New Particle Discovery Potential

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

CEPC

November 10th 2025,
Guangzhou, China

Juraj Klarić

University of Zagreb

The BSM Potential of CEPC

see talk by Yongchao Zhang

figure from CEPC WP 2505.24810

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see talk by Yongchao Zhang

see talk by Jorge de Blas

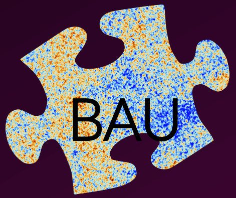


figure from CEPC WP 2505.24810

The BSM Potential of CEPC

see talk by Yongchao Zhang

see talk by Jorge de Blas

see talk by Lorenzo Calibbi

figure from CEPC WP 2505.24810

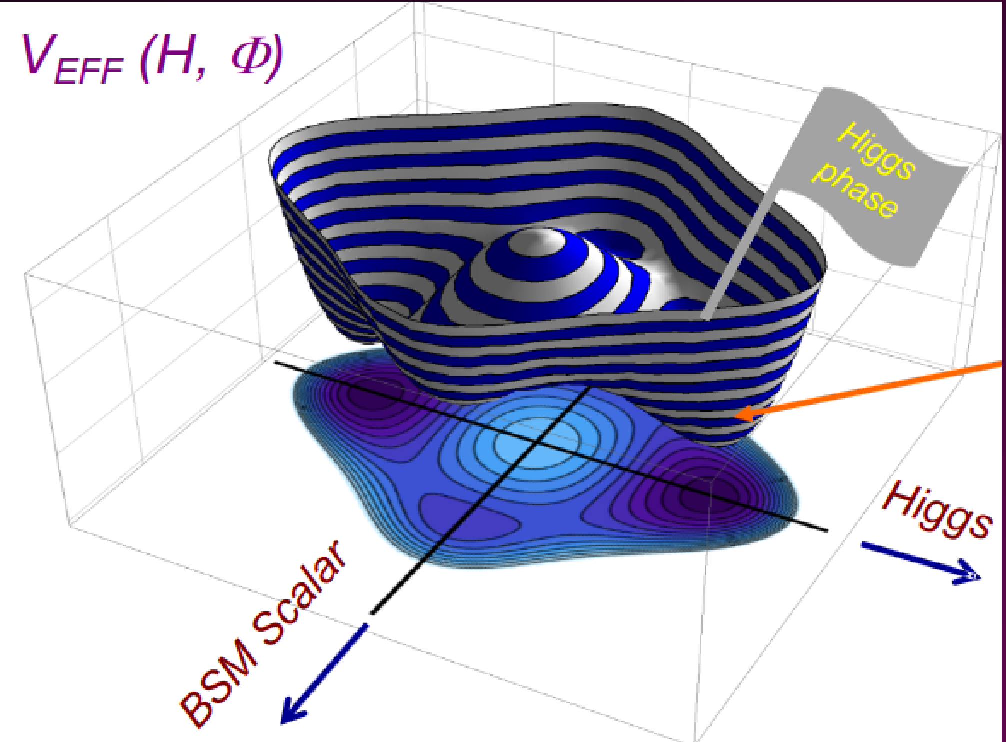
The Higgs Boson as a Portal to New Particles

see talk by Andreas Crivellin

Higgs and the thermal history of the Universe

BAU

- 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

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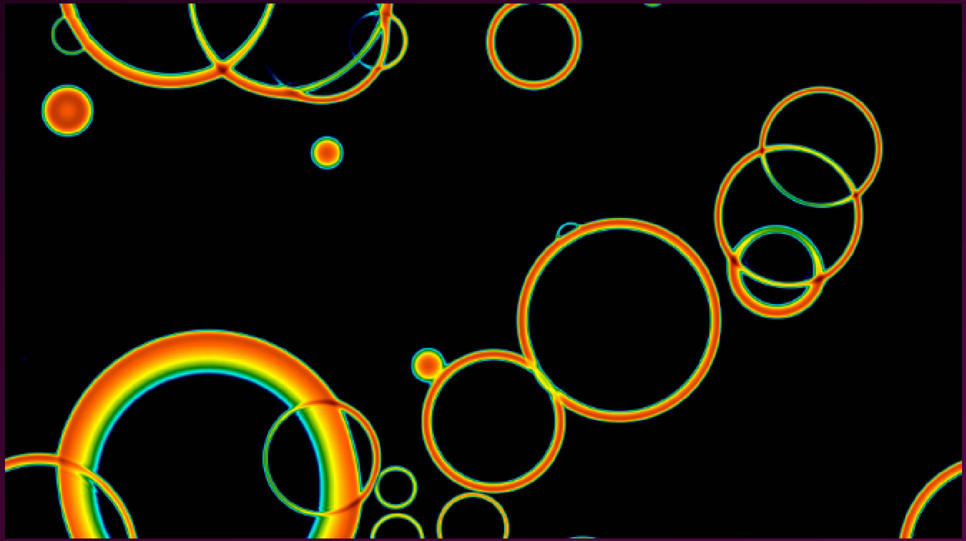
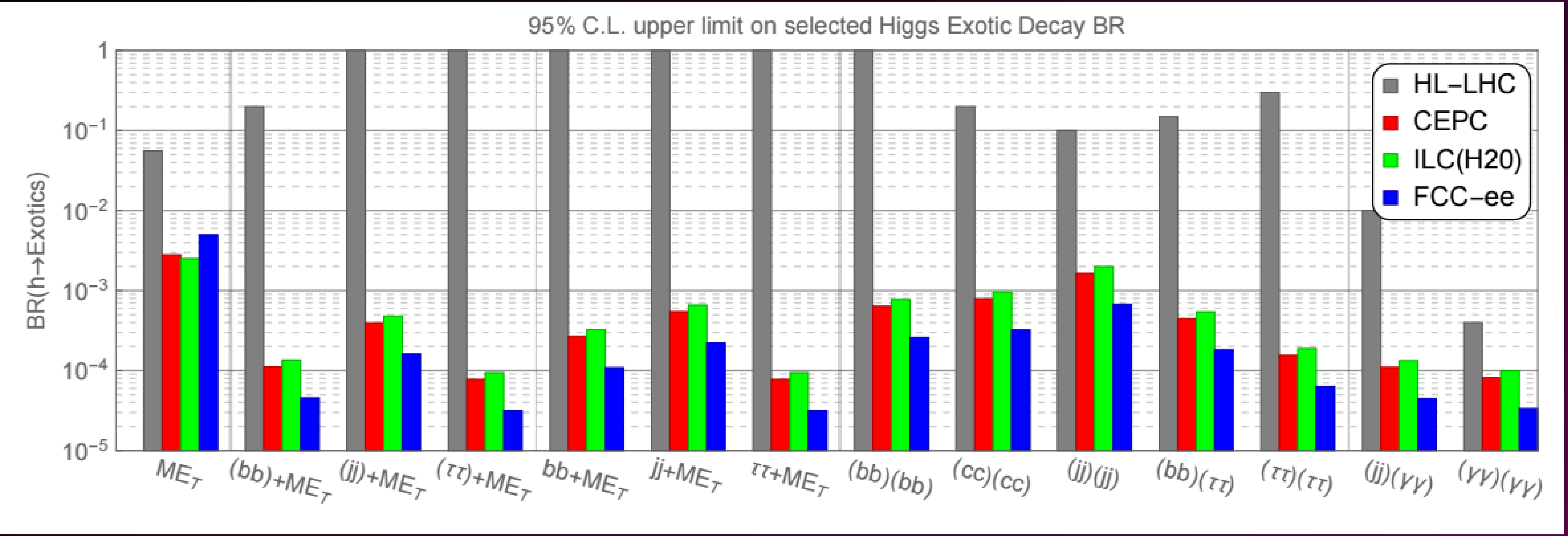


D. Weir 1705.01783

See talk by M.J. Ramsey -Musolf

Probes of EWPT in Exotic Higgs Decays?



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!

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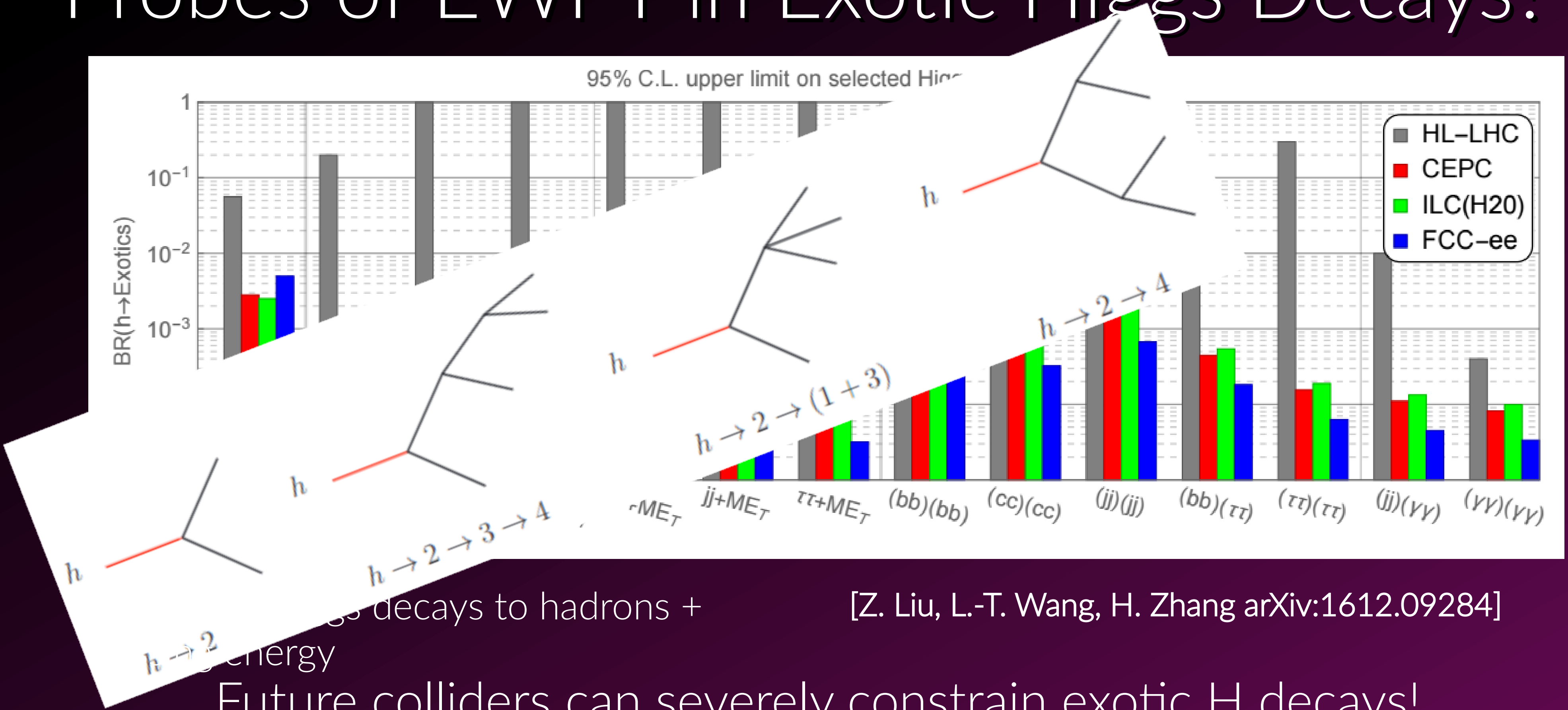

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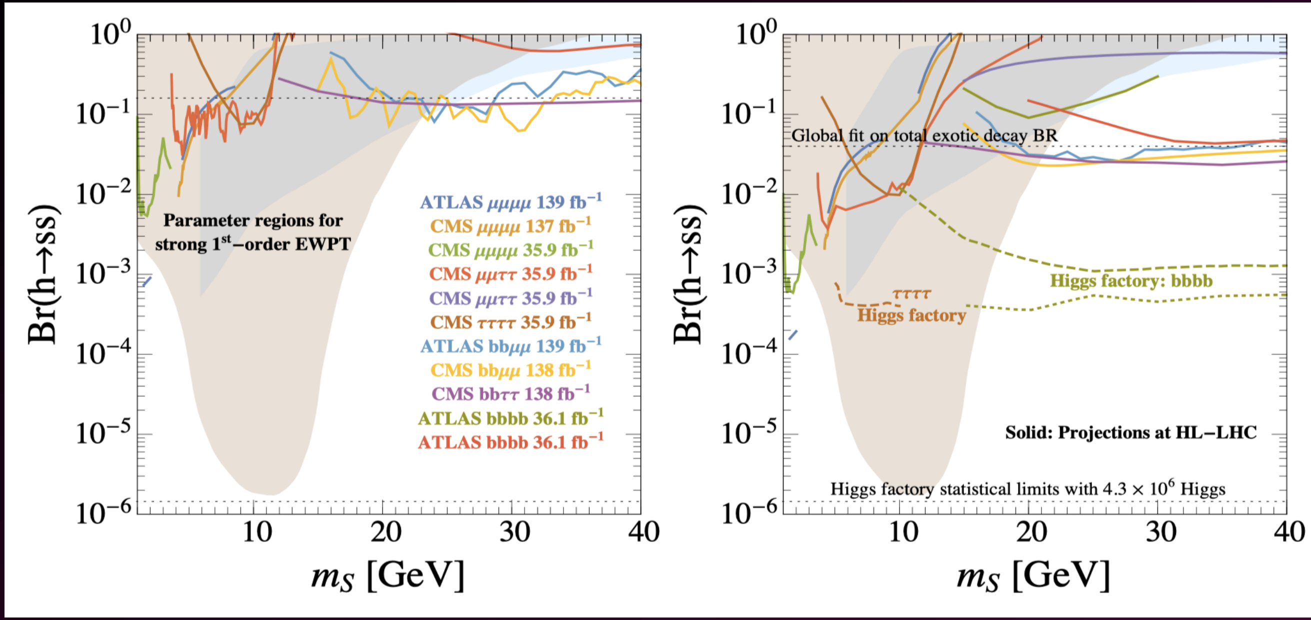
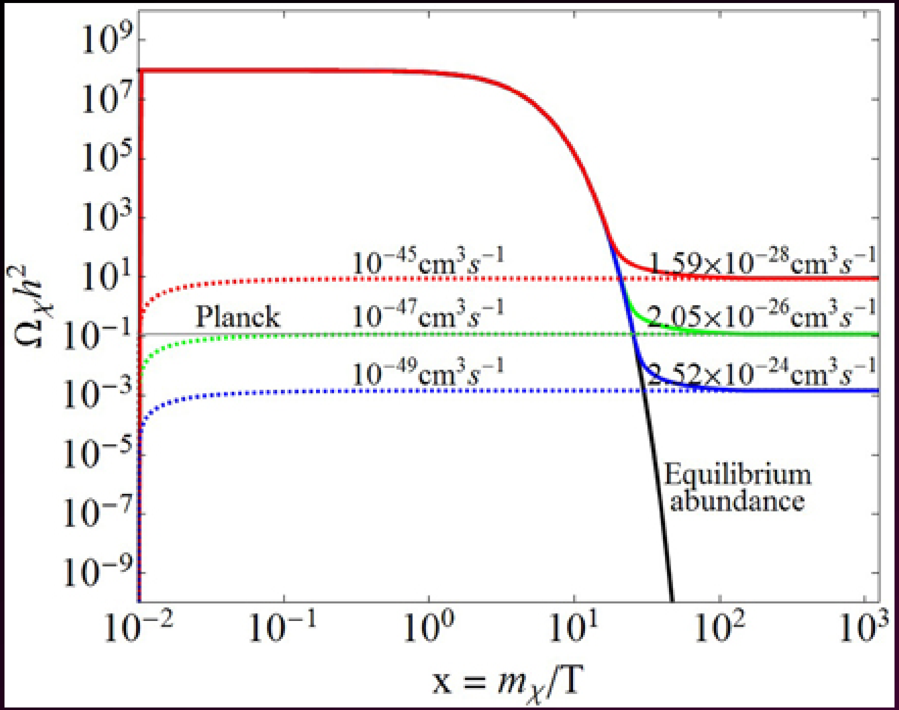


- Exotic decays at CEPC probe a large portion of 1st order EWPT parameter space
- Crucial channels at h-factories:
  - $h \to bbbb$
  - $h \to \tau\tau\tau\tau$

[Carena, Kozaczuk, Liu, Ou, Ramsey-Musolf, Shelton, Wang & Xie, 2203.08206]

Dark Matter and Dark Sectors

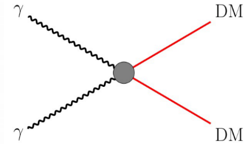
Dark Matter



[fig from 1311.5297]

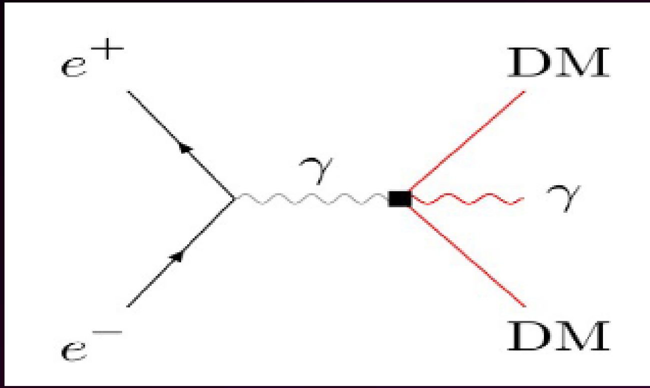
- A variety of DM scenarios could be tested:
  - WIMPs produced via thermal **freeze-out**
  - FIMPs produced via **freeze-in**
- Many possible production mechanisms
- If produced in an EFT regime, DM abundance sensitive reheating

$$Y_{\rm DM}(T) \sim \frac{5\times10^4\, M_{Pl}}{g_{*s}(T)\sqrt{g_*(T)}\,\pi^8}\left(\frac{T_{\rm RH}^5 - T^5}{\Lambda^6}\right)$$



see the talk by Sahabub Jahedi

Rich Dark Sectors



from the talk by Sahabub Jahedi

- Plethora of possible signatures
- Monophoton
- Dark Quarks:
  - dark showers
  - dark mesons
- orders of magnitude improvement at the **CEPC**

see talks by Changbin Xi and Linfeng Li

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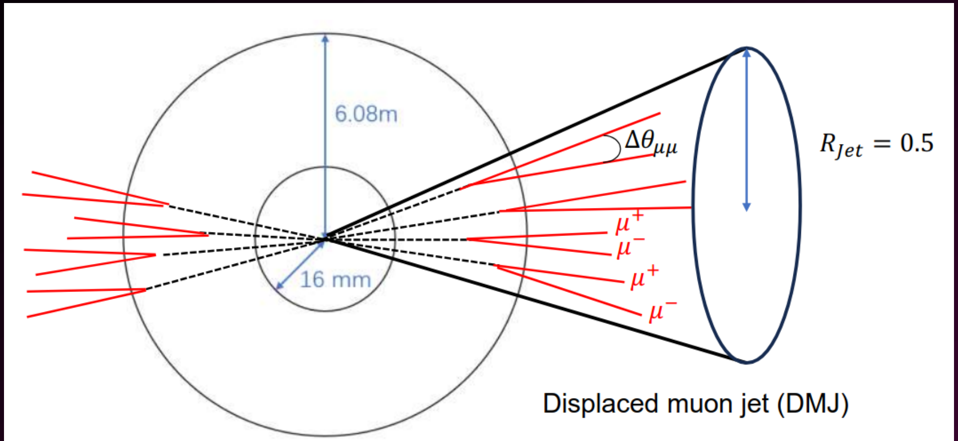

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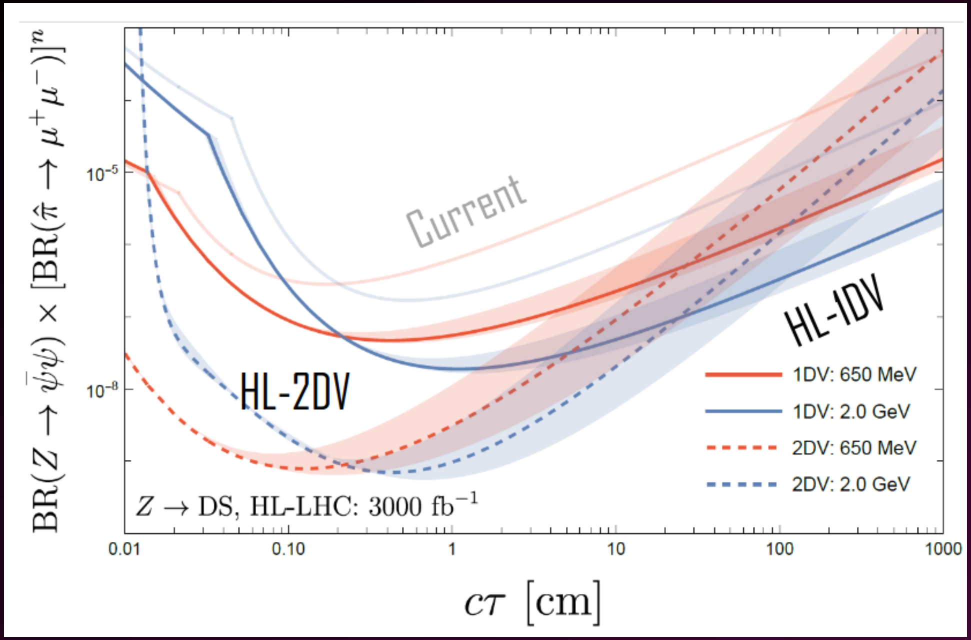

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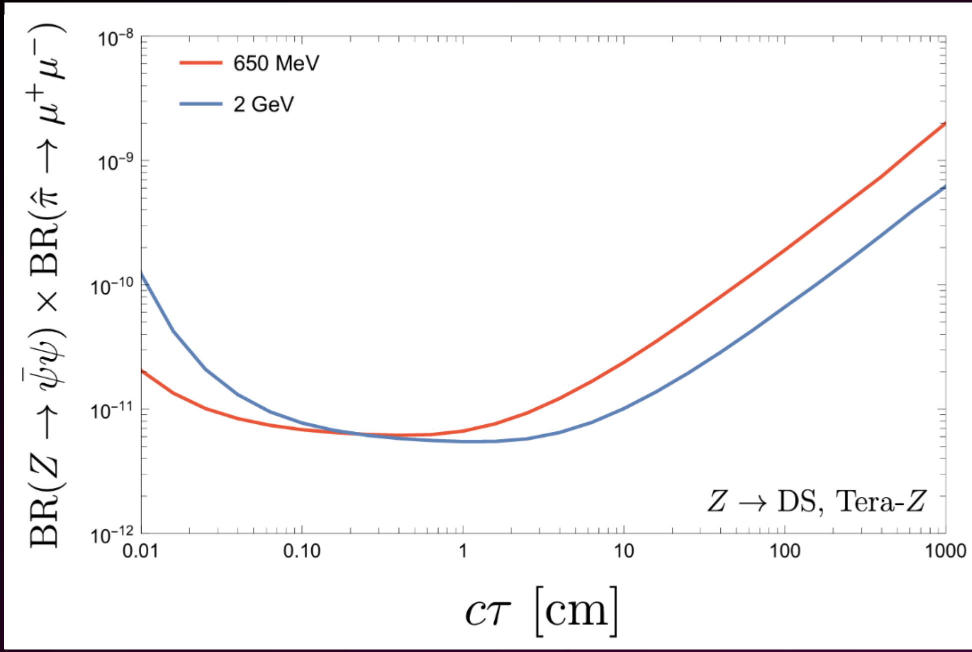

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Long-Lived Particles

Long-lived Particles

Renormalizable portals

- Scalars
- Vectors
- Fermions

Non-renormalizable portal

- Pseudo-scalars:
  Axions and axion-like particles

See talk by Xiang Chen, Ziyang Sun, Liang Li

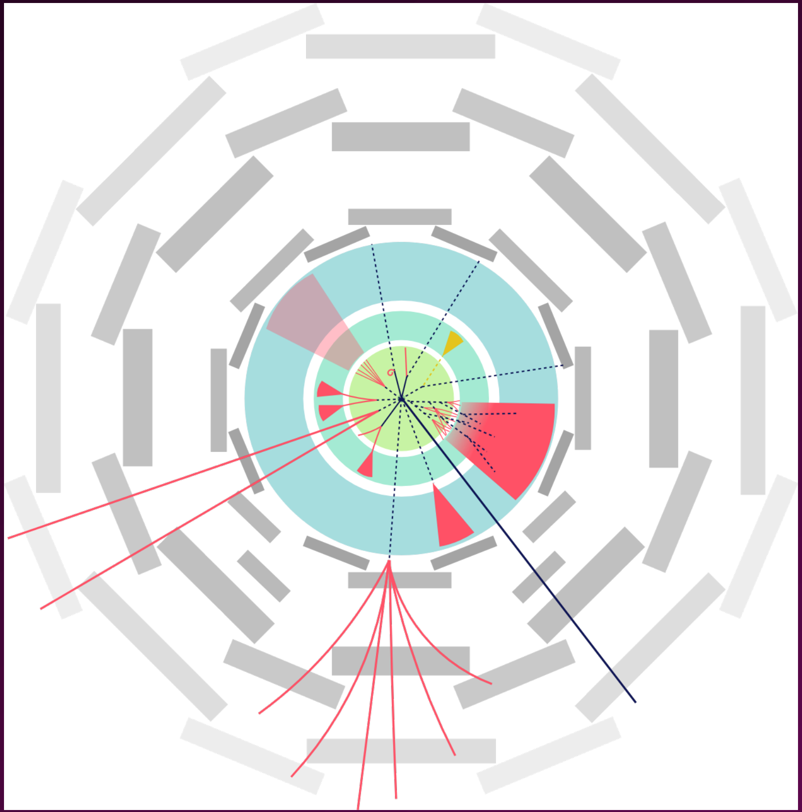


Image credit: Heather Russel

Axions and ALPs

- *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:

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

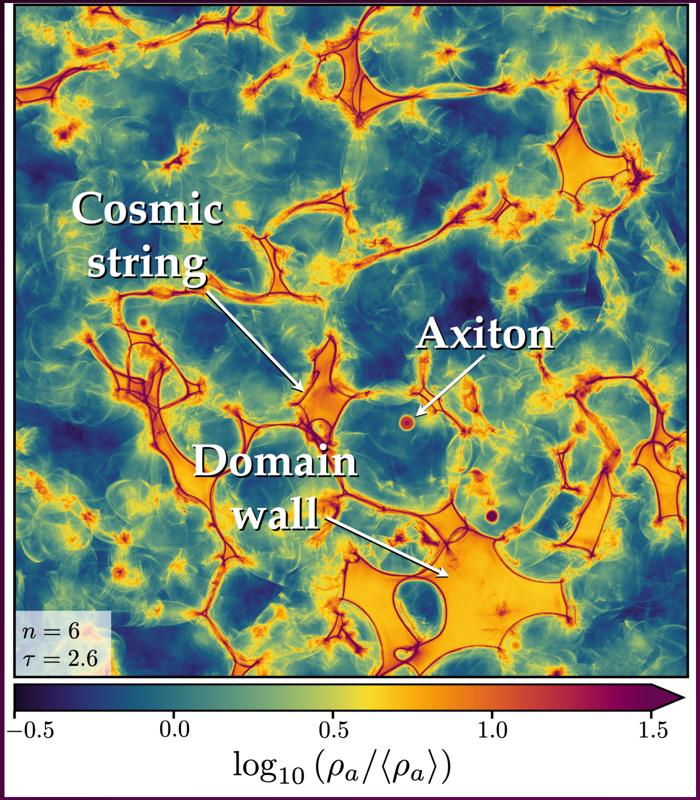


Figure from O'Hare et. al. 2112.05117

Sensitivity to ALPs

- Heavy ALPs can **mediators** between the SM and DM
  - Can easily reproduce the observed DM abundance
- mono-photon signature if the ALP is **long-lived** and escapes detection

from the talk by Shou-Shan Bao

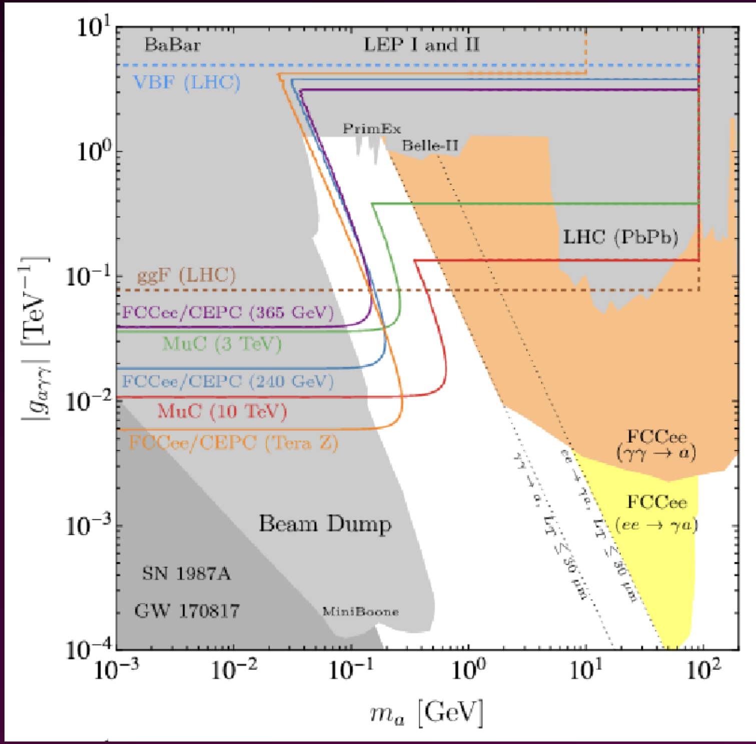
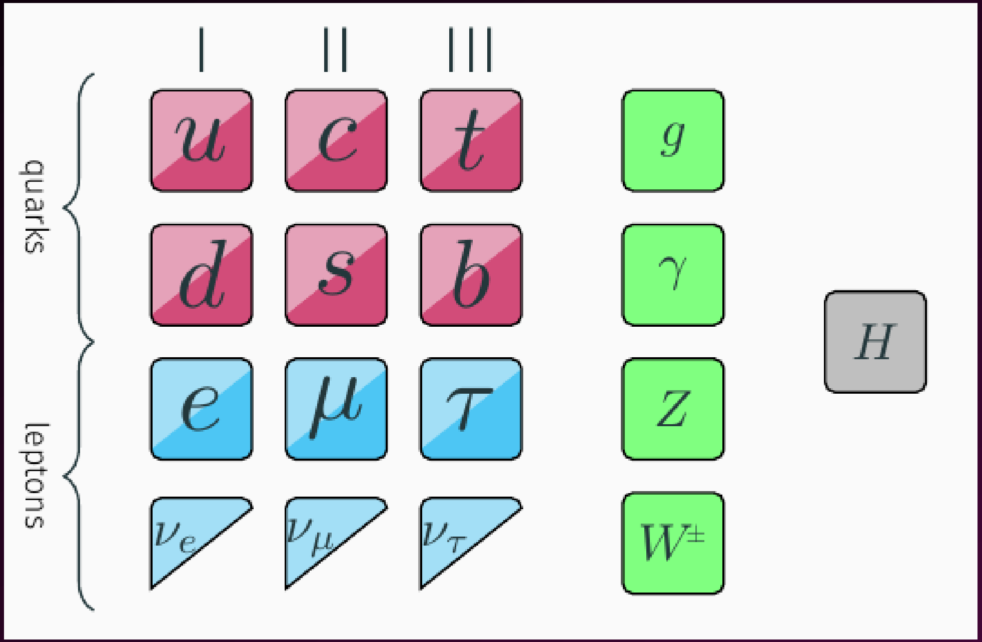
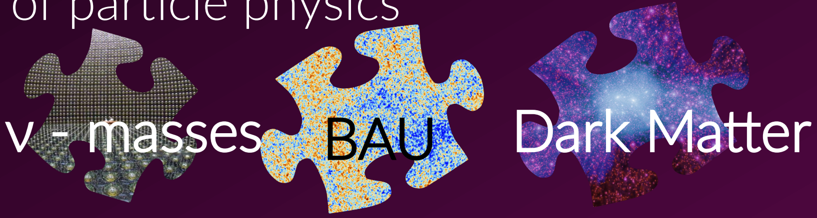


fig. from 2505.10023

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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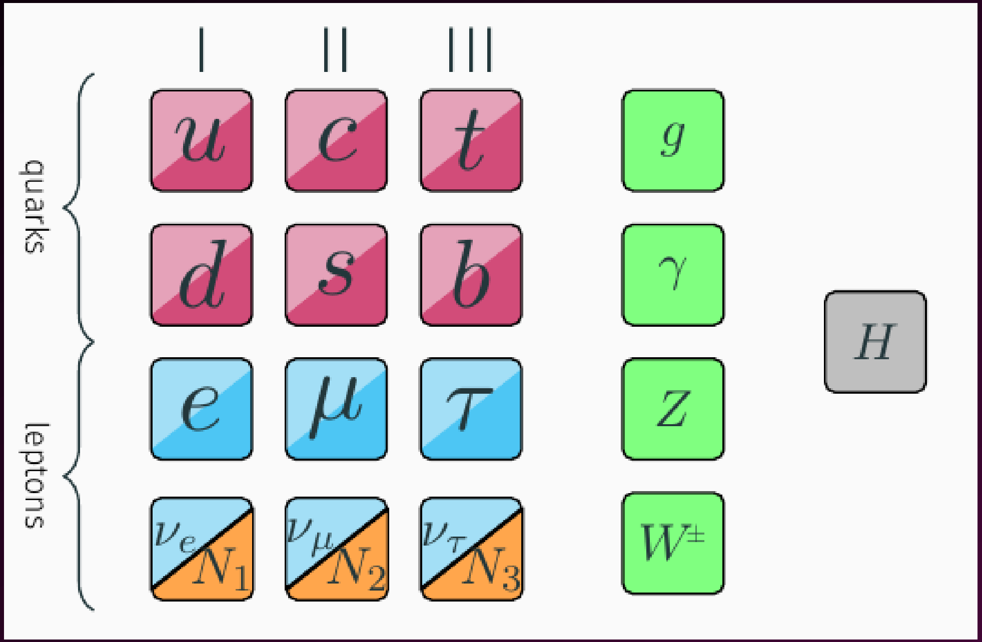

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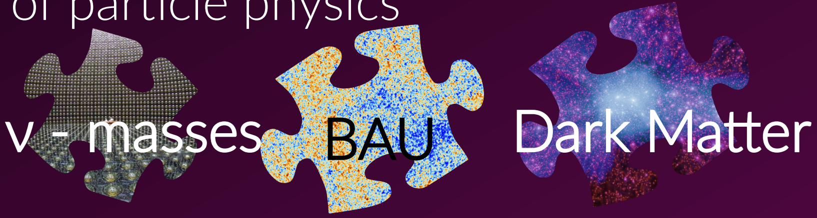

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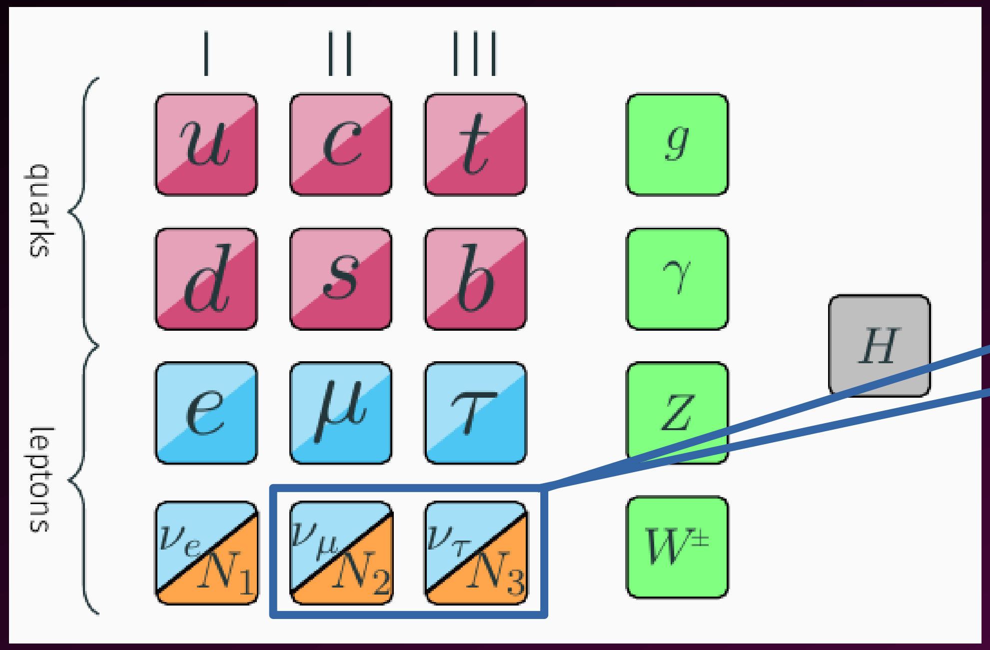

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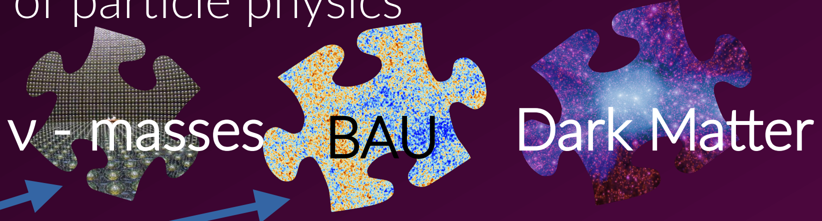

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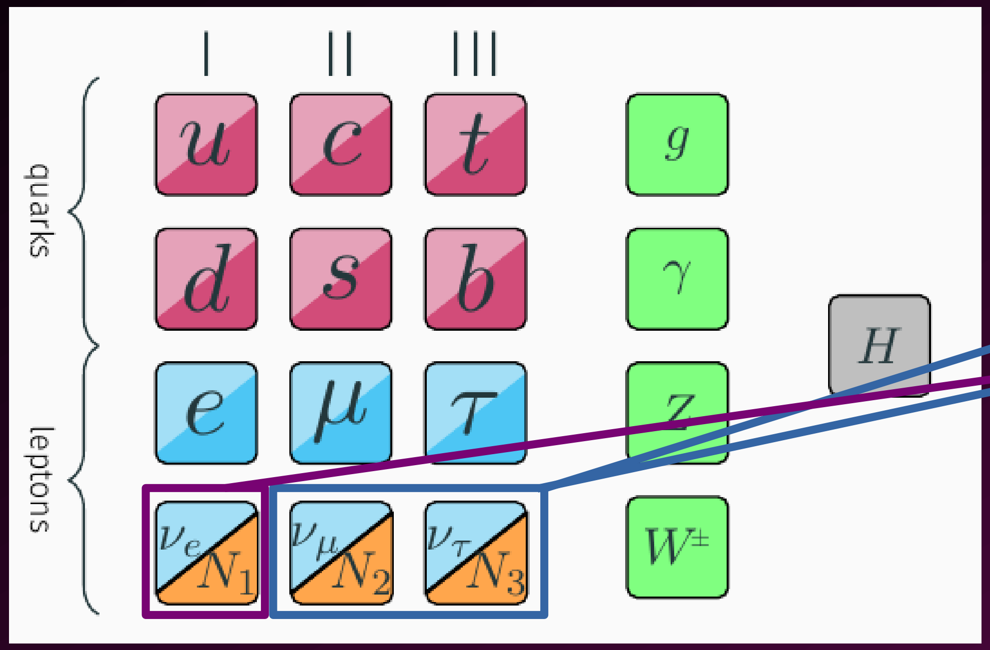

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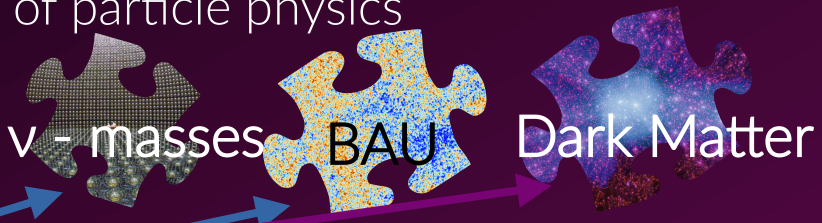

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The Seesaw Mechanism

How *Heavy* are HNLs?

The Seesaw Lagrangian

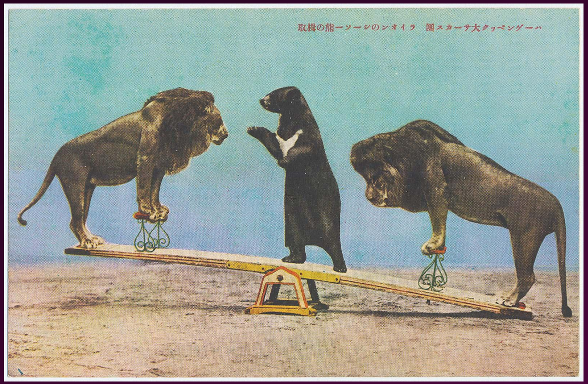
$$\mathrm{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

$$m_\nu = m_D$$

Neutrino masses

are extremely small

$$m_\nu \lesssim 0.8\,\mathrm{eV}$$



Unknown Japanese Artist,
MFA Boston

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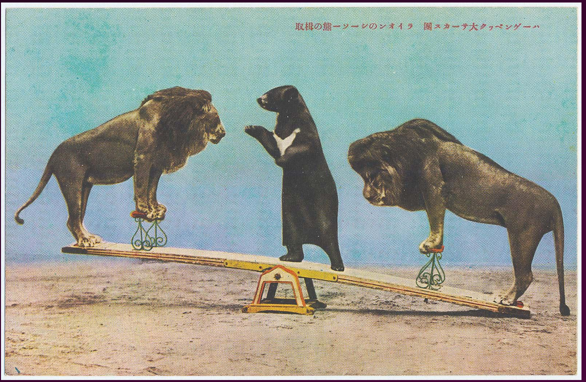

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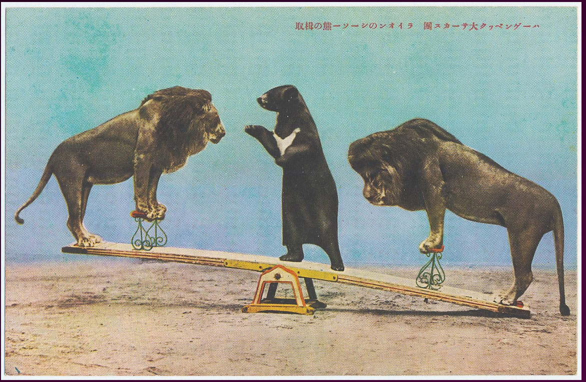

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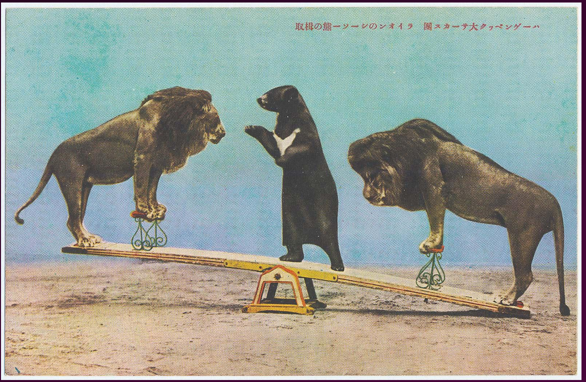

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10^{-1} 10^{3} 10^{7} 10^{11} 10^{15}

$M_M[\mathrm{GeV}]$

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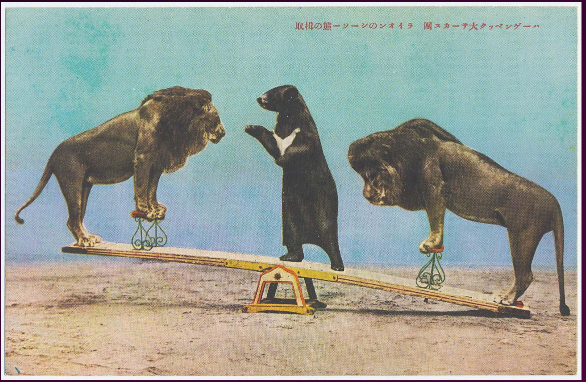

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Canonical type-I seesaw

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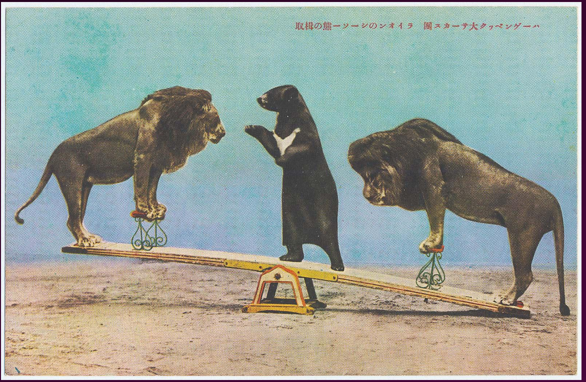

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Low-scale linear and inverse seesaws

Canonical type-I seesaw

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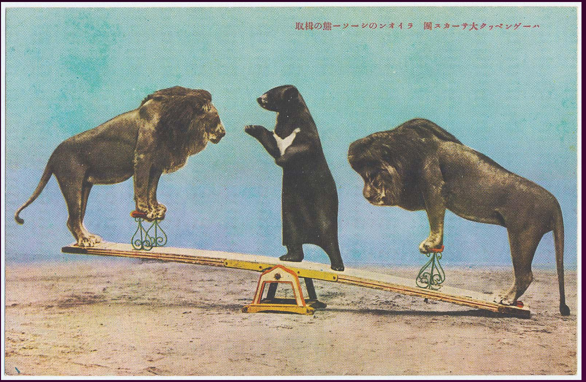

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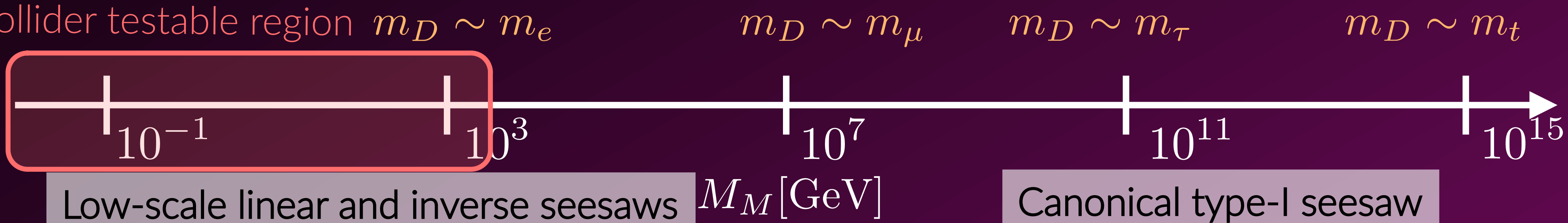
Collider testable region



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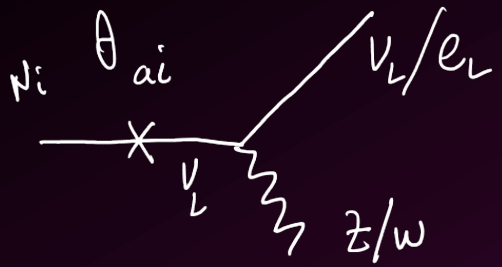

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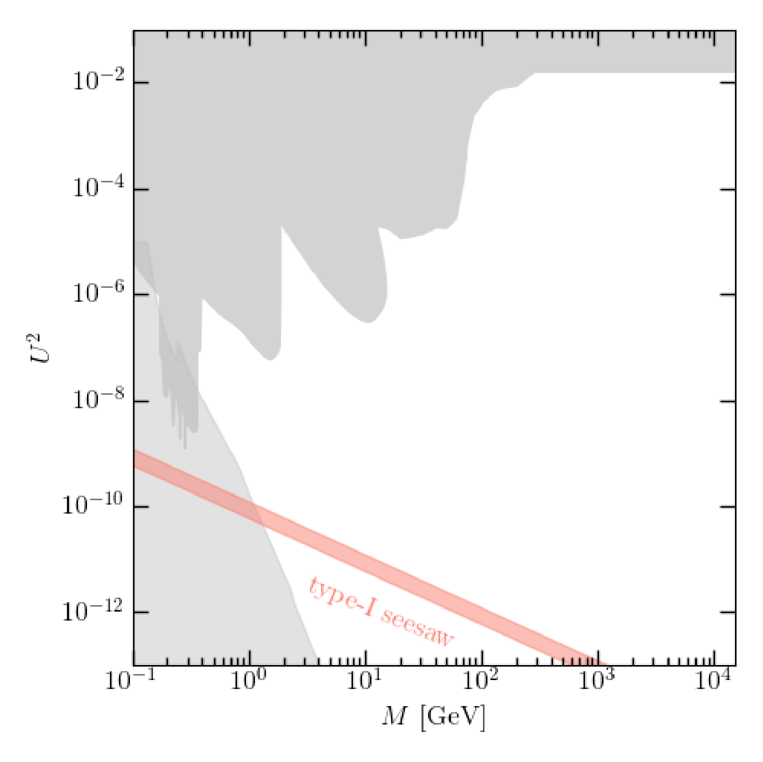
$$U^2 = \sum_{a,i} U_{ai}^2 \qquad U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

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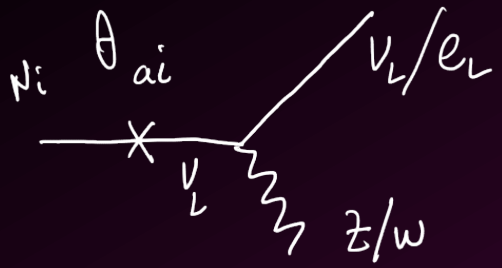

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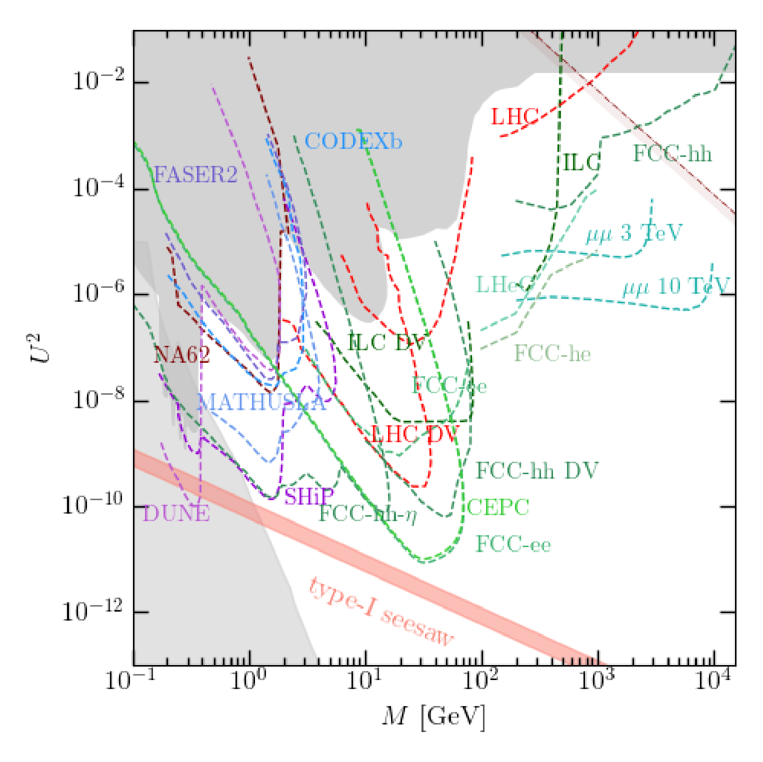

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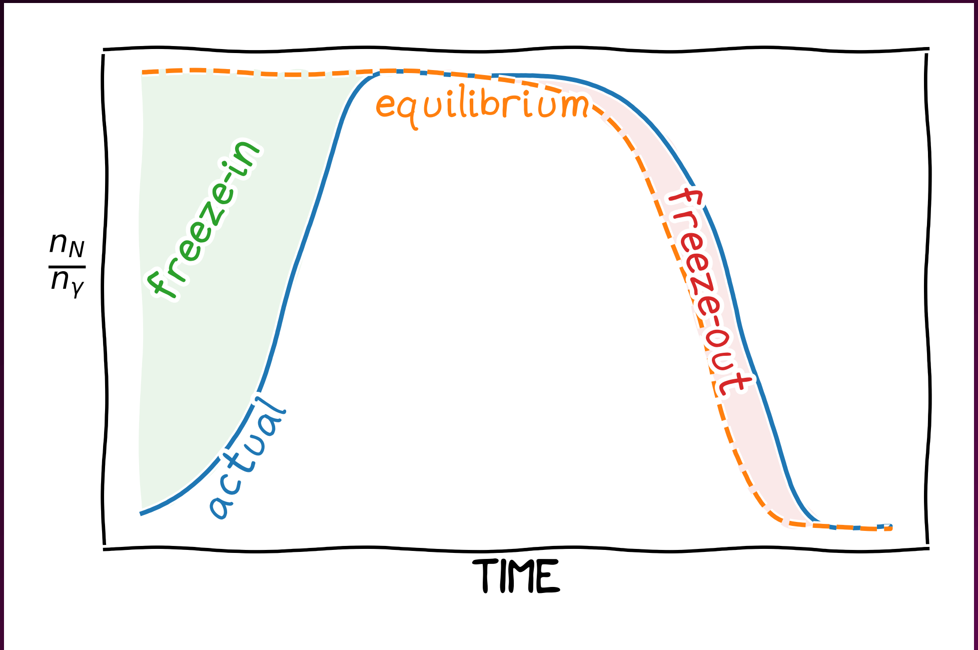
HNLs and the Baryon Asymmetry of the Universe

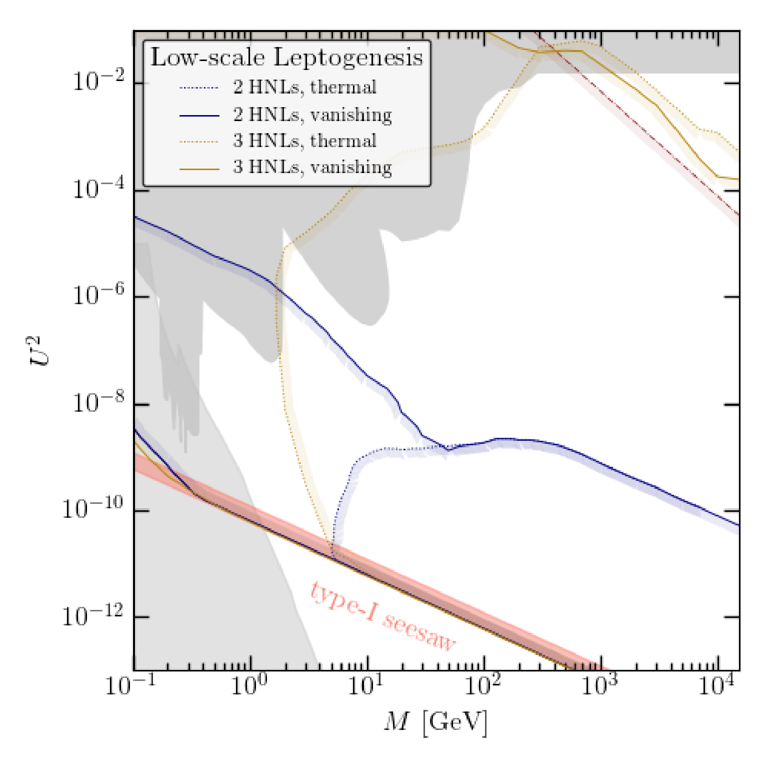
- Three [Sakharov '67] conditions:

1. Baryon number violation
   - sphaleron processes violate B+L ✓
   - L violation from HNLs ✓
2. C and CP violation
   - HNL decays and oscillations ✓
3. Deviation from equilibrium
   - freeze-in and freeze-out of HNLs ✓



The parameter space of leptogenesis

- 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
- Both **vanishing** *(no additional interactions)* and **thermal** *(high-scale additional interactions)* leptogeneses **within reach of CEPC**
- Leptogenesis **within reach** of HL-LHC
- High complementarity between **colliders** and **dedicated LLP** searches



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[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545 and Drewes/Georis/JK 2106.16226]

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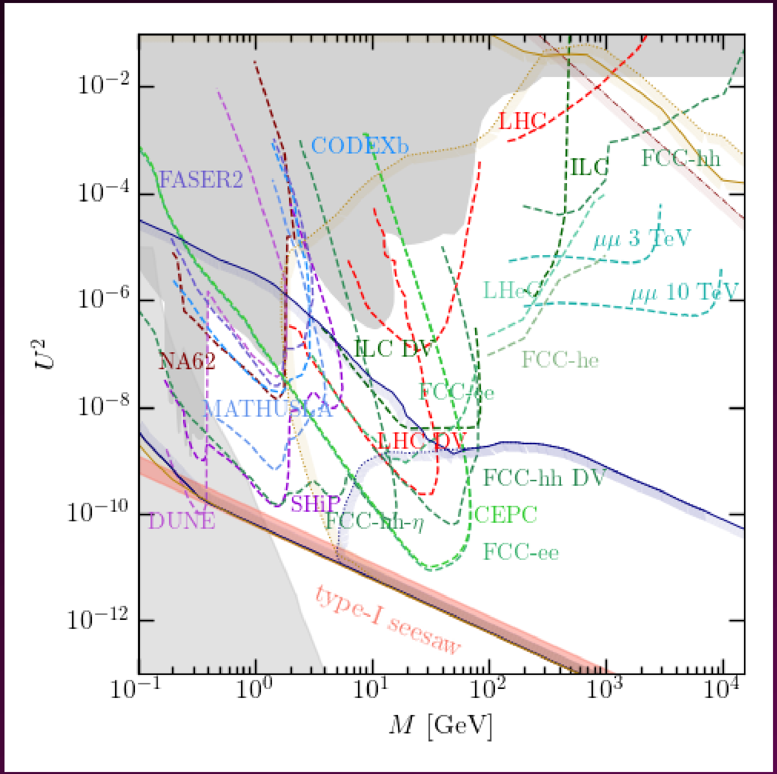

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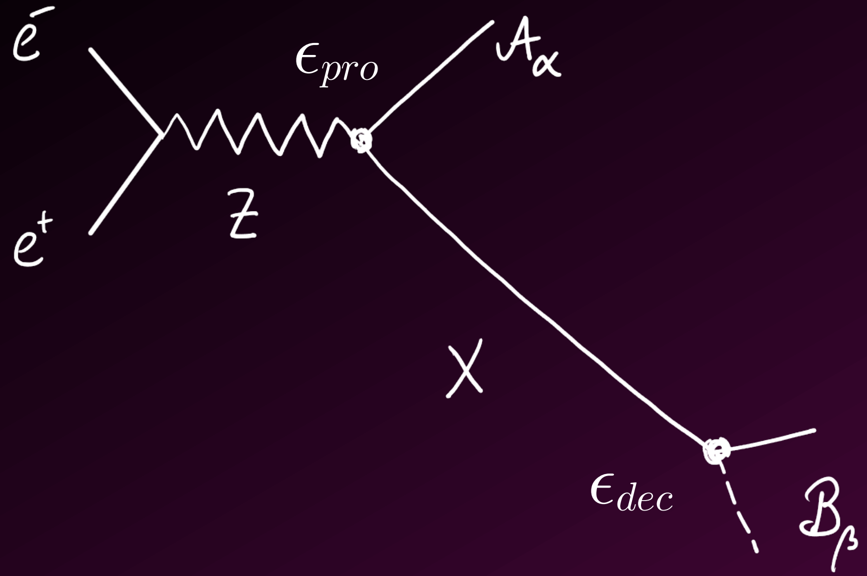
[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545 and Drewes/Georis/JK 2106.16226]

Sensitivity to LLPs at Z factories



- new particle $\boldsymbol{X}$ coupled to $\boldsymbol{Z}$ boson via small coupling $\epsilon_{pro} \ll 1$
- produced together with some SM particle A_α
- flies through the detector over a macroscopic distance l
- decay suppressed by $\epsilon_{dec} \ll 1$
- decays back into SM particles B_β

How to estimate Tera-Z sensitivity?

- Total number of produced X particles given by the fraction of Z-bosons

$$N_{pro} = N_Z \epsilon_{pro} \hat{Br}(Z \to XA)$$

- Decay length of X particle in lab frame

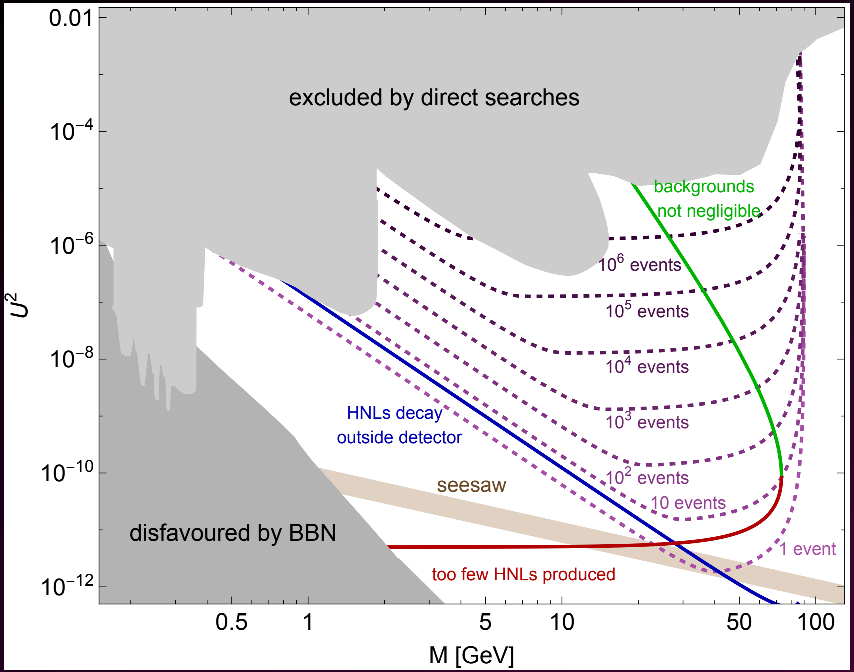
$$\lambda = \frac{p/m}{\Gamma}$$

- Number of observed events in detector of length l_1 with a minimal displacement l_0

$$N_{obs} = N_Z \epsilon_{pro} \hat{Br}(Z \to XA)[\exp(-l_0/\lambda) - \exp(-l_1/\lambda)]$$

from Drewes, Li, JK 2511.23461

HNLs at Tera-Z factories



We can disentangle the limits of HNL searches

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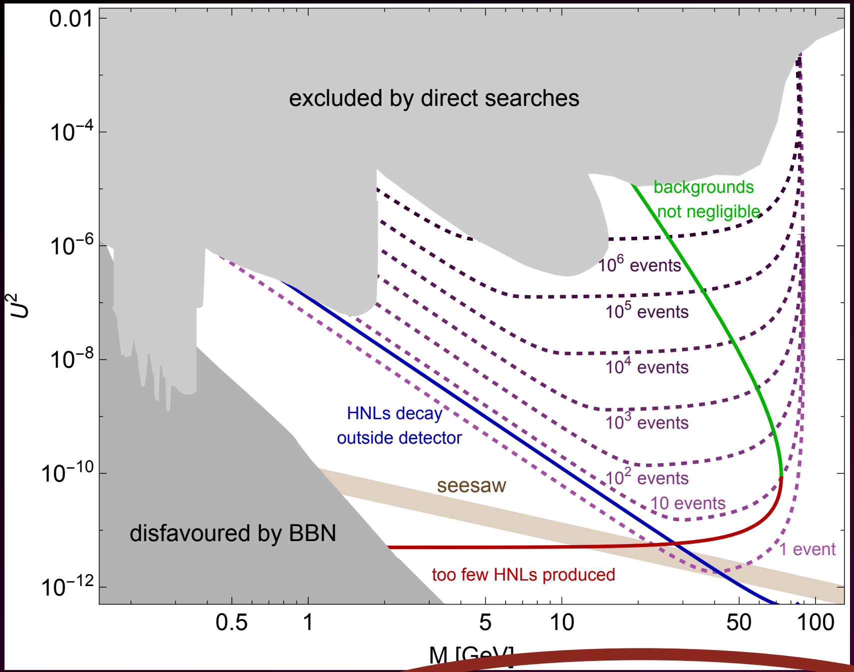

We can disentangle the limits of HNL searches

- total possible number of produced states

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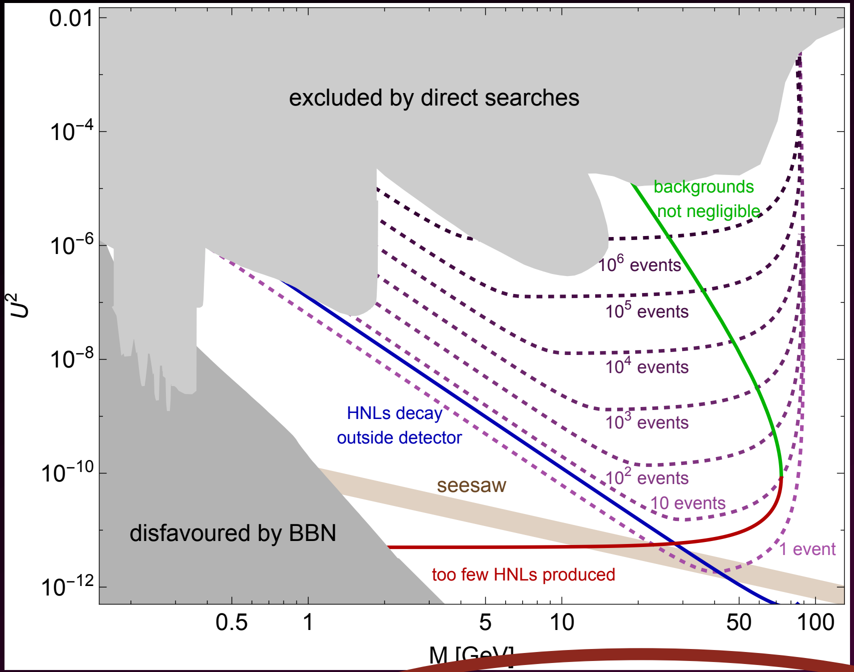
HNLs at Tera-Z factories

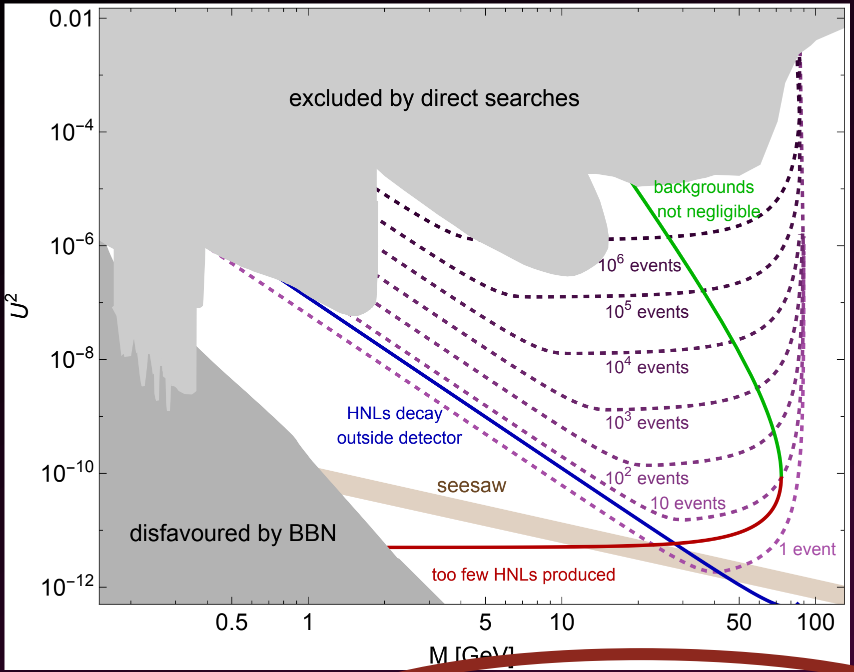


We can disentangle the limits of HNL searches

- total possible number of produced states
- Number of states that decay within the detector volume

$$N_{obs} = N_Z \epsilon_{pro} \hat{Br}(Z \to X A) [\exp(-l_0/\lambda) - \exp(-l_1/\lambda)]$$

HNLs at Tera-Z factories



We can disentangle the limits of HNL searches

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- states decay too fast to be observed as displaced vertices

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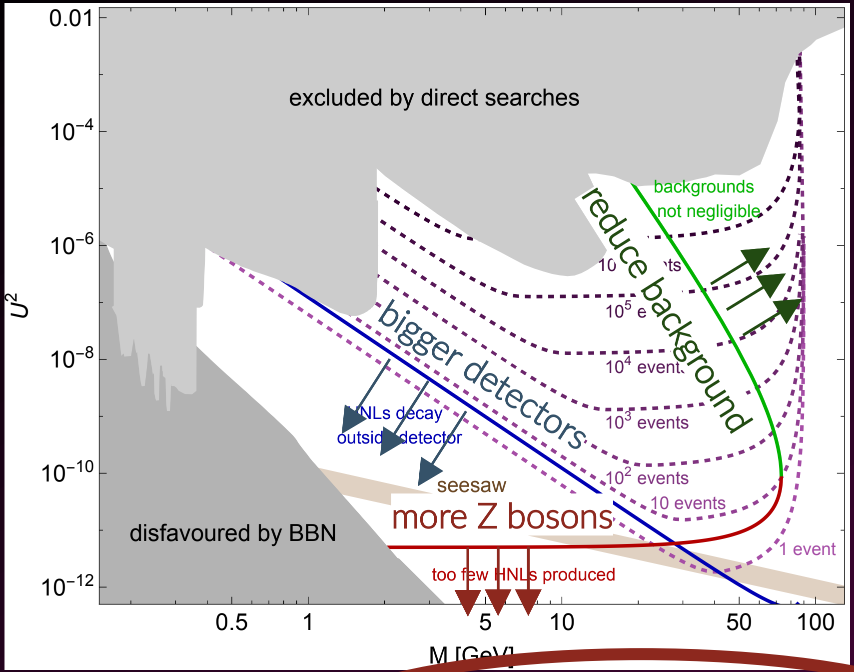
HNLs at Tera-Z factories



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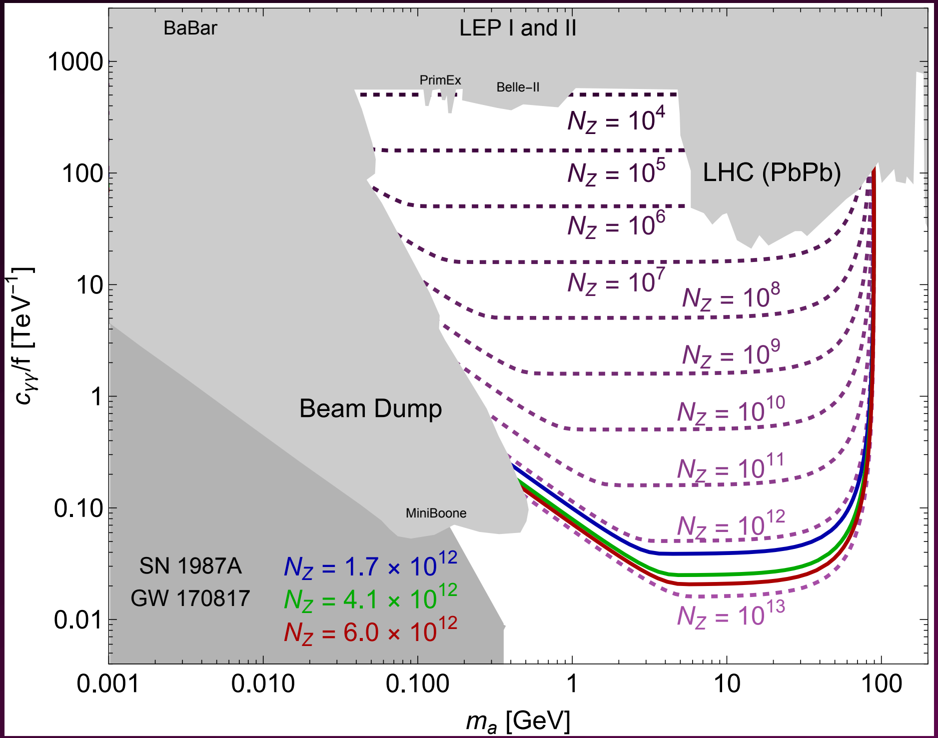
ALPs at Tera-Z factories

- Expected sensitivity highly depends on the number of Z-bosons
- Reduced background due to 3γ events: no displacement needed
- Sensitivity depends on production/decay coupling relations

$$c_{Z\gamma} = -s_w^2 c_{\gamma\gamma}$$



Beyond Discovery:

Tera-Z factories BSM testing facilities

HNL branching ratios

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

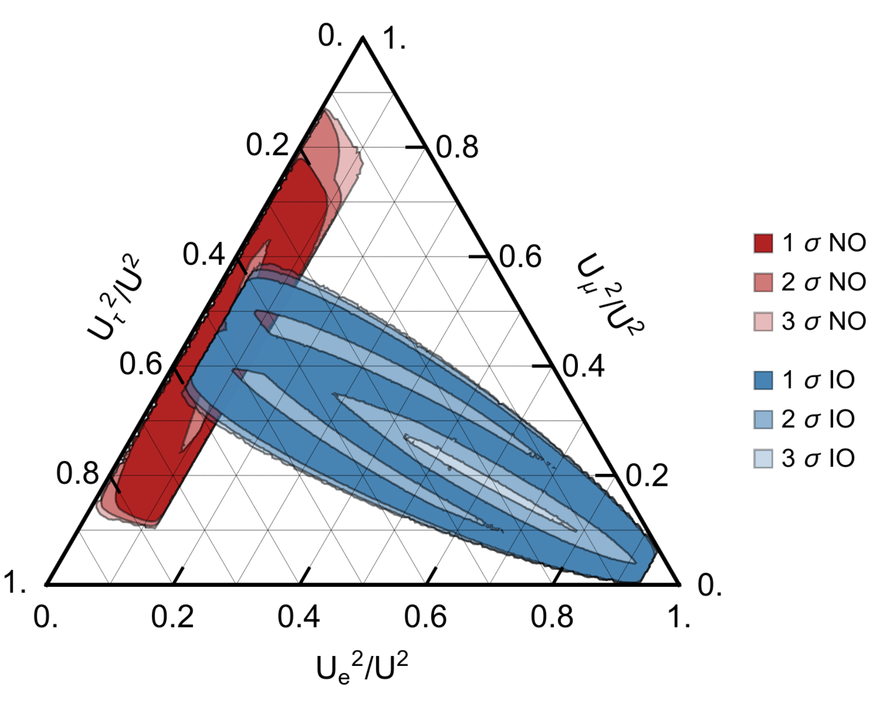
  [Snowmass white paper 2203.08039]

- 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 2412.10254]



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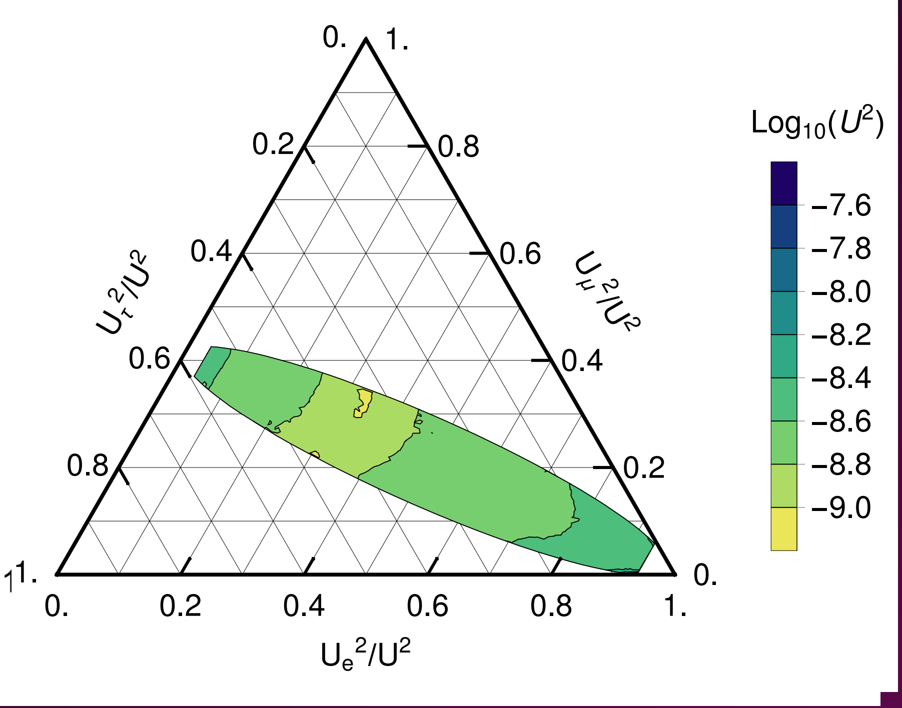

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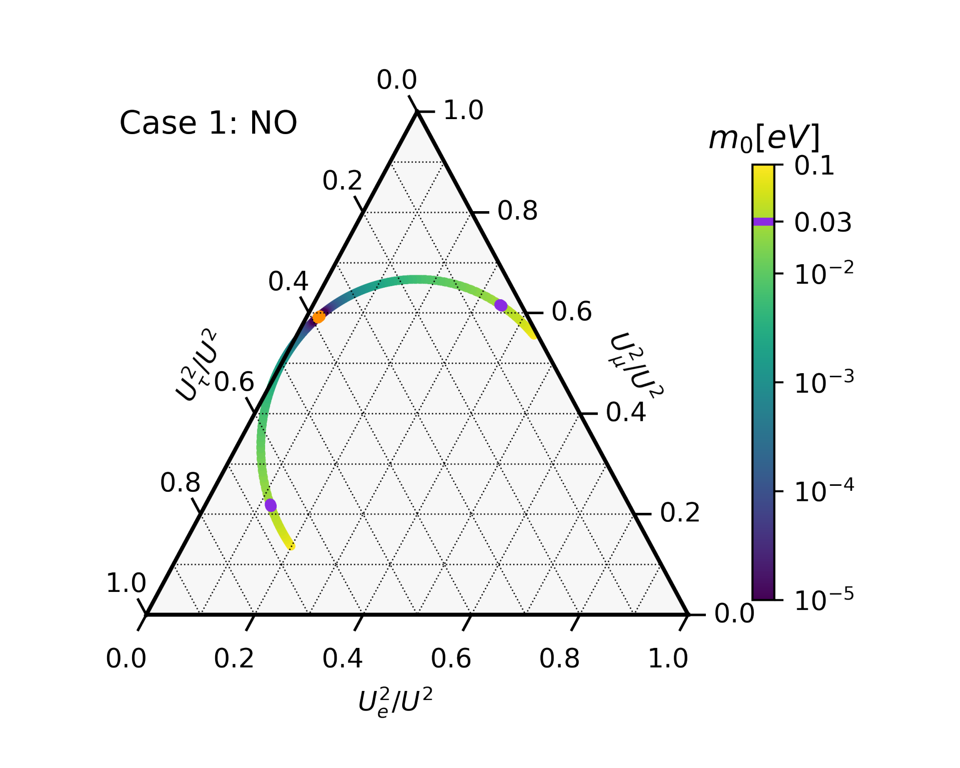


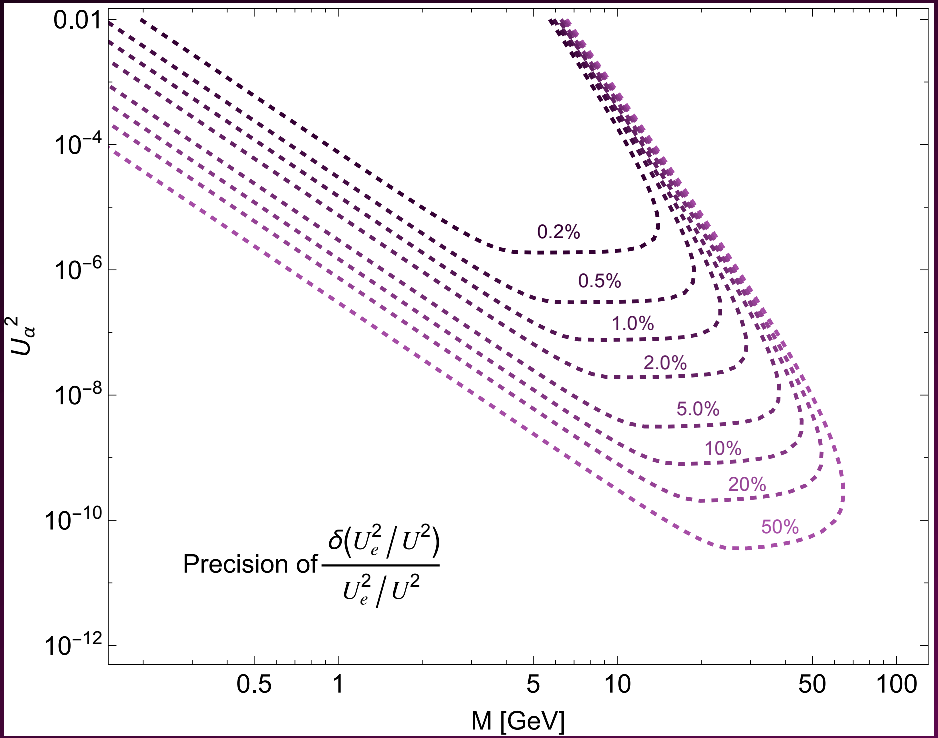
Precision BSM at Tera-Z

- Large number of events allows us to measure the HNL branching ratios
- Certain parts of parameter space can lead to sub-percent level precision measurements

$$\frac{\delta(N_{\rm obs}^{\mathcal{A}_\alpha,\mathcal{B}_\beta}/N_{\rm obs})}{N_{\rm obs}^{\mathcal{A}_\alpha,\mathcal{B}_\beta}/N_{\rm obs}} = \sqrt{\frac{1}{N_{\rm obs}^{\mathcal{A}_\alpha,\mathcal{B}_\beta}} - \frac{1}{N_{\rm obs}}}.$$

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

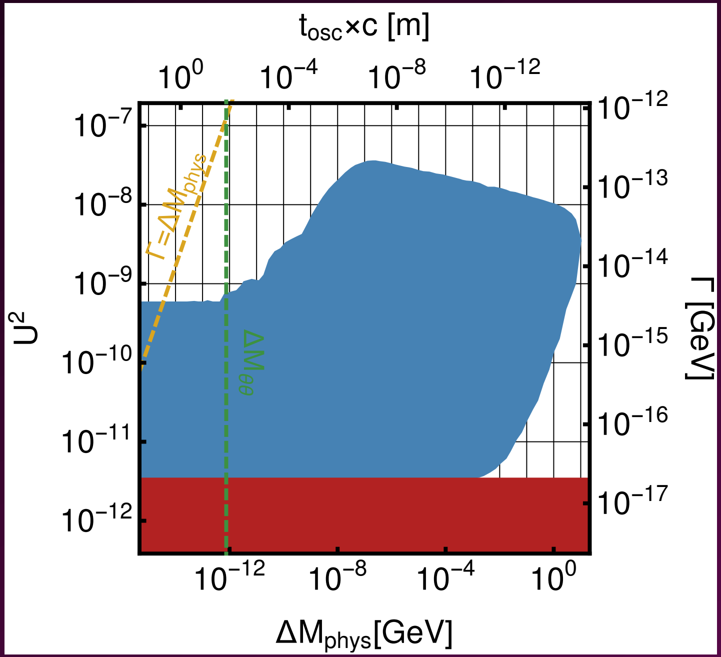
[Drewes, Li, JK 2511.23461]



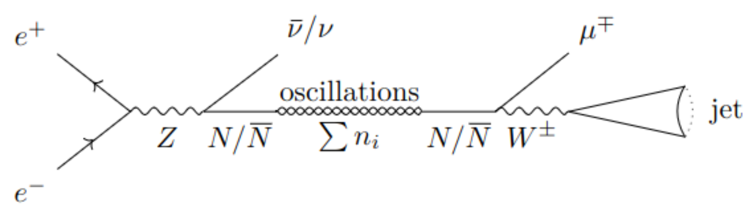
HNL properties at e⁺e⁻ colliders

Many more observables:

- Lepton Number Violation
- Lepton Flavor Violation
- HNL oscillations in colliders
  - Deeply related to leptogenesis!



[Antusch et. al. 1710.03744]

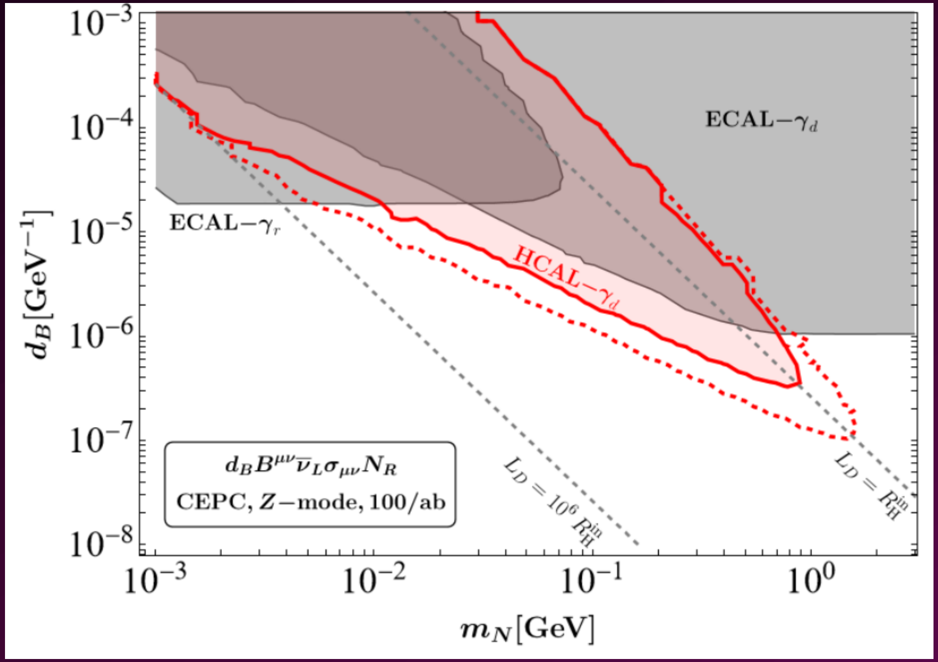


 [Antusch et. al. 2308.07297]

HNL properties at e^+e^- colliders

Many more observables:

- Lepton Number Violation
- Lepton Flavor Violation
- HNL oscillations in colliders
  - **Deeply related to leptogenesis!**
- Dipole portal operator couplings



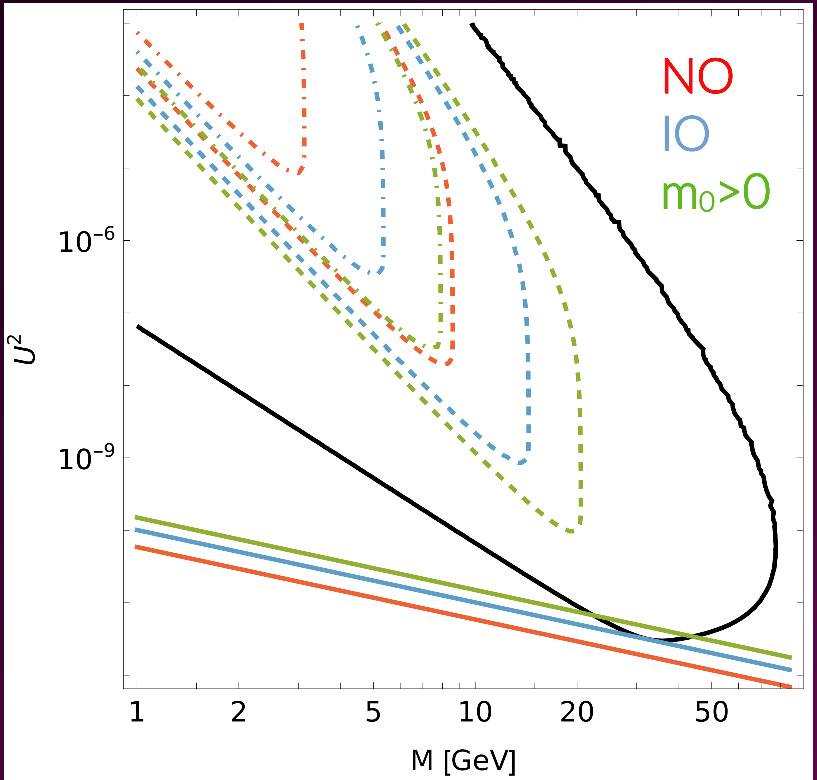
[Li, Liang, Jiang, arXiv:2510.26649]

see talk by Jinhan Liang

 [Antusch et. al. 2308.07297]

Reconstructing all parameters?

- Measuring all parameters is challenging with 2 HNLs due to degeneracies in observables
- Less degeneracy with 3 HNLs: for *kinematically distinguishable* HNLs, *all 9 mixing angles U^2_{ai} could be measured* independently.
- we can identify the region where all parameters can be measured at a Tera-Z factory



[Drewes/Georis/JK/Wendels 2407.13620]

Conclusions

- Exciting times ahead!
- Future colliders can **directly probe new BSM particles**
  (apologies if I missed your favorite BSM scenario)
- Explanations to **several puzzles of particle physics** are within the reach
- Future colliders can **go beyond discovery** and directly **test BSM scenarios**

Conclusions

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Thank you!

Back-up

Combined Bounds

IH + suppressed $0\nu\beta\beta$ + leptogenesis + direct searches