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

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arXiv: 2001.06522 [JHEP04(2020)197]

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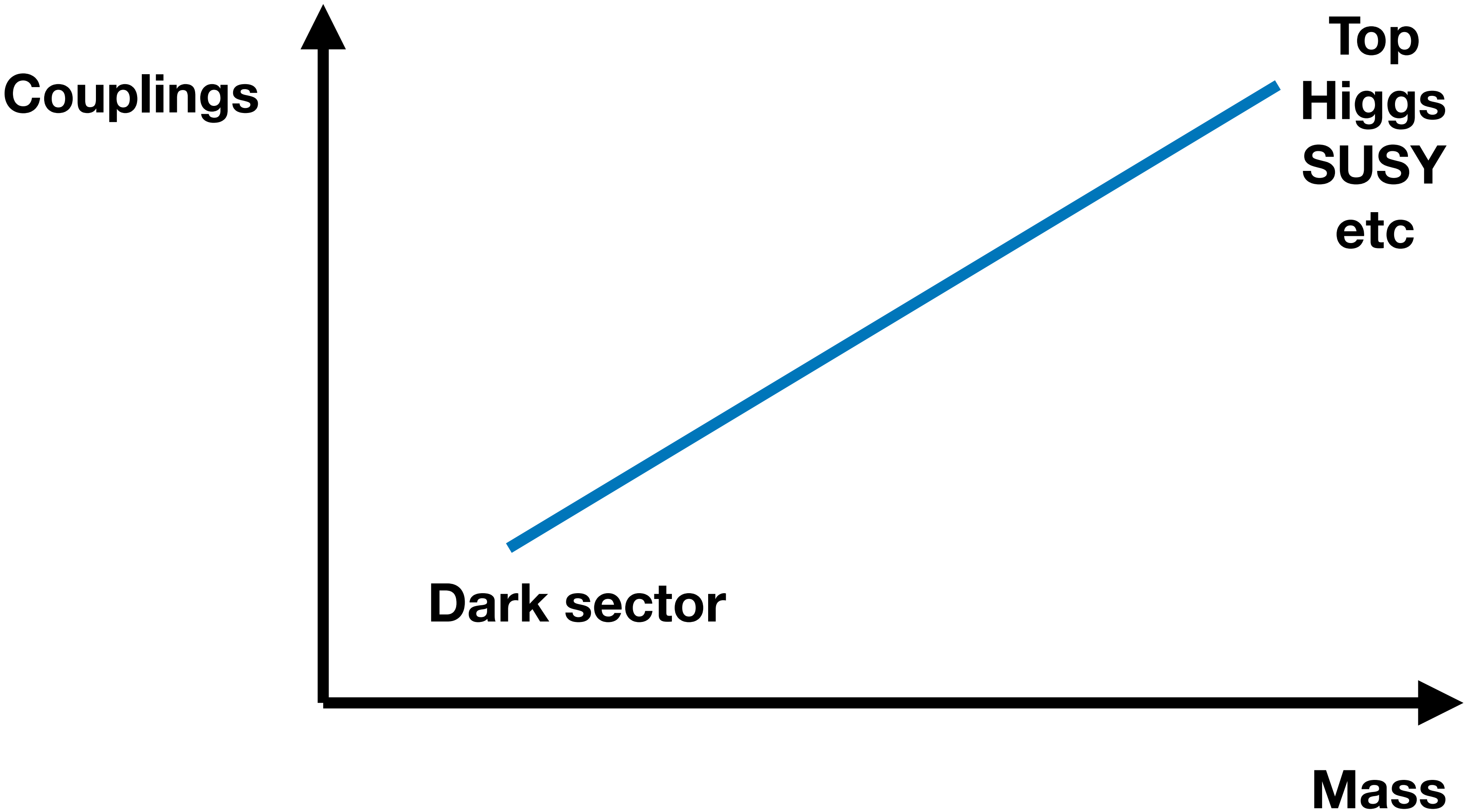
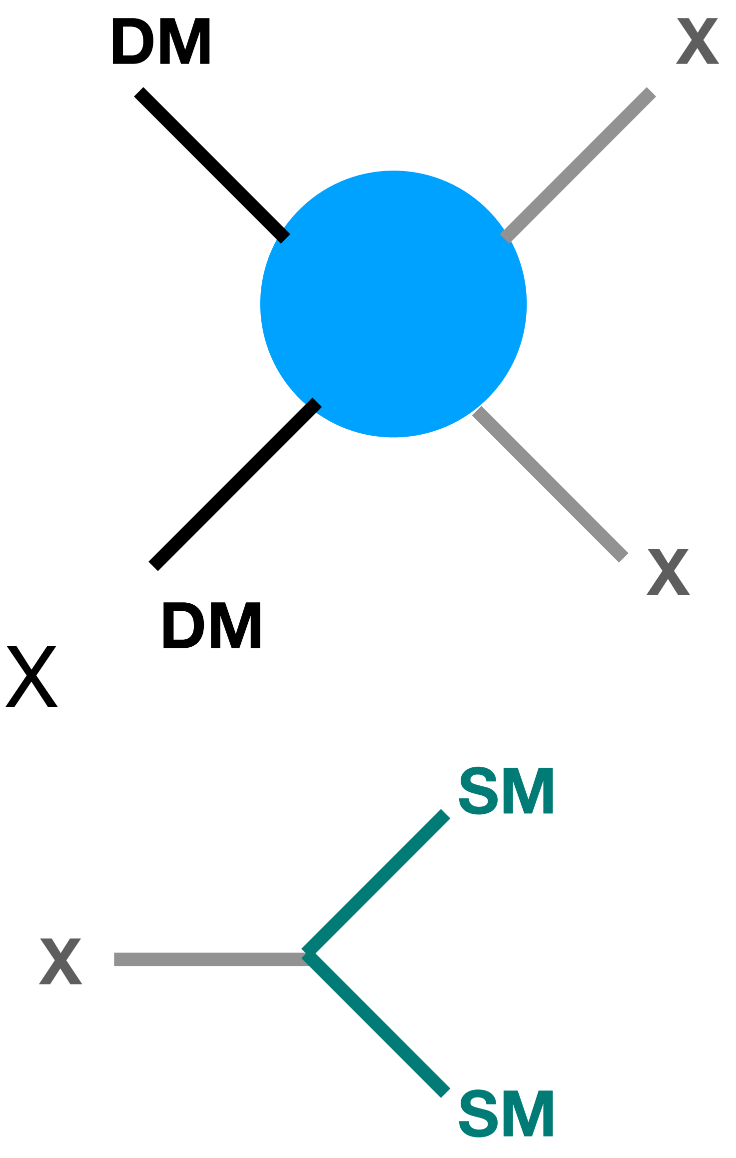
The heavy and the light



- 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: DM + DM → X + X
    - 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 $H^\dagger H \phi^2,\ H^\dagger H \phi$

$$\mathscr{L}_{\text{int}} \supset \sin\theta \times \phi \left(\sum_q \frac{m_q}{v} \bar{q} q + \sum_\ell \frac{m_\ell}{v} \bar{\ell} \ell + \cdots \right)$$

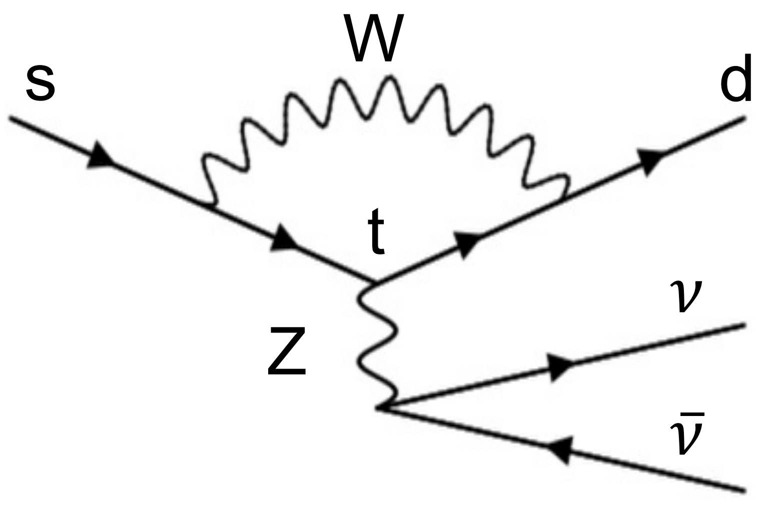
- More structures with multiple Higgs doublets
  - CP-even scalar mixing

$$H_1^\dagger H_1 \phi,\ H_2^\dagger H_2 \phi \cdots$$

  - CP-odd/even scalar mixing

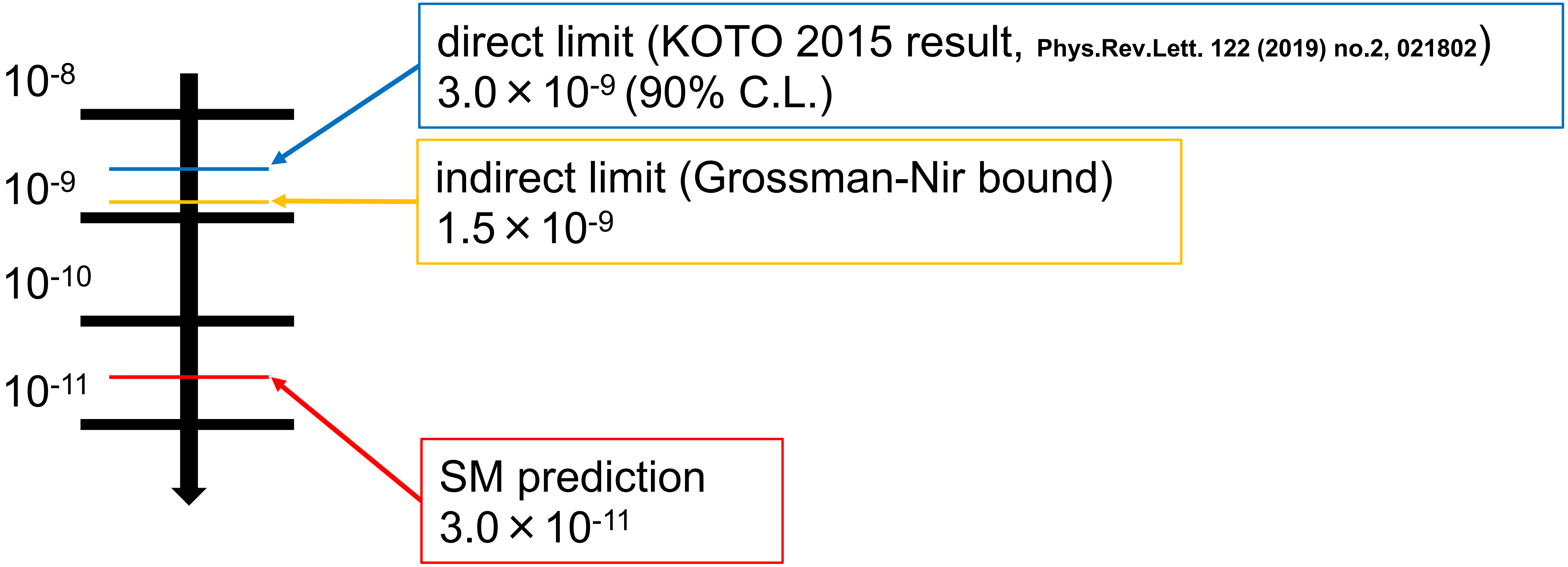
$$H_1^\dagger H_2 \phi + h.c. \cdots$$

$K_L \to \pi^0 \nu \bar{\nu}$ decay



- Direct CPV
- FCNC : highly suppressed decay
  - BR (SM) : 3×10^{-11}
- Small theoretical uncertainty（~2%）

→ Good probe for new physics search



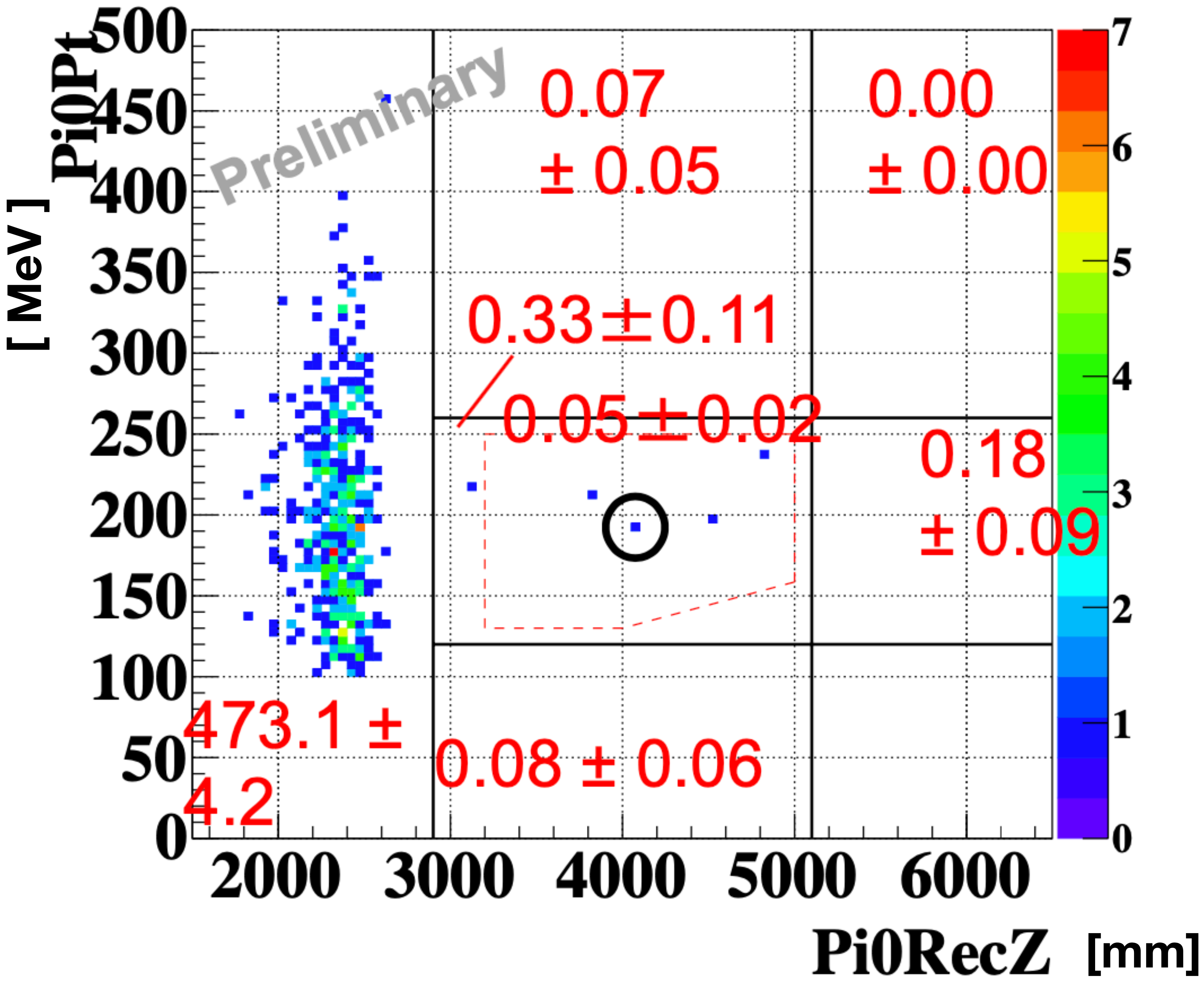
direct limit (KOTO 2015 result, **Phys.Rev.Lett. 122 (2019) no.2, 021802**)
3.0×10^{-9} (90% C.L.)

indirect limit (Grossman-Nir bound)
1.5×10^{-9}

SM prediction
3.0×10^{-11}

Slides from Satoshi Shinohara

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($K_L \to \pi^0 \nu\nu$)~ $2\text{x}10^{-9}$
- NA62/E949 constraints
  - BR($K^+ \to \pi^+ \nu\nu$) < $1.85\text{x}10^{-10}$
- Nir-Grossman bound
  - isospin symmetry $\Gamma\left(K_L(\bar{s}d) \to \pi^0(\bar{d}d)\nu\nu\right) \approx \Gamma\left(K^+(\bar{s}u) \to \pi^0(\bar{d}u)\nu\nu\right)$
  - Using lifetime of charged and neutral Kaons,
    BR($K^0 \to \pi^0 \nu\nu$) < 4.3 BR($K^+ \to \pi^+ \nu\nu$)

The constraint has tension with observed BRs!

Solution 1: long-lived particle

- A light particle (m< 200 MeV) from Kaon decay

$$K_L \to \pi^0 X, \quad K^+ \to \pi^+ X$$

- 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

$$K^+ \to \pi^+ \pi^0$$

- 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

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

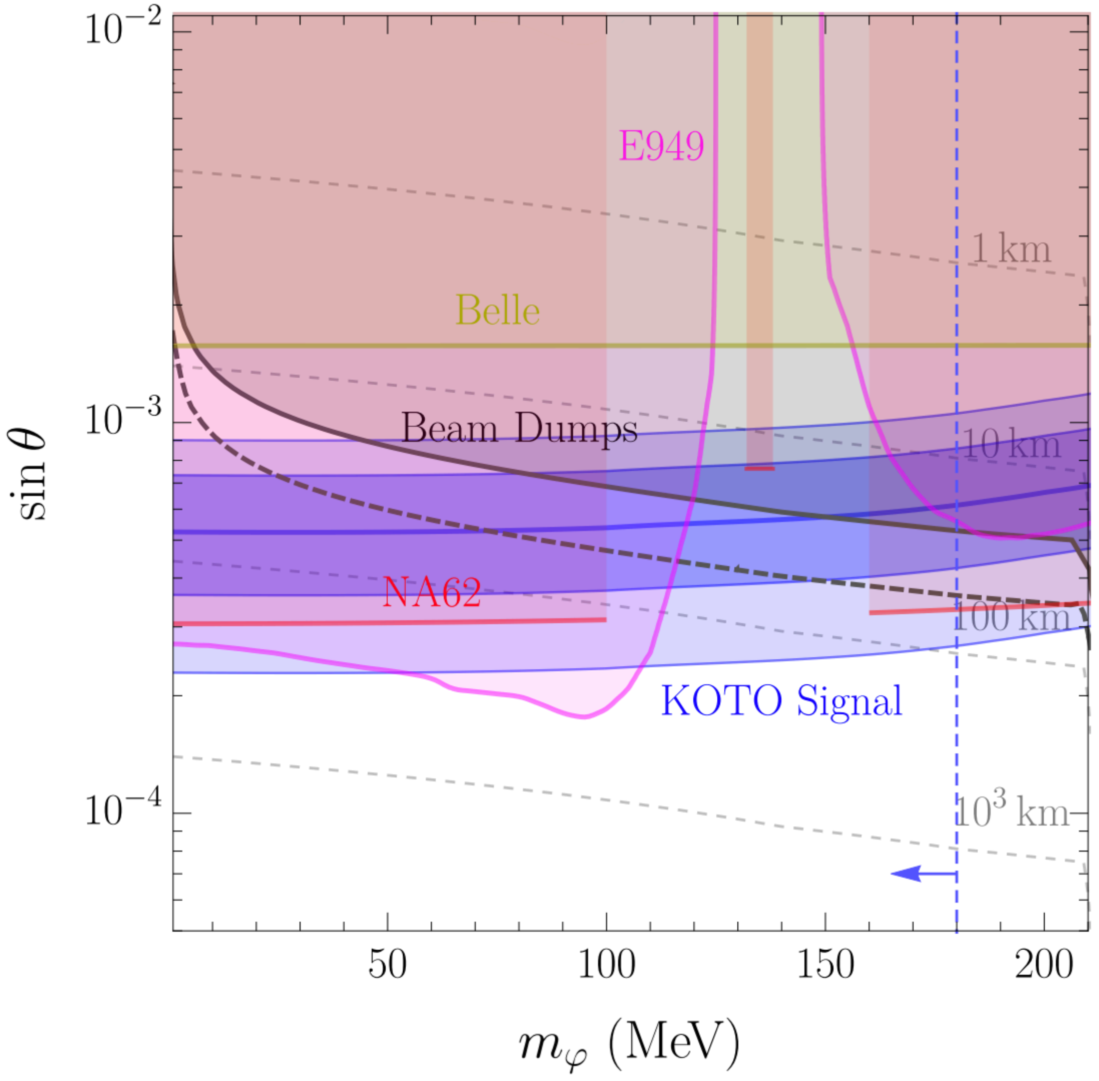
- The rates for the Kaon decay into ϕ and π from 1-loop

$$\Gamma(K_L \to \pi^0 \phi) = \frac{\left(\textbf{Re}\left[g(\sin\theta)\right]\right)^2}{16\pi m_K^3} \lambda^{1/2}(m_K^2, m_\pi^2, m_\phi^2),$$

$$g(\sin\theta) = \frac{3m_K^2}{32\pi^2 v^3} \sin\theta \sum_{q=u,c,t} m_q^2 V_{qd}^* V_{qs},$$

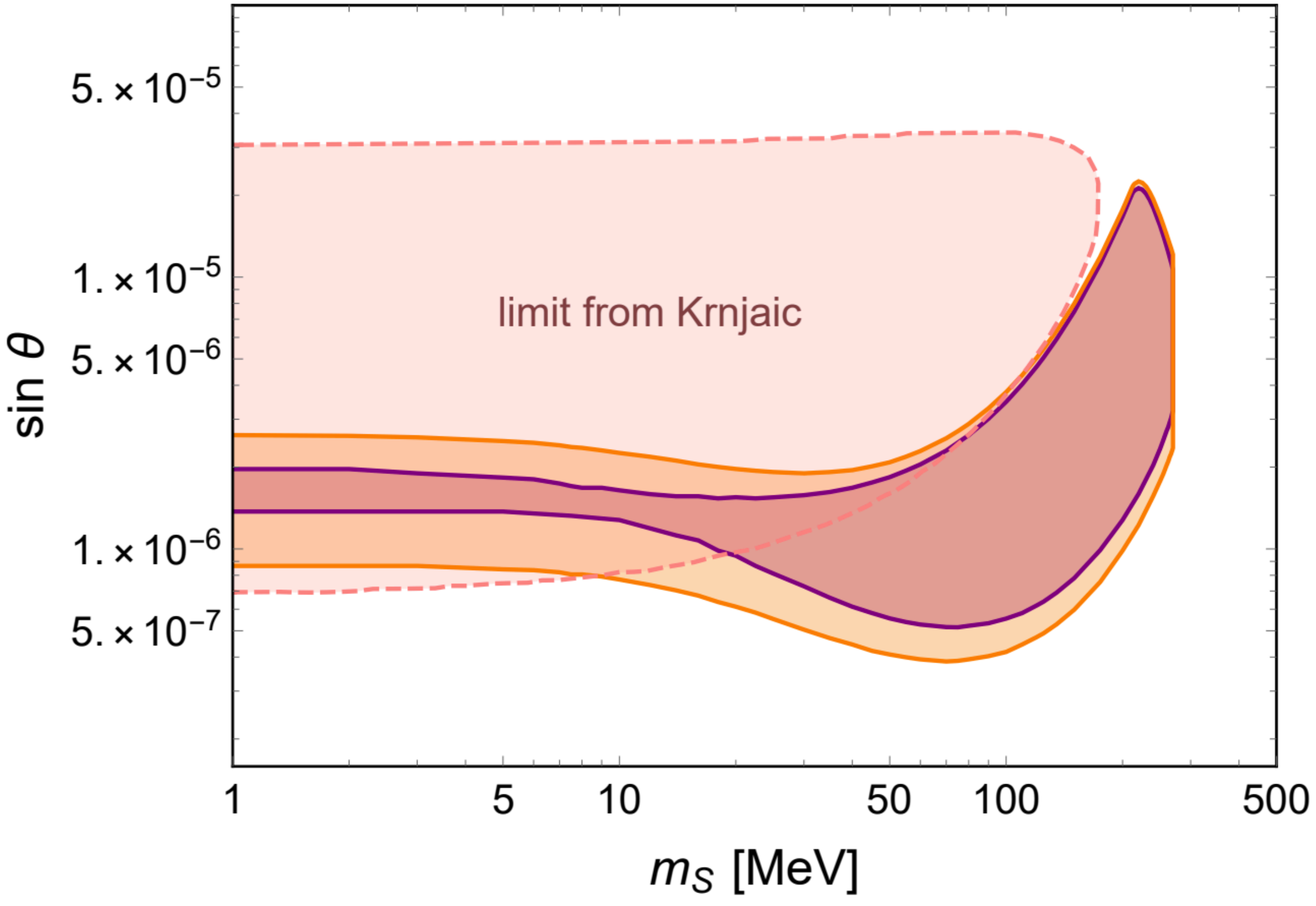
Long-lived scalar mediator fits to KOTO

- Charged Kaon exp forced mass ~ 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

$$K_L \to \pi^0 X, \quad K^+ \to \pi^+ X$$

- 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

$$K^+ \to \pi^+ \bar{\nu} \nu$$

- KOTO detector scale ~ 3 m, NA62 detector ~ 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

$$\mathscr{L}_{\rm yuk} = -\lambda_u \bar{Q}\tilde{\Phi}_2 u_R - \lambda_d \bar{Q}\Phi_2 d_R - \lambda_e \bar{L}\Phi_1 e_R + h.c.$$

- The light scalar mixing independently with two doublets

$$\mathscr{L}_{\rm eff} \supset \epsilon_q \sum_q \frac{m_q}{v}\phi \bar{q} q + \epsilon_\ell \sum_\ell \frac{m_\ell}{v}\phi \bar{\ell}\ell + \epsilon_W \frac{2m_W^2}{v}\phi W_\mu^+ W^{\mu -}$$

- The coupling to gauge boson is not independent

$$\epsilon_q \simeq \frac{\sin\theta_{2\phi}}{\sin\beta}, \quad \epsilon_\ell \simeq \frac{\sin\theta_{1\phi}}{\cos\beta}$$

- In the large tanβ limit, we obtain a simple relation

$$\epsilon_W \simeq \left(\sin\theta_{1\phi}\cos\beta + \sin\theta_{2\phi}\sin\beta\right)$$

$$\approx \epsilon_\ell \cos^2\beta + \epsilon_q \sin^2\beta \approx \epsilon_q,$$

Liu, McGinnis, Wagner., Wang, arXiv:2001.06522

Fixing the model parameters

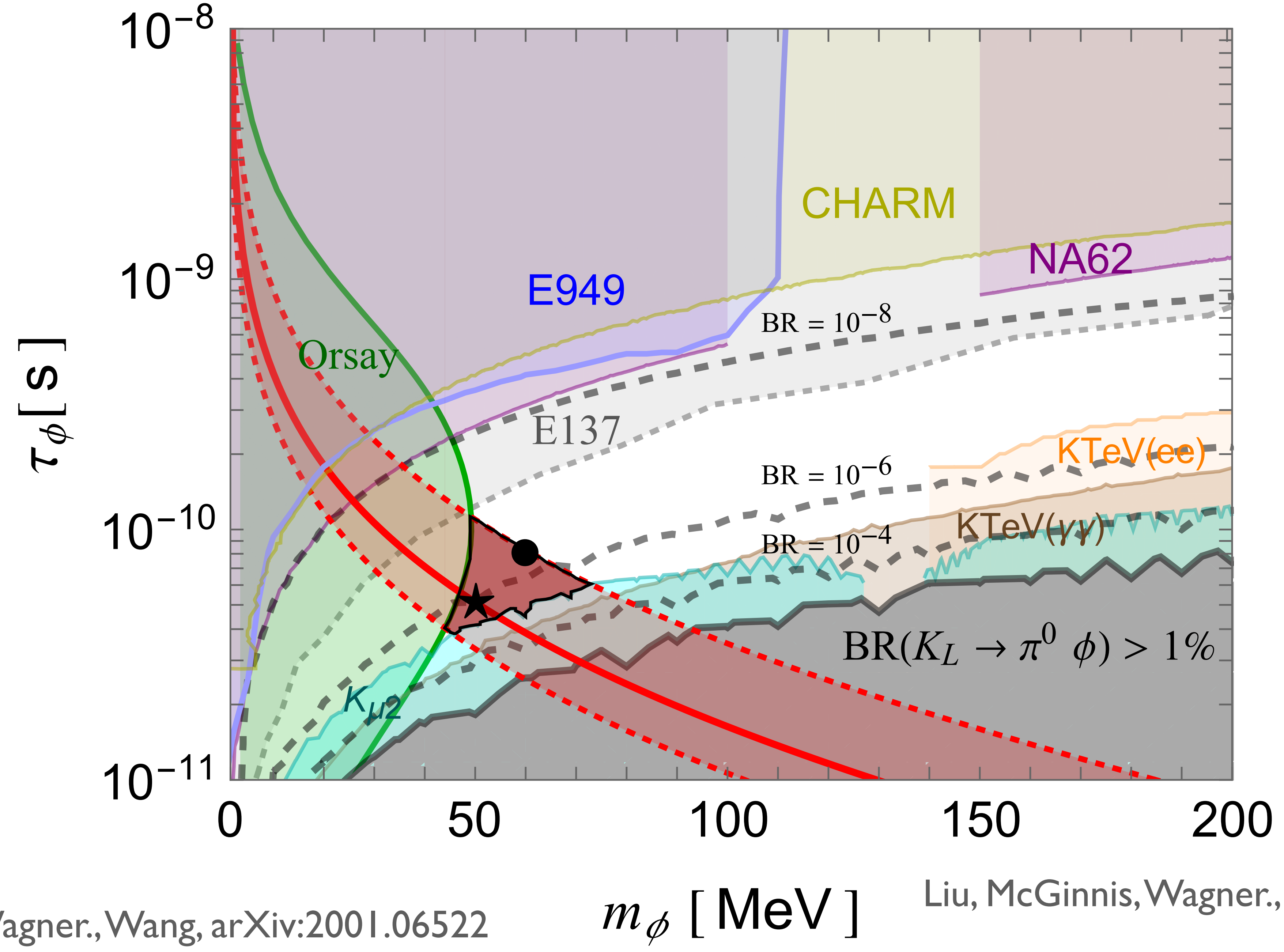
$$\mathscr{L}_{\text{eff}} \supset \epsilon_q \sum_q \frac{m_q}{v} \phi \bar{q} q + \epsilon_\ell \sum_\ell \frac{m_\ell}{v} \phi \bar{\ell} \ell + \epsilon_q \frac{2m_W^2}{v} \phi W_\mu^+ W^{\mu -}$$

- Three free parameters ϵ_q ϵ_ℓ m_ϕ

- Two requirements:
  - Muon g-2 fixes $\varepsilon_l \sim 1$
  - Branching ratio of neutral Kaon decay to ϕ fixes $\varepsilon_q \sim 0.01$
- Only mass parameter is free

Liu, McGinnis, Wagner., Wang, arXiv:2001.06522

The results



Liu, McGinnis, Wagner., Wang, arXiv:2001.06522

Liu, McGinnis, Wagner., Wang, arXiv:2001.06522

m_ϕ [MeV]	ϵ_q	ϵ_ℓ	BR$(K_L \to \pi^0\phi)$	τ [s]	$\tan\beta$	$\sin\alpha$	$\sin\theta_{1\phi}$	$\sin\theta_{2\phi}$
50	1.6×10^{-2}	1.22	1.7×10^{-6}	5.1×10^{-11}	100	-0.01	0.0122	1.6×10^{-2}
60	6.8×10^{-3}	0.87	3.2×10^{-7}	8.25×10^{-11}	100	-0.01	0.0087	6.8×10^{-3}

Summary

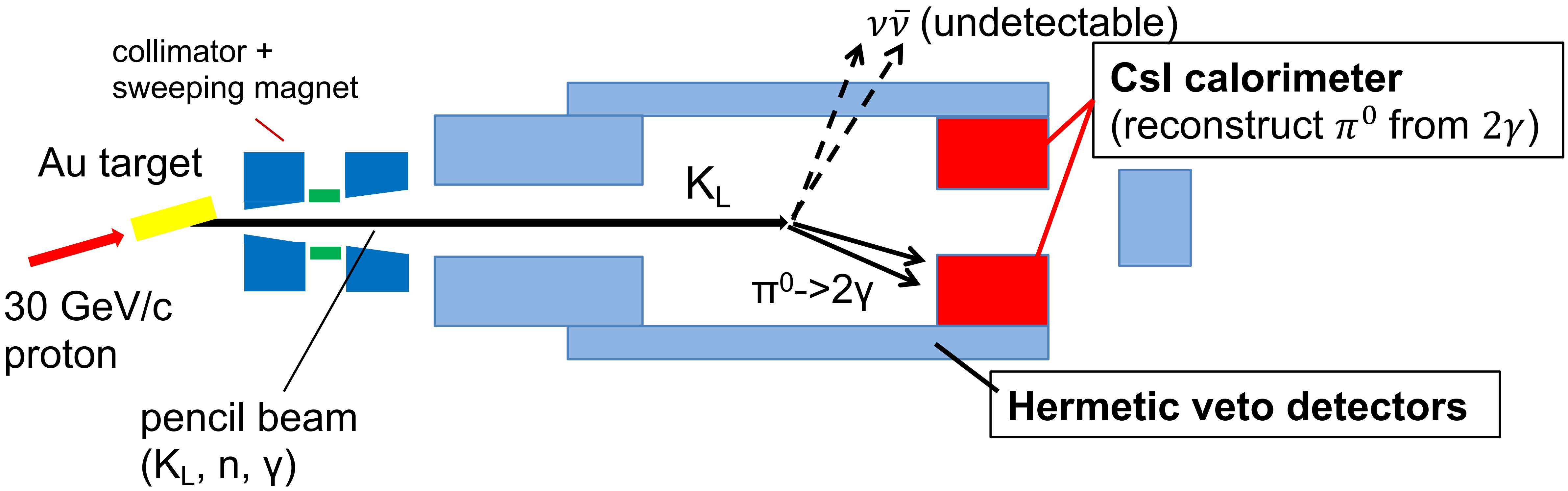
- Recent low energy anomalies might hint new light dark sector particles, but require further cross-checks from independent experiments
- We show the light scalars can be related to lepton g-2 and KOTO exp
- The muon g-2 could be explained by a scalar of mass of about 50 MeV and couplings to muons of 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

$K_L \to \pi^0 \nu\bar{\nu}$: $(\pi^0 \to)$ 2γ + nothing



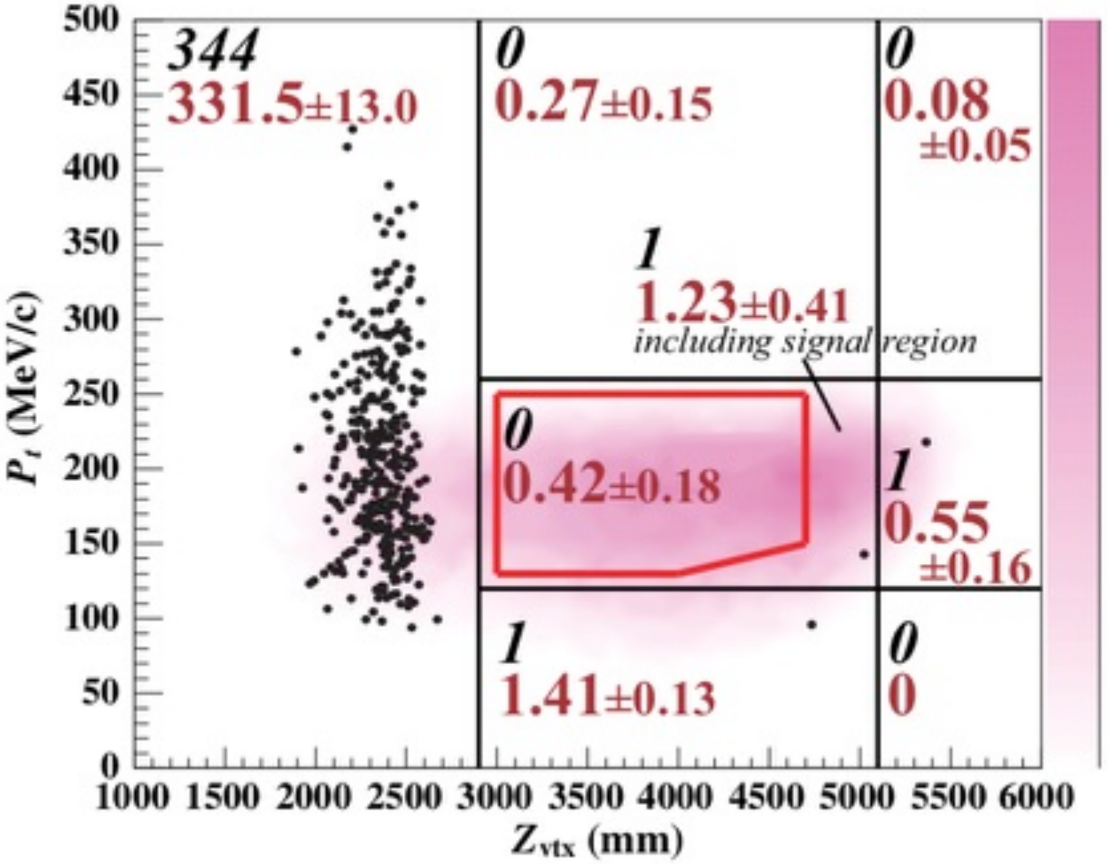
- Neutrinos are not detected

- A new weakly-coupled particle X either stable or decay outside of detector can mimic missing energy

$$K_L \to \pi^0 X$$

Result of 2015 physics run

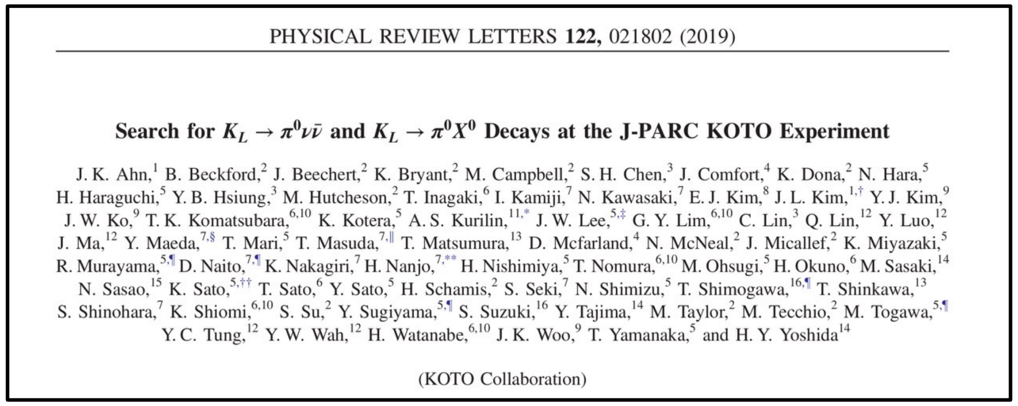
Phys. Rev. Lett. 122, 021802



observed

expectation

contour : $K_L \to \pi^0 \nu \bar{\nu}$ (MC)



PHYSICAL REVIEW LETTERS **122,** 021802 (2019)

Search for $K_L \to \pi^0 \nu \bar{\nu}$ and $K_L \to \pi^0 X^0$ Decays at the J-PARC KOTO Experiment

J. K. Ahn,[1] B. Beckford,[2] J. Beechert,[2] K. Bryant,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] N. Hara,[5] H. Haraguchi,[5] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[6] I. Kamiji,[7] N. Kawasaki,[7] E. J. Kim,[8] J. L. Kim,[1,†] Y. J. Kim,[9] J. W. Ko,[9] T. K. Komatsubara,[6,10] K. Kotera,[5] A. S. Kurilin,[11,*] J. W. Lee,[5,‡] G. Y. Lim,[6,10] C. Lin,[3] Q. Lin,[12] Y. Luo,[12] J. Ma,[12] Y. Maeda,[7,§] T. Mari,[5] T. Masuda,[7,‖] T. Matsumura,[13] D. Mcfarland,[4] N. McNeal,[2] J. Micallef,[2] K. Miyazaki,[5] R. Murayama,[5,¶] D. Naito,[7,¶] K. Nakagiri,[7] H. Nanjo,[7,**] H. Nishimiya,[5] T. Nomura,[6,10] M. Ohsugi,[5] H. Okuno,[6] M. Sasaki,[14] N. Sasao,[15] K. Sato,[5,††] T. Sato,[6] Y. Sato,[5] H. Schamis,[2] S. Seki,[7] N. Shimizu,[5] T. Shimogawa,[16,¶] T. Shinkawa,[13] S. Shinohara,[7] K. Shiomi,[6,10] S. Su,[2] Y. Sugiyama,[5,¶] S. Suzuki,[16] Y. Tajima,[14] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[5,¶] Y. C. Tung,[12] Y. W. Wah,[12] H. Watanabe,[6,10] J. K. Woo,[9] T. Yamanaka,[5] and H. Y. Yoshida[14]

(KOTO Collaboration)

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

➡ Upper limit (90% C.L.) :
$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$

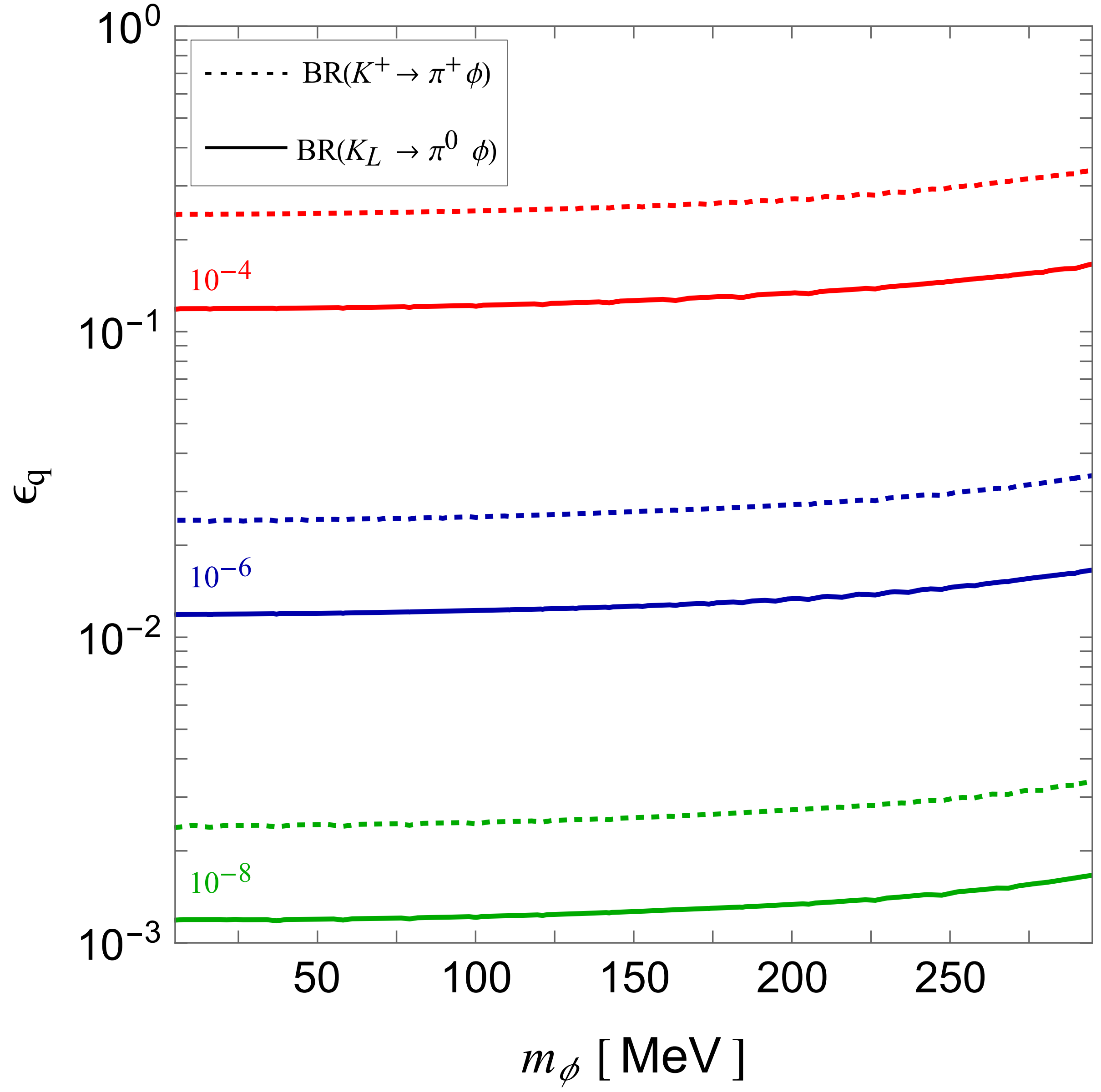
× 10 improvement from previous limit (KEK E391a)

Slides from Satoshi Shinohara

The Kaon decay branching ratio

- The effective BR fitted to KOTO experiment

$$\mathrm{BR}(K_L \to \pi^0\phi;\mathrm{KOTO}) = \epsilon_{\mathrm{eff}}\mathrm{BR}(K_L \to \pi^0\phi)e^{-\frac{L}{p_\phi}\frac{m_\phi}{\tau_\phi}}$$



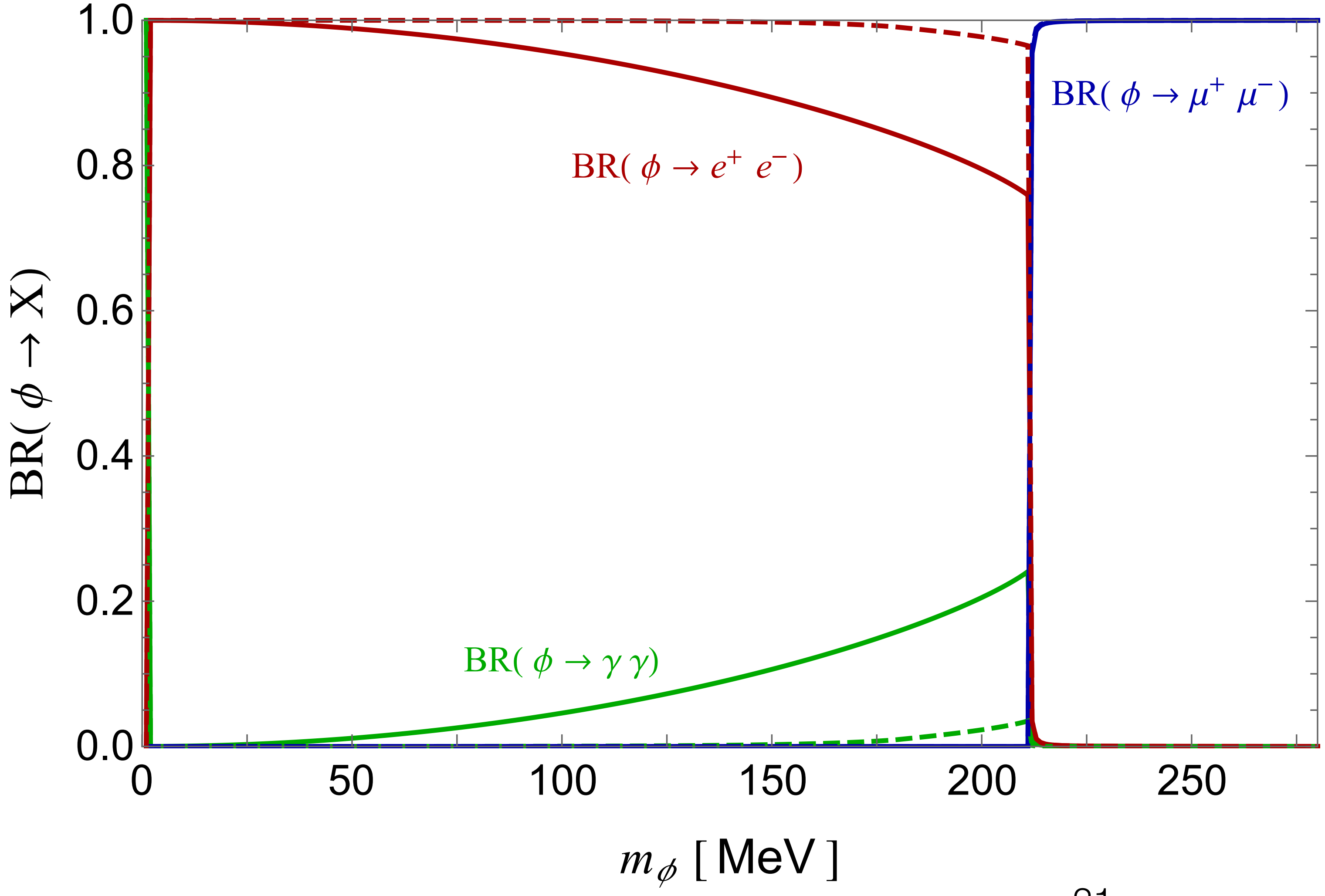
- The true BR for neutral Kaon and charged Kaon decay
- BR(KOTO) ~ $2\text{x}10^{-9}$ according to 3 obs events, relying on both quark coupling and lifetime
- Check charged Kaon BR to avoid constraints

The lifetime of ϕ

- The decay width for a light ϕ

$$\Gamma(\phi \to \ell\ell) = \frac{\epsilon_\ell^2 m_\ell^2}{8\pi v^2} m_\phi (1-\tau_\ell)^{3/2} \theta(m_\phi^2 - 4m_\ell^2)$$

$$\Gamma(\phi \to \gamma\gamma) = \frac{\alpha^2 m_\phi^3}{1024\pi^3} \left| \sum_q \frac{6\epsilon_q}{v} Q_q^2 A_{1/2}(\tau_q) + \sum_\ell \frac{2\epsilon_\ell}{v} A_{1/2}(\tau_\ell) + \frac{2\epsilon_W}{v} A_1(\tau_W) \right|^2$$



- Our model: $\epsilon_l \sim 1 >> \epsilon_q \sim 0.01$
- Dashed line for simple mixing model (with accidental cancellation in γγ)
- solid line for our model.
- In region of interest, the lifetime depends dominantly on ϵ_l and the decay into ee.

$$BR(\phi \to e^+e^-) \approx 100\,\%$$

Experimental constraints

- Proton beam dump
  - E949 and NA62: looking for $K^+ \to \pi^+ \bar{\nu}\nu$
  - CHARM: looking for displaced decay (480 m) from $K \to \pi + (ee/\gamma\gamma/\mu\mu)$
  - Kμ2: using stopped charged Kaon looking for $K^+ \to \pi^+ \phi$
  - KTeV/E799: looking for ee but requires $m_{ee} > 140$ MeV $K^0 \to \pi^0 e^+ e^-$
- Electron beam dump
  - Orsay: looking for the radiation of light particles decaying into electron pairs $eN \to eN\phi,\ \phi \to e^+e^-$
  - 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 avoided due to relative long lifetime $B \to K\phi,\ \phi \to e^+e^-$

Comments

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

- B physics measurement at LHCb

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

  - Our benchmark model

$$\mathrm{BR}(B \to K^*\phi) \simeq 10^{-4}, \quad \mathrm{BR}(\phi \to e^+e^-) \approx 100\,\%$$

  - However, LHCb requires a good quality vertex: ee pair vertex coincide with K* vertex, within vertex resolution L~ 5 mm

  - ϕ→ee lifetime ~ 1.5 cm, safe from LHCb constraints.

- KOTO can reexamine the vetoed events

$$K_L \to \pi^0\phi, \phi \to e^+e^-$$