New bounds on axion-like particles from MicroBooNE

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Based on arXiv:2202.03447 **(Accepted by JHEP)**

In collaboration with Pilar Coloma, Pilar Hernández

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CIDEGENT/2018/019

ALPs (axion-like particles)

pseudo-Nambu-Goldstone bosons

spontaneous global symmetry breaking

Ubiquitous in SM extensions

¿Why this name? → QCD axion, most motivated example

Outline

Goal?

Constraining new physics as ALPs with an effective field theory approach

Via?

Production

$K \to \pi a$

Detection

$a \to \ell^+\ell^-$ $a \to \gamma\gamma$

Where?

MicroBoone

Why?

-LAr TPC can measure and distinguish well the different types of signals
-previous studies of constraining Higgs portal scalar in MicroBoone

Results

What's next?

MicroBooNE collaboration arXiv:2106.00568

Effective Lagrangian

$$\delta\mathcal{L}_{\rm EW} = c_\phi \mathcal{O}_\phi + c_B \mathcal{O}_B + c_W \mathcal{O}_W$$

$$\Lambda \propto f_a = 1\text{TeV}$$

where c_i stand for the Wilson coefficients of each operator:

$$\mathcal{O}_\phi = i\frac{\partial^\mu a}{f_a}\phi^\dagger \overleftrightarrow{D}_\mu \phi \xrightarrow{\text{Hypercharge rotation}} \frac{\partial_\mu a(x)}{f_a}\sum_F \bar{\Psi}_F \gamma^\mu \Psi_F$$

$$\mathcal{O}_B = -\frac{a}{f_a} B_{\mu\nu}\widetilde{B}_{\mu\nu}$$

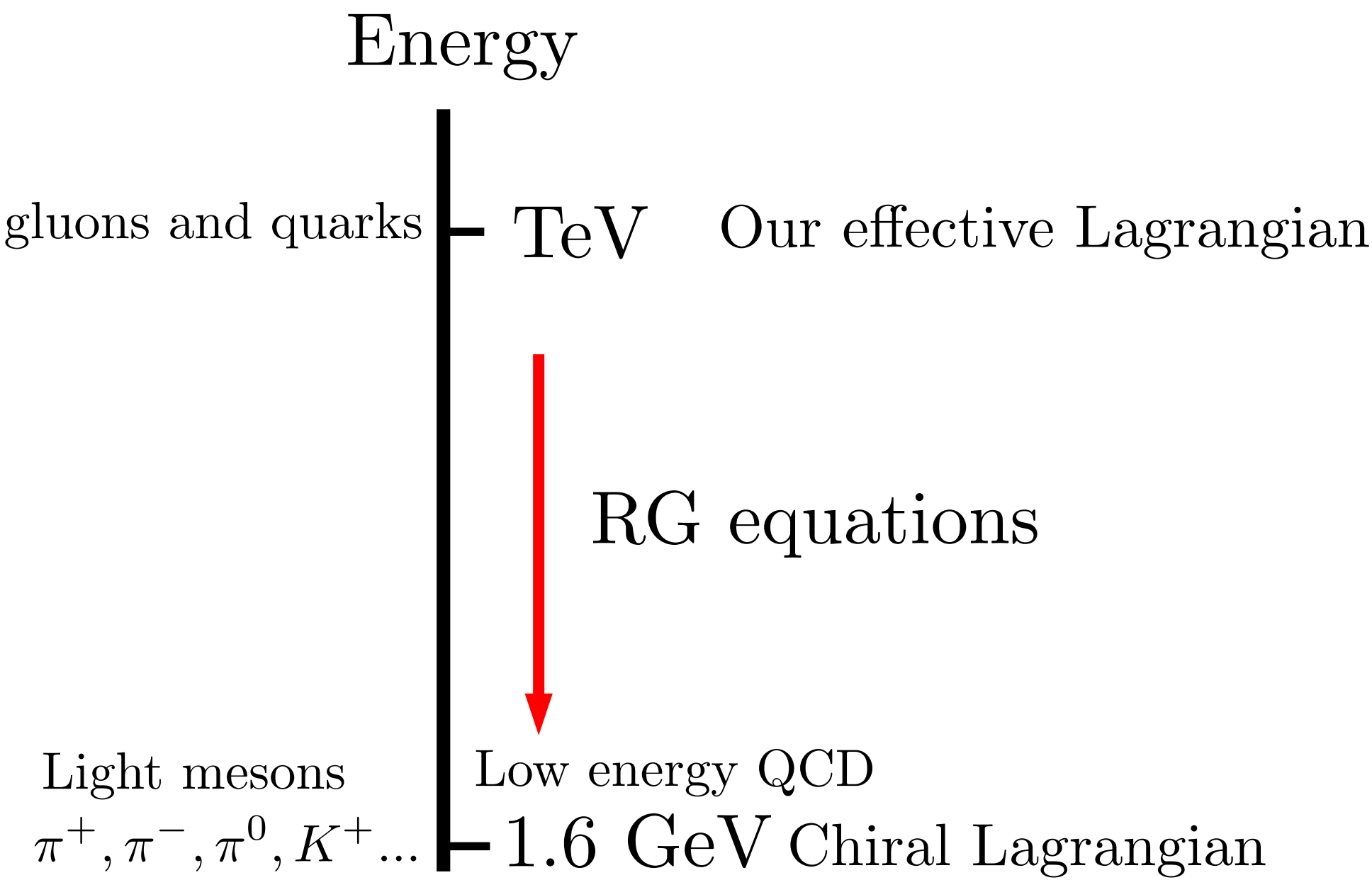
$$\mathcal{O}_W = -\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$$

M. B. Gavela, R. Houtz, et al. ArXiv:1901.02031

M. Bauer, M. Neubert, et al, arXiv:arXiv:2110.10698

H. Georgi, et al. Phys. Lett. B 169 (1986) 73.

ALPs Production



$K^+ \to \pi^+ a$

Computation

M. Bauer, M. Neubert, et al, arXiv:2012.12272

M. Bauer, M. Neubert, et al, arXiv:2102.13112

$$\Gamma\left(K^+ \to \pi^+ a\right) = \frac{m_K^3 \left|\left[k_Q\left(\mu_w\right)\right]_{sd}\right|^2}{64\pi} \lambda_{\pi a}^{1/2} \left(1 - \frac{m_\pi^2}{m_K^2}\right)^2 \propto coupling^2$$

$$\left.\frac{\left[k_Q\left(\mu_w\right)\right]_{ds}}{V_{td}^* V_{ts}}\right|_{\Lambda=1\mathrm{TeV}} \simeq \underbrace{-9.7 \times 10^{-3} c_W(\Lambda) + 8.2 \times 10^{-3} c_\phi(\Lambda)}_{\textbf{Leading terms}} - 3.5 \times 10^{-5} c_B(\Lambda)$$

Detection: ALPs decays

$$m_a > 2m_\ell$$

$$\Gamma\left(a \to \ell^+\ell^-\right) = |c_{\ell\ell}|^2 \frac{m_a m_\ell^2}{8\pi f_a^2} \sqrt{1 - \frac{4m_\ell^2}{m_a^2}} \propto m_\ell^2$$

$$c_{\ell\ell} = c_\phi + \text{small corrections}(c_W, c_B)$$

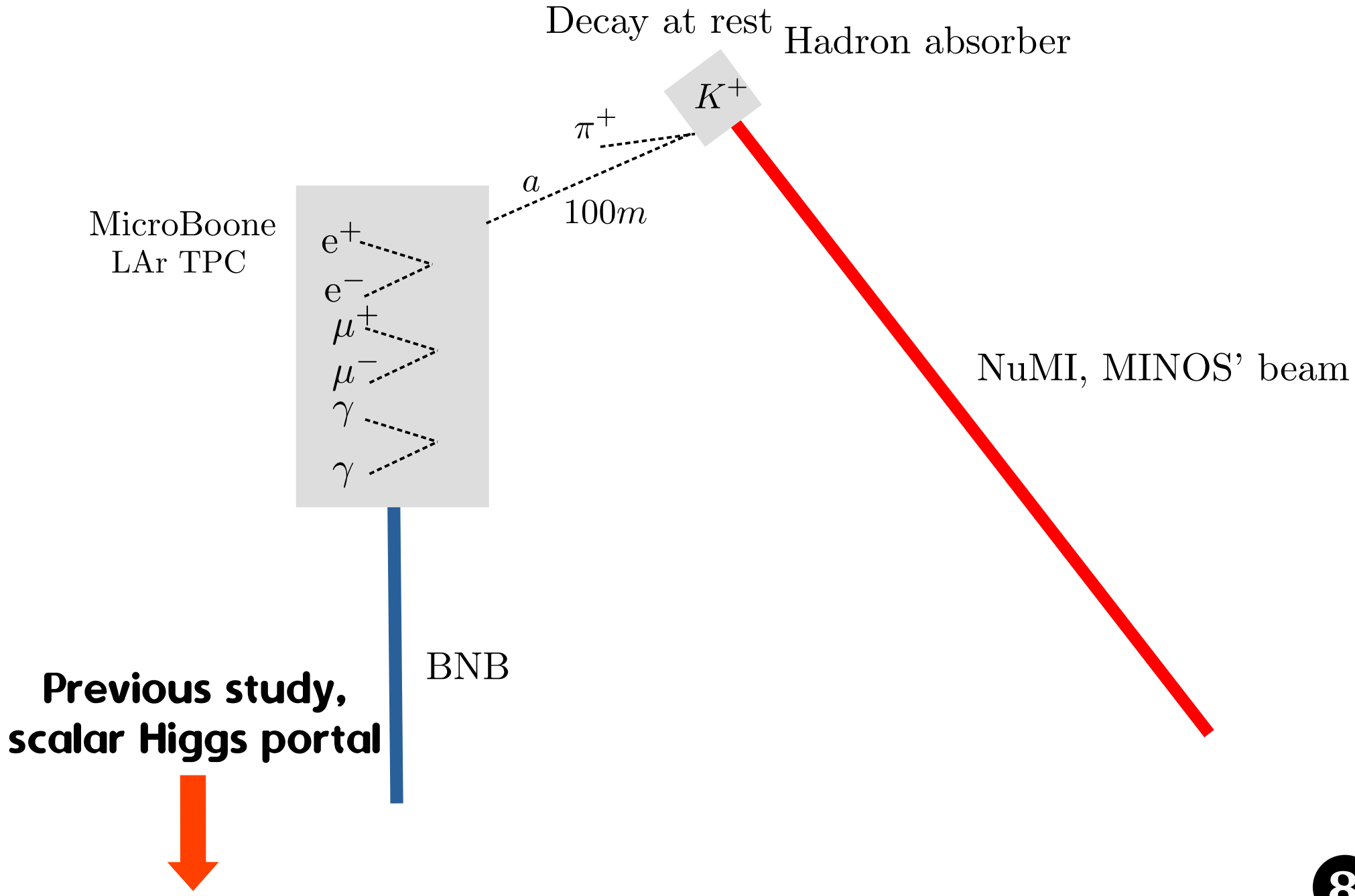
$$\Gamma(a \to \gamma\gamma) = |c_{\gamma\gamma}|^2 \frac{m_a^3}{4\pi f_a^2}$$

$$c_{\gamma\gamma} = c_W s_w^2 + c_B c_w^2 + \text{small corrections}(c_W, c_\phi)$$

Detection: ALPs decays

	c_ϕ dominated	c_W dominated
$m_a < 2m_\mu$	$\mathrm{BR}(\mathrm{a} \to e^+e^-) \approx 1$	$\mathrm{BR}(\mathrm{a} \to \gamma\gamma) \approx 1$
$m_a > 2m_\mu$	$\mathrm{BR}(\mathrm{a} \to \mu^+\mu^-) \approx 1$	$\mathrm{BR}(\mathrm{a} \to \gamma\gamma) \approx 1$

Experimental set-up



Previous study, scalar Higgs portal

MicroBooNE collaboration arXiv:2106.00568

Number of events

$$N_{\text{events}} = N_K \times \text{BR}(K \to \pi a) \times \text{BR}\,(a \to XX) \times$$
$$\times \text{Efficiency} \times \text{Detector Acceptance} \times P_{\text{decay}}$$

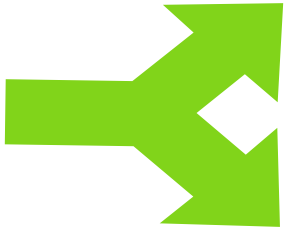
L_a = Lifetime of the ALPs

$\Delta\ell_{\text{ det}}$ = Detector length

$\ell_{det} = 100m$

Large couplings $e^{-\frac{\ell_{\text{det}}}{L_a}}$

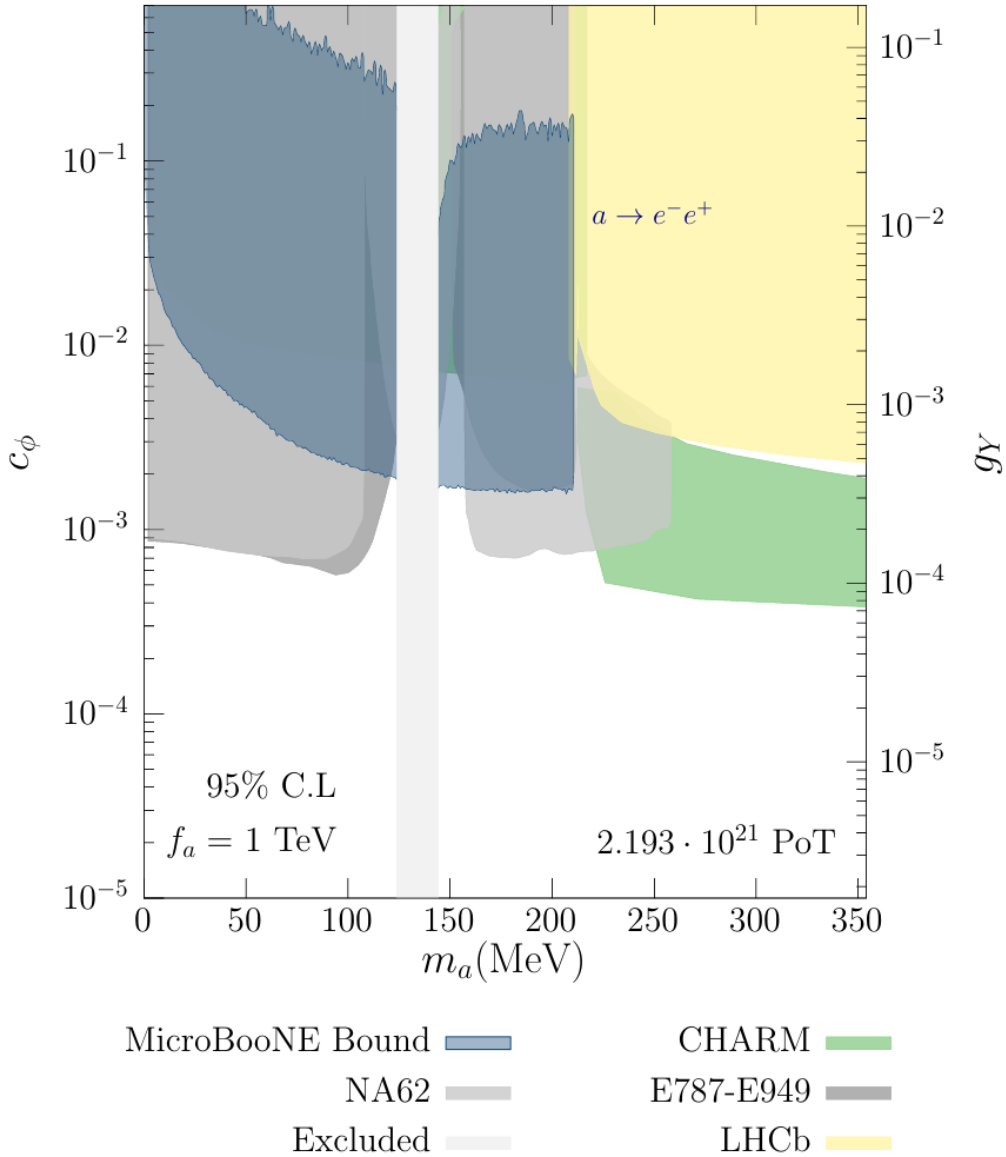
$$P_{\text{decay}} = e^{-\frac{\ell_{\text{det}}}{L_a}} \times \left[1 - e^{-\frac{\Delta\ell_{\text{det}}}{L_a}}\right]$$



Small couplings $1 - e^{-\frac{\Delta\ell_{\text{det}}}{L_a}} \propto (coupling)^2$

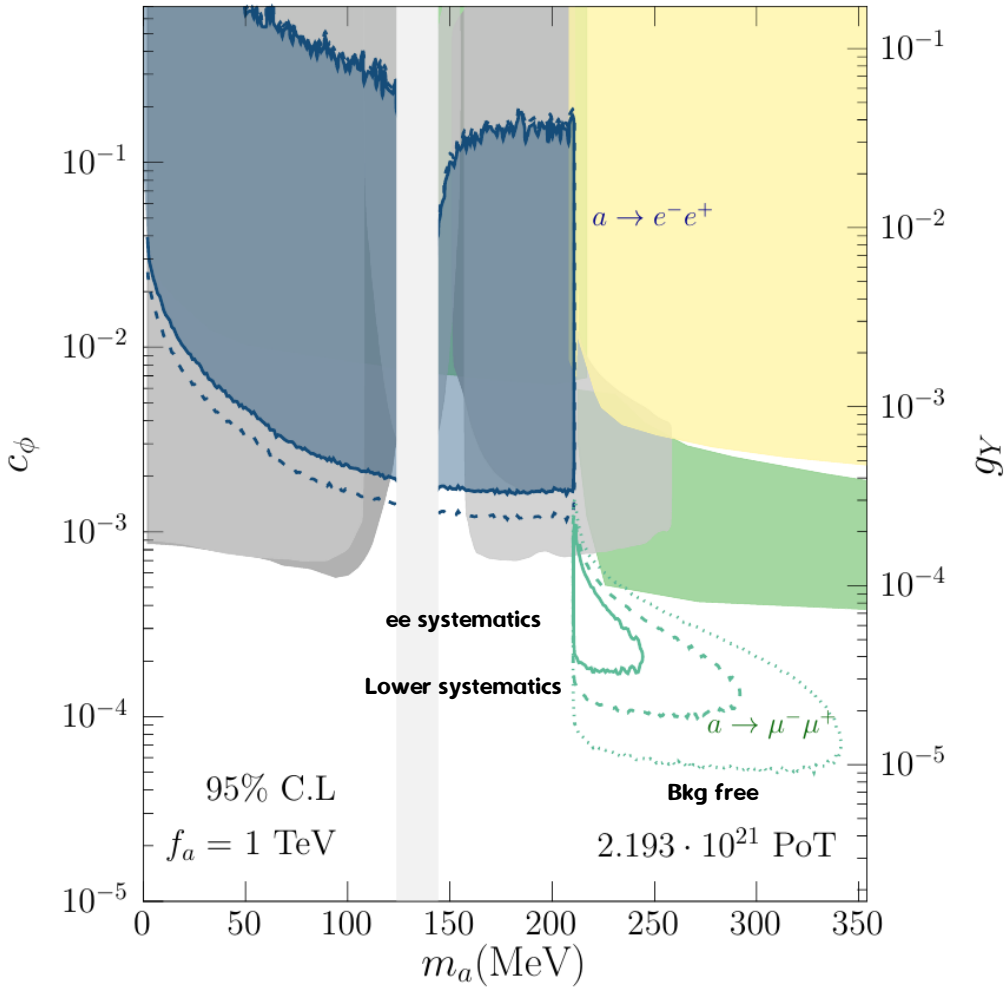
Main results

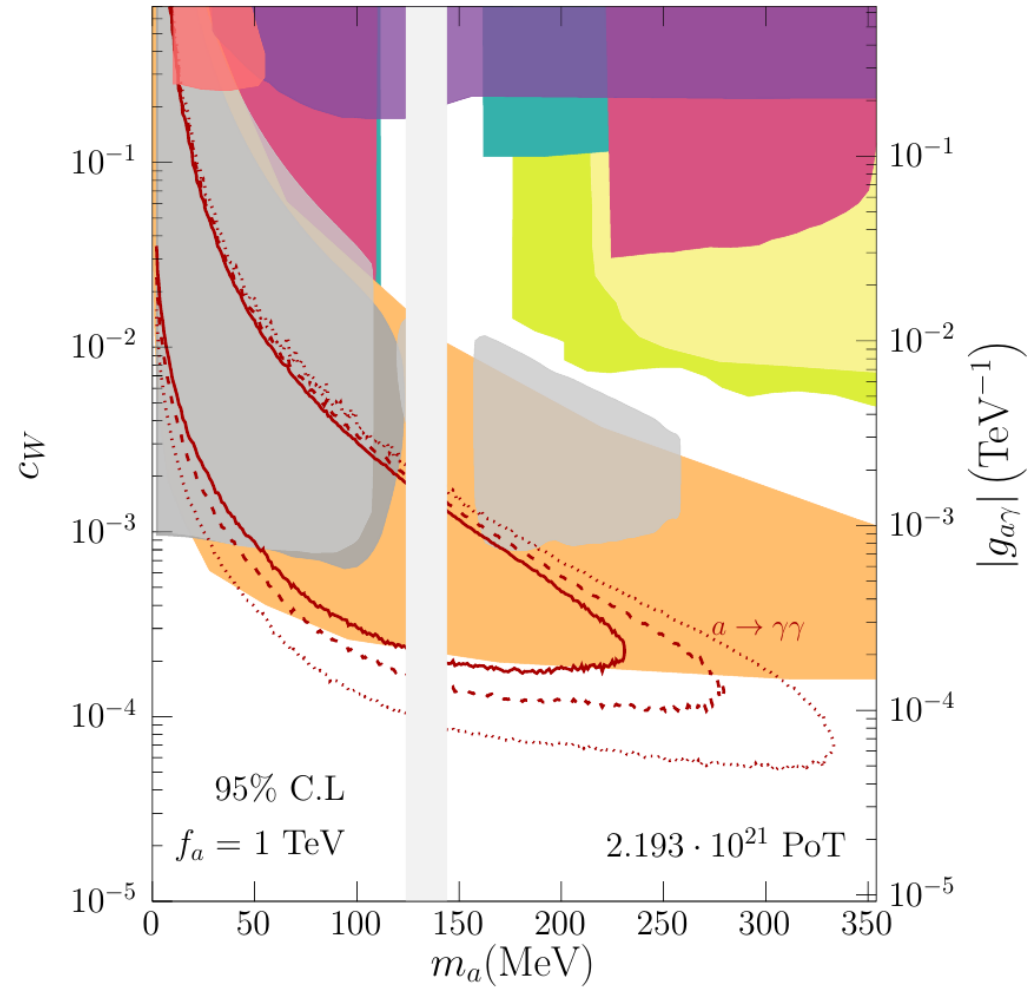
Bound using MicroBoone data



P. Coloma, P. Hernández, S. Urrea. arXiv:2202.03447

Future prospects





MicroBooNE Bound
e^-e^+, MicroBooNE
$\mu^-\mu^+$, MicroBooNE
$\gamma\gamma$, MicroBooNE
CHARM
E787-E949
LHCb
Excluded
BaBar
KTeV&NA48/2
E949&NA62
E137
NA62
LEP
NA64

P. Coloma, P. Hernández, S. Urrea. arXiv:2202.03447

MicroBooNE collaboration arXiv:2207.03840

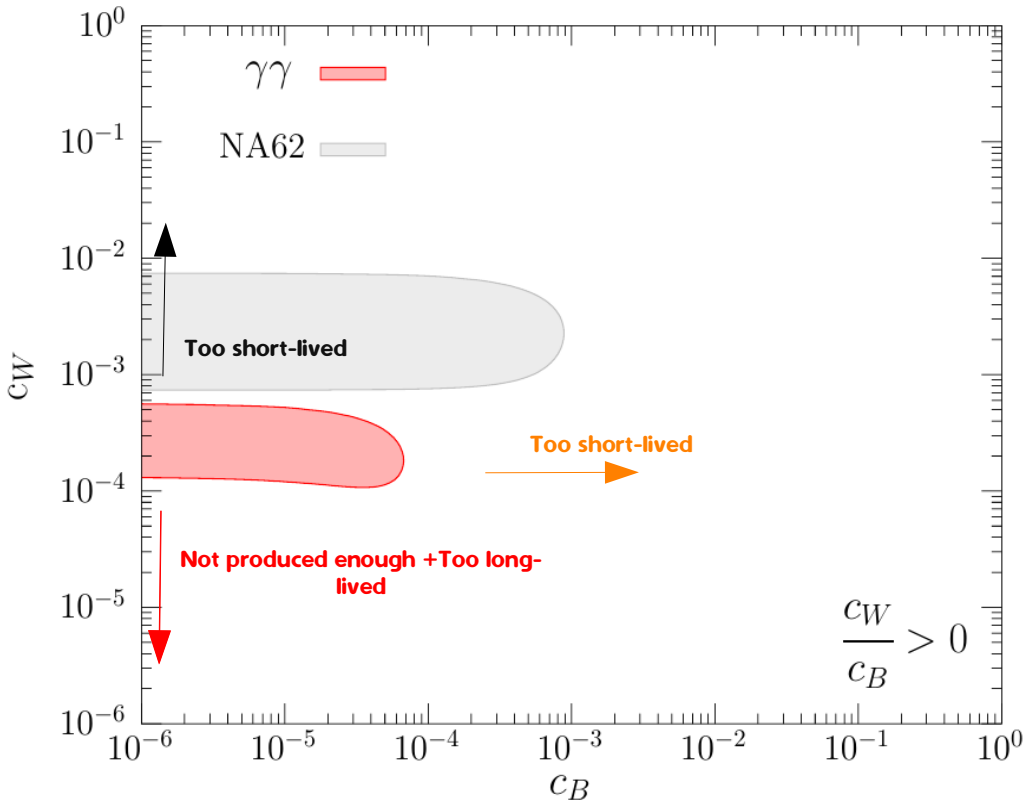
Recent paper(8th July), put out after our paper

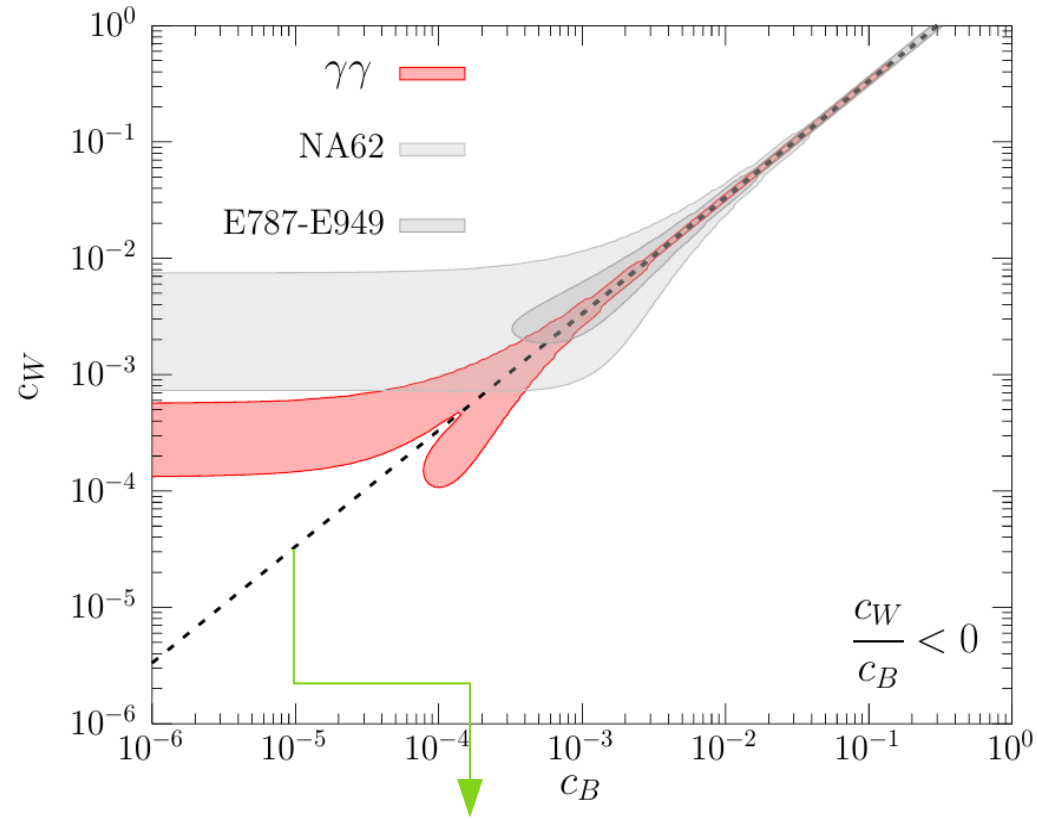
Higgs portal $\mu^-\mu^+$

Recasting to ALPs, in good agreement with our lower systematics line

More results

c_W vs c_B m_a =200MeV



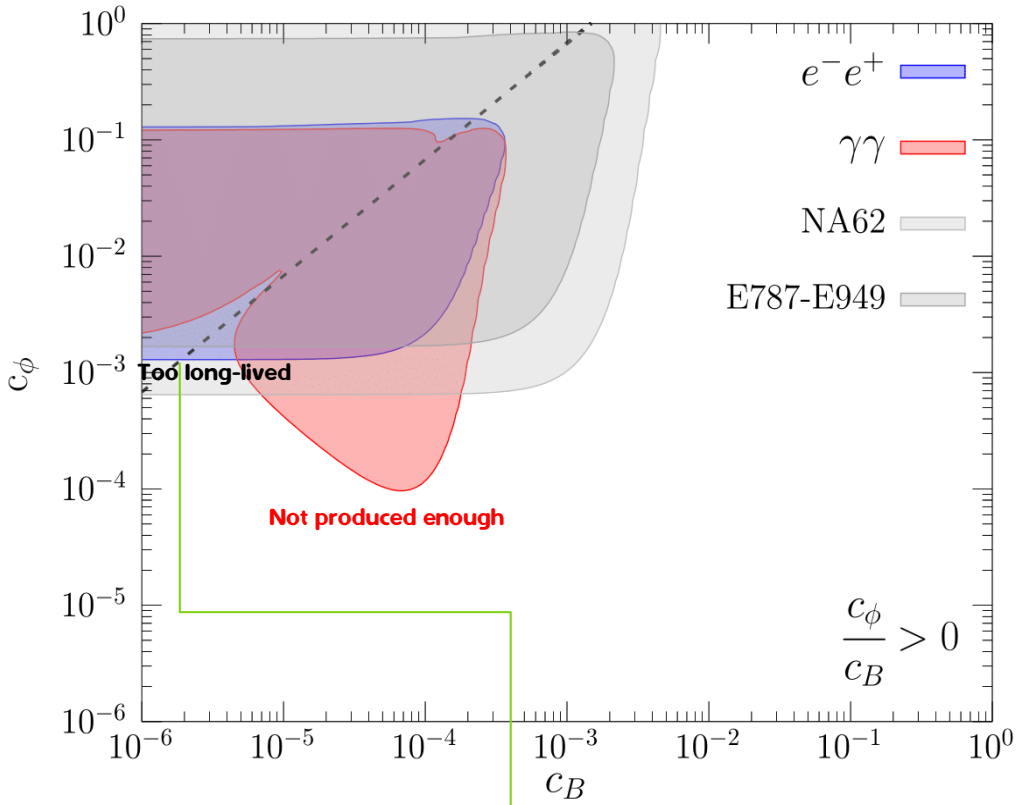


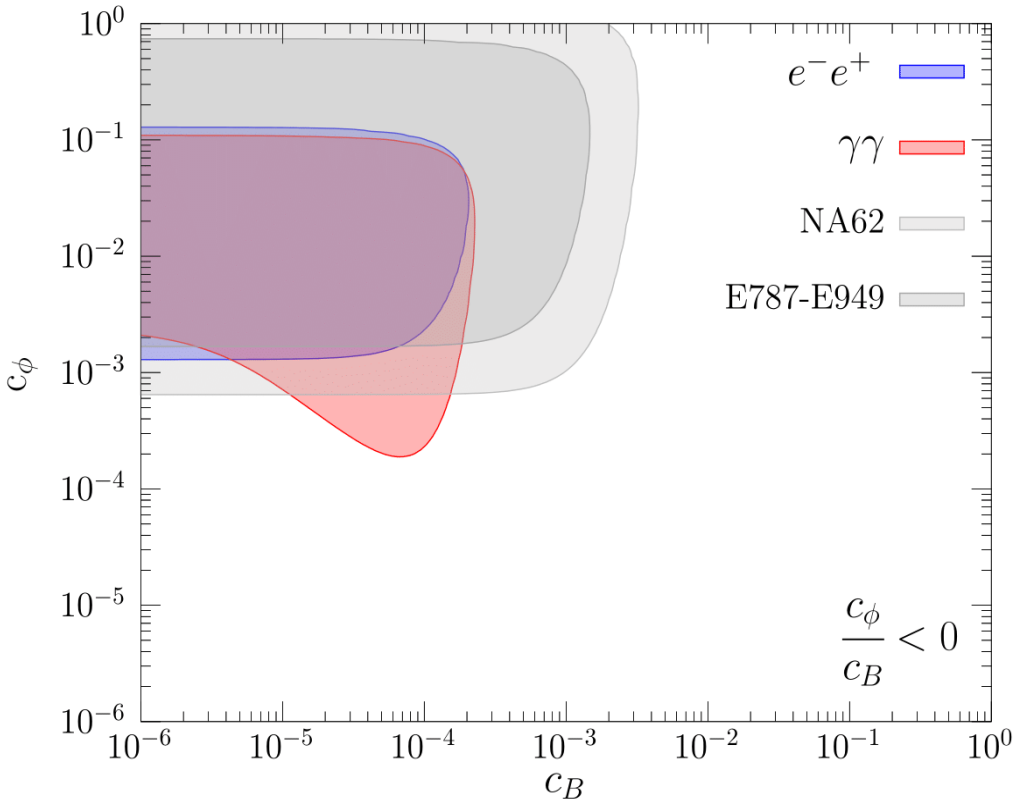
Detection

$$c_{\gamma\gamma} = c_W s_w^2 + c_B c_w^2 + \text{ small corrections } (c_W, c_\phi) \quad \Rightarrow \quad c_{\gamma\gamma} \approx 0 \quad \Leftrightarrow \quad c_W s_w^2 \sim c_B c_w^2$$

$$c_{\ell\ell} = c_\phi + \text{ small corrections } (c_W, c_B)$$

c_ϕ vs c_B m_a =200MeV





Detection

$$c_{\gamma\gamma} = c_W s_w^2 + c_B c_w^2 + c_\phi \frac{\alpha}{4\pi} \frac{m_a^2}{m_\pi^2 - m_a^2} + \text{ small corrections } (c_W, c_\phi)$$

$$c_{\ell\ell} = c_\phi + \text{ small corrections } (c_W, c_B)$$

$$c_{\gamma\gamma} \approx 0$$

$$c_B \sim m_a^2 / \left(m_a^2 - m_\pi^2\right) c_\phi \alpha / \left(4 c_w^2 \pi\right)$$

What's next?

-We encourage the MicroBoone collaboration to search for ALPs as well. Particularly the diphoton channel

-Probe this Physics in future experiments like DUNE(We are working on it! Soon in Arxive!)

Thank you

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

Gen-T

GENERALITAT VALENCIANA

HIDDeν

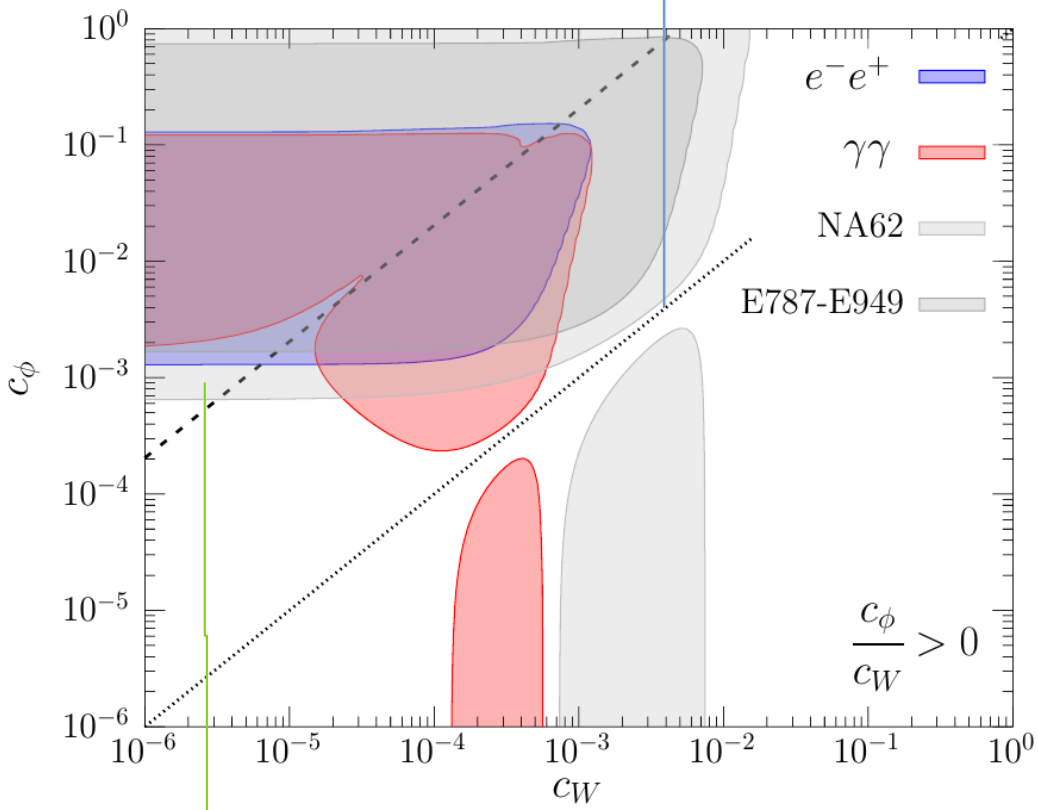
UAM Universidad Autónoma de Madrid

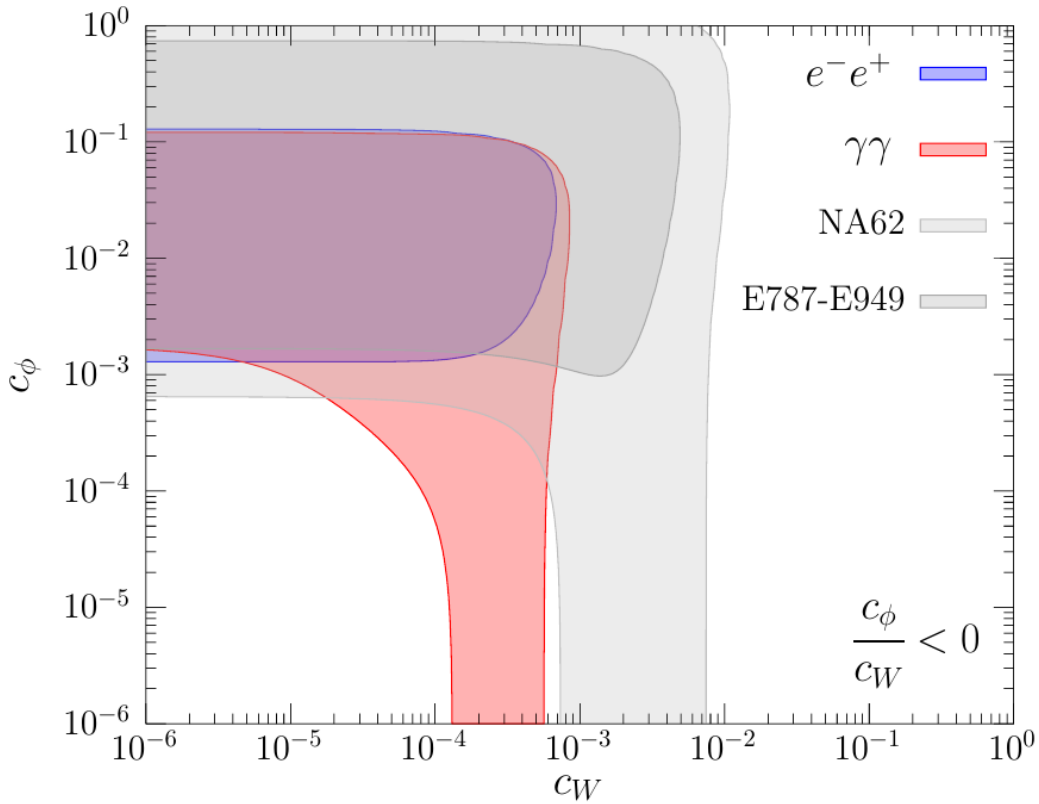
ift Instituto de Física Teórica UAM-CSIC

Back-up

Production

$$\left.\frac{[k_Q(\mu_w)]_{ds}}{V_{td}^* V_{ts}}\right|_{\Lambda=1\mathrm{TeV}} \simeq \underline{-9.7\times10^{-3} c_W(\Lambda) + 8.2\times10^{-3} c_\phi(\Lambda)} - 3.5\times10^{-5} c_B(\Lambda)$$





Detection

$$c_{\gamma\gamma} = c_W s_w^2 + c_B c_w^2 + c_\phi \frac{\alpha}{4\pi}\frac{m_a^2}{m_\pi^2 - m_a^2} + \text{ small corrections}\,(c_W, c_\phi)$$

$$c_{\ell\ell} = c_\phi + \text{ small corrections}\,(c_W, c_B)$$

$$c_{\gamma\gamma} \approx 0$$

$$c_W \sim m_a^2/\left(m_a^2 - m_\pi^2\right) c_\phi \alpha/\left(4 s_w^2 \pi\right)$$

Hypercharge rotation

$$ic_\phi \frac{\partial^\mu a}{f_a} \phi^\dagger \overleftrightarrow{D}_\mu \phi$$

$$\phi \to e^{ic_\phi \frac{a}{fa}} \phi$$

$$\Psi_F \to e^{2iY_F c_\phi \frac{a}{fa}} \Psi_F$$

$$\frac{\partial_\mu a(x)}{f_a} \left(\sum_q \bar{q}_R k_q \gamma^\mu q_R + \sum_Q \bar{Q}_L k_Q \gamma^\mu Q_L \right)$$

$$k_u(\Lambda) = -\frac{4}{3} c_\phi(\Lambda), \quad k_d(\Lambda) = \frac{2}{3} c_\phi(\Lambda), \quad k_Q(\Lambda) = -\frac{1}{3} c_\phi(\Lambda)$$

$$k_e(\Lambda) = 2c_\phi(\Lambda), \quad k_L(\Lambda) = c_\phi(\Lambda)$$

Loop functions

$$B_0 = \left(\sum_{f=c,t} N_c Q_f^2 B_1\left(\tau_f\right) - \sum_{f=b,\ell_\alpha^-} N_c Q_f^2 B_1\left(\tau_f\right) \right)$$

$$B_1(\tau) = 1 - \tau f^2(\tau)$$
$$B_2(\tau) = 1 - (\tau - 1) f^2(\tau)$$

$$f(\tau) = \begin{cases} \arcsin \frac{1}{\sqrt{\tau}}; & \tau \geq 1 \\ \frac{\pi}{2} + \frac{i}{2} \ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}; & \tau < 1 \end{cases}$$

$$\tau_f \equiv 4m_f^2/m_a^2, Q_f$$

Full expresions

$$c_{\gamma\gamma} = c_W \left[s_w^2 + \frac{2\alpha}{\pi} B_2\left(\tau_W\right) \right] + c_B c_w^2 - c_\phi \frac{\alpha}{4\pi} \left(B_0 - \frac{m_a^2}{m_\pi^2 - m_a^2} \right).$$

$$c_{\ell\ell} = c_\phi + \frac{3\alpha}{4\pi} \left(\frac{3c_W}{s_w^2} + \frac{5c_B}{c_w^2} \right) \log \frac{f_a}{m_W} + \frac{6\alpha}{\pi} \left(c_B c_w^2 + c_W s_w^2 \right) \log \frac{m_W}{m_\ell}$$