Zhuang

Light new physics

Renormalizable portals

- Scalars
- Vectors
- Fermions

Non-renormalizable portal

- Pseudo-scalars:
  Axions and axion-like particles

See the talks by Wang, Giappichini, Chen

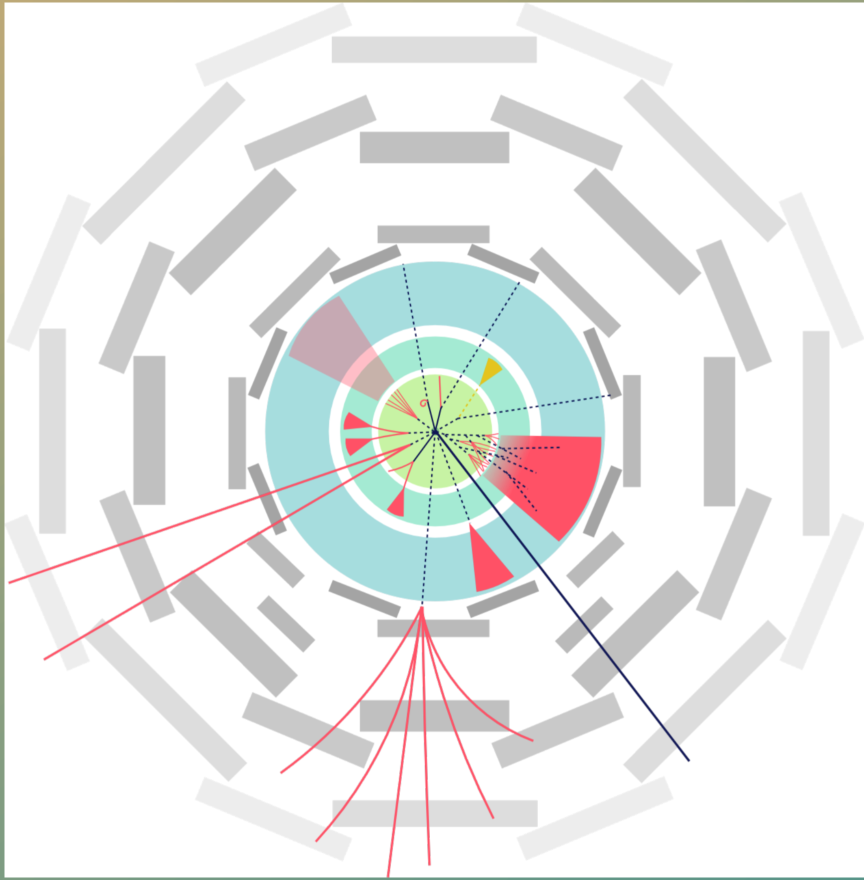


Image credit: Heather Russel

Axions and ALPs

Dark Matter

- *Pseudoscalar pseudo-Nambu-Goldstone bosons* arising from approximate BSM symmetries broken at some scale $f_a >> v$
- Light ALPs are excellent DM candidates through misalignment/decays of topological defects
- Coupling to the SM through the effective Lagrangian:

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

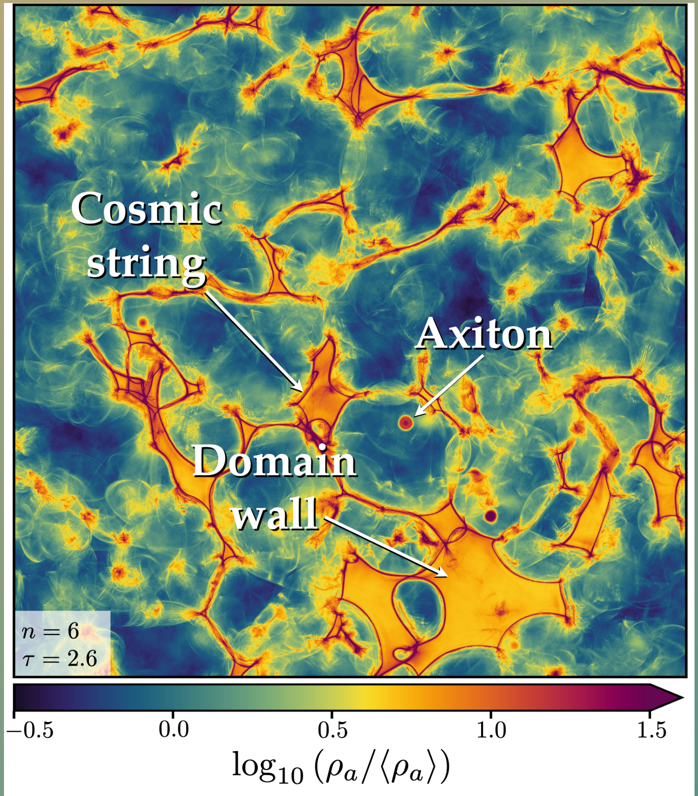


Figure from O'Hare et. al. 2112.05117

Heavy ALPs at future colliders

- Heavy ALPs can **mediators** between the SM and DM
  - Can easily reproduce the observed DM abundance
- Highly testable at Z factories
- May explain the **muon g-2** discrepancy [Liu et. al. 2210.09335]

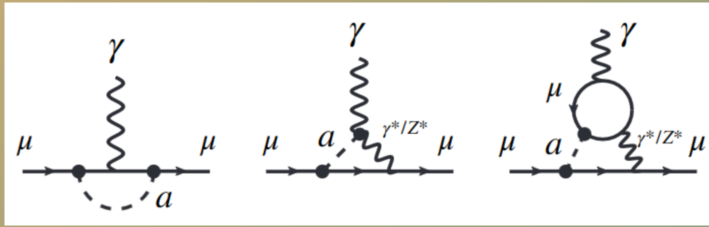
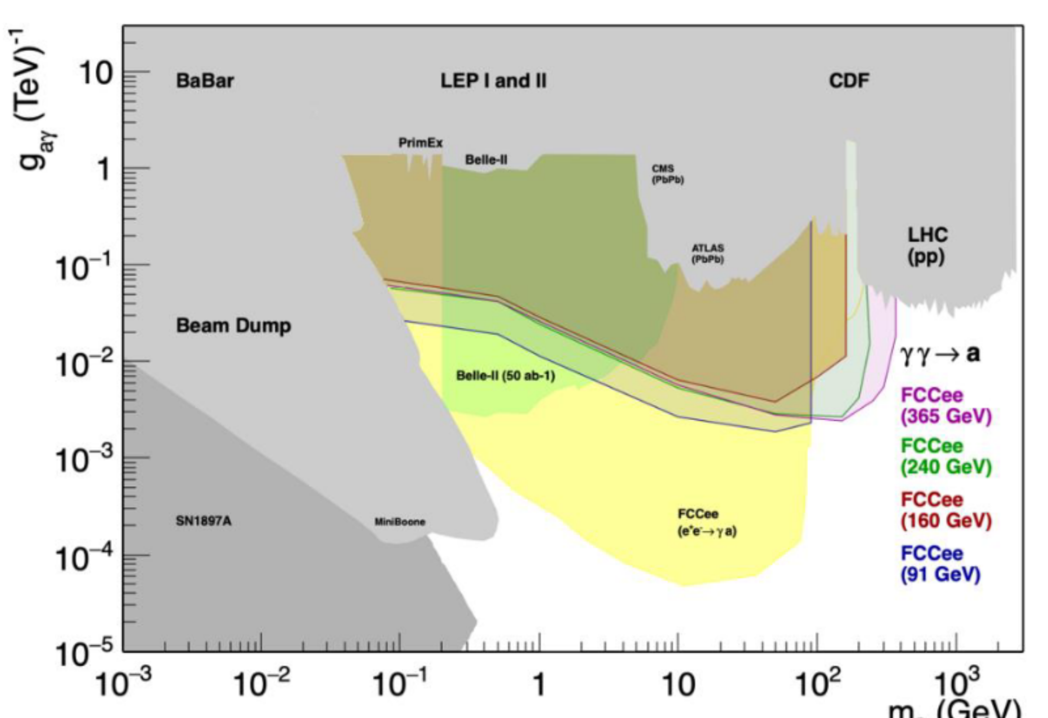


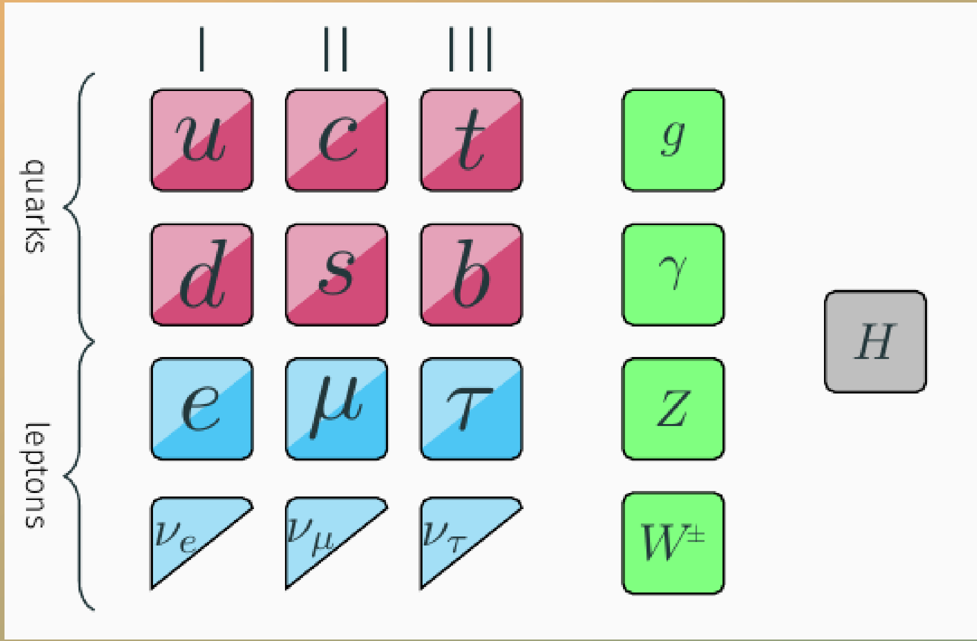
Fig. From [Liu et. al. 2210.09335]



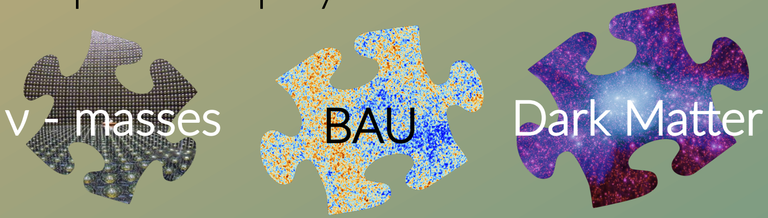
Phys. Rev. D 109, 055003

See the talk by S. Giappichini

The fermion portal



- Adding three singlet fermions can simultaneously solve several puzzles of particle physics



- The only renormalizable coupling is to the Higgs and leptons:
  - **H**eavy **N**eutral **L**eptons (HNLs)
- Non-renormalizable couplings in principle also possible

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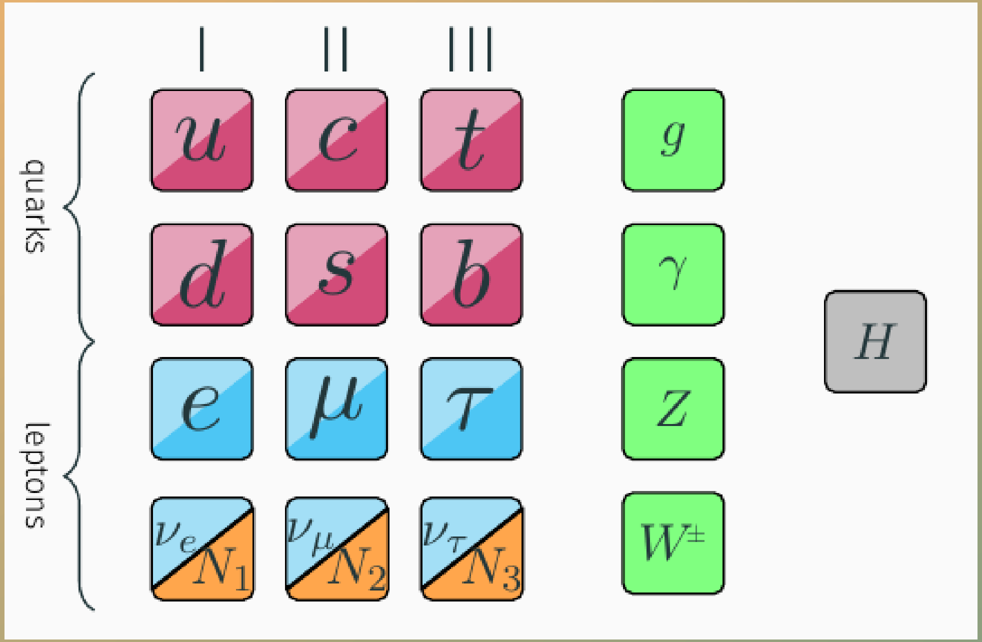

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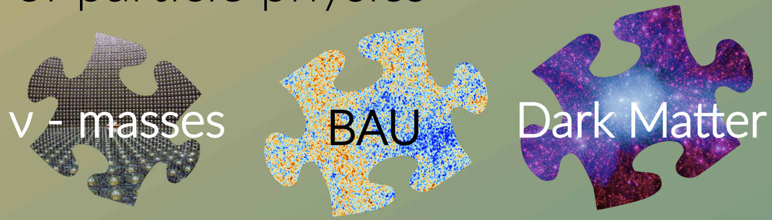

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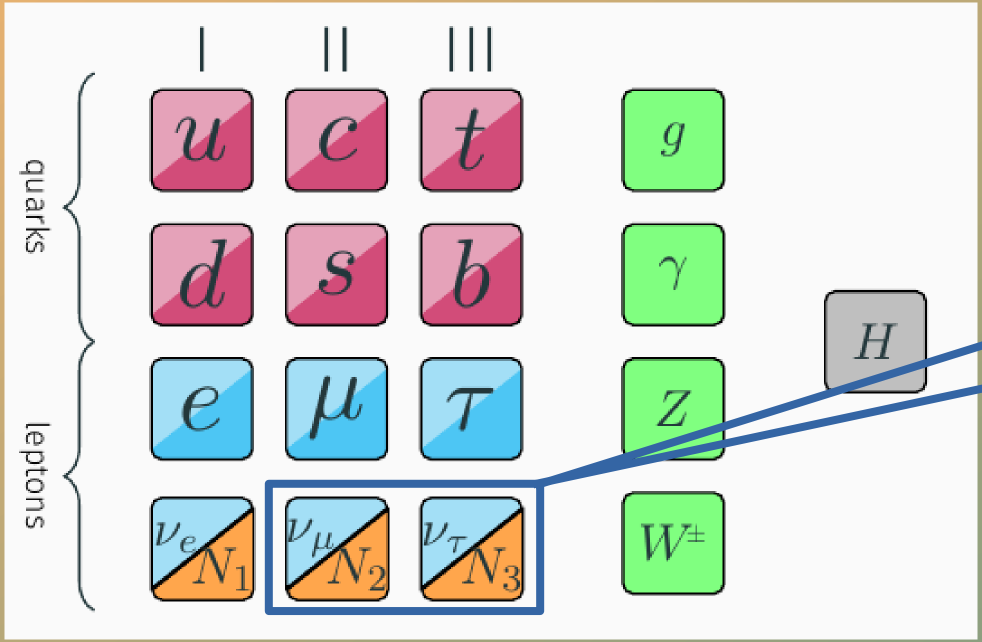

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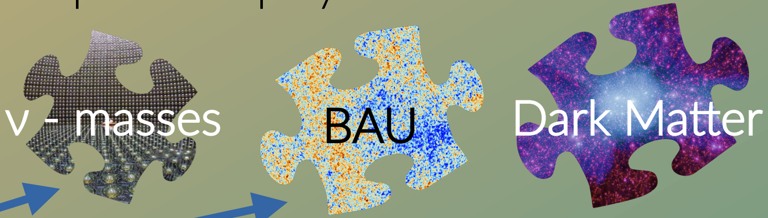

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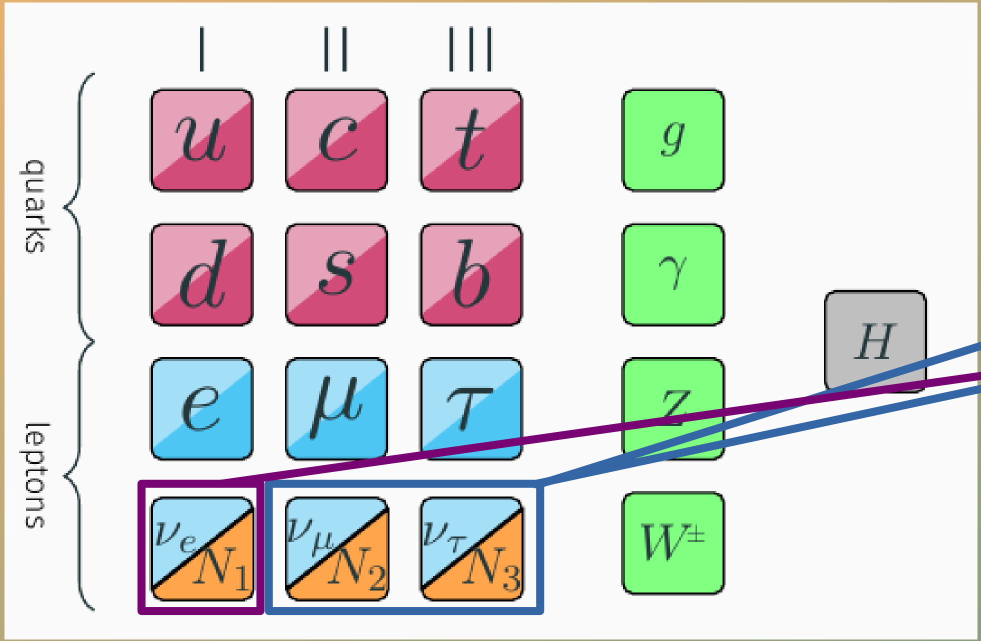

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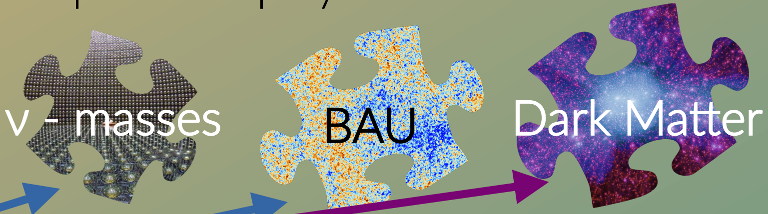

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HNLs and ν-masses

ν - masses

The see-saw Lagrangian

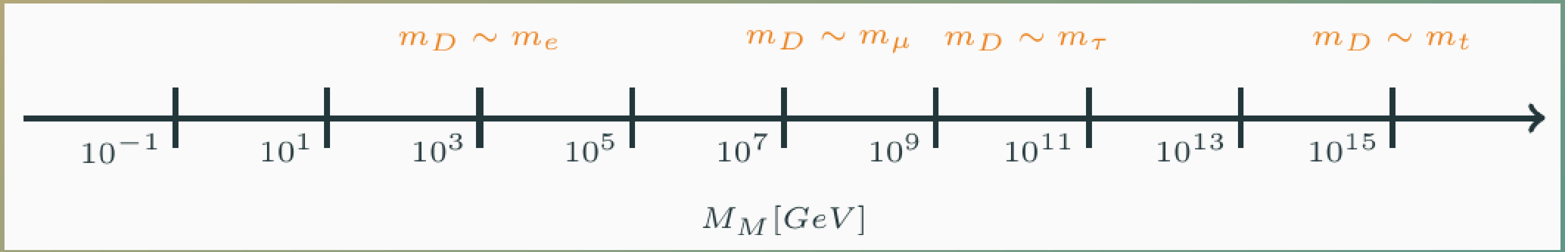
$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

The light neutrino masses

$$m_\nu = -m_D M_M^{-1} m_D^T$$

[Minkowski '77
Gell-Mann/Ramond/Slansky '79
Mohapatra/Senjanović '80
Yanagida '79
Schechter/Valle '80]

Canonical type-I seesaw



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Mohapatra '93
Mohapatra/Valle '86
Bernabeu/Santamaria/Vidal/Mendez/Valle '86
Gavela/Hambye/Hernandez/Hernandez '09
Branco/Grimus/Lavoura '89
Malinsky/Romao/Lavoura '89

Low-scale linear and inverse seesaws

The light neutrino masses

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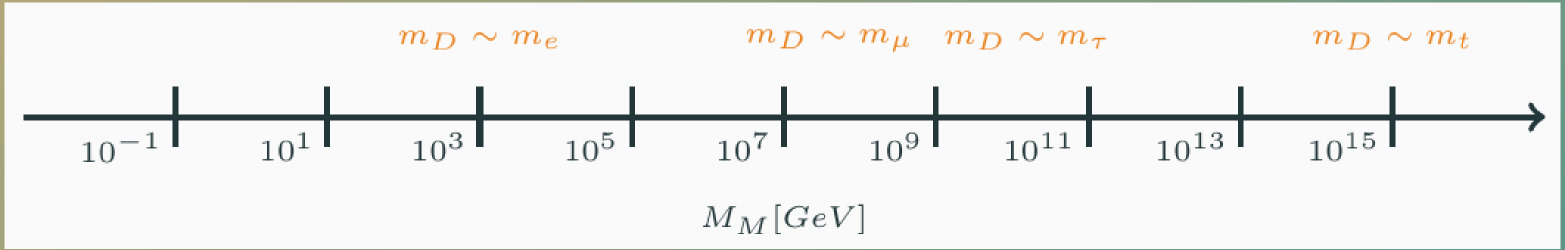
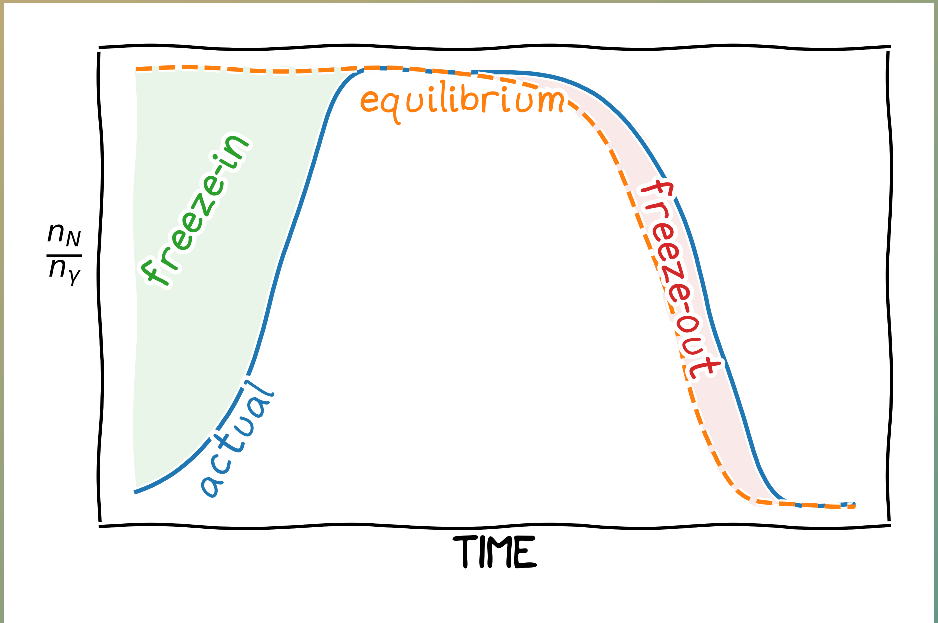


HNLs and the BAU

Ideal candidate to explain the BAU through **leptogenesis**. They easily satisfy the three **Sakharov conditions:**

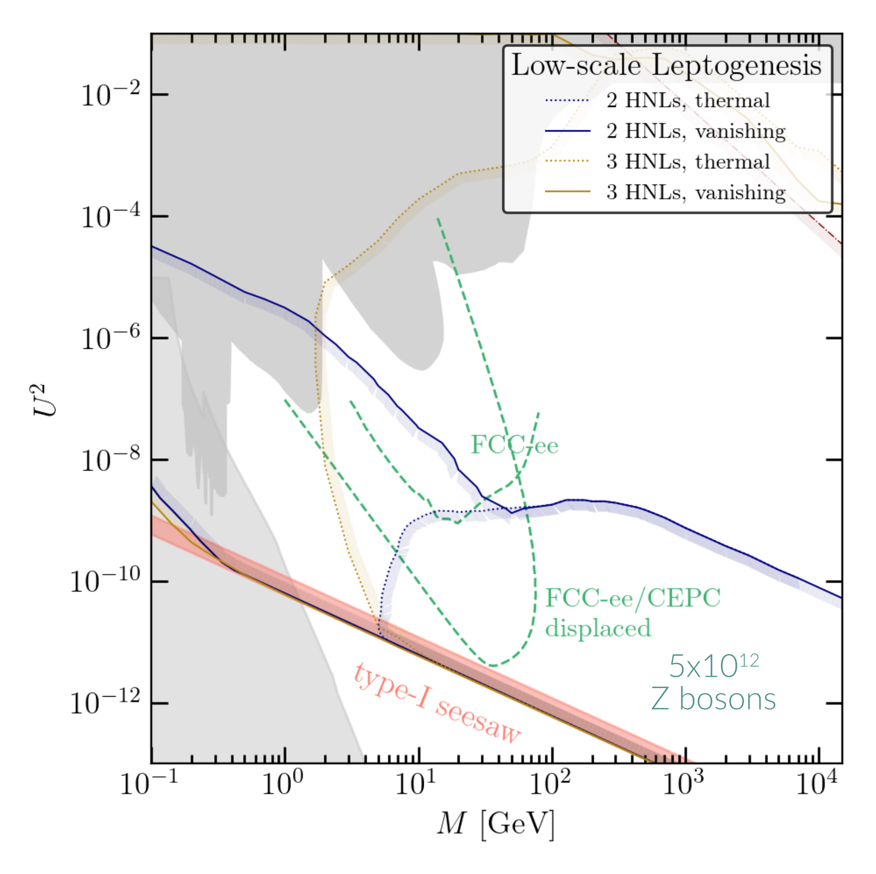
1) Baryon number violation
   - sphaleron processes
2) C and CP violation
   - HNL decays and oscillations
3) Deviation from equilibrium
   - freeze-in and freeze-out of HNLs



Fukugita/Yanagida '86, Liu/Segre '93, Pilaftsis '97, Pilaftsis/Underwood '04;'05, , Akhmedov/Rubakov/Smirnov '98, Asaka/Shaposhnikov '05

HNLs at future e^+e^- colliders

- With 2 HNLs leptogenesis is possible for ***all masses above 100 MeV***
- Leptogenesis is possible in the ***entire experimentally accessible parameter space*** for 3 HNLs
- Target seesaw region ***nearly within reach*** of future colliders!
- Dedicated LLP detectors could probe an even smaller HNL couplings and masses



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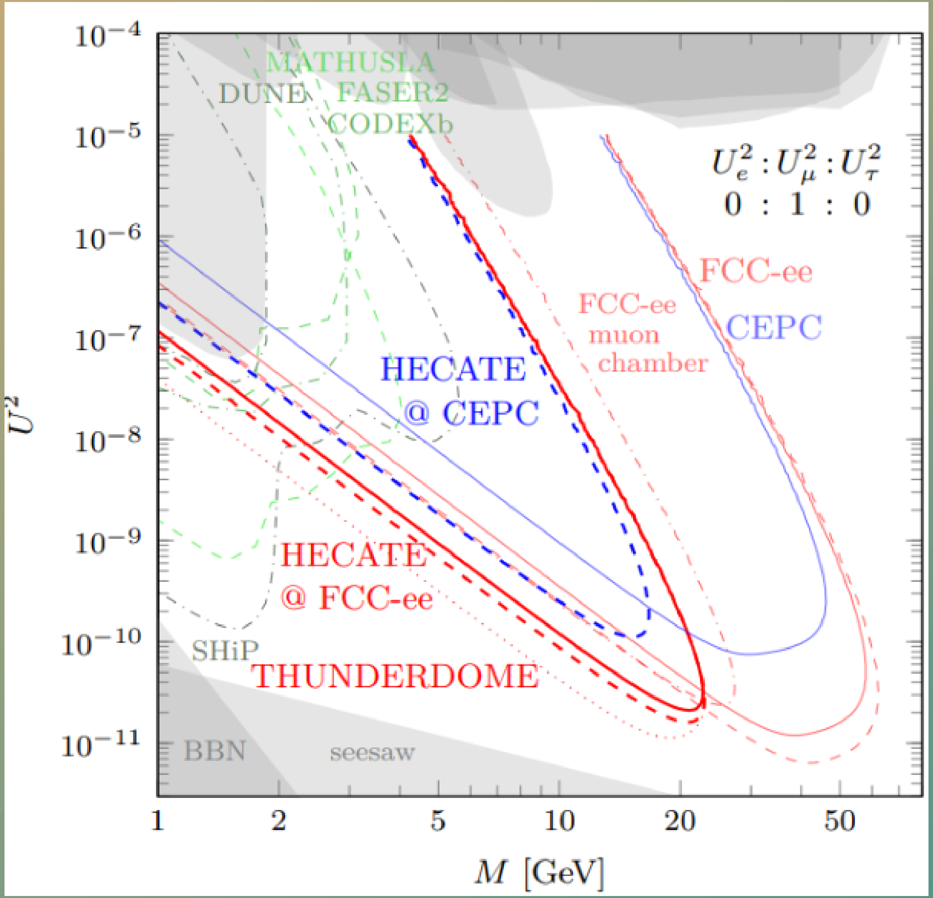


From the talk by S. Giappichini

HNL branching ratios

- HNL branching ratios are highly constrained by the measured parameters in the minimal model (2 HNLs)

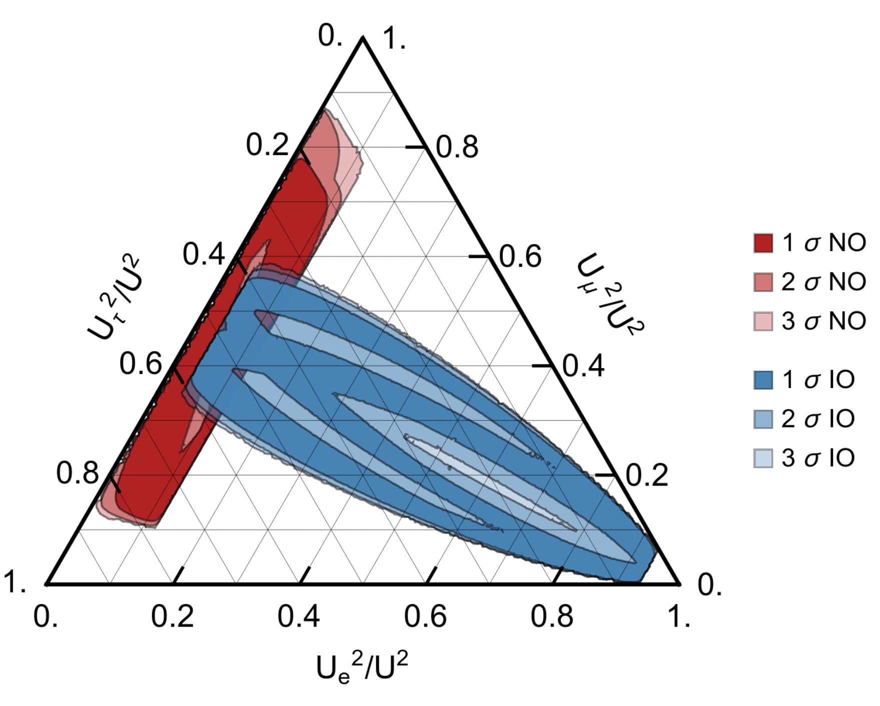
  [Snowmass white paper 2203.08039]

- Leptogenesis imposes further constraints on the branching ratios

  [Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

- Branching ratios become even more predictive when combined with Flavor and CP symmetries

  [Drewes/Georis/Hagedorn/JK 24xx.xxxx]



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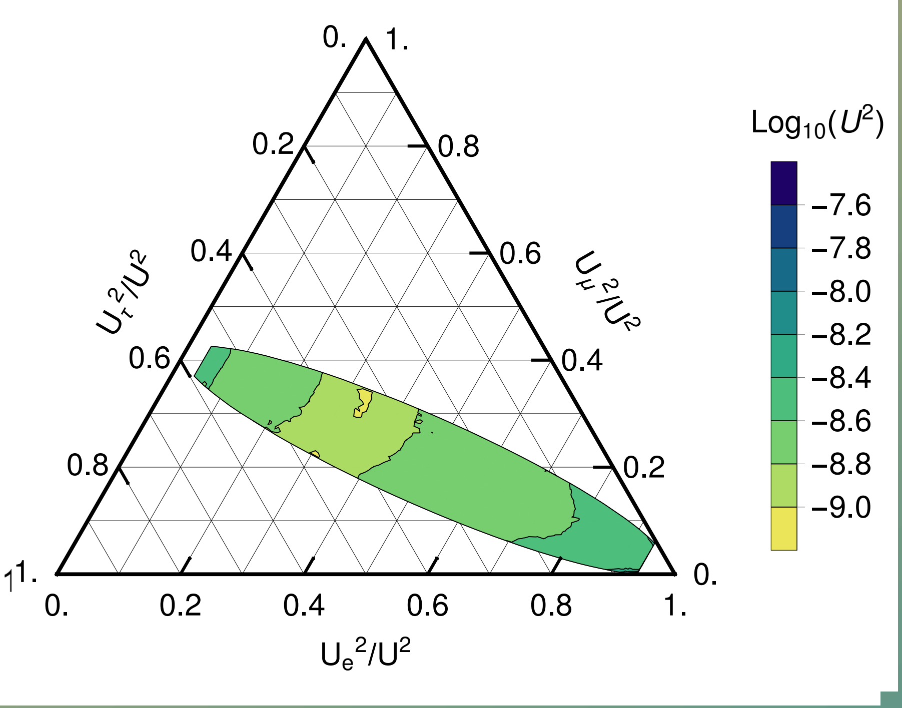

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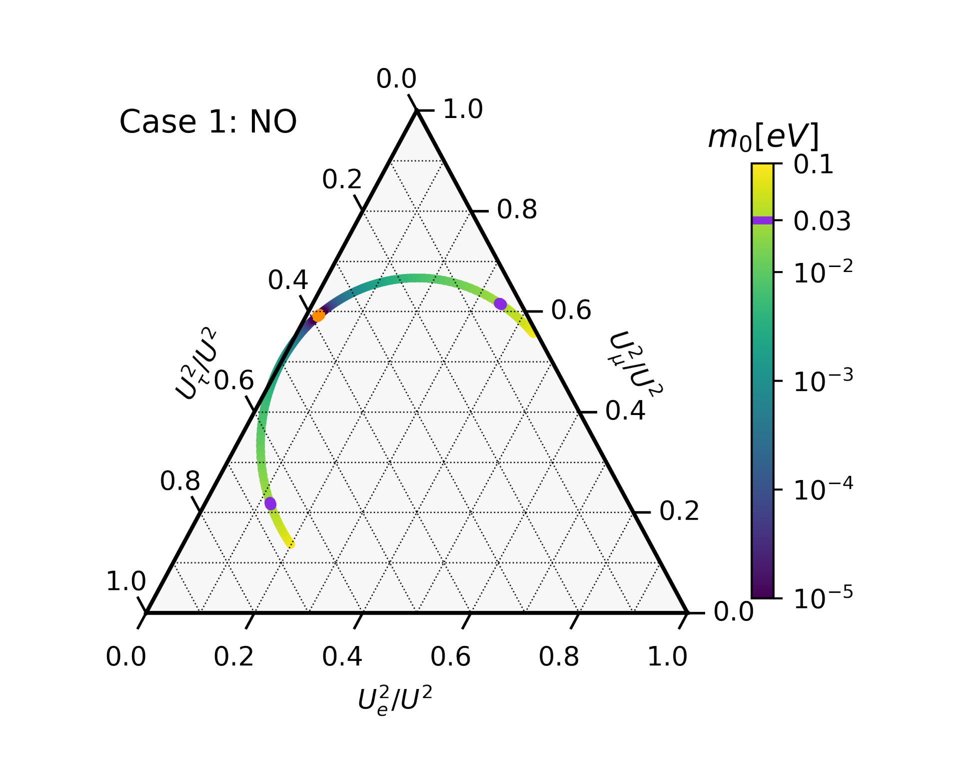
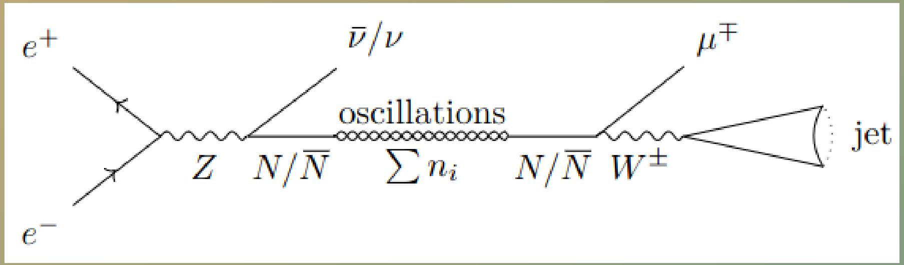
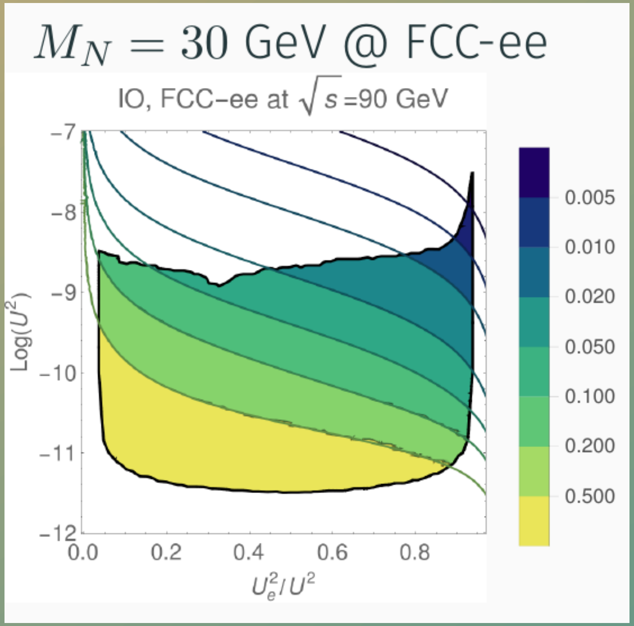


Testing HNL properties at e^+e^- colliders

- Large number of Z-bosons also lead to a substantial number of HNLs
- Sufficient event numbers 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

See the talk by B. M. S. Oliveira

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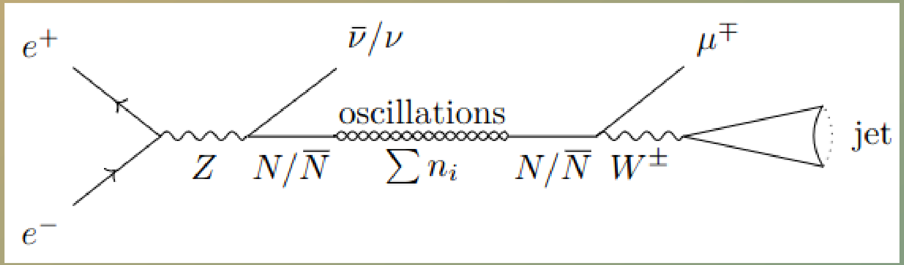

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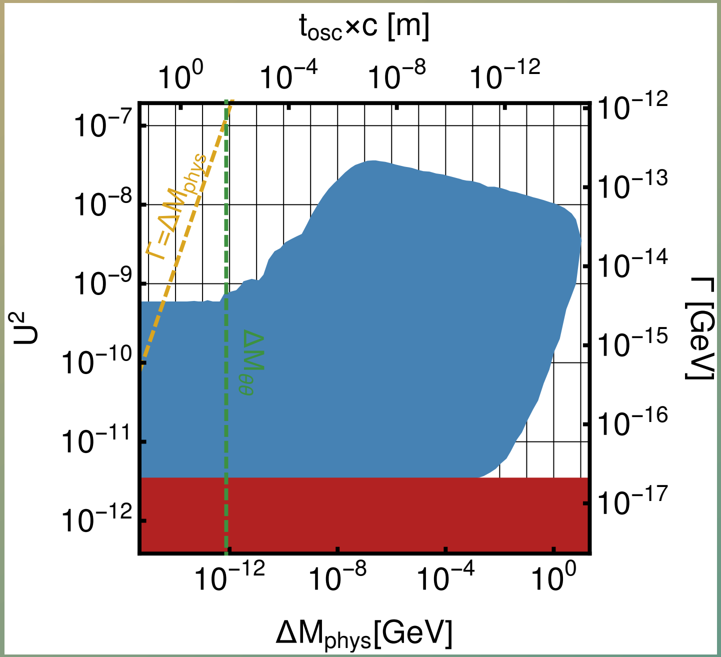

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Conclusions

- Exciting times ahead!
- Future colliders can probe BSM physics in both direct and indirect probes!
- Explanations to several puzzles of particle physics are within the reach of future colliders
- Future colliders can go beyond discovery and also do tests of certain BSM scenarios
  - Especially in the Z-pole run