Exploring dark sectors with muon beam experiments

Jonathan Kozaczuk

UCSD

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Based on: Chen, JK, Zhong, **JHEP 1810 (2018) 154**

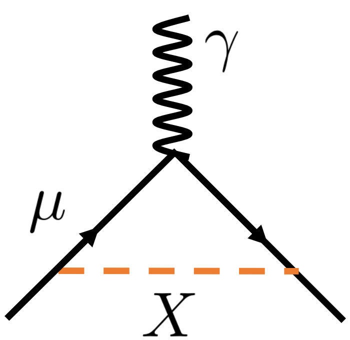
Motivation (see also Diego's talk)

Discrepancy in measured vs predicted muon anomalous magnetic moment

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (268 \pm 63 \pm 43) \times 10^{-11}$$

(~ 3.5σ discrepancy)

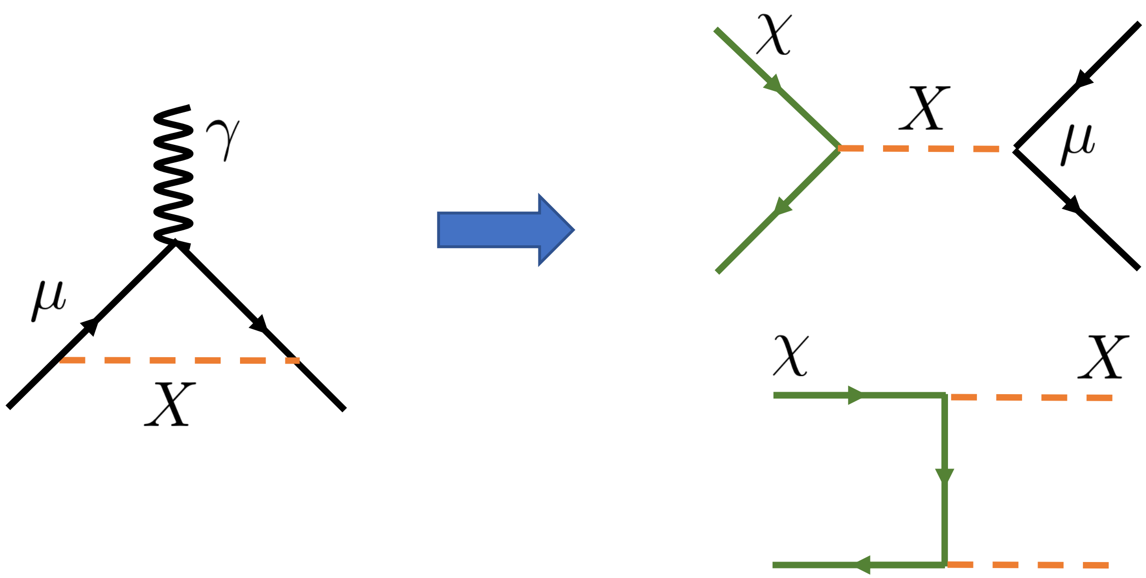
Possible solution: new scalar or vector coupled (at least) to muons



$$\Delta a_\mu = \frac{g_\mu^2}{8\pi^2} \int_0^1 dz \frac{(1-z)^2(1+z)}{(1-z)^2 + z(m_S/m_\mu)^2}$$

Connection to DM?

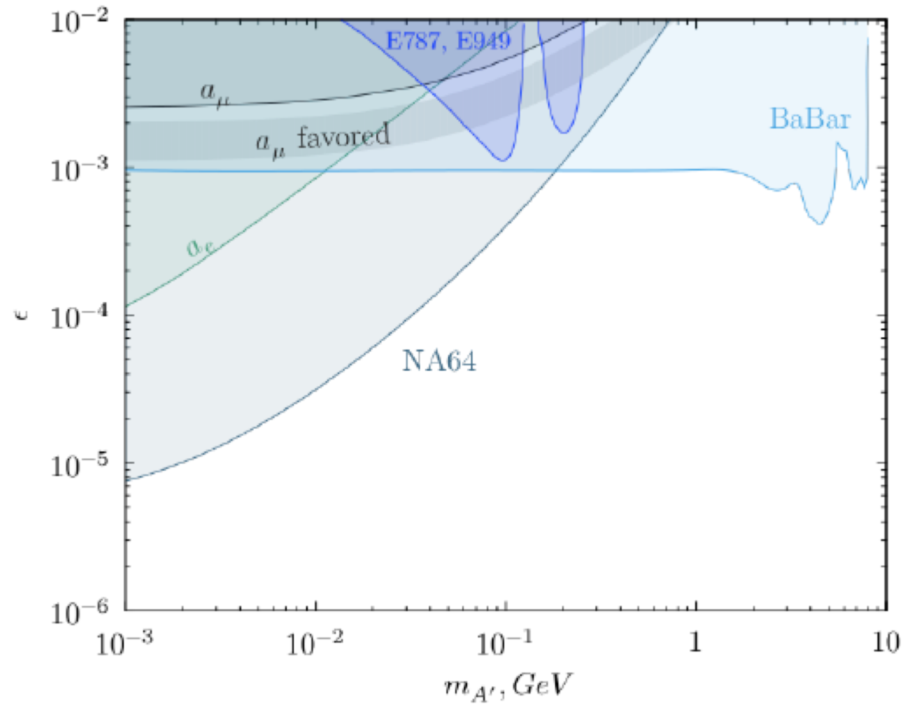
Light new scalars and vectors featured in models of light dark matter



Explanation of $(g\text{-}2)_\mu$ could provide mediator required for thermal DM

Connection to DM?

Simplest cases (dark photon, Higgs portal) already ruled out.



Banerjee, 1909.04363

Leptophilic forces with flavor-dependent couplings much less constrained

Rest of this talk: **lepton-** or **muon-specific scalars + Dirac fermion DM**

Light leptophilic DM

Focus on **leptophilic scalars**

$$\mathcal{L} \supset -g_\chi S \bar{\chi}\chi - \sum_{\ell=e,\mu,\tau} g_\ell S \bar{\ell}\ell$$

$$\text{Scalar mediator } (S) = \begin{cases} \text{Lepton-specific scalar:} & g_e : g_\mu : g_\tau = m_e : m_\mu : m_\tau \\ \text{Muon-specific scalar:} & g_\mu \neq 0,\ g_e = g_\tau = 0. \end{cases}$$

Couplings can arise from gauge-invariant dim-5 operators

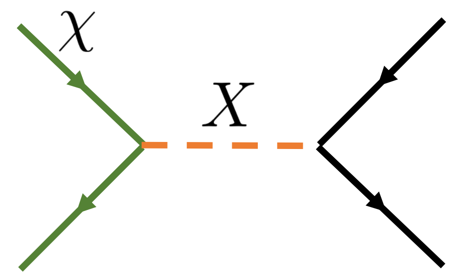
Possible UV completions: lepton-specific 2HDM+S, VL-leptons+S,...

Muon-specific forces require non-minimal flavor structure, but can still be viable [see e.g. Batell, Freitas, Ismail, McKeen, **Phys. Rev. D 98, 055026 (2018)**]

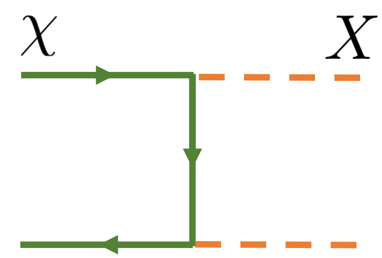
Light leptophilic DM

Different mass hierarchies lead to different pheno

$m_\chi < m_S/2$: Invisible decays (for small S couplings to SM), annihilates to SM



$m_S/2 \lesssim m_\chi \lesssim m_S$: Decays to SM, annihilates to SM

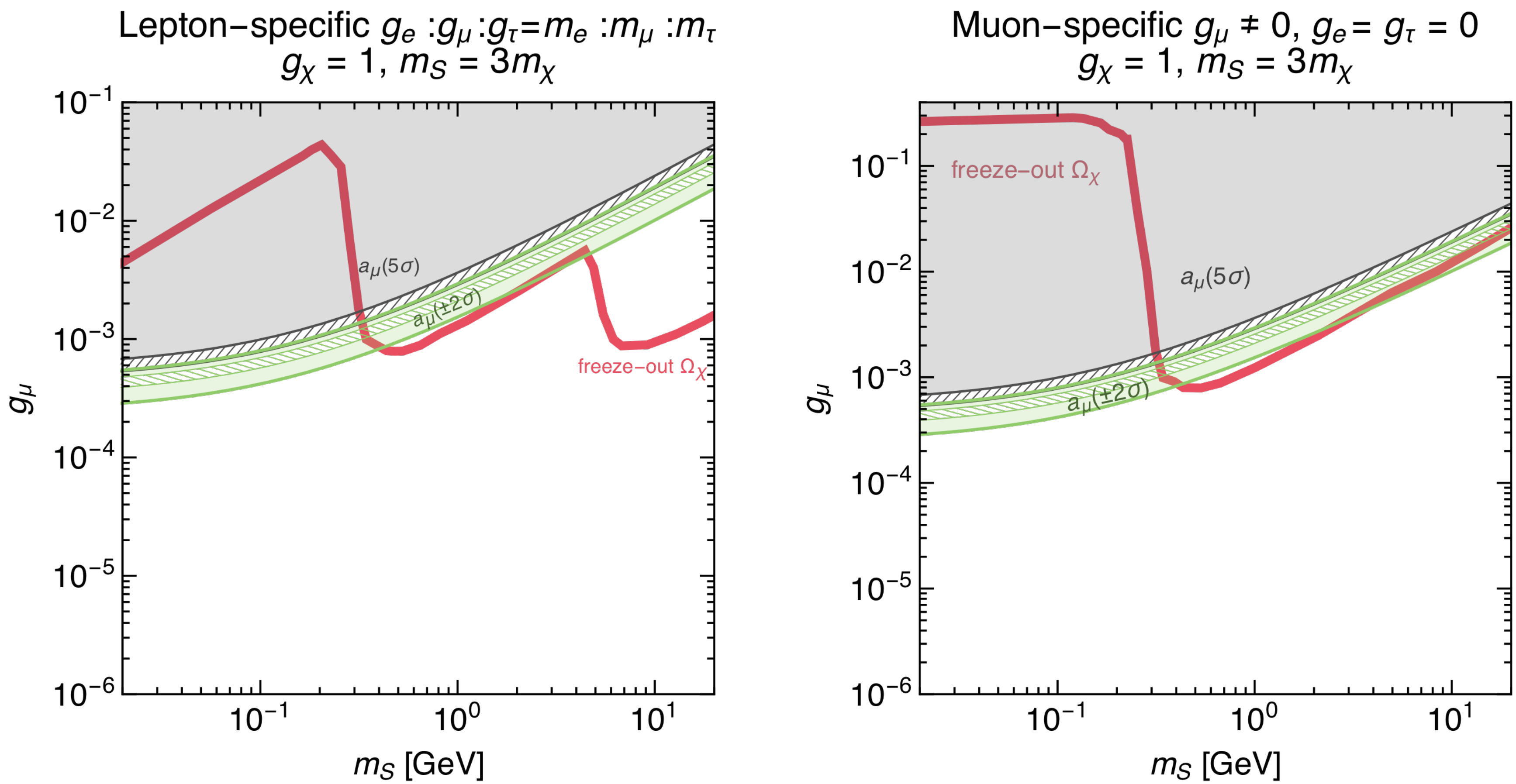


$m_S < m_\chi$: Decays to SM, secluded annihilation

Focus on $m_\chi < m_S/2$ with predominantly invisible decays. Pessimistic from accelerator standpoint; provides concrete thermal targets

$$\langle \sigma v \rangle = \frac{1}{8\pi} \frac{g_D^2 g_\ell^2}{m_\chi} \frac{(m_\chi^2 - m_\ell^2)^{3/2}}{(m_S^2 - 4m_\chi^2)^2} \langle v_{\rm rel}^2 \rangle$$

Light leptophilic DM targets



Similar targets motivated for vectors [see Kahn, Krnjaic, Tran, Whitbeck, **JHEP 1809 (2018) 153**; Berlin, Blinov, Krnjaic, Schuster, Toro, **Phys. Rev. D 99, 075001 (2019)**]

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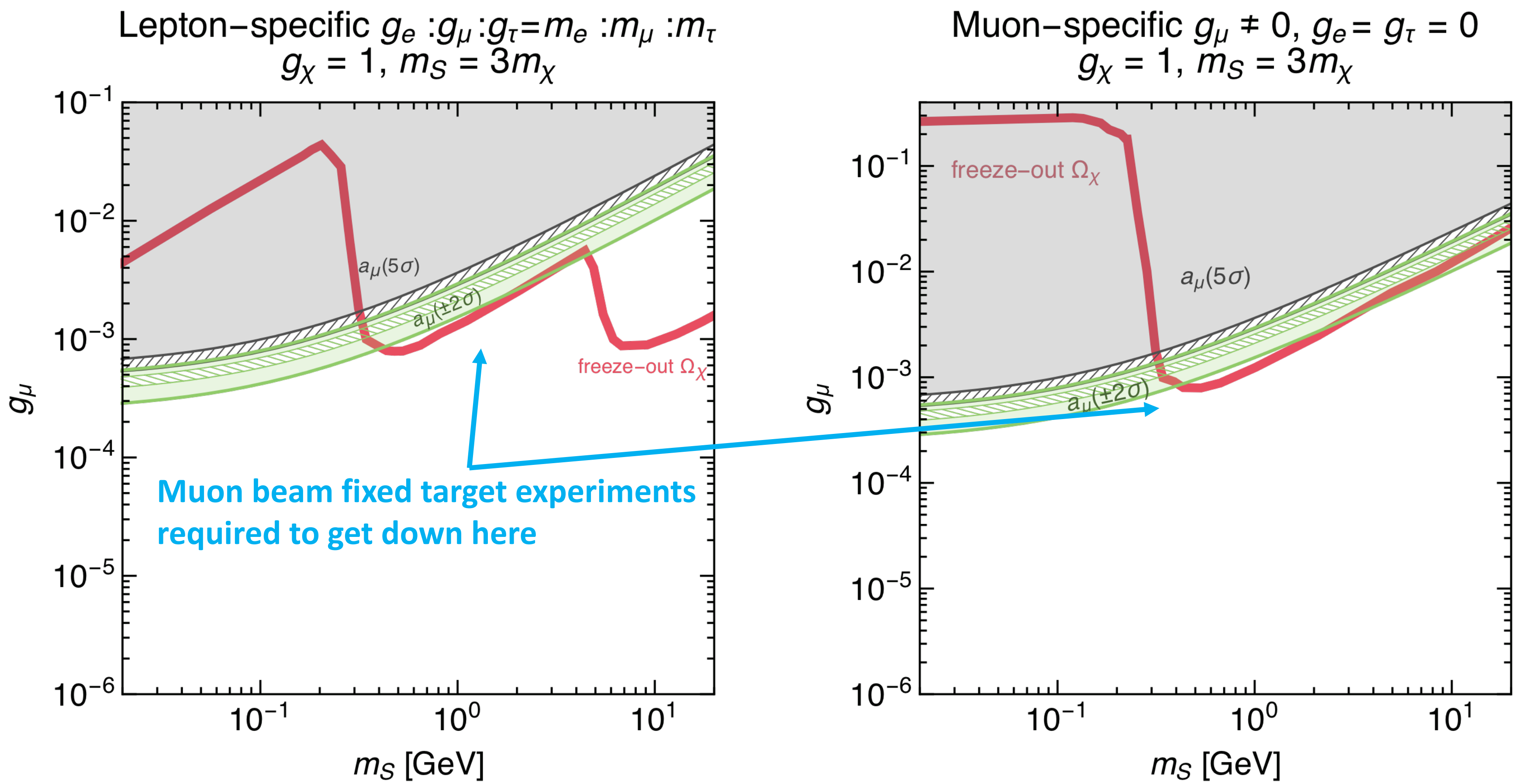

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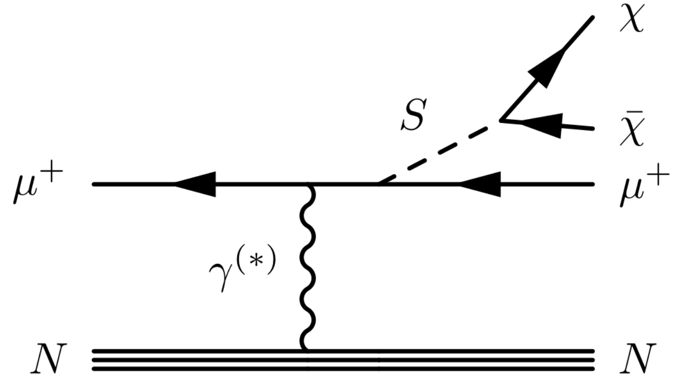
Muon beam missing momentum experiments

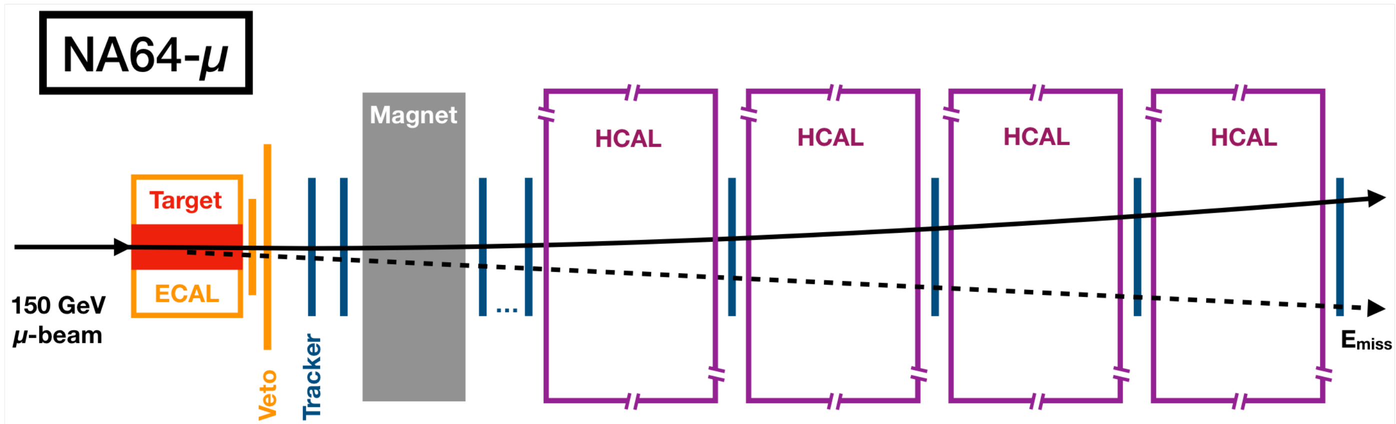


Two main proposals:

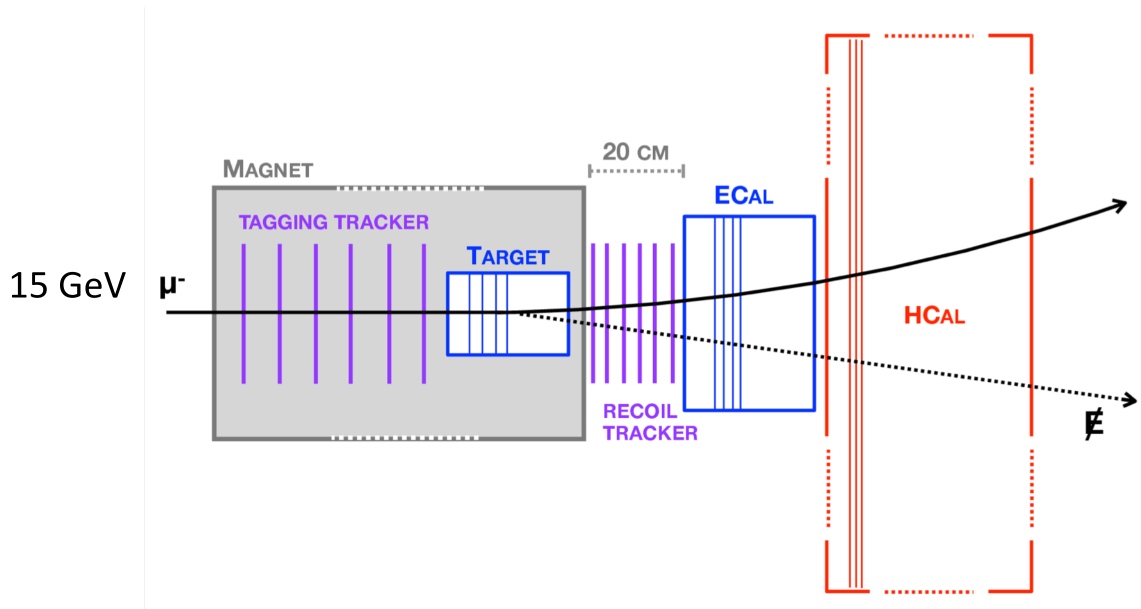
- **NA64-μ** [Gninenko, Krasnikov, Matveev, **Phys. Rev. D 91, 095015 (2015)**]
- **M³** [Kahn, Krnjaic, Tran, Whitbeck, **JHEP 1809 (2018) 153**]

Muon beam missing momentum experiments

NA64-μ

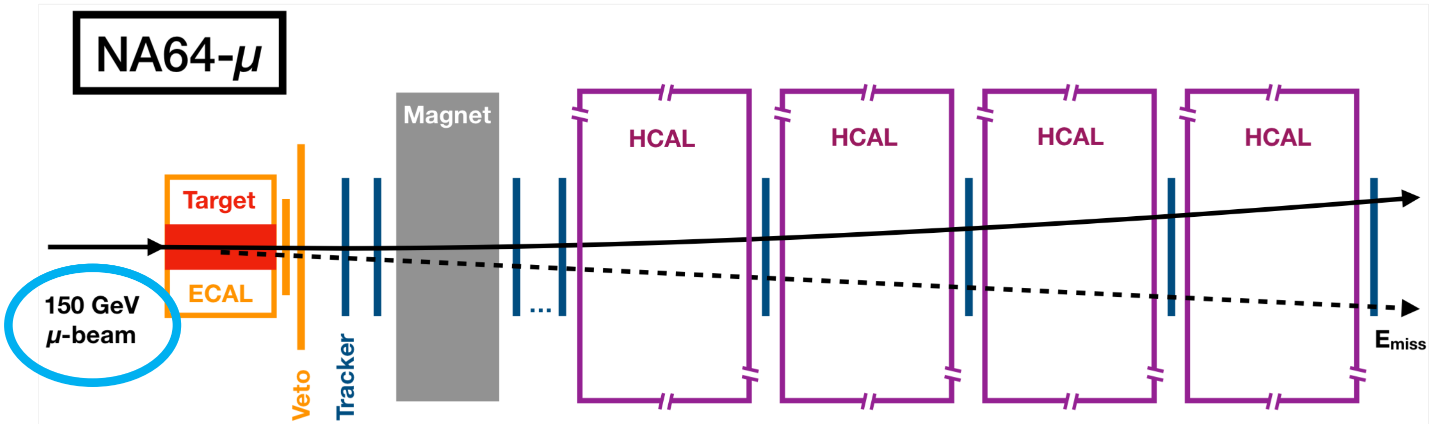


M³



Muon beam missing momentum experiments

NA64-μ



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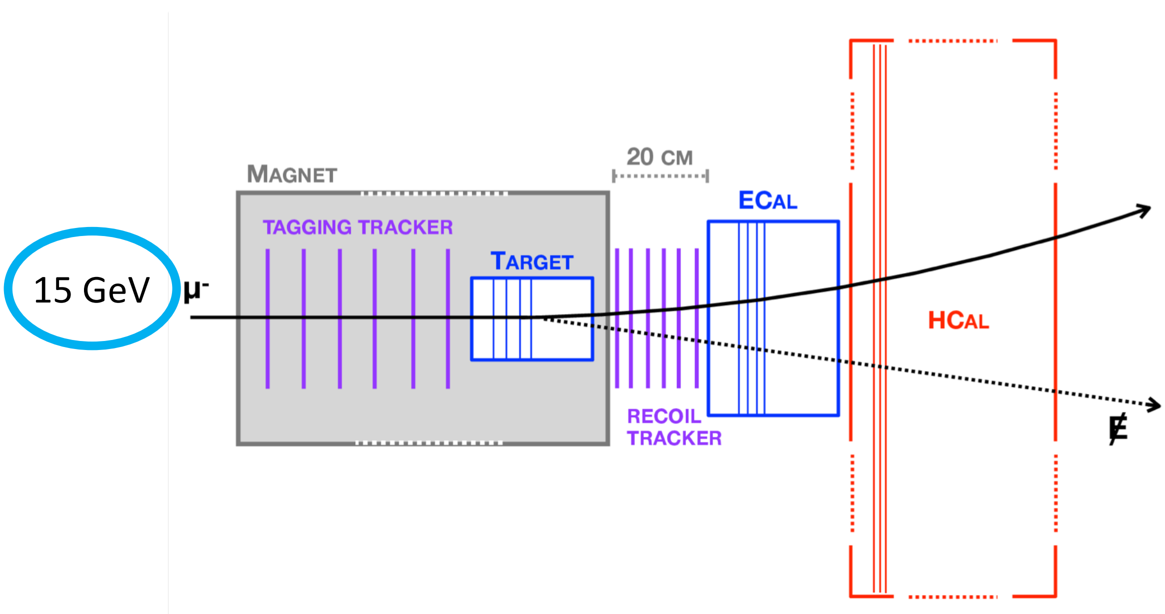
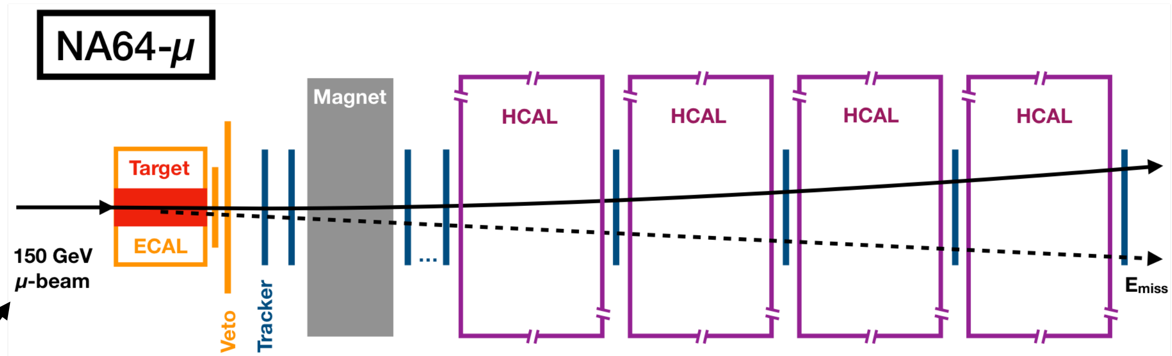


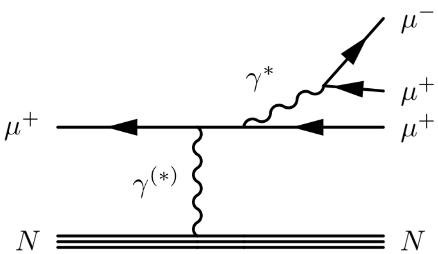
NA64-μ

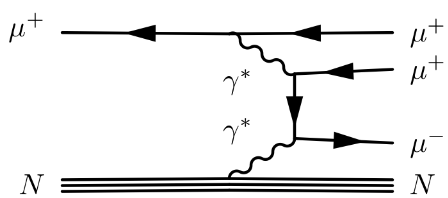


Muon beam from CERN SPS (2x10^8 muons/spill)

Signal: one scattered muon with energy between 15-100 GeV and small $E_{ECAL}+E_{HCAL}$

Dominant background after selection: muon pair production

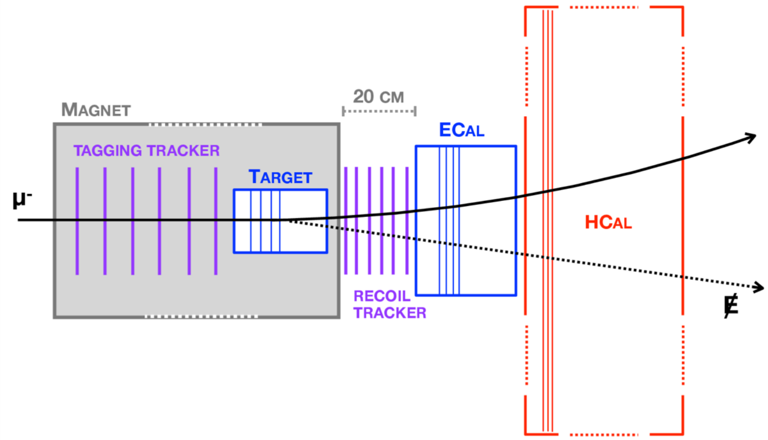




→ 1 fake signal event/10^{12} muons.
Other backgrounds <10^{-13}
[Gninenko, Krasnikov, Matveev, **Phys. Rev. D 91, 095015 (2015)**]

M^3

Kahn, Krnjaic, Tran, Whitbeck, **JHEP 1809 (2018) 153**



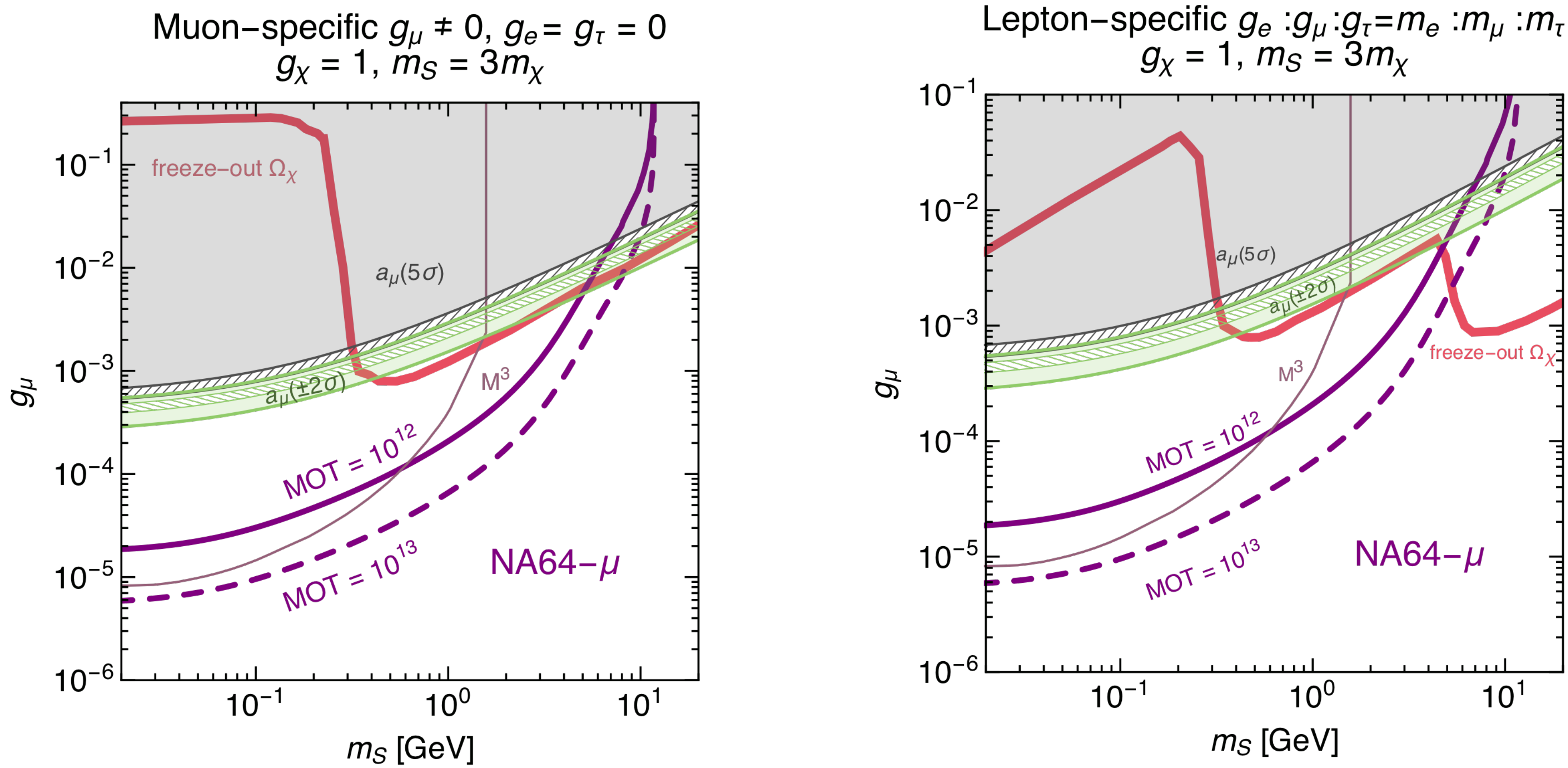
Phase 1: Muons from Fermilab MTest beamline (10^5 muons/spill). **10^{10} MOT**

Phase 2: Upgraded Neutrino Line (10^6-10^7 muons/spill). **10^{13} MOT**

Can reduce the muon trident background below 10^{-13} by counting photoelectrons in the HCAL (“1 vs 2”).

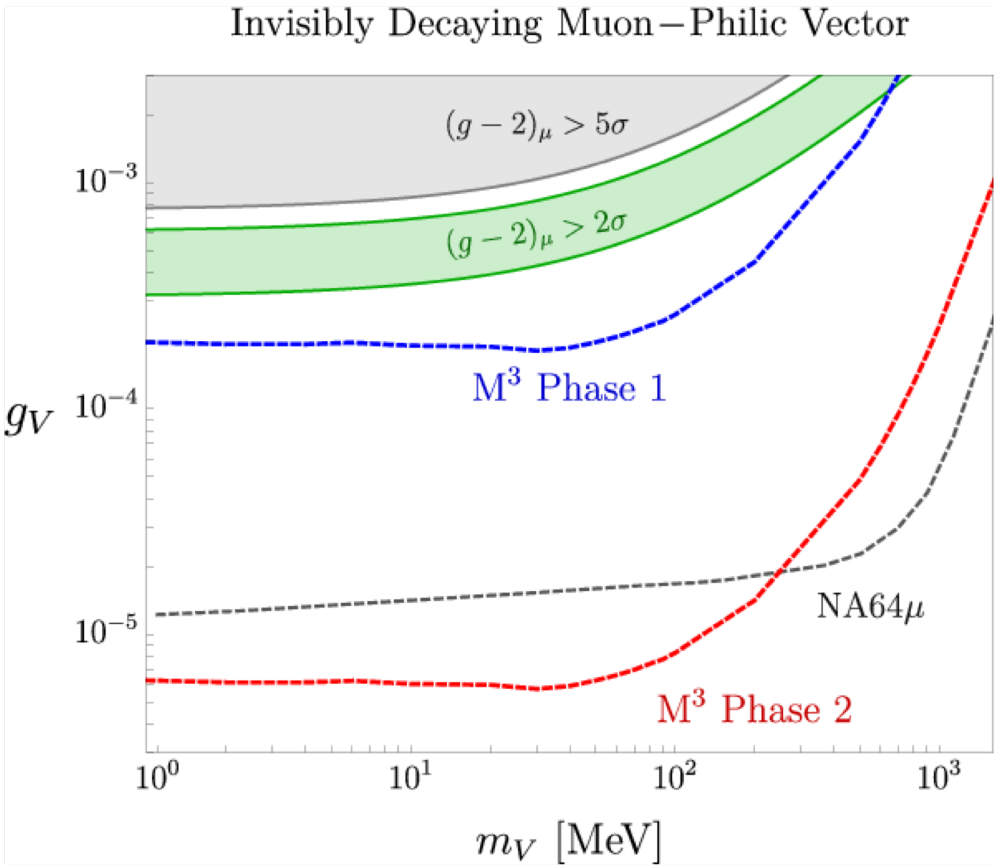
Same technique can be used at NA64-μ

Projections



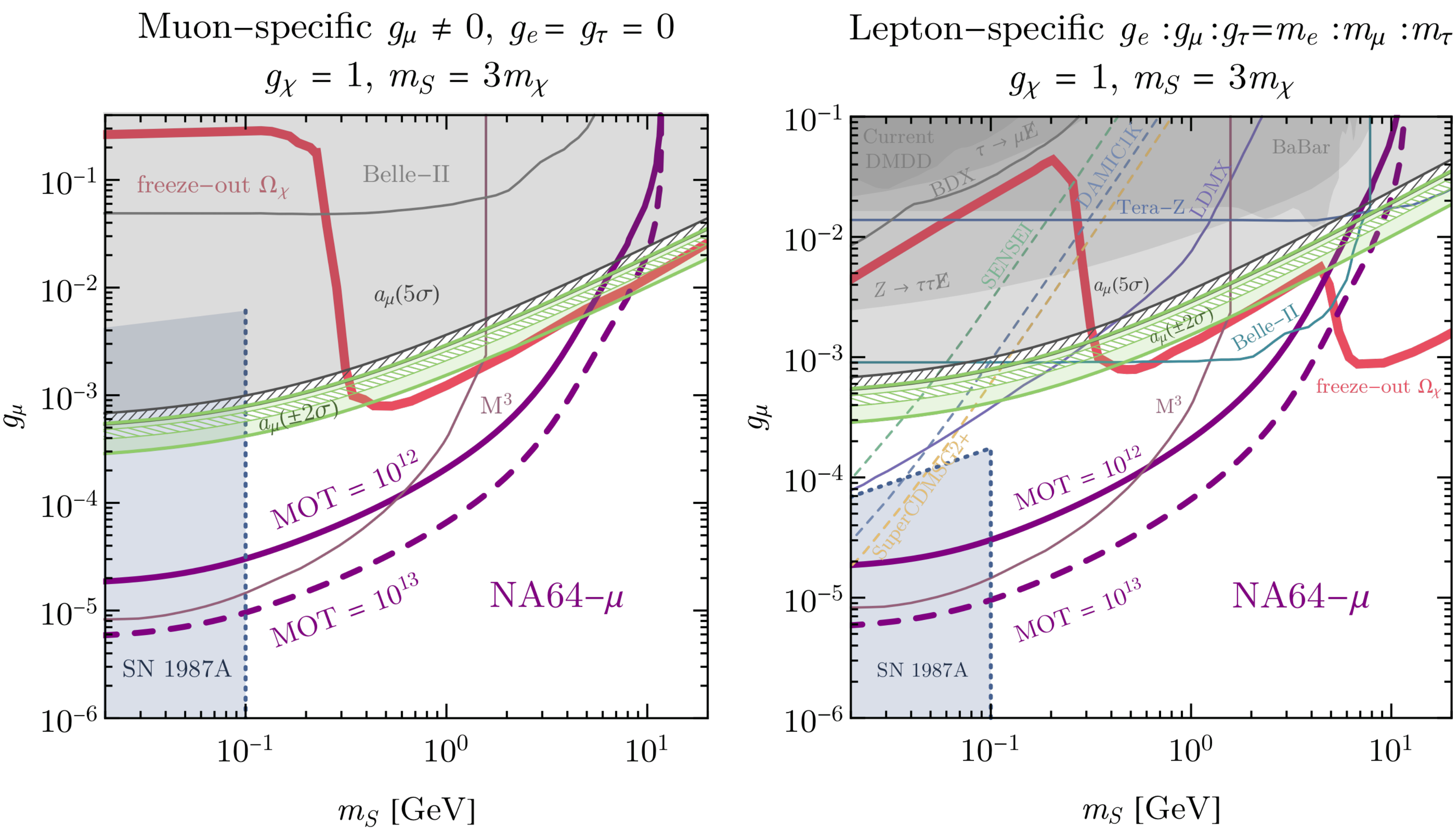
Muon beam fixed target experiments can probe new leptophilic forces up to ~1-10 GeV

Projections

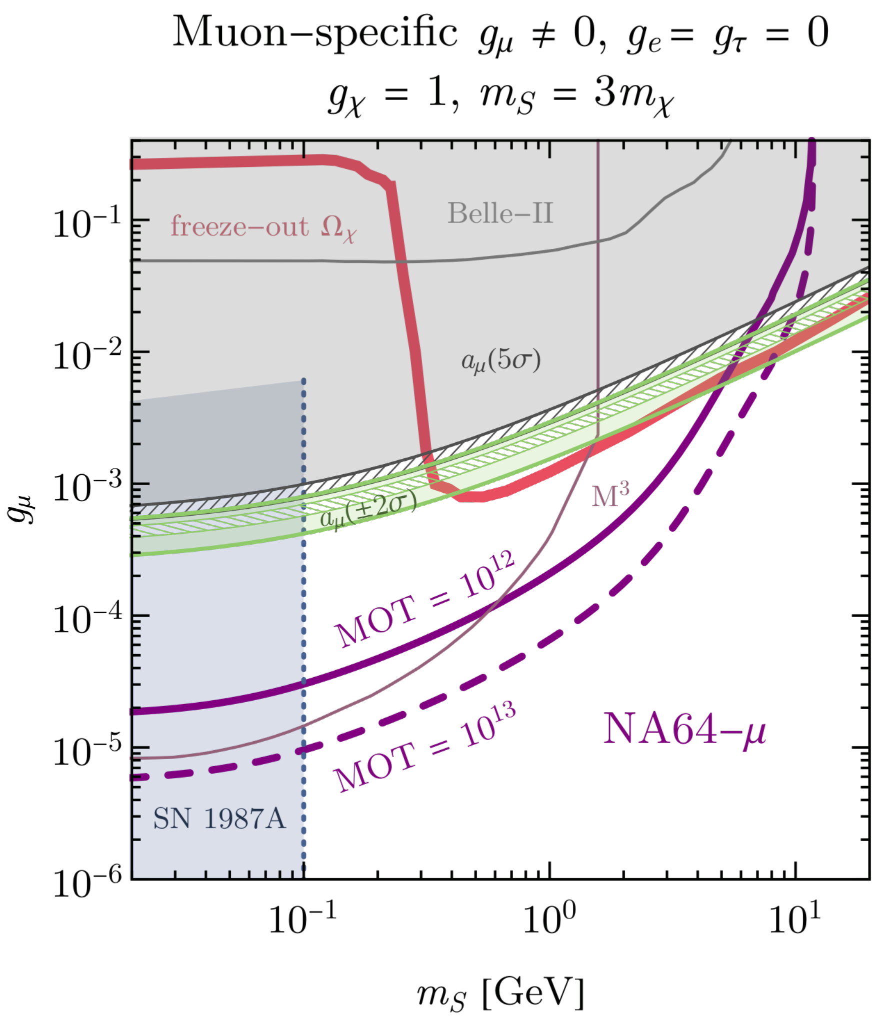


$U(1)_{\mu-\tau}$ vectors also covered. Above 400 MeV, $(g\text{-}2)_\mu$ band excluded by neutrino-nucleus scattering measurements

Other probes



Other probes (muon-specific)



Main constraints arise from effective coupling to photons

$$\mathcal{L} \supset -\frac{1}{4} g_{\gamma\gamma} S F_{\mu\nu} F^{\mu\nu}$$

$$g_{\gamma\gamma} = \frac{\alpha}{2\pi} \left| \sum_{\ell = e,\mu,\tau} \frac{g_\ell}{m_\ell} F_{1/2}\left(\frac{4m_\ell^2}{p_S^2}, \frac{q^2}{4m_\ell^2} \right) \right|$$

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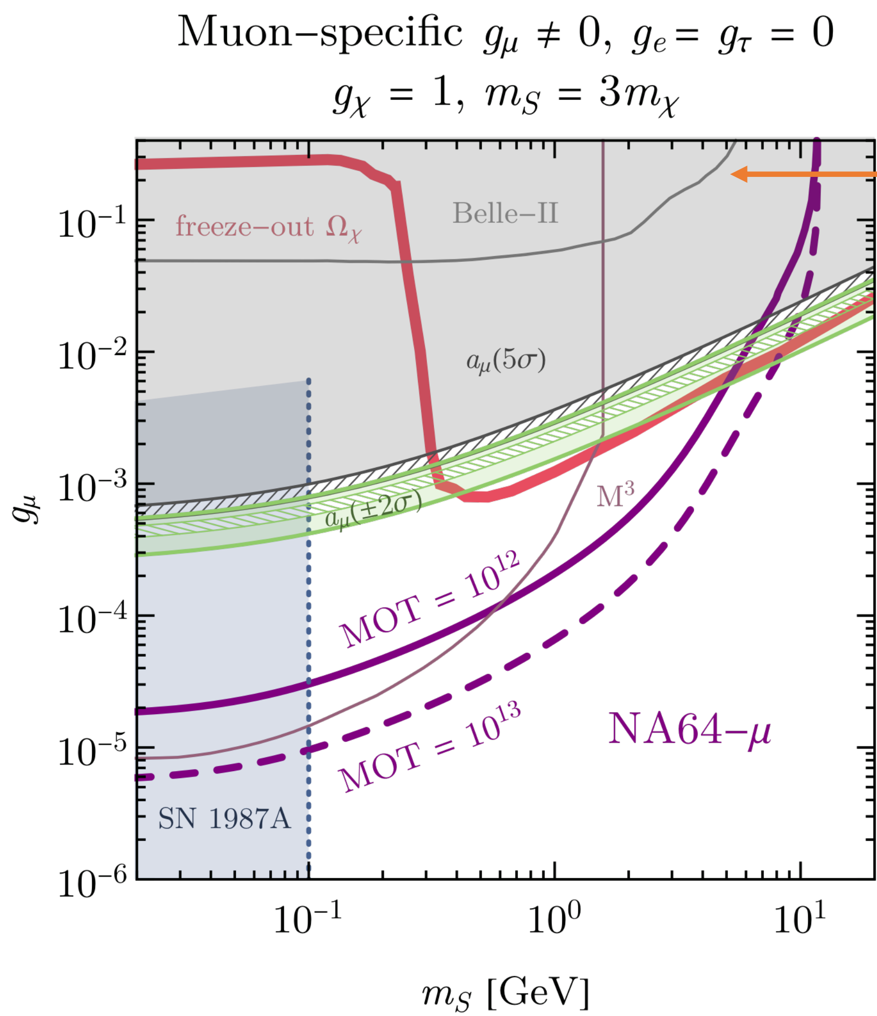
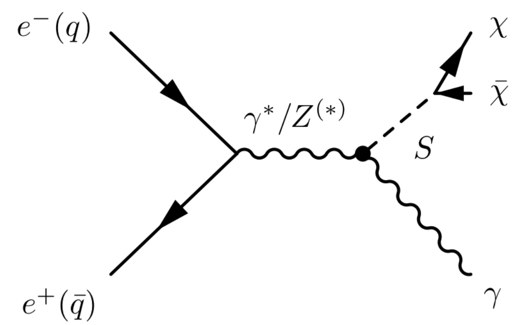


Main constraints arise from effective coupling to photons

- Mono-photon signatures at e^+e^- colliders



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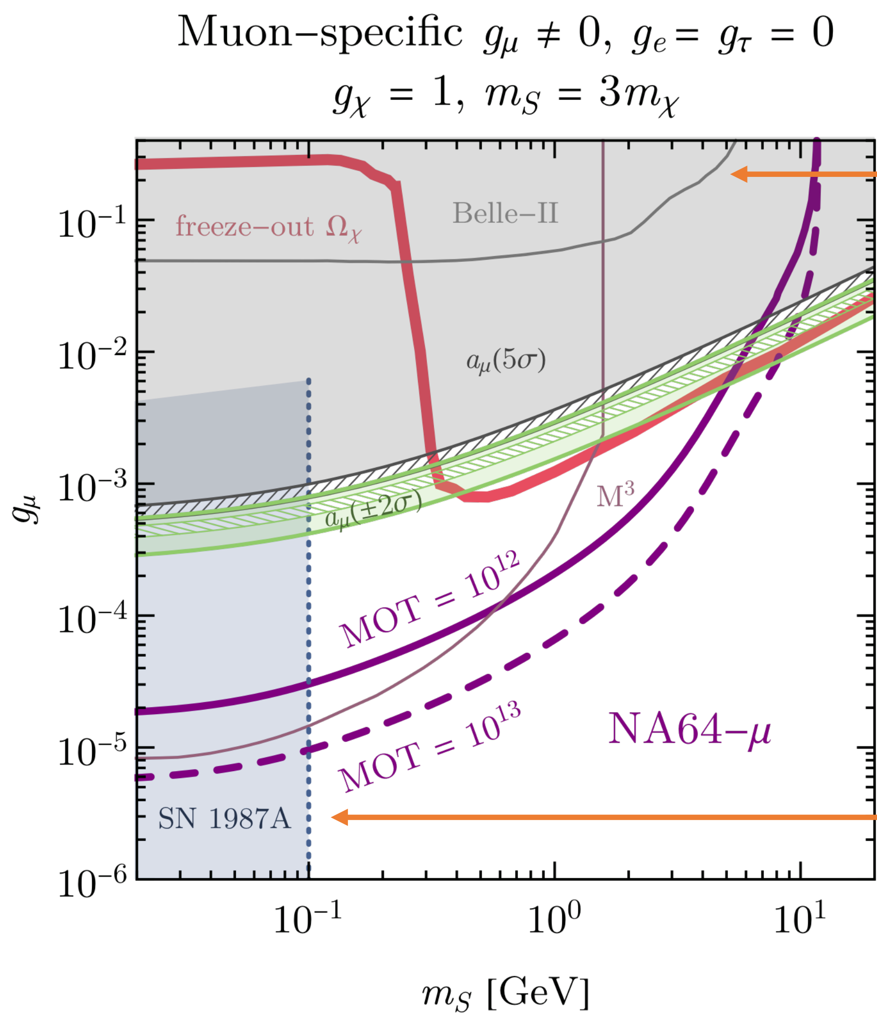

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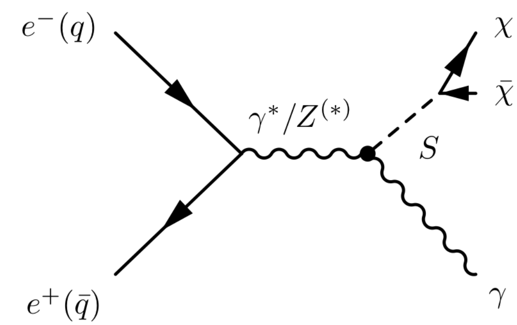


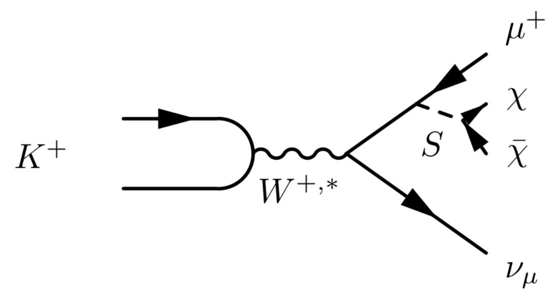
- Production and energy loss in supernovae. Efficient trapping for large enough $g_{S\gamma\gamma}$ from e.g. $\chi\gamma \to \chi\gamma$. Requirement:

$$(n_\gamma \sigma_{\chi\gamma\to\chi\gamma})^{-1} \lesssim r_{\rm core} \approx 1\,\mathrm{km}$$

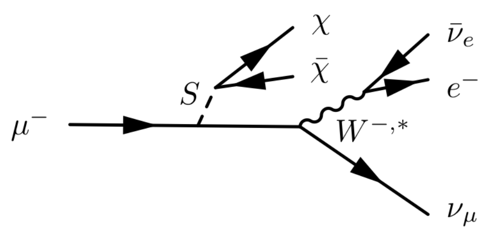
Other probes (muon-specific)

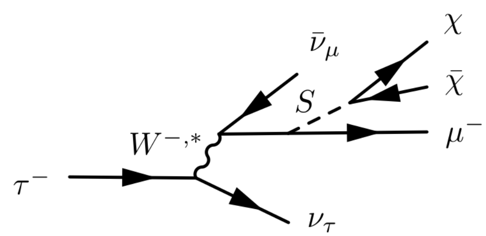
Other handles:

- Kaon decays (see Diego's talk)

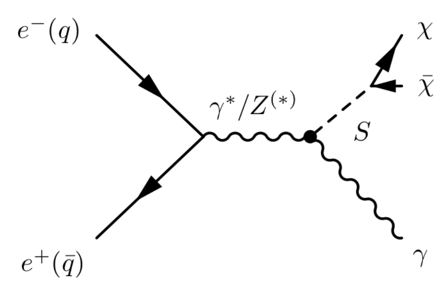


- Mu and tau decays



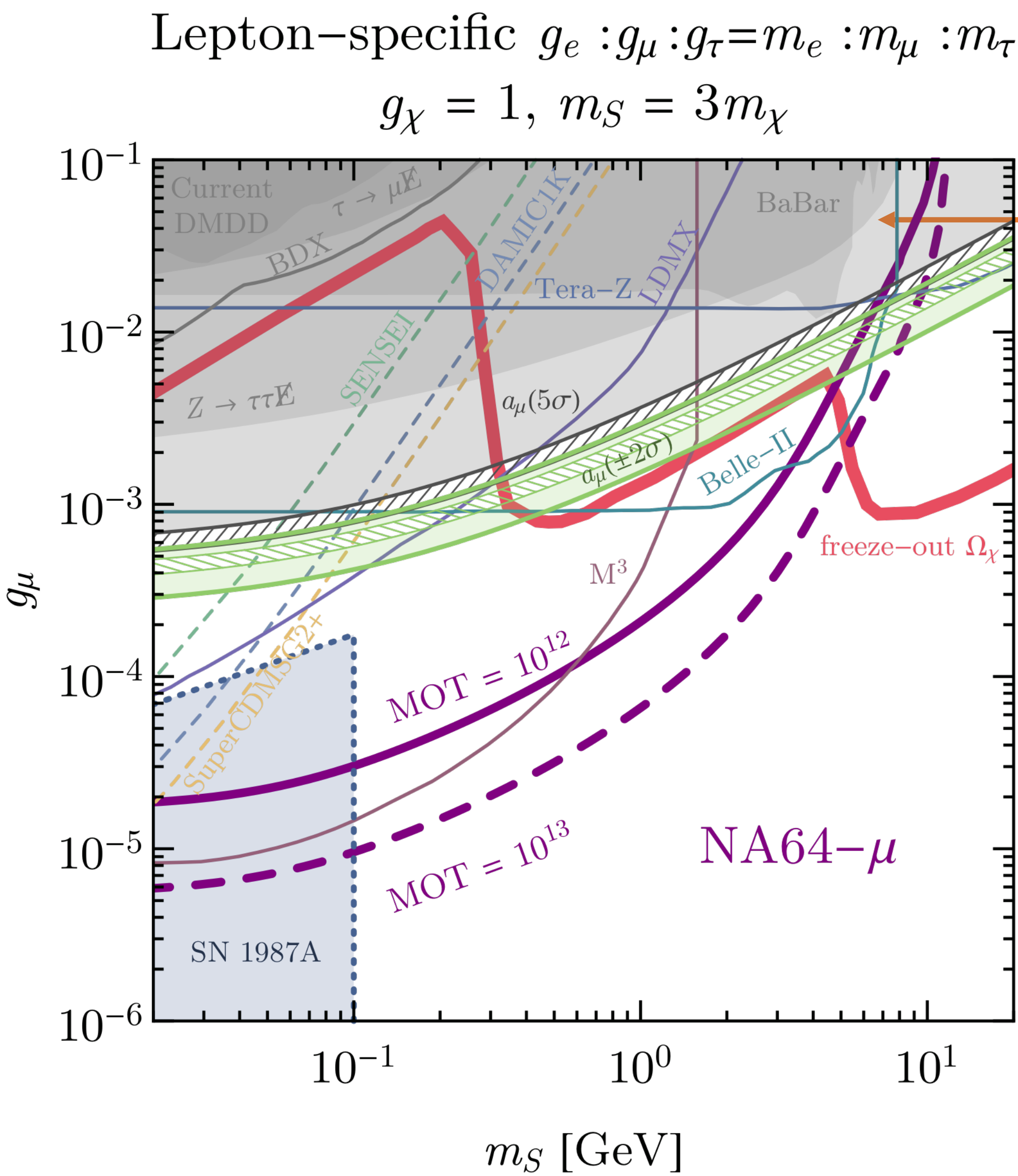


- Z → S γ at high-energy e⁺e⁻ colliders



Besides measurements at K factories, these measurements cannot compete with muon beams

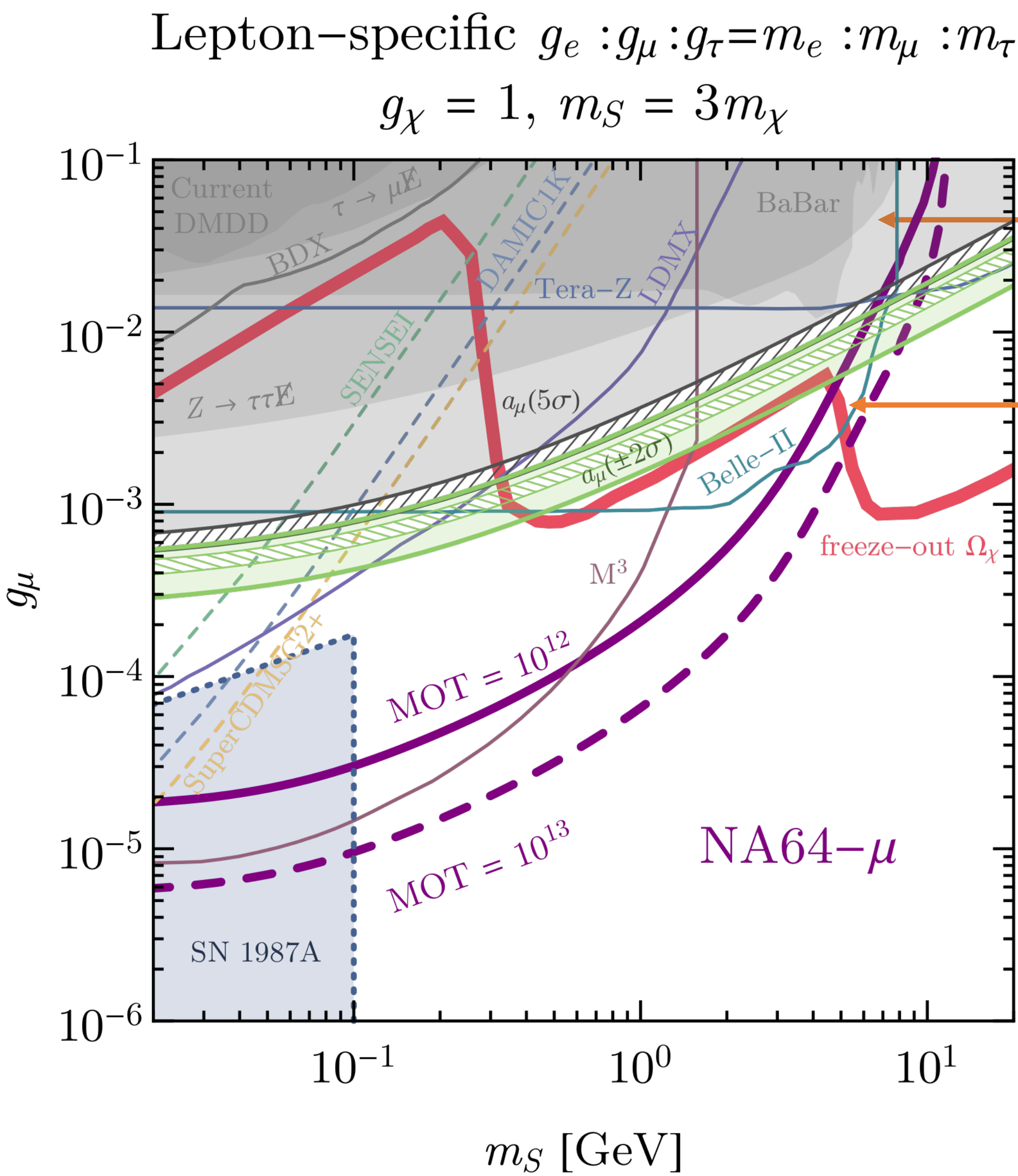
Other probes (lepton-specific)



Many more probes of the lepton-specific case:

- Strongest existing constraint still $(g\text{-}2)_\mu$

Other probes (lepton-specific)



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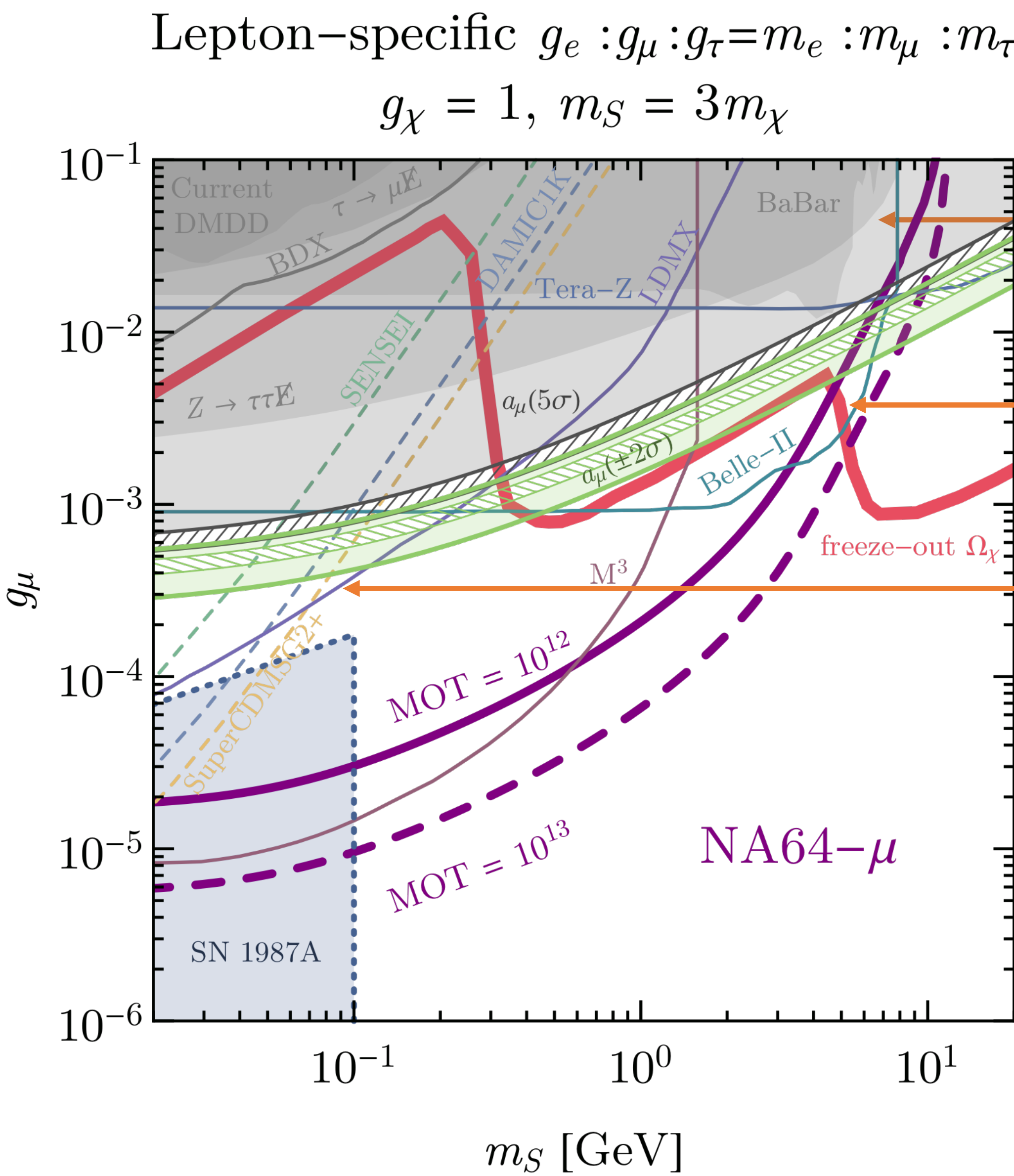

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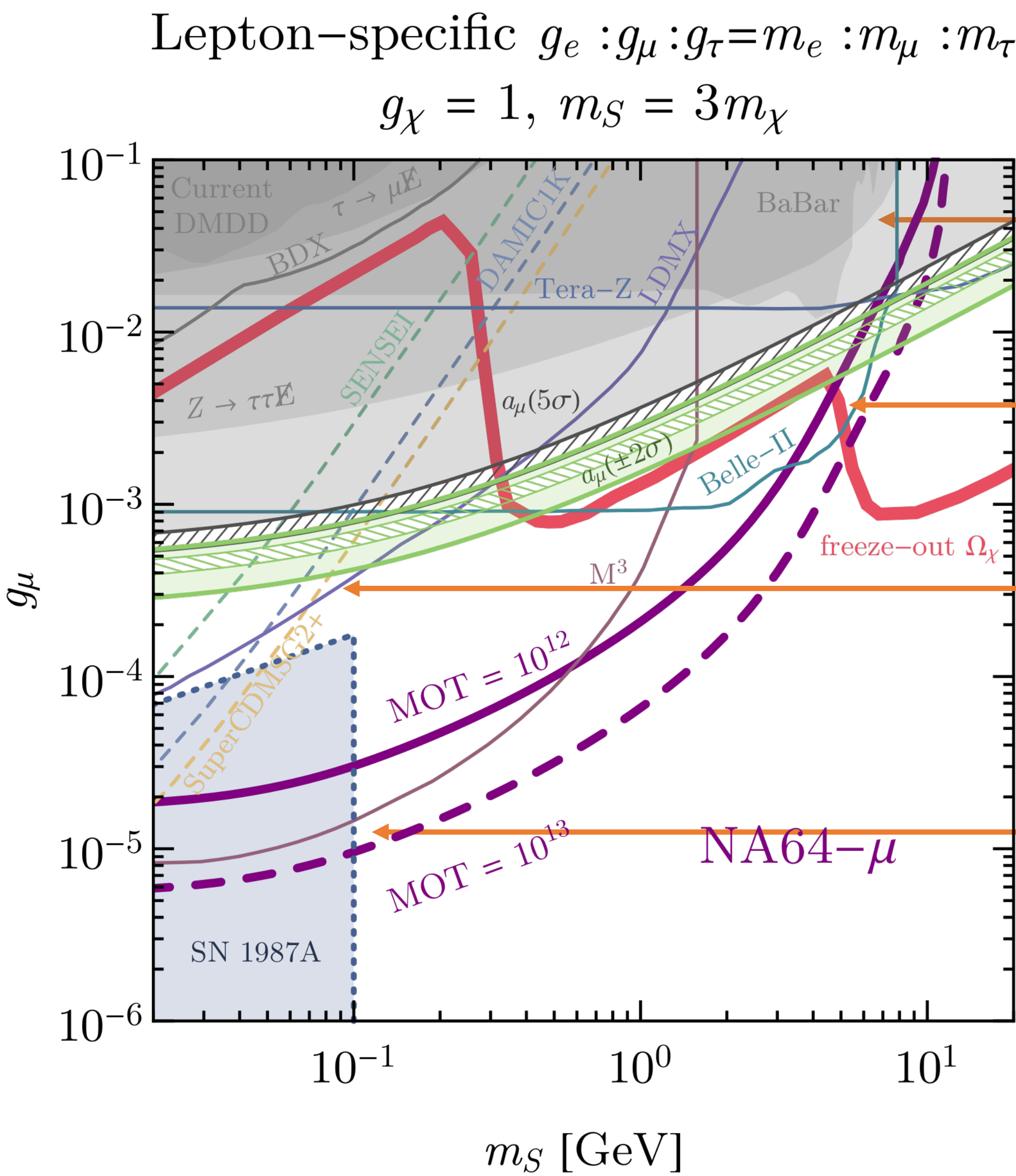

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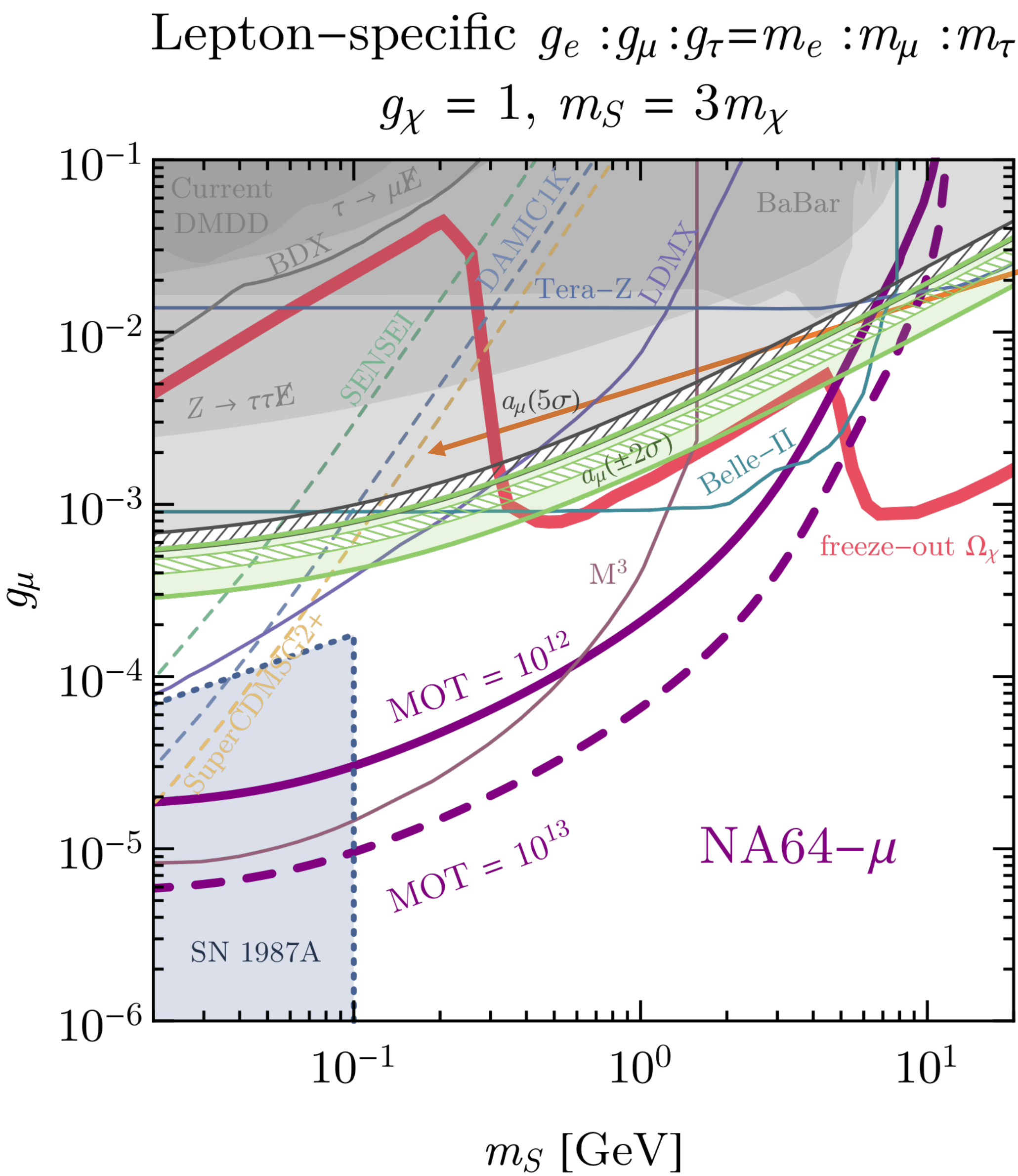
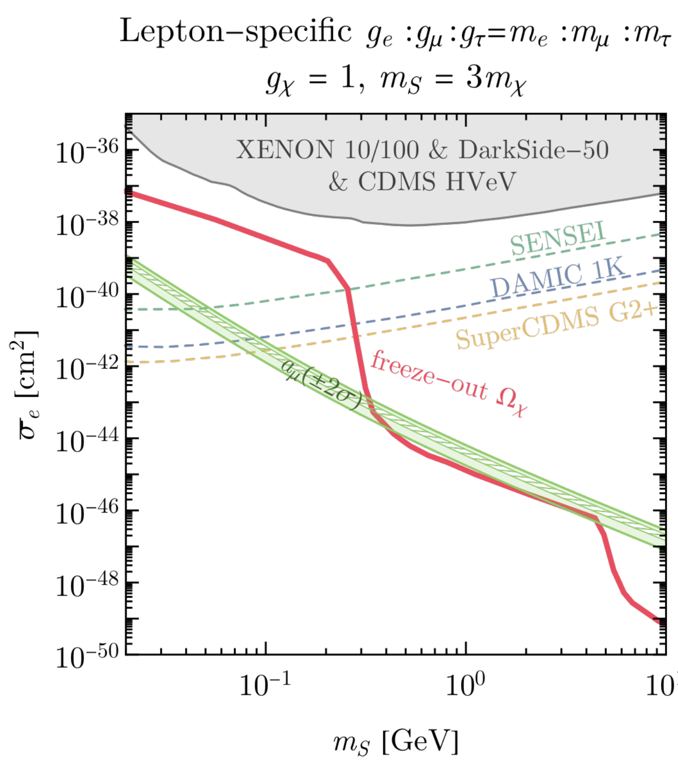
- Mono-photon signatures at e^+e^- colliders now arise at tree-level
- Signal at electron beam fixed target (e.g. LDMX) and beam-dump experiments (e.g. BDX)
- More efficient trapping in supernovae; lower bound relaxed relative to muon-specific case

Other probes (lepton-specific)



Many more probes of the lepton-specific case:

- Direct detection now has sensitivity through electron recoils



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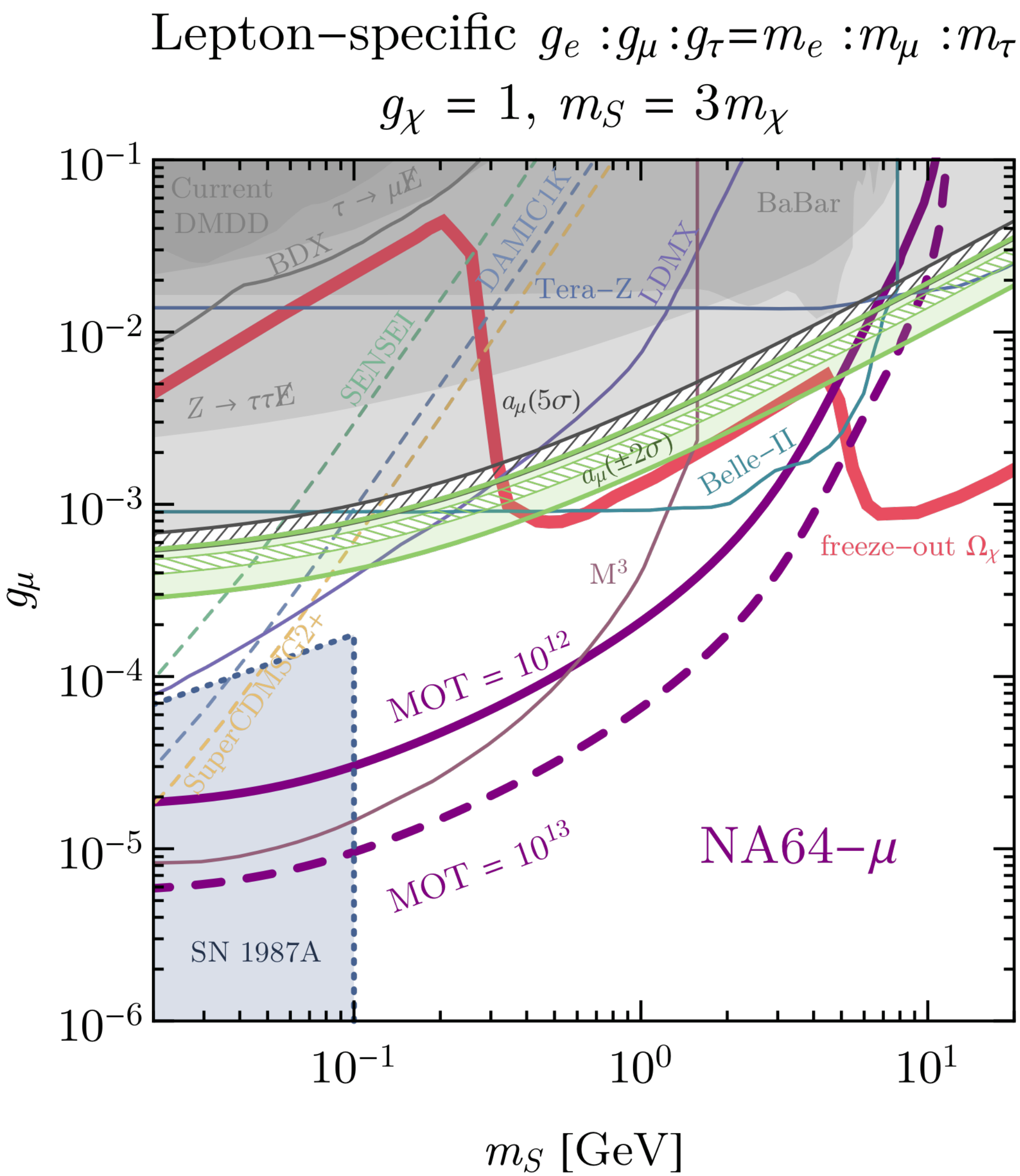
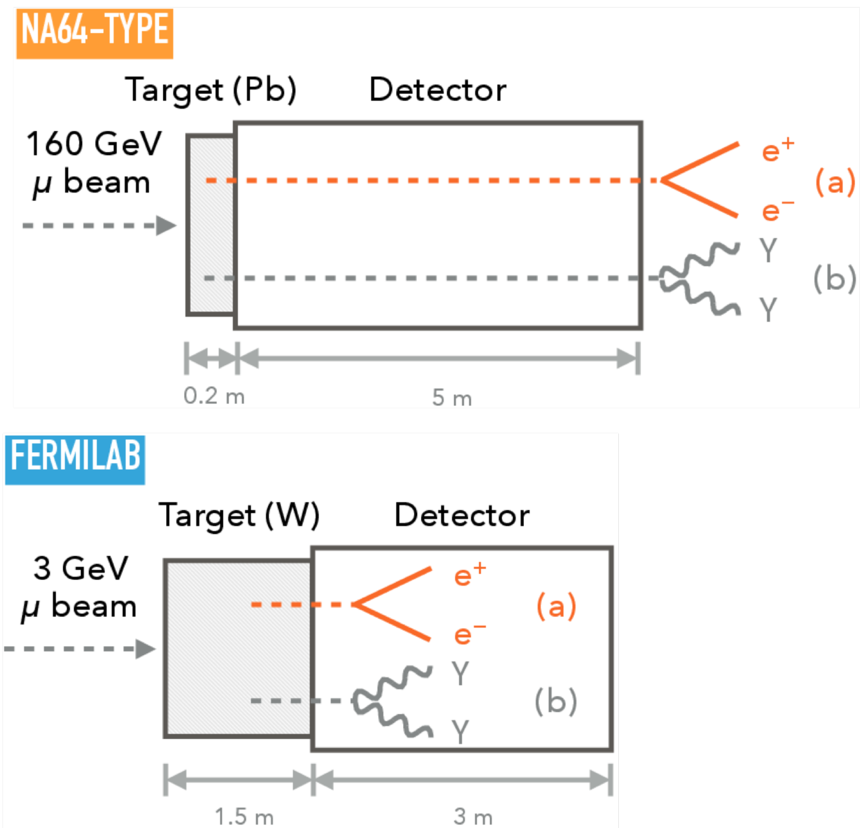


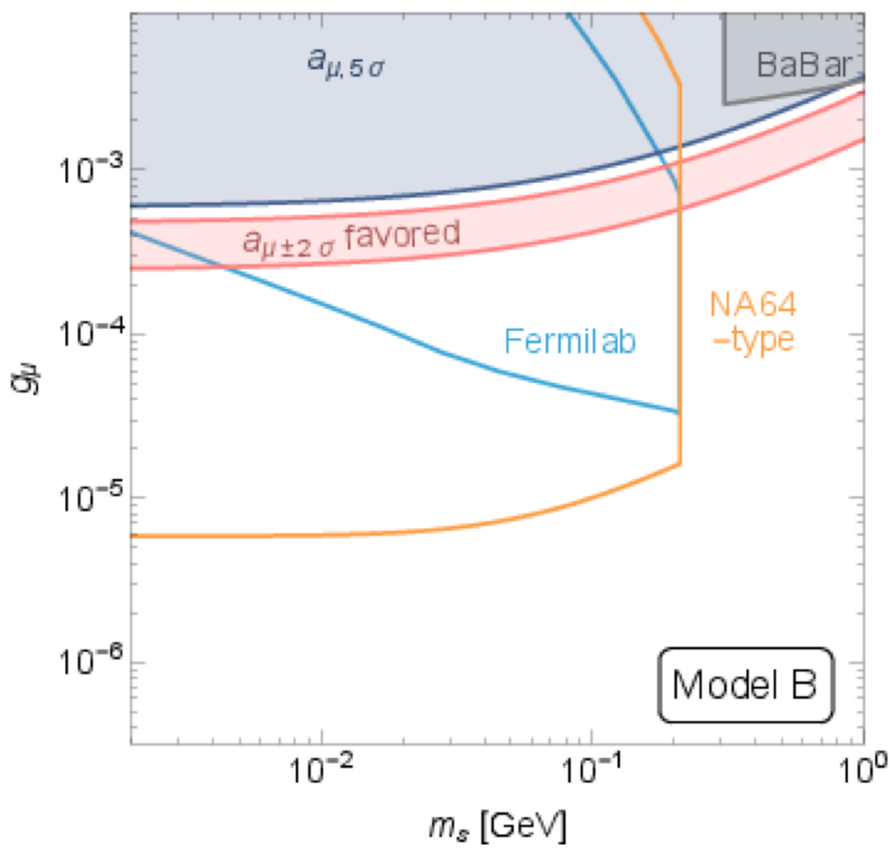
Muon beam experiments still required to conclusively probe $(g\text{-}2)_\mu$ – motivated leptophilic DM

More fun with muon beams

Experiments like NA64-μ and M^3 can also probe visibly-decaying leptophilic mediators

Chen, Pospelov, Zhong, **Phys.Rev. D95 (2017) no.11, 115005**



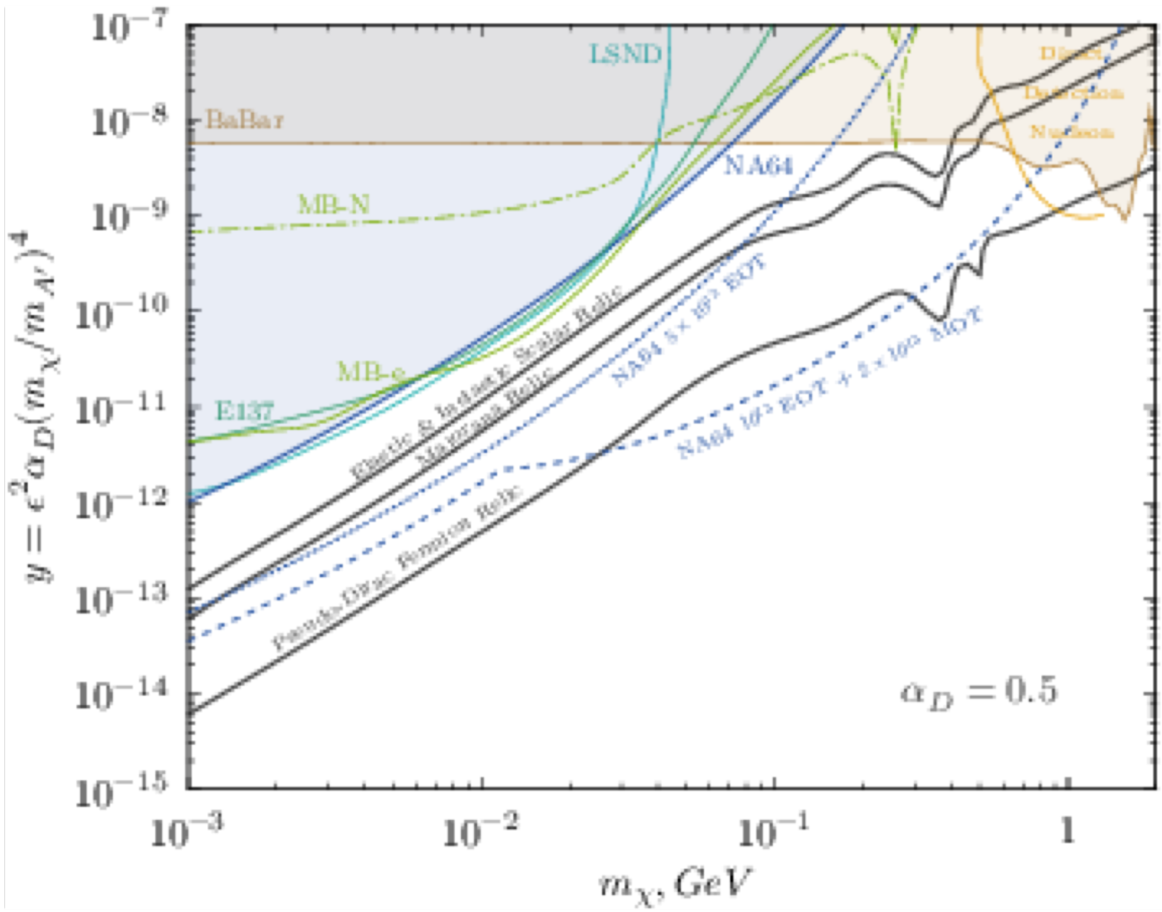


More fun with muon beams

Can also probe other simple DM scenarios

E.g. **U(1) hidden sector**:

Gninenko, Kirpichnikov, Kirsanov, Krasnikov, **Phys.Lett. B796 (2019) 117-122**

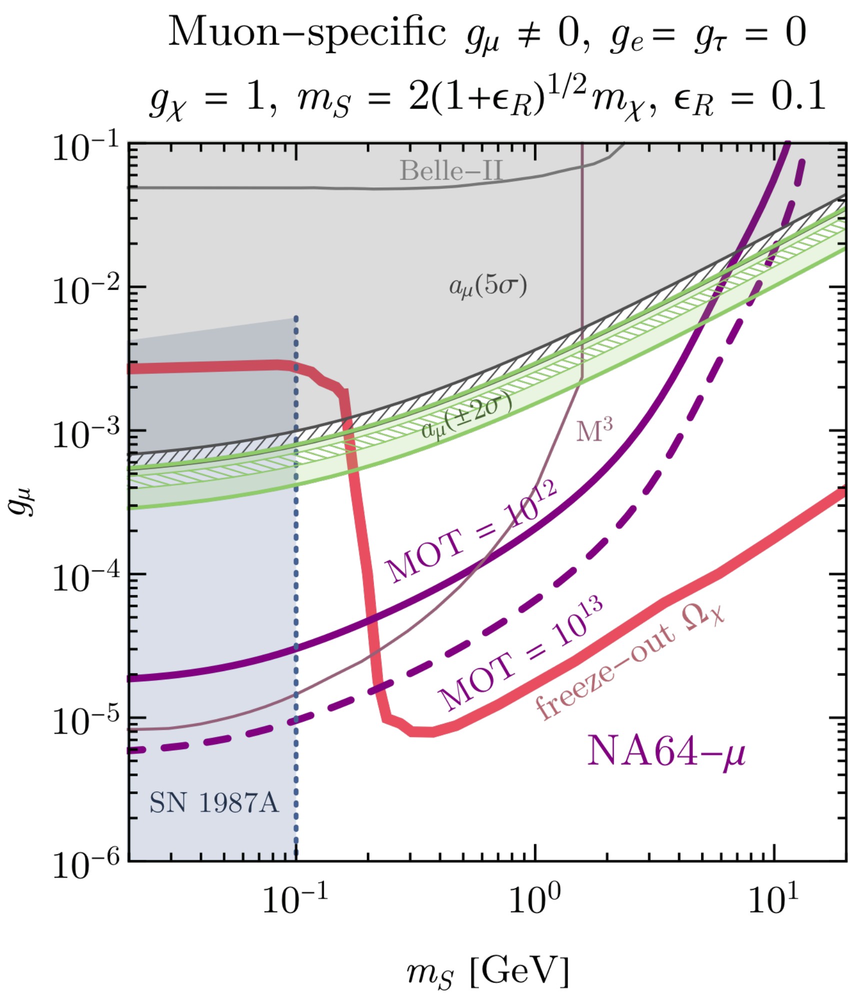


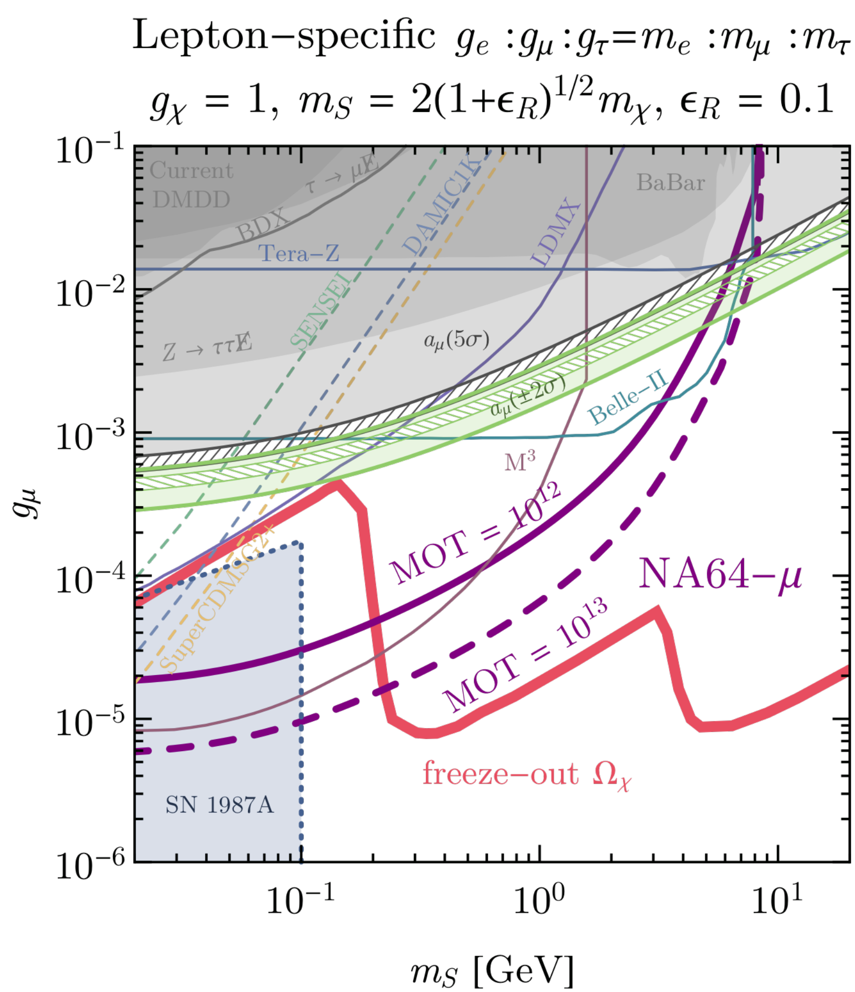
Takeaway:

Muon beam fixed target experiments provide unique opportunities to probe light hidden sector explanations of the $(g\text{-}2)_\mu$ discrepancy and beyond.

Backup

Different choices for the DM mass





Constraints on g_χ