A Light Scalar Explanation of Muon g–2 and the KOTO Anomaly

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The heavy and the light

- Dark sector particles
  - New light weakly coupled particles
  - Do not interact with the known strong, weak, or electromagnetic forces
The motivation for dark sector particles

1. Existence of dark matter
   - do not interact with strong, weak, or electromagnetic forces
   - A zoo of similar particles in the dark sector as in the visible sector

2. The null detection of dark matter
   - Secluded annihilation: $\text{DM} + \text{DM} \rightarrow \text{X} + \text{X}$
   - $\text{X}$ is light and weakly coupled to visible sector
The motivation for light dark sector particles

3. The experiment status

- Technically difficult to increase E
- Easier to accumulate higher luminosity

4. The low energy experiment hints

- Lepton e/mu g-2 (light scalar at ~100 MeV) 1806.10252 Davoudiasl et al …
- KOTO: neutral K decay into pi0 + MET (light scalar < 200 MeV) 1909.11111 Kitahara et al …
- MiniBooNE: (dark neutrino/boson at 10~100MeV) 1807.09877 Bertuzzo et al …
- Atomki: Be8/He4 decay into a 17 MeV ee resonance 1604.07411 Feng et al …
Dark sector model: the Higgs portals

• SM Higgs portal model \( H^\dagger H \phi^2, \ H^\dagger H \phi \)

\[
\mathcal{L}_{\text{int}} \supset \sin \theta \times \phi \left( \sum_q \frac{m_q}{v} \bar{q}q + \sum_{\ell} \frac{m_\ell}{v} \bar{\ell}\ell + \ldots \right)
\]

• More structures with multiple Higgs doublets

• CP-even scalar mixing

\[ H_1^\dagger H_1 \phi, \ H_2^\dagger H_2 \phi \ldots \]

• CP-odd/even scalar mixing

\[ H_1^\dagger H_2 \phi + h . \ c . \ \ldots \]
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

- Direct CPV
- FCNC : highly suppressed decay
  - BR (SM) : $3 \times 10^{-11}$
- Small theoretical uncertainty (~2%)
  → Good probe for new physics search

$3.0 \times 10^{-9}$ (90% C.L.)

Indirect limit (Grossman-Nir bound)
$1.5 \times 10^{-9}$

SM prediction
$3.0 \times 10^{-11}$
Results from 2016 to 2018 runs

Satoshi Shinohara at KAON2019, 10-13 September, 2019, Perugia, Italy.
Problem to generate a model: Nir-Grossman bound

• **KOTO signal**
  - Bkg = 0.05(0.02), obs = 3 → BR(K_L \rightarrow \pi^0 \nu \nu) \sim 2 \times 10^{-9}

• **NA62/E949 constraints**
  - BR(K^+ \rightarrow \pi^+ \nu \nu) < 1.85 \times 10^{-10}

• **Nir-Grossman bound**
  - isospin symmetry \( \Gamma (K_L (\bar{s}d) \rightarrow \pi^0 (\bar{d}d) \nu \nu) \approx \Gamma (K^+(\bar{s}u) \rightarrow \pi^0 (\bar{d}u) \nu \nu) \)
  - Using lifetime of charged and neutral Kaons, BR(K^0 \rightarrow \pi^0 \nu \nu) < 4.3 \times \text{BR}(K^+ \rightarrow \pi^+ \nu \nu)

The constraint has tension with observed BRs!
Solution 1: long-lived particle

- A light particle (m < 200 MeV) from Kaon decay
  \[ K_L \rightarrow \pi^0 X, \quad K^+ \rightarrow \pi^+ X \]
  - If it is long-lived enough to escape KOTO detector (few meters), it can mimic the missing energy
  - But an isospin symmetric model is constrained by charged Kaon experiment (Nir-Grossman bound)
    - The way out: charged Kaon experiments veto the region when X mass close to pion mass, due to large bkg from
      \[ K^+ \rightarrow \pi^+ \pi^0 \]
    - Therefore, long lived particle with mass ~ 140 MeV is viable

George W.S. Hou 2016
Model building: long-lived scalar with simple mixing to SM Higgs

- **SM Higgs portal**

\[
\mathcal{L}_{\text{int}} \supset \sin \theta \times \phi \left( \sum_q \frac{m_q}{v} \bar{q} q + \sum_\ell \frac{m_\ell}{v} \bar{\ell} \ell + \frac{2m_W^2}{v} \phi W^+_\mu W^-_{\mu} + \ldots \right)
\]

- **The rates for the Kaon decay into \( \phi \) and \( \pi \) from 1-loop**

\[
\Gamma(K_L \to \pi^0 \phi) = \left( \text{Re} \left[ g(\sin \theta) \right] \right)^2 \frac{\lambda^{1/2}(m_K^2, m_\pi^2, m_\phi^2)}{16\pi m_K^3} V^* \sum_{q=u,c,t} m_q^2 V_{q\ell} V_{\ell s},
\]

\[
g(\sin \theta) = \frac{3m_K^2}{32\pi^2 v^3} \sin \theta \sum_{q=u,c,t} m_q^2 V^*_{q\ell} V_{\ell s},
\]
Long-lived scalar mediator fits to KOTO

• Charged Kaon exp forced mass $\sim 140$ MeV

• highly constrained by astrophysical bounds?

See Samuel Homiller’s talk
D. Egana-Ugrinovic et al, 1911.10203

See Yongchao Zhang’s talk
Bhupal Dev et al, 1911.12334
Bhupal Dev et al, 2005.00490
Solution 2: short-lived particle

- A light particle ($m < 200$ MeV) from Kaon decay
  \[ K_L \rightarrow \pi^0 X, \quad K^+ \rightarrow \pi^+ X \]

- If it is long-lived enough to escape KOTO detector (few meters), it can mimic the missing energy

- The way out: it is short-lived to decay inside the charged Kaon experiment, thus vetoed in measurement of
  \[ K^+ \rightarrow \pi^+ \bar{\nu} \nu \]

- KOTO detector scale $\sim 3$ m, NA62 detector $\sim 150$ m

- $X$ lifetime has to be $0.1$ nano-seconds $\sim 3$ cm

Kitahara et al, 1909.11111
Our Model building: short-lived scalar mixing with extended Higgs sector

- **Type-X 2HDM**: one SM-like doublet coupling to quarks and one doublet coupling to leptons

\[ \mathcal{L}_{\text{yuk}} = -\lambda_u \bar{Q} \tilde{\Phi}_2 u_R - \lambda_d \bar{Q} \tilde{\Phi}_2 d_R - \lambda_e \bar{L} \tilde{\Phi}_1 e_R + h.c. \]

- The light scalar mixing independently with two doublets

\[ \mathcal{L}_{\text{eff}} \supset \epsilon_q \sum_q \frac{m_q}{v} \phi \bar{q} q + \epsilon_\ell \sum_\ell \frac{m_\ell}{v} \phi \bar{\ell} \ell + \epsilon_W \frac{2m_W^2}{v} \phi W^+ W^- \]

- The coupling to gauge boson is not independent

\[ \epsilon_q \approx \frac{\sin \theta_{2\phi}}{\sin \beta}, \quad \epsilon_\ell \approx \frac{\sin \theta_{1\phi}}{\cos \beta} \]

- In the large \( \tan \beta \) limit, we obtain a simple relation

\[ \epsilon_W \approx (\sin \theta_{1\phi} \cos \beta + \sin \theta_{2\phi} \sin \beta) \approx \epsilon_\ell \cos^2 \beta + \epsilon_q \sin^2 \beta \approx \epsilon_q, \]
Fixing the model parameters

\[ \mathcal{L}_{\text{eff}} \supset \epsilon_q \sum_q \frac{m_q}{v} \phi \bar{q} q + \epsilon_\ell \sum_\ell \frac{m_\ell}{v} \phi \bar{\ell} \ell + \epsilon_q \frac{2m_W^2}{v} \phi W^+_\mu W^{\mu -} \]

- Three free parameters: \( \epsilon_q, \epsilon_\ell, m_\phi \)

- Two requirements:
  - Muon g-2 fixes \( \epsilon_\ell \sim 1 \)
  - Branching ratio of neutral Kaon decay to \( \phi \) fixes \( \epsilon_q \sim 0.01 \)

- Only mass parameter is free
The results

![Graph showing results with a grid of data points and regions labeled with experiment names and BR values.](image)

### Table

<table>
<thead>
<tr>
<th>$m_\phi$ [MeV]</th>
<th>$\epsilon_q$</th>
<th>$\epsilon_\ell$</th>
<th>BR($K_L \to \pi^0 \phi$)</th>
<th>$\tau$ [s]</th>
<th>tan $\beta$</th>
<th>sin $\alpha$</th>
<th>sin $\theta_{1\phi}$</th>
<th>sin $\theta_{2\phi}$</th>
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<td>50</td>
<td>$1.6 \times 10^{-2}$</td>
<td>1.22</td>
<td>$1.7 \times 10^{-6}$</td>
<td>$5.1 \times 10^{-11}$</td>
<td>100</td>
<td>-0.01</td>
<td>0.0122</td>
<td>$1.6 \times 10^{-2}$</td>
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<tr>
<td>60</td>
<td>$6.8 \times 10^{-3}$</td>
<td>0.87</td>
<td>$3.2 \times 10^{-7}$</td>
<td>$8.25 \times 10^{-11}$</td>
<td>100</td>
<td>-0.01</td>
<td>0.0087</td>
<td>$6.8 \times 10^{-3}$</td>
</tr>
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Summary

• Recent low energy anomalies might hint new light dark sector particles, but require further cross-checks from independent experiments.

• We show the light scalars can be related to lepton g-2 and KOTO exp.

• The muon g-2 could be explained by a scalar of mass of about 50 MeV and couplings to muons of the order of the SM Higgs ones.

• Such a scalar can also lead to an explanation of the KOTO excess, for appropriate values of the quark couplings.

• The model can be validated by the vetoed di-electron events in KOTO experiment.

Thank you!
Backup slides
KOTO experiment setup

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} : (\pi^0 \rightarrow) \ 2\gamma + \text{nothing} \]

- Neutrinos are not detected
- A new weakly-coupled particle \( X \) either stable or decay outside of detector can mimic missing energy

\[ K_L \rightarrow \pi^0 X \]
Result of 2015 physics run

Phys. Rev. Lett. 122, 021802

- Single event sensitivity: 
  \[(1.30 \pm 0.01_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-9}\]
  - No event in the signal region

- Upper limit (90% C.L.):
  \[\text{Br}(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9}\]
  \times 10 improvement from previous limit (KEK E391a)
The Kaon decay branching ratio

• The effective BR fitted to KOTO experiment

\[
\text{BR}(K_L \rightarrow \pi^0 \phi; \text{KOTO}) = \epsilon_{\text{eff}} \text{BR}(K_L \rightarrow \pi^0 \phi) e^{-\frac{L}{\tau_\phi} \frac{m_\phi}{p_\phi}}
\]

• The true BR for neutral Kaon and charged Kaon decay

• \( \text{BR}(\text{KOTO}) \sim 2 \times 10^{-9} \)
  according to 3 obs events, relying on both quark coupling and lifetime

• Check charged Kaon BR to avoid constraints
The lifetime of $\phi$

- The decay width for a light $\phi$

  \[
  \Gamma(\phi \rightarrow \ell' \ell') = \frac{e^2 \ell^2}{8\pi v^2} m_\phi (1 - \tau_\ell) m_\phi (1 - \tau_\ell) \theta (m_\phi^2 - 4m_\ell^2) \]

  \[
  \Gamma(\phi \rightarrow \gamma \gamma) = \frac{\alpha^2 m_\phi^3}{1024\pi^3} \left| \sum_q \frac{6e_q}{v} Q_q^2 A_{1/2}(\tau_q) + \sum_\ell \frac{2e_\ell}{v} A_{1/2}(\tau_\ell) + \frac{2e_\ell}{v} A_{1/2}(\tau_\ell) \right|^2
  \]

- Our model: $\varepsilon_\ell \sim 1 \gg \varepsilon_q \sim 0.01$

- Dashed line for simple mixing model (with accidental cancellation in $\gamma \gamma$)

- solid line for our model.

- In region of interest, the lifetime depends dominantly on $\varepsilon_\ell$ and the decay into $\ell \ell$. 

  $\text{BR}(\phi \rightarrow e^+ e^-) \approx 100\%$
Experimental constraints

- Proton beam dump
  - E949 and NA62: looking for $K^+ \rightarrow \pi^+\bar{\nu}\nu$
  - CHARM: looking for displaced decay (480 m) from $K \rightarrow \pi + (ee/\gamma\gamma/\mu\mu)$
  - Kµ2: using stopped charged Kaon looking for $K^+ \rightarrow \pi^+\phi$
  - KTeV/E799: looking for ee but requires $m_{ee} > 140$ MeV
  - $K^0 \rightarrow \pi^0 e^+ e^-$

- Electron beam dump
  - Orsay: looking for the radiation of light particles decaying into electron pairs $eN \rightarrow eN\phi$, $\phi \rightarrow e^+ e^-$
  - Similar experiment E137, although analysis was done for a dark photon, mixing with the photon and have to be reinterpreted in the scalar framework.

- B physics and collider constraints: like $B \rightarrow K\phi$, $\phi \rightarrow e^+ e^-$ avoided due to relative long lifetime
Comments

• Main difference between short-lived scalar (cm) and long-lived scalar (100 km)

• B physics measurement at LHCb

\[
\text{BR}(B^0 \to K^* e^+ e^-) = 3.1^{+0.94}_{-0.88} \times 10^{-7}, \quad \text{BR}(B^0 \to K^* e^+ e^-)^{\text{th}} = (2.3 \pm 0.6) \times 10^{-7}
\]

• Our benchmark model

\[
\text{BR}(B \to K^* \phi) \approx 10^{-4}, \quad \text{BR}(\phi \to e^+ e^-) \approx 100 \%
\]

• However, LHCb requires a good quality vertex: ee pair vertex coincide with K\(^*\) vertex, within vertex resolution L\~\ 5 mm

• \(\phi\rightarrow\text{ee}\) lifetime \~\ 1.5 cm, safe from LHCb constraints.

• KOTO can reexamine the vetoed events

\[
K_L \rightarrow \pi^0 \phi, \phi \rightarrow e^+ e^-
\]