Dark Sector Searches via Muon Beam-Dump Experiments

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Workshop on Potential Fermilab Muon Campus & Storage Ring Experiments, 05/26/2021

Outline

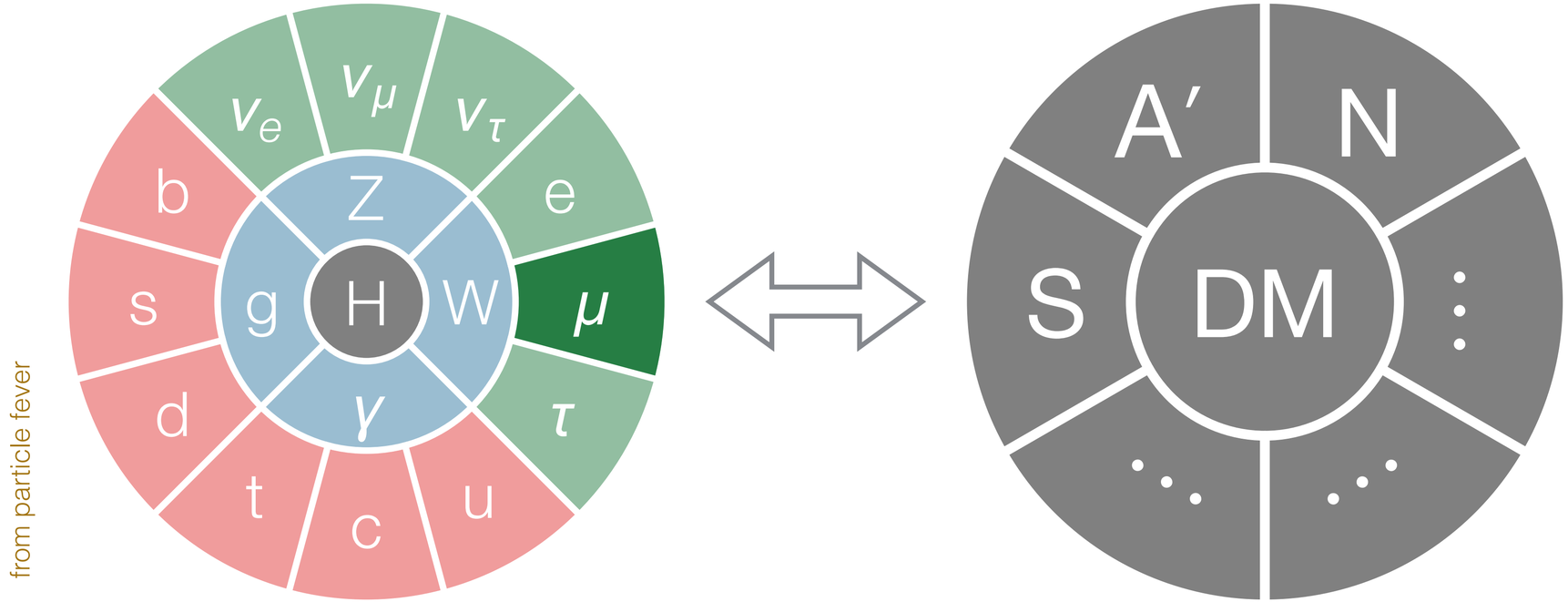
- Motivation
- Proposed experimental setup
- Projected sensitivity
- Summary

Accumulated muon anomalies

- Muon related-anomalies appear in several particle experiments:
  - Muon anomalous magnetic moment (4.2σ) — Muon g-2 ’21
  - Lepton flavor non-universality in B meson decays (~3σ) — LHCb ’17, ’21, Belle ‘19
  - Proton charge radius of muonic hydrogen spectroscopy (in tension w/ some H spectroscopy & e-p scattering exp.) — Pohl+ ’10, Antognini+ ’13, See review Gao & Vanderhaegh ‘21
  - …

How to interpret?

- Statistics/Experimental systematics/Theoretical systematics
- Or a muonic dark sector? e.g. Pospelov '09, Tucker-Smith & Yavin '10, Sierra+ '15, Crivellin+ '15, Liu+ '16

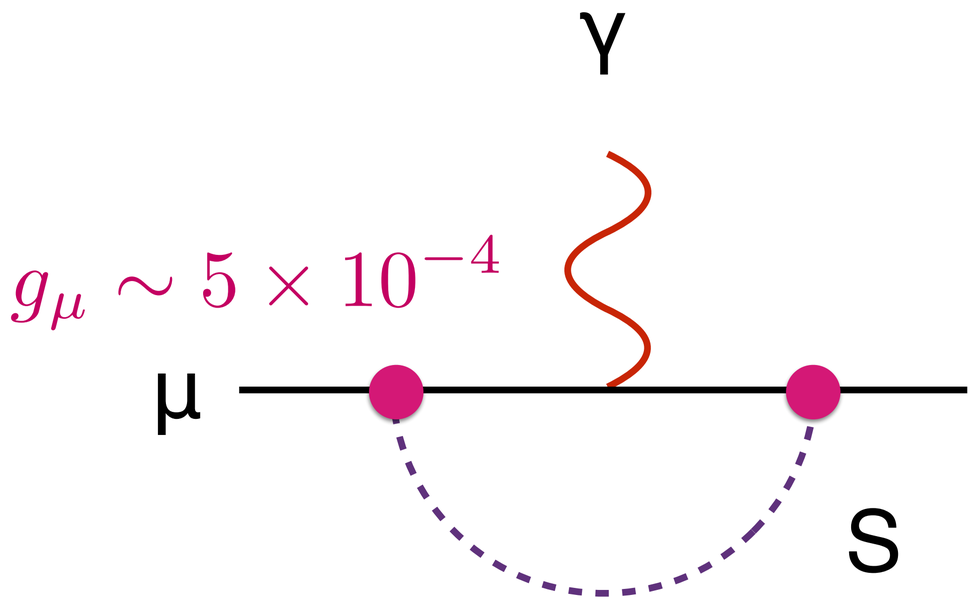


from particle fever

Minimal model to solve (g-2)$_\mu$ anomaly

- Introduce a **new** light scalar S
  ($\mathrm{MeV} < m_S < 2m_\mu$)
- Couples to muons, not quarks
- S visibly decays to SM particles

$$\Delta a_\mu \sim \frac{g_\mu^2}{16\pi^2}\frac{m_\mu^2}{m_S^2} \sim 10^{-9}$$



Minimal model to solve (g-2)$_\mu$ anomaly

model A

$$\mathcal{L} \supset -g_e S\bar{e}e - g_\mu S\bar{\mu}\mu - g_\tau S\bar{\tau}\tau$$

w/ $g_\ell \propto m_\ell$

model B

$$\mathcal{L} \supset -g_\mu S\bar{\mu}\mu$$

Originated from $\mathcal{O}_5 = \frac{c_i}{\Lambda} S\bar{L}_i H E_i$

Batell+ '18

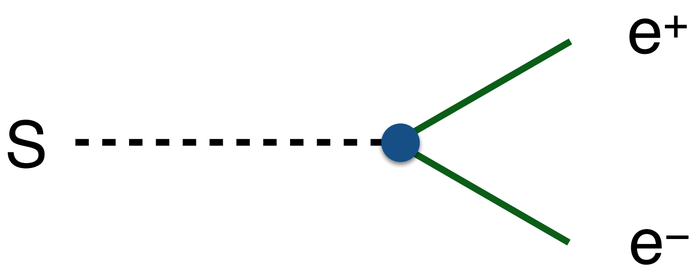
with Minimal Flavor Violation

under "flavor-specific" hypothesis

Dominant decay channels

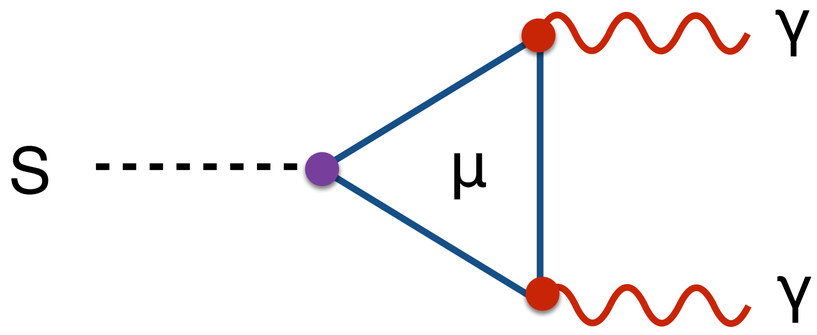
$\mathrm{MeV} < m_S < 2m_\mu$

model A



m_e-suppressed

model B



loop-suppressed

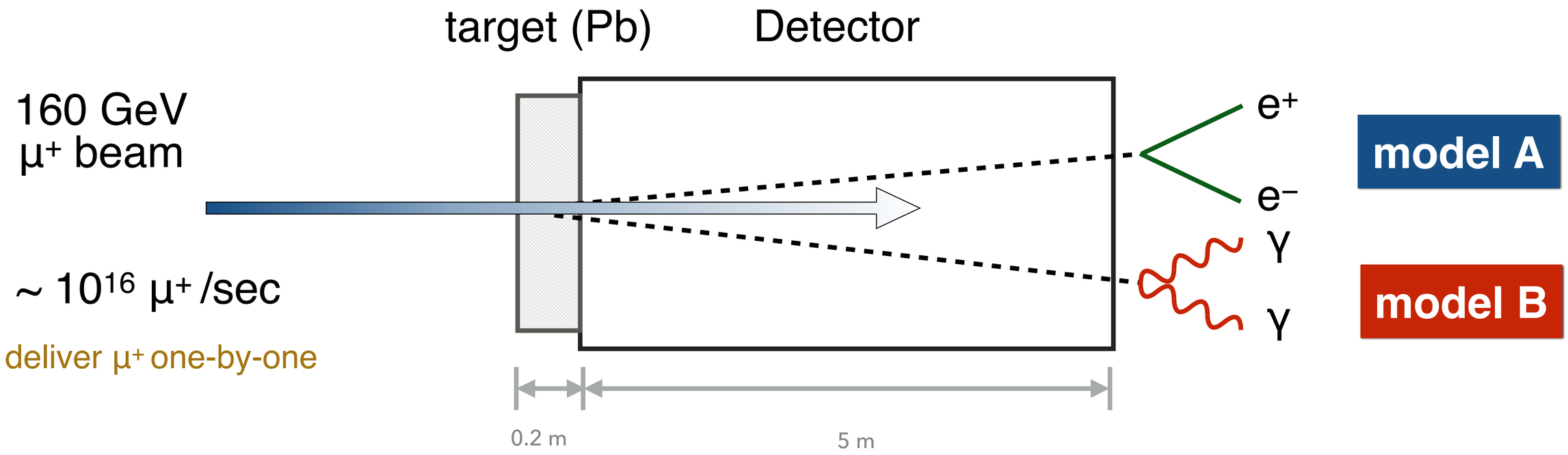
for $g_\mu \sim 10^{-4}$, $m_S \sim 100$ MeV, decay length: O (10 cm) ~ O (10 m)

Look at muon-beam dump experiments

- Muon-beam dump experiments are good place to look for dark scalars (and other light dark particles):
  - focus on the couplings to muons
  - sensitive to displaced decays
  - can be integrated to other muon experiments
- **We look into two searches**

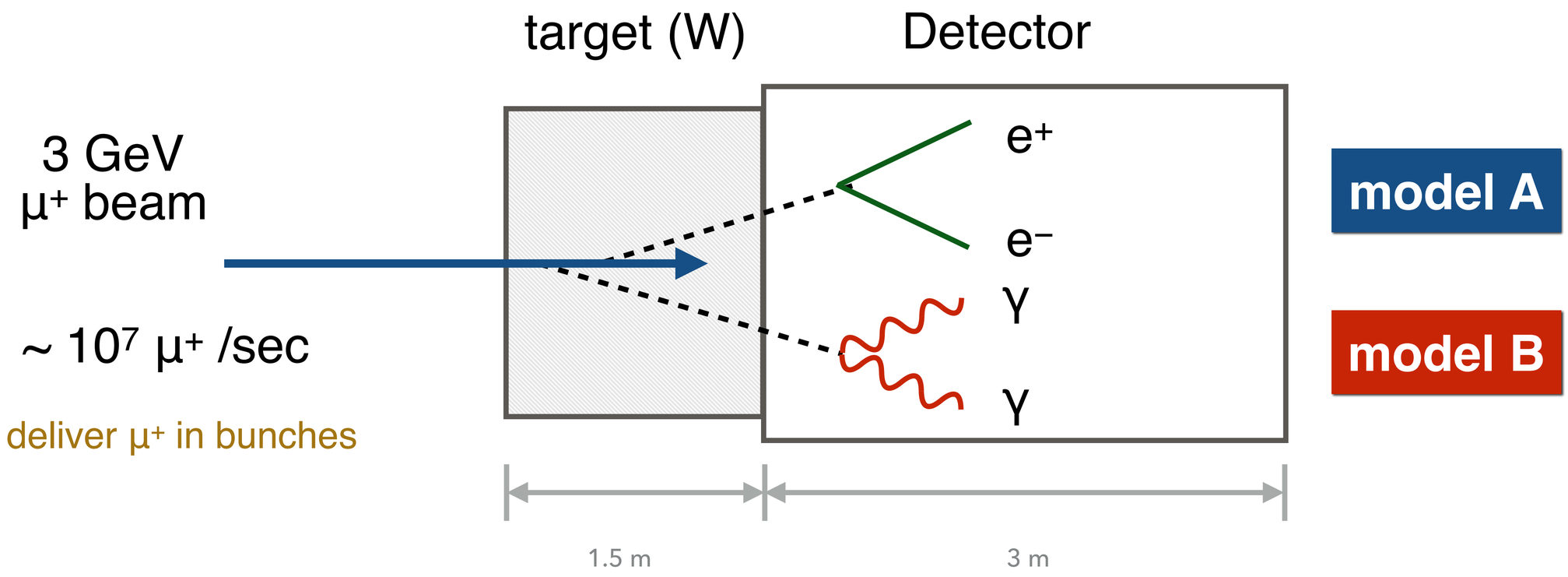
NA64 setup (NA64-μ)

NA64 is a fixed-target experiment at CERN (test run of NA64-μ starts soon)



large missing energy of μ beam ($E_{miss} \gtrsim E_{beam}/3$)

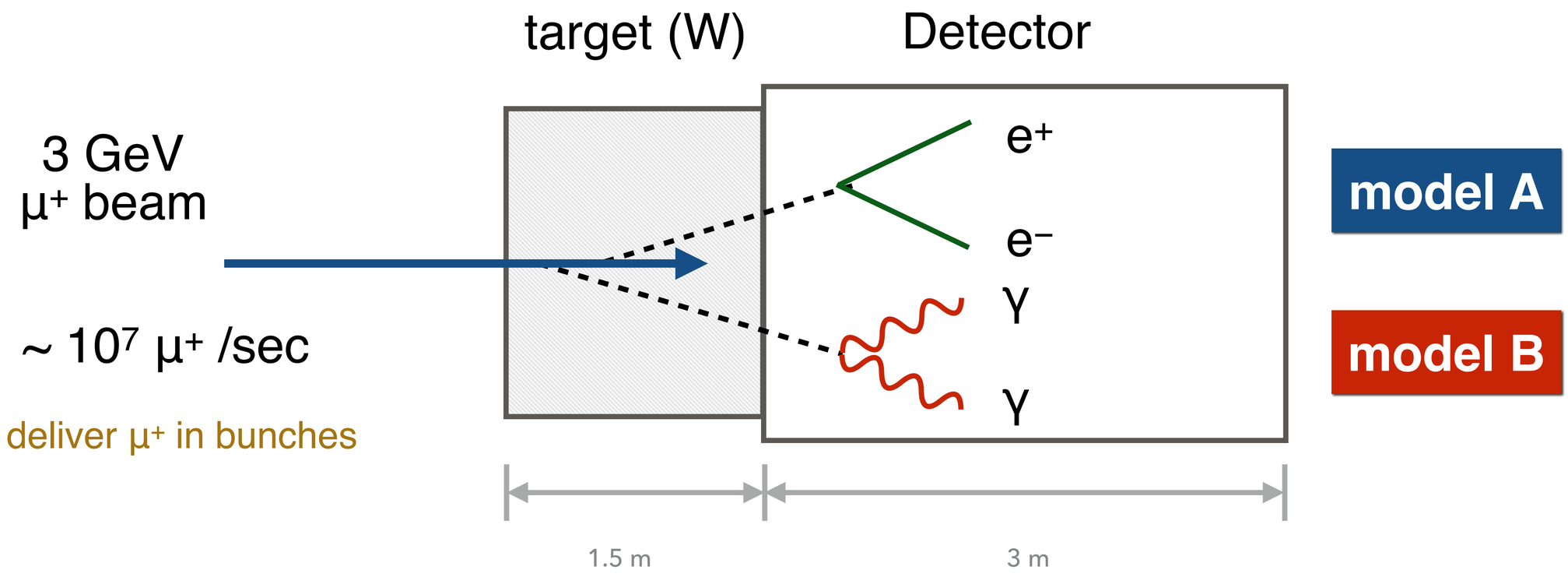
Fermilab setup (FNAL-μ)



Tracks from displaced vertices/anomalous energy deposit

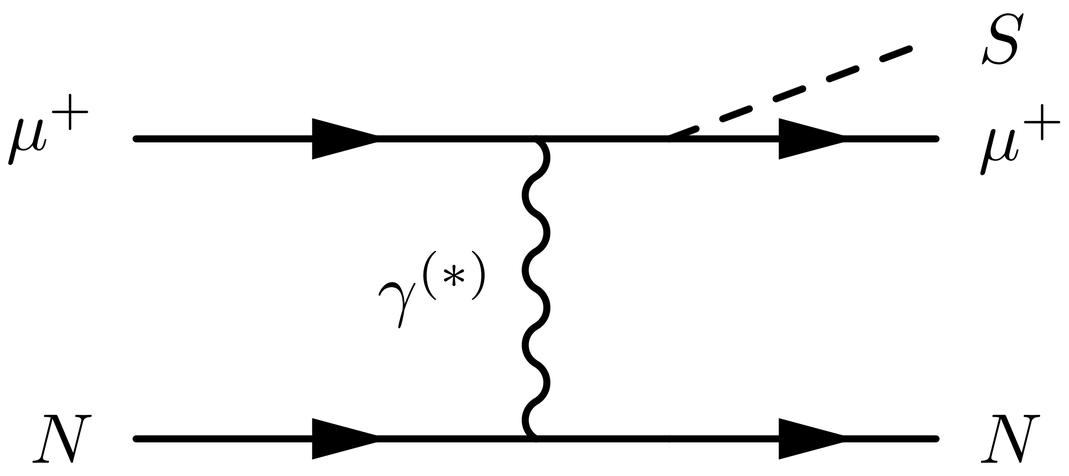
Fermilab setup

1. ***Simple***
2. ***Compact (could go into g-2 hall)***
3. ***Could run in parallel w/ g-2 exp.***



Tracks from displaced vertices/anomalous energy deposit

Signal



$\mathrm{MeV} < m_S < 2m_\mu$

(+ another diagram)

y: muon penetration length

$x \equiv E_S/E_\mu$

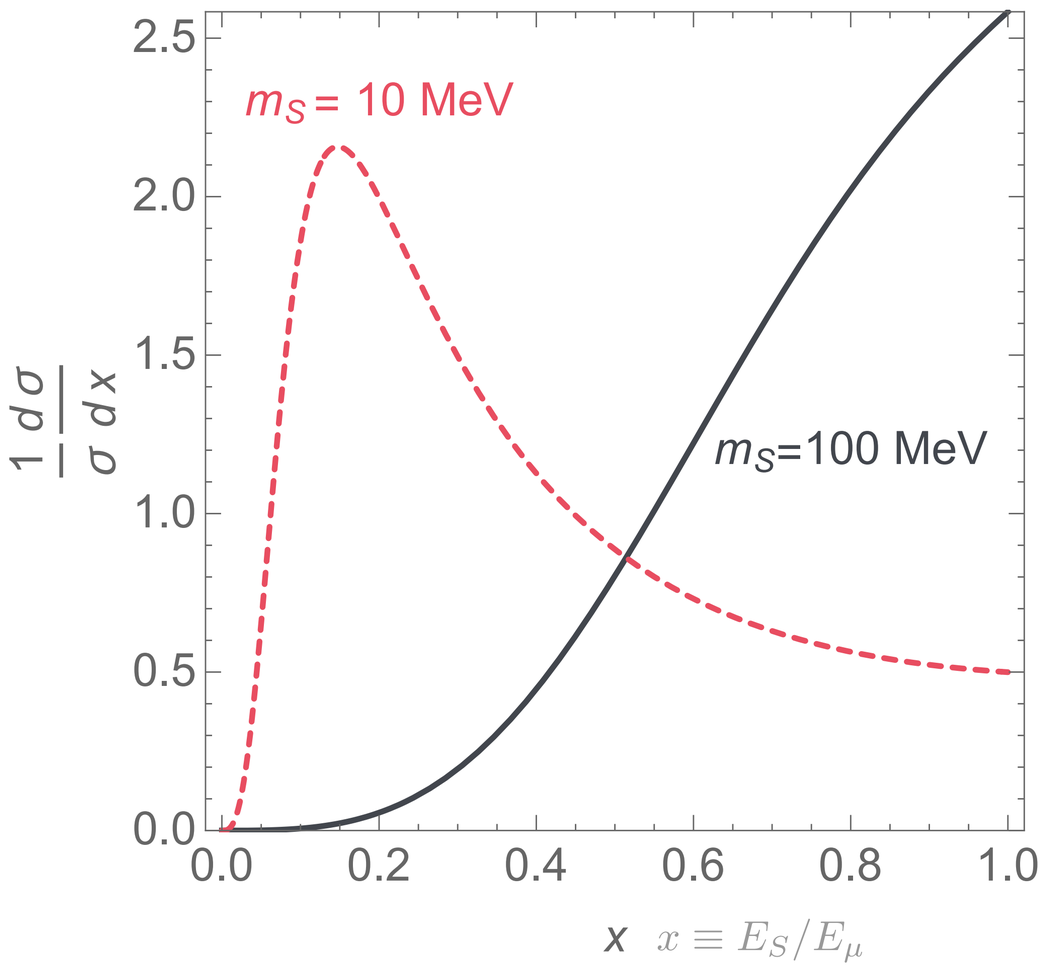
z: *S* decay volume

$$N_S = N_{\mathrm{MOT}} \int_{y_{\mathrm{min}}}^{y_{\mathrm{max}}} \mathrm{d}y\, n_{\mathrm{atom}} \int_{x_{\mathrm{min}}}^{1} \mathrm{d}x\, \frac{\mathrm{d}\sigma_{2\to 3}}{\mathrm{d}x} \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z\, P(S\,\mathrm{decay})$$

Evaluated by a modified MadGraph w/ G_2 form-factor added

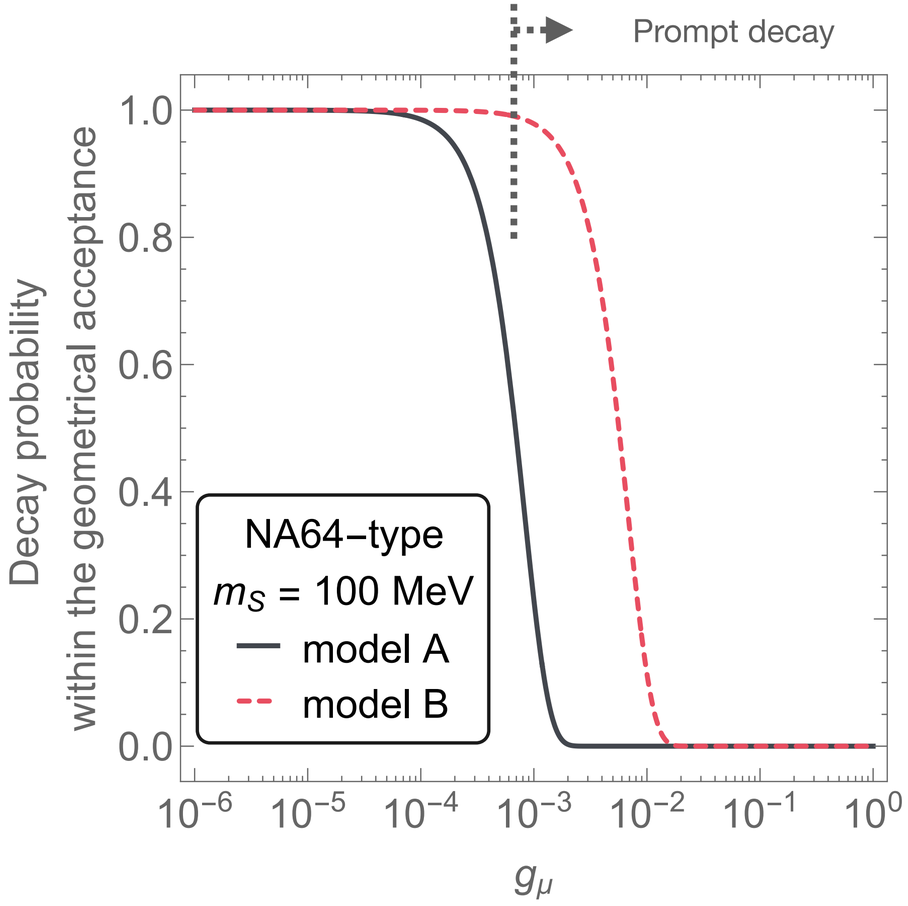
Signal

- Energy of S changes w/ m_S
- Significant amount of energy when $m_S \to m_\mu$

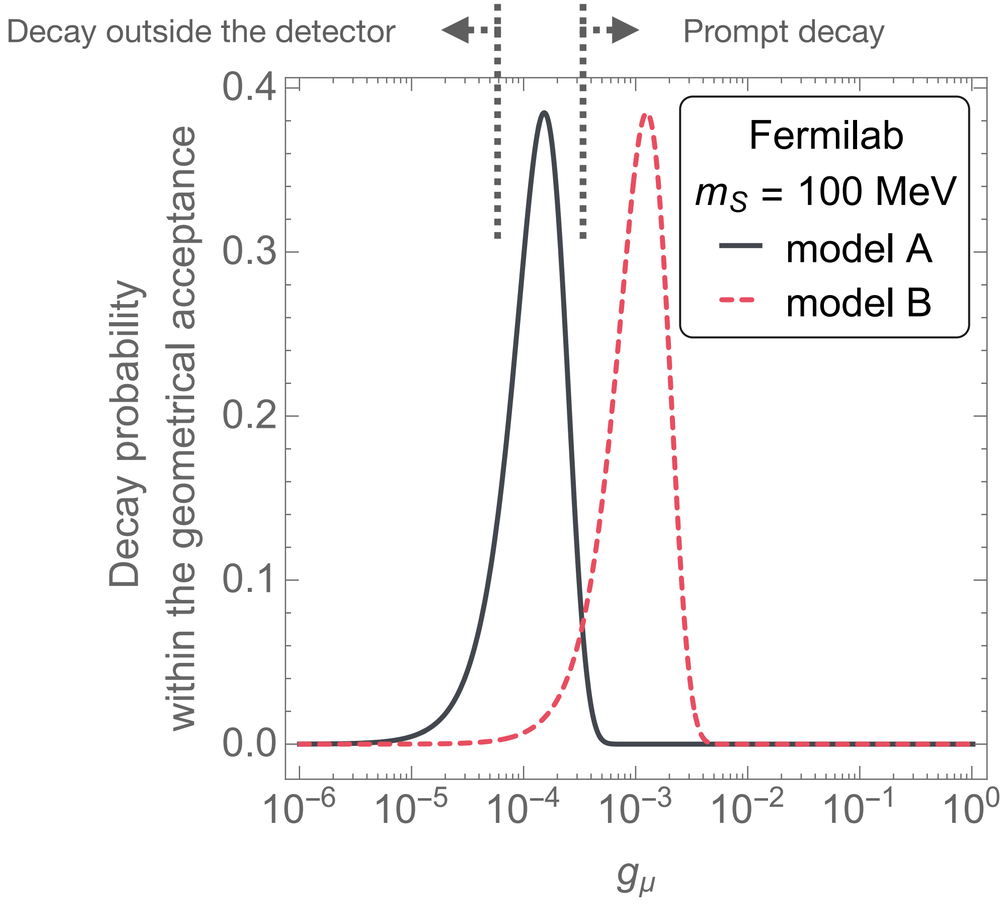


Signal

NA64-μ: missing energy



FNAL-μ: displaced decays



Backgrounds

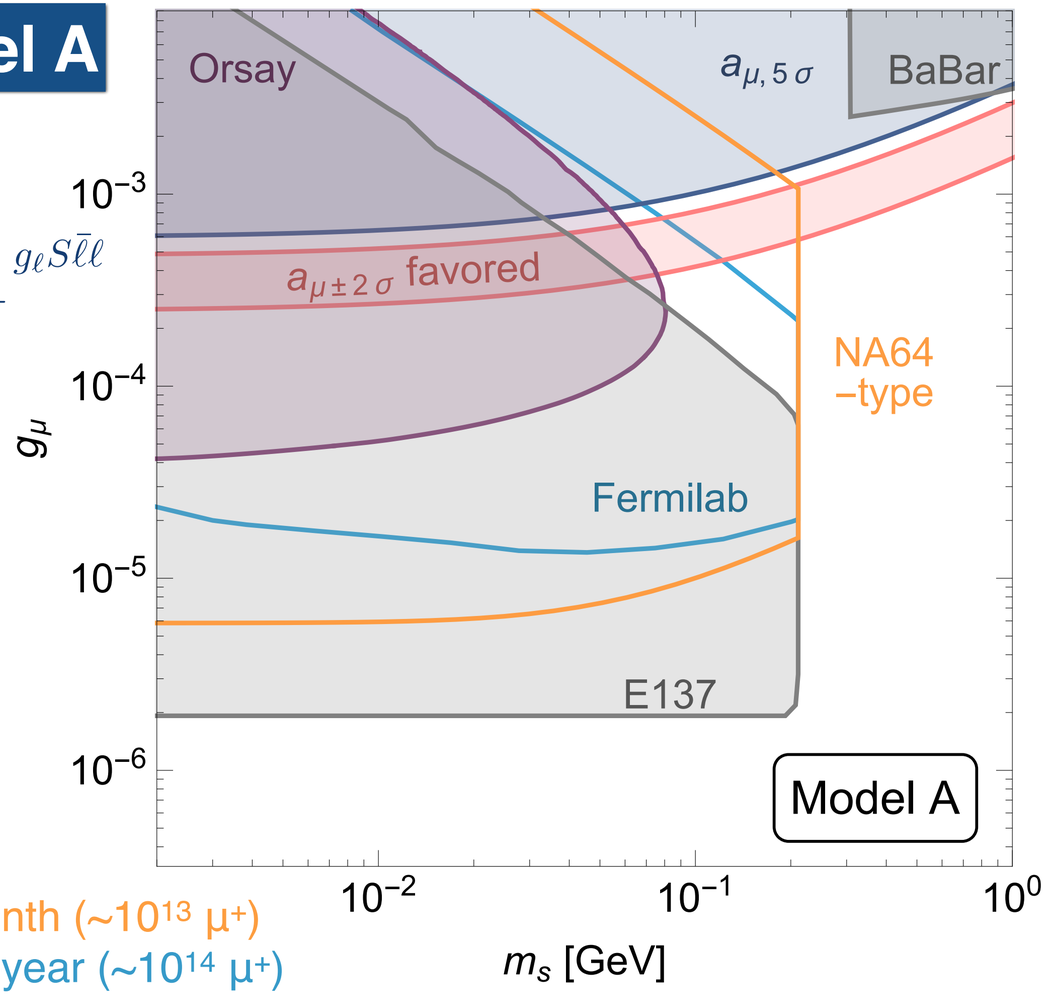
- Long-lived neutral particles / accidental backgrounds
- Negligible backgrounds for our search setups
  - NA64-μ w/ the requirement $E_{miss} > 50$ GeV Gninenko+ '15 Banerjee+ '17
  - FNAL-μ: We estimate K_L decays are negligible during one-year run

✳Rough estimations. Need specialized simulations.

Projected sensitivity to dark scalar

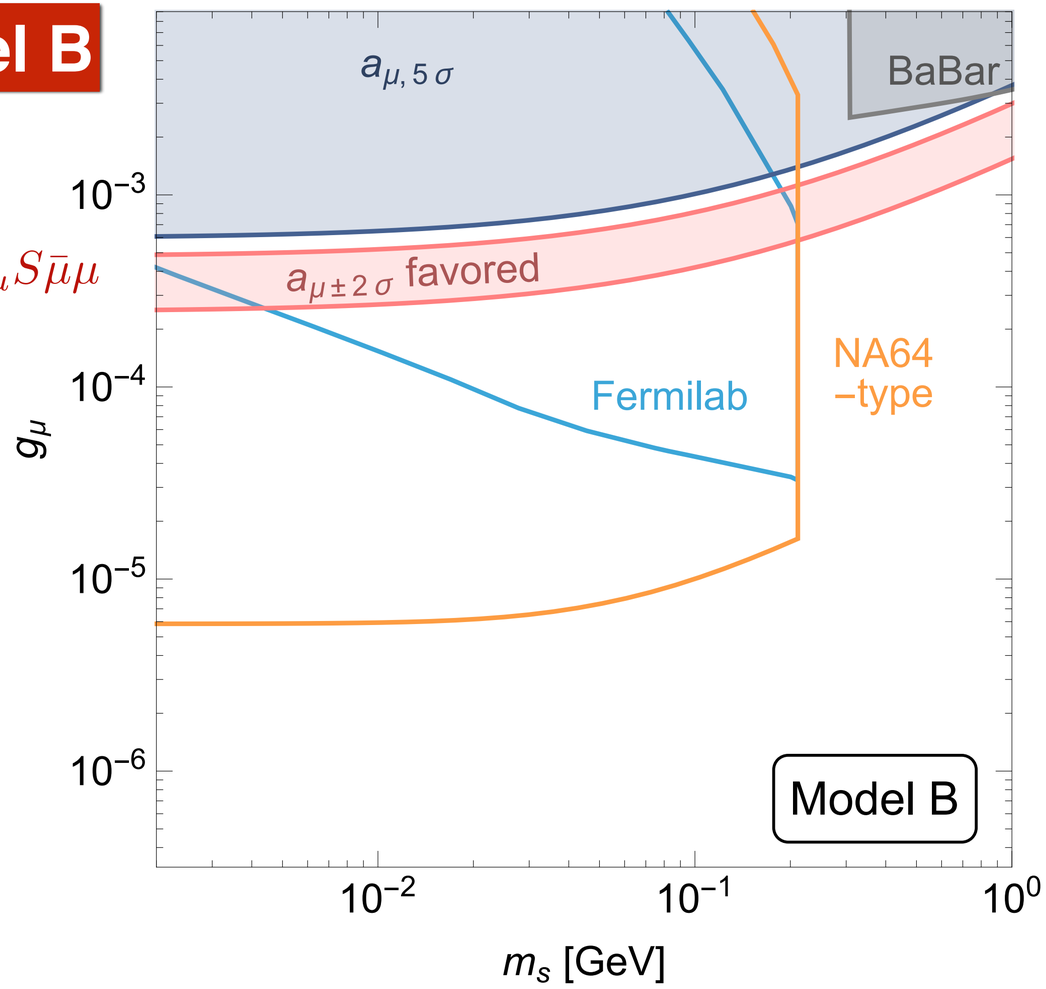
model A

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



model B

$$\mathcal{L} \supset -g_\mu S \bar{\mu}\mu$$



NA64: 3-month (~10^{13} μ^+)
Fermilab: 1-year (~10^{14} μ^+)

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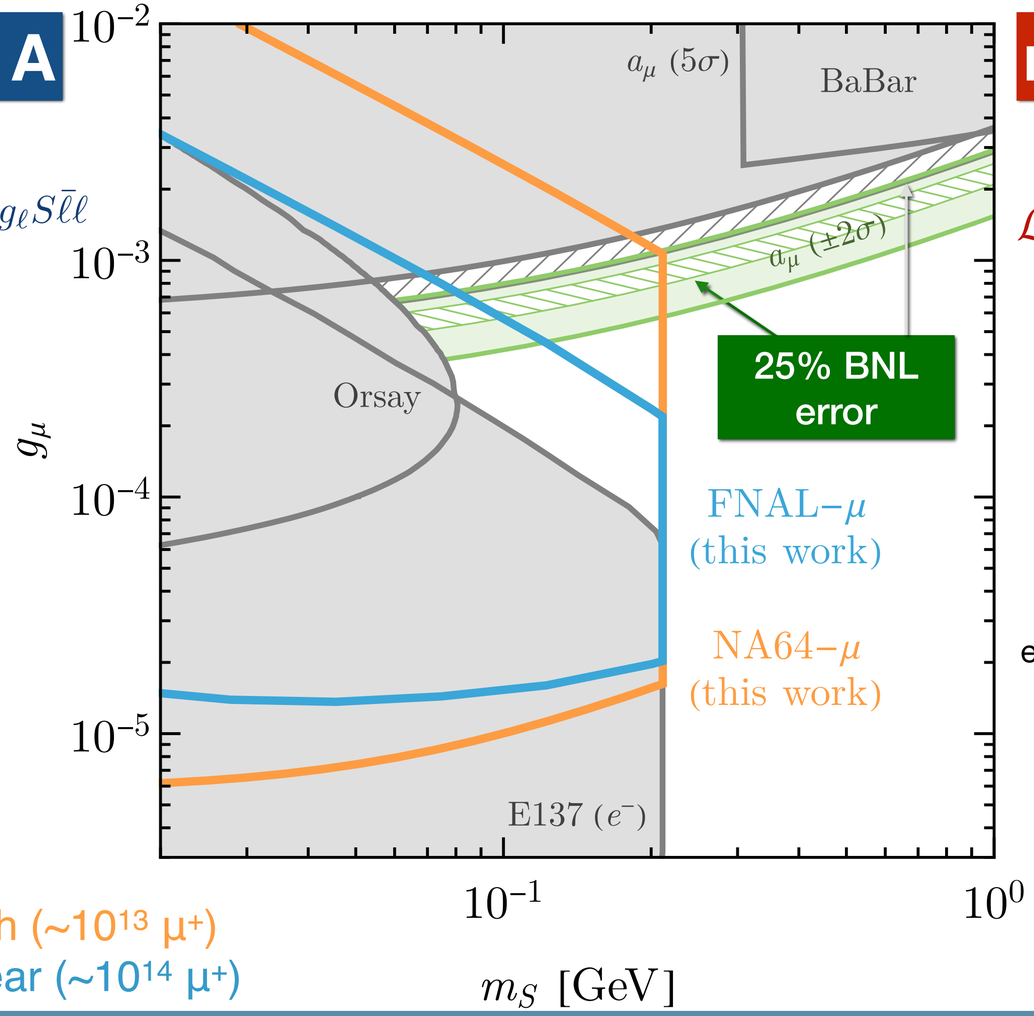
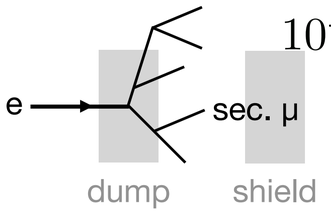
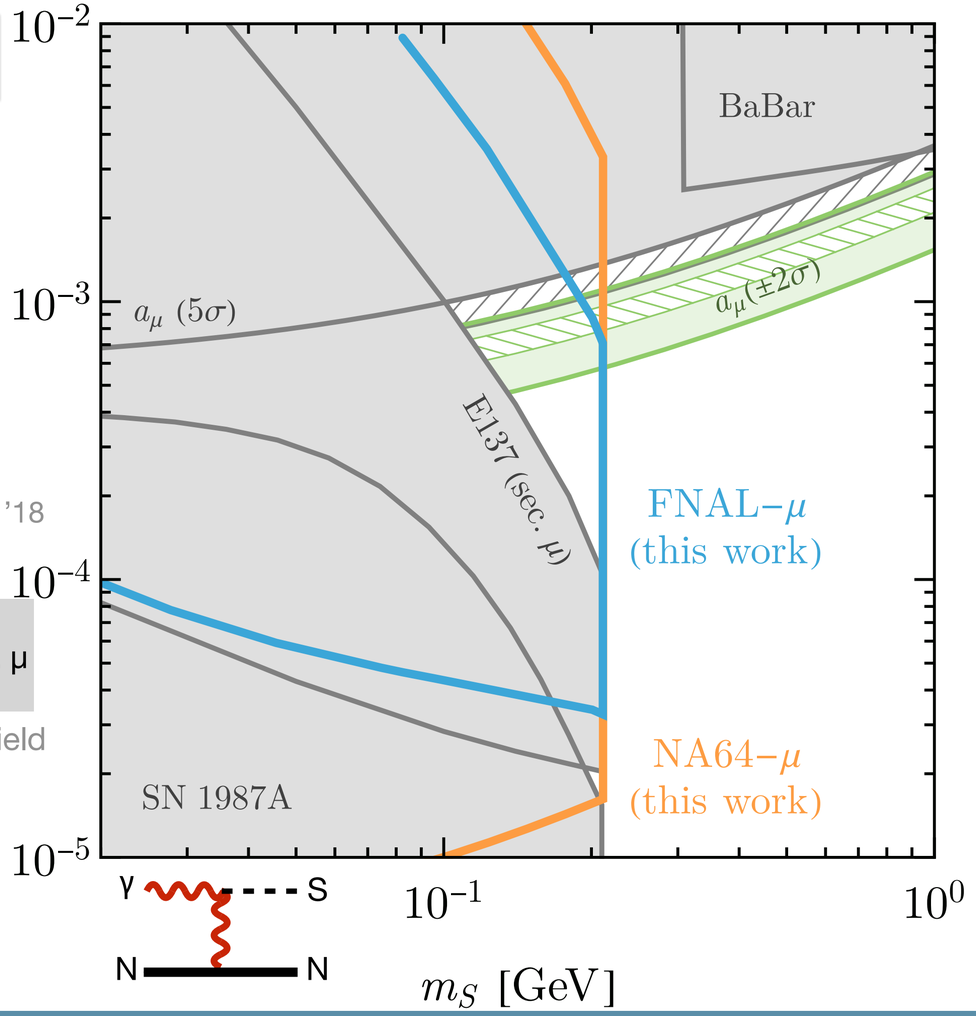


model B

$$\mathcal{L} \supset -g_\mu S\bar{\mu}\mu$$

Marsicano + (YZ) '18





NA64: 3-month (~10^{13} μ+)
Fermilab: 1-year (~10^{14} μ+)

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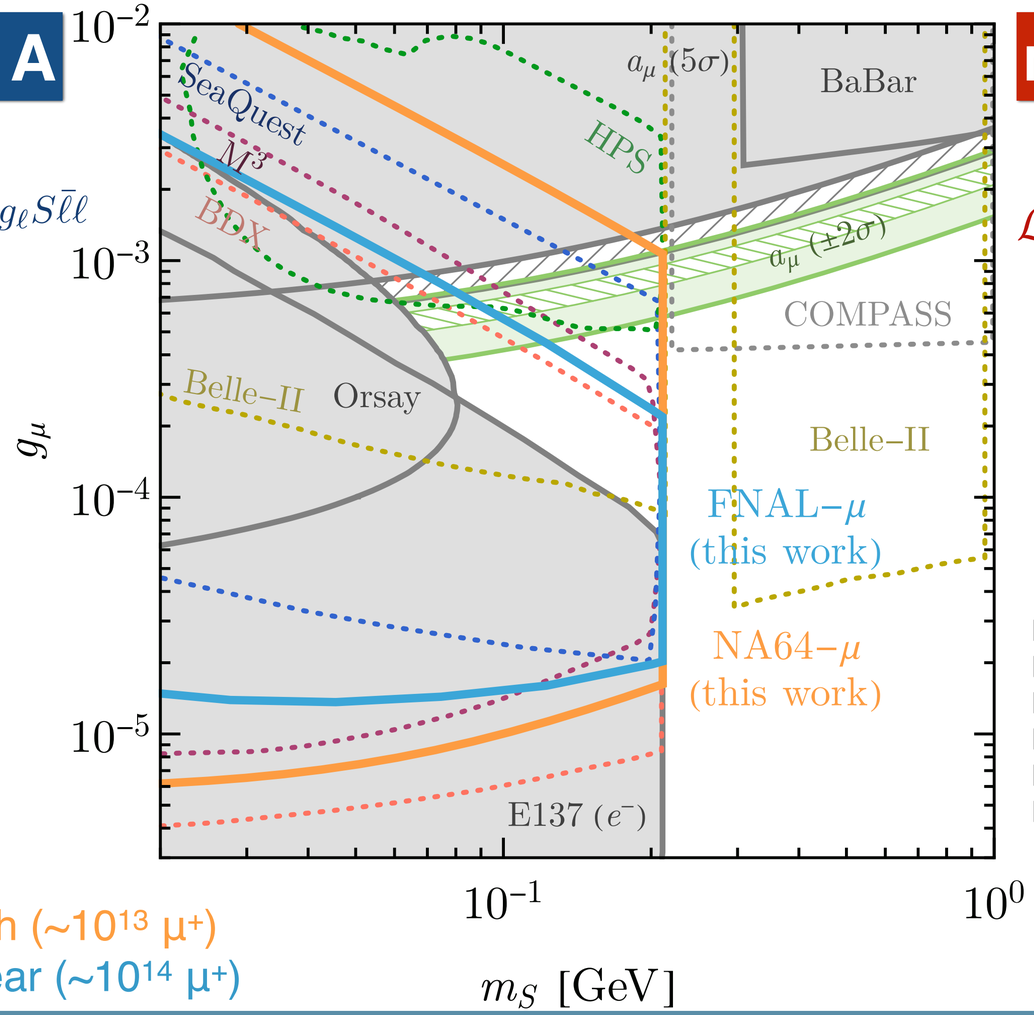

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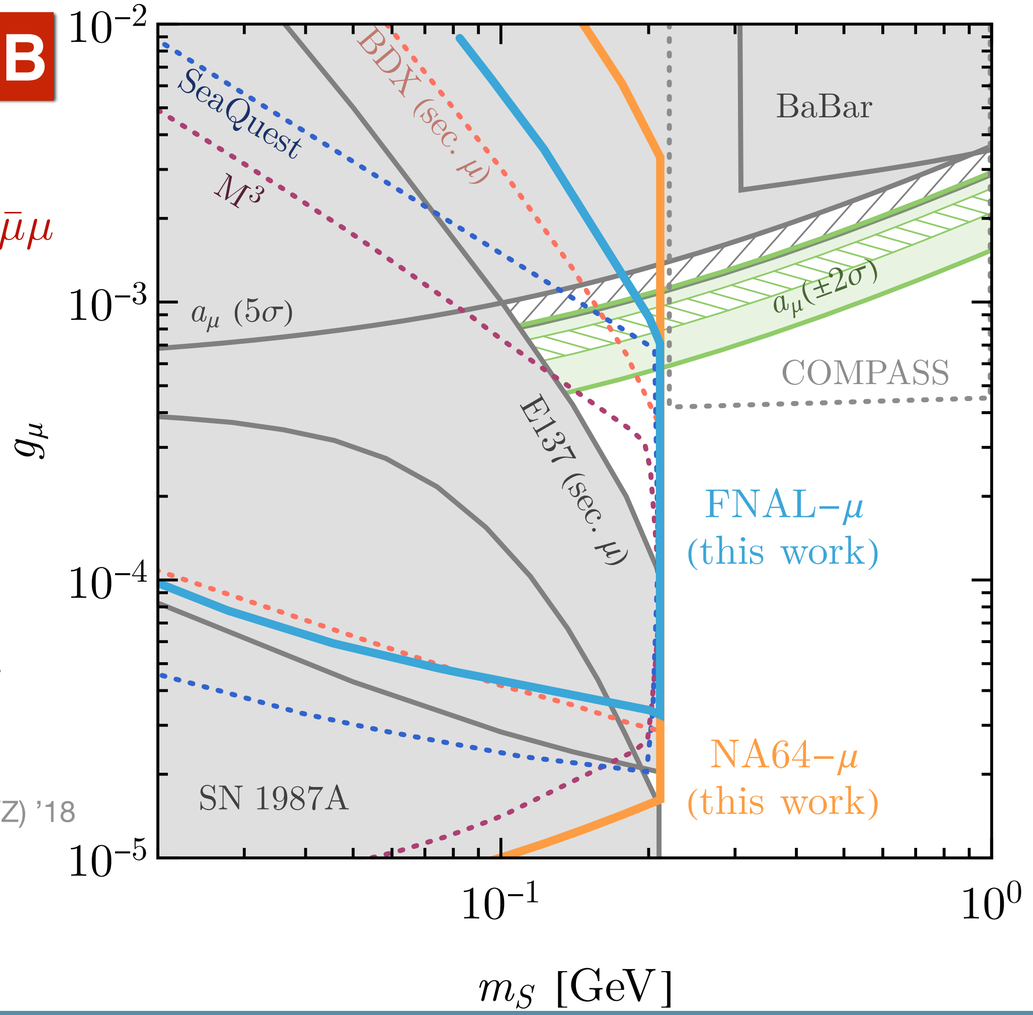

Essig+ '10
Battaglieri+ '14
Batell+ '16
Kahn+ '18
Berlin+ '18
Marsicano + (YZ) '18

NA64: 3-month (~10^{13} μ^+)
Fermilab: 1-year (~10^{14} μ^+)

Summary

- Several anomalies in particle experiments point to muons. There may be a muonic dark sector.
- Muon beam-dump experiments can effectively probe dark scalars, w/ predominant muon coupling, that explain (g-2)μ anomaly
- FNAL-μ can be easily implemented at FNAL muon campus w/ modest modifications/additions to the existing exp. infrastructure.