# Muon Beam Experiments to Probe the Dark Sector

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# Muon anomalies

- Muon g-2 anomaly:
  - ~3.5 sigma deviation from SM prediction

    [Bennett et al, Phys.Rev. D73,072003 ]
  - More precise measurement at Fermilab (g-2)
  - Improved SM calculation based on lattice QCD

    [Benayoun et al. 1407.4021]
  - New Physics?

- Proton size anomaly: ~7 sigma
  - Muonic hydrogen lamb shift [Mohr et al, Science 353, 669]

- Lepton flavor non-universality in B physics $R_K$ and $R_{K^*}$, each has around 2.5 sigma deviation from SM

  [LHCb, 2014 and 2017]

# Dark Sector

***Portal:***

Scalar

Pseudo-scalar

Neutrino

Vector

:

:

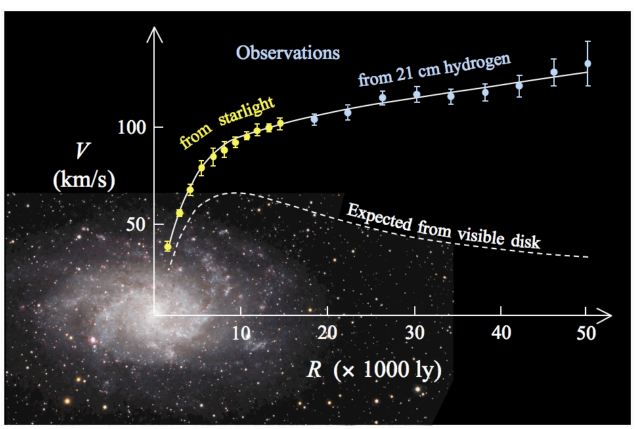
Mediators

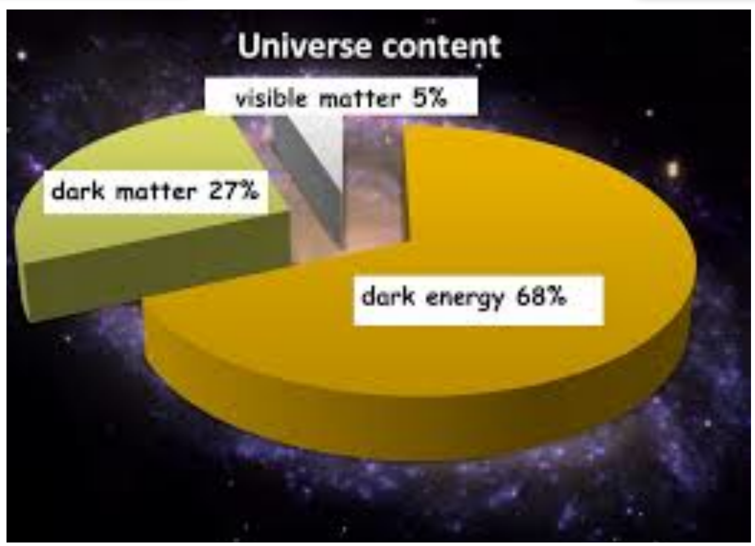
## Standard Model

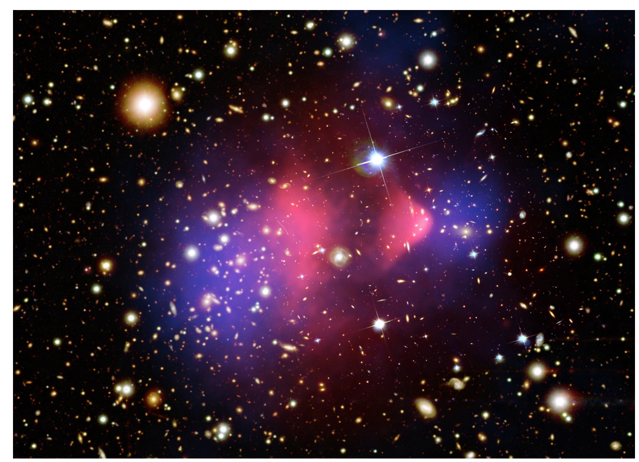
SU(3)xSU(2)xU(1)

## Dark Sector

Dark gauge group??



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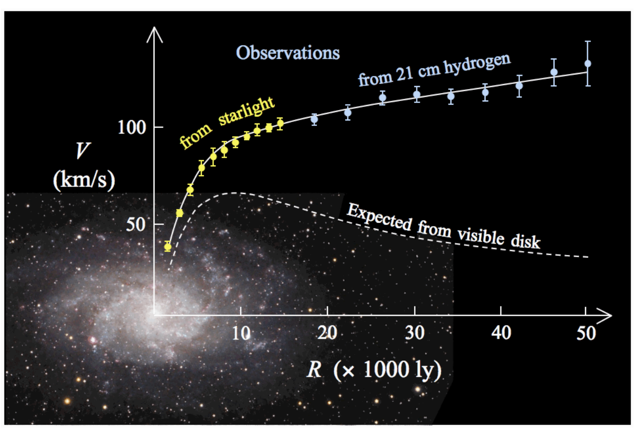
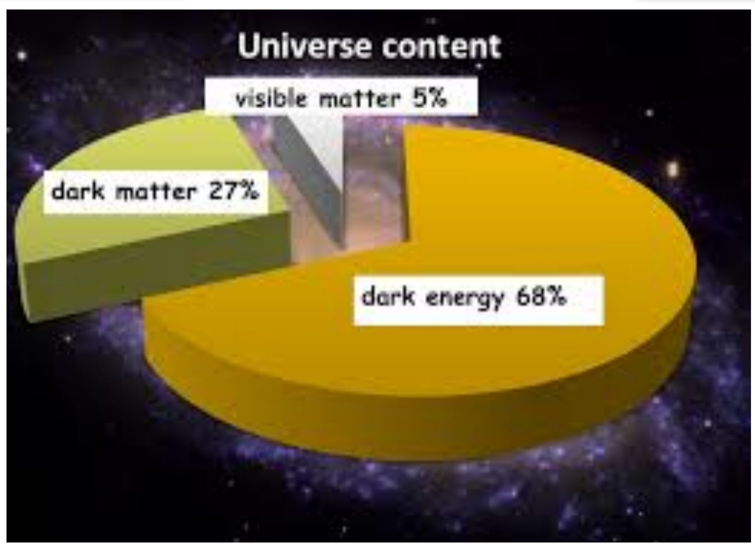
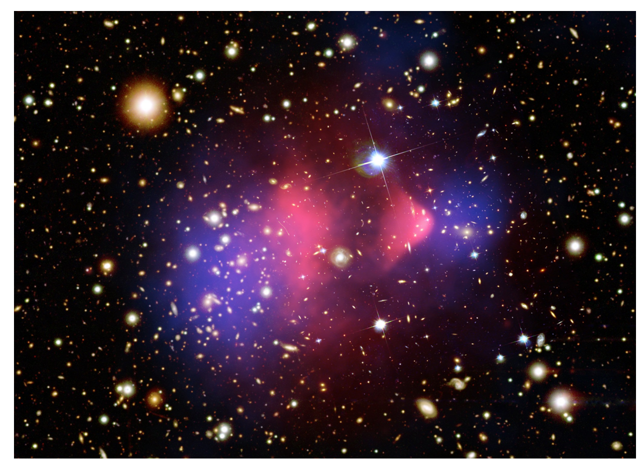


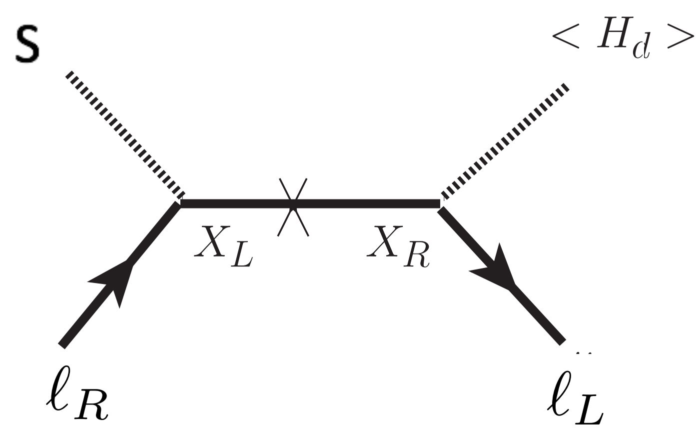
# Theory for lepto-philic dark scalar

- Effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \sum_{l=e,\mu,\tau} g_\ell S\bar{\ell}\ell,$$

Assuming $g_e : g_\mu : g_\tau = m_e : m_\mu : m_\tau$

- UV completion:
  - Dark Higgs($H_d$) + S + Vector-like leptons (X)



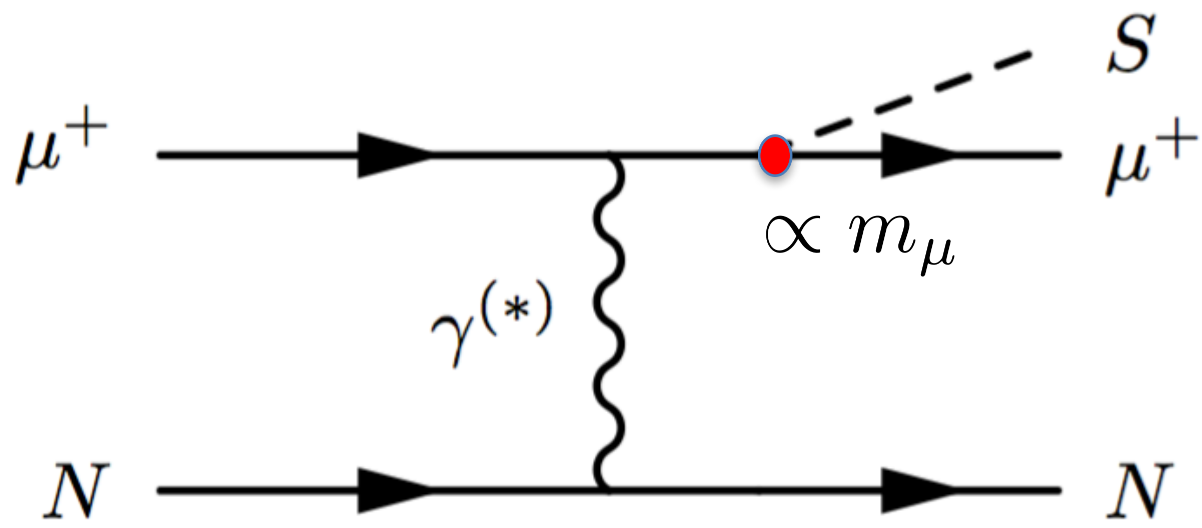

[Chen, Davoudiasl, Marciano, Zhang, Phys.Rev. D93, 035006]

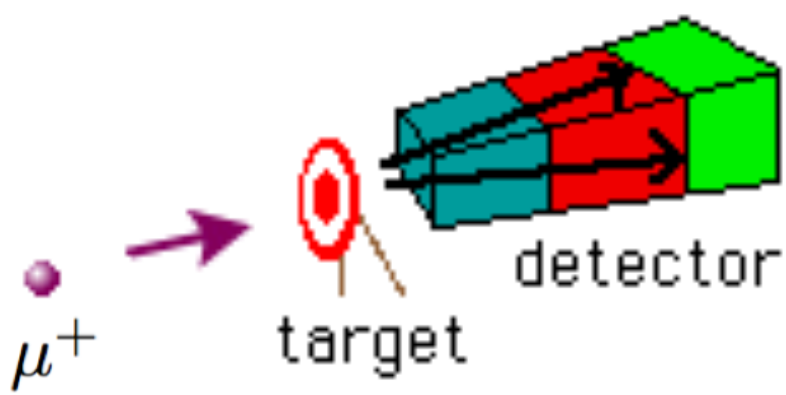
  - Lepton-specific 2HDM + S w/ MFV

[Batell, Lange, McKeen, Pospelov, Ritz, Phys.Rev. D95, 075003 ]

# Production

- Scalar bremsstrahlung from a muon beam hitting a fixed target



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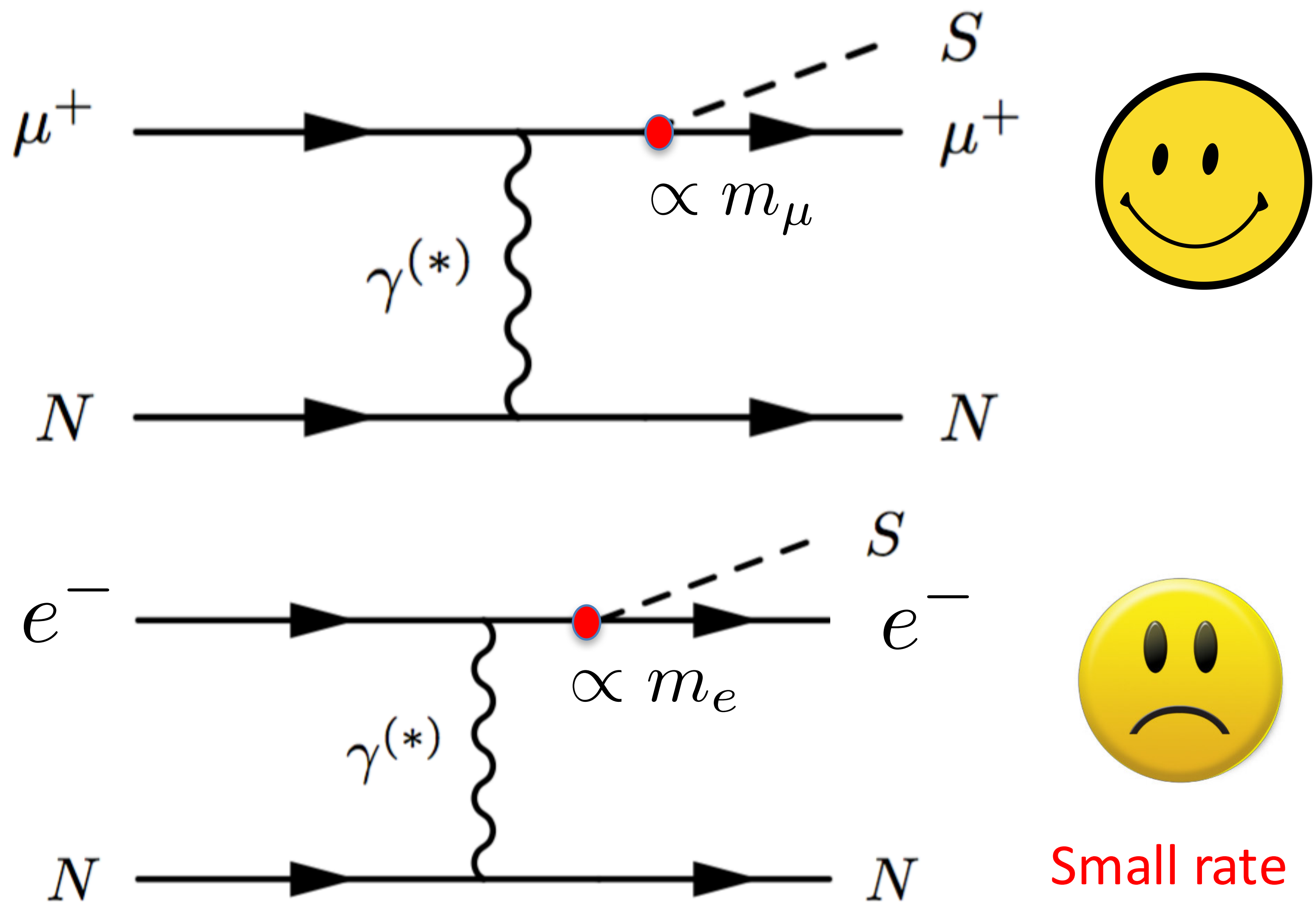
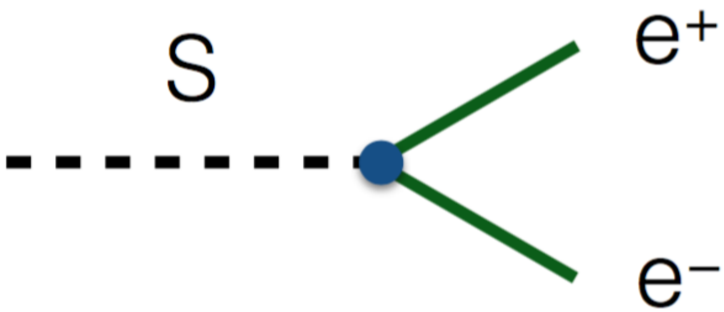


# Decay

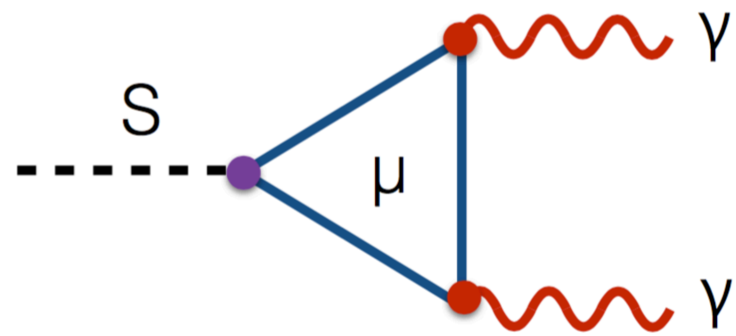
- Dominant decay channels: (for $2m_e < m_S < 2m_\mu$ )

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

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




Assuming $g_\ell \propto m_\ell$



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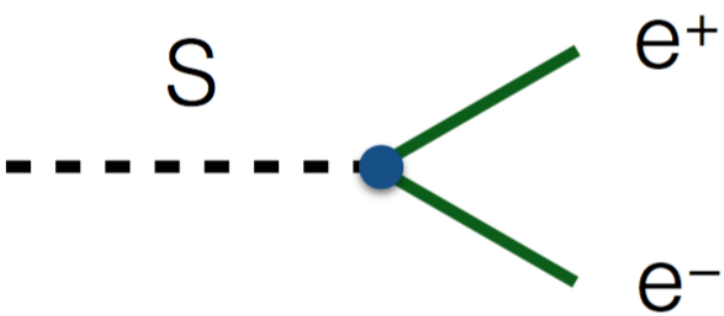
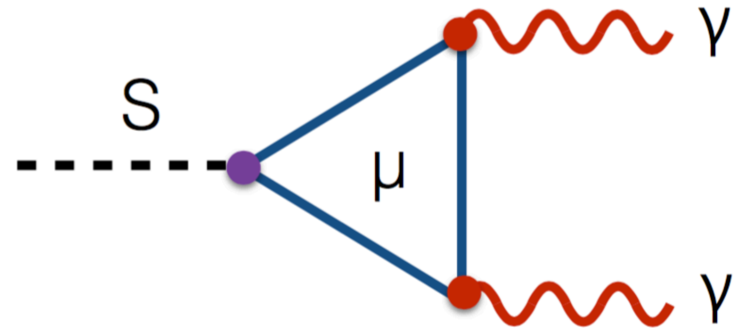



Assuming $g_\ell \propto m_\ell$

- Decay length ( $L_S$ ): for $m_S = 100\ \text{MeV},\ g_\mu = 10^{-3}$

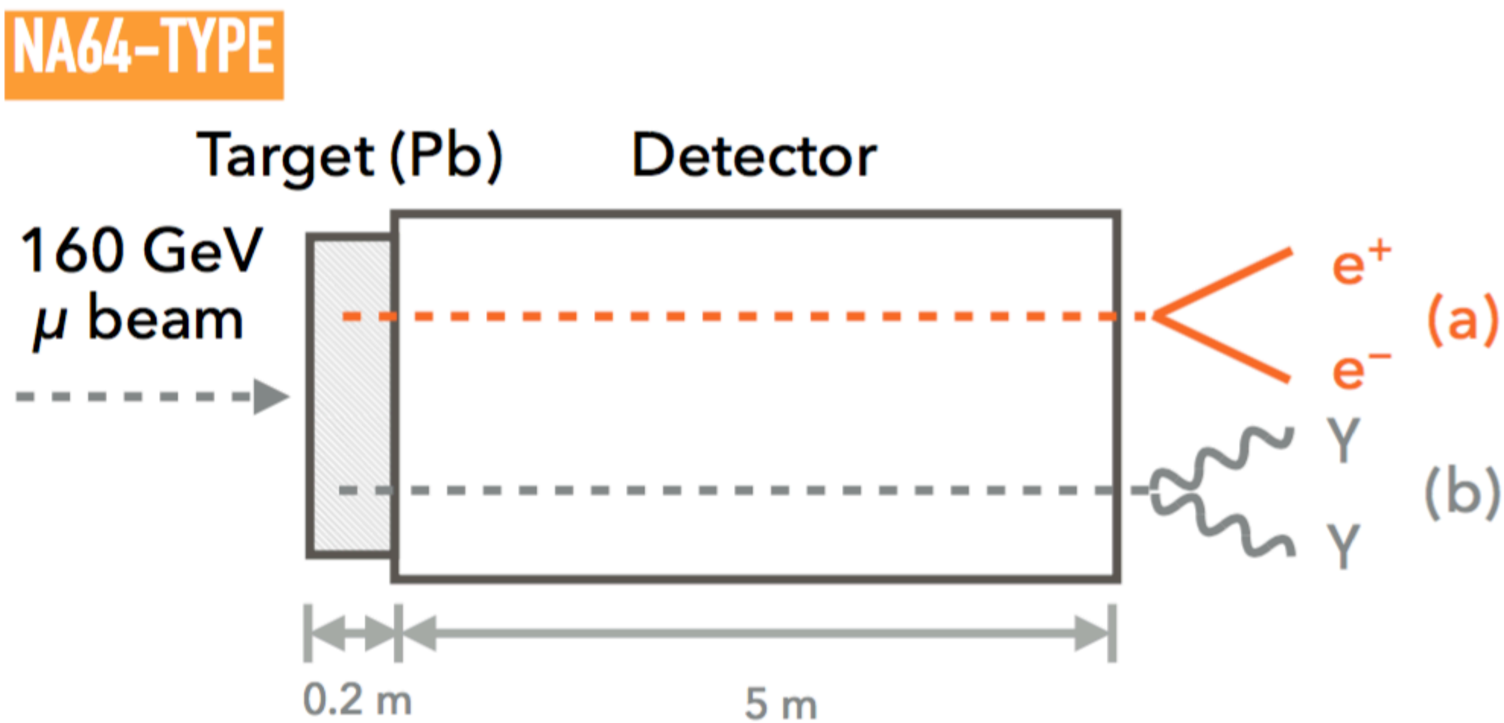
$$L_S = \beta_S \gamma_S \tau_S$$

$$L_S \sim 5\ \text{cm},\ \text{Model A}$$

$$L_S \sim 5\ \text{m},\ \text{Model B}$$

# Proposal for two types of experiments

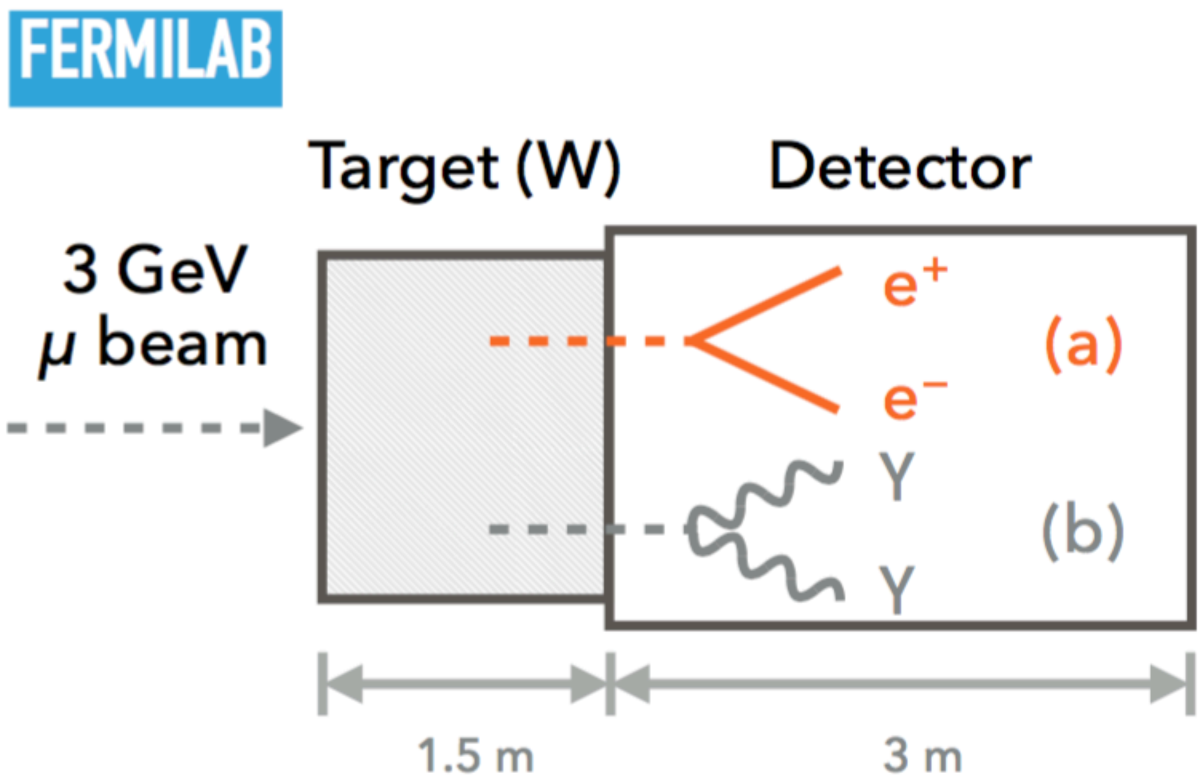
- Missing energy (NA 64 at CERN)




- Using lead as target
- Luminosity: assuming $10^6$ muons/sec for a 3-month run
- Signal: recoiled muon losing more than 1/3 of it’s energy

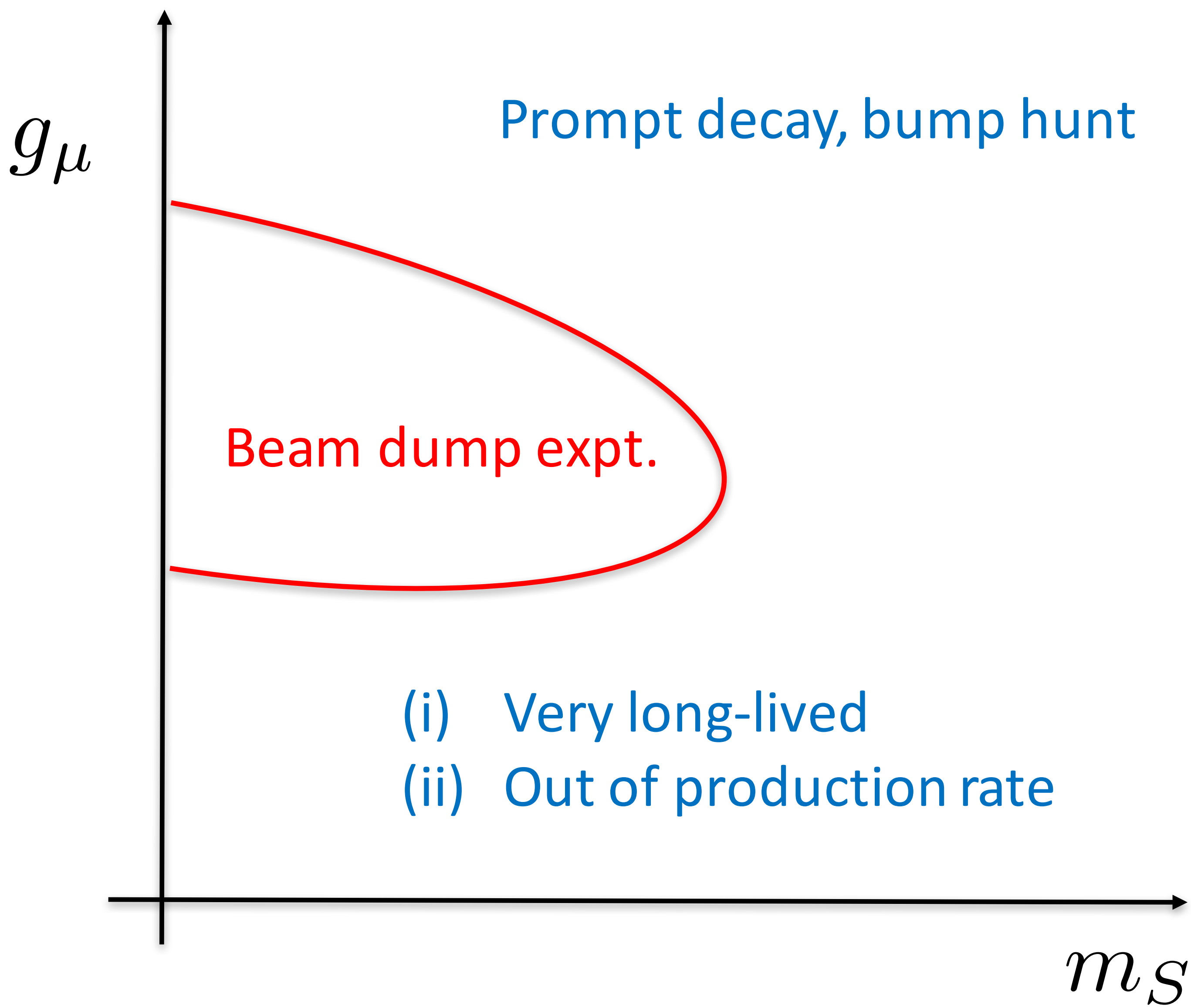
# Proposal for two types of experiments

- Visible decay: can use the existing muon beam facilities at Fermilab



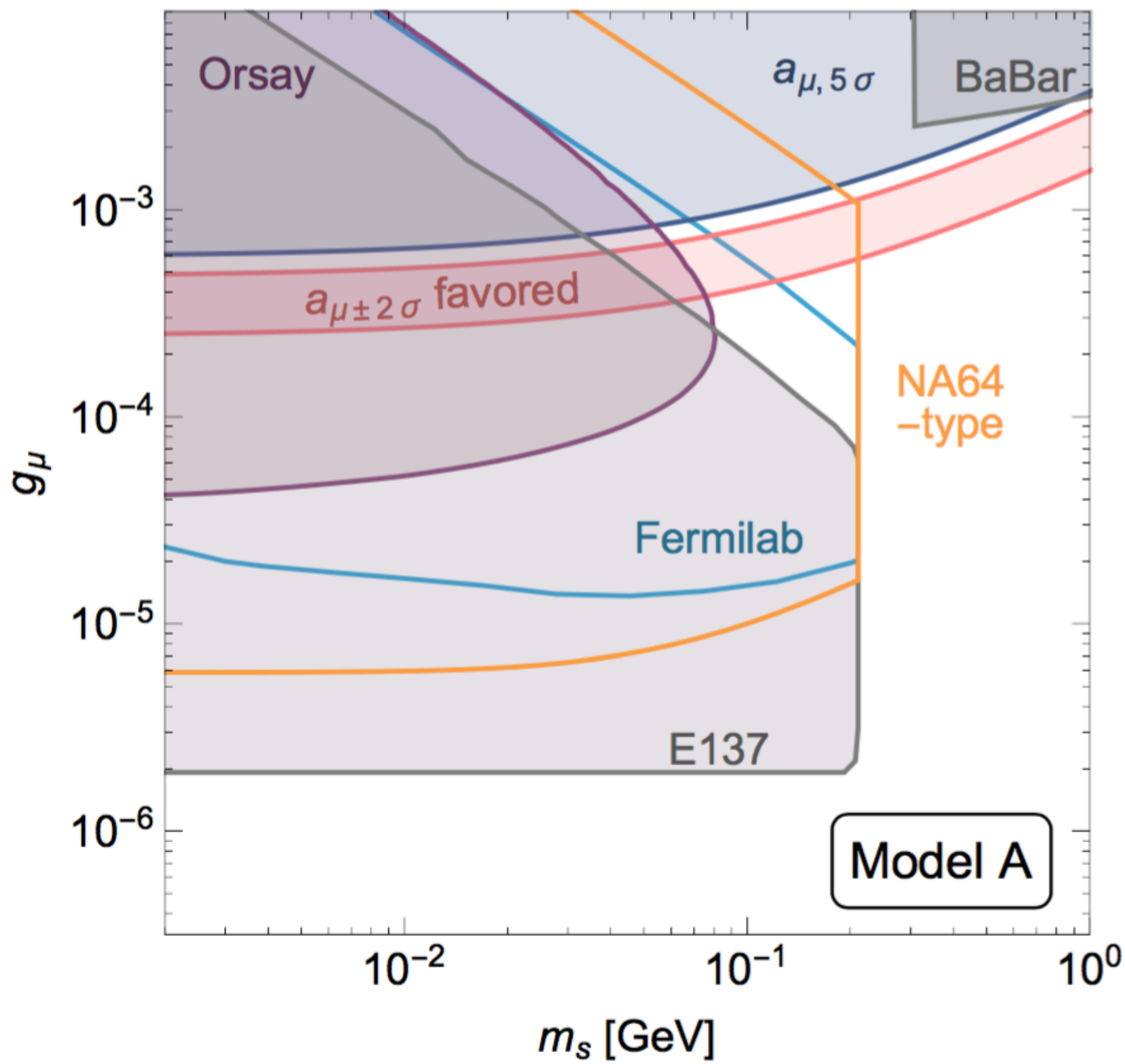

- Using tungsten as target
- Luminosity: assuming $10^7$ muons/sec for 1 year of running
- Signal: displaced vertices reconstructed from $e^+e^-$ or $\gamma\gamma$

# Parameter space



# Results: model A

- 95% CL, ~$10^{13}$ muons for NA 64 and ~$10^{14}$ muons for Fermilab



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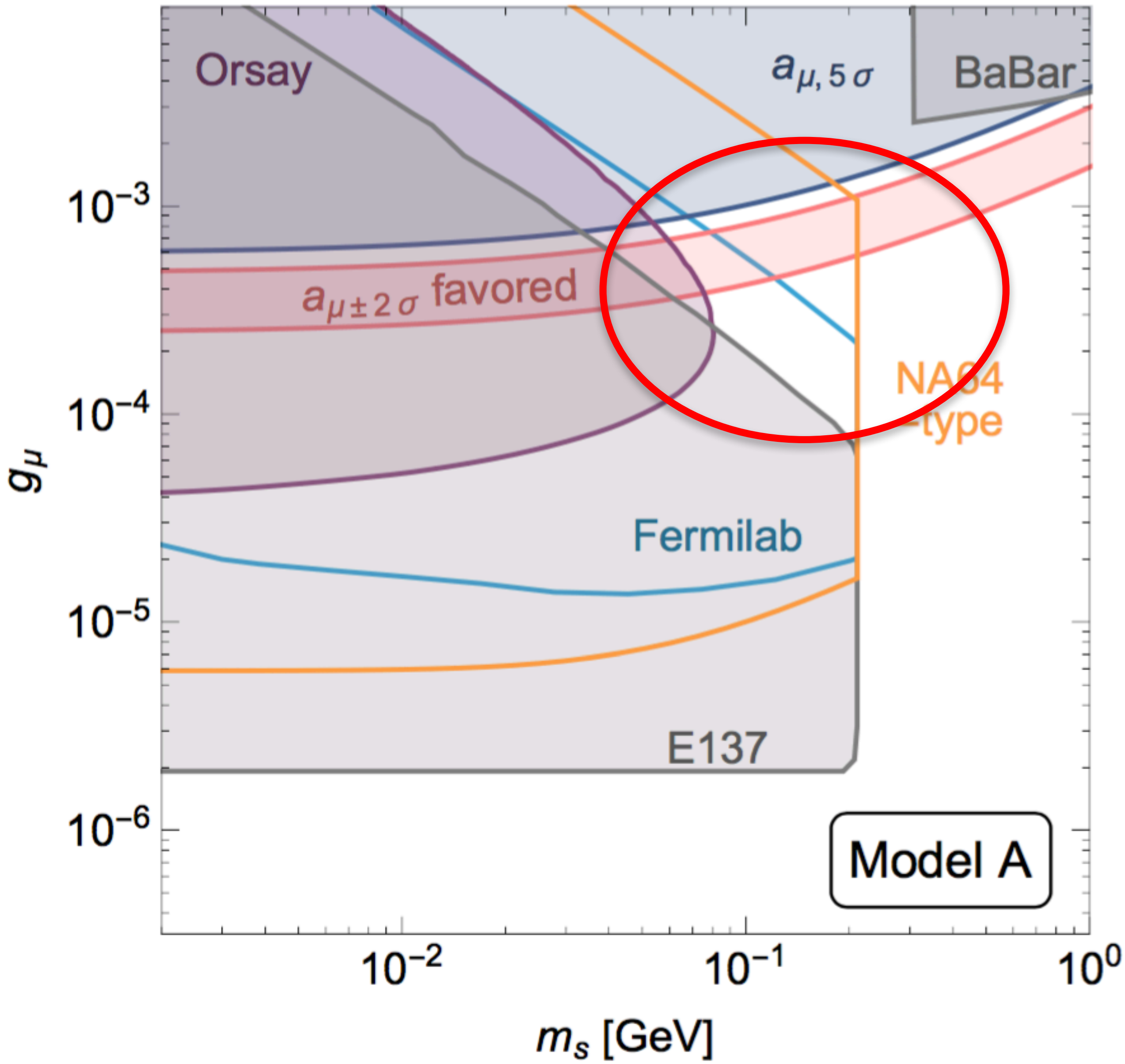
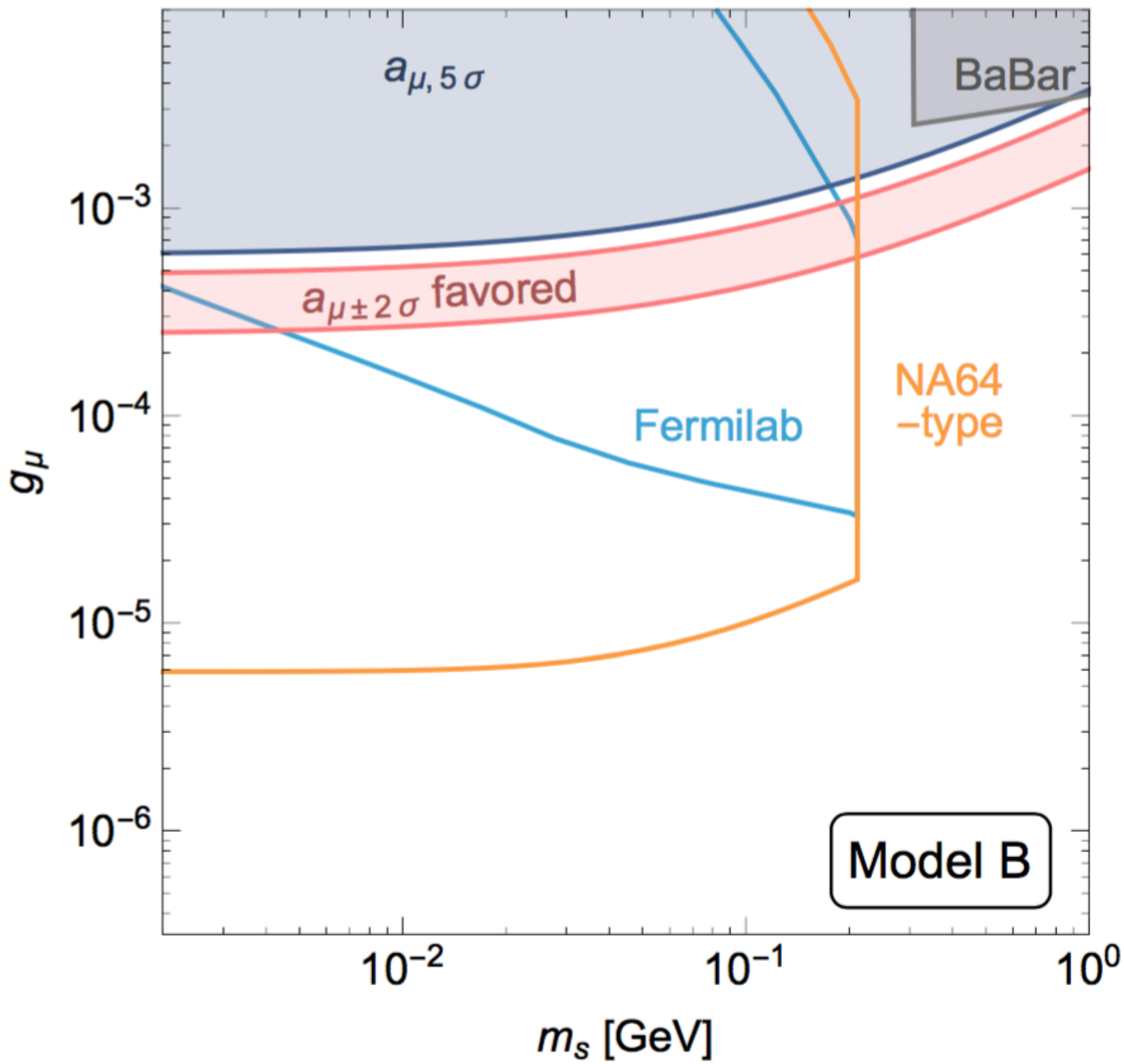


# Results: model B

- 95% CL, ~$10^{13}$ muons for NA 64 and ~$10^{14}$ muons for Fermilab



# Take home message

- Muon sector is interesting. A light scalar may potentially solve or relax g-2 anomaly

- Two types of experiments that can search for such scalar are proposed
  - Missing energy: NA64-type
  - Muon beam dump: Fermilab

- With minimal modifications, muon beam experiments can be used to probe the dark sector using our proposal

# BACKUP SLIDES

# Background

- NA 64-type: potential background comes from low-energy tail in the energy distribution of beam muons and in our study we assume that it is negligible

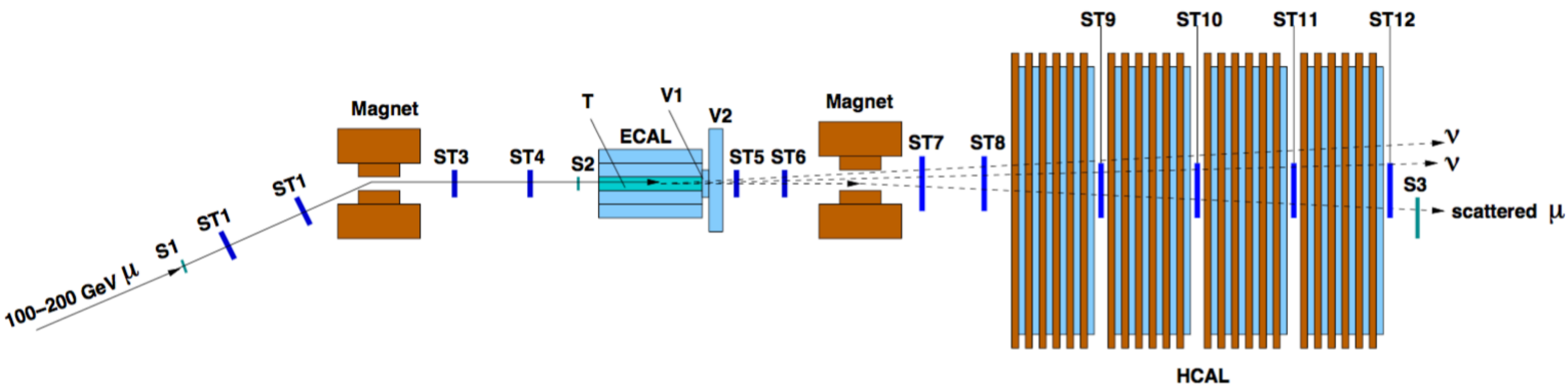
  [Gninenko, Phys.Rev. D91 (2015) 095015]

- Fermilab:
  - Neutral Kaon decays

$$K_L \to \pi^+\pi^-\pi^0 \text{ and } K_L \to 3\pi^0 \text{ decays}$$

# Setup

- Setup for NA64 muon mode:




[Gninenko et al, Phys.Rev. D91 (2015) 095015]

- Decay length

$$L_S = 25\ \text{cm} \times \left(\frac{5\times 10^{-4}}{g_\mu}\right)^2 \times \left(\frac{100\ \text{MeV}}{m_S}\right)^2, \quad \text{Model A},$$

$$L_S = 20\ \text{m} \times \left(\frac{5\times 10^{-4}}{g_\mu}\right)^2 \times \left(\frac{100\ \text{MeV}}{m_S}\right)^4, \quad \text{Model B}.$$

- Number of events

$$\begin{aligned} N_S =& N_\mu \int_{y_{\min}}^{y_{\max}} \mathrm{d}y\, n_{\text{atom}} \int_{x_{\min}}^{1} \mathrm{d}x \frac{\mathrm{d}\sigma_{2\to 3}}{\mathrm{d}x} \int_{z_{\min}}^{z_{\max}} \mathrm{d}z P(z) \\ =& N_\mu \int_{y_{\min}}^{y_{\max}} \mathrm{d}y\, n_{\text{atom}} \int_{x_{\min}}^{1} \mathrm{d}x \frac{\mathrm{d}\sigma_{2\to 3}}{\mathrm{d}x} \left(e^{-\frac{z_{\min}}{L_S}} - e^{-\frac{z_{\max}}{L_S}}\right) \end{aligned}$$