Dark Sectors at Future Lepton Beam Dump Experiments

Douglas Tuckler
TRIUMF & Simon Fraser University

Theoretical Physics Seminar
Fermilab
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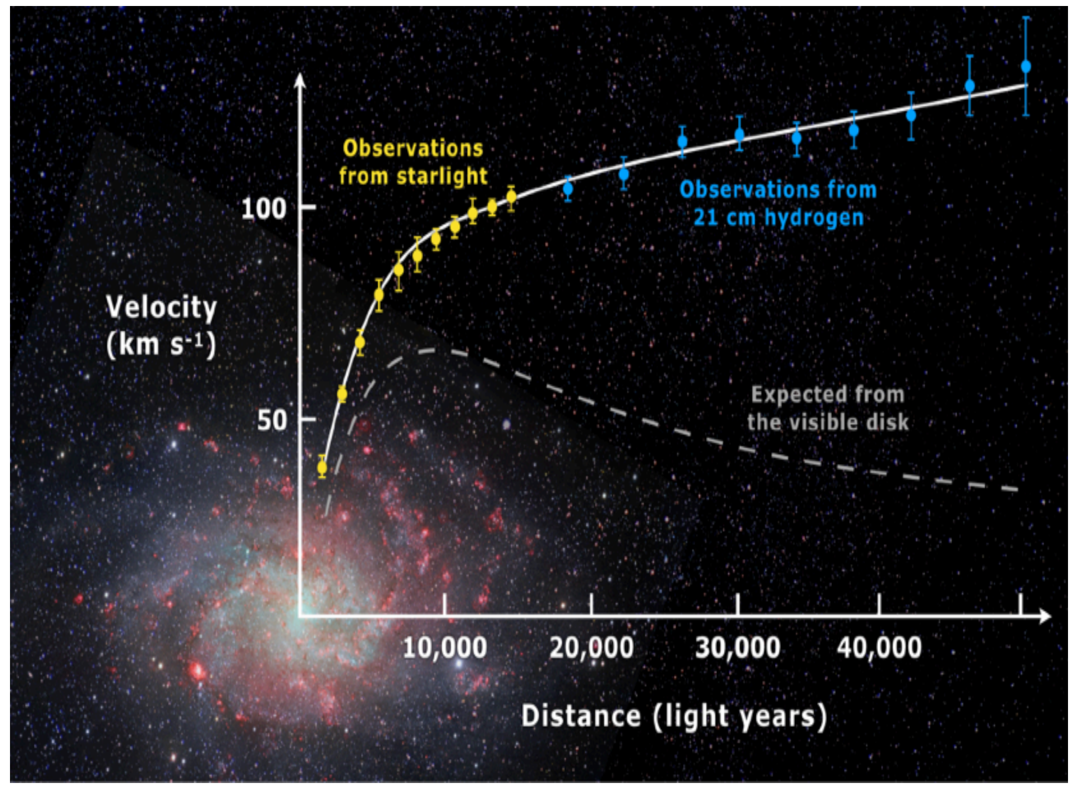
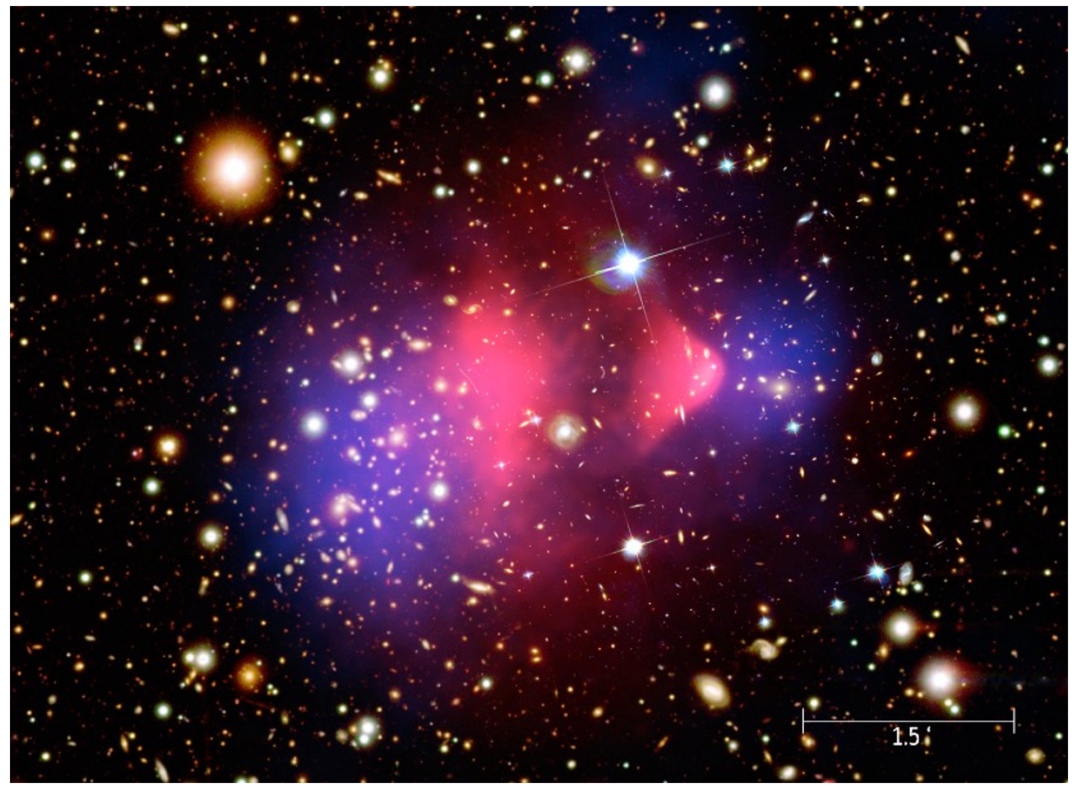
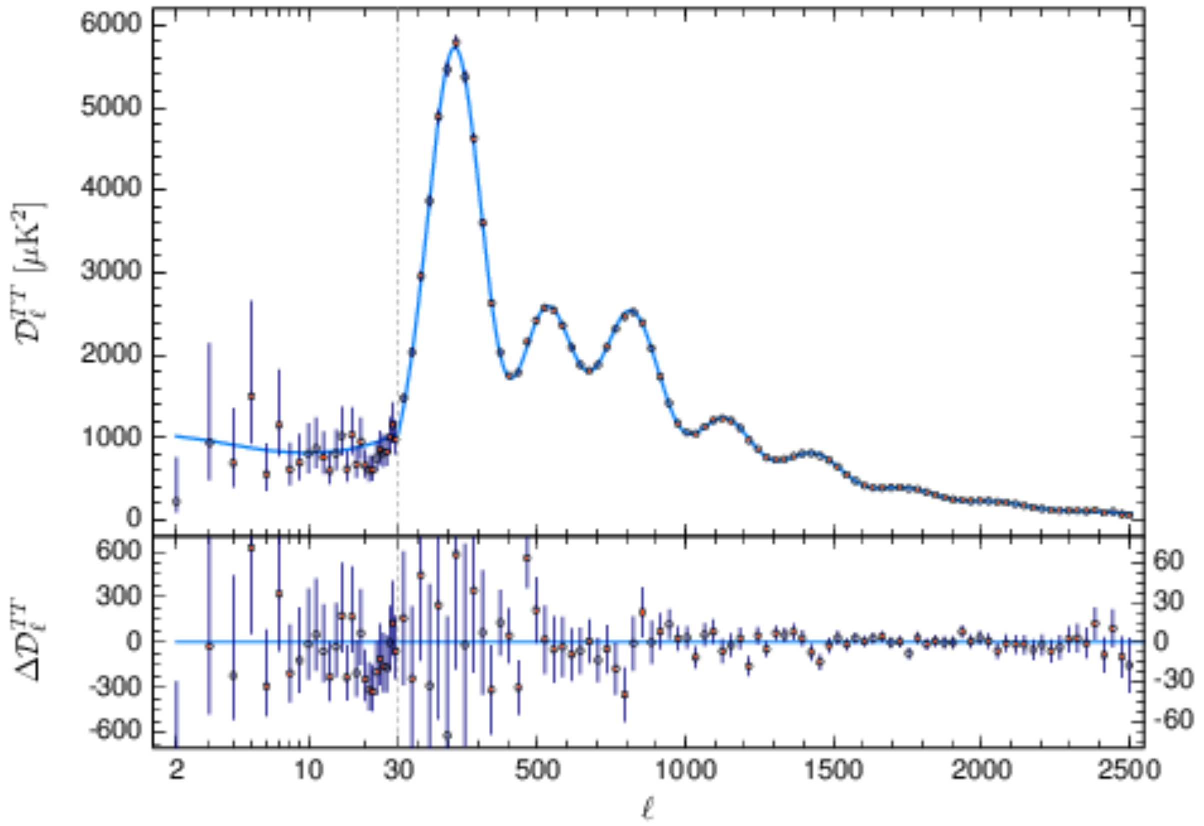
Evidence for Dark Matter



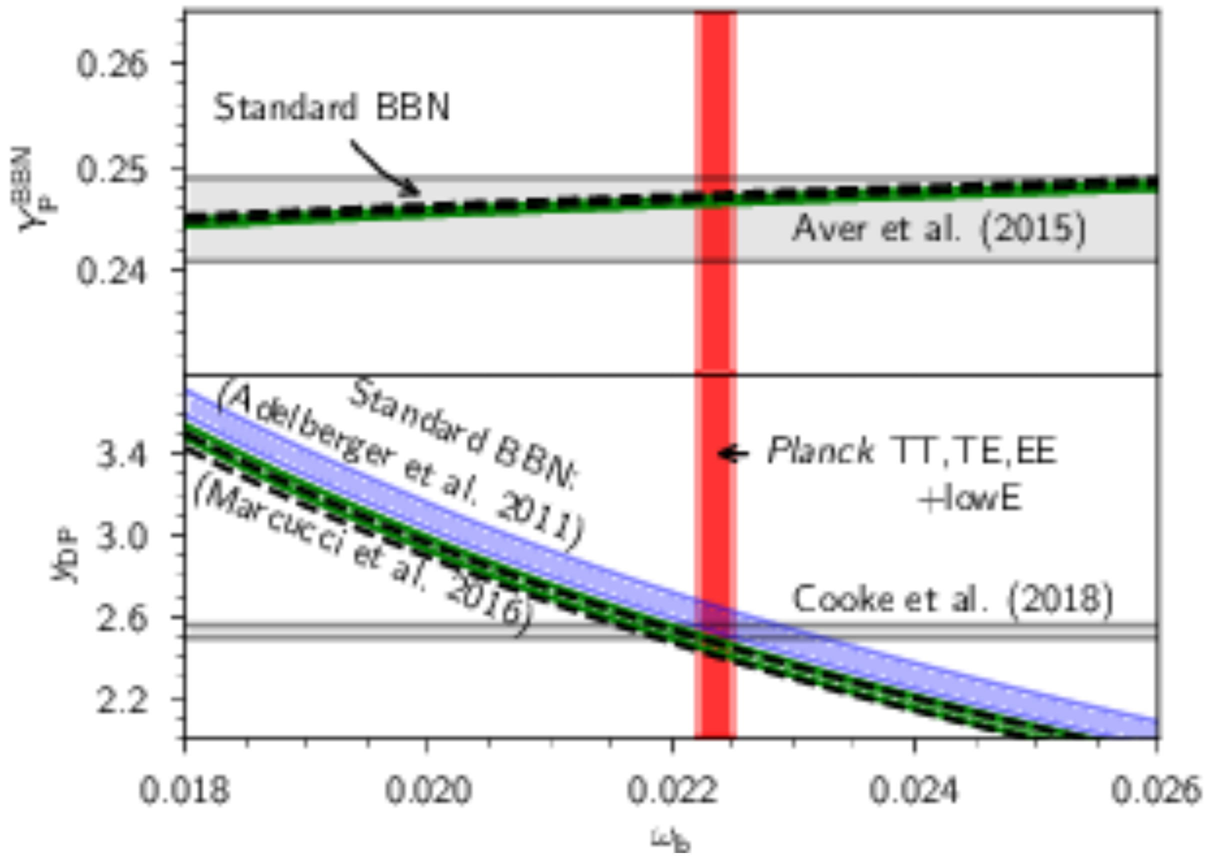
Galaxy rotation curves



Gravitational Lensing



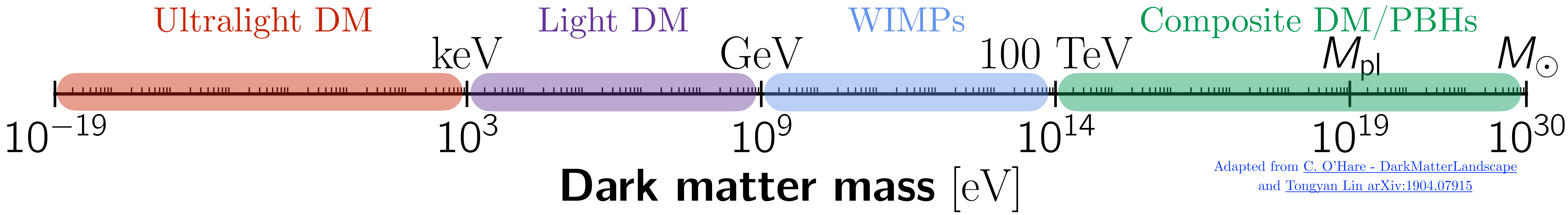
CMB



BBN

These observations tell us only about the *macroscopic* properties of DM. How can we probe the *microscopic* properties i.e. mass, non-gravitational interactions?

What even is DM?

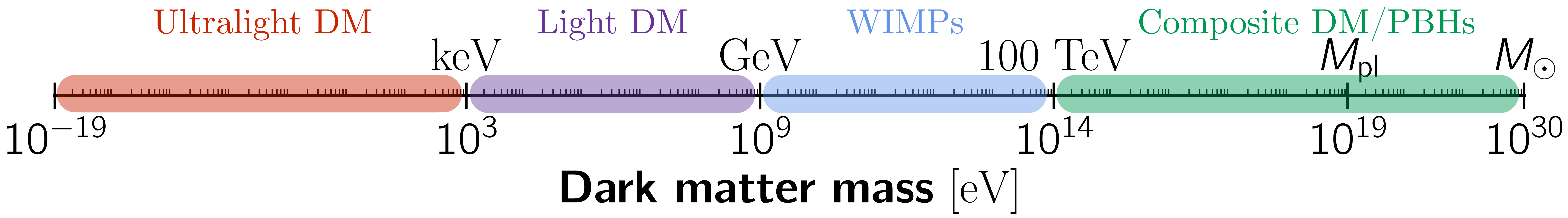


Adapted from C. O'Hare - DarkMatterLandscape
and Tongyan Lin arXiv:1904.07915

How do we narrow down this parameter space?

Thermal Dark Matter

- Guiding principle: DM was in *thermal equilibrium* with the SM at early times
- Advantages:
    1. Predictive - minimum annihilation cross section
    2. Narrows down the DM mass range substantially



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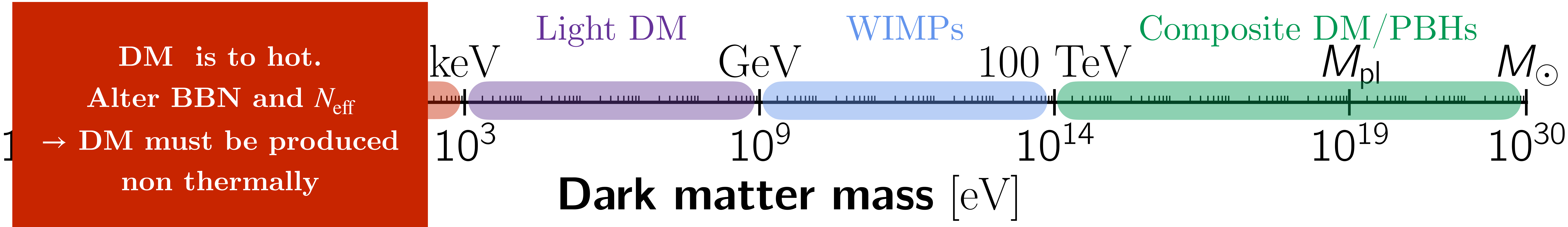

DM is to hot.
Alter BBN and N_{eff}
→ DM must be produced non thermally

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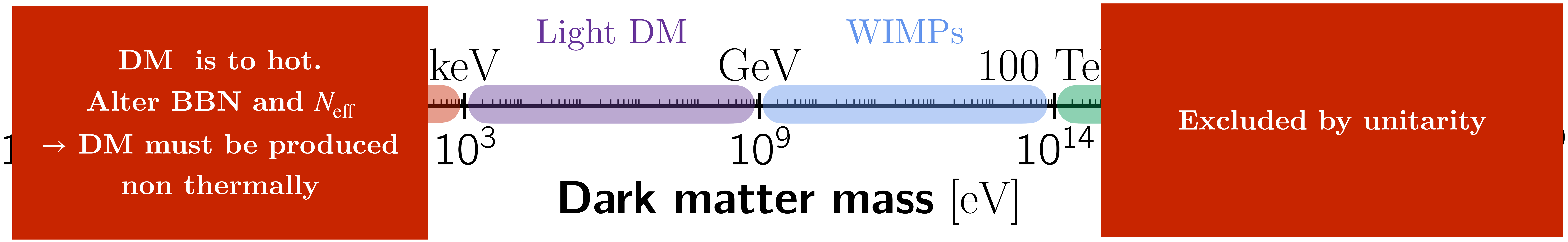

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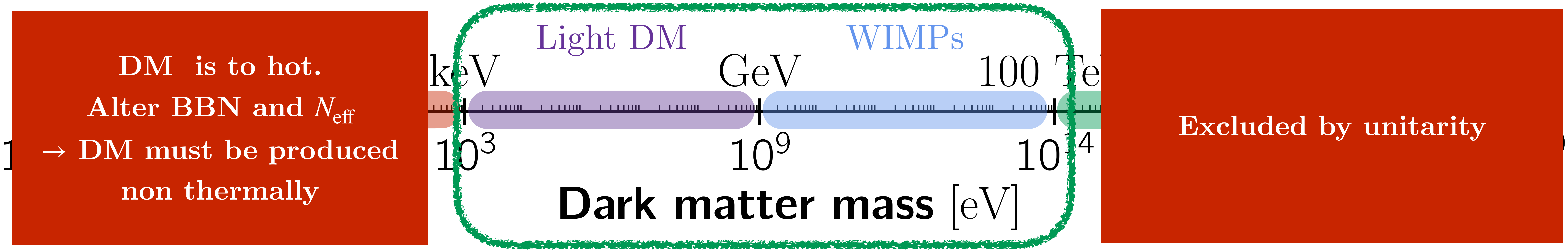
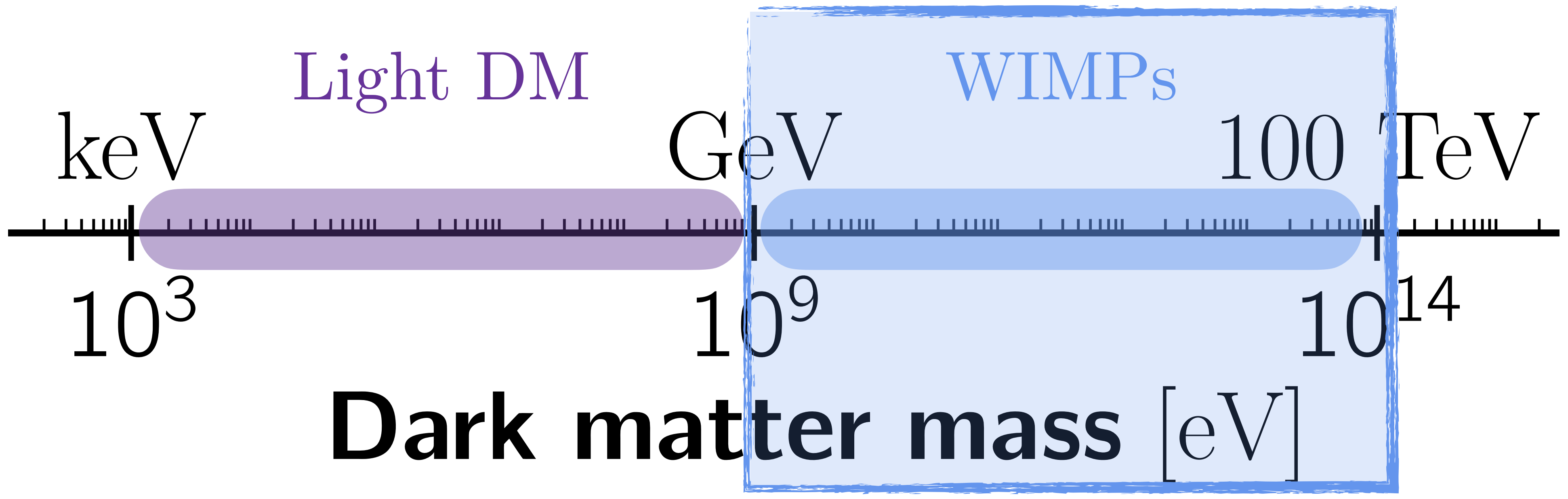


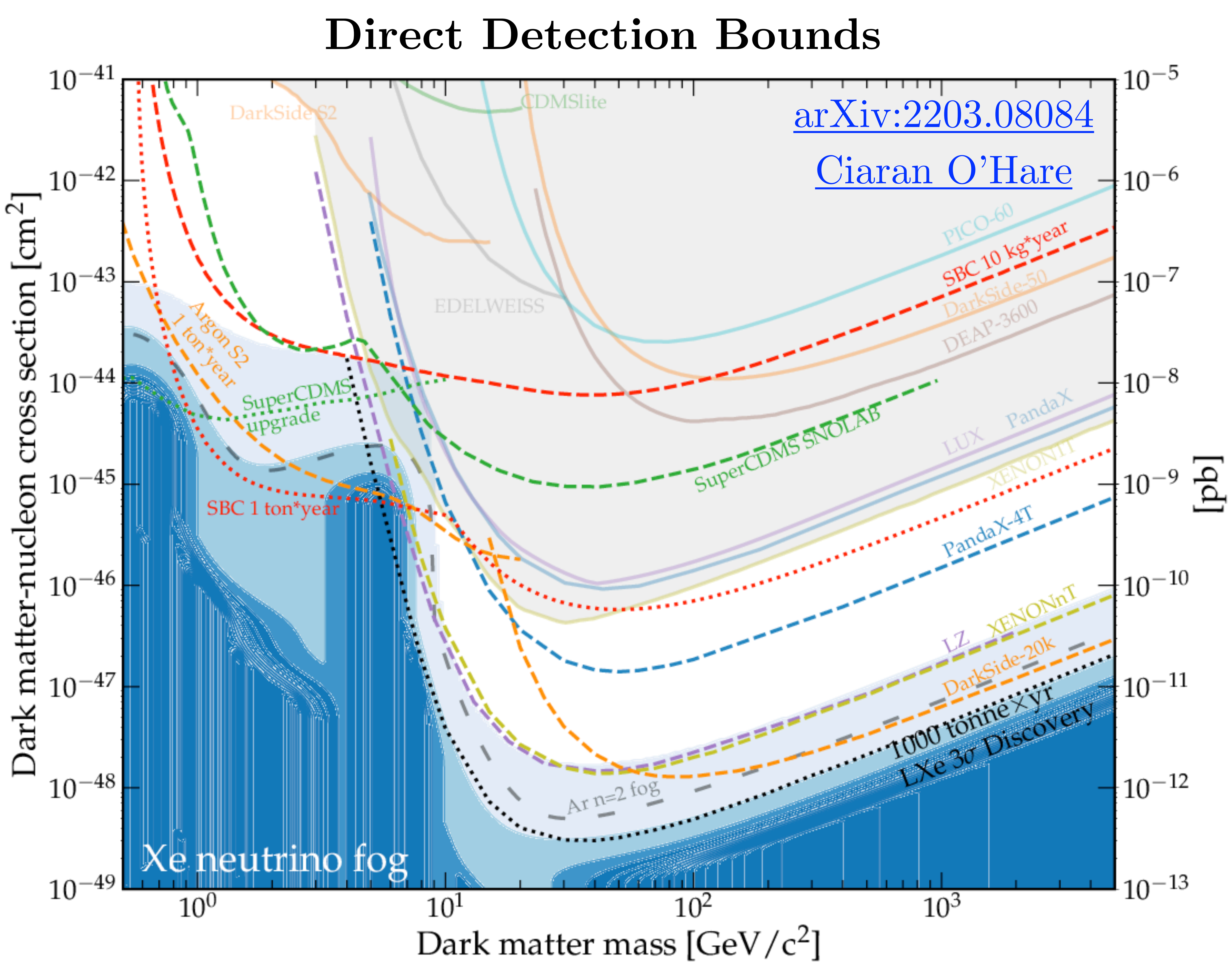
Thermal DM Target:

MeV - 100 TeV

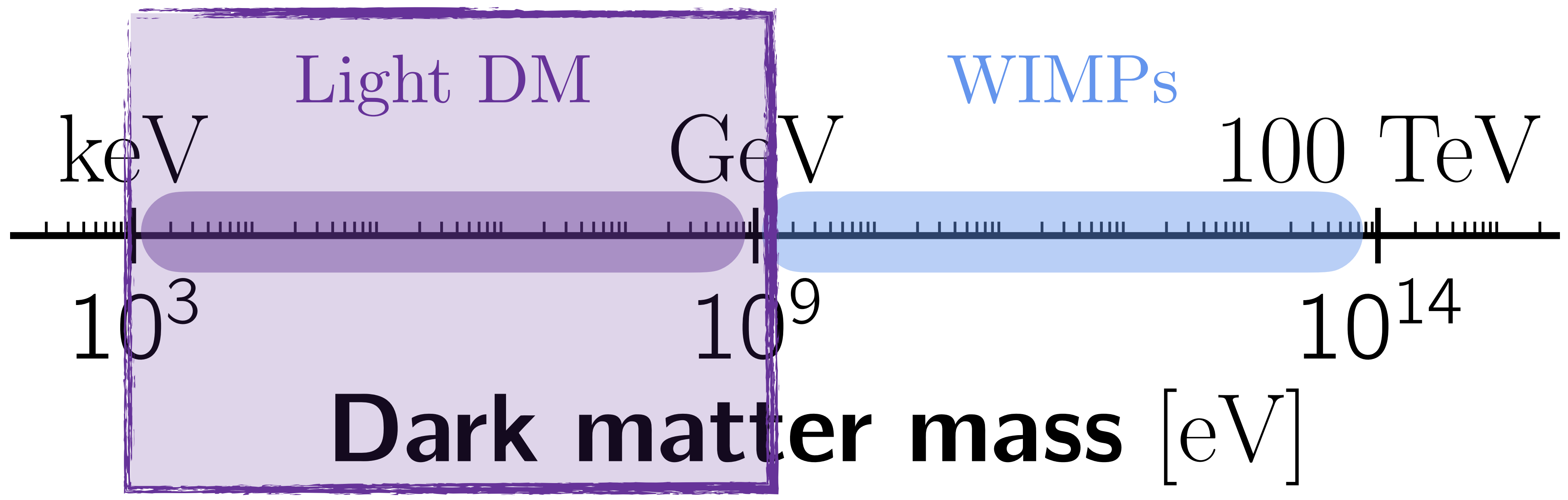
Weakly Interacting Massive Particles

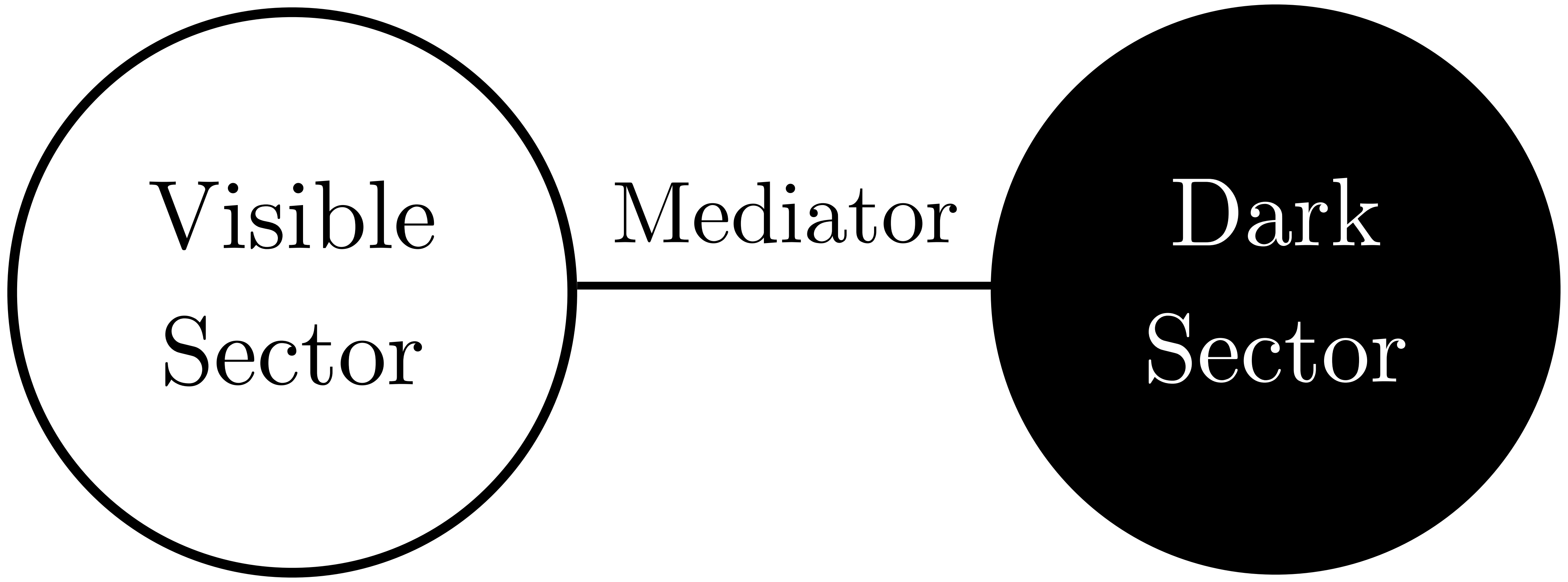


- WIMP miracle - correct relic abundance with weak coupling strengths and $m_\chi \sim 100$ GeV
- Direct detection bounds are becoming very constraining. Push to smaller couplings. *How to get beyond the neutrino floor?*
- *Alternative: go to lower masses where there are weaker bounds*



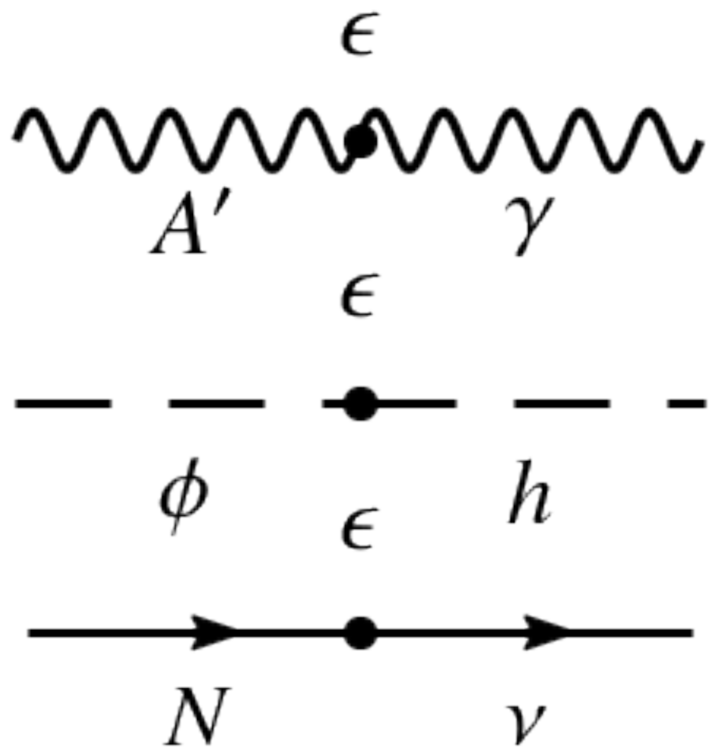
Light Dark Matter and Dark Sectors





- Lee-Weinberg bound → light DM requires **new light mediators**
- Light mediators must be **SM singlets** → **portal models**
- **Dark sectors** = DM + mediator + other SM singlet particles

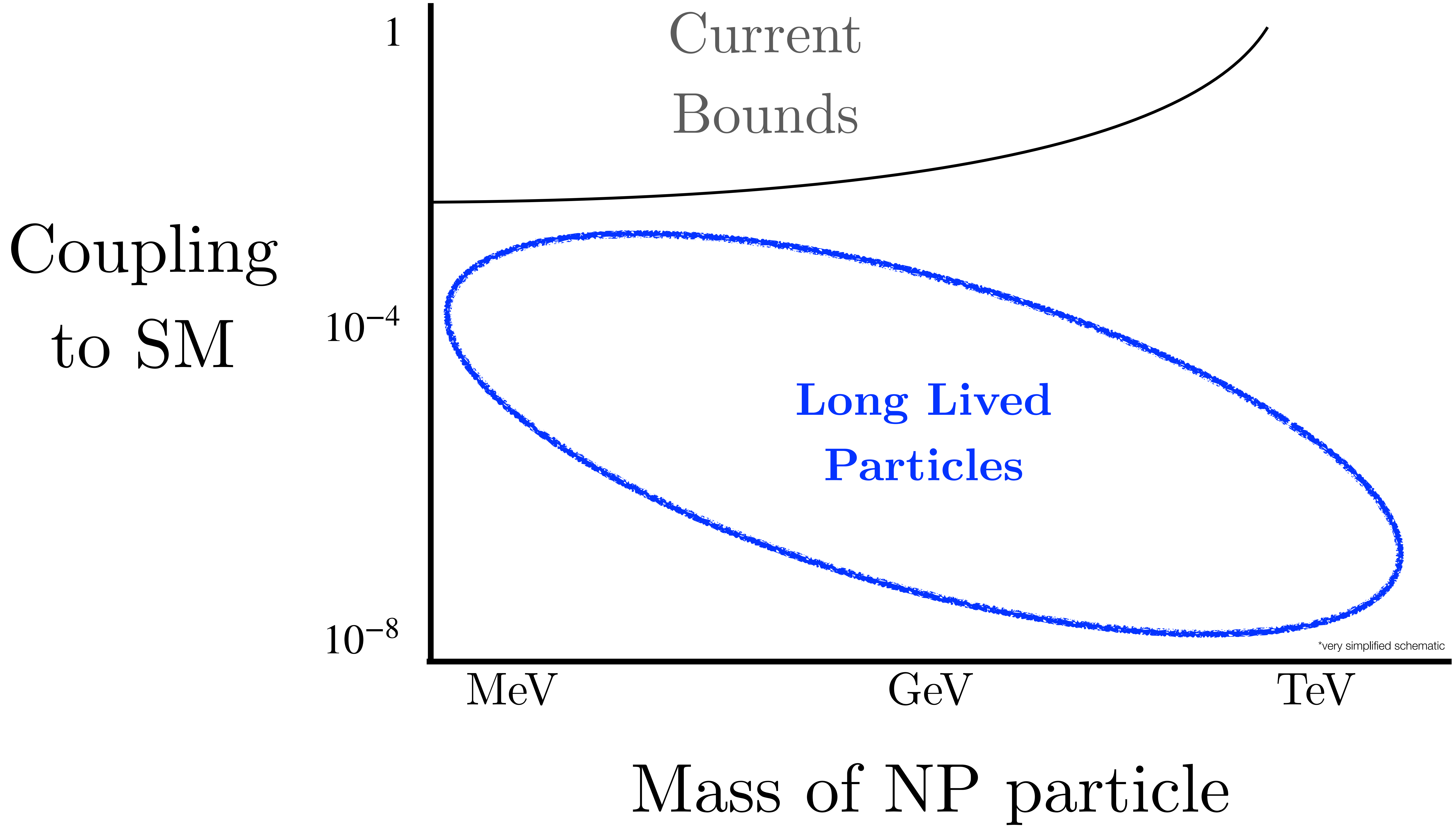
1. Dark Photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$
2. Dark Higgs: $\epsilon |h|^2 |s|^2$
3. Heavy Neutrino: $\epsilon \ell h N$



$\epsilon \sim e^2/16\pi^2 \sim 10^{-4}$ → feebly interacting particle (FIPs)

Searching for New Physics

- Feature of dark sectors: feeble coupling → *long-lived particles*



Searching for New Physics

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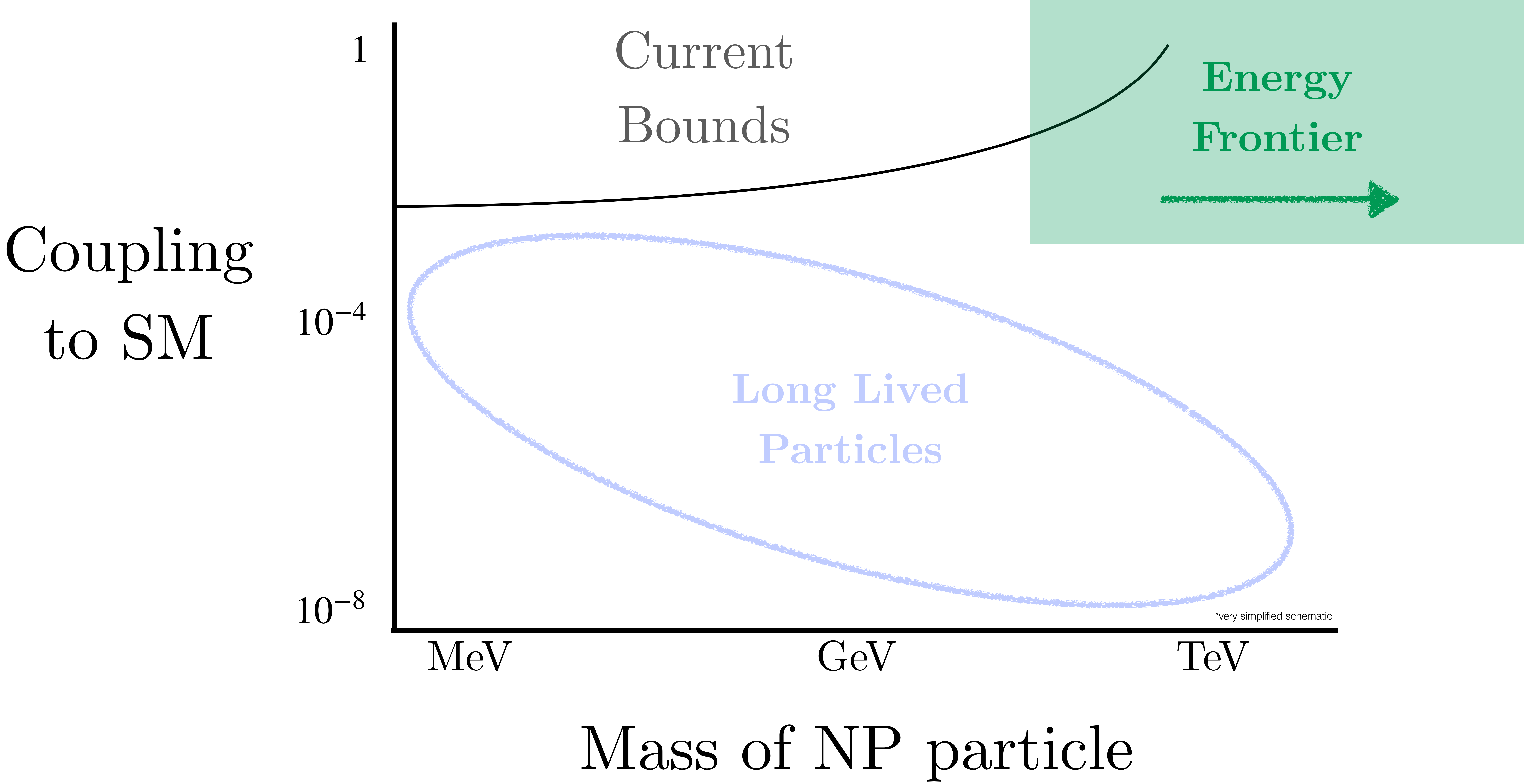

International
UON Collider
Collaboration

Searching for New Physics

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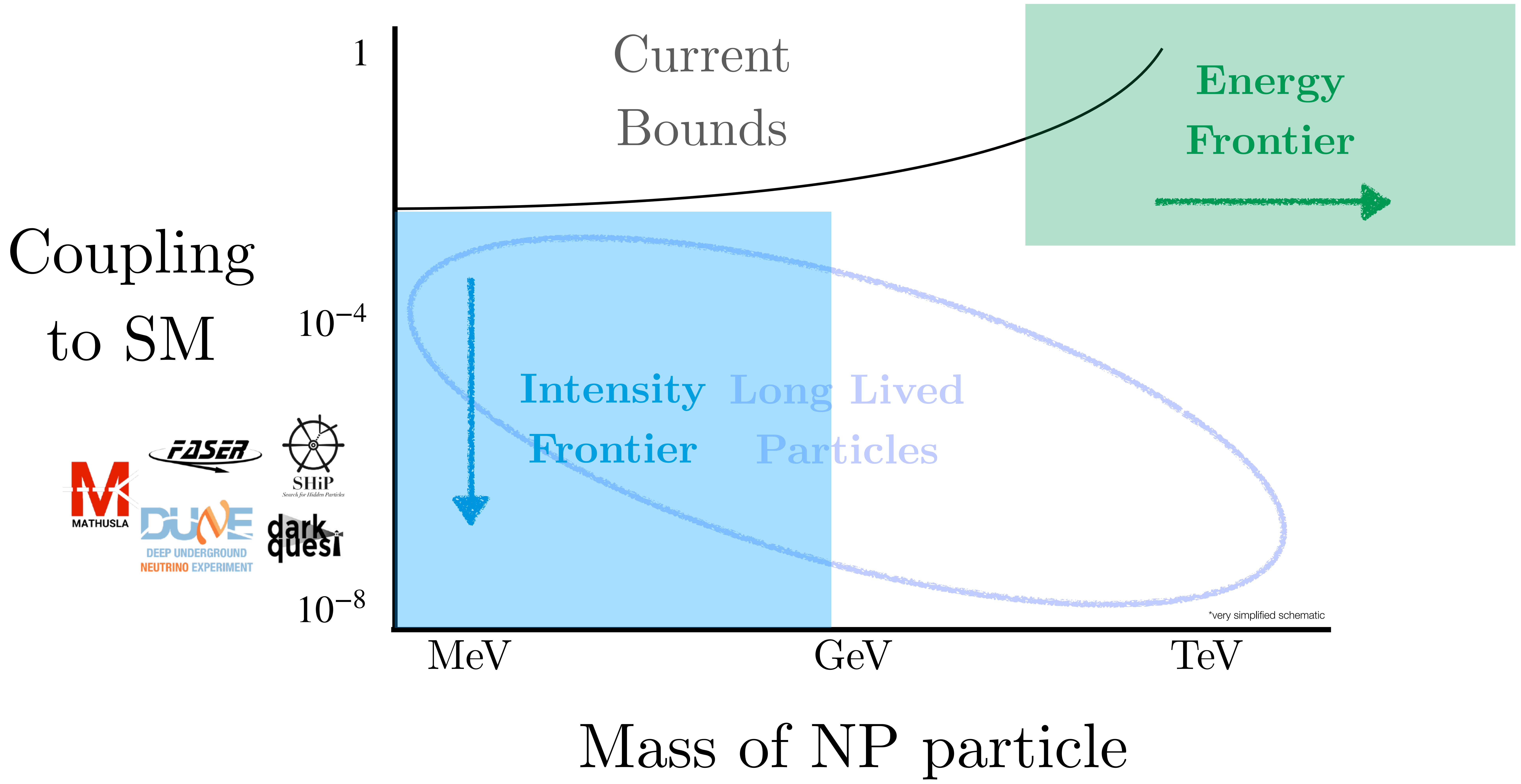

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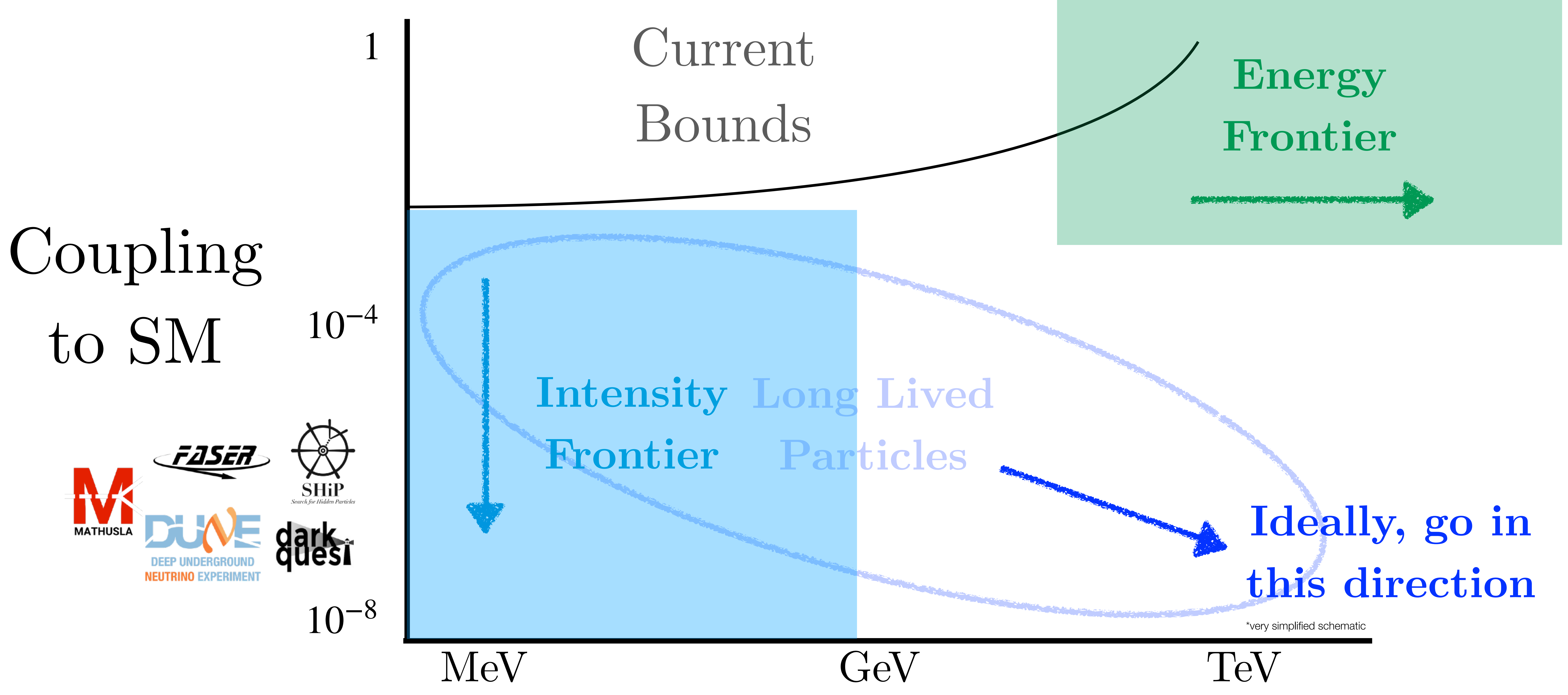

Mass of NP particle

Intensity Frontier: Proton Beam Dump Experiment

- Proton beam dumps/fixed target experiments
  - Large number protons-on-target → high flux of BSM particles
  - Long decay volumes to probe feebly coupled, long-lived particles

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}	$\sim 10^{19}$	$\sim 10^{15}$	-

Low CM energy → limited mass reach

- TeV proton beams? Only option is the LHC → $\sim 10^{17}$ POT/  year. Not good for FIPs/LLPs (LEvEL proposal arXiv:2103.00009 K. J. Kelly, P. Machado et al.)

* DarkQuest and SHiP recently approved and received funding!

Electron Beams?

Table 1. Summary of experimental initiatives, facilities, and key features.

Snowmass RF6 report arXiv:2206.04220

Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline	Refs.
US-based						
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running	section 3.15, [16]
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running	section 4.5, [17]
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running	[18]
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade	section 3.5, [19]
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024	section 3.17, [20]
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed	section 3.1, [21]
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed	section 3.16, [22]
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)	section 3.23, [23]
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)	[24]
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed	section 3.25, [25]
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed	[26]
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed	section 3.13, [27]
International						
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running	section 3.2, [28]
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)	section 3.4, [29]
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)	section 3.3, [30]
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned	section 3.18, [31]
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned	[32]
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.9, [33]
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running	section 3.19, [34]
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)	section 3.6
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running	section 3.20, [35]
NA64-mu	SPS-M2 @ CERN	muon FT	100-160 GeV	Missing X	commissioning	section 3.21
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)	section 3.24, [35]
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)	section 3.22, [36]
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)	section 3.8 [37]
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)	section 3.14, [38]
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.10, [33]
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.12, [39]
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.27, [40]
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.27, [40]
DarkLight	ARIEL @ TRIUMF	electron FT	30-100 MeV		Construction, running? (2023/2024)	

= electrons

= muons

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= electrons

= muons

Besides NA64, ~GeV beams.

Can we go to higher electron beam energies?

Future e^+e^- Colliders

- Proposals for high-energy electron-positron colliders for precision Higgs/EW studies

250/500/1000 GeV	380/3000 GeV	250/550/3000 GeV
International Linear Collider	Compact Linear Collider	Cool Copper Collider

Idea: build a dark sector facility at future e^+e^- colliders to study FIPs/LLPs with beam dump experiments and/or far detectors

Advantages of Future Electron Colliders

- Large beam energies compared to past/current experiments
  - $E_e \sim 100$ GeV - few TeV
  - *Staged energy approach*. No need to build a new facility for higher energy beams!

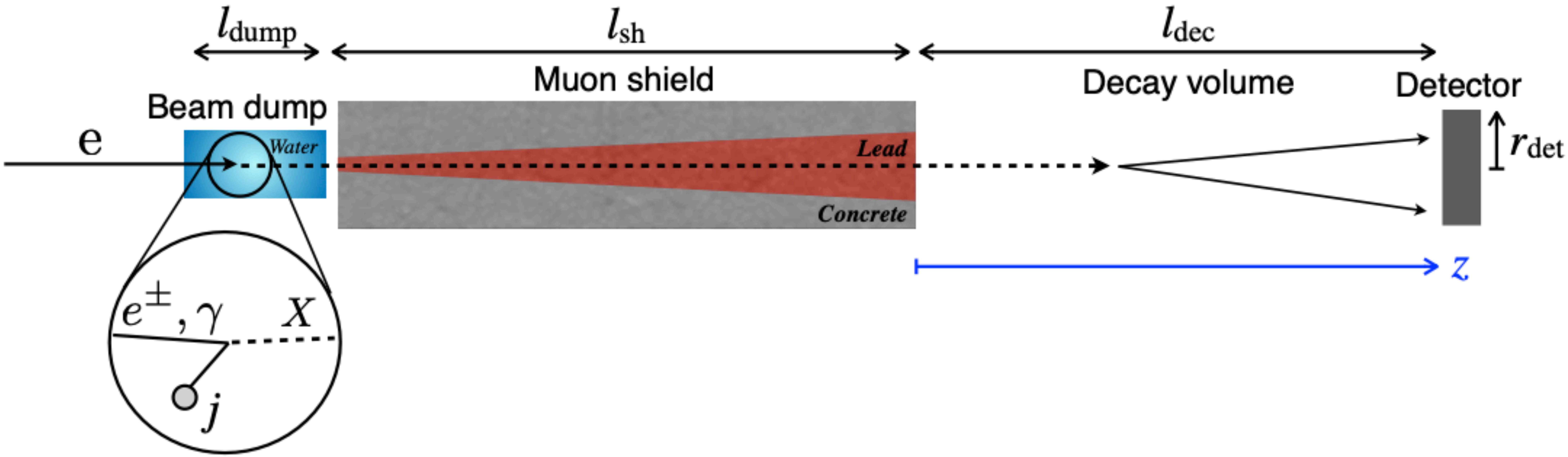
- High intensity - $\sim 10^{21}$ electrons-on-target/year

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

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}

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

Electron Beam Dump Set Up

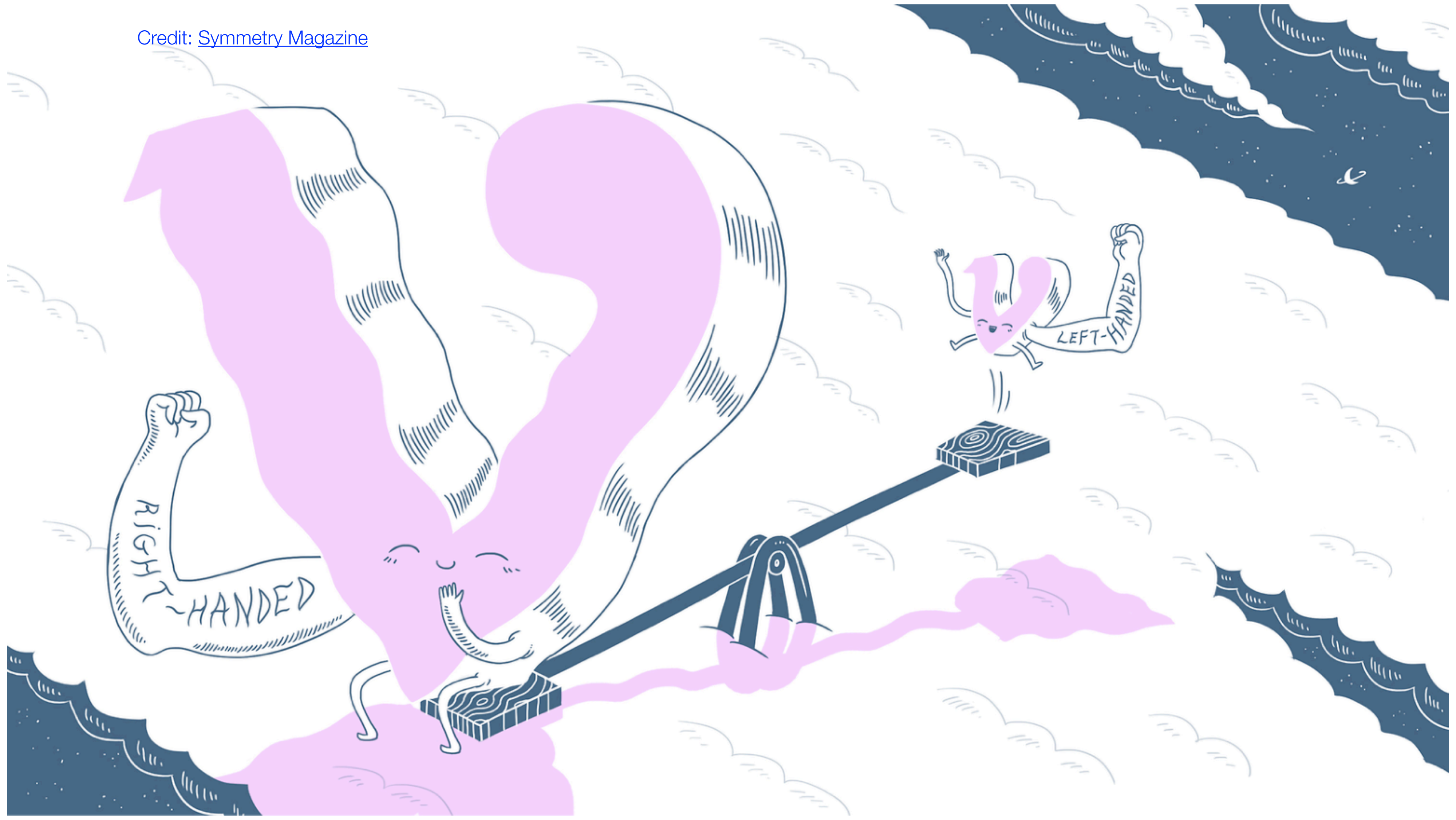


E_e [GeV]	ℓ_{dump}	ℓ_{sh}	ℓ_{dec}	r_{det}
125 500 1500	10m	70m	50m	2m

Case Study: Heavy Neutral Leptons

- Extend the SM by a singlet fermion N_R (right-handed neutrino, heavy neutral lepton, sterile neutrino). SM neutrinos get mass via seesaw mechanism

$$\mathcal{L} \supset Y \bar{L} \tilde{H} N_R + \frac{1}{2} M_N \bar{N}_R N_R \overset{\text{EWSB}}{\to} m_D \bar{\nu}_L N_R + M_N \bar{N}_R N_R$$



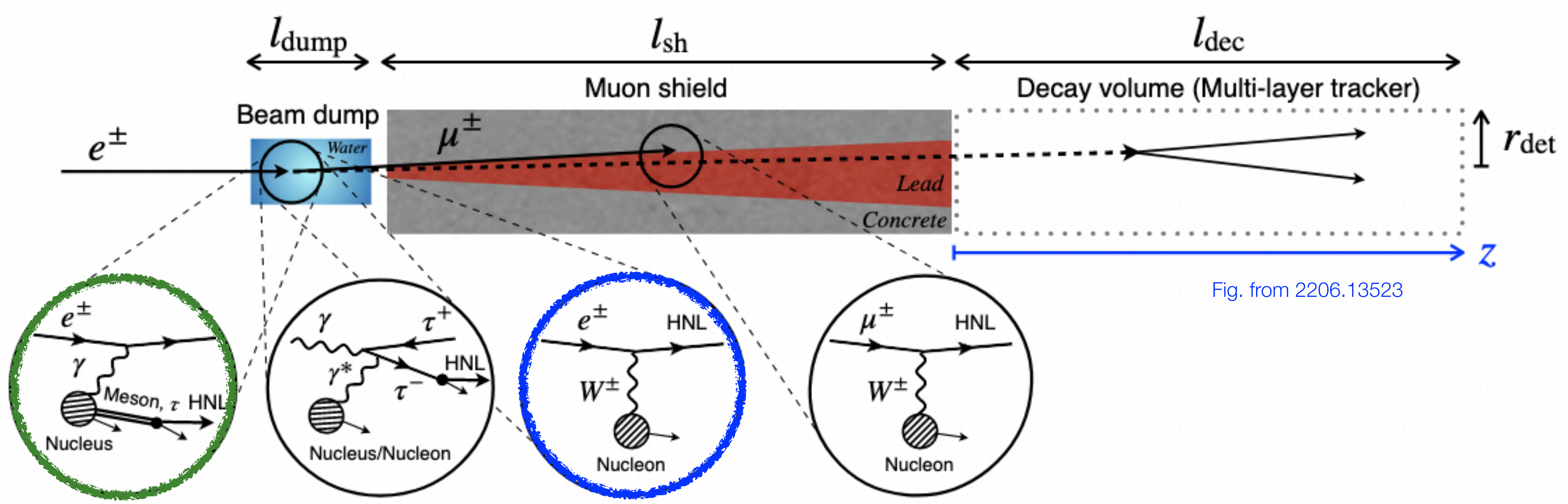
Credit: Symmetry Magazine

- Weak interactions induced my mixing with active neutrinos

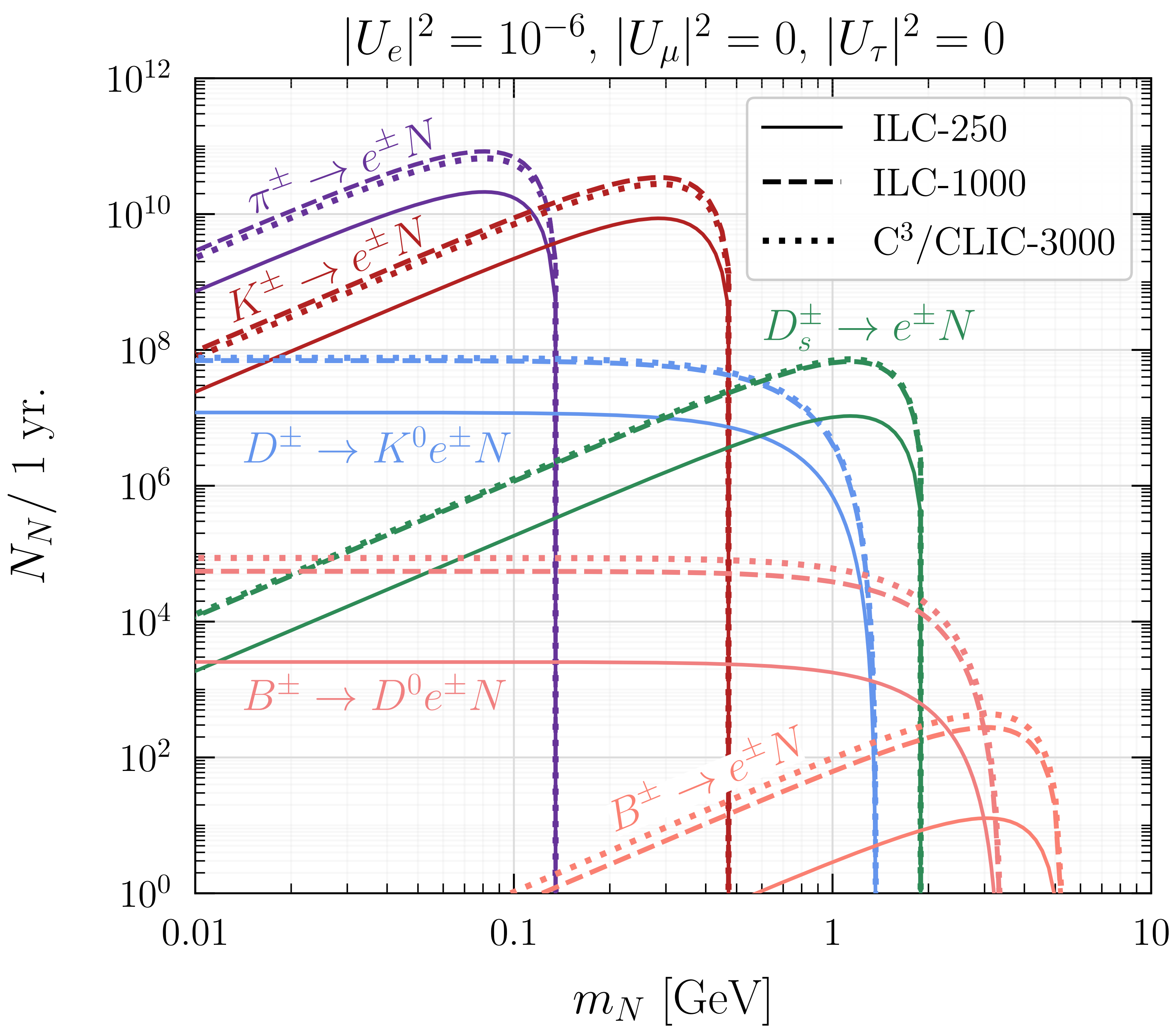
$$\mathcal{L} \supset \frac{g_2}{\sqrt{2}} U_\alpha W_\mu^- \ell_\alpha^\dagger \bar{\sigma}^\mu N + \frac{g_2}{2\cos\theta_W} U_\alpha Z_\mu \nu_\alpha^\dagger \bar{\sigma}^\mu N$$

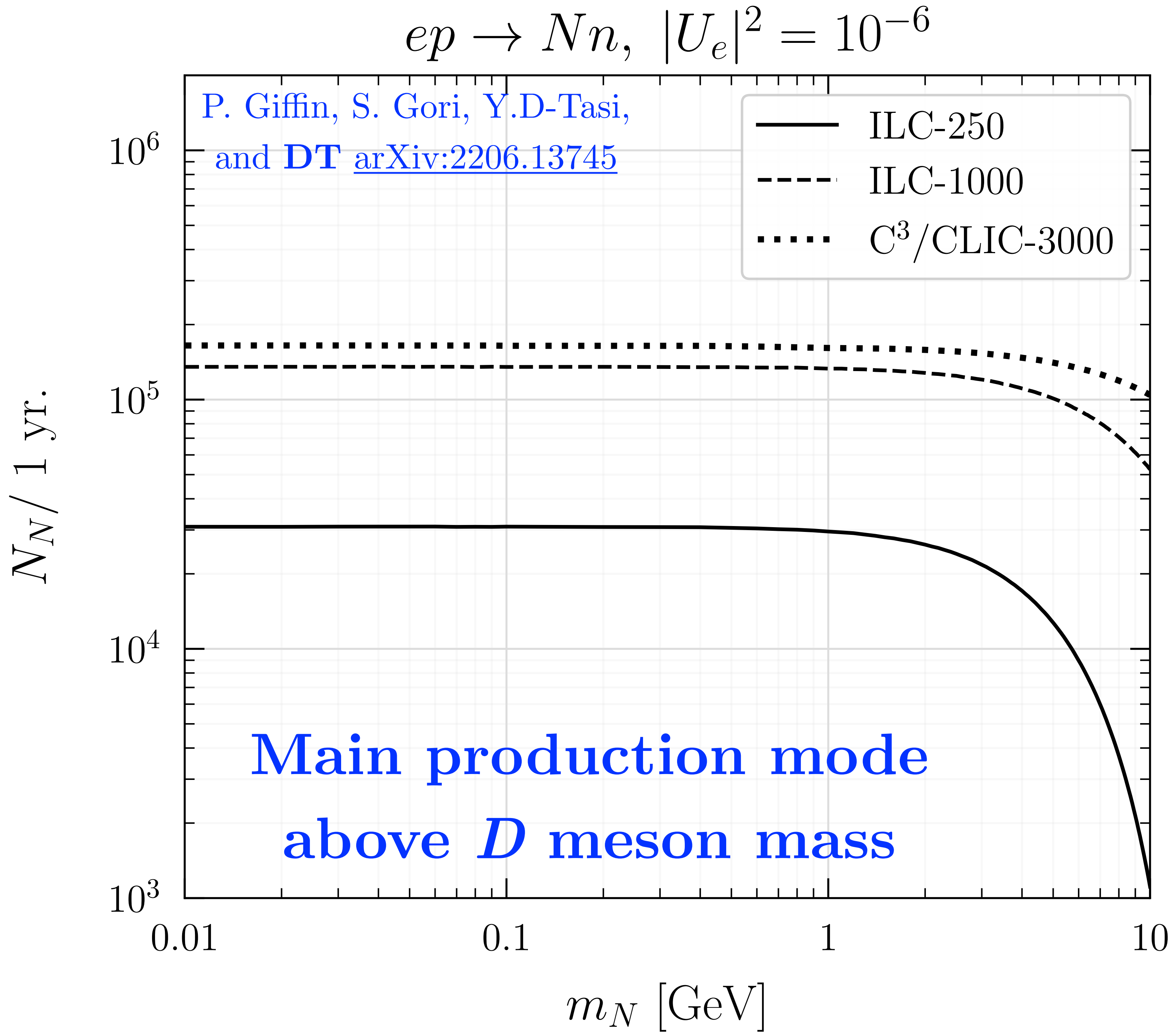
- N_R is produced in any process where a SM neutrino is produced

HNL Production in Electron Beam Dump



Meson Decays

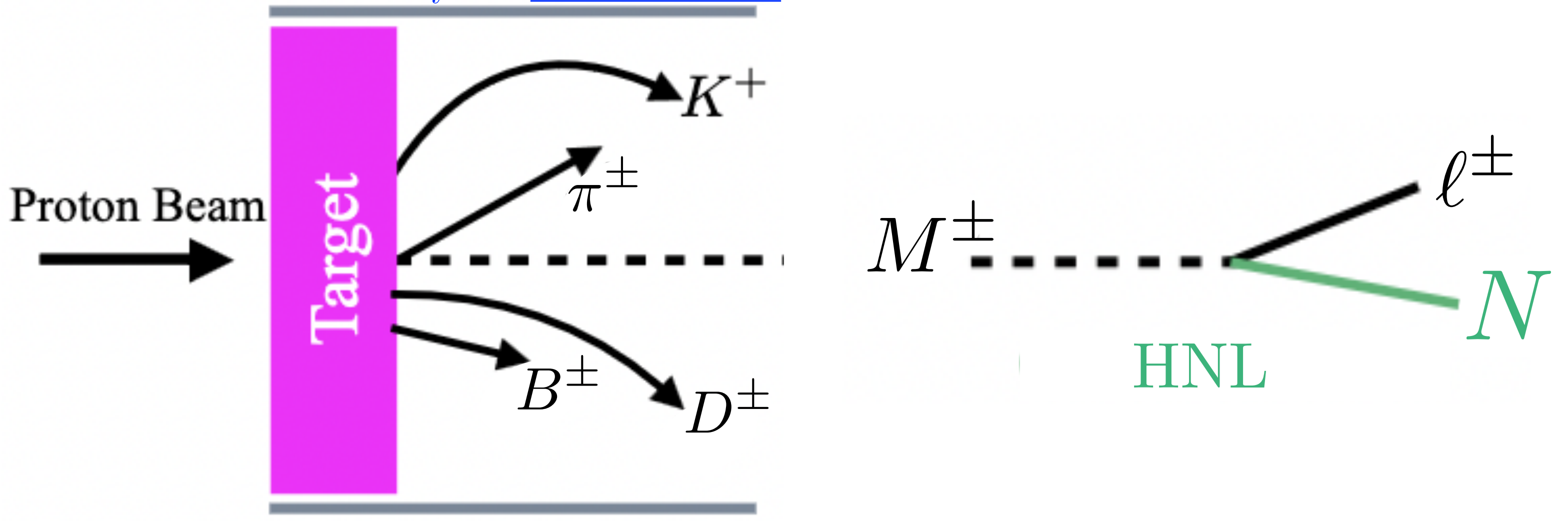


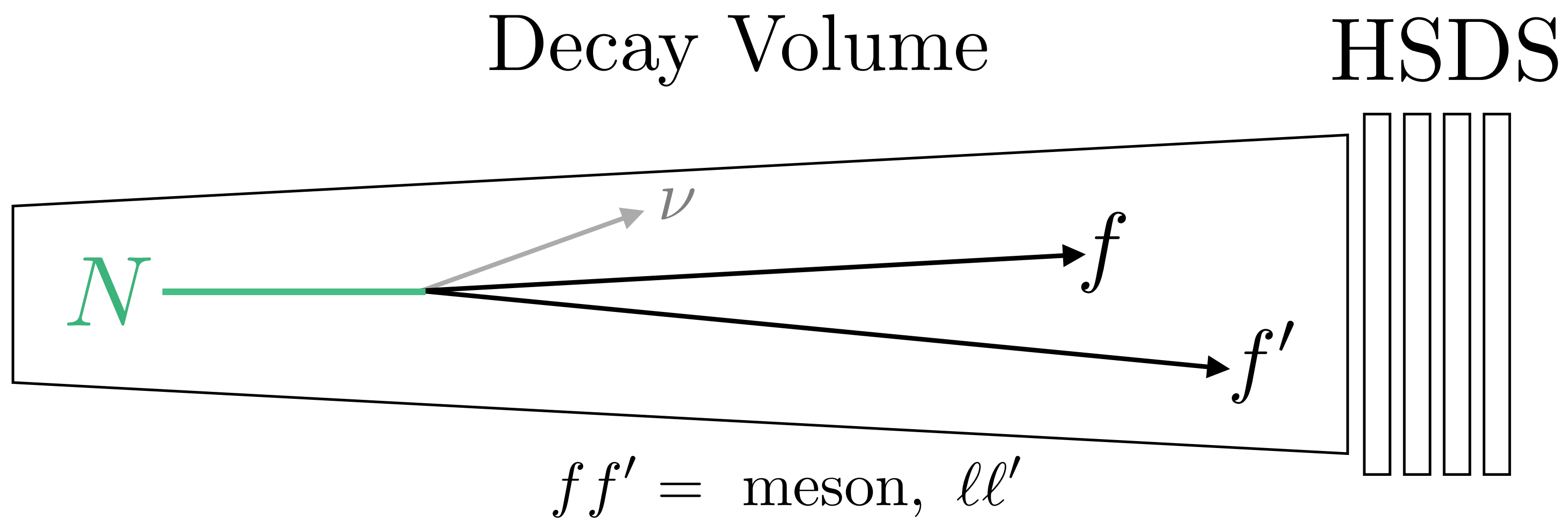


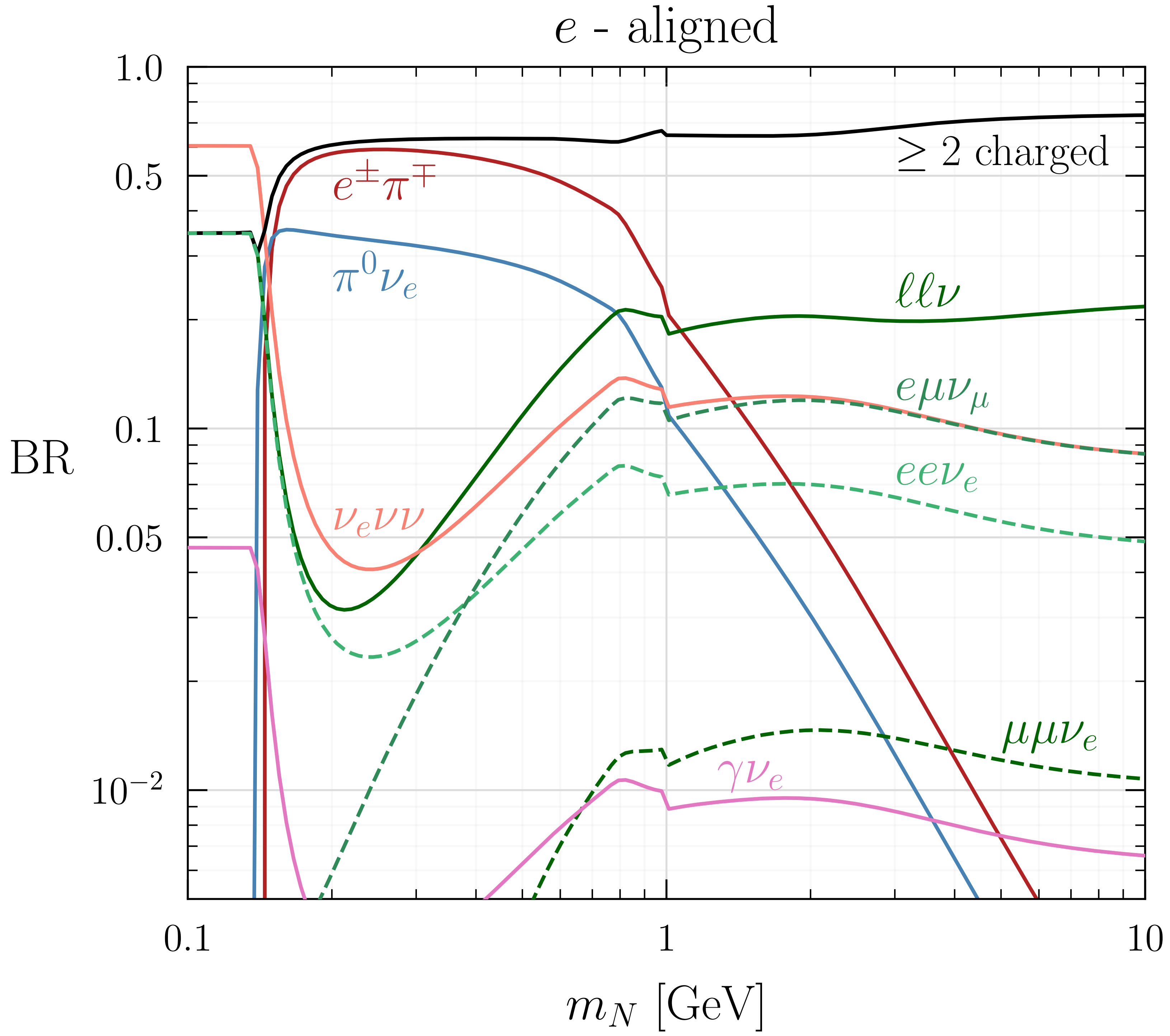
Direct CC Production

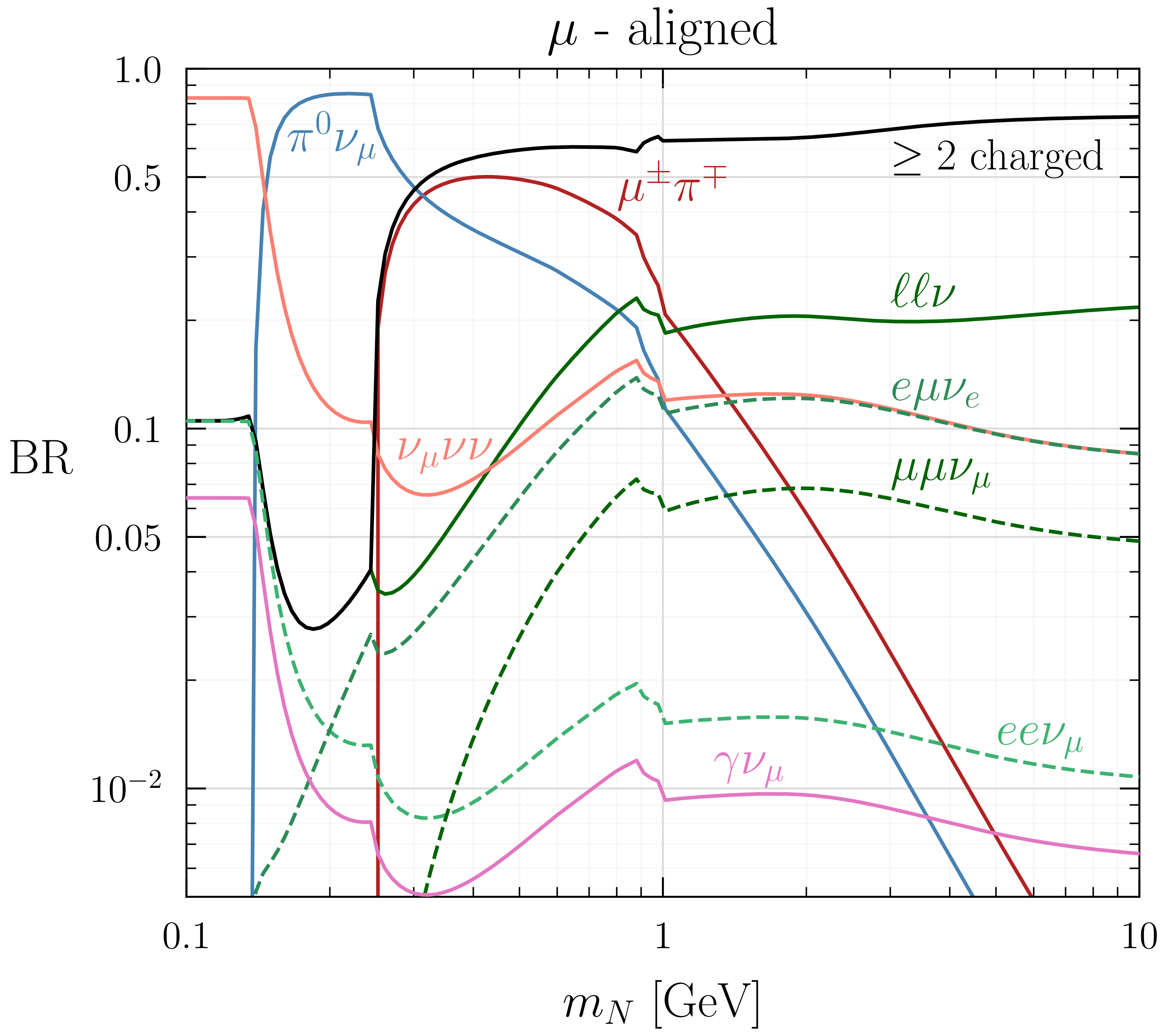
HNL Decays

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



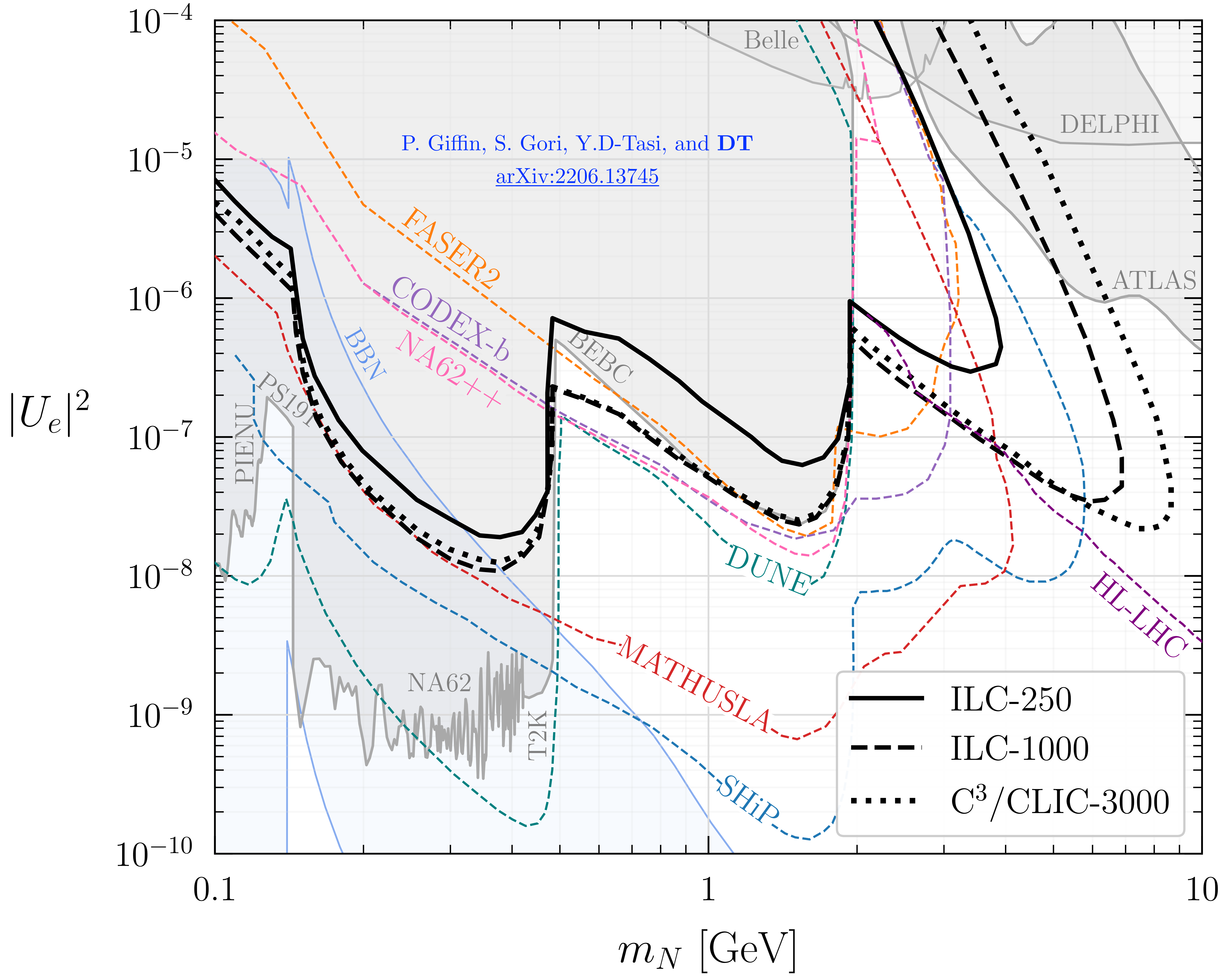






Look for two charged particles in the final state

Sensitivity: Electron Mixed HNLs



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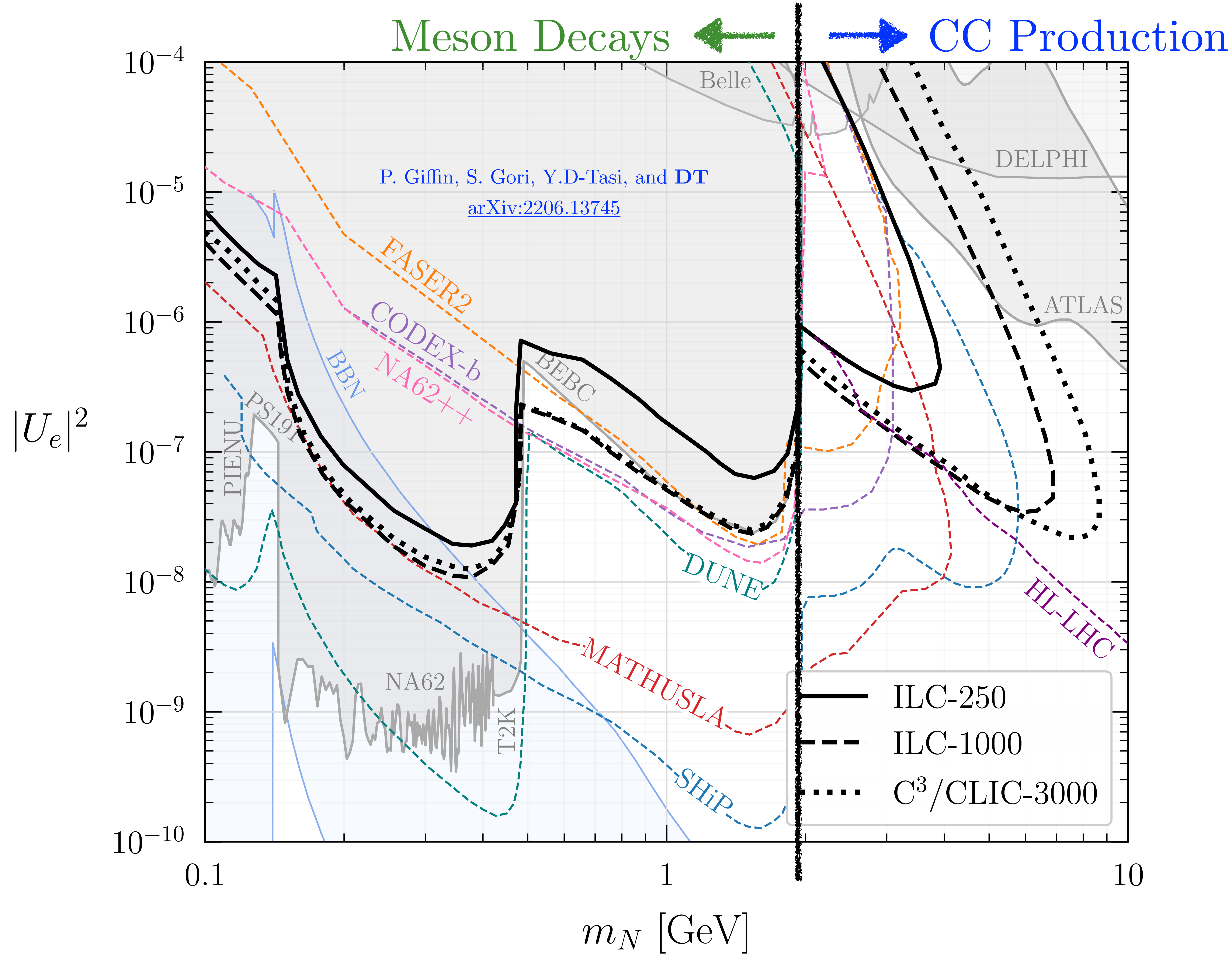

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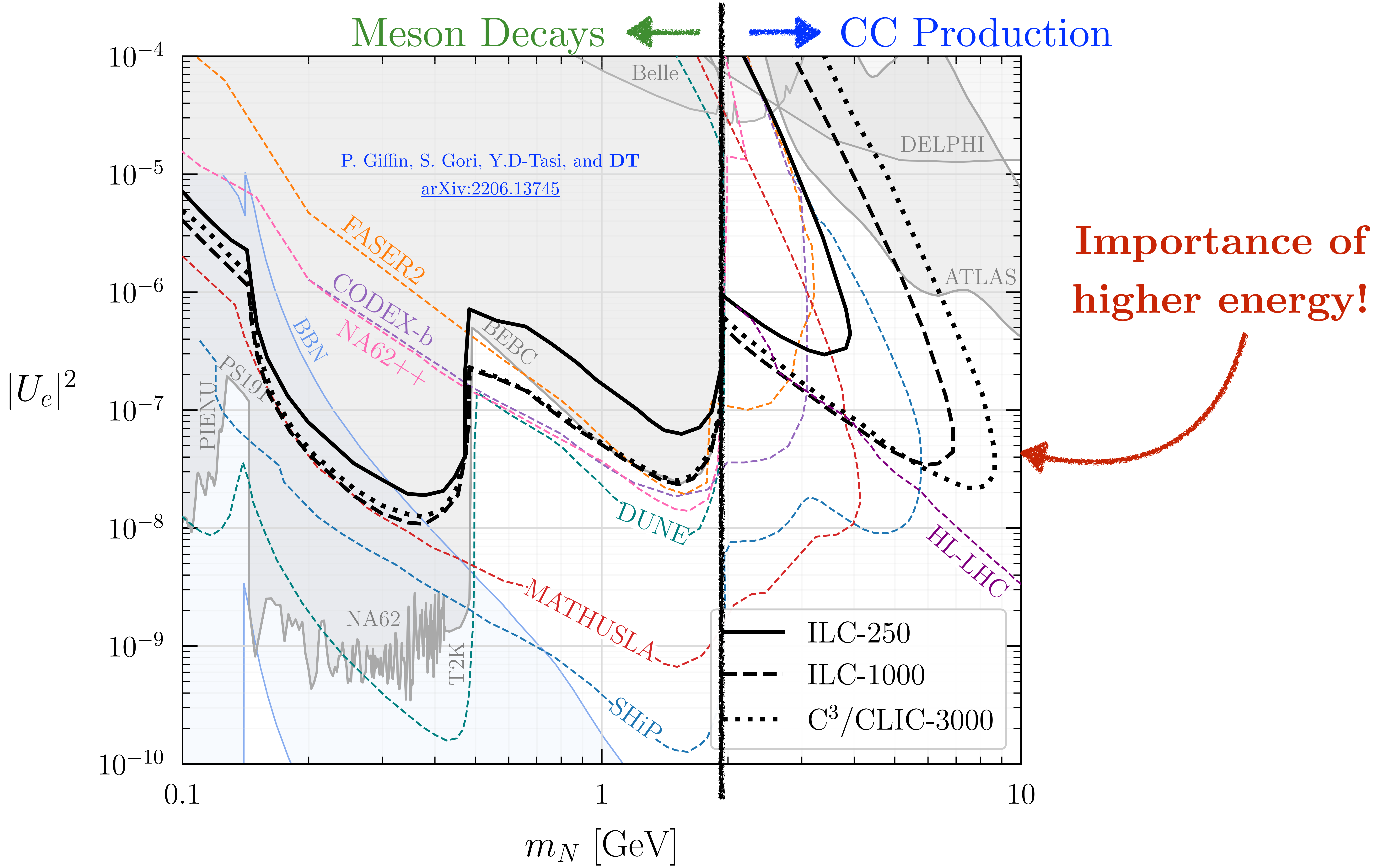
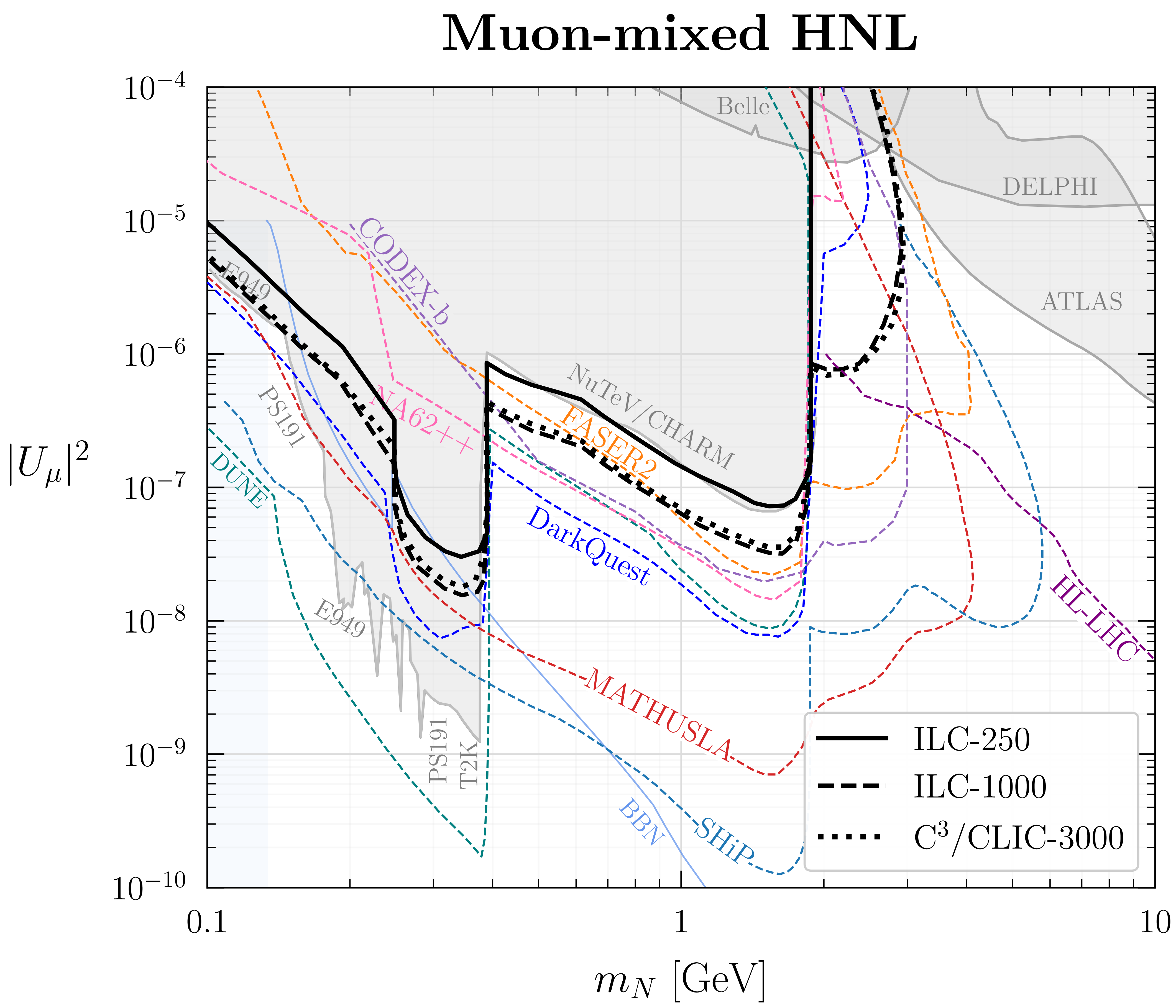
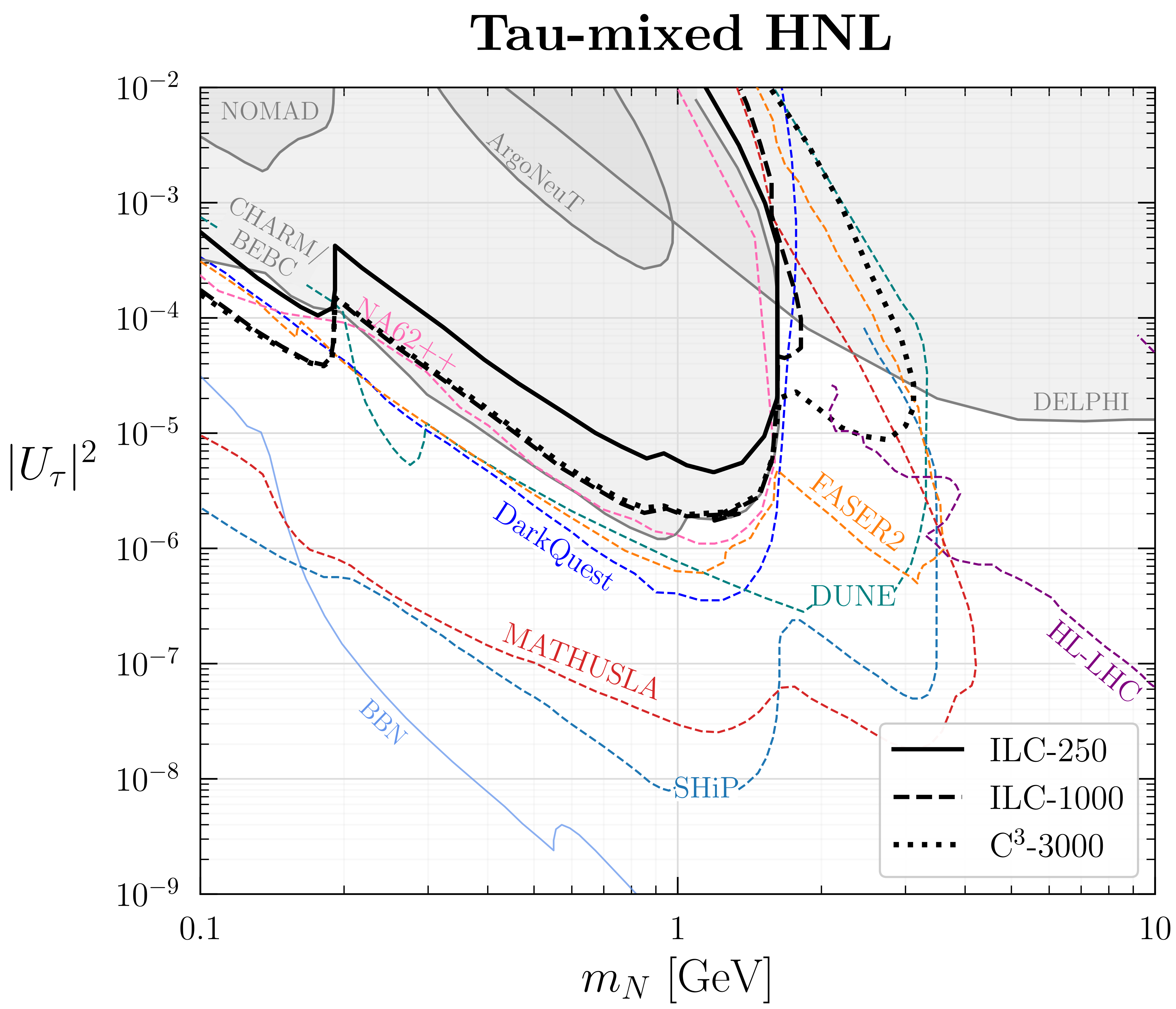
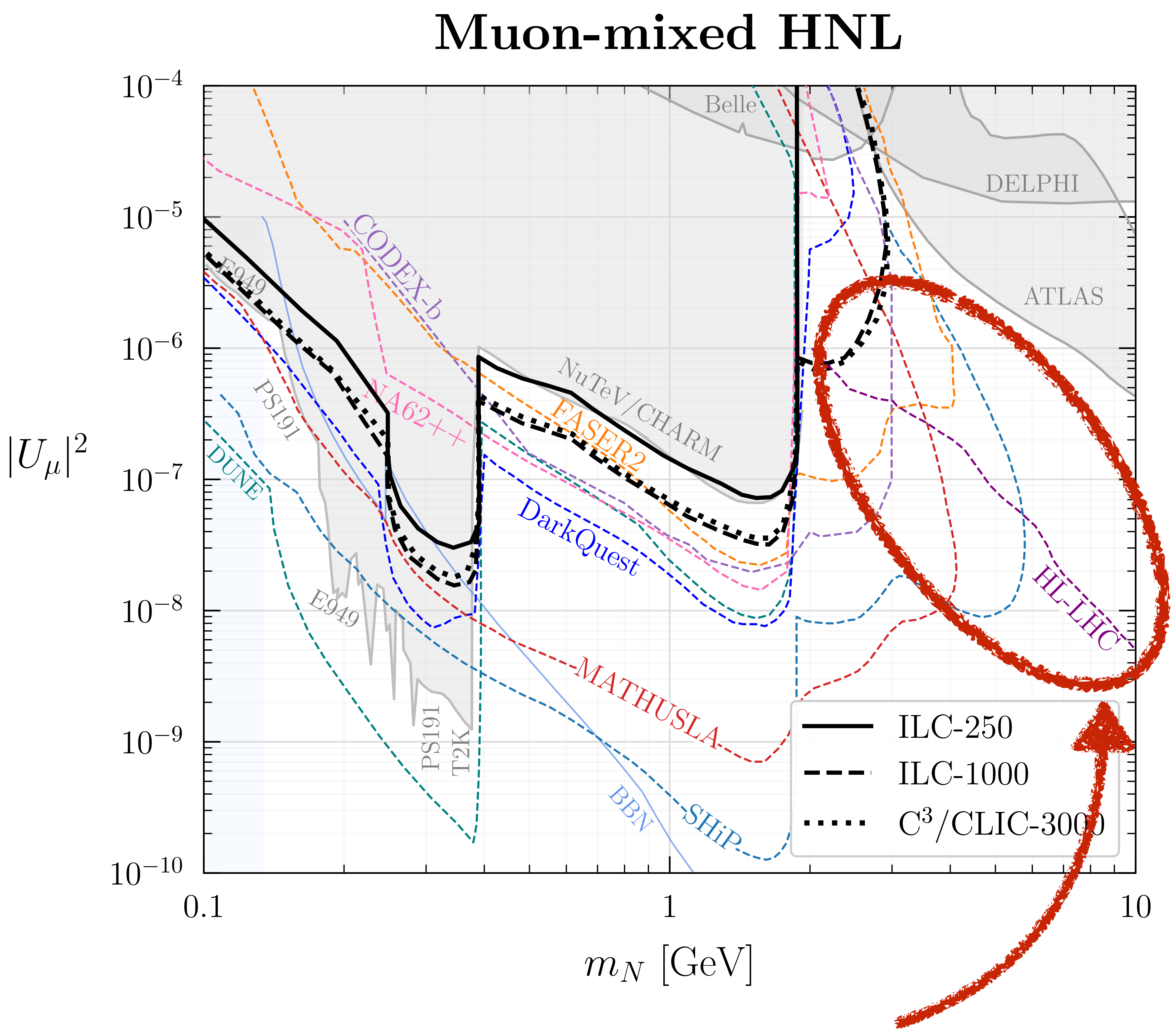


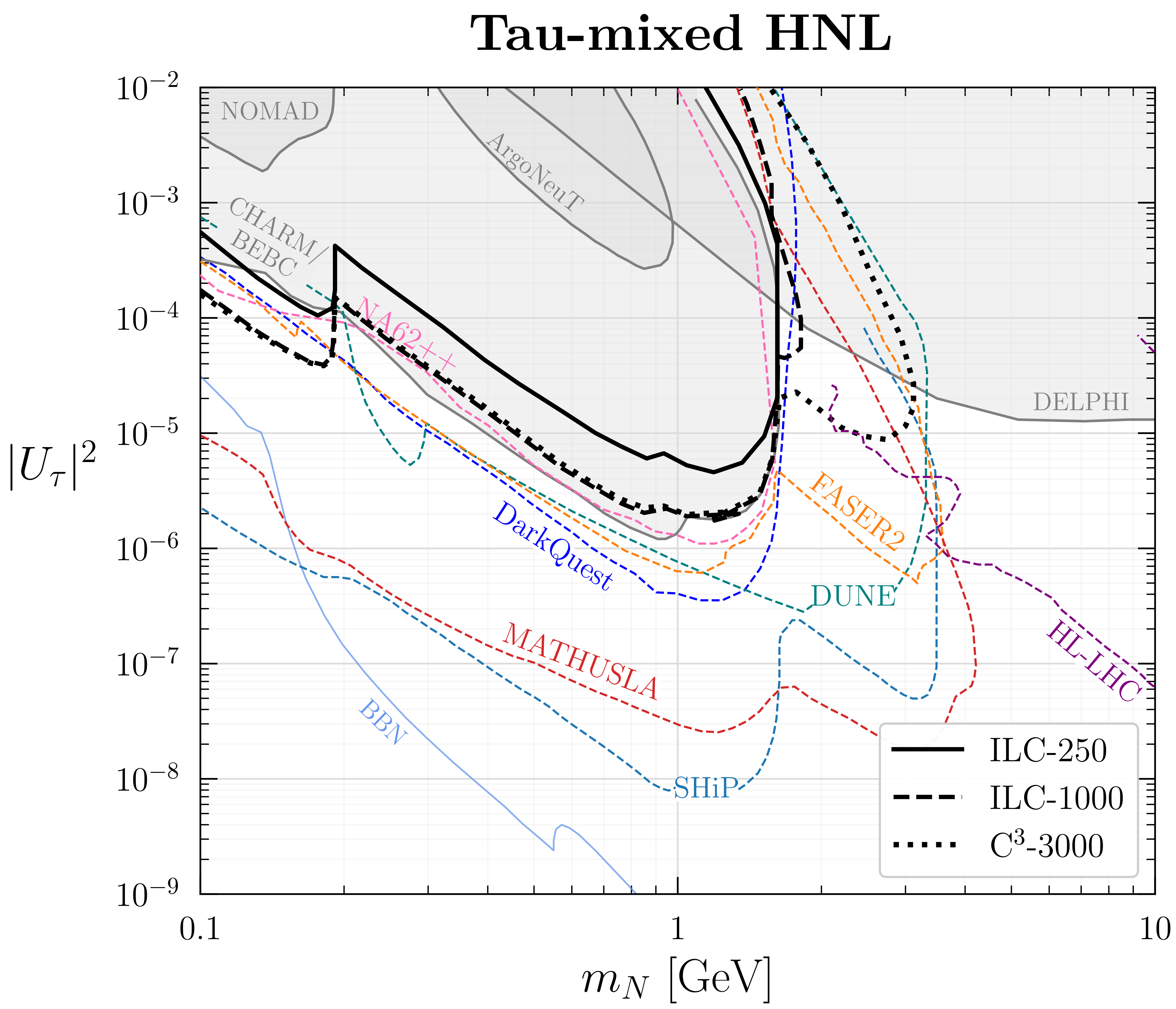
Sensitivity: Muon and Tau Mixed HNLs





Sensitivity: Muon and Tau Mixed HNLs

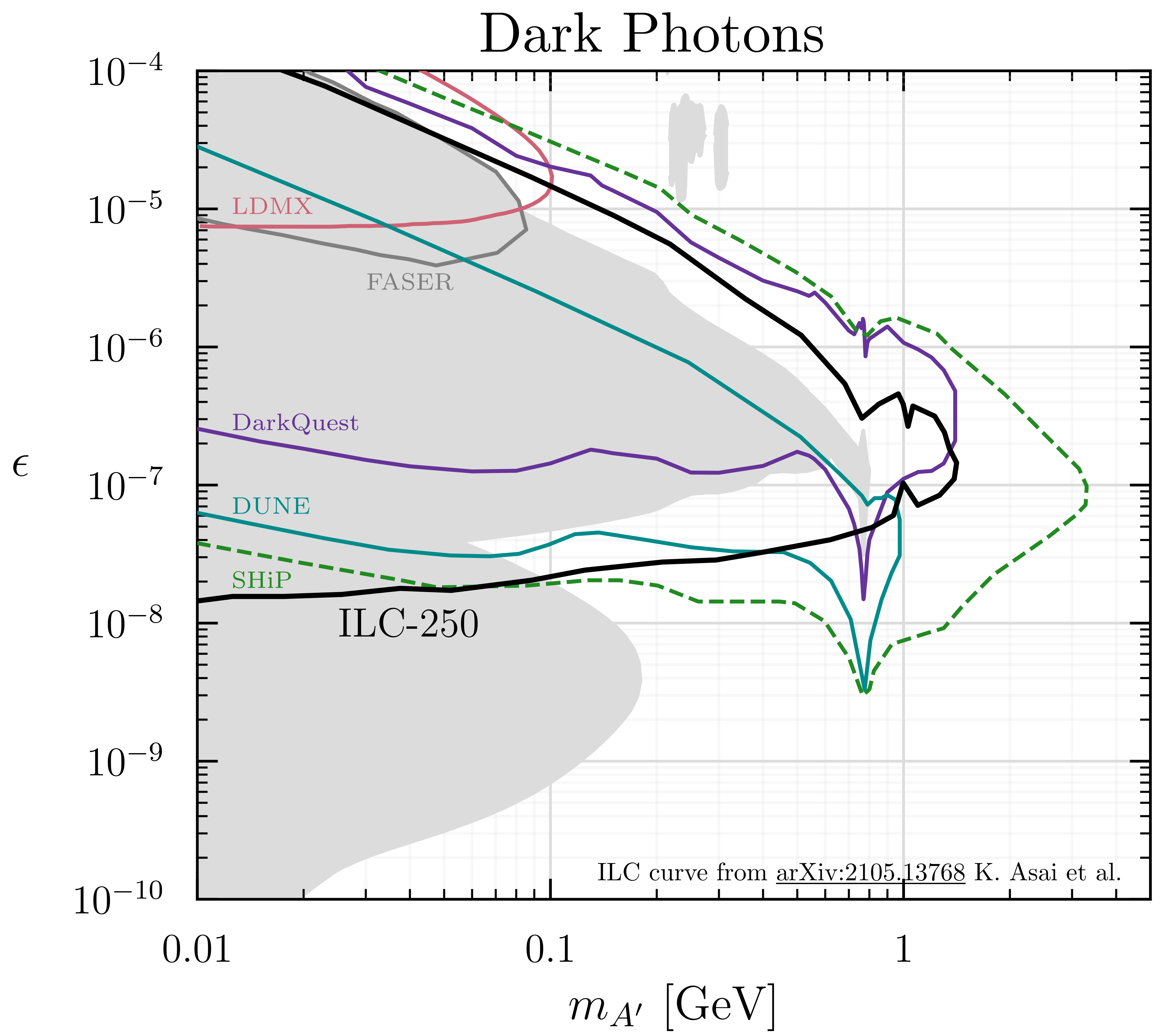


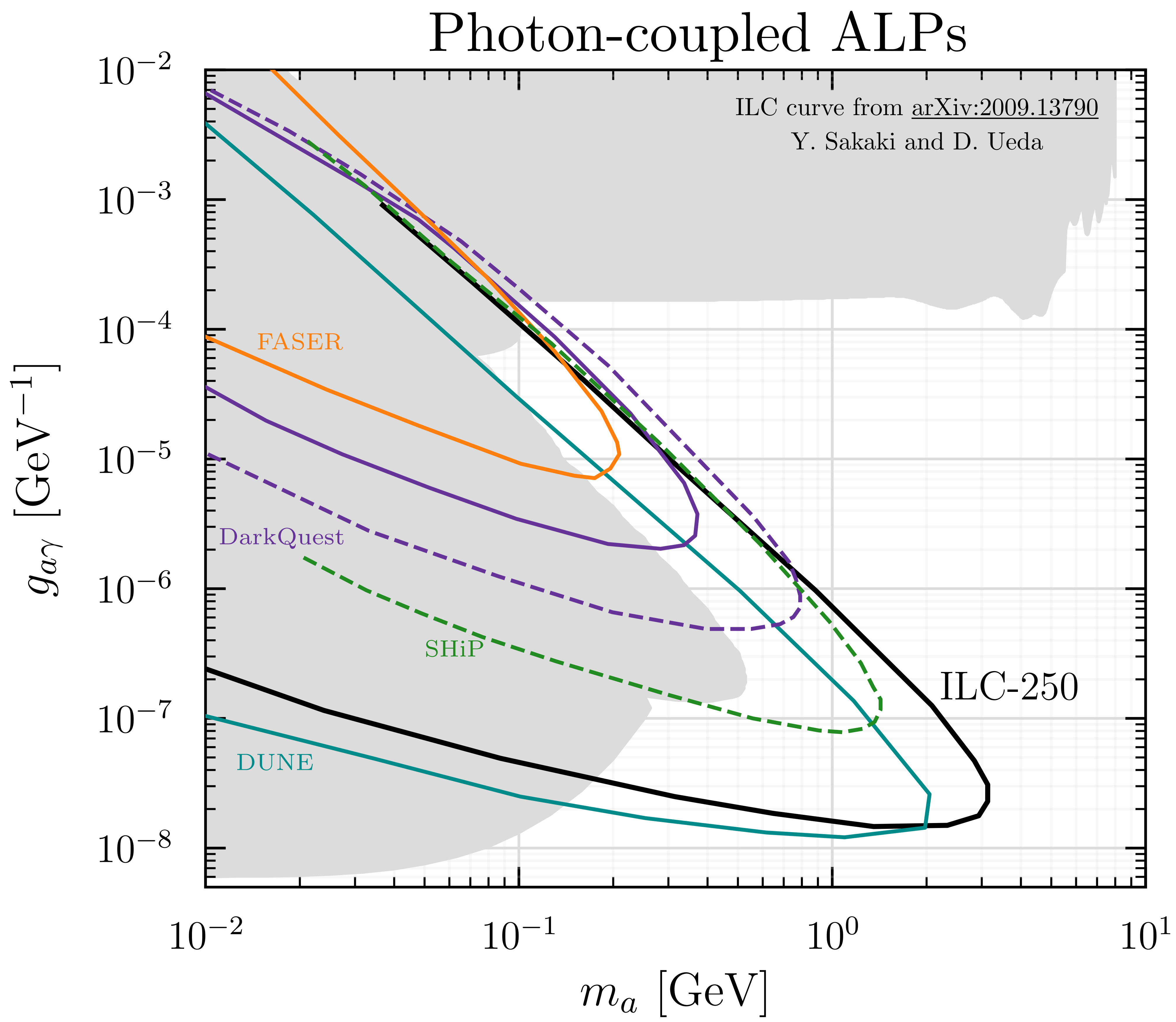


Far, far future: CC production @ TeV muon beam dump exp??

Infinite future: CC production @ TeV tau beam dump exp???

ILC Beam Dump Reach for Other Models





Reach @ ILC-1000/ C3-3000?

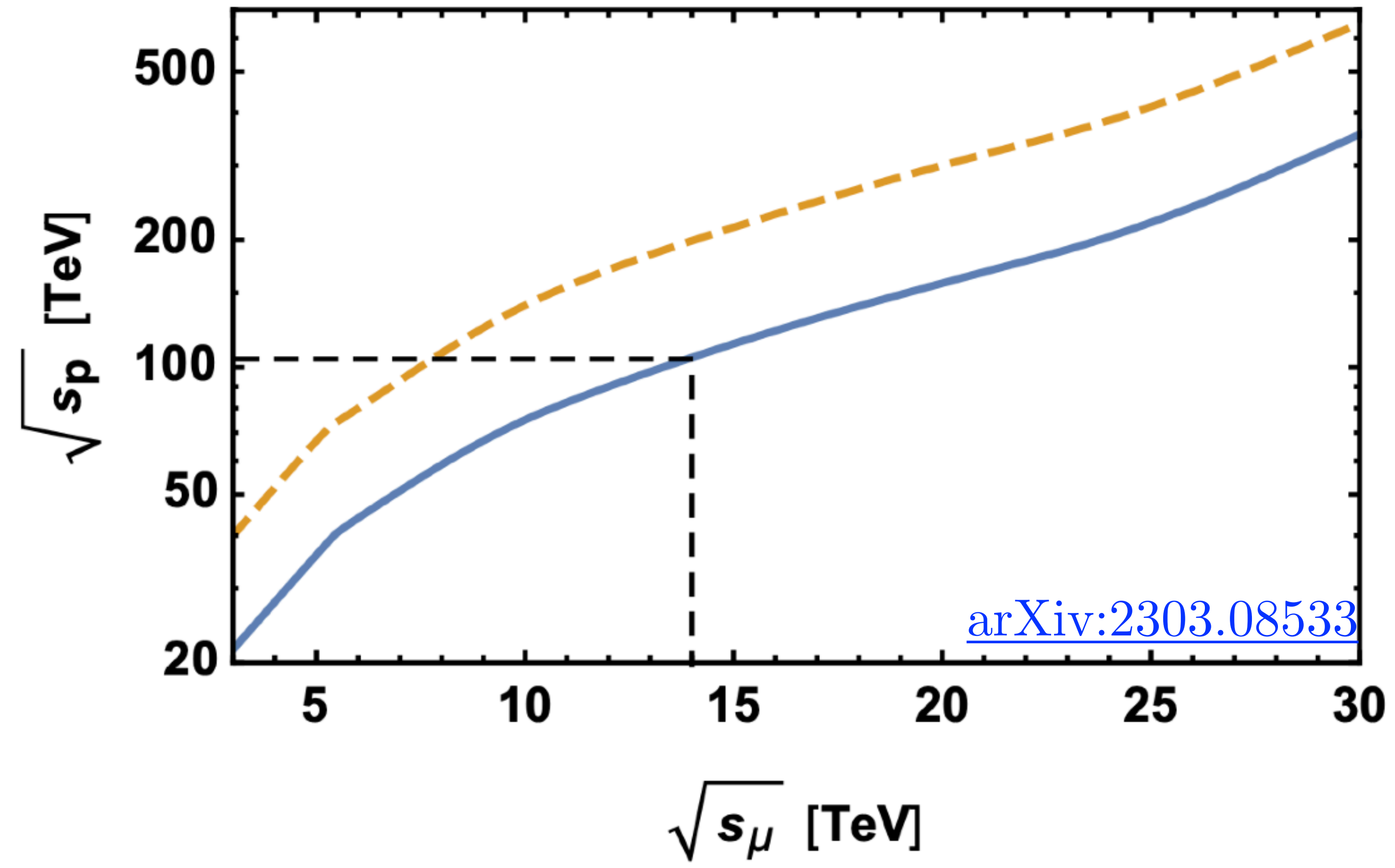
ILC Beam Dump experiment has complementary sensitivity for dark photons/ ALPs compared to SHiP, DarkQuest, FASER, DUNE, etc.

Energy Frontier is Intensity Frontier

We can maximize the physics potential of high energy e^+e^- machines beyond the main interaction point to look for light new physics $\rightarrow$ beam dump experiments or far detectors.

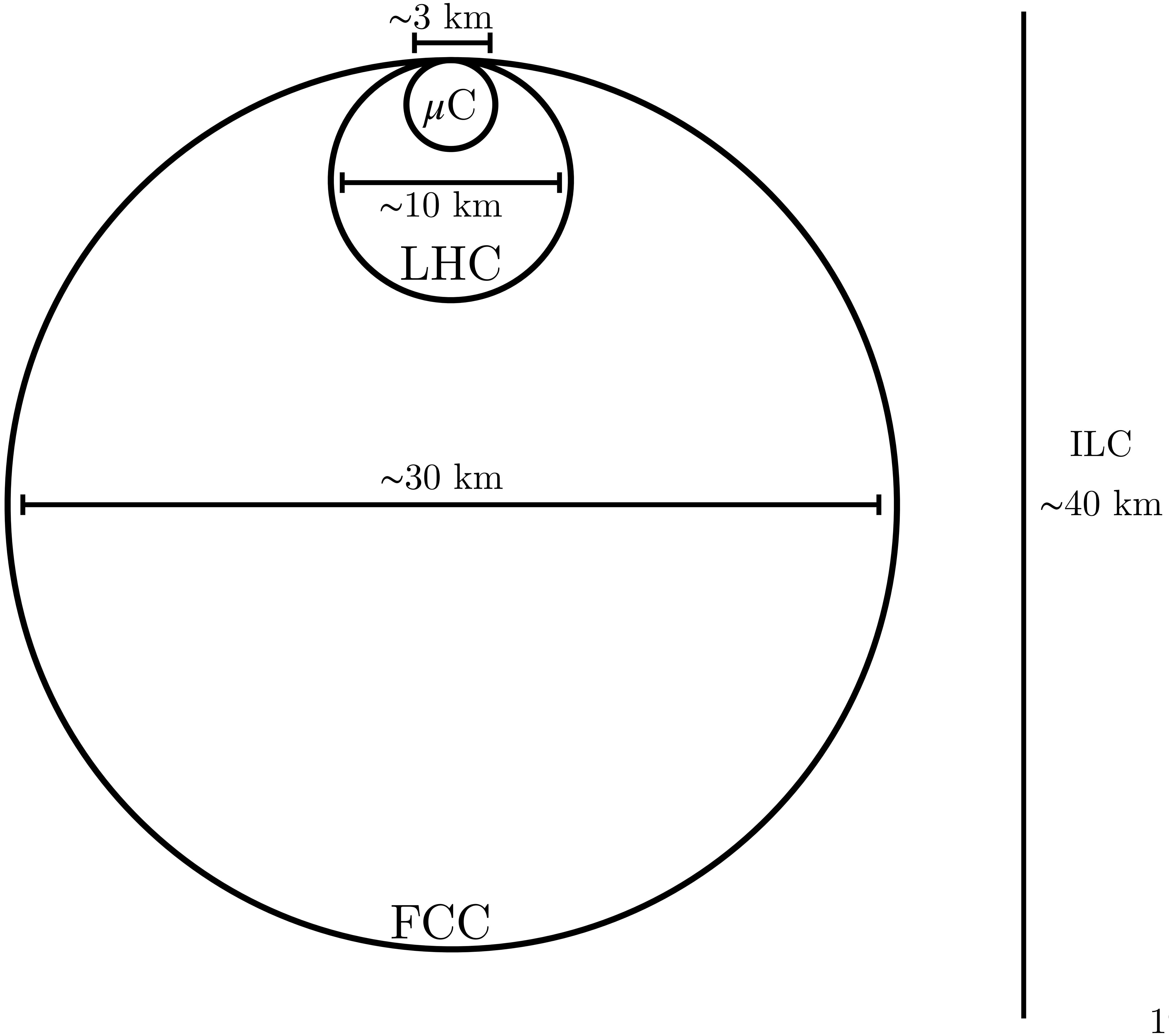
Muon Colliders

- *Muons are fundamental* $\rightarrow \sqrt{s_\mu} \approx \sqrt{s}$



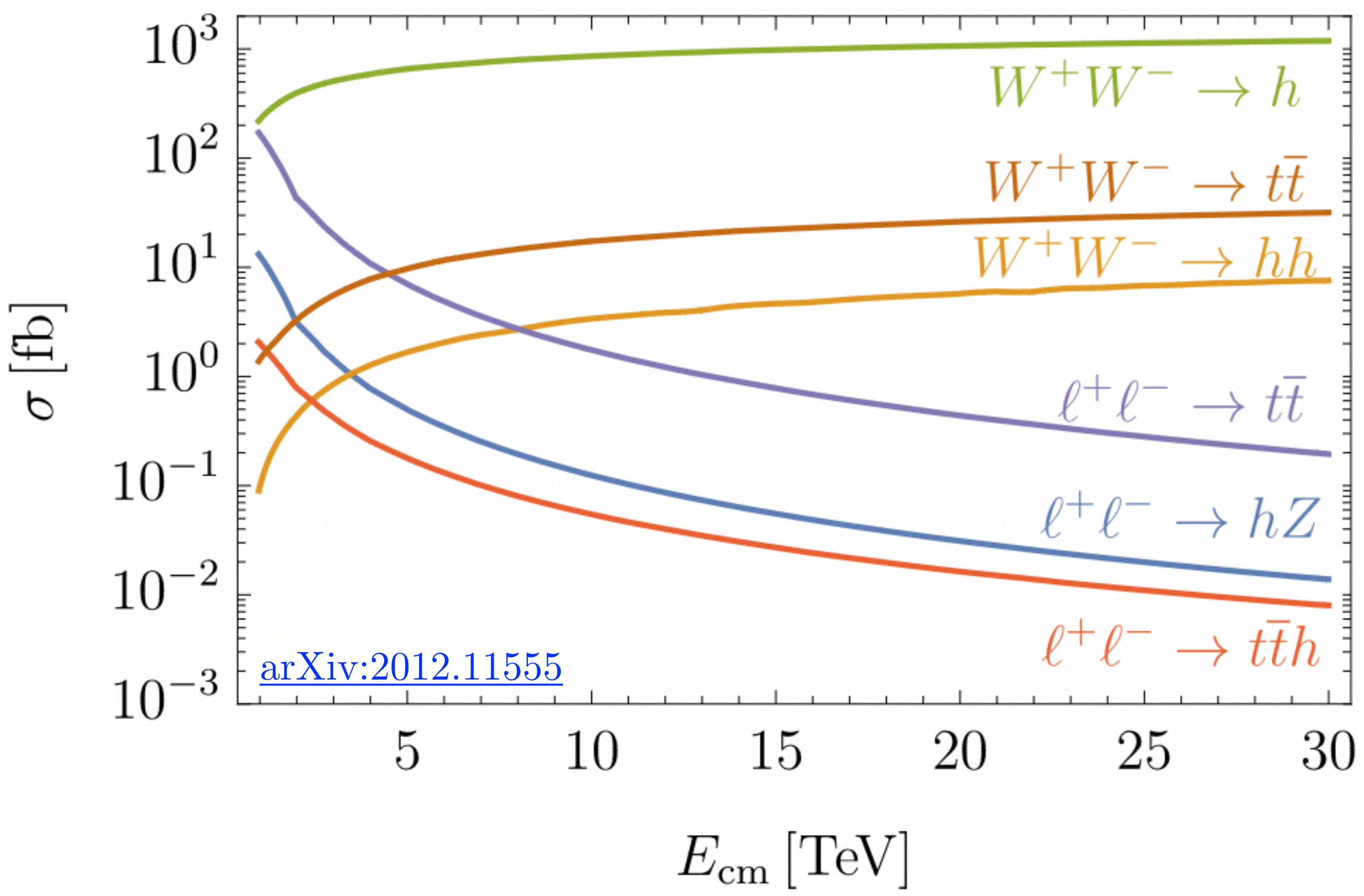
- No color charge $\rightarrow$ *clean environment* w.r.t *pp* colliders
- $m_\mu > m_e \rightarrow$ *lower synchrotron radiation*

Smaller collider at higher energies compared to *pp* or *ee* colliders

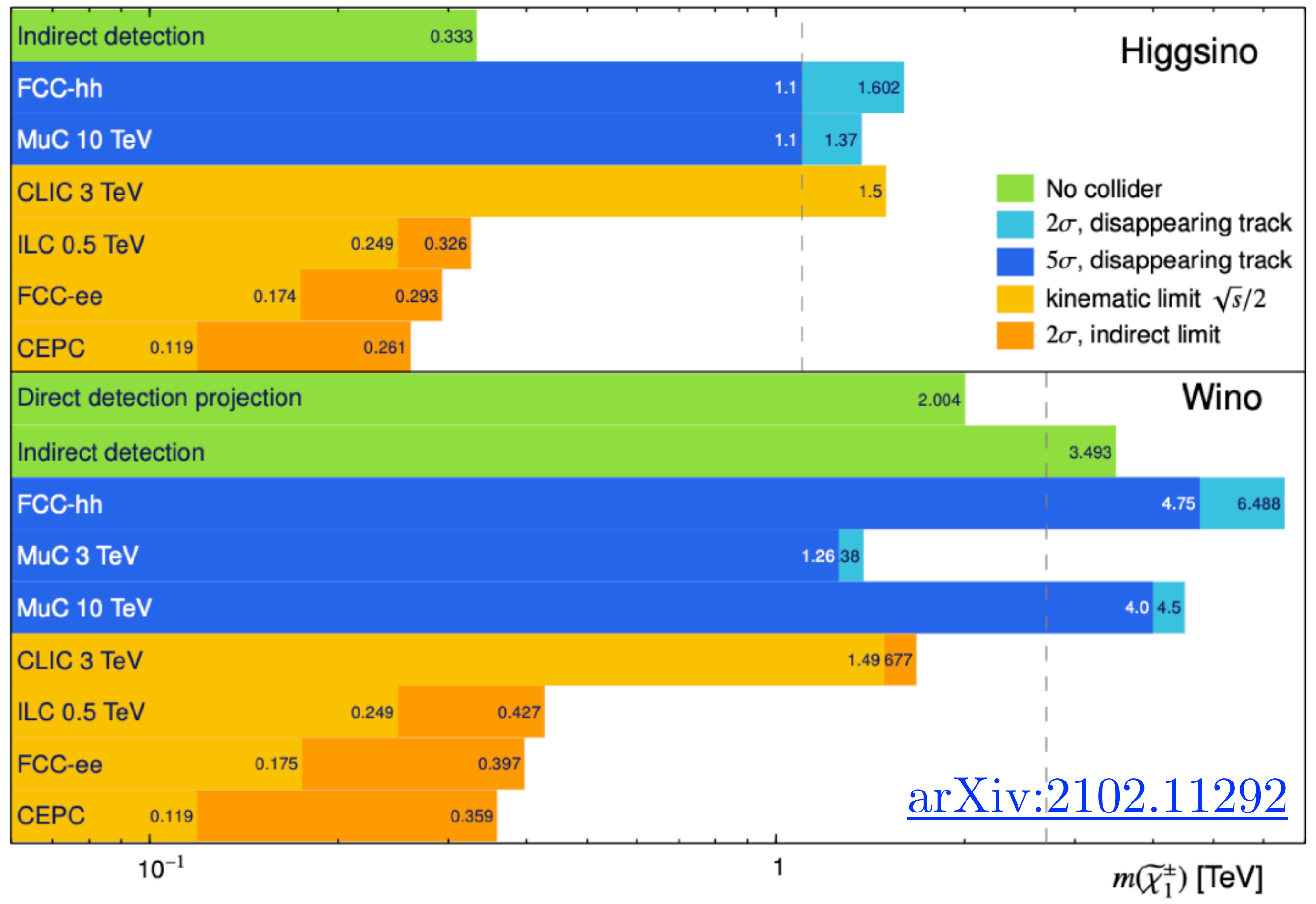


Muon Colliders

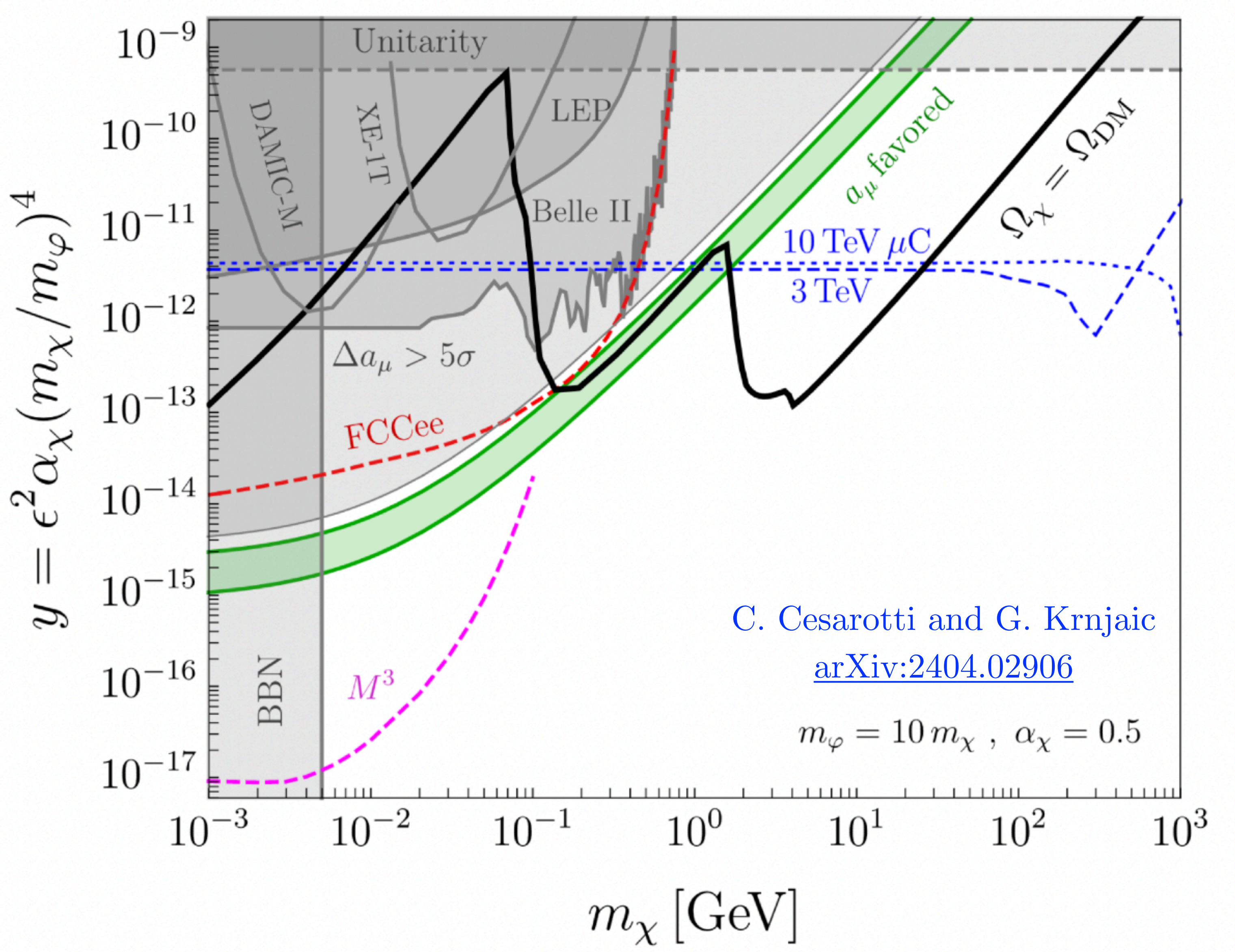
Muon collider ↔ gauge boson collider → *precision* EW/Higgs physics



High energy → reach for heavy new physics



2nd generation → muon-specific new physics?



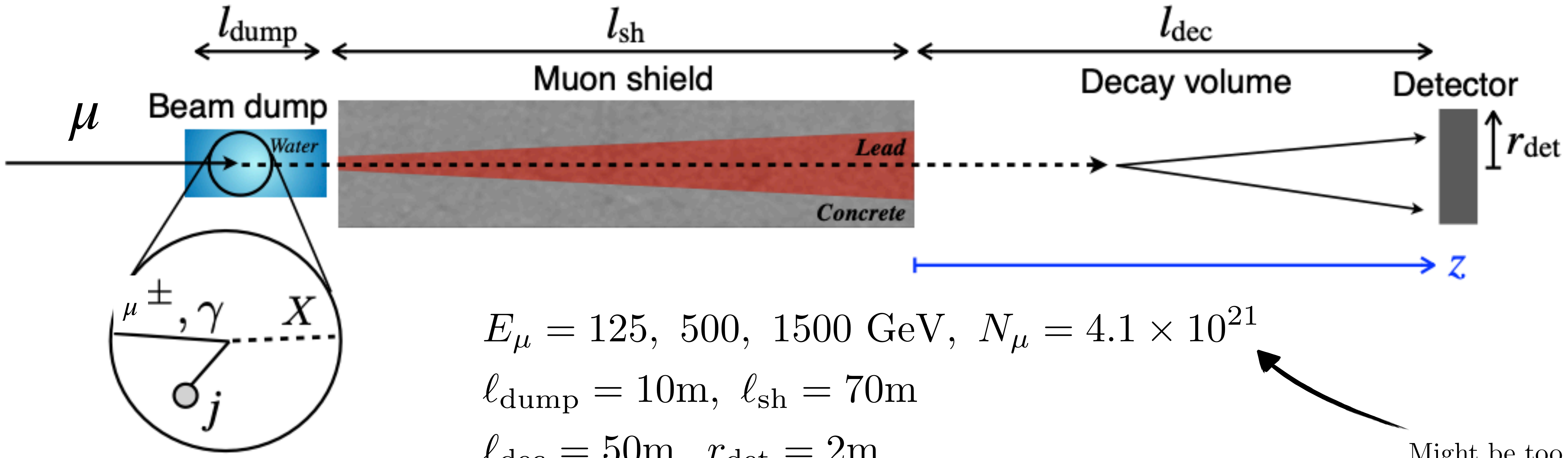
Muon Collider is both an *energy and precision* machine!

Can we maximize the physics potential beyond the main detectors?

Muon Beam Dump Experiment

- Muons beams will be dumped periodically. *Why not put a beam dump experiment at a muon collider?*
  - High energies and staged approach from 100s of GeV to multi-TeV muon beams. Opportunities for dark sector searches at every stage.
  - High intensity: 10^{18} - 10^{22} muons-on-target/year

- FIPs/LLP sensitivity if we assume a set up exactly like ILC beam dump? Use heavy neutral leptons as a case study.



$E_\mu = 125,\ 500,\ 1500$ GeV, $N_\mu = 4.1 \times 10^{21}$

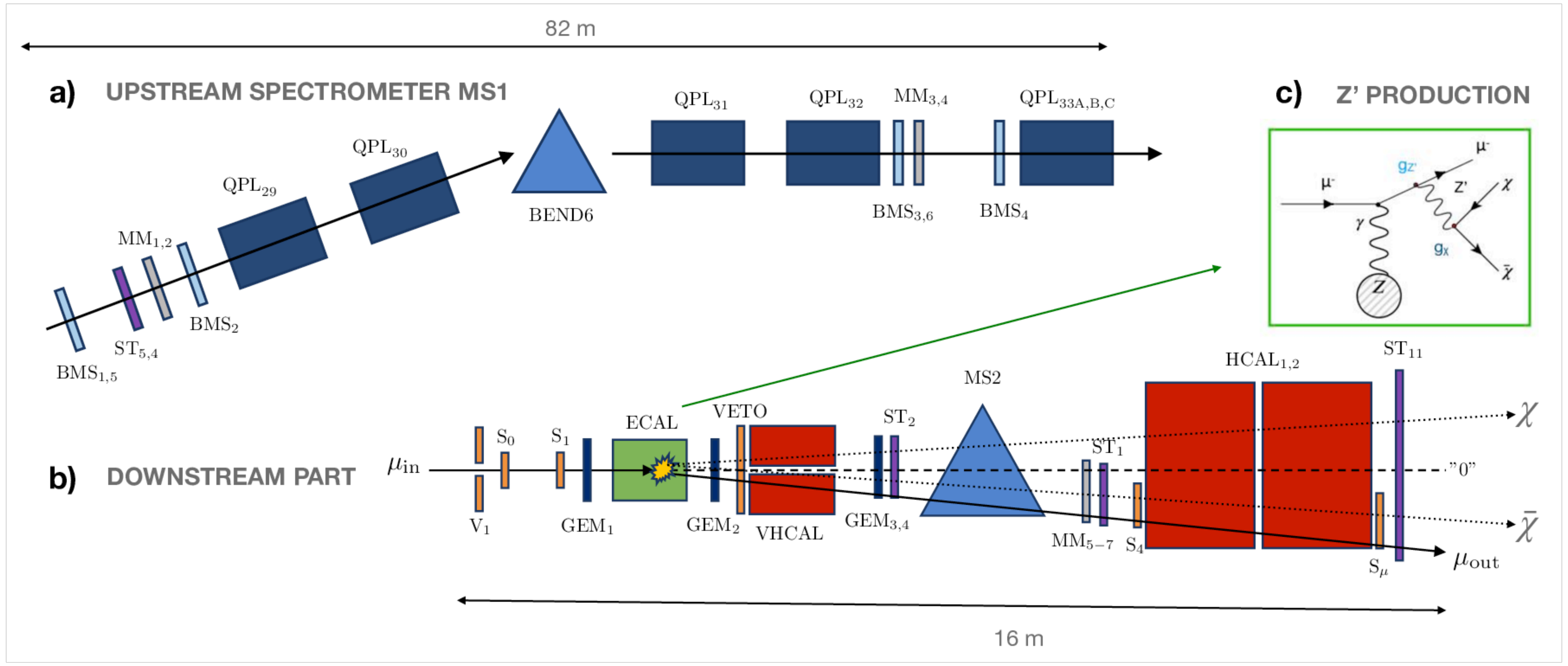
$\ell_{\rm dump} = 10{\rm m},\ \ell_{\rm sh} = 70{\rm m}$

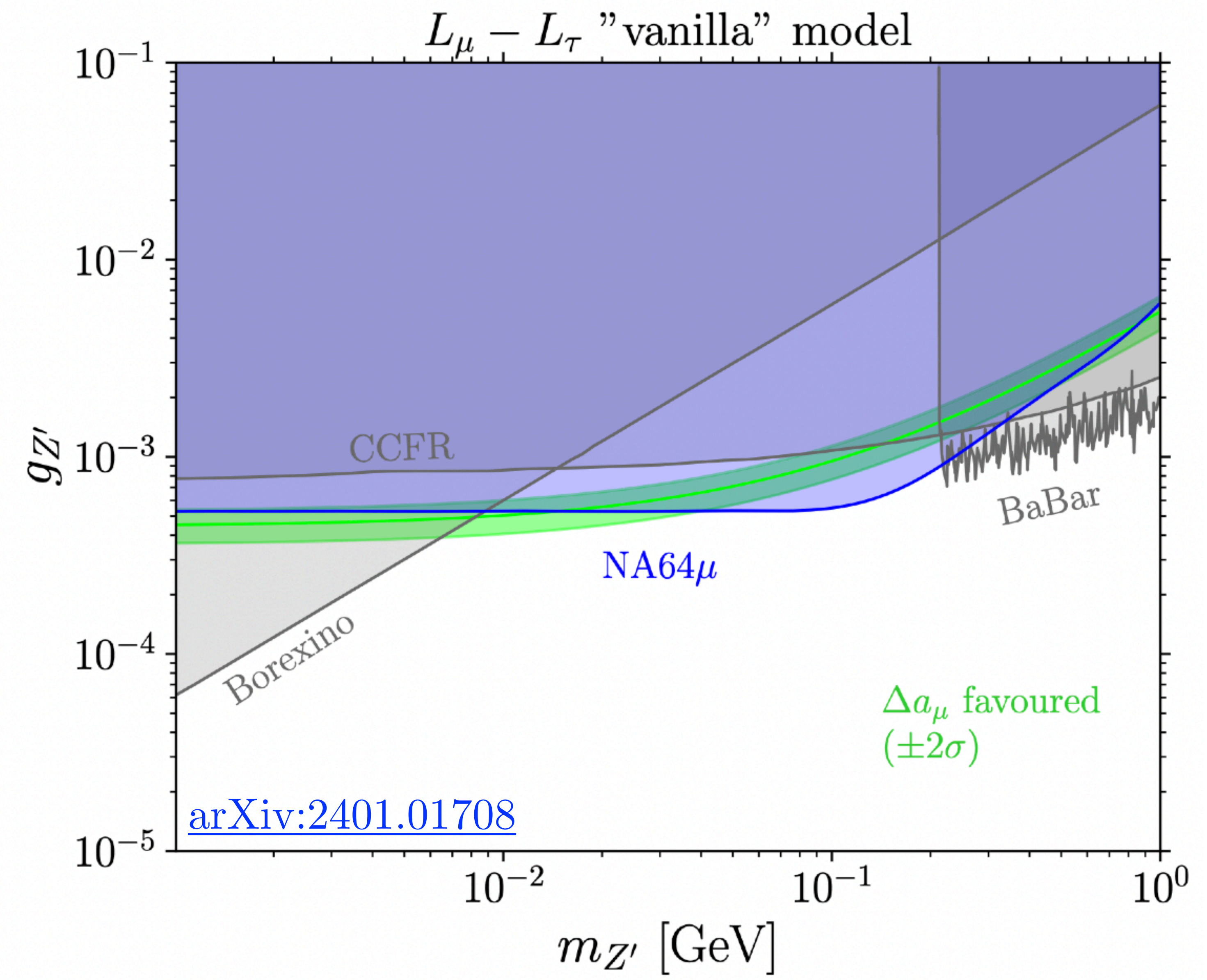
$\ell_{\rm dec} = 50{\rm m},\ r_{\rm det} = 2{\rm m}$

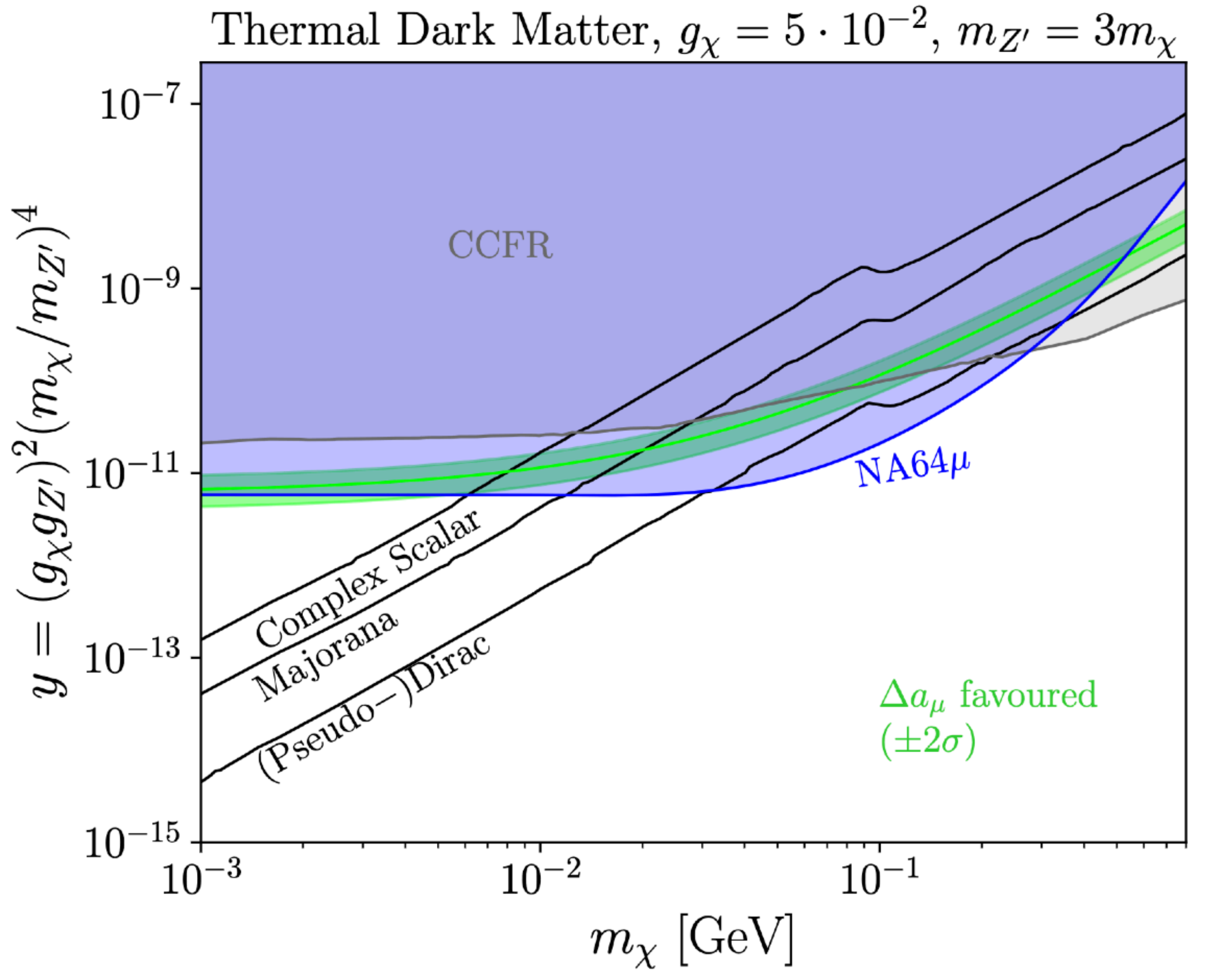
Might be too optimistic but we want a direct comparison with ILC beam dump

Aside on NA64

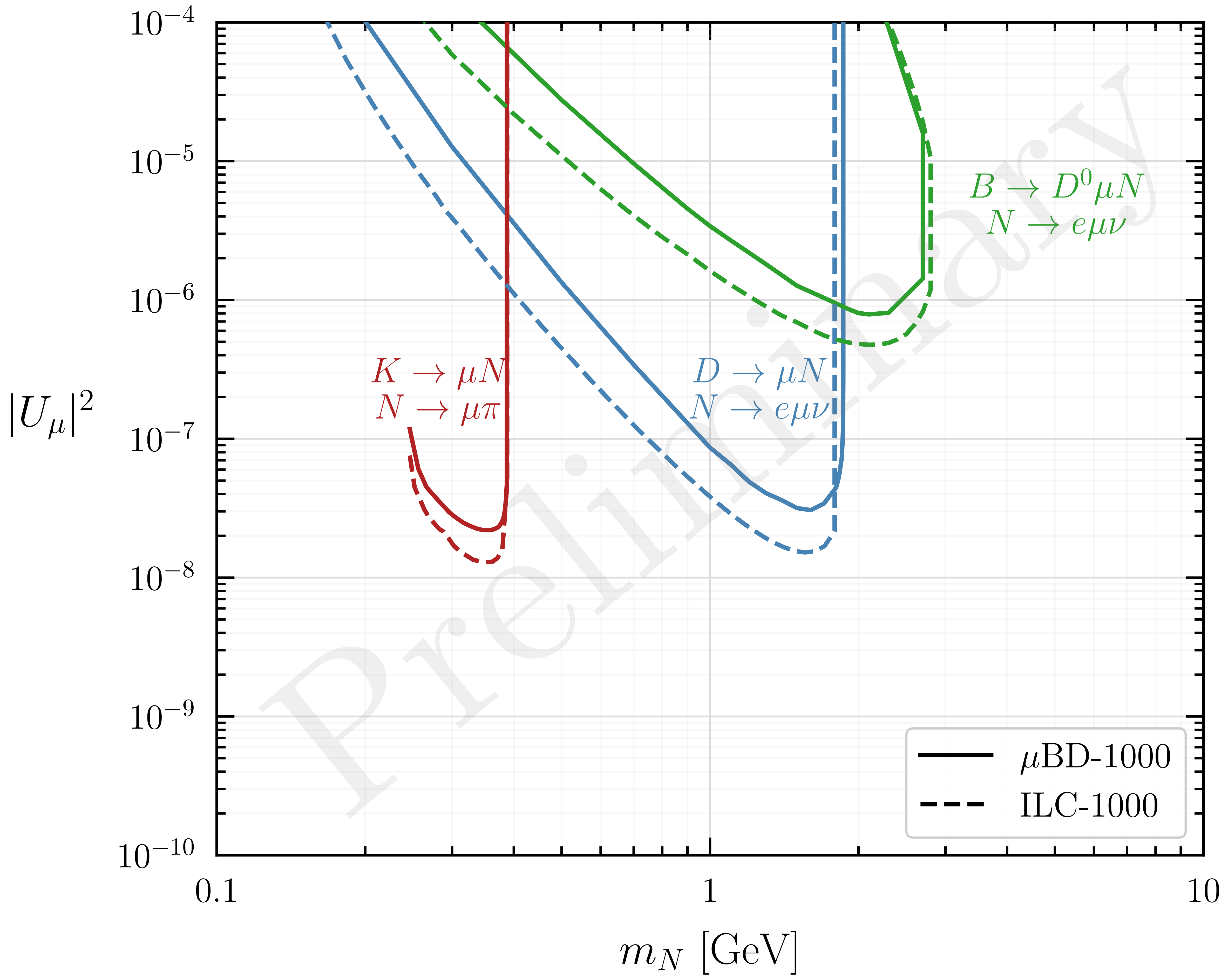
- High energy muon beam dump experiment is not so crazy. NA64μ running at CERN!
  - 160 GeV muon beam
  - $\sim 10^{10}$ muons-on-target
  - Missing energy/missing momentum technique



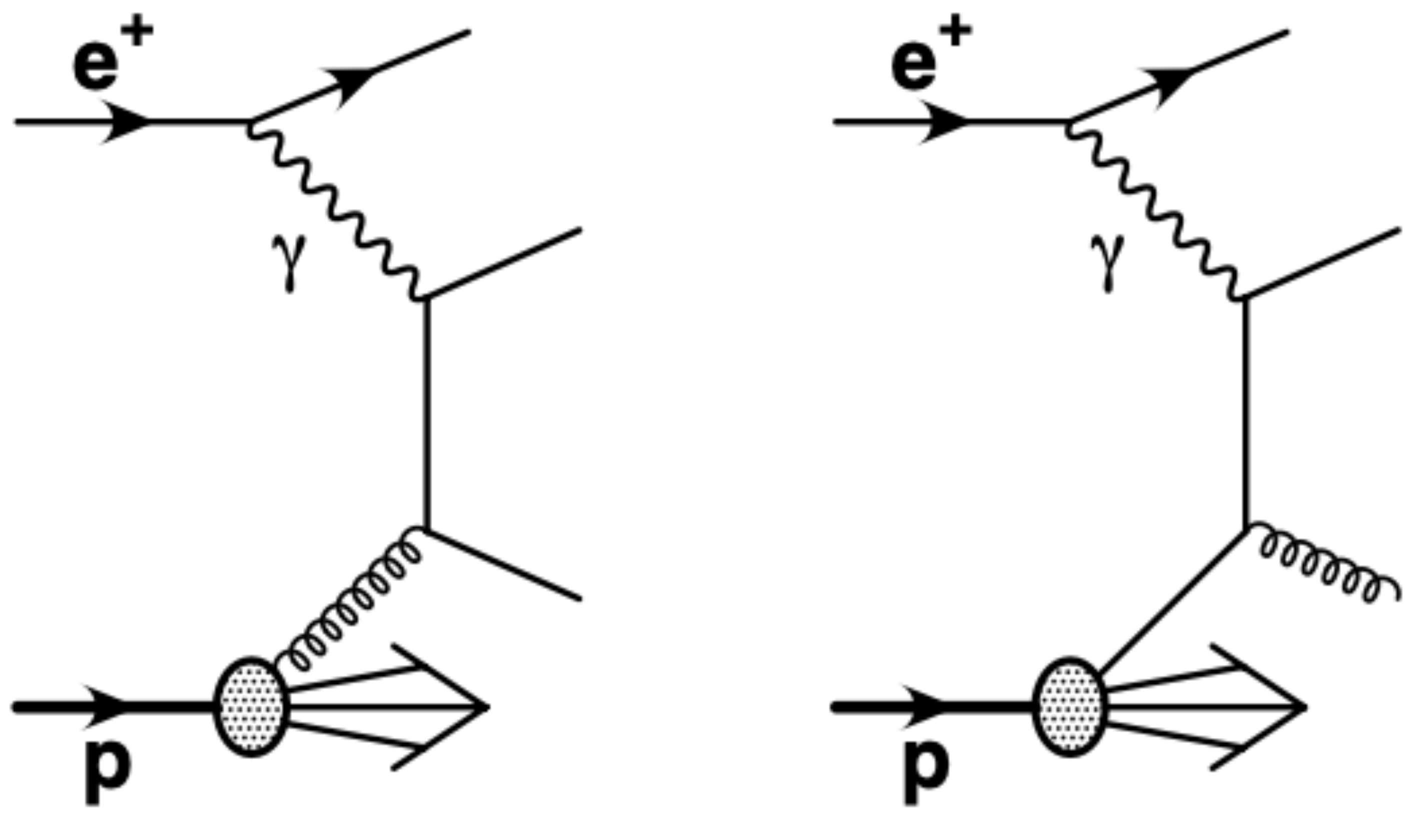




HNLs @ Muon Beam Dump



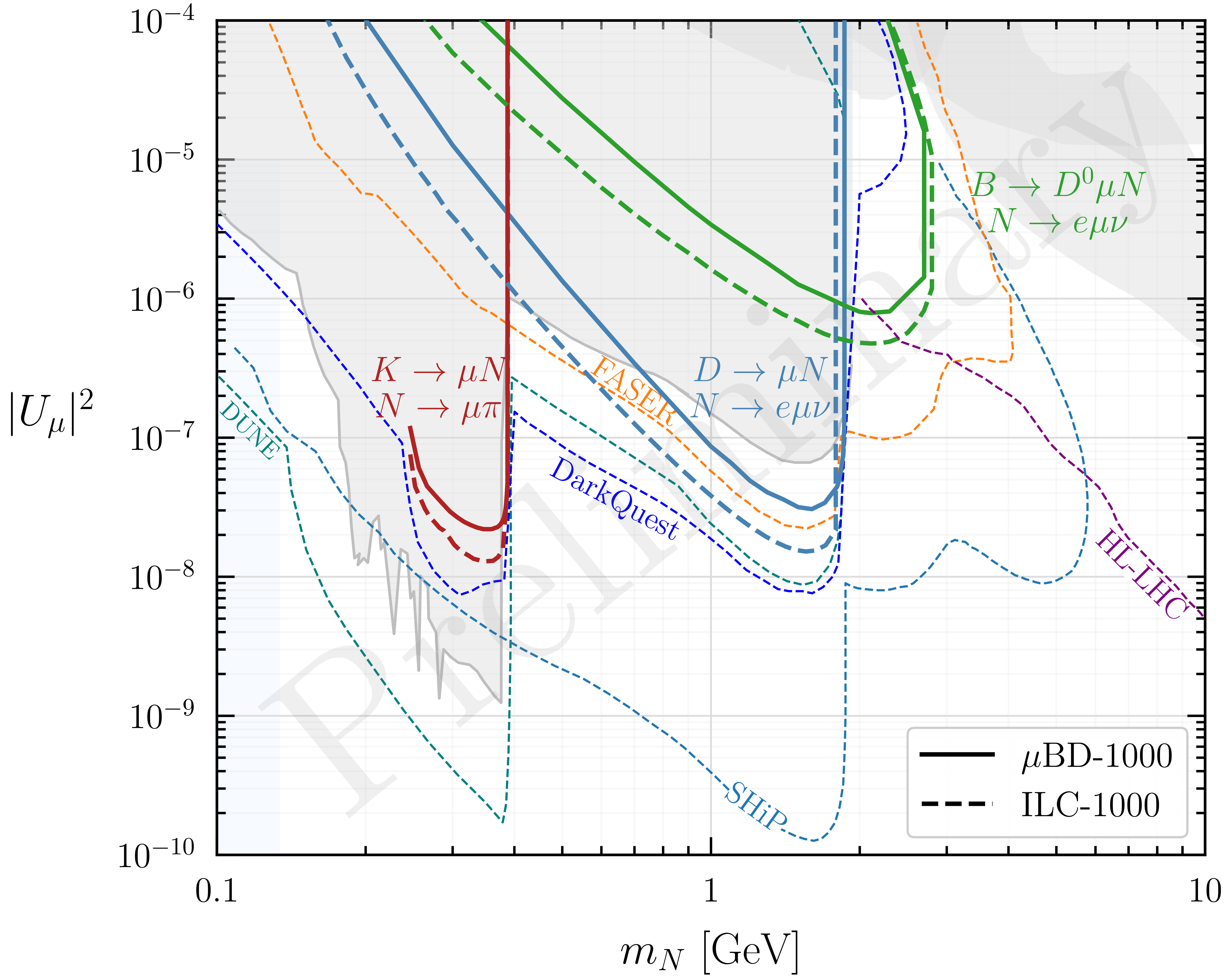
- Lower meson production rate → slightly weaker sensitivity



$$\sigma(\ell p \to \ell + \text{jets}) \sim \sigma_0 \times f_{\gamma/\ell} \times f_{g/p}$$

$f_{\gamma/\ell}$ = probability for of lepton radiating off a photon $\sim 1/m_\ell$

HNLs @ Muon Beam Dump



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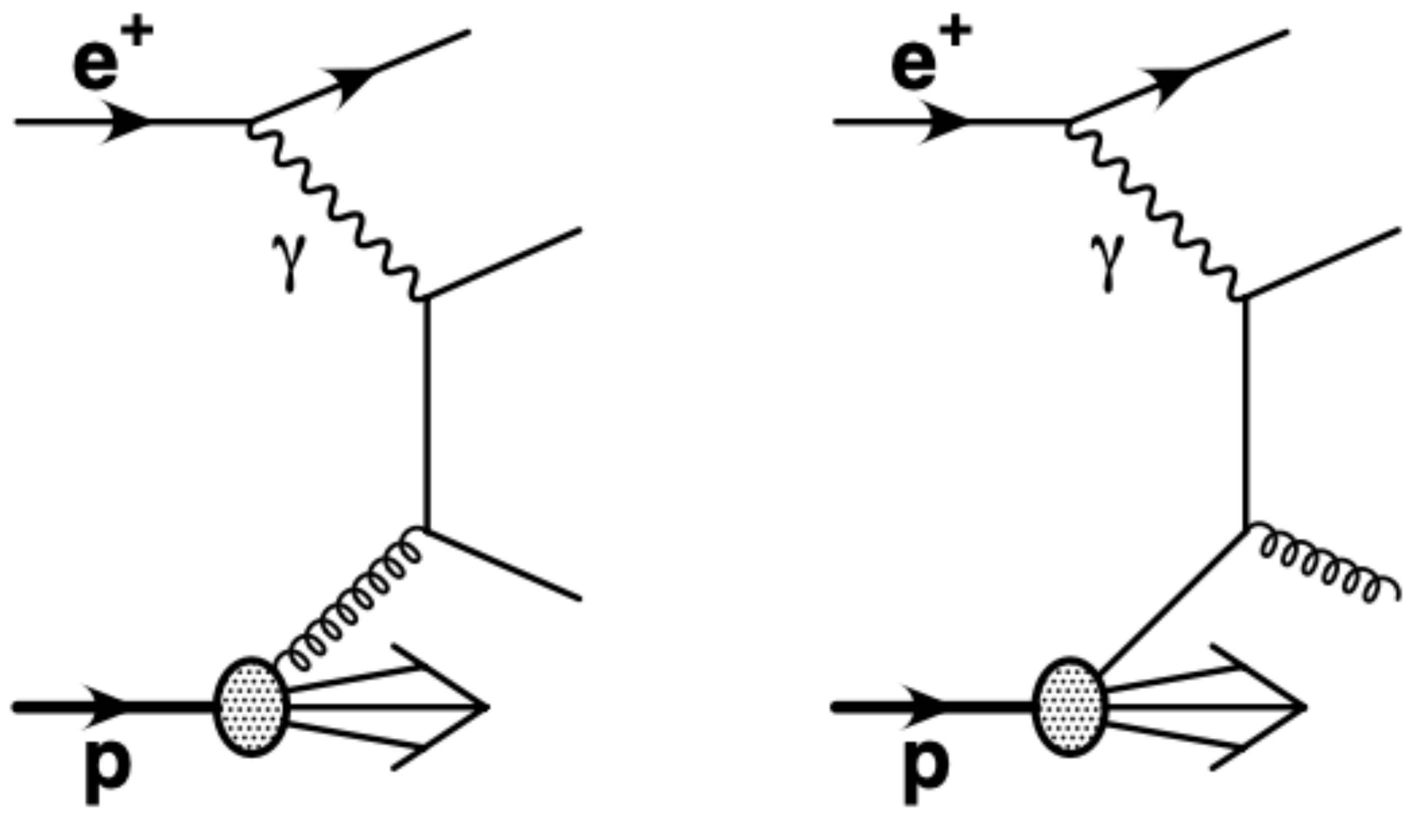

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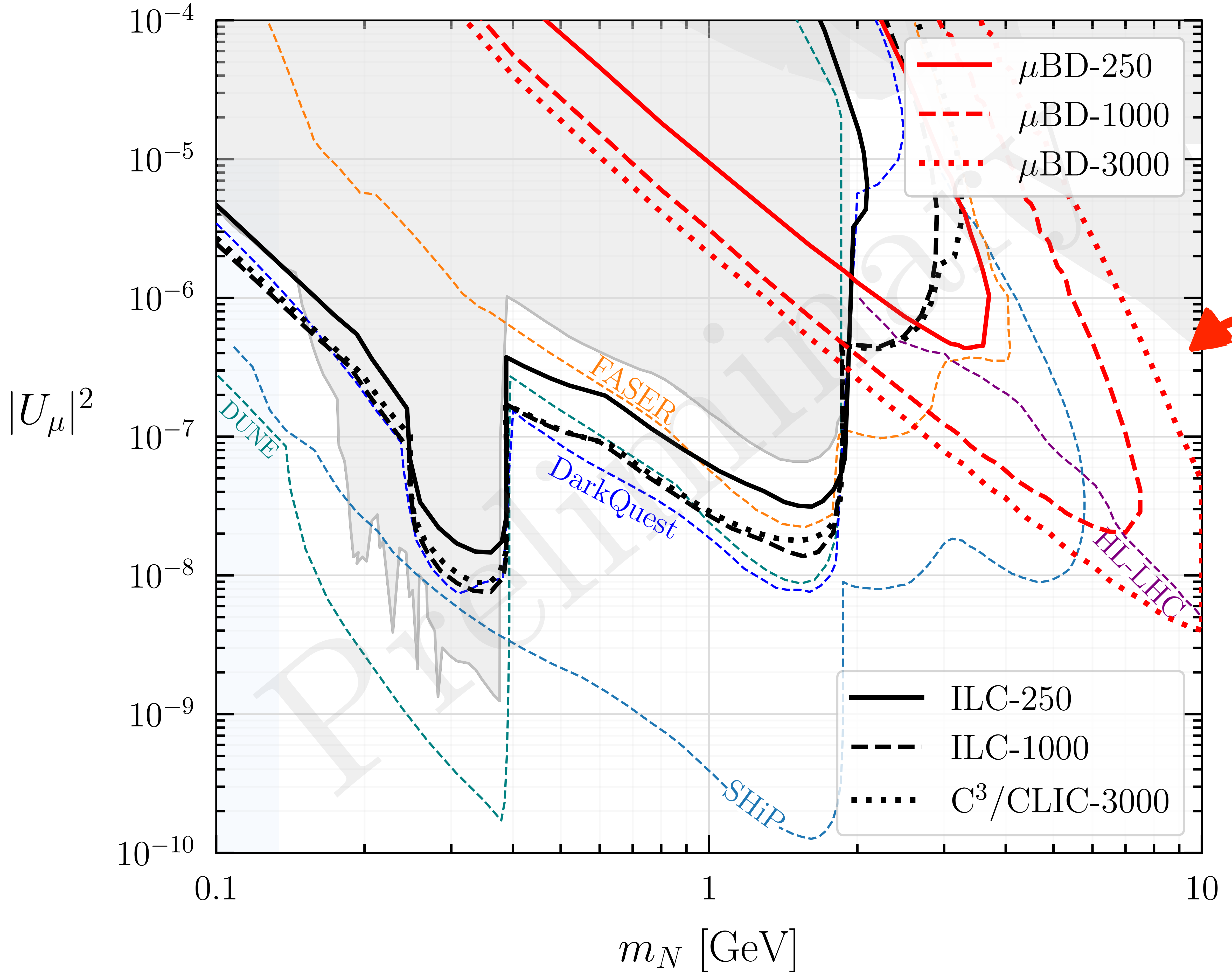
Despite the lower production rate, muon beam dump is still complementary to DarkQuest, FASER.

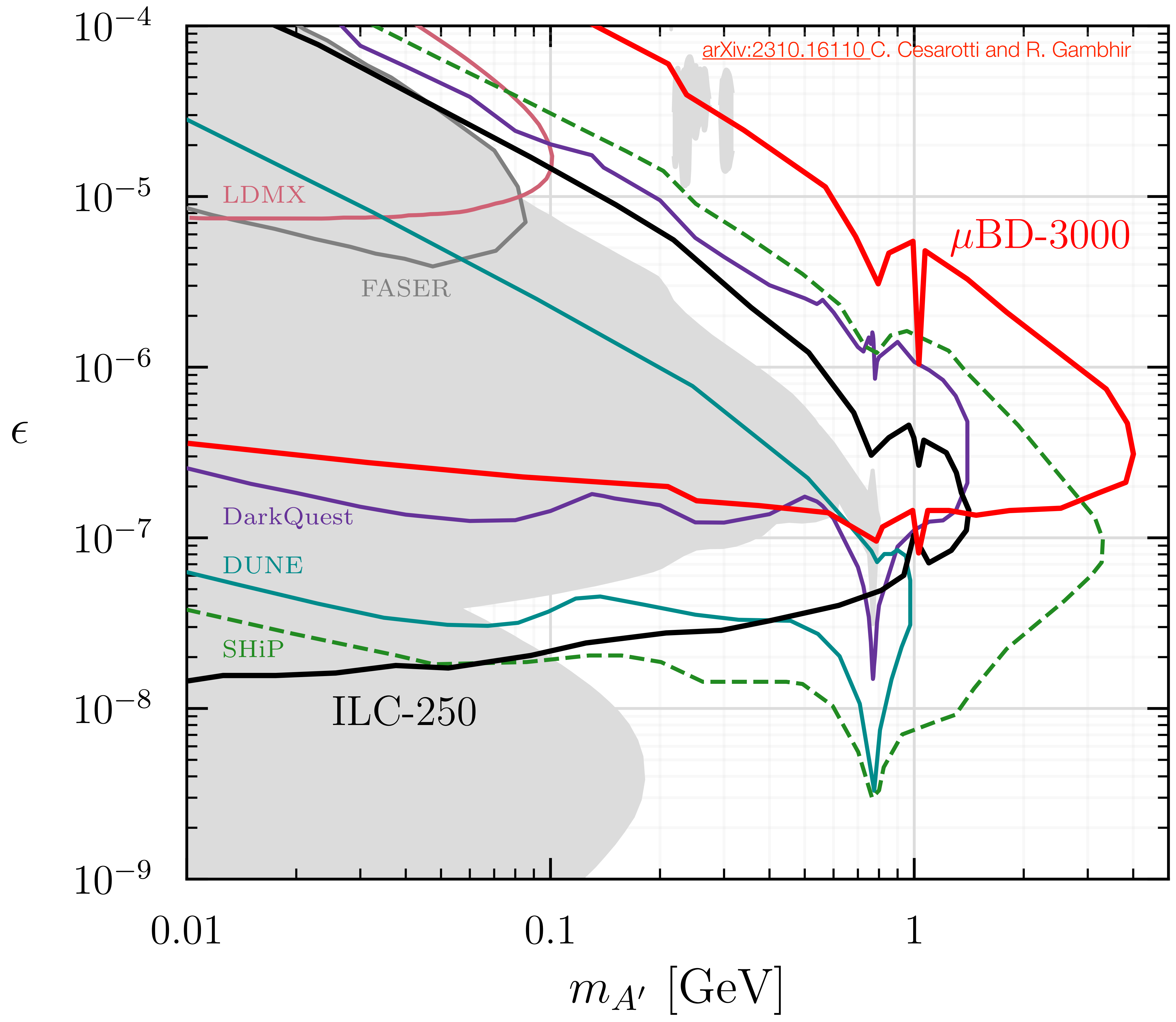
HNLs @ Muon Beam Dump

- Direct production of muon-mixed HNL via charged-current scattering is now available!



Reach beyond HL-LHC projections!

Additional Models: Dark Photons



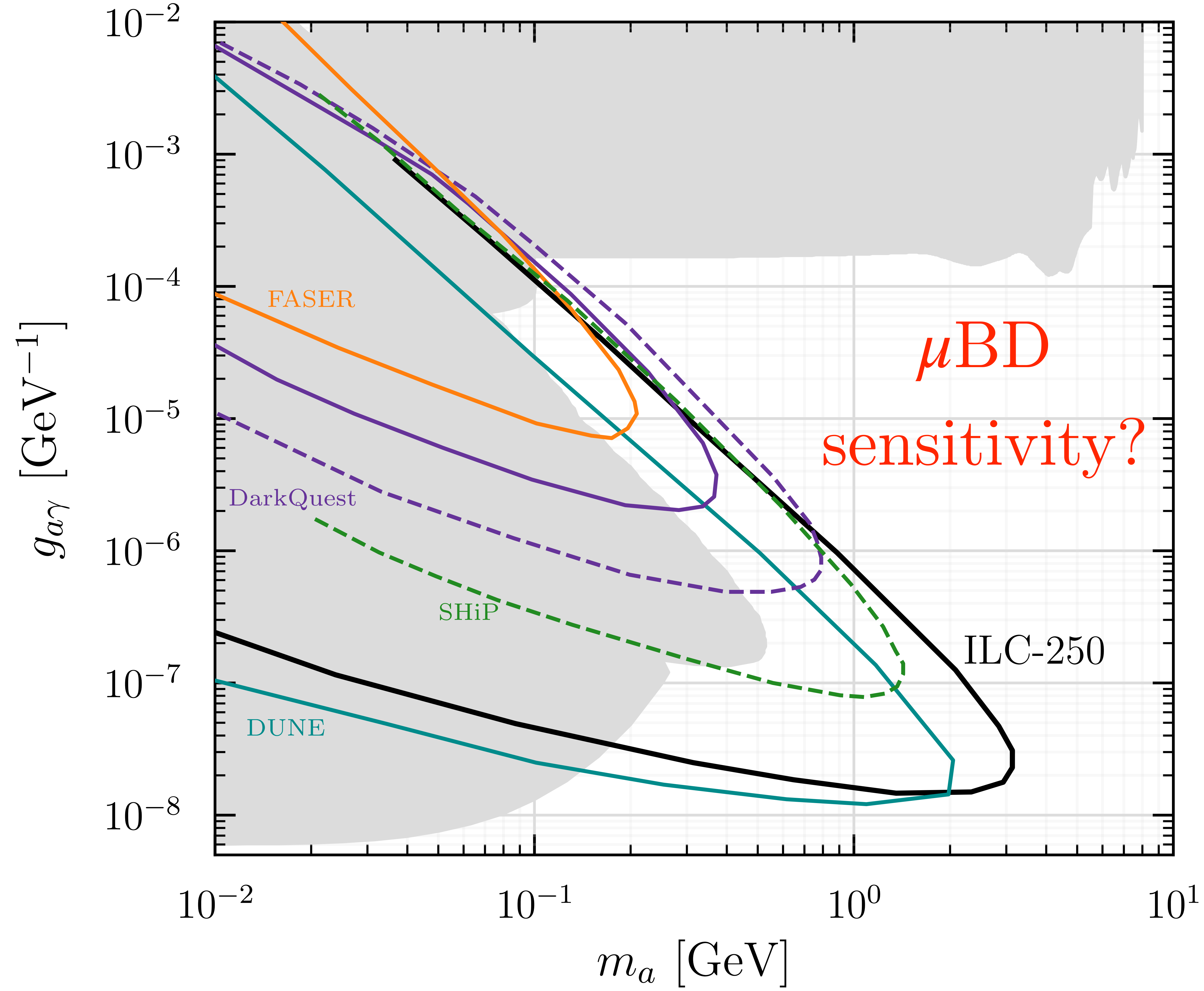
Lead Target

$E_\mu = 1.5$ TeV, $N_\mu = 10^{20}$/year

$L_{tar} = 5m, L_{sh} = 10m, L_{dec} = 100m$

Complementary reach to DarkQuest and ILC beam dump. Higher energy is important to reach higher masses.

Future work: ALPs



- Muon beam dump reach for ALPs?
  - Production via Primakoff?
  - Production from ALP-meson mixing?
- Expect similar reach to ILC beam dump; could push to higher masses
- Work in progress!
- *Other dark sector benchmarks for Muon Beam Dump physics case?*

Muon colliders are a promising direction to go in post-LHC. Staged approach to a full energy means we don't have to wait for new physics searches. Opportunities for auxiliary detectors (beam dumps, far detectors) to search for dark sectors exists, similar to ILC.

Summary

Higgs Precision

EW Physics

Heavy NP

Future Lepton Colliders
(ILC, C^3, Muon Collider)

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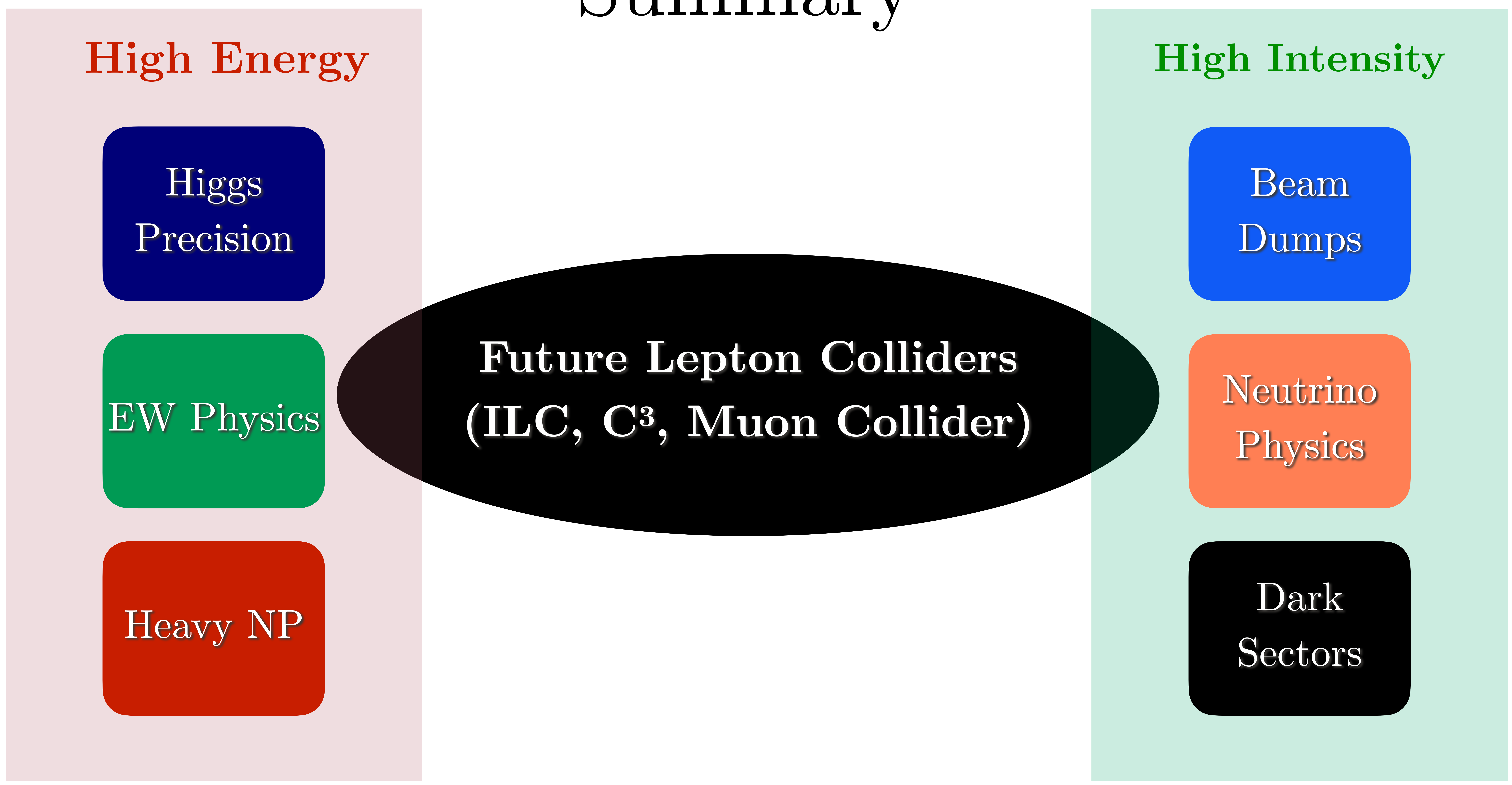
High Energy
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(ILC, C³, Muon Collider)
High Intensity
Beam Dumps
Neutrino Physics
Dark Sectors

Summary

High Energy

- Higgs Precision
- EW Physics
- Heavy NP

Future Lepton Colliders (ILC, C^3, Muon Collider)

High Intensity

- Beam Dump
- Neutrino Physics
- Dark Sectors

Opportunities for synergy between these two frontiers to maximize the physics potential

Thanks! Questions?

Back up

Meson Production

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

Pythia total hadronic cross section

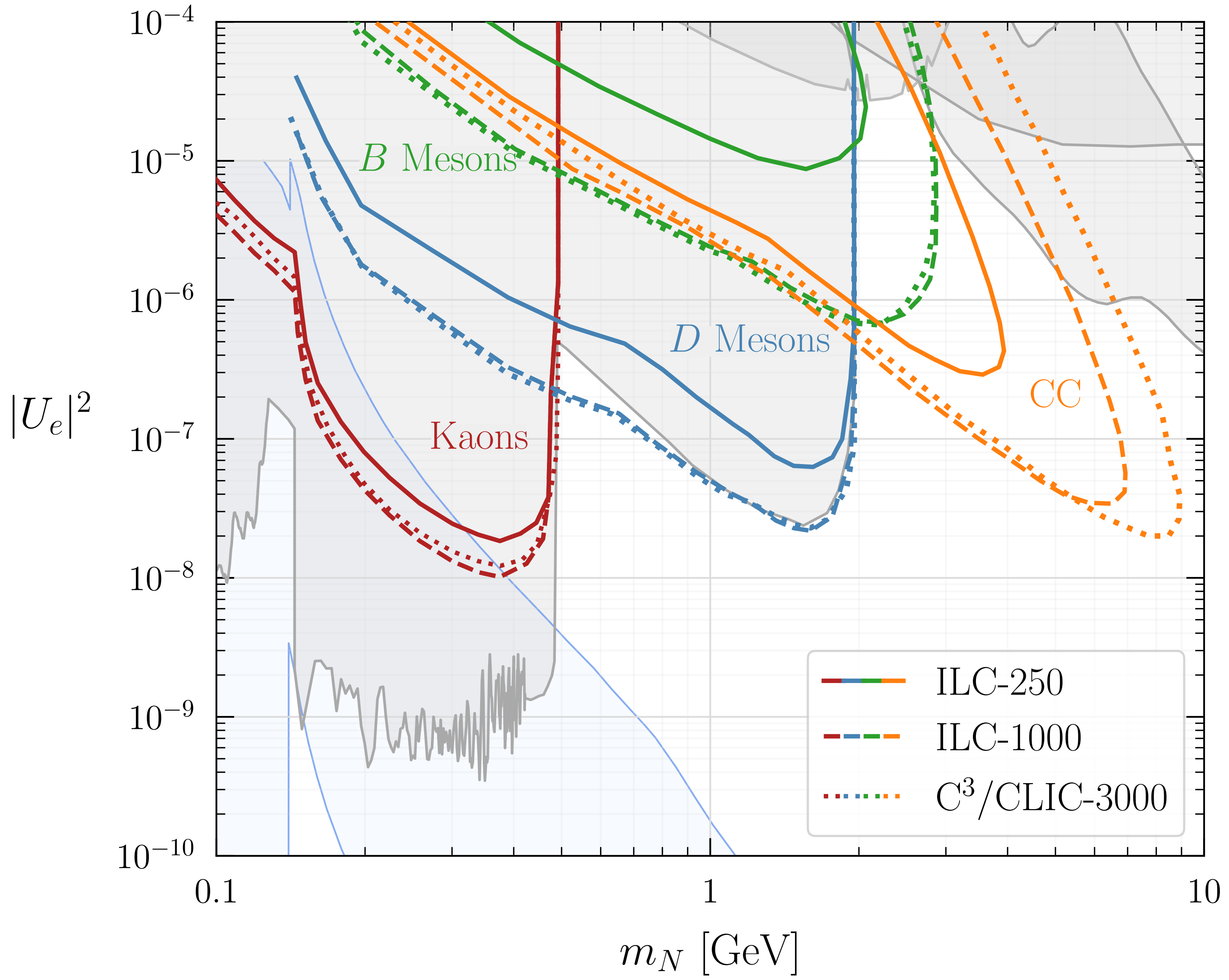
$$n_M \equiv \frac{N_M}{\mathrm{EOT}} = \frac{\sigma_{\mathrm{SoftQCD}}}{\sigma_{eN}} \frac{N_{M,\mathrm{MC}}}{N_{\mathrm{MC}}^{\mathrm{tot}}}$$

Total *ep* cross section

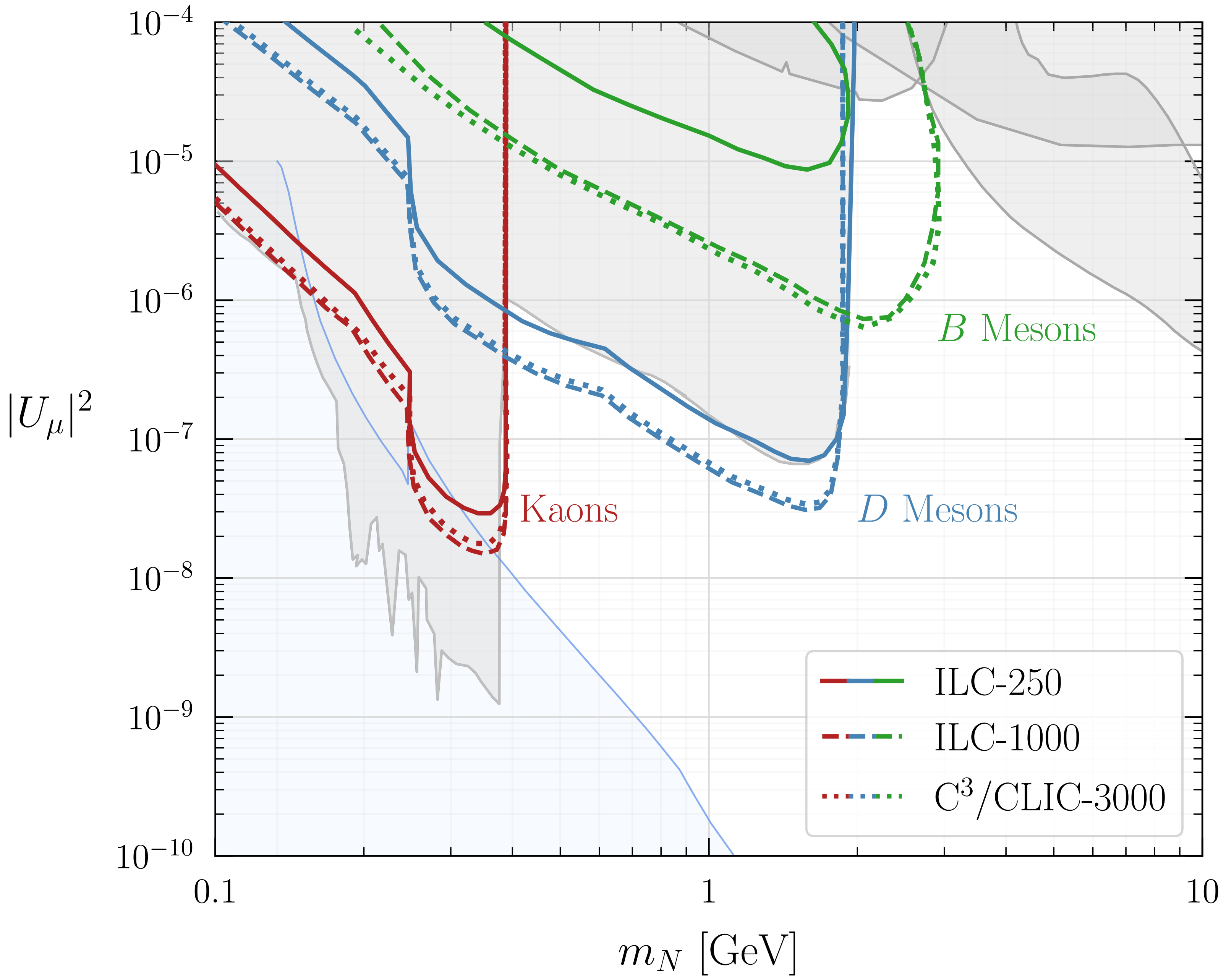
- Additional factor of cross section ratios takes into account that not all *ep* collisions are hadronic/SoftQCD interactions
  - For *pp* collisions $\sigma_{\mathrm{SoftQCD}} \approx \sigma_{pN}$

HNL Sensitivity by Production Mode

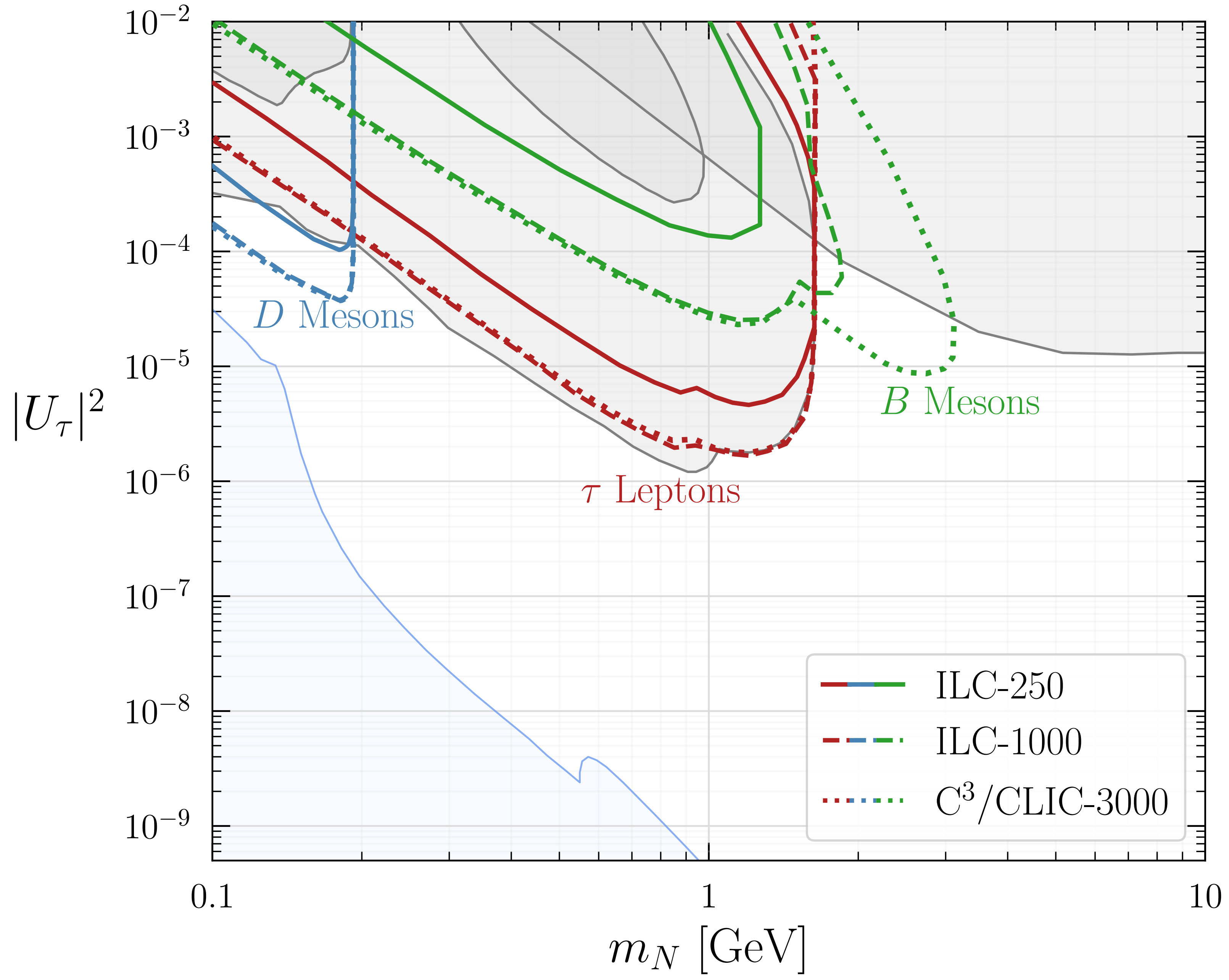
Electron-mixed HNL



Muon-mixed HNL



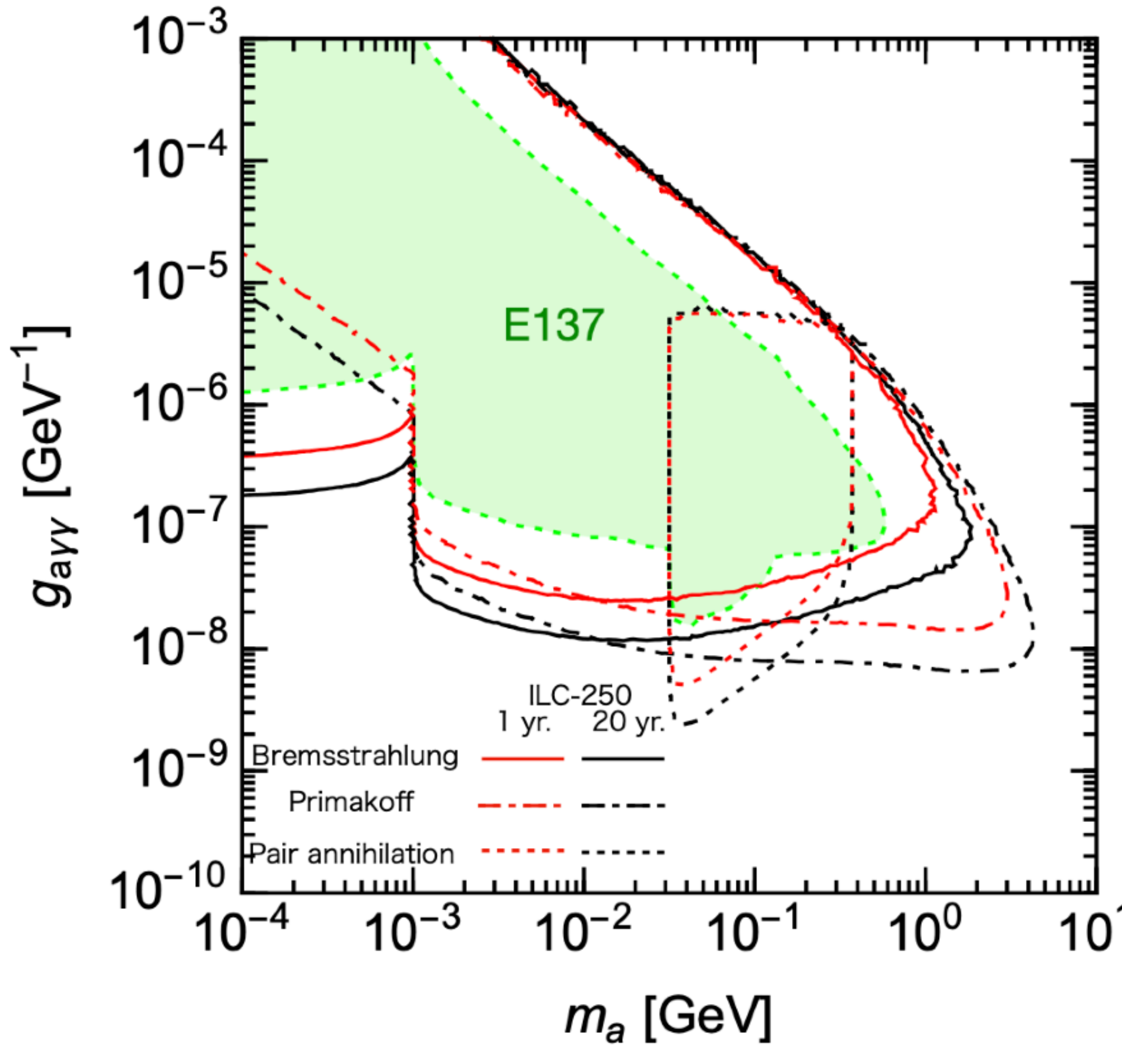
Tau-mixedHNL

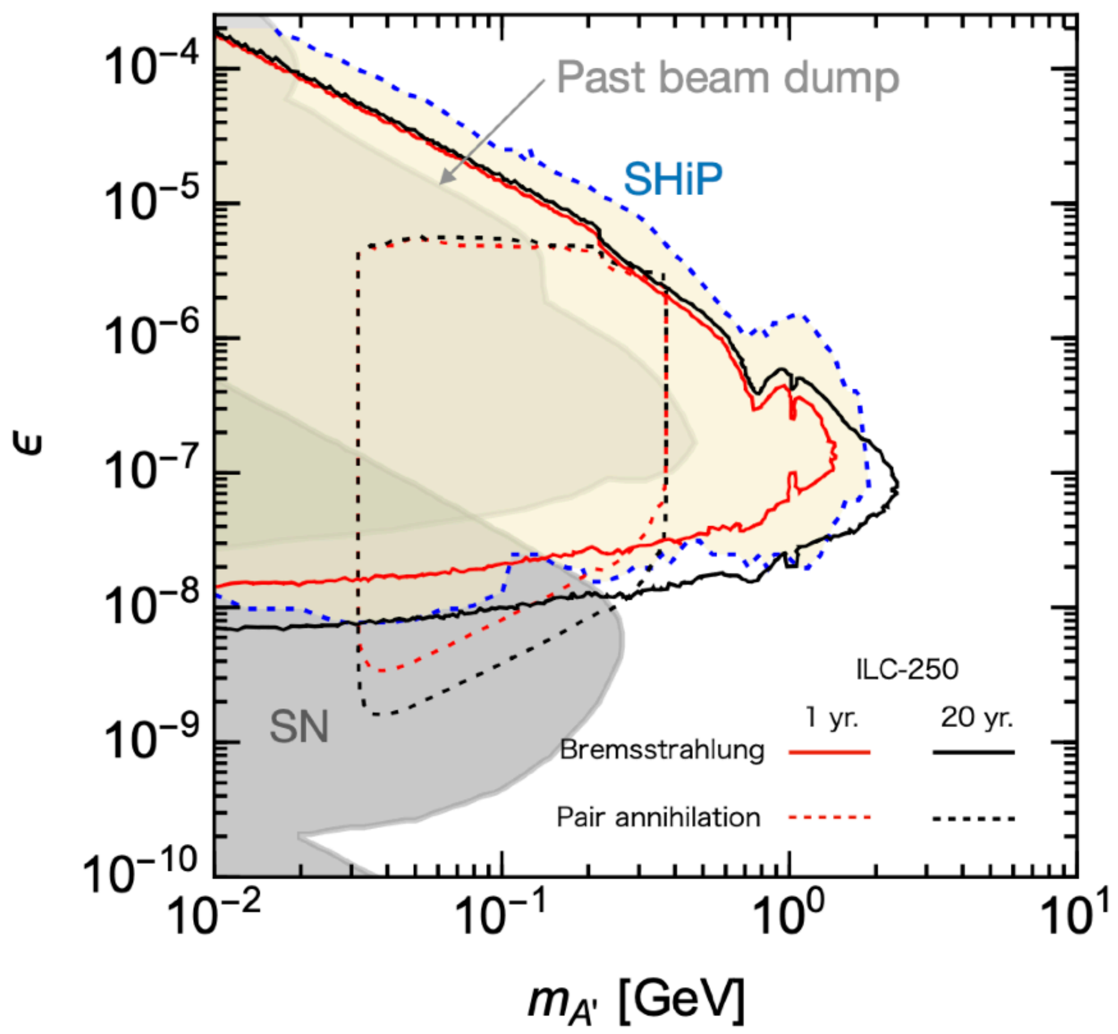


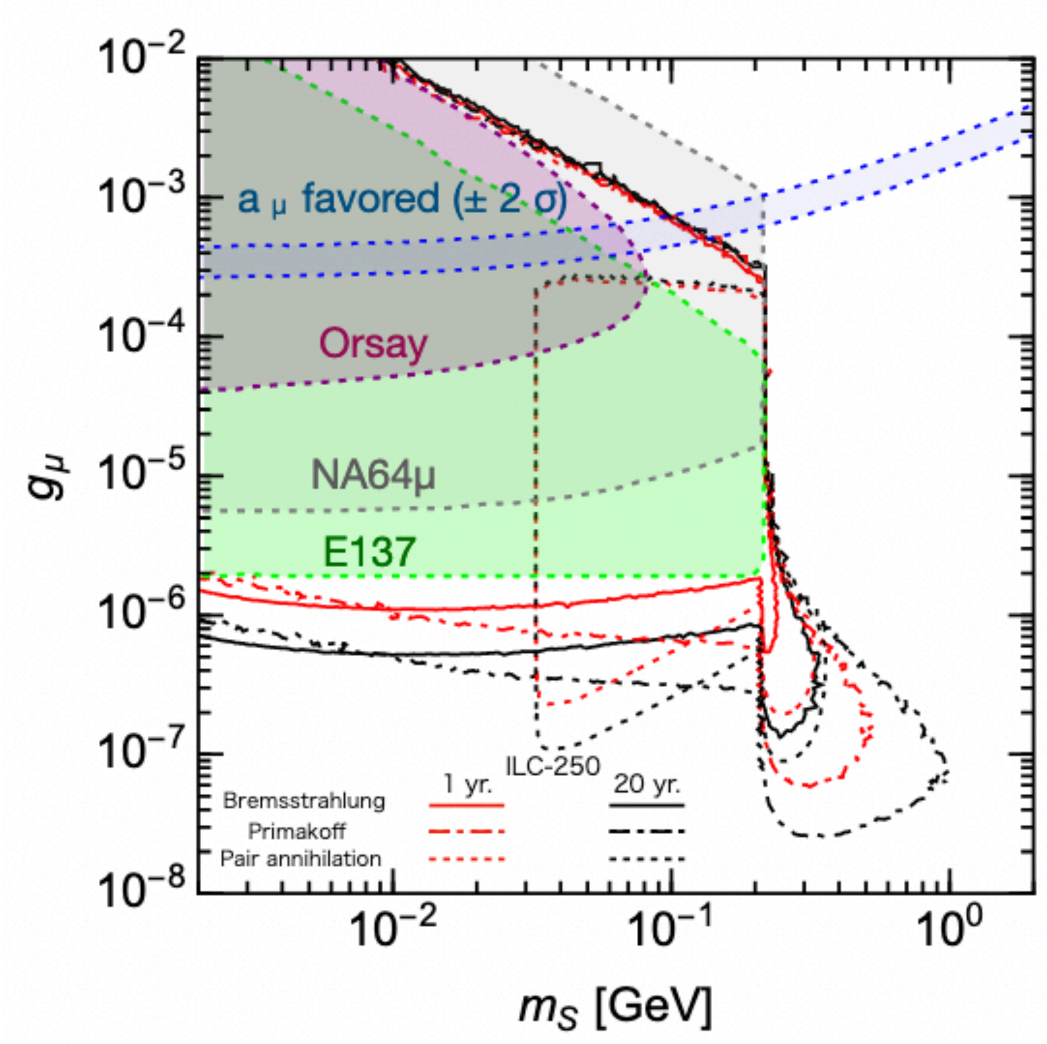
More BSM @ ILC Beam Dump

Axion-like Particles | Dark Photon | Muon-philic Scalar

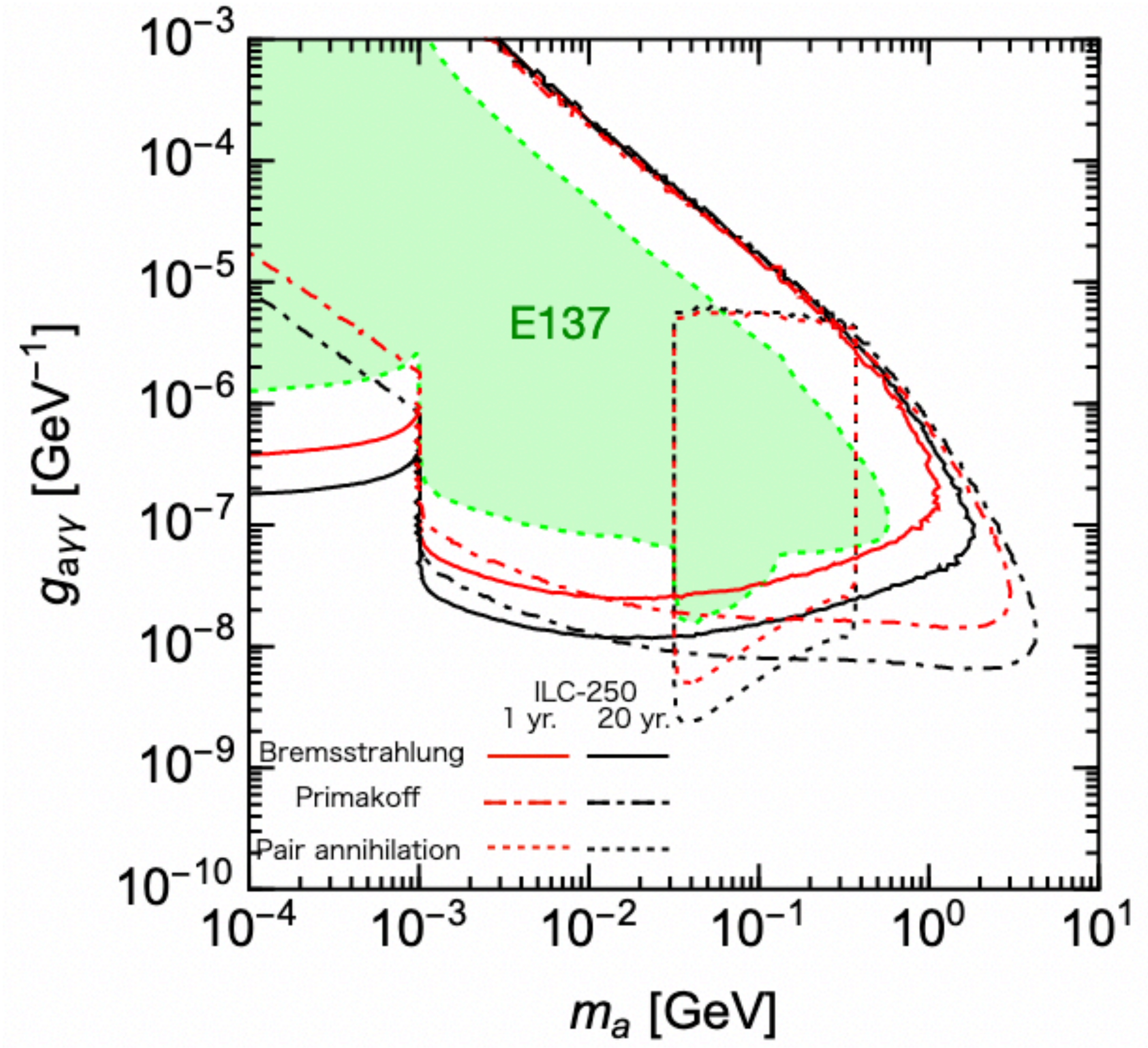
Electron Beam

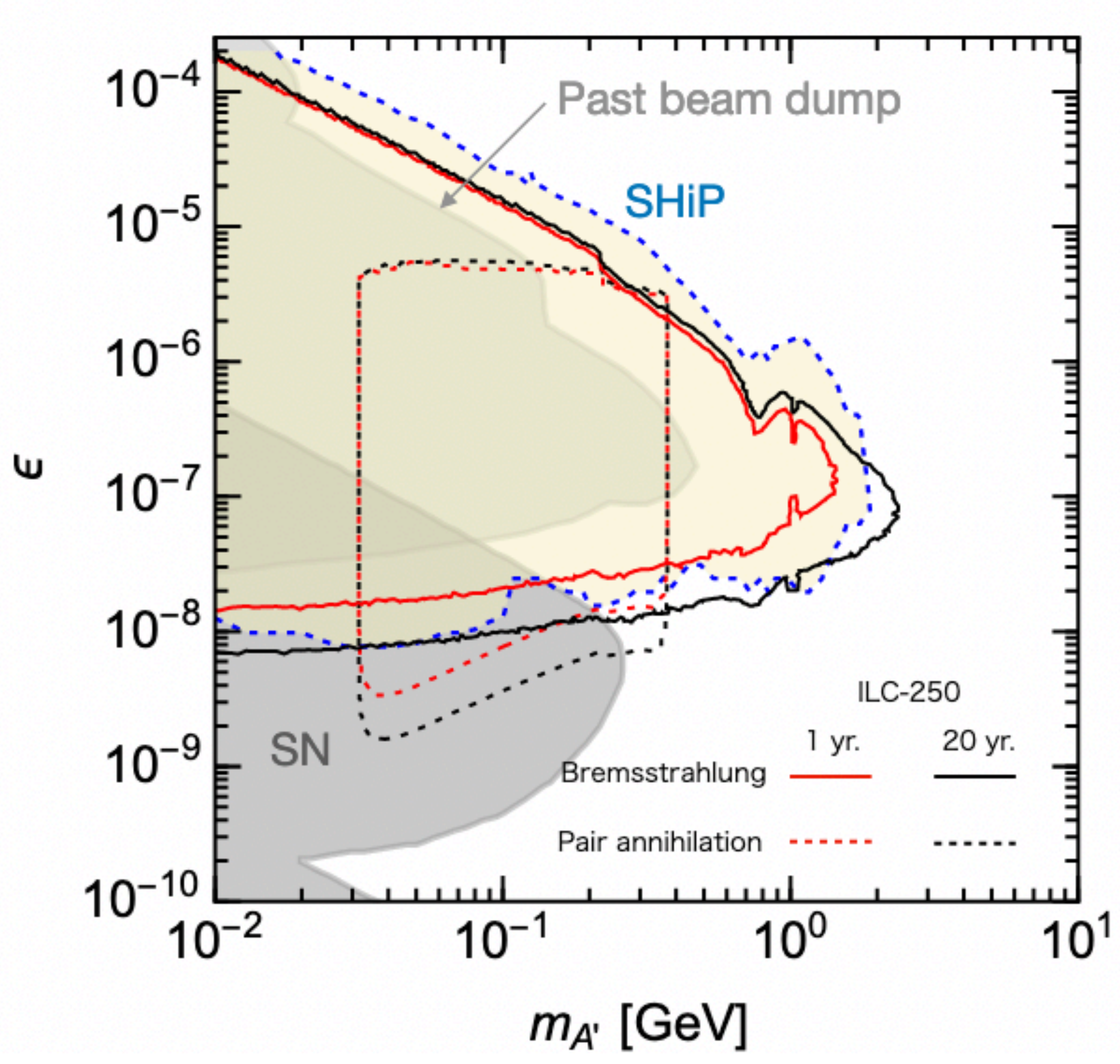


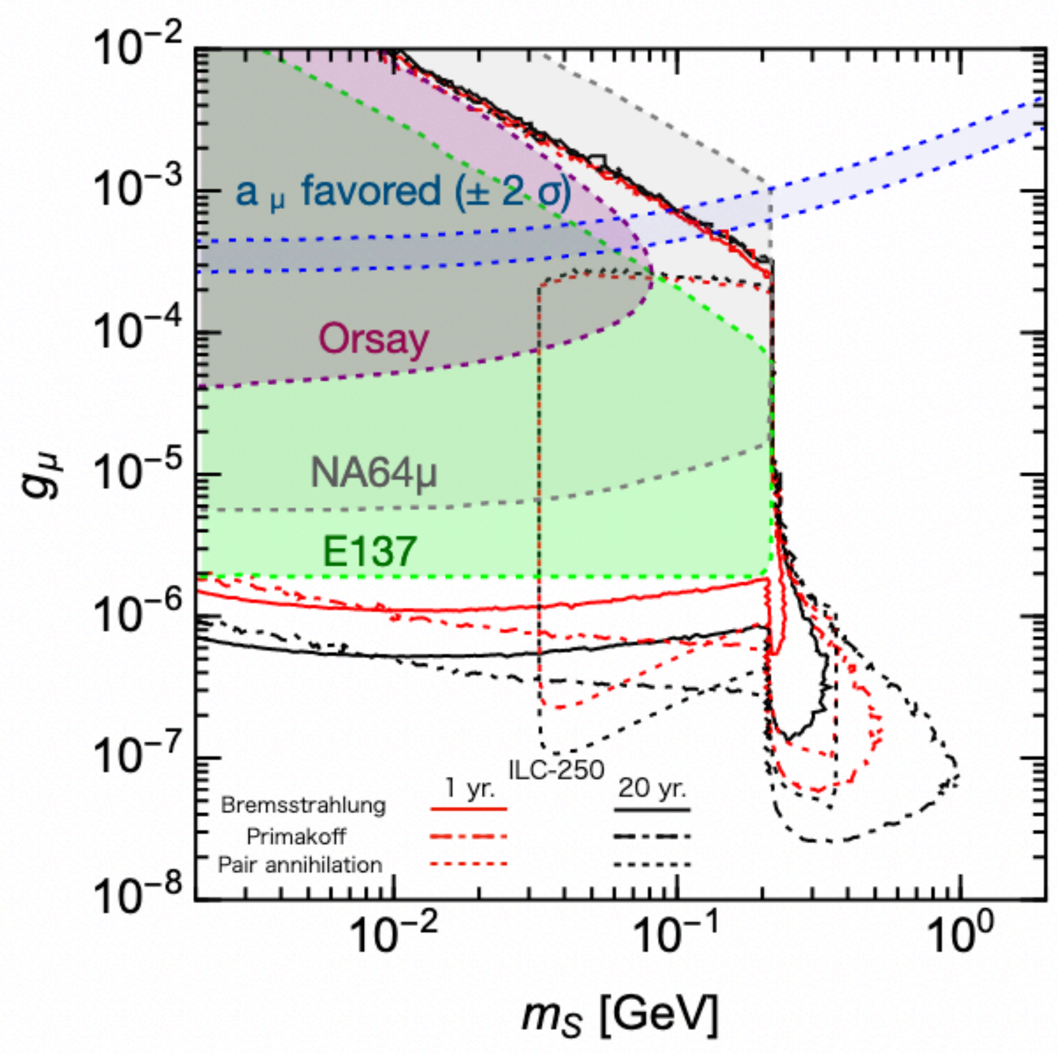




Positron Beam



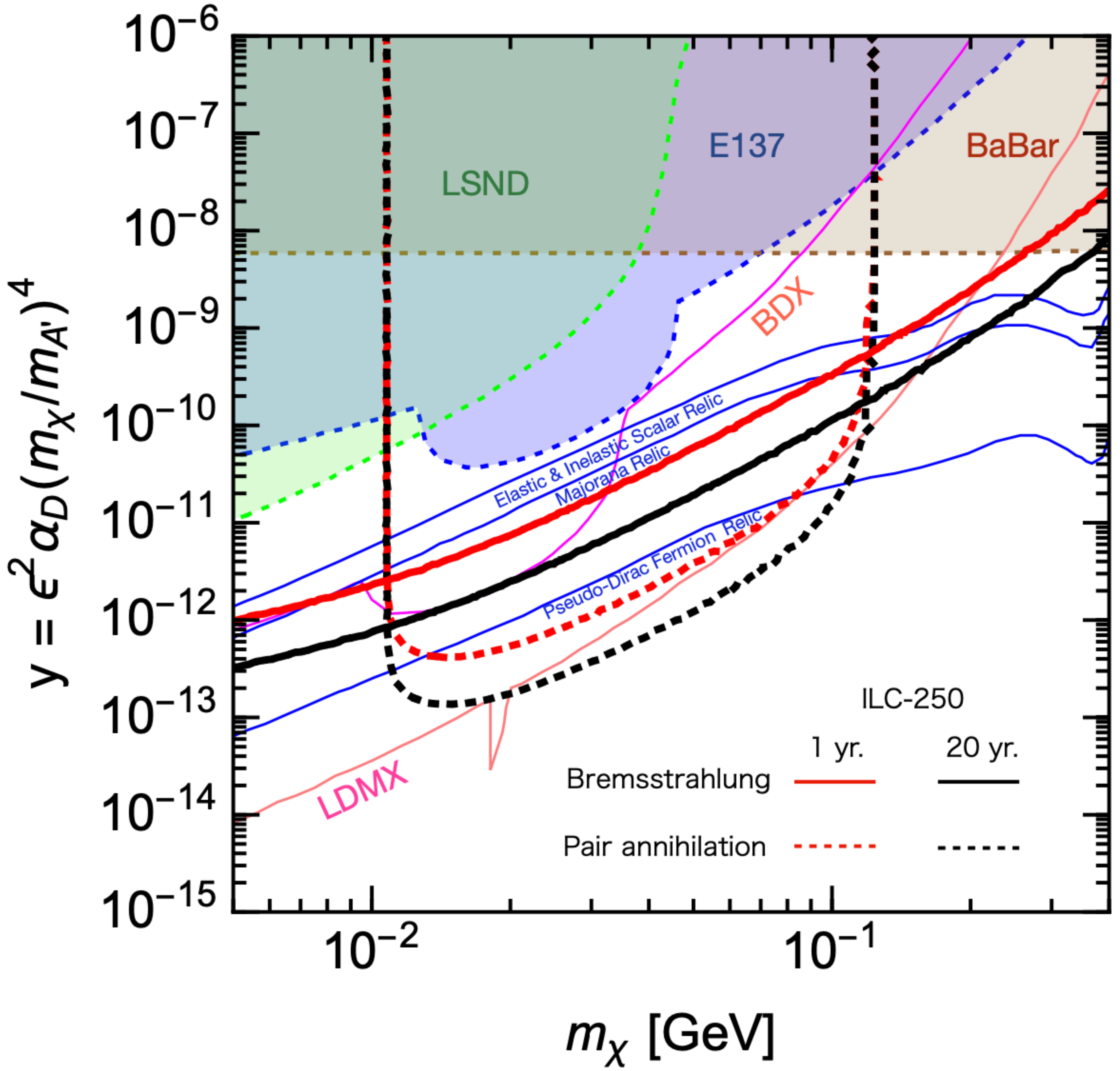




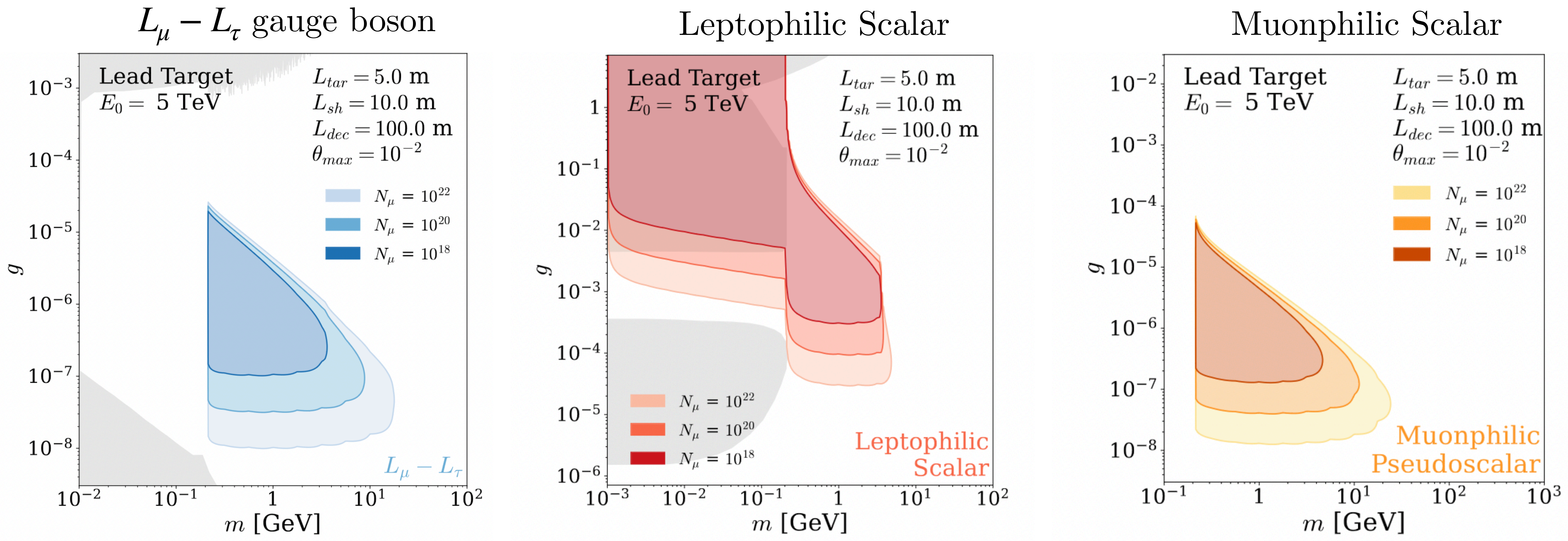
K. Asai, S. Iwamoto, Y. Sakaki, and D Ueda arXiv:2105.13768

Invisible Searches @ ILC Beam Dump

- Dark photon decays invisibly to DM particles. DM scatters in a detector far from the beam dump.



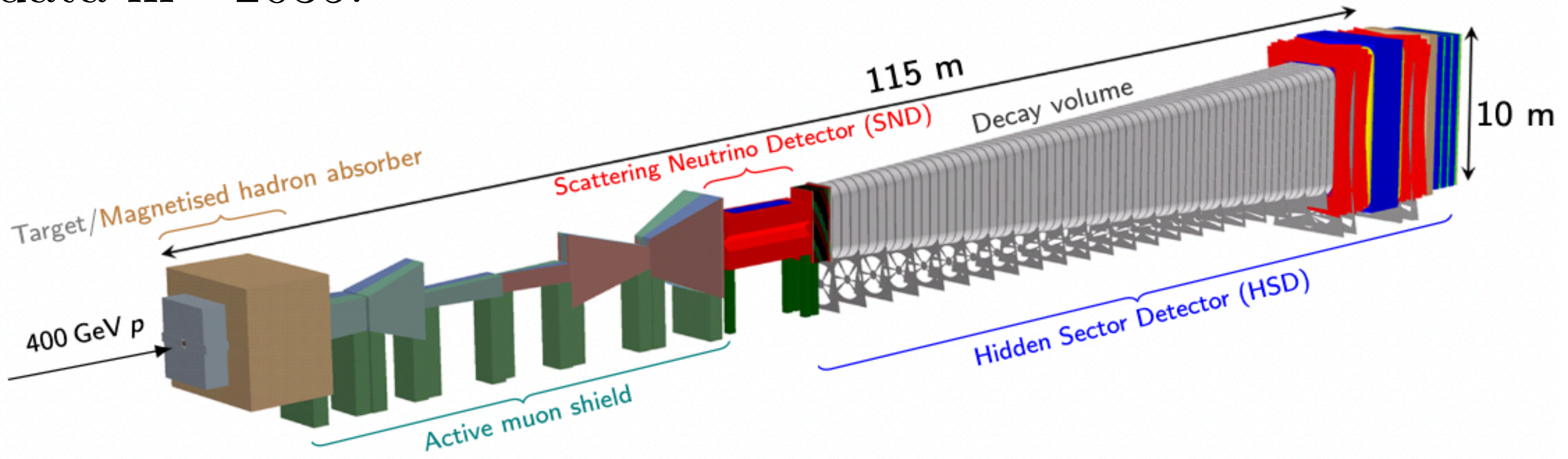
More BSM @ Muon Beam Dump



arXiv:2310.16110 C. Cesarotti and R. Gambhir

SHiP Experiment

- *SHiP has set sail!* Approved for construction. Data taking expected to start taking data in ~2035.



- Dedicated experiment at CERN for FIPs/LLPs
- High intensity proton beam: $\sim 10^{20}$ protons-on-target
- High energy: 400 GeV proton beam
- Lots of studies done to understand detector, bkgs., etc. https://cds.cern.ch/collection/SHiP%20Reports

SHiP Sensitivity

- SHiP beats most current/proposed experiments

arXiv:2207.06905 B. Batell, N. Blinov, C. Hearty, and R. McGehee