A new perspective in searching for ALP from flavor physics

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with

H. Ishida (KEK) and S. Matsuzaki (Jilin U.)

based on: arXiv:2006.02725

Introduction

- There are still several problems in the SM

- One of these problems is strong CP problem

QCD Lagrangian: $\mathcal{L} \supset m_u e^{i\theta_u} u u^c + m_d e^{i\theta_d} d d^c + \theta \frac{g_s^2}{32\pi^2} G\widetilde{G}$

➡ Physical answer depend only on $\bar{\theta} = \theta + \theta_u + \theta_d$

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➡ Physical answer depend only on $\bar{\theta} = \theta + \theta_u + \theta_d$

- Neutron EDM → $d_n \sim 10^{-16}\bar{\theta}$ e cm

apply constraint …

$$\bar{\theta} \lesssim 10^{-10}$$

Why so small…?

Introduction

- Well-known solution: Axion, Axion-Like Particles (ALPs)

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{F_a}G\widetilde{G}$$

Peccei and Quinn, PRL **38** (1977) 1440; PRD **16** (1977) 1791
Weinberg, PRL **40** (1978) 223
Wilczek, PRL **40** (1978) 279

- *a* has appropriate value → strong CP problem is solved

$$a \simeq -\bar{\theta}F_a$$

- These particles are well motivated theoretically
  - *Accidental axion and ALPs* arising from the breaking of accidental global $U(1)$ symmetries that appear as low energy remnants of exact discrete symmetries – the latter being postulated in purely field theoretic set ups[12,13] or occurring automatically in orbifold compactifications of the heterotic string[14].

Ringwald, arXiv:1407.0546 [hep-ph] (proceedings)

✓ In particular, we focus on ALP in this work

Introduction

- They have rich phenomenological interests
  - ✓ DM candidates Preskill, Wise, Wilczek, PLB **120** (1983) 127
  - ✓ Flavor puzzle Wilczek, PRL **49** (1982) 1549
  - ✓ Inflation Freese, Frieman, Olinto, PRL **65** (1990) 3233
  - ✓ Flaxion Ema, Hamaguchi, Moroi, Nakayama, JHEP **01** (2017) 096
  - ✓ Axiflavon Calibbi, Goertz, Redigolo, Ziegler, Zupan, PRD **95** (2017) 095009
  - ✓ …

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  - ✓ …
- An interesting and important feature: photon coupling

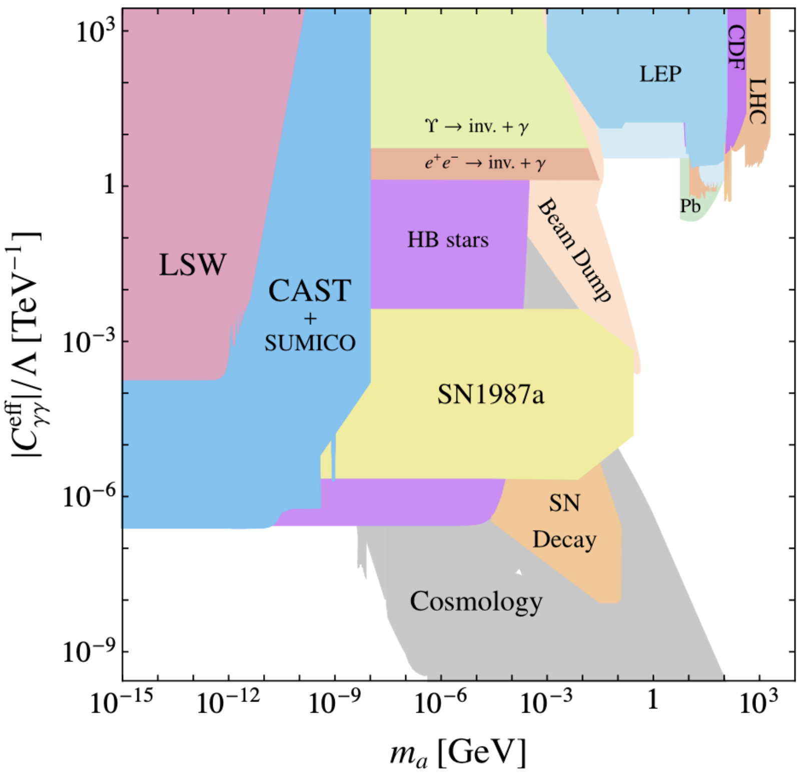
$$\mathcal{L}_{a\gamma\gamma} = C^{\rm eff}_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

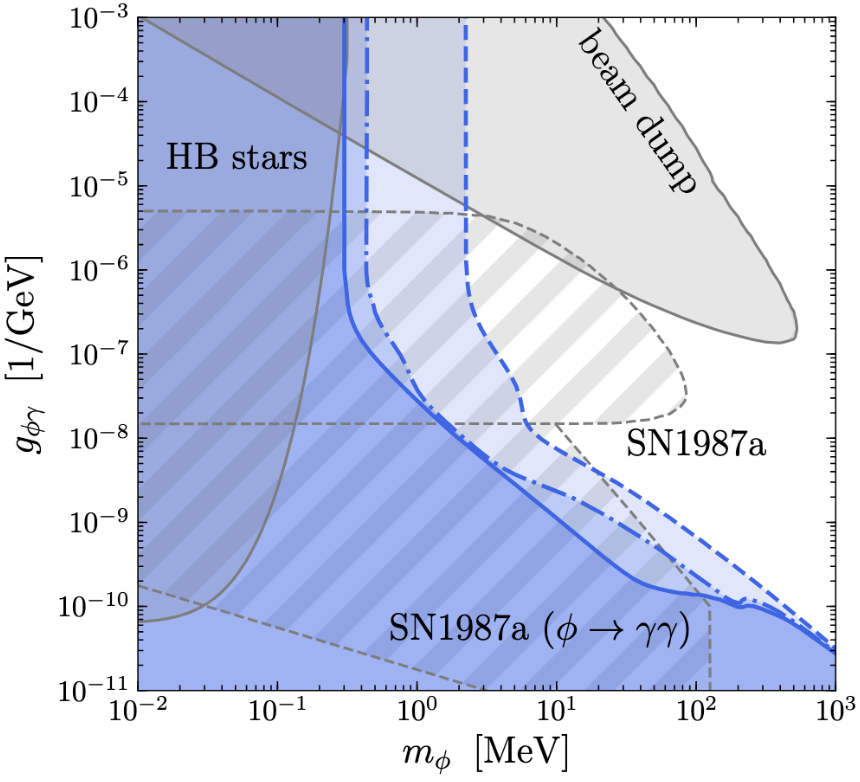
→ some signal in the experiments is expected

Introduction

- Current status of constraints on axion-photon coupling

examples:





Bauer, Neubert, Thamm, JHEP **12** (2017) 044

Depta, Hufnagel, Schmidt-Hoberg, arXiv:2002.08370 [hep-ph]

Note: notation of *a*-*γ*-*γ* coupling should be checked…

Introduction

- When m_a = 140 MeV, around pion mass, ALP signals are hidden behind the pion background

  → constraint from beam dump experiments can be omitted

- In this sense, there are remarkable “loopholes” around this mass region

  → it is difficult to search this region by beam dump experiment

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  → it is difficult to search this region by beam dump experiment

- We propose how to search in this mass region:

  by using

  Flavor physics induced by ALP

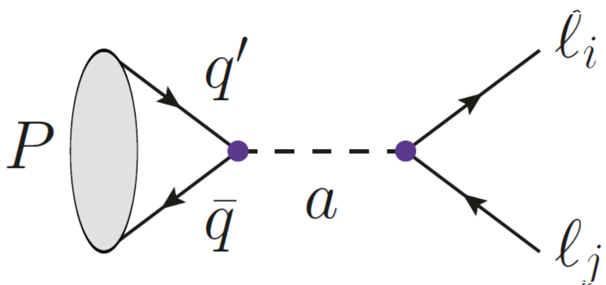
Introduction

- ALP generally couples to fermions

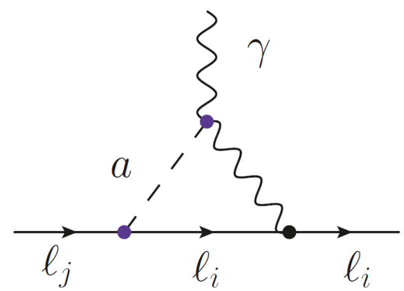
$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f}\left[(g_V^f)_{ij}\bar{f}_i\gamma^\mu f_j + (g_A^f)_{ij}\bar{f}_i\gamma^\mu\gamma_5 f_j\right]$$

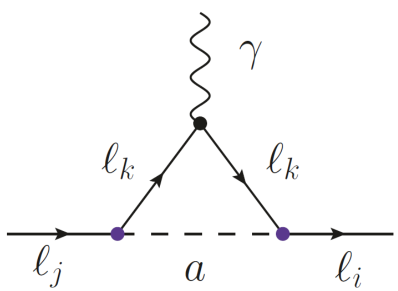
- Both tree- and loop-level processes are induced

✓ Leptonic meson decay



✓ Lepton flavor violations (LFVs), muon g-2





- Combined measurements of these processes will leave some hints of ALPs

Introduction

- Short summary:

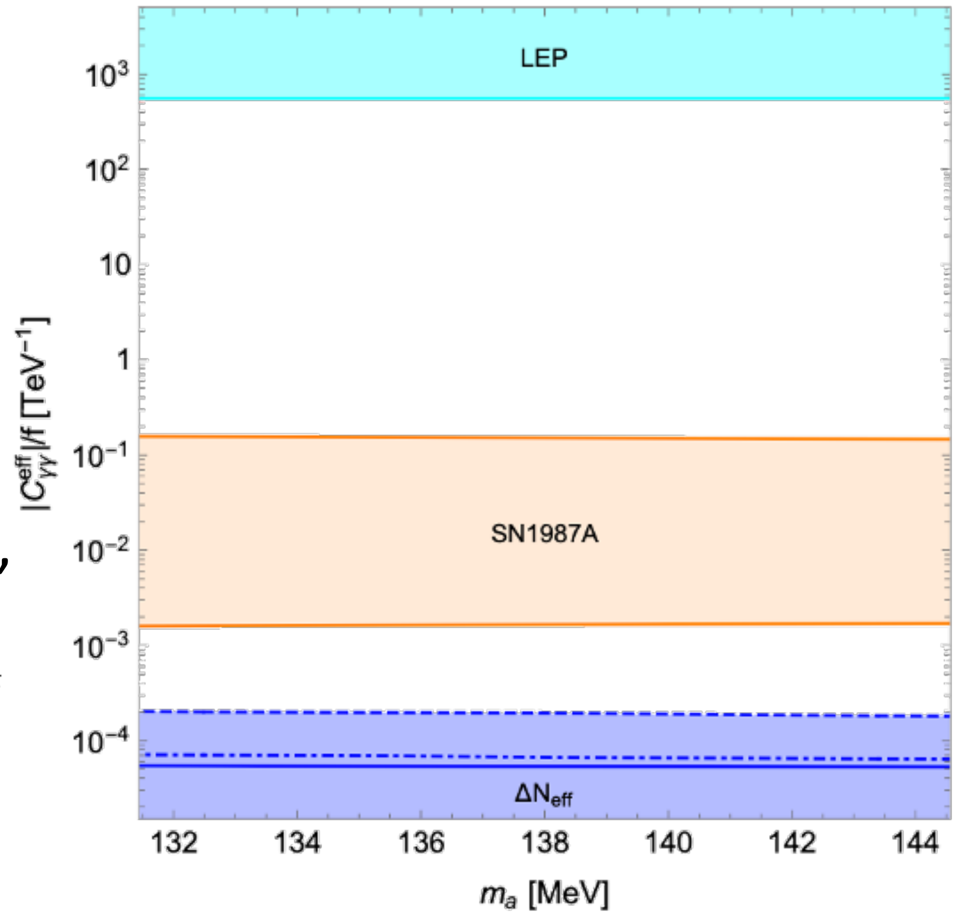
  we can determine $C_{\gamma\gamma}^{\text{eff}}$ by complementary measurements

- Significant help to explore the parameter space of ALP

- Our conclusion:

  we will cover all the blank area,

$$\frac{0.0002}{\text{TeV}} \lesssim \left| \frac{C_{\gamma\gamma}^{\text{eff}}}{f} \right| \lesssim \frac{0.00164}{\text{TeV}}, \quad \frac{0.157}{\text{TeV}} \lesssim \left| \frac{C_{\gamma\gamma}^{\text{eff}}}{f} \right| \lesssim \frac{556}{\text{TeV}}$$



Model Details

Ishida, Matsuzaki, YS, arXiv:2006.02725

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- Lagrangian

- couplings to fermions (flavor-violating ones)

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2f}\left[(g_V^d)_{ij}\bar{d}_i\gamma^\mu d_j + (g_A^d)_{ij}\bar{d}_i\gamma^\mu\gamma_5 d_j\right] + \frac{\partial_\mu a}{2f}\left[(g_V^\ell)_{ij}\bar{\ell}_i\gamma^\mu \ell_j + (g_A^\ell)_{ij}\bar{\ell}_i\gamma^\mu\gamma_5 \ell_j\right]$$

- couplings to photon

$$\mathcal{L}_{a\gamma\gamma} = C_{\gamma\gamma}^{\text{eff}}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Note: for our discussions, couplings to up-type quarks and neutrinos are irrelevant, then we omit it

Model Details

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Related couplings to our discussions:

$$(g^d_{V,A})_{23} \quad (g^d_A)_{33} \quad (g^\ell_{V,A})_{12} \quad (g^\ell_A)_{22} \quad C^{\rm eff}_{\gamma\gamma}$$

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- Should check the following processes:

B_s-$\overline{B_s}$ mixing

$\Upsilon \to \gamma a$ with $\mu^+\mu^-$

$B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$

$(g-2)_\mu \quad \mu \to e\gamma$

CP asymmetry in $B^0 \to K^0_S \pi^0 \gamma$

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B_s-$\overline{B_s}$ mixing $\longleftrightarrow$ $(g^d_{V,A})_{23}$

$\Upsilon \to \gamma a$ with $\mu^+\mu^-$ $\longleftrightarrow$ $(g^d_A)_{33}$

$B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$ $\longleftrightarrow$ $(g^d_A)_{23} \quad (g^\ell_{V,A})_{12} \quad (g^\ell_A)_{22}$

$(g-2)_\mu \quad \mu \to e\gamma$ $\longleftrightarrow$ $(g^\ell_{V,A})_{12} \quad (g^\ell_A)_{22} \quad C^{\rm eff}_{\gamma\gamma}$

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Ishida, Matsuzaki, YS, arXiv:2006.02725

- Observable - relation to the couplings
  - B_s-$\overline{B_s}$ mixing (from lattice results)

Dowdall *et al.*, PRD **100** (2019) 094508
Camalich, Pospelov, Voung, Ziegler, Zupan, PRD **102** (2020) 015023

$$\frac{\Delta m_{B_s}}{m_{B_s}} = \left| 0.077(8)\,\mathrm{GeV}^2 \left(\frac{(g_A^d)_{23}}{2f}\right)^2 - 0.020(2)\,\mathrm{GeV}^2 \left(\frac{(g_V^d)_{23}}{2f}\right)^2 \right|$$

compare

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{\langle B_s^0 | \mathcal{L}_{\mathrm{eff}}^{\mathrm{SM+NP}} | \overline{B_s}^0 \rangle}{\langle B_s^0 | \mathcal{L}_{\mathrm{eff}}^{\mathrm{SM}} | \overline{B_s}^0 \rangle}$$

$$\Delta m_{B_s} = 2 \left| \langle B_s^0 | \mathcal{L}_{\mathrm{eff}} | \overline{B_s}^0 \rangle \right| \quad \text{in SM } C_{B_s} = 1 \text{ and } \phi_{B_s} = 0$$

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$\Delta m_{B_s} = 2 \left| \langle B_s^0 | \mathcal{L}_{\mathrm{eff}} | \overline{B_s}^0 \rangle \right|$ in SM $C_{B_s} = 1$ and $\phi_{B_s} = 0$

  - $\Upsilon \to \gamma a$ with $\mu^+\mu^-$

$$\frac{\mathrm{BR}(\Upsilon \to \gamma a)}{\mathrm{BR}(\Upsilon \to \mu\mu)} = \frac{m_b^2}{2\pi\alpha} \left(\frac{(g_A^d)_{33}}{f} \right)^2$$

Wilczek, PRL **39** (1977) 1304

Experimental results: $\begin{cases} \mathrm{BR}(\Upsilon \to \mu\mu) = 2.48 \times 10^{-2} \ (\mathrm{PDG}) \\ \mathrm{BR}(\Upsilon \to \gamma a) < 4.5 \times 10^{-6} \ \ (\mathrm{BaBar,\ 90\%\ CL}) \end{cases}$

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Ishida, Matsuzaki, YS, arXiv:2006.02725

- Observable - relation to the couplings

- $B_s \to \mu^+\mu^-$

Altmannshofer, Paradisi, Straub, JHEP **1204** (2012) 008

➢ $$\frac{\mathrm{BR}(B_s \to \mu^-\mu^+)}{\mathrm{BR}(B_s \to \mu^-\mu^+)_{\mathrm{SM}}} = |S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |P|^2$$

$$S = \frac{m_{B_s}^2}{2m_\mu} \frac{C_S - C_S'}{|C_{10}^{\mathrm{SM}}|} = 0; \;\; P = \frac{m_{B_s}^2}{2m_\mu} \frac{C_P - C_P'}{C_{10}^{\mathrm{SM}}} + \frac{C_{10} - C_{10}'}{C_{10}^{\mathrm{SM}}}; \;\; C_P - C_P' = g_{\mathrm{SM}}^{-1} \frac{m_\mu}{m_{B_s}^2 - m_a^2} \frac{(g_A^d)_{23}}{f} \frac{(g_A^\ell)_{22}}{f}$$

$$g_{\mathrm{SM}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi}$$

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➢ $$\mathrm{BR}(B_s \to e^\pm\mu^\mp) \simeq \frac{m_{B_s}^3 f_{B_s}^2}{32\pi\Gamma_{B_s}} \frac{[\lambda(1, r_1^2, r_2^2)]^{1/2}}{(1 - r_a^2)^2} \left| \frac{(g_A^d)_{23}}{f} \right|^2 \frac{c_{e\mu}^2}{f^2} r_2^2$$

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx \quad r_i = \frac{m_{\ell_i}}{m_{B_s}} \quad r_a = \frac{m_a}{m_{B_s}} \quad c_{e\mu} \equiv \frac{1}{\sqrt{2}} \sqrt{|(g_V^\ell)_{12}|^2 + |(g_A^\ell)_{12}|^2}$$

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Experimental results and SM prediction:

$$\mathrm{BR}(B_s \to \mu^-\mu^+)_{\mathrm{exp}} = (3.0 \pm 0.4) \times 10^{-9}$$
$$\mathrm{BR}(B_s \to \mu^-\mu^+)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

PDG & Bobeth *et al.*, PRL **112** (2014) 101801

$$\mathrm{BR}(B_s \to e^\pm\mu^\mp)_{\mathrm{exp}} < 5.4(6.3) \times 10^{-9}$$
$$(90\% \;(95\%)\; \mathrm{CL})$$

LHCb Collab., JHEP **1803** (2018) 078

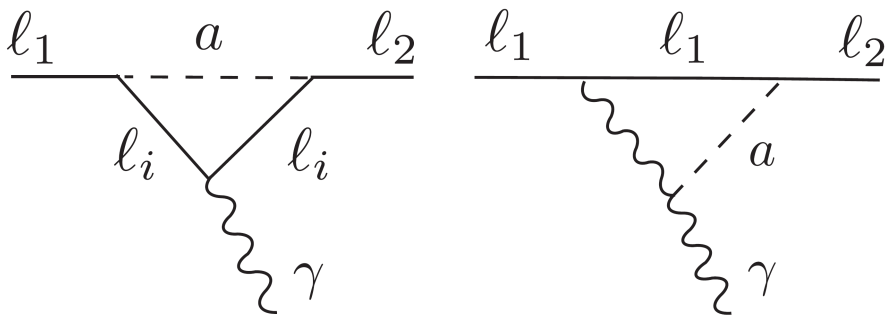
Model Details

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Observable - relation to the couplings

- $(g-2)_\mu \quad \mu \to e\gamma$

Note: loop contributions →



$$\Delta a_\mu = -\frac{m_\mu^2[(g_A^\ell)_{22}]^2}{16\pi^2 f^2}\left[h_1(x) + \frac{2\alpha C_{\gamma\gamma}^{\text{eff}}}{\pi (g_A^\ell)_{22}}\left(\ln\frac{\Lambda^2}{\mu^2} - h_2(x)\right)\right]$$

$$\Gamma(\mu \to e\gamma) = \frac{\alpha m_\mu^5 c_{e\mu}^2}{4096\pi^4 f^4}\left|(g_A^\ell)_{22} g_1(x) + \frac{\alpha}{\pi} C_{\gamma\gamma}^{\text{eff}} g_2(x)\right|^2$$

h1(x), h2(x), g1(x), g2(x): loop function

Bauer, Neubert, Thamm, JHEP **1712** (2017) 044
Bauer, Neubert, Renner, Schnubel, Thamm, PRL **124** (2020) 211803

Model Details

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Observable - relation to the couplings
  - CP asymmetry in $B^0 \to K_S^0 \pi^0 \gamma$

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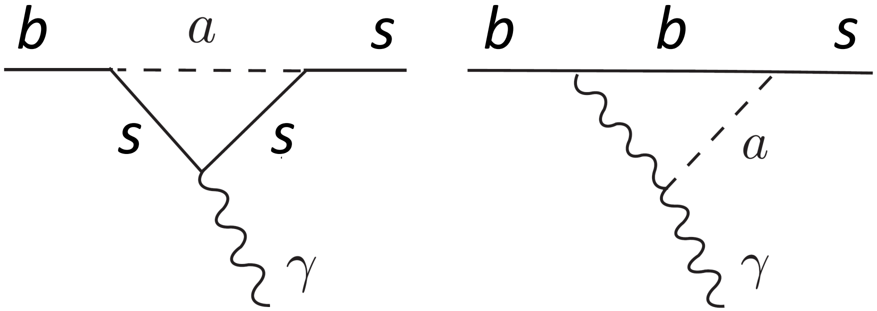

$$S_{CP} \equiv \frac{\mathrm{Im}\left[e^{-2i\beta_{\mathrm{CKM}}}\left(C_7^* C_7' + C_7 C_7'^*\right)\right]}{|C_7|^2 + |C_7'|^2}$$

$$C_7^{(\prime)} = C_7^{(\prime)\mathrm{SM}} + C_7^{(\prime)\mathrm{NP}}$$

Kou, *et al.*, PTEP **2019** (2019) 123C01

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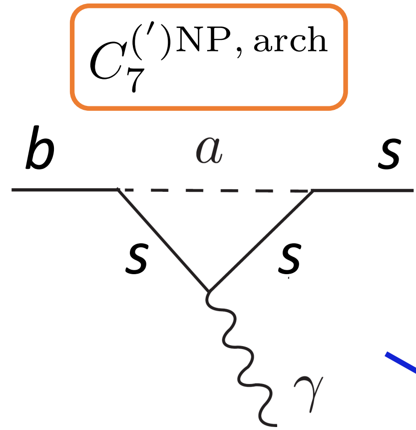

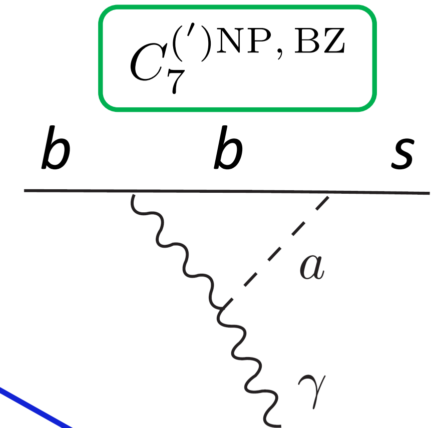

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Kou, *et al.*, PTEP **2019** (2019) 123C01

- $C_7^{(\prime)\mathrm{NP,\,arch}}$ and $C_7^{(\prime)\mathrm{NP,\,BZ}}$ can be estimated by loop calc.

Arch diagram: Lindner, Platscher, Queiroz, Phys. Rept. **731** (2018) 1

BZ-type diagram: Marciano, Masiero, Paradisi, Passera, PRD **94** (2016) 115033

Model Details

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Reference values for numerical analysis

$$C_{B_s} = 1.11$$

$$\frac{\mathrm{BR}(\Upsilon \to \gamma a)}{\mathrm{BR}(\Upsilon \to \mu\mu)} \simeq 1.81 \times 10^{-4}$$

$$\frac{\mathrm{BR}(B_s \to \mu^- \mu^+)_{\mathrm{exp}}}{\mathrm{BR}(B_s \to \mu^- \mu^+)_{\mathrm{SM}}} \simeq 0.822$$

$$\mathrm{BR}(B_s \to e^\pm \mu^\mp) = 8 \times 10^{-10}$$

$$\Delta a_\mu = 2.61 \times 10^{-9}$$

$$\mathrm{BR}(\mu \to e\gamma) = 6 \times 10^{-14}$$

future prospects

LHCb Collab., arXiv:1808.08865
MEG proposal, arXiv:1301.7225

B_s-$\overline{B_s}$ mixing ↔	$(g^d_{V,A})_{23}$
$\Upsilon \to \gamma a$ with $\mu^+\mu^-$ ↔	$(g^d_A)_{33}$
$B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$ ↔	$(g^d_A)_{23}$ $(g^\ell_{V,A})_{12}$ $(g^\ell_A)_{22}$
$(g-2)_\mu$ $\mu \to e\gamma$ ↔	$(g^\ell_{V,A})_{12}$ $(g^\ell_A)_{22}$ $C^{\mathrm{eff}}_{\gamma\gamma}$
CP asymmetry in $B^0 \to K^0_S \pi^0 \gamma$ ↔	$(g^d_{V,A})_{23}$ $(g^d_A)_{33}$ $C^{\mathrm{eff}}_{\gamma\gamma}$

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➡ Check the prediction of S_{CP} (as function of $C^{\mathrm{eff}}_{\gamma\gamma}$)

Note: SM prediction $S^{\mathrm{SM}}_{CP} \simeq -0.0269$

Numerical Results

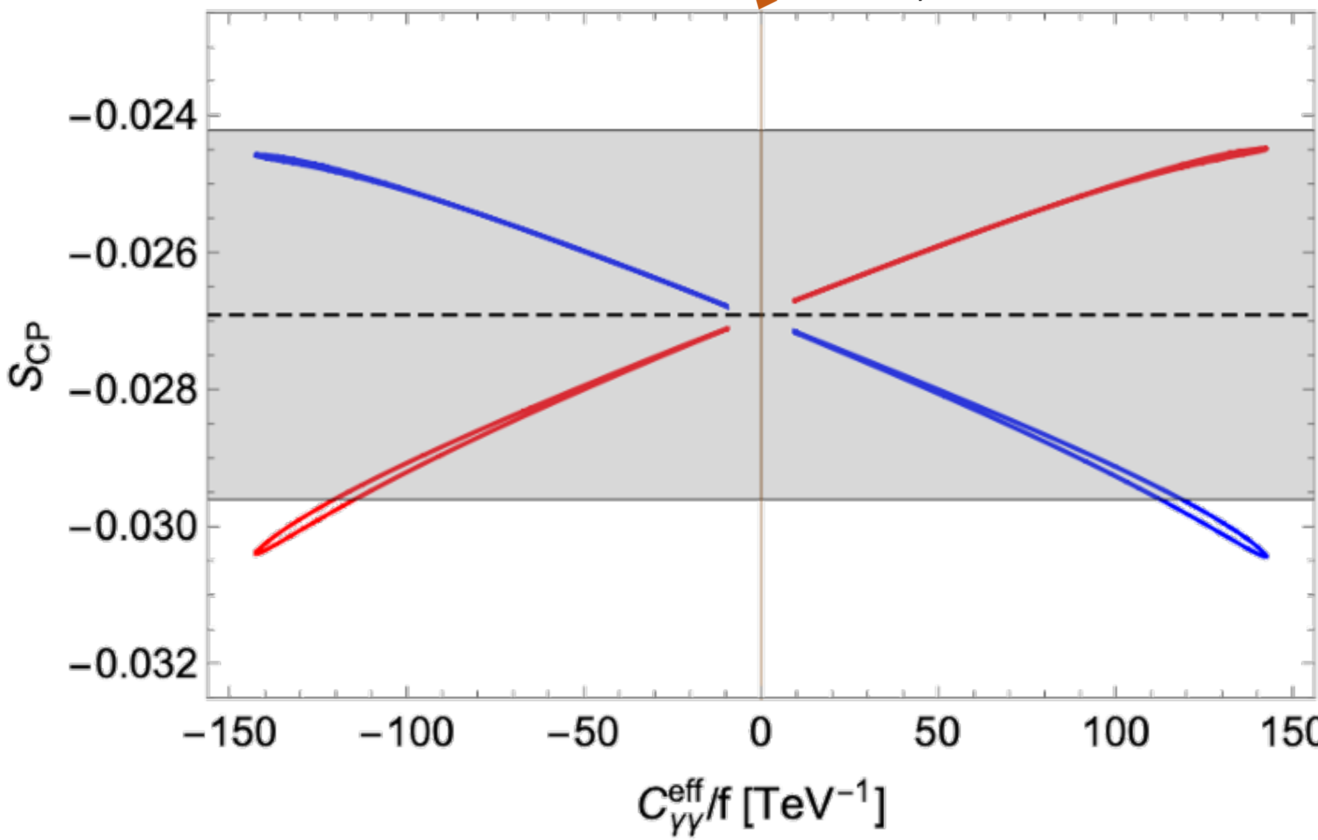
Numerical Results

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Result for reference values

constraints from SN1987A & ΔN_{eff}

red, blue: different overall sign of $(g_V^d)_{23}$



← SM pred.

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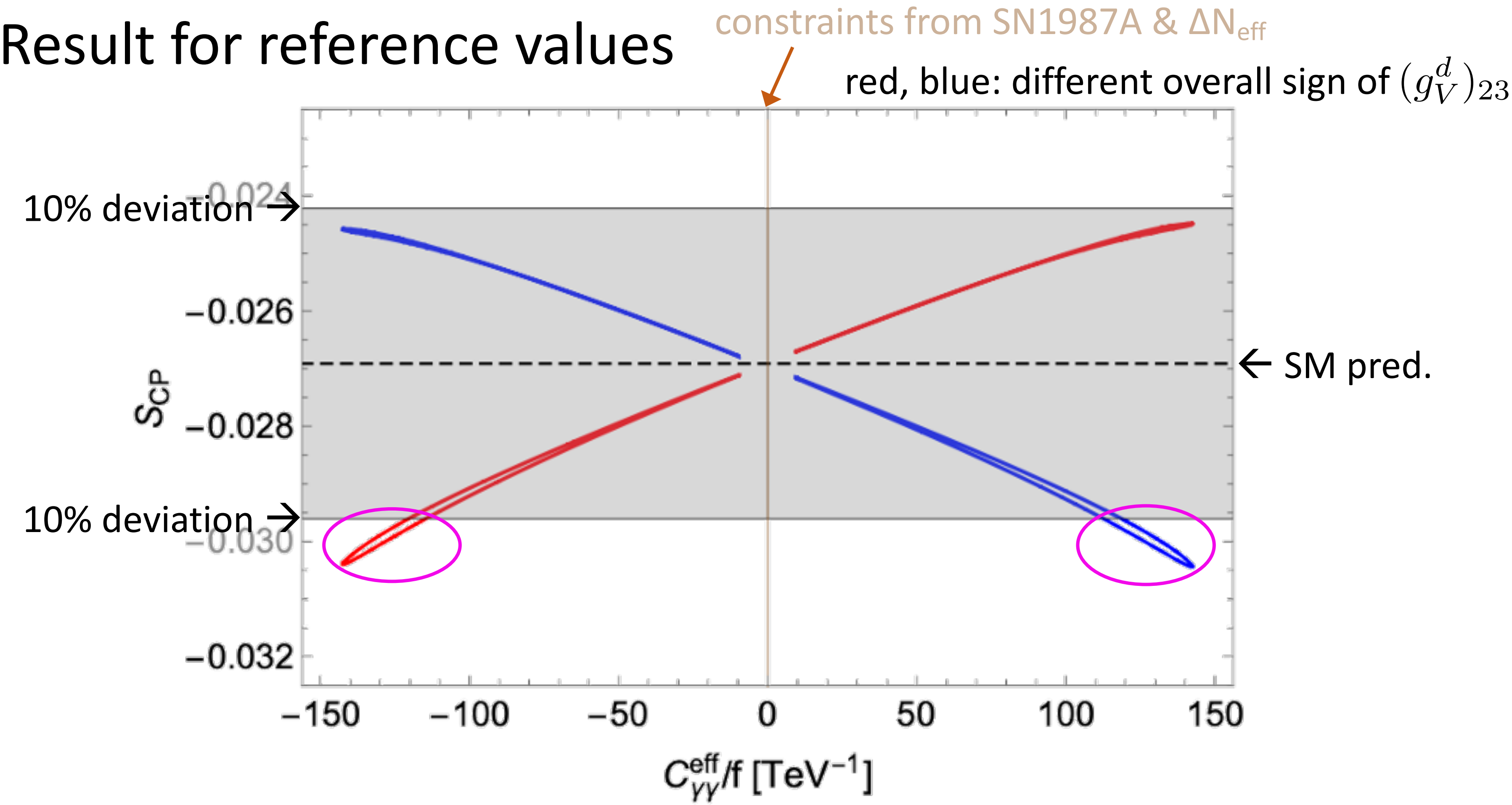
Ishida, Matsuzaki, YS, arXiv:2006.02725

- Result for reference values



predictions deviates by > 10% from SM prediction!

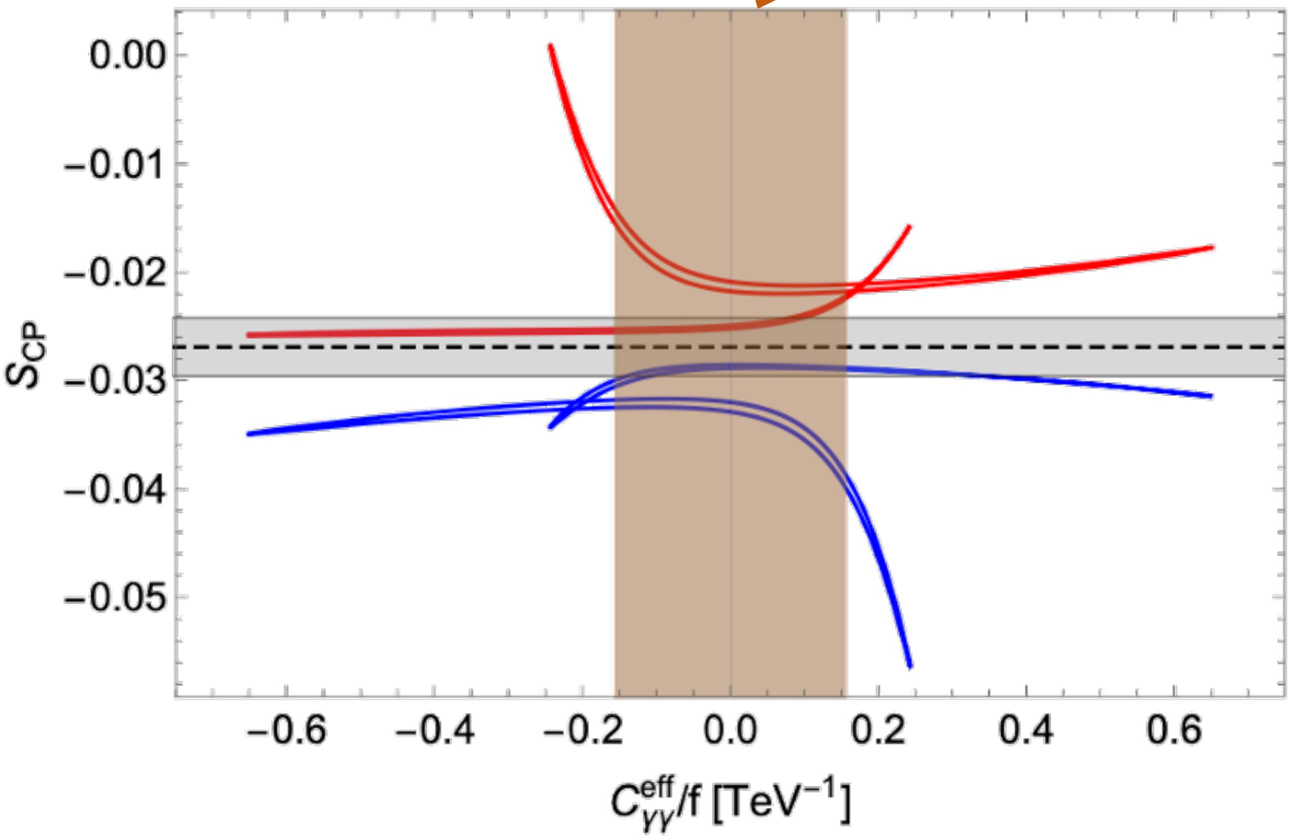
Numerical Results

Ishida, Matsuzaki, YS, arXiv:2006.02725

- Case where $\Delta a_\mu = 0$

constraints from SN1987A & $\Delta N_{\rm eff}$

red, blue: different overall sign of $(g_V^d)_{23}$



← SM pred.

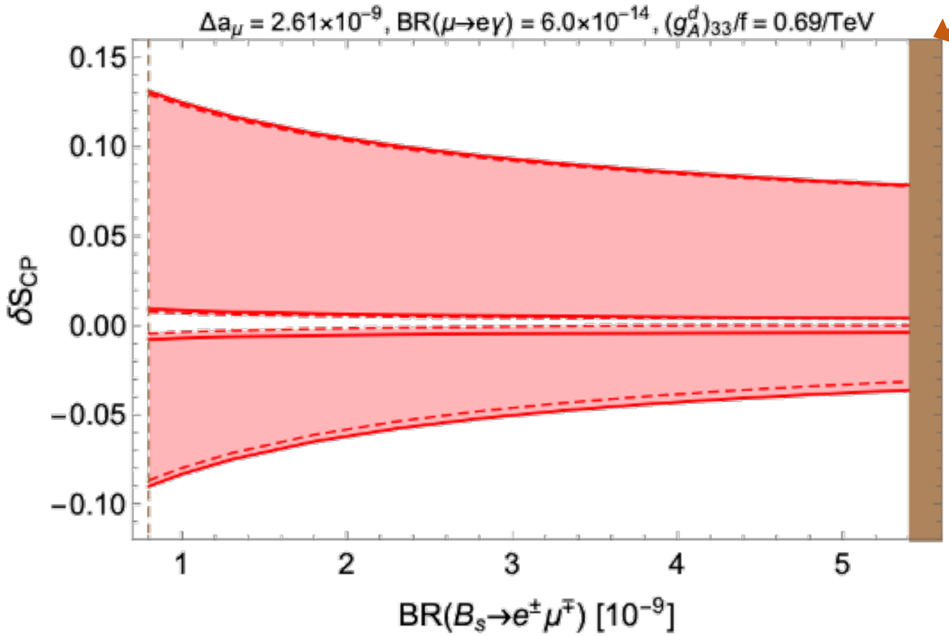
Predictions can be largely deviated from SM prediction!

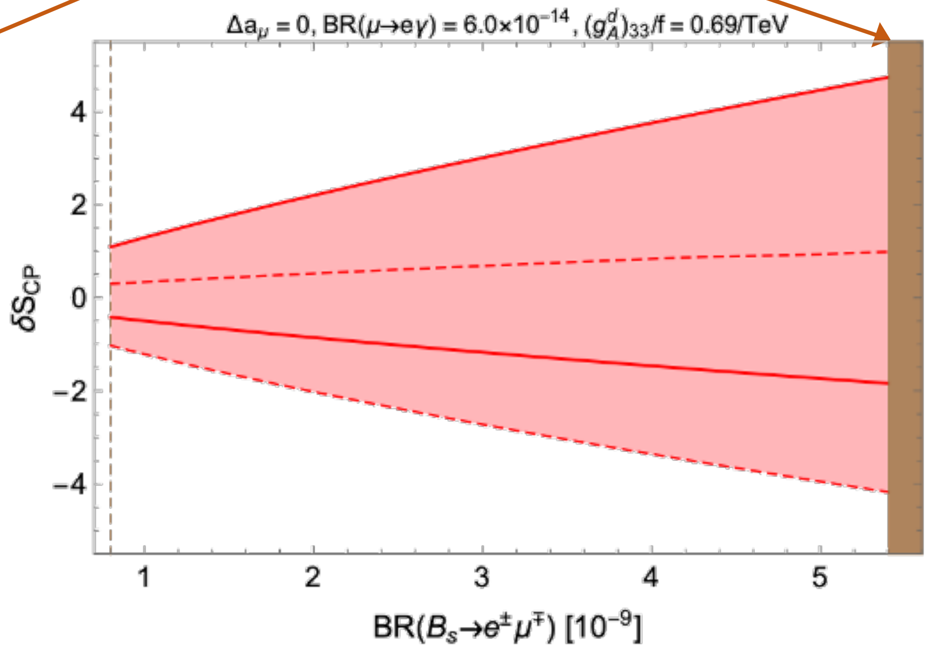
Numerical Results

Ishida, Matsuzaki, YS, arXiv:2006.02725

- $\mathrm{BR}(B_s \to e^{\pm}\mu^{\mp})$ dependence

current bound on BR(B_s --> e μ)





$$\delta S_{CP} = \frac{S_{CP}^{\mathrm{pred}}}{S_{CP}^{\mathrm{SM}}} - 1$$

solid: $C_{\gamma\gamma}^{\mathrm{eff}} \geq 0$

dashed: $C_{\gamma\gamma}^{\mathrm{eff}} < 0$

Note: we also check different parameter set and find that $\delta S_{CP} \simeq \mathcal{O}(10)\%$!!!

Conclusion

Conclusion

- We discuss flavor physics of 140 MeV ALP

  B_s-$\overline{B_s}$ mixing $\Upsilon \to \gamma a$ with $\mu^+\mu^-$ $B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$

  $(g-2)_\mu$ $\mu \to e\gamma$ CP asymmetry in $B^0 \to K_S^0\pi^0\gamma$ Key

- We find $\delta S_{CP} \simeq \mathcal{O}(10)\%$ with and without Δa_μ deviation

  also any update on $B_s \to e^\pm\mu^\mp$ and $\mu \to e\gamma$

- However, the experimental situation is not interesting

$$S^{\mathrm{SM}}_{K_S^0\pi^0\gamma} \sim -2\frac{m_s}{m_b}\sin 2\phi_1 = -(2.3 \pm 1.6)\%$$

Belle II physics book, Kou et. al., PTEP **2019** (2019) 123C01

$$S^{\mathrm{exp}}_{K_S^0\pi^0\gamma} = -0.16 \pm 0.22$$

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$K_S^0\pi^0\gamma$	0.20	0.12	0.10	0.07	0.031	0.021

But we hope future experiments to have a potential to give us some hints

Conclusion

Thank you for your attention☺

- We discuss flavor physics of 140 MeV ALP

B_s-$\overline{B_s}$ mixing $\quad \Upsilon \to \gamma a$ with $\mu^+\mu^-$ $\quad B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$

$(g-2)_\mu \quad \mu \to e\gamma \quad$ CP asymmetry in $B^0 \to K^0_S \pi^0 \gamma$ Key

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Back up slides

Back up

- Relevant operators

$$O_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_{R(L)} b) F_{\mu\nu}$$

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_P^{(\prime)} = m_b (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

Back up

- Details of dep. on couplings

B_s-$\overline{B_s}$ mixing ↔	$(g^d_{V,A})_{23}$
$\Upsilon \to \gamma a$ with $\mu^+\mu^-$ ↔	$(g^d_A)_{33}$
$B_s \to \mu^+\mu^-$ and $e^\pm\mu^\mp$ ↔	$(g^d_A)_{23}$ $(g^\ell_{V,A})_{12}$ $(g^\ell_A)_{22}$
$(g-2)_\mu$ $\mu \to e\gamma$ ↔	$(g^\ell_{V,A})_{12}$ $(g^\ell_A)_{22}$ $C^{\rm eff}_{\gamma\gamma}$
CP asymmetry in $B^0 \to K^0_S \pi^0 \gamma$ ↔	$(g^d_{V,A})_{23}$ $(g^d_A)_{33}$ $C^{\rm eff}_{\gamma\gamma}$

➢ $\Delta a_\mu \neq 0$

Numerical results → large $C^{\rm eff}_{\gamma\gamma}$ is favored

Naively, BZ-type diagram is dominant (and this is true!)

For Bs --> μ μ, small *b*-*s*-*a* couplings needs large μ-μ-*a* couplings

μ --> *e* γ requires same dep. for $C^{\rm eff}_{\gamma\gamma}$

When BR(B_s --> *e* μ) becomes small, δS_{CP} becomes (slightly) large!

➢ $\Delta a_\mu = 0$

Numerical results → small $C^{\rm eff}_{\gamma\gamma}$ is favored

Naively, ALP-arch diagram is dominant (and this is true!)

To cancel Δa_μ, $c_{e\mu}$ is also small

The size of *b*-*s*-*a* couplings is important

When BR(B_s --> *e* μ) becomes small, δS_{CP} also becomes small!