New bounds on axion-like particles from neutrino experiments

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Based on arXiv:2202.03447
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In collaboration with Pilar Coloma, Pilar Hernández

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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

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

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

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

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

where c_i stand for the Wilson coefficients of each operator:

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

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

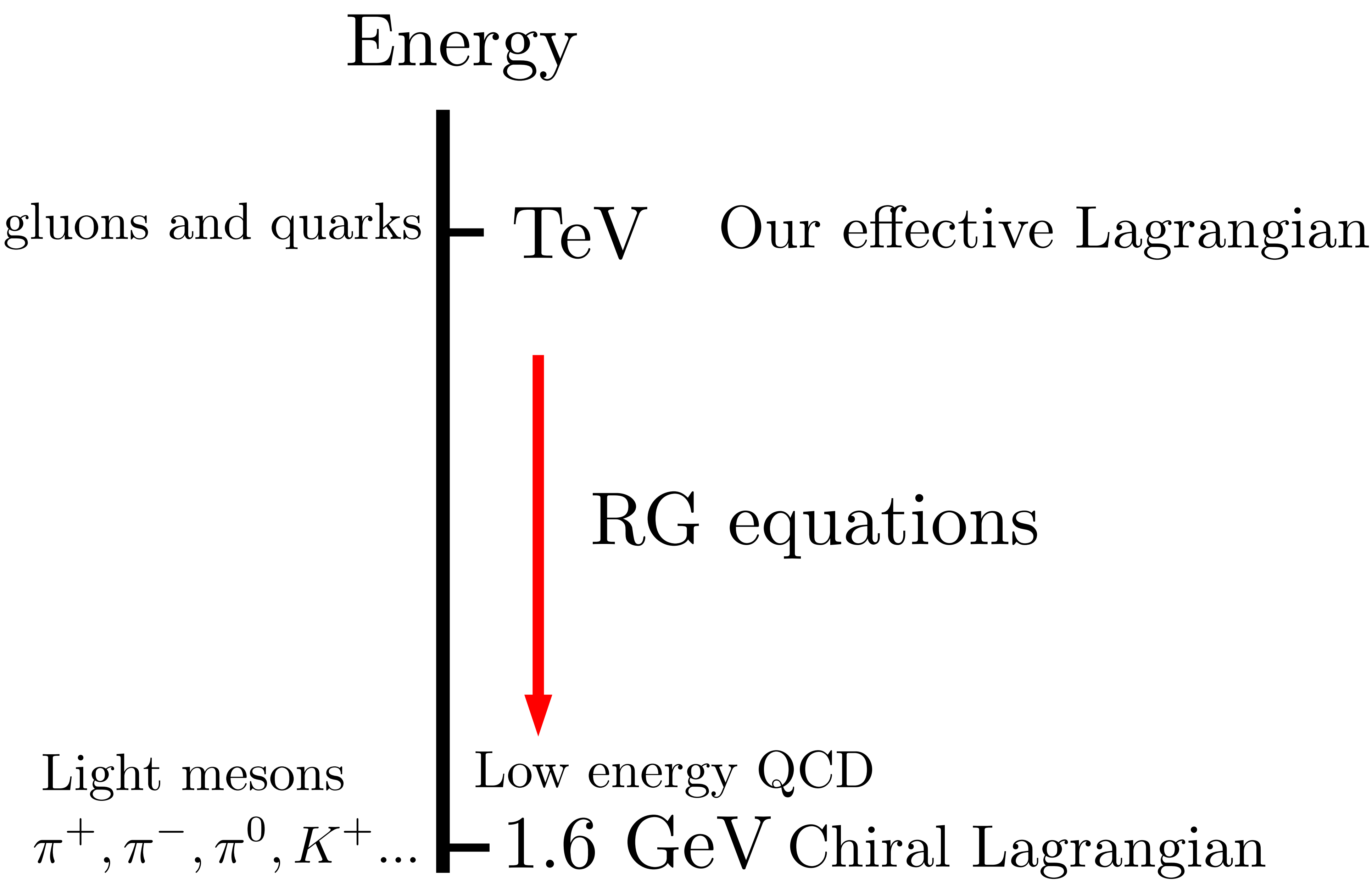
$$\mathcal{O}_W = -\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$$

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

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

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

Leading terms

Detection: ALPs decays

$$m_a > 2m_\ell$$

⬆

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

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

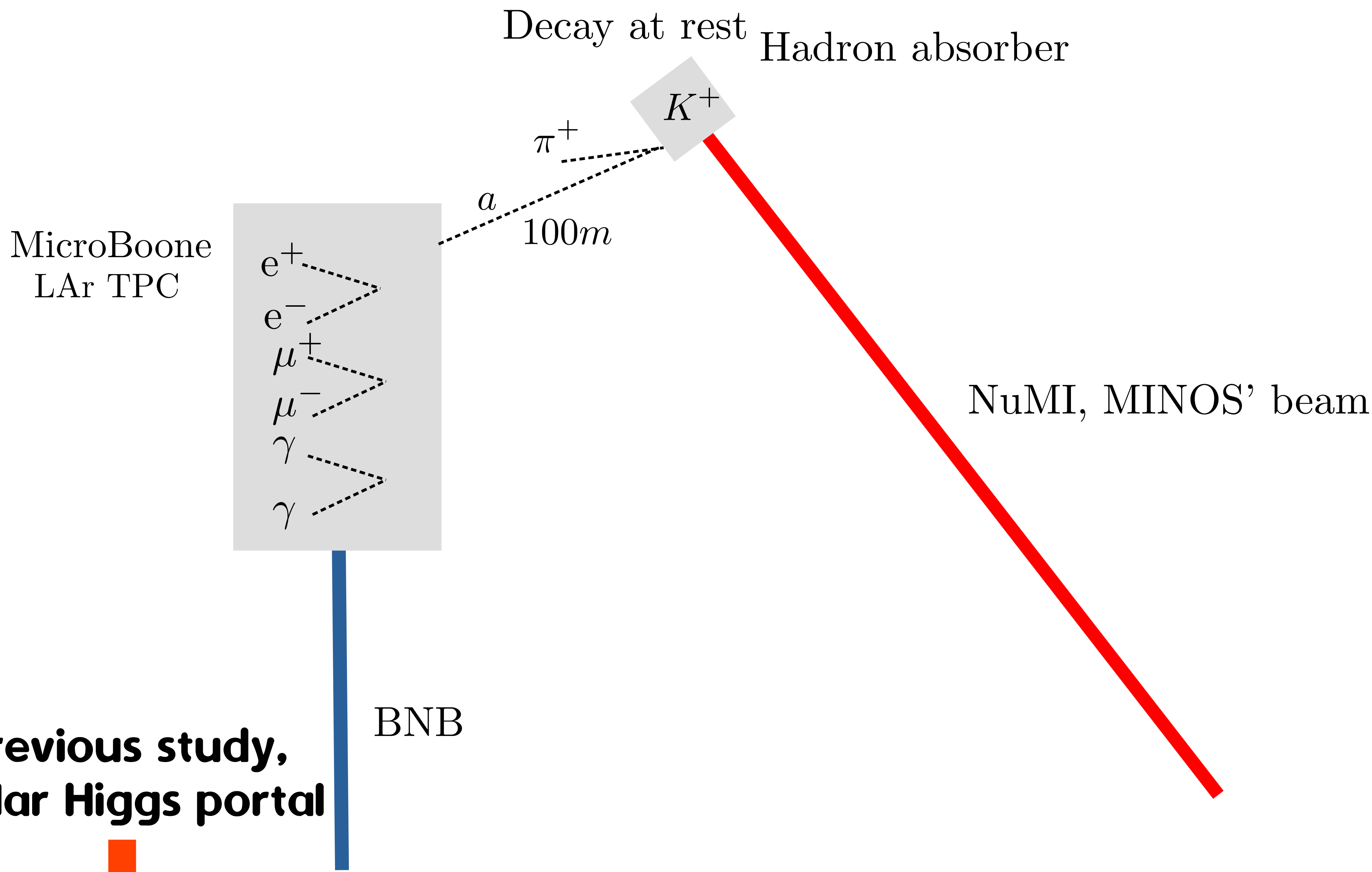
$$\Gamma(a \to \gamma\gamma) = |c_{\gamma\gamma}|^2 \, \frac{m_a^3}{4\pi f_a^2}$$

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

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

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

$L_a = \text{Lifetime of the ALPs}$

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

$\ell_{det} = 100m$

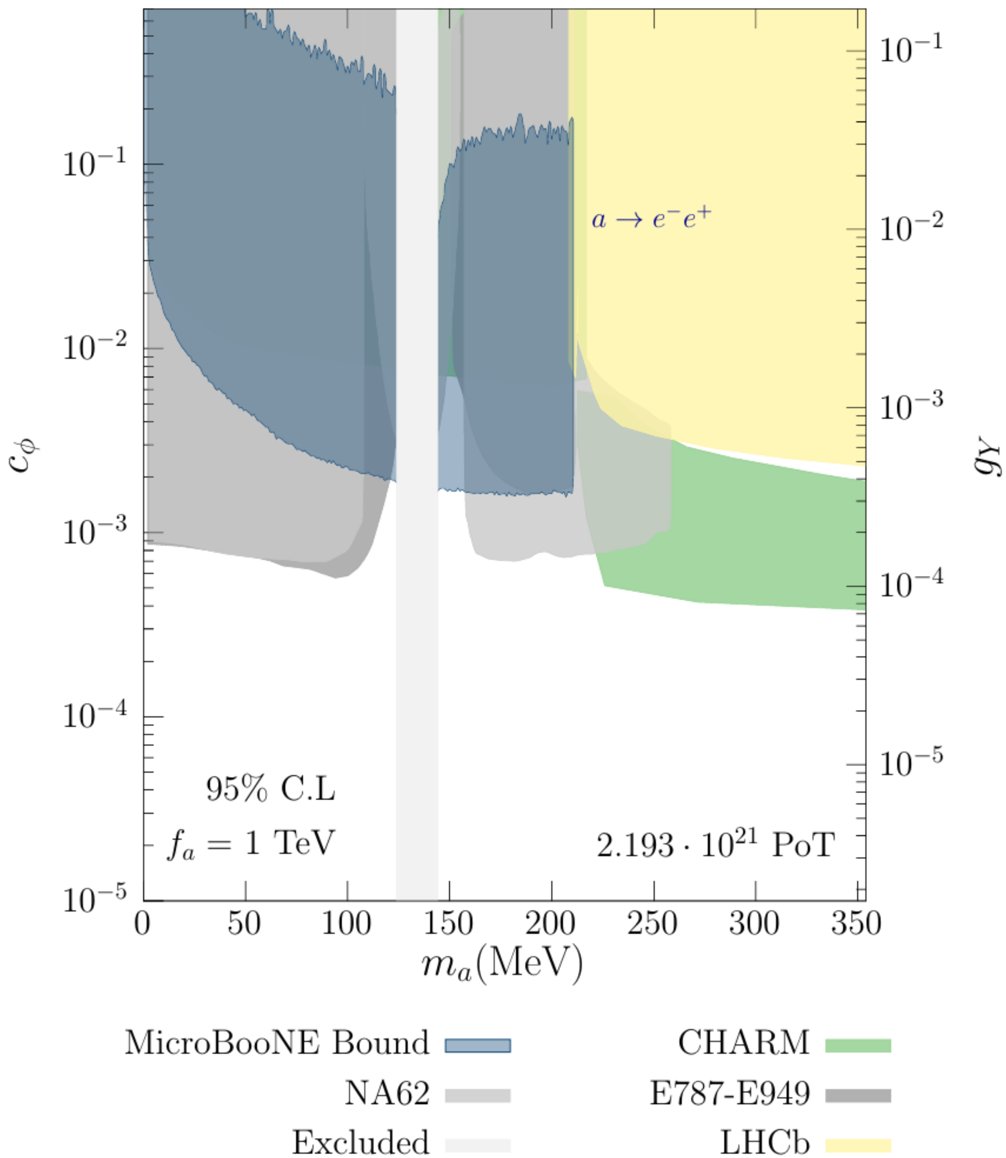
Large couplings $e^{-\frac{\ell_{\text{det}}}{L_a}}$

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

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

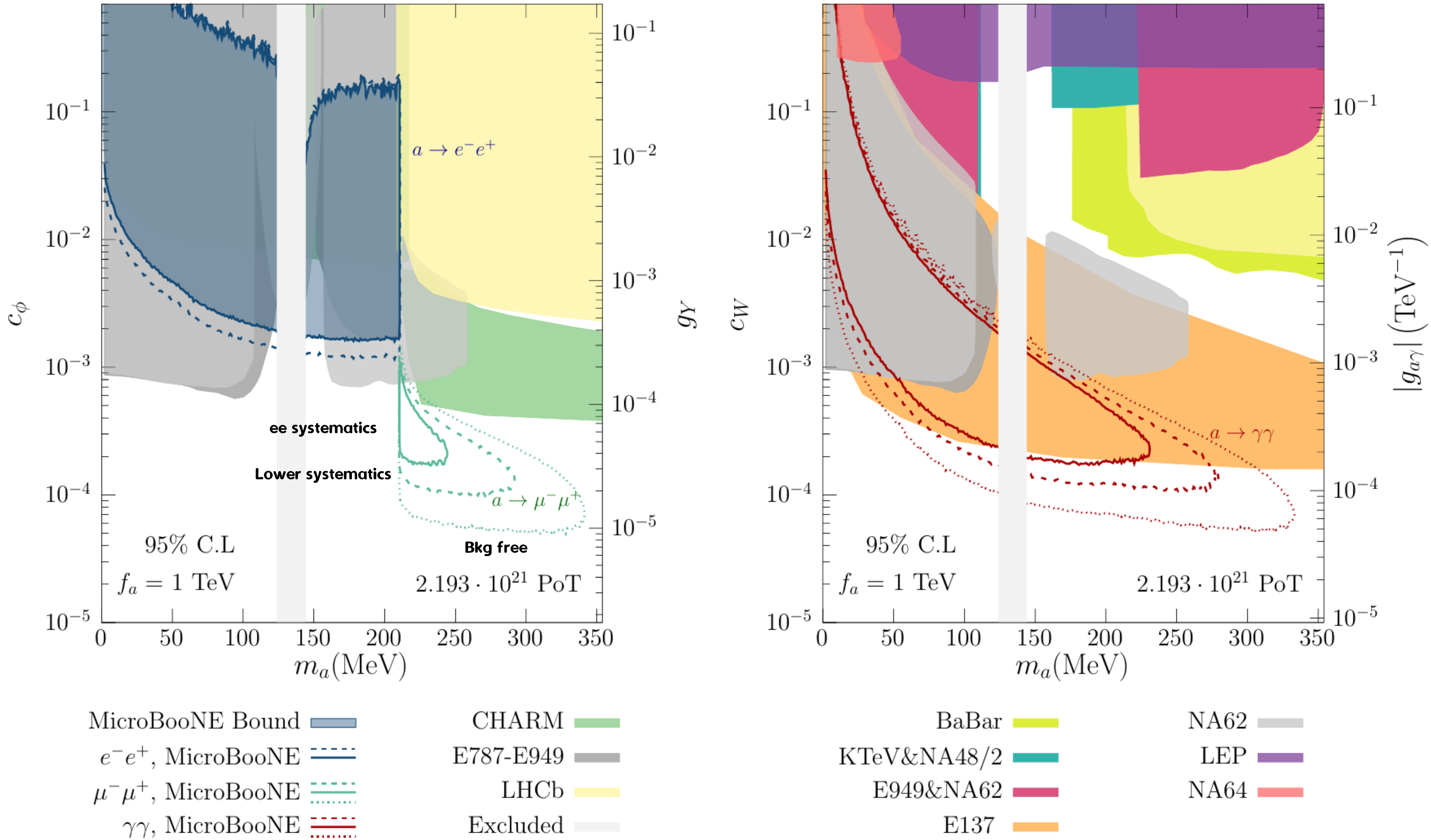
Main results

Bound using MicroBoone data



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

Future prospects



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

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

Back-up

Hypercharge rotation

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

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

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

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

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

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

Loop functions

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

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

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

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

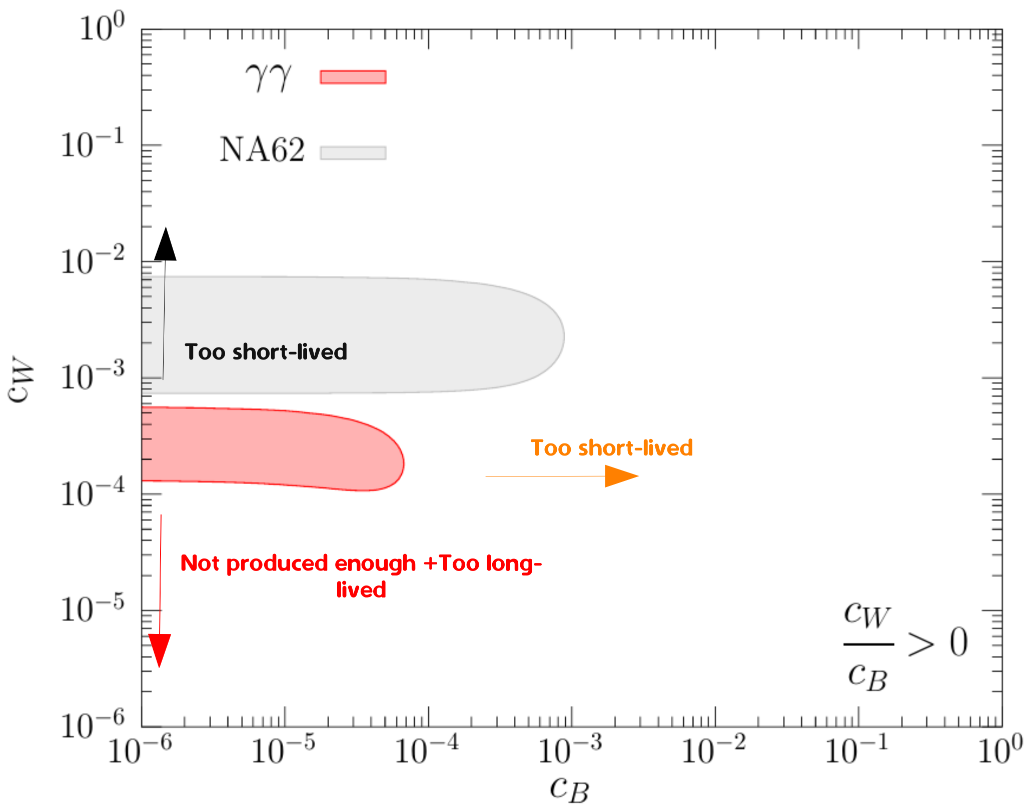
Full expresions

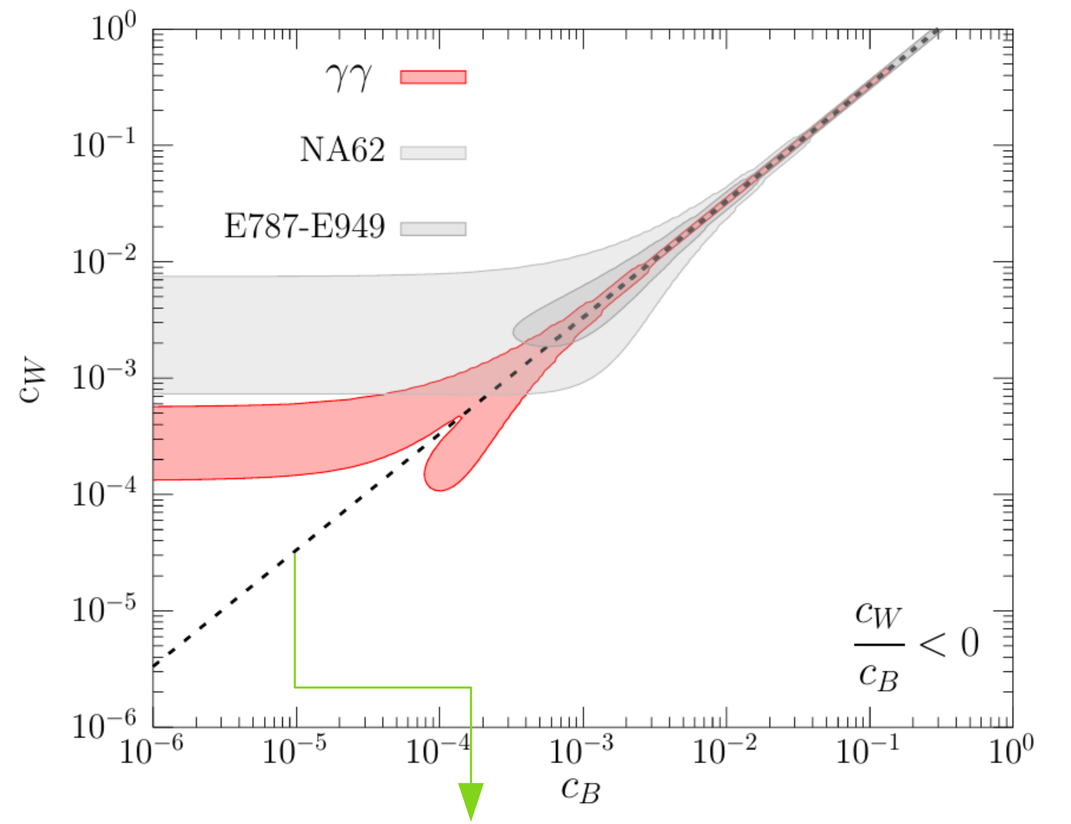
$$c_{\gamma\gamma} = c_W \left[s_w^2 + \frac{2\alpha}{\pi} B_2\left(\tau_W\right) \right] + c_B c_w^2 - c_\phi \frac{\alpha}{4\pi} \left(B_0 - \frac{m_a^2}{m_\pi^2 - m_a^2} \right).$$

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

More results

c_W vs c_B m_a =200MeV



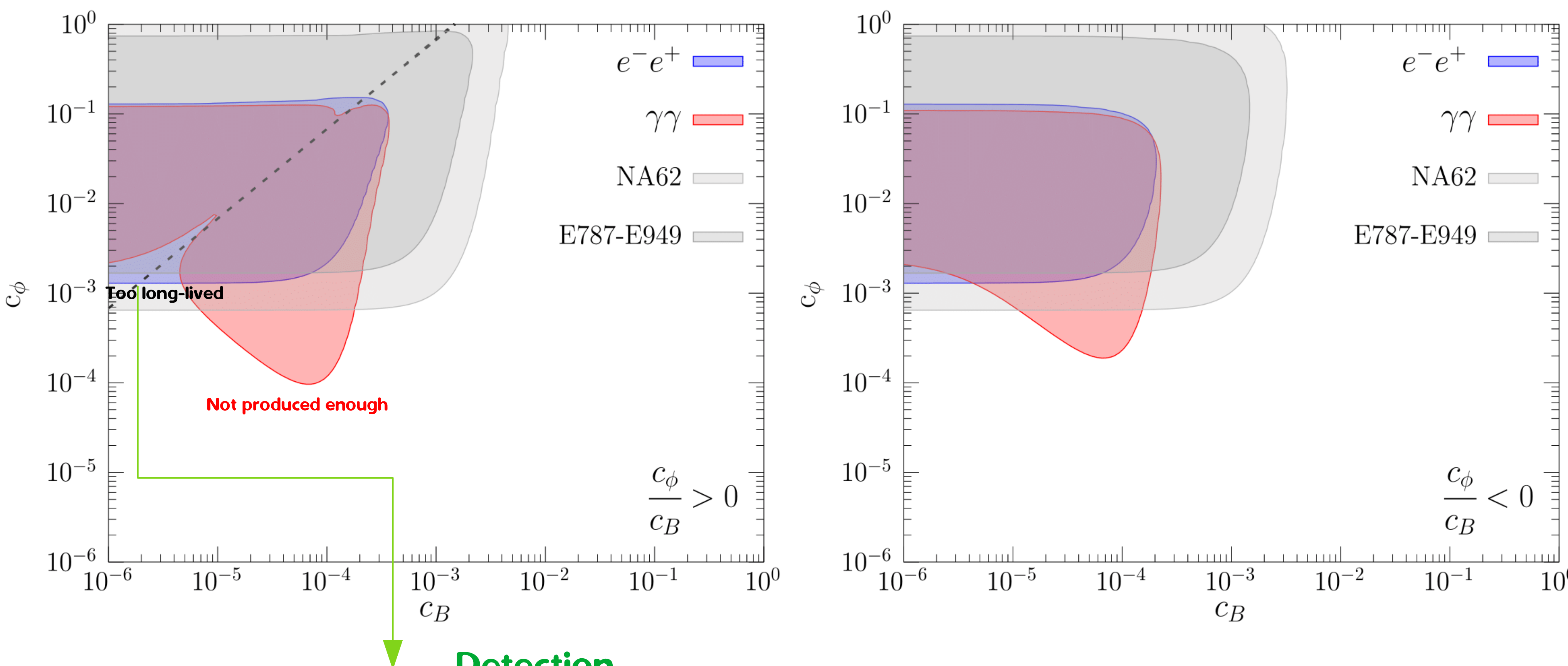


Detection

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

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

c_ϕ vs c_B m_a =200MeV



Detection

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

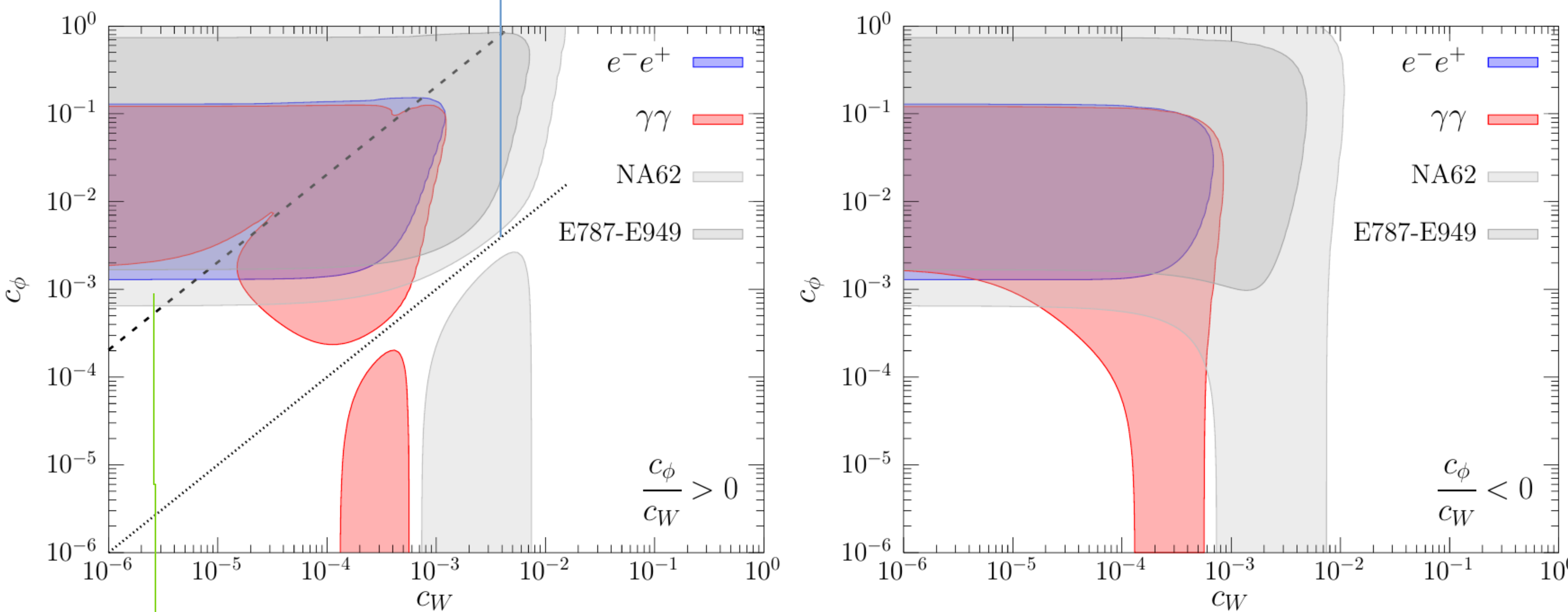
$$c_{\ell\ell} = c_\phi + \text{ small corrections} \, (c_W, c_B)$$

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

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

Production

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



Detection

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

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

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