Dark Sectors at Future Lepton Beam Dump Experiments

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Physics Potential of Future Collider
TRIUMF Theory Workshop
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How do we maximize the physics potential of future colliders?

How do we maximize the physics potential of future colliders?

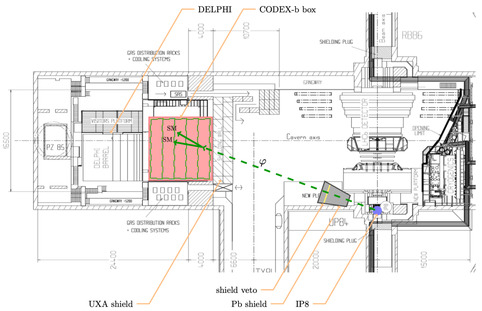
Auxiliary Detectors!

Detectors *outside* the main interaction point

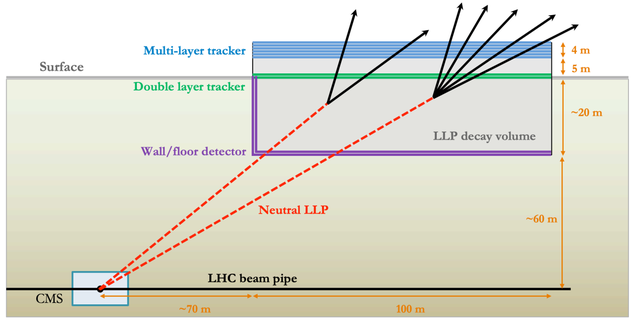
Auxiliary@LHC

PROPOSED

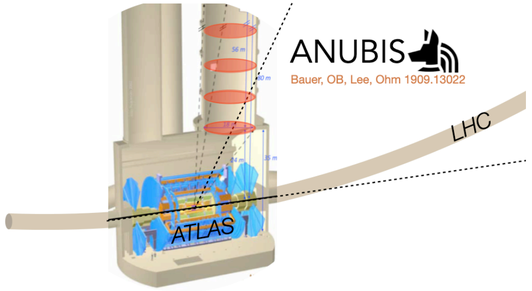
CODEX-b



MATHUSLA



ANUBIS

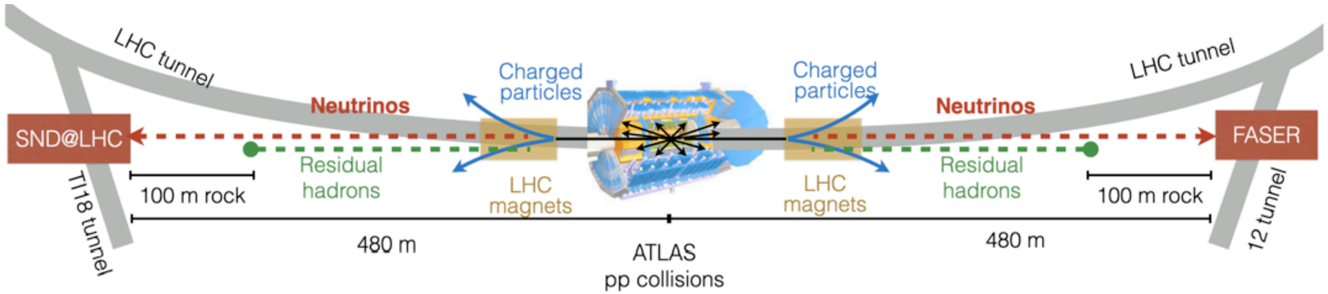


[See Caleb's talk on Wednesday!]

EXISTING

LHC

Scattering and Neutrino Detector
at the LHC



FASER

[See Roshan's talk on Thurs.]

Auxiliary@LHC

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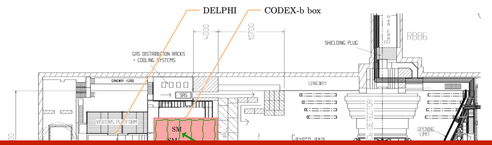

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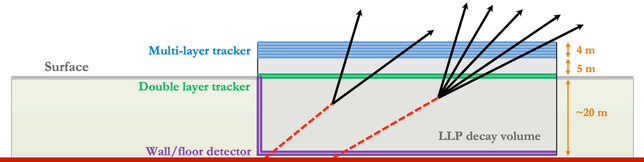

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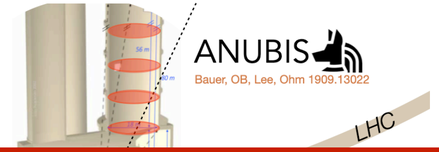

We should do this at future colliders!

EXISTING

LHC

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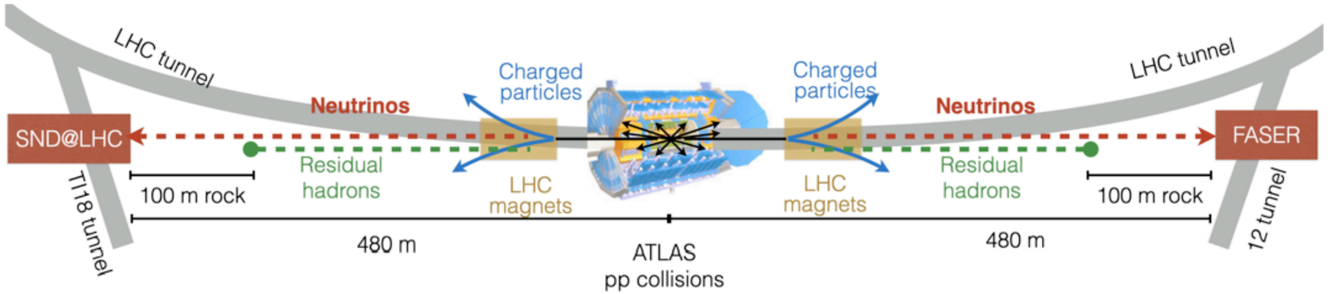

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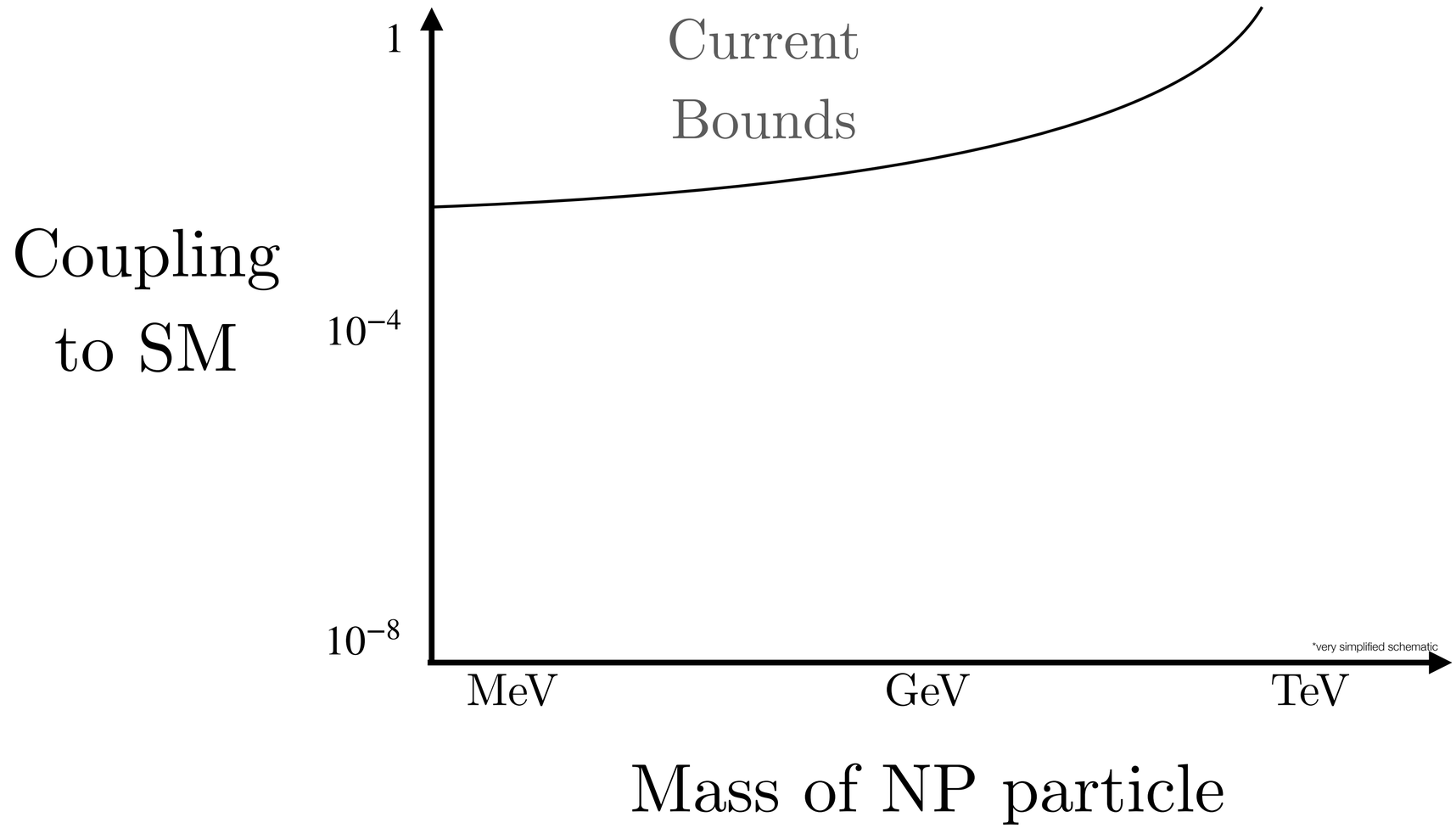
Searching for New Physics

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



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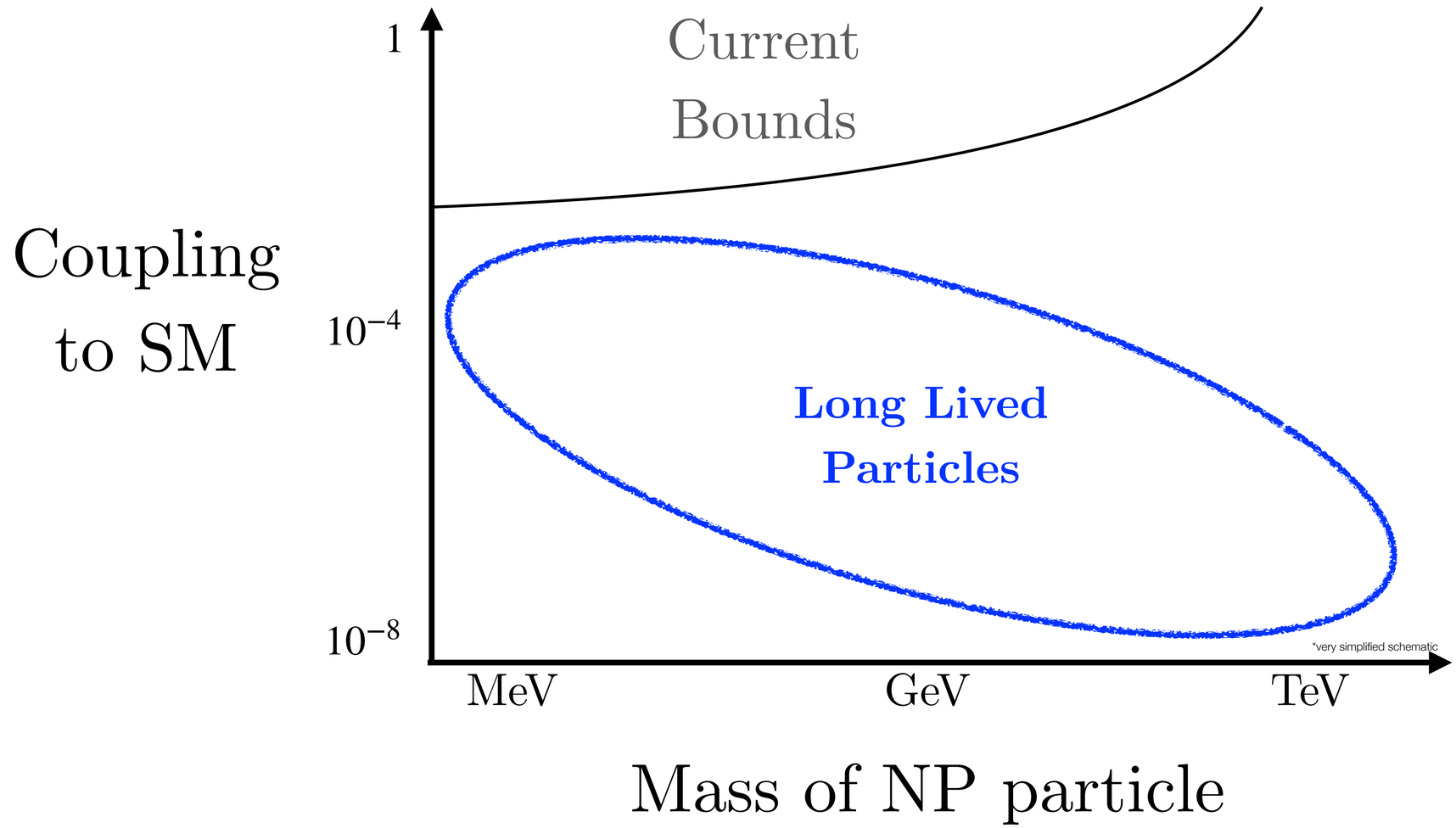

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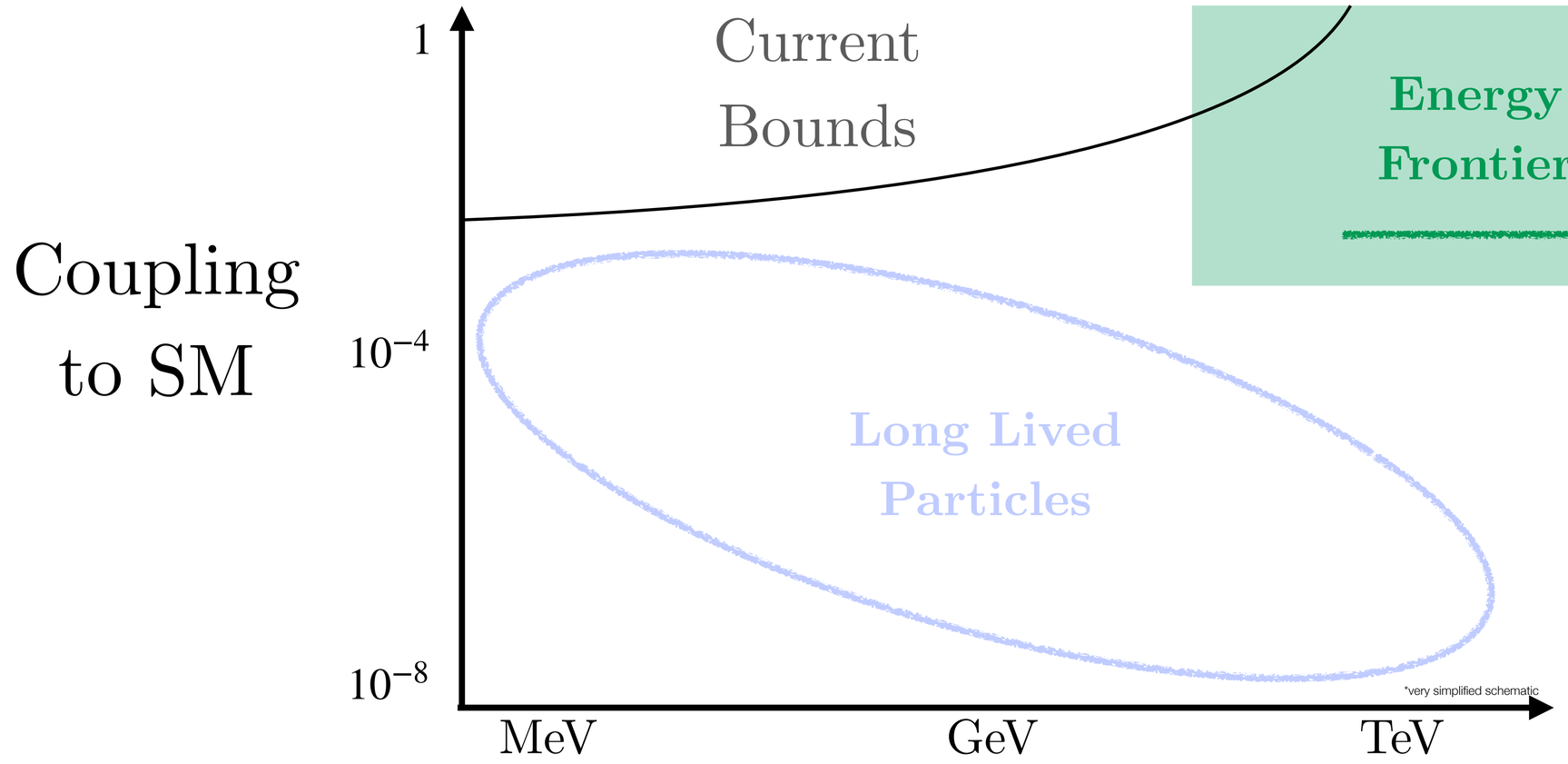

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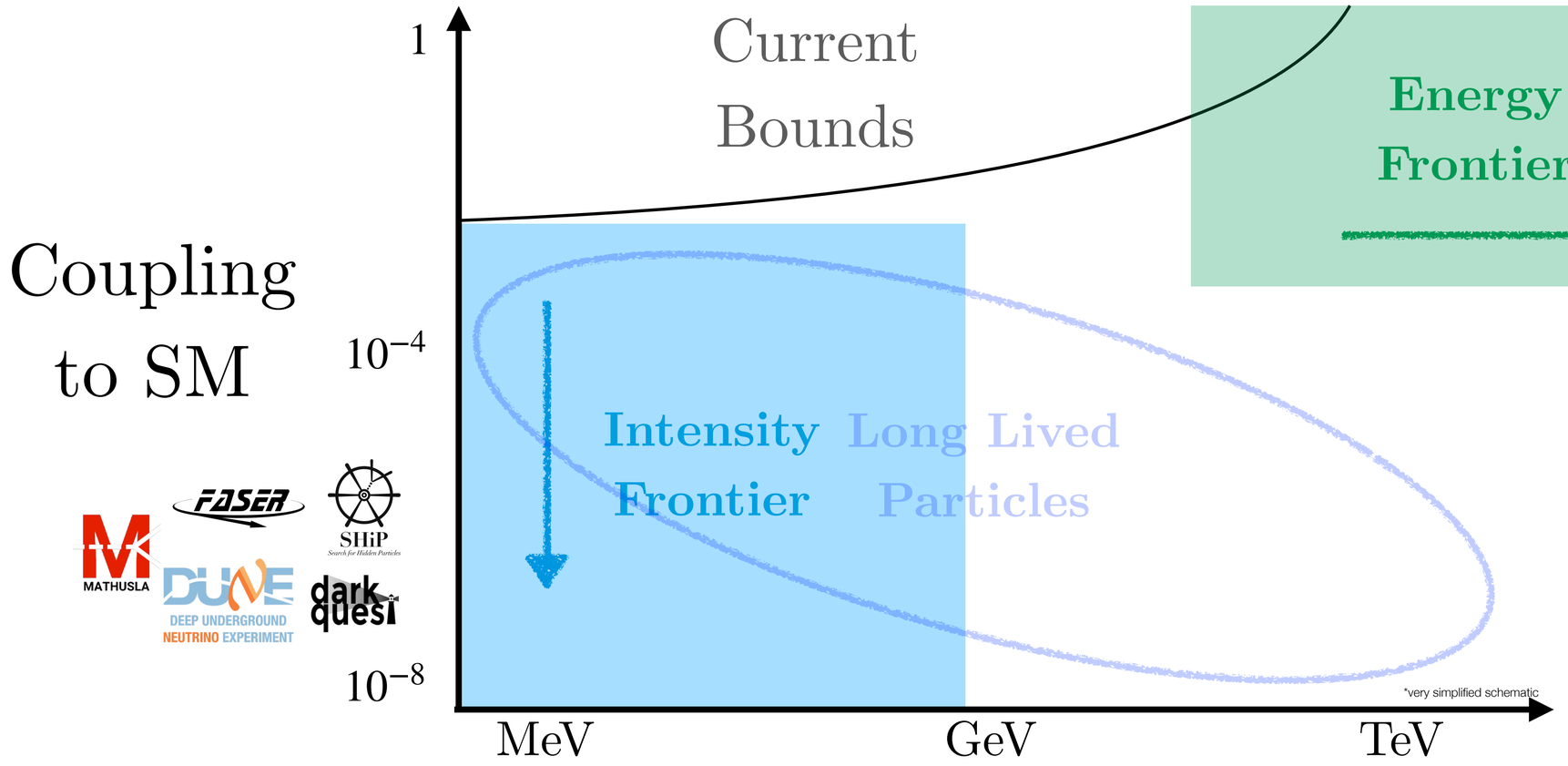

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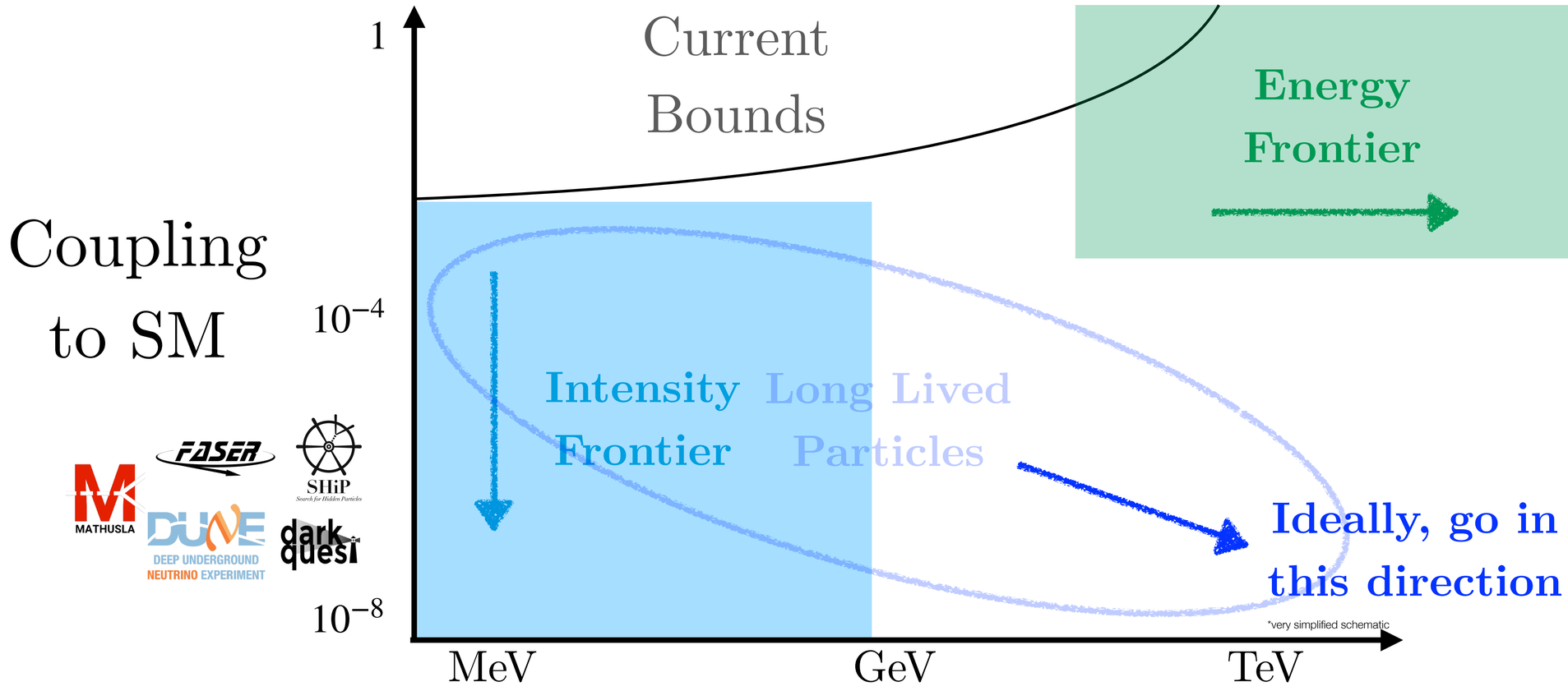


Future e^+e^- Colliders

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

250/500/1000 GeV

International Linear Collider

380/3000 GeV

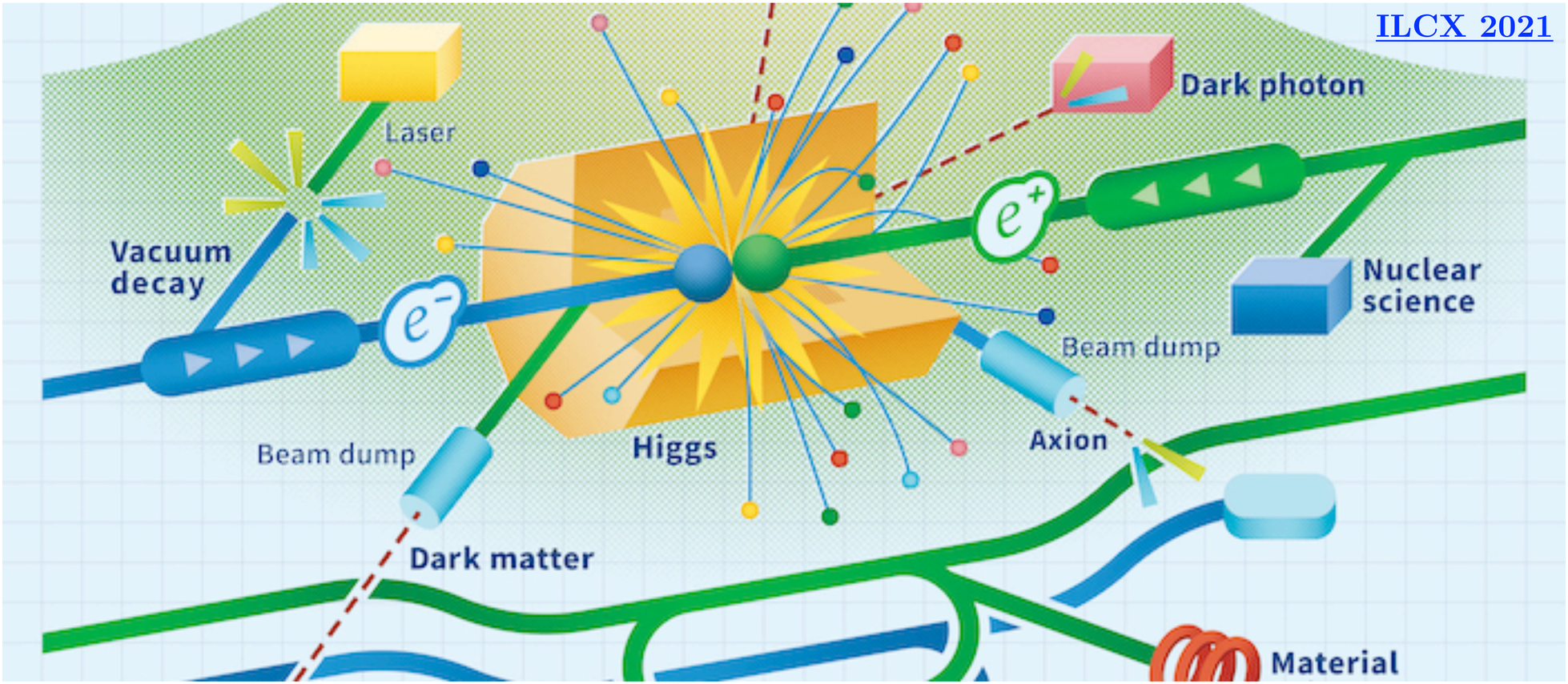
Compact Linear Collider

250/550/3000 GeV

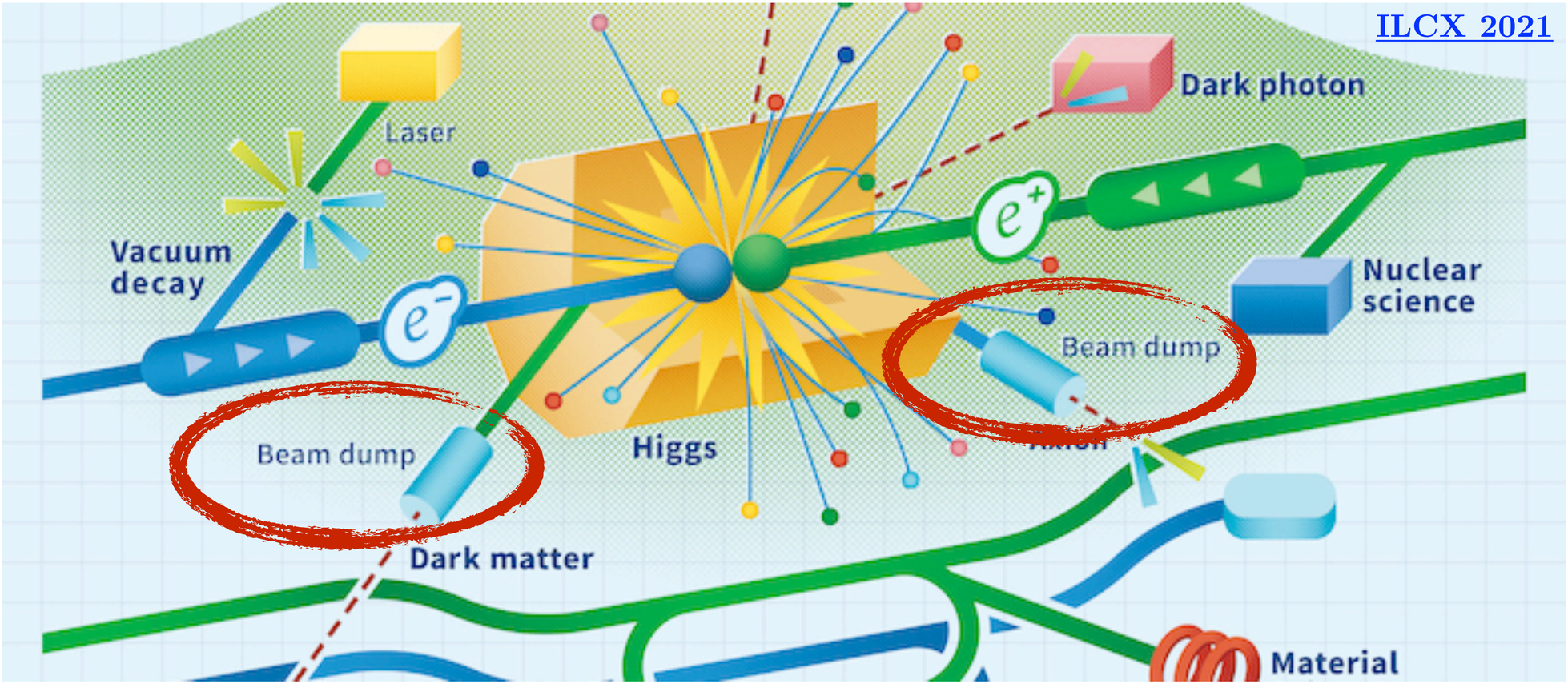
Cool Copper Collider

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

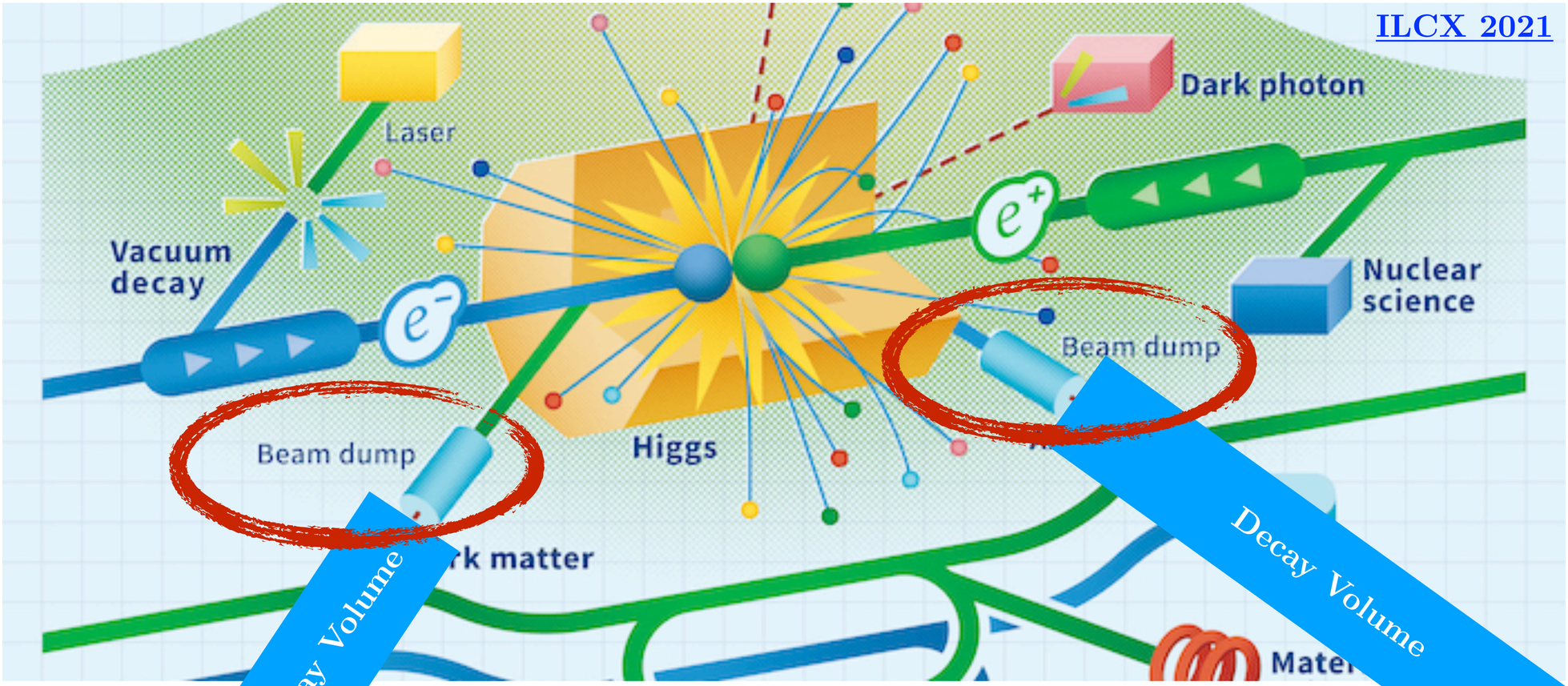
Future e^+e^- Colliders



Future e^+e^- Colliders



Future e^+e^- Colliders



Advantages of Future Electron Colliders

High Energy

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

High Intensity

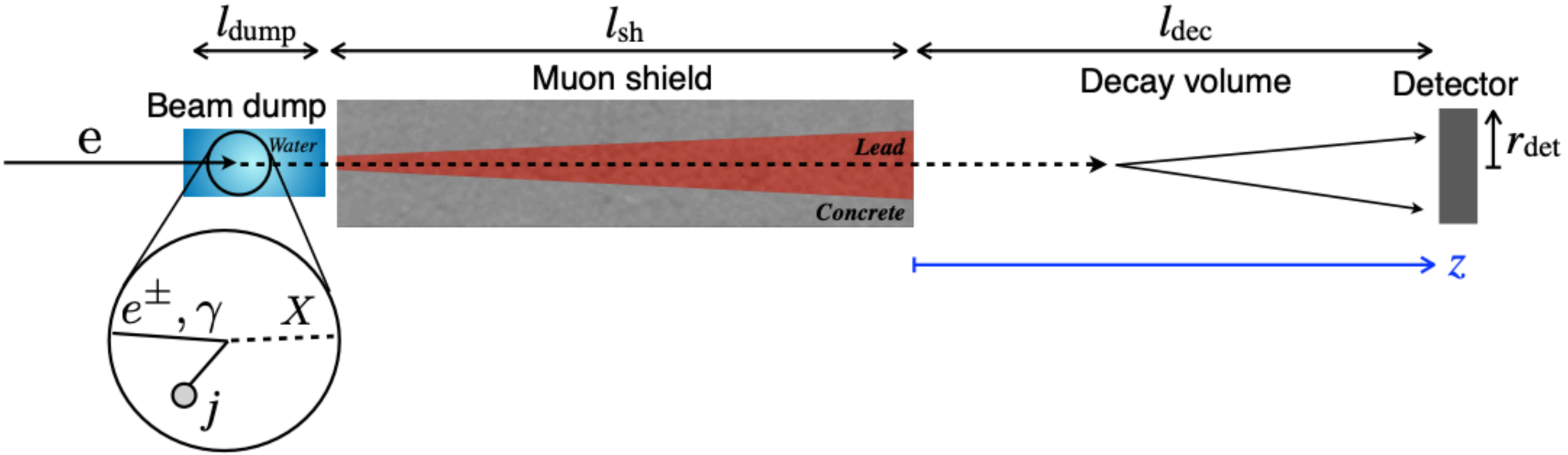
Collider-$\sqrt{s}$ [GeV]	EOT/year
ILC-250/1000	4.1×10^{21}
C^3-250	3.1×10^{21}
C^3-3000	1.8×10^{21}
CLIC-3000	1.8×10^{21}

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

New Production Modes

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

Electron Beam Dump Set Up

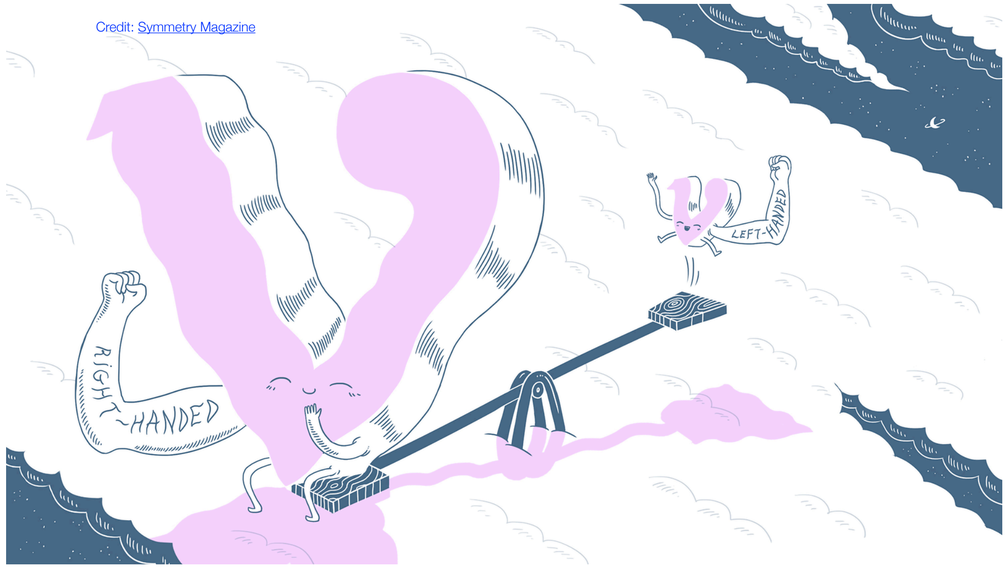


E_e [GeV]	$\ell_{\rm dump}$	$\ell_{\rm sh}$	$\ell_{\rm dec}$	$r_{\rm det}$
125 500 1500	10m	70m	50m	2m

Case Study: Heavy Neutral Leptons

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

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



- Weak interactions induced by mixing with active neutrinos
- HNL is produced in any process where a SM neutrino is produced

HNL Production in Electron Beam Dump

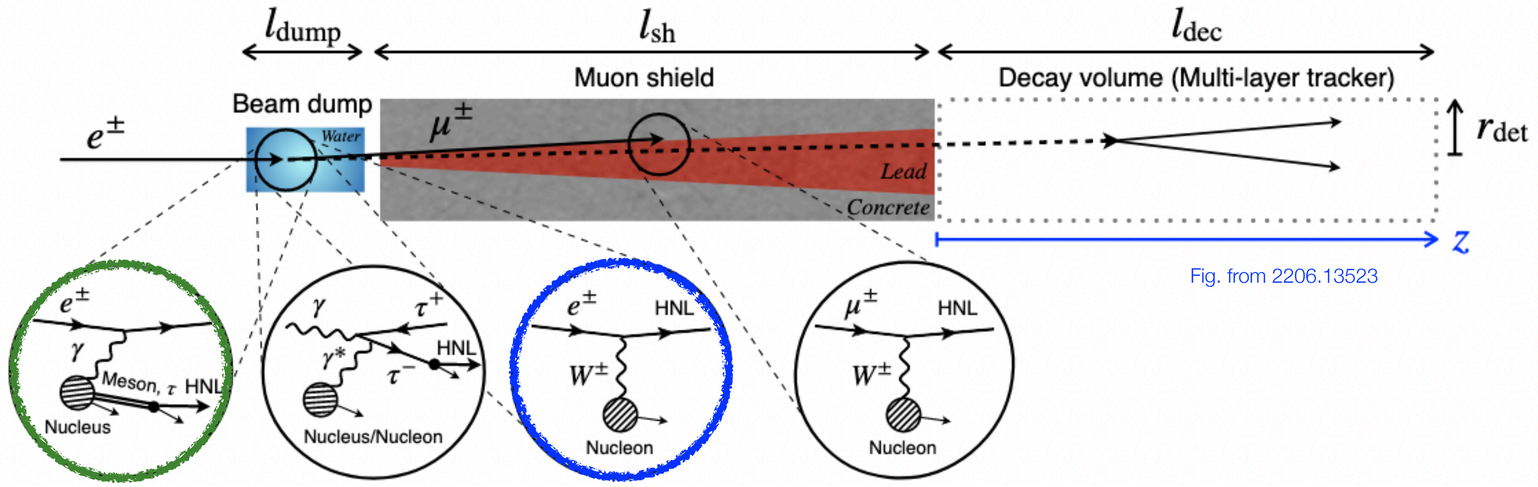
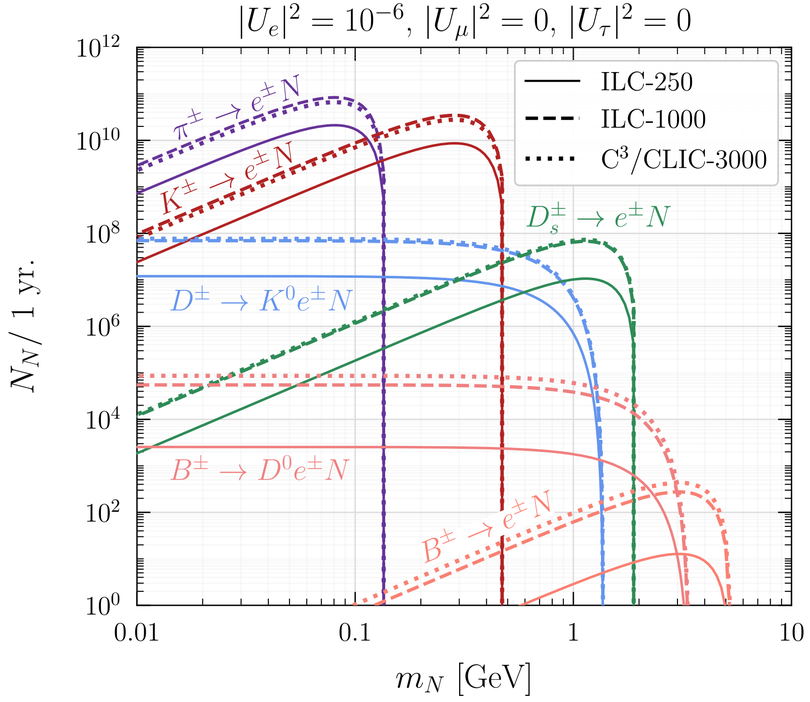
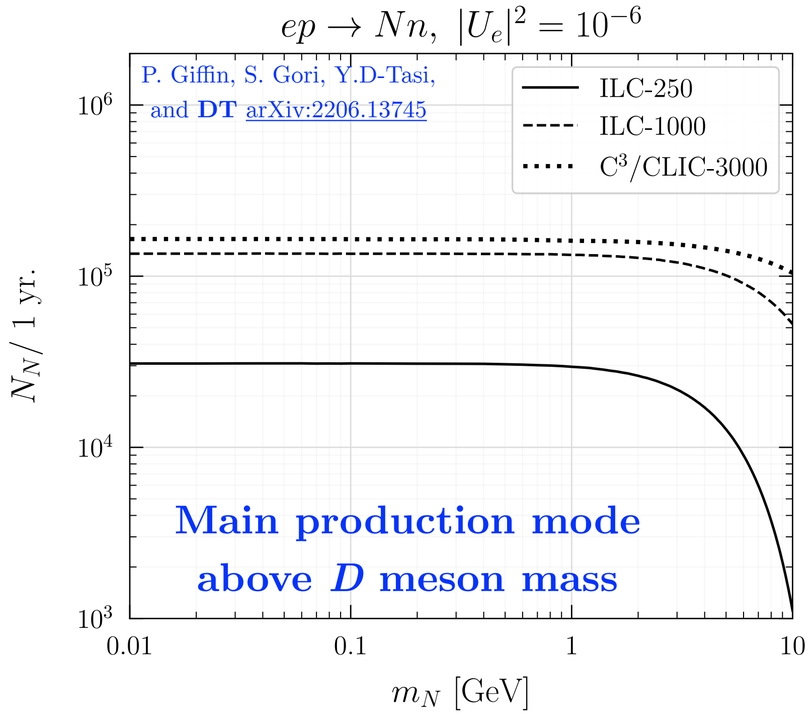


Fig. from 2206.13523

Meson Decays

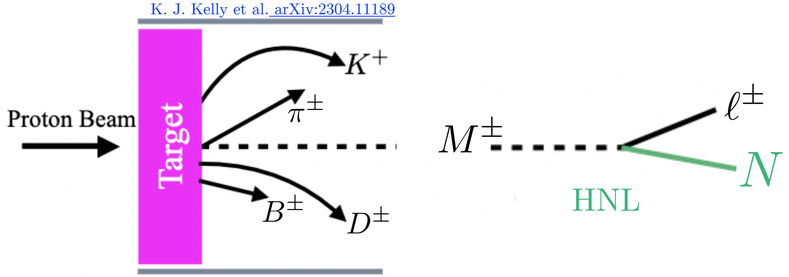


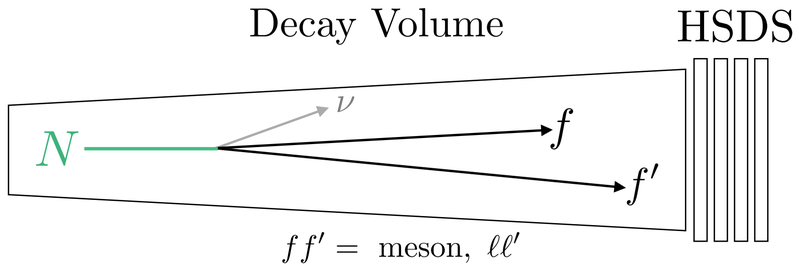


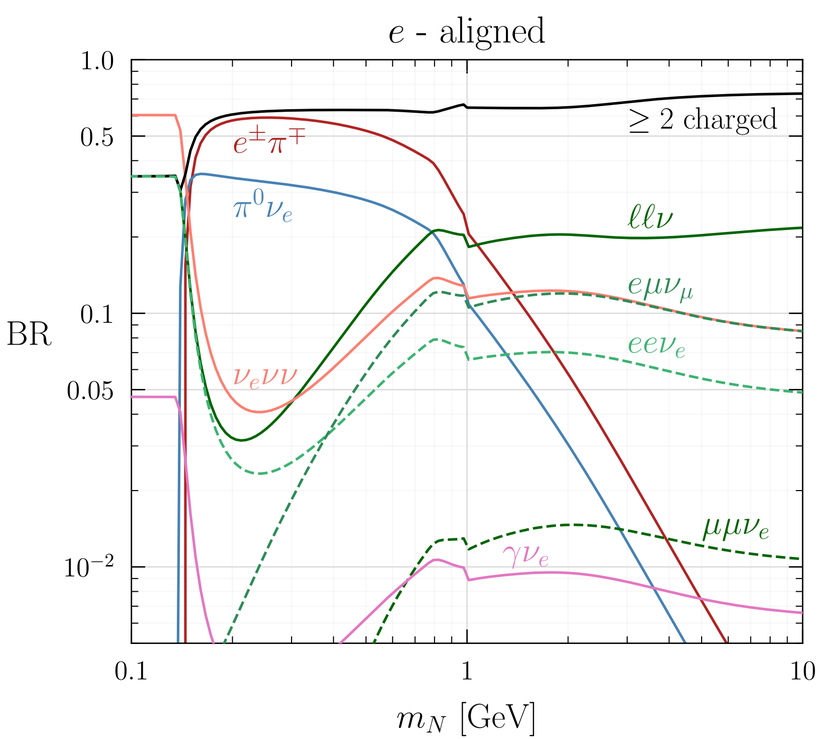
Direct CC Production

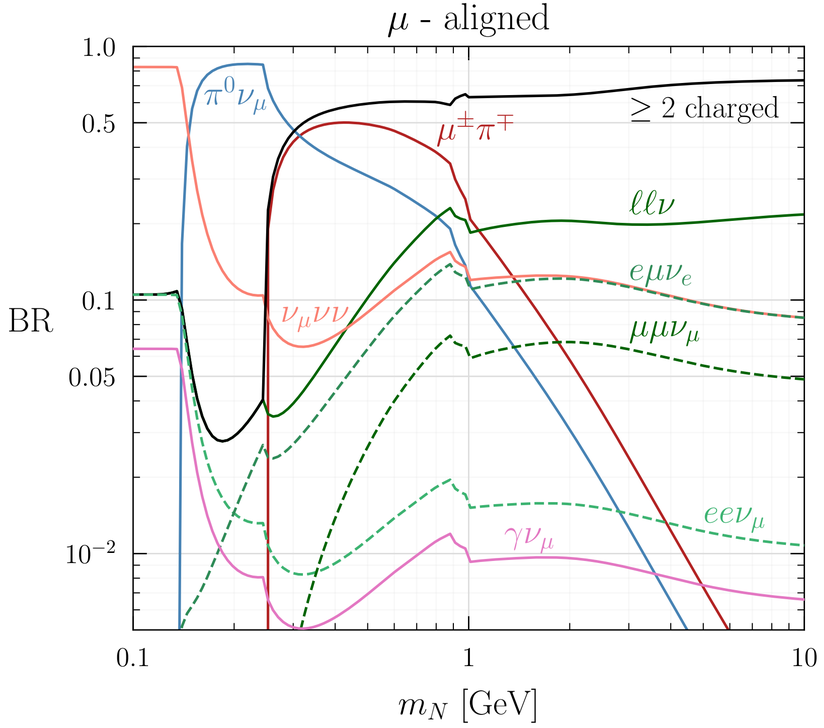
HNL Decays

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



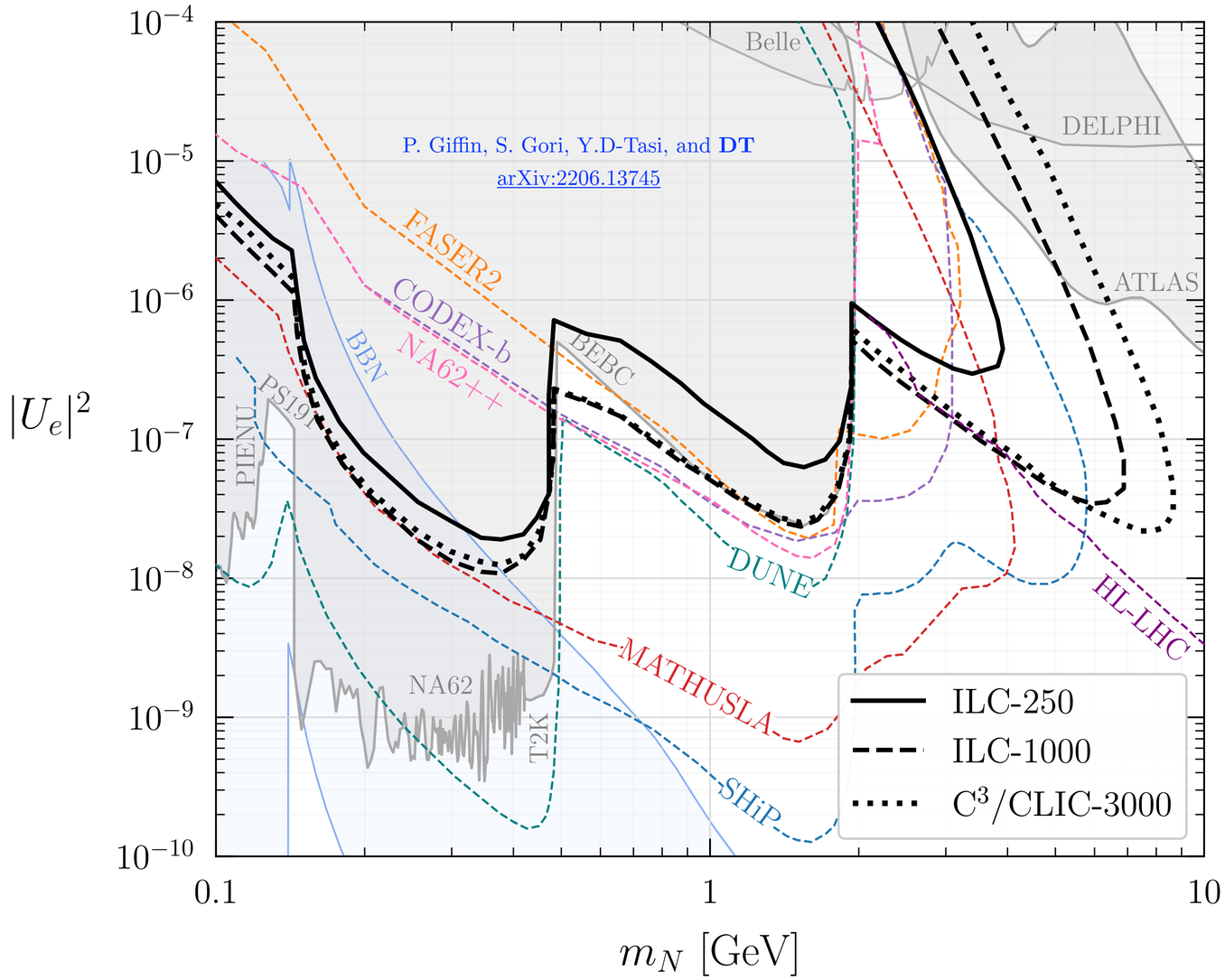






Look for two charged particles in the final state

Sensitivity: Electron Mixed HNLs



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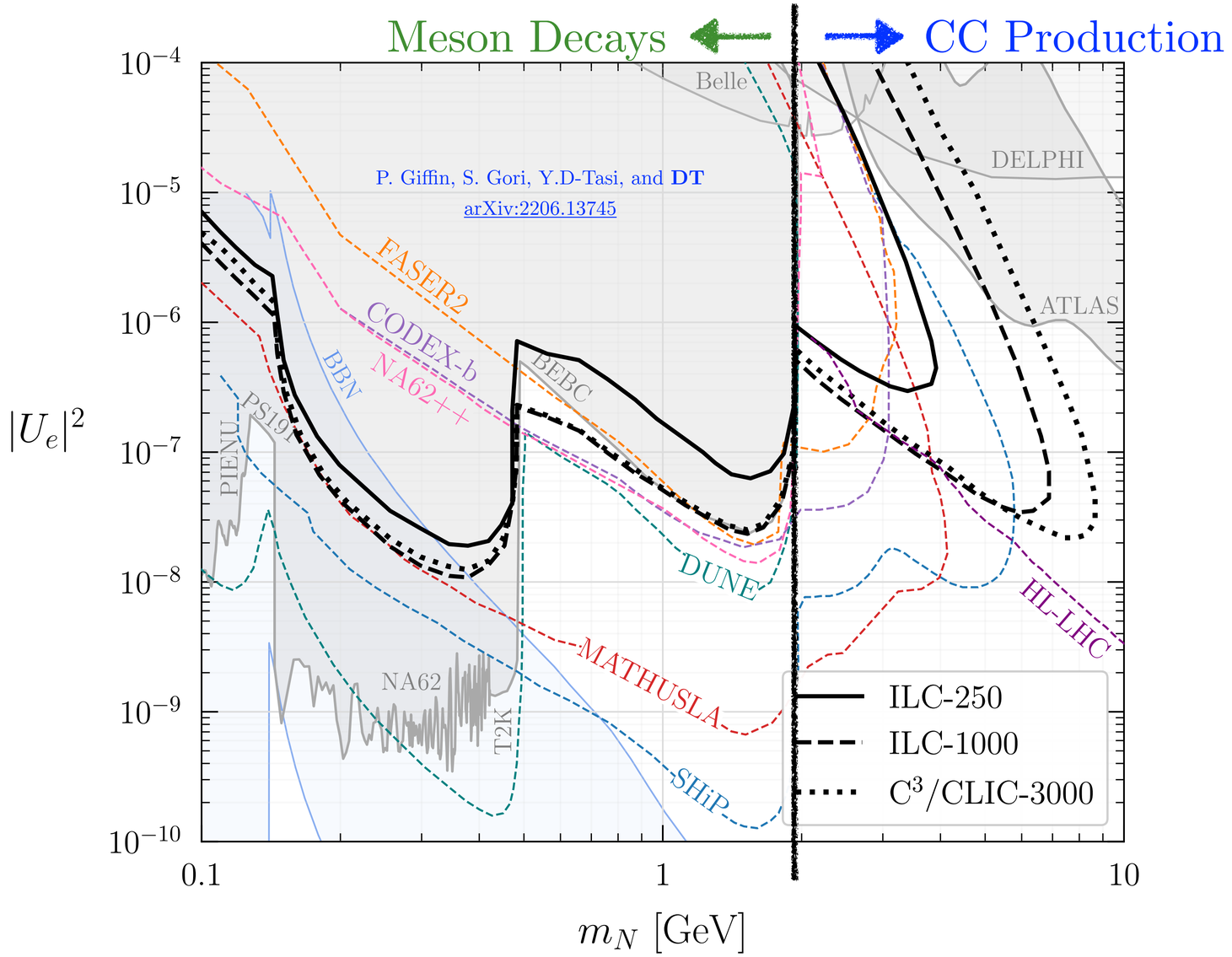

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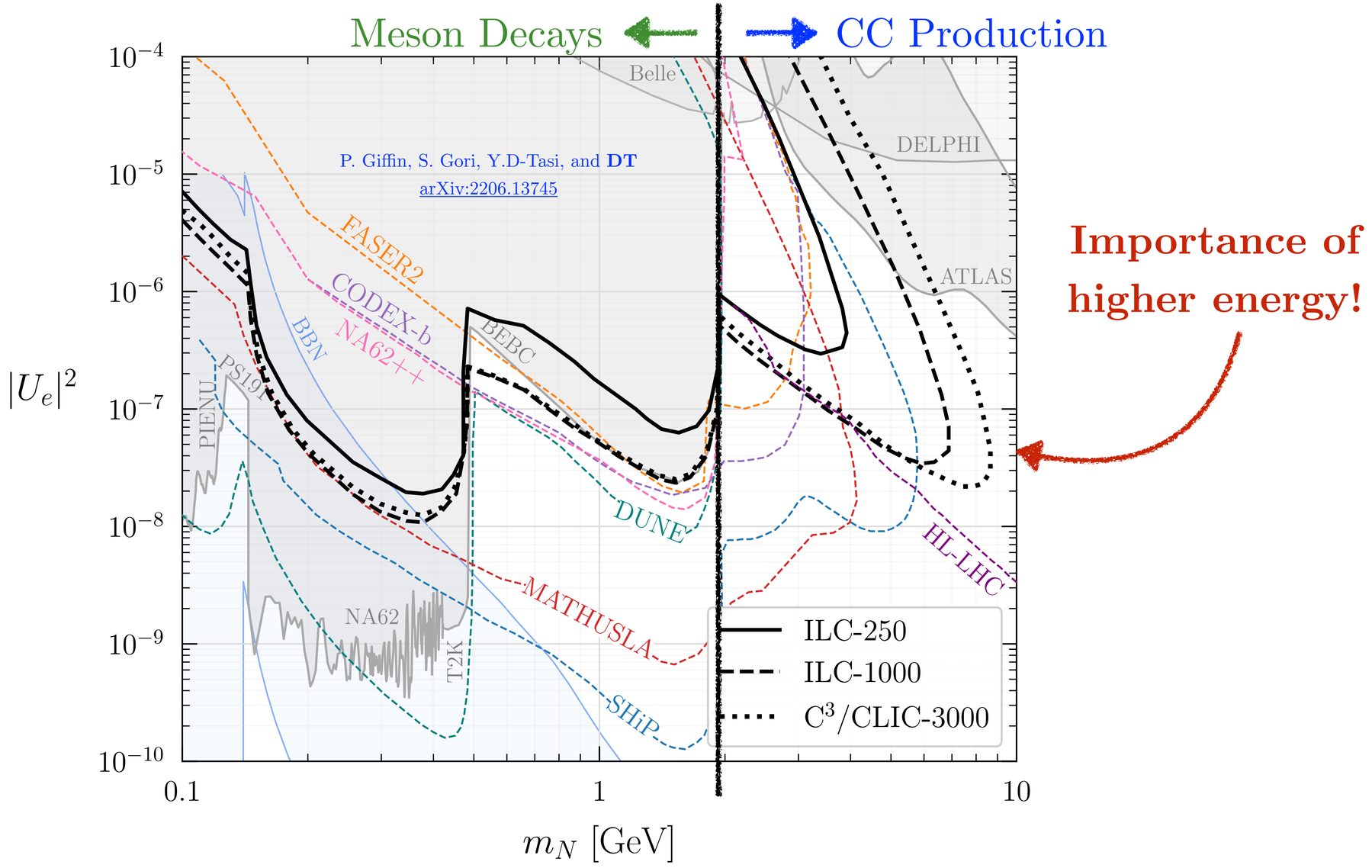
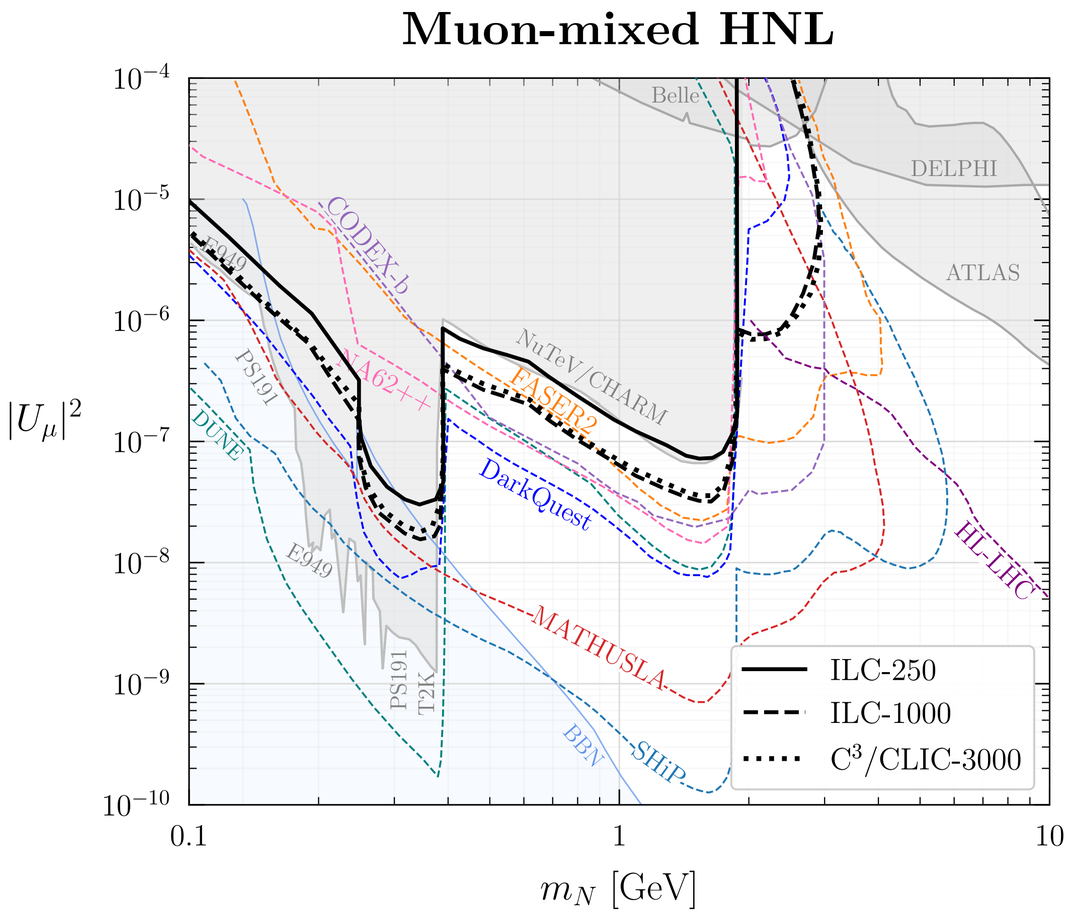
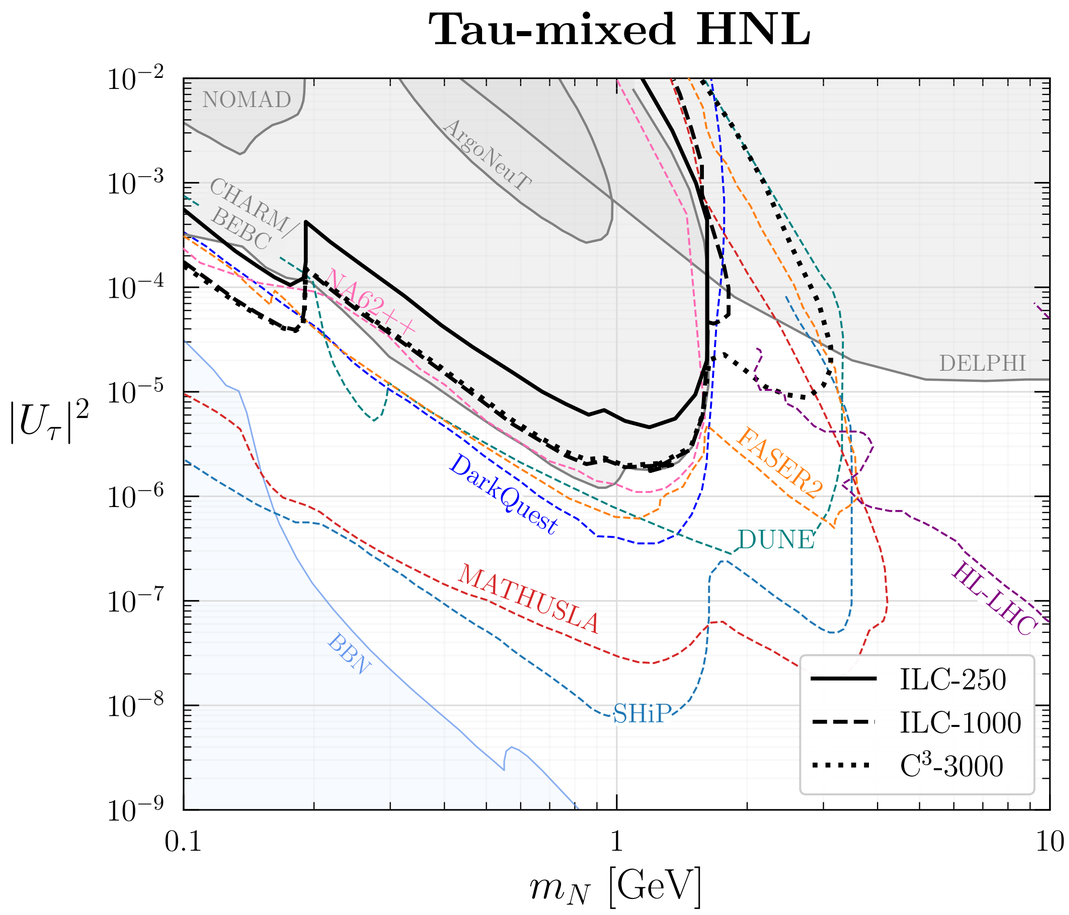


Importance of higher energy!

Sensitivity: Muon and Tau Mixed HNLs





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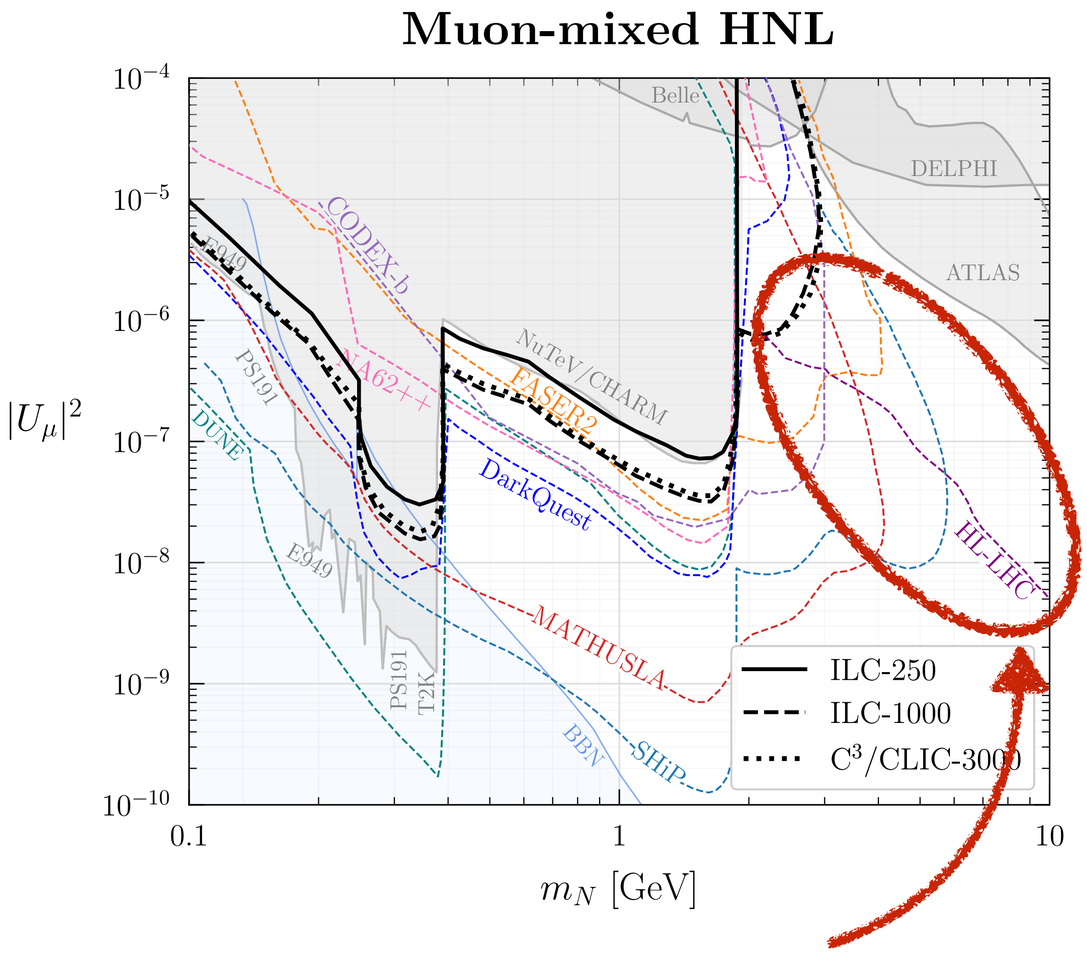
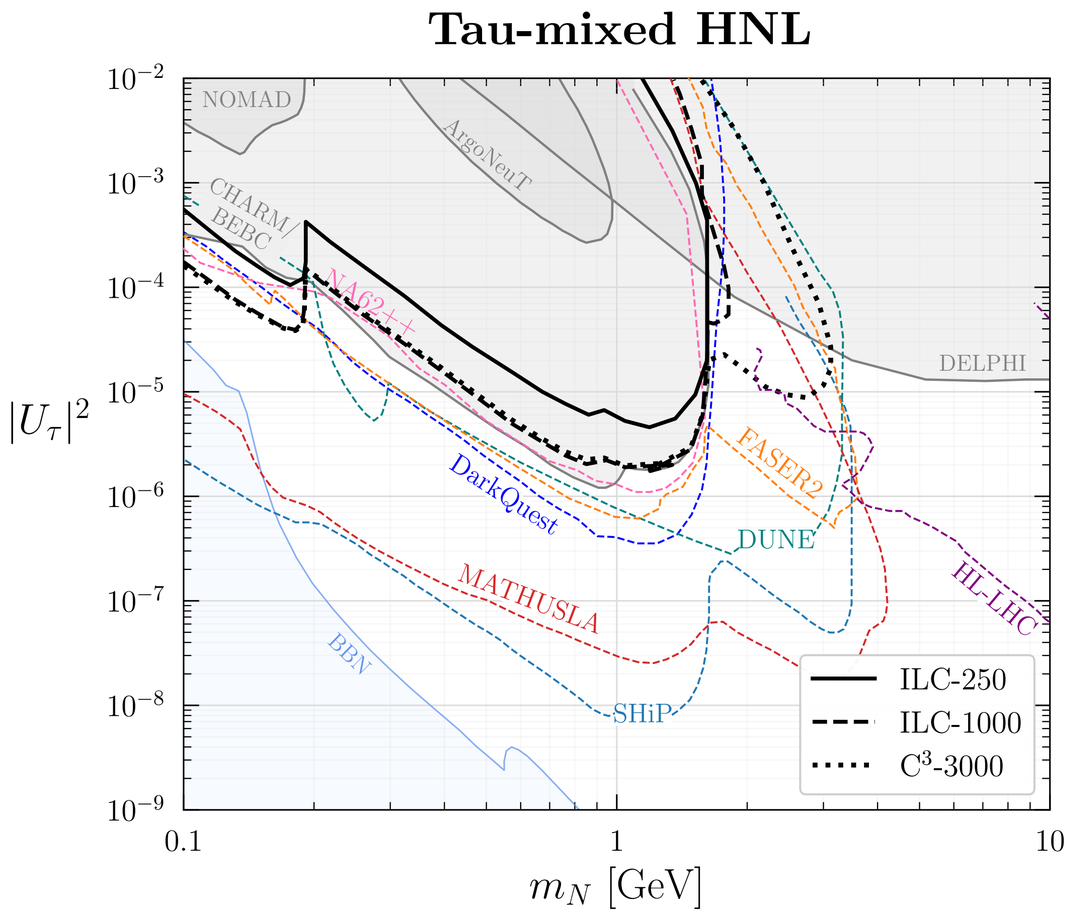
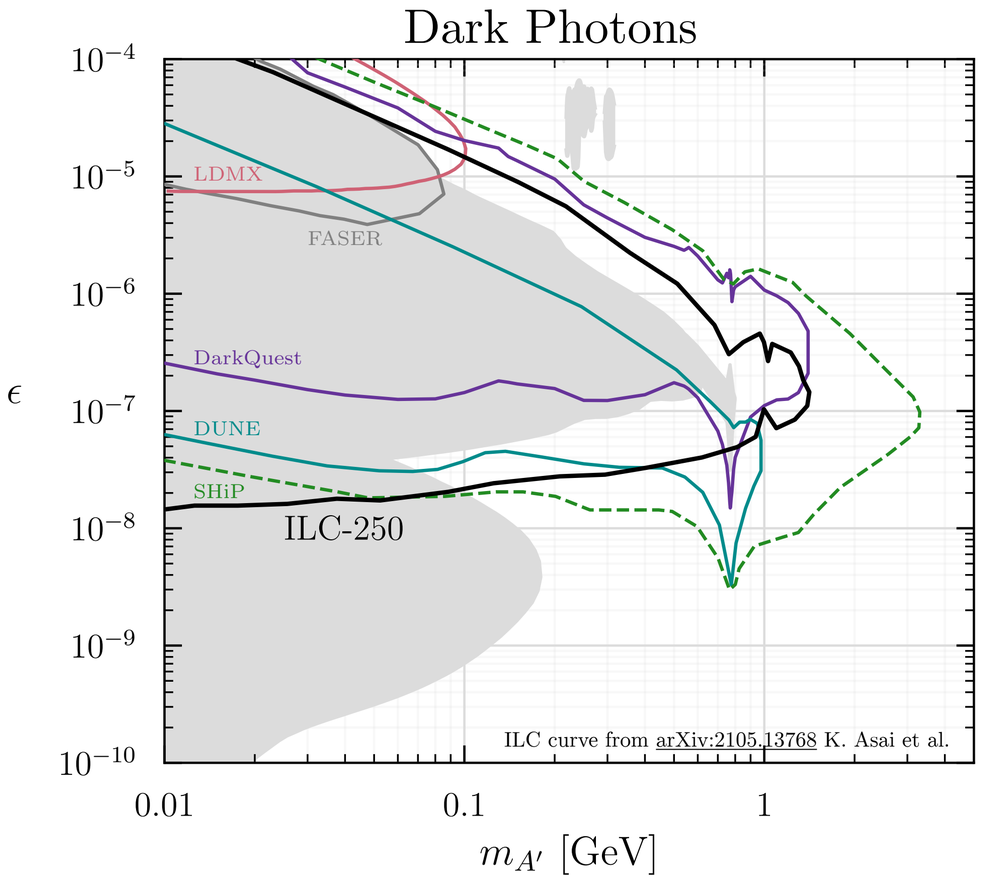


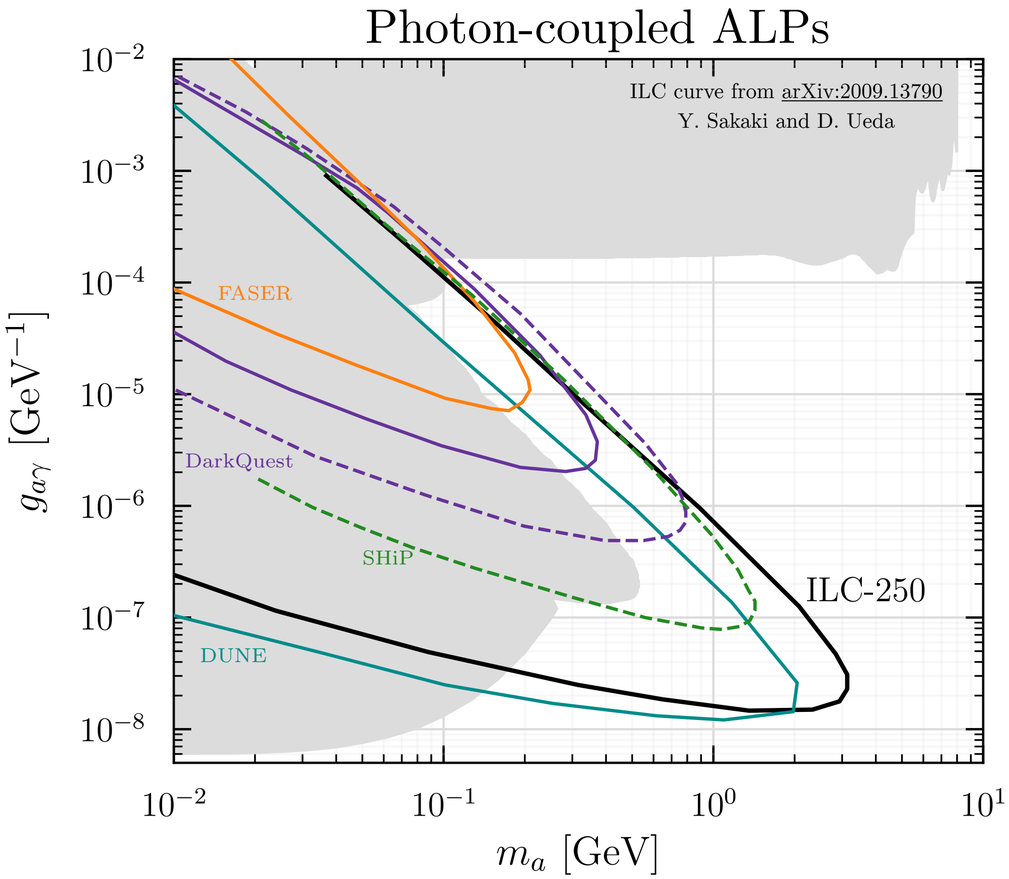


Far, far future: CC production @ TeV muon beam dump exp??

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

ILC Beam Dump Reach for Other Models





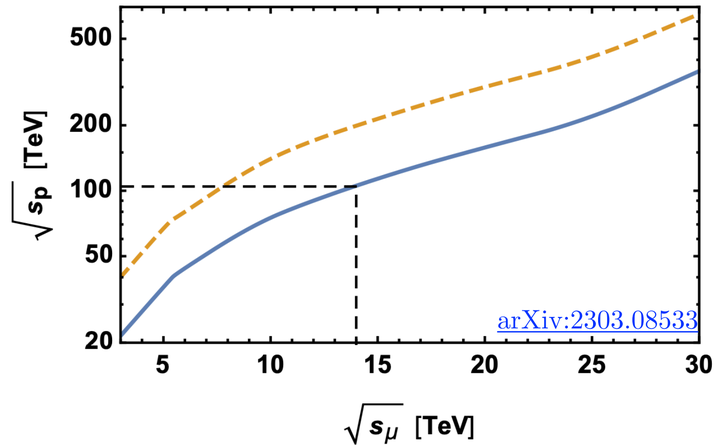
Reach @ ILC-1000/ C3-3000?

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

We can maximize the physics potential of high energy e^+e^- machines beyond the main interaction point with **beam dump experiments**

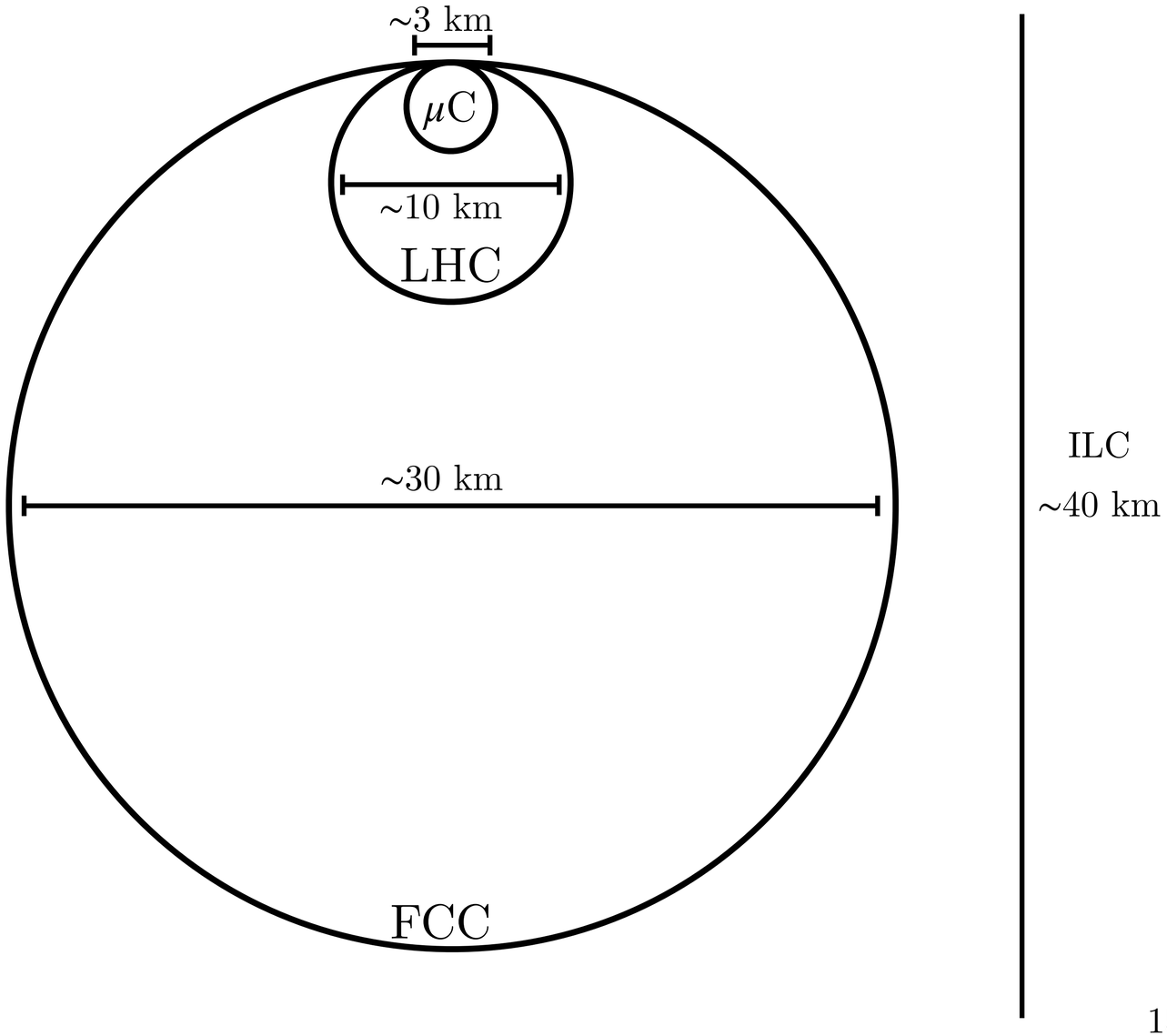
Muon Colliders

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



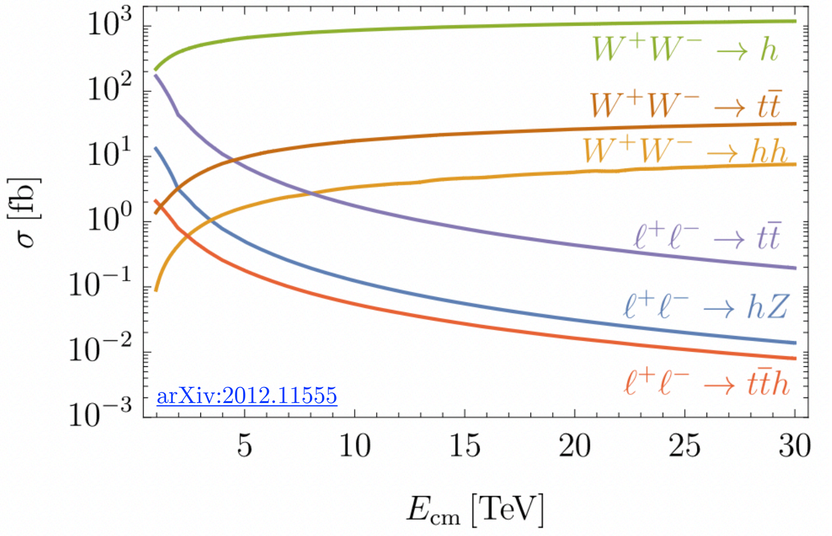
- No color charge → *clean environment* w.r.t pp colliders
- $m_\mu > m_e \rightarrow$ *lower synchrotron radiation*

Smaller collider at higher energies compared to pp or ee colliders

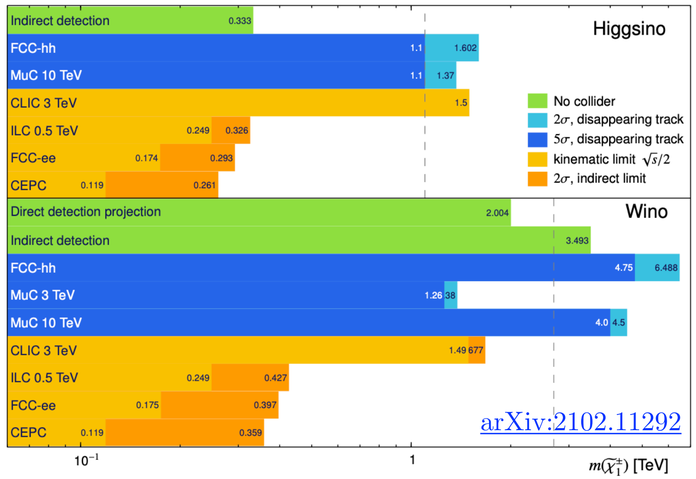


Muon Colliders

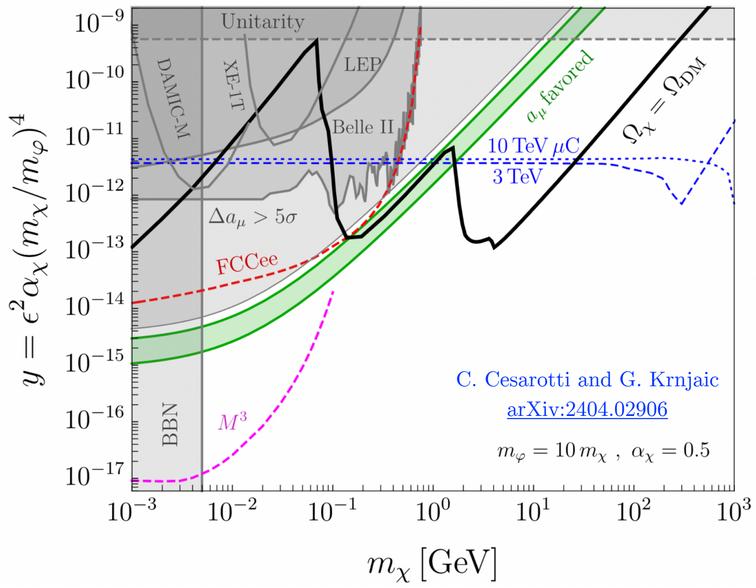
Muon collider ↔ gauge boson collider → *precision* EW/Higgs physics



High energy → reach for heavy new physics



2nd generation → muon-specific new physics?

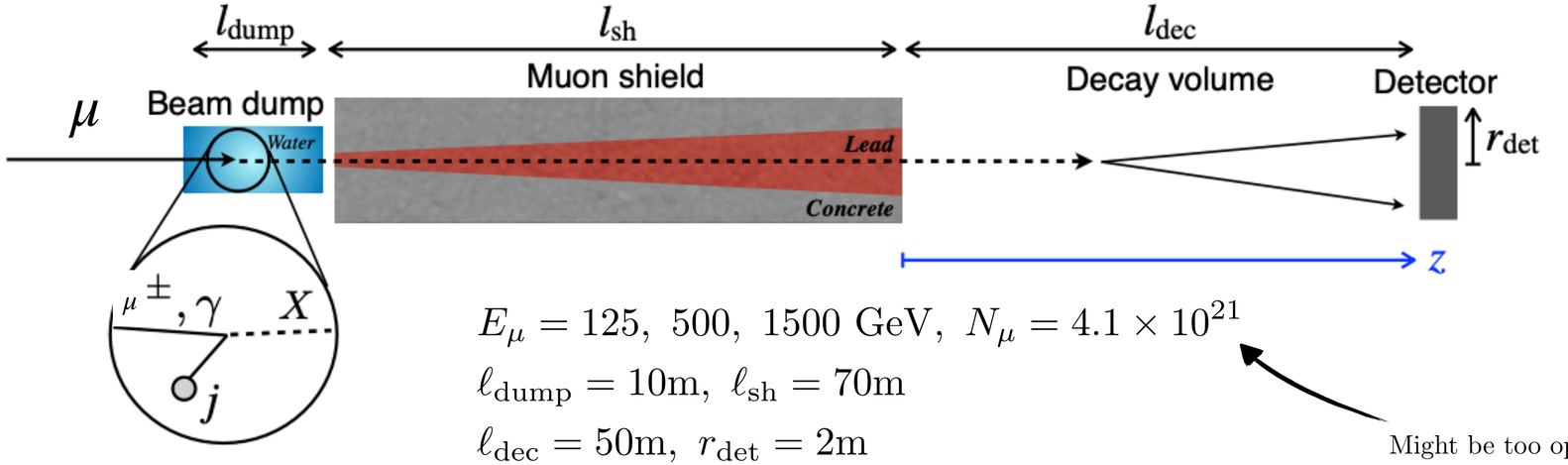


Muon Collider is both an *energy and precision* machine!

Can we maximize the physics potential beyond the main detectors?

Muon Beam Dump Experiment

- Muons beams can 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, including demonstration phases
  - 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, $N_\mu = 4.1 \times 10^{21}$

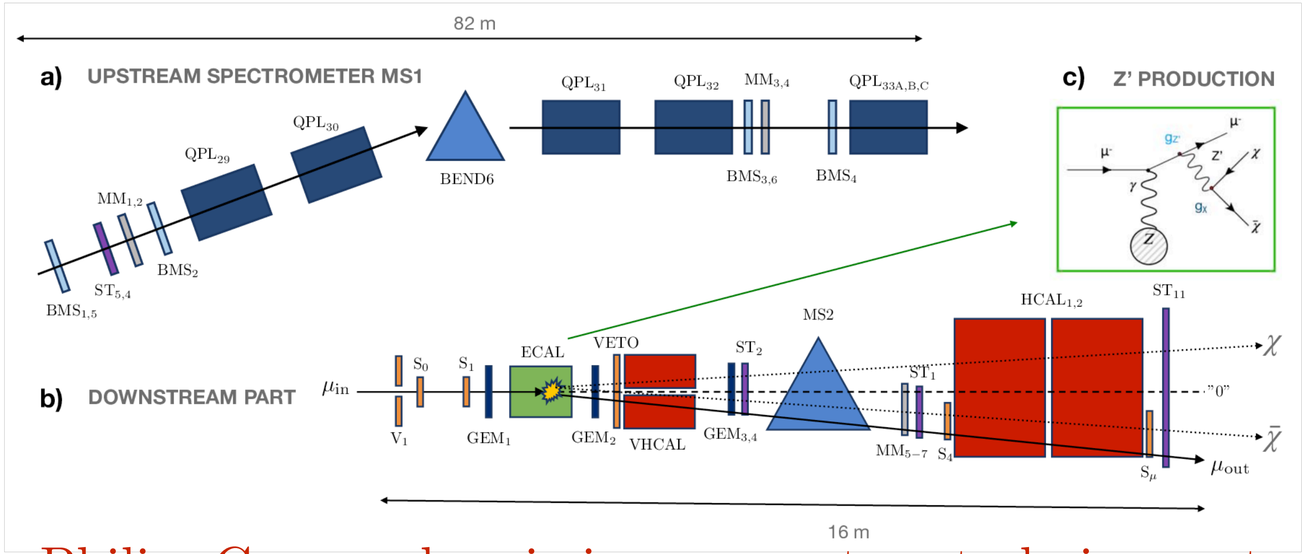
$\ell_{\rm dump} = 10$m, $\ell_{\rm sh} = 70$m

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

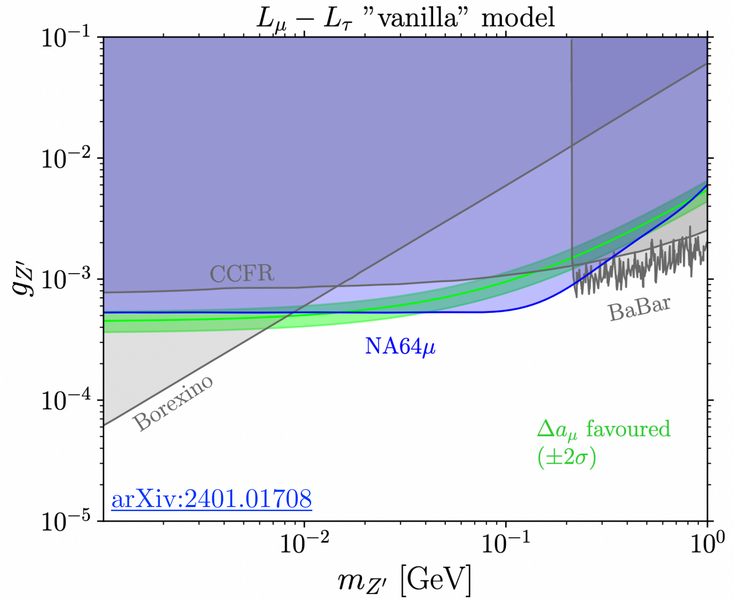
Might be too optimistic but we want a direct comparison with ILC beam dump

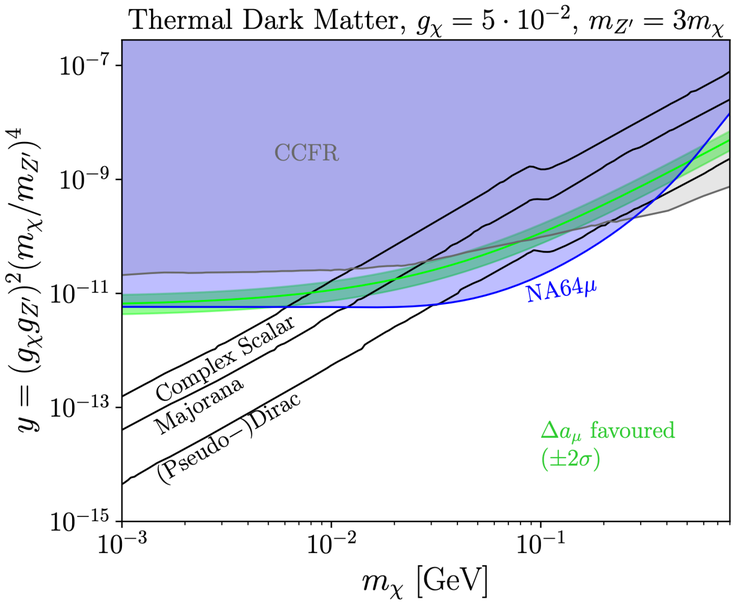
Aside on NA64

- 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

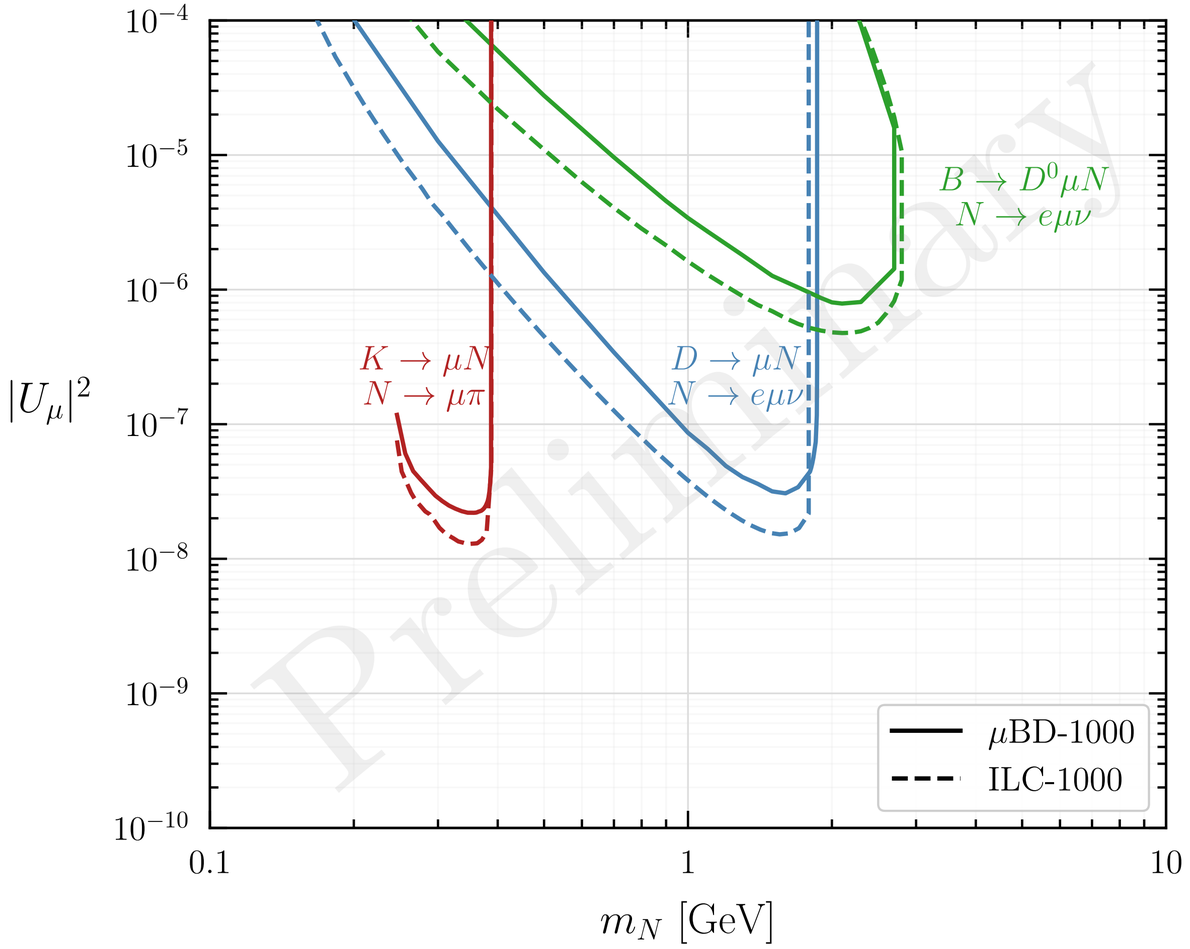


Philip: Can we do missing momentum techniques at future muon beam dump exps??

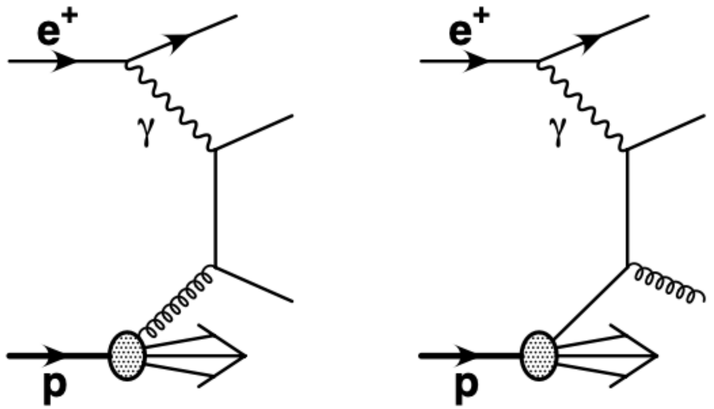




HNLs @ Muon Beam Dump



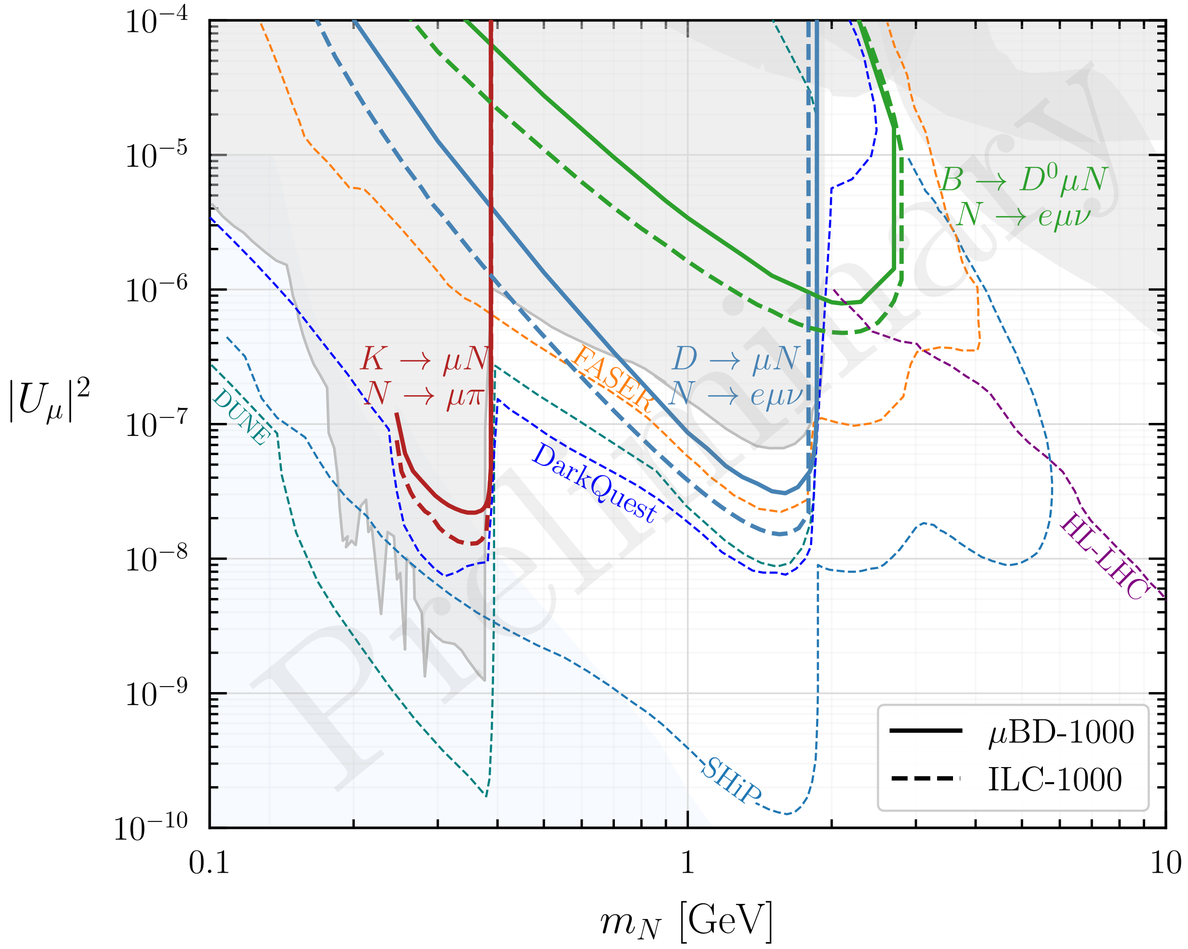
- Lower meson production rate → slightly weaker sensitivity



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

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

HNLs @ Muon Beam Dump



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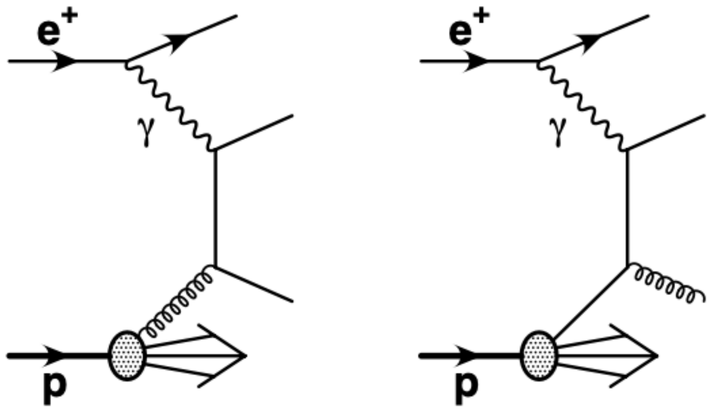

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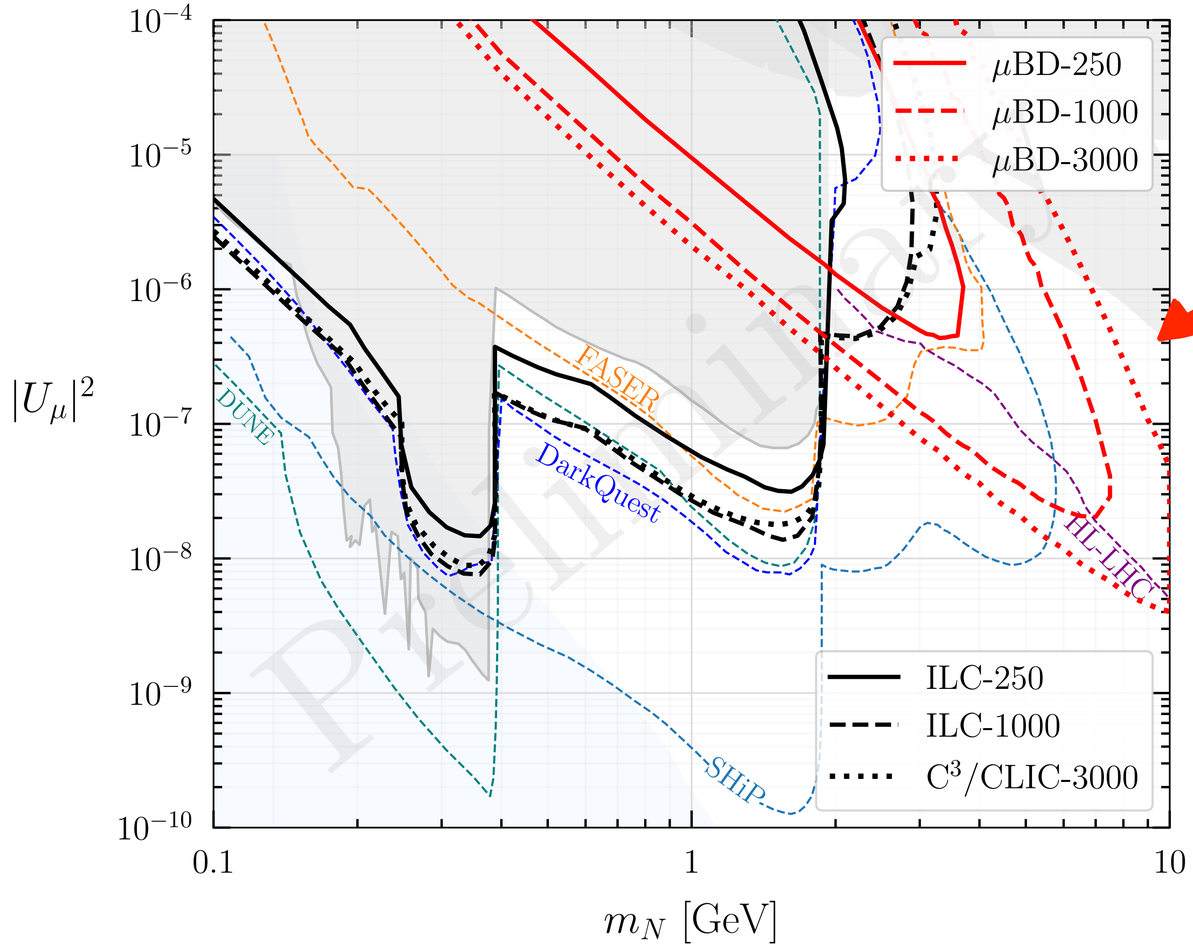
$f_{\gamma/\ell}$ = probability for of lepton radiating off a photon $\sim 1/m_\ell$

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

HNLs @ Muon Beam Dump

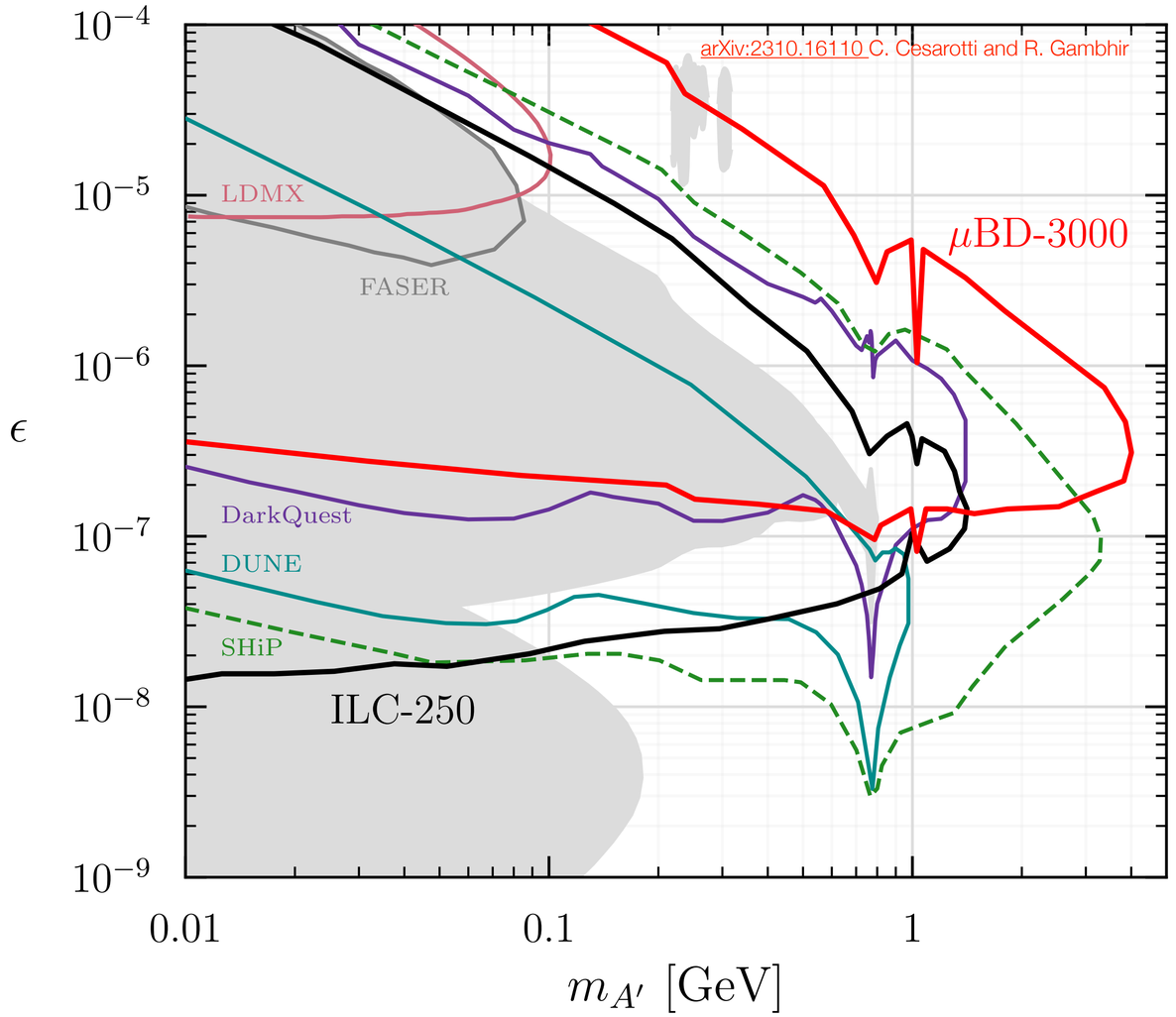
- Direct production of muon-mixed HNL via charged-current scattering is now available!



Reach beyond HL-LHC projections!

Benefits of *high energy* and *new production channels*

Additional Models: Dark Photons



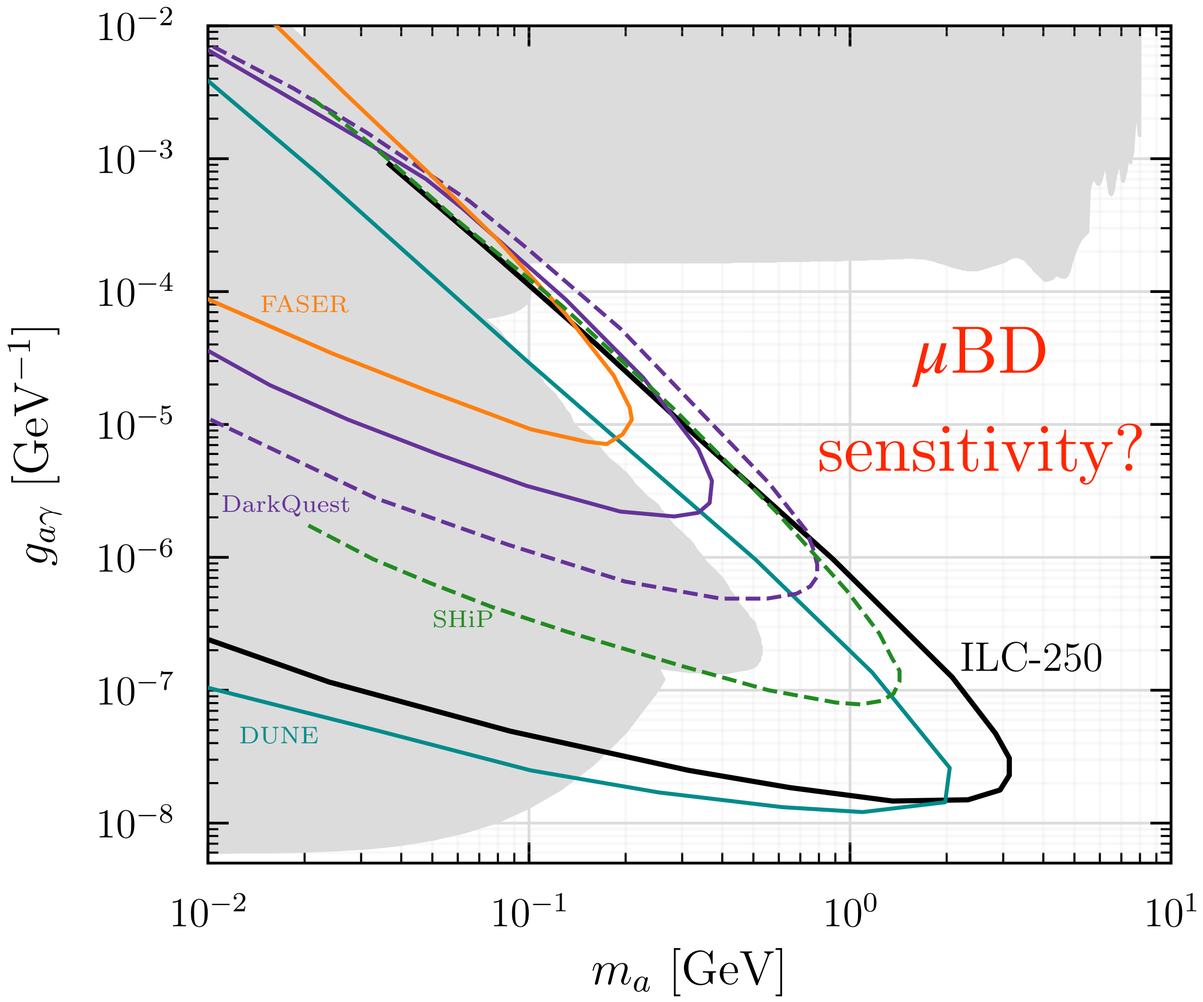
Lead Target

$E_\mu = 1.5$ 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.*

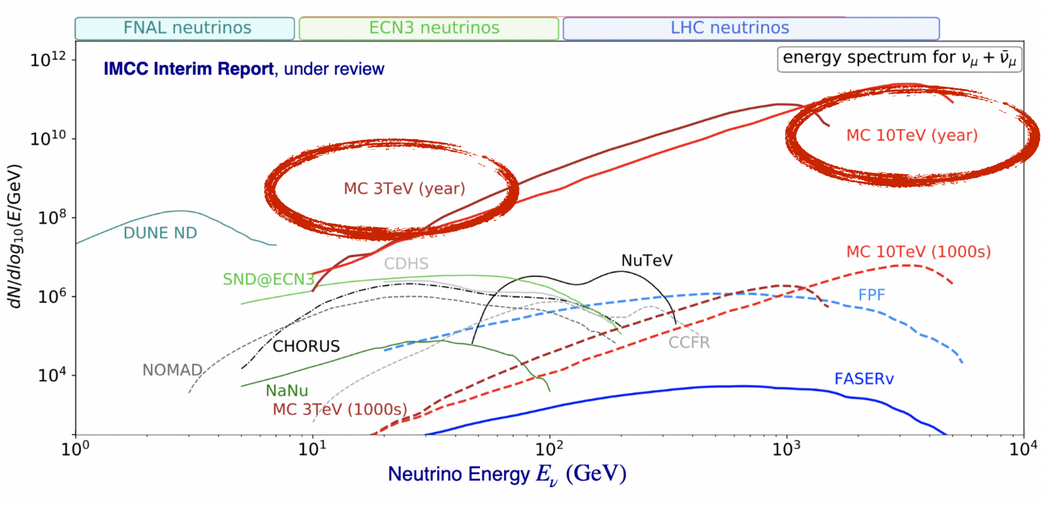
Future work: ALPs

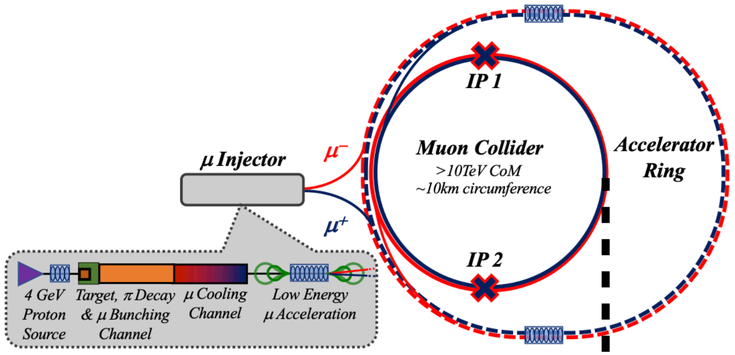


- Muon beam dump reach for ALPs?
  - Production via Primakoff?
  - Production from ALP-meson mixing?
- Expect similar reach to ILC beam dump; could push to higher masses
- Work in progress!
- *Other dark sector benchmarks for Muon Beam Dump physics case?*

Other Physics Opportunities?

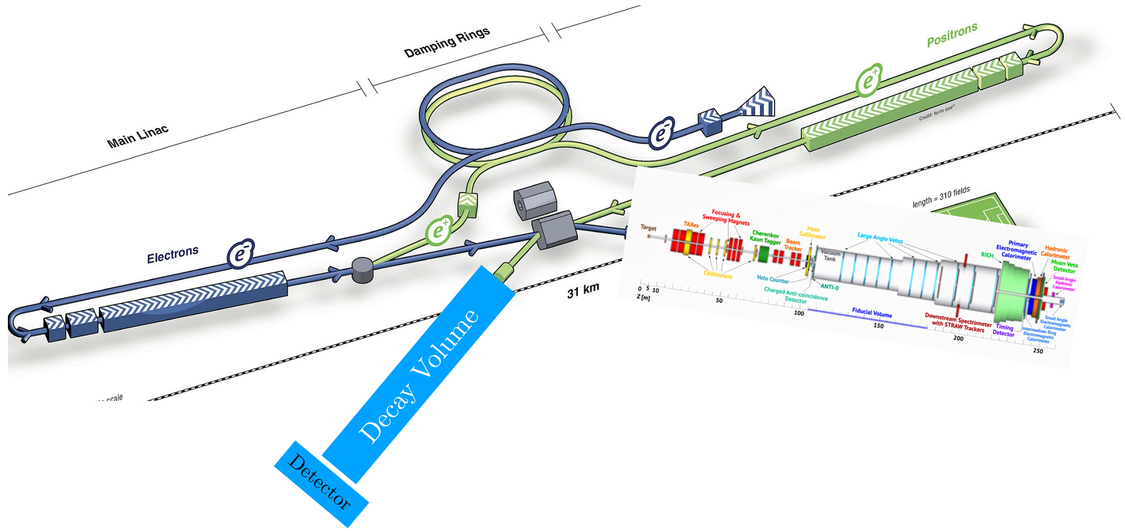
Neutrino Physics





μFPF

Kaon Physics



Notes and next steps

Shamelessly stolen from Laura's talk

Both MuC and e^+e^-

- Both proposals look at several other new physics models, not just dark photons
  - E.g. Long lived particles, light scalar bosons, ALPs, leptophilic gauge bosons…
- Length parameters and target materials will need to be optimized for overall best case scenario for new physics
  - Better Monte Carlo, proposed detectors?
- Only one proposal each so far

e^+e^- Collider

- ILC-250 proposal only experimental design thus far
  - No dedicated proposals for other potential e^+e^- colliders, or higher energy ILC
  - Will have two beam dumps, can accommodate more than one experiment
- Shorter time scale

Muon Collider

- Much more R&D to take place on muon collider technology in coming years
  - Opportunities for additional smaller experiments during this R&D phase, with some dedicated proposals already in place (e.g. neutrino measurements)
- Beam dump experiments would also lend well to precision SM measurements

Notes and next steps

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First beam dump study at CLIC and C³!

Muon Collider

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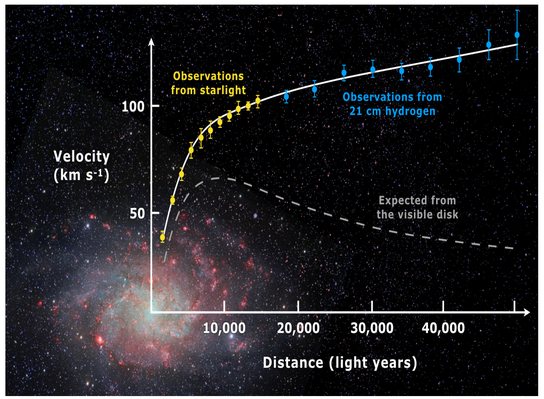
Summary

- High energy lepton colliders are also *intensity machines!*
- *Beam dump experiments* to probe feebly coupled dark sector particles
  - Electron/muon beam dump experiments are *complementary to proton beam dump experiments* for dark sectors/LLP searches
  - Reach higher masses for dark photons/ALPs compared to SHiP, DarkQuest
- *Many physics opportunities* for SM and BSM physics beyond the main detectors!

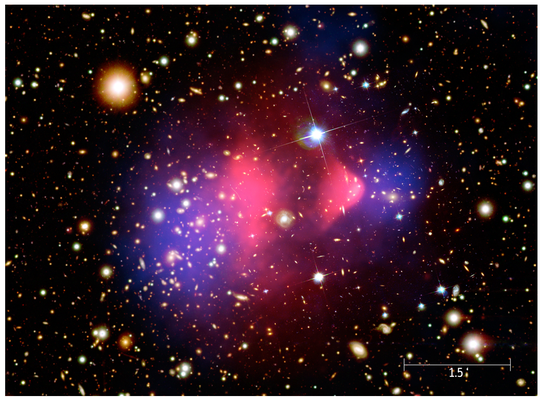
Thanks! Questions?

Back up

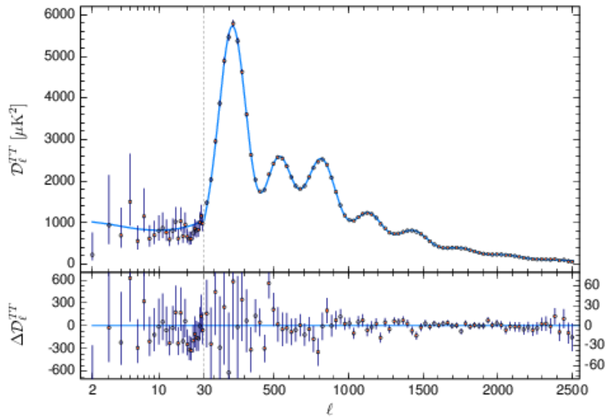
Evidence for Dark Matter



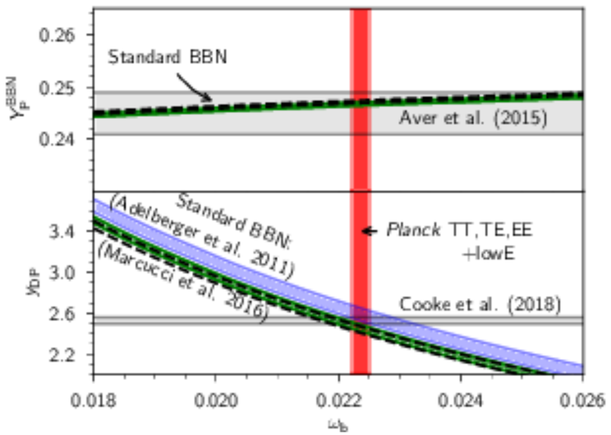
Galaxy rotation curves



Gravitational Lensing



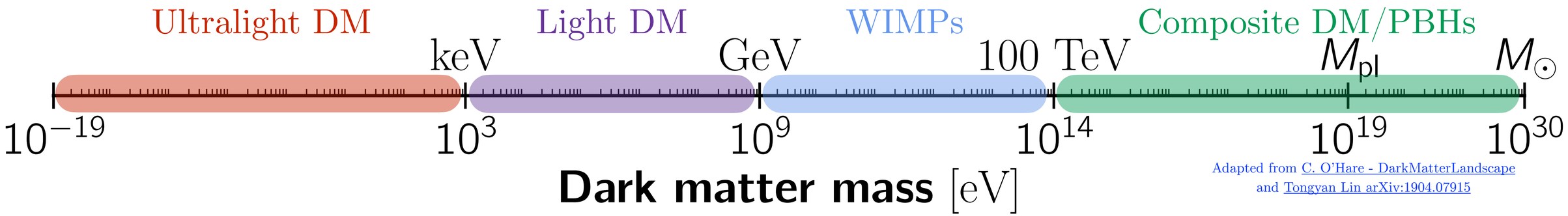
CMB



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?

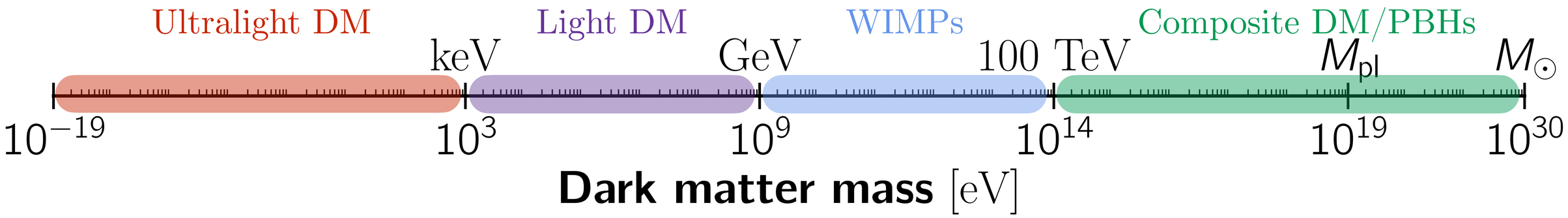


Adapted from C. O'Hare - DarkMatterLandscape and Tongyan Lin arXiv:1904.07915

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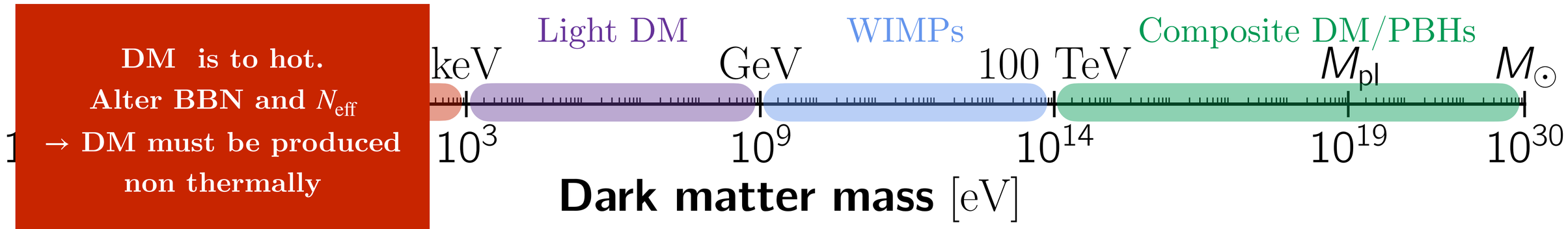
DM is to hot.
Alter BBN and N_{eff}
→ DM must be produced non thermally



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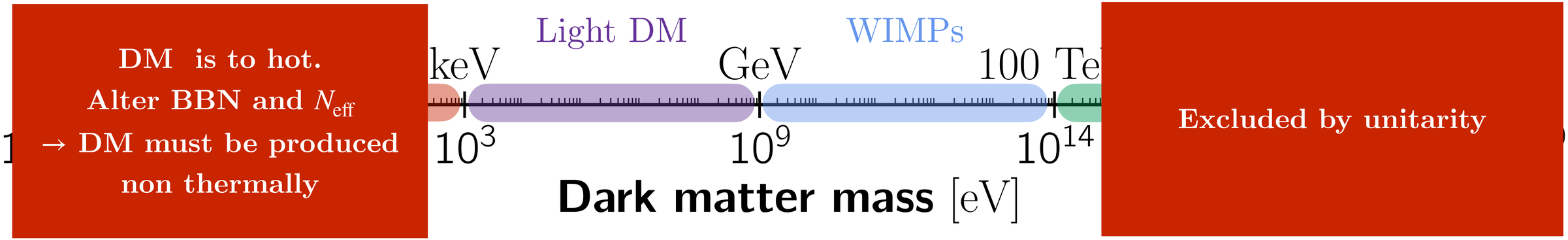

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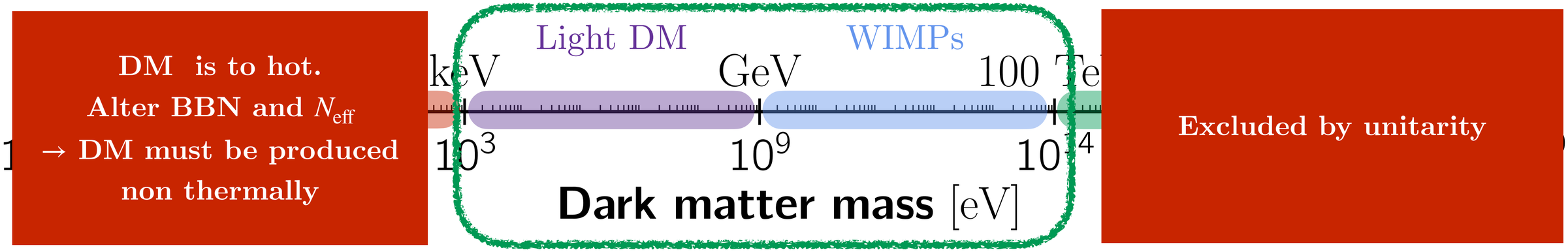
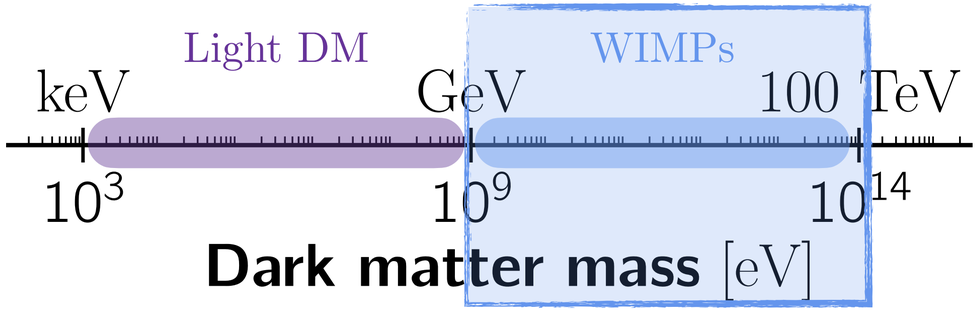


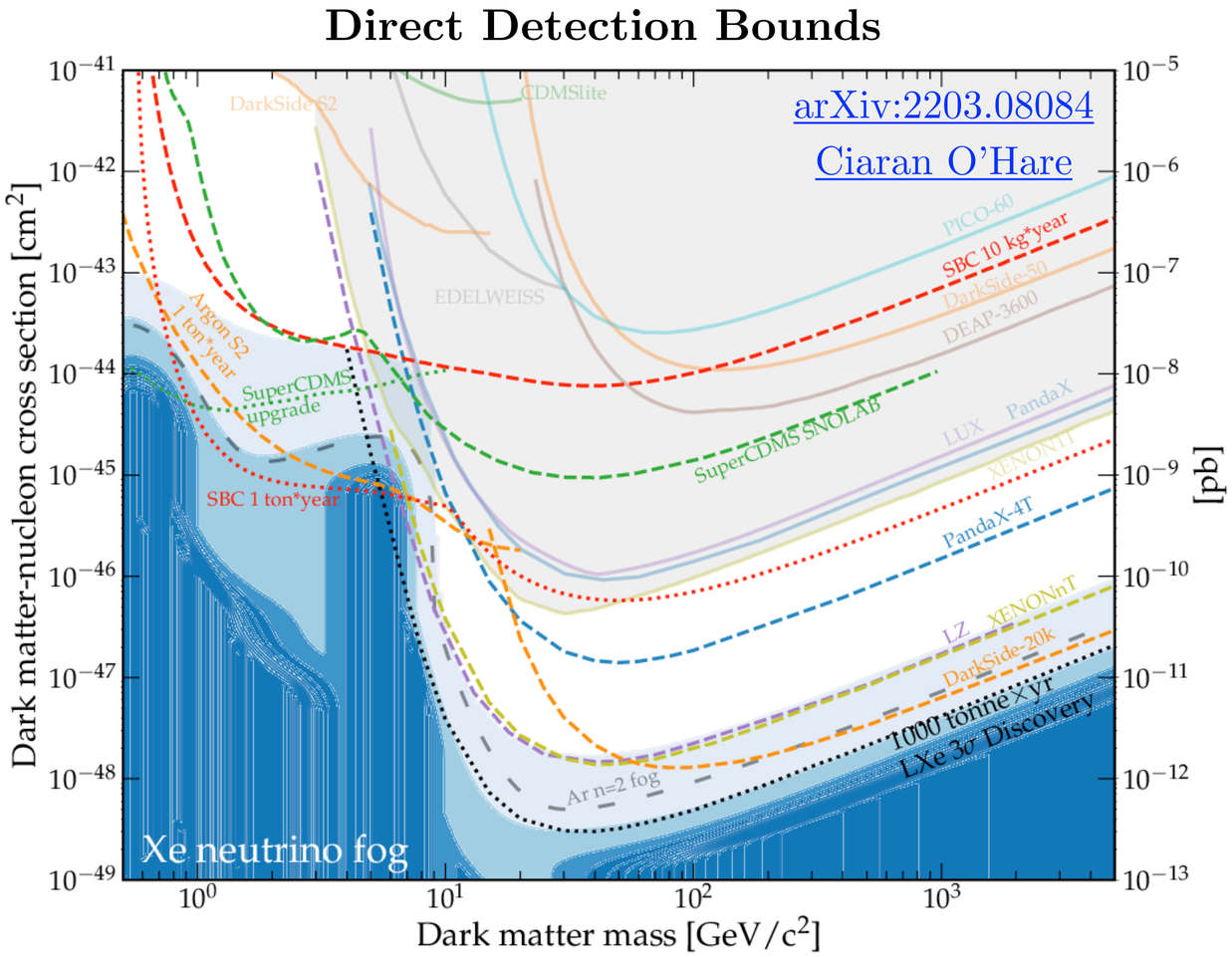
Thermal DM Target:

MeV - 100 TeV

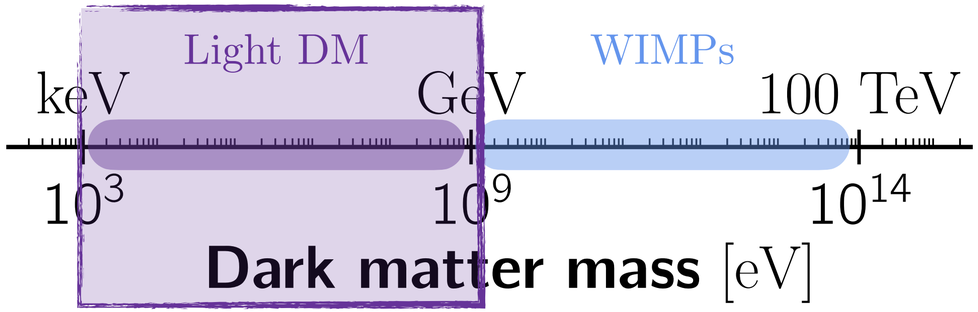
Weakly Interacting Massive Particles

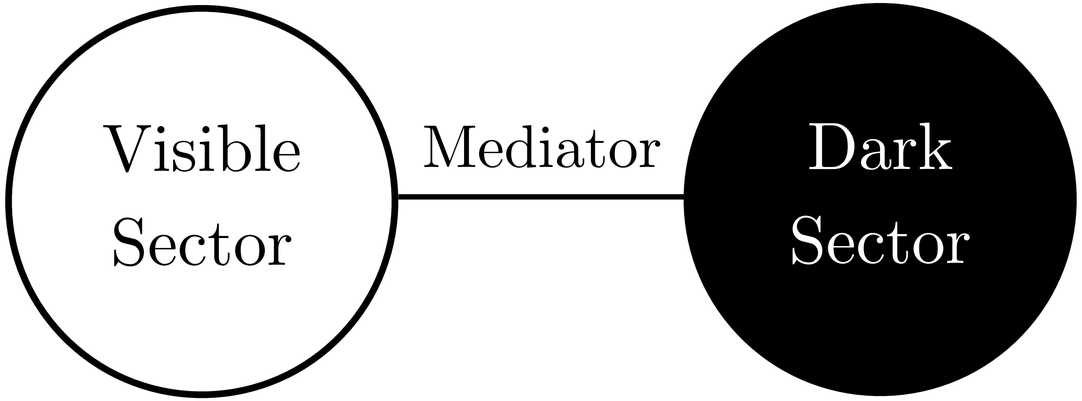


- WIMP miracle - correct relic abundance with weak coupling strengths and $m_\chi \sim 100$ GeV
- Direct detection bounds are becoming very constraining. Push to smaller couplings. *How to get beyond the neutrino floor?*
- *Alternative: go to lower masses where there are weaker bounds*



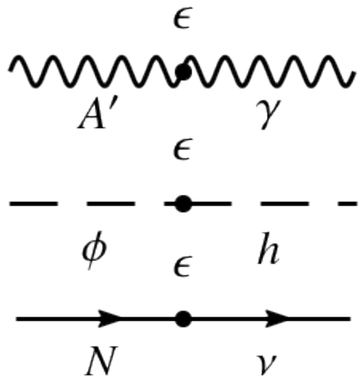
Light Dark Matter and Dark Sectors





- 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)

Meson Production

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

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

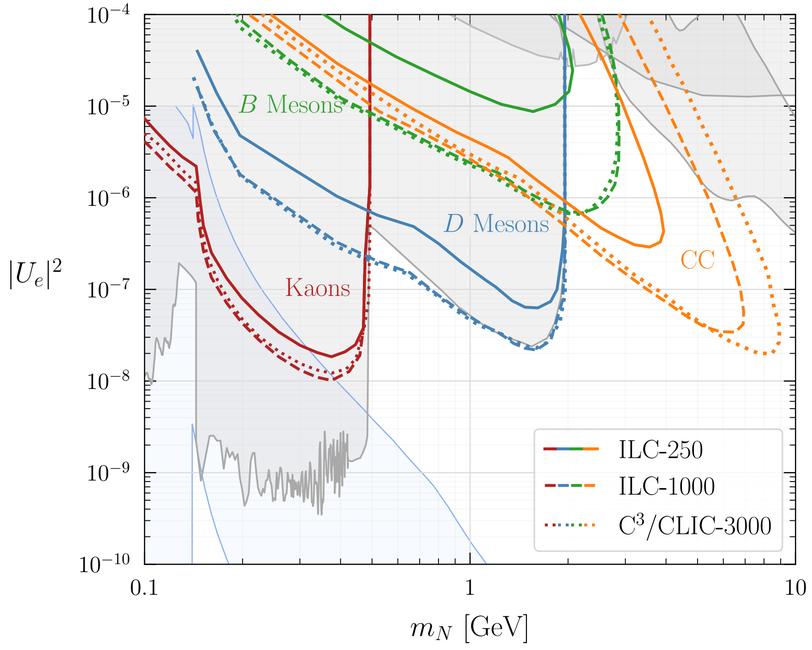
Pythia total hadronic cross section

Total ep cross section

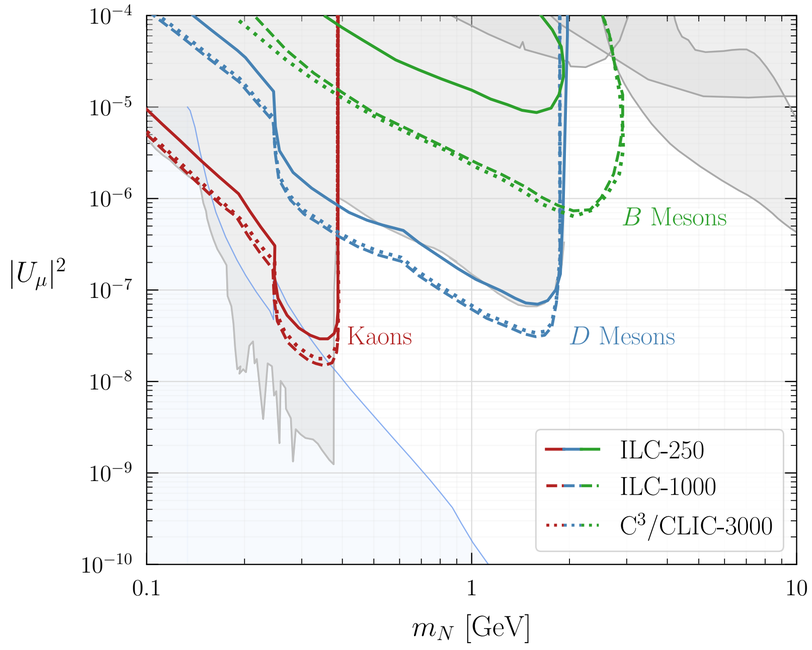
- Additional factor of cross section ratios takes into account that not all ep collisions are hadronic/SoftQCD interactions
  - For pp collisions $\sigma_{\mathrm{SoftQCD}} \approx \sigma_{pN}$

HNL Sensitivity by Production Mode

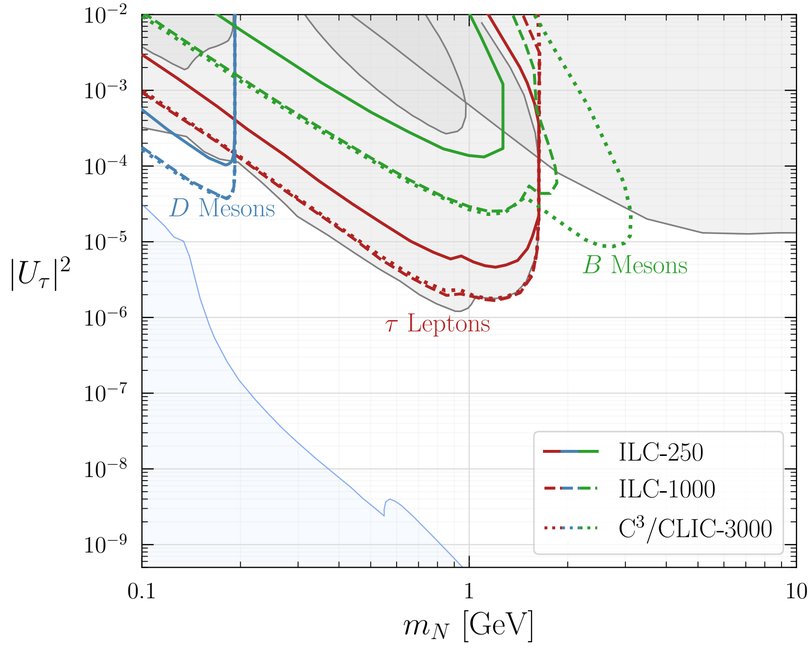
Electron-mixed HNL



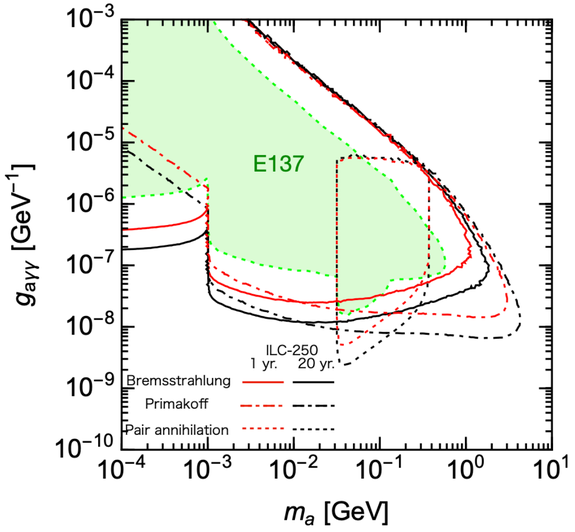
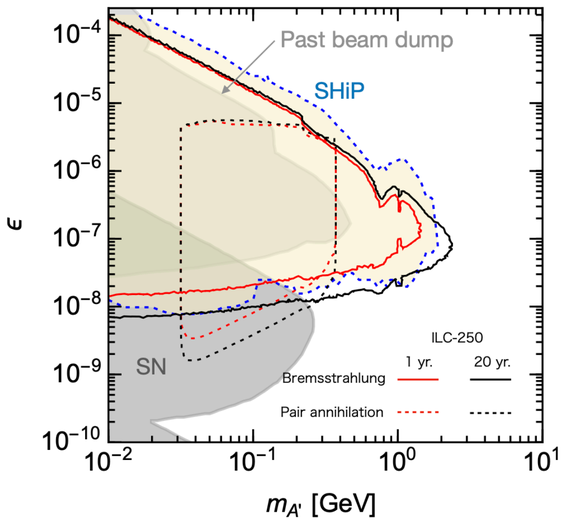
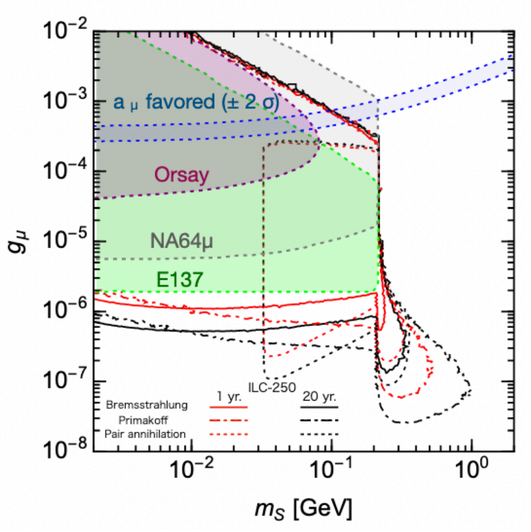
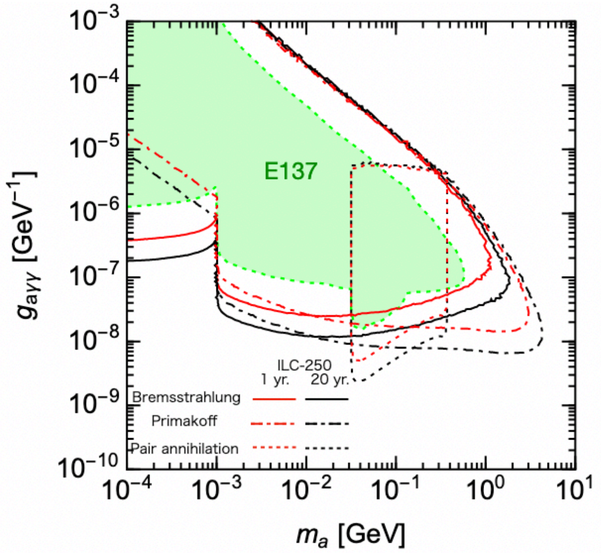
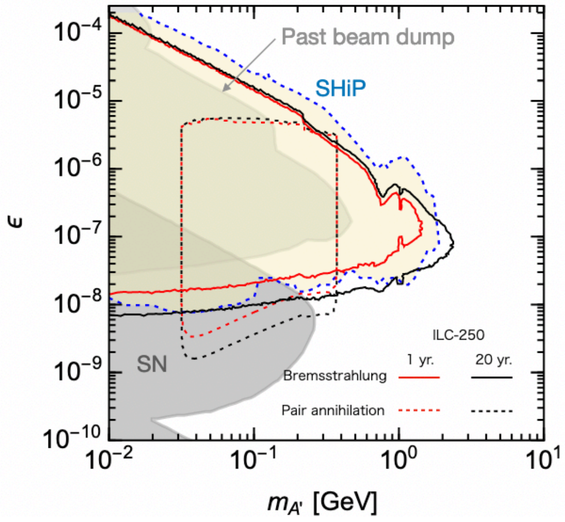
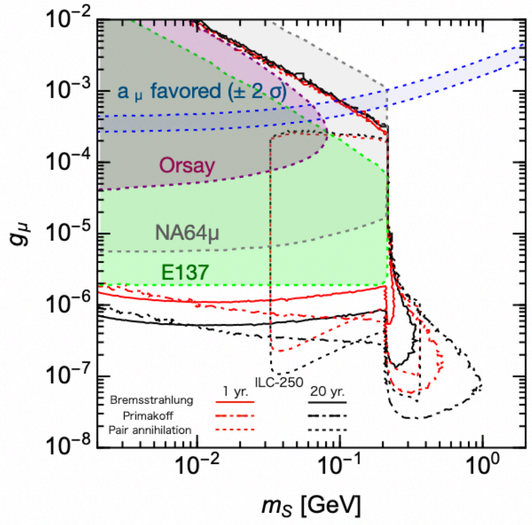
Muon-mixed HNL



Tau-mixedHNL



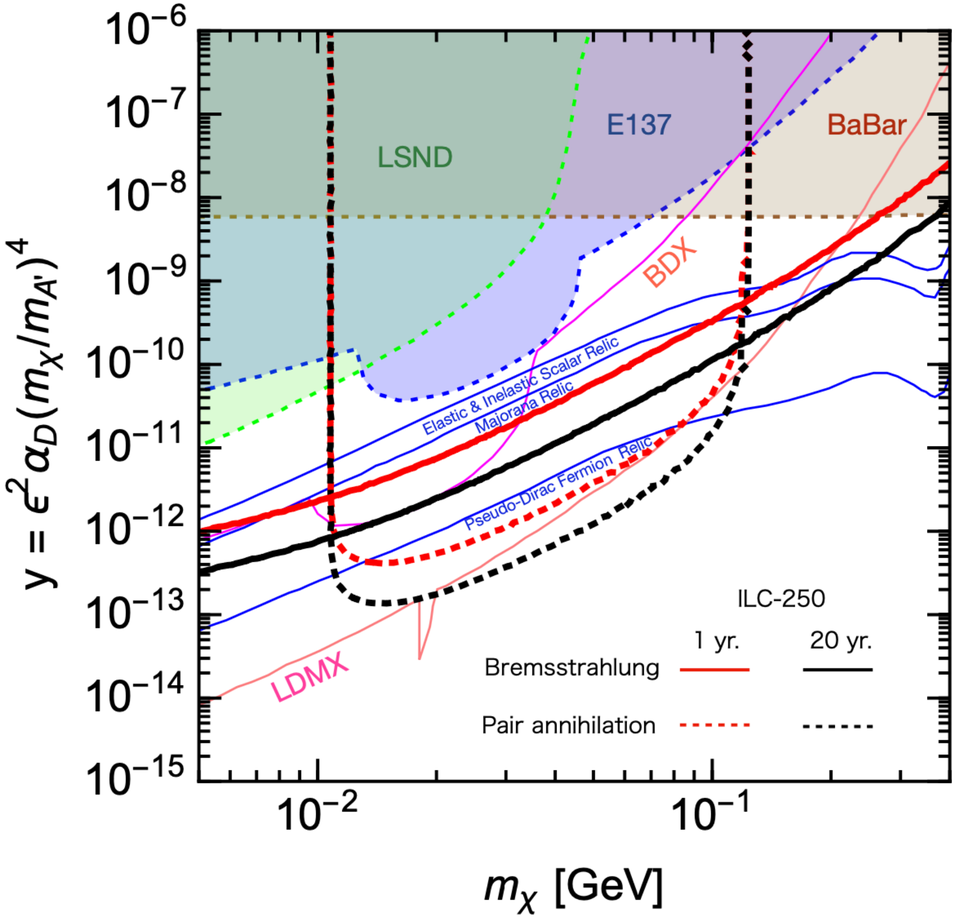
More BSM @ ILC Beam Dump

	Axion-like Particles	Dark Photon	Muon-philic Scalar
Electron Beam			
Positron Beam			

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

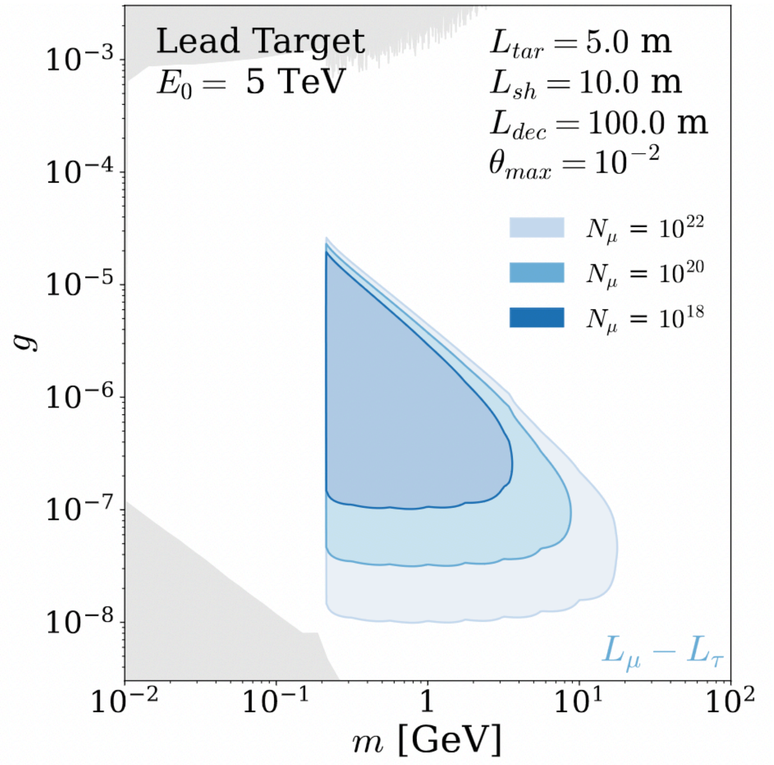
Invisible Searches @ ILC Beam Dump

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

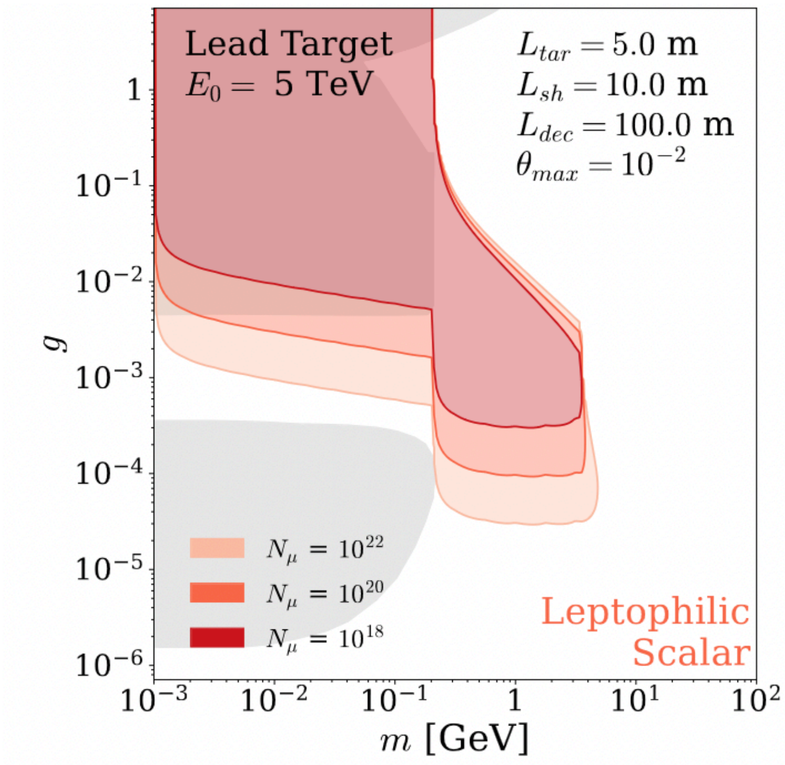


More BSM @ Muon Beam Dump

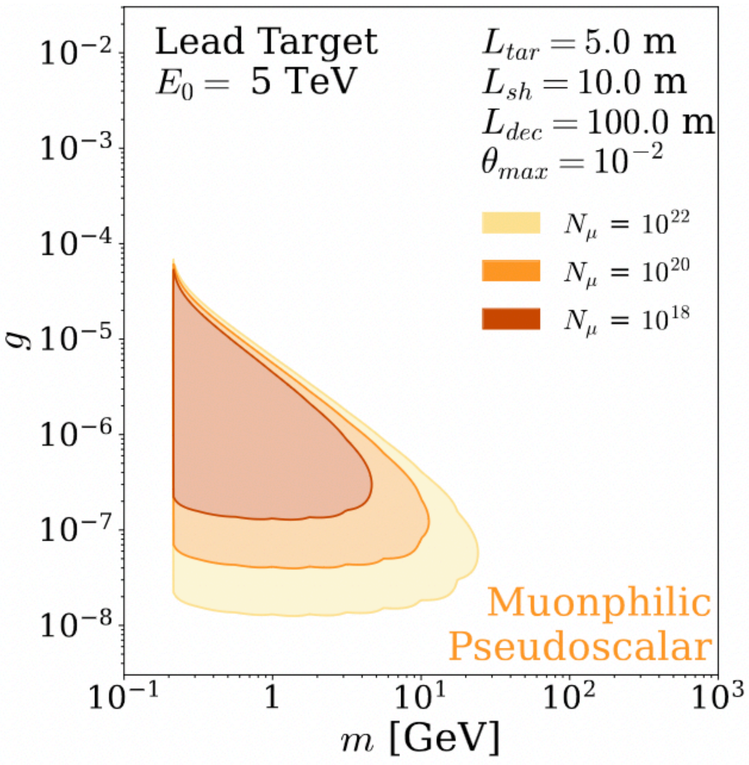
$L_\mu - L_\tau$ gauge boson



Leptophilic Scalar



Muonphilic Scalar



arXiv:2310.16110 C. Cesarotti and R. Gambhir

Intensity Frontier: Proton Beam Dump Experiment

- Proton beam dumps/fixed target experiments
  - Large number protons-on-target → large flux of BSM particles
  - Long decay volumes → probe feeble couplings/long lifetimes

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

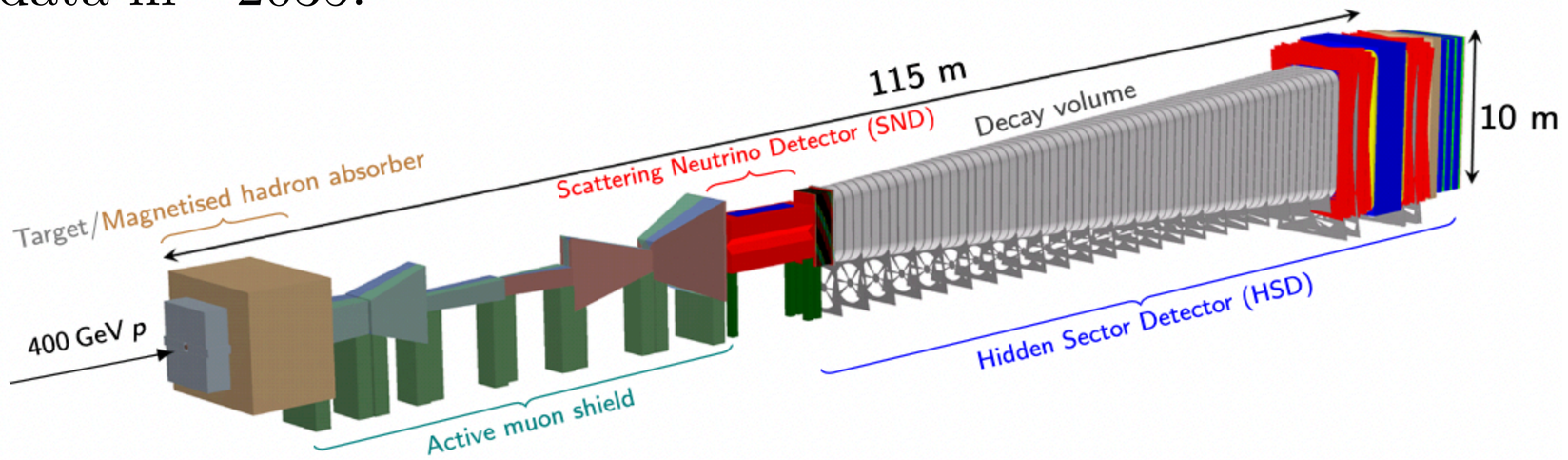
Low CM energy → limited mass reach

- 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!

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