LCWS 2026 · 12 NOVEMBER 2026

Heavy Neutral Leptons at Beam Dump Experiments of Future Lepton Colliders

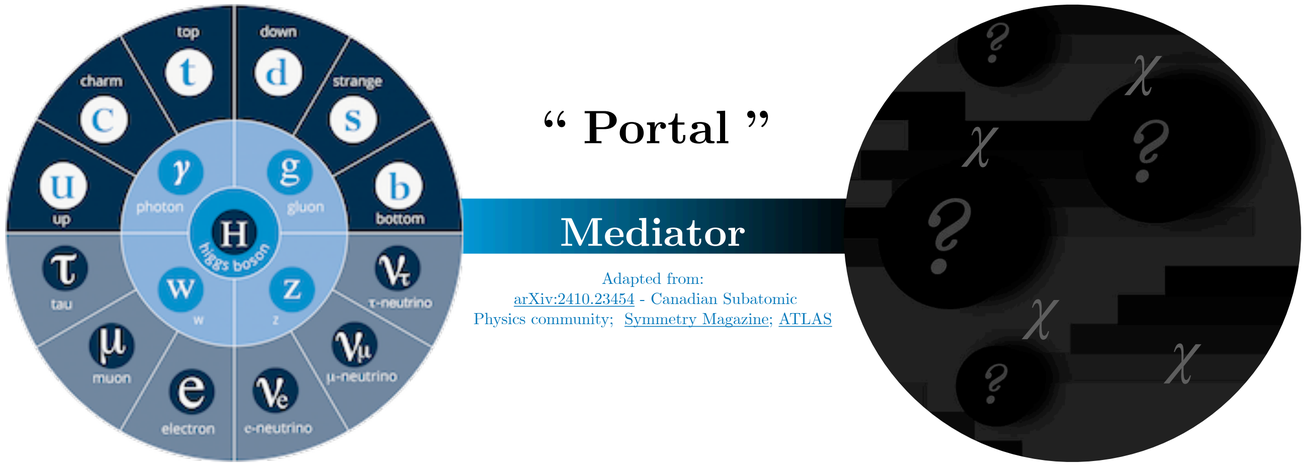
...and the case for a dark sector facility at future e^+e^- colliders

Douglas Tuckler · TRIUMF & Simon Fraser University

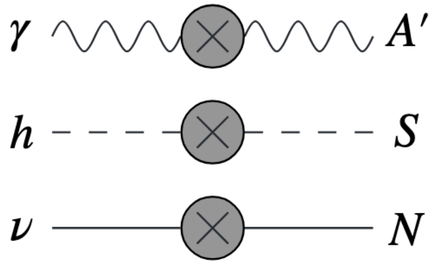
Based on P. Giffin, S. Gori, Y.-D. Tsai, and D. Tuckler, arXiv:2206.13745

Dark Sectors & Long-Lived Particles

Particles that do not interact through SM forces.

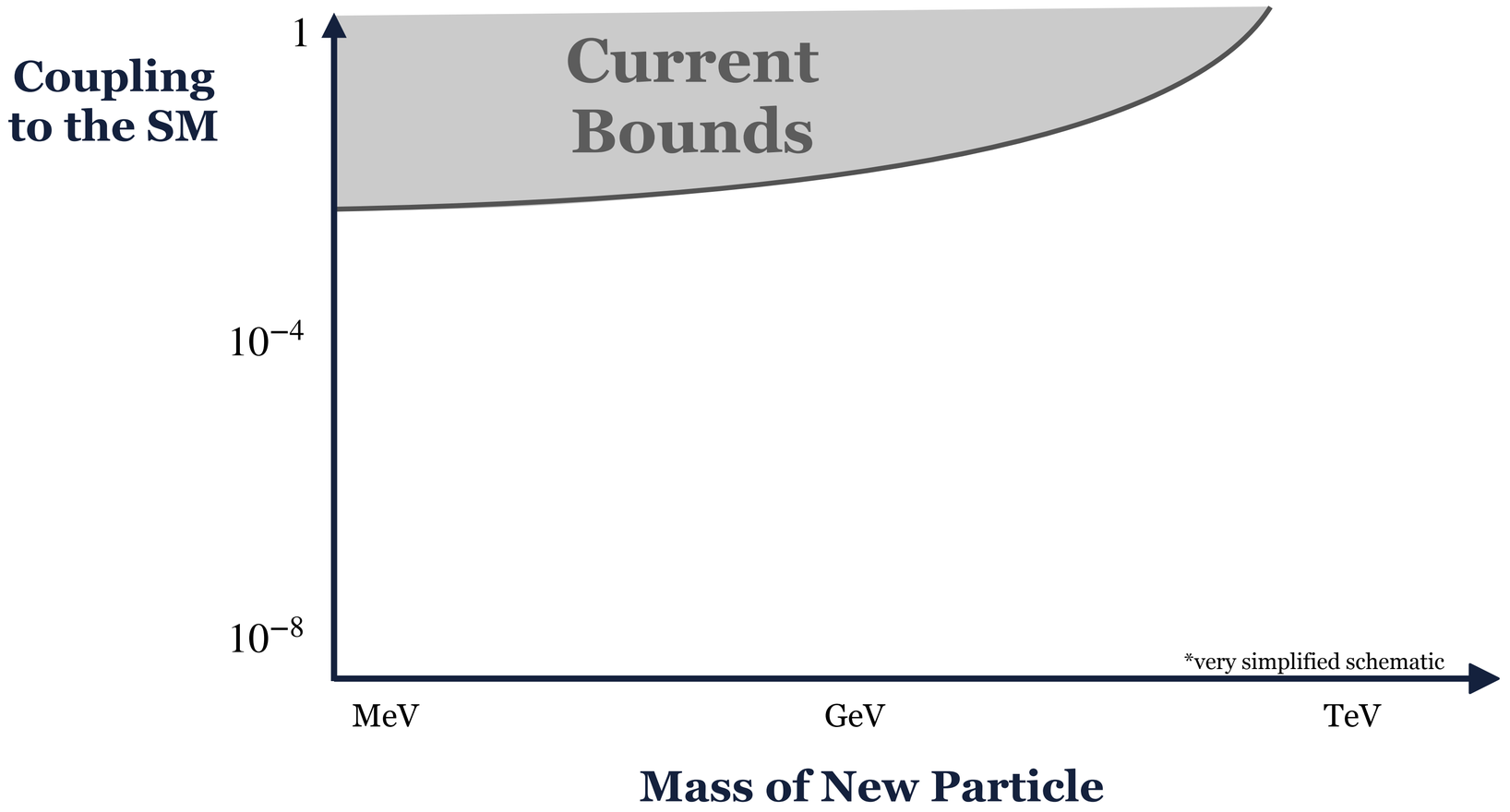


1. **Dark Photon:** $\mathcal{L} \supset \epsilon F'_{\mu\nu} F^{\mu\nu}$
2. **Dark Higgs:** $\mathcal{L} \supset \epsilon |H|^2 |S|^2$
3. **Heavy Neutrino:** $\mathcal{L} \supset \epsilon \bar{L} \tilde{H} N$

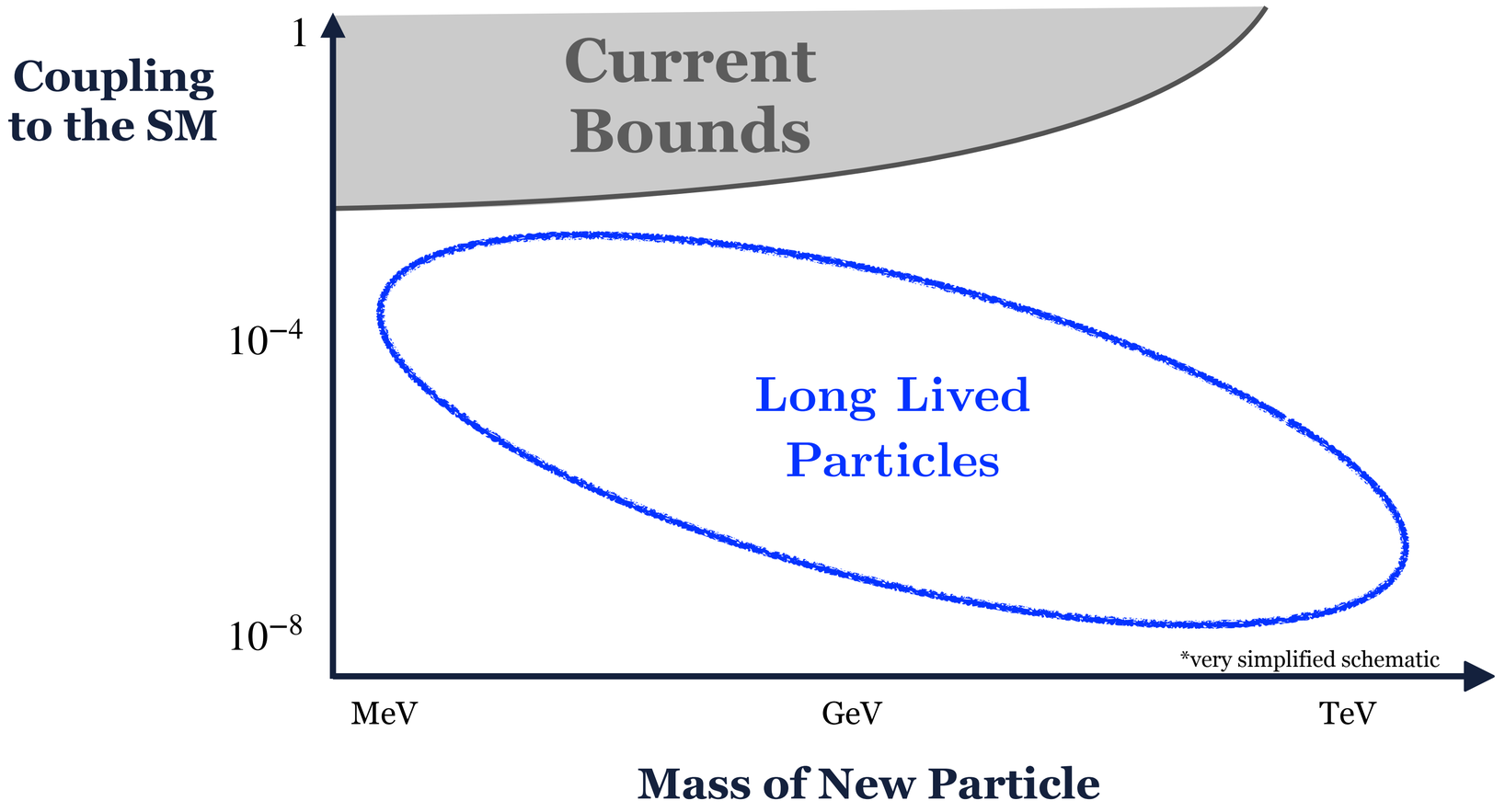


- Motivations:
  - Dark matter
  - Strong CP Problem
  - Neutrino mass generation
- Feature particles with *long lifetimes*, hidden from conventional experimental searches.
  - Models with small mass splittings (e.g. inelastic DM)
  - Models with very small couplings (e.g. DM freeze-in, seesaw mechanisms)

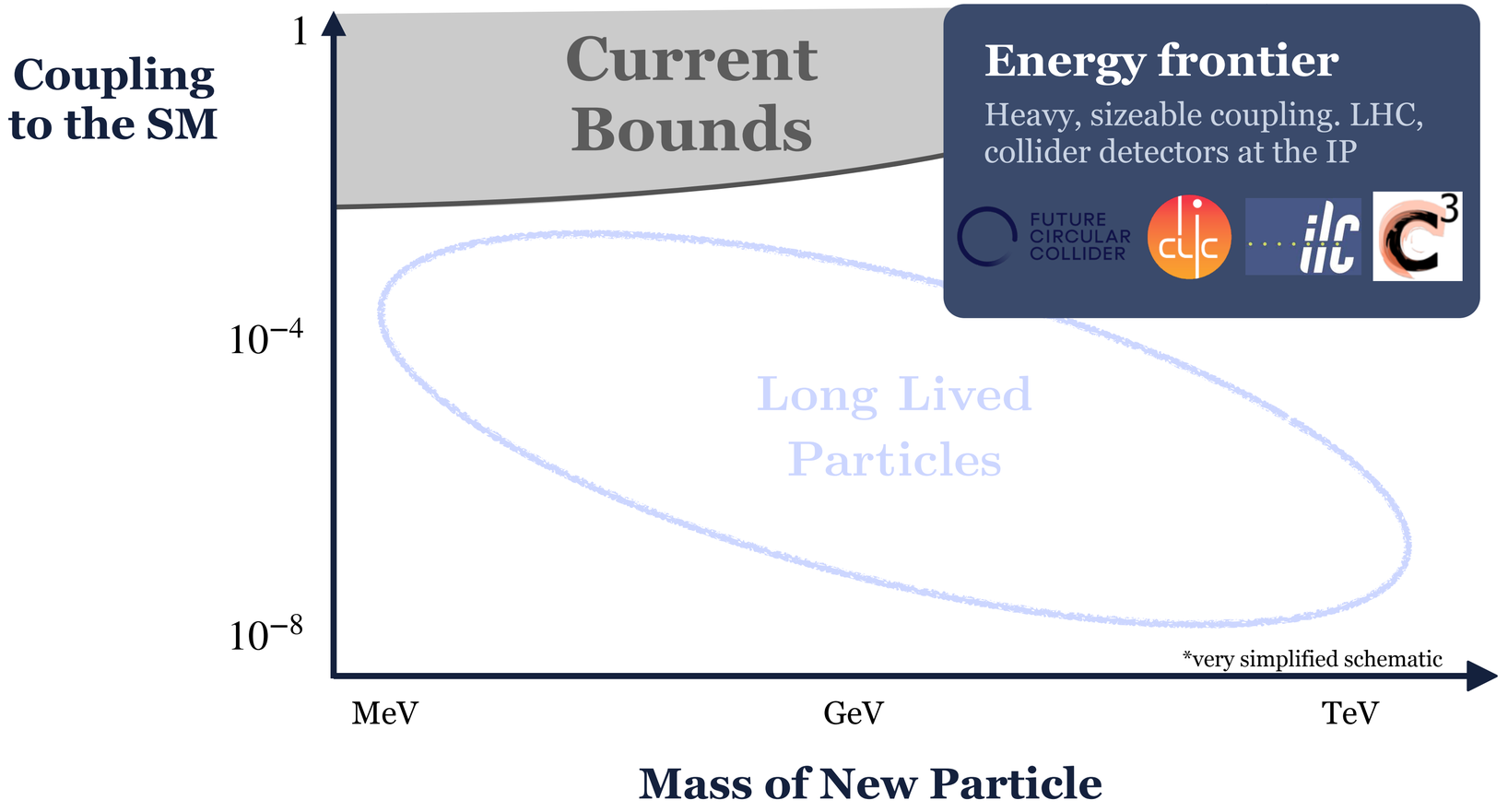
Searching for New Physics



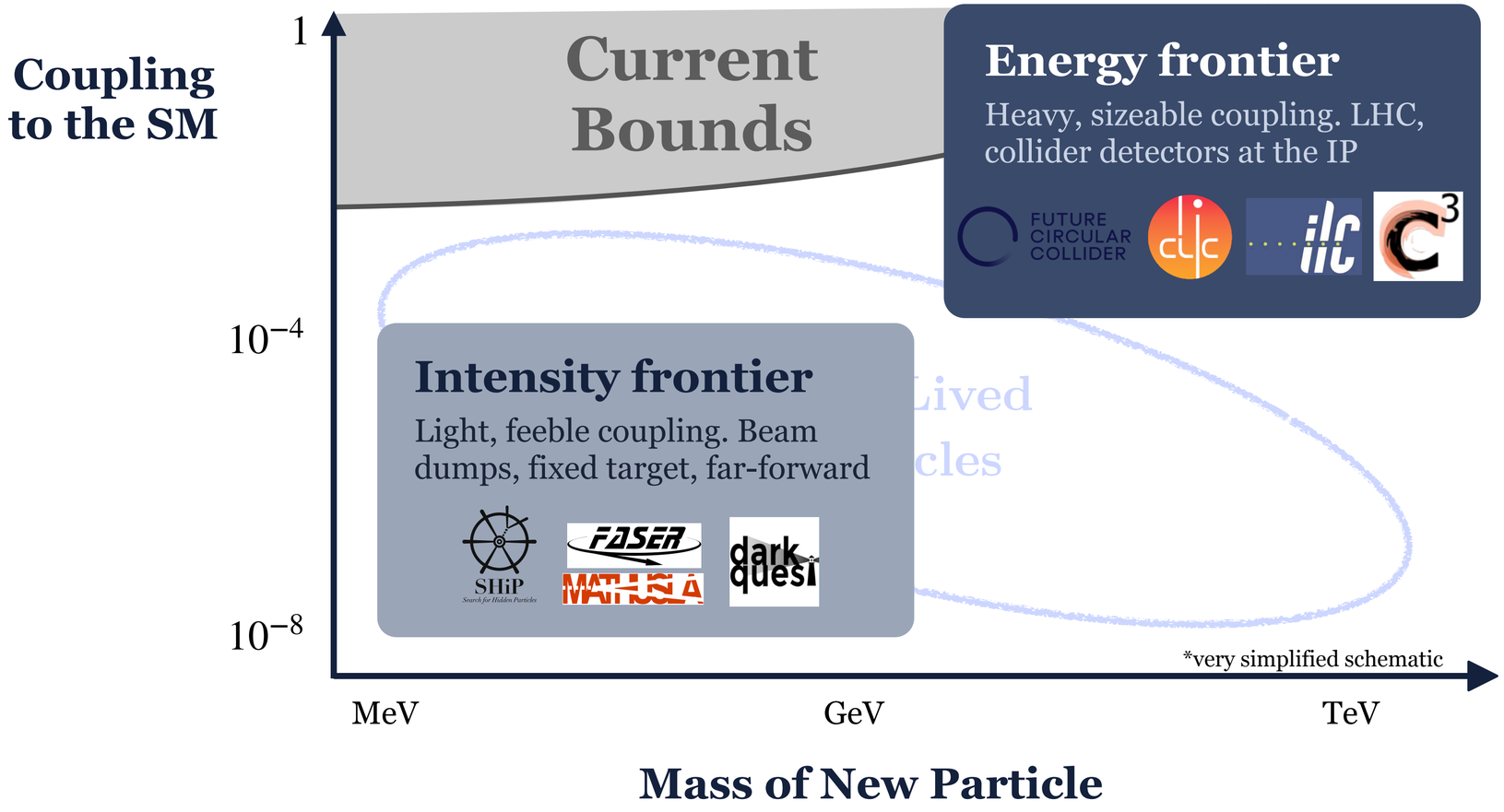
Searching for New Physics



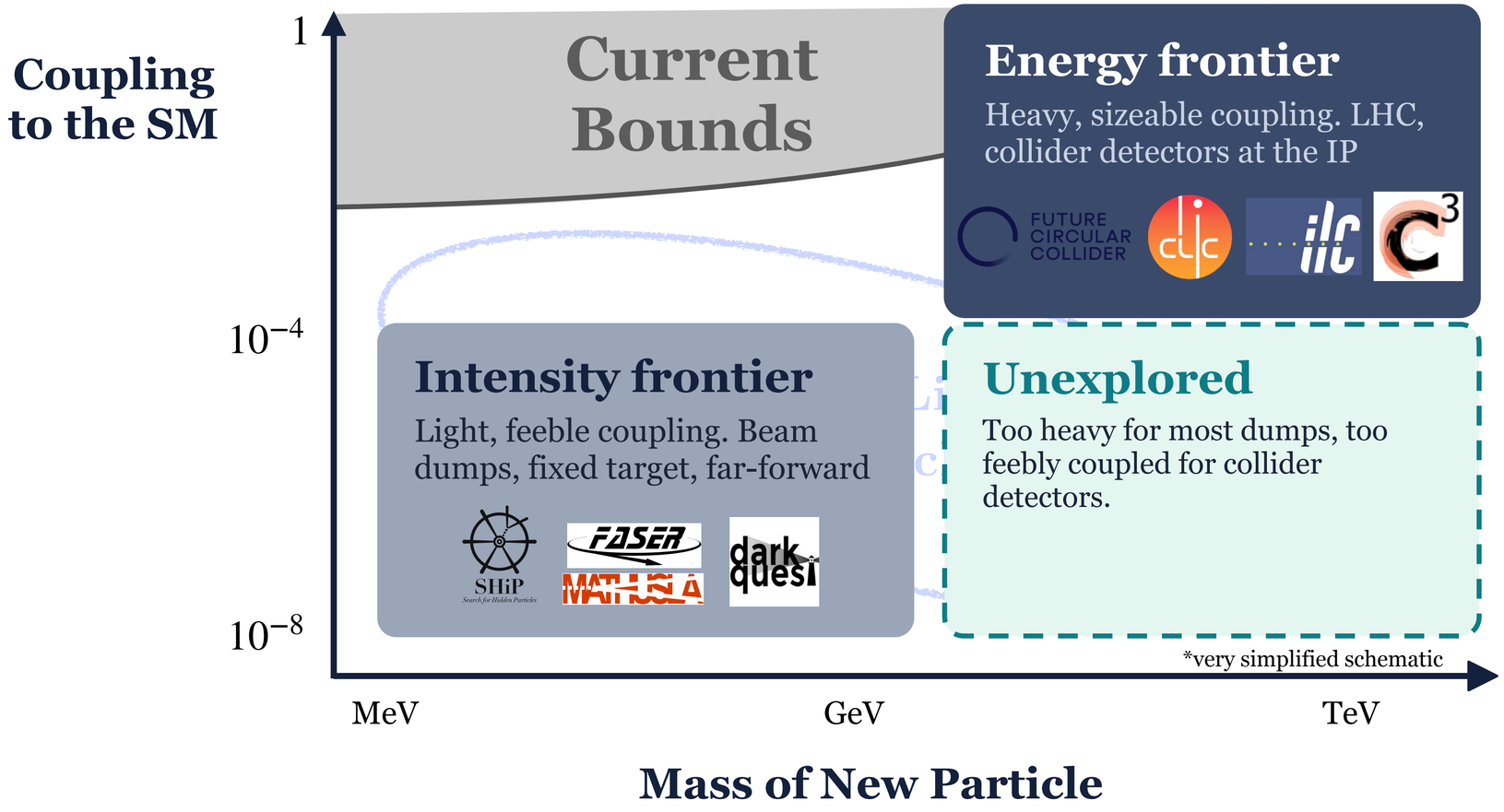
Searching for New Physics



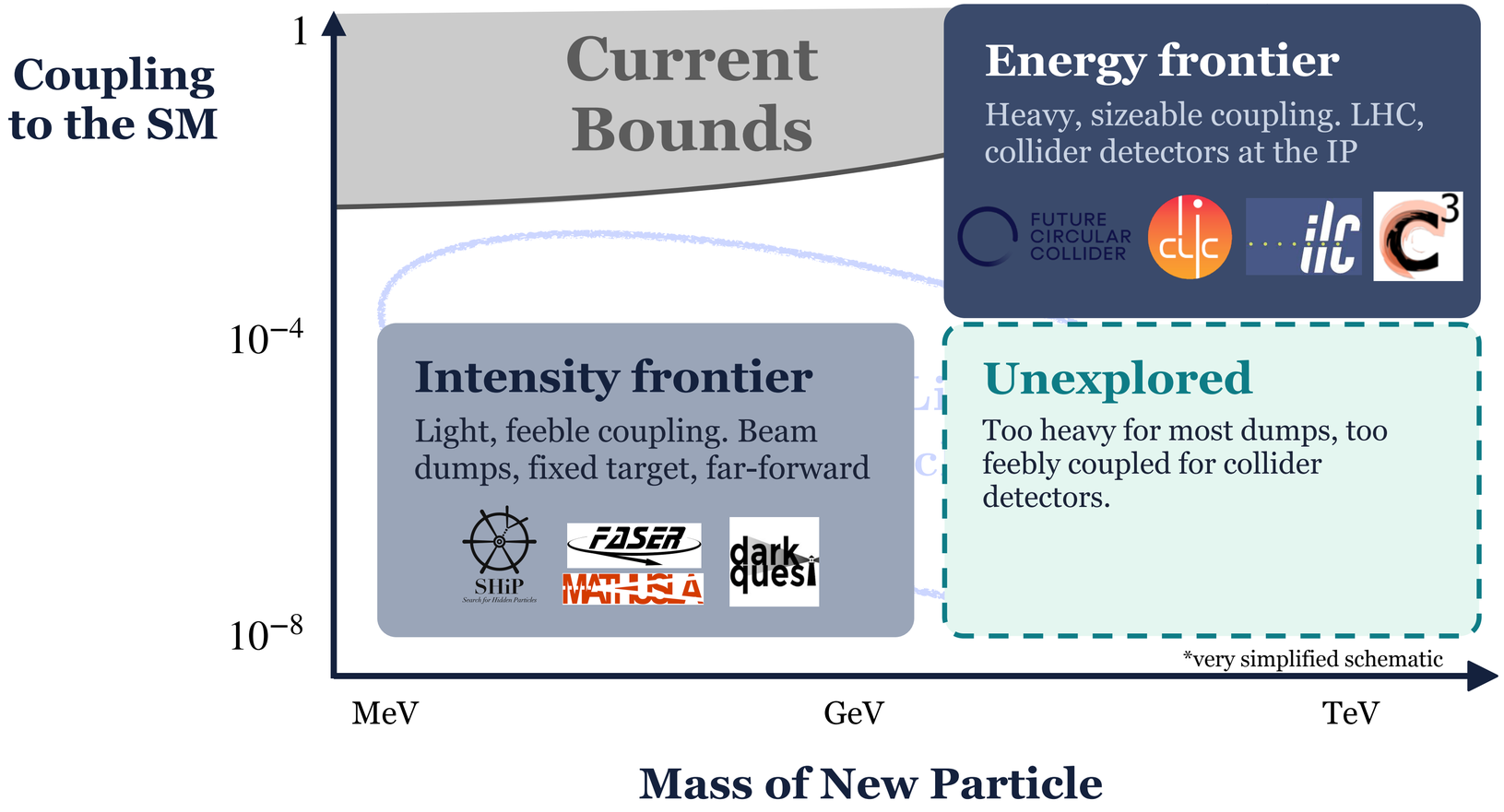
Searching for New Physics



Searching for New Physics



Searching for New Physics



Need both high-energy and high-intensity to reach LLPs beyond a few GeV.

Proton Beam Dump Experiments

High-intensity proton beam striking a dense target.

- Large number of protons-on-target ⇒ large BSM particle production rates
- Long decay volumes to probe long-lived particles.
- Main drawback: low centre-of-mass energy ⇒ limited mass reach

Experiment	E_p [GeV]	ℓ_{det}	POT/year	$N_{K^\pm}$	$N_{D^\pm}$	$N_{B^\pm}$
SHiP*	400	~ 100 m	4×10^{19}	$\sim 10^{19}$	$\sim 10^{17}$	$\sim 10^{13}$
DarkQuest*	125	~ 10 m	10^{18}	$\sim 10^{17}$	$\sim 10^{15}$	$\sim 10^{8}$
DUNE	120	~ 500 m	1.1×10^{21}	$\sim 10^{19}$	$\sim 10^{15}$	-

- TeV proton beams? LHC main beam dump with ~10^{17} protons-on-target/year. LLP production rates are too low, but more studies are needed.

* DarkQuest and SHiP approved and received funding!

Future Linear Colliders

High energy experiments but **also high-intensity!**



International Linear Collider



Compact Linear Collider



Cool Copper Collider

C.O.M energy:	250/500/1000 GeV	380/3000 GeV	250/550/3000 GeV
EOT / year:	4.1×10^{21}	$3.1 \times 10^{21}/1.8 \times 10^{21}$	1.8×10^{21}

Future Linear Colliders

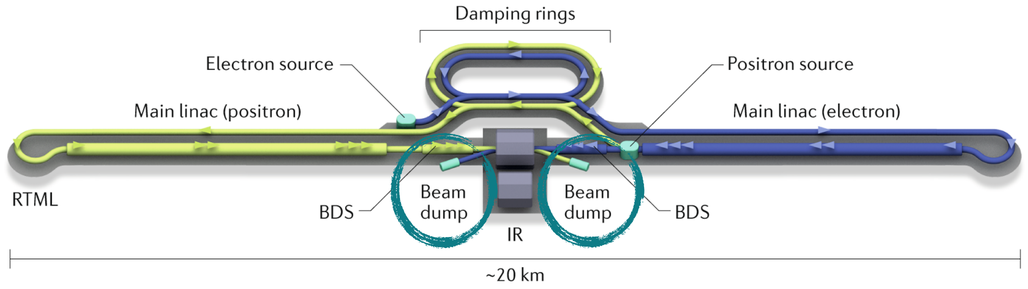
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International Linear Collider

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EOT / year:	4.1×10^{21}	$3.1 \times 10^{21}/1.8 \times 10^{21}$	1.8×10^{21}



Linear colliders dump ~10^{21} electrons per year!

What can we do with them?

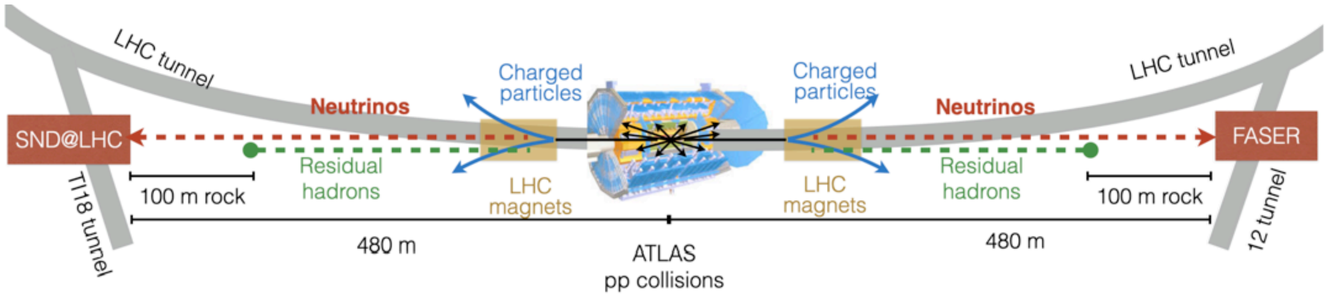
Precedent

Lessons from the LHC

Detectors outside interaction points to explore physics beyond target design of main detectors.

EXISTING

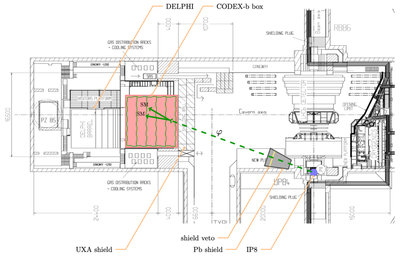
LHC
Scattering and Neutrino Detector
at the LHC



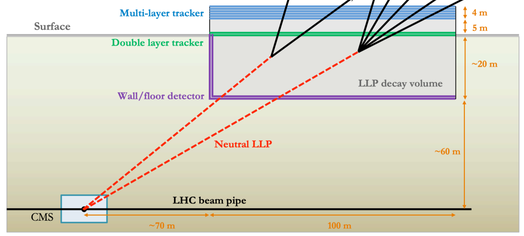
FASER

PROPOSED

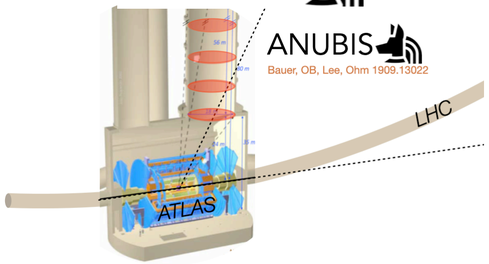
CODEX-b



MATHUSLA



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Precedent

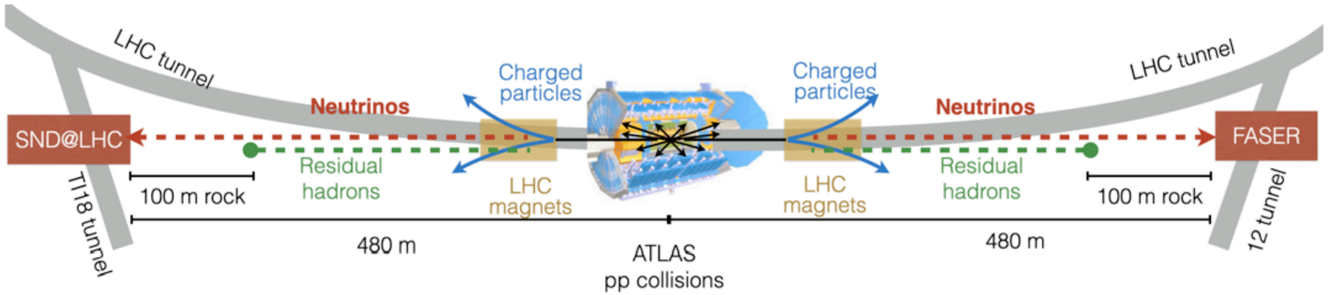
Lessons from the LHC

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EXISTING

LHC

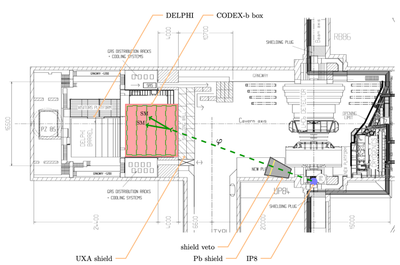
Scattering and Neutrino Detector
at the LHC



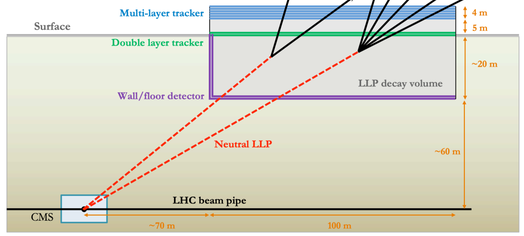
FASER

PROPOSED

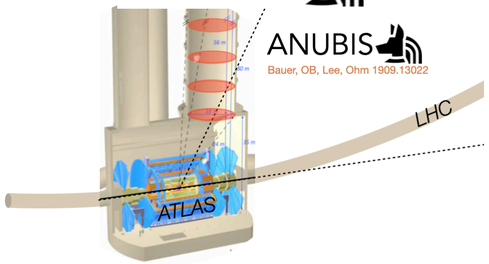
CODEX-b



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Idea: build a dark sector facility at future linear colliders that utilizes the beam dumps to study dark sectors and LLPs

Advantages of Future Lepton Colliders

1. High Energy

- $E_e \sim$ 100 GeV - few TeV
- *Staged energy approach*. No need to build a new facility for higher energy beams!

2. High Intensity

Collider-$\sqrt{s}$ [GeV]	EOT/year
ILC-250/1000	4.1×10^{21}
C^3-250	3.1×10^{21}
C^3-3000	1.8×10^{21}
CLIC-3000	1.8×10^{21}

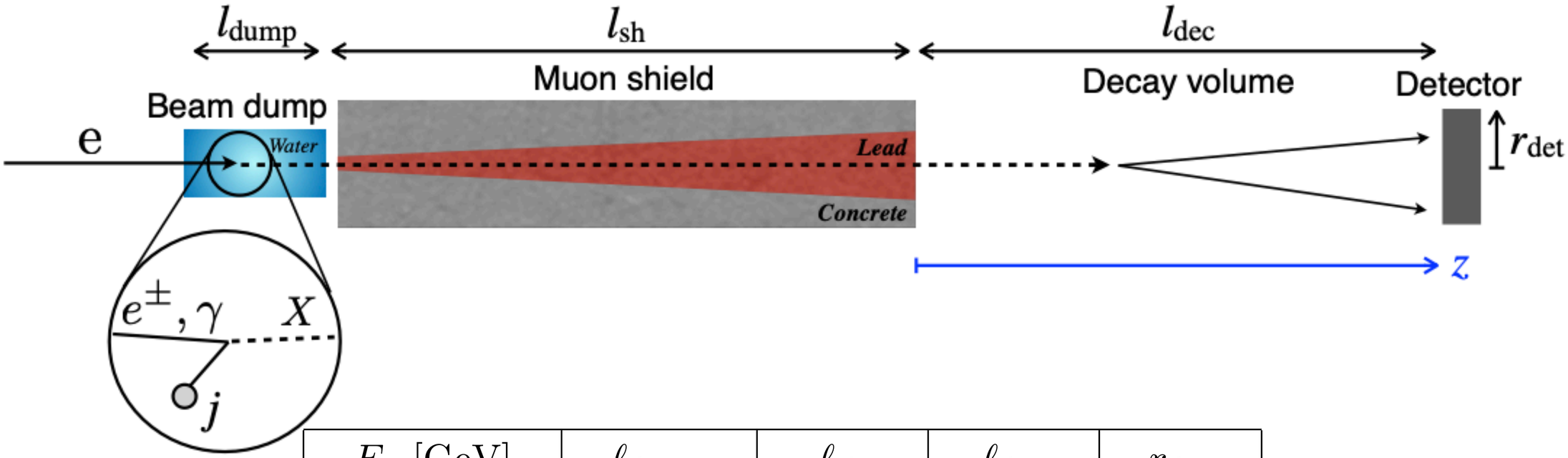
SHiP $\sim 10^{19}$ POT/year

3. New Production Modes

- e^- beam → charged-current scattering production of heavy neutral leptons
- e^+ beam → pair annihilation production of dark photons/ALPs

Beam Dump at Linear Colliders

Follow the proposal for a beam dump experiment at ILC



E_e [GeV]	$\ell_{\rm dump}$	$\ell_{\rm sh}$	$\ell_{\rm dec}$	$r_{\rm det}$
125 500 1500	10m	70m	50m	2m

Case Study: Heavy Neutral Leptons

- Gauge singlet fermion that mixes with the SM neutrino
  - Plays a role in neutrino mass generation (e.g. seesaw mechanism)
  - Potential connection with the matter-antimatter asymmetry (e.g. leptogenesis)
  - Portal to the dark sector (e.g. neutrinophilic dark matter)

$$\mathcal{L} \supset Y \bar{L} \tilde{H} N_R \xrightarrow{\text{EWSB}} \frac{g_2}{\sqrt{2}} U_\alpha W_\mu^- \ell_\alpha^\dagger \bar{\sigma}^\mu N + \frac{g_2}{2 \cos\theta_W} U_\alpha Z_\mu \nu_\alpha^\dagger \bar{\sigma}^\mu N$$

Charged Current — Neutral Current

- HNL is produced in any process that produces a SM neutrino, suppressed by $|U_\alpha|^2$.
- The HNL subsequently decays to SM particles (mesons and leptons) if they are lighter than 10 GeV.

Production in Electron Beam Dump

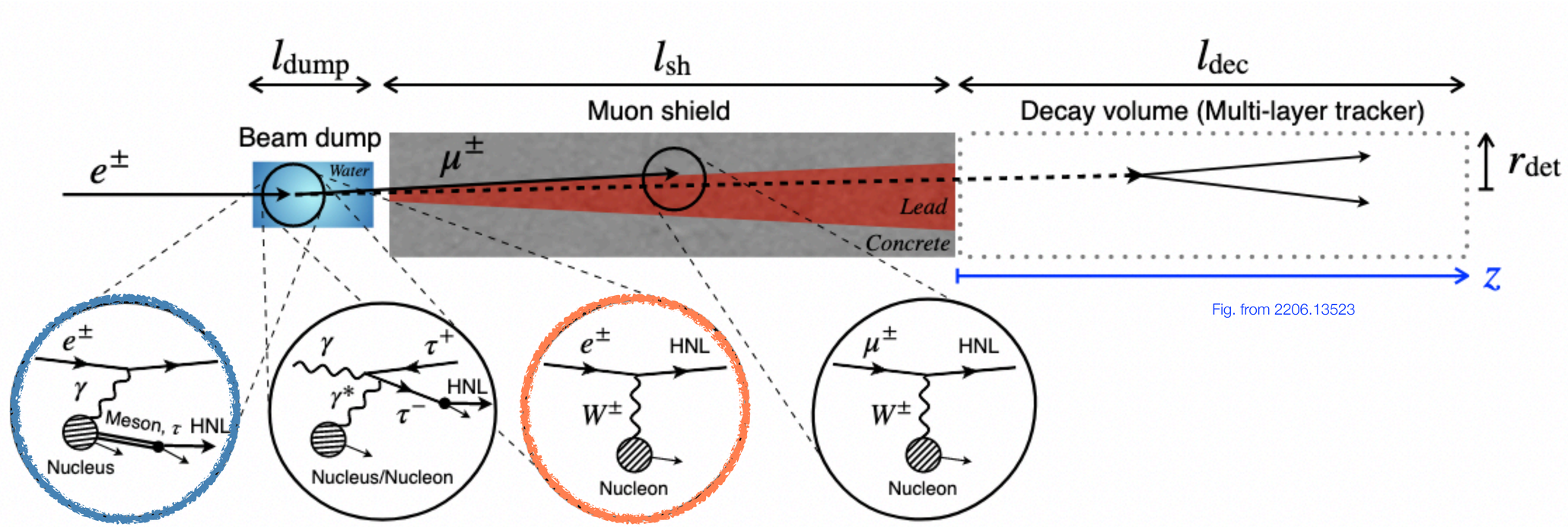


Fig. from 2206.13523

- **Mesons decays:** photoproduction of mesons in the beam dump that then decay to HNLs. Also present in proton beam dump experiments.
- **Charged-Current Scattering:** direct production in electron-proton scattering through weak interactions. *Unique to lepton collider!*

Production I: Meson Decays

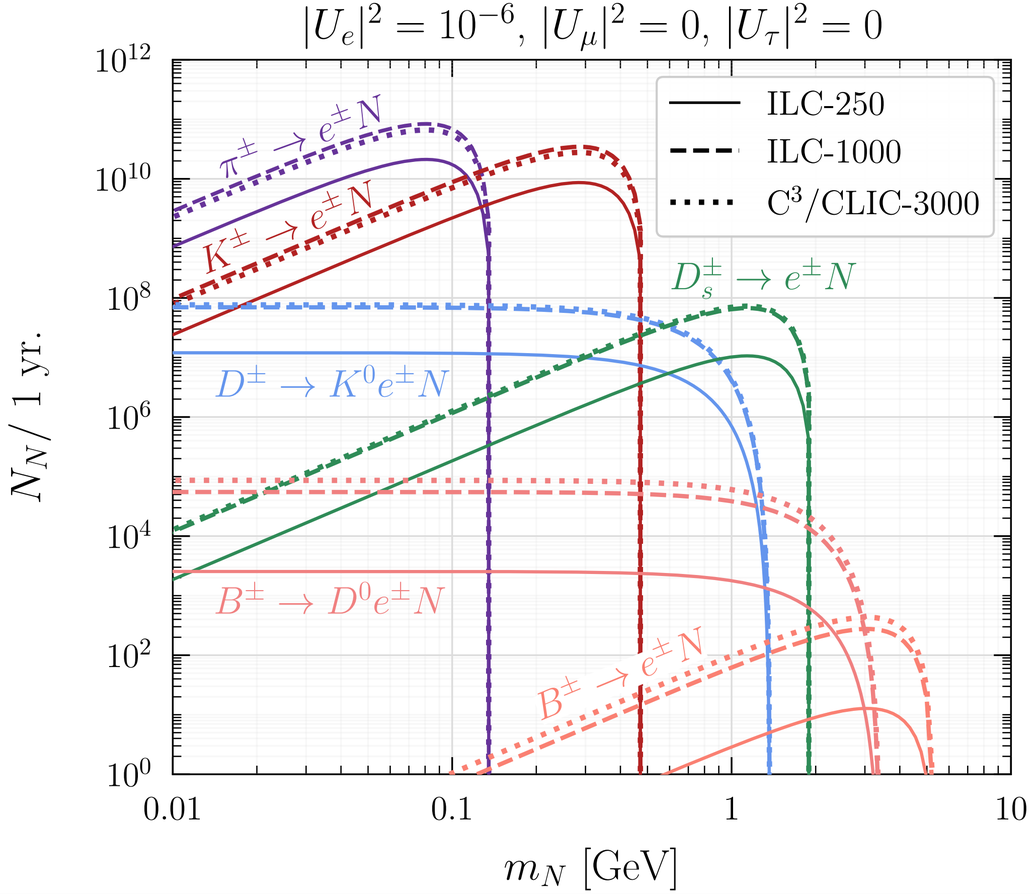
Number of HNLs produced from meson decays assuming 4 ×10²¹ EOT/year

$$N_N = N_M \mathrm{BR}(M \to N + X)$$

Number of mesons and τ leptons per year

	ILC-250	ILC-1000	C³-250	C³/CLIC-3000
$\pi^\pm$	1.5×10^{16}	6.0×10^{16}	1.2×10^{16}	4.8×10^{16}
$K^\pm$	3.9×10^{15}	1.5×10^{16}	3.0×10^{15}	1.2×10^{16}
K^0_L	3.8×10^{14}	1.5×10^{15}	2.9×10^{14}	1.2×10^{15}
$D^\pm$	1.4×10^{14}	7.8×10^{14}	1.0×10^{14}	8.6×10^{14}
$D^\pm_s$	3.8×10^{13}	2.5×10^{14}	2.9×10^{13}	2.6×10^{14}
$B^\pm$	1.0×10^{11}	2.2×10^{12}	7.5×10^{10}	3.4×10^{12}
$\tau^\pm$	2.2×10^{12}	1.4×10^{13}	1.5×10^{12}	1.5×10^{13}

Electron-mixed HNL



Production I: Meson Decays

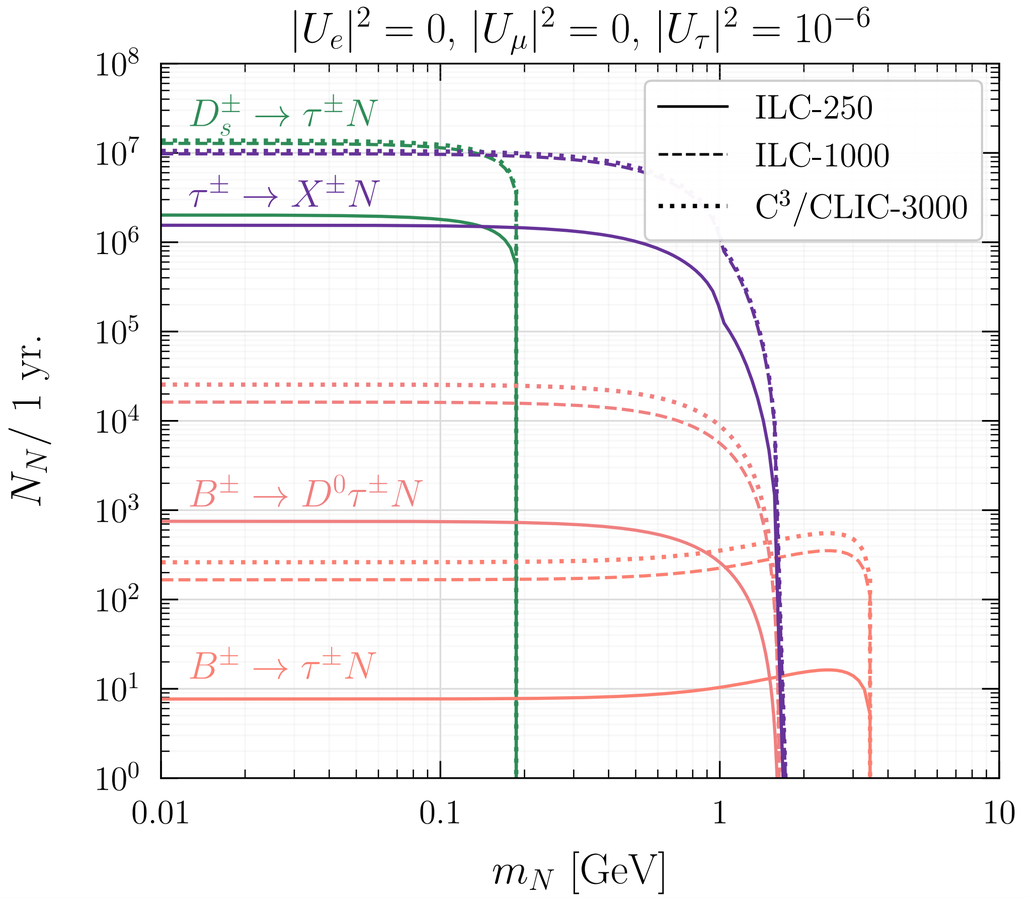
Number of HNLs produced from meson decays assuming 4×10^{21} EOT/year

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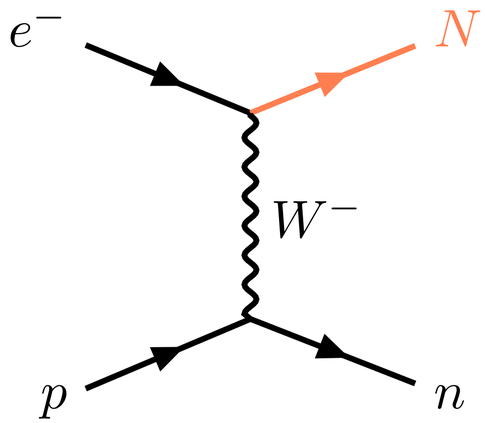
	ILC-250	ILC-1000	C^3-250	C^3/CLIC-3000
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$B^\pm$	1.0×10^{11}	2.2×10^{12}	7.5×10^{10}	3.4×10^{12}
$\tau^\pm$	2.2×10^{12}	1.4×10^{13}	1.5×10^{12}	1.5×10^{13}

Tau-mixed HNL



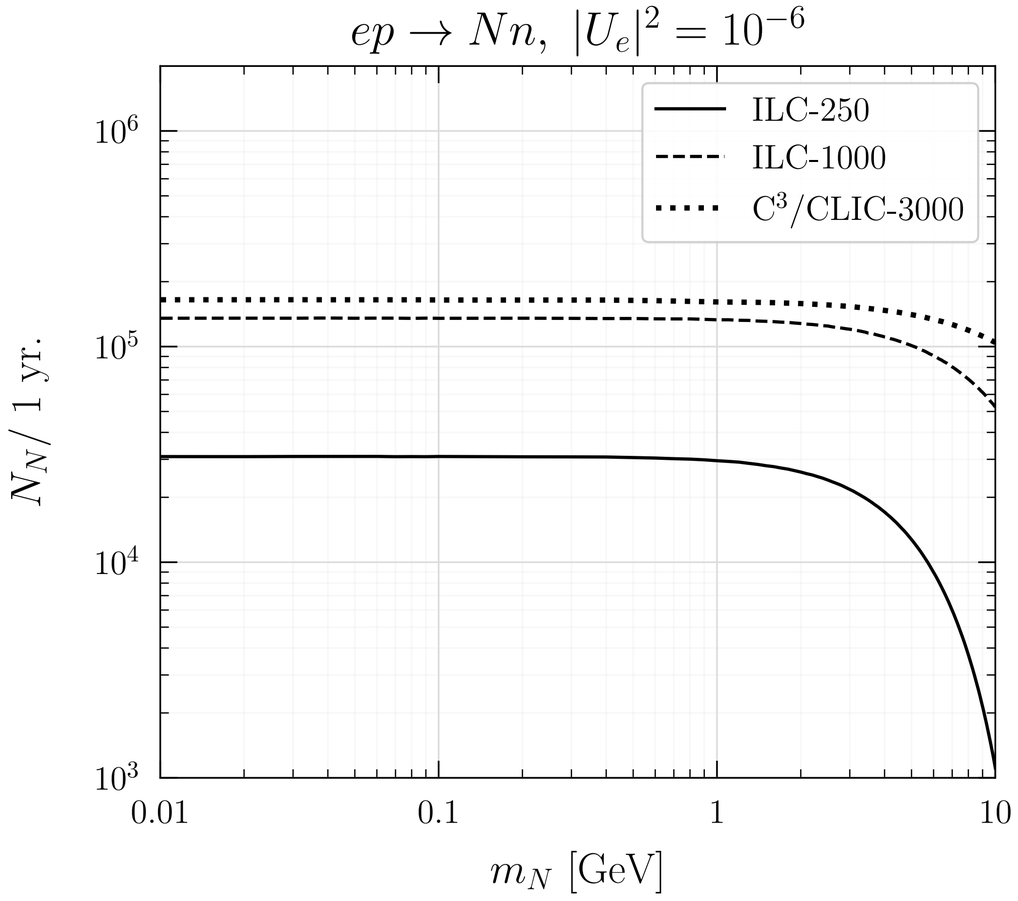
Production II: Charged-Current Scattering

Production mode only for electron-mixed HNLs



$$N_N = \sigma(ep \to Nn)\mathcal{L}_{\text{eff}}$$

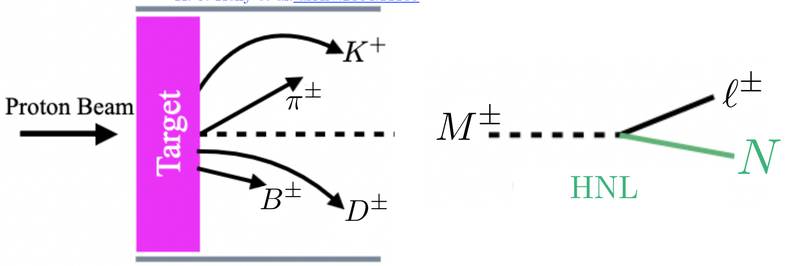
Effective Luminosity: $\mathcal{L}_{\text{eff}} \simeq \dfrac{Z(X_0/g)N_A}{A}\,\text{EOT}_\text{s}\,,$

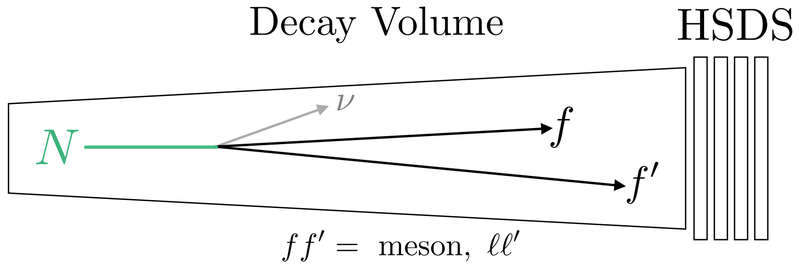


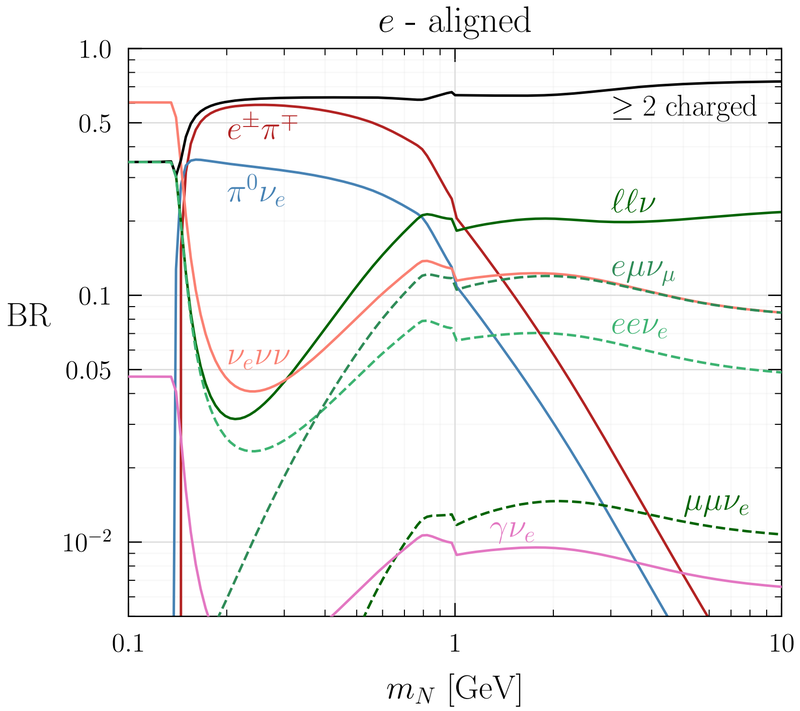
Charged-Current Scattering is the main production mode above 2 GeV.

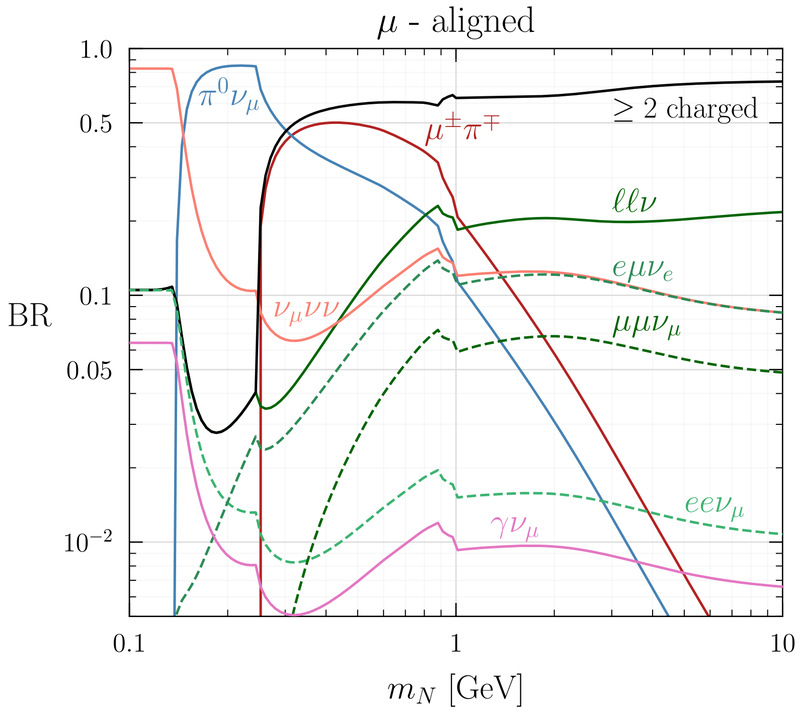
Heavy Neutral Lepton Decays

Shamelessly stolen and adapted from
K. J. Kelly et al. arXiv:2304.11189





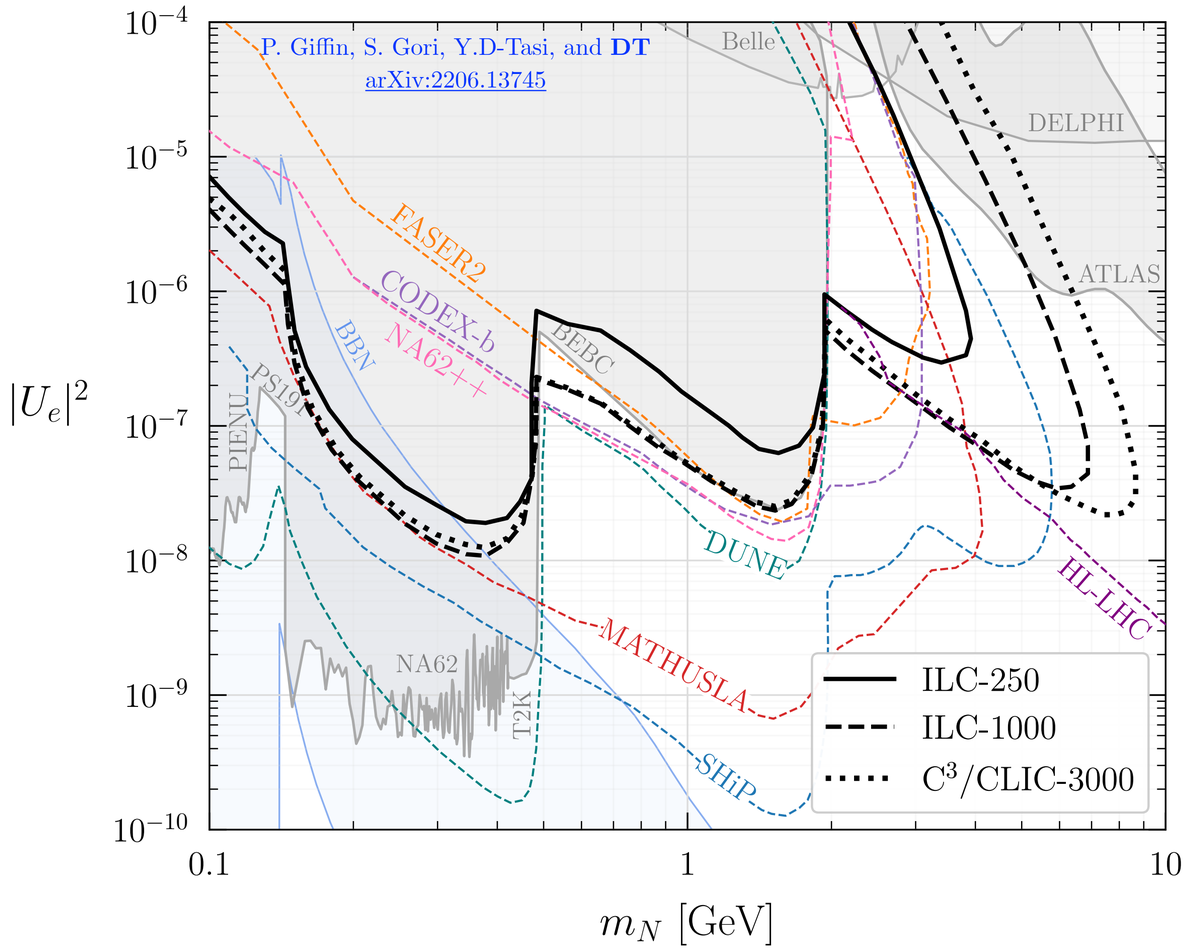




Look for two charged particles in the final state

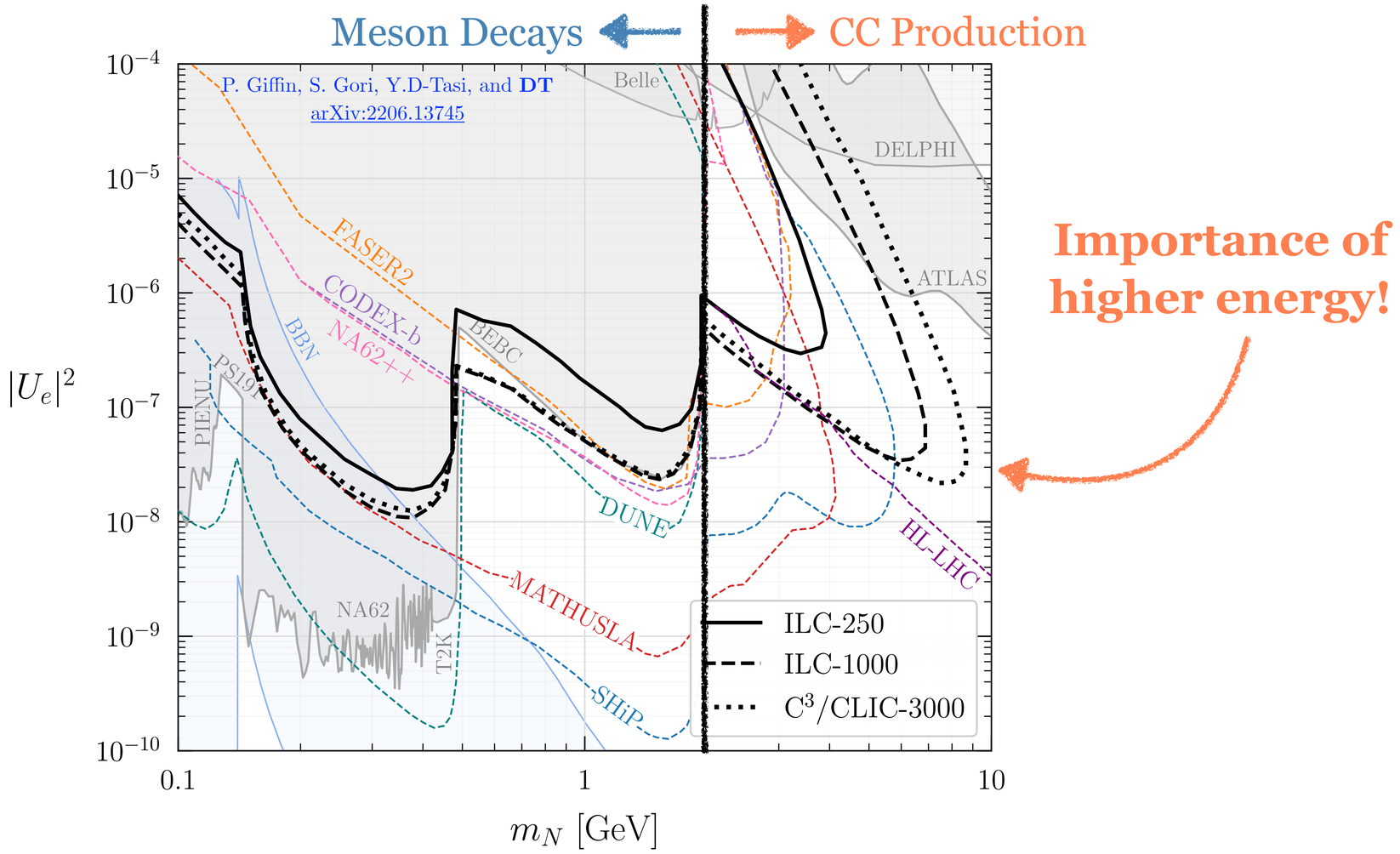
Sensitivity: Electron-Mixed HNLs

Sensitivity for one year of operation (4×10^{21} EOT) and *10 signal events*.



Sensitivity: Electron-Mixed HNLs

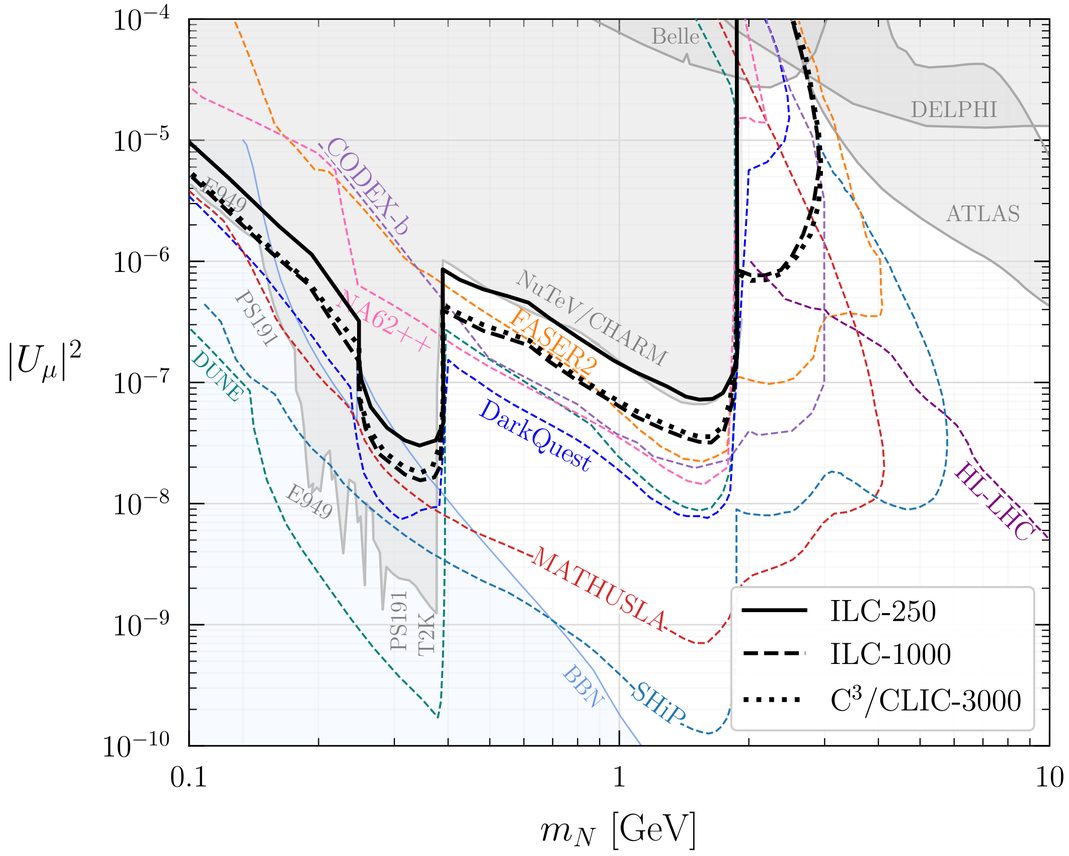
Sensitivity for one year of operation (4×10^{21} EOT) and *10 signal events*.



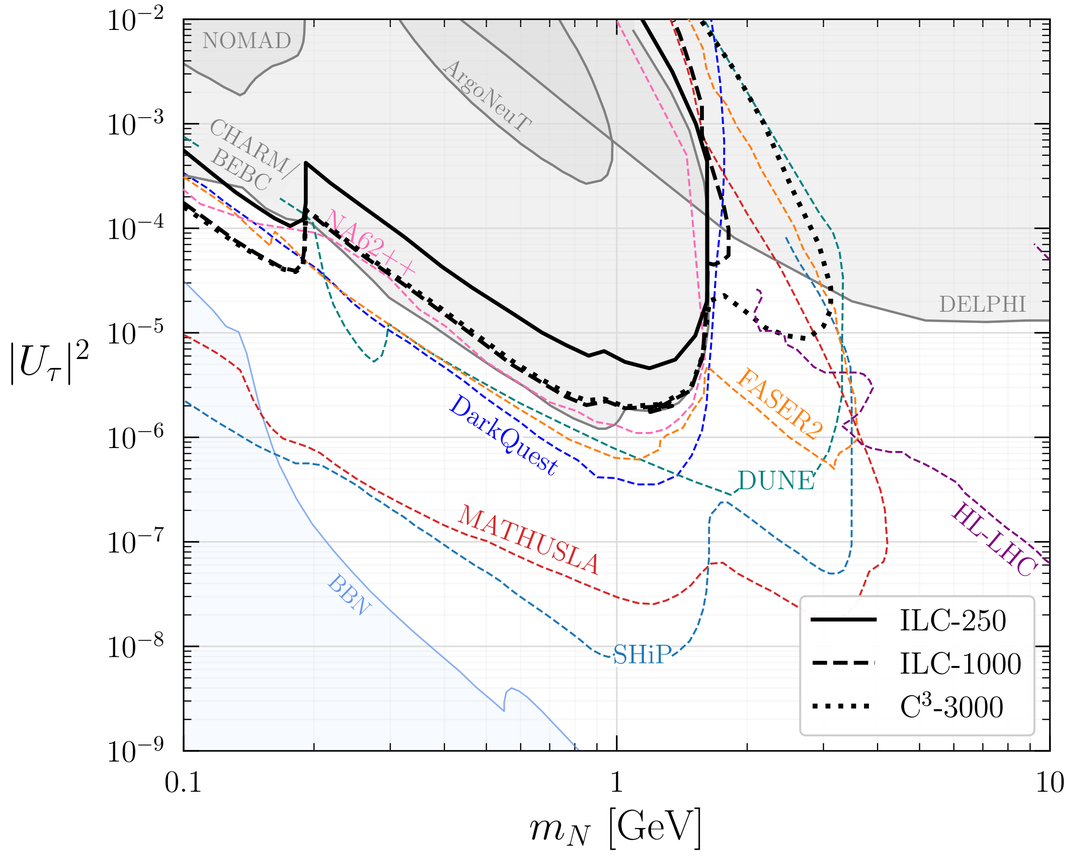
Importance of higher energy!

Sensitivity: Muon- and Tau-Mixed HNLs

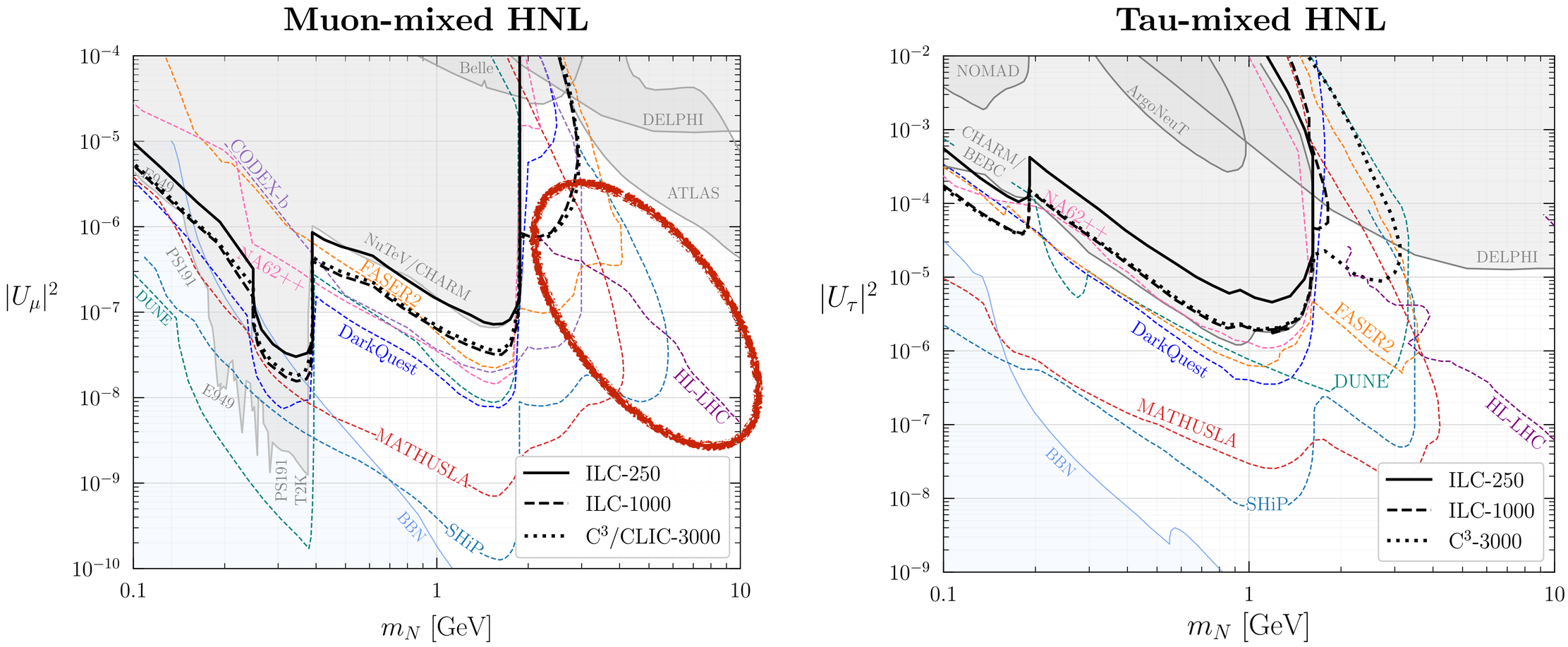
Muon-mixed HNL



Tau-mixed HNL



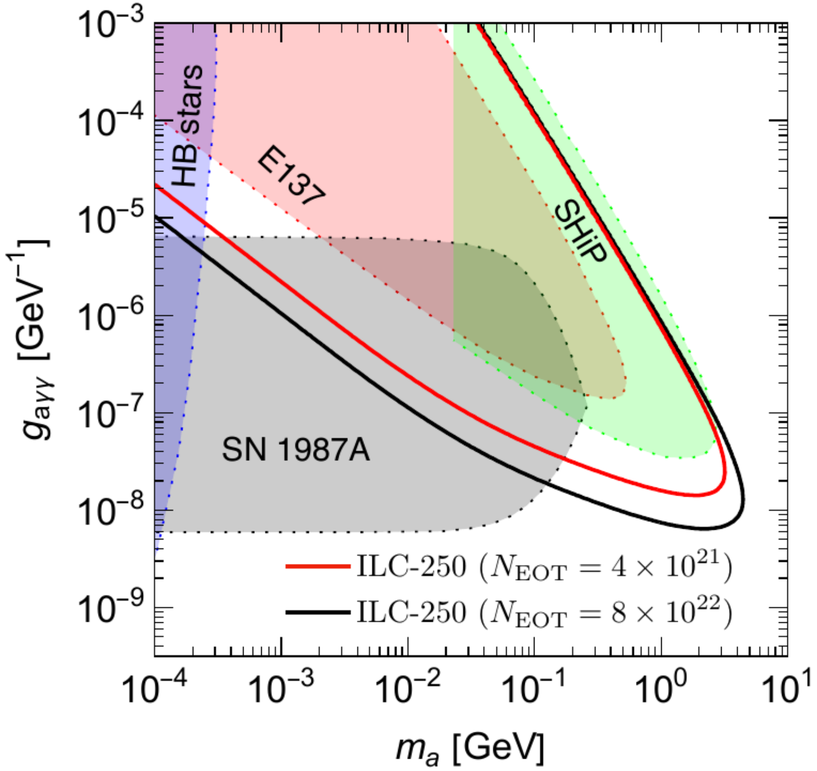
Sensitivity: Muon- and Tau-Mixed HNLs



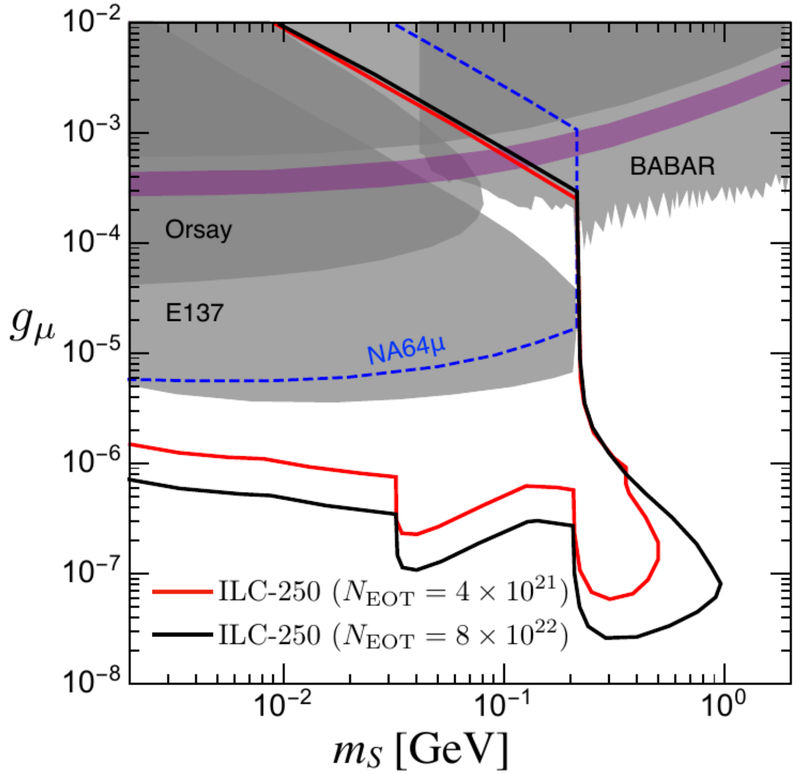
Far, far future: CC production @ TeV muon beam dump exp??

Additional Models

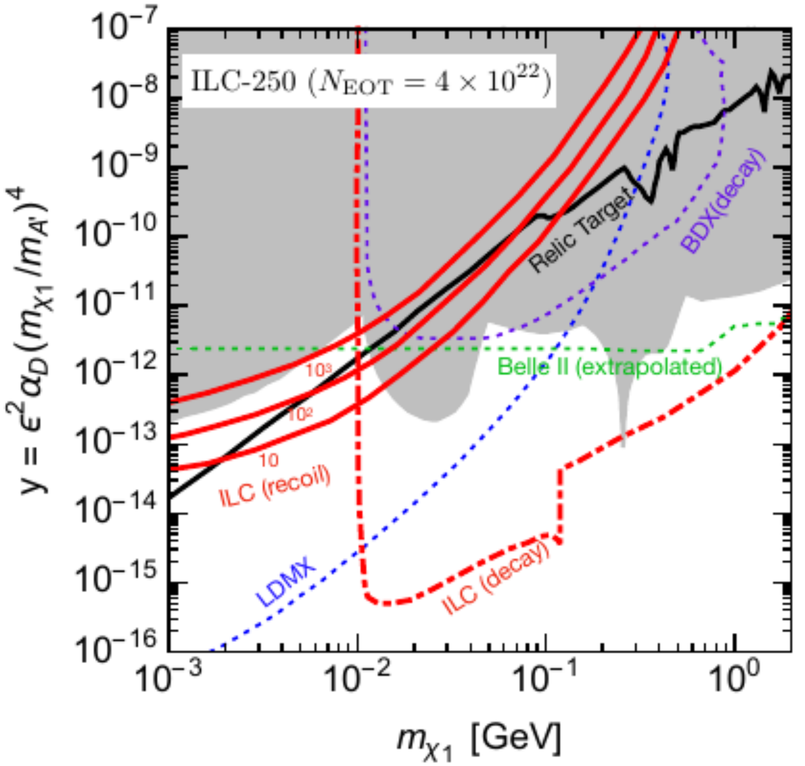
Photon-coupled ALP



Muon-philic Scalar



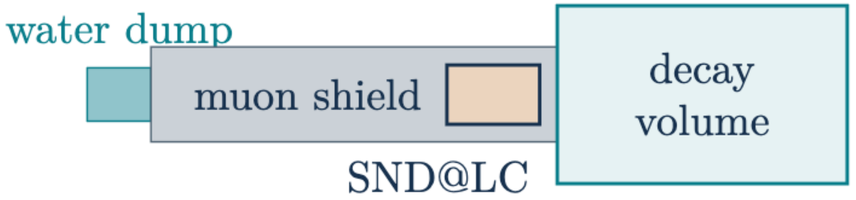
Dark Matter

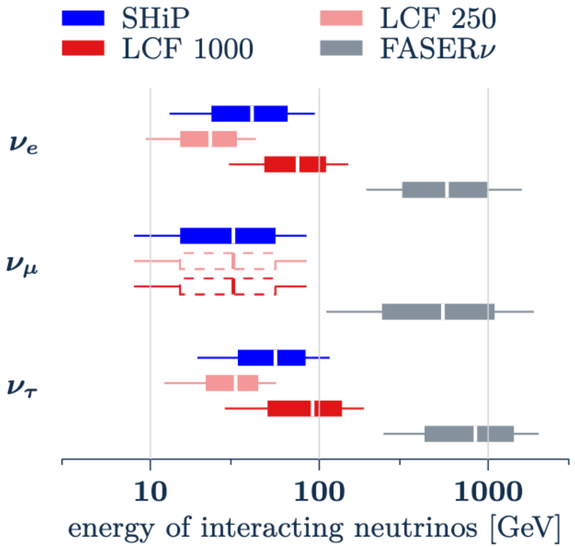


Complementary coverage for a variety of BSM scenarios!

Other Physics Opportunities

Neutrino Physics



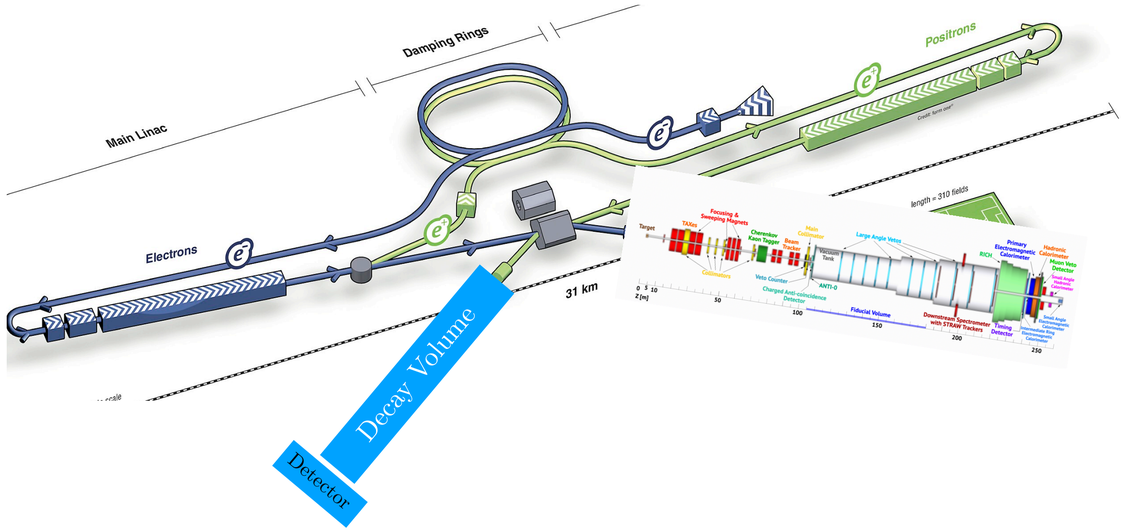


See M. Ovchynnikov talk for more details

Kaon Physics







NA62 both a kaon and dark sector experiment.
HIKE@LCF Beam Dump would also give us both!

Summary

1. A beam dump experiment at a future linear collider is **high intensity and high energy.** Broad physics potential: long-lived particles, dark matter, neutrinos, and more!

2. **Complementarity with proton beam experiments** (e.g. SHiP, DarkQuest, LHC). Production mechanisms for BSM particles that are unique to lepton beams (e.g. charged-current production of HNLs)

3. We should start designing this now!
   - **Cheap:** the beam and the dump will already be there! We just need to invest a little in a decay volume an detector.
   - **Parasitic:** runs for the entire lifetime of the collider. No dedicated beam time.
   - **Timely:** infrastructure is being designed now.

Every linear collider comes with a free lepton beam dump experiment! Let's start planning for it now.

Backup

Meson Production Simulation

- Use Pythia to simulate an electron striking a proton at rest
- Number of mesons/EOT:

$$n_M \equiv \frac{N_M}{\mathrm{EOT}} = \frac{\sigma_{\mathrm{SoftQCD}}}{\sigma_{eN}} \frac{N_{M,\mathrm{MC}}}{N_{\mathrm{MC}}^{\mathrm{tot}}}$$

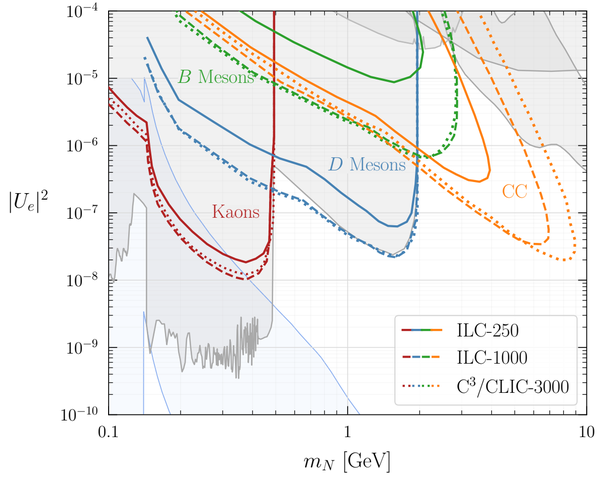
Pythia total hadronic cross section

Total *ep* cross section

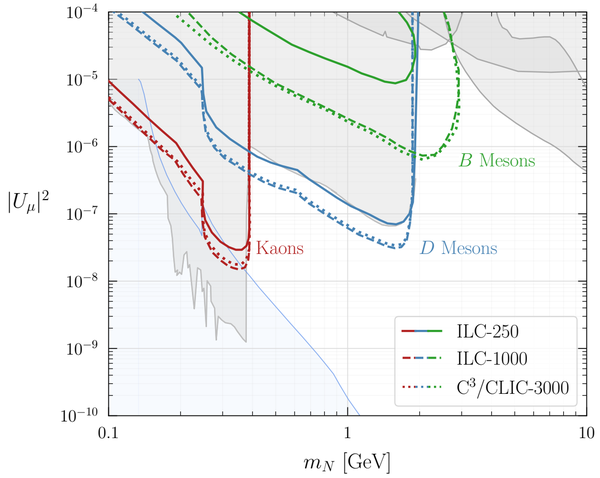
- Additional factor of cross section ratios takes into account that not all *ep* collisions are hadronic/SoftQCD interactions
  - For pp collisions $\sigma_{\mathrm{SoftQCD}} \approx \sigma_{pN}$

Additional HNL Sensitivity Plots

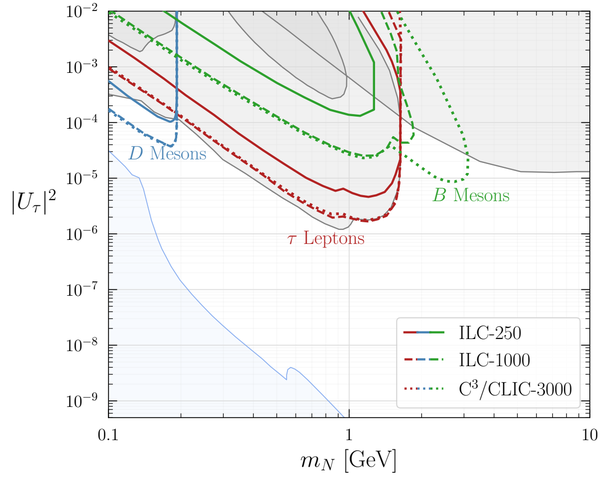
Electron-mixed HNL



Muon-mixed HNL



Tau-mixedHNL



Varying the shield length

