

# Beam Dump Experiments at High Energy Electron Colliders

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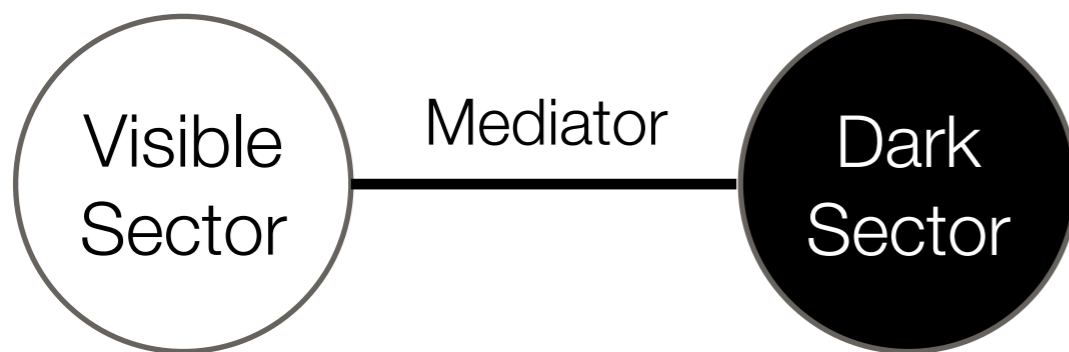
Douglas Tuckler  
Carleton University

Based on work with P. Giffin, S. Gori, and Y.D. Tsai  
arXiv:2206.13745

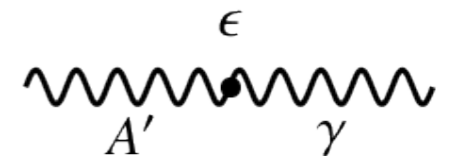
12th Workshop of the LLP Community  
Nov. 1, 2022

# Dark Sectors

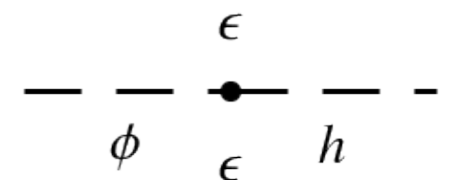
- Motivated due to the role they play in **sub-GeV thermal DM**
- Connection to open questions e.g. **neutrino masses, the Strong CP problem, hierarchy problem**, and **experimental anomalies** e.g.  $(g - 2)_\mu$ ,  $B$  anomalies
- Minimal/portal models for dark sectors



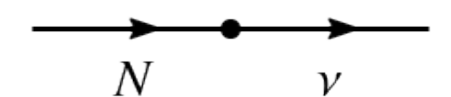
1. Vector:  $\epsilon F^{\mu\nu} F'_{\mu\nu}$



2. Scalar:  $\epsilon |h|^2 |\phi|^2$

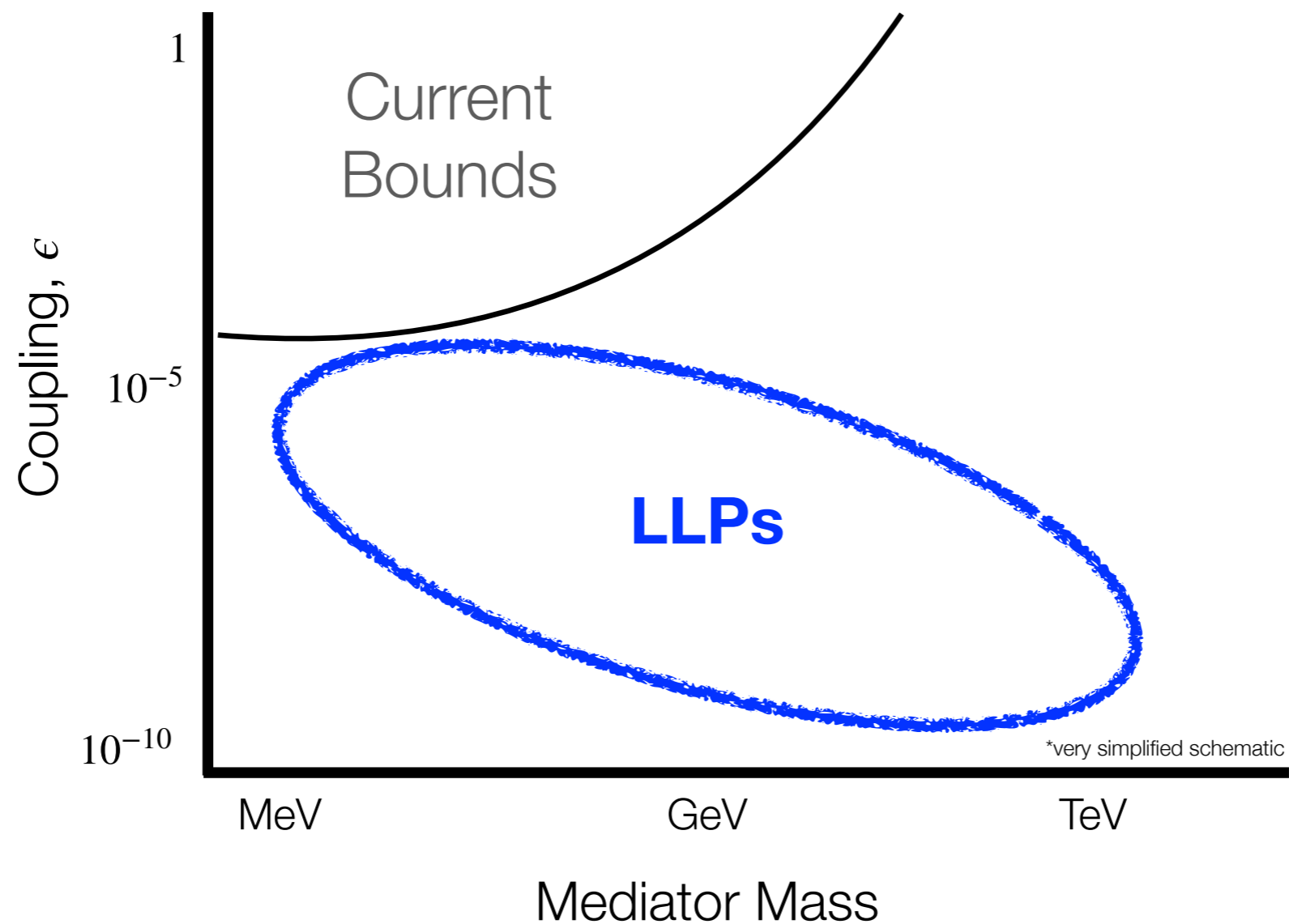


3. Neutrino:  $\epsilon \ell h N$



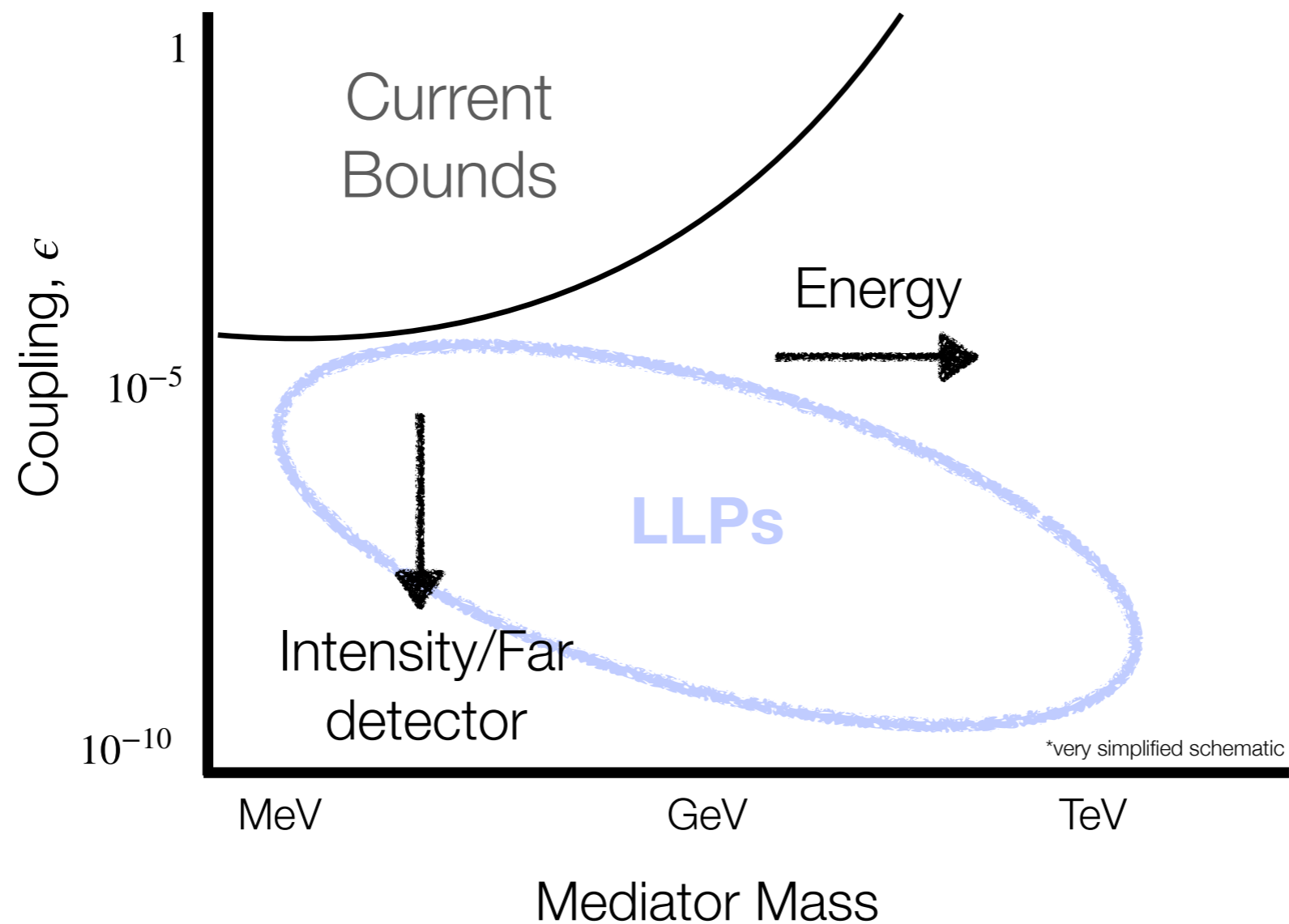
# Dark Sectors and Long Lived Particles

- **Long-lived particles** = decay length  $\gg$  scale of detector. **Generic feature of dark sector models** due to e.g. kinematic suppression or small couplings



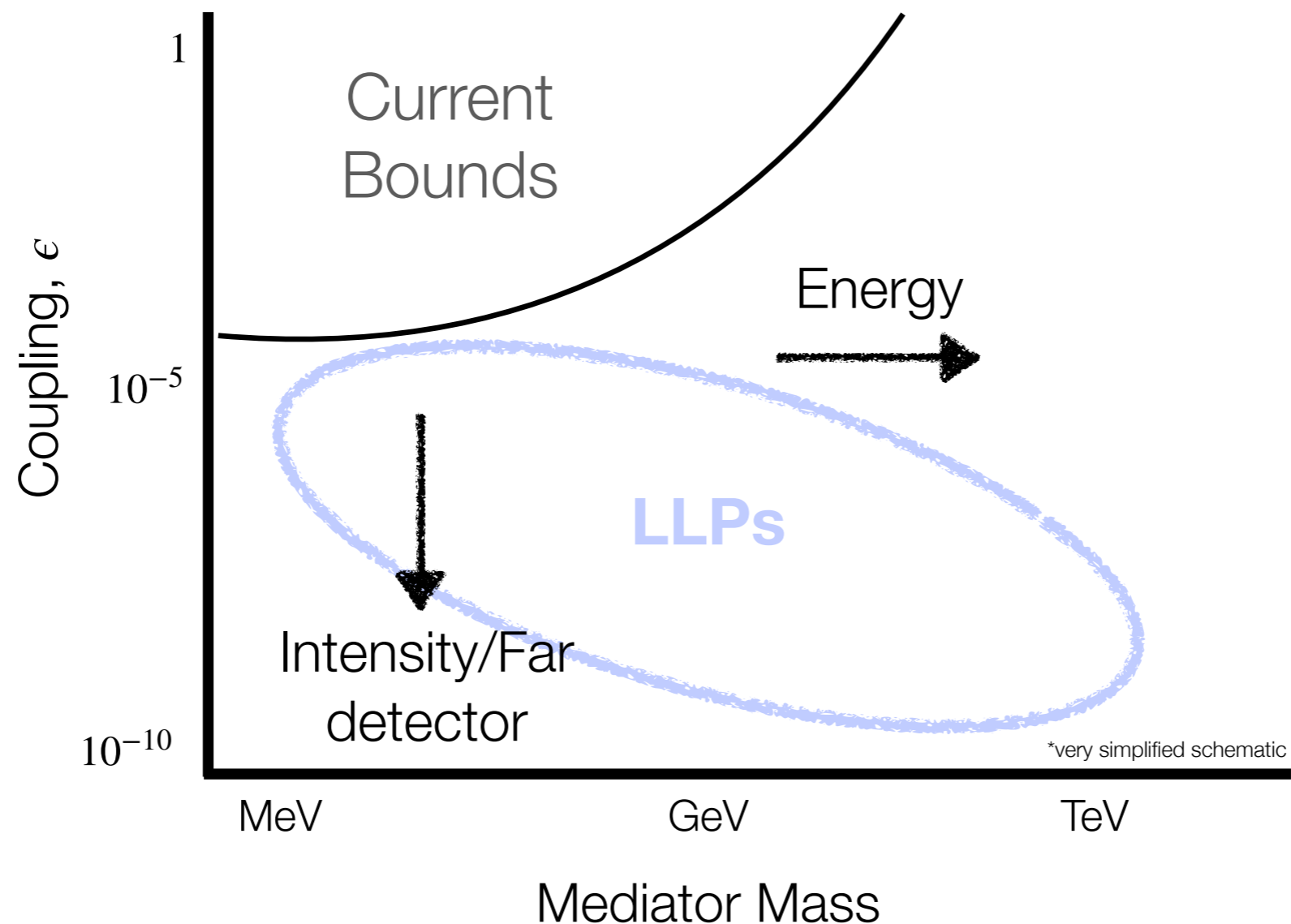
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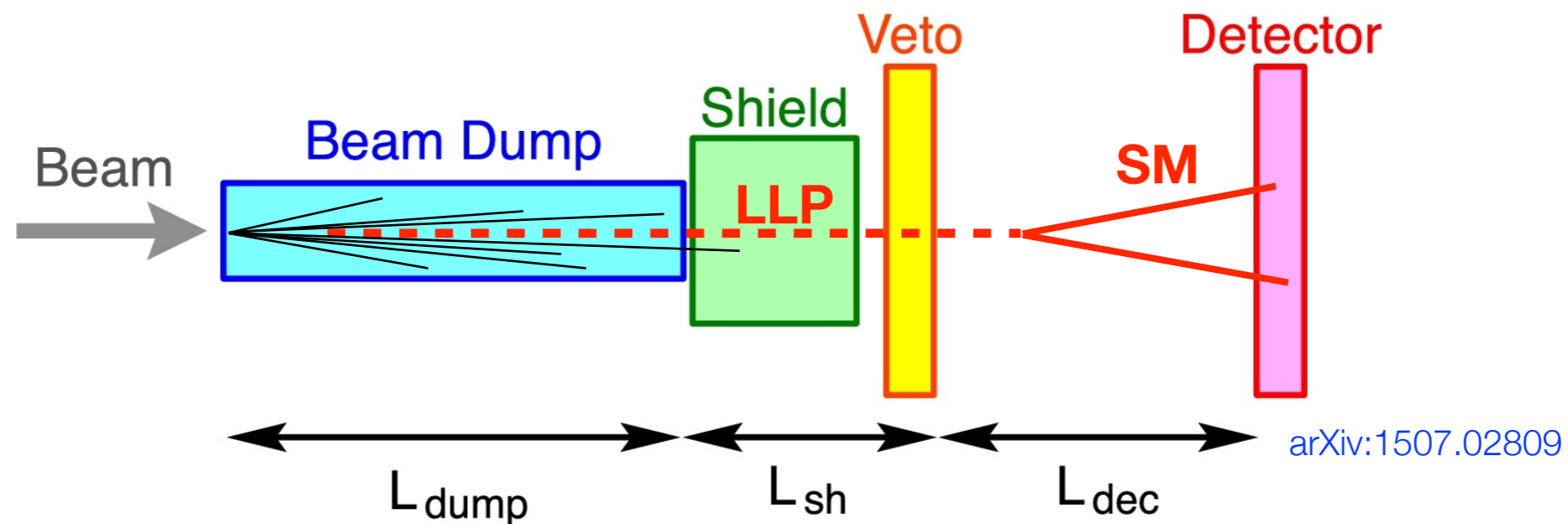
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**How to get the best of both worlds?**

# Long Live Particles @ Beam Dump Experiments

- Small couplings  $\rightarrow$  long-lived mediators. Here, beam dump experiments shine due to **high intensities and long decay volumes!**



- Many, many proposals for proton-based experiments at LHC/Fermilab e.g. SHiP, SHADOWS, DarkQuest, DUNE.  $\mathcal{O}(100)$  GeV proton beam.
- Past and proposed electron beam dump experiments are low energy e.g. LDMX, BDX;  $\mathcal{O}(10)$  GeV electron beam. **What about utilizing the beams of high energy electron colliders?**

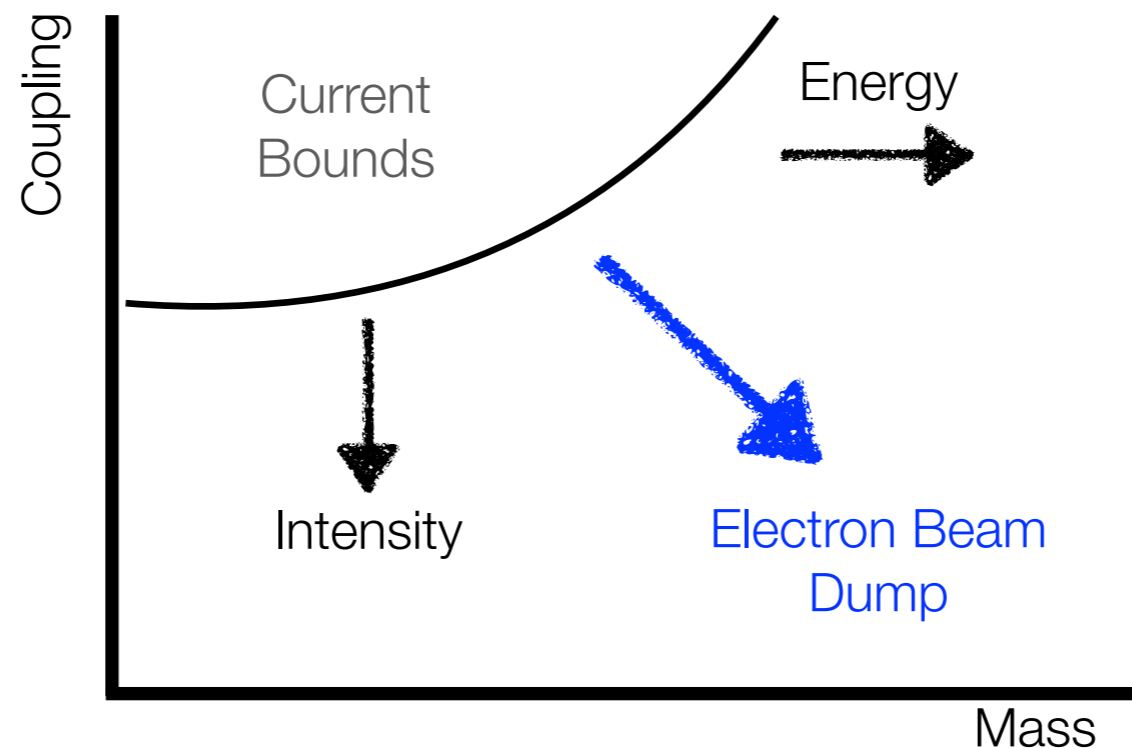
# Advantages of Linear Electron Colliders

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- High energy electron colliders motivated as a precision Higgs program, but are just as well situated to probe the dark sector/LLPs!
- **Large beam energies:** 125 GeV, 500 GeV, 1.5 TeV compared to past/current beam dump experiments. **Staged energy approach!** No need to build a new, higher energy facility.
- **High Intensity:**  $\sim 10^{21}$  electrons-on-target/year
- **New Production Modes:**
  - $e^-$  beam  $\rightarrow$  Charged current scattering for heavy neutral leptons
  - $e^+$  beam  $\rightarrow$  pair annihilation production of dark photons/ALPs

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# Future Linear Electron Colliders

$\sqrt{s} = 250/500/1000$  GeV



International Linear Collider

380/3000 GeV



Compact Linear Collider

250/550/3000 GeV



Cool Copper Collider

Collider- $\sqrt{s}$ [GeV]	ILC-250/1000	C <sup>3</sup> -250	C <sup>3</sup> -3000	CLIC-3000
Bunches/Train	1312	133	75	312
Train Rep. Rate [Hz]	5	120	120	50
Bunch Charge [nC]	3.2	1	1	0.6
Effective Luminosity [ $\text{cm}^{-2} \text{s}^{-1}$ ]	$1.6 \times 10^{39}$	$1.2 \times 10^{39}$	$6.9 \times 10^{38}$	$6.9 \times 10^{38}$
EOT/Year	$4.1 \times 10^{21}$	$3.1 \times 10^{21}$	$1.8 \times 10^{21}$	$1.8 \times 10^{21}$

# ILC Beam Dump Experiment Configuration

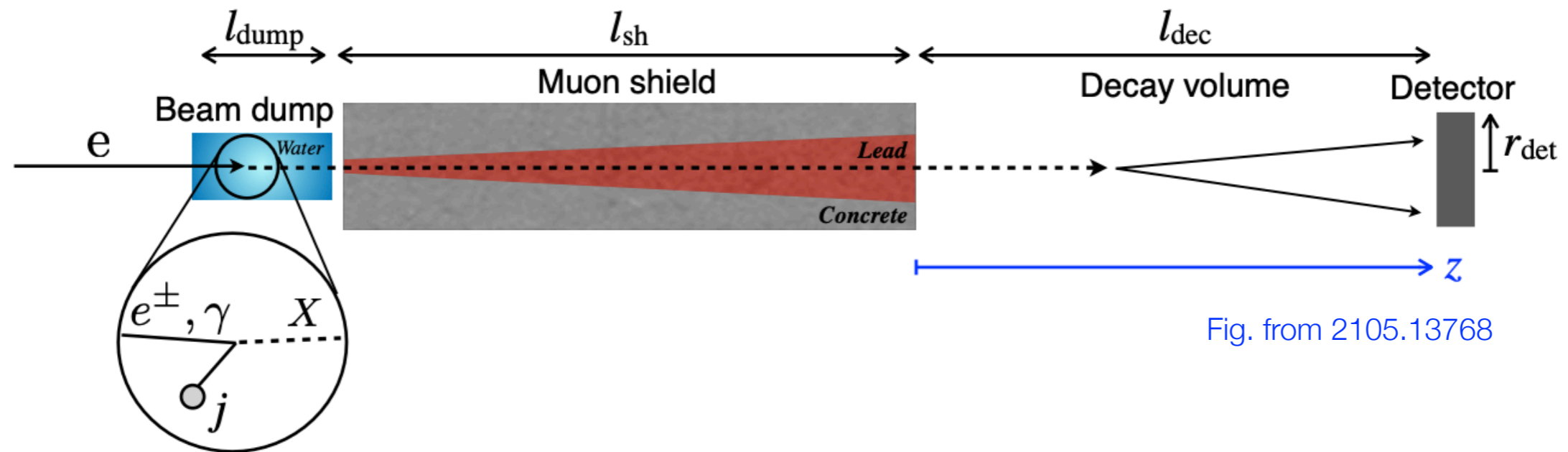


Fig. from 2105.13768

- 11m beam dump contain water
- 70 m muon shield made of lead and concrete
- 50 meter decay volume. Cylindrical detector with 2 meter radius.
- Optimal beam dump configuration for CLIC/C<sup>3</sup> has not been discussed! Highly dependent on installation site, but current studies can assume a similar set up as ILC.

**Unique opportunity: a facility to search for dark sectors can be designed from scratch!**

# Case Study: Heavy Neutral Leptons [arXiv:2206.13745](https://arxiv.org/abs/2206.13745)

- Heavy neutral leptons are a well-motivated extension of the SM (e.g. neutrino masses, baryon asymmetry, and dark matter)
- Dominant production from **meson decays** and **directly in charged-current scattering for electron-mixed HNLs**
  - Secondary production from muons produced in the beam dump and from lepton pair production

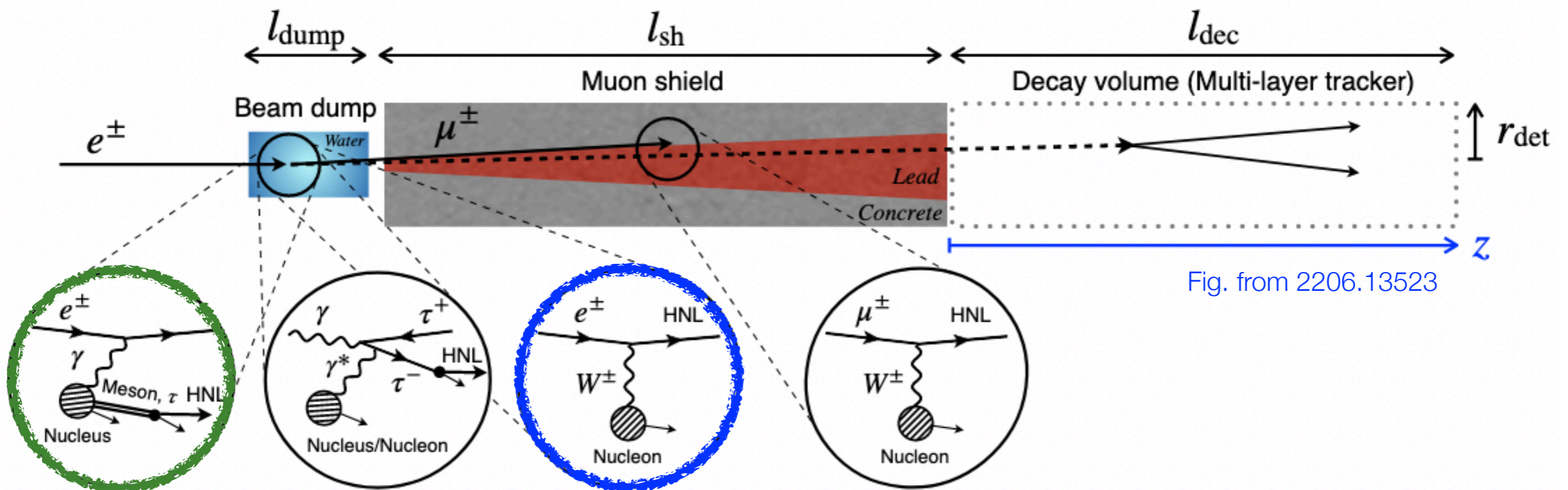
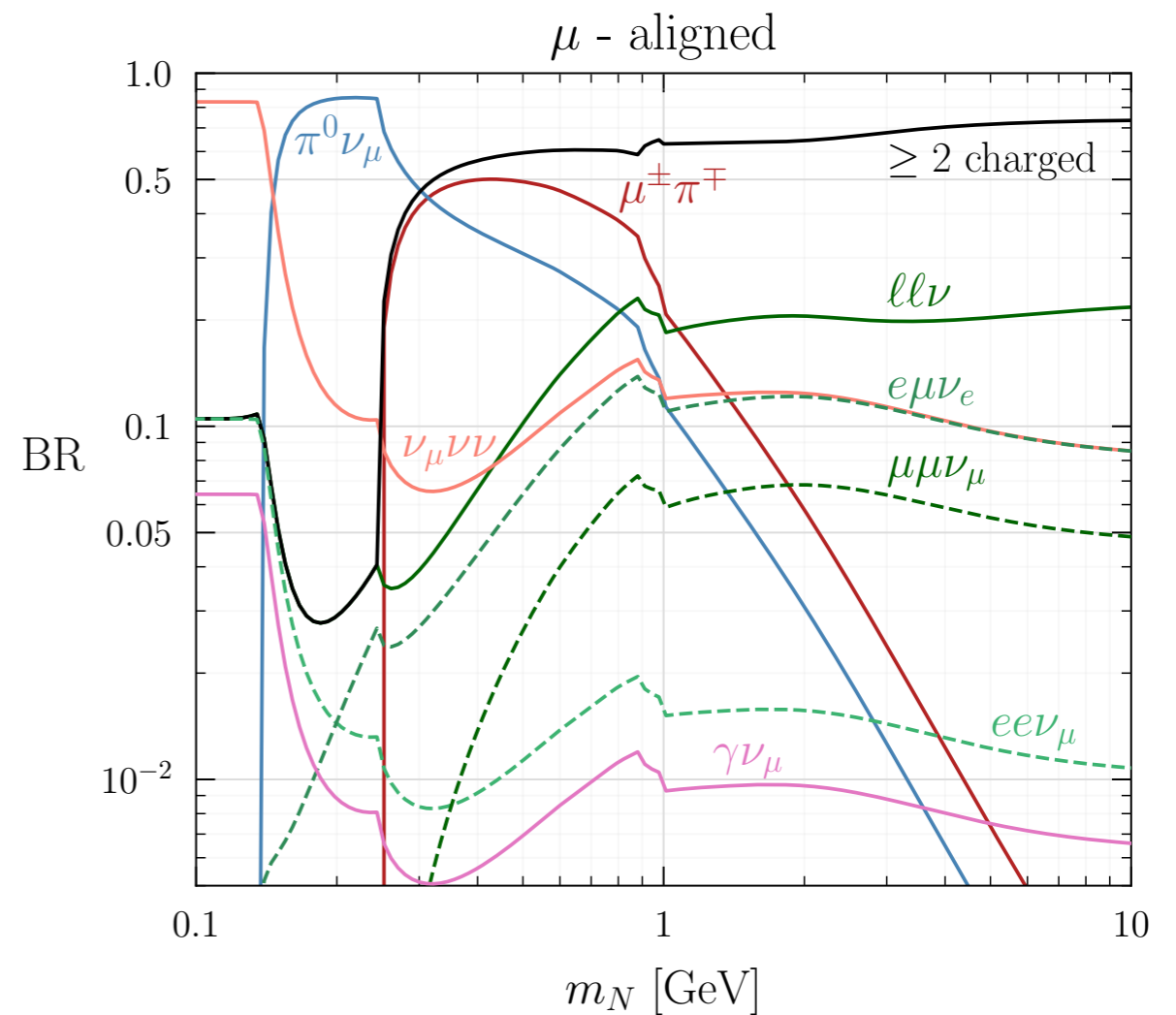
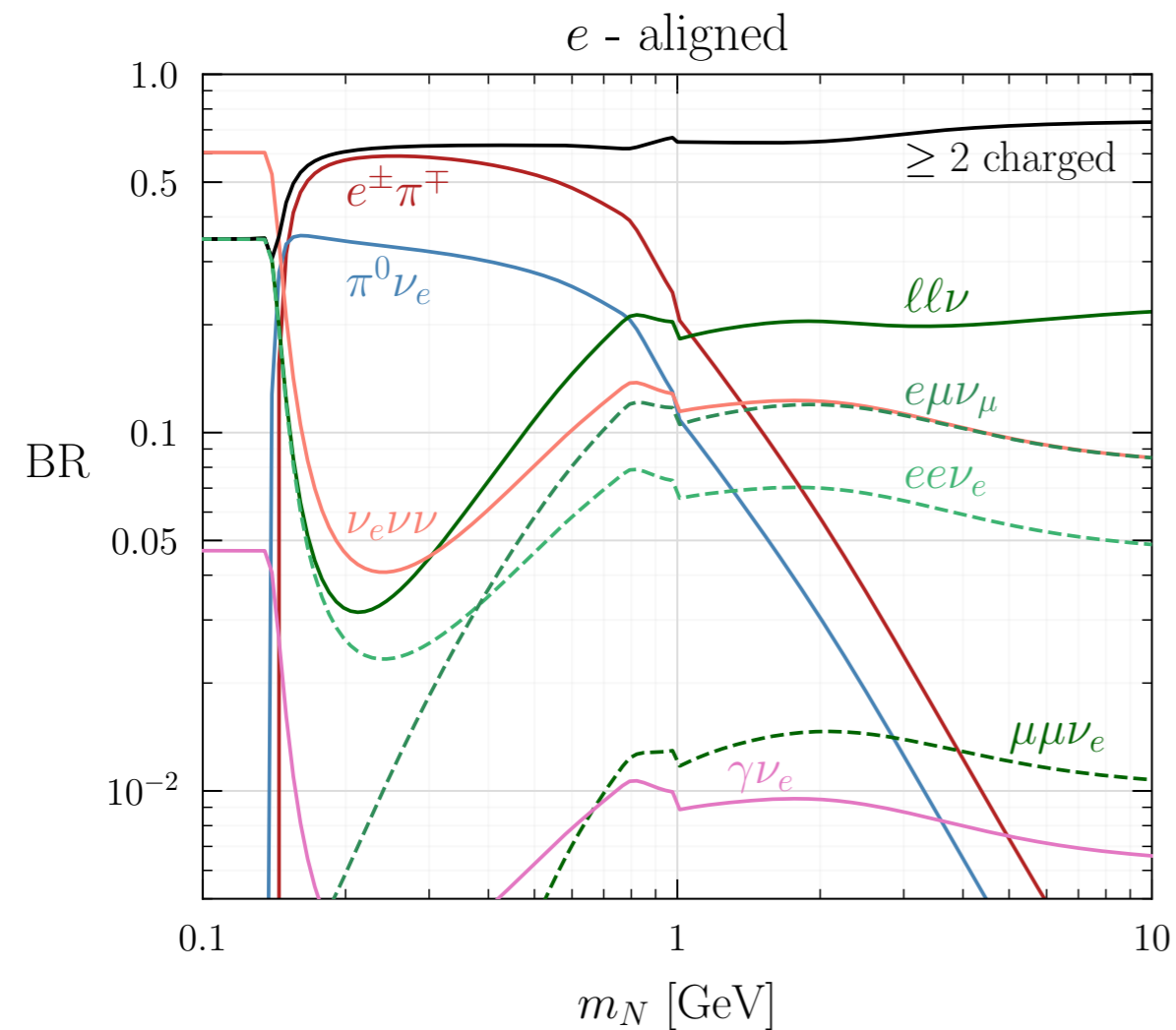


Fig. from 2206.13523

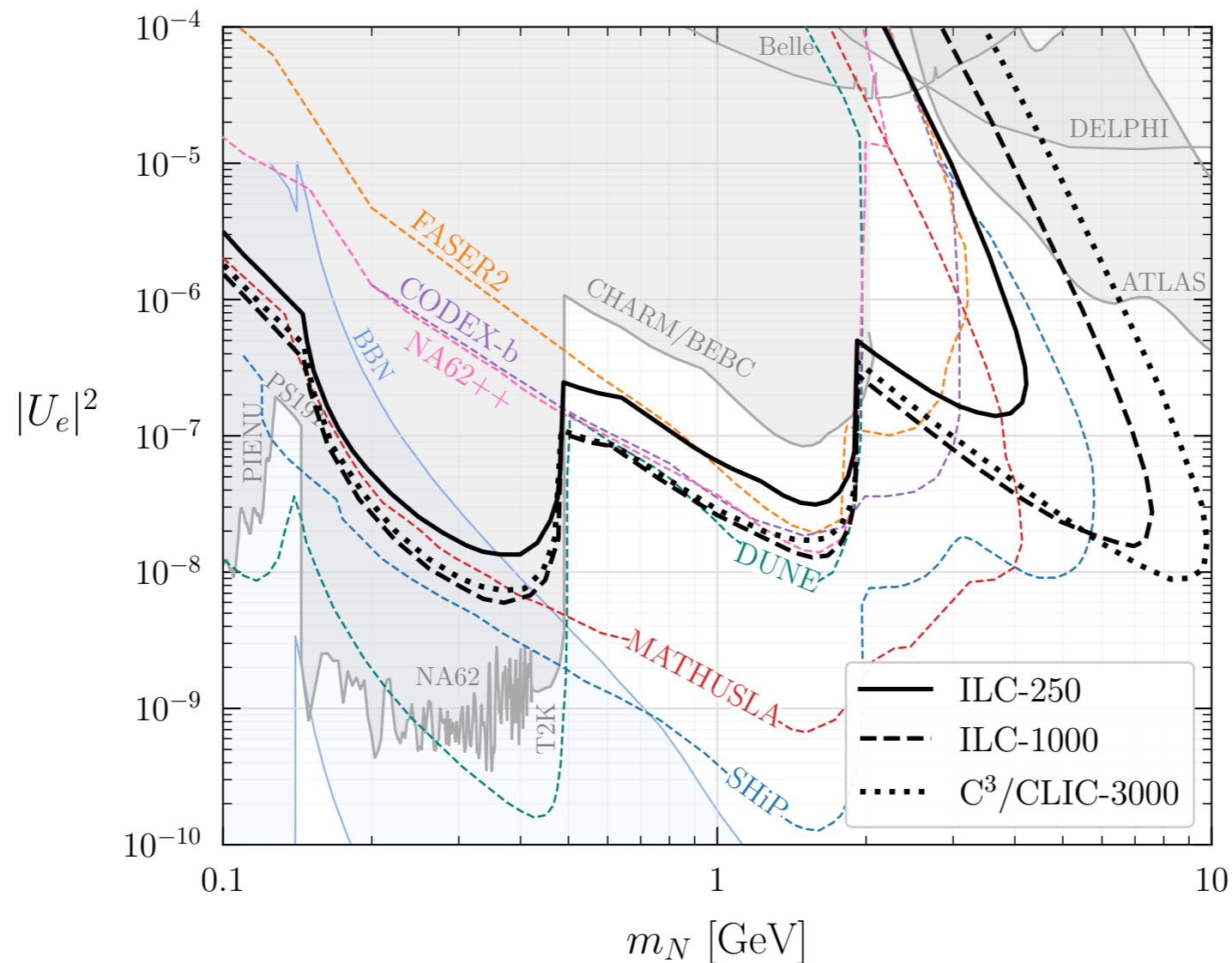
# HNL Decays

- Decay to two charged SM particles dominate



# Sensitivity for Electron Mixed HNLs

- Taking into account production and decay of HNLs, geometric acceptance/efficiency, and requiring 10 signal events for a background free run

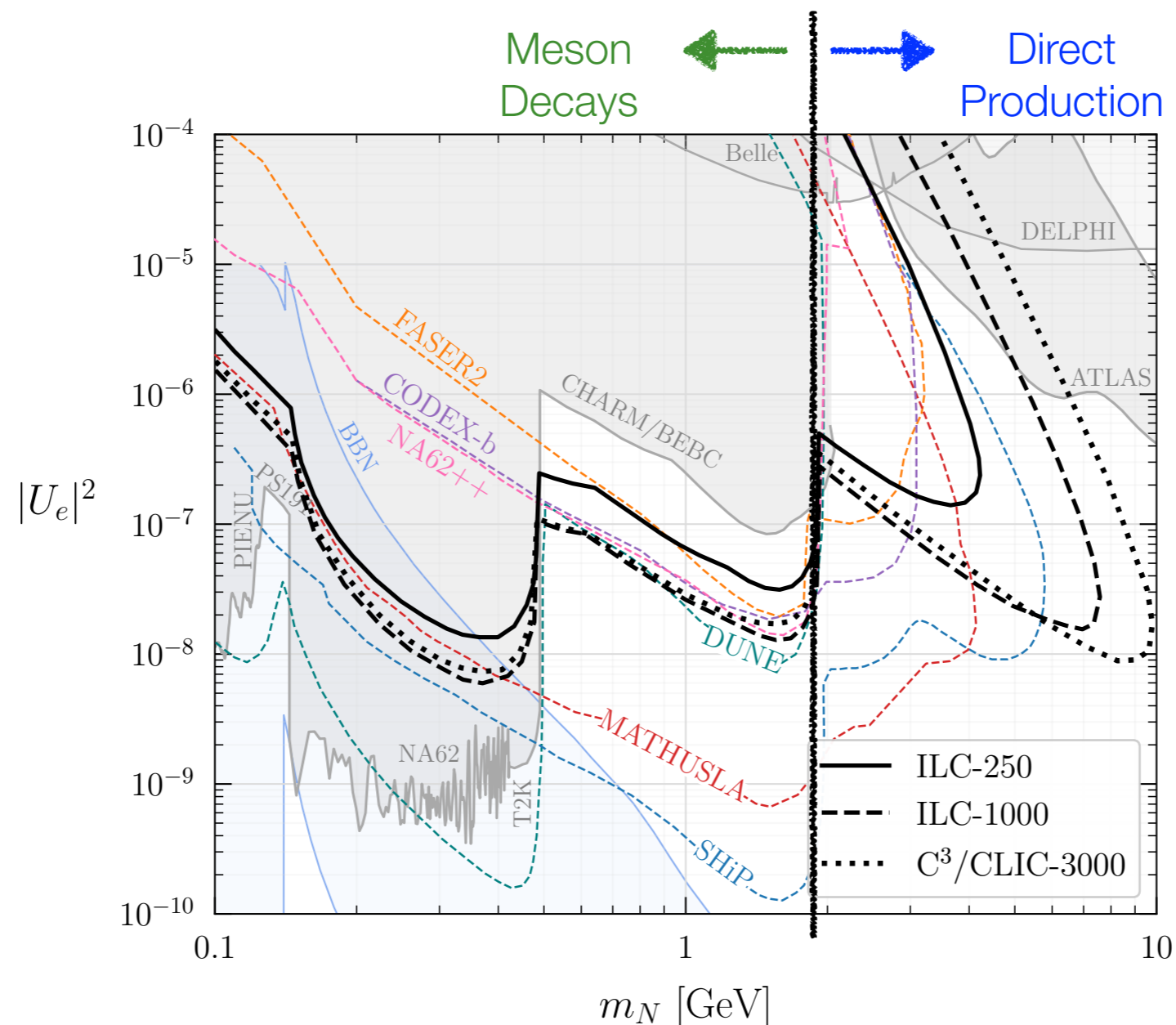


P. Giffin, S. Gori, Y.D-Tasi, and DT  
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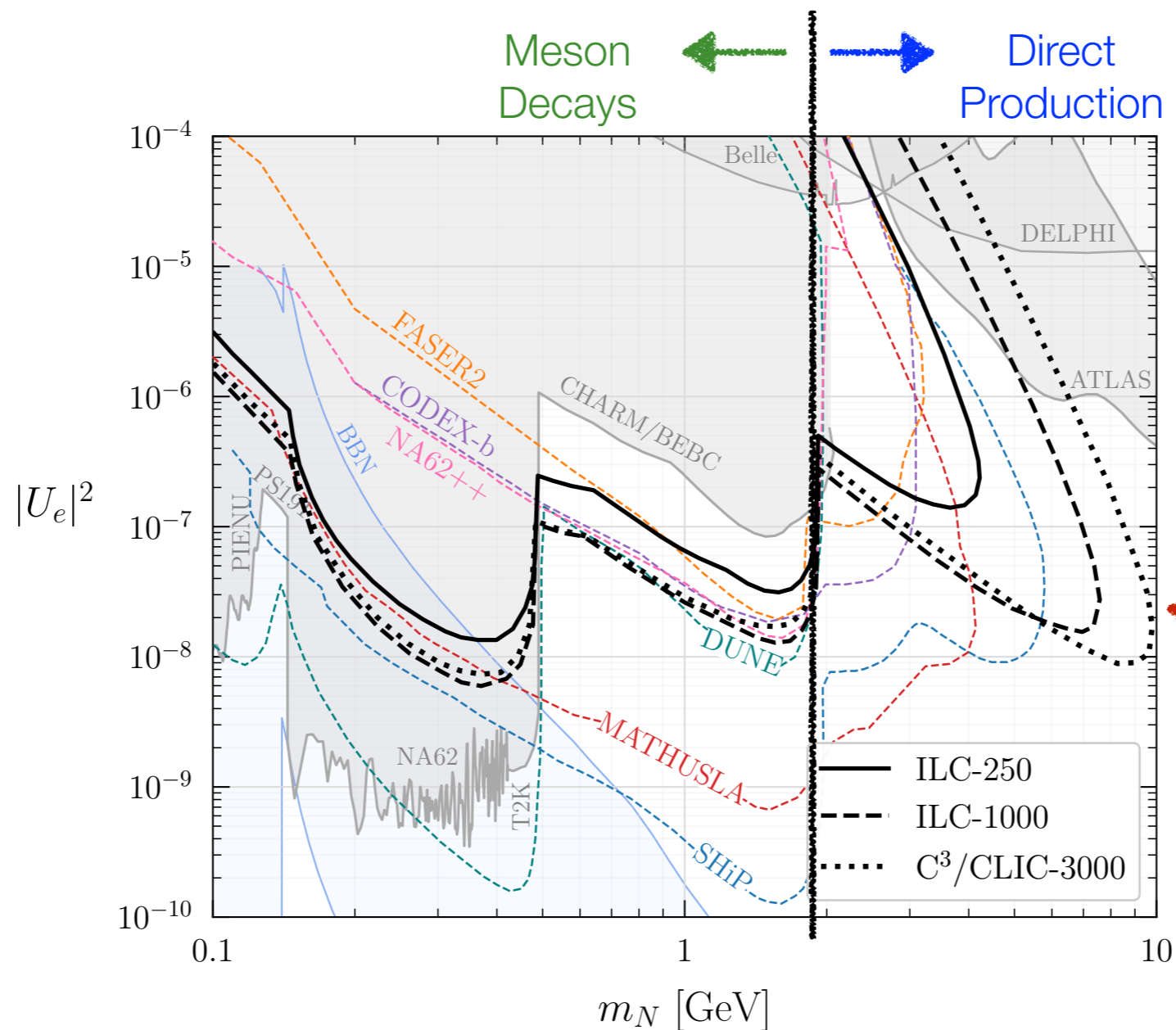


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**Importance of higher energy!**

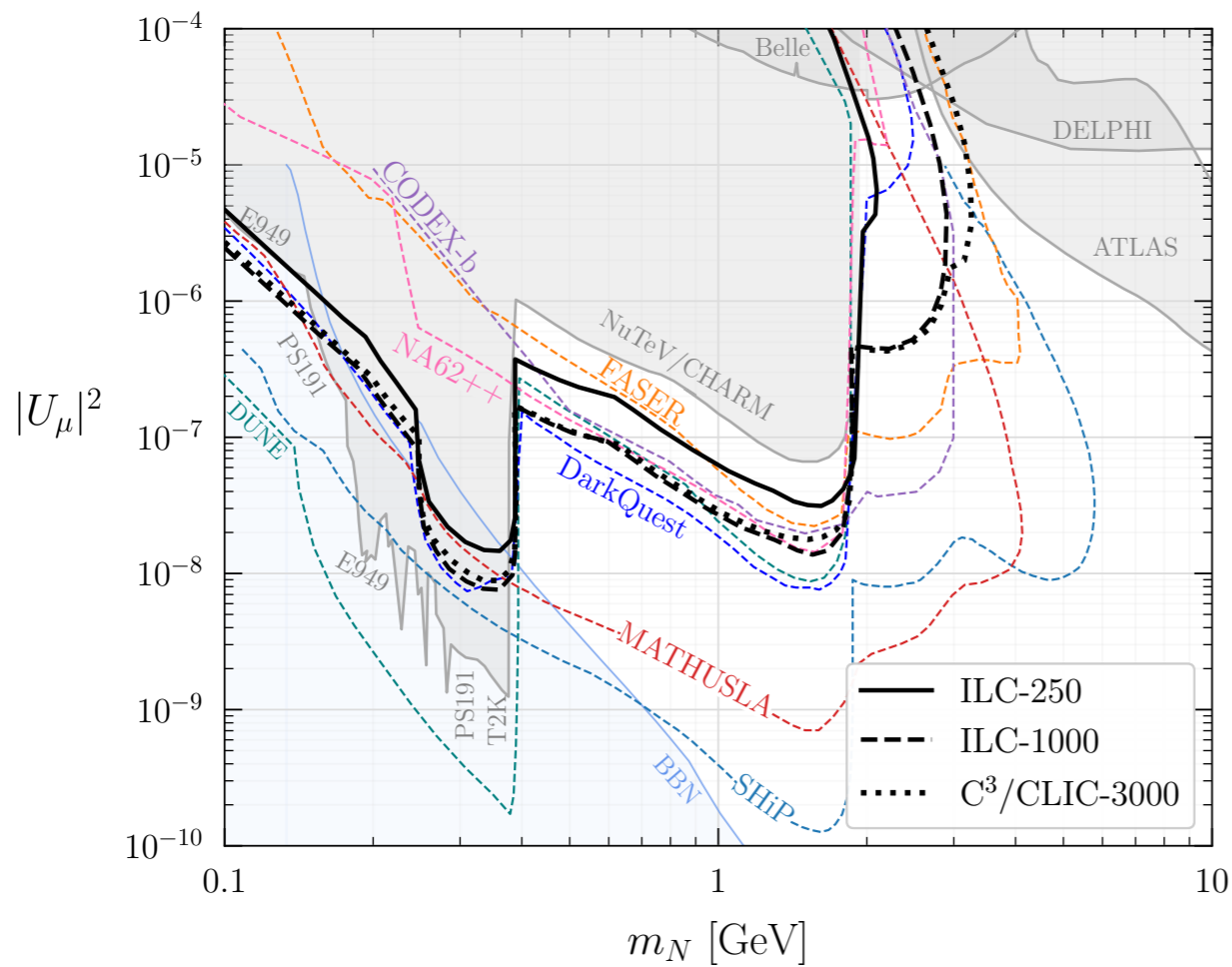
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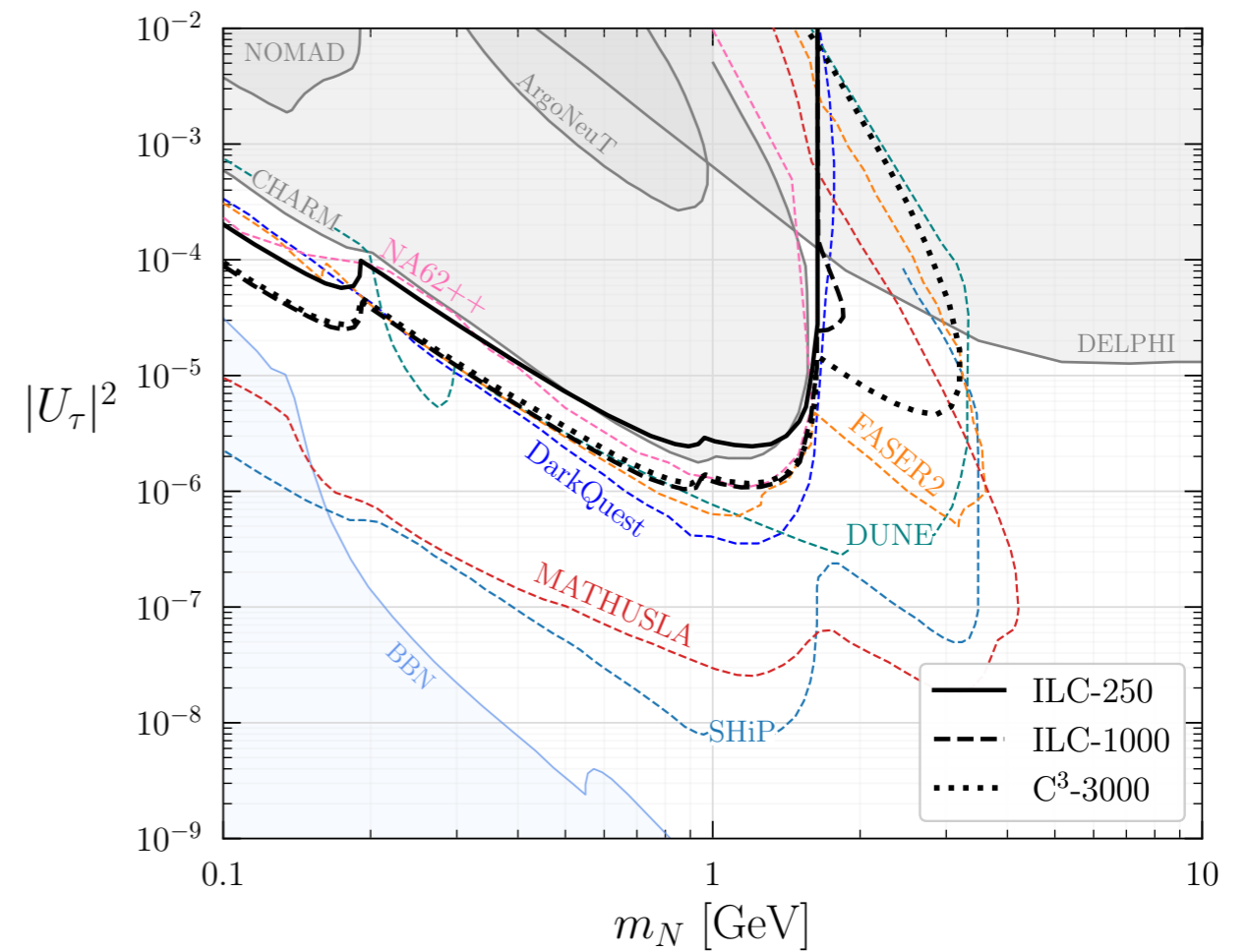
# Sensitivity for Muon and Tau Mixed HNLs

- Muon-mixed and Tau-mixed HNLs at an electron beam dump produced from meson decays

## Muon-mixed HNL



## Tau-mixed HNL

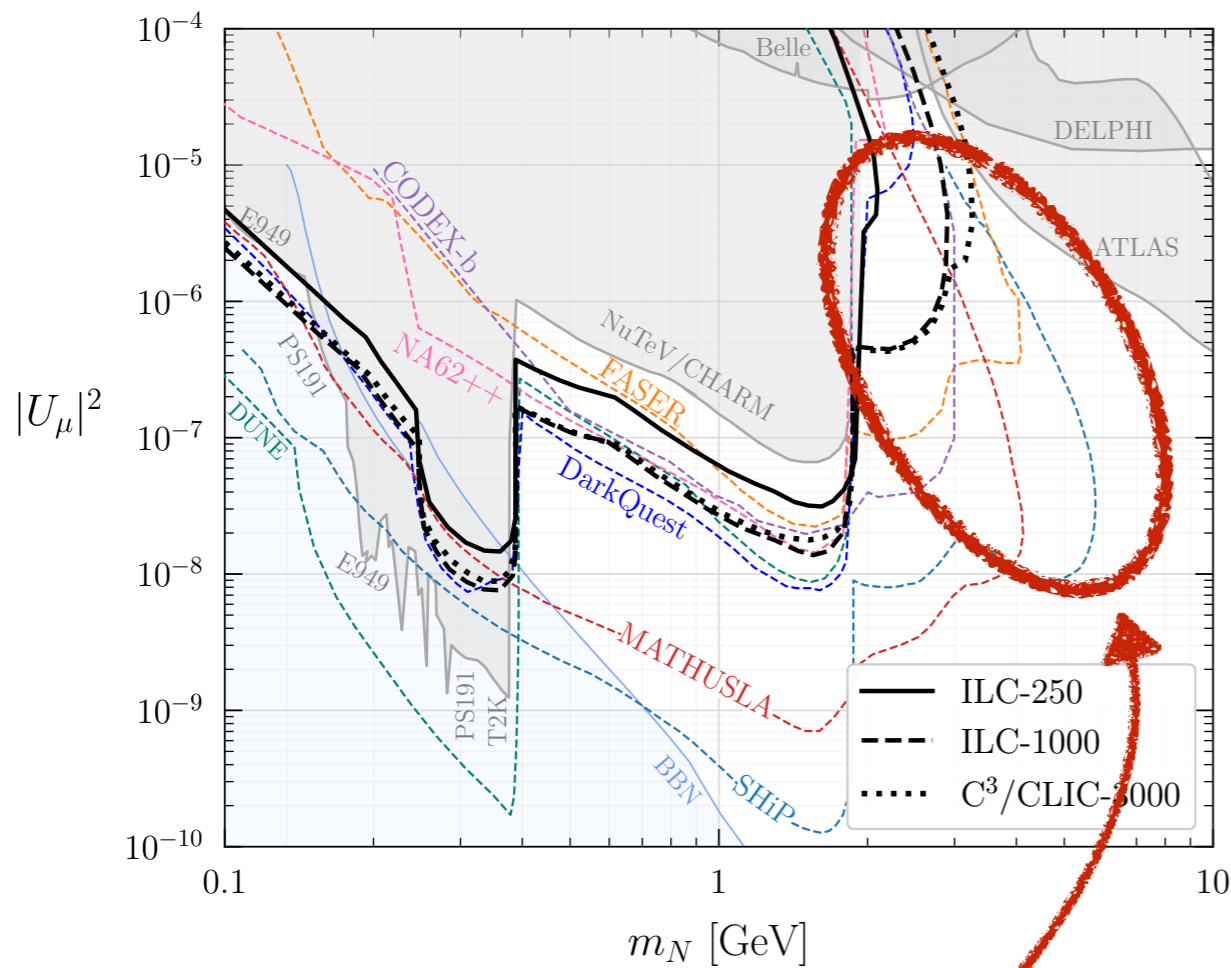




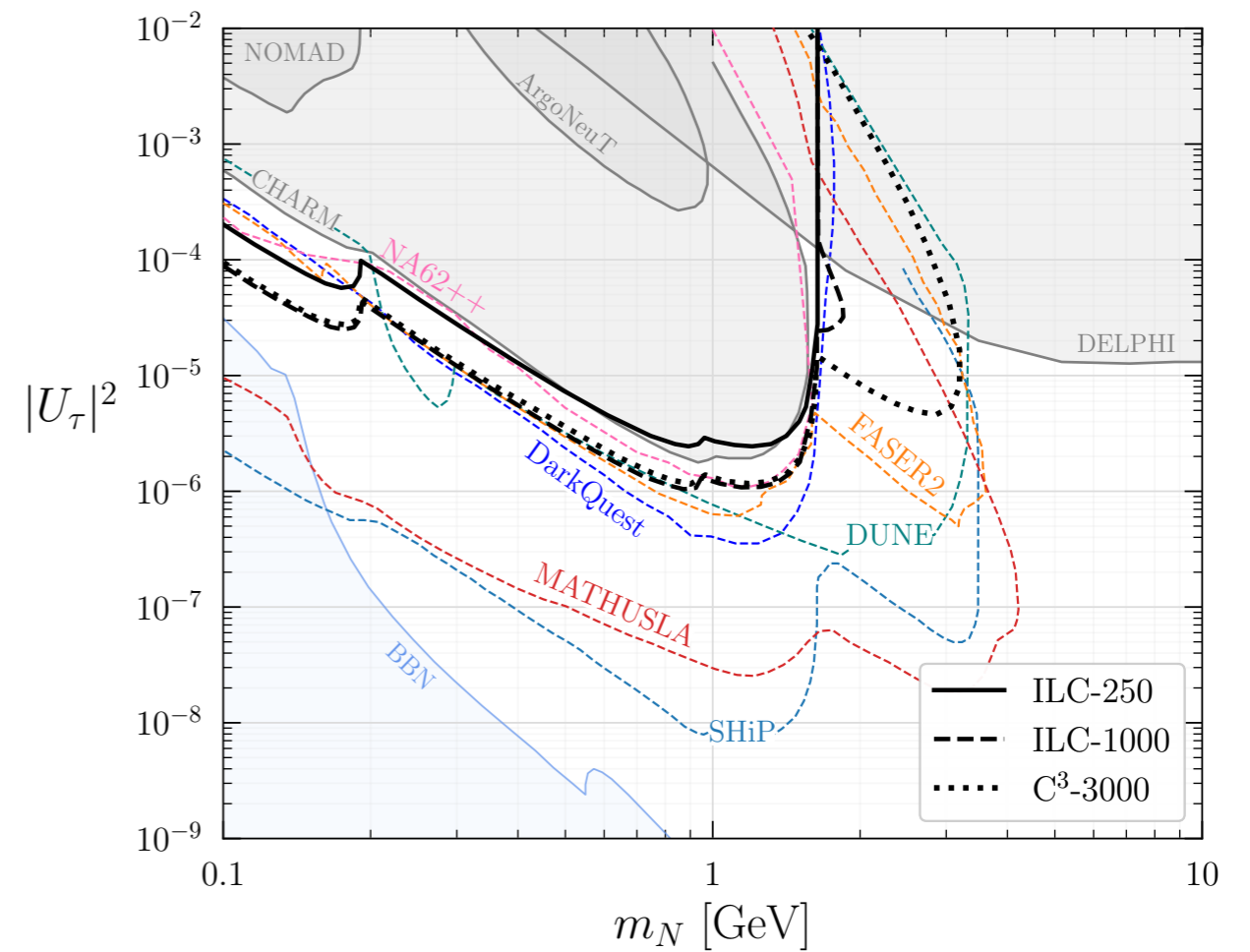
# Sensitivity for Muon and Tau Mixed HNLs

- Muon-mixed and Tau-mixed HNLs at an electron beam dump produced from meson decays

## Muon-mixed HNL



## Tau-mixed HNL



**Far, far future: CC production @ TeV muon beam dump??** Work in progress by Cari Cesarotti, Sam Homiller

# Summary

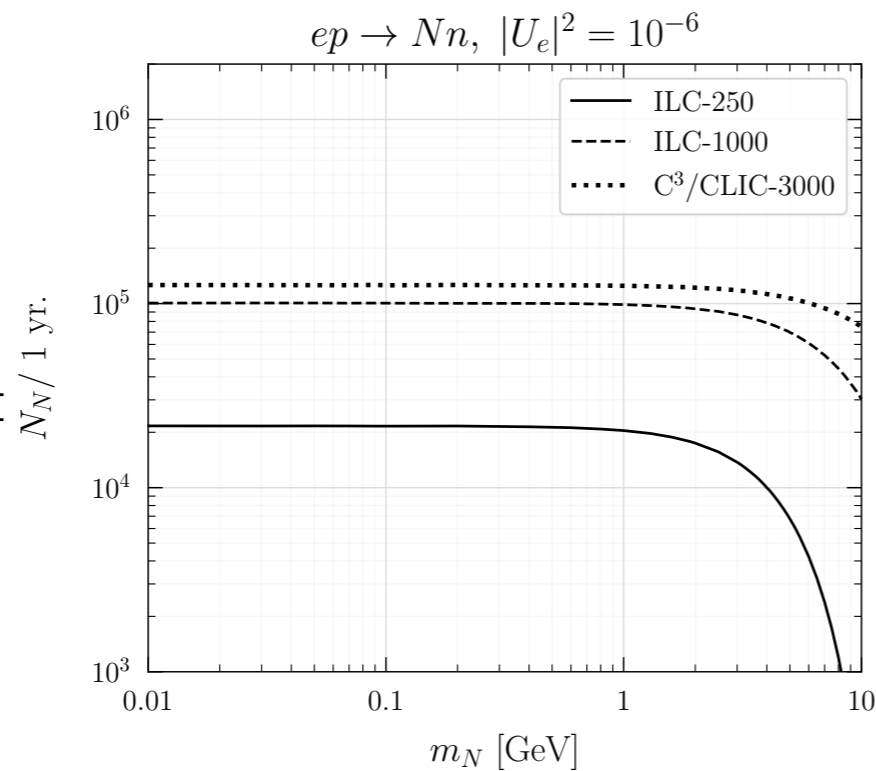
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- Beam dump experiments at linear collider are great for dark sector/LLP searches: **high energy and high intensity**
- Minimal models (e.g dark photon, leptophilic Higgs, ALPs, HNLs) have been studied but the **dark sector/LLP landscape is vast and rich. Lots more studies to be done!**
- Nice **complementarity** with collider searches, proton beam dump experiments, far/auxiliary detectors @ LHC
- **Unique opportunity to build a dark sector facilities from scratch!**
  - Beam Dump experiments
  - Far/Transverse detectors for LLPs produced in main IP

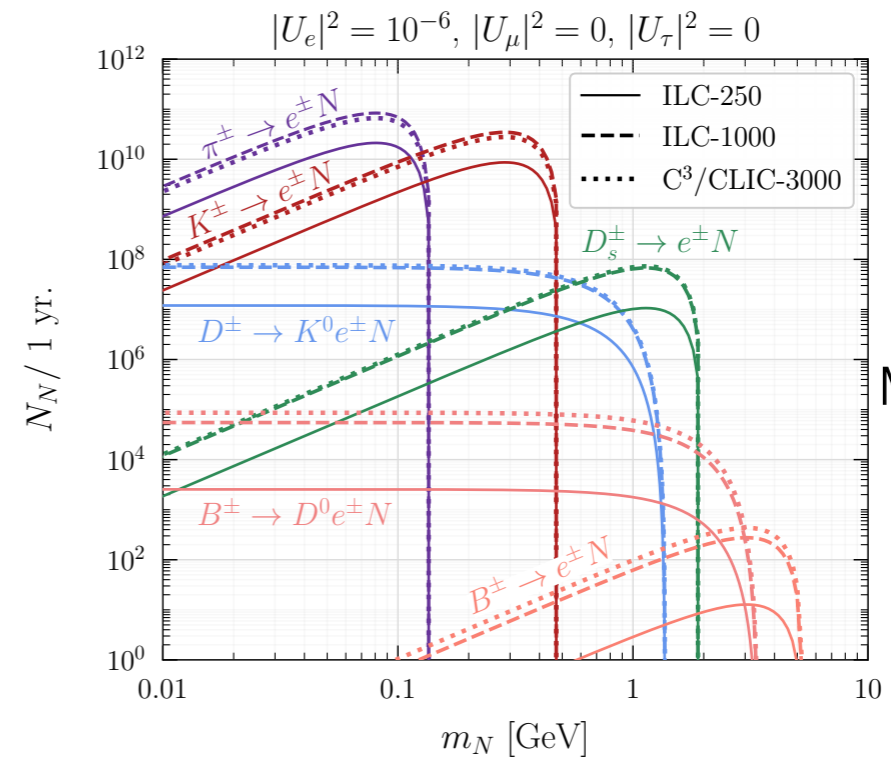
Thanks!  
Questions?

# Number of HNLs Produced

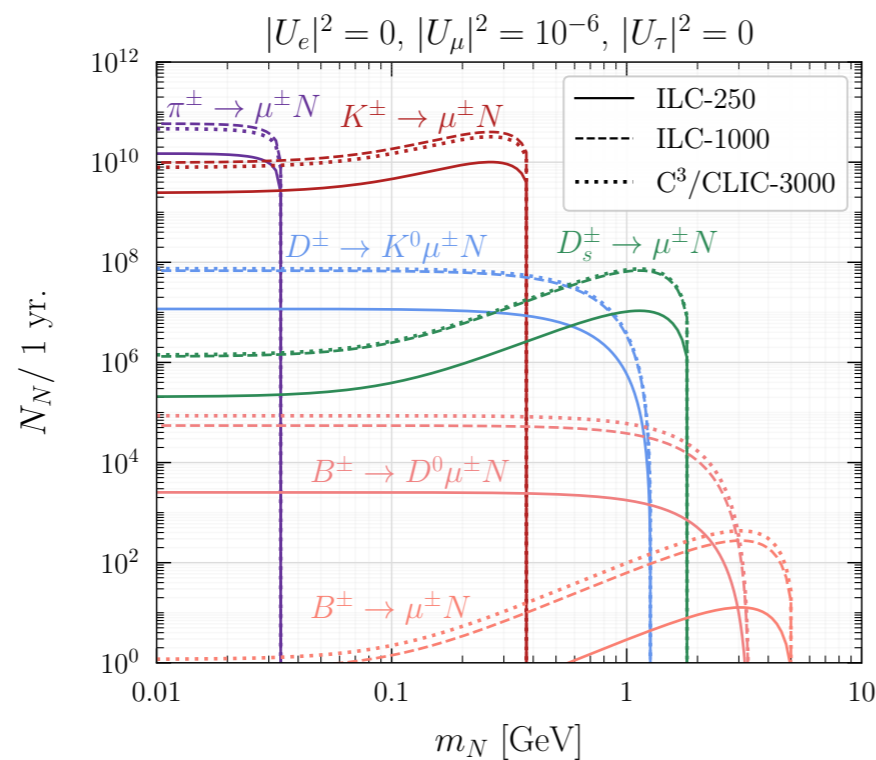
Electron mixed HNL, Charged Current



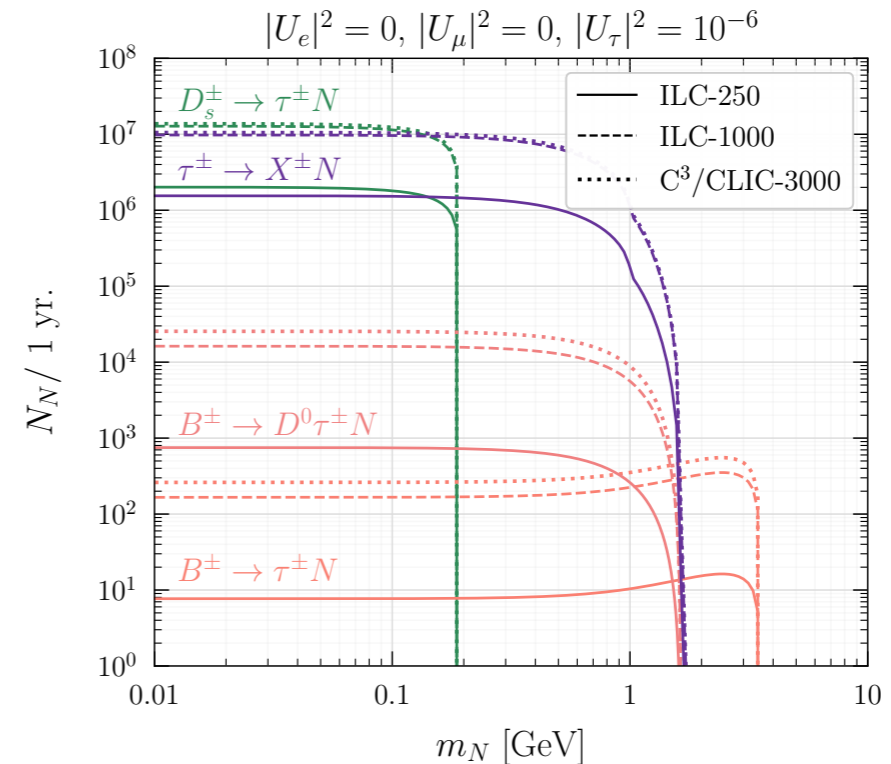
Electron mixed HNL, Meson decays



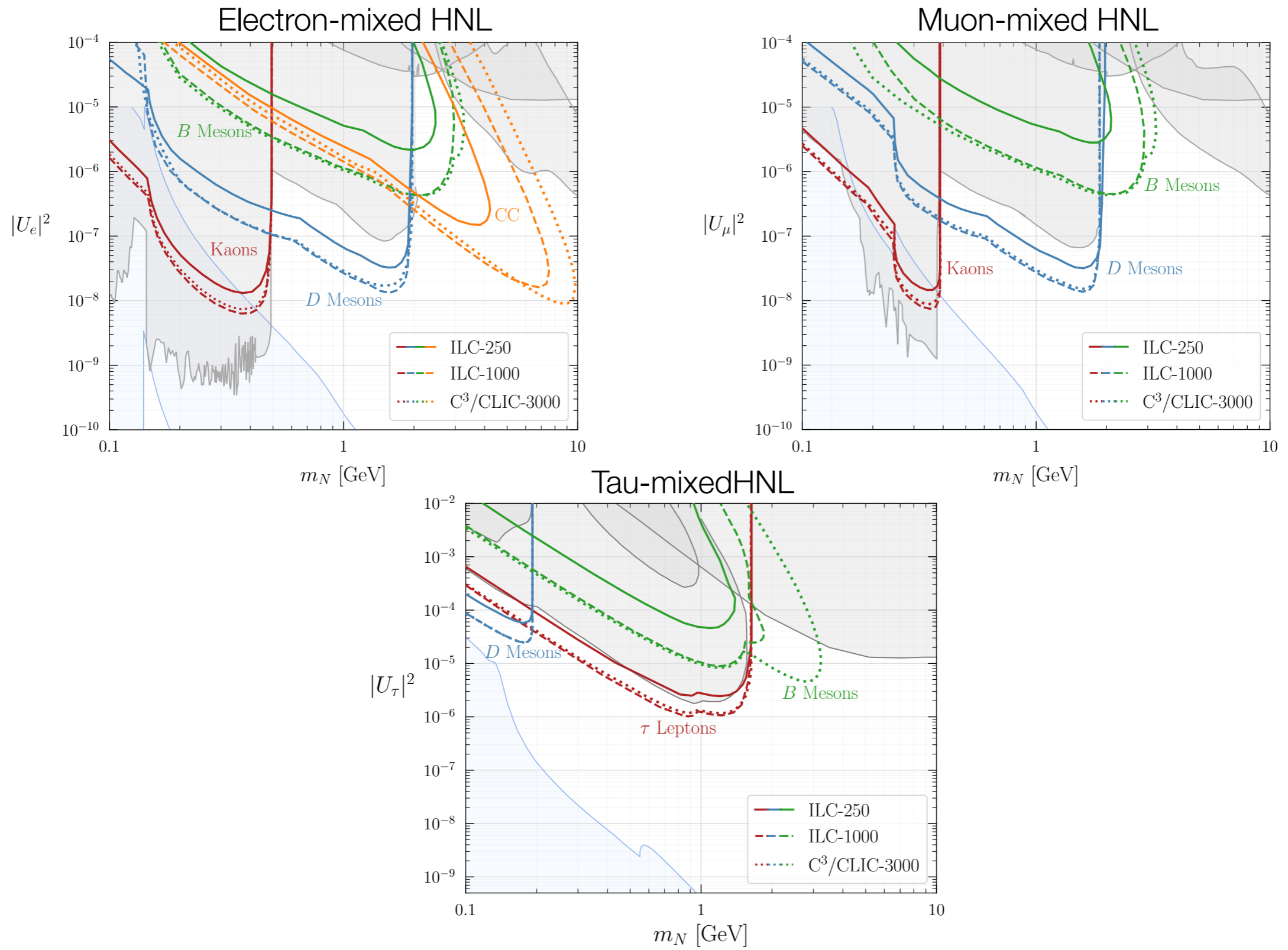
Muon mixed HNL



Tau mixed HNL



# Sensitivity by Production Mode

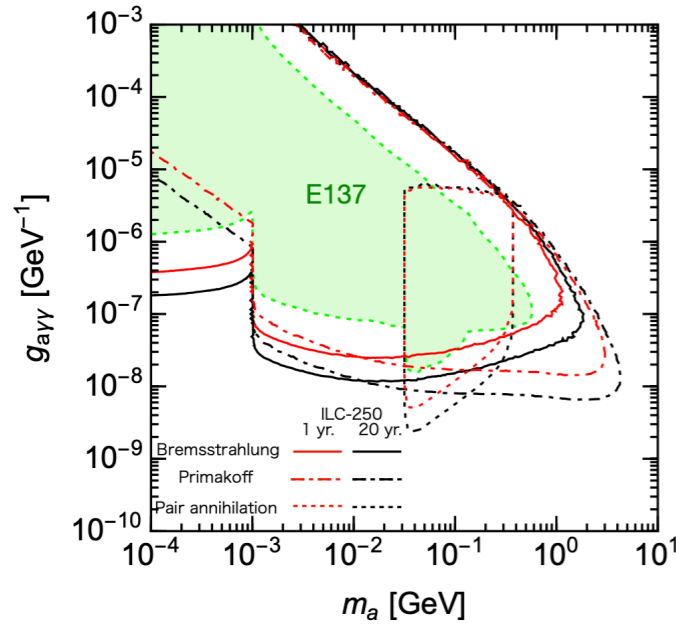


# Additional BSM Scenarios

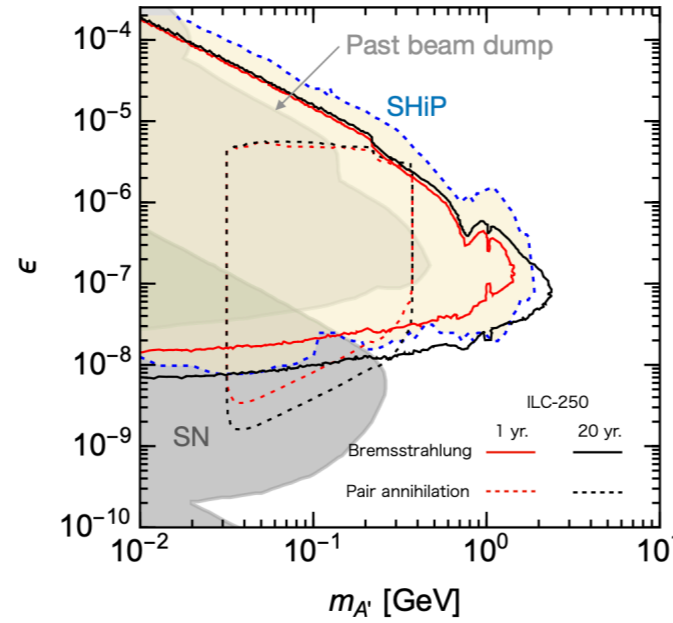
- Existing BSM studies for an ILC beam dump experiment.

Electron Beam

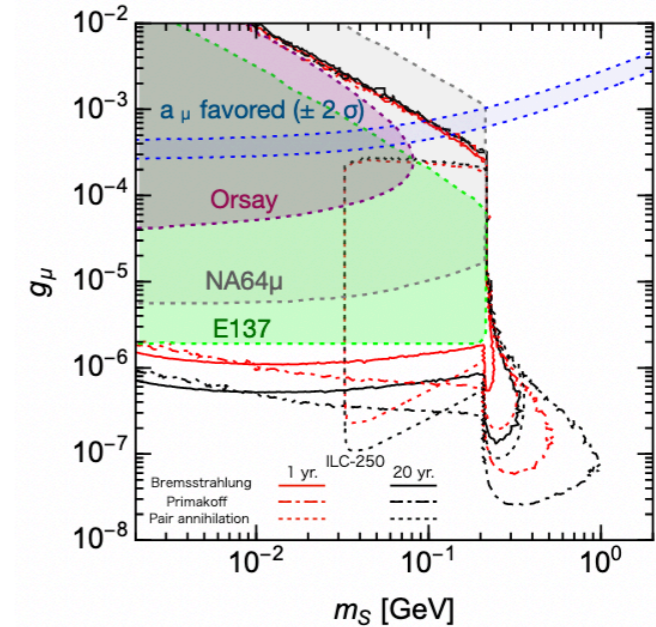
### Axion-like Particles



### Dark Photon



### Muon-philic Scalar



Positron Beam

