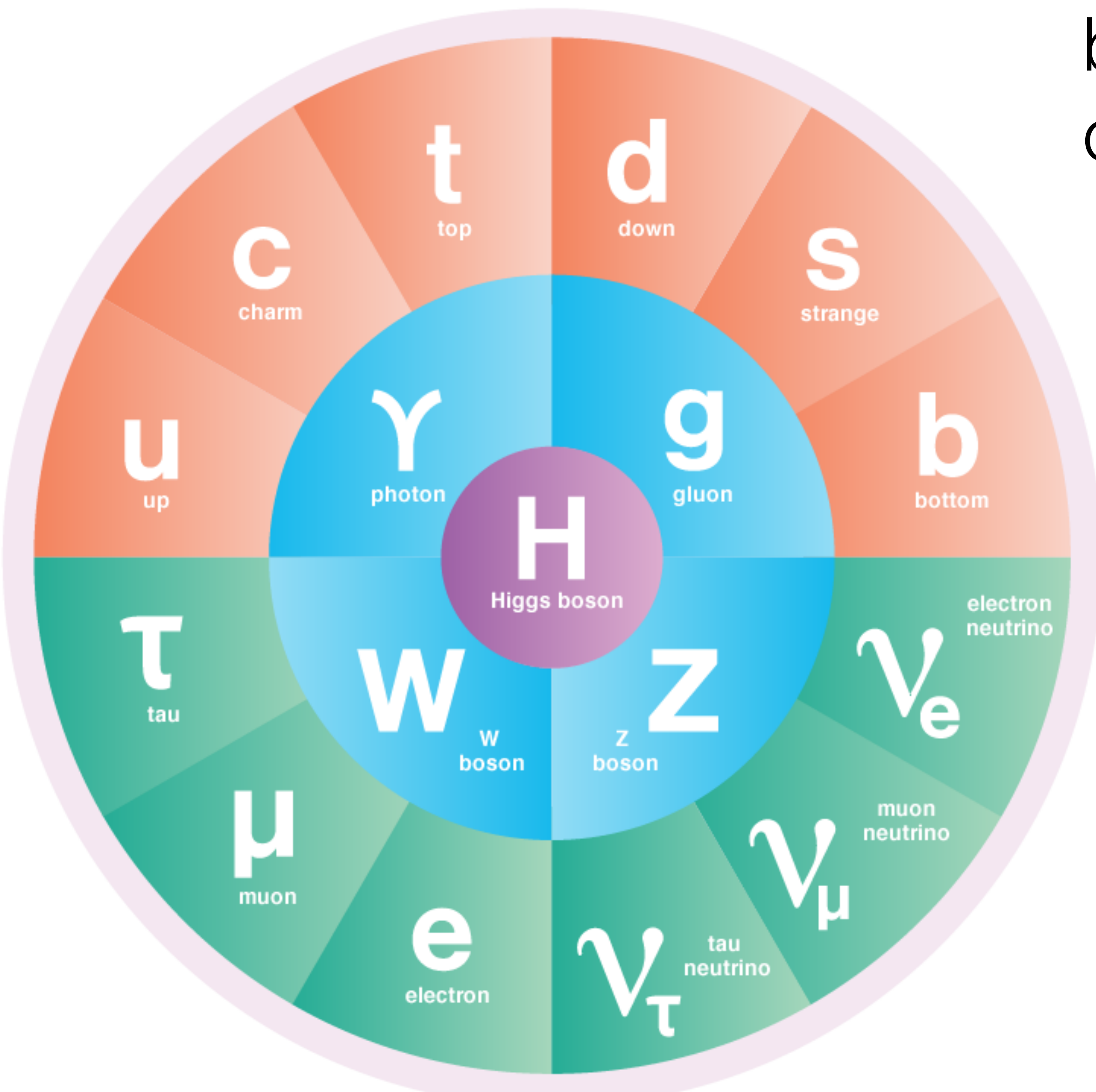
The Standard Model is complete

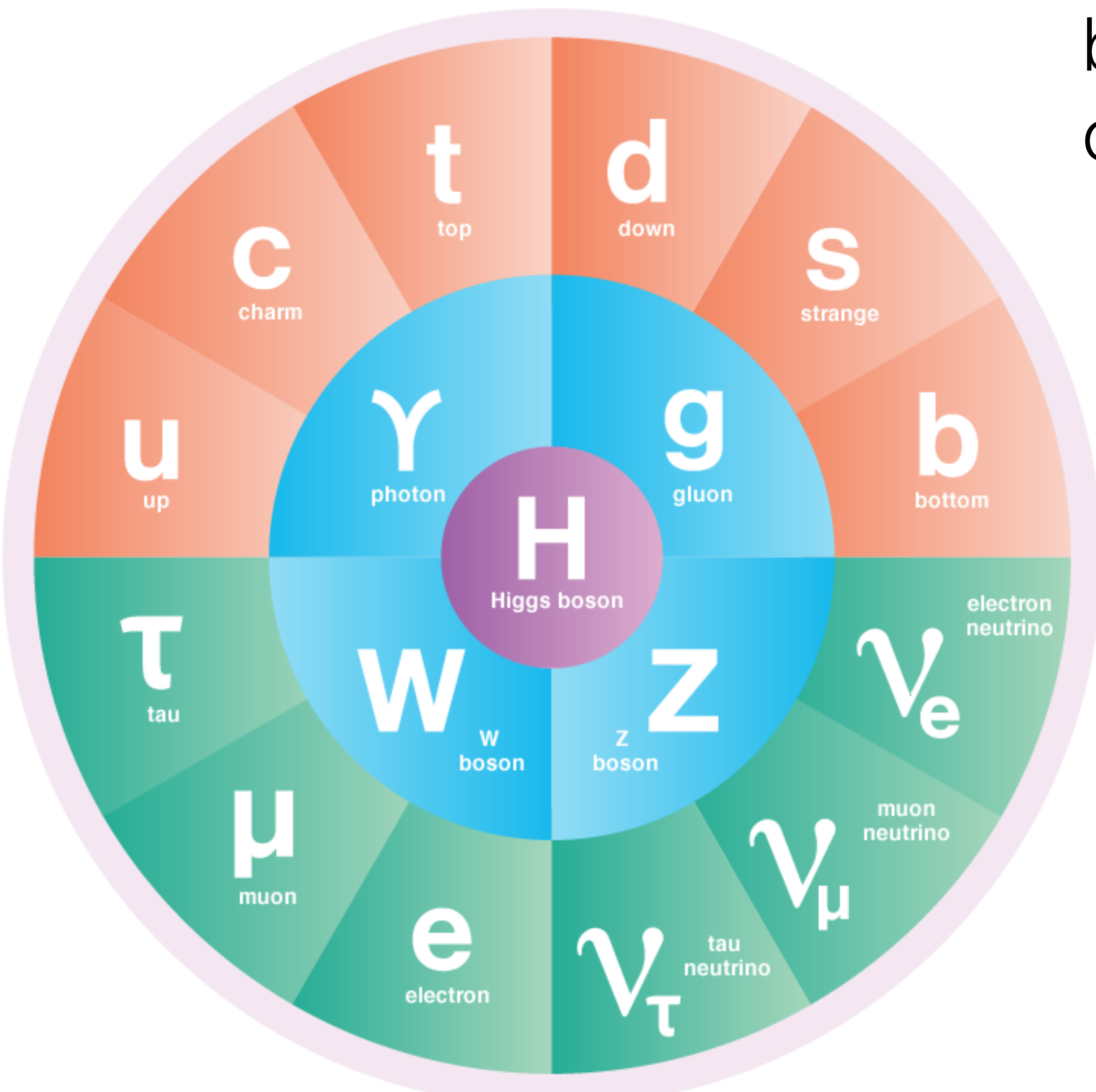


With the discovery of the Higgs boson the Standard Model is complete.

The LHC has confirmed that there are no strongly coupled new states close to the TeV scale (unless they hide).

We are less sure about very heavy states or weakly coupled New Physics.

The Standard Model is complete



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The LHC has confirmed that there are no strongly coupled new states close to the TeV scale (unless they hide).

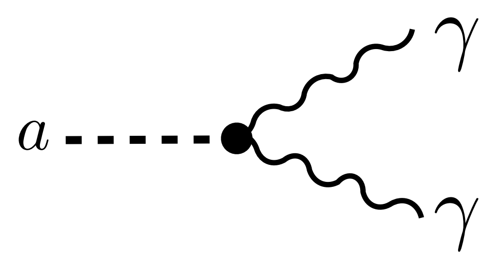
We are less sure about very heavy states or weakly coupled New Physics.

More generally: There is a lifetime gap.

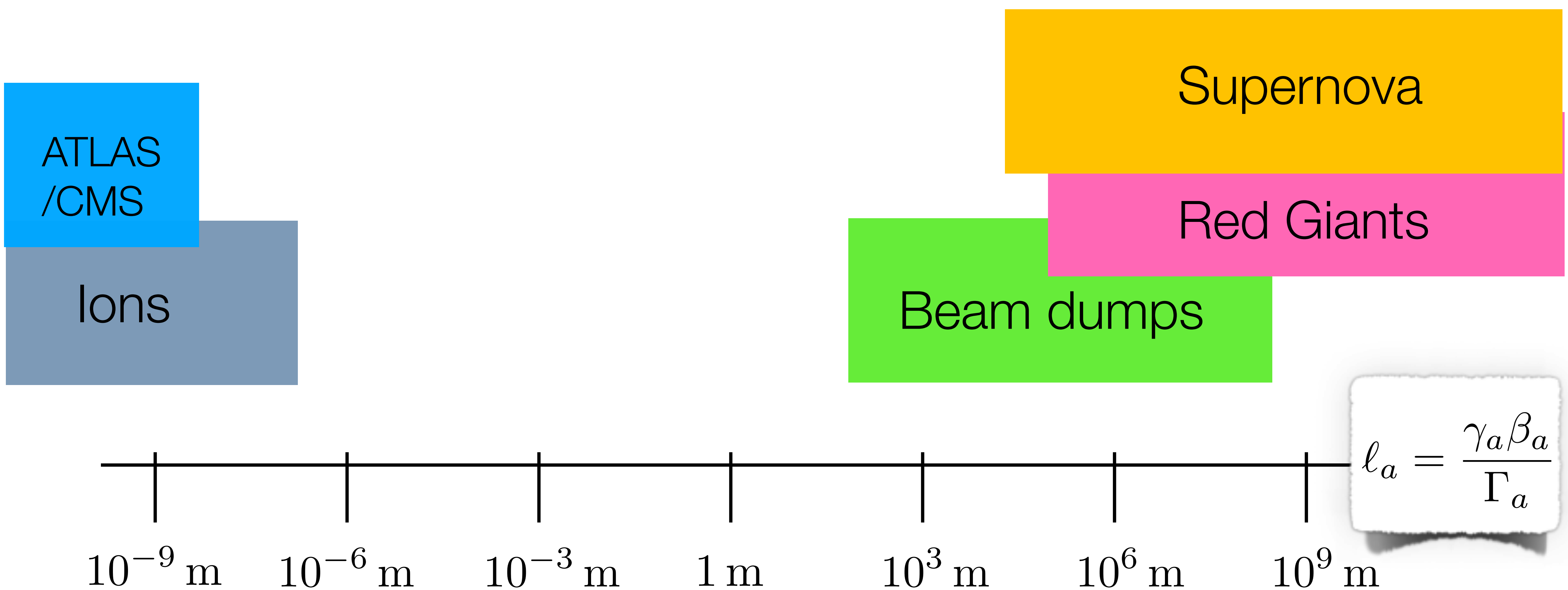
The lifetime gap

Example: Axion-like particle with perturbative coupling to photons

$$\mathcal{L} = c_{\gamma\gamma} \frac{\alpha}{4\pi f} a \, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



$$\Gamma_a = \frac{\alpha^2}{64\pi^3 f^2} c_{\gamma\gamma}^2 m_a^3$$



$c_{\gamma\gamma}/f \lesssim 1/10 \text{ GeV}^{-1}$

The lifetime gap

Example: Axion-like particle with perturbative coupling to photons

Typically: Long lifetime = Weak couplings and small masses

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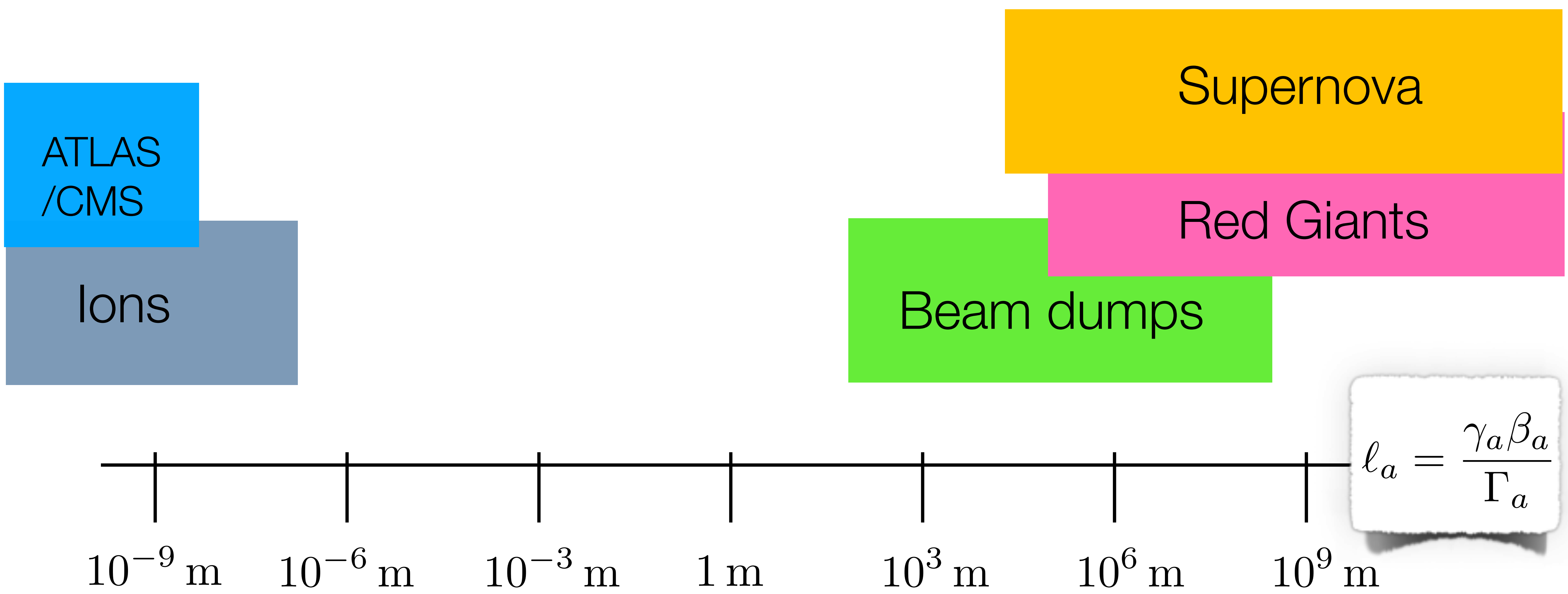

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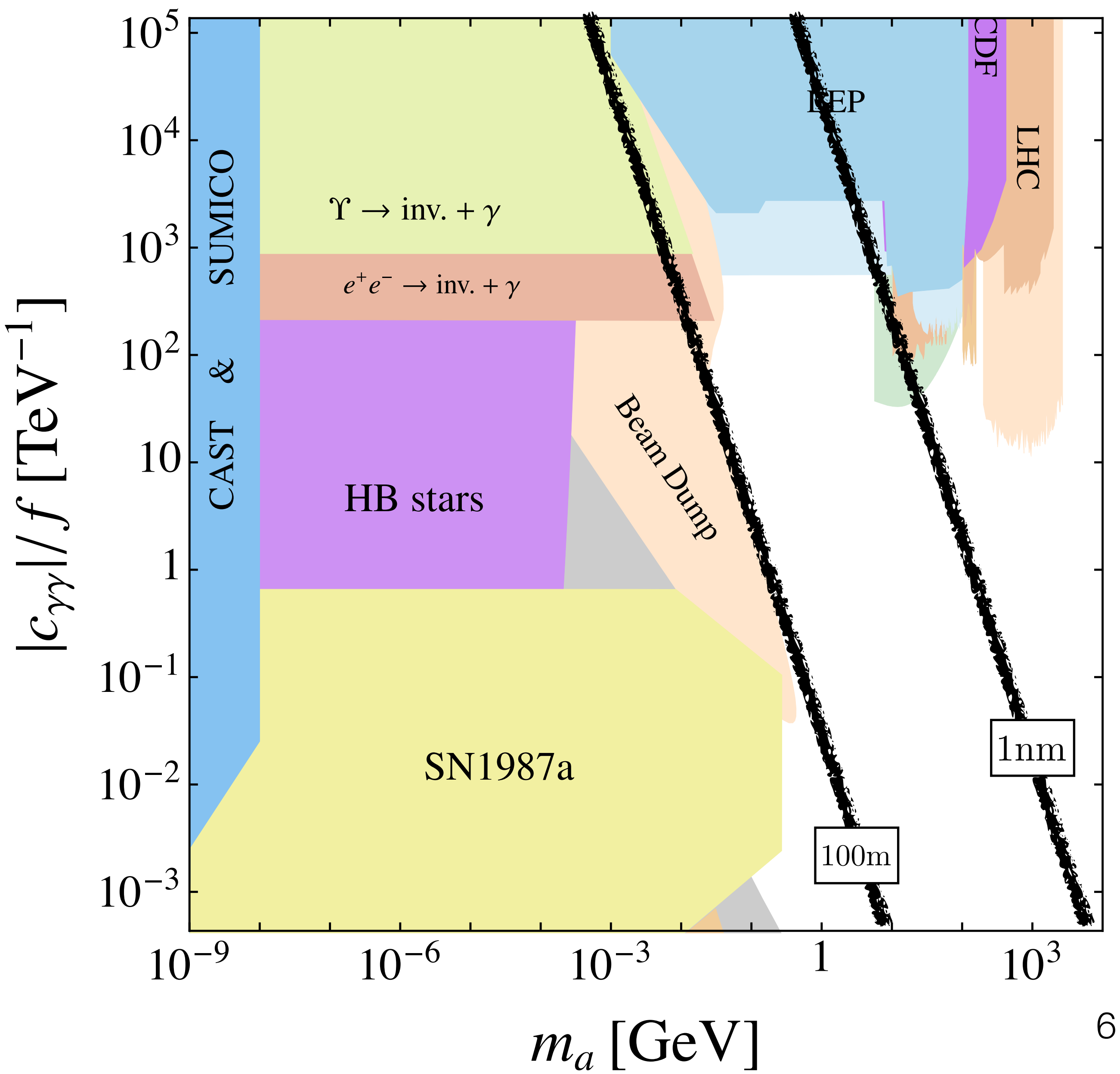


Why would a new particle be light and weakly coupled?

Feebly interacting particles

New light states with sizeable couplings are largely ruled out.

Many UV theories predict new heavy states with sizeable couplings to the SM.

Light and weak interactions seem to be independent conditions, is this theoretically motivated ?

Goldstone bosons

(New Gauge Bosons)

Goldstone bosons

Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

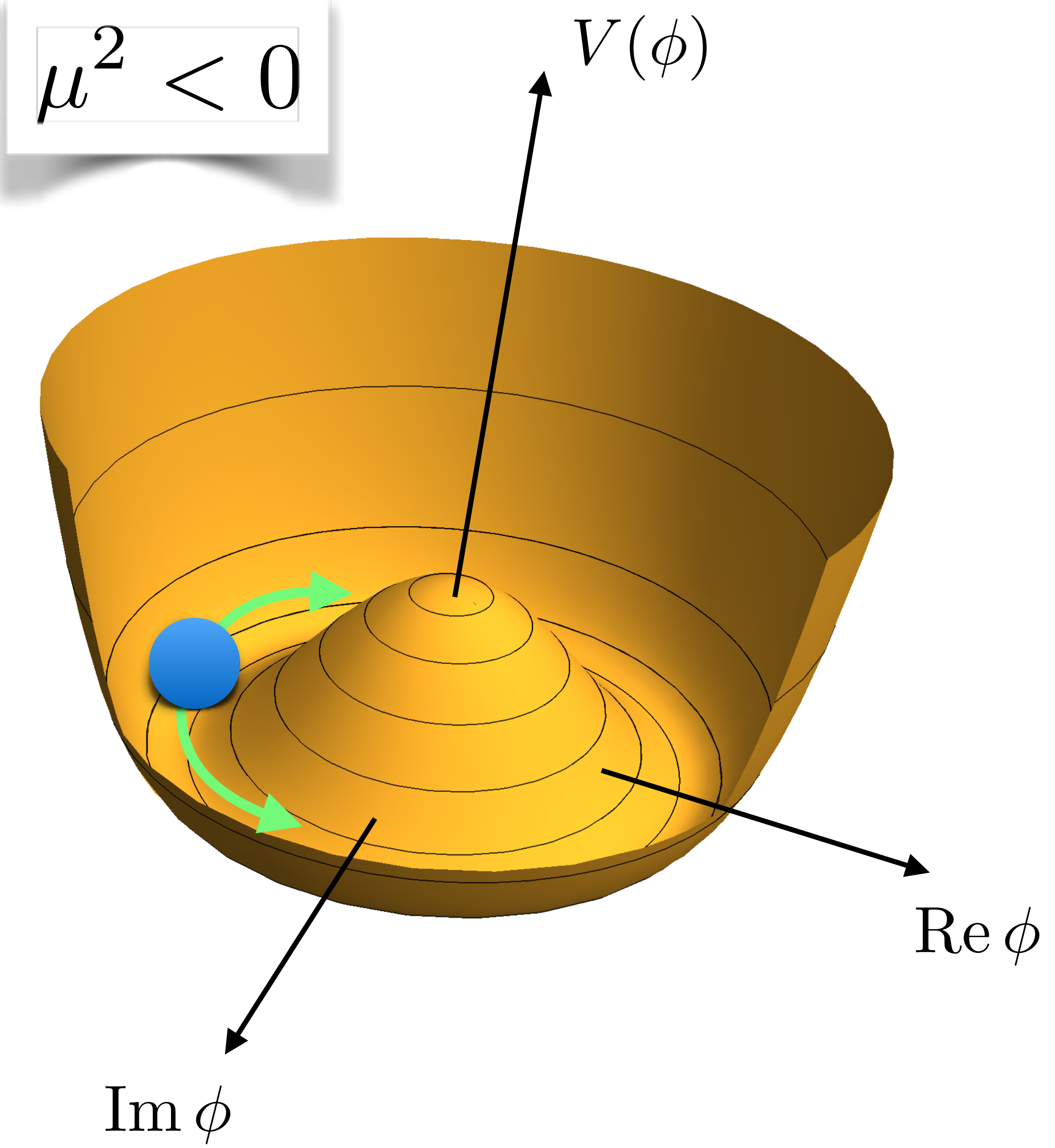
$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda\,(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f}$$

$$m_s^2 = 4\lambda f^2 = |\mu^2|$$

$$m_a^2 = 0$$

$\mu^2 < 0$



Goldstone bosons

Since the GB corresponds to the phase of a complex field, it is protected by a shift symmetry

$$\phi = (f + s)e^{ia/f}$$

it is protected by a shift symmetry

$$e^{ia(x)/f} \rightarrow e^{i(a(x)+c)/f} = e^{ia(x)/f}\, e^{ic/f}$$

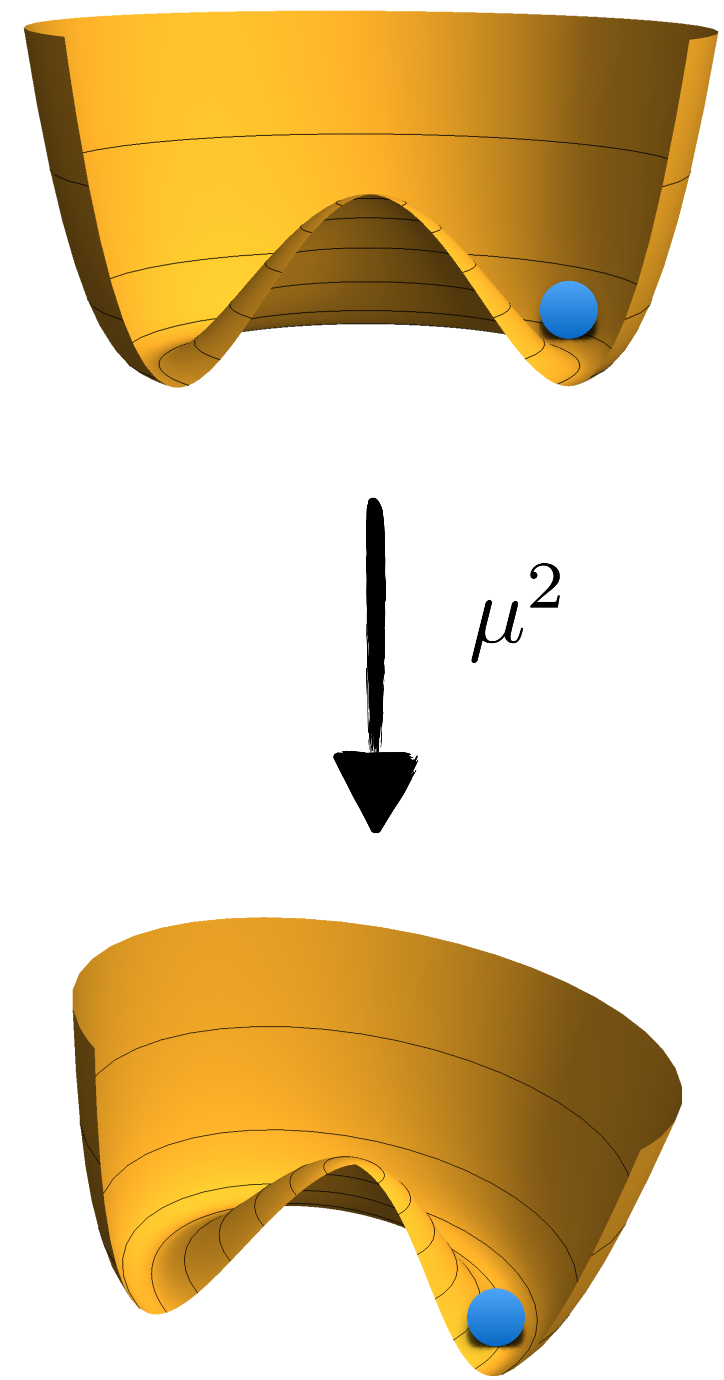
This symmetry forbids a mass term, and all couplings are suppressed by the UV scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots$$

Goldstone bosons

An exactly massless boson is very problematic.

The global symmetry can be broken by explicit masses or anomalous effects



$$\mathcal{L} = \frac{1}{2}\partial_\mu a\,\partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\,\bar{\mu}\gamma_\nu\mu + \ldots + \frac{1}{2}m_a^2 a^2$$

$$m_a = \frac{\mu^2}{f}$$

explicit breaking

Small masses ⟷ Small couplings

Goldstone bosons

The most famous example is the pion

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i\not{D}\, q_L + \bar{q}_R i\not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

Goldstone bosons

Scales at f

The most famous example is the pion

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ALP

Goldstone bosons = Axion-like particles

Any UV-theory with a spontaneously broken (approximate) global symmetry gives rise to a pseudo-Nambu Goldstone boson.

Historically known as Axion-like particles, because of the Peccei-Quinn solution to the strong CP problem

$$\theta G_{\mu\nu}\tilde{G}^{\mu\nu} \longrightarrow \theta G_{\mu\nu}\tilde{G}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi f} a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\left\langle \frac{\partial V_{\text{eff}}}{\partial a} \right\rangle = c_{GG}\frac{\alpha_s}{4\pi f}\langle G_{\mu\nu}\tilde{G}^{\mu\nu}\rangle\Big|_{\langle a\rangle} = 0 \longrightarrow \langle a\rangle = 0$$

Peccei, Quinn, PRL 38 (1977) Weinberg, PRL 40, 1978 Wilczek, PRL 40, 1978

Goldstone bosons

Most general dimension five Lagrangian

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f}\sum_i \frac{c_i}{2}\,\bar{\psi}_i\gamma_\mu\gamma_5\psi_i + c_{GG}\frac{\alpha_s}{4\pi f}a\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

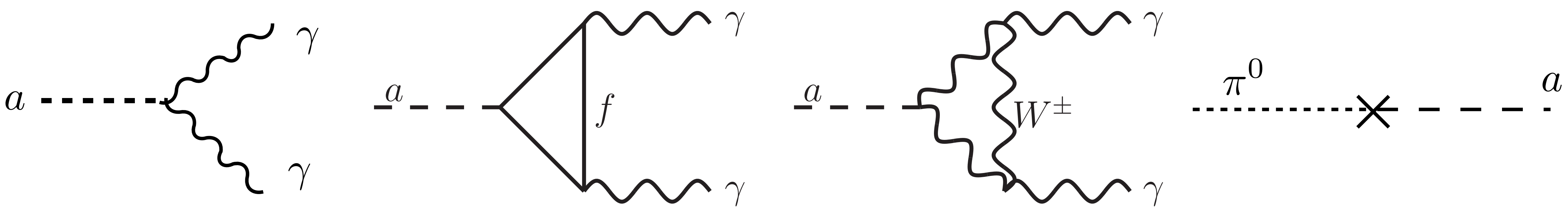
$$+\,c_{\gamma\gamma}\frac{\alpha}{4\pi f}a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + c_{\gamma Z}\frac{\alpha}{4\pi s_w c_w f}a\,F_{\mu\nu}\tilde{Z}^{\mu\nu} + c_{ZZ}\frac{\alpha}{4\pi s_w^2 c_w^2 f}a\,Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

Many possible signature. I will focus on photons here, because photons are hard to avoid.

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Couplings to Photons

It is very hard to construct a "photo-phobic" ALP



$$c_{\gamma\gamma}^{\text{eff}}(m_a \gg \Lambda_{\text{QCD}}) = c_{\gamma\gamma} + \sum_f N_C^f Q_f^2\, c_{ff}\, B_1(\tau_f) + \frac{2\alpha}{\pi s_W^2} c_{WW} B_2(\tau_W)\,.$$

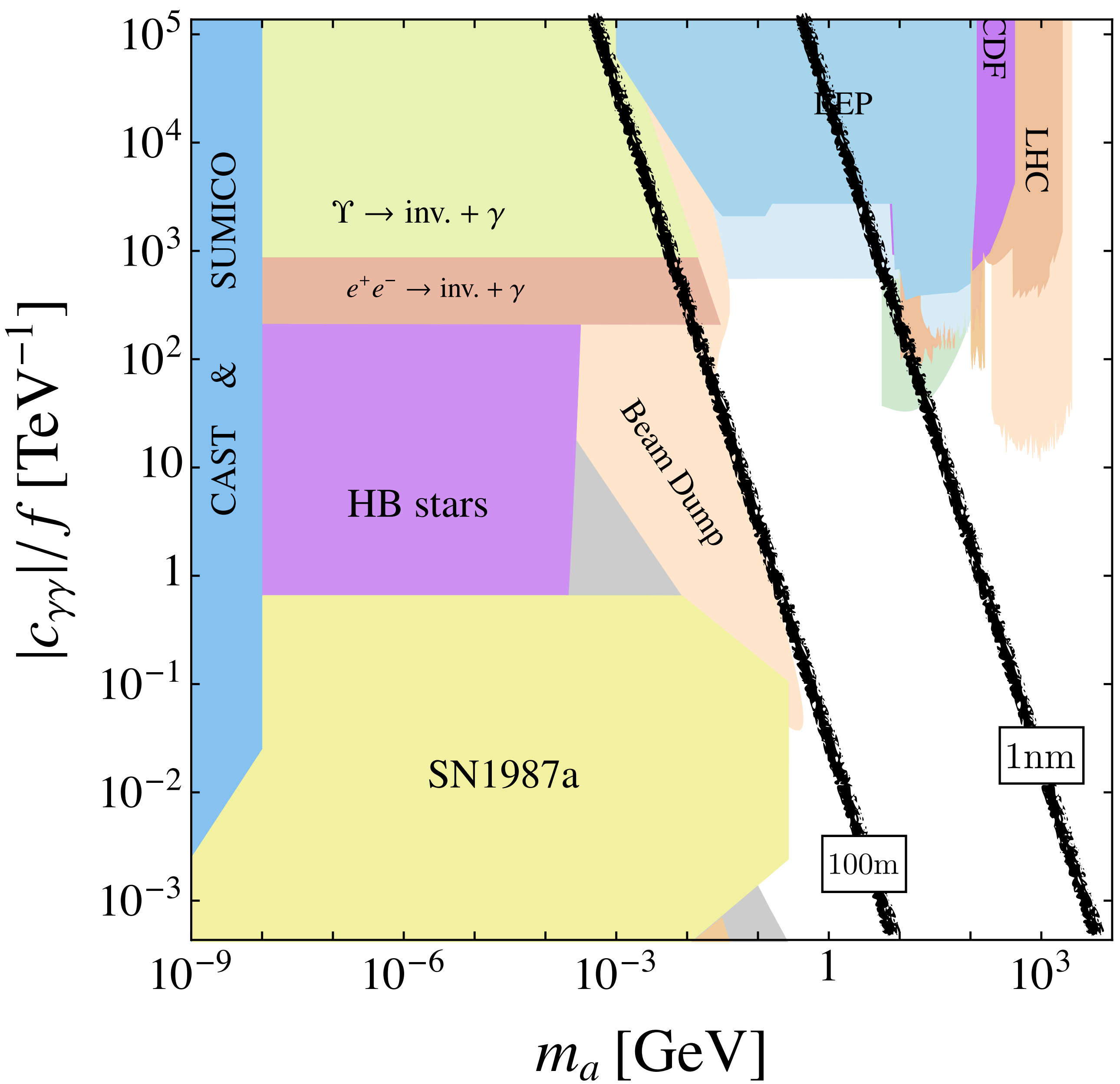
ALP-pion mixing

$$c_{\gamma\gamma}^{\text{eff}}(m_a \lesssim \Lambda_{\text{QCD}}) = c_{\gamma\gamma} - (1.92 \pm 0.04) c_{GG} - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[c_{GG}\frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{2}\right]$$
$$+ \sum_q N_Q^2 c_{qq} B_1(\tau_q) + \sum_\ell c_{\ell\ell}\, B_1(\tau_\ell) + \frac{2\alpha}{\pi}\frac{c_{WW}}{s_w^2} B_2(\tau_W)$$

MB, Neubert, Thamm, Eur.Phys. J.C **79**

How to close the gap?

Different strategies:



1. High statistics

2. (Very) displaced vertices

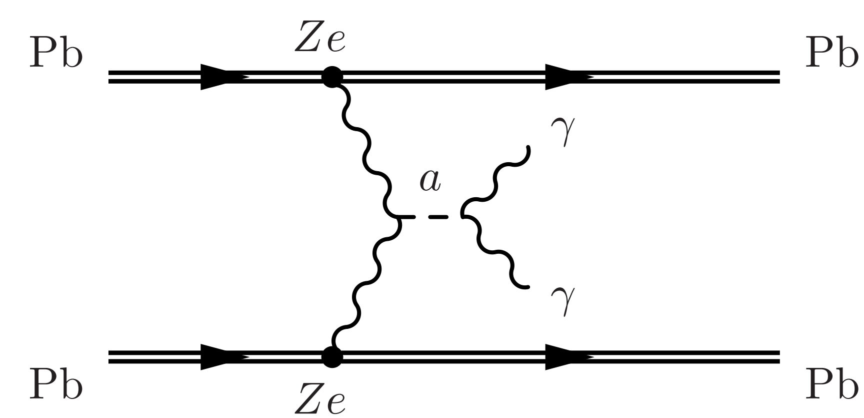
3. Exotic decays

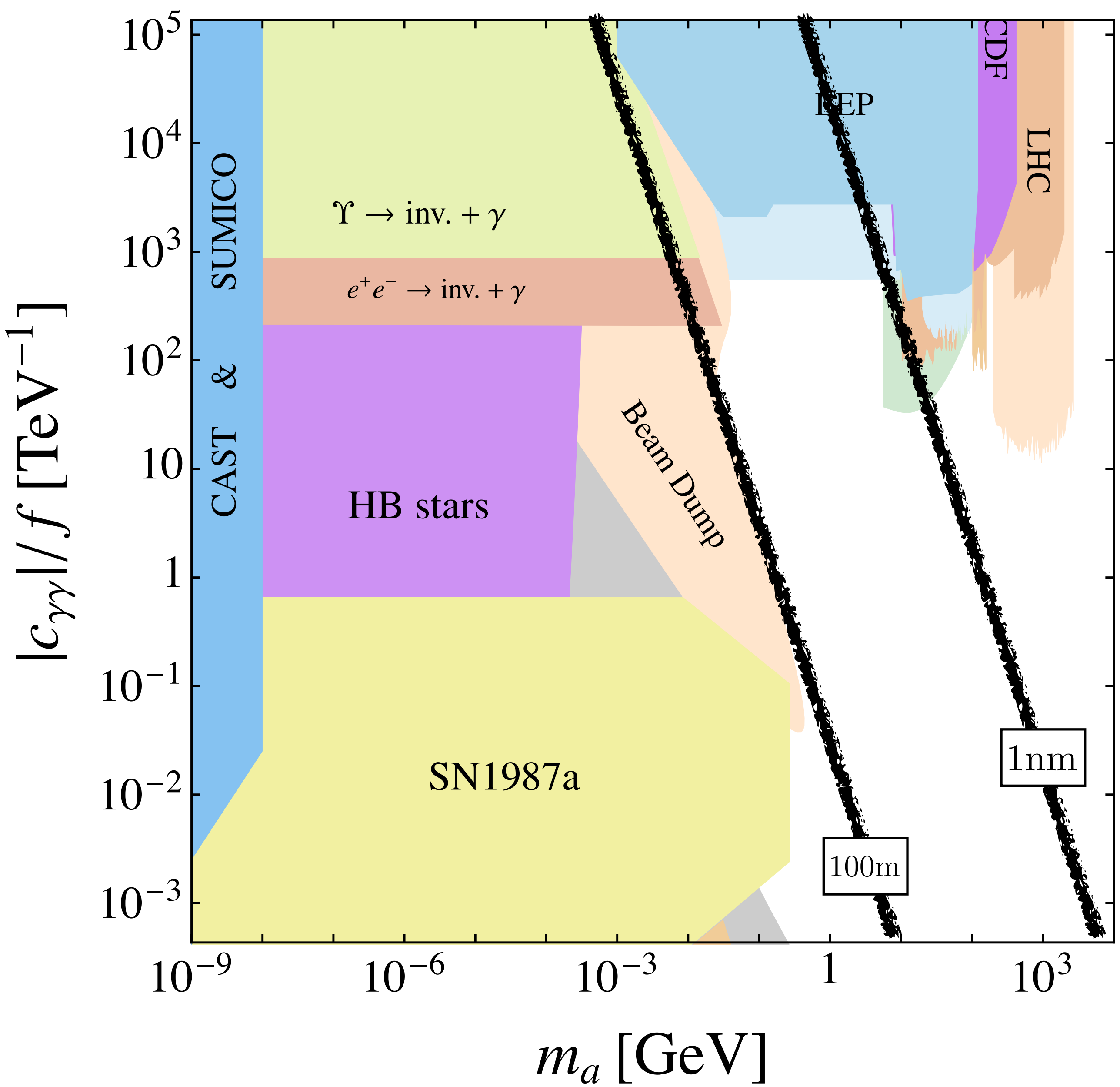
4. Flavour Observables

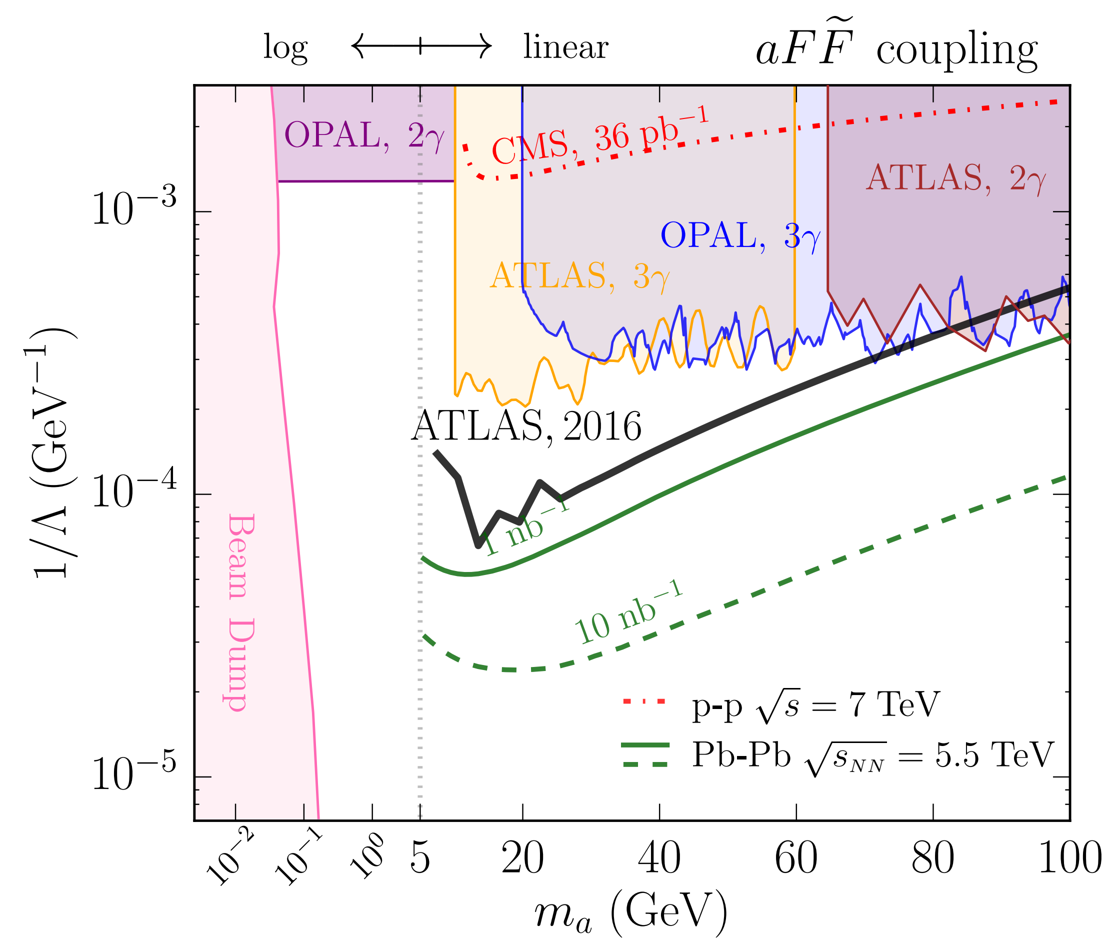
How to close the gap?

High statistics:

Photon fusion in Ion scattering







Knapen et al. Phys. Rev. Lett. **118** (2017)

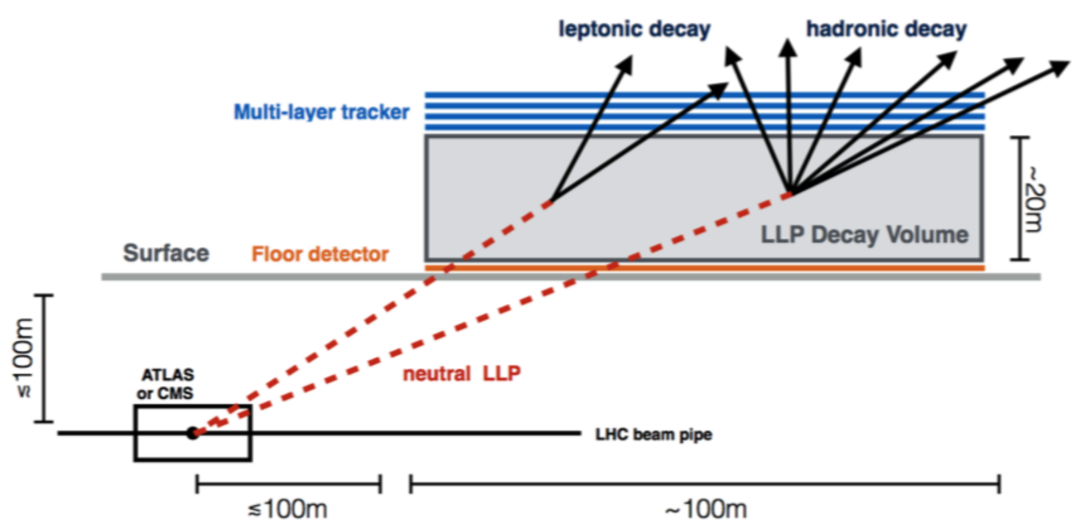
ATLAS, Nature Phys **13**, no. 9, 852 (2017)

CMS 1810.04602

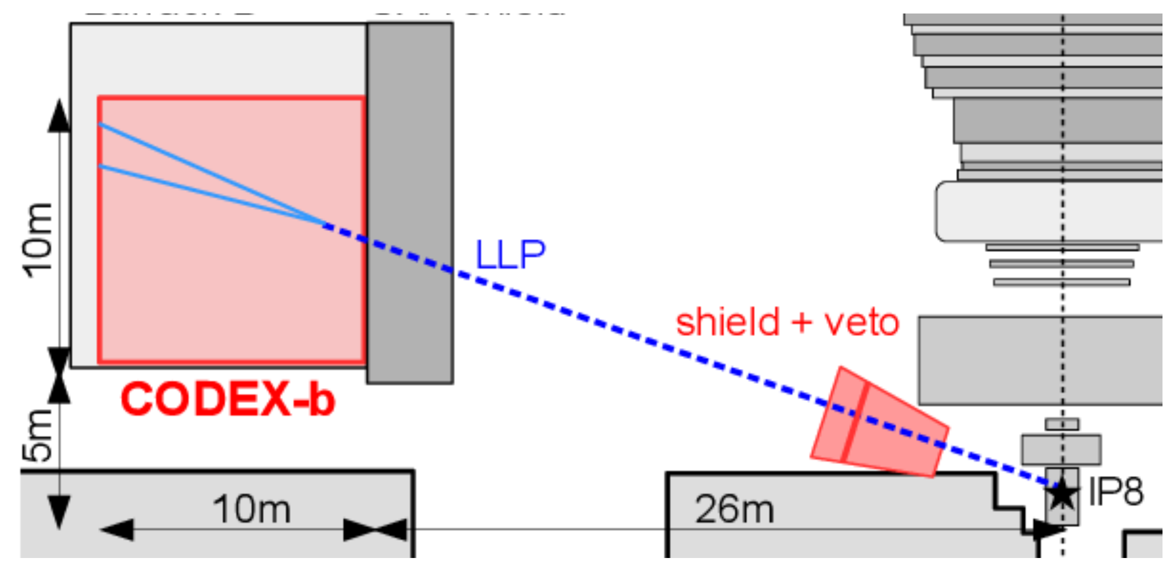
How to close the gap?

(Really) displaced vertices:

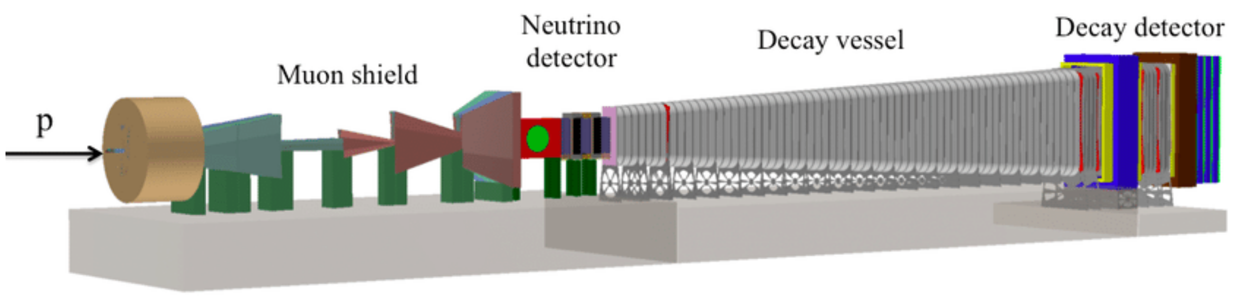
MATHUSLA Chou et al 1606.06298



CodexB Gligorov et al 1708.09395

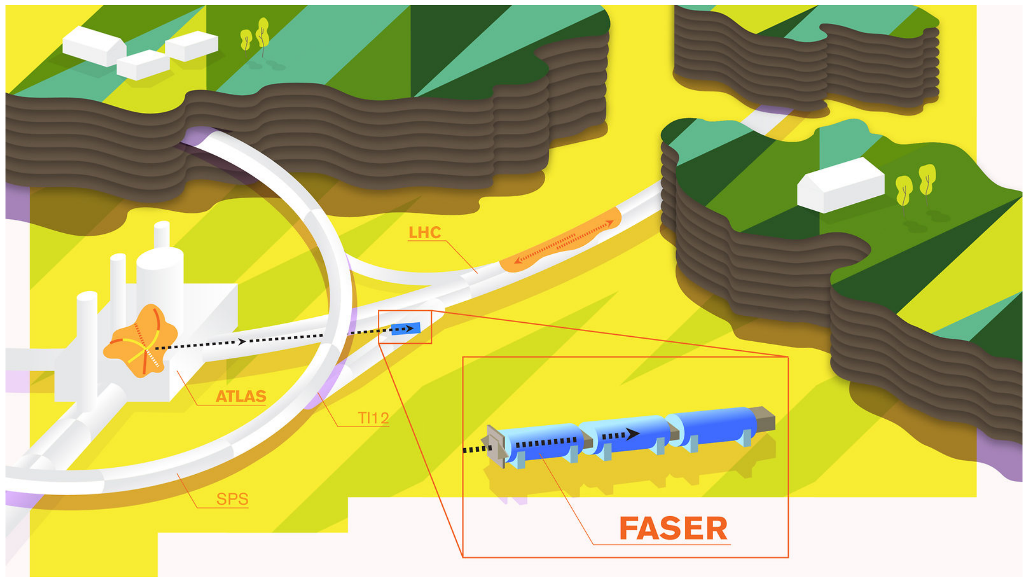


SHiP



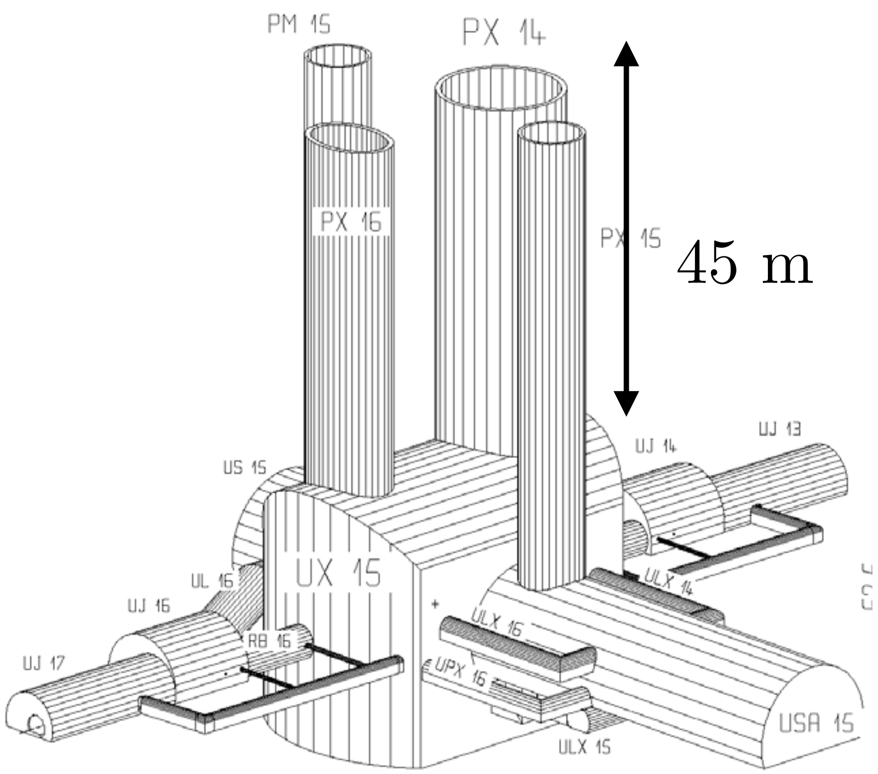
Alekhin et. al. Rept. Prog. Phys. **79**, 124201 (2016)

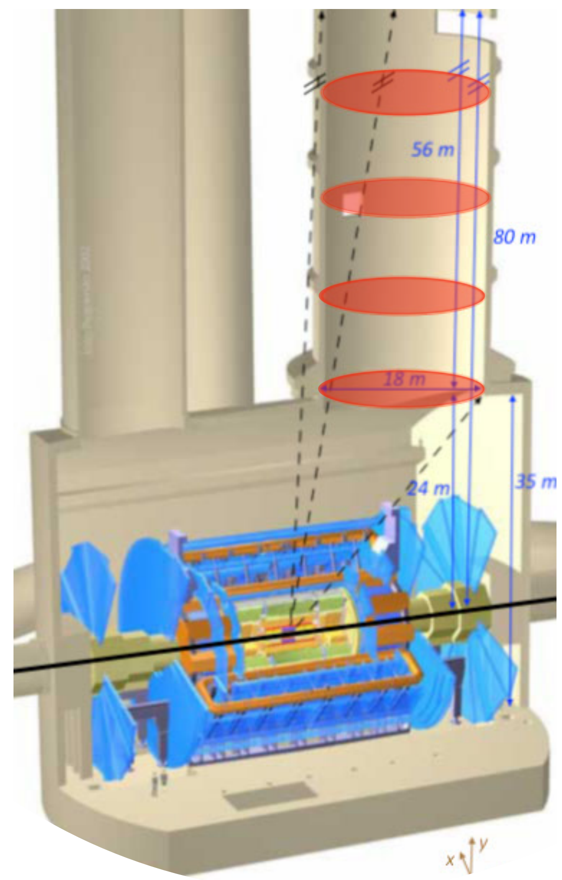
FASER Feng, et al 1710.09387

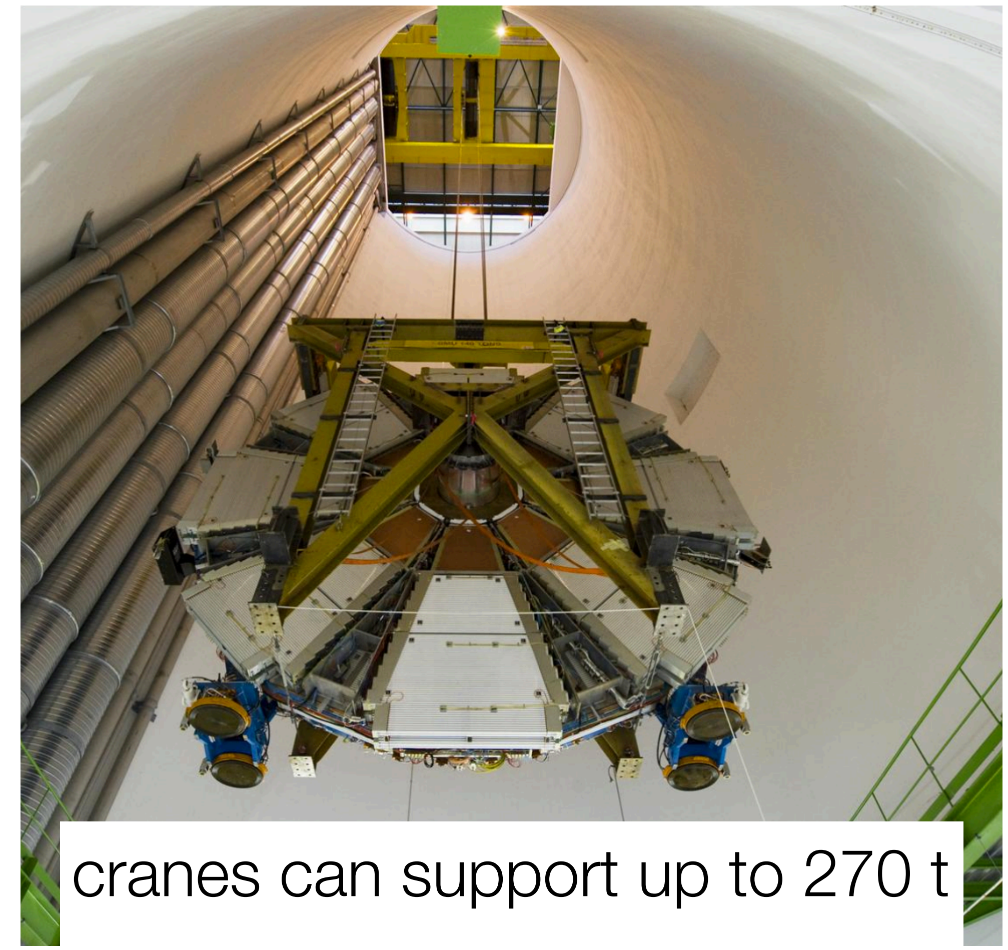


How to close the gap?

ANUBIS MB, Brandt, Lee, Ohm 1909.13022

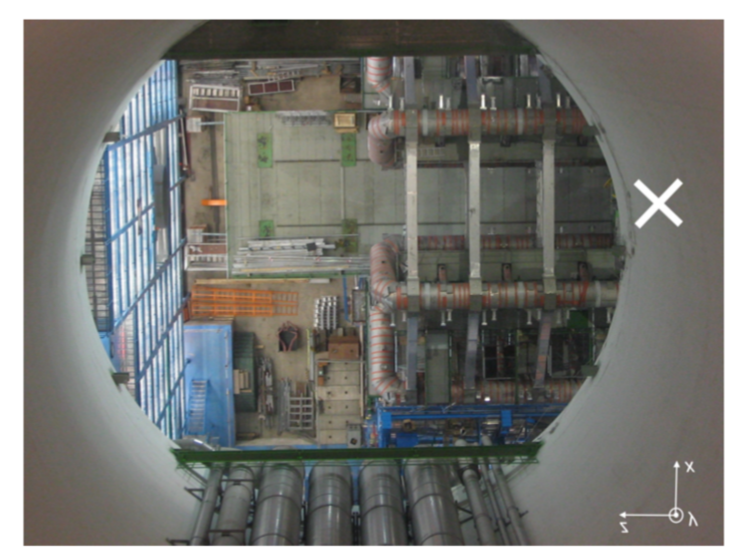






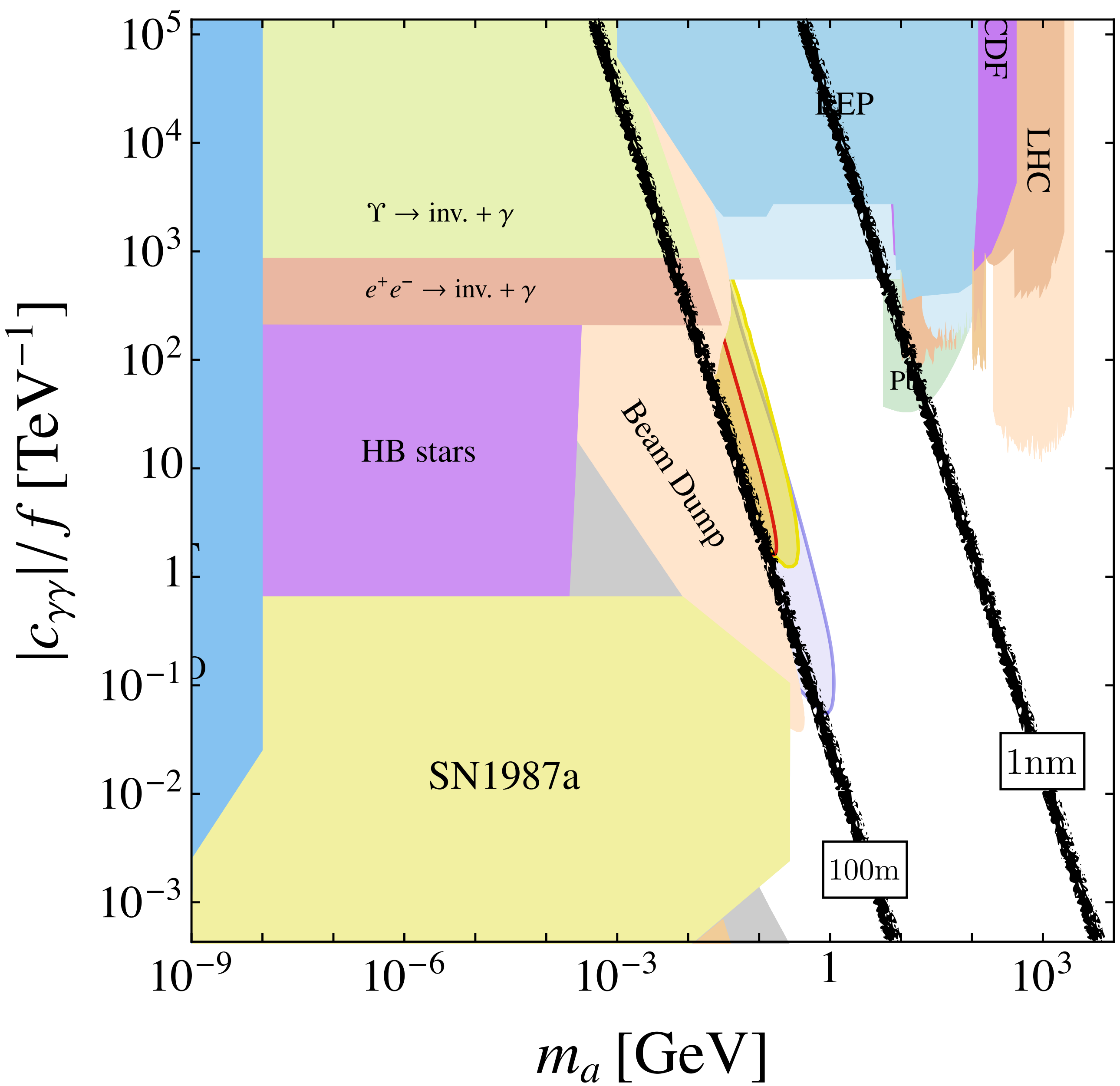
We propose to instrument the ATLAS service shaft.

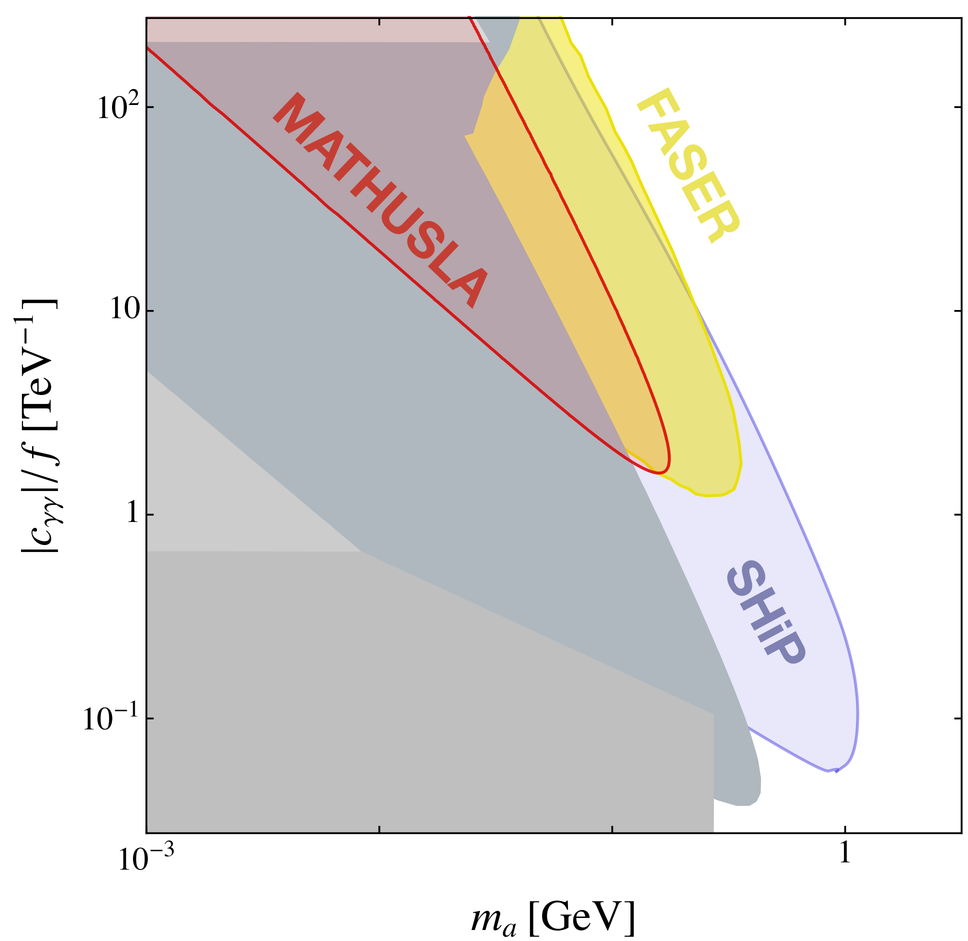
4 tracking stations and active veto, costs < 10 m



How to close the gap?

(Really) displaced vertices: MATHUSLA, FASER, SHiP, CodexB, ANUBIS



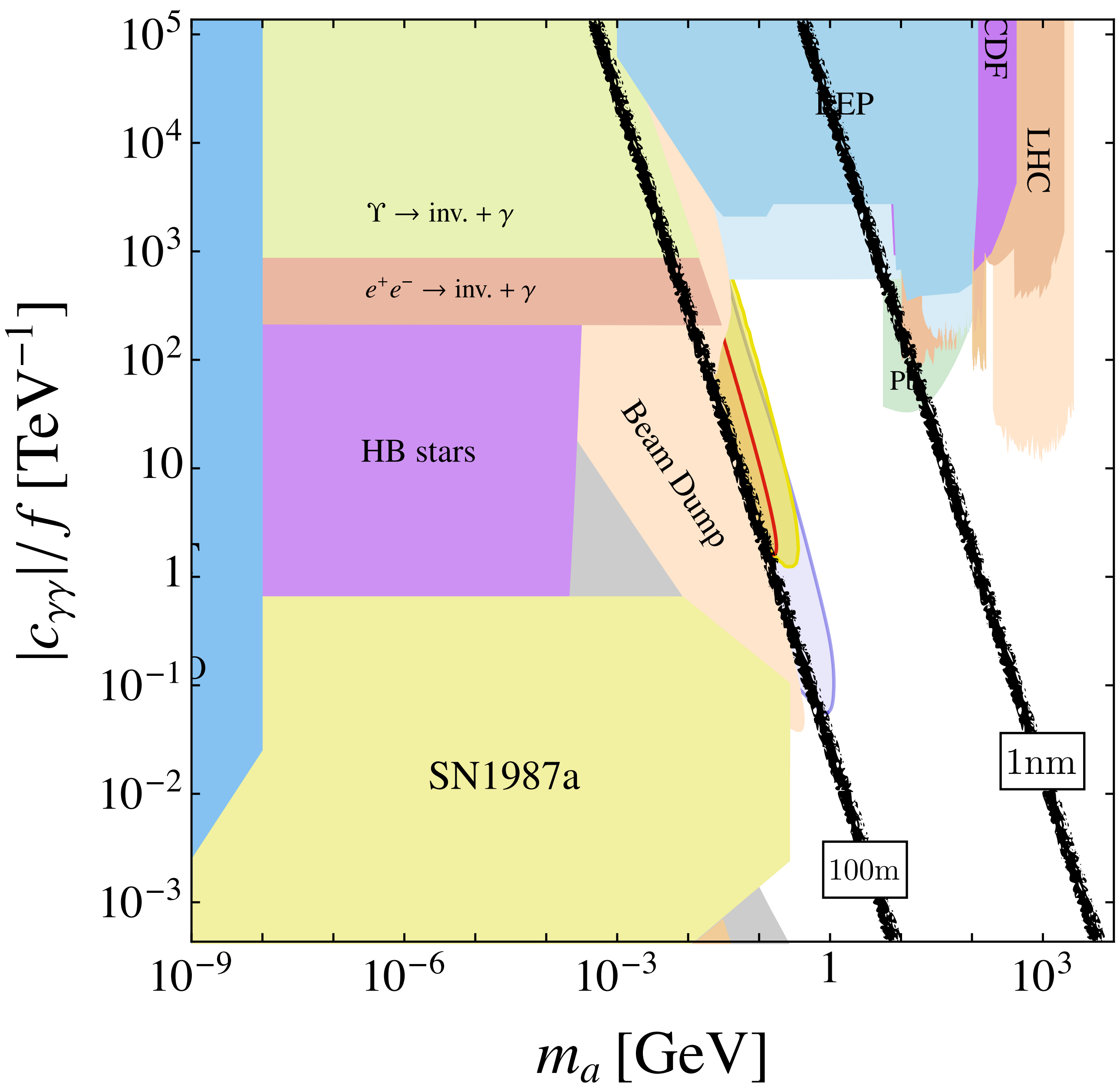


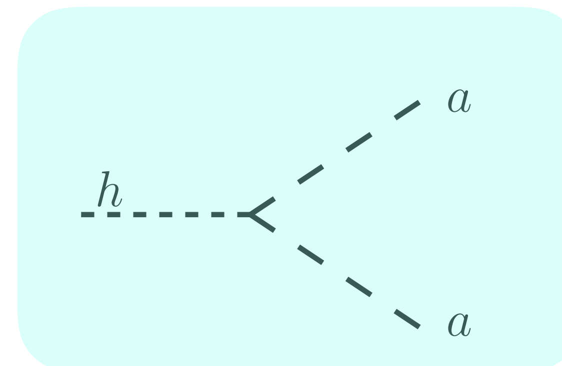
MB, Neubert, Thamm, Eur.Phys. J.C **79**

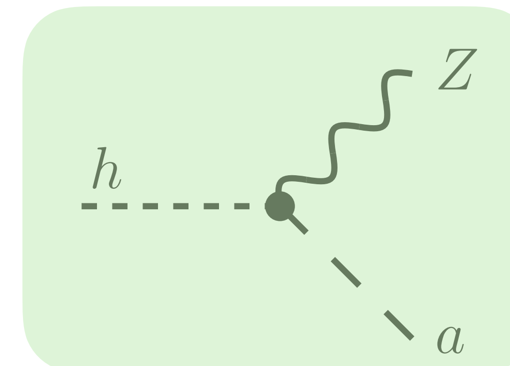
How to close the gap?

Big Advantage of the LHC:

The only place to make the Higgs!







$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi + \frac{c_{Zh}^5}{f}\left(\partial^\mu a\right)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2} + \frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\phi^\dagger\phi$$

MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

How to close the gap?

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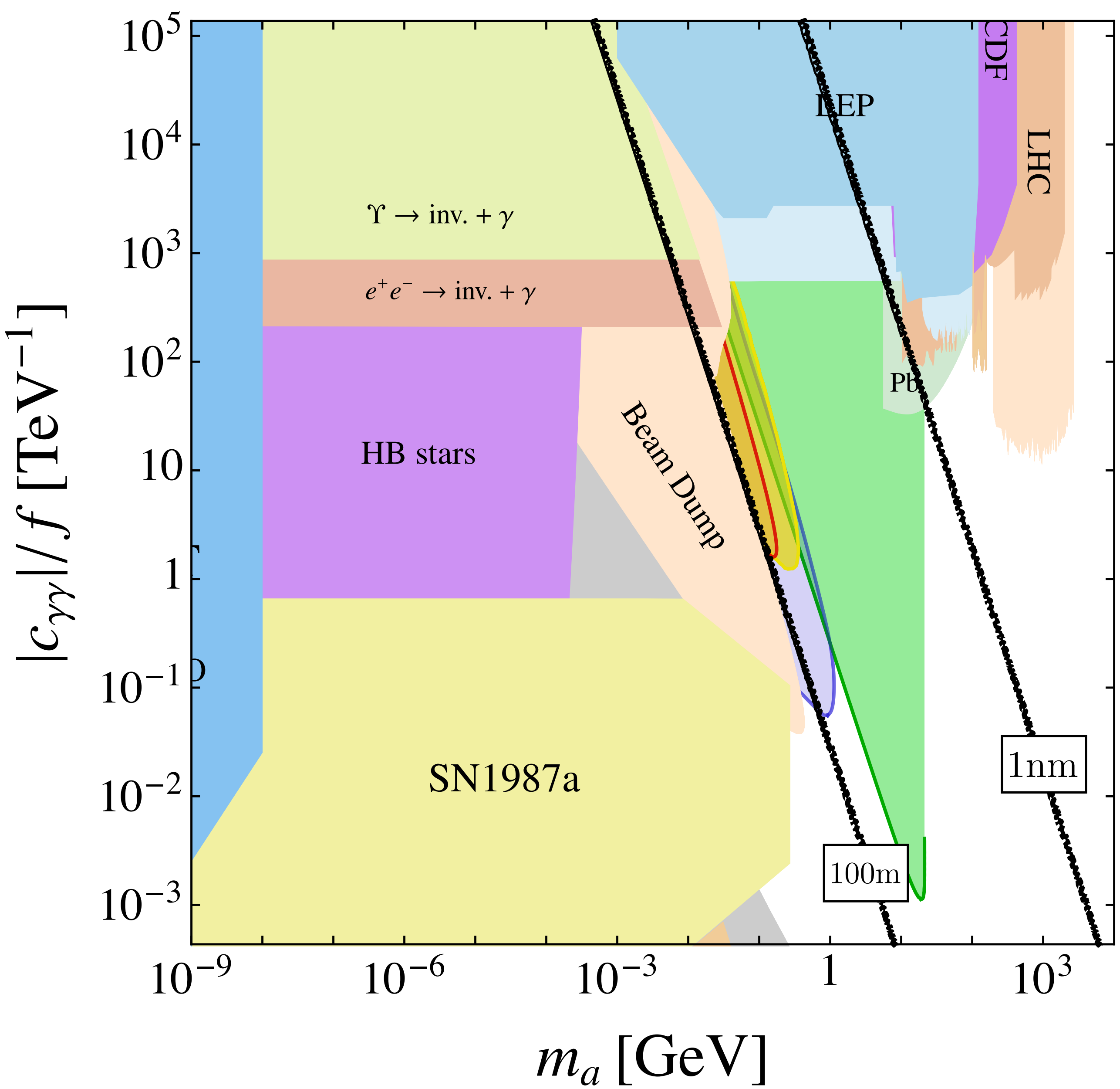
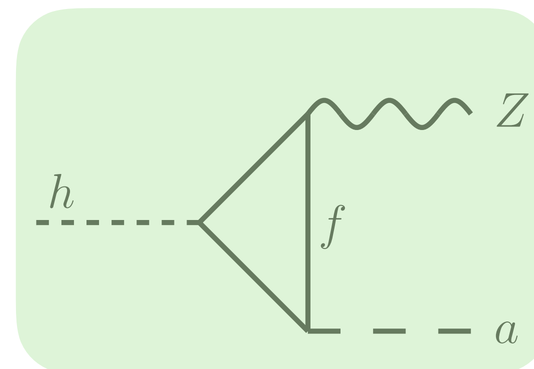
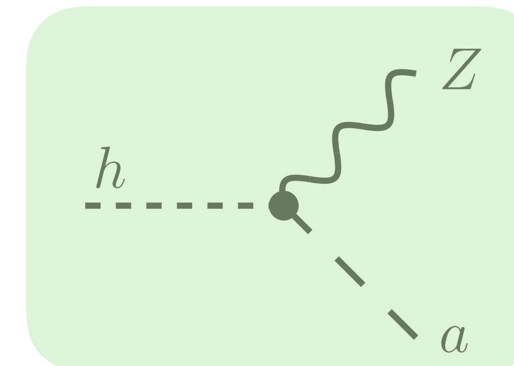


Theoretically interesting:





$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi$$

$$+\frac{c_{Zh}^5}{f}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2}$$

$$+\frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\phi^\dagger\phi$$

$$\text{Br}(h \to Za) < 1\,‰ \qquad c_{Zh}^{\text{eff}} = 0.015$$

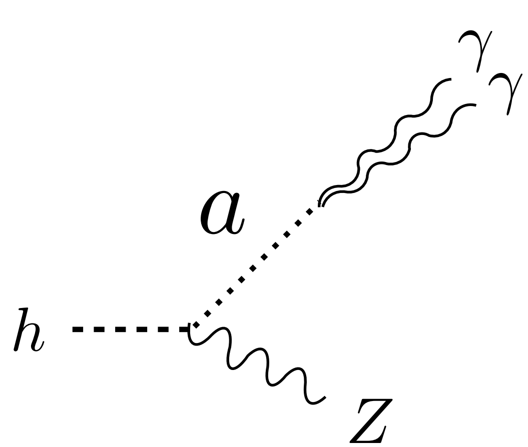
MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

How to close the gap?

Many experimental signatures:

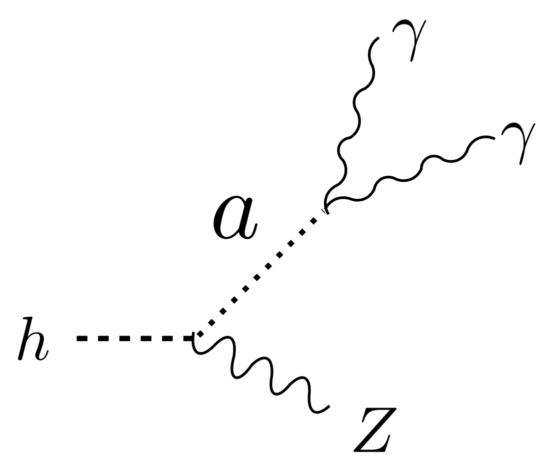
Low mass, small coupling



$\mathrm{Br}(h \to Z\gamma) > \mathrm{Br}_{\mathrm{SM}}(h \to Z\gamma)$

Always enhanced!

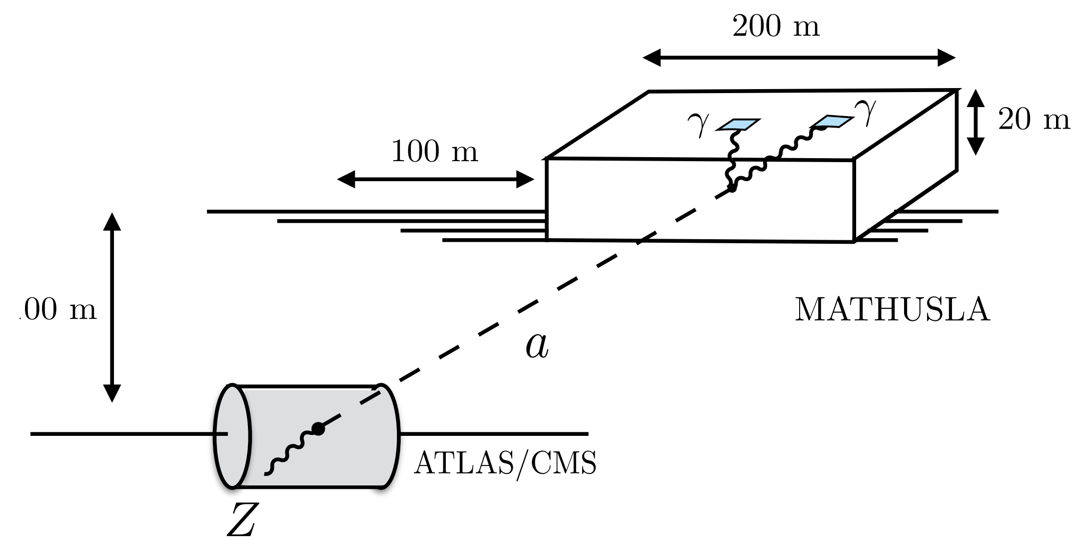
medium mass, small coupling



Exotic signatures

$h \to Z\gamma\gamma$

very small coupling



Very challenging exotic signatures

$h \to Z + E_{T,\,\mathrm{miss}}$

$a \to \gamma\gamma$

How to close the gap?

Flavour-violating ALP-couplings to quarks

$$\frac{\partial_\mu a}{f} \sum_{\substack{q=u,d,\\ s,c,b}} \left(\bar{q}_L \boldsymbol{K}_Q^{\text{eff}} \gamma^\mu q_L + \bar{q}_R \boldsymbol{K}_q^{\text{eff}} \gamma^\mu q_R \right)$$

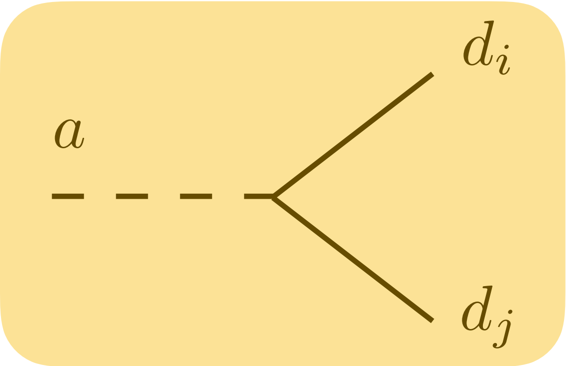
$f/c_{ds} \gtrsim 2 \times 10^{10}$ TeV

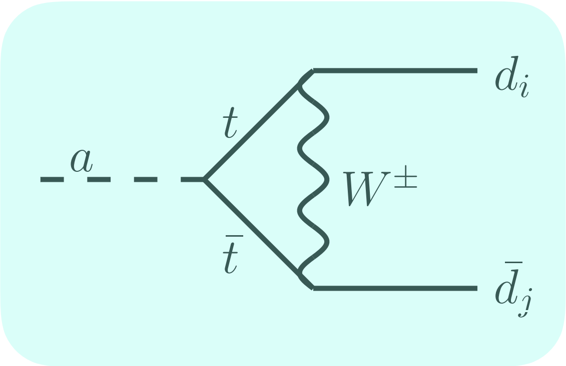
Observable	Mass Range [MeV]	ALP decay mode	Constrained coupling c_{ij}	Limit (95% CL) on $c_{ij} \cdot \left(\frac{\text{TeV}}{\Lambda}\right) \cdot \sqrt{\mathcal{B}}$
$\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)$	$0 < m_a < 265$ $(*)$	Long-lived	$\lvert K_D + K_d \rvert_{ds}$	4.9×10^{-9}
$\mathcal{B}(B^+ \to K^+ \bar{\nu}\nu)$	$0 < m_a < 4785$	Long-lived	$\lvert K_D + K_d \rvert_{sb}$	6.9×10^{-6}
$\mathcal{B}(B \to K^* \bar{\nu}\nu)$	$0 < m_a < 4387$	Long-lived	$\lvert K_D - K_d \rvert_{sb}$	5.1×10^{-6}
$\mathcal{B}(K^+ \to \pi^+ \gamma\gamma)$	$m_a < 108$	$\gamma\gamma$	$\lvert K_D + K_d \rvert_{ds}$	2.1×10^{-8}
$\mathcal{B}(K^+ \to \pi^+ \gamma\gamma)$	$220 < m_a < 354$	$\gamma\gamma$	$\lvert K_D + K_d \rvert_{ds}$	2.4×10^{-7}
$\mathcal{B}(K_L^0 \to \pi^0 \gamma\gamma)$	$m_a < 110$	$\gamma\gamma$	$\text{Im}(K_D + K_d)_{ds}$	1.4×10^{-8}
$\mathcal{B}(K_L^0 \to \pi^0 \gamma\gamma)$	$m_a < 363$	$\gamma\gamma$	$\text{Im}(K_D + K_d)_{ds}$	1.2×10^{-7}
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)$	$140 < m_a < 362$	e^+e^-	$\text{Im}(K_D + K_d)_{ds}$	2.9×10^{-9}
$d\mathcal{B}/dq^2(B^0 \to K^{*0} e^+ e^-)_{[0.0,0.05]}$	$0 < m_a < 224$	e^+e^-	$\lvert K_D - K_d \rvert_{sb}$	6.4×10^{-7}
$d\mathcal{B}/dq^2(B^0 \to K^{*0} e^+ e^-)_{[0.05,0.15]}$	$224 < m_a < 387$	e^+e^-	$\lvert K_D - K_d \rvert_{sb}$	9.3×10^{-7}
$\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-)$	$210 < m_a < 350$	$\mu^+\mu^-$	$\text{Im}(K_D + K_d)_{ds}$	4.0×10^{-9}
$\mathcal{B}(B^+ \to K^+ a(\mu^+\mu^-))$	$250 < m_a < 4700$ $(\dagger)$	$\mu^+\mu^-$	$\lvert K_D + K_d \rvert_{sb}$	4.4×10^{-8}
$\mathcal{B}(B^0 \to K^{*0} a(\mu^+\mu^-))$	$214 < m_a < 4350$ $(\dagger)$	$\mu^+\mu^-$	$\lvert K_D - K_d \rvert_{sb}$	5.1×10^{-8}
$\mathcal{B}(B^+ \to K^+ \tau^+ \tau^-)$	$3552 < m_a < 4785$	$\tau^+\tau^-$	$(K_D + K_d)_{sb}$	8.2×10^{-5}

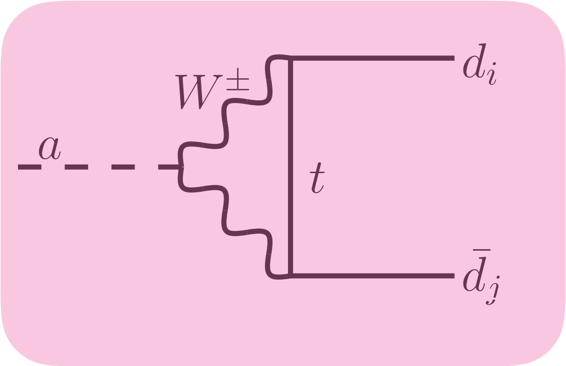
MB, Neubert, Renner, Schnubel, Thamm, 20….

Flavour-violating couplings to quarks

What about loop-induced flavour-couplings?





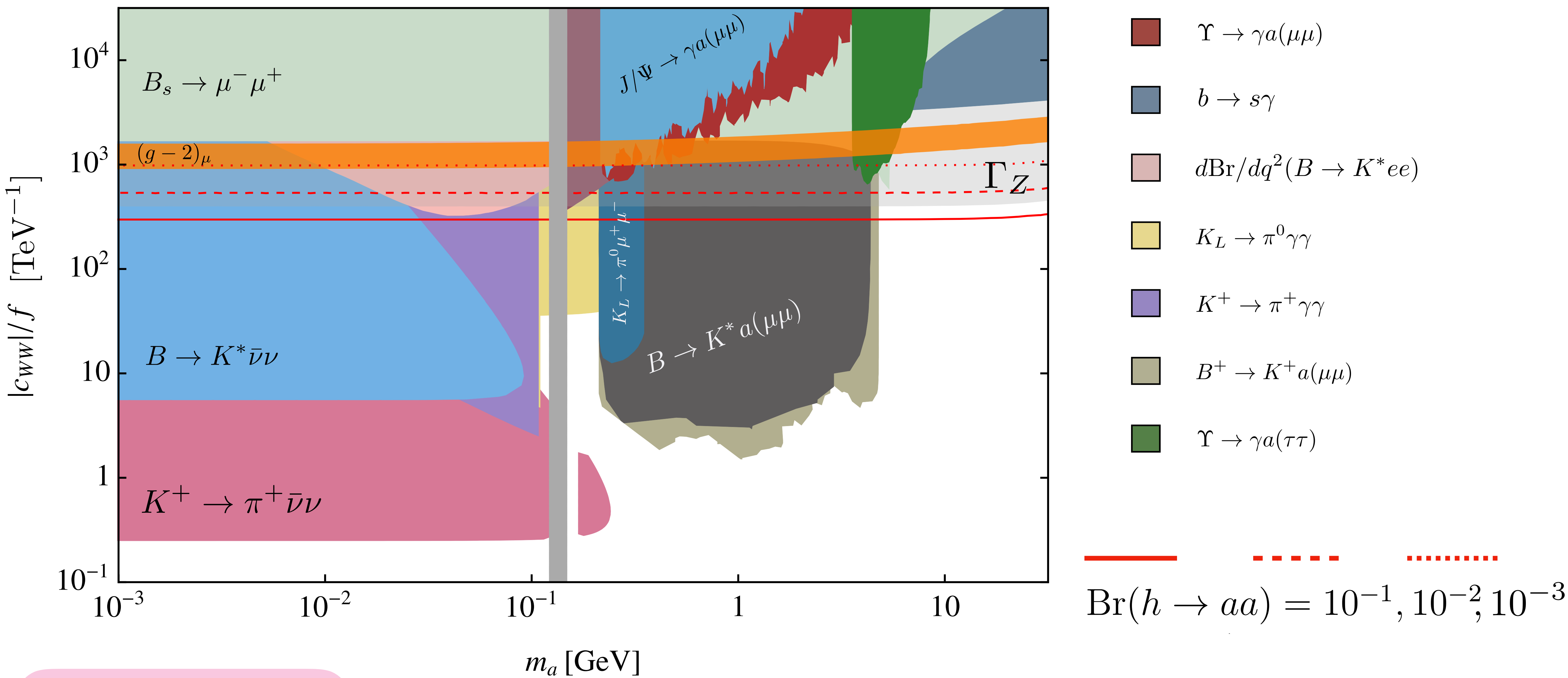


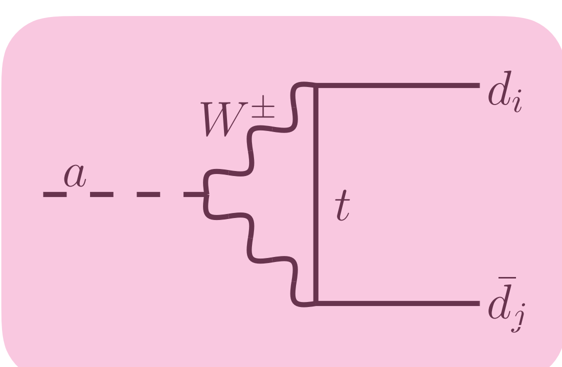
$$
\begin{aligned}
(K_D)^{\text{eff}}_{ij} &= (K_D)_{ij}(\mu) + \frac{y_t^2}{16\pi^2}\bigg\{ V^*_{mi} V_{nj} (K_U)_{mn} (\delta_{m3} + \delta_{n3}) \left[-\frac{1}{4} \ln \frac{\mu^2}{m_t^2} + \frac{3}{8}\, \frac{1 - x_t^2 + 2 \ln x_t}{(1-x_t)^2} \right] \\
&\quad + V^*_{ti} V_{tj} (K_U)_{33} + V^*_{ti} V_{tj} (K_u)_{33} \left[\frac{1}{2} \ln \frac{\mu^2}{m_t^2} - \frac{7 - 8x_t + x_t^2 + 6 \ln x_t}{4\,(1-x_t)^2} \right] \\
&\quad - 6g^2\, C_{WW}\, V^*_{ti} V_{tj}\, \frac{1 - x_t + x_t \ln x_t}{(1-x_t)^2} \bigg\} , \\
(K_d)^{\text{eff}}_{ij} &= (K_d)_{ij} \,,
\end{aligned}
$$

$$
\frac{\partial_\mu a}{f} \sum_{\substack{q=u,d,\\ s,c,b}} \left(\bar{q}_L \boldsymbol{K}^{\text{eff}}_Q \gamma^\mu q_L + \bar{q}_R \boldsymbol{K}^{\text{eff}}_q \gamma^\mu q_R \right)
$$

MB, Neubert, Renner, Schnubel, Thamm, 19….

Flavour-violating couplings to quarks

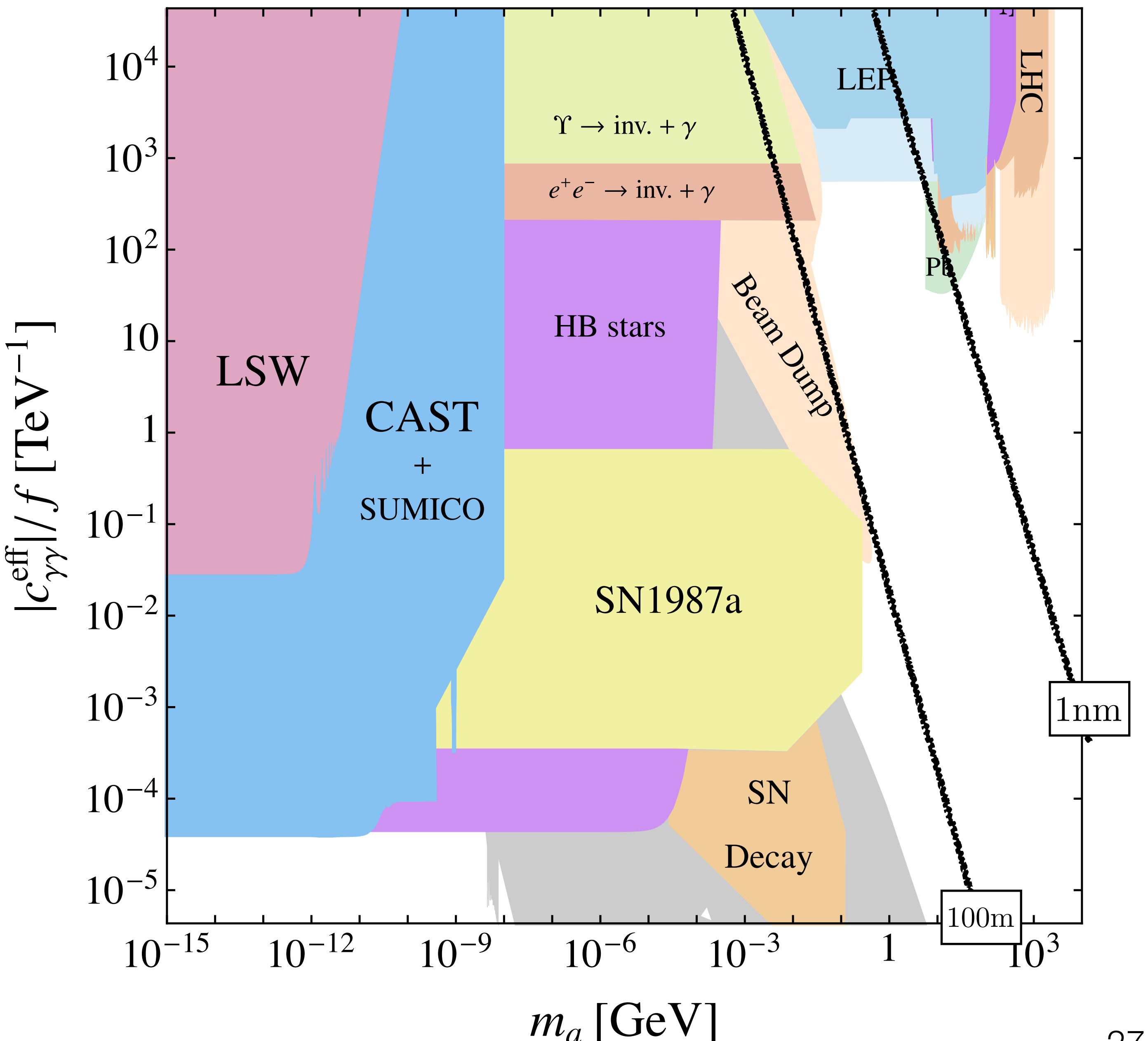


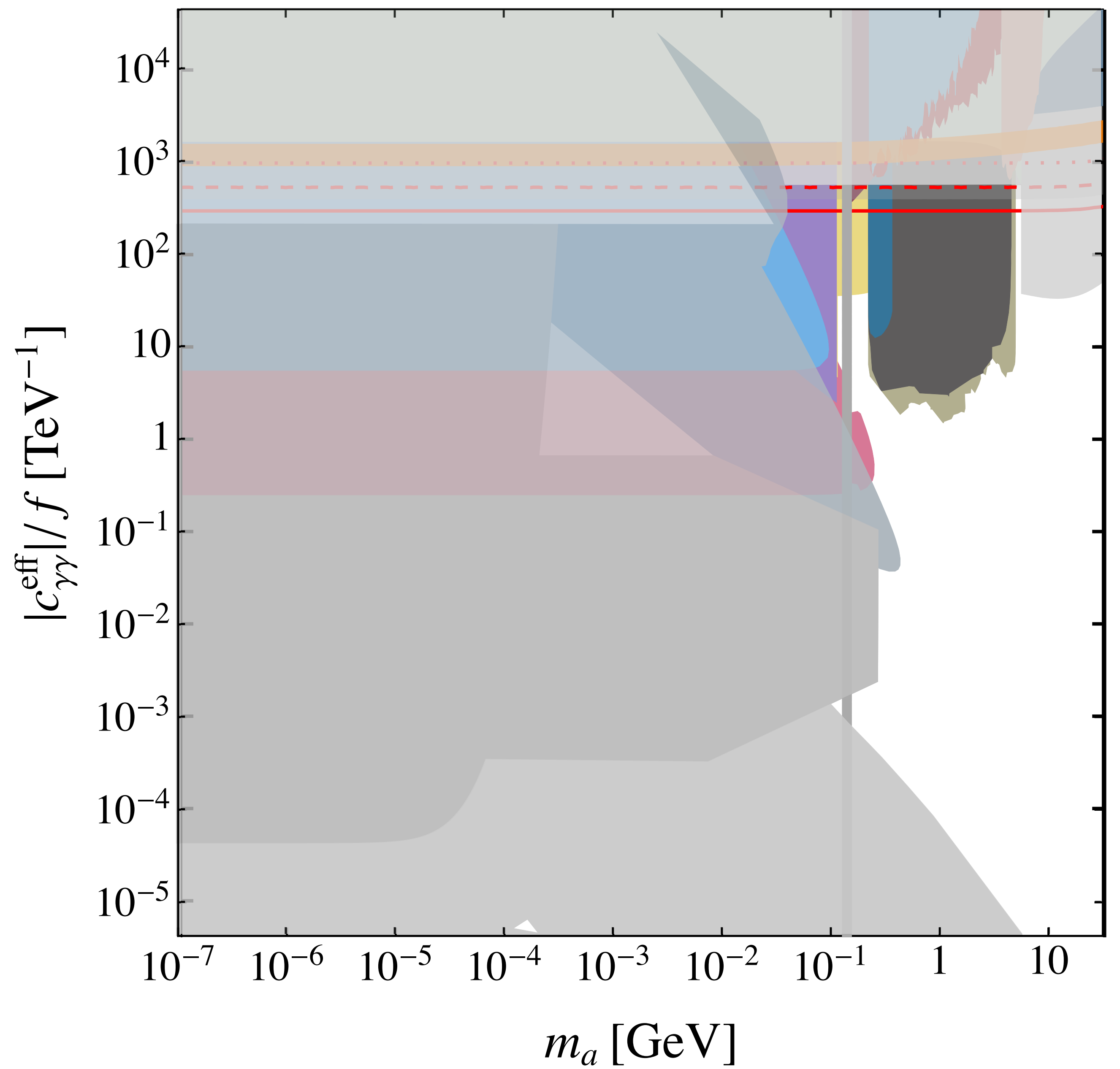


Relevant for ALP - photon couplings if the UV theory has an SU(2) coupling.

How to close the gap?

Flavour bounds can close the gap if $c_{\gamma\gamma} = c_{WW}$





Flavour-violating ALP couplings to leptons

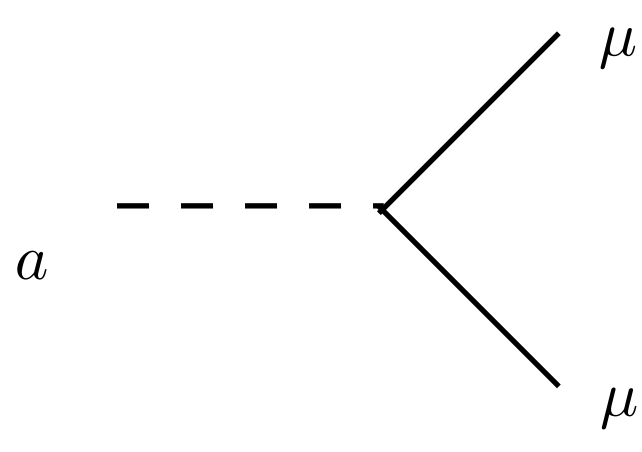
pseudoscalar coupling

$$\frac{\partial a}{f}\sum_i \bar{\ell}_i (k_E)_{ij}\gamma_\mu P_L \ell_j + \bar{\ell}_i (k_e)_{ij}\gamma_\mu P_R \ell_j = \frac{a}{f}\sum_i \bar{\ell}_i \left[(k_e)_{ij} - (k_E)_{ij}\right](m_i + m_j)\gamma_5 \ell_j$$
$$+ \bar{\ell}_i \left[(k_e)_{ij} + (k_E)_{ij}\right](m_i - m_j)\ell_j$$

scalar coupling

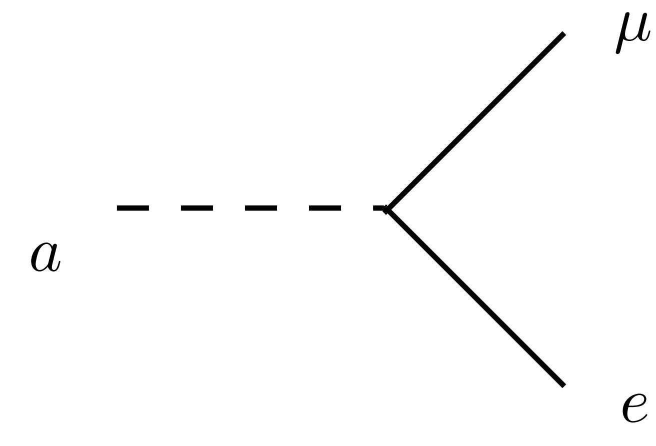
Flavour conserving

$$c_{\mu\mu} = (k_e)_{\mu\mu} - (k_E)_{\mu\mu}$$



Flavour violating

$$c_{\mu e} = \sqrt{|(k_e)_{\mu e}|^2 + |(k_E)_{\mu e}|^2}$$



Flavour-violating couplings to leptons

Lepton Flavour constraints provide very strong limits on ALP couplings as well.

$f/c_{\mu e} \gtrsim 2 \times 10^8\,\mathrm{TeV}$

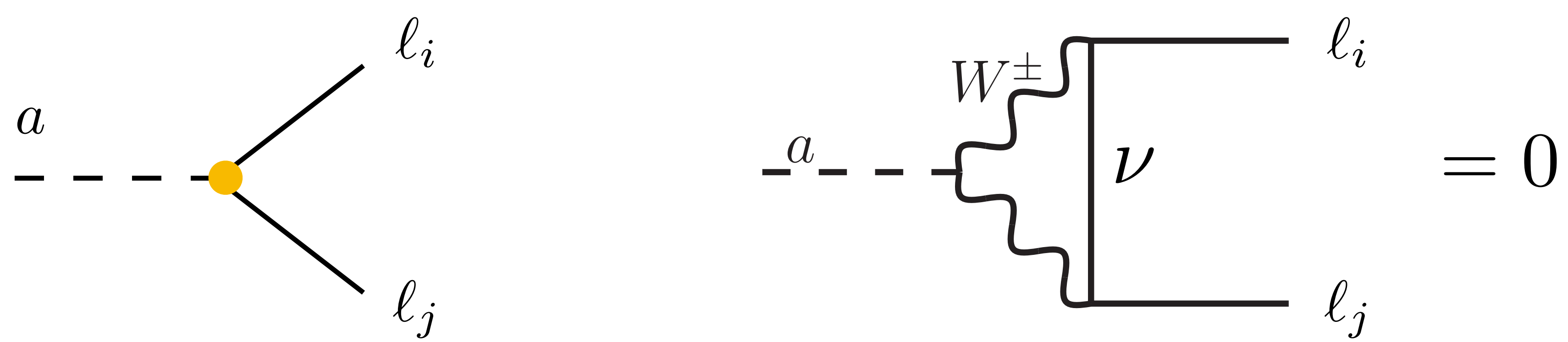
Observable	Mass Range [MeV]	ALP decay mode	Constrained coupling c	Limit (95% CL) on $\lvert c\rvert \cdot \left(\frac{\mathrm{TeV}}{\Lambda}\right) \cdot \sqrt{\mathcal{B}}$
$\mathcal{B}(\mu \to ea(\text{invisible}))$	$13 < m_a < 80$	Long-lived	$\sqrt{\lvert K_e^{e\mu}\rvert^2 + \lvert K_L^{e\mu}\rvert^2}$	3.8×10^{-7}
$\mathcal{B}(\mu \to ea(\text{invisible}))$	$0 < m_a < 13$	Long-lived	$\sqrt{\lvert K_e^{e\mu}\rvert^2 + \lvert K_L^{e\mu}\rvert^2}$	1.5×10^{-6}
$\mathcal{B}(\tau \to ea(\text{invisible}))$	$0 < m_a < 1600$	Long-lived	$\sqrt{\lvert K_e^{e\tau}\rvert^2 + \lvert K_L^{e\tau}\rvert^2}$	2.3×10^{-4}
$\mathcal{B}(\tau \to \mu a(\text{invisible}))$	$0 < m_a < 1600$	Long-lived	$\sqrt{\lvert K_e^{\mu\tau}\rvert^2 + \lvert K_L^{\mu\tau}\rvert^2}$	3.2×10^{-4}
$\mathcal{B}(\mu \to e\gamma\gamma)$	$0 < m_a < 105$	$\gamma\gamma$	$\sqrt{\lvert K_e^{e\mu}\rvert^2 + \lvert K_L^{e\mu}\rvert^2}$	2.6×10^{-6}
$\mathcal{B}(\mu \to 3e)$	$0 < m_a < 105$	e^+e^-	$\sqrt{\lvert K_e^{e\mu}\rvert^2 + \lvert K_L^{e\mu}\rvert^2}$	3.1×10^{-7}
$\mathcal{B}(\tau^- \to \mu^- e^+ e^-)$	$200 < m_a < 1671$	e^+e^-	$\sqrt{\lvert K_e^{\mu\tau}\rvert^2 + \lvert K_L^{\mu\tau}\rvert^2}$	6.1×10^{-7}
$\mathcal{B}(\tau \to 3e)$	$200 < m_a < 1776$	e^+e^-	$\sqrt{\lvert K_e^{e\tau}\rvert^2 + \lvert K_L^{e\tau}\rvert^2}$	7.5×10^{-7}
$\mathcal{B}(\tau \to 3\mu)$	$211 < m_a < 1671$	$\mu^+\mu^-$	$\sqrt{\lvert K_e^{\mu\tau}\rvert^2 + \lvert K_L^{\mu\tau}\rvert^2}$	6.6×10^{-7}

MB, Neubert, Renner, Schnubel, Thamm, 20….

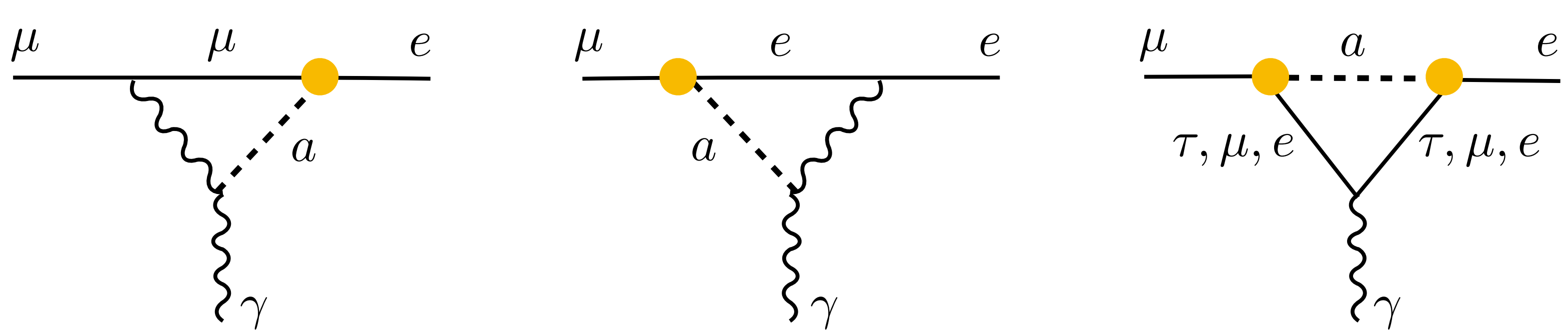
Cornella, Paradisi, Sumensari, 1911.060279

Flavour-violating couplings to leptons

Without tree-level flavour violating couplings to leptons there are no loop-induced LFV ALP couplings, because the SM conserves lepton flavour



If they are present they induce dipole moments



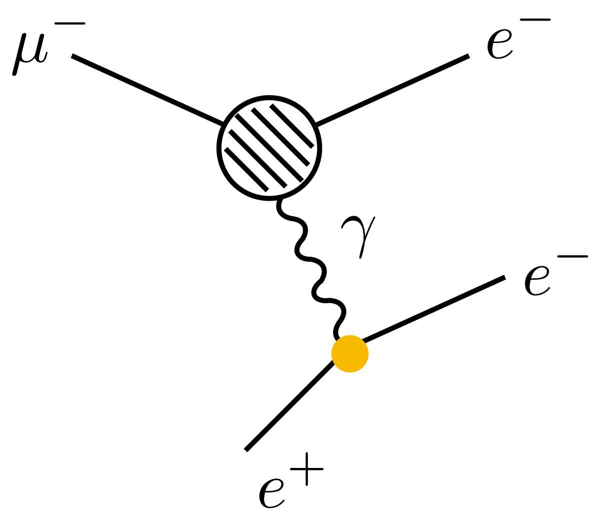
MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

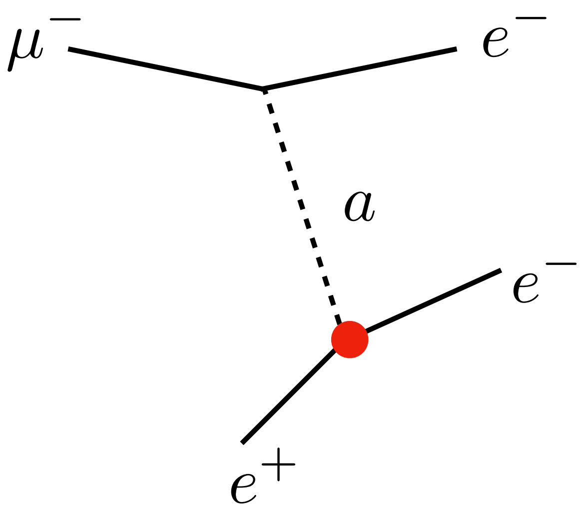
MB, Neubert, Renner, Schnubel, Thamm, 19….

Flavour-violating couplings to leptons

Even though they are loop-suppressed, dipole moment can be more important than tree-level terms

Example: $\mu \to eee$





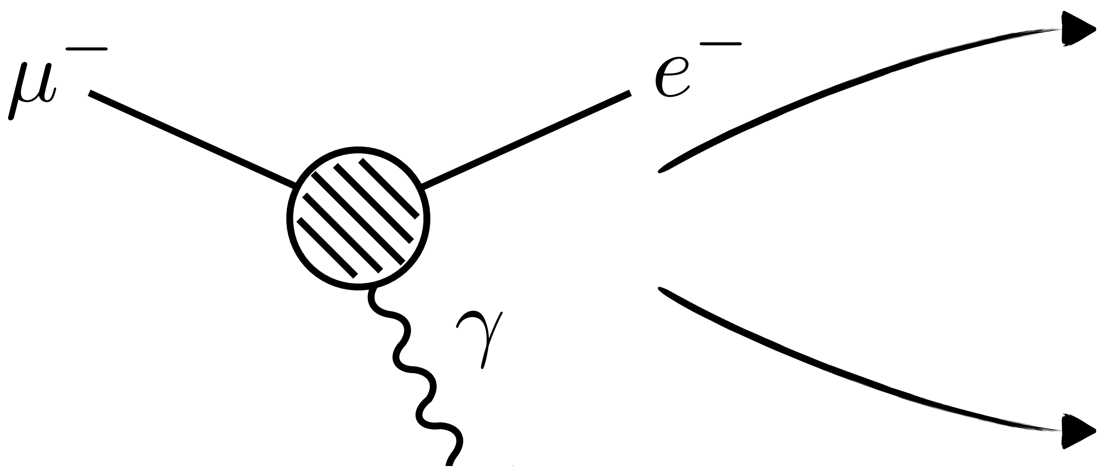
Enhanced by the QED coupling over the electron Yukawa and a potentially large logarithm.

MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

MB, Neubert, Renner, Schnubel, Thamm, 20….

Flavour-violating couplings to leptons

Dipoles also give rise to new constraints
and to anomalous magnetic dipole moments



$$\Gamma(\mu \to e\gamma) = \frac{m_\mu^3}{8\pi}\left(1 - \frac{m_e^2}{m_\mu^2}\right)\left[|F_2(0)|^2 + |F_2^5(0)|^2\right]$$

$$\Delta a_\mu = \frac{2m_\mu}{e} F_2(0)$$

MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

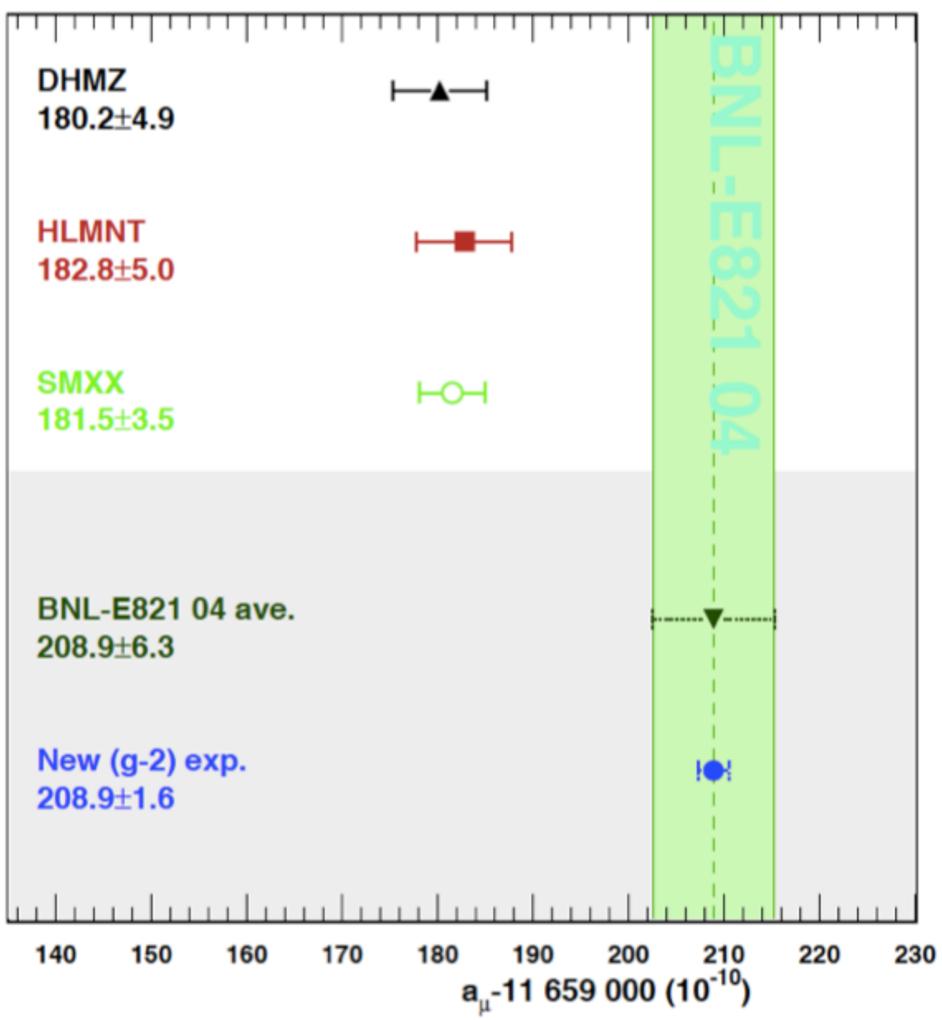
MB, Neubert, Renner, Schnubel, Thamm, 20….

ALPs and (g-2)$_\mu$

The anomalous magnetic moment of the muon

$$a_\mu = (g-2)_\mu/2$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6)\cdot 10^{-10}$$



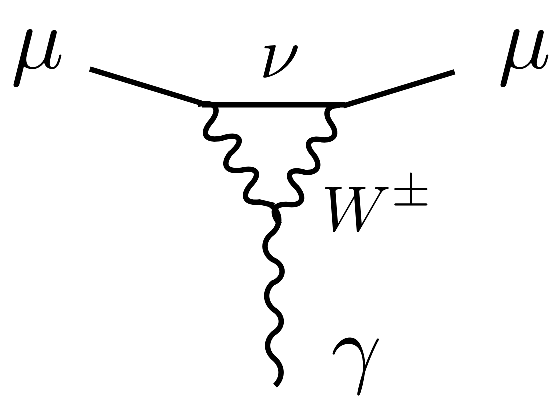
[Gohn 1506.00608]

Currently: $3.6\,\sigma$ discrepancy

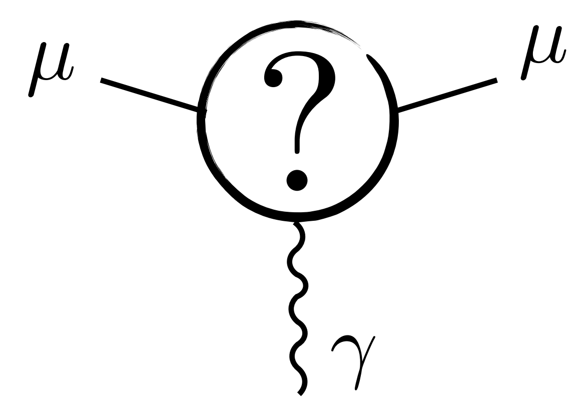
Future: $\gtrsim 5\,\sigma$?

SM

$$\delta a_\mu^W \approx \frac{g^2}{20\pi^2}\frac{m_\mu^2}{M_W^2} \approx 400\times 10^{-11}$$



NP



$$M = \mathcal{O}(\mathrm{TeV})$$

ALPs and (g-2)$_e$

Recently, also a deviation in the electron anomalous magnetic dipole moment has been reported

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14} \qquad 2.4\sigma$$

Not as significant, and with the opposite sign, but

$$\frac{\Delta a_e}{\Delta a_\mu} \approx -12.6\,\frac{m_e^2}{m_\mu^2}$$

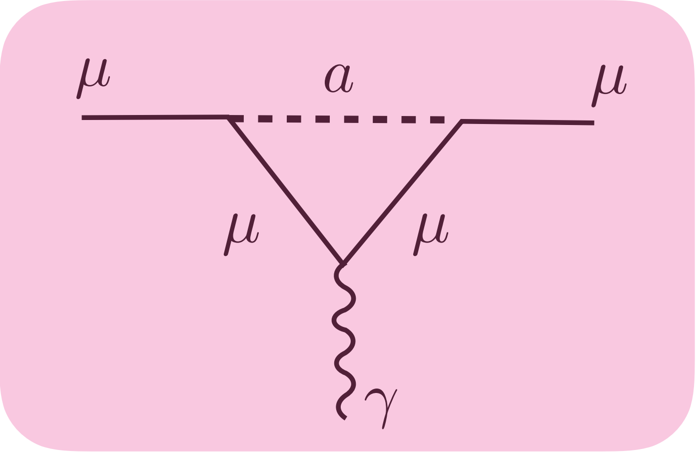
Could an ALP explain either -or both- anomalies?

Parker, Yu, Zhong, Renner, Estey, Müller, Science **360** (2018) 191

ALPs and (g-2)

Could an ALP explain either -or both- anomalies?

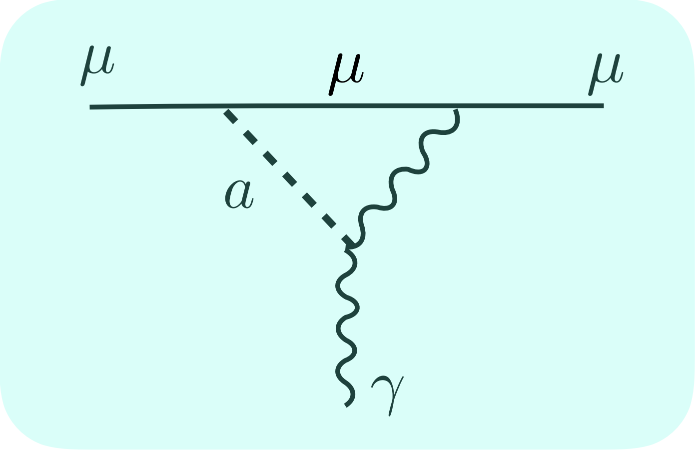
Without flavour violation



$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6) \cdot 10^{-10} \,,$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14} \,.$$

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2} \left\{ K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\, h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\, c_{\mu\mu}\, C_{\gamma\gamma} \left[\ln \frac{\mu^2}{m_\mu^2} + \delta_2 + 3 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right) \right] \right\}$$

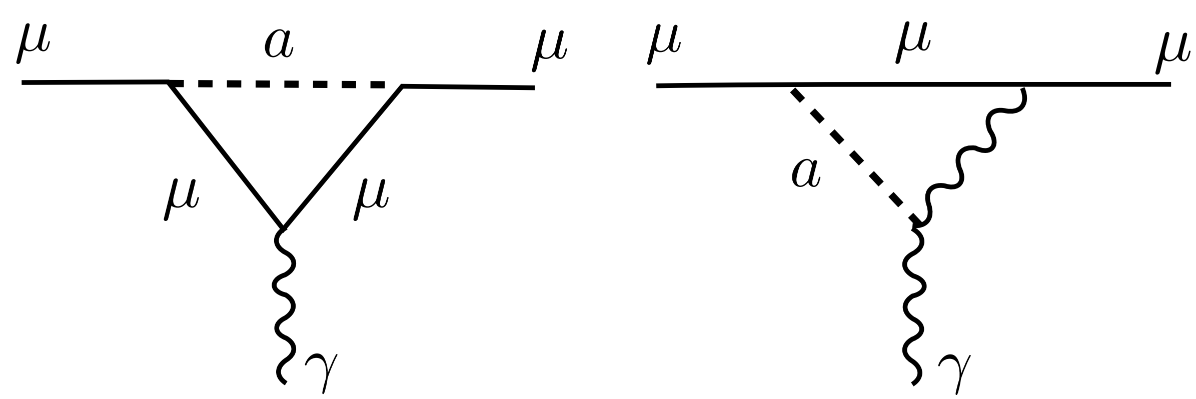


Photon coupling loop-induced from electron coupling

MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

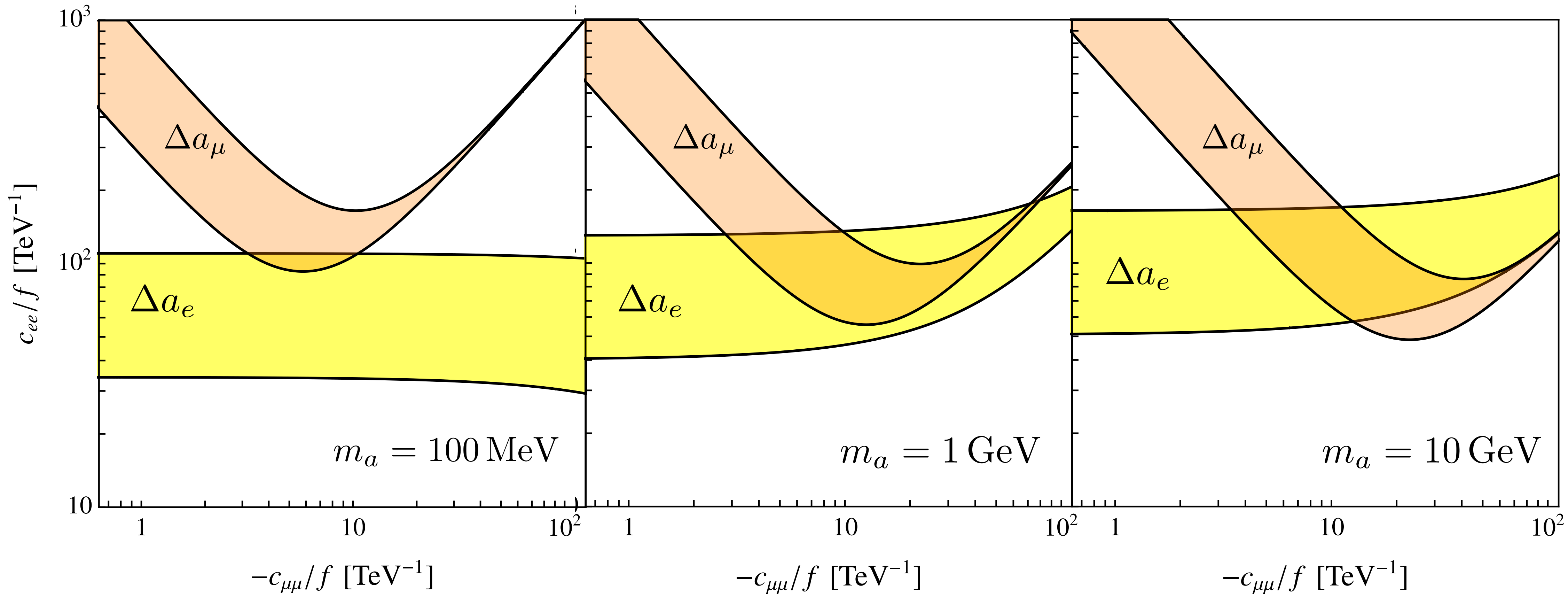
MB, Neubert, Renner, Schnubel, Thamm, 20….

ALPs and (g-2)



$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6) \cdot 10^{-10}\,,$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14}\,.$$



Large flavour non-universal couplings can provide a solution.

$$c_{\mu\mu} = (k_e)_{\mu\mu} - (k_E)_{\mu\mu}$$

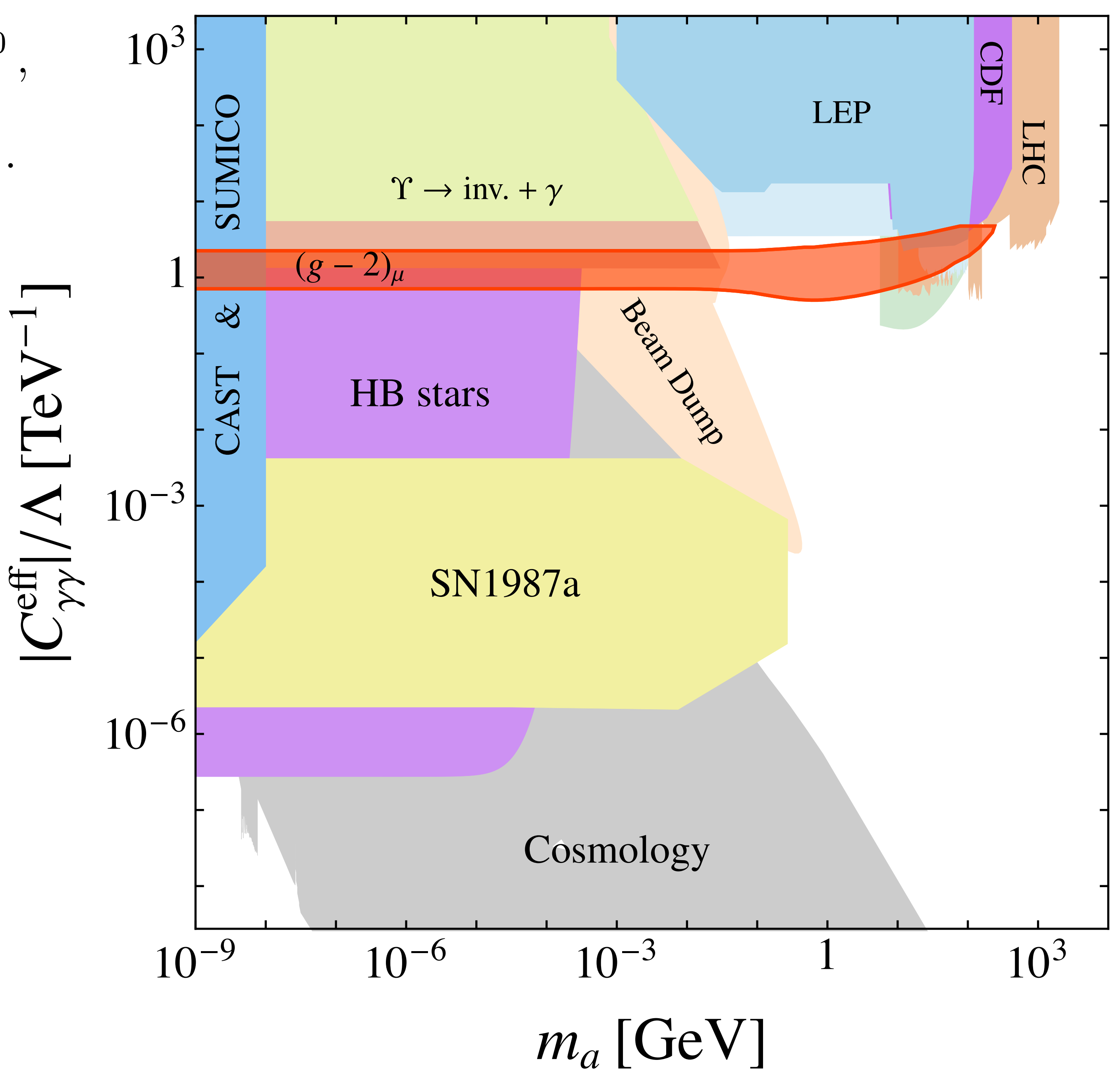
MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

MB, Neubert, Renner, Schnubel, Thamm, 20….

ALPs and (g-2)

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6) \cdot 10^{-10} \,,$$
$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14} \,.$$

Only possible for ALPs above the 100 MeV scale.



MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

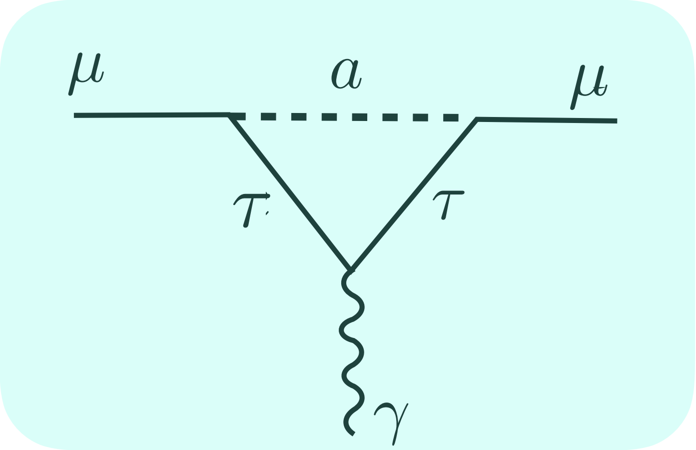
MB, Neubert, Renner, Schnubel, Thamm, 20….

ALPs and (g-2)

With flavour violation

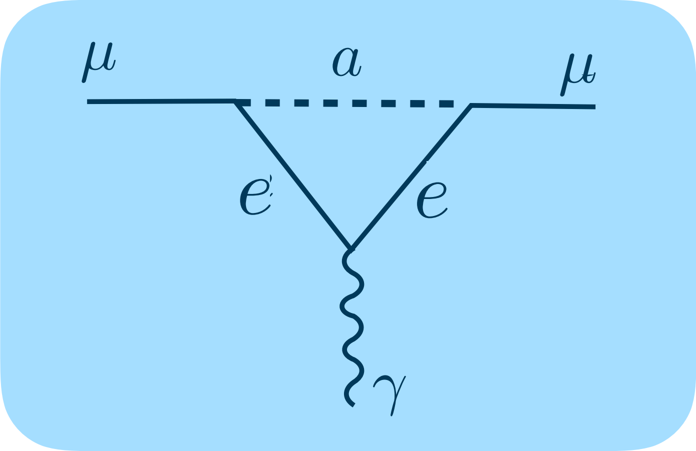
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6) \cdot 10^{-10}\,,$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14}\,.$$



$$\Delta a_\mu = \frac{2m_\mu}{e} F_2(0) = \frac{m_\mu m_\tau}{16\pi^2\,\Lambda^2}\,{\rm Re}\big[(k_E^{\tau\mu})^* k_e^{\tau\mu}\big]\, h(x_\tau) + \mathcal{O}\Big(\frac{m_\mu}{m_\tau}\Big)$$

$$\Delta a_\mu = -\frac{m_e m_\mu}{32\pi^2\Lambda^2}\Big(|k_E^{\mu e}|^2 + |k_e^{\mu e}|^2\Big)\, j(x_\mu) + \mathcal{O}\Big(\frac{m_e}{m_\mu}\Big)$$



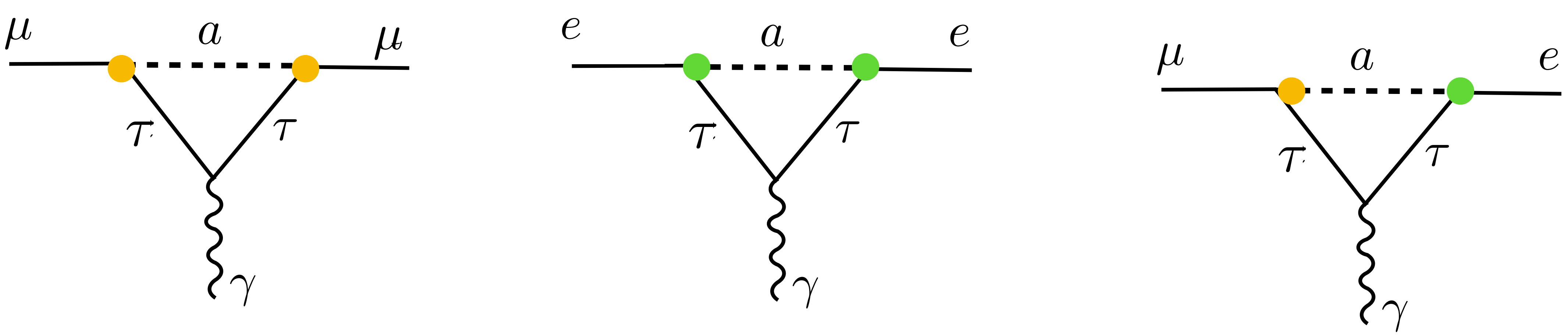
Flavour-violating couplings can give either sign depending on the mass hierarchies

MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

MB, Neubert, Renner, Schnubel, Thamm, 20….

ALPs and (g-2)

Tau couplings alone cannot explain both anomalies



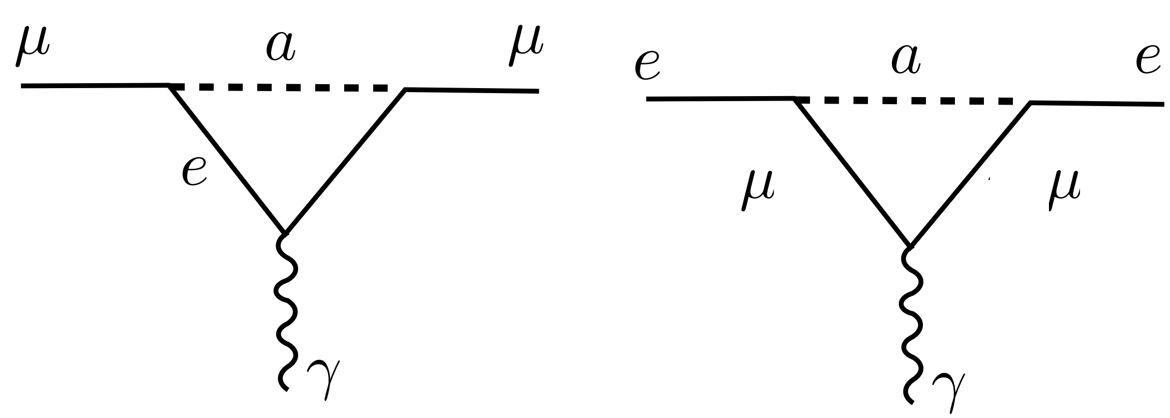
$$\Gamma(\mu \to e\gamma) = \frac{m_\mu^3 m_\tau^2}{1024\pi^3\Lambda^4}\left(1 - \frac{m_e^2}{m_\mu^2}\right)\left[|(K_e)_{23}(K_E)_{31}|^2 + |(K_E)_{23}(K_e)_{31}|^2\right] g_2(0, m_\tau, m_a)^2$$

$\mu \to e\gamma$

$$\left[|(K_e)_{23}(K_E)_{31}|^2 + |(K_E)_{23}(K_e)_{31}|^2\right]^{1/2} \leq 6 \times 10^{-7}\frac{\Lambda^2}{\text{TeV}^2};$$

MB, Neubert, Renner, Schnubel, Thamm, 20….

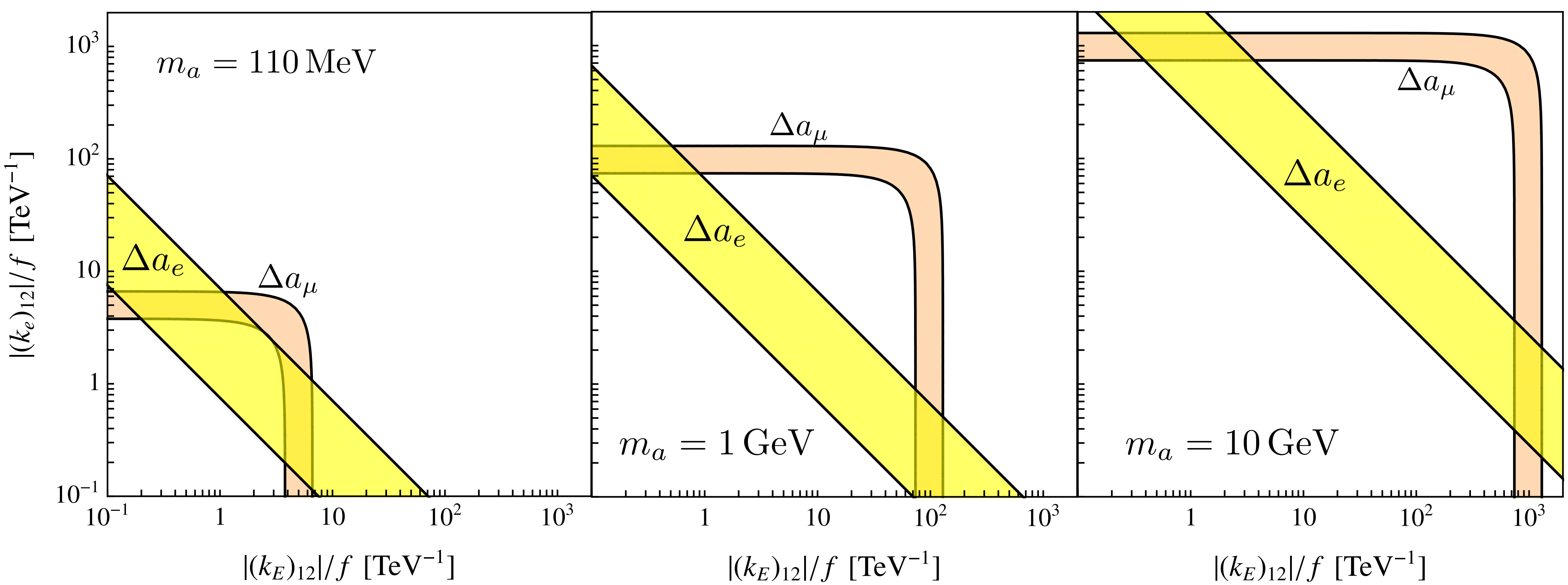
ALPs and (g-2)



With flavour violation

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.3 \pm 7.6) \cdot 10^{-10}\,,$$

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = (-87 \pm 36) \cdot 10^{-14}\,.$$

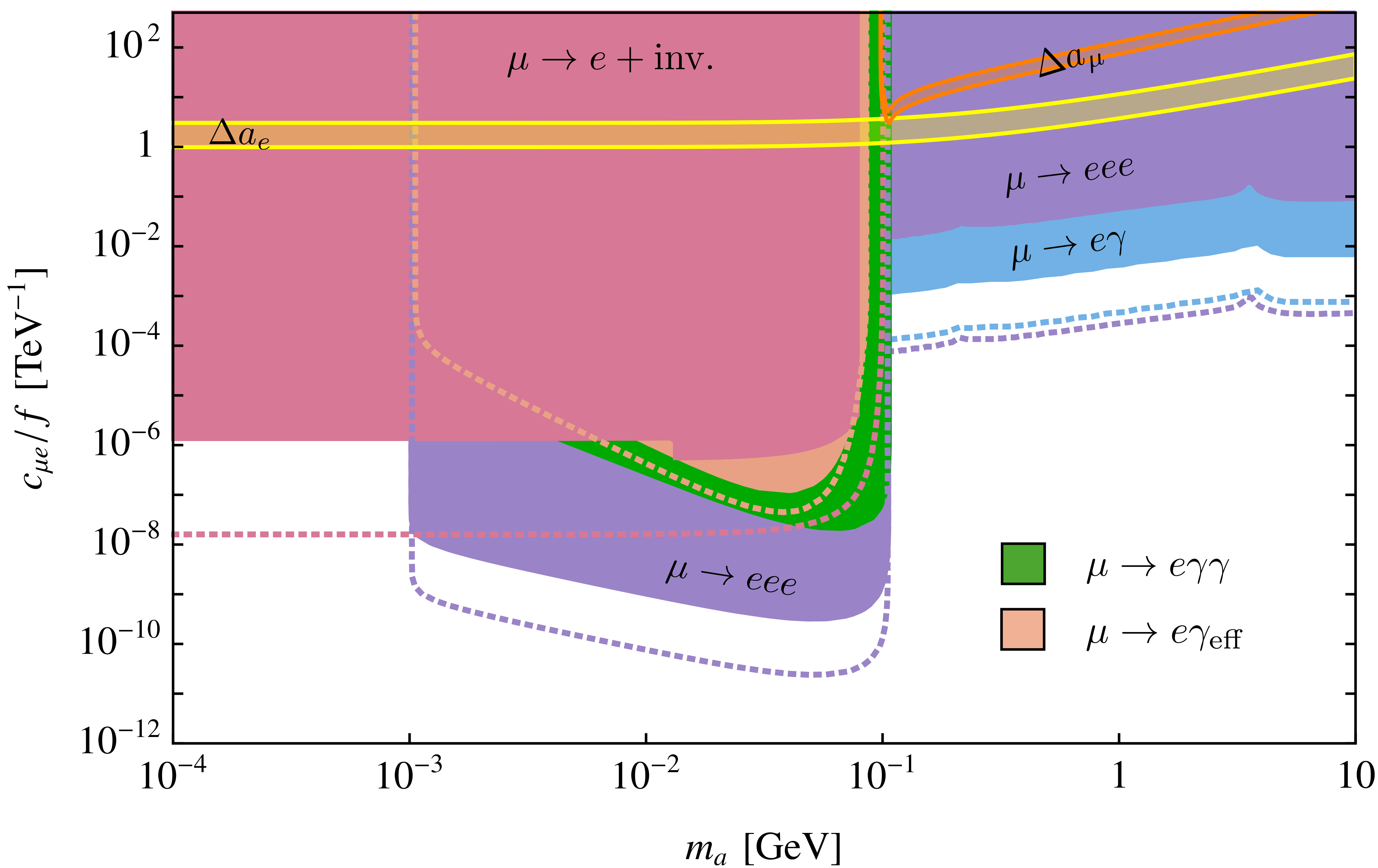


Flavour violating couplings can provide a solution.

MB, Neubert, Renner, Schnubel, Thamm, 1908.00008

MB, Neubert, Renner, Schnubel, Thamm, 20….

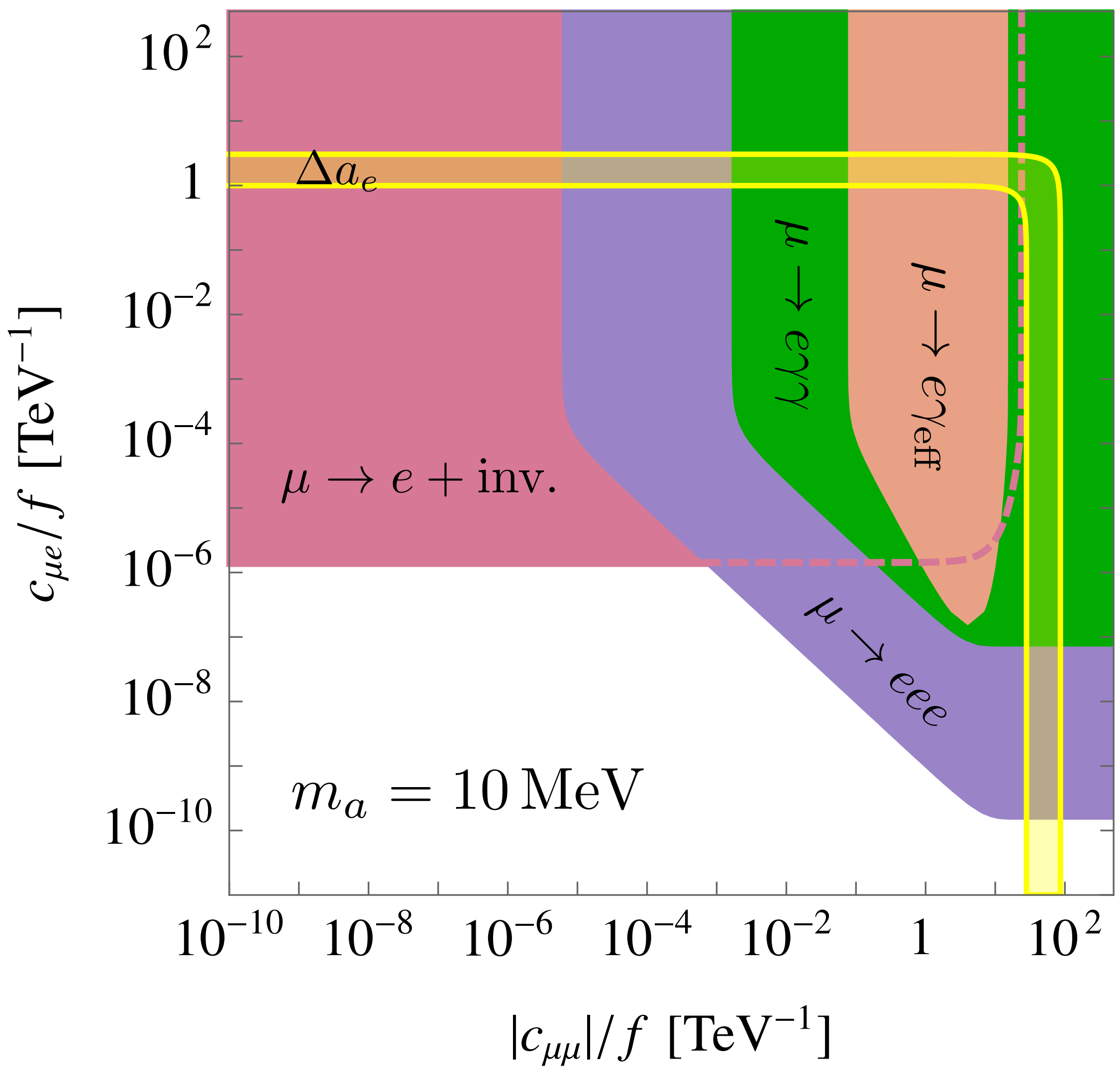
Bounds from mu-e couplings

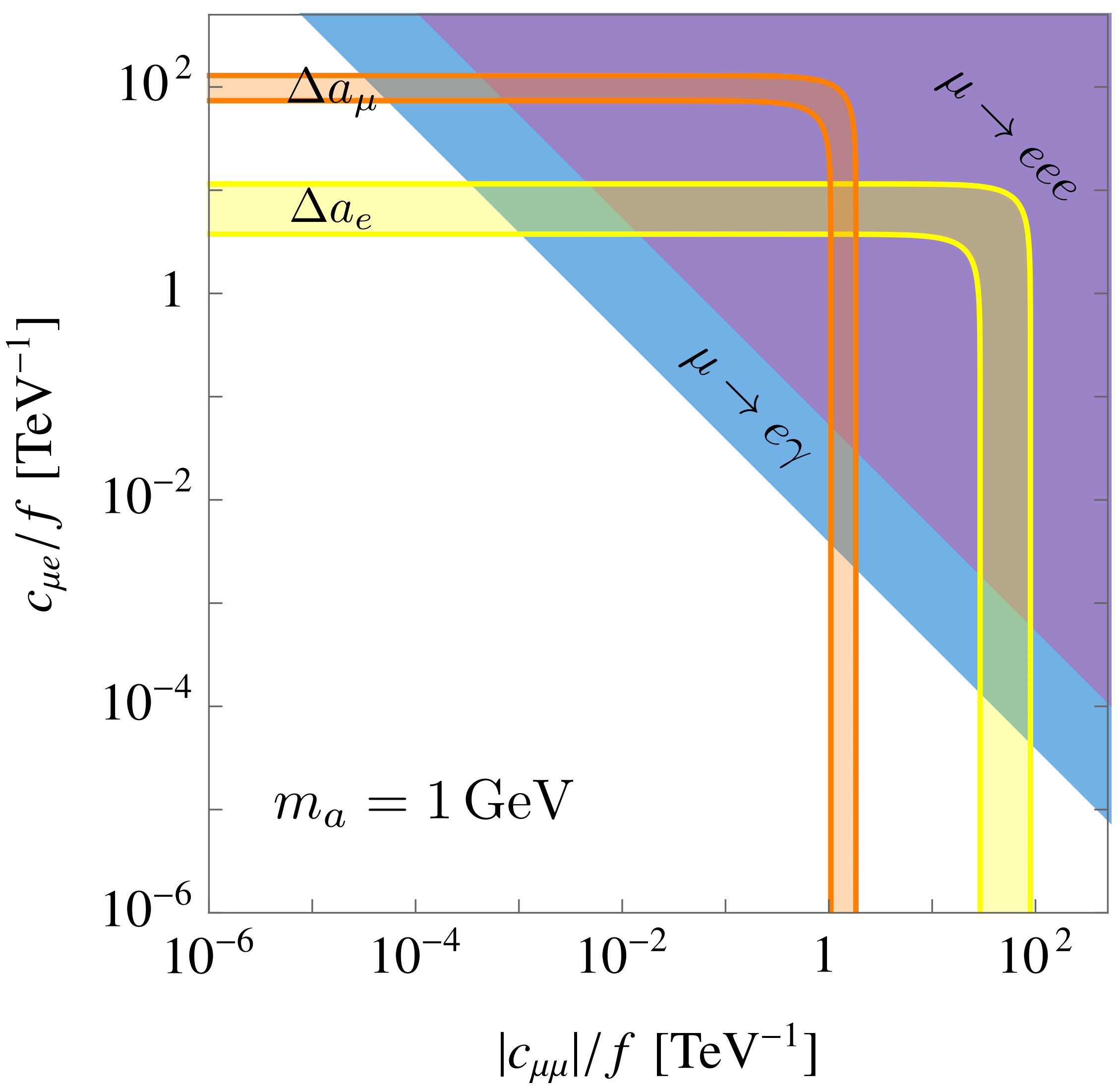


$c_{\mu e} = \sqrt{|(k_e)_{\mu\mu}|^2 + |(k_E)_{\mu\mu}|^2}$

$c_{\ell\ell}/f = 1 \text{ TeV}^{-1}$

Bounds from mu-e couplings





$$c_{\mu\mu} = (k_e)_{\mu\mu} - (k_E)_{\mu\mu}$$

$$c_{\mu e} = \sqrt{|(k_e)_{\mu e}|^2 + |(k_E)_{\mu e}|^2}$$

Conclusions

ALPs could be harbingers of a New Physics sector at a large scale not directly accessible by collider searches

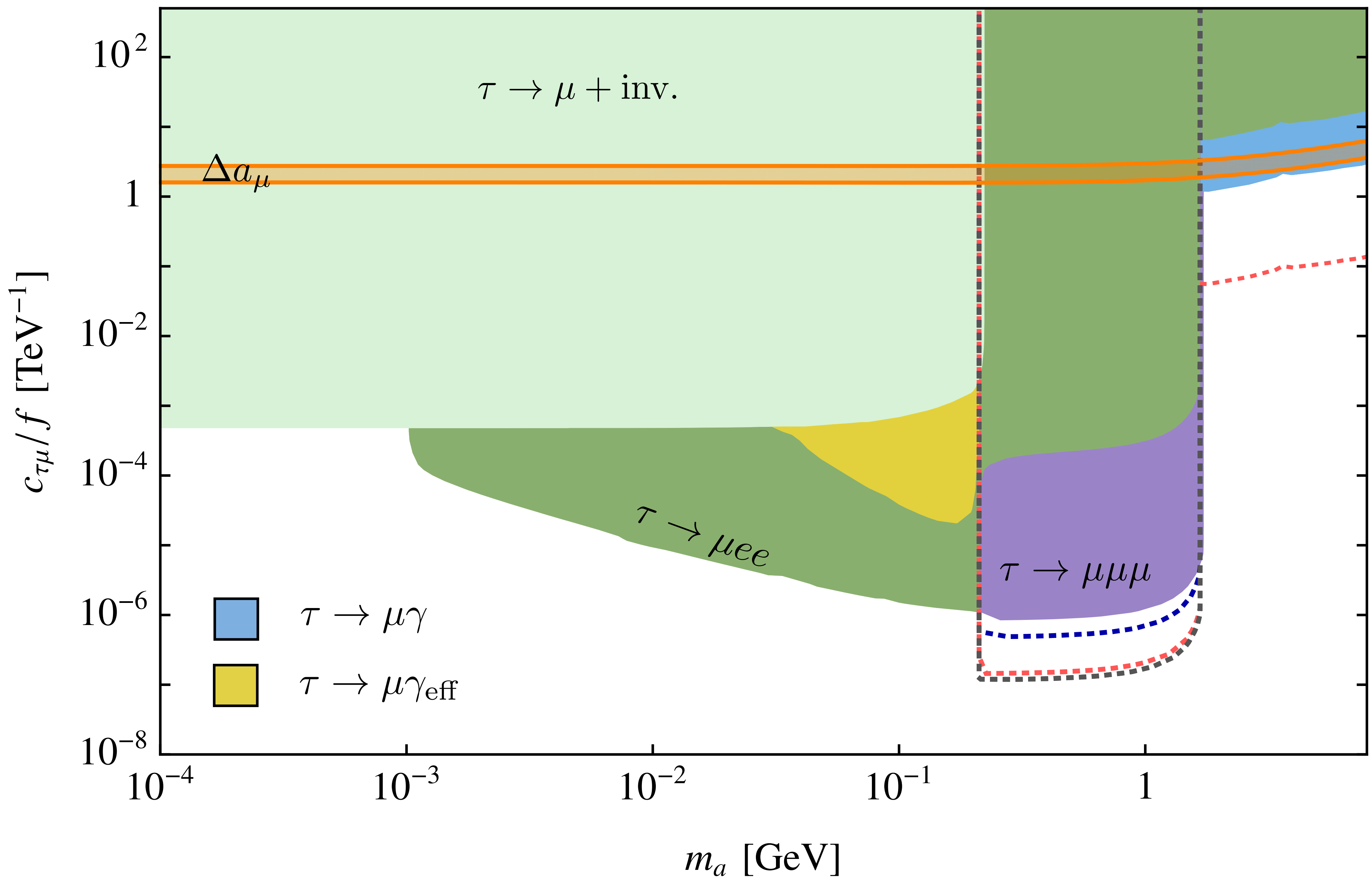
ALP couplings are set by the symmetries of this new sector.

Flavour searches are important to constrain this symmetry structure.

The tension in the lepton anomalous magnetic moments could be a sign of lepton-flavour violating ALPs.

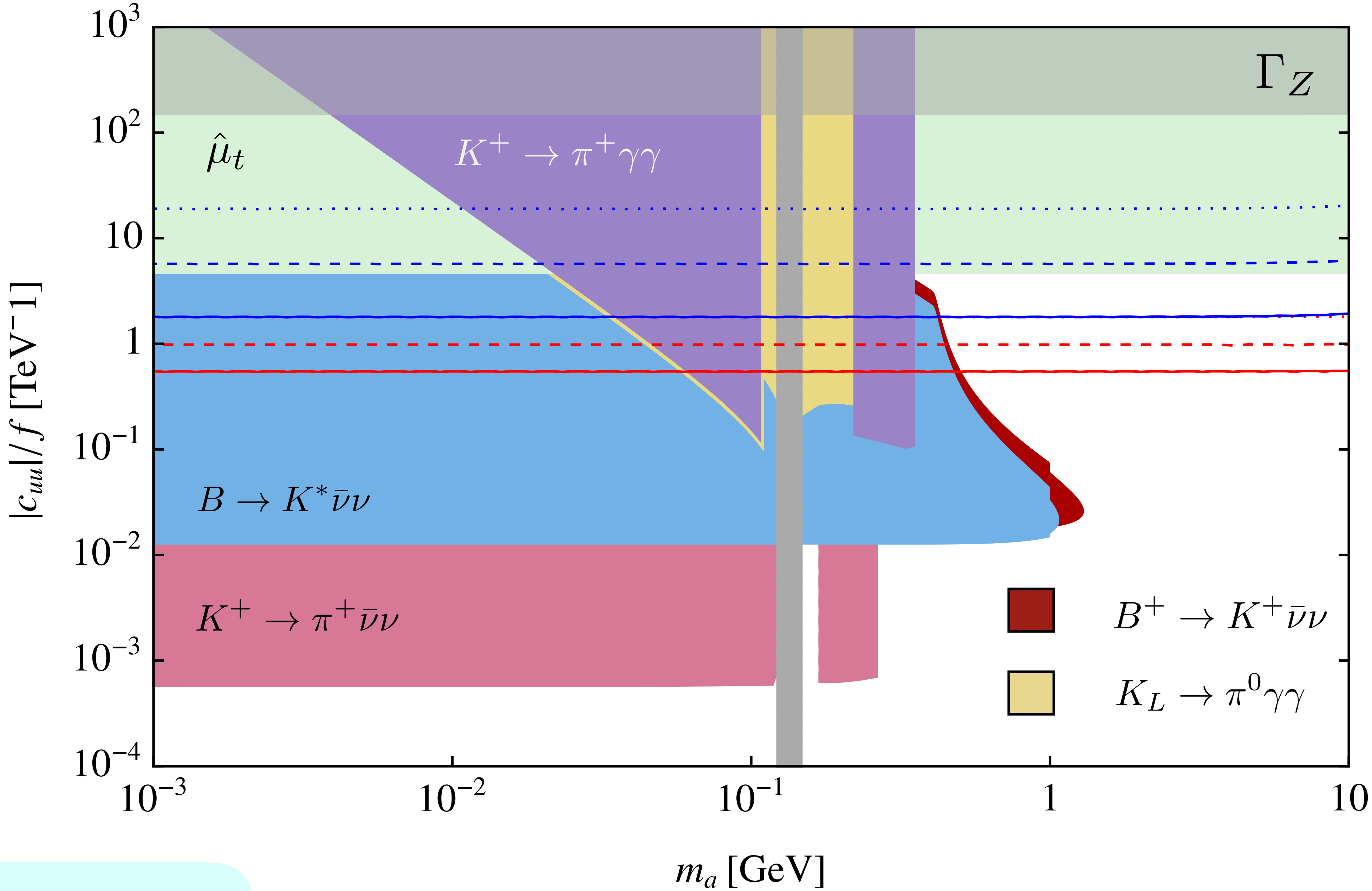
Backup

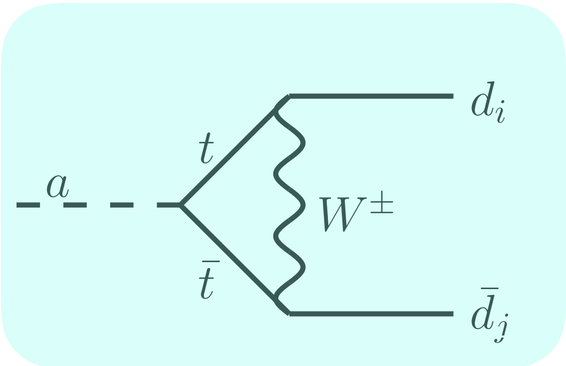
Bounds from tau-mu couplings



$c_{\ell\ell}/f = 1\ \text{TeV}^{-1}$

Bounds from up-quark couplings

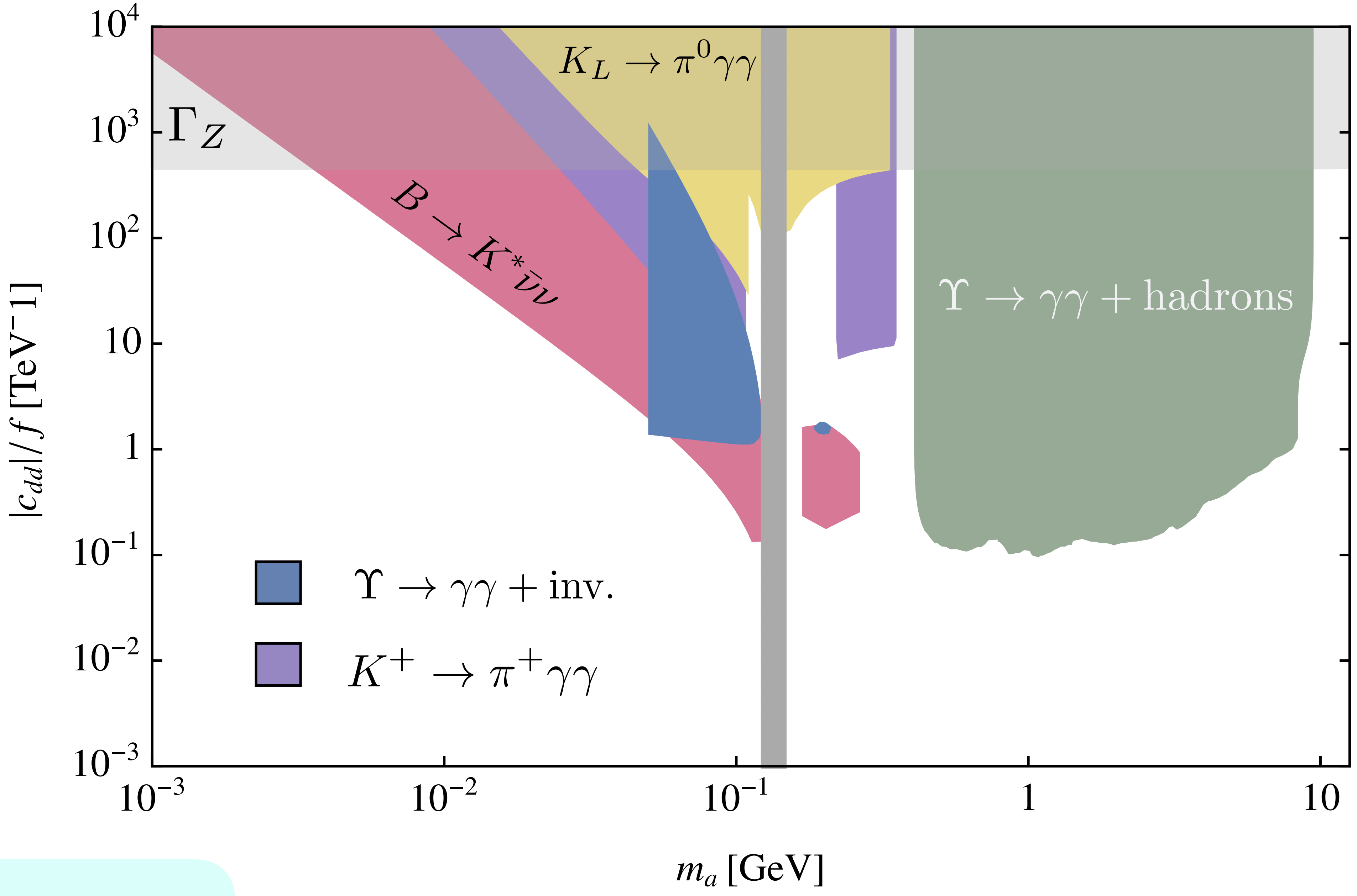


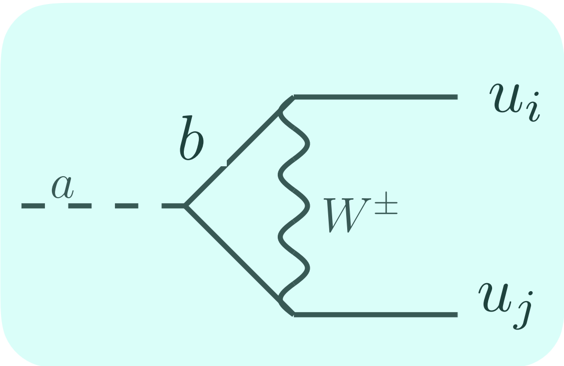


$\mathrm{Br}(h \to aa) = 10^{-1}, 10^{-2}, 10^{-3}$

$\mathrm{Br}(h \to aZ) = 10^{-1}, 10^{-2}, 10^{-3}$

Bounds from down-quark couplings





New Gauge Bosons

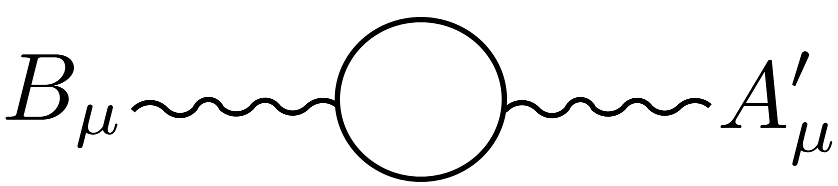
New light gauge bosons have long history

Holdom Phys.Lett 166B, (1986)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}D_\mu S D^\mu S$$

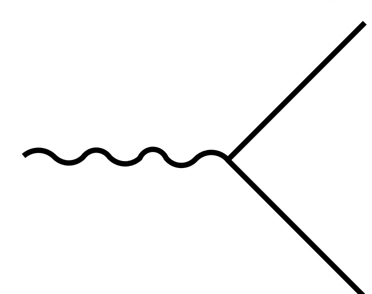
Hidden Photon mass term

$$m_{A'} = g_X \langle S \rangle$$



$$\epsilon \propto \frac{g_X e}{8\pi^2} \log \frac{\Lambda^2}{m^2}$$

Small masses ⟷ Small couplings

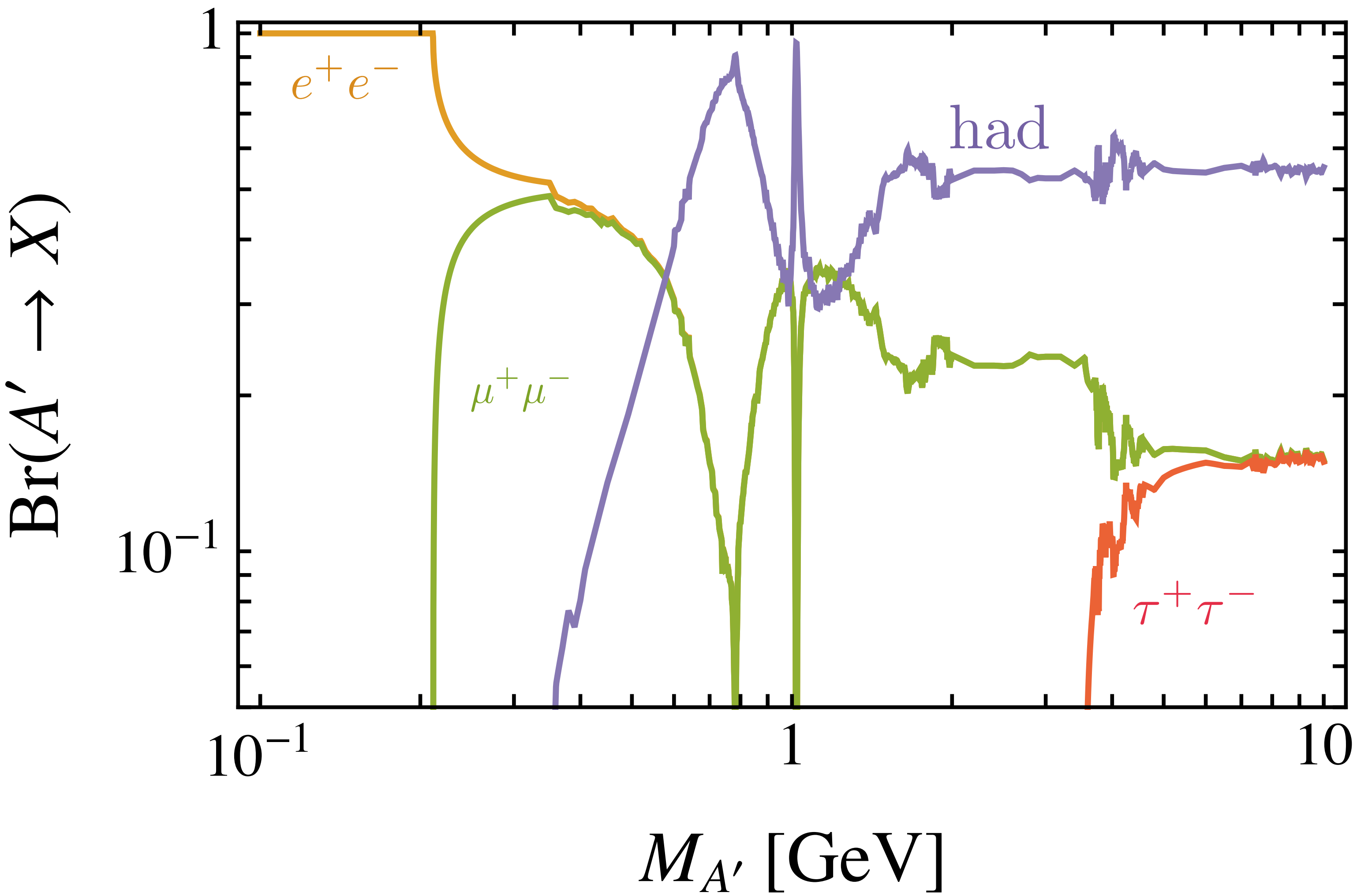


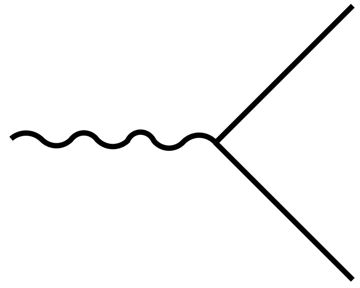
$$e A_\mu J^\mu_{\mathrm{EM}} - \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

Universal

New Gauge Bosons

The new light gauge boson couples like a a massive photon

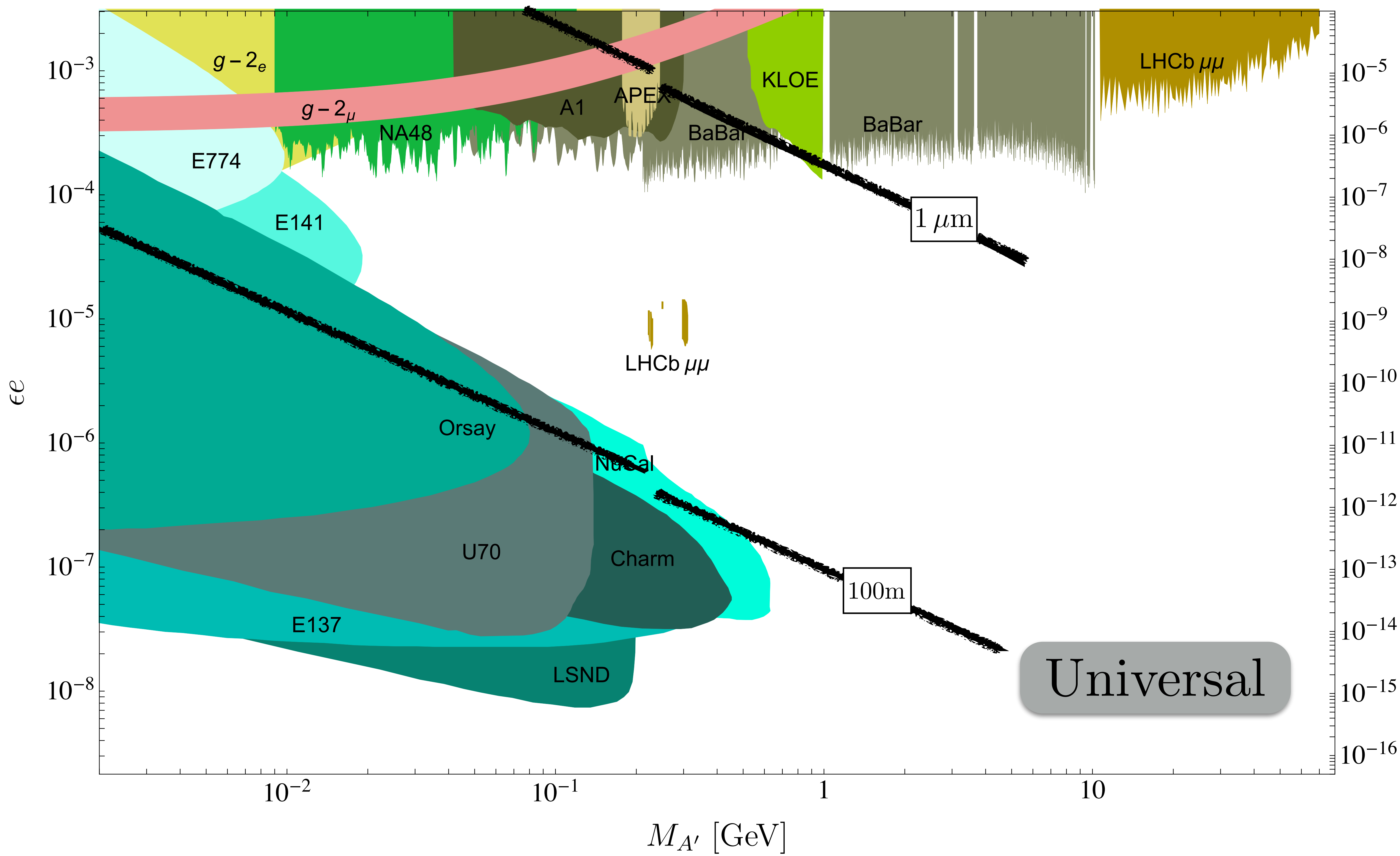




$$eA_\mu J^\mu_{\mathrm{EM}} - \epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$

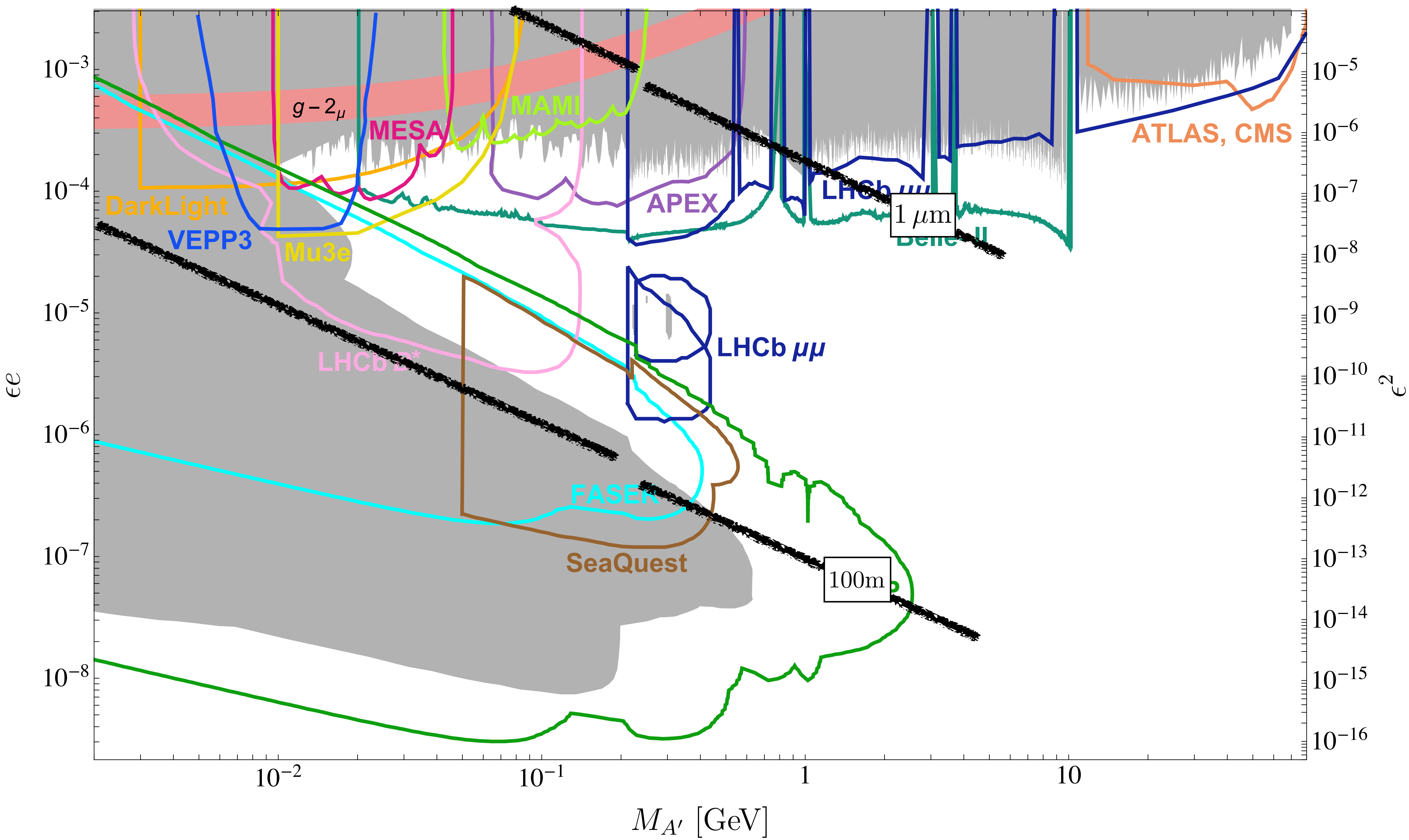
Universal

New Gauge Bosons



MB, Foldenauer Jaeckel, JHEP **1807** 094 (2018)

New Gauge Bosons



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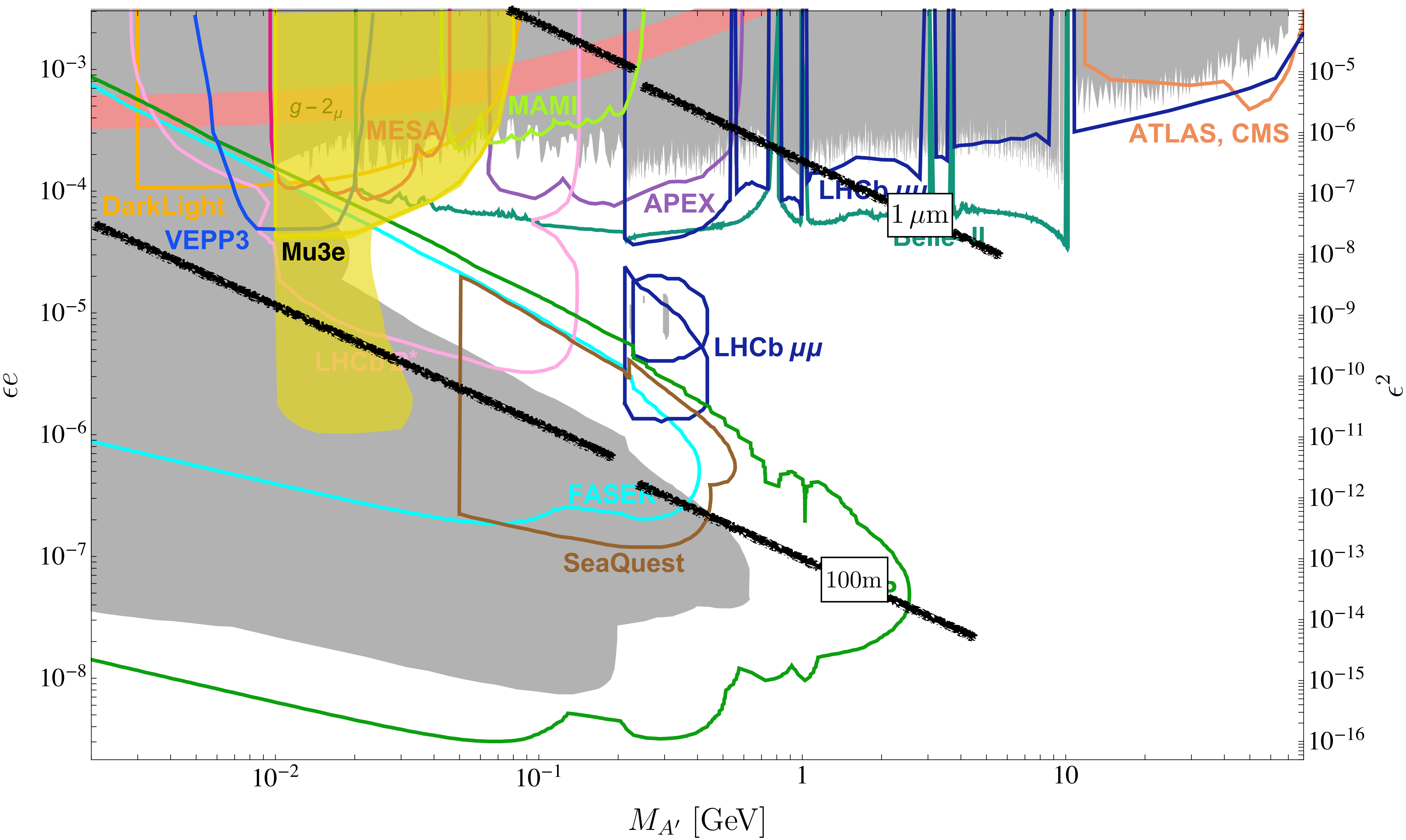
New Gauge Bosons

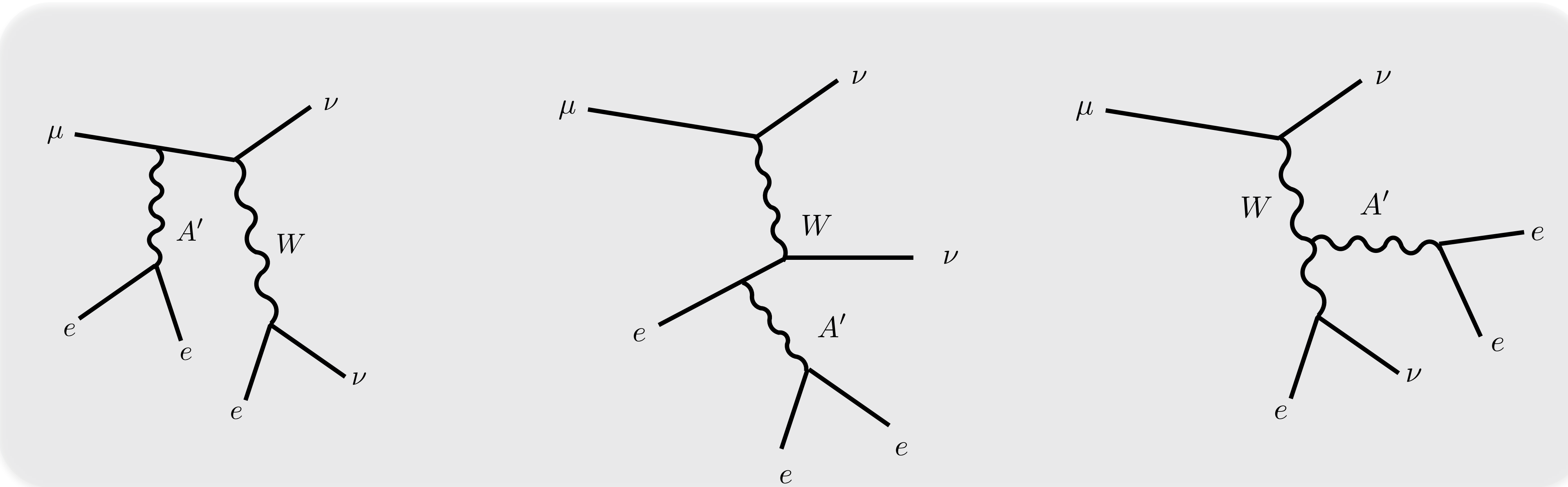


MB, Foldenauer Jaeckel, JHEP **1807** 094 (2018)

New Gauge Bosons

The Mu3e experiment can search for light hidden photons

$$\mu^+ \to \gamma' e^+ \nu_e \bar{\nu}_\mu \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$$

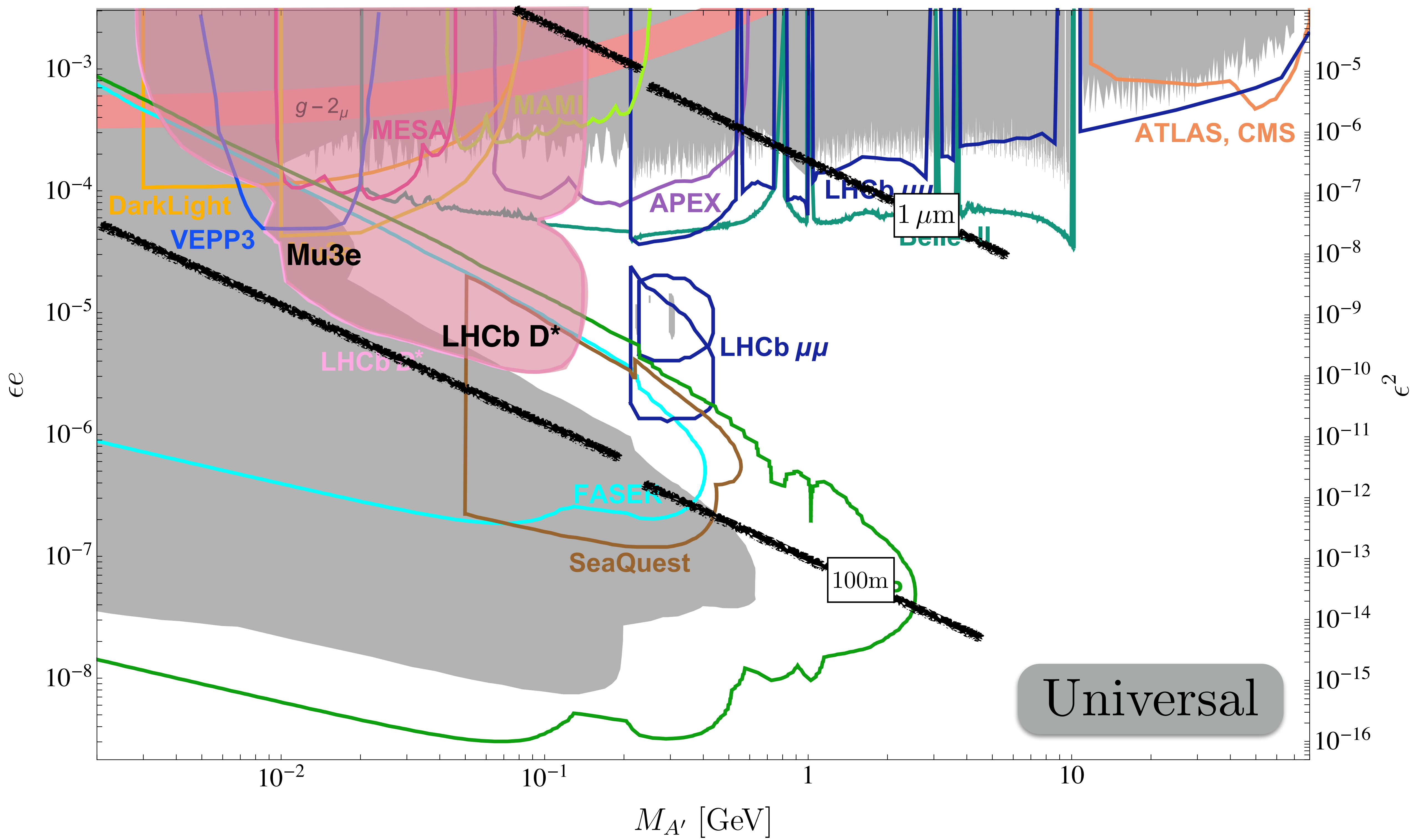


Universal

Prompt decays [Echenard, Essig, Zhong, *1411.1770]*

Displaced vertices [Mu3E collaboration, *in prep.]*

New Gauge Bosons

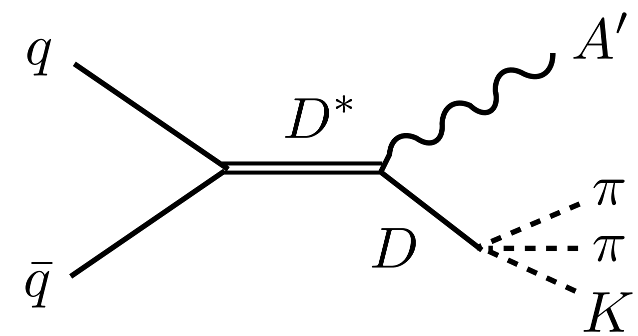


MB, Foldenauer Jaeckel, JHEP **1807** 094 (2018)

New Gauge Bosons

LHCb can search for hidden photons in rare charm decays

$$D^* \to D\gamma \to D\gamma' \to De^+e^-$$



Taking advantage of large statistics:
About 14 Trillion D* mesons in Run III (15 /fb)

$$\mathrm{Br}(D^* \to D\gamma) = 38\%$$

$$\mathrm{Br}(D^* \to D\pi) = 62\%$$

Universal

Ilten et al. Phys. Rev. Lett. **116**, no. 25, 251803 (2016)

LHCb, Phys. Rev. Lett. **120**, 061801 (2018)

New Gauge Bosons

New gauge bosons with gauge couplings to the SM

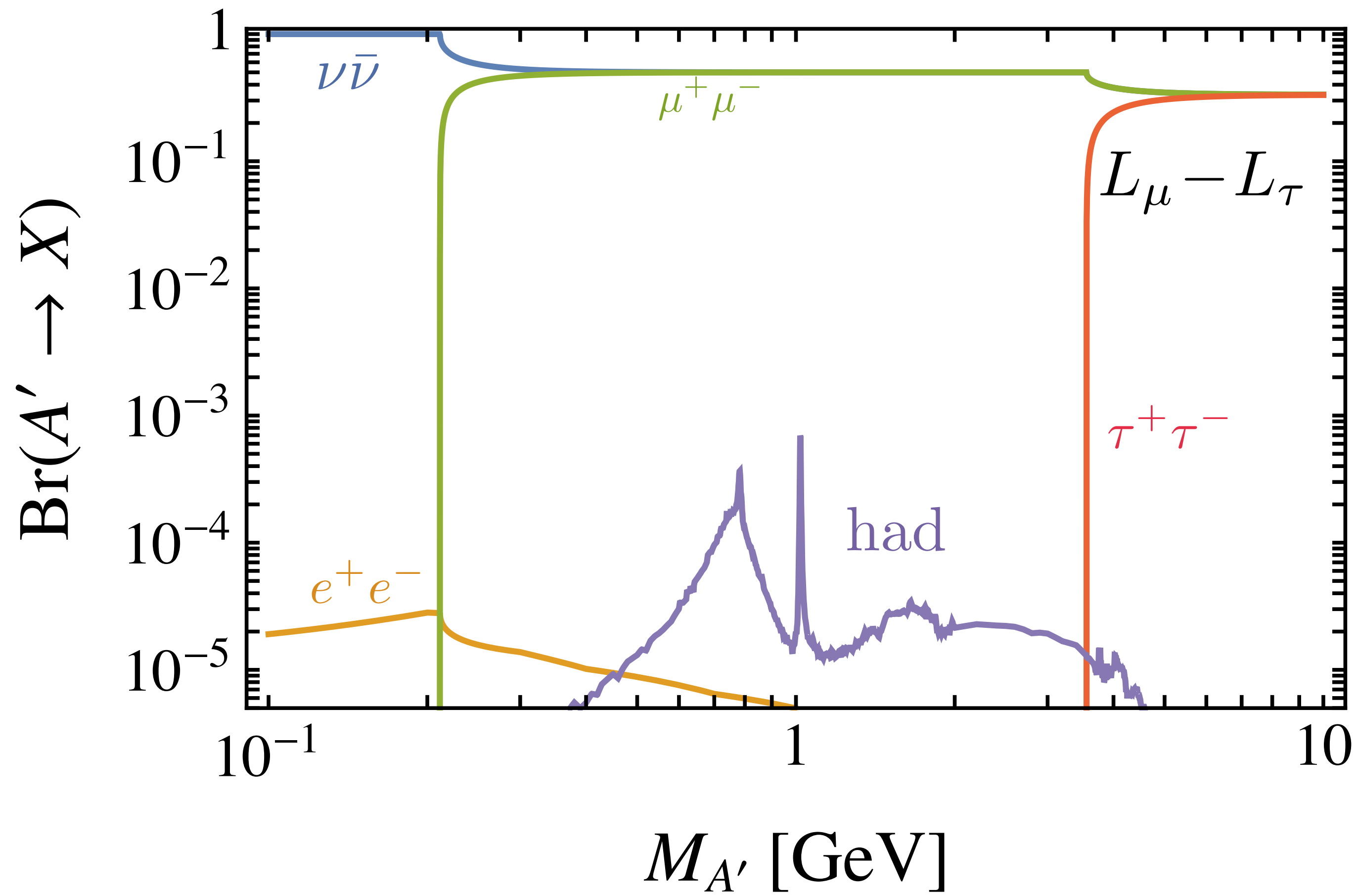
There is a limited number of possible new light gauge bosons consistent with the SM (= anomaly free, and able to reproduce mixing structures).

Universal | B - L | $L_\mu - L_e$ | $L_e - L_\tau$ | $L_\mu - L_\tau$

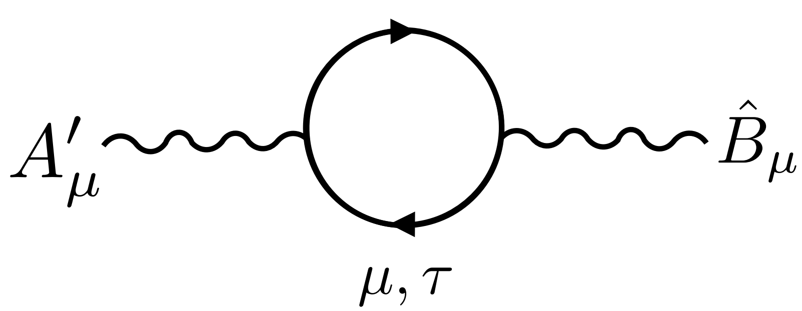
New Gauge Bosons

$L_\mu - L_\tau$

BRs very different from the universal case



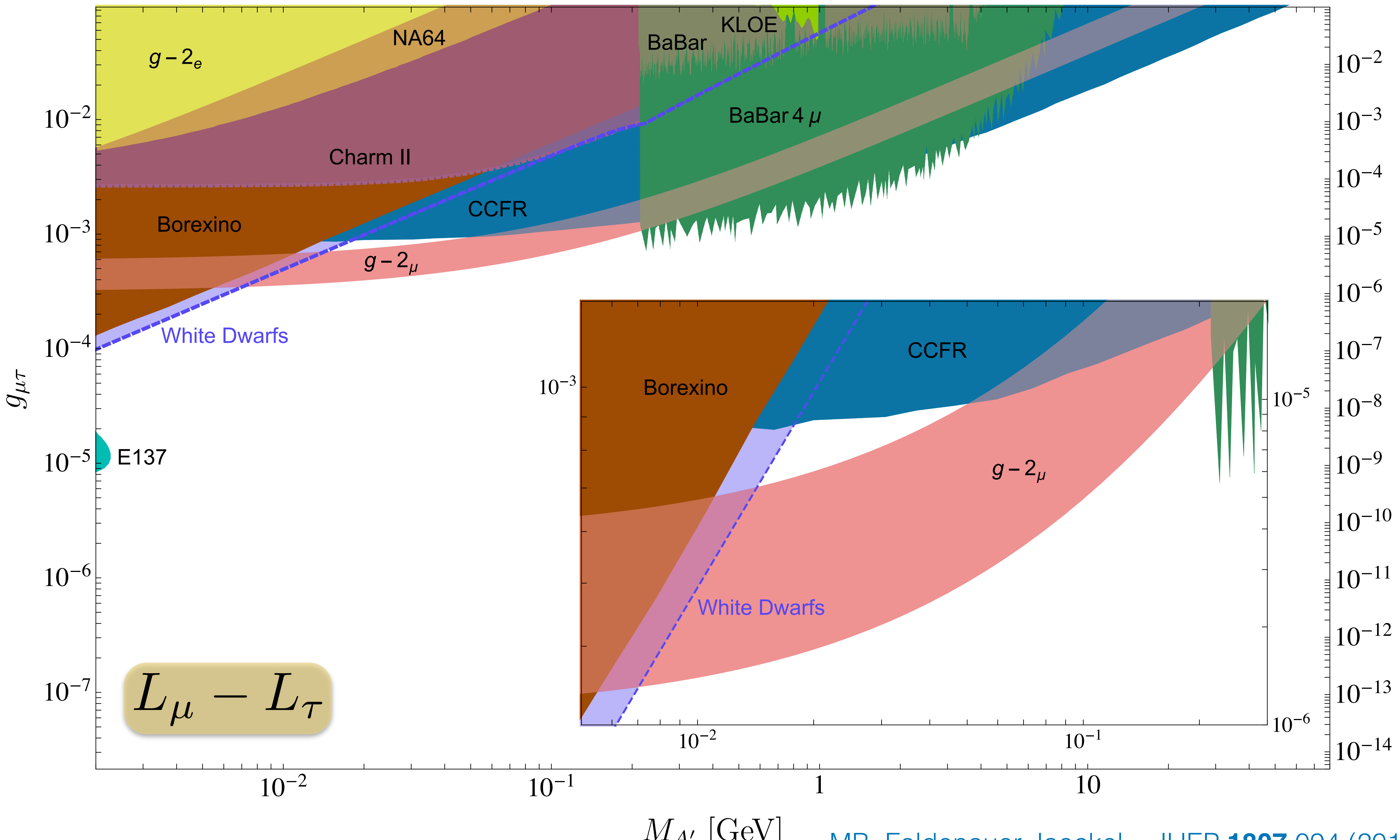
Couplings to the SM are loop-induced and finite (!)



$$\epsilon = -\frac{e\,g}{8\pi^2} \log \frac{m_\tau^2}{m_\mu^2} \approx \frac{g}{50}$$

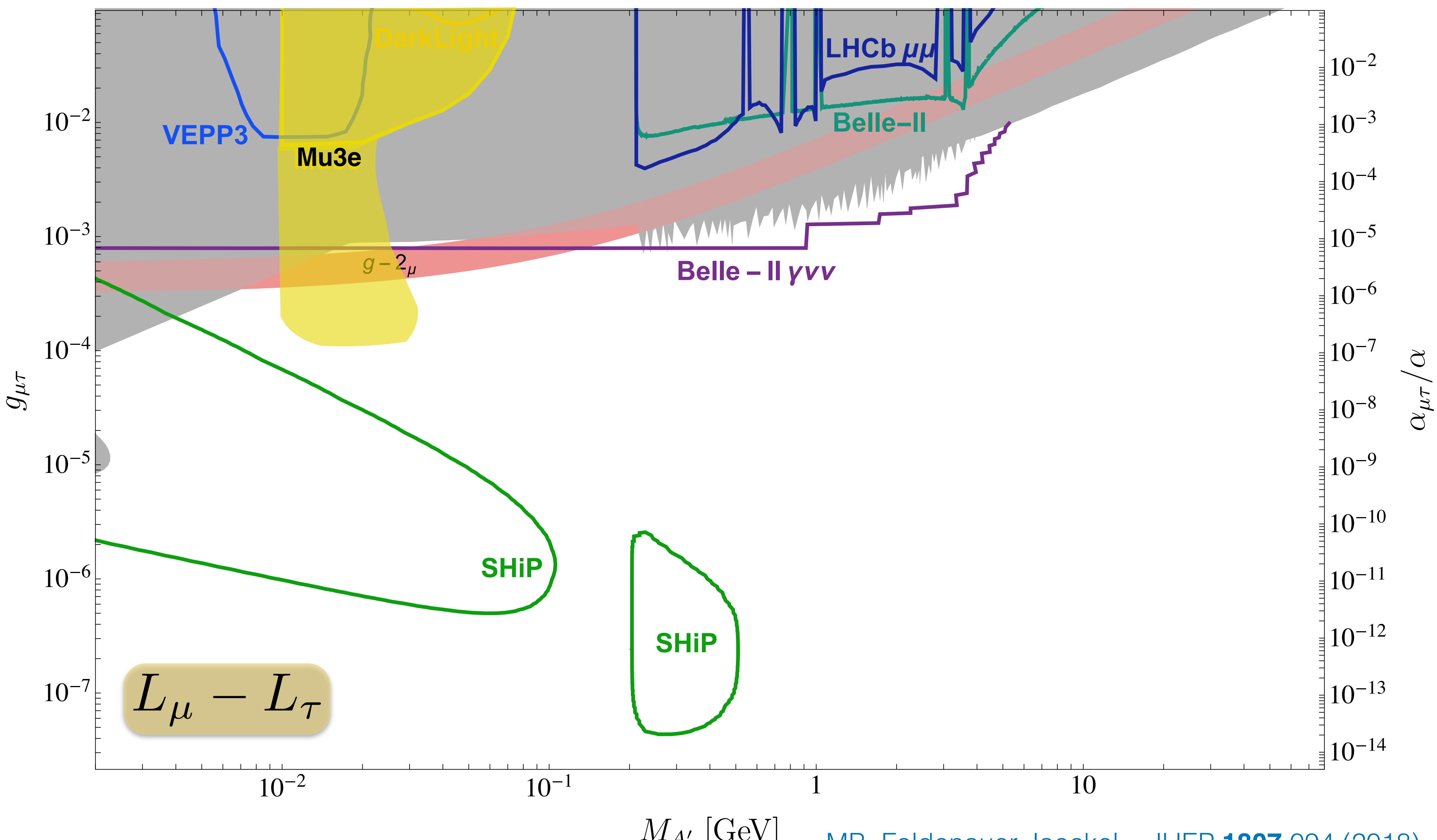
…couplings to hadrons and electrons are suppressed.

New Gauge Bosons



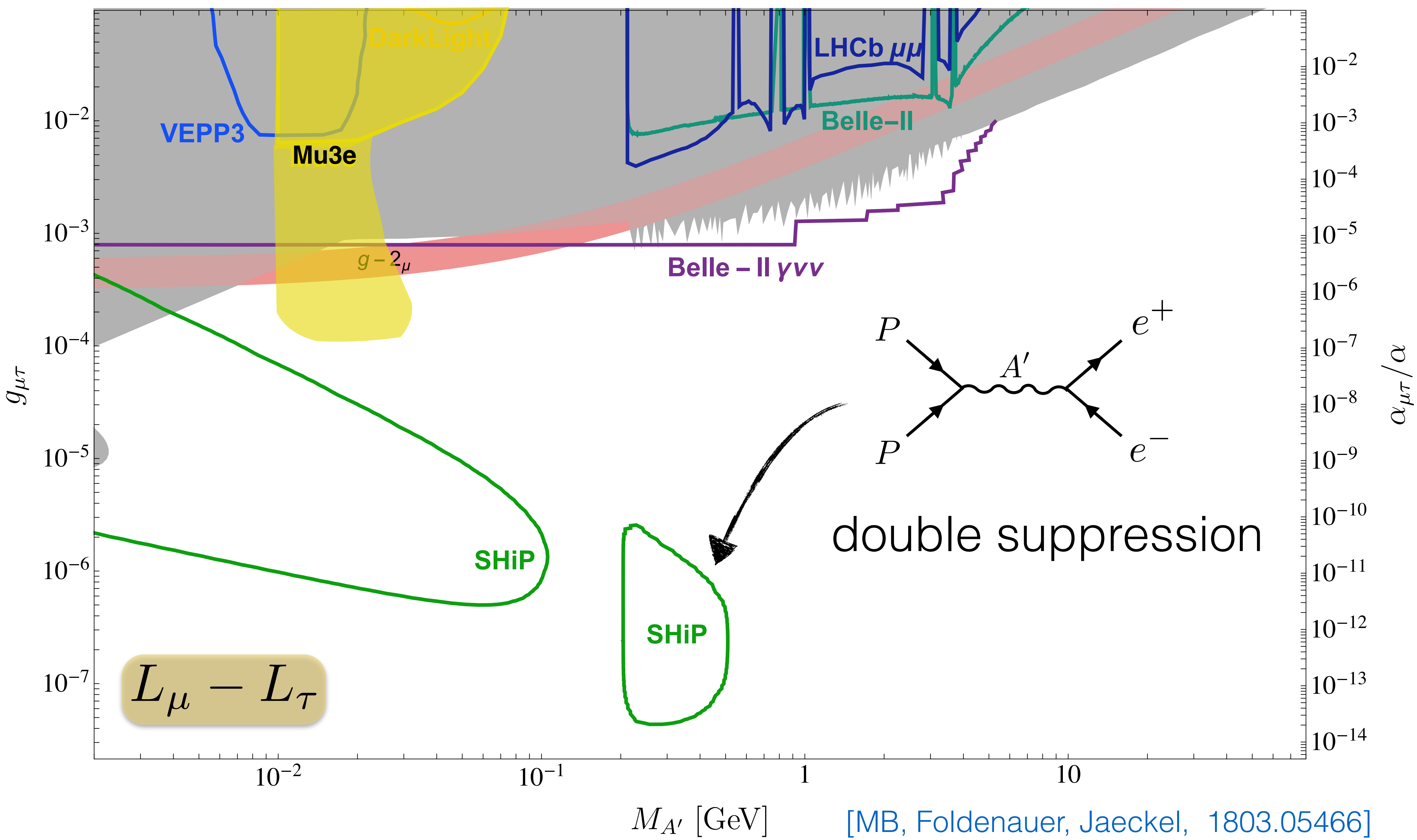
MB, Foldenauer Jaeckel, JHEP **1807** 094 (2018)

New Gauge Bosons



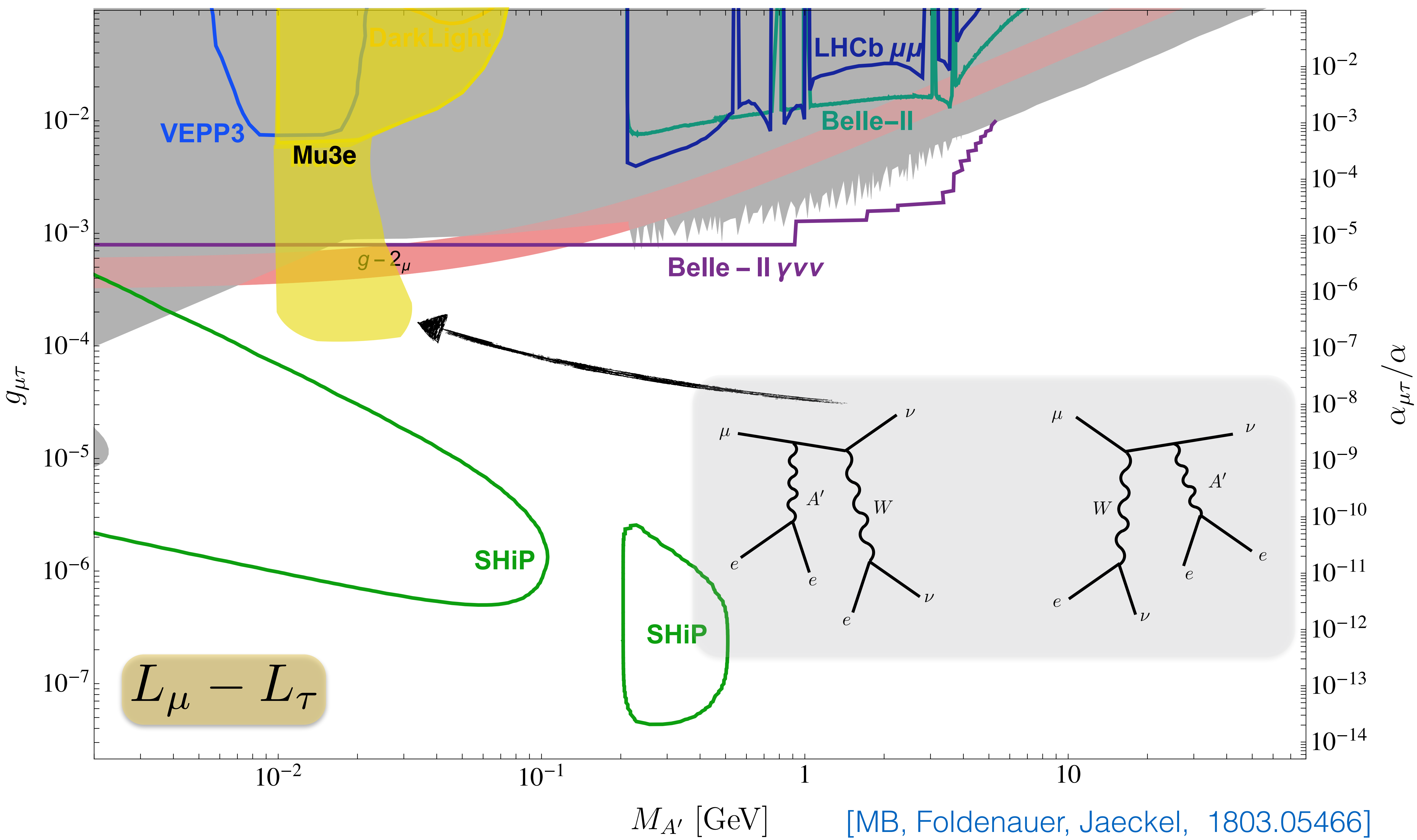
MB, Foldenauer Jaeckel, JHEP **1807** 094 (2018)

New Gauge Bosons



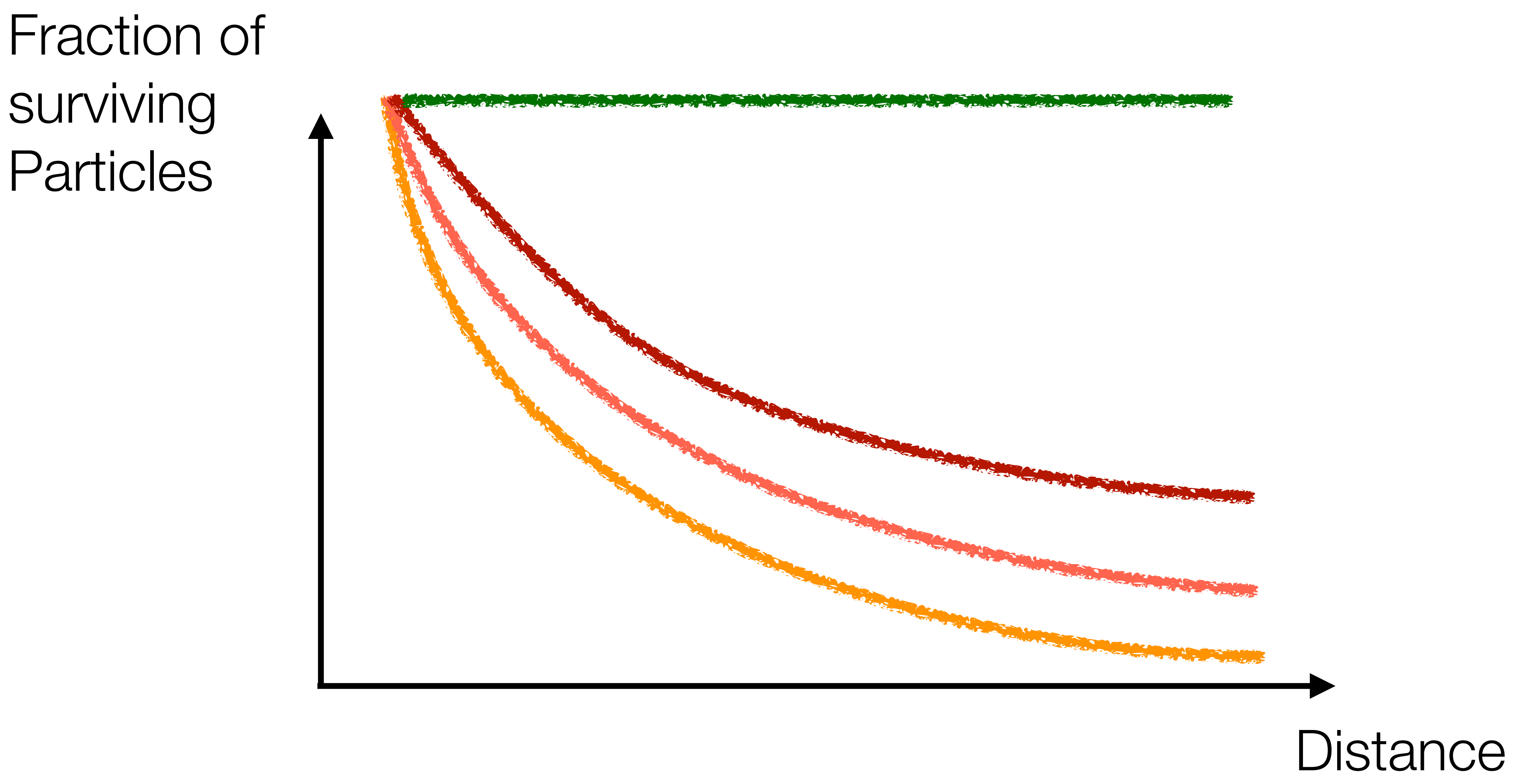
[MB, Foldenauer, Jaeckel, 1803.05466]

New Gauge Bosons



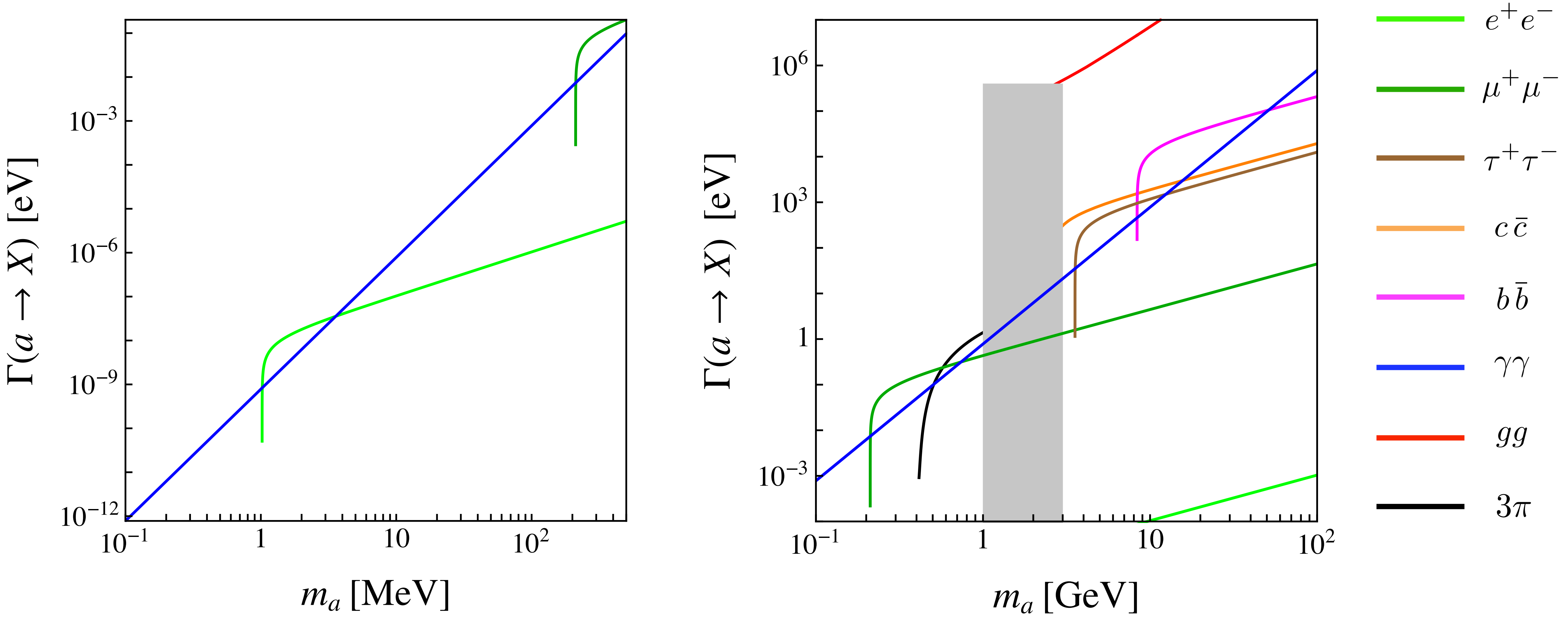
[MB, Foldenauer, Jaeckel, 1803.05466]

Particle Lifetimes

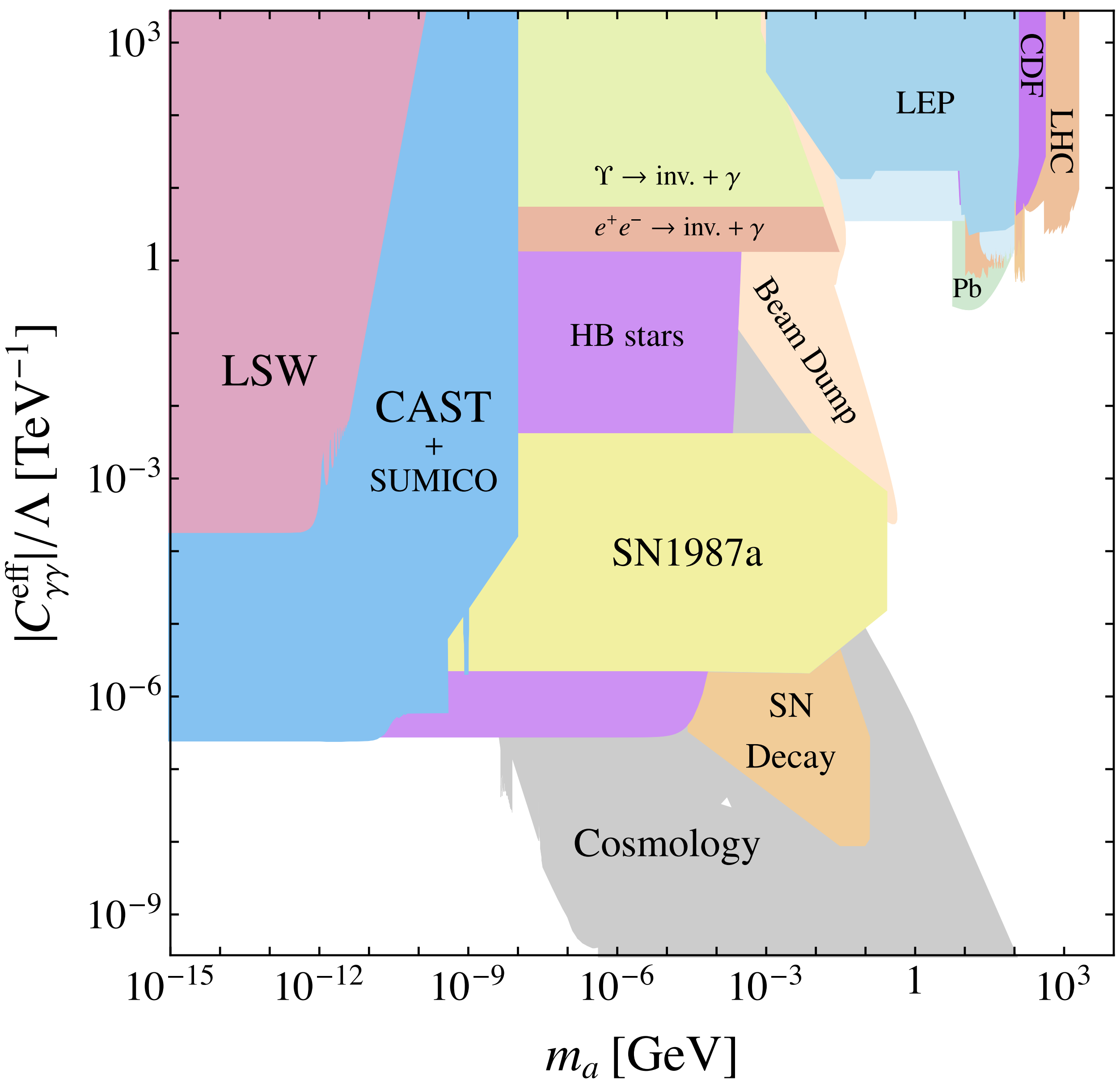


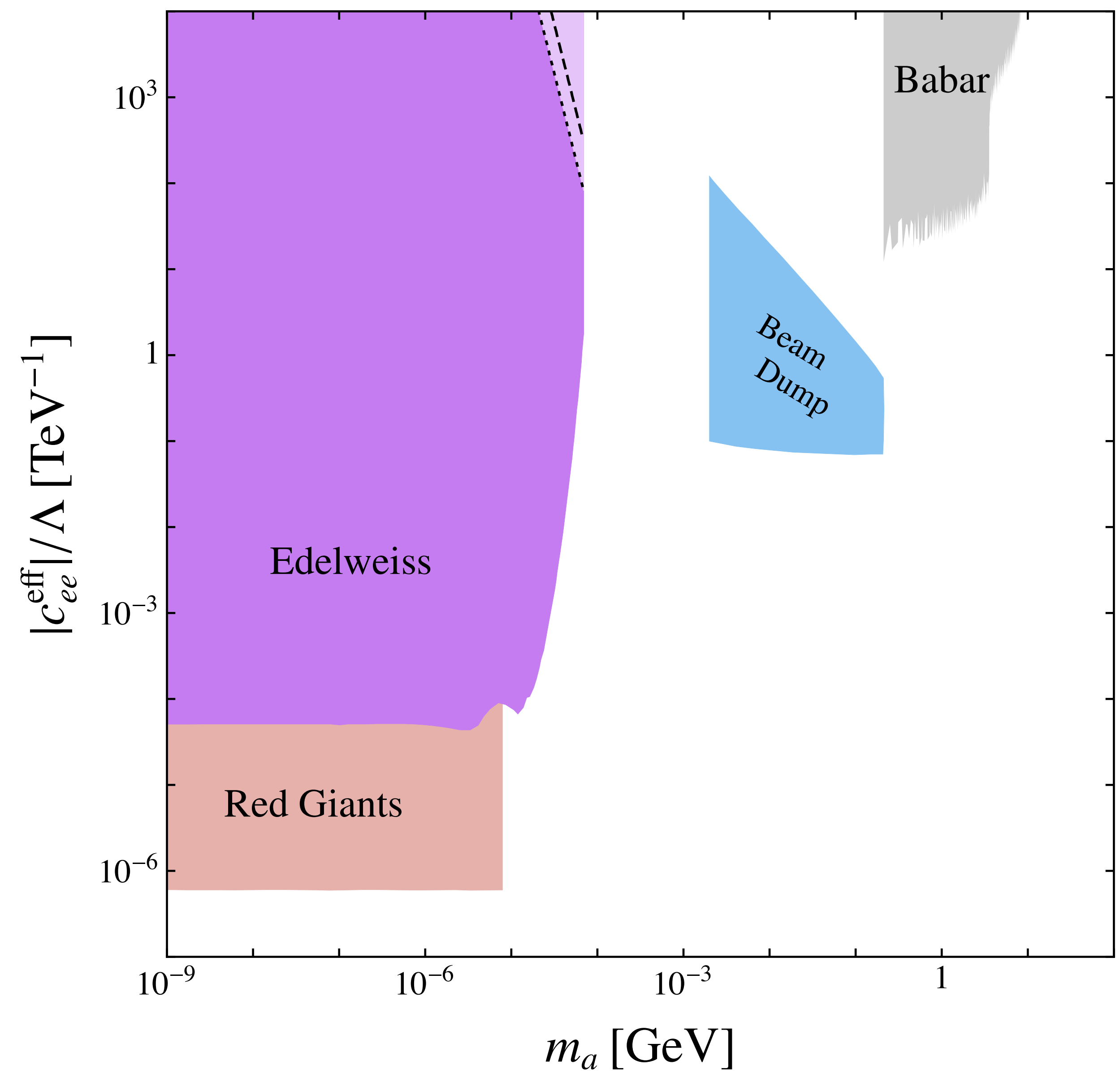
ALP Decays into SM particles

Partial ALP widths for all Wilson coefficients set to 1.



Bounds on ALPs





Jaeckel, Spannowsky, Phys. Lett. B 753, 482 (2016)

Armengaud et al., JCAP 1311, 067 (2013) …and others

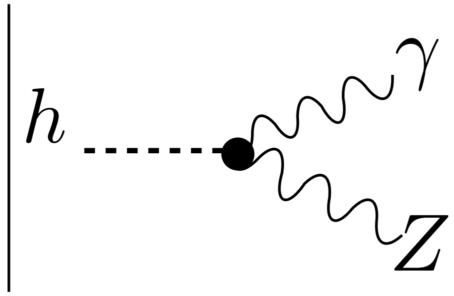
Macroscopic Lifetime

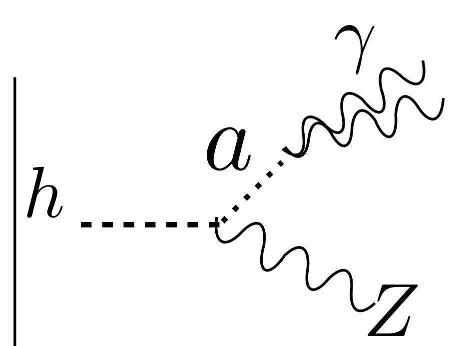
If the alps are light, they are strongly boosted! The LHC only has a finite angular resolution putting a limit on the angle for which single photons can be separated from pairs,

$$\gamma_a < 625 \qquad\qquad \gamma_a = \begin{cases} \dfrac{m_h^2 - m_Z^2 + m_a^2}{2m_a m_h}\,, & \text{for } h \to Za\,, \\[2mm] \dfrac{m_h}{2m_a}\,, & \text{for } h \to aa\,. \end{cases}$$

Exciting possibility:

$$\sigma_{\text{eff}}(h \to Z\gamma) = \Big| \quad \Big|^2 + \Big| \quad \Big|^2$$

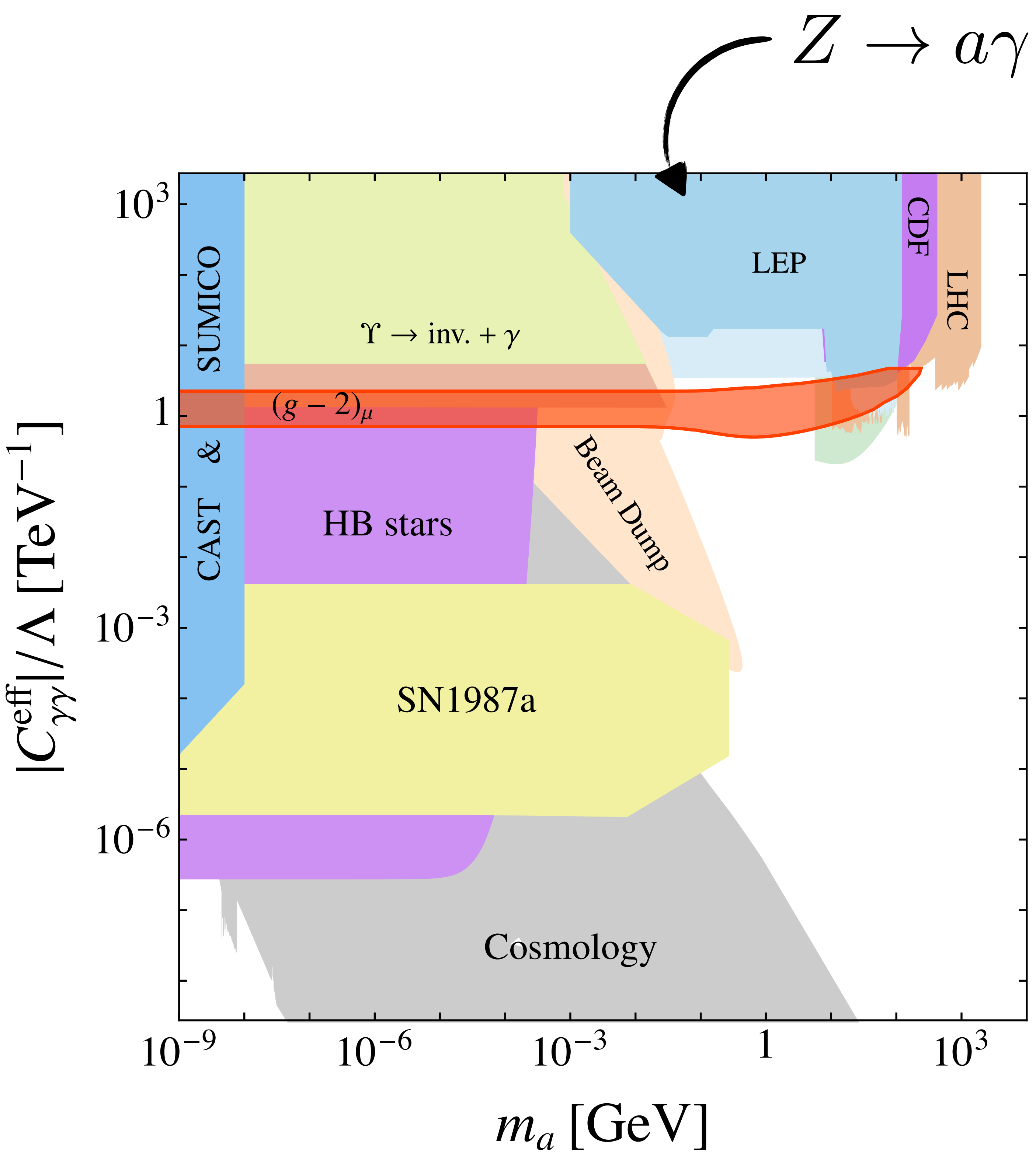




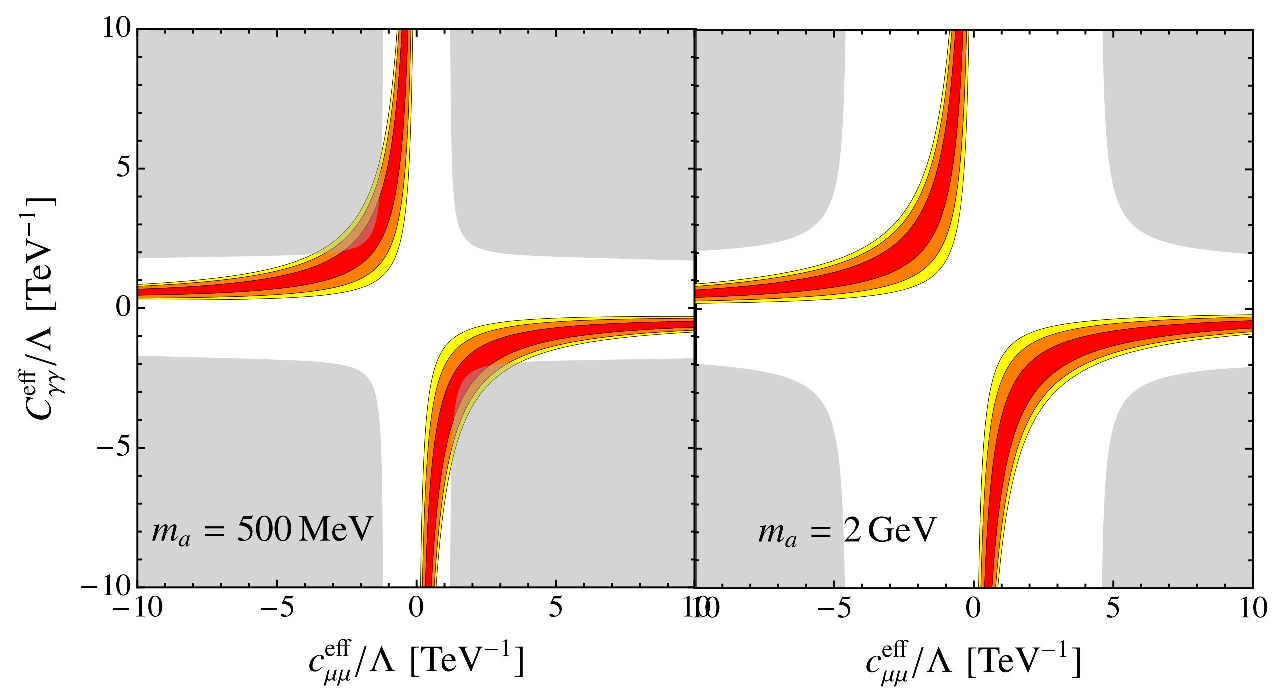
ATLAS Collaboration, ATLAS-CONF-2012-079.

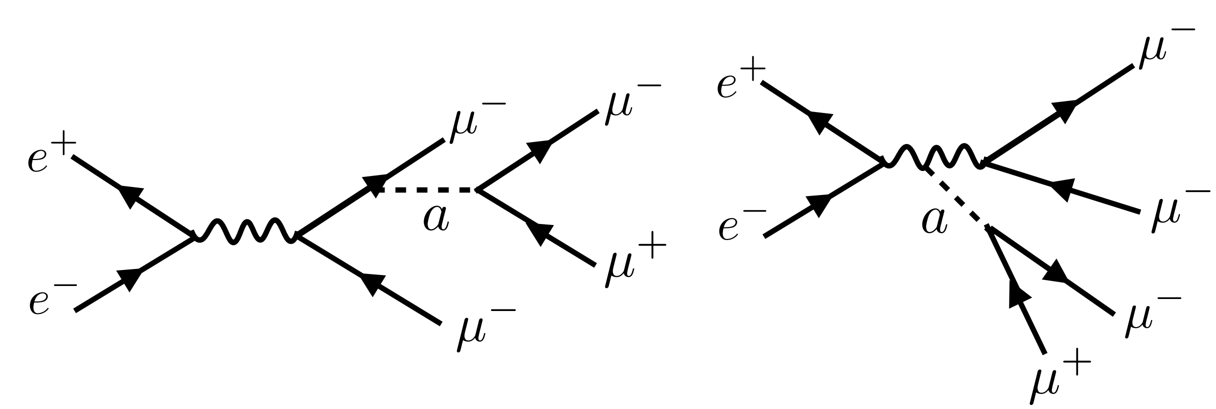
MB, Neubert, Thamm, 1708.00443

ALPs and $(g\text{-}2)_\mu$



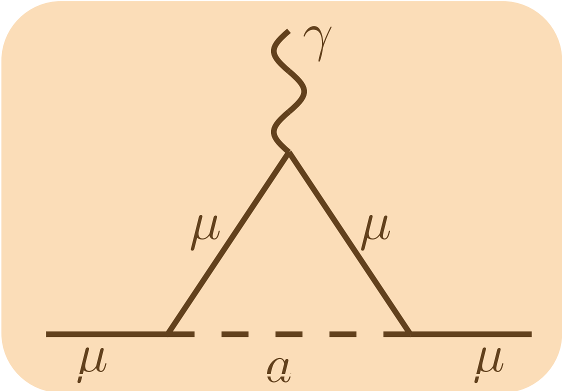
LHC competes with e+ e- colliders

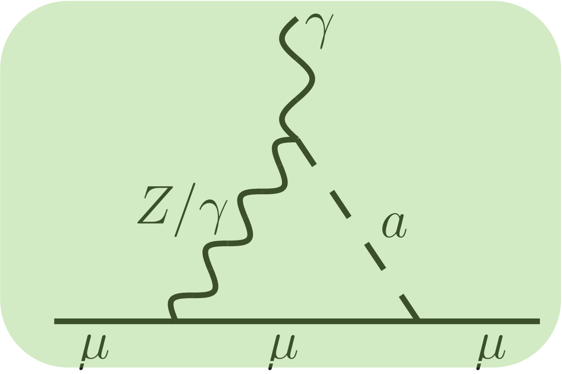




BABAR, Phys. Rev. D 94, 011102
MB, Neubert, Thamm, 1708.00443

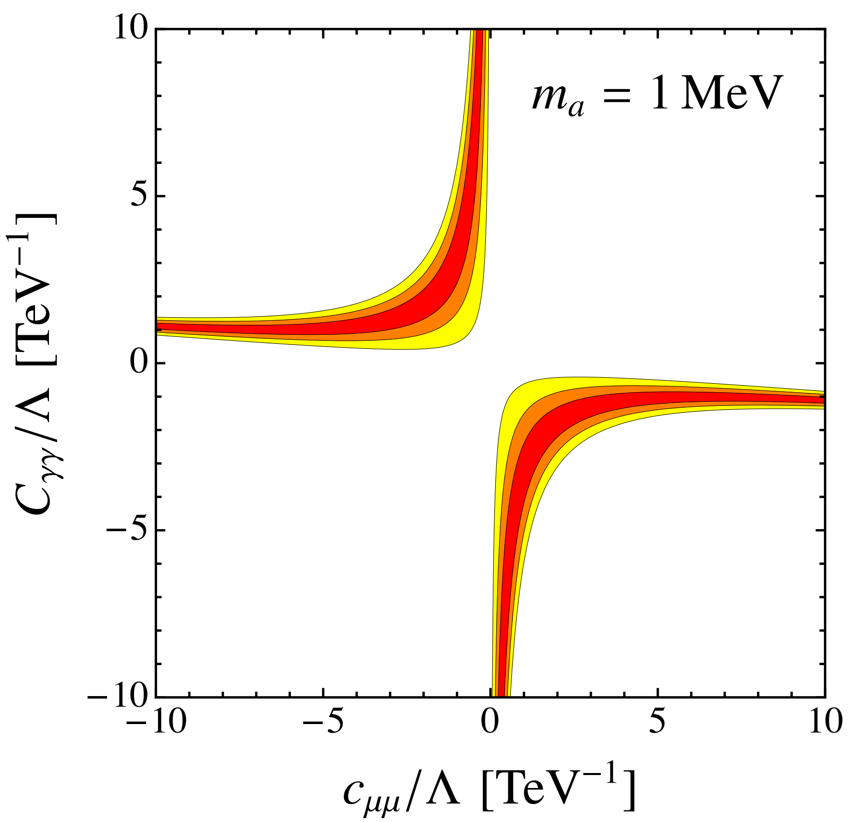
ALPs and (g-2)$_\mu$

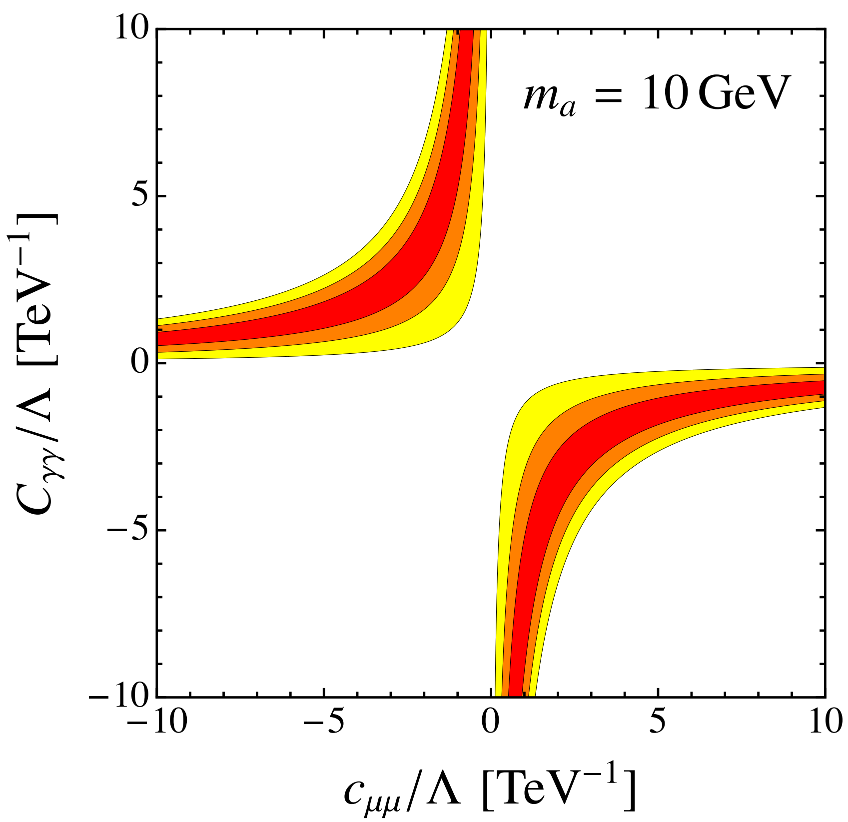




$$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right] - \frac{\alpha}{2\pi}\,\frac{1-4s_w^2}{s_w c_w}\,c_{\mu\mu}\,C_{\gamma Z}\left(\ln\frac{\mu^2}{m_Z^2} - \frac{3}{2}\right)\right\}$$

ALPs can explain (g-2)$_\mu$ for rather sizable photon couplings

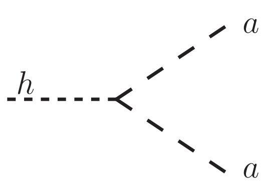


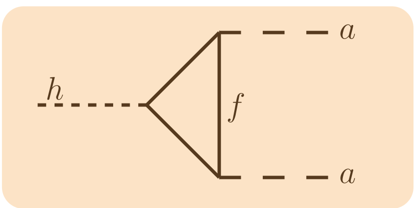


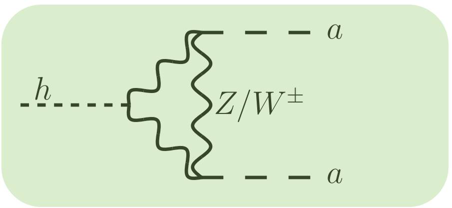
Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94, 115033 (2016)
MB, Neubert, Thamm, JHEP 1712 044 (2017)

Exotic Higgs Decays

$$h \to aa \qquad \Gamma(h \to aa) = \frac{v^2 m_h^3}{32\pi\Lambda^4} \left|C_{ah}^{\text{eff}}\right|^2 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

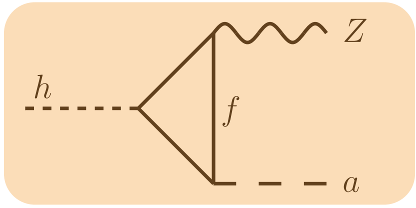


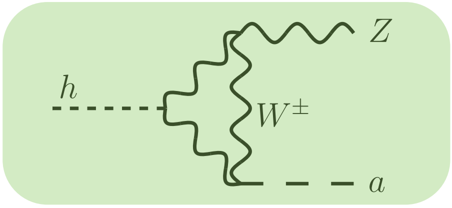


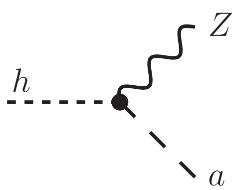


$$C_{ah}^{\text{eff}} \approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\left(C_{WW}^2 + C_{ZZ}^2\right)$$

$$h \to Za \qquad \Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left|C_{Zh}^{\text{eff}}\right|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$







$$C_{Zh}^{\text{eff}} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

The Puzzle of the top contribution

This is not new. Integrating out New Physics leads to the operators

$$\mathcal{O}_1 = c_1 \frac{\alpha_s}{4\pi v^2} G^a_{\mu\nu} G^{\mu\nu}_a H^\dagger H \qquad \mathcal{O}_2 = c_2 \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\left(\frac{H^\dagger H}{\mu^2}\right)$$

with consequences for Higgs pair production. The top only generates c_2 and $C^{(5)}_{Zh}$.

Pierce, Thaler, Wang, JHEP 0705, 070 (2007)

The Puzzle of the top contribution

Vectorlike Quarks

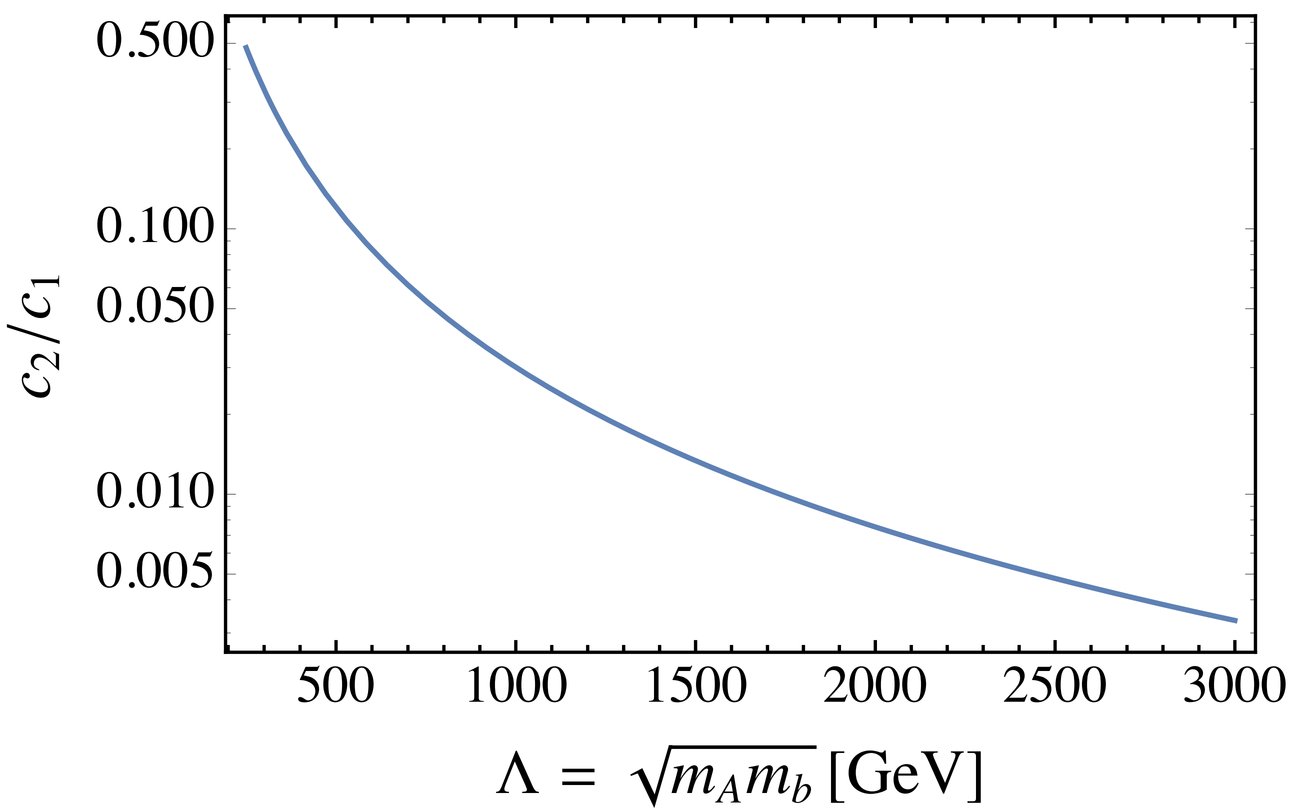
$$-\mathcal{L}_{\text{mass}} = \lambda_1 \left(QHT^c + Q\tilde{H}B^c\right) + \lambda_2 \left(Q^c\tilde{H}T + Q^cHB\right) + m_A QQ^c + m_B(TT^c + BB^c) + \text{h.c.},$$

generate

$$c_1 = \frac{4}{3}\frac{-\beta}{(1-\beta)^2}$$

$$c_2 = \frac{4}{3}\frac{1}{(1-\beta)^2}$$

$$\beta \equiv \frac{2m_A m_B}{\lambda_1\lambda_2 v^2}.$$



$$\mathcal{O}_1 = c_1 \frac{\alpha_s}{4\pi v^2} G^a_{\mu\nu} G^{\mu\nu}_a H^\dagger H$$

$$\mathcal{O}_2 = c_2 \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\left(\frac{H^\dagger H}{\mu^2}\right)$$

Pierce, Thaler, Wang, JHEP 0705, 070 (2007)