Direct searches for BSM at FCC-ee

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Fostering Swiss collaboration towards a future circular collider
Université de Genève
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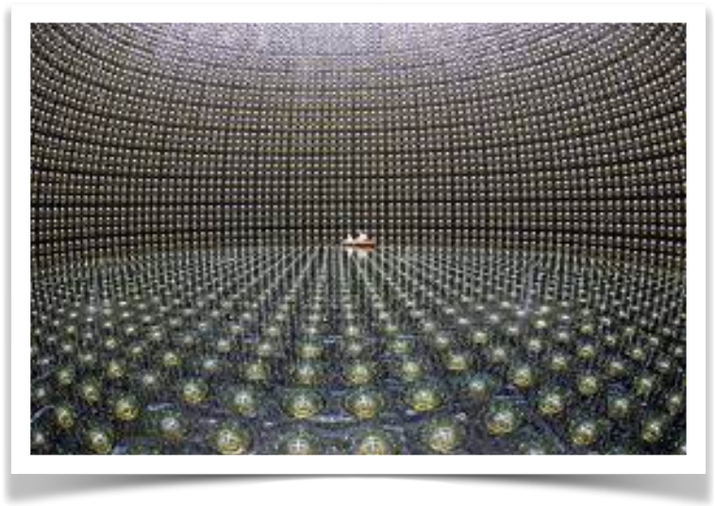
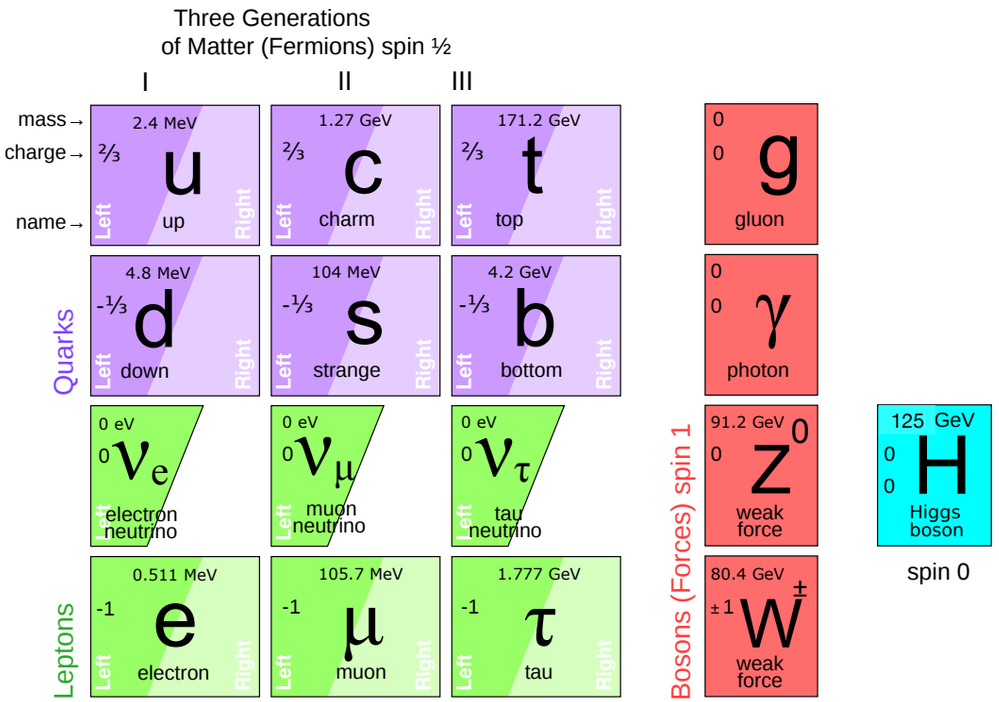
Beyond the Standard Model physics





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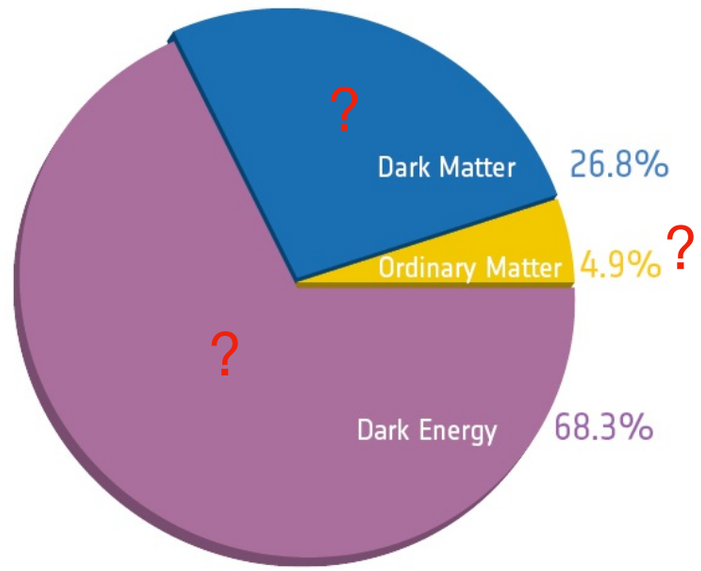


Empirical evidence

- **Neutrino masses and oscillations**
- **Dark matter**
- **Origin of baryonic matter**

Theoretical evidence

- **Hierarchy problems**
- **…**

Beyond the Standard Model physics

Many models to explain a few observable parameters

- **Neutrino masses and oscillations:** 3 angles, 2 mass splittings, 1 phase
- **Dark matter:** Ω_{DM}
- **Origin of baryonic matter** $\eta = n_B/n_\gamma$

A possible guidance in the model space?

Beyond the Standard Model physics

A possible projection of “space of theories”

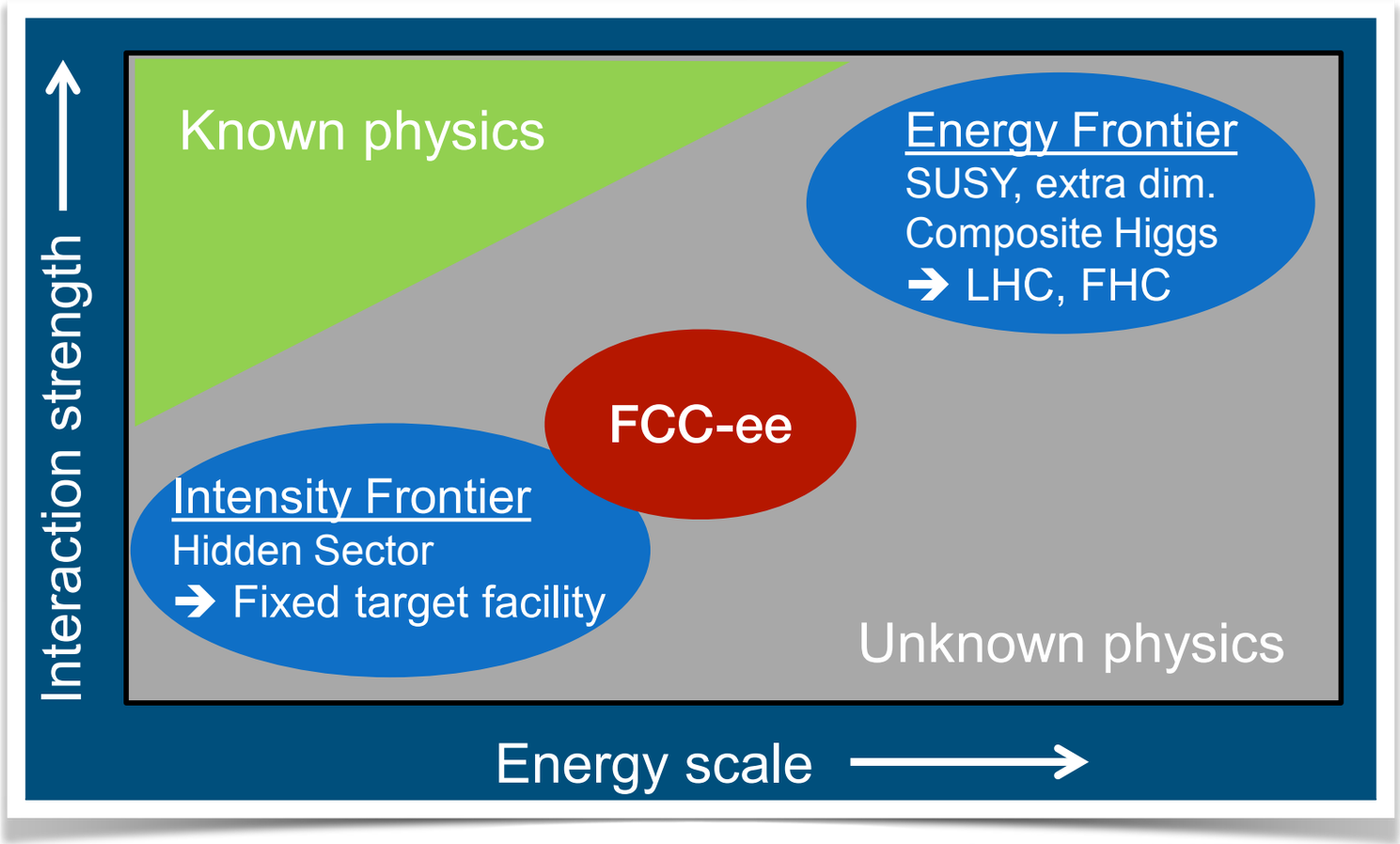


Image: SHiP physics case 1504.04855

5×10^{12} Z^0 bosons

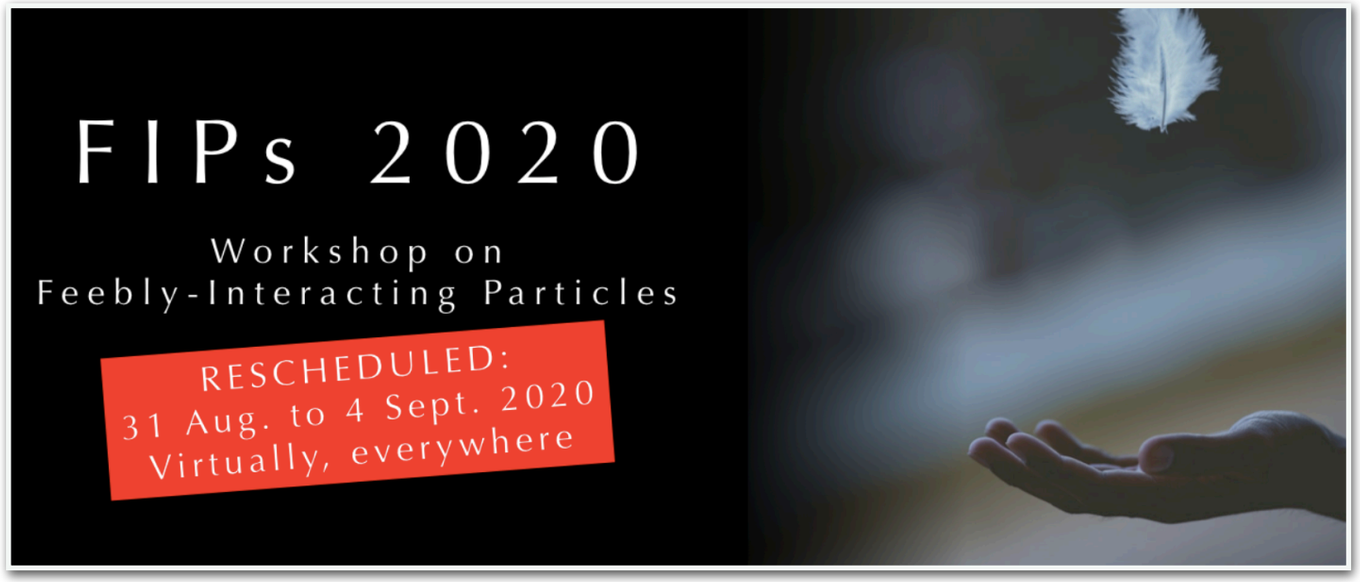
10^8 WW pairs

10^6 Higgses

10^6 $t\bar{t}$ pairs

Feebly-interacting particles

At FCC-ee $\sqrt{s} \sim 90 - 365$ GeV. The new particles at this scales must be feebly coupled.



https://indico.cern.ch/event/864648/
https://arxiv.org/abs/2102.12143

[490 participants]

The Physics Beyond Colliders Study Group [https://pbc.web.cern.ch]
Working Group Report: https://arxiv.org/abs/1901.09966

Physics Briefing Book
https://arxiv.org/abs/1910.11775

Feebly-interacting particles: the four portals

New particles (DM candidates, mediators, heavy neutrinos) must be SM singlets.
Therefore possible couplings are limited by the gauge invariance.

The lowest dimension portals:

Portal	Coupling
Dark Photon, $A^{'}_{\mu}$	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

Specific benchmark models:
PBC report https://arxiv.org/abs/1901.09966

* FIPs 2020 Workshop Report
mentions the fifth portal — millicharged particles

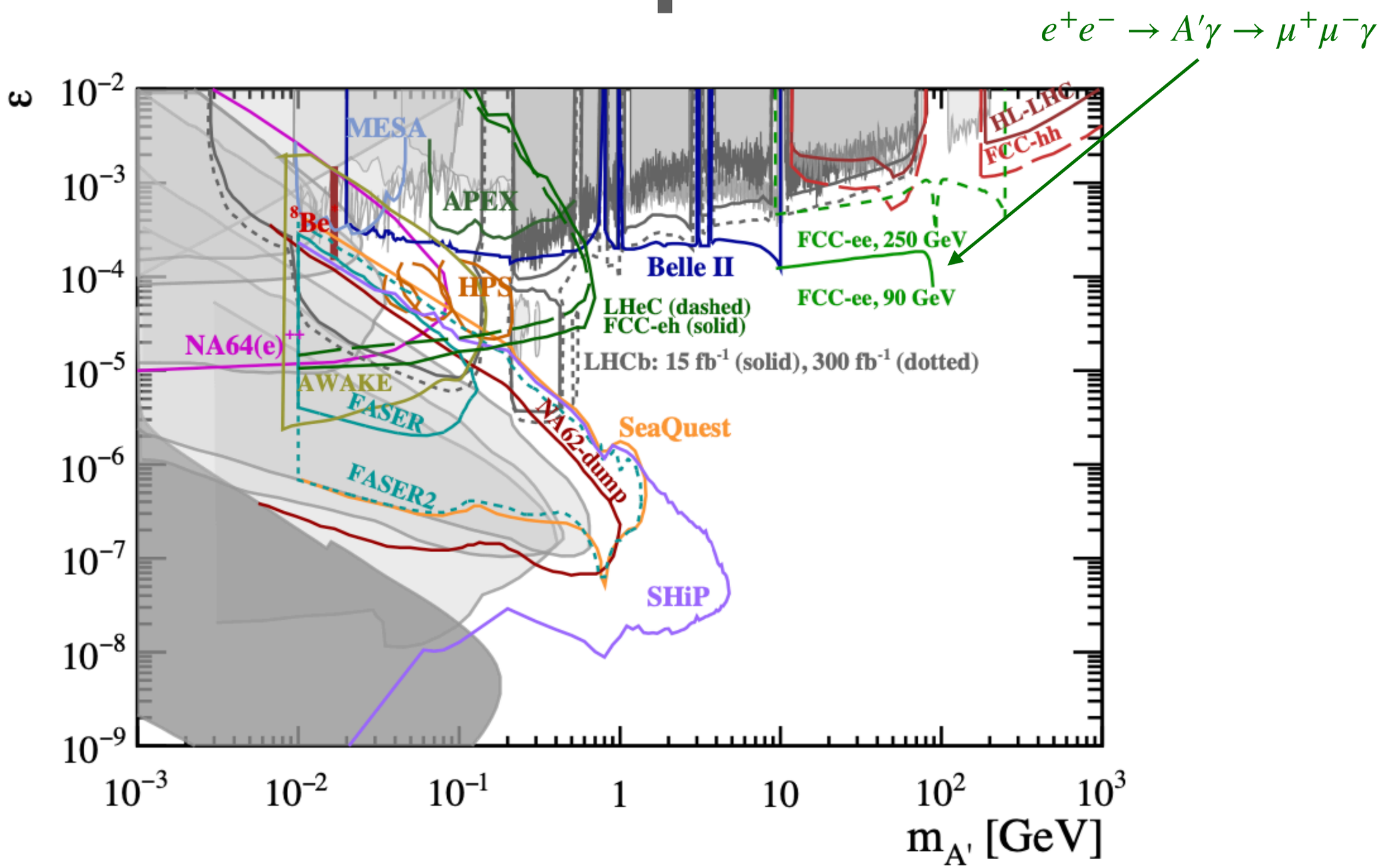
Vector portal

$$-\epsilon F'_{\mu\nu} F^{\mu\nu}$$

- Dark photon A'_μ kinetically mixes with the usual photon A_μ
- Just two parameters $m_{A'}$ and ϵ
- Appears in different models. Can be a mediator for DM
- In the mass range we are considering it is *not* a DM candidate

Recent comprehensive review by Fabbrichesi, Gabrielli, and Lanfranchi
https://arxiv.org/abs/2005.01515
Also PBC report https://arxiv.org/abs/1901.09966
And FIPs 2020 https://arxiv.org/abs/2102.12143

Vector portal



Source: Fabbrichesi, Gabrielli, and Lanfranchi
https://arxiv.org/abs/2005.01515

FCC-ee limits: Karliner, Low, Rosner, and Wang
http://arxiv.org/abs/1503.07209

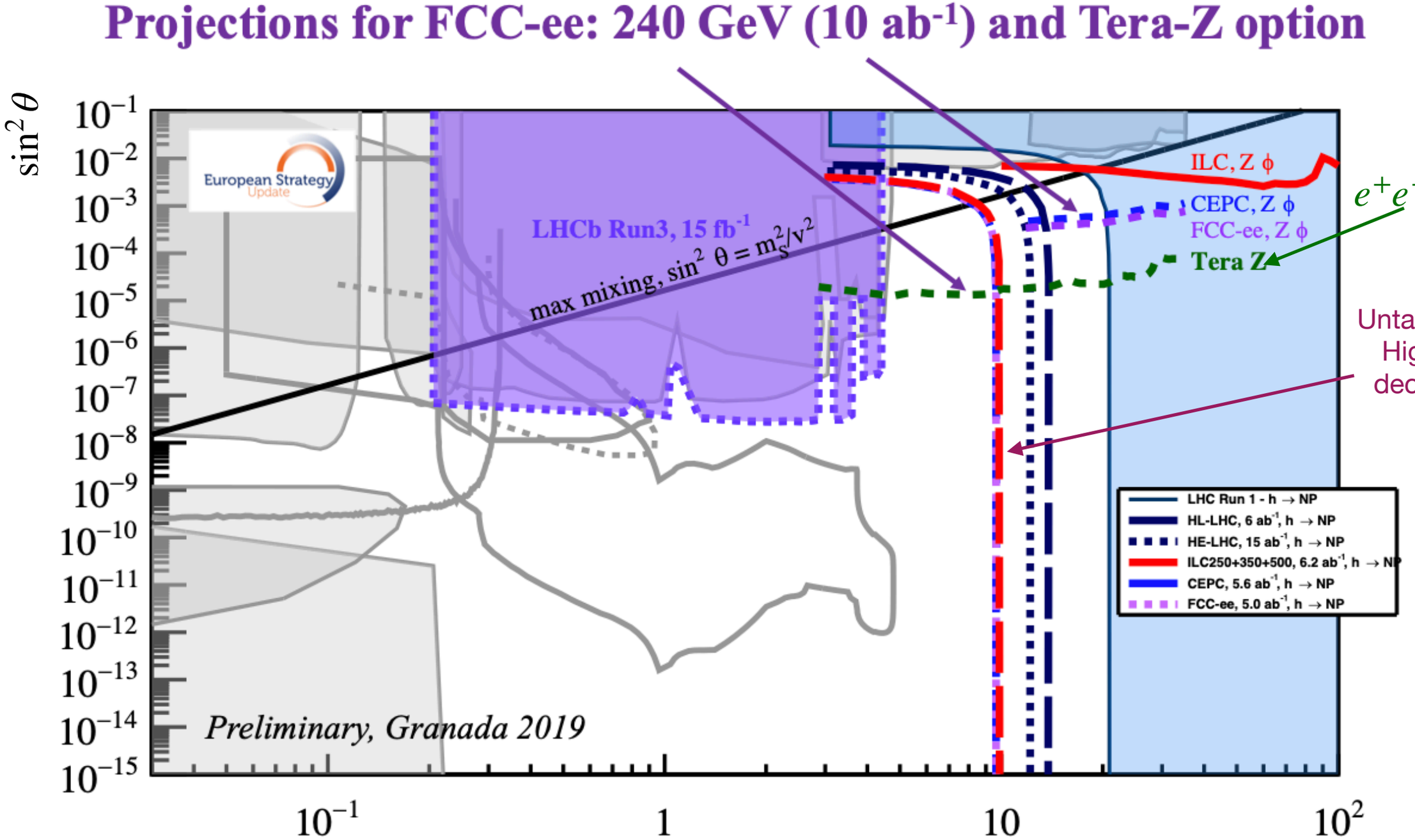
Scalar portal

$$\left(\mu S + \lambda S^2\right) H^\dagger H$$

- Singlet scalar S
- At low energies: parameters m_S and $\sin^2\theta$, $\theta = \dfrac{\mu v}{m_h^2 - m_S^2}$
- Appears in different models. Can be a mediator for DM, a relaxion,

See, e.g., Frugiuele, Fuchs, Perez, and Schlaffer arXiv:1807.10842
PBC report https://arxiv.org/abs/1901.09966
And FIPs 2020 https://arxiv.org/abs/2102.12143

Scalar portal



Plot Gaia Lanfranchi, Granada [link], also Physics Briefing Book
https://arxiv.org/abs/1910.11775
Data: Frugiuele, Fuchs, Perez, and Schlaffer arXiv:1807.10842

Pseudo-scalar portal

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

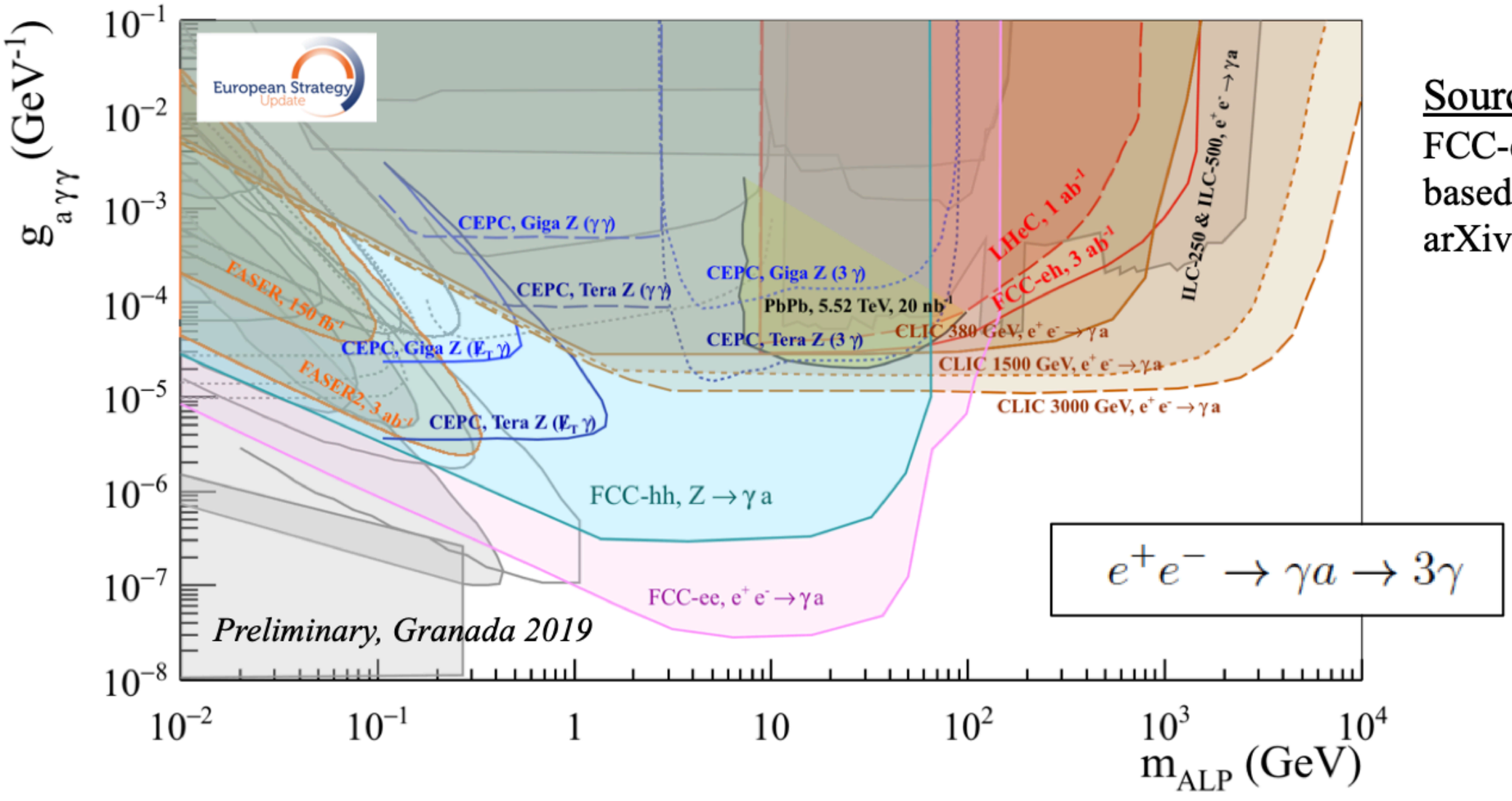
photon dominance

- Axion-like particle a with mass m_a
- *Effective interaction* (unlike other portals)
- Mostly studied in the sub-eV mass range

PBC report https://arxiv.org/abs/1901.09966,
FIPs 2020 https://arxiv.org/abs/2102.12143

Pseudo-scalar portal

Prospects for FCC-ee : combination of data at the Z-pole, 2 m_W and 240 GeV.



Source:
FCC-ee physics groups based on Bauer et al., arXiv:1808.10323

From Gaia Lanfranchi, Granada [link]

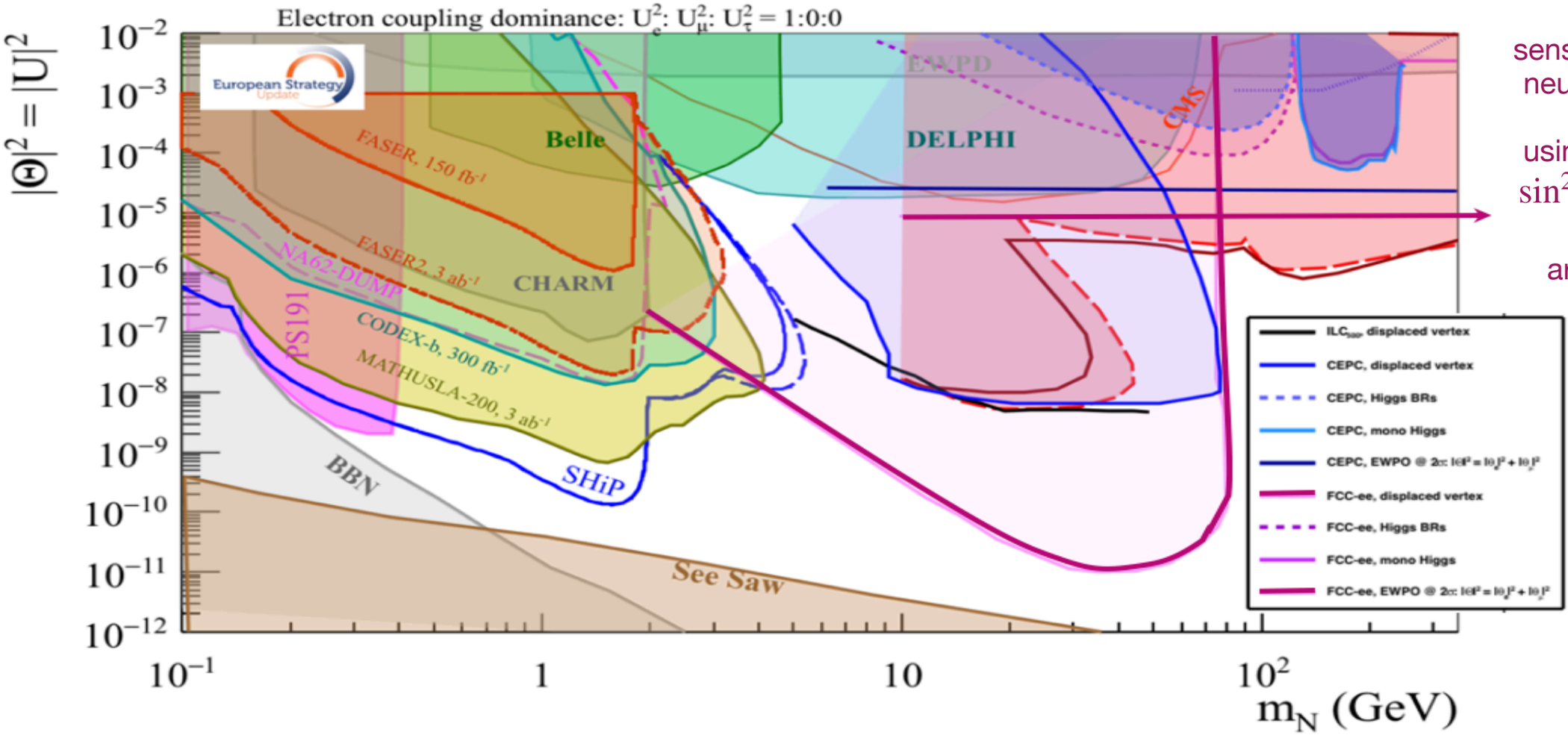
Neutrino portal: Heavy Neutral Leptons

$$-F_{\alpha I}\bar{L}_{\alpha}\tilde{\Phi}N_I - \frac{M_{IJ}}{2}\bar{N}_I^c N_J$$

- Heavy Neutral Leptons (also Right-Handed Neutrino, Sterile Neutrino) — singlet fermions which mix with neutrino
  $\nu_{L_\alpha} = U_{\alpha i}^{PMNS}\nu_i + \Theta_{\alpha I}N_I^c$
- Singlets => Majorana masses ($0\nu\beta\beta$, Same-sign dileptons)
- Seesaw mechanism
- Neutrino oscillation data does not fix the mass scale

See, e.g., PBC report https://arxiv.org/abs/1901.09966
And FIPs 2020 https://arxiv.org/abs/2102.12143

Neutrino portal: Heavy Neutral Leptons

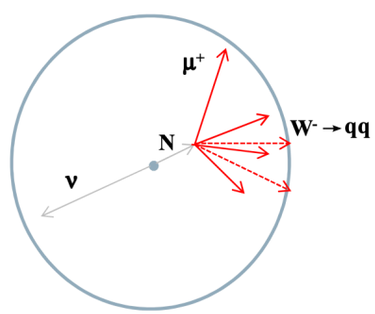


sensitivity to mixing of neutrinos to the dark sector,
using EWPOs (GF vs $\sin^2\theta_W^{eff}$ and mZ, mW, tau decays)
arxiv:2011.04725

Plot from the Physics Briefing Book
https://arxiv.org/abs/1910.11775

FCC sensitivity: FCC-ee study Team collaboration, Blondel, Graverini, Serra and Shaposhnikov

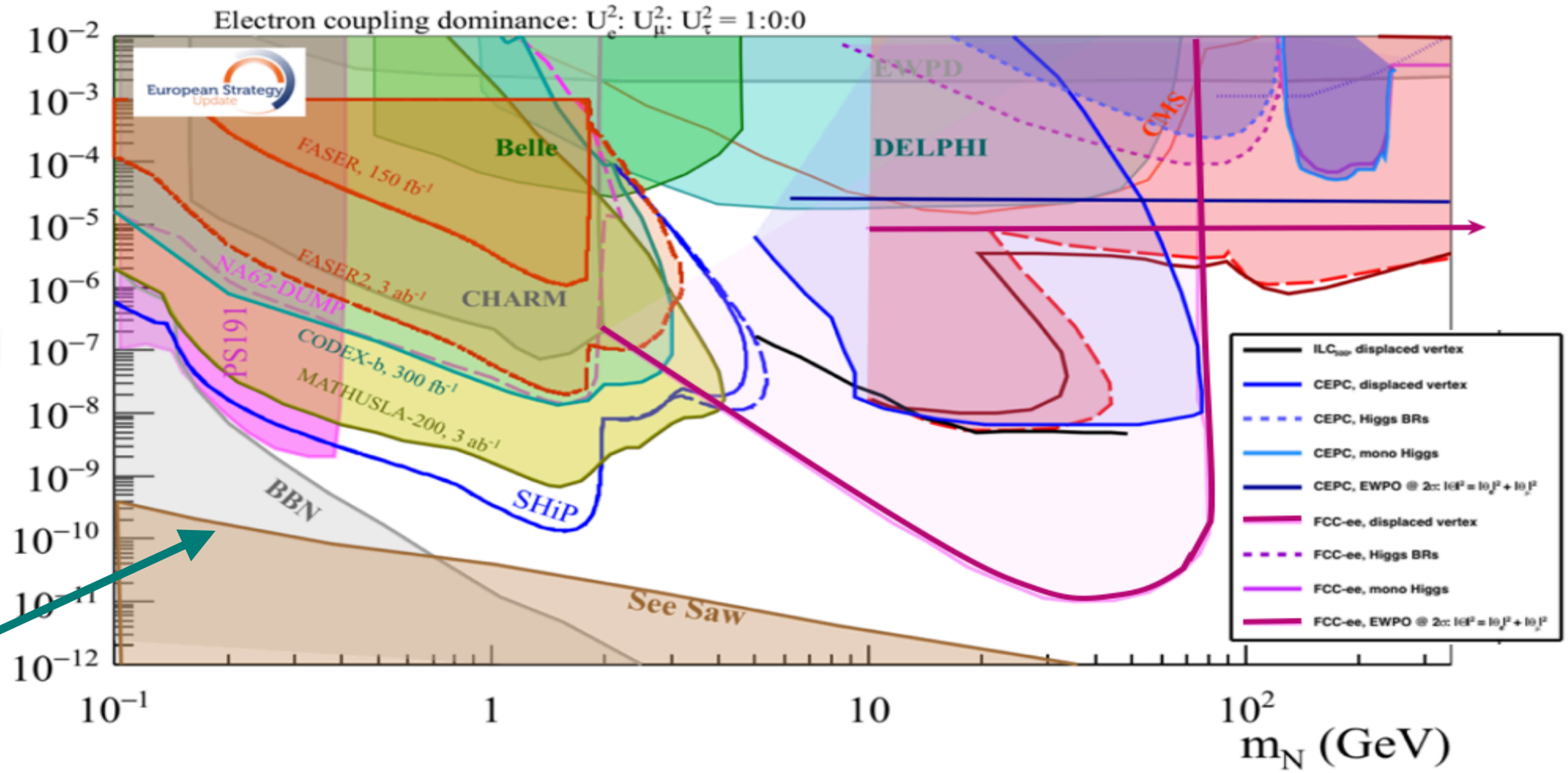
Update: Antusch, Cazzato, Fischer https://arxiv.org/abs/1612.02728



Neutrino portal: Heavy Neutral Leptons

$$\nu_{L_\alpha} = U^{PMNS}_{\alpha i}\nu_i + U_{\alpha I}N^c_I,$$

$|\Theta|^2 = |U|^2$



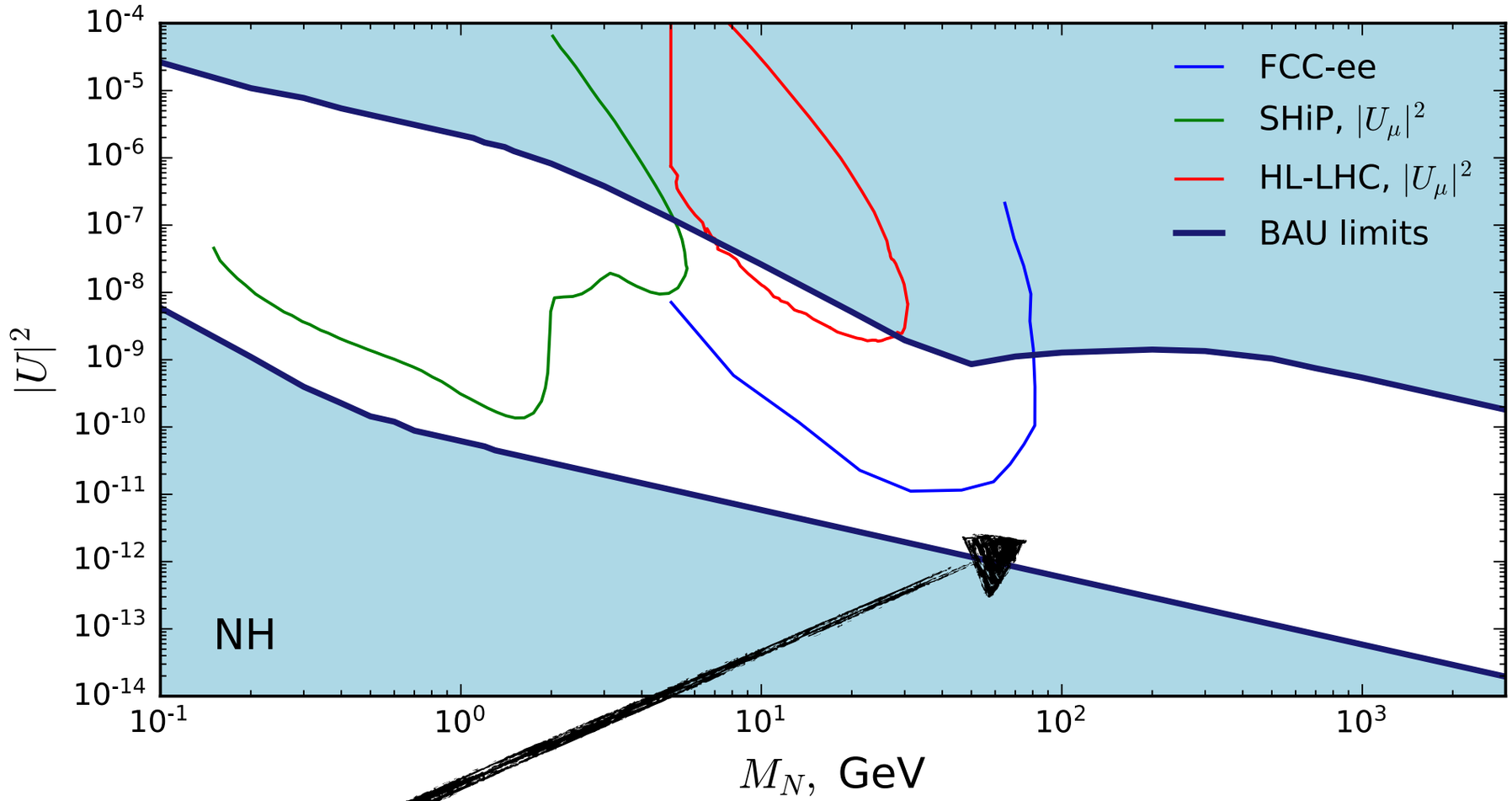
The “seesaw” limit is applicable for at least two HNLs explaining neutrino masses. In the case of two HNLs the mixings with single flavours are ruled out by neutrino oscillation data.

New “guidelines” FIPs 2020

Reinterpretation of the ATLAS prompt HNL search
Tastet, Ruchayskiy, IT https://arxiv.org/abs/2107.12980

Heavy Neutral Leptons: Leptogenesis

Apart from the neutrino masses, HNLs can be responsible for the generation of matter-antimatter asymmetry (Baryon asymmetry of the Universe)



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Klarić, Shaposhnikov, IT 2008.13771

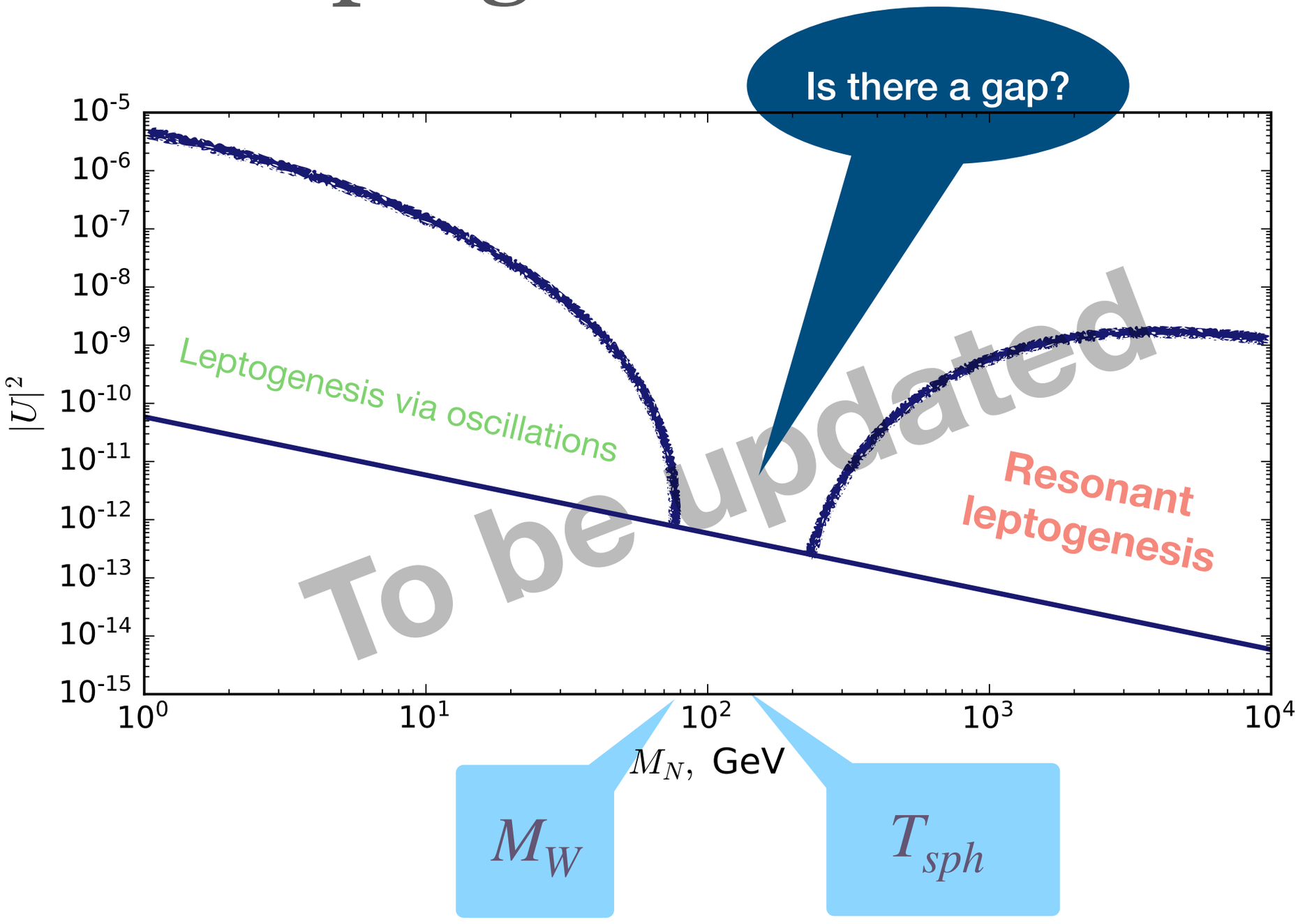
FCC line: Antusch, Cazzato, Fischer https://arxiv.org/abs/1612.02728

Summary

- FCC-ee
  - intensity frontier experiment operating at high energies
  - Great potential for the direct search for feebly interacting particles
    - Unparalleled sensitivity to Heavy Neutral Leptons
- In general, new physics is not associated with a specific scale => synergy between experiments is crucial (HL-LHC, SHiP, FCC-ee, FCC-eh, FCC-hh)

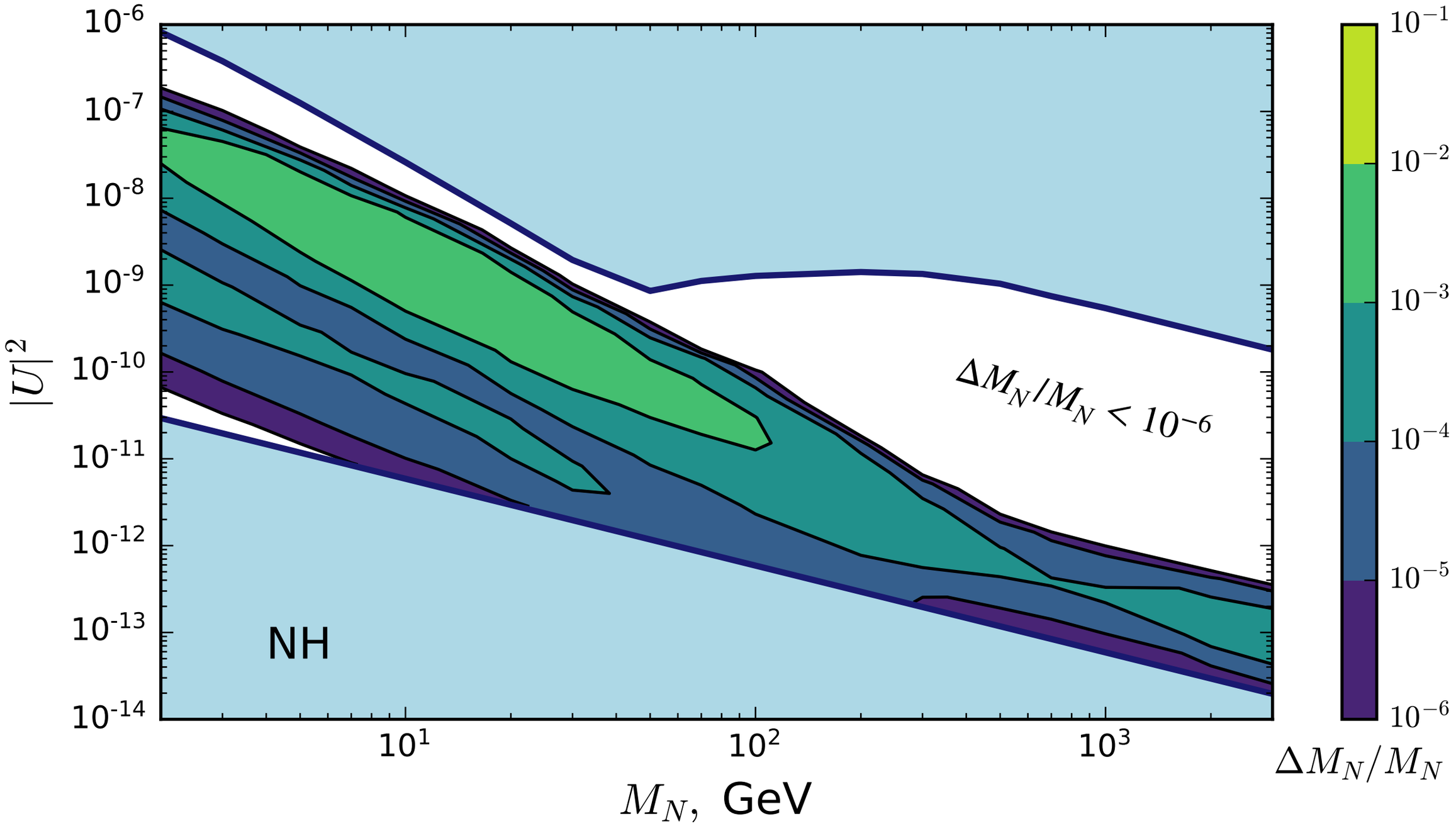
Backup slides

Different leptogenesis mechanisms?

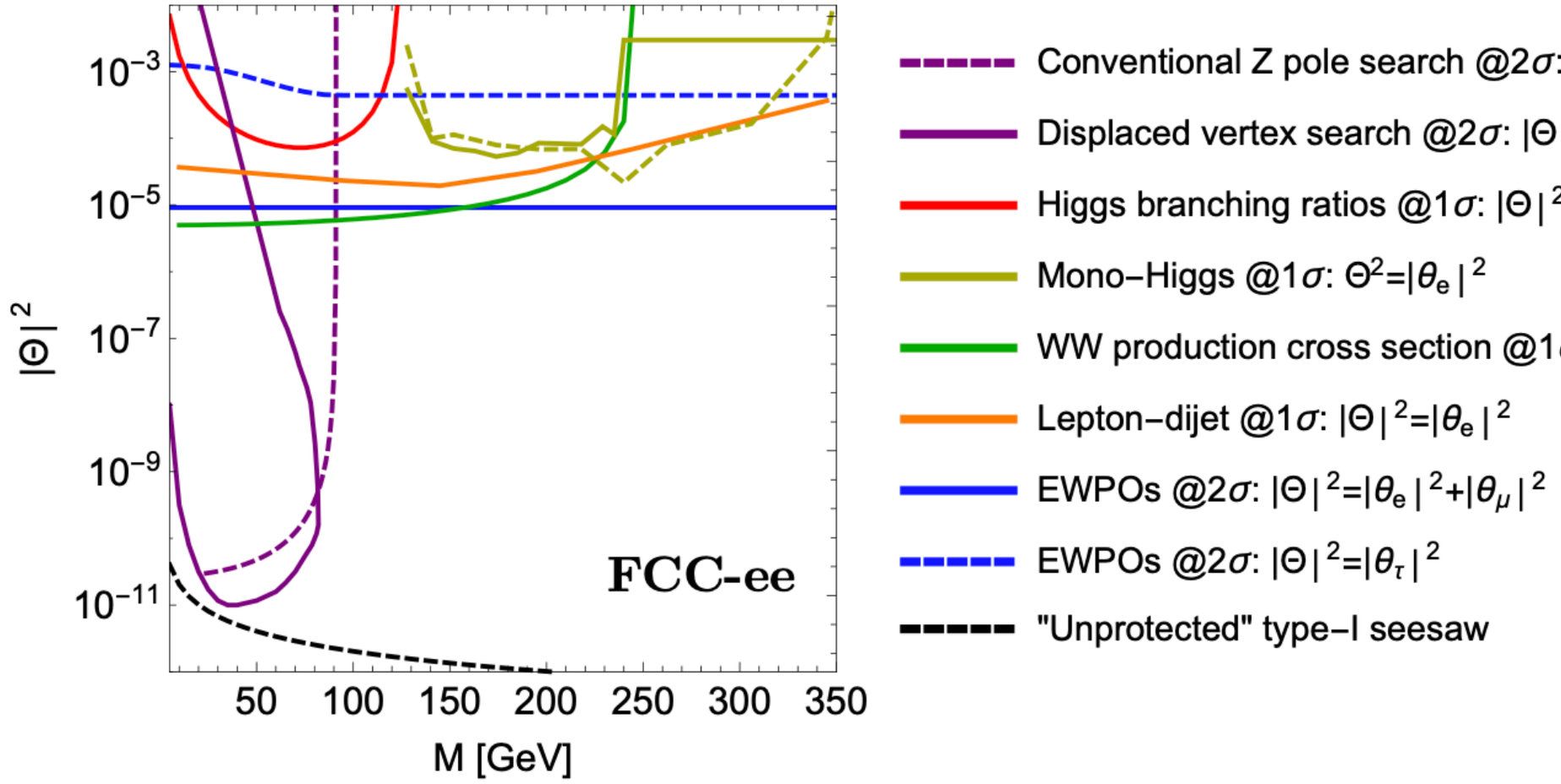


Mass splitting (NH)

The mass splitting required for successful leptogensis can be quite large



Neutrino portal: Heavy Neutral Leptons



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