Looking for New Physics in the low energy experiments

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1810.11028 [JHEP 1903 (2019) 008]

2001.06522 [JHEP 2004 (2020) 197]

The 2020 international workshop on the high energy Circular Electron-Positron Collider

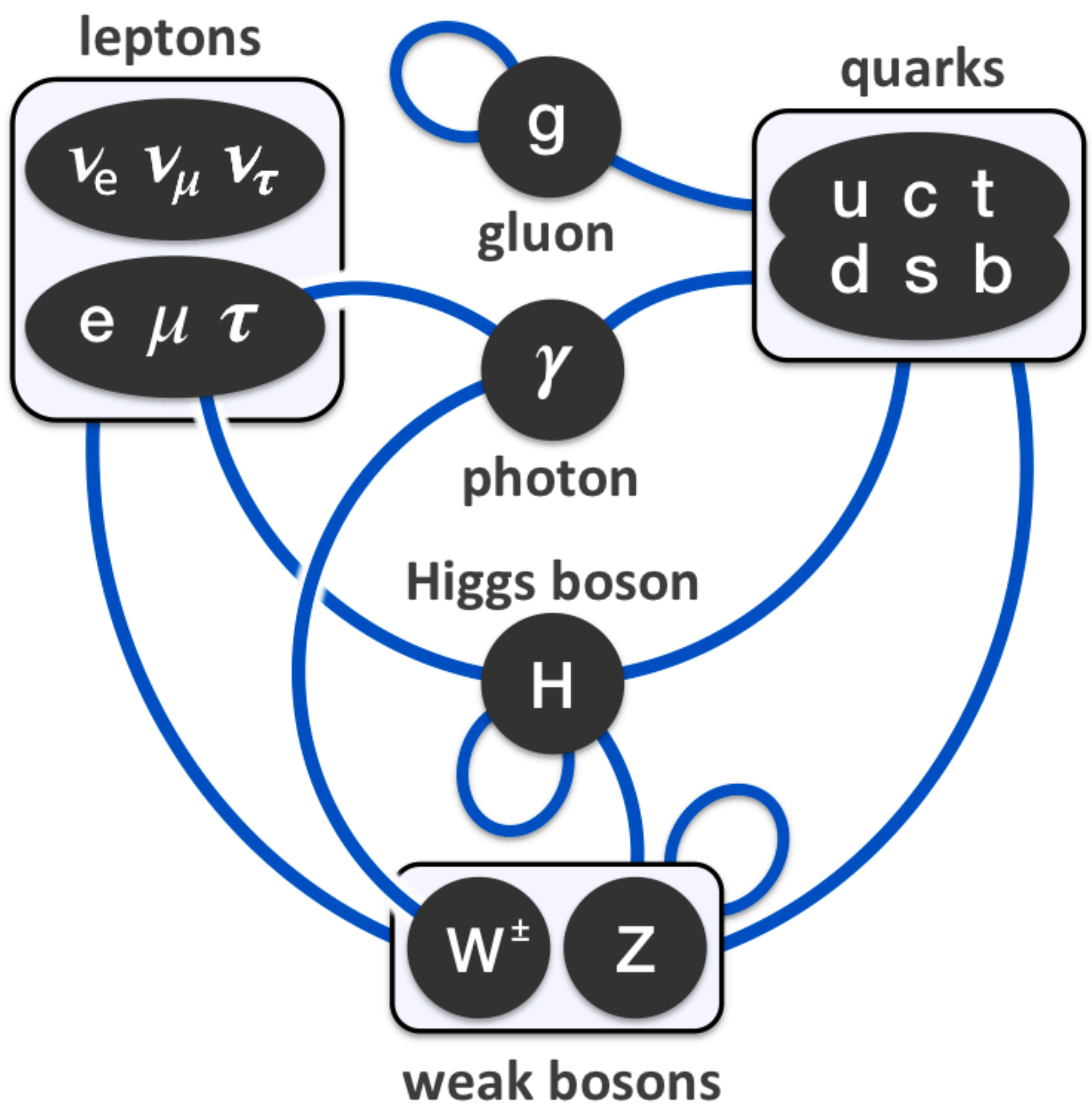
10/28/2020 @ SJTU, Shanghai

The outline

- The motivation for new physics in the low energy
- The lepton g-2
- The KOTO experiment
- Summary

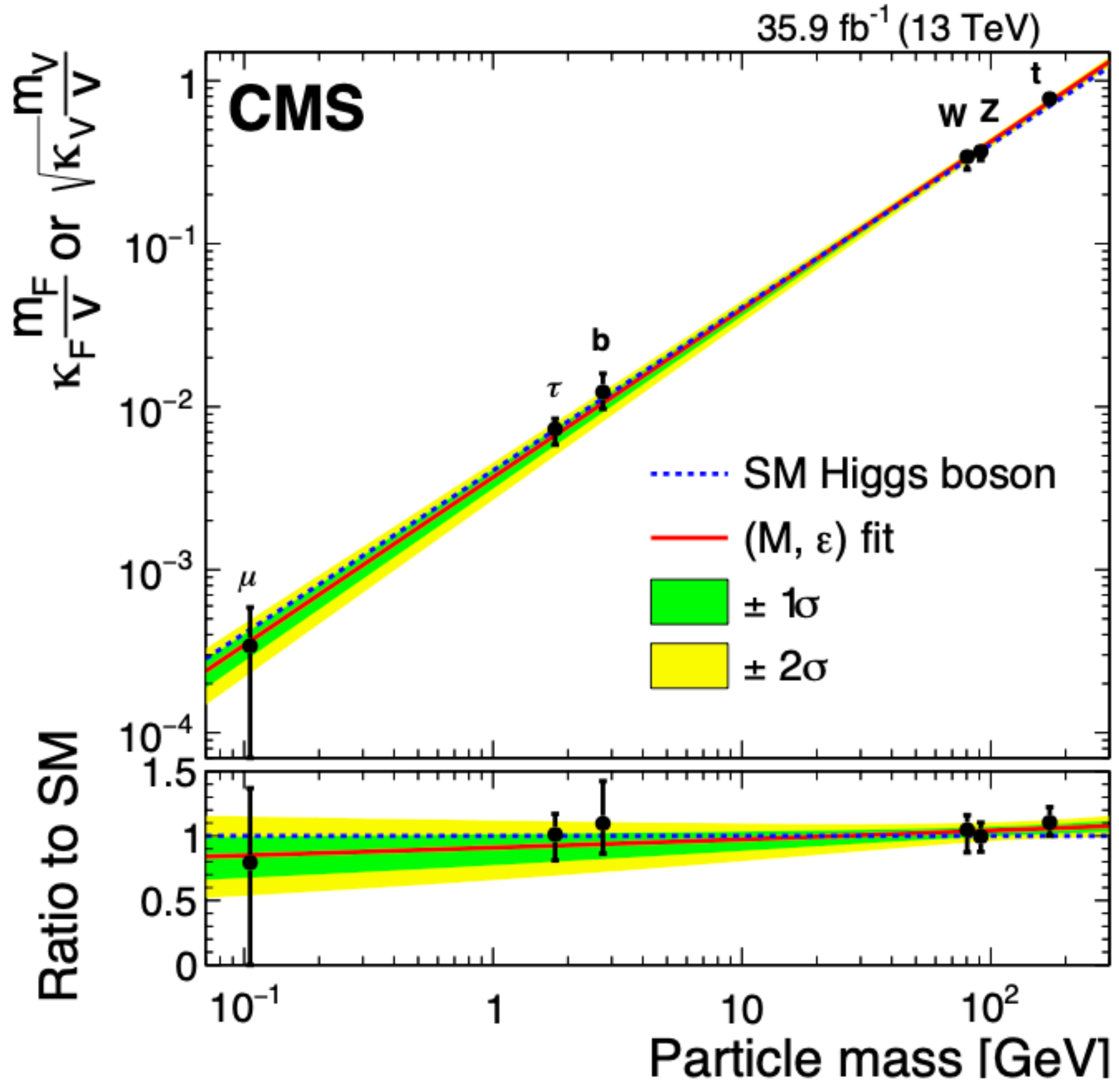
The Standard Model

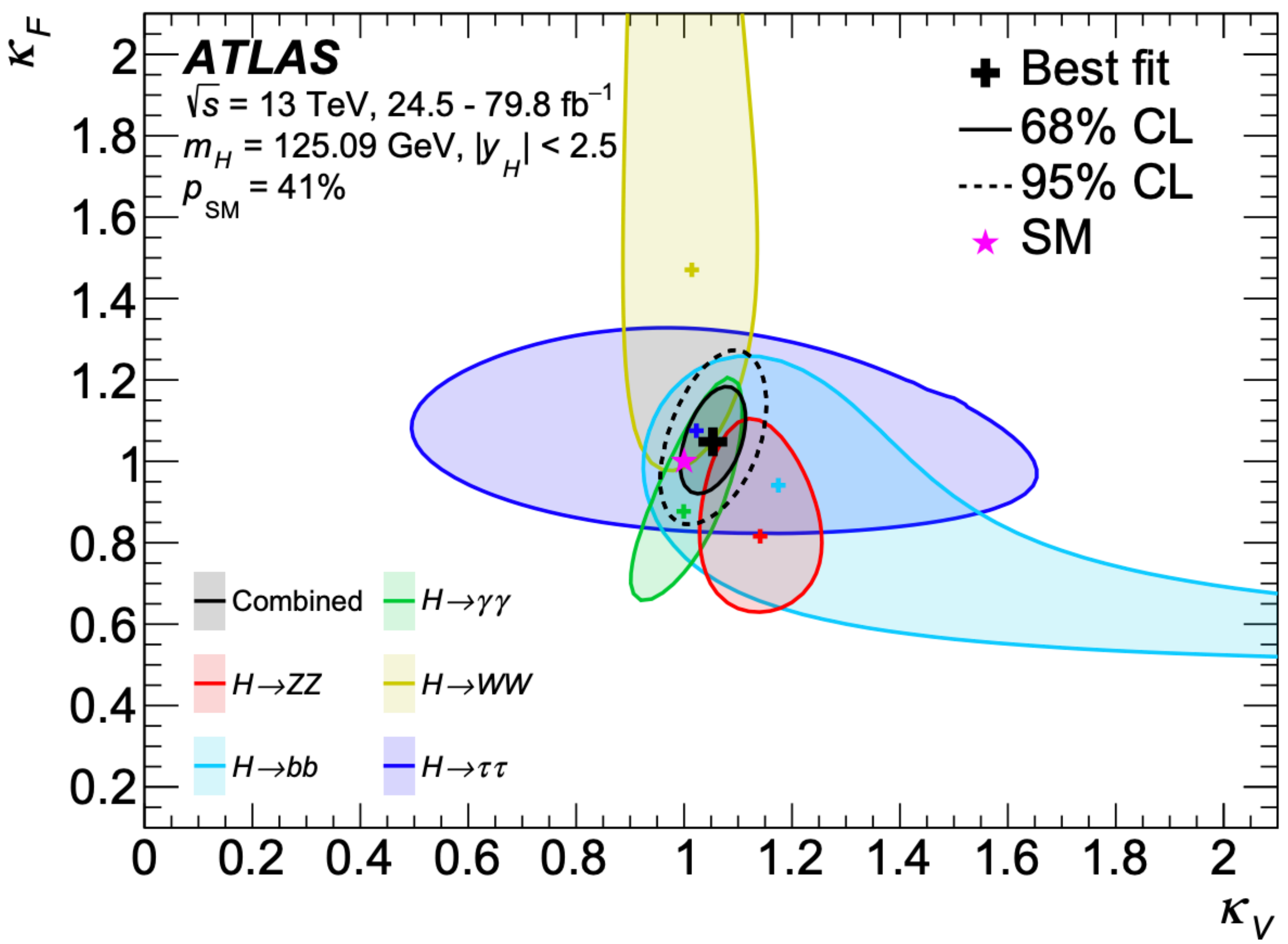
- A unified story for strong, weak and electromagnetic interactions.



The 125 GeV Higgs

- Its properties are very close to the SM predictions.

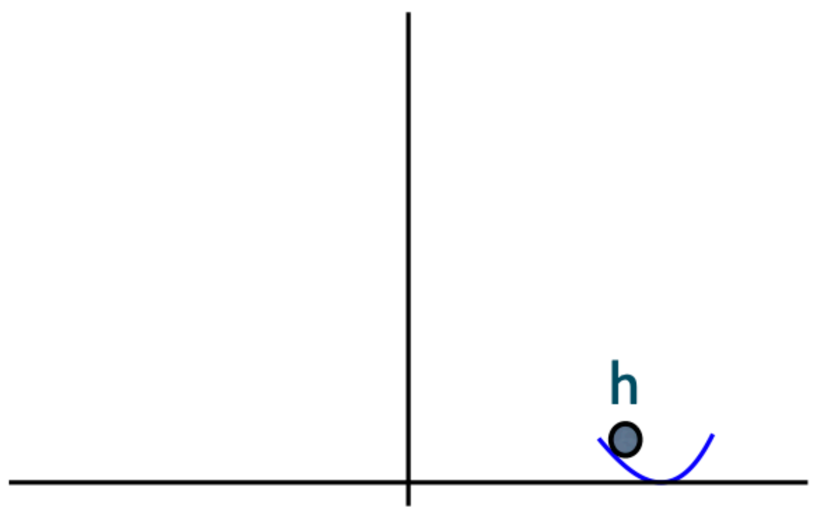


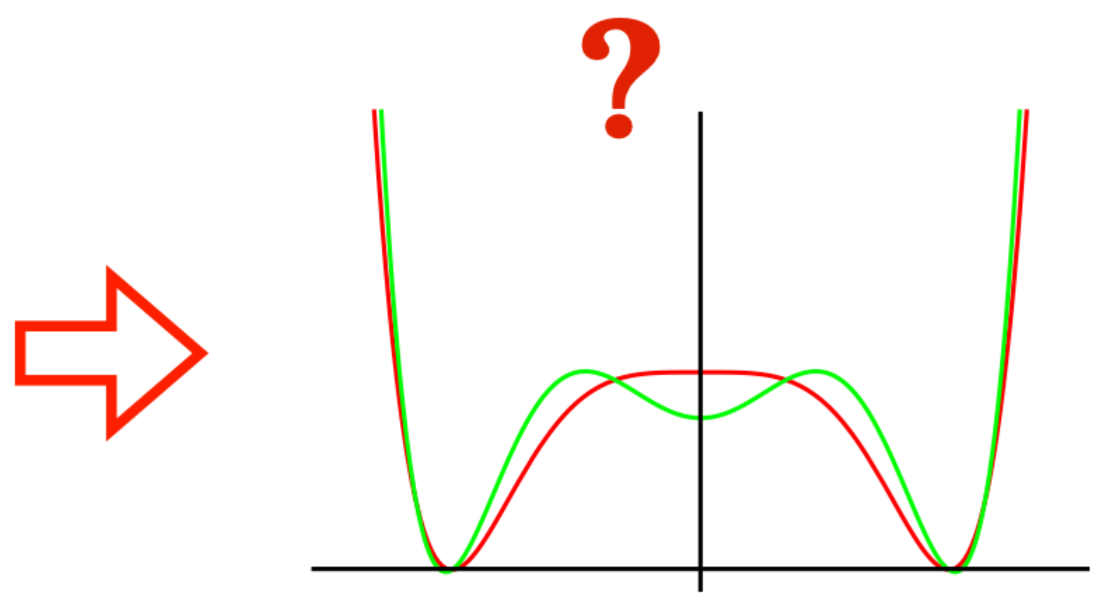


1909.02845

The 125 GeV Higgs

- Precision measurement for Higgs is necessary
  - The nature of the electroweak phase transition

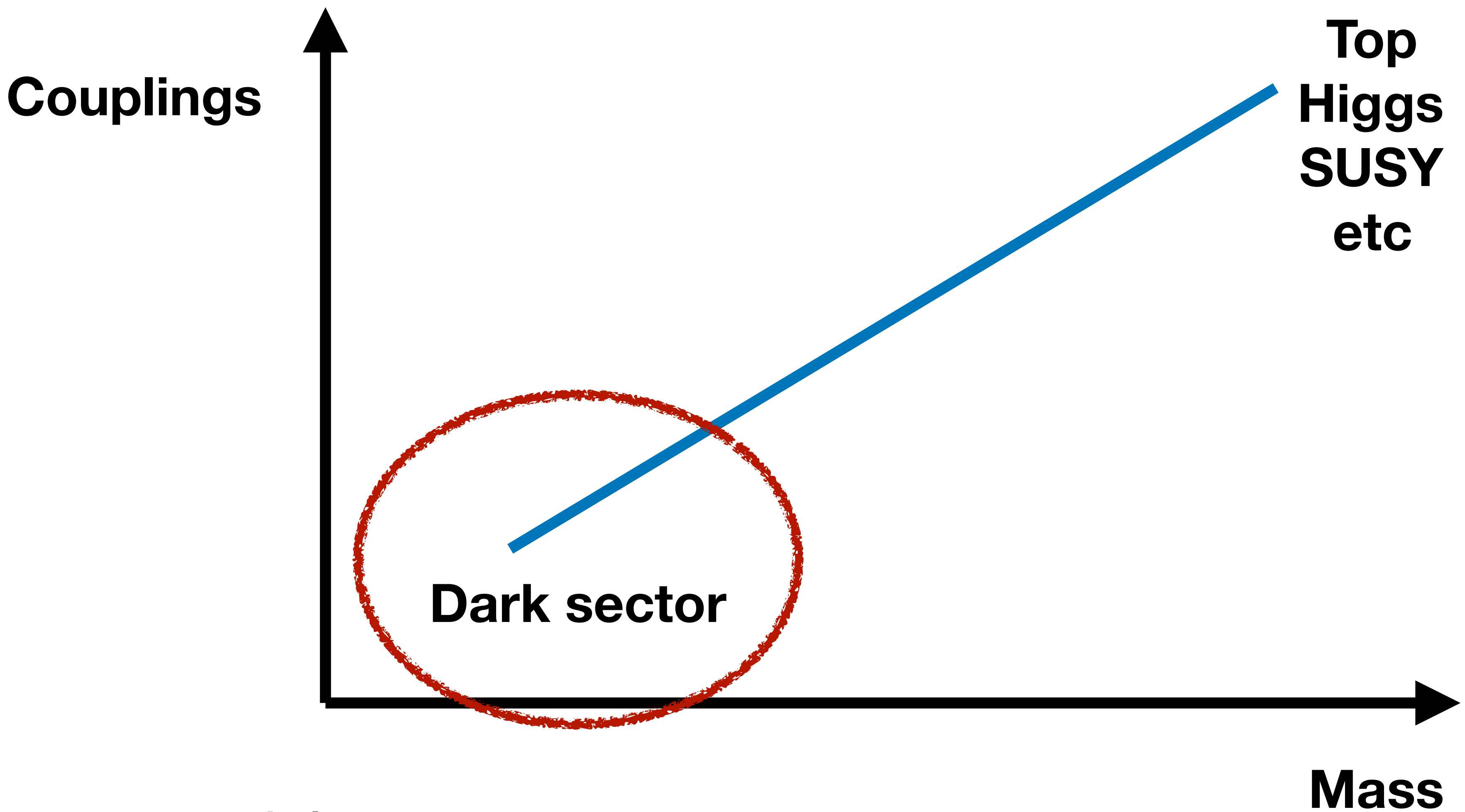




1511.06495

Still need the CEPC to further explore the SM Higgs.

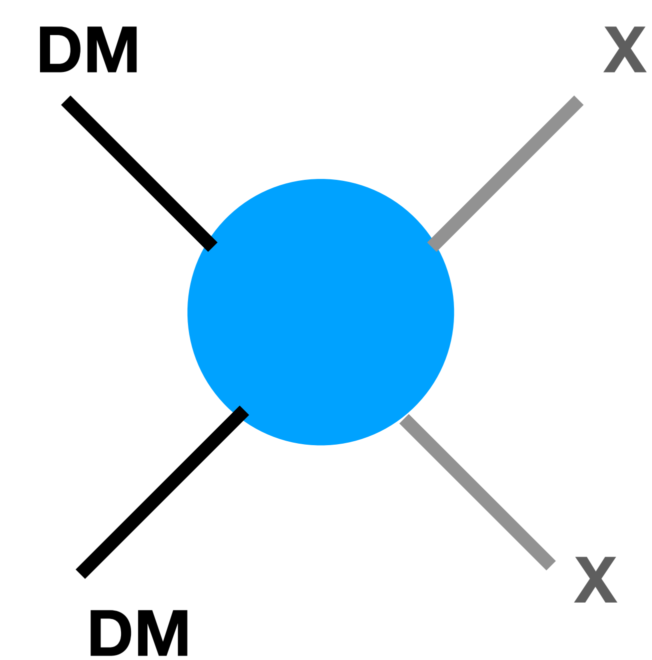
The heavy and the light

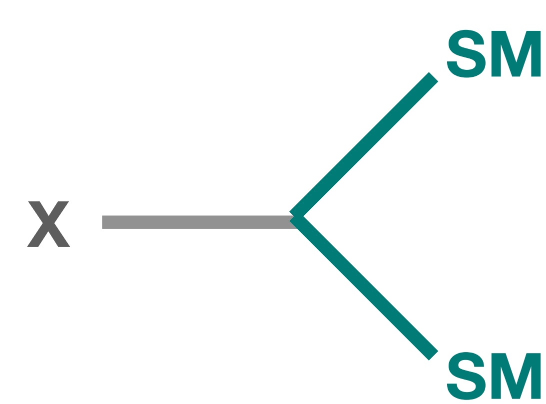


- Dark sector particles
  - New light weakly coupled particles
  - Do not interact with the known strong, weak, or electromagnetic forces

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

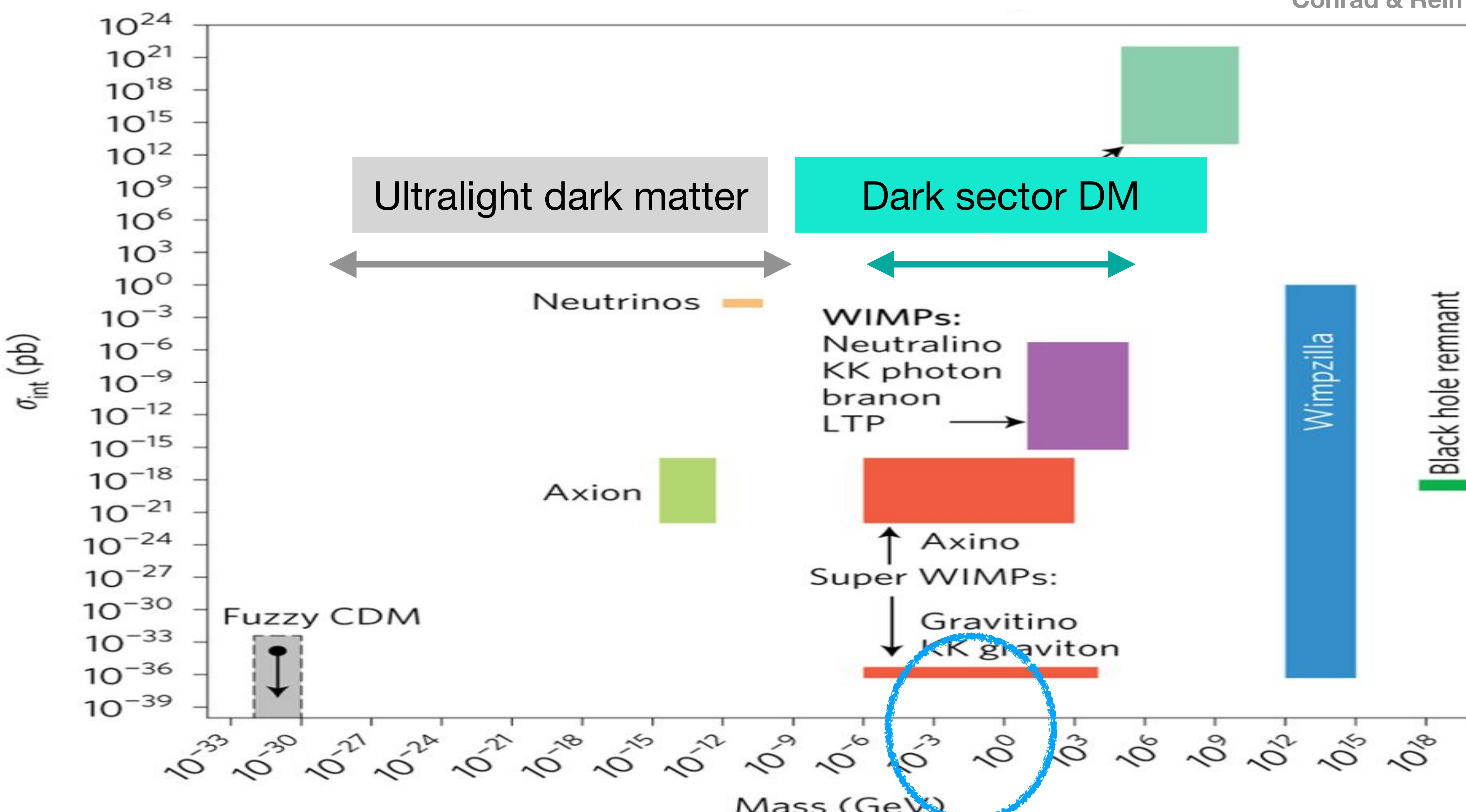




The motivation for dark sector particles

- 3. The experiment status
  - Technically difficult to increase E
  - Easier to accumulate higher luminosity

Conrad & Reimer



The motivation for dark sector particles

- 4. The low energy experiment hints
  - Lepton e/mu g-2 1806.10252 Davoudiasl et al …
  - KOTO: neutral K decay into π^0 + 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 …
  - R(K), R(D) etc…
  - XENON1T electronic recoil

The examples of dark sector models

- Kinetic mixing portal $B_{\mu\nu}F'^{\mu\nu}$
- Neutrino portal LH
- Higgs portal $H^\dagger H$
- Higher dimensional operators $\frac{a}{\Lambda}\tilde{F}F, \frac{a}{\Lambda}\tilde{G}G$

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

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

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The muon MDM

- The muon g-2 calculation

$$a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm Had} + a_\mu^{\rm EW}$$

  - Hadronic uncertainty dominated

$$a_\mu^{\rm Had}(\text{vac pol}) = (688 \pm 4) \times 10^{-10}$$

$$a_\mu^{\rm Had}(\gamma \times \gamma) \simeq 10 \times 10^{-10}$$

  - EW uncertainty

$$a_\mu^{\rm EW} = (15.1 \pm 0.4) \times 10^{-10}$$

- Positive value and a 3.7 σ

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm th} = (27.4 \pm 7.3) \times 10^{-10}$$

- The difference is close to EW contribution suggesting New Physics at the Weak scale: SUSY etc

The e MDM

- The electron g-2 calculation

$$a_e^{\rm th} = a_e^{\rm QED} + a_e^{\rm Had} + a_e^{\rm EW}$$

  - QED up to 10th order

$$(\alpha/\pi)^5 \sim 7 \times 10^{-14}$$

  - EW and Had (light-light) are small due to small m_e

$$a_e^{\rm th} = (115965218164.3 \pm \mathbf{2.5} \pm \mathbf{2.3} \pm \mathbf{1.6} \pm \mathbf{76.3}) \times 10^{-14}$$

QED **Had (l-l)+EW** α

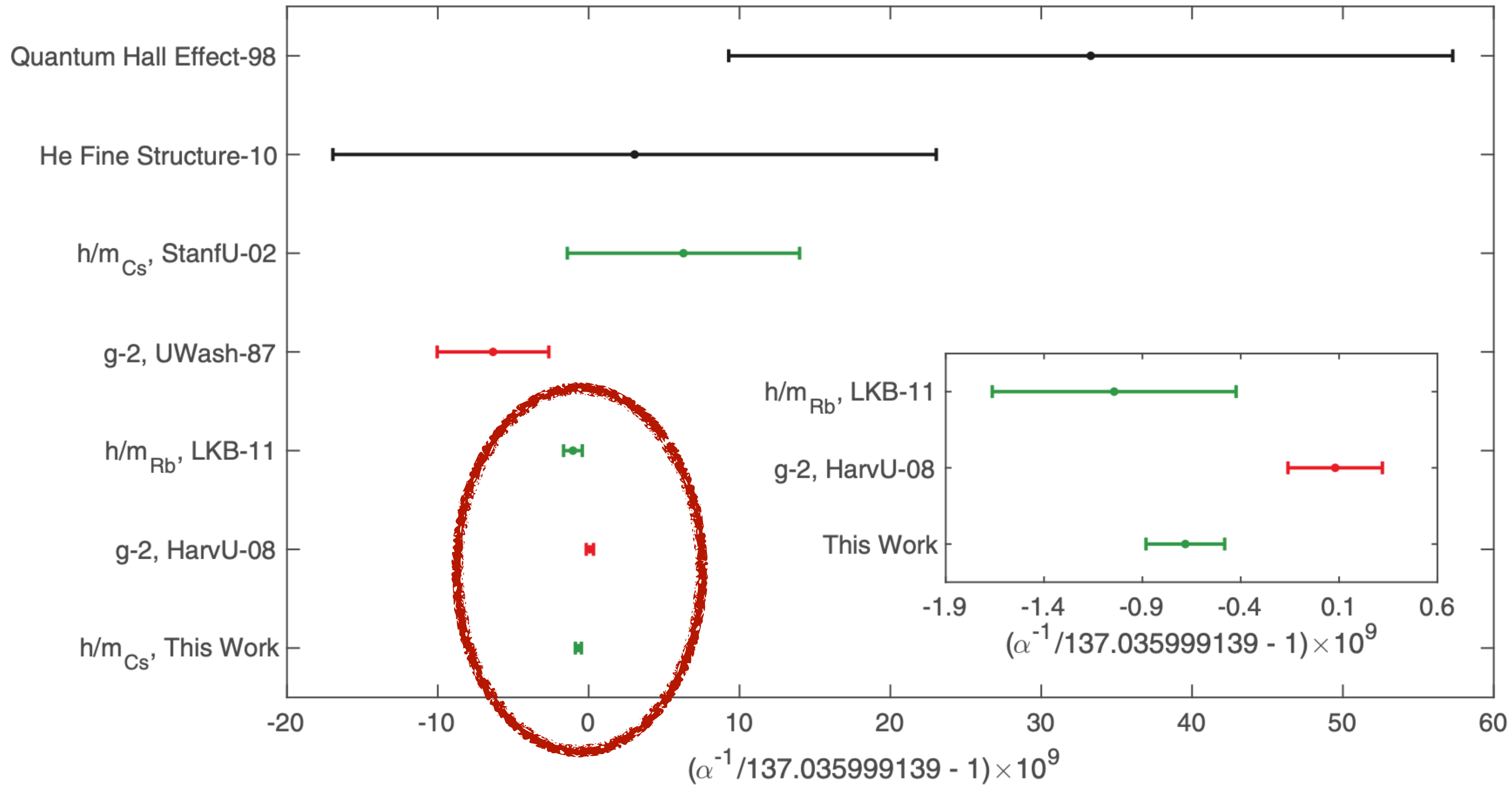
Aoyama et al 1412.8284, old fine structure constant from Rb measurement

- Fine structure constant induces the largest uncertainty for a_e
- Fine structure constant calculated via a_e has better uncertainty than direct measurement.

The e MDM

- The most recent fine structure constant measurement

Parker et al., Science 360, 191–195 (2018)



$$a_e^{\rm th} = (115965218161 \pm 23) \times 10^{-14}$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm th} = (-88 \pm 36) \times 10^{-14}$$

- Negative value and a 2.4 σ discrepancy

A combined explanation for e/mu g-2?

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm th} = (27.4 \pm 7.3) \times 10^{-10}$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm th} = (-88 \pm 36) \times 10^{-14}$$

- A naive estimate $\dfrac{m_e^2}{m_\mu^2}\Delta a_\mu \approx 6.4 \times 10^{-14}$

- Possible solutions for negative and sizable a_e correction
  - Higher order operator: 2-loop Barr-Zee
  - Heavy leptons
  - Charged Higgs/2HDM
  - Chargino-sneutrino/bino-slepton
  - Leptoquark with mixed chirality

Our model: a light complex scalar for e/mu g-2

J. Liu, C.E.M.Wagner, X.Wang, arXiv:1810.11028

- Scalar ϕ_R and pseudo-scalar ϕ_I coupling to leptons

$$\mathscr{L}_{\rm int} = i g_I \phi_I \bar{\ell} \gamma_5 \ell + g_R \phi_R \bar{\ell} \ell$$

- 1-loop contribution to g-2

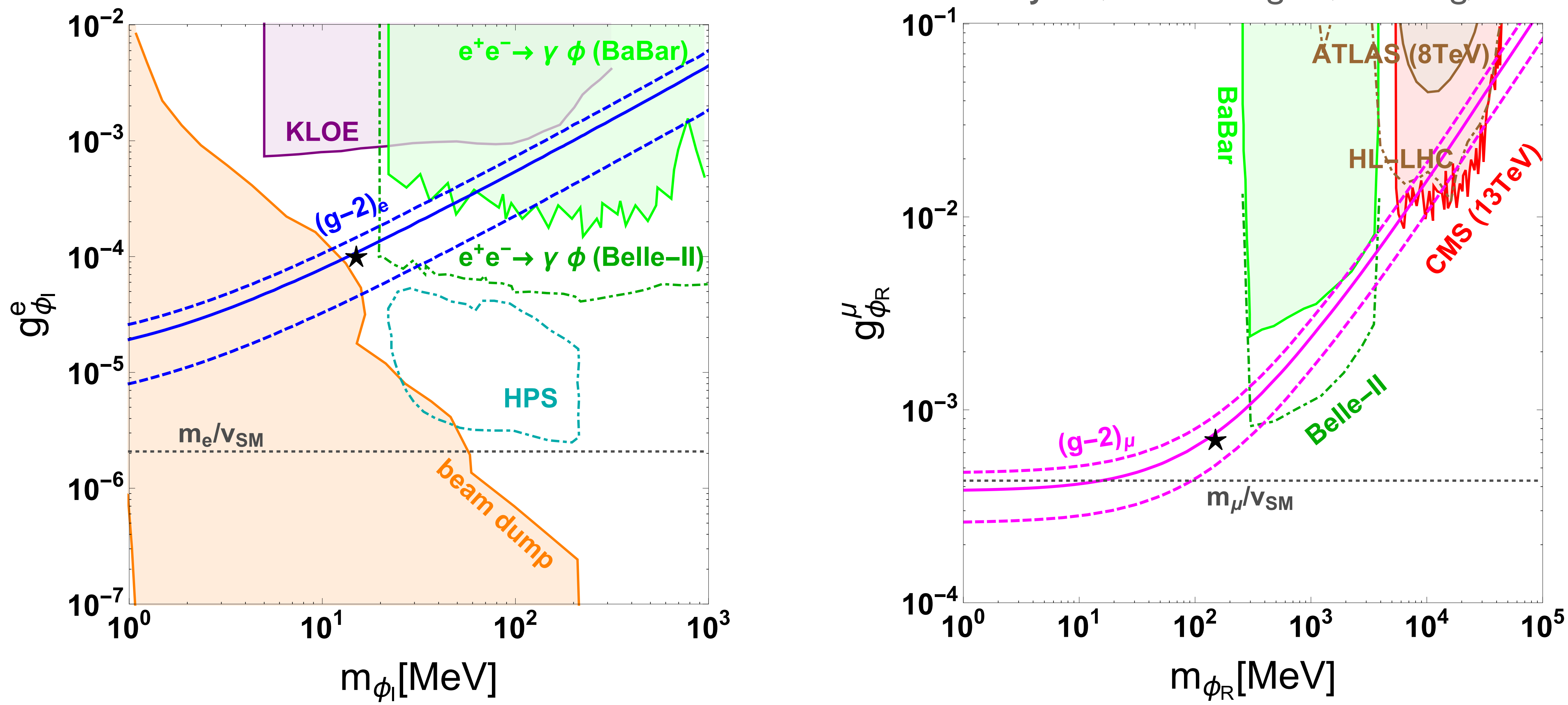
$$\Delta a_\ell = \frac{1}{8\pi^2} \int_0^1 dx \frac{(1-x)^2\big((1+x)g_R^2 - (1-x)g_I^2\big)}{(1-x)^2 + x\left(m_\phi/m_\ell\right)^2} .$$

- Scalar leads to positive contribution, while pseudo-scalar leads to negative contribution

Scalar explanations for e/mu g-2

- If we have $\mathscr{L}_{\rm int} = i g^e_{\phi_I}\phi_I \bar{e}\gamma_5 e + g^\mu_{\phi_R}\phi_R\bar{\mu}\mu$

J. Liu, C.E.M. Wagner, X. Wang, arXiv:1810.11028



The e/mu g-2 discrepancies can be solved!
The sign difference backed up by CP symmetry!

One combined story instead of two separate stories?

A complex scalar EFT story

- We assume the scalar and pseudo-scalar originated from the real and imaginary components of a complex singlet scalar

- Due to flavor symmetry, it can couple to e linearly, while mu quadratically

$$\mathscr{L}_{\rm EFT} = \frac{\phi^*}{\Lambda_e}\bar{L}_e H e_R + y_\mu \bar{L}_\mu H \mu_R + \frac{\phi^*\phi}{\Lambda_\mu^2}\bar{L}_\mu H \mu_R + H.c.$$

- After the scalars got vevs

$$H = \frac{1}{\sqrt{2}}\left(v + h + iG^0\right), \quad \phi = \frac{1}{\sqrt{2}}\left(v_\phi + \phi_R + i\phi_I\right)$$

- We obtain

$$m_e = \frac{v v_\phi}{2\Lambda_e}, \quad m_\mu = \frac{y_\mu v}{\sqrt{2}} + \frac{v v_\phi^2}{2\sqrt{2}\Lambda_\mu^2},$$

$$g_{\phi_R}^{e,\rm EFT} = -\,g_{\phi_I}^{e,\rm EFT} = \frac{v}{2\Lambda_e} = \frac{m_e}{v_\phi}, \quad g_{\phi_R}^{\mu,\rm EFT} = \frac{v_\phi v}{\sqrt{2}\Lambda_\mu^2}$$

  - Pseudo-scalar couples to e only, providing negative a_e
  - Scalar couples to e with same coupling, provides positive a_e but is heavier to suppress positive contribution
  - Only scalar couples to mu, leading to positive a_μ

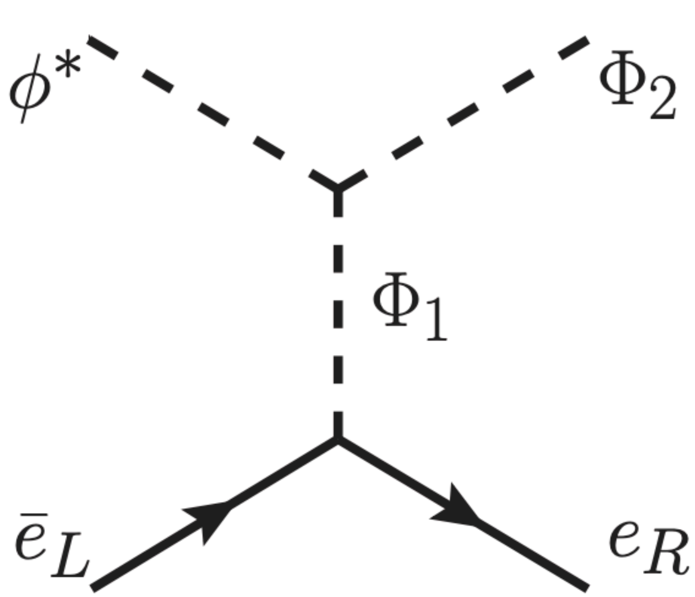
A complex scalar UV story

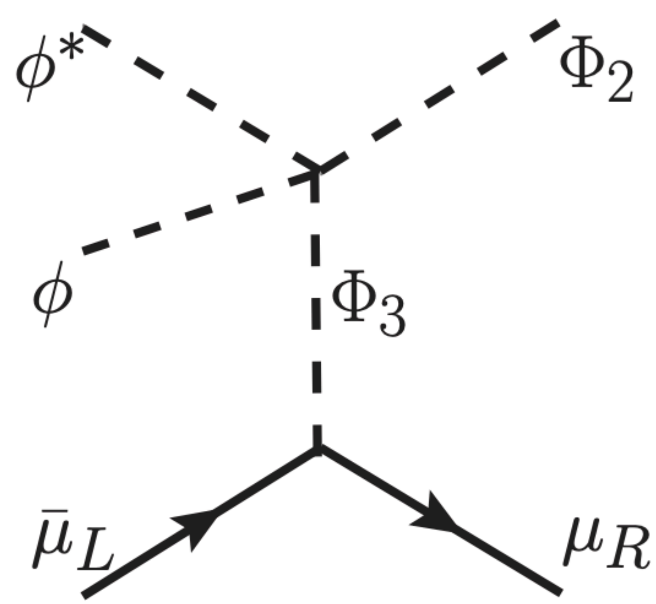
J. Liu, C.E.M.Wagner, X.Wang, arXiv:1810.11028

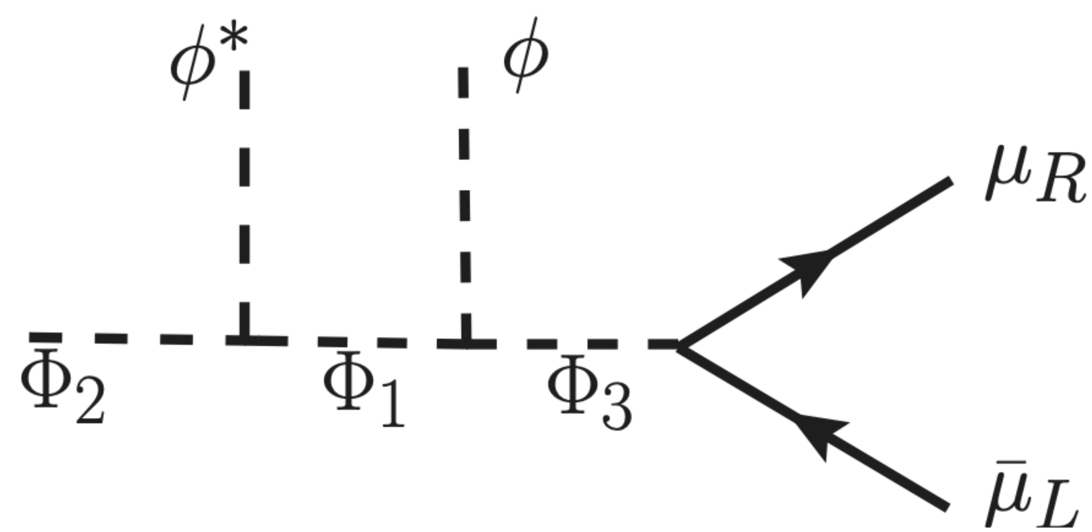
- One can obtain EFT model with SM extension with Higgs doublets
- PQ-like symmetry broken softly

filed	$SU(2)_L$	$U(1)_Y$	$U(1)^e_{\rm PQ}$
Φ_1	2	$\frac{1}{2}$	2
Φ_2	2	$\frac{1}{2}$	0
Φ_3	2	$\frac{1}{2}$	0
ϕ	1	0	-2
L_e	2	$\frac{1}{2}$	1
e_R	1	-1	-1

- Scalar portals: $\phi^*\Phi_1^\dagger\Phi_2,\ \phi^*\Phi_1^\dagger\Phi_3,\ \phi\phi^*\Phi_2^\dagger\Phi_3$







- Integrating out heavy scalars leads to EFT $\mathscr{L}_{\rm EFT} \supset \dfrac{\phi^*}{\Lambda_e}\bar{L}_e H e_R + \dfrac{\phi^*\phi}{\Lambda_\mu^2}\bar{L}_\mu H \mu_R + H.c.$

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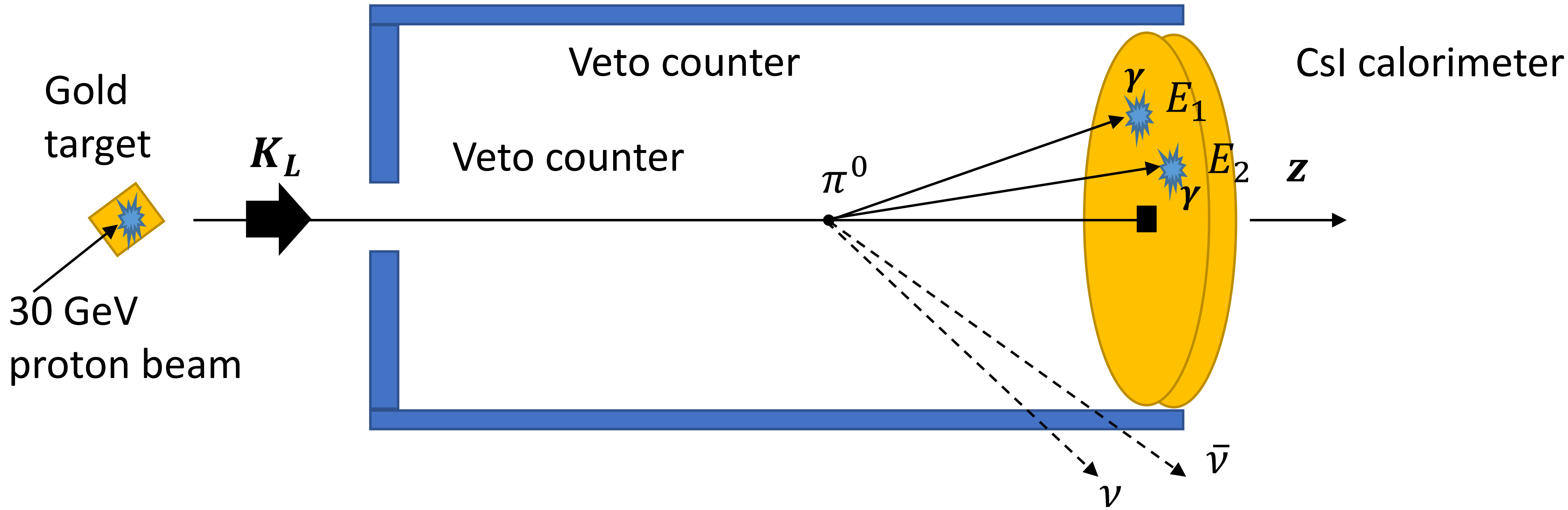
Experimental principle

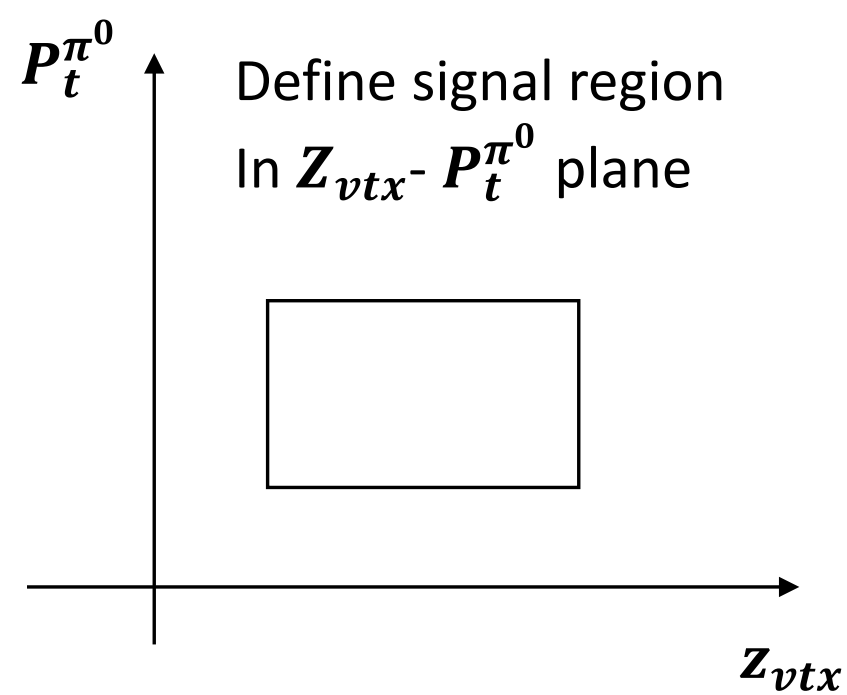


- Signature of $K_L \to \pi^0 \nu\bar{\nu}$ decay
  - Measure energy and hit position of two γ's by the CsI calorimeter
  - Neutrinos are not measured
    → Require no signal in the hermetic veto counters

Signature of signal → $2\gamma + nothing$

  - Calculate decay z-position assuming

$$M_{\pi^0}^2 = M_{\gamma\gamma}^2 = 2E_1E_2\left(1 - \cos\theta_{\gamma\gamma}\right)$$



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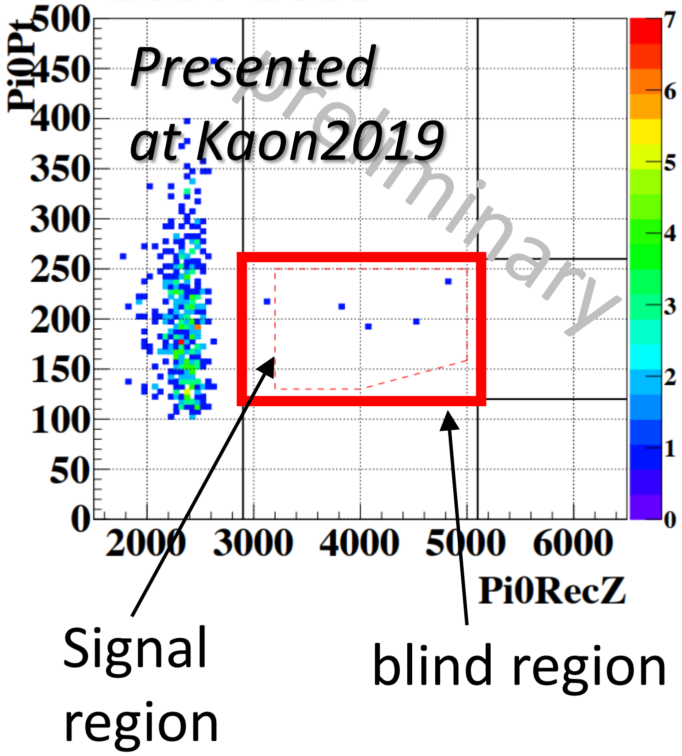
Post-unblind studies of 2016-2018 analysis

Data taken during 2016-2018



Expected # of BGs in the signal region

	source		#BG (90% C.L.)	#BG (68% C.L.)
U	KL	$K_L \to 2\pi^0$	<0.09	<0.05
		$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
U		$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
		Ke3 (overlapped pulse)	<0.09	<0.05
		$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
		Ke3 (π^0 production)	<0.04	<0.02
		Ke3 (π^+ beta decay)	<0.01	<0.01
N		radiative Ke3	<0.046	<0.023
		Ke4	<0.04	<0.02
		$K_L \to ee\gamma$	<0.09	<0.05
		$K_L \to \pi^+\pi^-$	<0.03	<0.02
		$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
		$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

	source		#BG (90% C.L.)	#BG (68% C.L.)
	K+/-	$K^\pm \to \pi^0\pi^\pm$	0.03±0.03	0.03±0.03
N		$K^\pm \to \pi^0 e^\pm \nu$	0.30±0.09	0.30±0.09
		$K^\pm \to \pi^0 \mu^\pm \nu$	<0.07	<0.04
	Neutron	Upstream π^0	0.001±0.001	0.001±0.001
		Hadron cluster	0.02 ±0.00	0.02 ±0.00
		CV-pi0	<0.10	<0.05
		CV-eta	0.03±0.01	0.03±0.01
	Total	central value	0.39±0.10	0.39±0.10

U: Updated from Kaon2019
N: New

- Adopted blind analysis technique and opened the blind region in the summer of 2019.
  - $\mathrm{SES} = \frac{1}{N_{K_L}\epsilon_{sig}} = 7.1 \times 10^{-10}$ or 0.04 SM events expected.
- We found four candidate events in the signal region and carefully checked our analysis.
  - One event was due to mistake of the application of cuts (N_{obs}: 4 → 3)
  - New concern: K^+, dominant contribution but syst. uncertainty remained.

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2016-2018 analysis BG table (updated, preliminary)

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
	$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
	Ke3 (overlapped pulse)	<0.09	<0.05
	$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
	Ke3 (π^0 production)	<0.04	<0.02
	Ke3 (π^+ beta decay)	<0.01	<0.01
	radiative Ke3	<0.046	<0.023
	Ke4	<0.04	<0.02
	$K_L \to ee\gamma$	<0.09	<0.05
	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

source		#BG (90% C.L.)	#BG (68% C.L.)	
K+/-	$K^\pm \to \pi^0\pi^\pm$	0.09±0.09	0.09±0.09	New
	$K^\pm \to \pi^0 e^\pm \nu$	0.90±0.27	0.90±0.27	New
	$K^\pm \to \pi^0 \mu^\pm \nu$	<0.21	<0.12	
Neutron	Upstream π^0	0.001±0.001	0.001±0.001	
	Hadron cluster	0.02 ±0.00	0.02 ±0.00	
	CV-pi0	<0.10	<0.05	
	CV-eta	0.03±0.01	0.03±0.01	
Total	central value	1.05±0.28	1.05±0.28	New

from $K^\pm$ decays

= $\underline{(0.33 \pm 0.08)}$ × **uncertainties of simulation**

Prediction by MC simulation

Uncertainty of flux → x 3.0

Uncertainty of the estimation of acceptance → ongoing using K^+ control sample

- ☐ BG table was updated based on the result of the $K^\pm$ flux.
- ☐ Tentative total BG estimation → 1.05 ± 0.28

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Problem to generate a model: Nir-Grossman bound

- KOTO signal (~2.2 σ)
    - Bkg = 1.05(+-0.28), obs= 3 → BR($K_L \to \pi^0 \nu\nu$)~ 2×10^{-9}
- NA62/E949 constraints
    - BR($K^+ \to \pi^+ \nu\nu$) < 1.85×10^{-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 observed BRs have moderate tension with bound.

Solution: 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

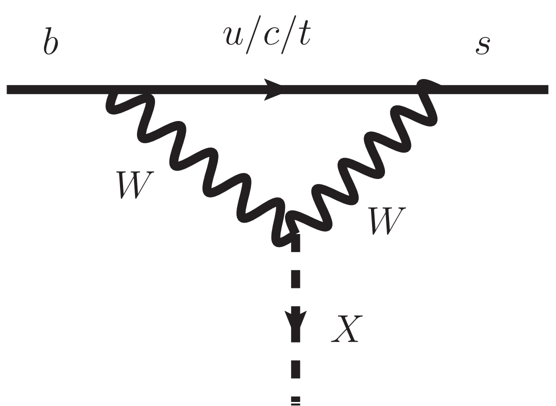
- SM Higgs portal

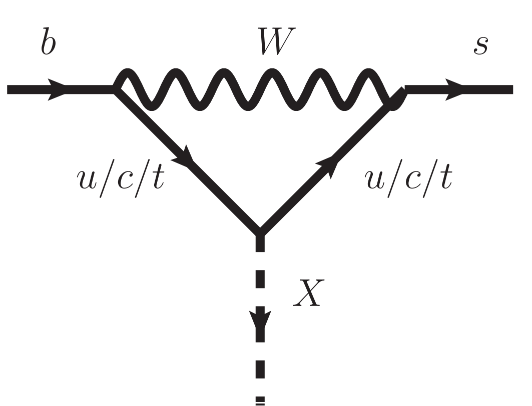
$$\mathcal{L}_{\text{int}} \supset \sin\theta \times \phi \left(\sum_q \frac{m_q}{v} \bar{q} q + \sum_\ell \frac{m_\ell}{v} \bar{\ell}\ell + \frac{2m_W^2}{v} \phi W_\mu^+ W^{\mu -} + \cdots \right)$$

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

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

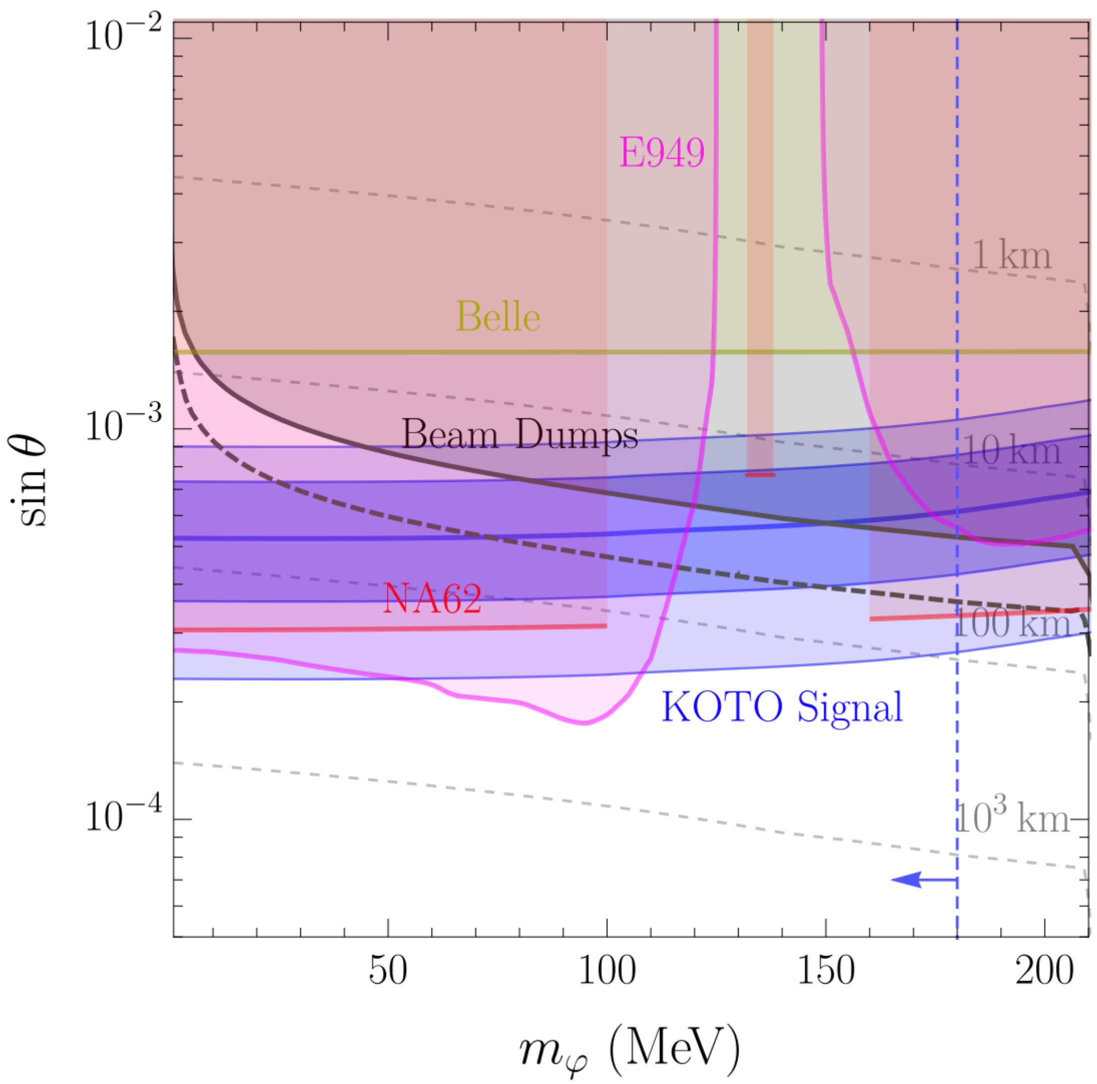
$$g(\sin\theta) = \frac{3m_K^2}{32\pi^2 v^3} \sin\theta \sum_{q=u,c,t} m_q^2 V_{qd}^* V_{qs},$$



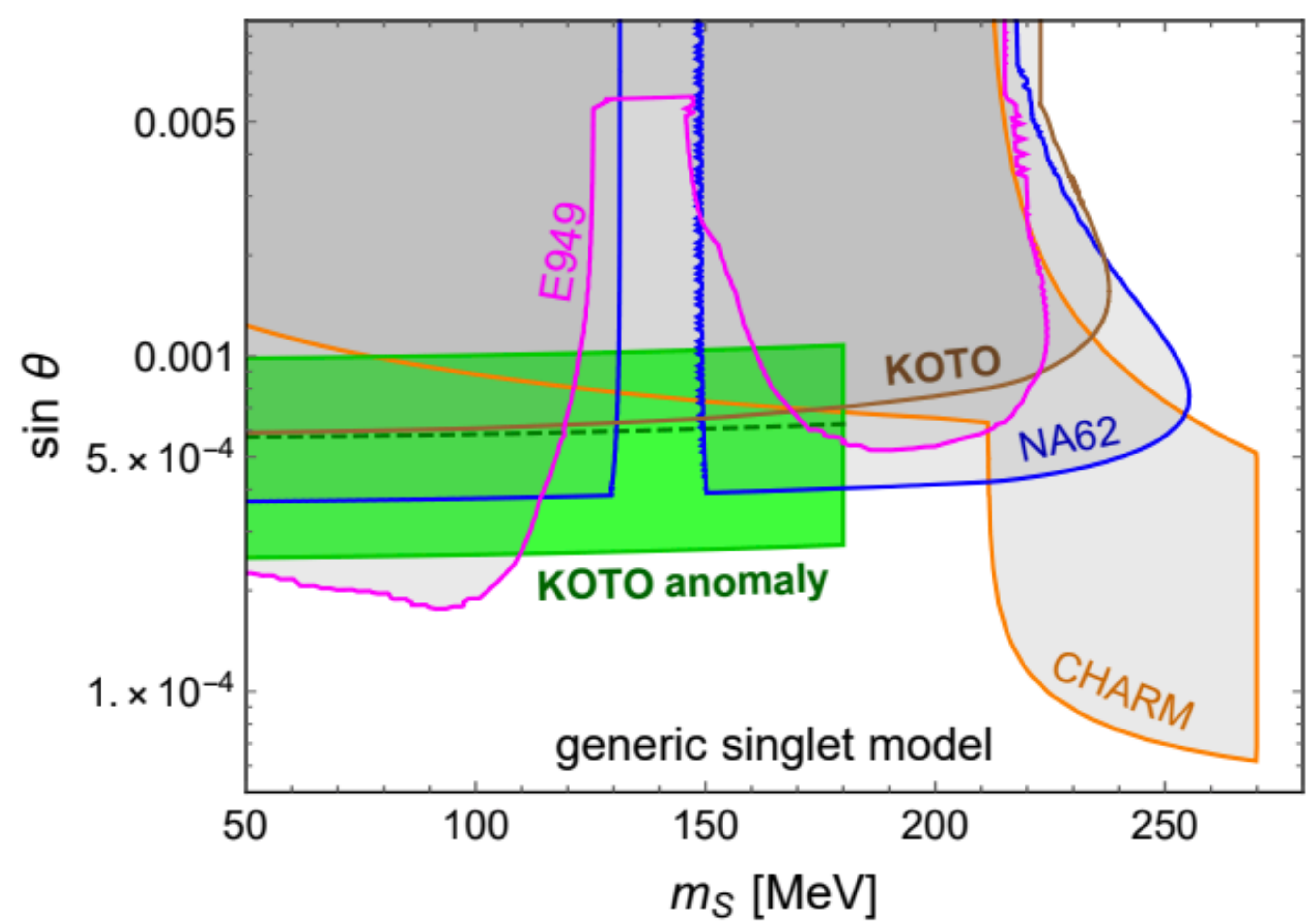


Long-lived scalar mediator fits to KOTO

- Charged Kaon EXP forces scalar mass to be near 140 MeV



Patrick Meade et al, 1911.10203
Phys.Rev.Lett. 124 (2020) 191801



R. Mohapatra et al, 1911.12334

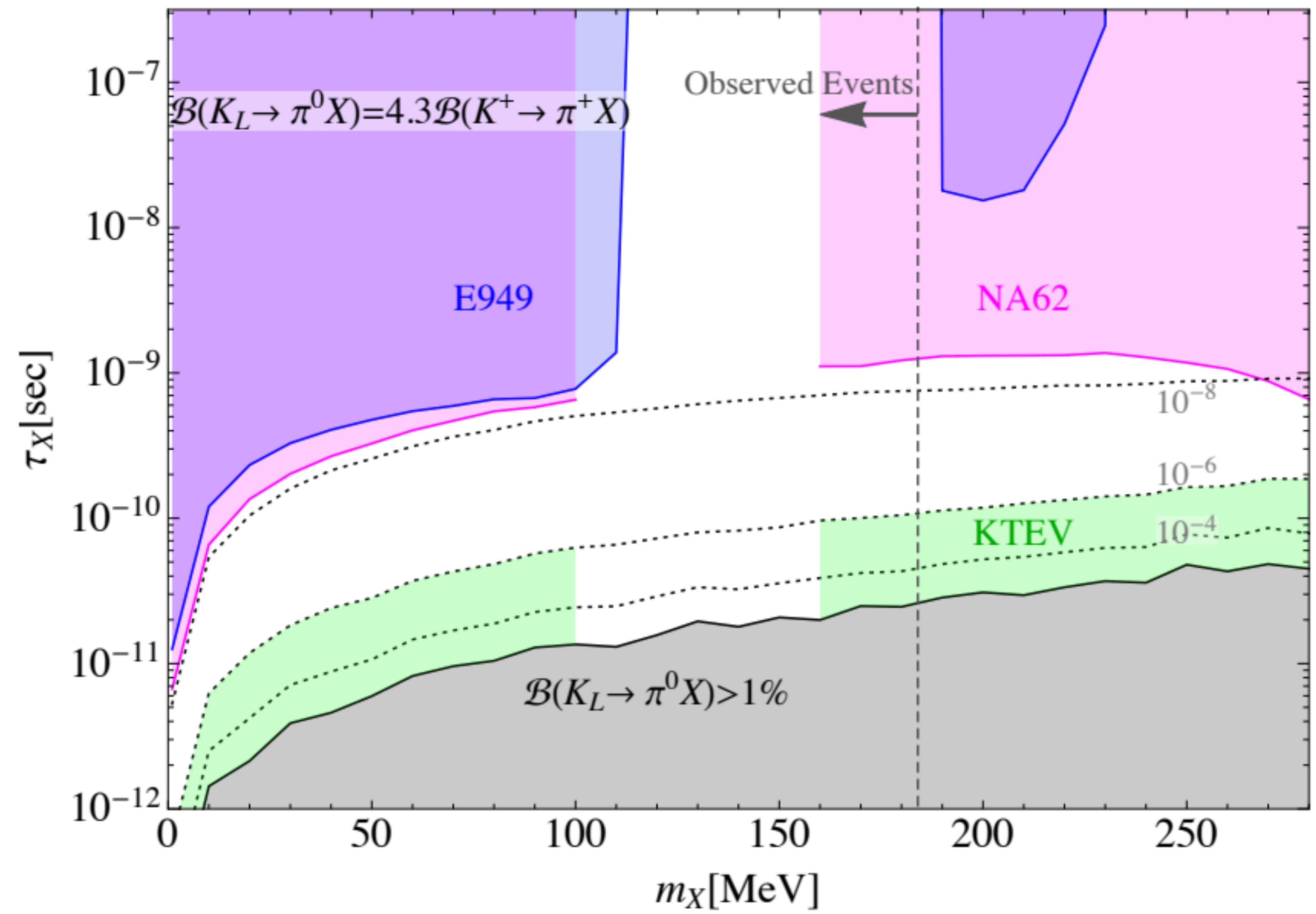
Solution: short-lived particle

- 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 with nano-sec lifetime can work, but why ns?

Kitahara et al, 1909.11111
Phys.Rev.Lett. 124 (2020) 071801

Our answer: because of muon g-2!

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

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

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

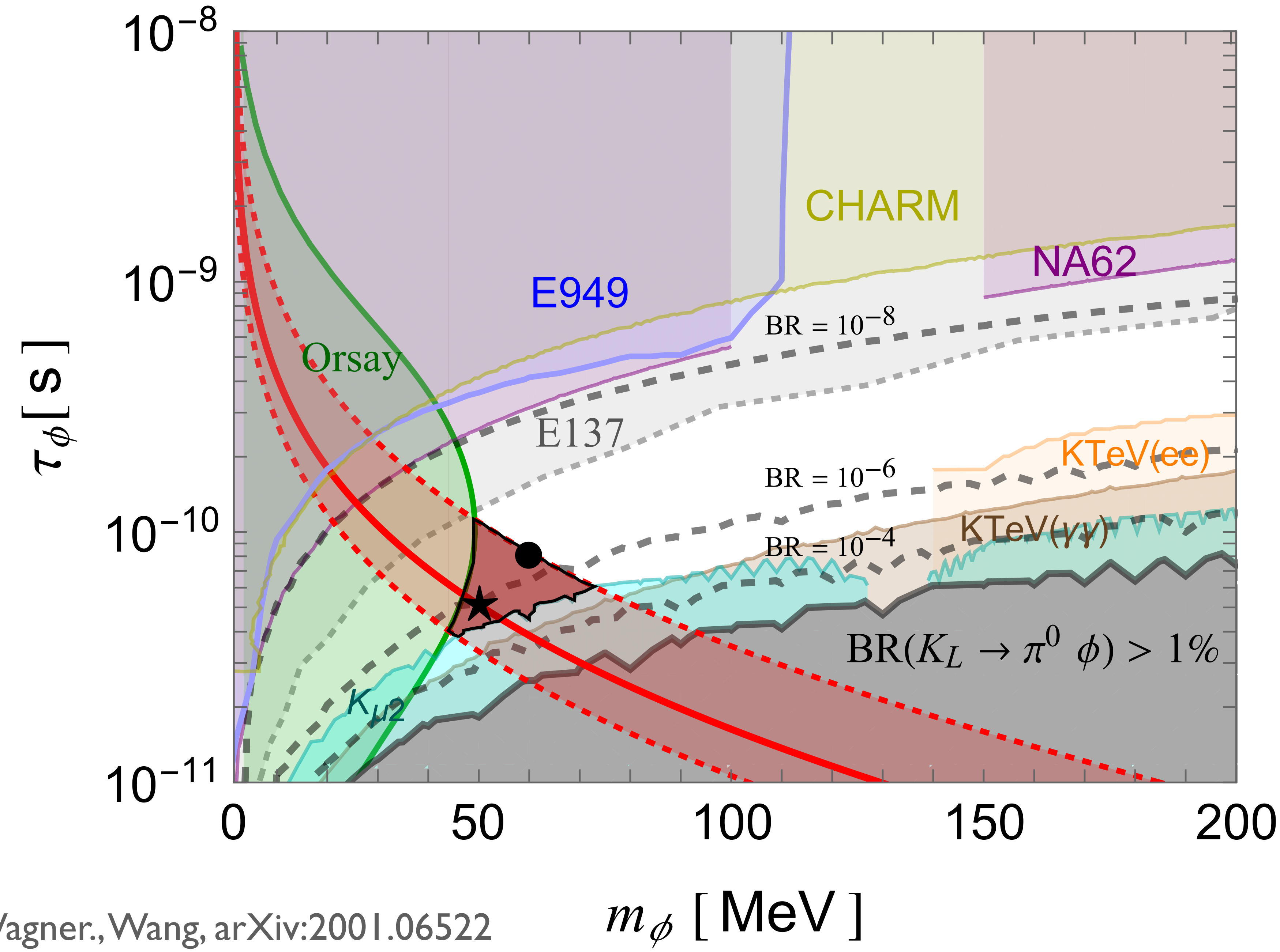
- Three free parameters $\epsilon_q \quad \epsilon_\ell \quad m_\phi$
- Two requirements:
  - Muon g-2 fixes ε_l
  - Branching ratio of neutral Kaon decay to ϕ fixes ε_q
- Only mass parameter is free m_ϕ

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

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 $B \to K\phi,\ \phi \to e^+ e^-$

The results



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}

Comments

- B physics measurement at LHCb

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

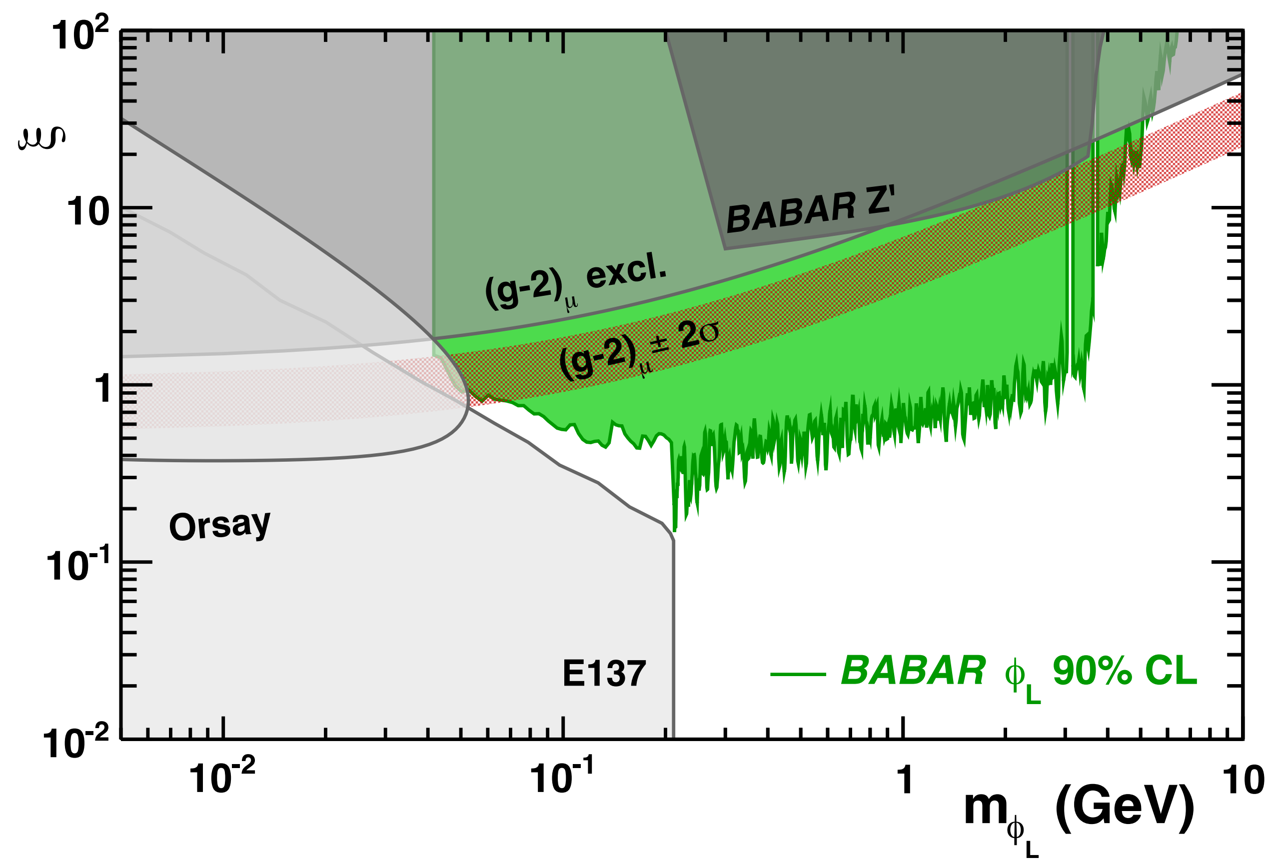
  - Our benchmark model

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

  - However, LHCb requires a good quality vertex, while the light ϕ is displaced, so still safe

- Recent BaBar search still left a silver corner.

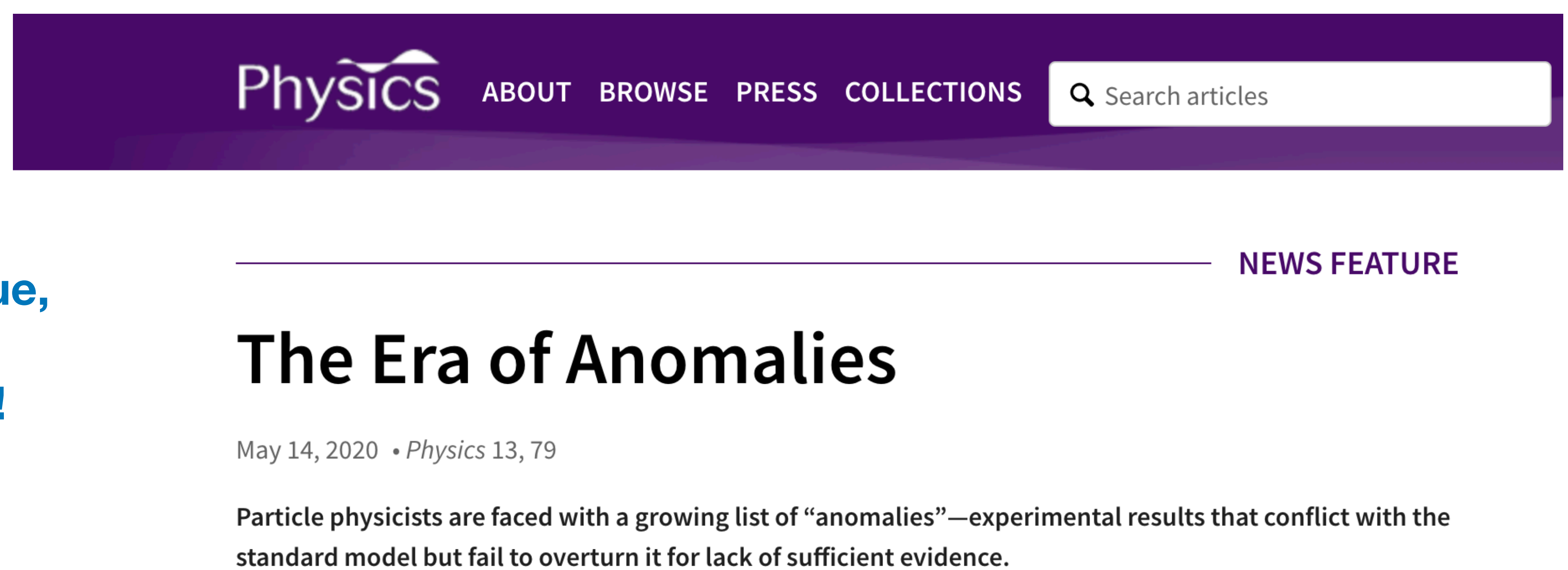
arXiv: 2005.01885



Summary

- Light dark sector particles can be motivated by dark matter property and its null detection
- Recent low energy anomalies might hint new light 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 less likely to remain is the electron g-2, but if a pseudo-scalar of about 17 MeV is its explanation, it may also address the Atomki nuclear transition anomaly
- 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 anomalies may not be true, but still gain lots of attention. Waiting for future exp results!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NEWS FEATURE

The Era of Anomalies

May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of "anomalies"—experimental results that conflict with the standard model but fail to overturn it for lack of sufficient evidence.