axion like particles at colliders and beyond

Yotam Soreq

PBC meets theory: informal discussion about PBC selected topics
11 June, 2020

axion like particles

- originally - the Axion propose as a solution to the strong CP problem
- appear in many BSM scenarios
- portal to dark matter and/or dark sector
- if very light, it is a dark matter candidate
- predicted by string theory

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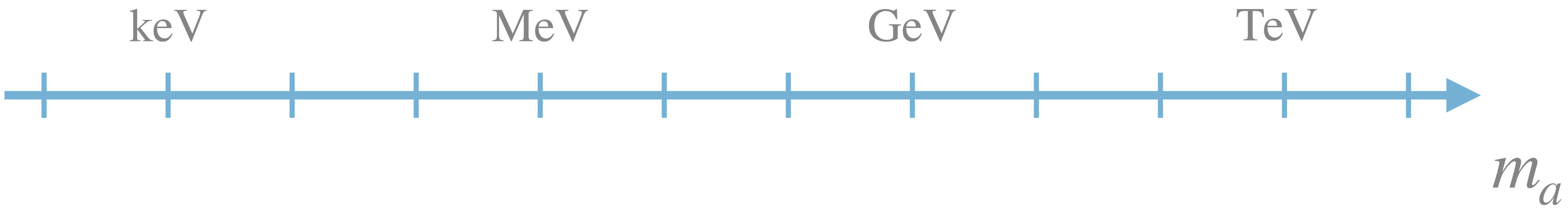
→ **well motivated BSM scenario**

axion like particles

pseudo-scalar and pNGB

$$\mathscr{L}_{\text{eff}} = -\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$\Lambda \gg m_a$



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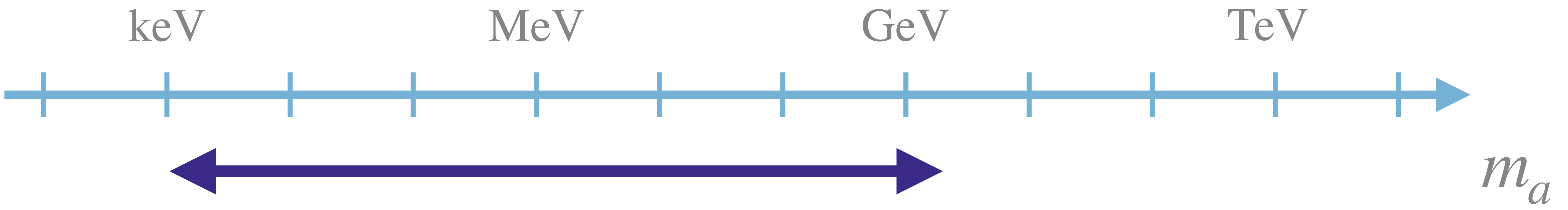

photon beam (PrimEx, GlueX),
K-factories (KOTO, NA62)
and hadronic decays

axion like particles

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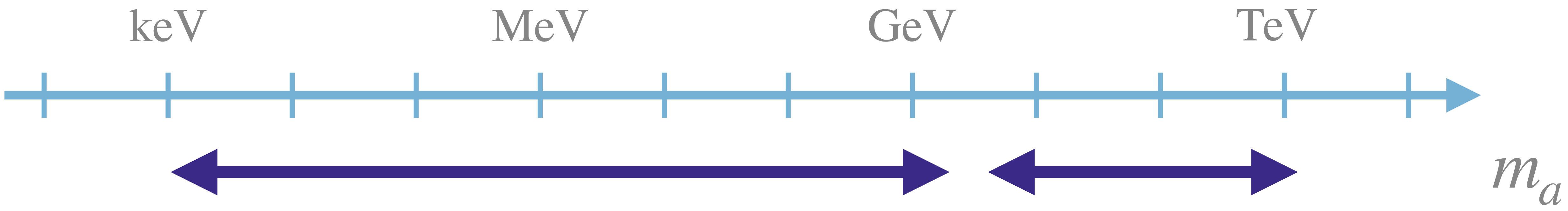

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LHC/LEP/
future collider

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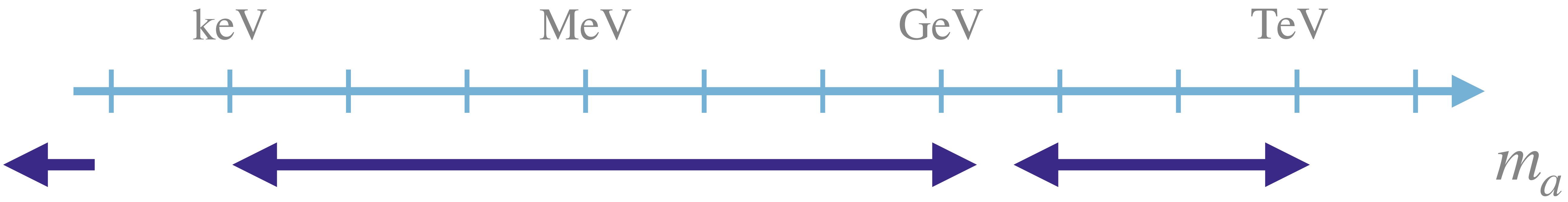


precision

photon beam (PrimEx, GlueX),
K-factories (KOTO, NA62)
and hadronic decays

LHC/LEP/
future collider

ALPs at the MeV to the GeV scale

Aloni, YS, Williams - 1811.03474
Aloni, Fanelli,YS, Williams - 1903.03586

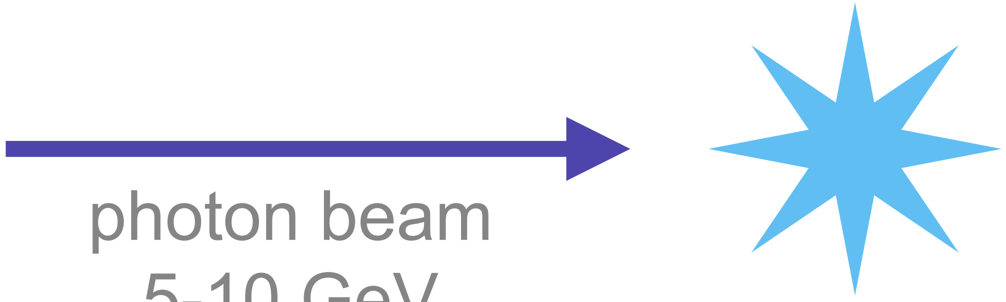
ALPs at the MeV to the GeV scale

$$\mathscr{L}_{\rm eff} = -\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$c_g \neq 0 \text{ or } c_\gamma \neq 0$$

- probing at photon beam (Primakoff like) experiments
- estimate of hadronic decay rates

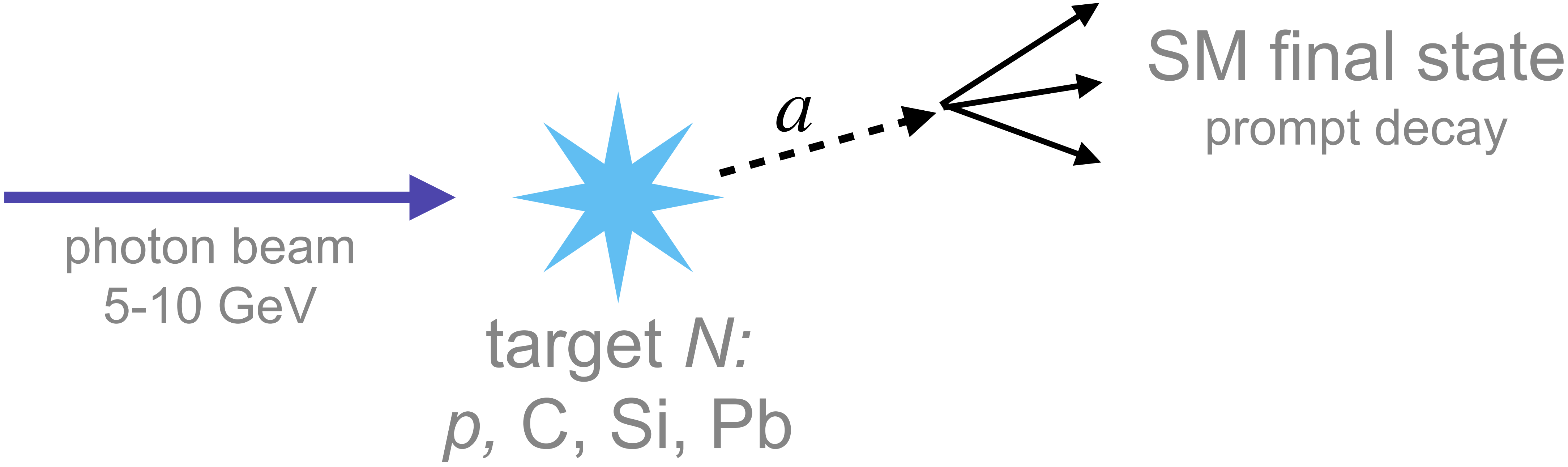
ALPs at Primakoff like experiments



photon beam
5-10 GeV

target *N:*
p, C, Si, Pb

ALPs at Primakoff like experiments



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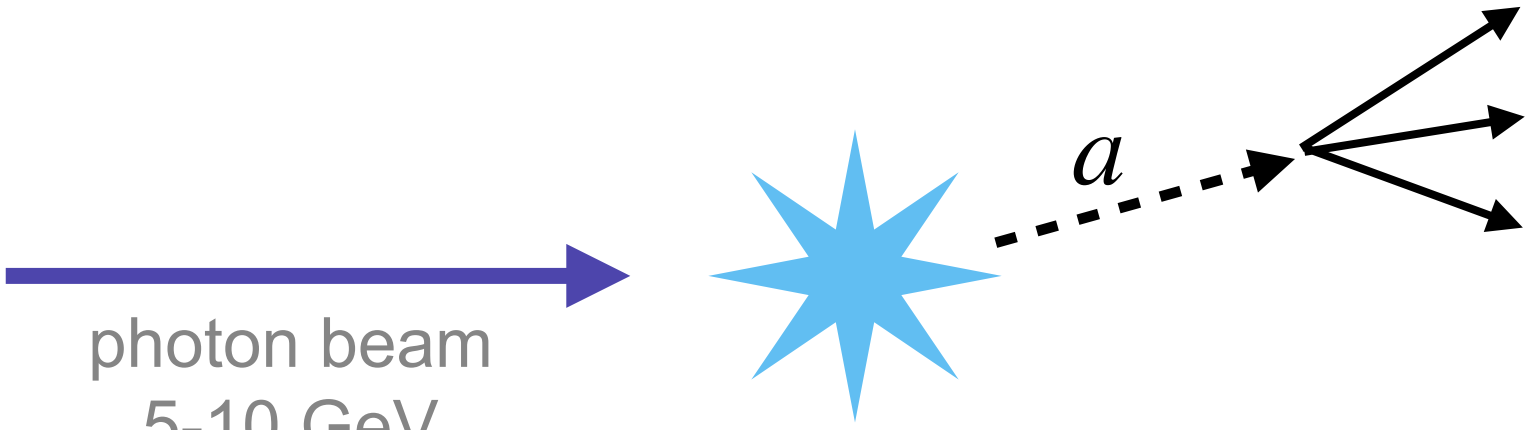
a

SM final state
prompt decay

ALPs at Primakoff like experiments



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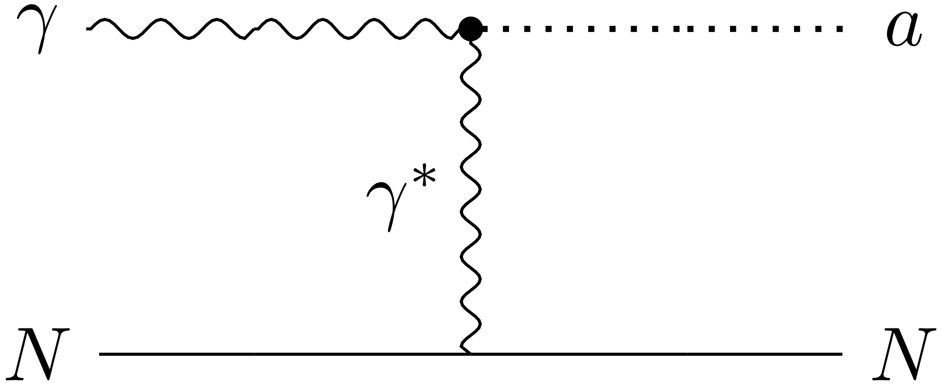
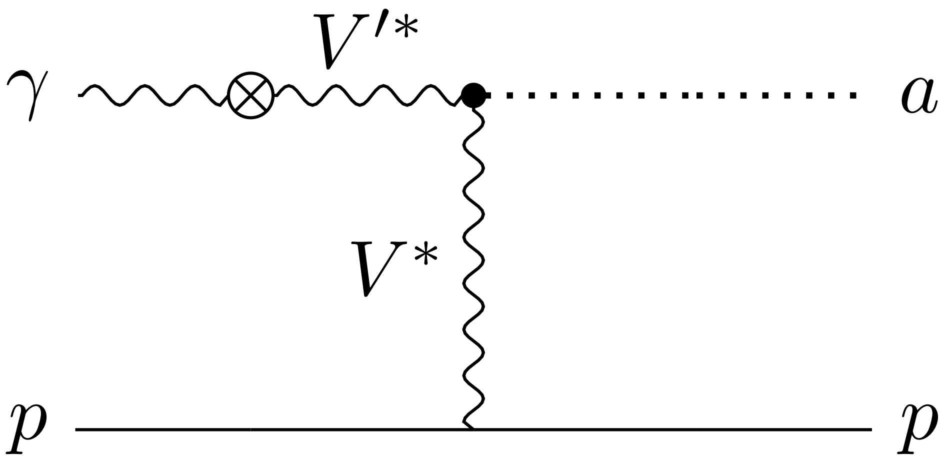


$$\frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$



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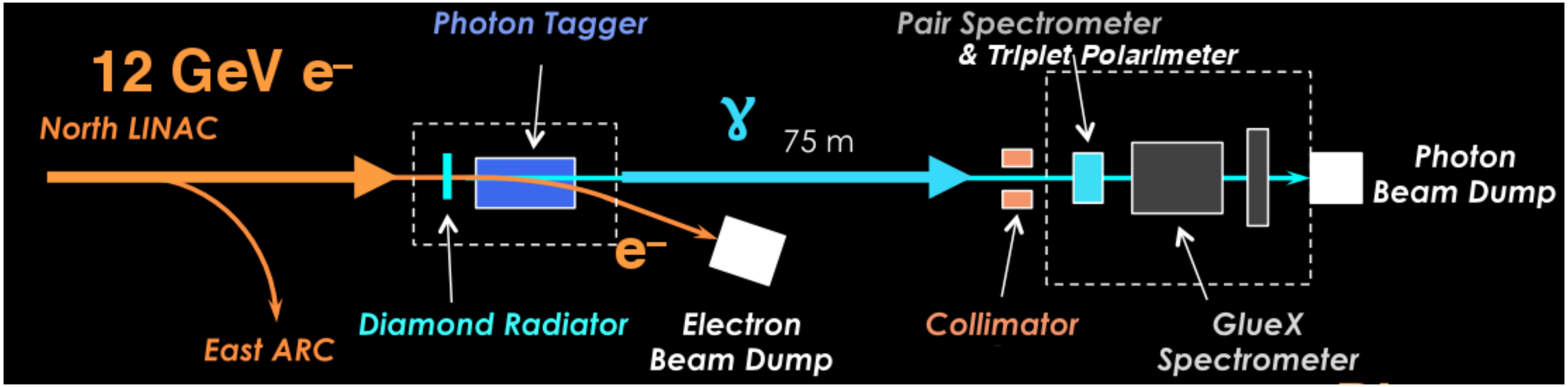
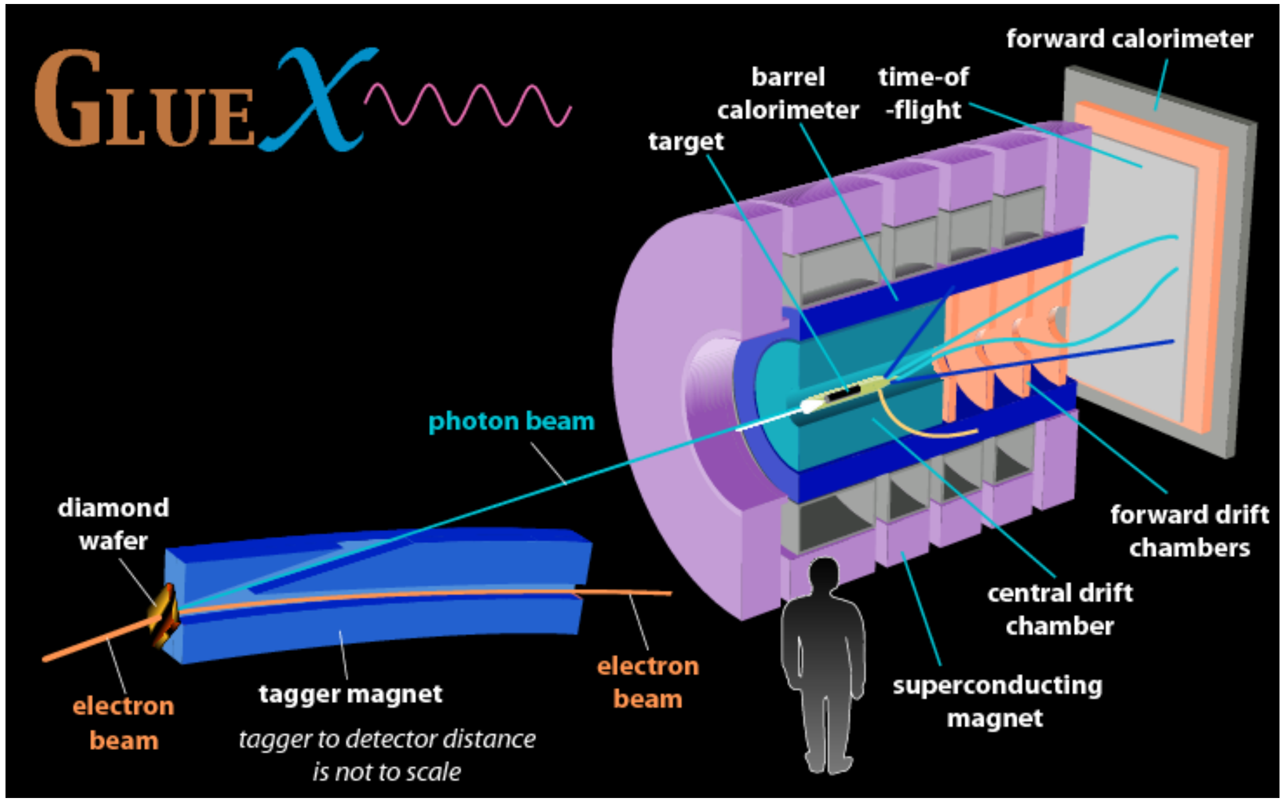
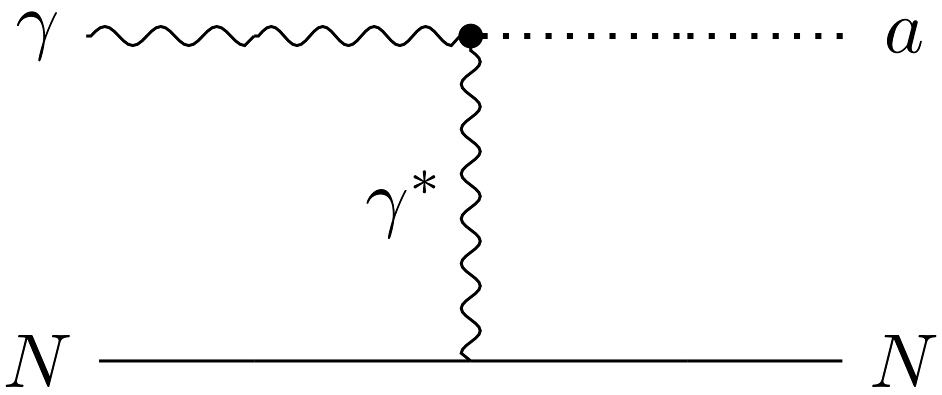




tagger to detector distance is not to scale

ALP photons coupling



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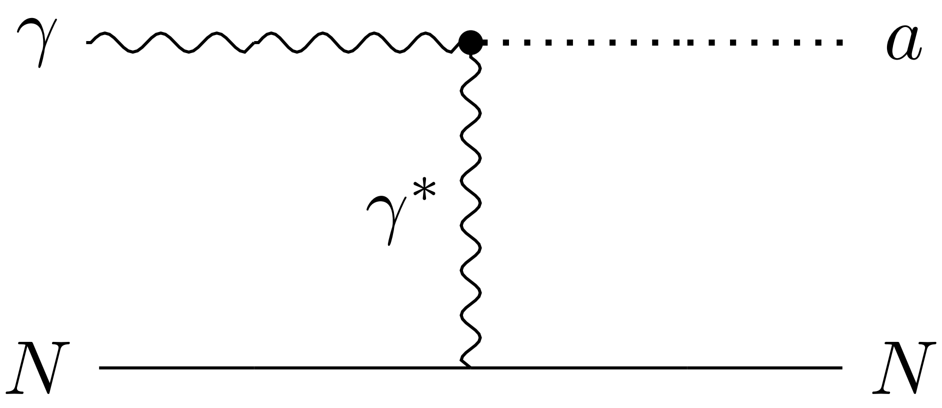

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$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \alpha\, \underbrace{Z_N^2}_{\text{target charge}} \underbrace{F_N^2(t)}_{\text{form factor}} \Gamma_{a\to\gamma\gamma}\, \underbrace{\mathcal{H}(m_N, m_a, s, t)}_{\text{kinematical function}}$$

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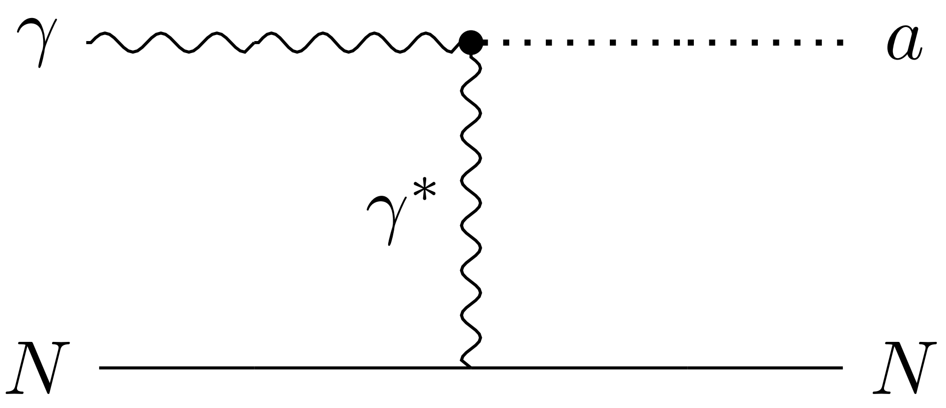

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Primakoff production of ALPs and $P = \pi^0, \eta$ are similar

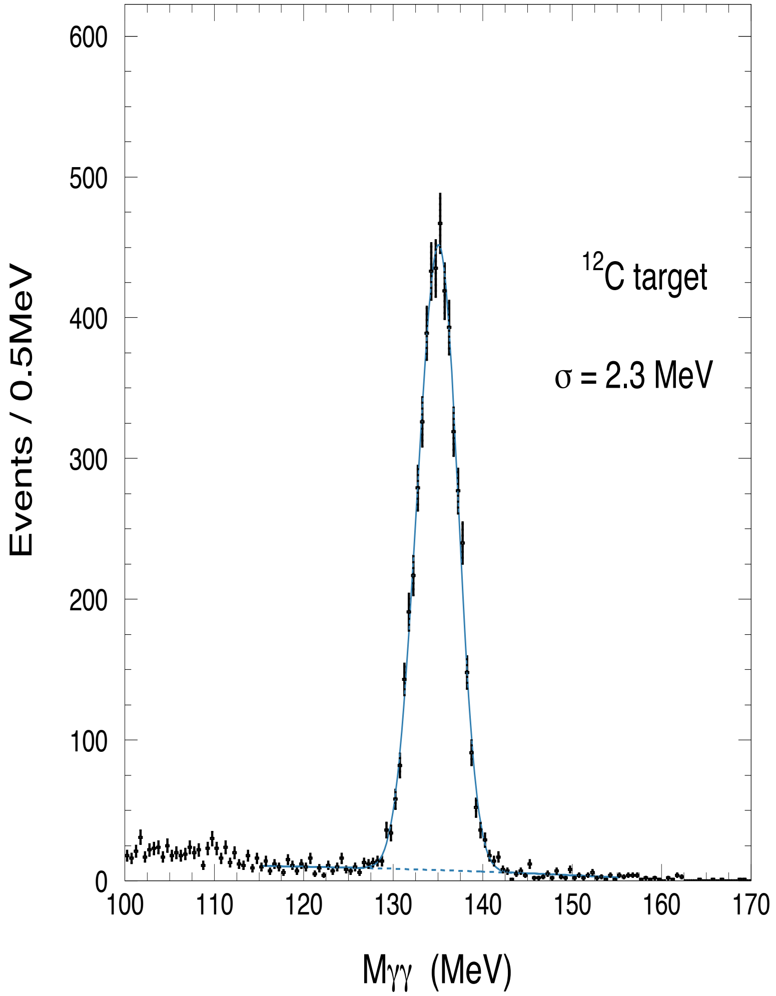
$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \frac{\Gamma_{a\to\gamma\gamma}}{\Gamma_{P\to\gamma\gamma}} \frac{\mathscr{H}(m_N, m_a, s, t)}{\mathscr{H}(m_N, m_p, s, t)} \frac{d\sigma^{\text{elastic}}_{\gamma N\to PN}}{dt}$$

at the forward region

data-driven signal normalization

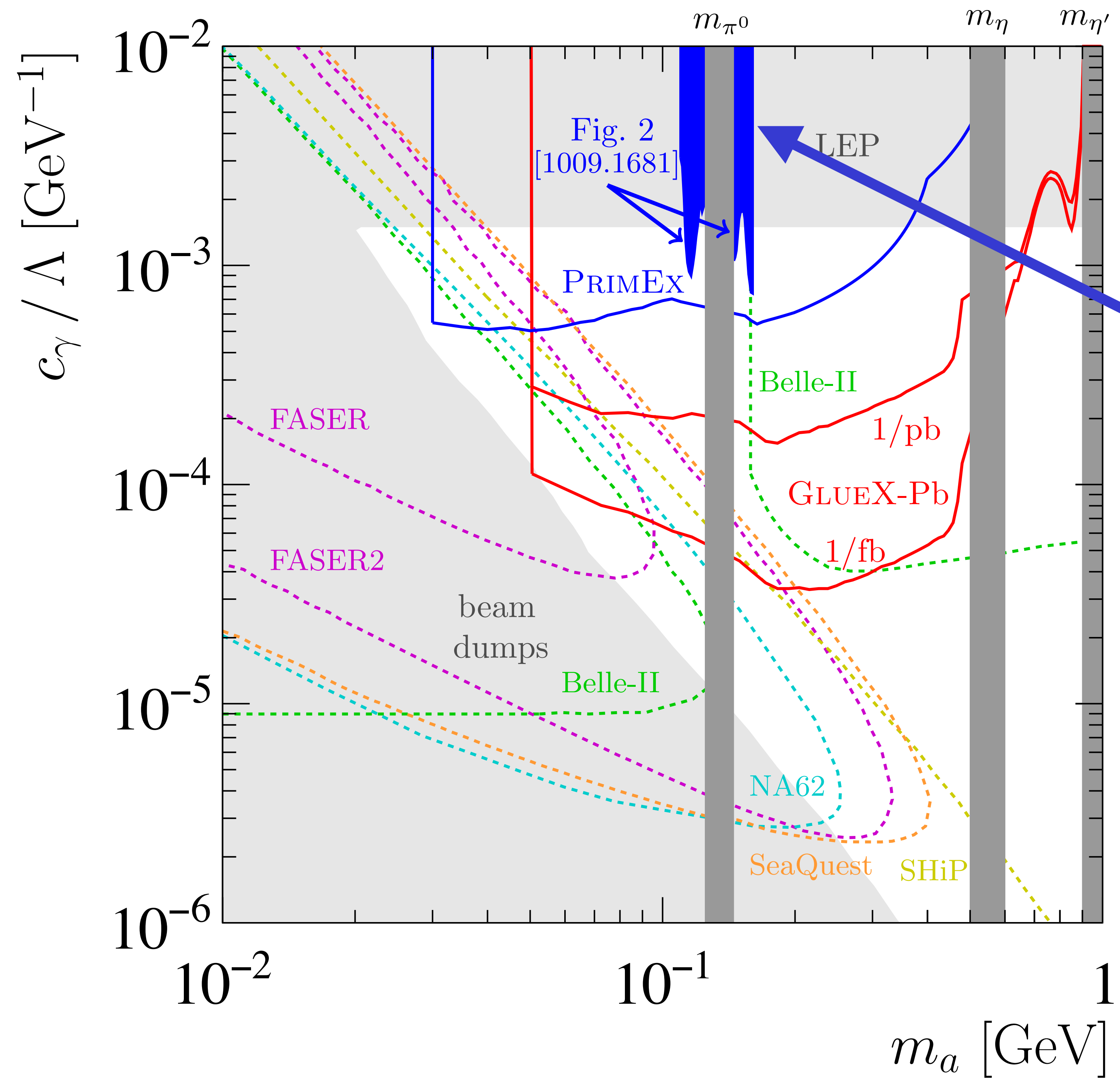
(cancel form-factor and flux dependence)

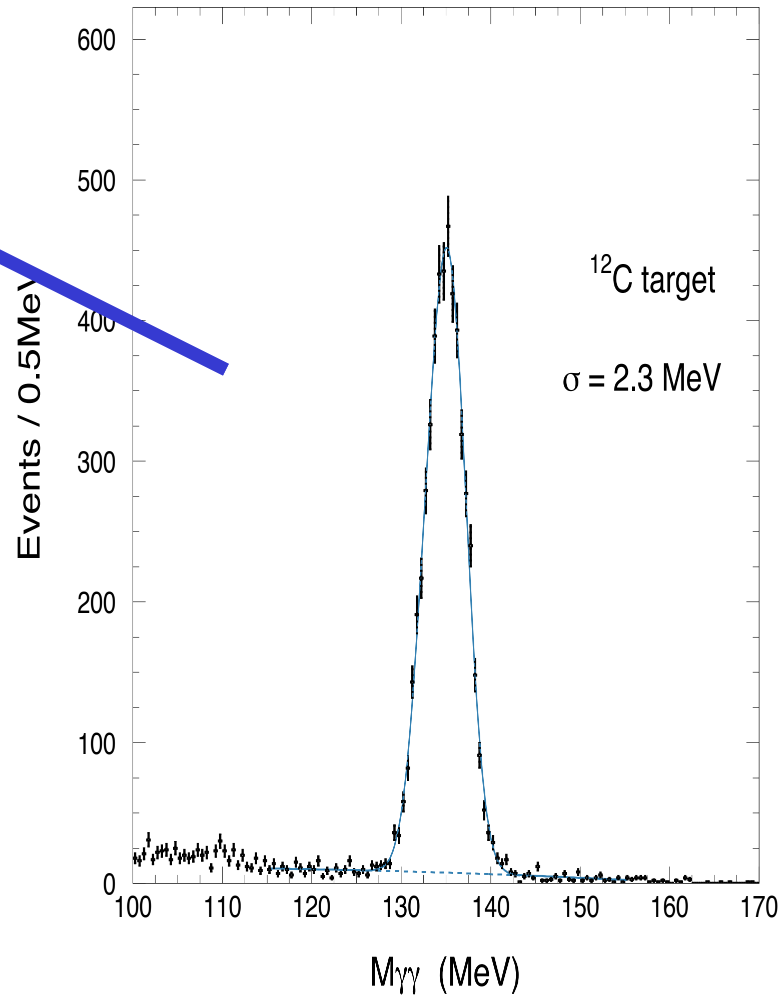
ALP photons coupling



PrimEx - 1009.1681

ALP photons coupling





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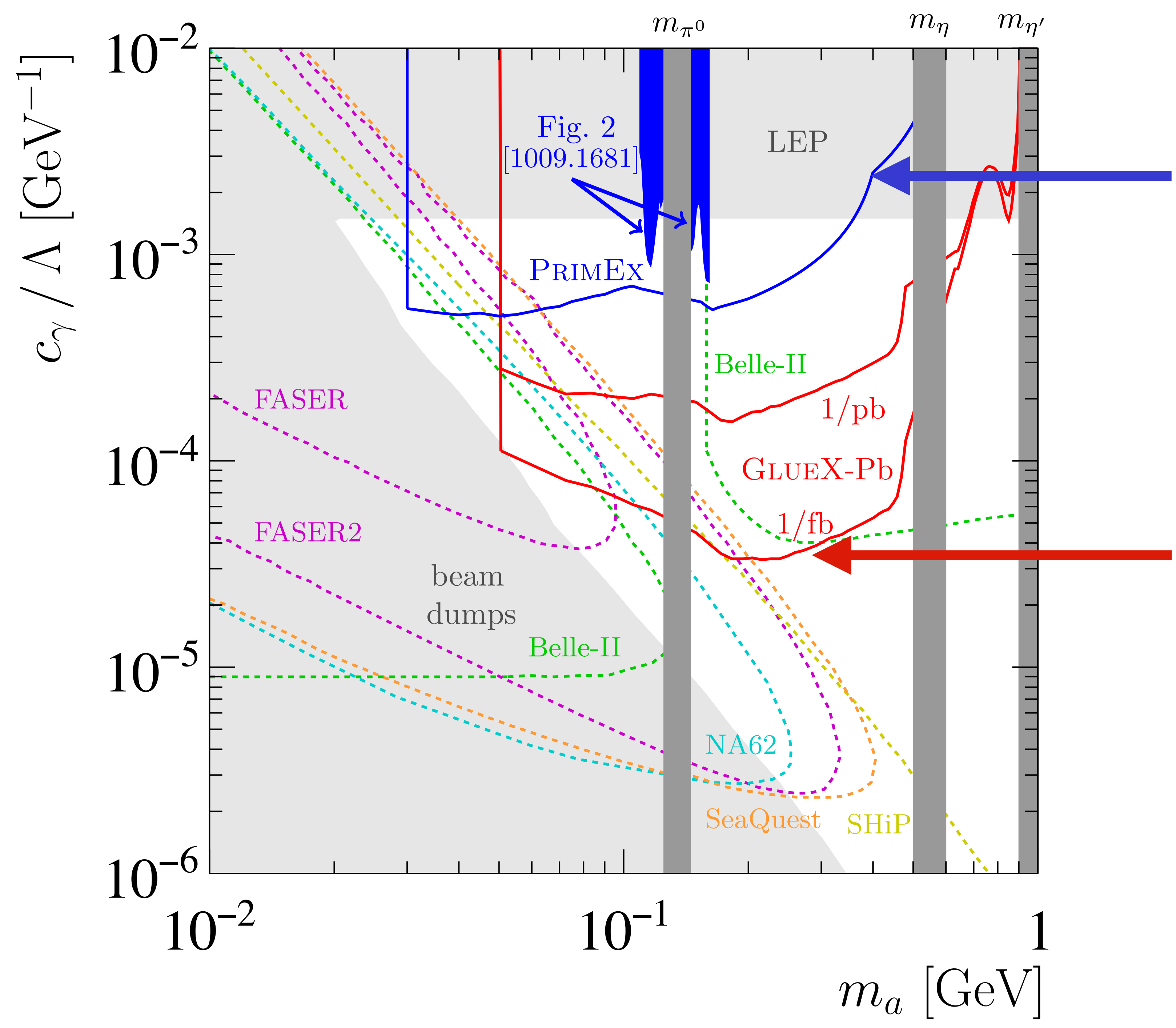

on tape PrimEx data

projection for GlueX

ALP gluons coupling

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$$F_a = |\Lambda/(32\pi^2 c_g)|$$

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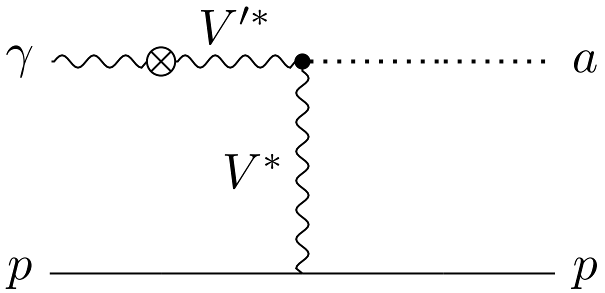
GlueX
p traget



$$\frac{d\sigma_{\gamma p\to ap}}{dt} \approx \left(\frac{f_\pi}{F_a}\right)^2 \left[|\langle a\pi^0\rangle|^2 \frac{d\sigma_{\gamma p\to\pi^0 p}}{dt} + |\langle a\eta\rangle|^2 \frac{d\sigma_{\gamma p\to\eta p}}{dt} \right]$$

$a-\pi^0, \eta$ mixing

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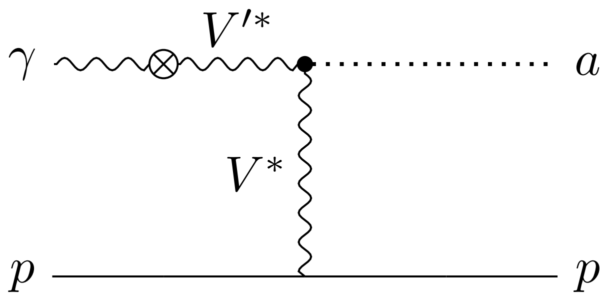

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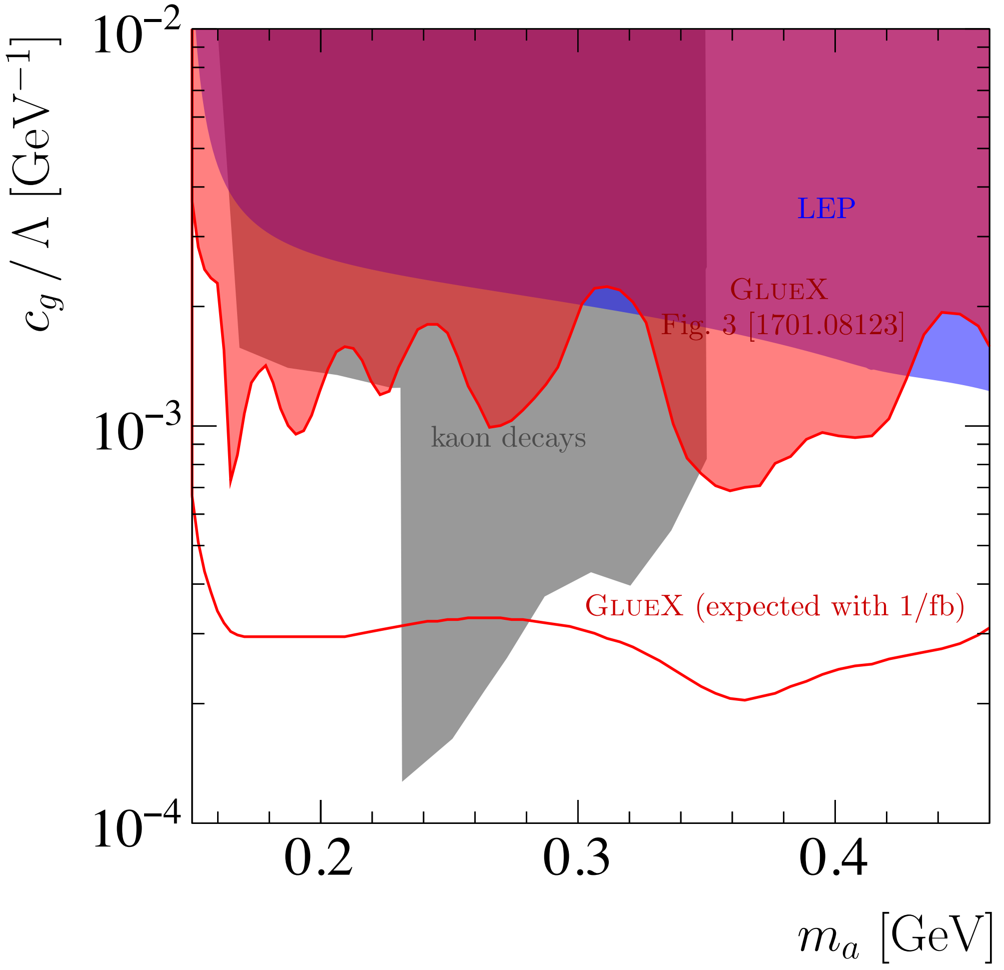

$\gamma\gamma$ final state

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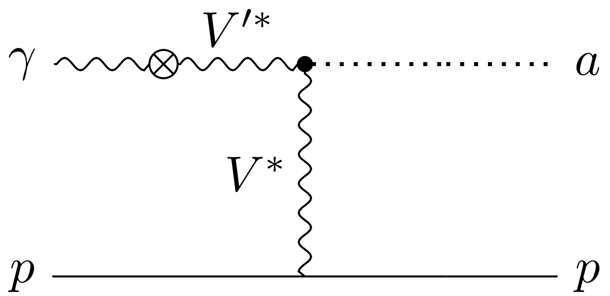
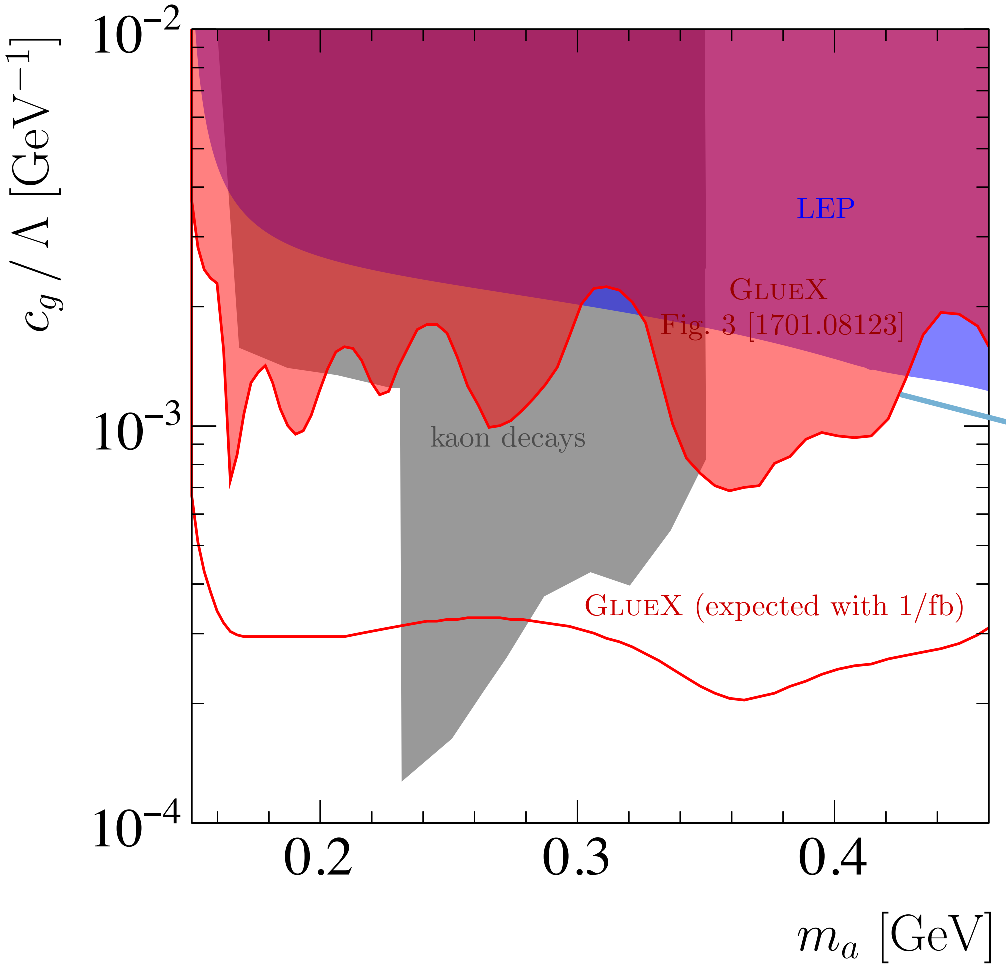


KOTO

$K_L \to \pi^0 a \to 4\gamma$



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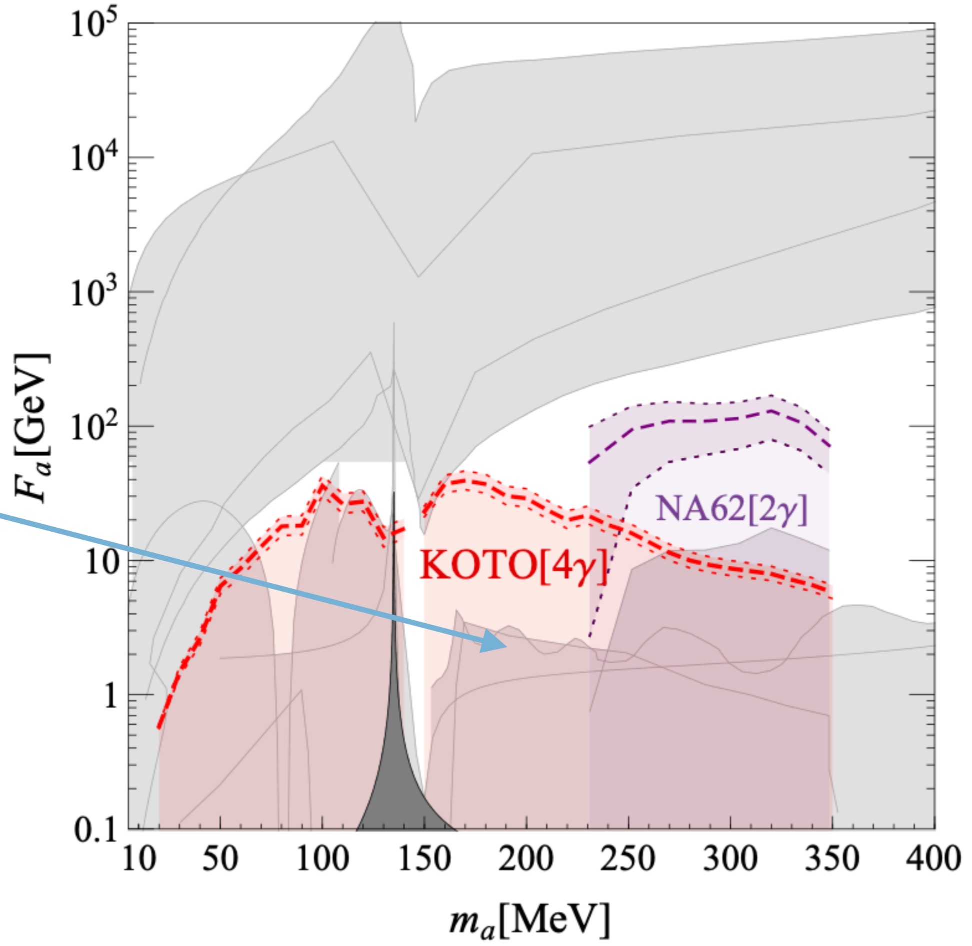

Gori, Perez, Tobioka - 2005.05170

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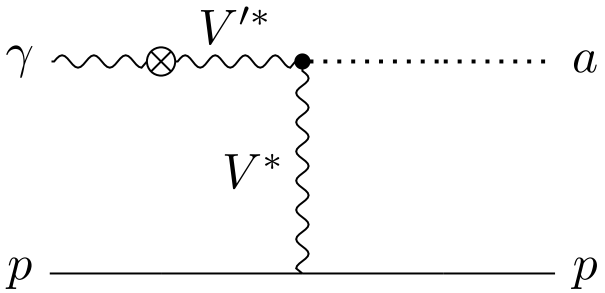

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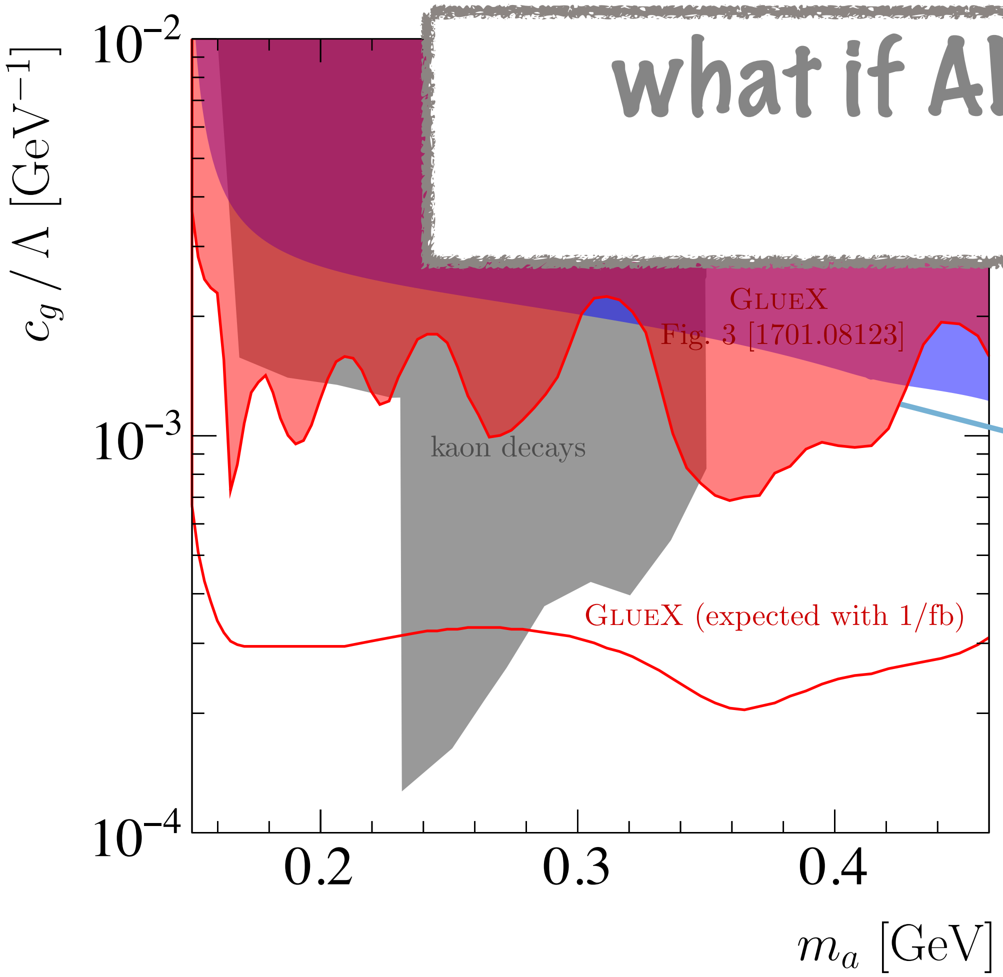
what if ALP can decay hadronically?

($m_a > 3m_\pi$)



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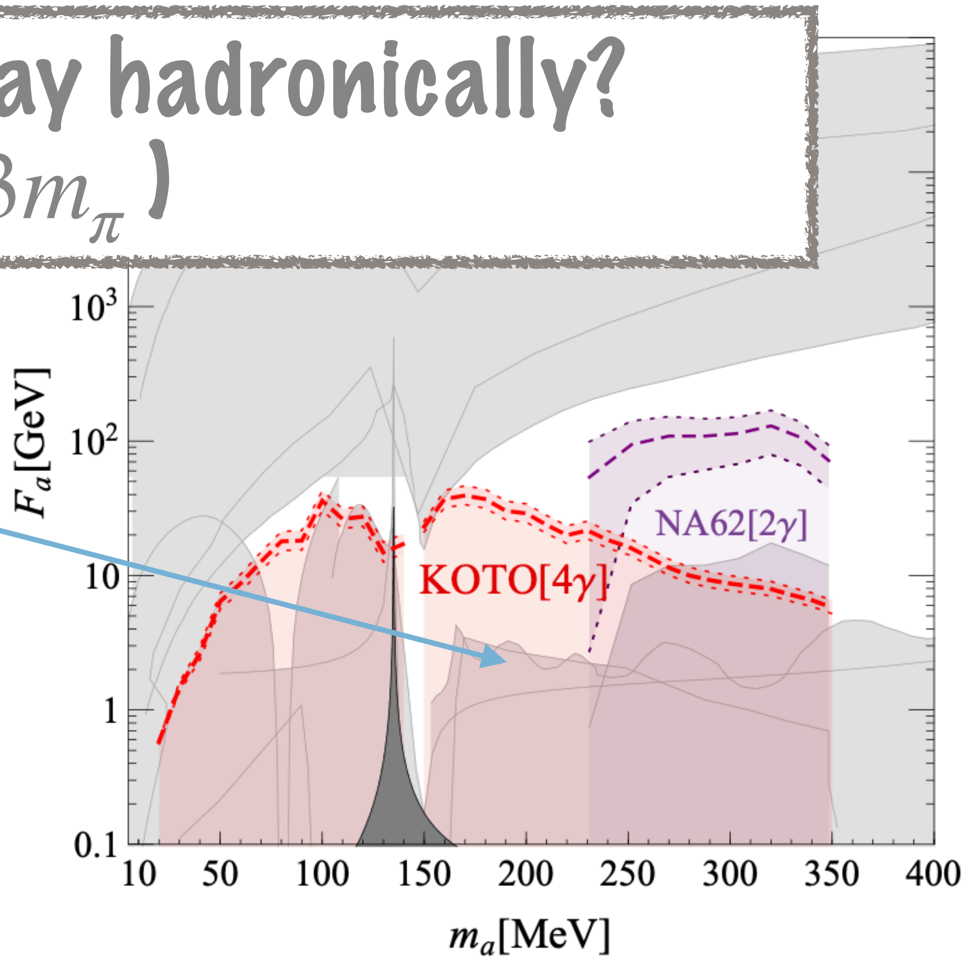

Gori, Perez, Tobioka - 2005.05170

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How to estimate hadronic rates for ALPs with QCD scale mass?

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$m_a \lesssim \mathrm{GeV}$

chiral PT

?????

$m_a \gtrsim 2\,\mathrm{GeV}$

pQCD

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$e^+e^- \to$ hadrons ➡ information on specific $U(3)_{\text{flavor}}$ combinations

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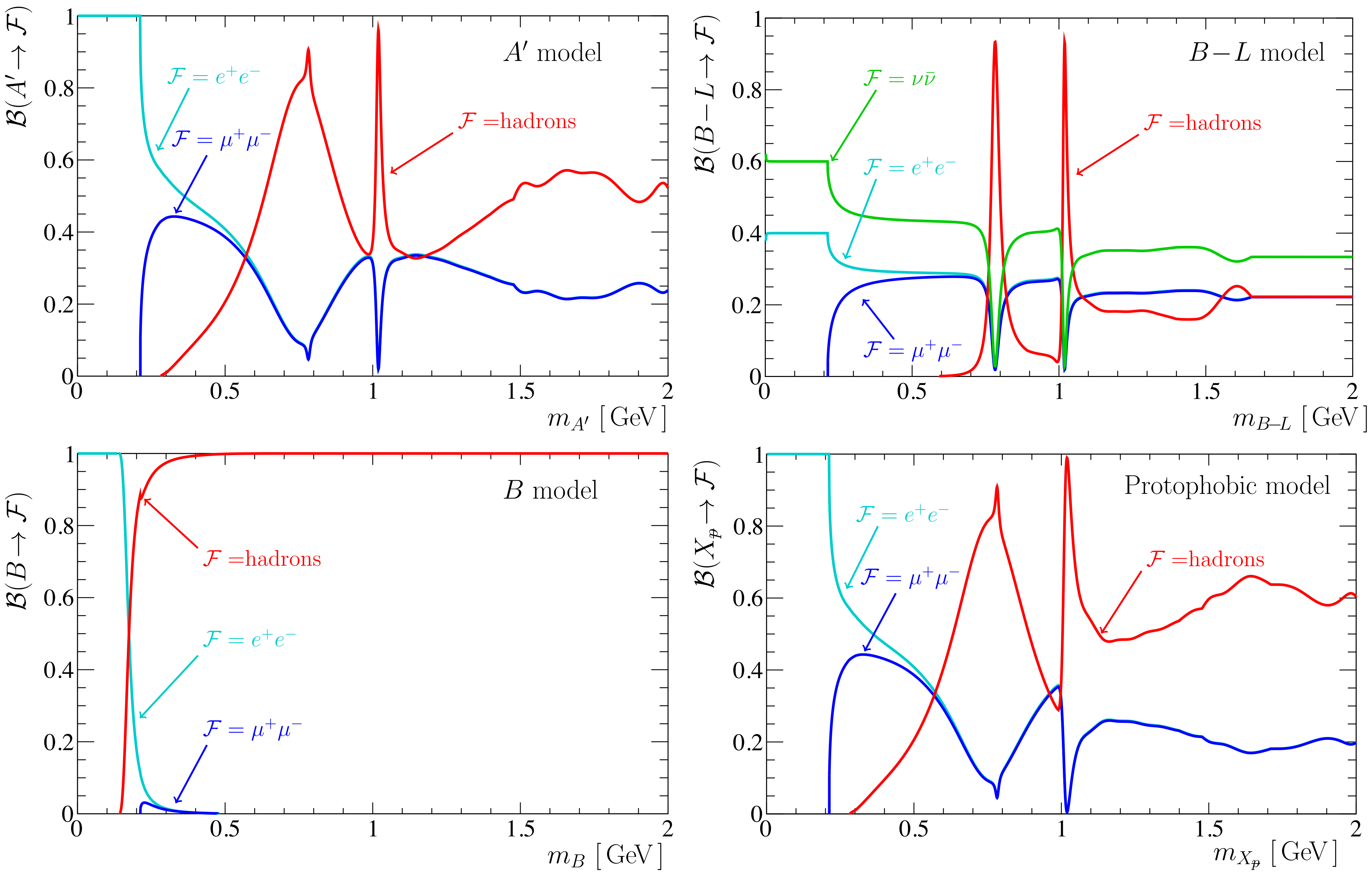
$e^+e^- \to$ hadrons → information on specific $U(3)_{\mathrm{flavor}}$ combinations

directly deduce the hadronic rates of vectors

ALP gluons coupling



Ilten, YS, Williams, Xue, 1801.04847

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ALPs hadronic rates?

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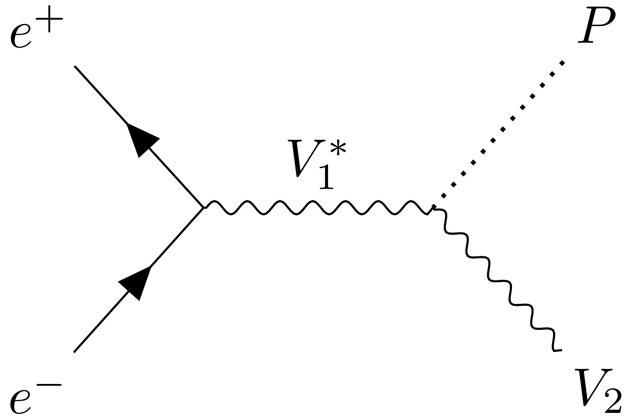

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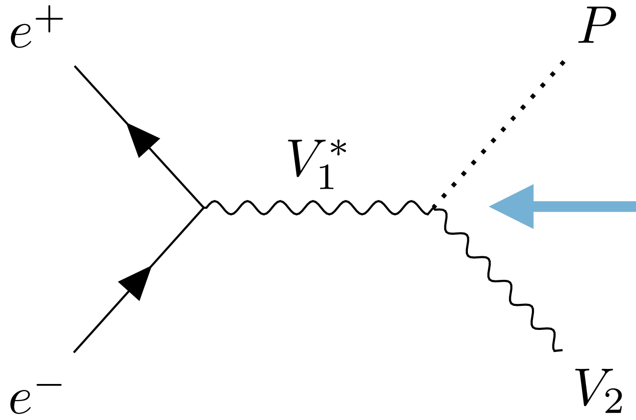
one Lorentz structure

modified VMD



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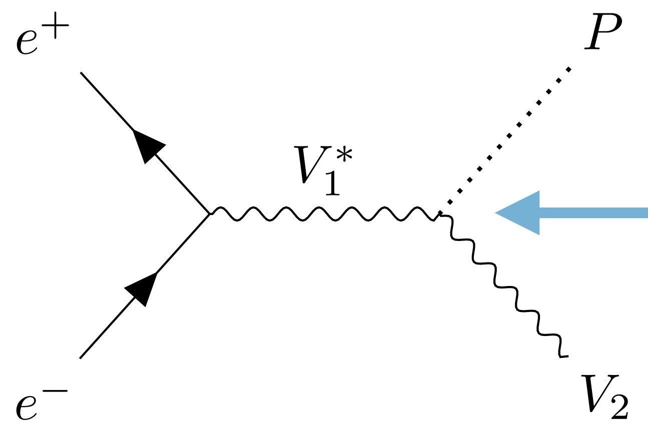

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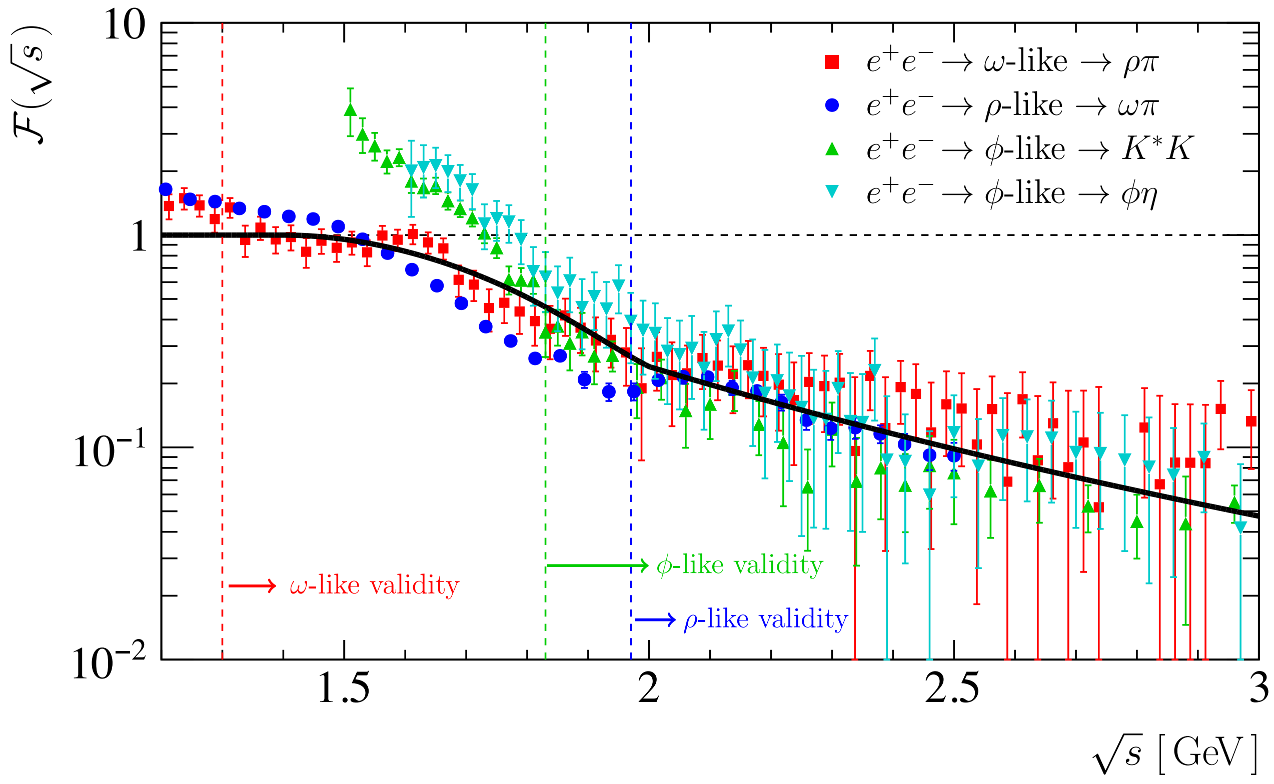

from data

$$\mathcal{F}(m) = \begin{cases} 1 & \text{for } m < 1.4\,\text{GeV} \\ \text{interpolation} & \text{for } 1.4 \leq m \leq 2\,\text{GeV} \\ \left[\frac{\beta_{\mathcal{F}}}{m}\right]^4 & \text{for } m > 2\,\text{GeV} \end{cases}$$

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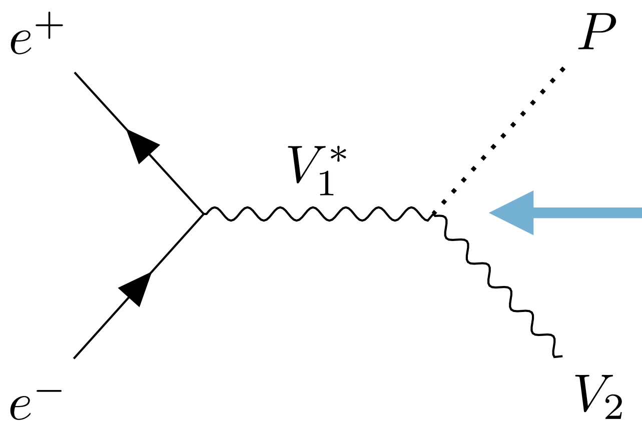

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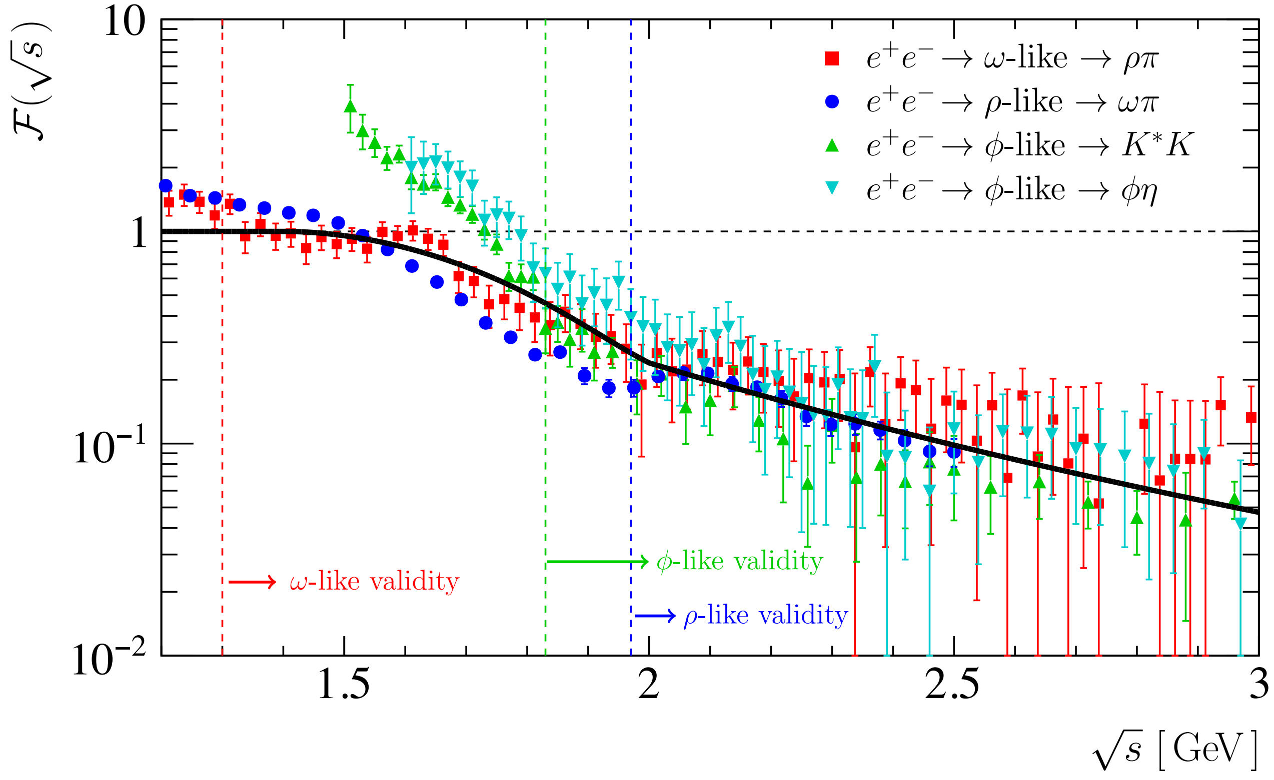

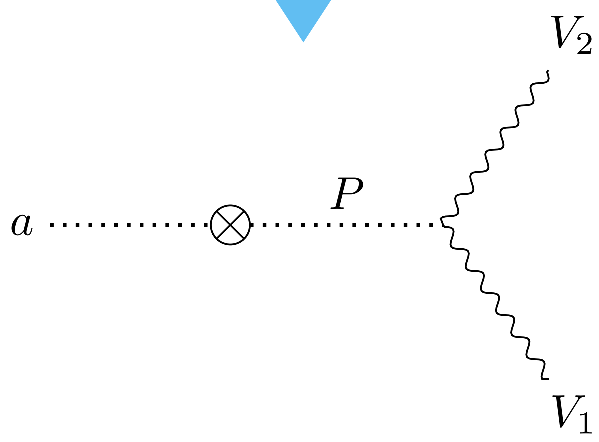

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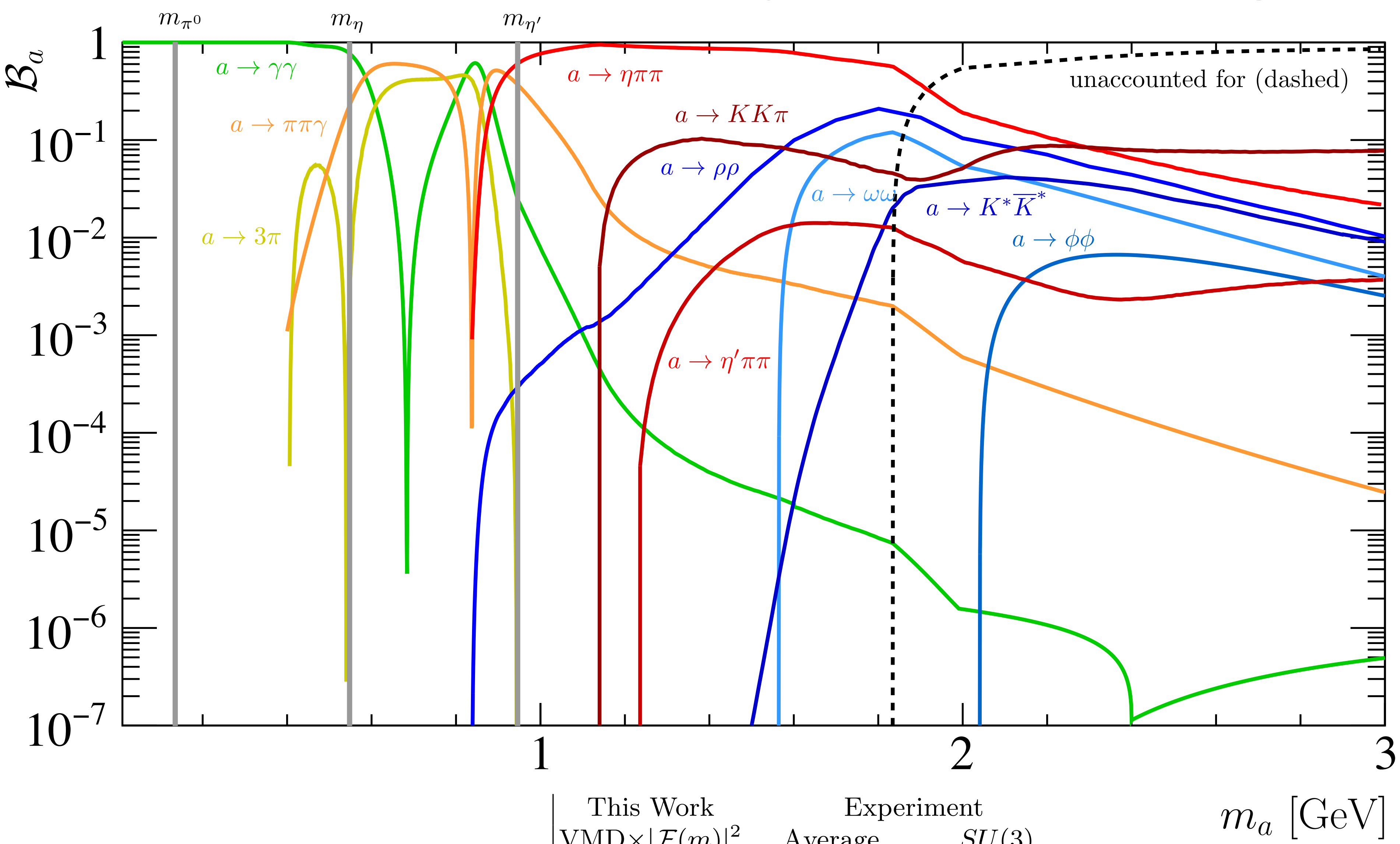
replace P by $P-a$ mixing



	This Work VMD×$\lvert\mathcal{F}(m)\rvert^2$	Experiment Average	 $SU(3)$
$\mathcal{B}(\eta_c \to \rho\rho)$	1.0%	$1.8 \pm 0.5\%$	$1.10 \pm 0.14\%$
$\mathcal{B}(\eta_c \to \omega\omega)$	0.40%	$0.20 \pm 0.10\%$	$0.44 \pm 0.06\%$
$\mathcal{B}(\eta_c \to \phi\phi)$	0.25%	$0.28 \pm 0.04\%$	$0.28 \pm 0.04\%$
$\mathcal{B}(\eta_c \to K^*\overline{K}^*)$	0.91%	$0.91 \pm 0.26\%$	$1.00 \pm 0.13\%$

cross check: η_c

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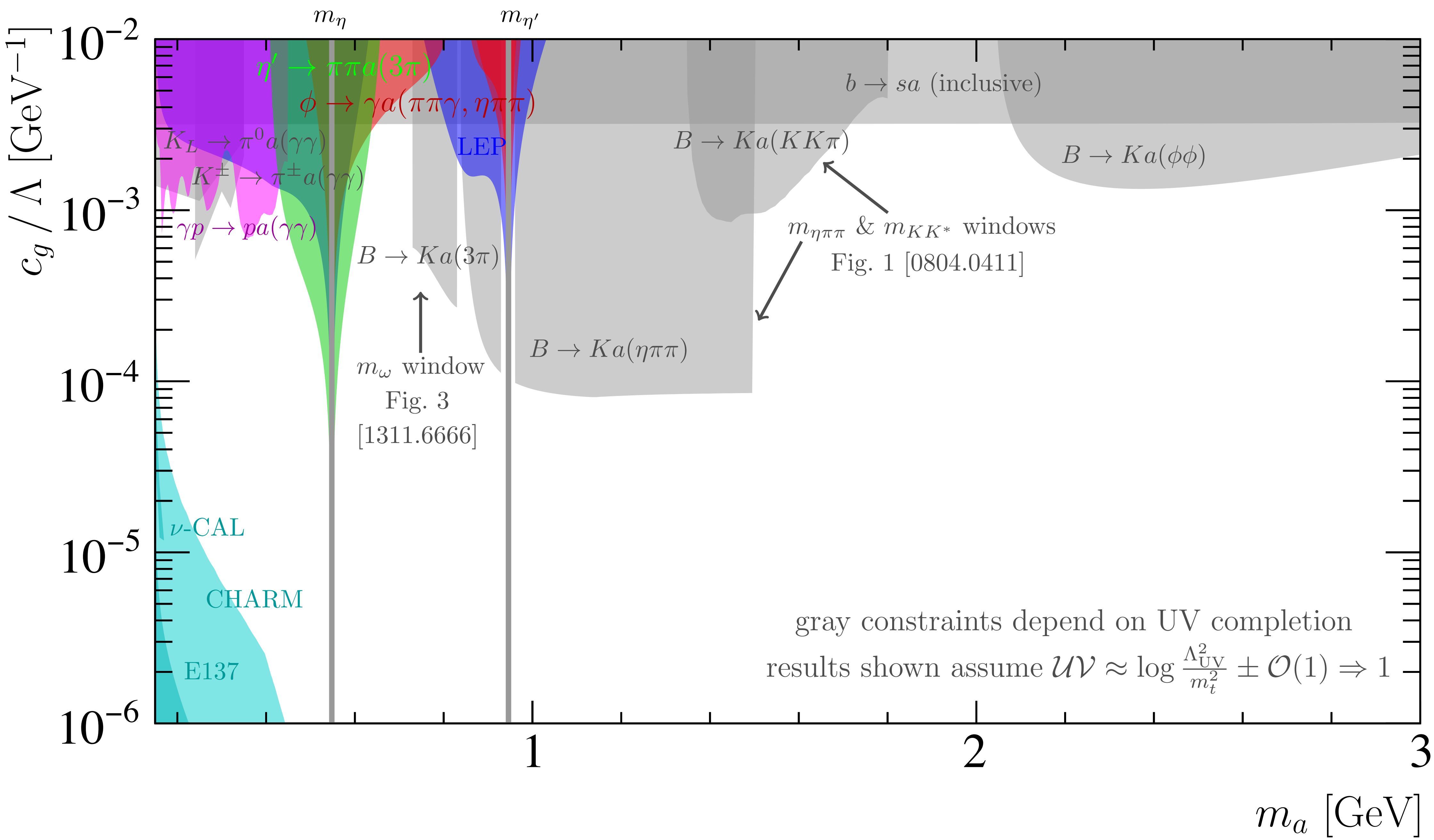
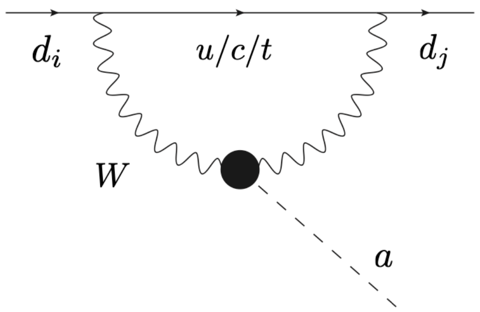


aWW and rare Kaon decays

$$-\frac{g_{aW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$K \to \pi a$ by the SM FCNC loop



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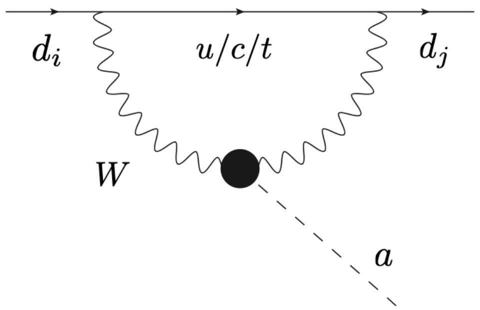
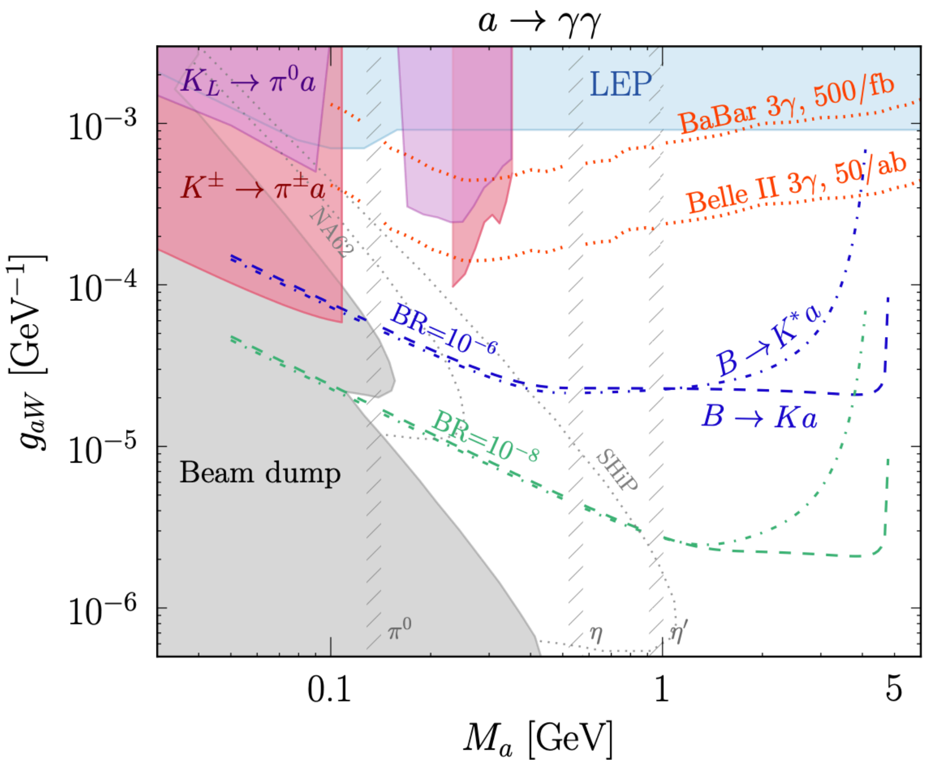
$K \to \pi a$ by the SM FCNC loop



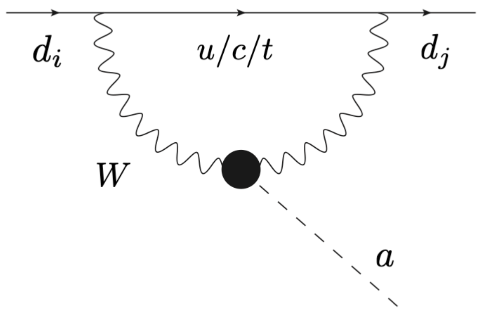


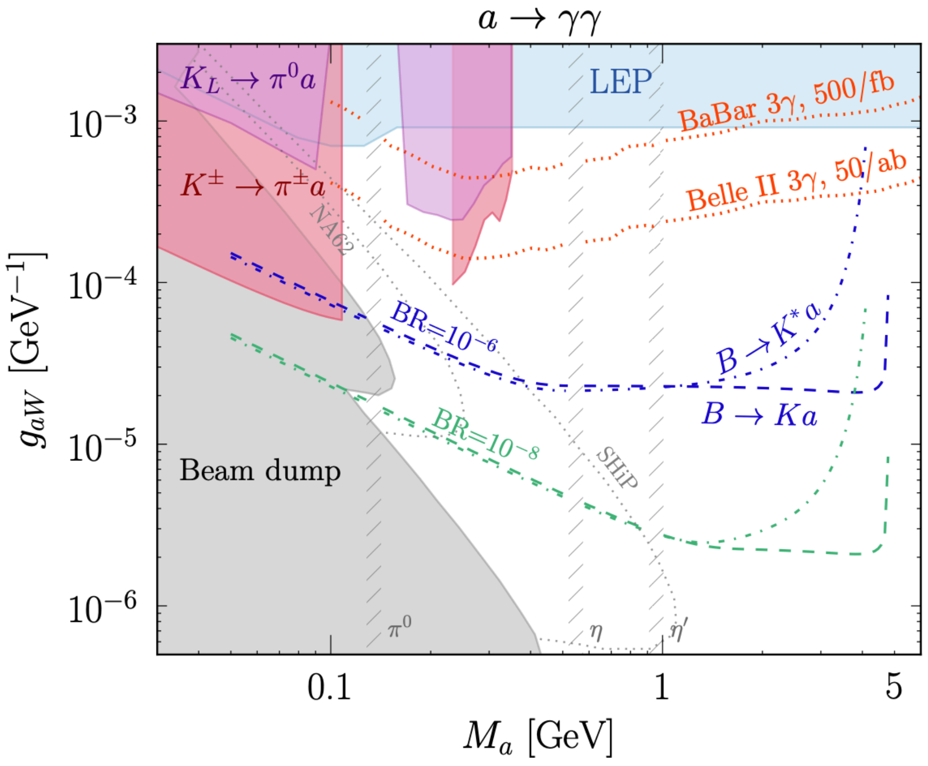
Izaguirre, Lin, Shuve - 1611.09355

aWW and rare Kaon decays

$$-\frac{g_{aW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$

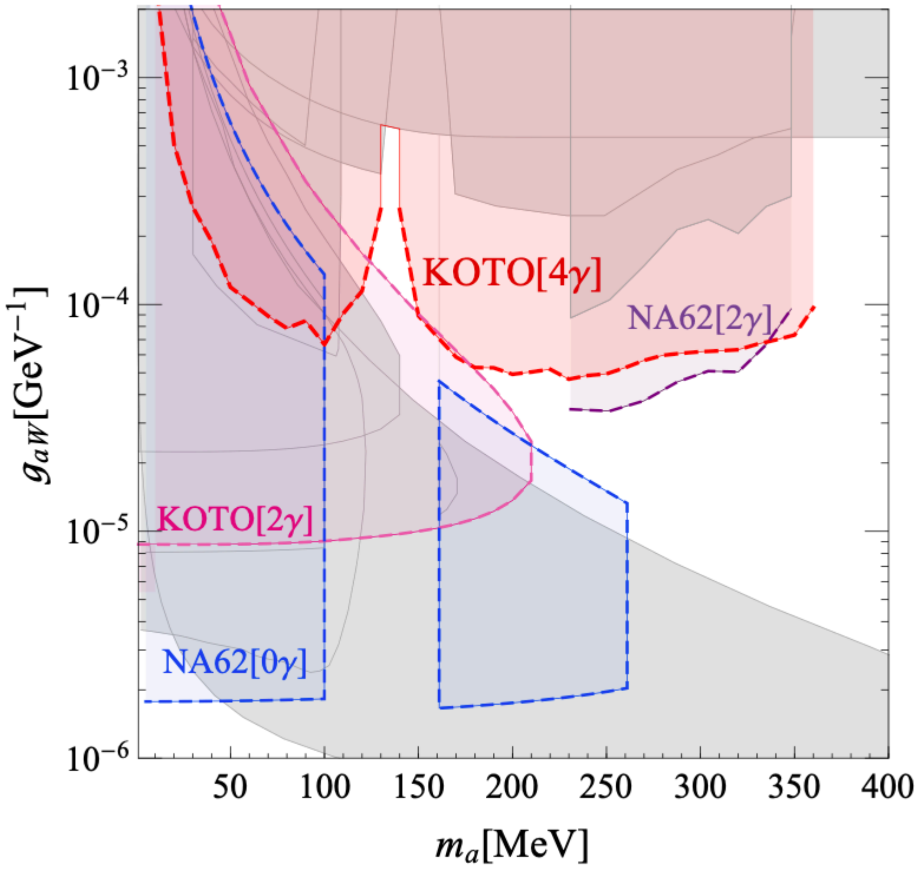
$K \to \pi a$ by the
SM FCNC loop





Izaguirre, Lin, Shuve - 1611.09355

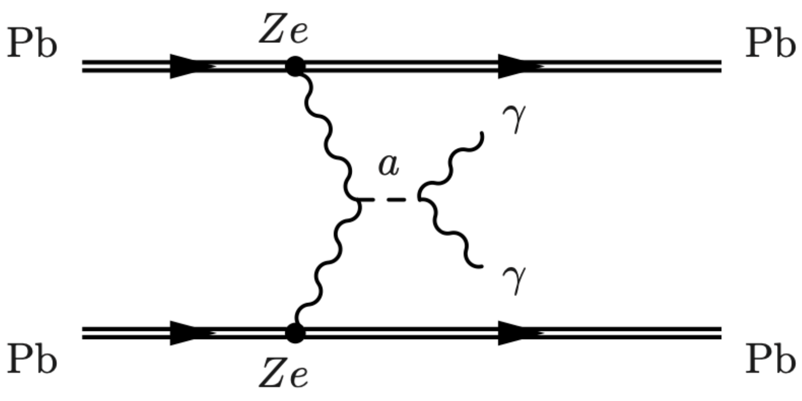
KOTO: $K_L \to \pi^0 a \to 4\gamma$

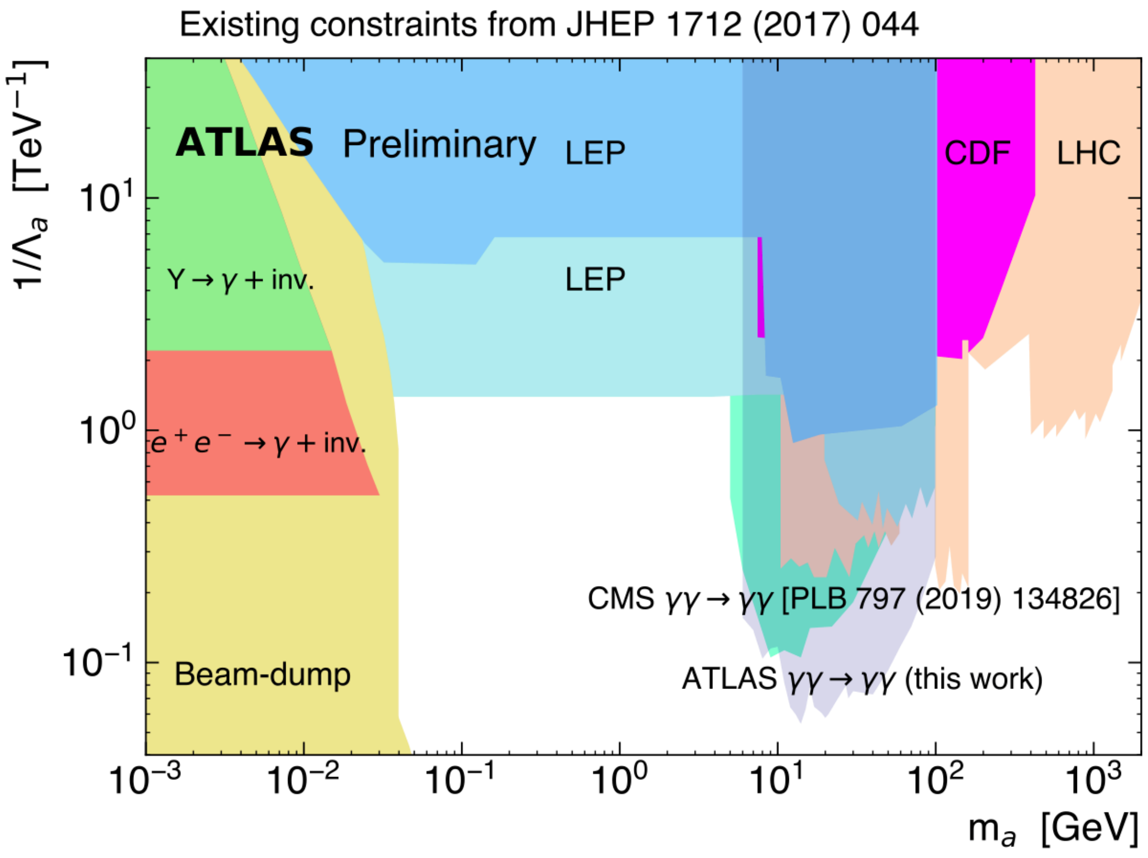


Gori, Perez, Tobioka - 2005.05170

higher ALP masses

heavy ion collisions at the LHC



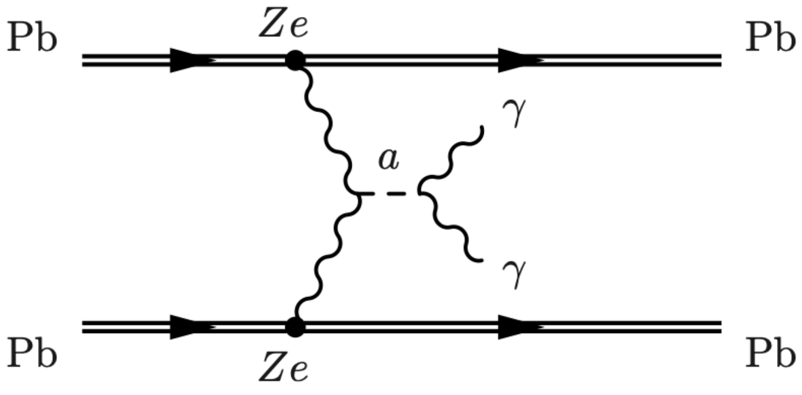


Knapen, Lin, Lou, Melia - 1607.06083
ALTAS, CMS

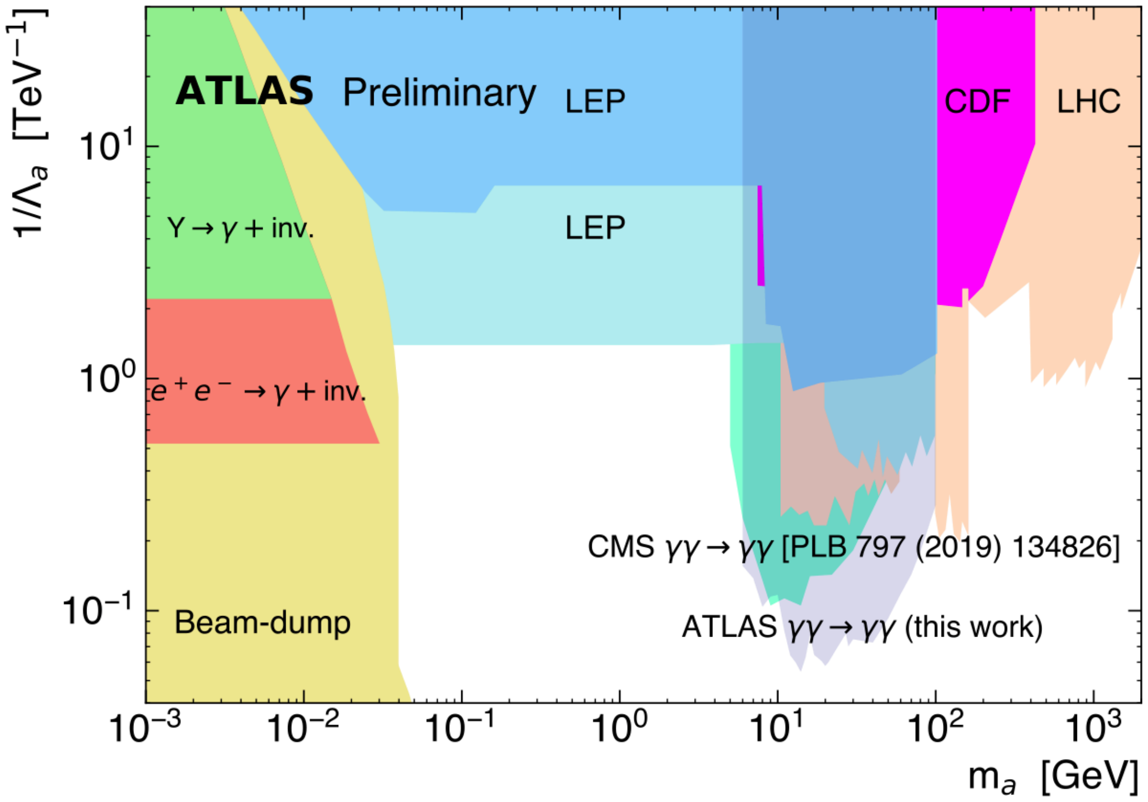
see also Bauer et al 1708.00443,1808.10323

higher ALP masses

heavy ion collisions at the LHC

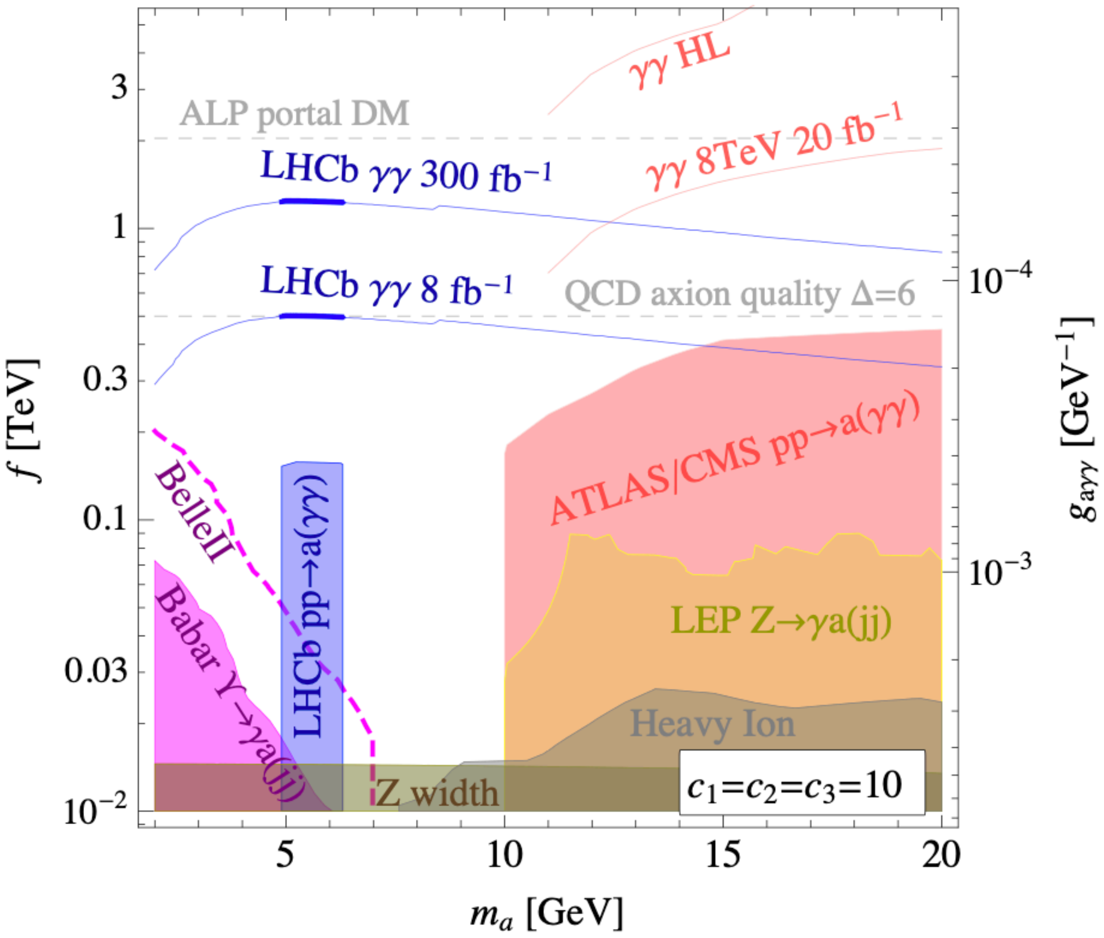


Existing constraints from JHEP 1712 (2017) 044



Knapen, Lin, Lou, Melia - 1607.06083
ALTAS, CMS

$\gamma\gamma$ resonance at the LHC



Mariotti, Redigolo, Sala, Tobioka - 1710.01743
Vidal, Mariotti, Redigolo, Sala, Tobioka - 1810.09452

see also Bauer et al 1708.00443,1808.10323

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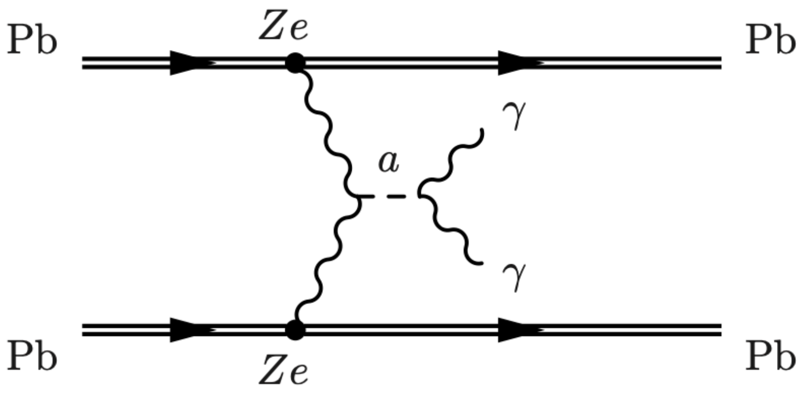

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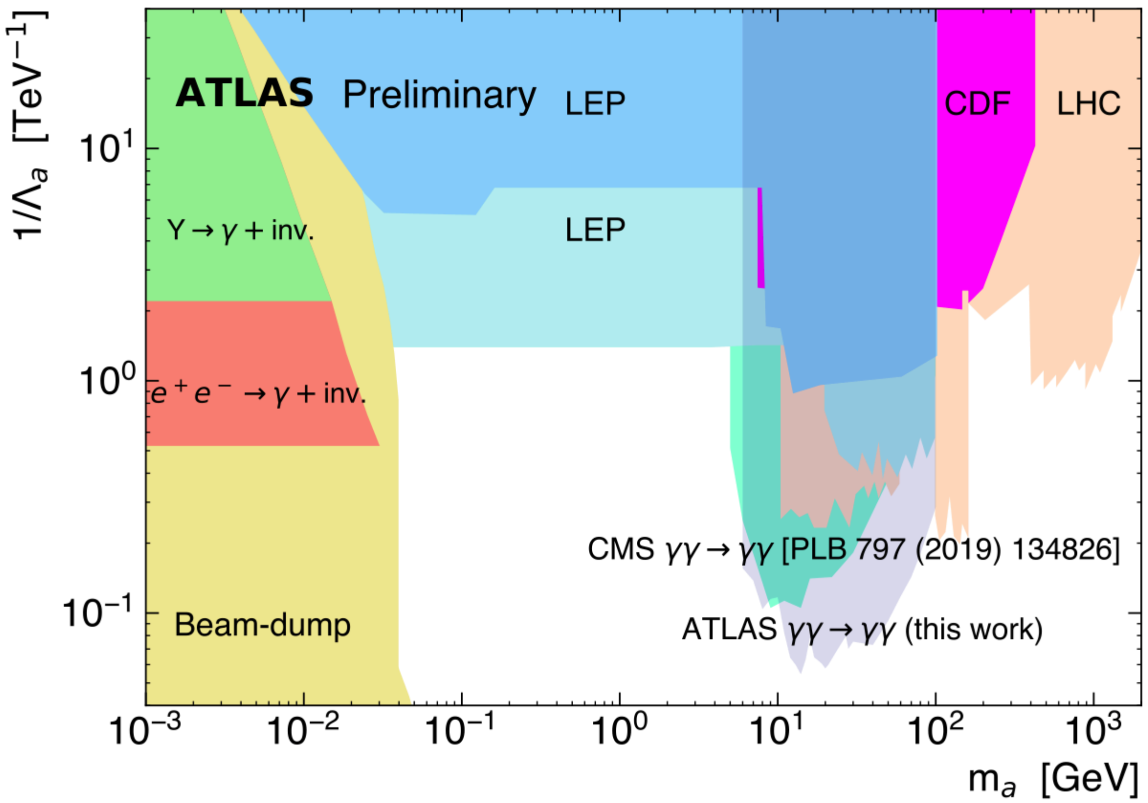

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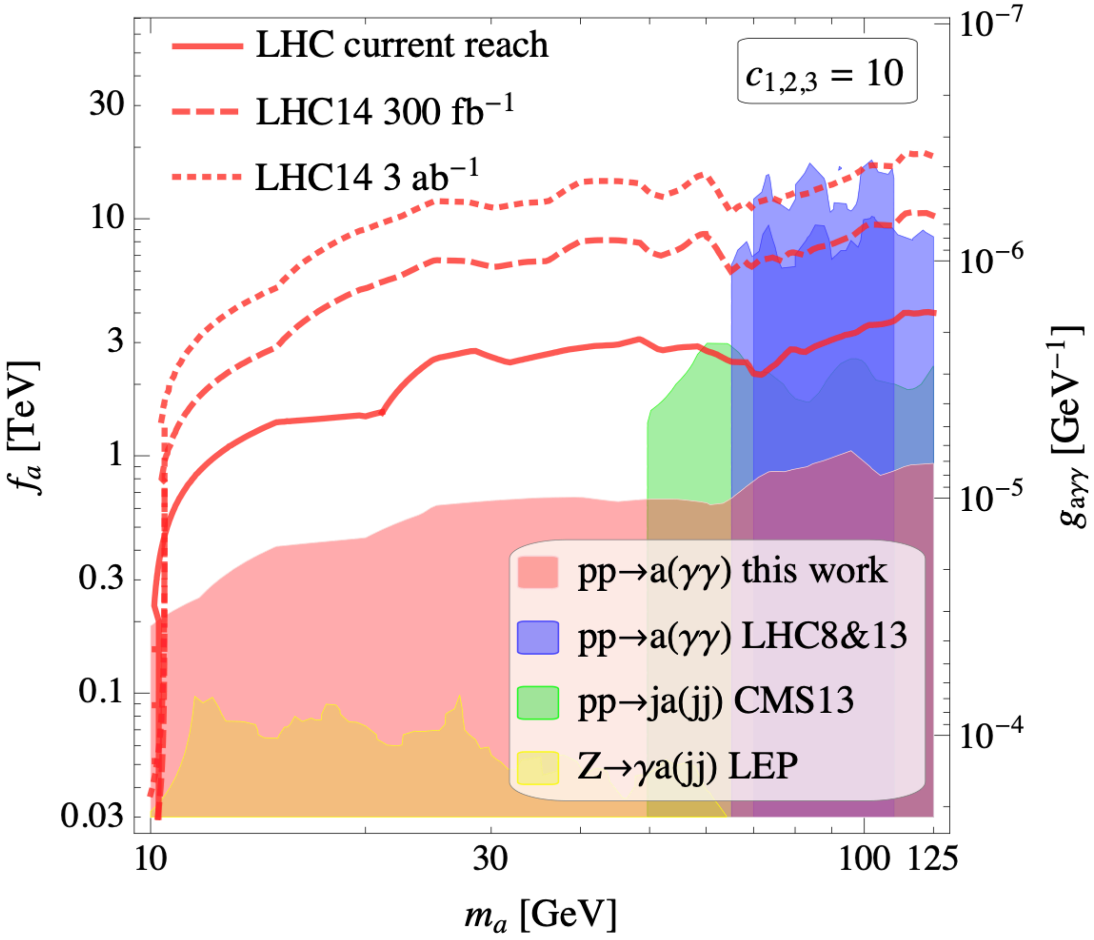

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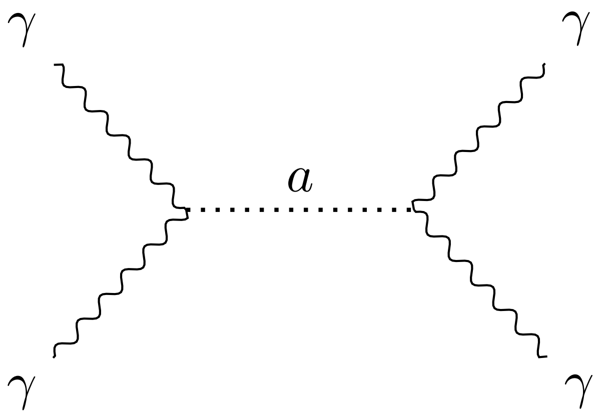
Probing ALPs and the Axiverse with Superconducting Radiofrequency Cavities

Bogorad, Hook, Kahn, YS - 1902.01418

the idea

probing off-shell ALPs via non-linear QED in a cavity

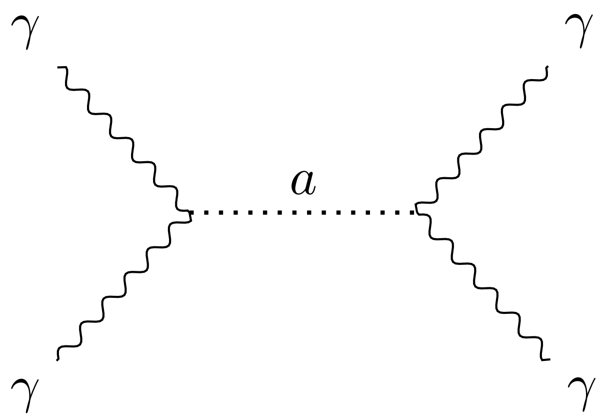


$$\propto (F^{\mu\nu}\tilde{F}_{\mu\nu})^2 \propto (E \cdot B)^2$$

non-linear Maxwell equations

the idea

probing off-shell ALPs via non-linear QED in a cavity



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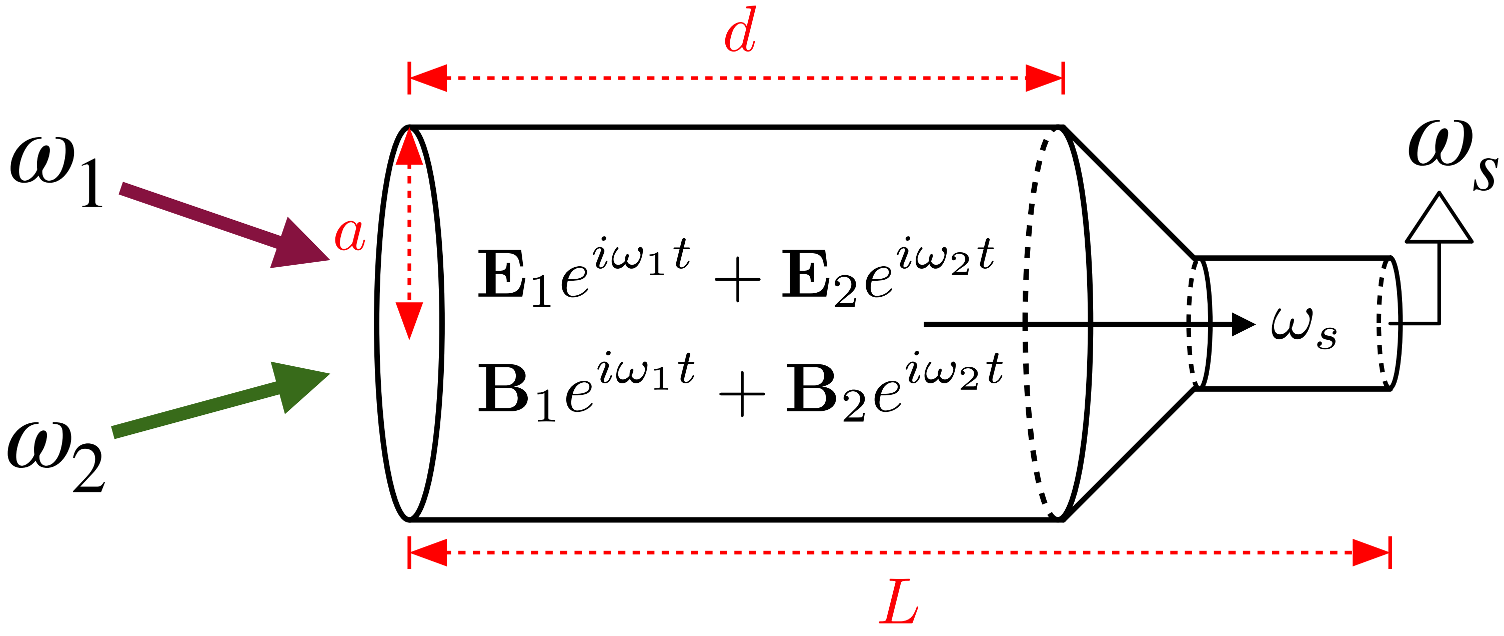
non-linear Maxwell equations

pump

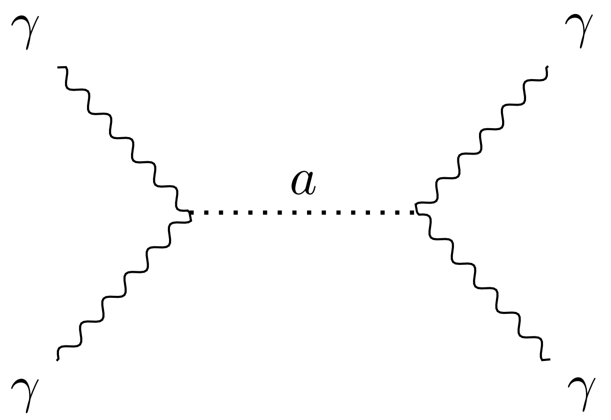


$$\omega_s = \pm\,\omega_1 \pm \omega_1 \pm \omega_2$$

measure

the idea

probing off-shell ALPs via non-linear QED in a cavity



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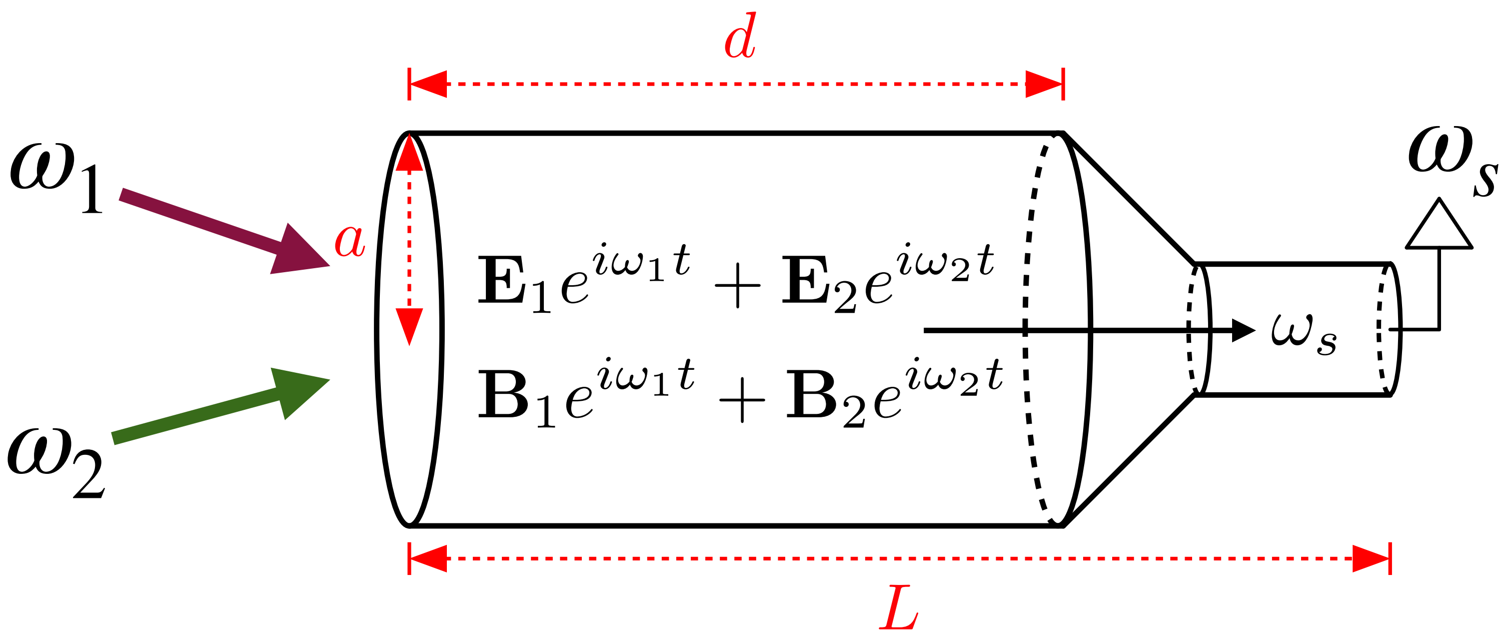


$$\omega_s = \pm\,\omega_1 \pm \omega_1 \pm \omega_2$$

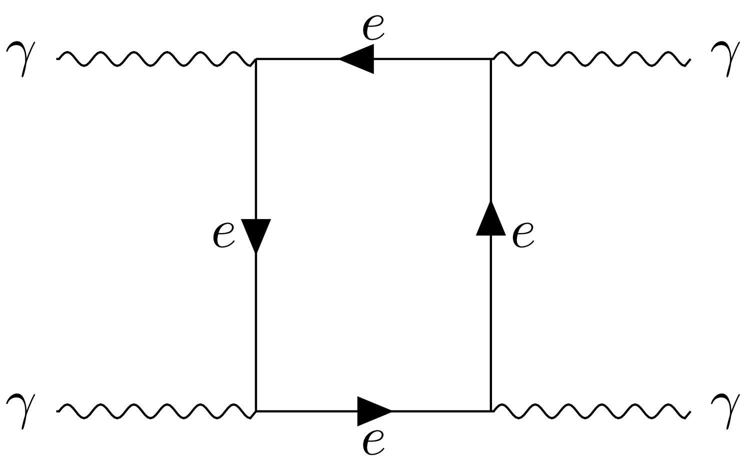
pump

measure

advantages:

- probes large range of masses - broadband
- does not rely on ALP been dark matter

the Euler Heisenberg effect



$E \ll m_e$

non-linear QED

$$\propto c_1(F^{\mu\nu}F_{\mu\nu})^2 + c_2(F^{\mu\nu}\tilde{F}_{\mu\nu})^2$$

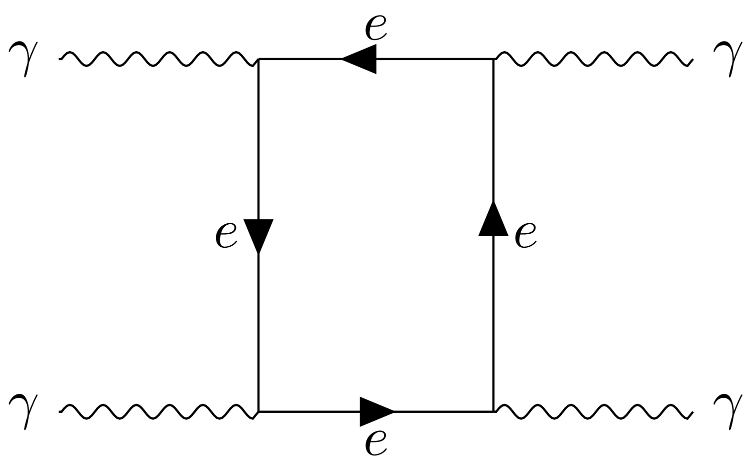
Hiesenberg Euler, 1936
Schwinger, 1951

never been measured below the electron mass!

measured at measured at high energies
(light by light scattering)

ATLAS, 2017

the Euler Heisenberg effect



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ALP vs EH

$$\frac{c_\gamma/\Lambda}{m_a} \gtrsim \mathcal{O}(1) \times \frac{\alpha}{m_e^2} \simeq \frac{10^{-10}\,\mathrm{GeV}^{-1}}{10^{-6}\,\mathrm{eV}}$$

comparable to the current limit on ALPs (by CAST)

Evans and Rafelski, 1810.06717

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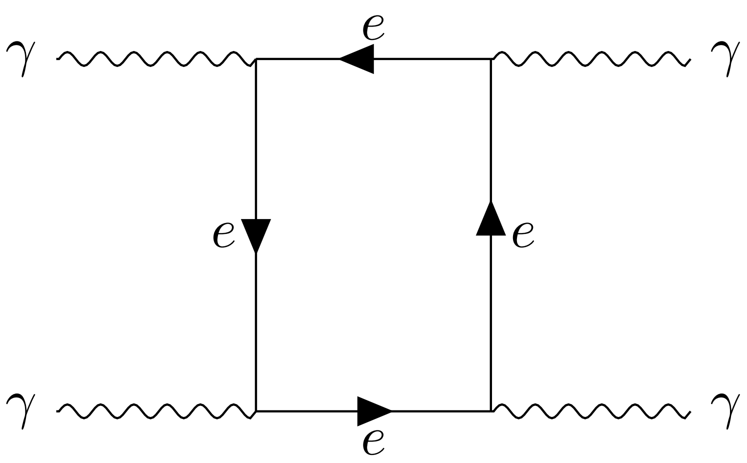

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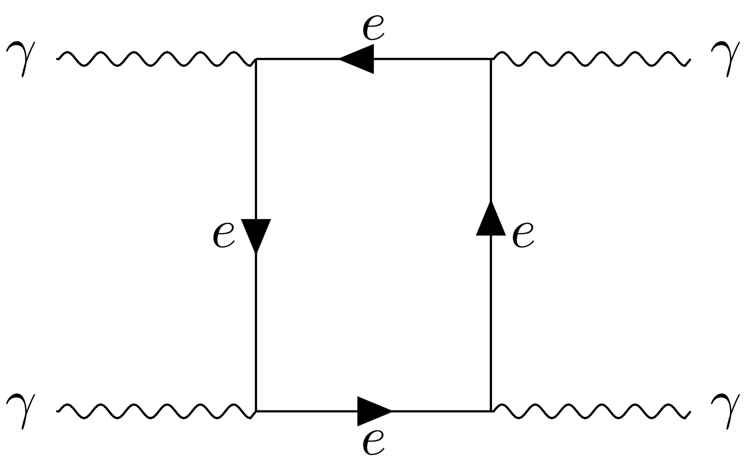
Evans and Rafelski, 1810.06717

improve current bounds → sensitivity to EH

detecting the EH effect by superconducting radiofrequency cavities



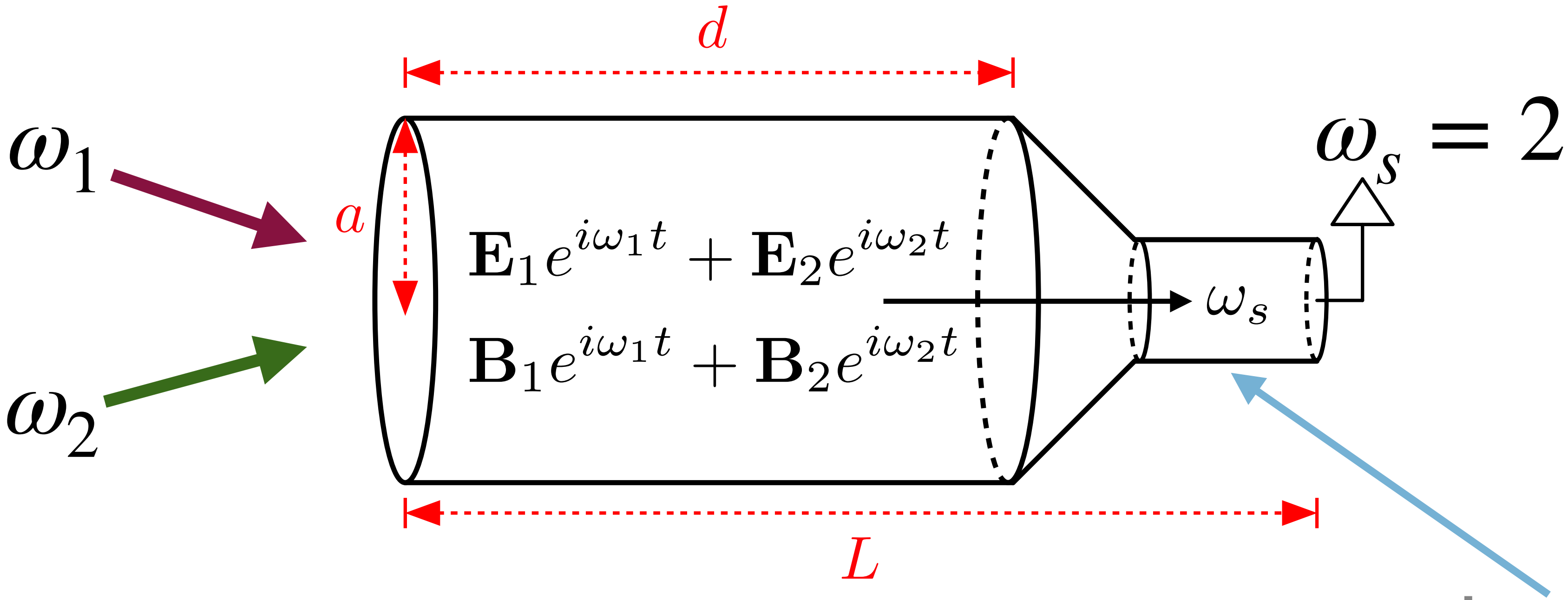
$E \ll m_e$

non-linear QED in the SM

$$\propto c_1(F^{\mu\nu}F_{\mu\nu})^2 + c_2(F^{\mu\nu}\tilde{F}_{\mu\nu})^2$$

Hiesenberg Euler, 1936
Schwinger, 1951

pump



$$\omega_s = 2\omega_1 - \omega_2$$

measure

readout by using filtering geometry

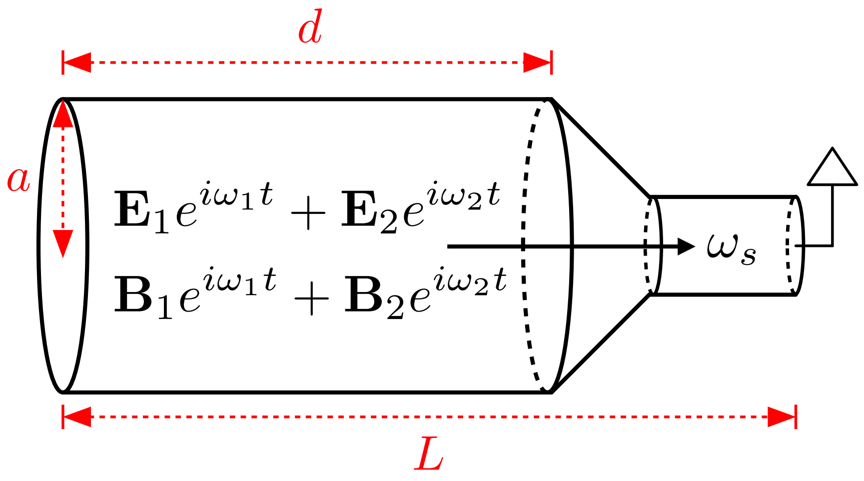
$$\omega_s > \omega_1, \omega_2$$

Brodin, Marklund, Stenflo, PRL, 2001
Eriksson, Brodin, Marklund, Stenflo, PRA, 2004

sensitivity to ALPs

$$\frac{c_\gamma}{\Lambda} = \begin{cases} \left(\frac{4TL}{Q_s V E_0^6 K_0^2}\sqrt{\frac{B}{t}}\,\mathrm{SNR}\right)^{1/4}\omega_s & m_a \ll \omega_s \\ \left(\frac{4TL}{Q_s V E_0^6 K_\infty^2}\sqrt{\frac{B}{t}}\,\mathrm{SNR}\right)^{1/4} m_a & m_a \gg \omega_s \end{cases}$$

SNR = 5



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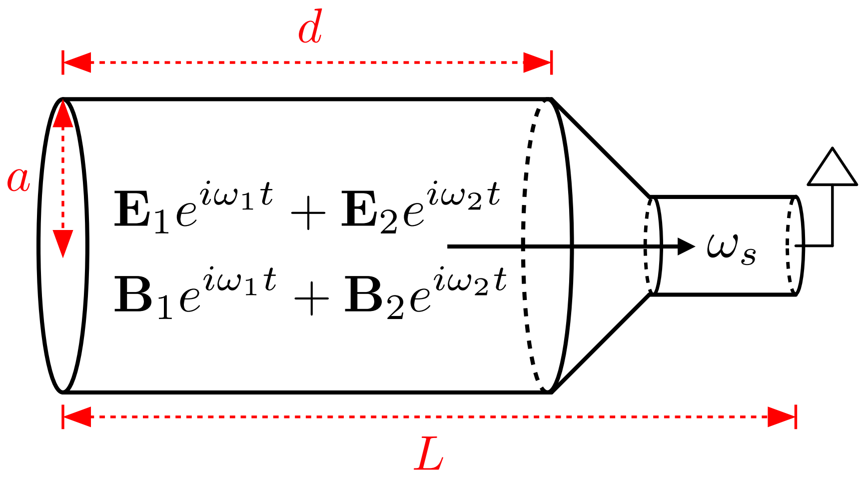
$\mathrm{SNR} = 5$



$a = 0.5\,\mathrm{m}\,,\ d = 1.56\,\mathrm{m}\,,\ V = 1.23\,\mathrm{m}^3$

$\omega_1 = \mathrm{TE}_{011}\,,\ \omega_2 = \mathrm{TM}_{010}\,,\ \omega_s = \mathrm{TM}_{020}$

$\omega_s/(2\pi) = 527\,\mathrm{MHz}$

$K_0 = 0.4\,,\ K_\infty = 0.18$

$E_0 = 45\,\mathrm{MV/m} \qquad T = 1.5\,\mathrm{K}$

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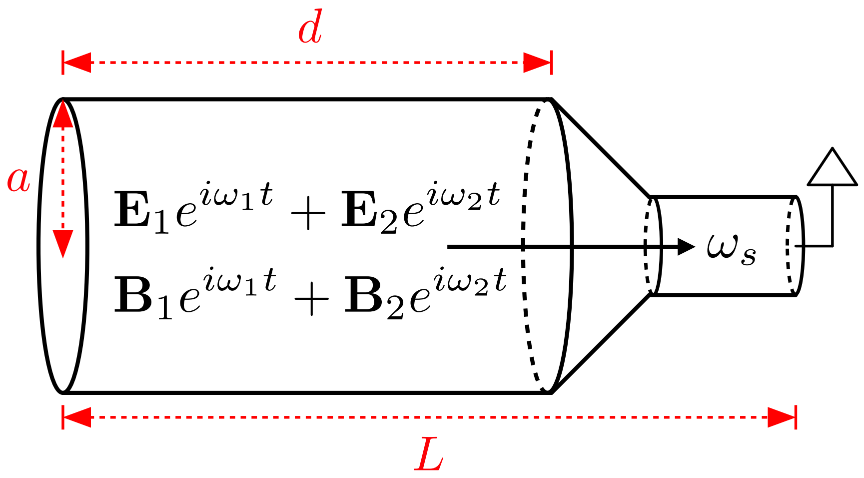

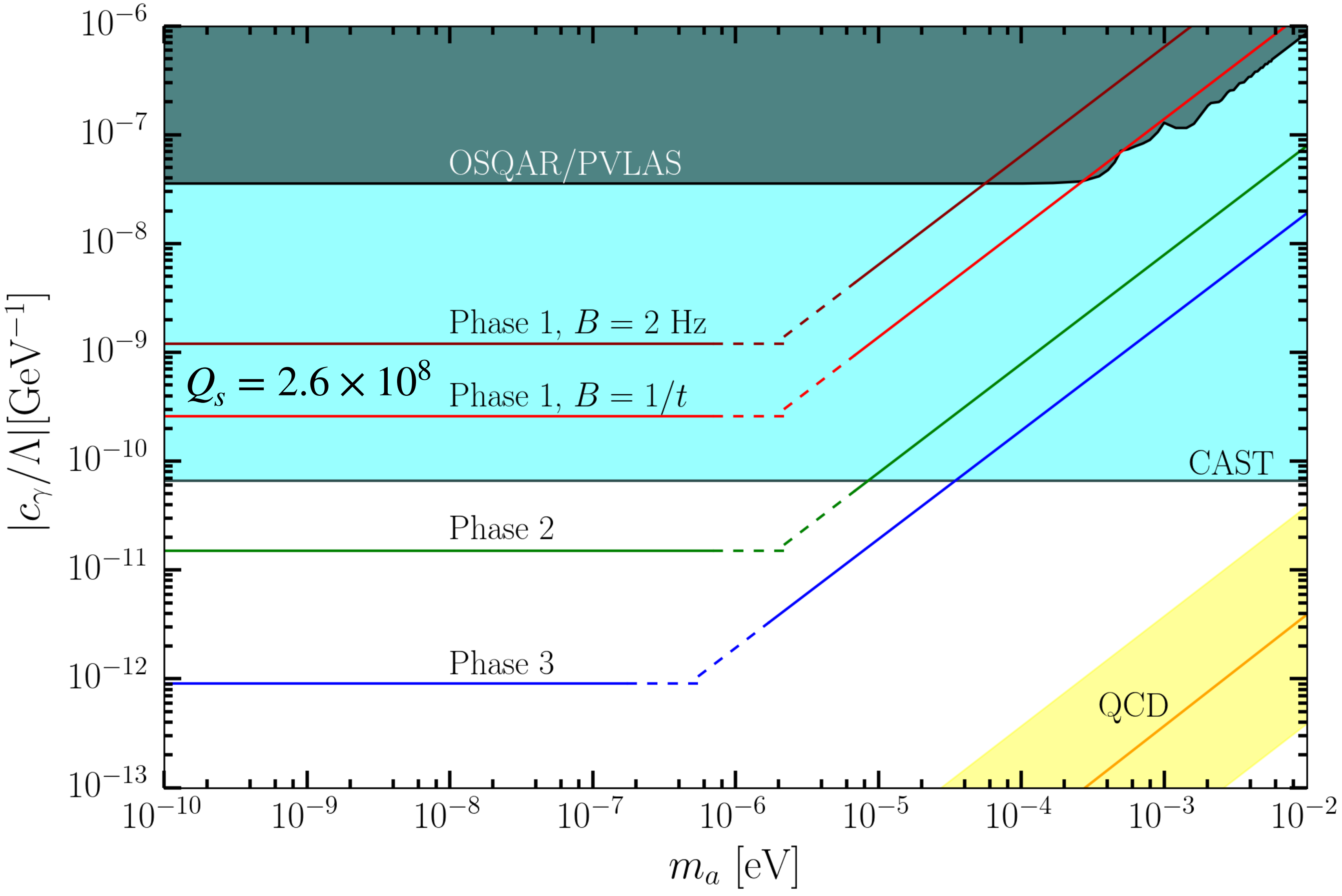

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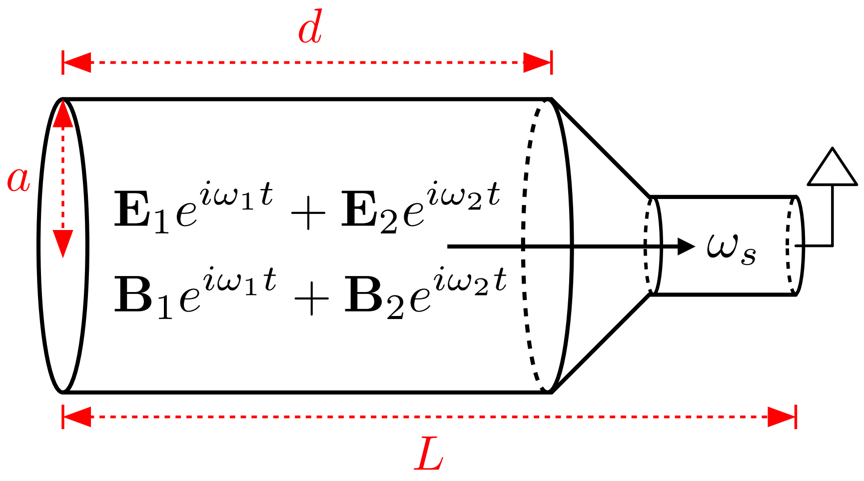

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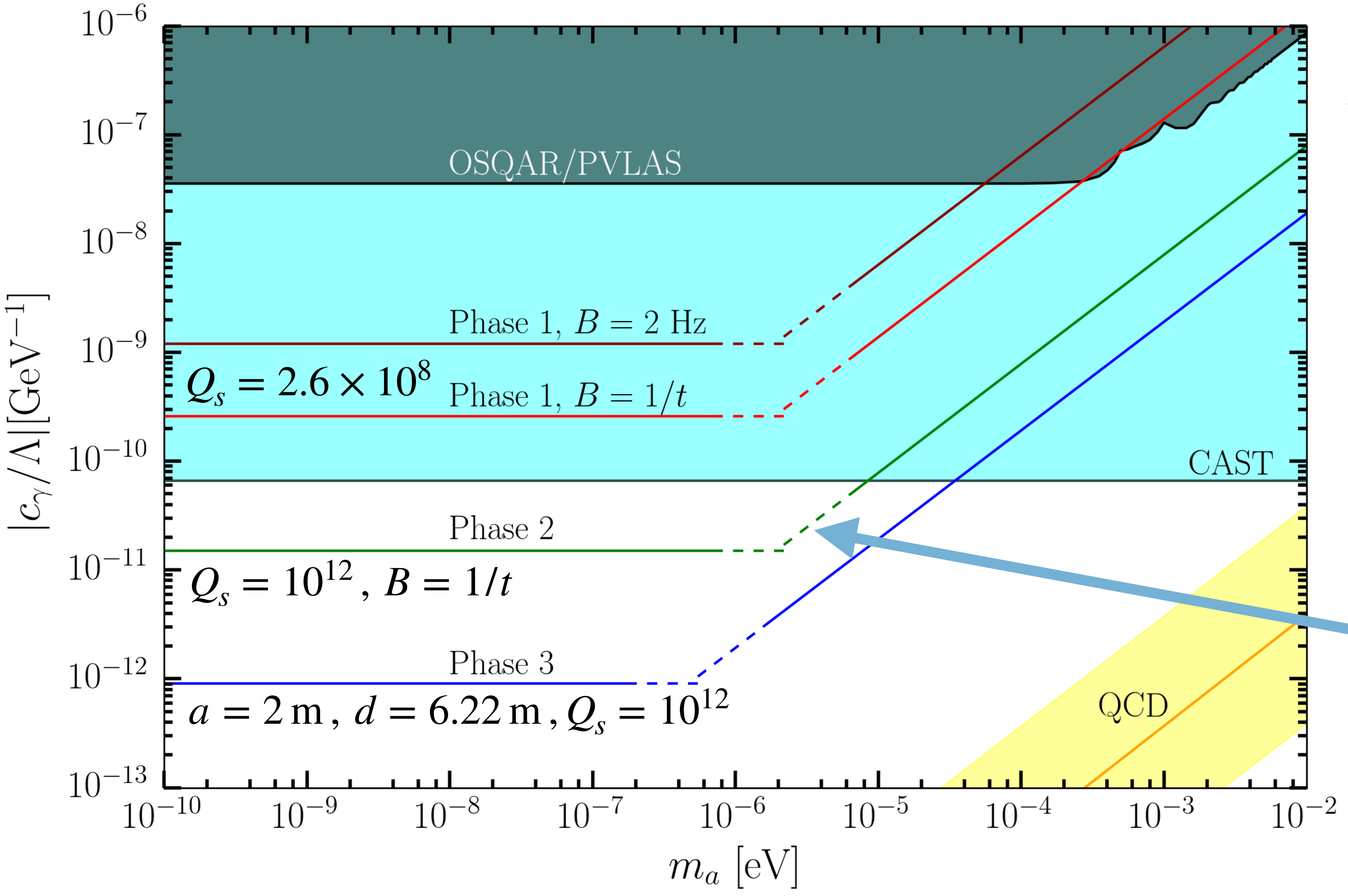


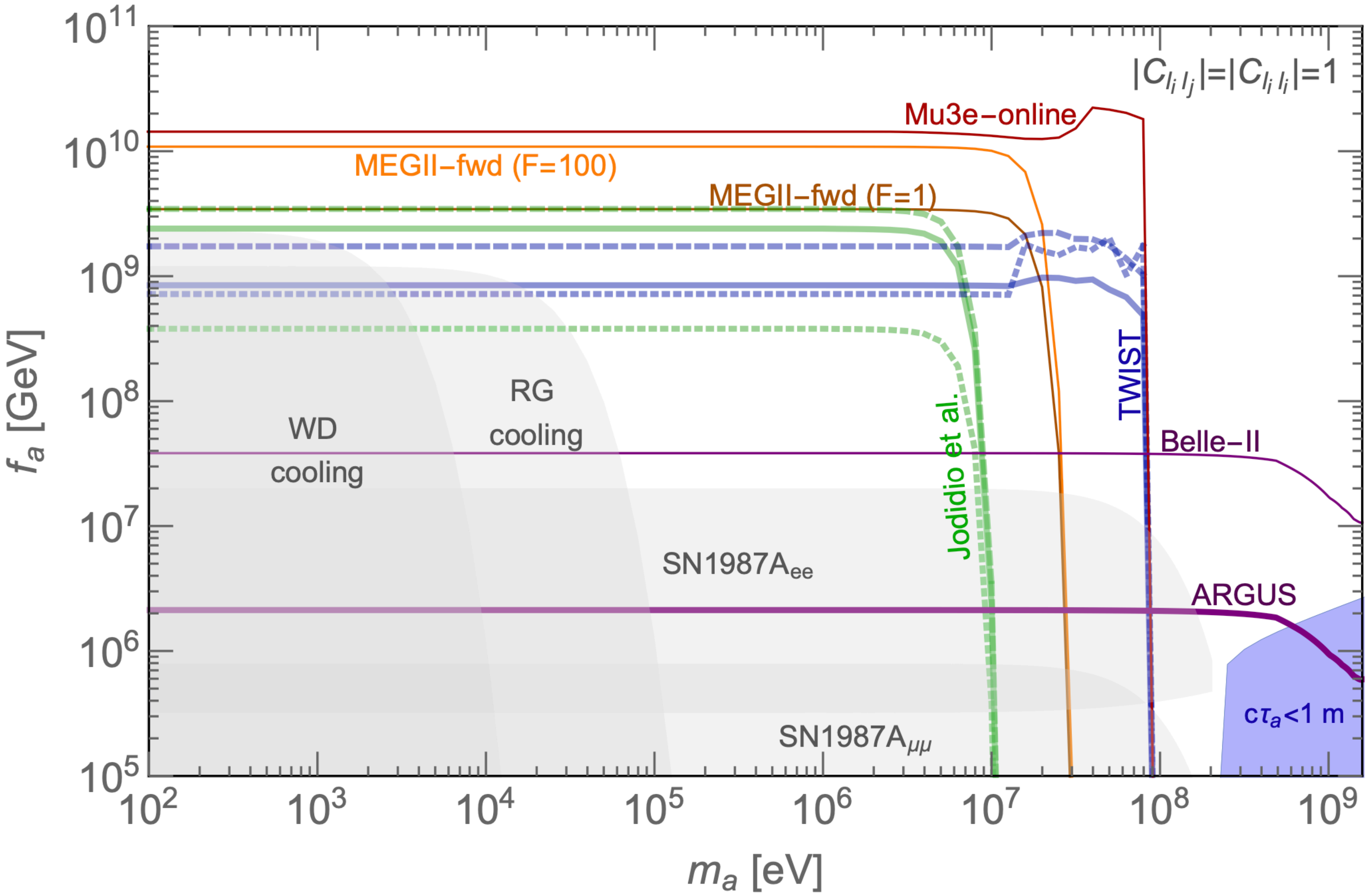
20 days run to detect EH!

Outlook

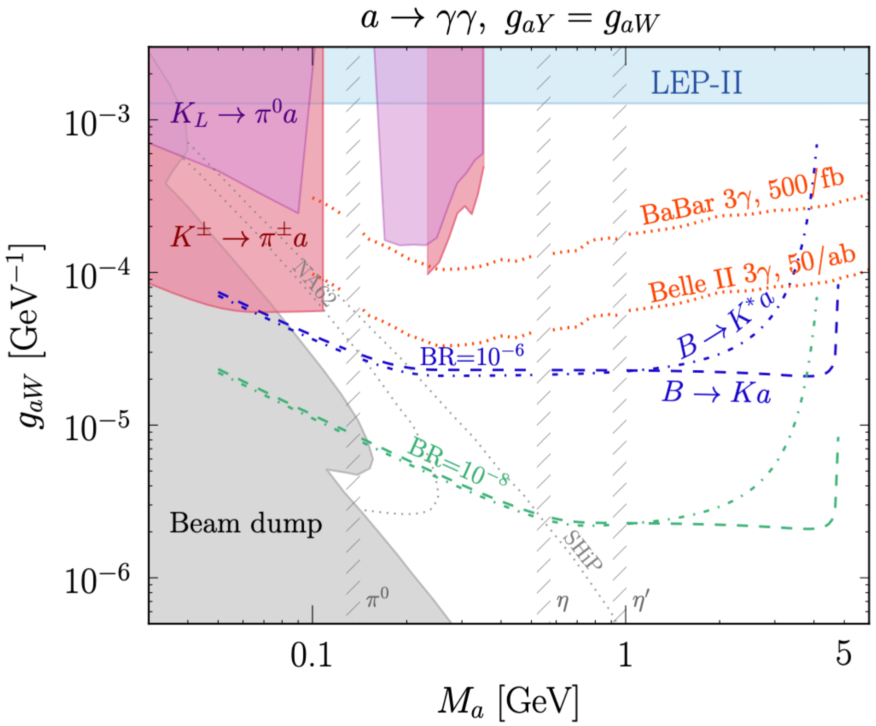
- on tape PrimEx data can improve the sensitive to ALP with QCD mass scale, future GlueX data will improve it by order of magnitude
- ALPs hadronic rates can be estimated from data
- future rare kaon decay is a promising channel to probe ALPs
- higher ALPs masses can be probed by LHC searches (heavy ion/$\gamma\gamma$ resonances)

Backups

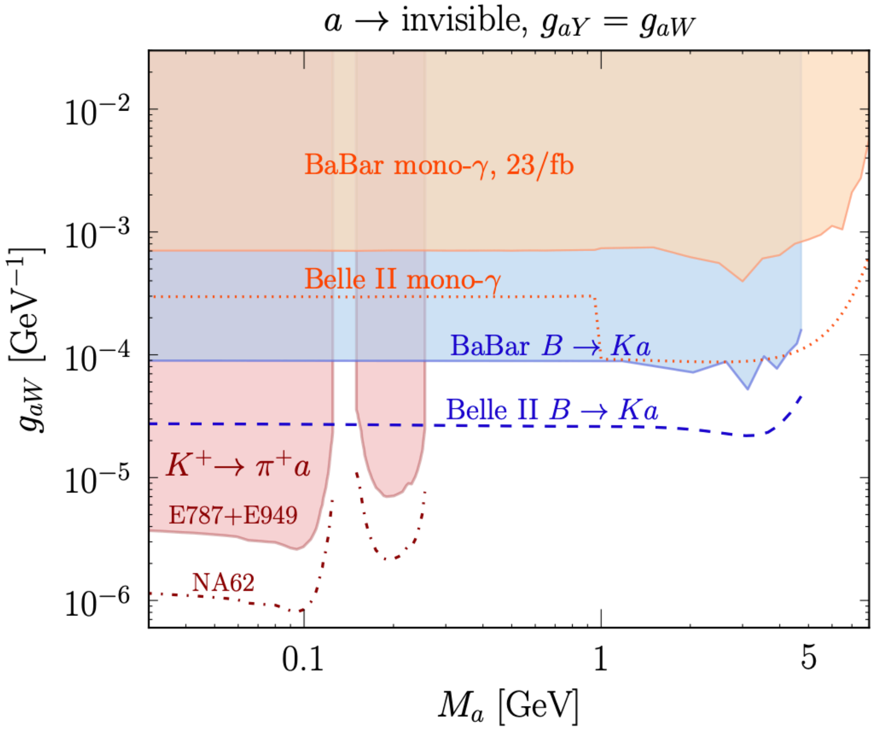
ALP and LFV



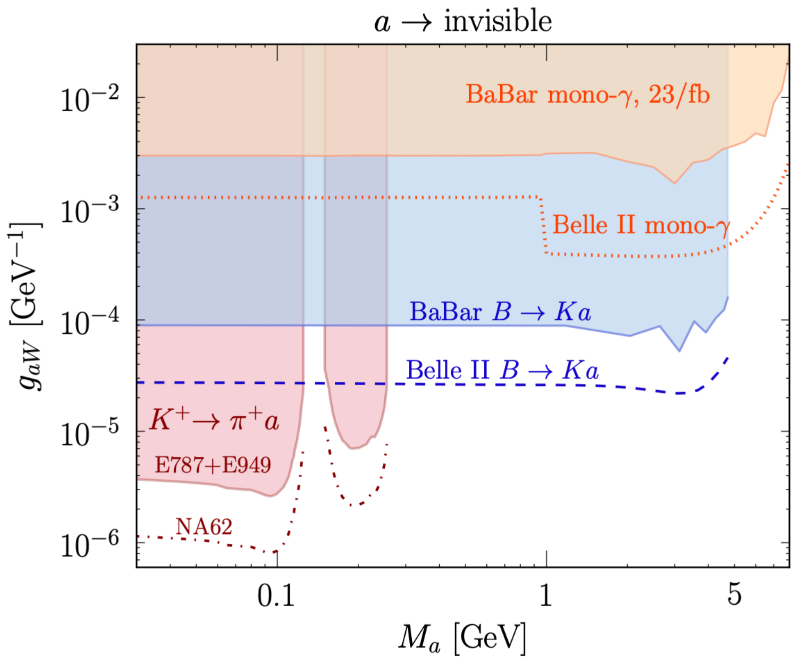
Calibbi, Redigolo, Ziegler, Zupan - 2006.04795
and Cornella, Praradisi, Sumensari - 1911.06279



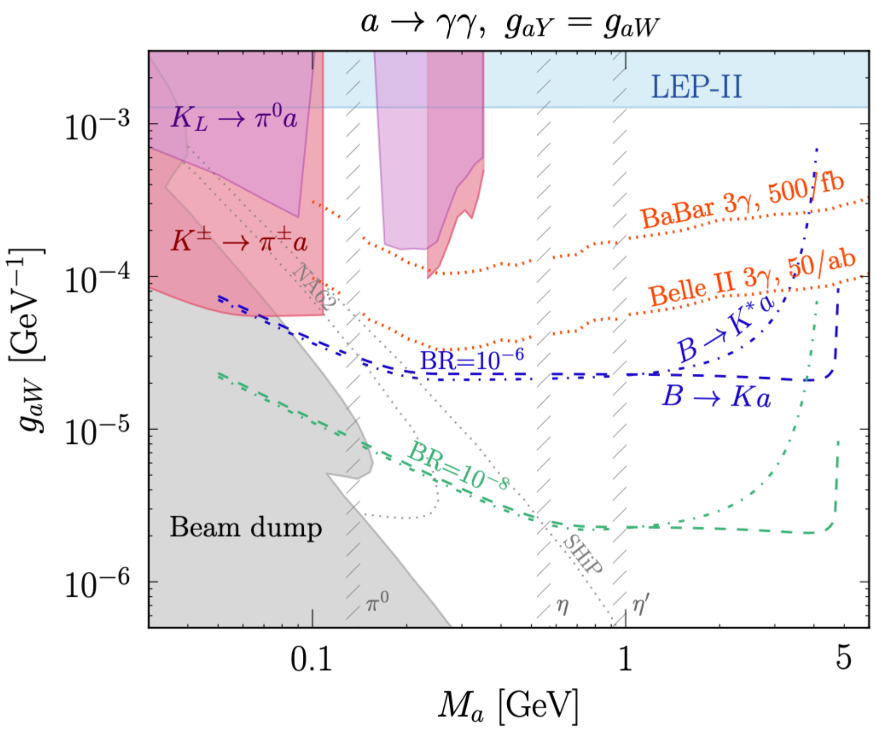
$a \to \gamma\gamma,\ g_{aY} = g_{aW}$
LEP-II
$K_L \to \pi^0 a$
$K^\pm \to \pi^\pm a$
NA62
BaBar 3γ, 500/fb
Belle II 3γ, 50/ab
$B \to K^* a$
BR=10^{-6}
$B \to Ka$
BR=10^{-8}
SHiP
Beam dump
π^0
η
η'
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g_{aW} [GeV^{-1}]
0.1
1
5
M_a [GeV]



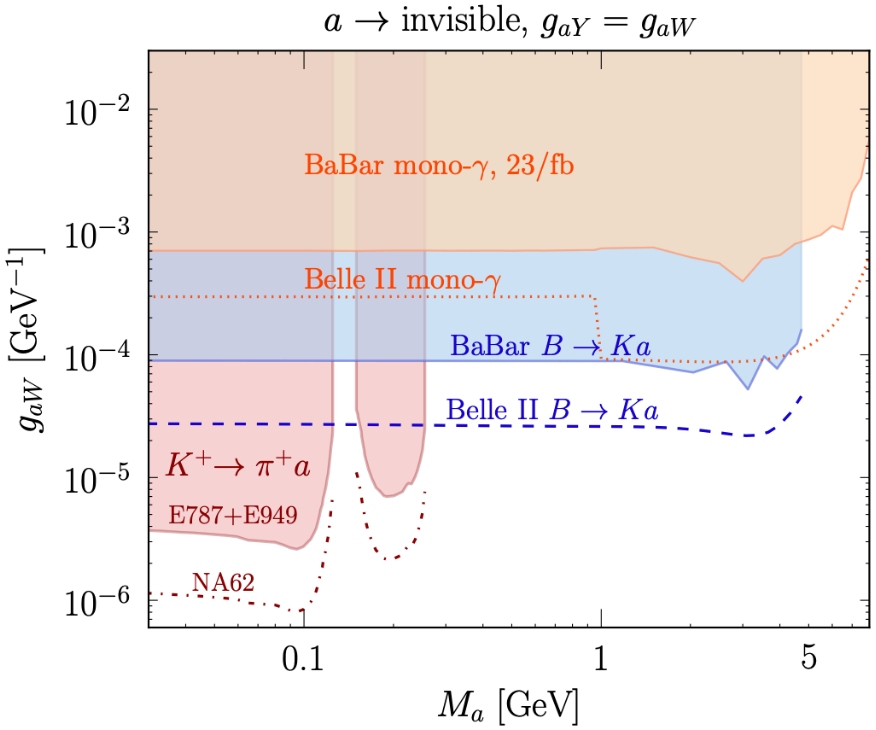
$a \to$ invisible, $g_{aY} = g_{aW}$
BaBar mono-γ, 23/fb
Belle II mono-γ
BaBar $B \to Ka$
Belle II $B \to Ka$
$K^+ \to \pi^+ a$
E787+E949
NA62
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g_{aW} [GeV^{-1}]
0.1
1
5
M_a [GeV]



$a \to$ invisible
BaBar mono-γ, 23/fb
Belle II mono-γ
BaBar $B \to Ka$
Belle II $B \to Ka$
$K^+ \to \pi^+ a$
E787+E949
NA62
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g_{aW} [GeV^{-1}]
0.1
1
5
M_a [GeV]



$a \rightarrow \gamma\gamma,\ g_{aY} = g_{aW}$



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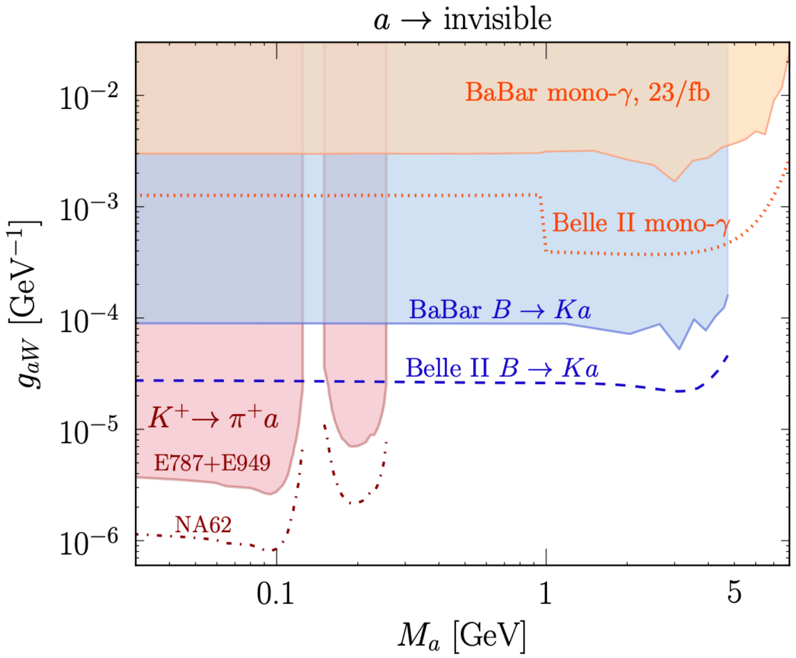

$a \rightarrow$ invisible

Izaguirre, Lin, Shuve - 1611.09355

Sensitivity to ALPs

Sensitivity to ALPs

the number of signal photons

quality factor

cavity volume

pump field strength

$$N_s = \frac{1}{2\omega_s}\int d^3x\,|\,E_a(x)\,|^2 = \frac{Q_s^2\,V\,E_0^6}{2\omega_s}\,\frac{c_\gamma^4}{\Lambda^4}\begin{cases}\dfrac{K_0^2}{\omega_s^4} & m_a \ll \omega_s \\[2ex] \dfrac{K_\infty^2}{m_a^4} & m_a \gg \omega_s\end{cases}$$

electric field of the induced ALP current

modes overlap

Sensitivity to ALPs

the number of signal photons

quality factor

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$$N_s = \frac{1}{2\omega_s}\int d^3x\,|E_a(x)|^2 = \frac{Q_s^2\,V\,E_0^6}{2\omega_s}\,\frac{c_\gamma^4}{\Lambda^4}\begin{cases}\dfrac{K_0^2}{\omega_s^4} & m_a \ll \omega_s\\[2ex] \dfrac{K_\infty^2}{m_a^4} & m_a \gg \omega_s\end{cases}$$

electric field of the induced ALP current

modes overlap

signal-to-noise ratio (SNR)

(Dicke radiometer equation)

time

$$\mathrm{SNR} \approx \frac{N_s}{N_{\mathrm{th}}}\,\frac{1}{2\,L\,Q_s}\sqrt{\frac{t}{B}}$$

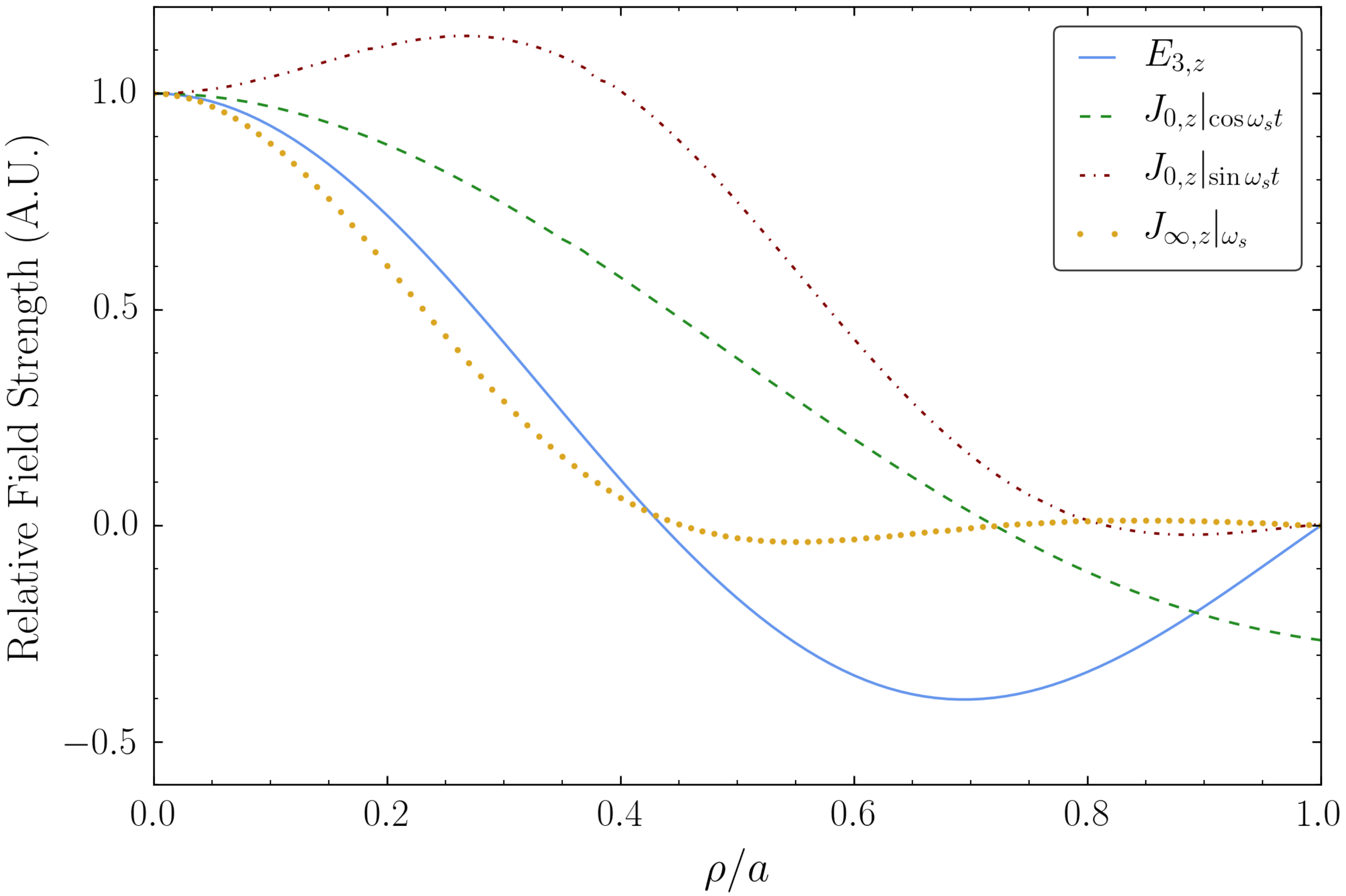
signal bandwidth

thermal noise photons

Temperature/ω_s

cavity's length

Overlap

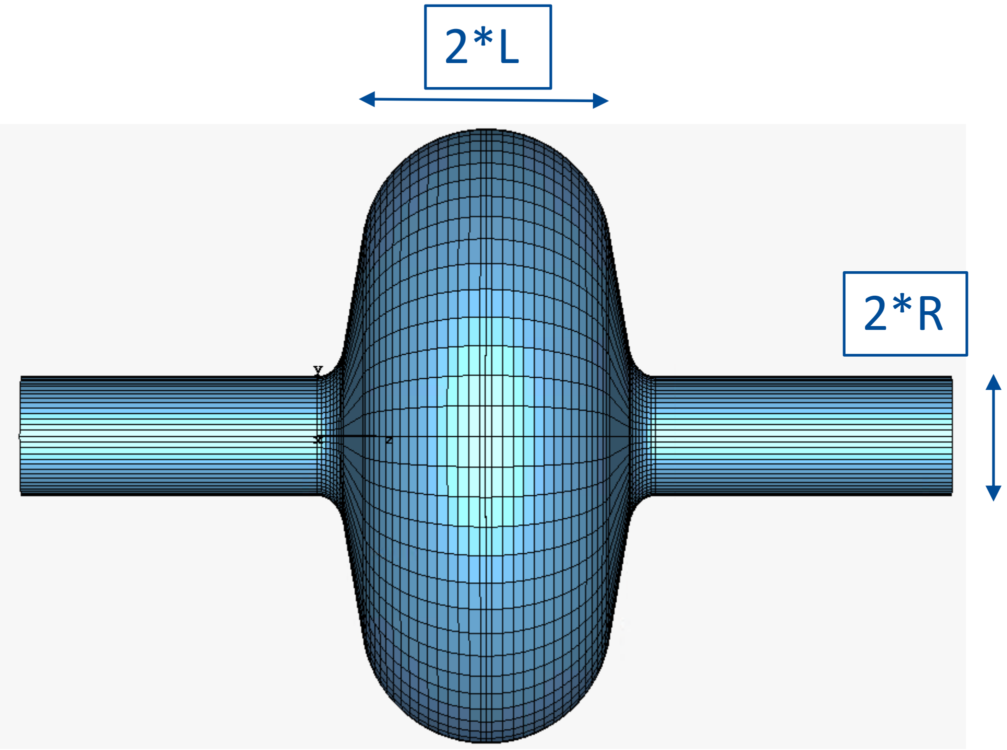

Relative Field Strength (A.U.)
1.0
0.5
0.0
-0.5
0.0
0.2
0.4
0.6
0.8
1.0
ρ/a
$E_{3,z}$
$J_{0,z}|_{\cos\omega_s t}$
$J_{0,z}|_{\sin\omega_s t}$
$J_{\infty,z}|_{\omega_s}$

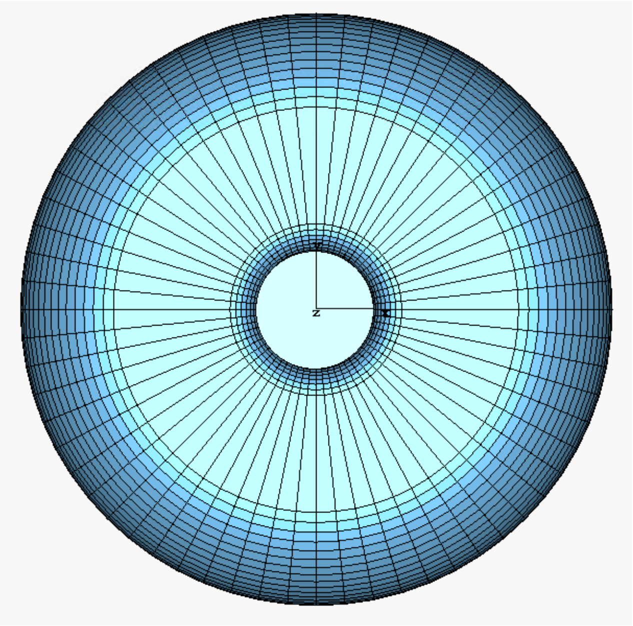
Cavity vs LSW

$$\left.\frac{N_s}{N_i}\right|_{\mathrm{LSW}} \sim \left(\frac{c_\gamma}{\Lambda}\right)^4 B_{\mathrm{prod.}}^2 B_{\mathrm{det.}}^2 L^4 \qquad \left.\frac{N_s}{N_i}\right|_{\text{cavity}} \sim Q_s^2 \left(\frac{c_\gamma}{\Lambda}\right)^4 E_0^4 L^4$$

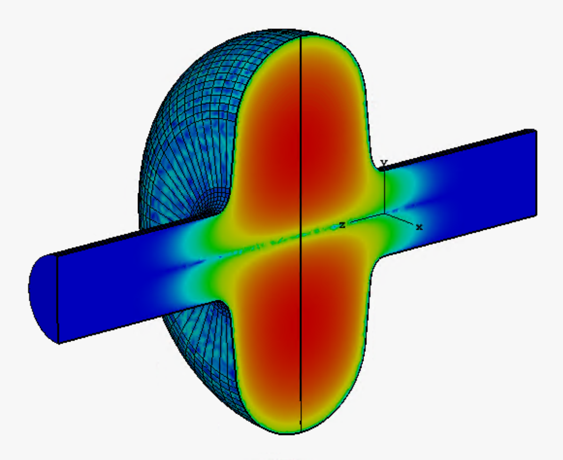
$$\mathrm{SNR} = \frac{P_s}{T}\sqrt{\frac{t}{B}} \approx \frac{N_s}{N_{\mathrm{th}}}\frac{1}{2\,L\,Q_s}\sqrt{\frac{t}{B}}$$

the cavity in practice at Fermilab

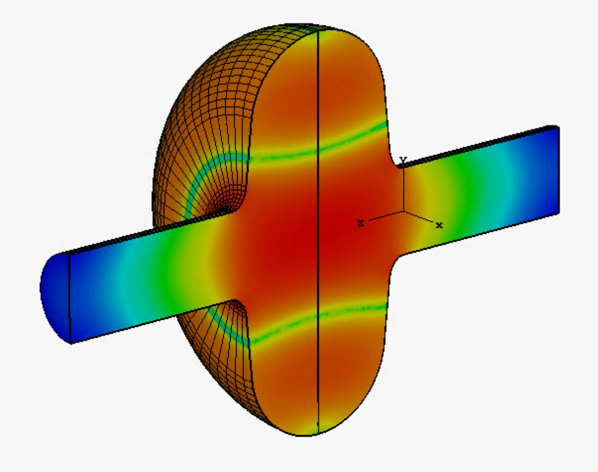




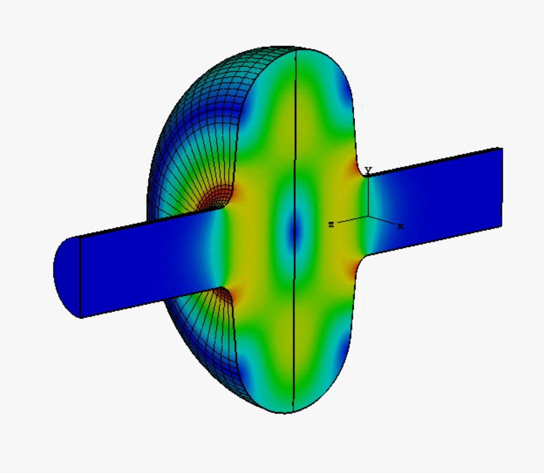
TE011 (ω_1)



TM021 (ω_2)



TM012 (ω_3)



Disentangling EH and ALPs

Proof of concept with rectangular cavity

pump 3 modes:

$$E_p = r_1 E_1 + r_{1'} E_{1'} + r_2 E_2$$

$$\mathrm{TE}_{221}/\mathrm{TM}_{221}/\mathrm{TM}_{121}$$

signal mode:

$$\mathrm{TM}_{163}$$

matching condition

$$\omega_s = 2\omega_1 - \omega_2$$

$$K_\infty = 0.047 r_2 (r_1^2 - 0.18 r_{1'}^2)$$

$$K_{\mathrm{EH}} = 0.059 r_2 (r_1^2 - 8.24 r_{1'}^2)$$

ALP photons coupling

$$\mathscr{H}(m_N, m_a, s, t) \equiv 128\pi \frac{m_N^4}{m_a^3} \frac{m_a^2 t(m_N^2 + s) - m_a^4 m_N^2 - t((s - m_N^2)^2 + st)}{t^2(s - m_N^2)^2(t - 4m_N^2)^2}$$