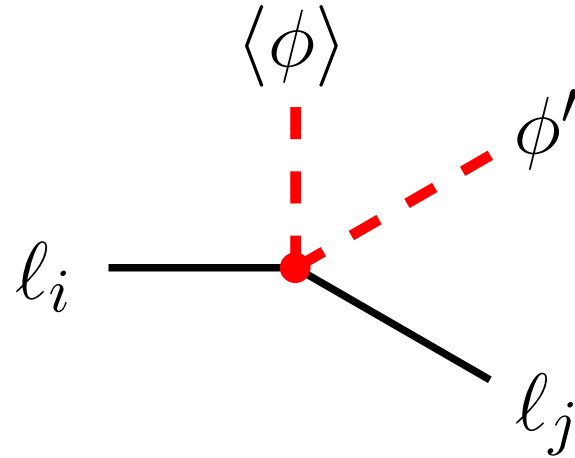


Direct detection of ultralight dark matter with charged-lepton-flavor-violation

FPCP 2025 @ University of Cincinnati
June 5th, 2025

Tony Menzo

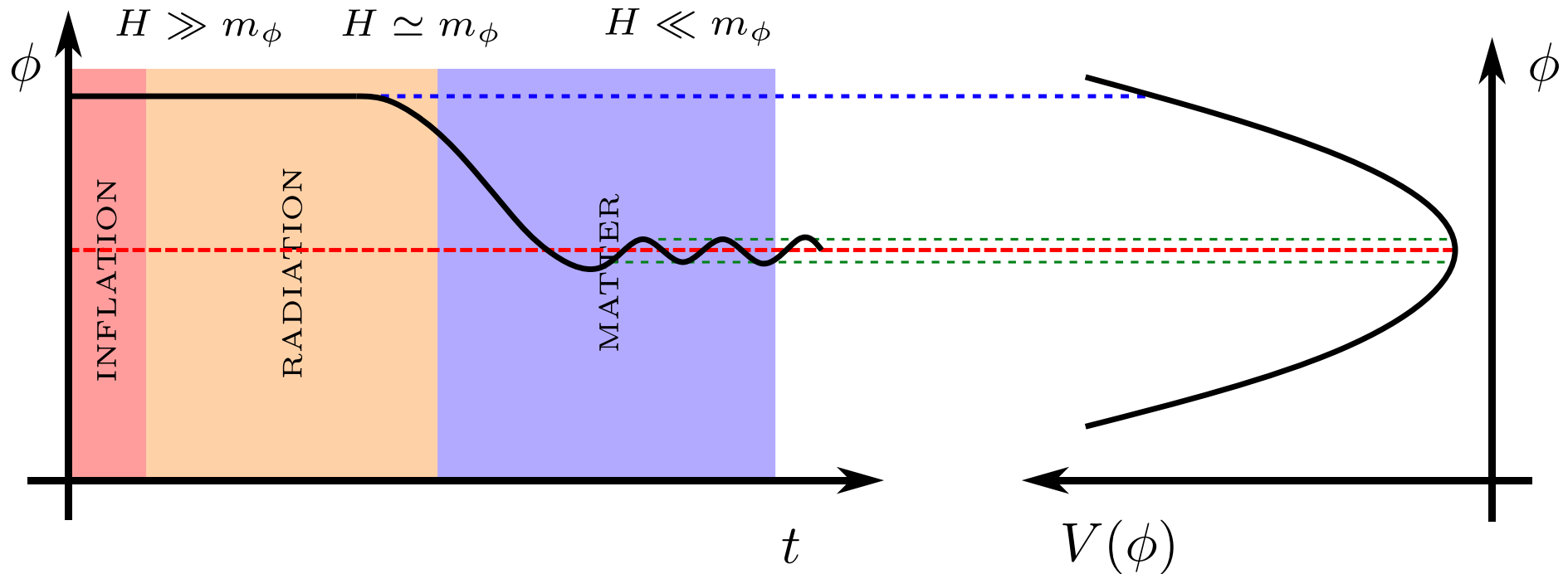
PhD candidate, University of Cincinnati



Based on [2503.07722](#) with Innes Bigaran, Patrick Fox, Yann Gouttenoire, Roni Harnik, Gordan Krnjaic, and Jure Zupan

Standard lore - ULDM

EOM:
$$\int d^4x \sqrt{-g} \left(\frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 \right) \rightarrow \ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2 \phi}{a^2} + m_\phi^2 \phi = 0$$



Standard lore - ULDM

For $m_\phi \lesssim \text{eV}$ the de Broglie volume admits a huge occupation number

$$N \sim n \lambda_{\text{dB}}^3 \sim \frac{\rho_\phi}{m_\phi} \left(\frac{1}{m_\phi v} \right)^3 \simeq 10^3 \left(\frac{1 \text{ eV}}{m_\phi} \right)^4 \left(\frac{10^{-3}}{v} \right)^3 \left(\frac{\rho_\phi}{10^{-42} \text{ GeV}^4} \right)$$

ULDM can be accurately described as a classical wave

$$\phi_c(\mathbf{x}, t) = \phi_0(\mathbf{x}) \cos(m_\phi t + \delta)$$

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi} \quad \rho_\phi = 0.4 \text{ GeV}/\text{cm}^3 \simeq 10^{-42} \text{ GeV}^4$$

Standard lore - ULDM

For $m_\phi \lesssim \text{eV}$ the de Broglie volume admits a huge occupation number

$$N \sim n \lambda_{\text{dB}}^3$$

ULDM ca

Each mass has an associated “timescale”

$$\tau_\phi = \frac{2\pi}{m_\phi} \simeq 4\text{s} \left(\frac{10^{-15}\text{eV}}{m_\phi} \right)$$

$$\left(\frac{\rho_\phi}{42 \text{ GeV}^4} \right)$$

wave

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi}$$

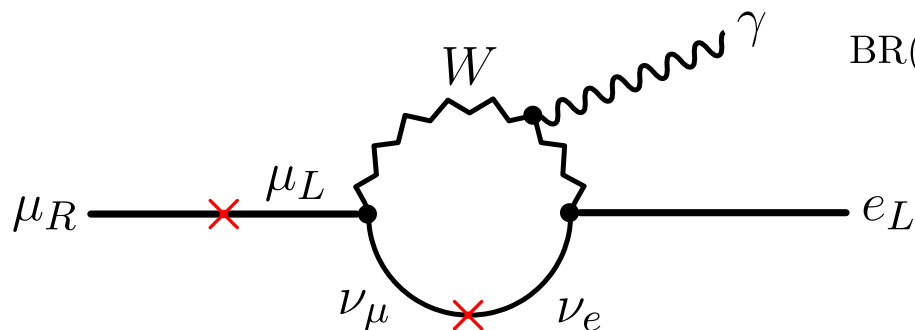
$$\rho_\phi = 0.4 \text{ GeV}/\text{cm}^3 \simeq 10^{-42} \text{ GeV}^4$$

Standard lore - CLFV

- The Standard Model (SM) has an accidental global flavor symmetry

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- Because $m_\nu \neq 0$ charged-lepton-flavor violation (CLFV) can occur at one-loop



$$\text{BR}(\mu \rightarrow e\gamma) \simeq \frac{3\alpha}{32\pi M_W^4} |U_{\mu 3} U_{e 3}^* \Delta m_{31}^2 + U_{\mu 2} U_{e 2}^* \Delta m_{21}^2|^2 \simeq 10^{-54}$$

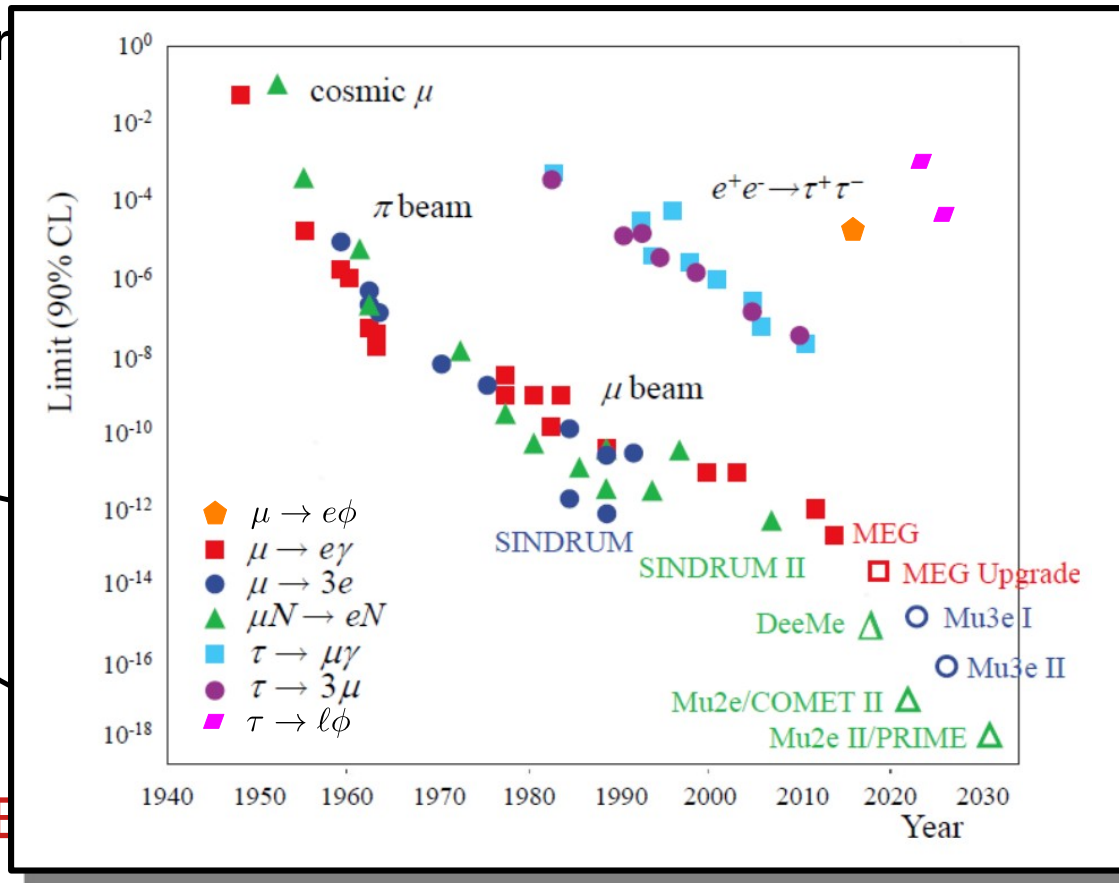
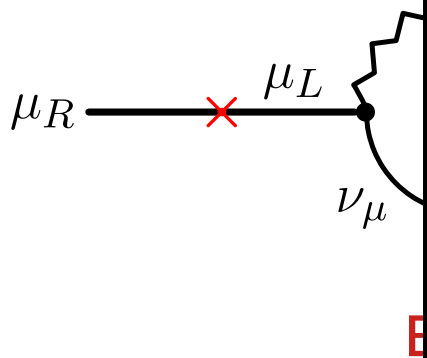
$$\text{BR}(\mu \rightarrow eee) \simeq \frac{\alpha}{3\pi} \left(\log \frac{m_\mu^2}{m_e^2} - 3 \right) \times \text{BR}(\mu \rightarrow e\gamma)$$

$$\text{CR}(\mu N \rightarrow e N) \simeq \alpha \times \text{BR}(\mu \rightarrow e\gamma)$$

Bottom line: Observing CLFV = new physics

Standard lore - CLFV

- The Standard Model
- Because m_ν is tiny, CLFV processes occur at one-loop



symmetry

can occur at

$$|U_{\mu 2} U_{e 2}^* \Delta m_{21}^2|^2 \simeq 10^{-54}$$

$$\left. \begin{array}{l} 3 \\ 3 \end{array} \right) \times \text{BR}(\mu \rightarrow e \gamma)$$

$$\text{BR}(\mu \rightarrow e \gamma)$$

Why CLFV ULDM?

Detecting a CLFV signal does not immediately imply DM is the source.

Detecting a *time-dependent* CLFV signal is a smoking gun signal of DM.

Minimal analysis can convert intensity frontier experiments into dark matter detectors

Outline

- 1) What operators are phenomenologically viable?
- 2) Explicit realization of operator structure
- 3) Experimental sensitivity and reach (Mu3e)

CLFV ULDM

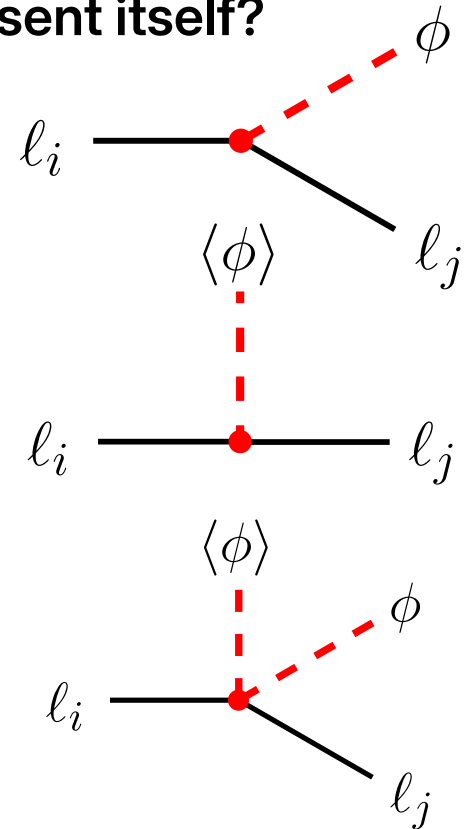
How and where does time-modulation present itself?

Two types of time-dependence:

- Manifestation in mass matrix

$$m_{ij} = \text{diag}(m_e, m_\mu, m_\tau) + y_{ij}\phi_c$$

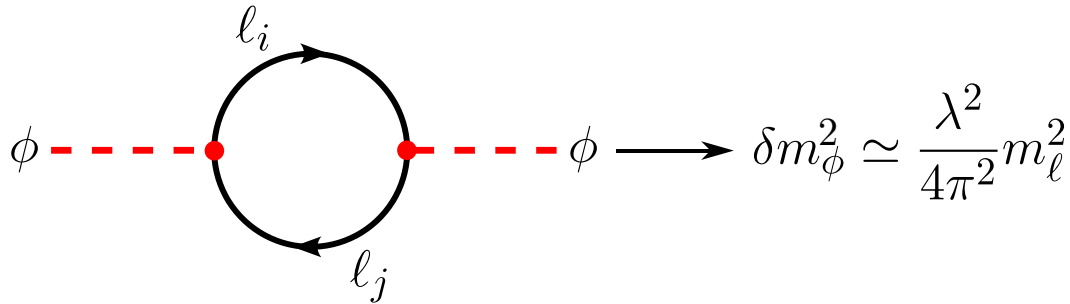
- Manifestation in decay/scattering rates
 - Inherently higher dimensional



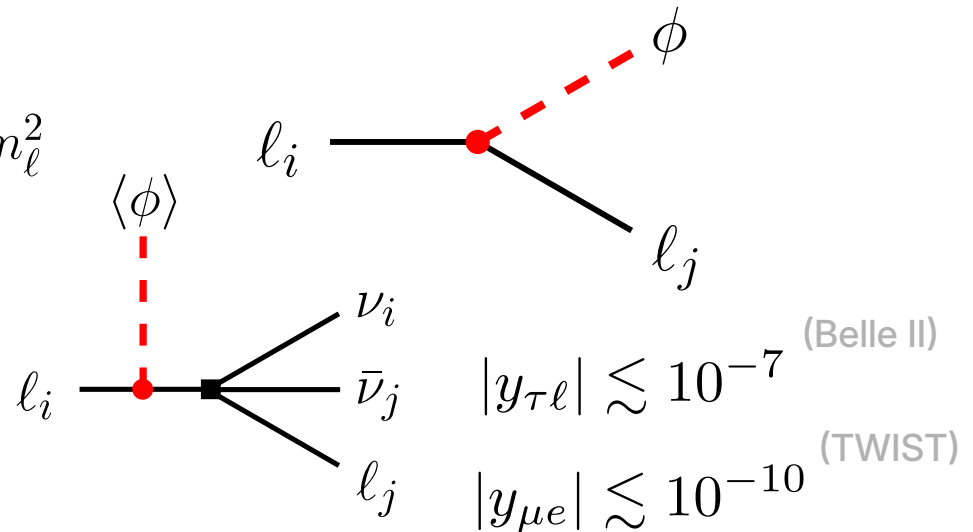
Journey towards phenomenologically viable operator

First guess: $\frac{C_{ij}}{\Lambda} \phi H \bar{L}_i l_j \rightarrow y_{ij} \phi \bar{l}_i l_j$

1. Fine-tuning



2. No time-modulation



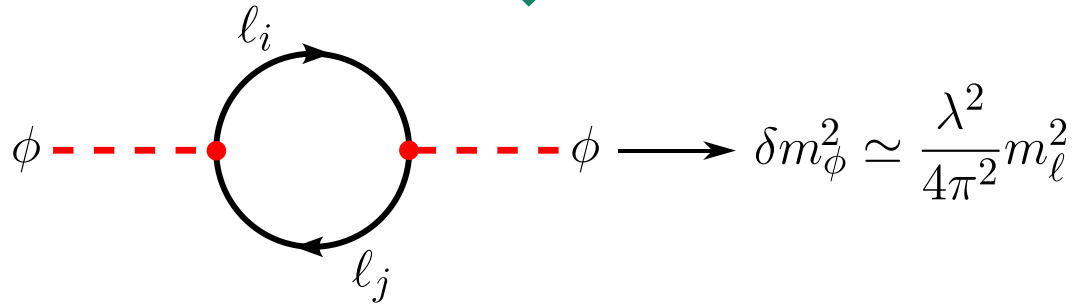
3. SM rate-modulation

Journey towards phenomenologically viable operator

First guess: $\frac{C_{ij}}{\Lambda} \phi H \bar{L}_i \ell_j \rightarrow y_{ij} \phi \bar{l}_i l_j$

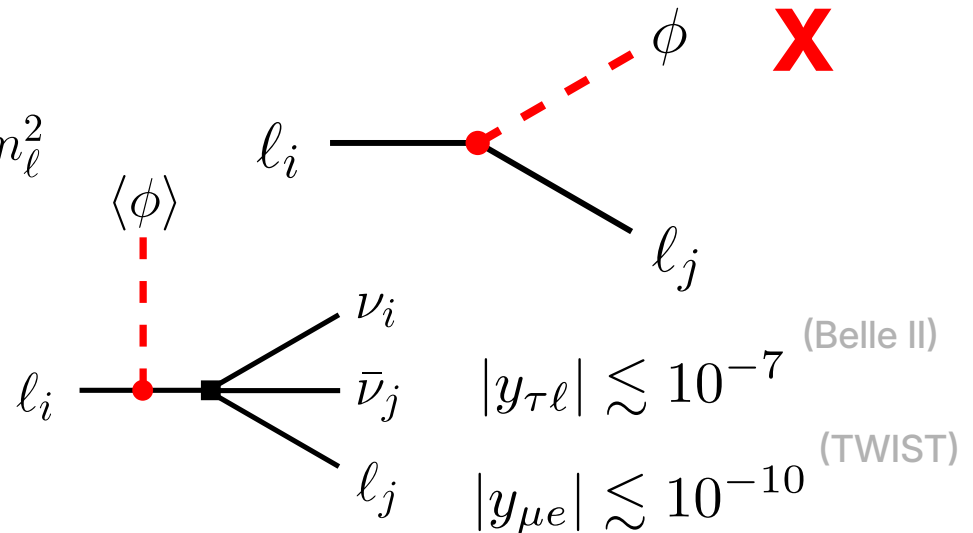
1. Fine-tuning

“✓”



2. No time-modulation

X



3. SM rate-modulation

X

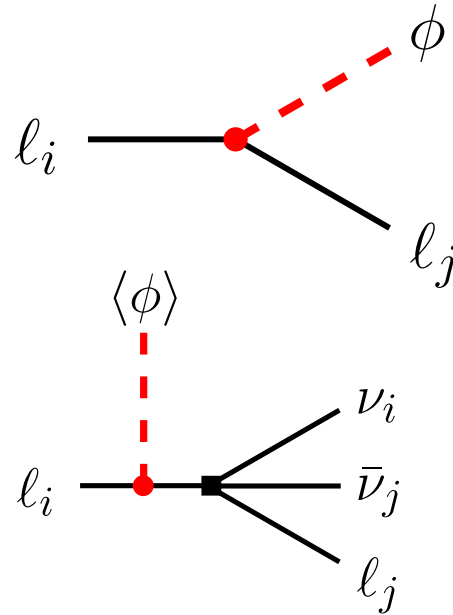
Journey towards phenomenologically viable operator

Second guess: $\frac{C_{ij}}{\Lambda} \partial_\mu \phi (\bar{l}_i \gamma^\mu \gamma^5 l_j)$

1. Fine-tuning: ✓

2. Time-modulation: ✗

3. SM-modulation: ✗



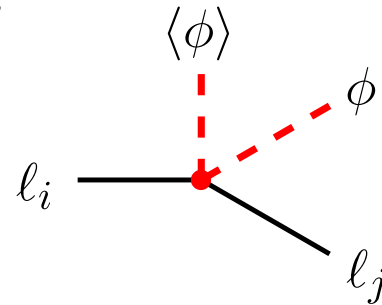
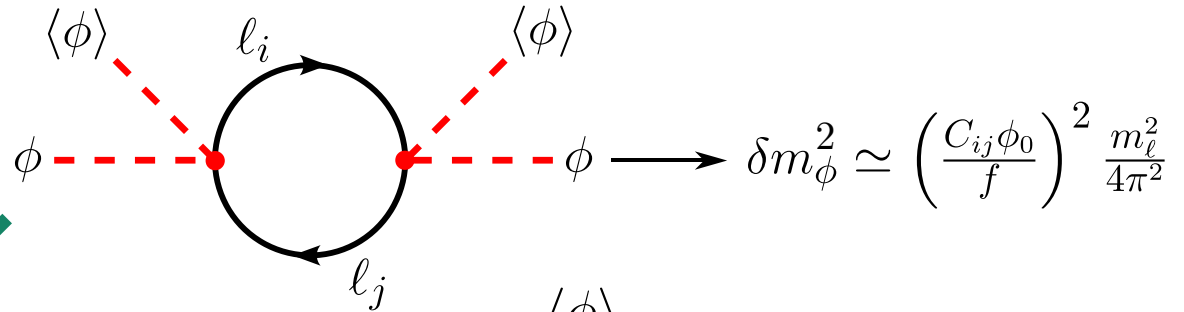
Journey towards phenomenologically viable operator

Third guess: $\frac{C_{ij}}{f} \phi^2 (\bar{l}_i l_j)$

1. Fine-tuning: **X**

2. Time-modulation: **✓**

3. SM-modulation: **✓**



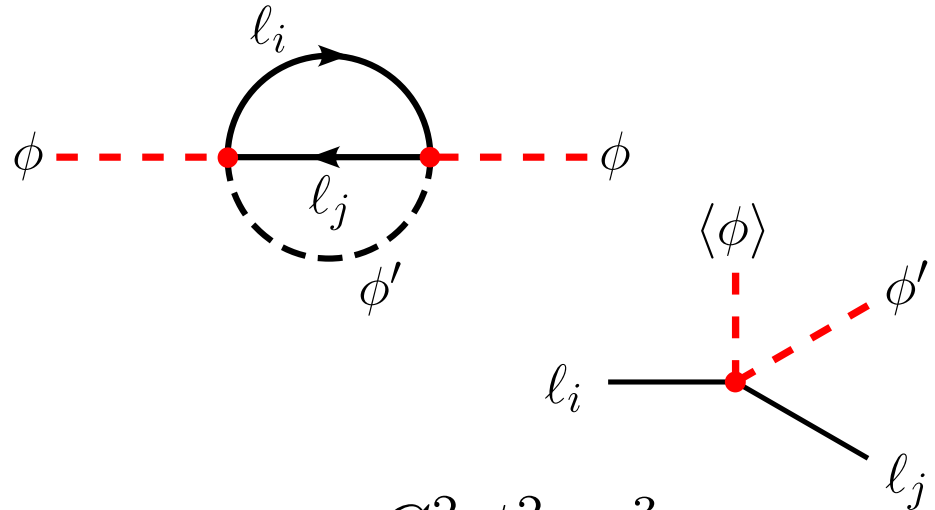
Journey towards phenomenologically viable operator

Fourth guess: $\frac{C_{ij}}{f} \phi \phi' (\bar{l}_i l_j)$ or $\frac{C_{ij}}{f^2} \phi \partial_\mu \phi' (\bar{l}_i \gamma^\mu l_j)$

1. Fine-tuning: "✓"/✓

2. Time-modulation: ✓

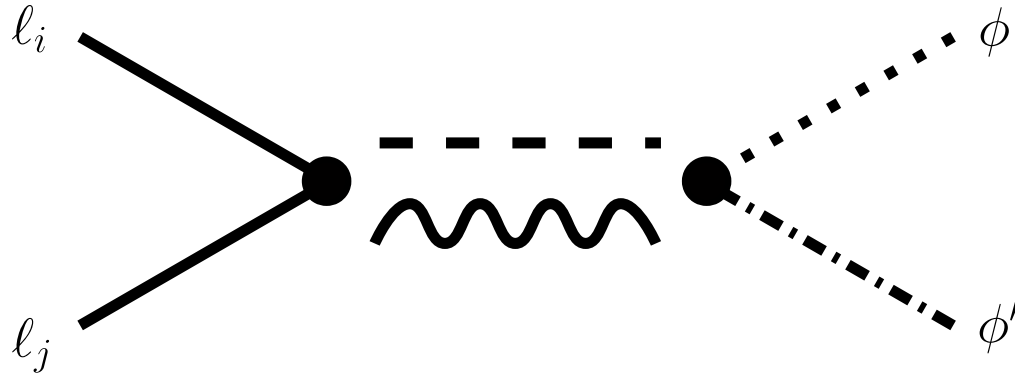
3. SM-modulation: ✓



$$\mathcal{B}(l_i \rightarrow l_j \phi) = \frac{C_{ij}^2 \phi_0^2}{64\pi f^4} \frac{m_{l_i}^3}{\Gamma_{l_i}} \cos^2(m_\phi t + \delta)$$

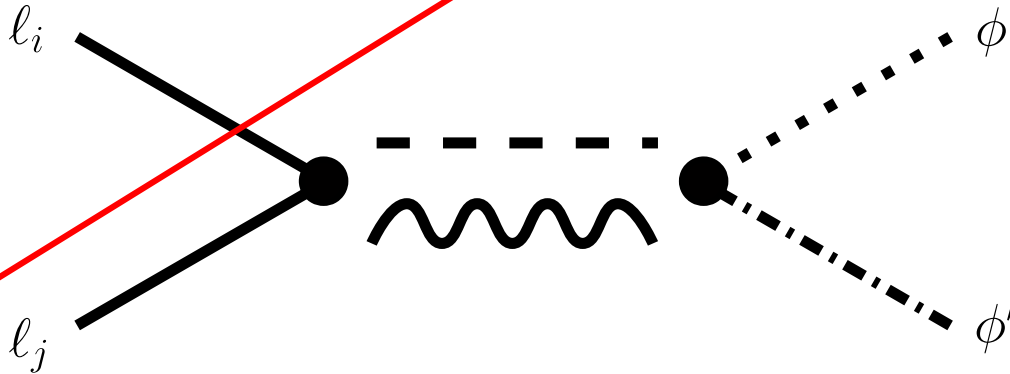
Explicit realization

Consider: $\frac{C_{ij}}{f^2} \phi \partial_\mu \phi' (\bar{l}_i \gamma^\mu l_j)$



Explicit realization

Consider: $\frac{C_{ij}}{f^2} \phi \partial_\mu \phi' (\bar{l}_i \gamma^\mu l_j)$



→ Non-abelian pseudo-NGB + portal

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$

$$SU(3)_L \times SU(3)_R \times U(1)_D \rightarrow SU(3)_V \times U(1)_D$$

$$D_\mu \equiv \partial_\mu + ig_D A'_\mu [Q, U] \quad U = \exp \left(i\sqrt{2}\Pi_D / f_D \right)$$

$$\Pi_D = \begin{pmatrix} \frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & \pi_D^+ & K_D^+ \\ \pi_D^- & -\frac{\pi_D^0}{\sqrt{2}} + \frac{\eta_{D8}}{\sqrt{6}} & K_D^0 \\ K_D^- & \bar{K}_D^0 & -\sqrt{\frac{2}{3}}\eta_{D8} \end{pmatrix}$$

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$

$$\mathcal{L}_D \supset \frac{f_{UV}^2}{8} (D_\mu U D^\mu U^\dagger) + \frac{f_{UV}^2}{8} (\chi^\dagger U + U^\dagger \chi) + \dots$$

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$ $\rightarrow U \rightarrow e^{i\alpha}U$

$$\mathcal{L}_D \supset \frac{f_{UV}^2}{8} (D_\mu U D^\mu U^\dagger) + \frac{f_{UV}^2}{8} (\chi^\dagger U + U^\dagger \chi) + \dots$$

Explicit realization

- Non-abelian pseudo-NGB + U(1)_D

$$\mathcal{L}_D \supset \frac{f_{UV}^2}{8} (D_\mu U D^\mu U^\dagger) + \frac{f_{UV}^2}{8} (\chi^\dagger U + U^\dagger \chi) + \dots$$

$$Q \rightarrow q_U \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & q_U \\ 0 & q_U & 0 \end{pmatrix}$$

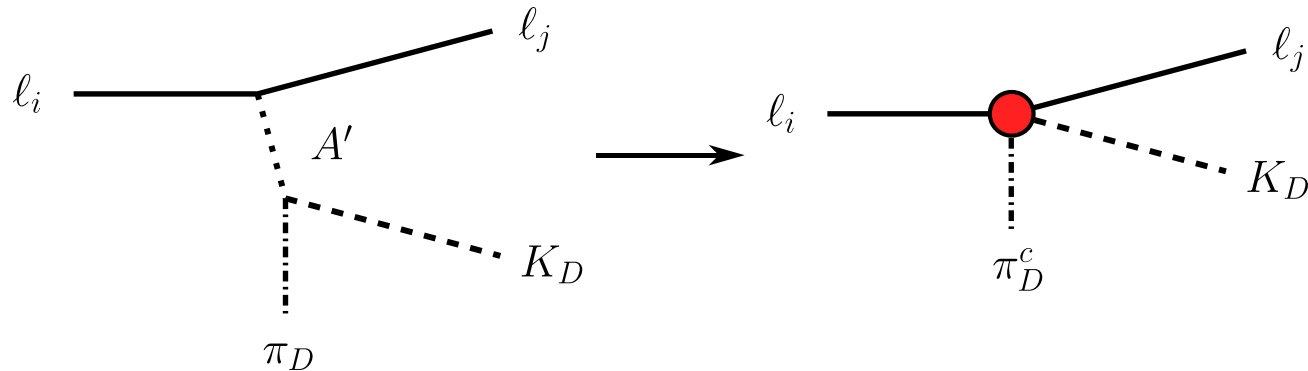
$$\supset -g' q_U A'_\mu (\pi_D^+ i \partial^\mu K_D^- - K_D^- i \partial^\mu \pi_D^+ + \text{h.c.}) + \dots$$

Explicit realization

- Non-abelian pseudo-NGB + $U(1)_D$

$$\supset -g' q_U A'_\mu (\pi_D^+ i \partial^\mu K_D^- - K_D^- i \partial^\mu \pi_D^+ + \text{h.c.}) + \dots$$

Charge the SM under $U(1)_D$: $-\mathcal{L}_{\text{portal}} = ig' c_{ij} \ell_i \gamma^\mu A'_\mu \ell_j + \text{h.c.}$



Explicit realization

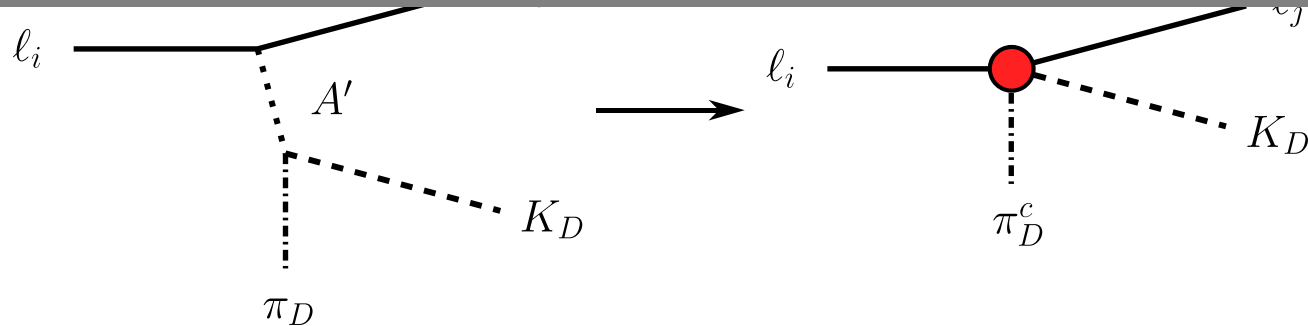
- Non-abelian pseudo-NGB + $U(1)_D$

$$\supset -g' q_U A'_\mu (\pi_D^+ i \partial^\mu K_D^- - K_D^- i \partial^\mu \pi_D^+ + \text{h.c.}) + \dots$$

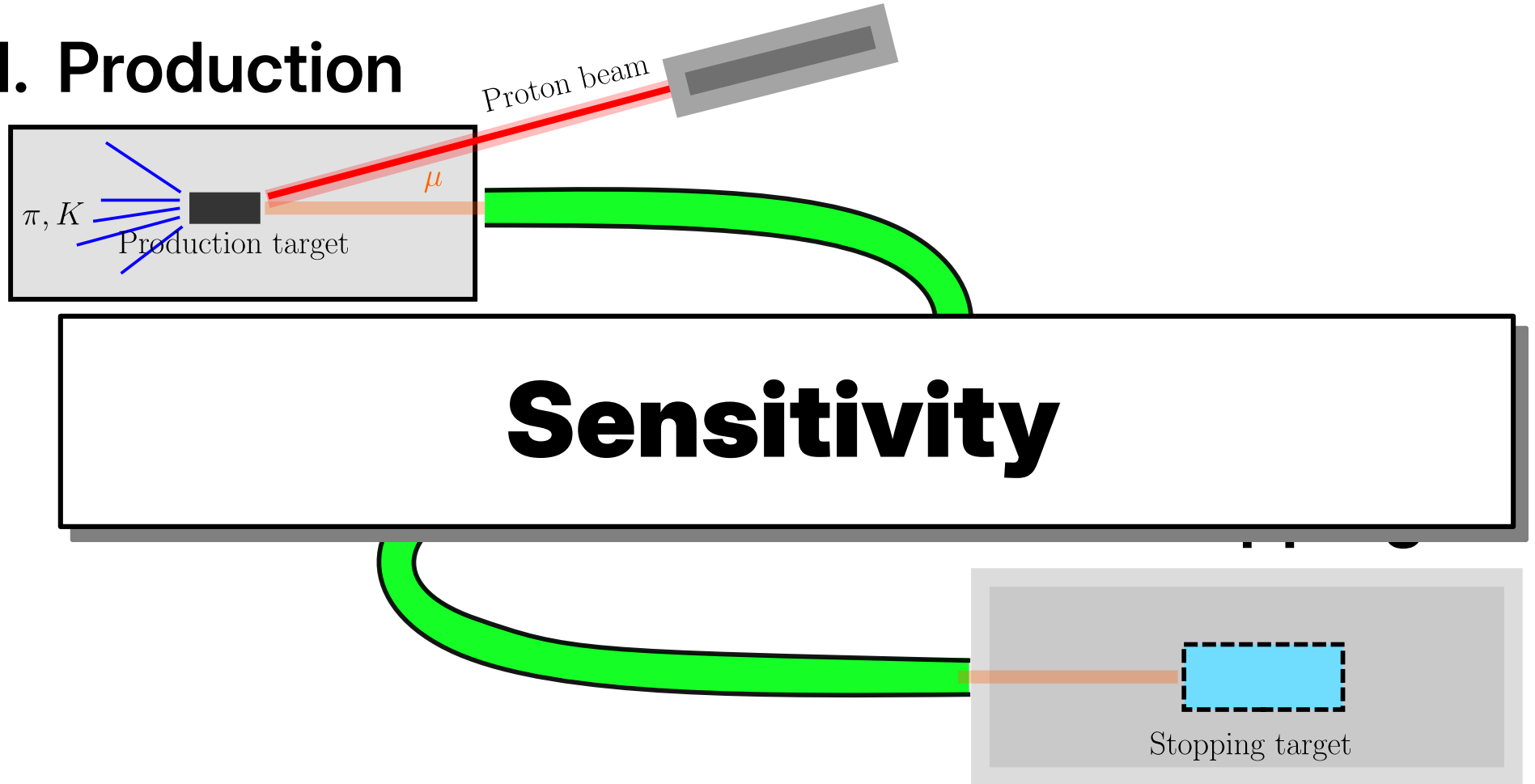
Charge t

$$\supset \frac{c_{ij} q_U g'^2}{m_{A'}^2} (\bar{\psi}_i \gamma^\mu \psi_j) (\pi_D^+ \partial_\mu K_D^-) + \dots$$

h.c.



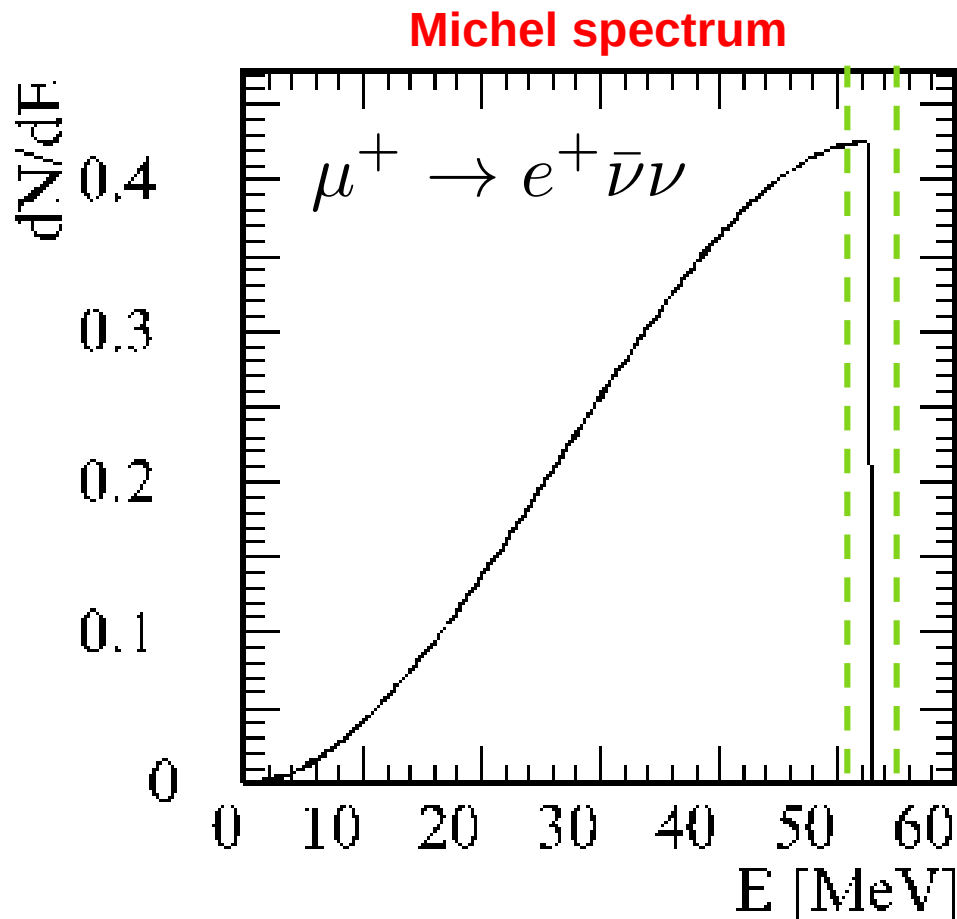
1. Production



Sensitivity (Mu3e)

Consider, for example, Mu3e.

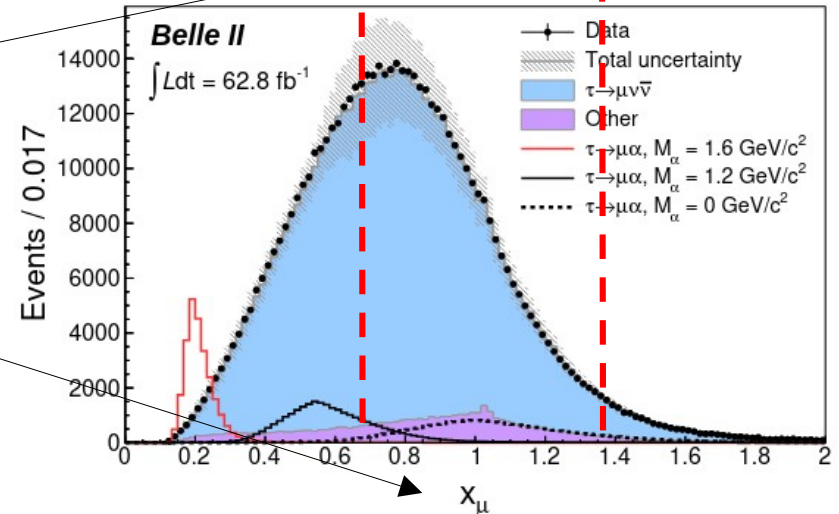
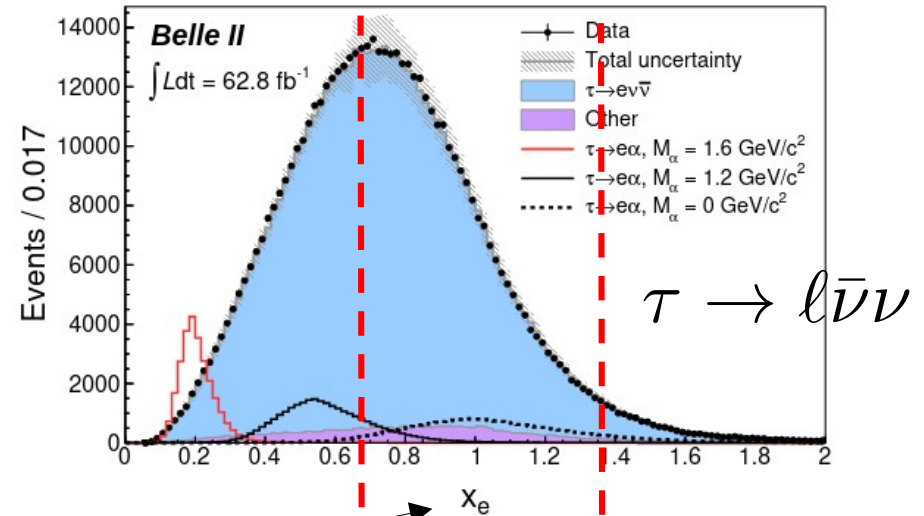
- Will run for $T \sim 300$ days
- $\sim 10^{15}$ muon decays
- $\sim 10^{13}$ of which will lie in the final kinematic bin
- $\sim 10^8$ muon decays/s



Sensitivity (Belle-II)

- Analysis: **2212.03634**
- $N_\tau \sim 10^8$
- Require three charged hadrons on tag side, one charged lepton on signal side

$$x_\ell \equiv \frac{E_\ell^*}{m_\tau/2}$$



Sensitivity

- Sensitivity can essentially be determined by:

$$m_\phi, \quad T, \quad N_{\text{total}}$$

- Statistical uncertainty + systematic uncertainty maximally correlated across all time bins

$$\sigma_{\text{stat}} = \sqrt{N_{\text{bg}}/n_{\text{bin}}} \quad , \quad \sigma_{\text{sys}} = \alpha N_{\text{bg}}/n_{\text{bin}}$$

$$\chi^2 = \sum_{k,p=1}^{n_{\text{bin}}} S_k C_{kp}^{-1} S_p = \frac{1}{N_{\text{bg},1}} \sum_{k=1}^{n_{\text{bin}}} S_k^2 - \frac{\alpha^2}{1 + \alpha^2 n_{\text{bin}} N_{\text{bg},1}} \left(\sum_{k=1}^{n_{\text{bin}}} S_k \right)^2$$

Sensitivity

$$\chi^2 = \sum_{k,p=1}^{n_{\text{bin}}} S_k C_{kp}^{-1} S_p = \frac{1}{N_{\text{bg},1}} \sum_{k=1}^{n_{\text{bin}}} S_k^2 - \frac{\alpha^2}{1 + \alpha^2 n_{\text{bin}} N_{\text{bg},1}} \left(\sum_{k=1}^{n_{\text{bin}}} S_k \right)^2$$

$$S_k = 2\mathcal{B}_{\text{sig}} f_{\text{sig}} \frac{N_{\text{tot}}}{T} \int_{(k-1)\Delta t}^{k\Delta t} dt \cos^2(m_\phi t + \delta)$$

$$= \mathcal{B}_{\text{sig}} f_{\text{sig}} \frac{N_{\text{tot}}}{T} \left[\Delta t + \frac{\sin(2km_\phi \Delta t + 2\delta) - \sin(2(k-1)m_\phi \Delta t + 2\delta)}{2m_\phi} \right]$$

Three interesting limits:

1. Signal does not oscillate over the duration of the experiment
2. Signal oscillates but time bins cannot resolve the oscillations
3. Signal oscillates and time bins resolve the oscillations

Systematics
dominate

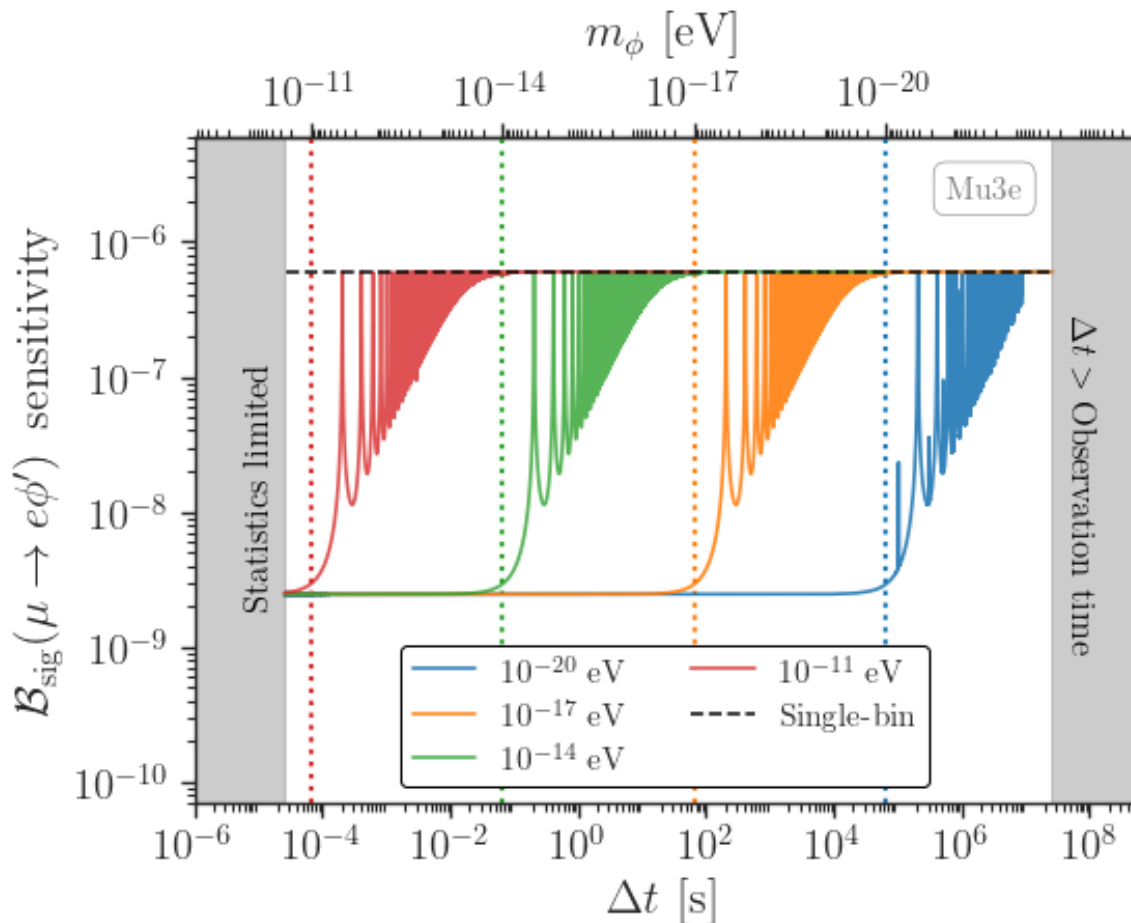
Statistics
dominate

Sensitivity

Assumptions:

- 1) Asimov dataset
- 2) Continuous running
- 3) Time-independent systematics
- 4) Simplified decoherence

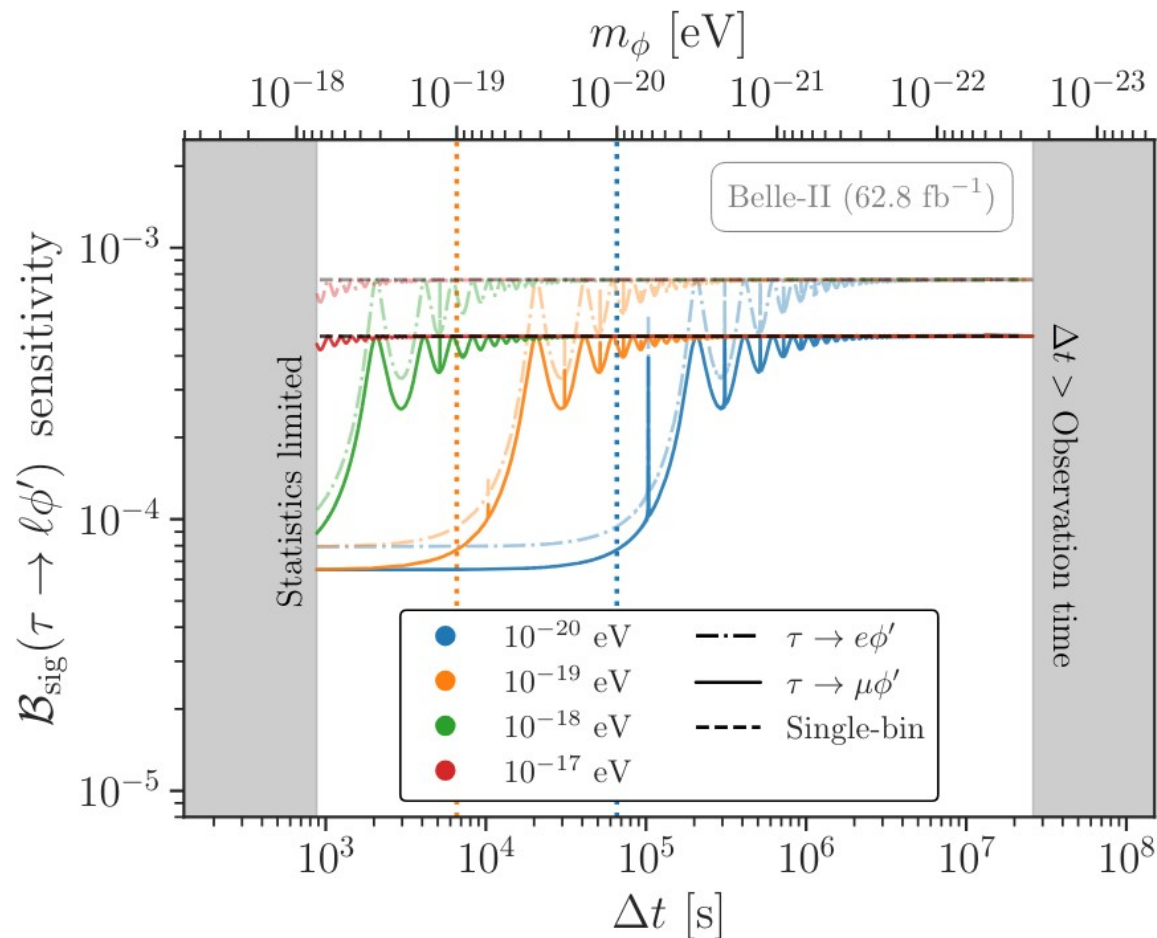
- **Notably, the sensitivity to ULDM mass is limited by statistics, not experimental time resolution**



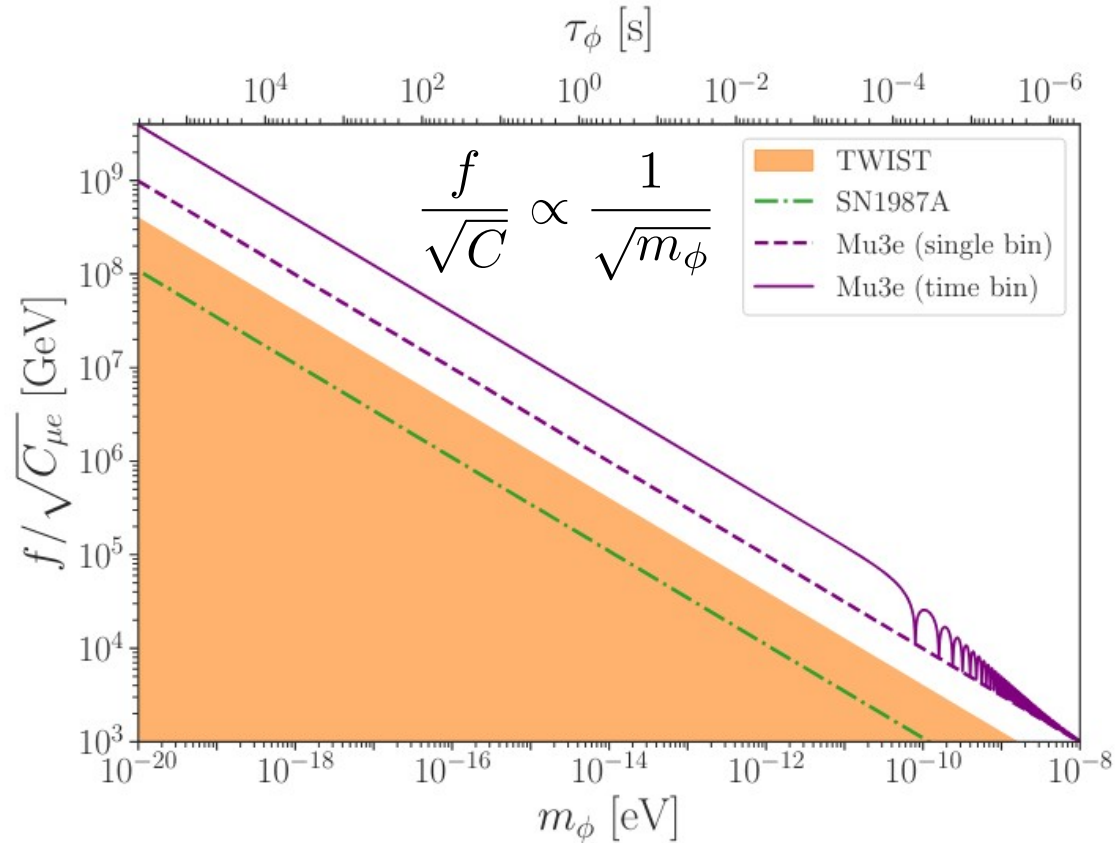
Sensitivity

Assumptions:

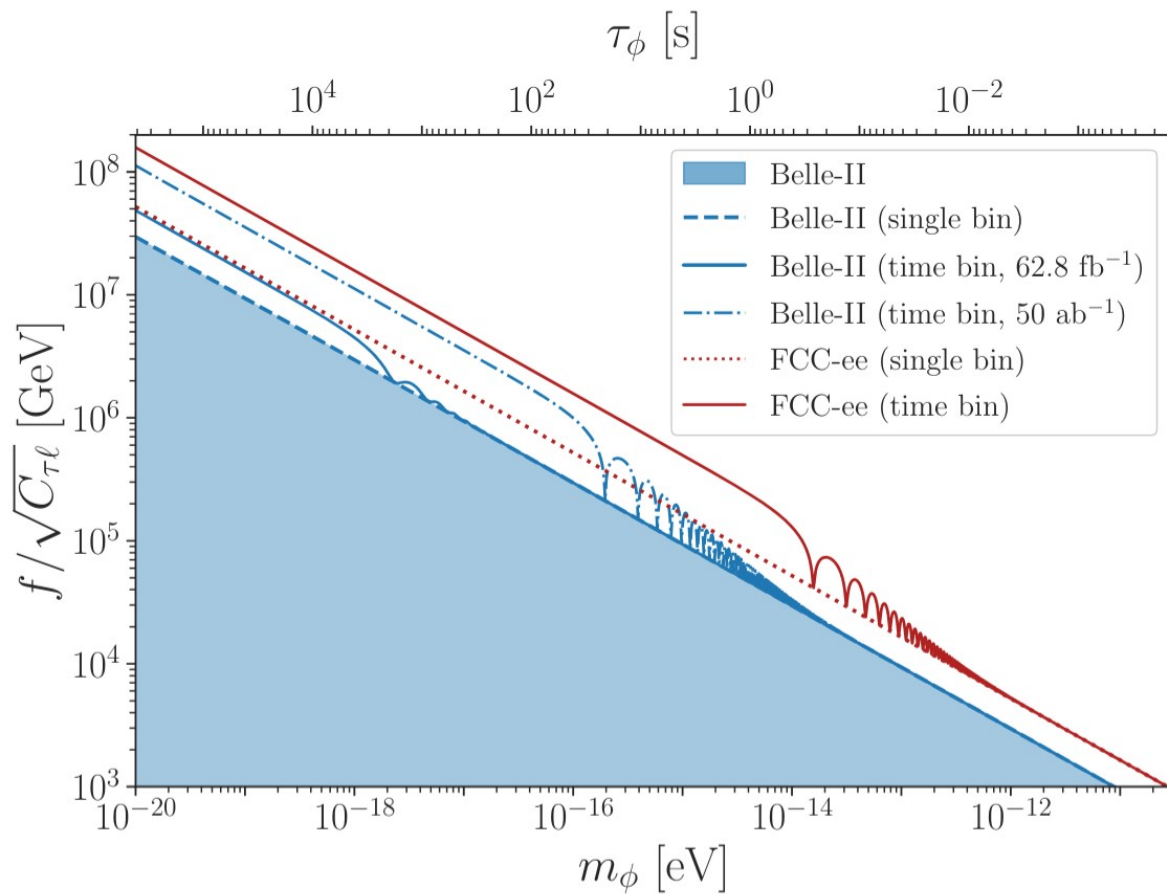
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Reach



Reach



Conclusions

- Detecting a time-dependent CLFV signal is a smoking gun for dark matter. In this way, intensity frontier experiments can function also as dark matter detectors.
- Time-dependent analyses can overcome systematics dominated measurements.

What's next:

- Quark sector
- Cosmology of UV realizations (Maleknejad, McDonough 2205.12983)

Conclusions

- Detecting a time-dependent CLFV signal is a smoking gun for dark matter. In this way, intensity frontier experiments can function also as dark matter detectors.
- Time-dependent analyses can overcome systematics dominated measurements.

What's next:

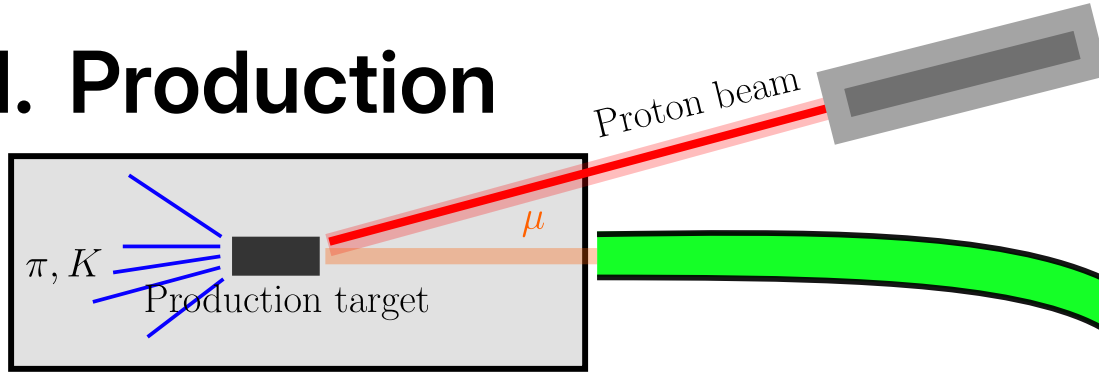
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Thank you :)

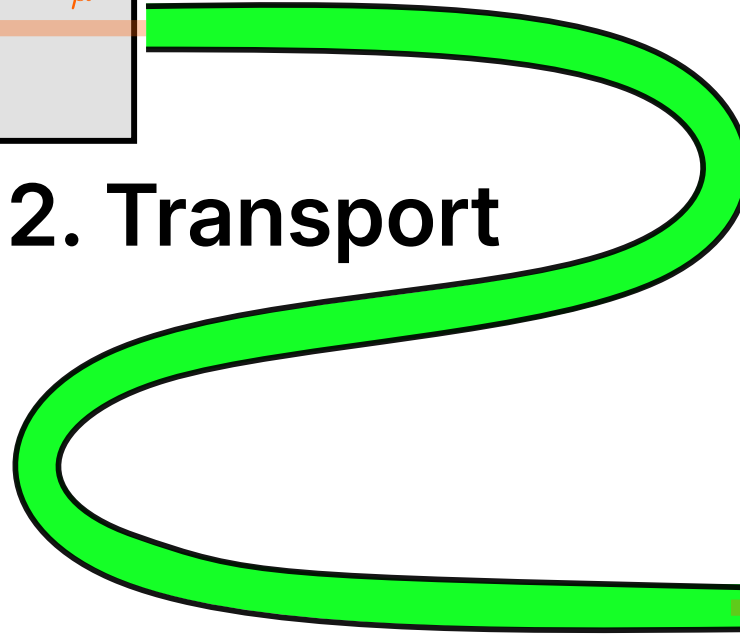
Back-up

Mu3e experiment

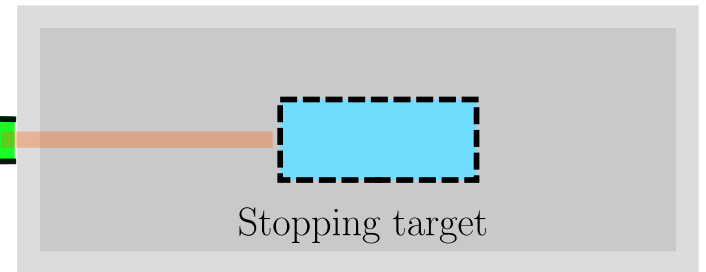
1. Production



2. Transport



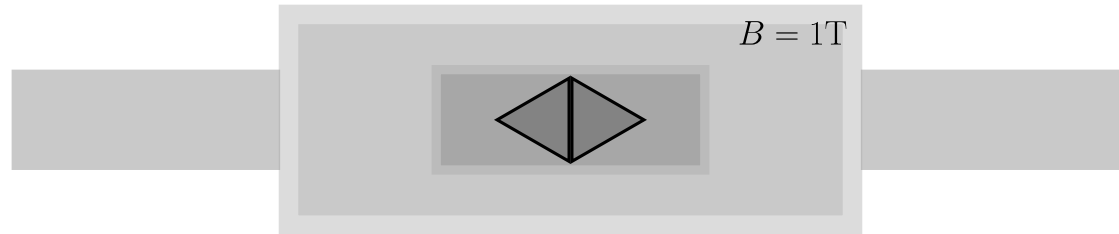
3. Stopping



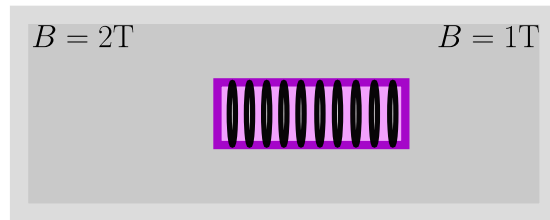
4. Detection (phenomenology is influenced by detector)

Mu3e (μ^+)

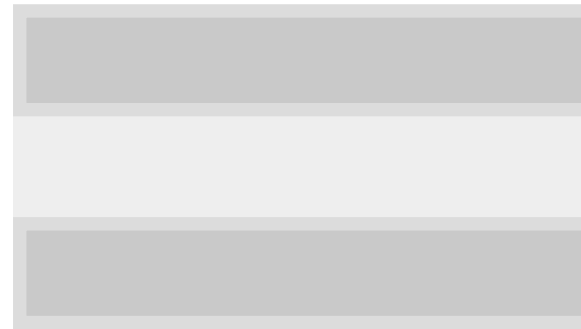
* requires $p_T > 10$ MeV



Mu2e (μ^-)



* requires $p_T > 90$ MeV



Michel spectrum errors at Mu3e

NNLO, NNLL

2211.01040

