ALPs up to the QCD scale

Yotam Soreq

Portorož 2019: Precision era in High Energy Physics
16 April, 2019

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 can be a dark matter candidate
* predicted by string theory

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 can be a dark matter candidate
* predicted by string theory

→ **well motivated BSM scenario**

Axion Like Particles

pseudo-scalar and pNGB

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

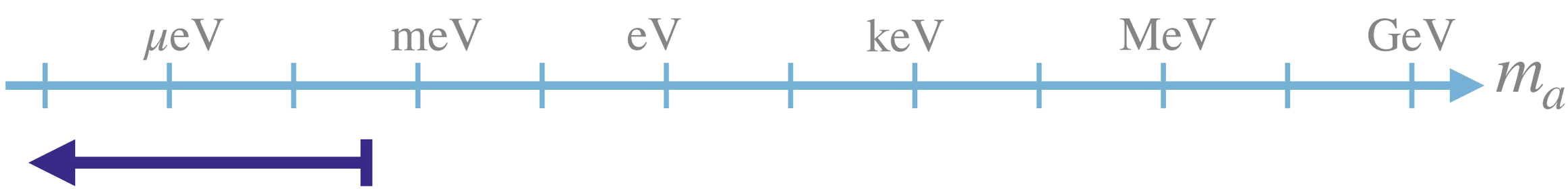
$$\Lambda \gg m_a$$

Axion Like Particles

pseudo-scalar and pNGB

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

$$\Lambda \gg m_a$$



$c_\gamma = 1\,, c_g = 0$

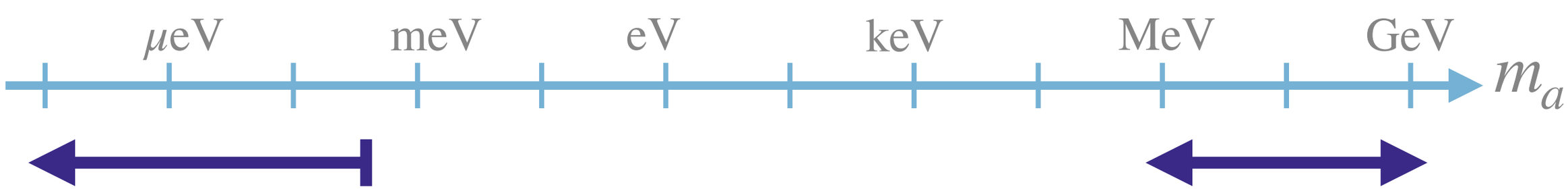
superconducting
radiofrequency cavities

Axion Like Particles

pseudo-scalar and pNGB

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

$$\Lambda \gg m_a$$



$c_\gamma = 1\,, c_g = 0$

superconducting radiofrequency cavities

$c_g \neq 0$ or $c_\gamma \neq 0$

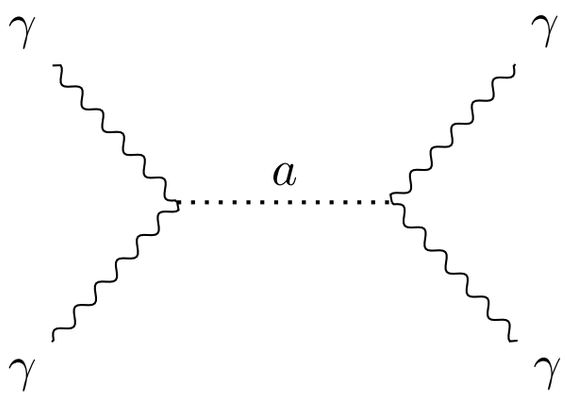
photon beam experiments (PrimEx, GlueX) and hadronic decays

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

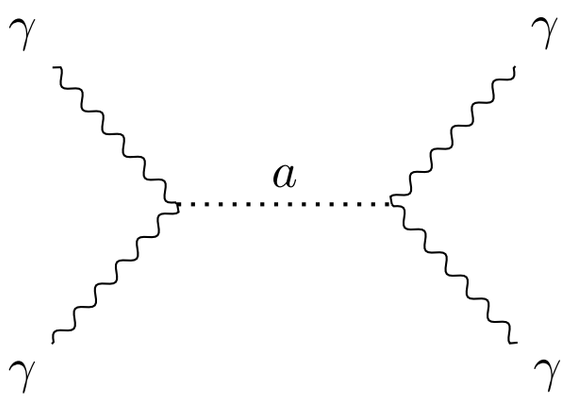


$$\propto (F^{\mu\nu}\tilde{F}_{\mu\nu})^2 \propto (E \cdot B)^2$$

non-linear Maxwell equations

The Idea

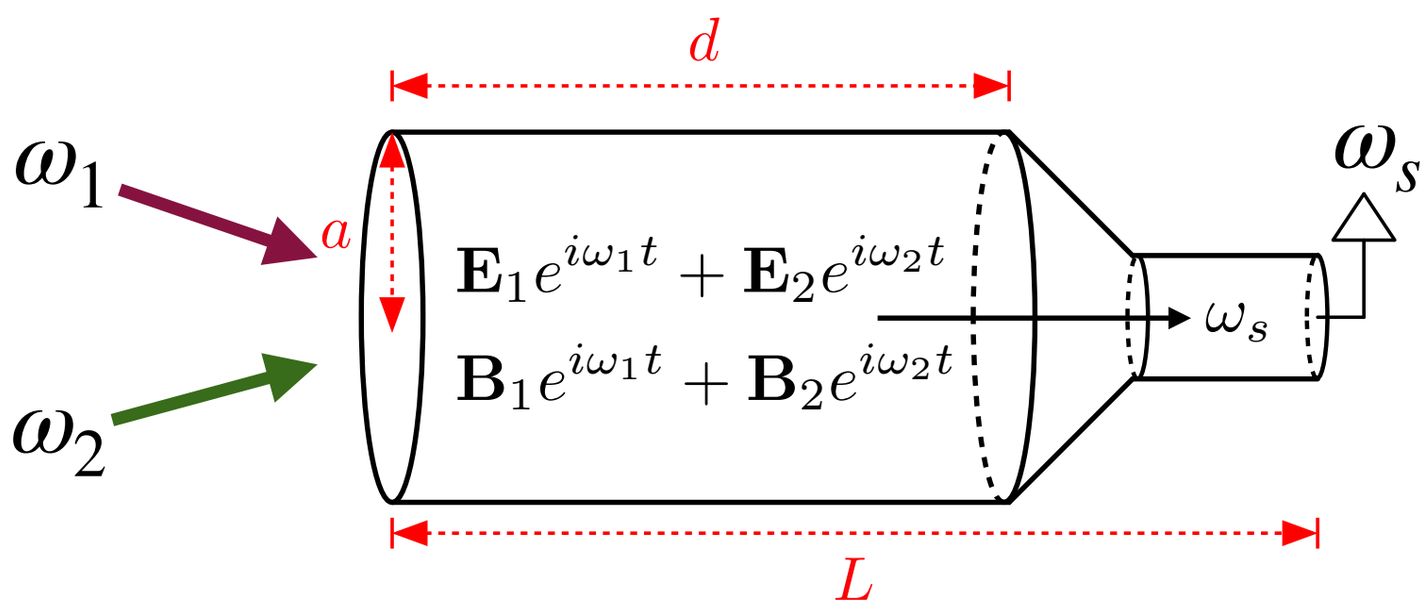
probing off-shell ALPs via non-linear QED in a cavity



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

non-linear Maxwell equations

pump

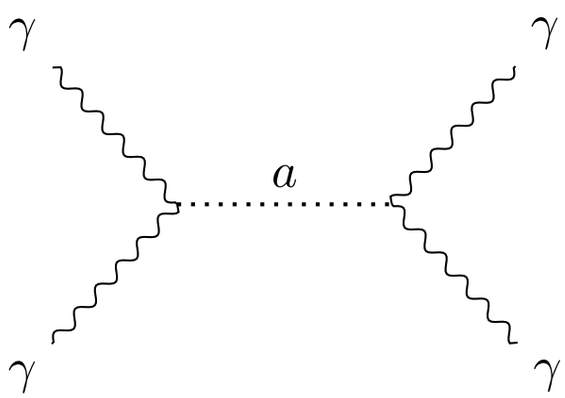


$$\omega_s = \pm\,\omega_1 \pm \omega_1 \pm \omega_2$$

measure

The Idea

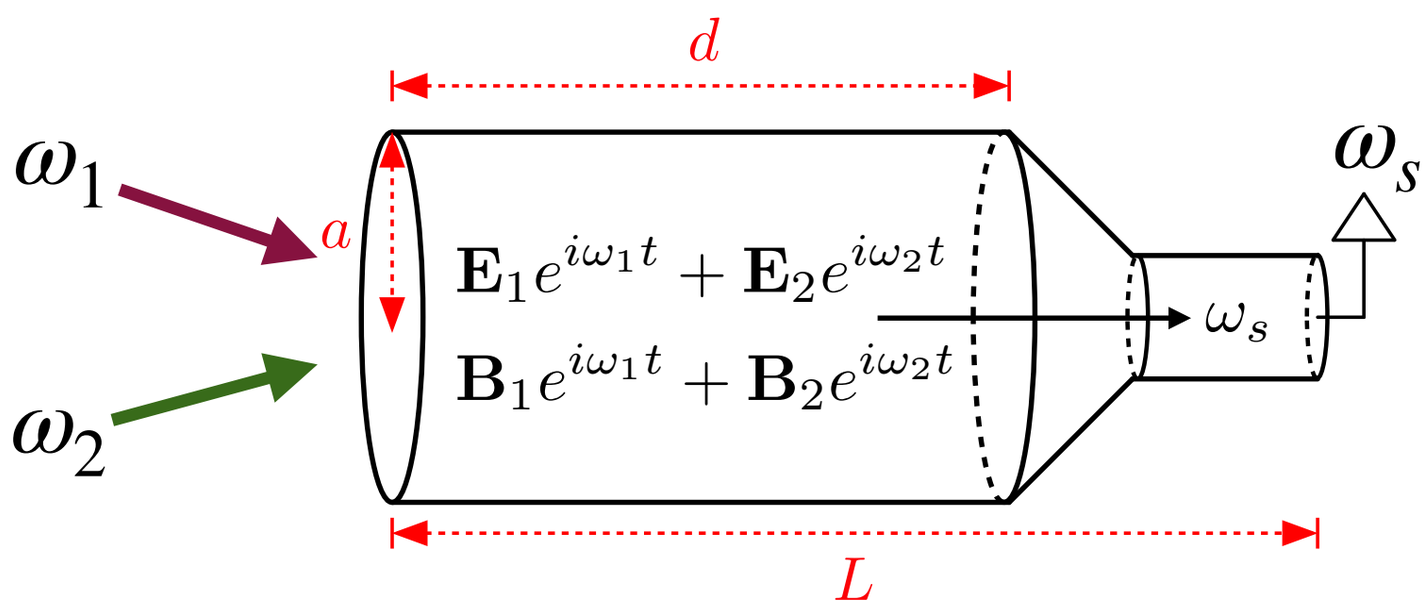
probing off-shell ALPs via non-linear QED in a cavity



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

non-linear Maxwell equations

pump



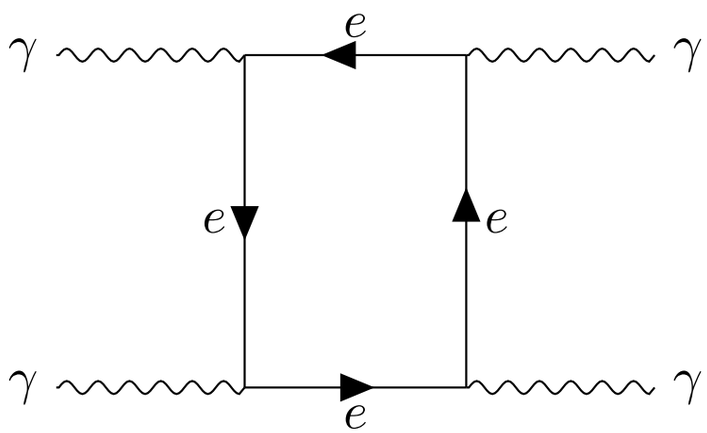
$$\omega_s = \pm\,\omega_1 \pm \omega_1 \pm \omega_2$$

measure

advantages:

* probes large range of masses - broad band
* does not rely on ALP been dark matter

The Euler Heisenberg effect



$E \ll m_e$

non-linear QED

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

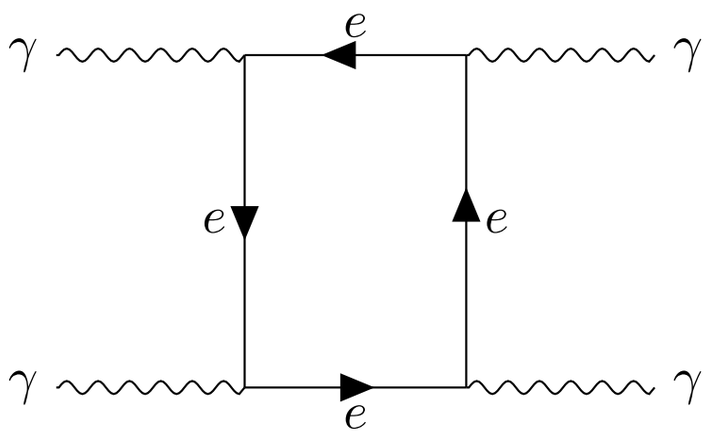
Hiesenberg Euler, 1936
Schwinger, 1951

never been measured below the electron mass!

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

ATLAS, 2017

The Euler Heisenberg effect



$E \ll m_e$

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

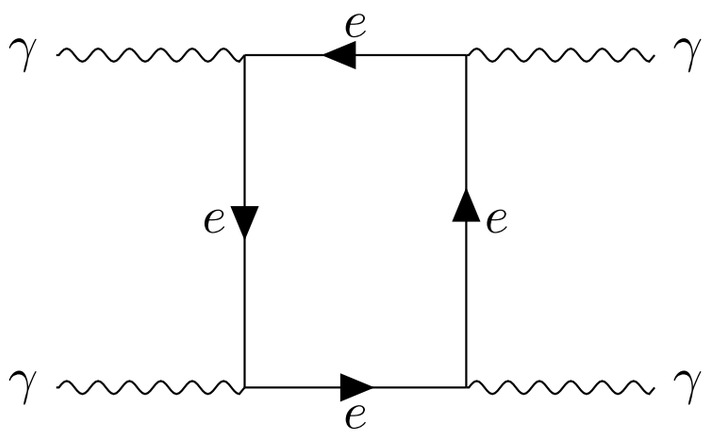
ALP vs EH

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

comparable to the current limit on ALPs (by CAST)

Evans and Rafelski, 1810.06717

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

ALP vs EH

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

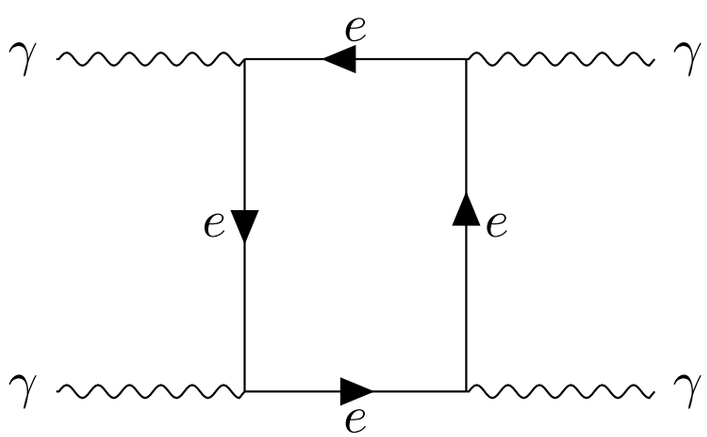
comparable to the current limit on ALPs (by CAST)

Evans and Rafelski, 1810.06717

improve current bounds

sensitivity to EH

Detecting the EH effect by Superconducting radiofrequency cavities



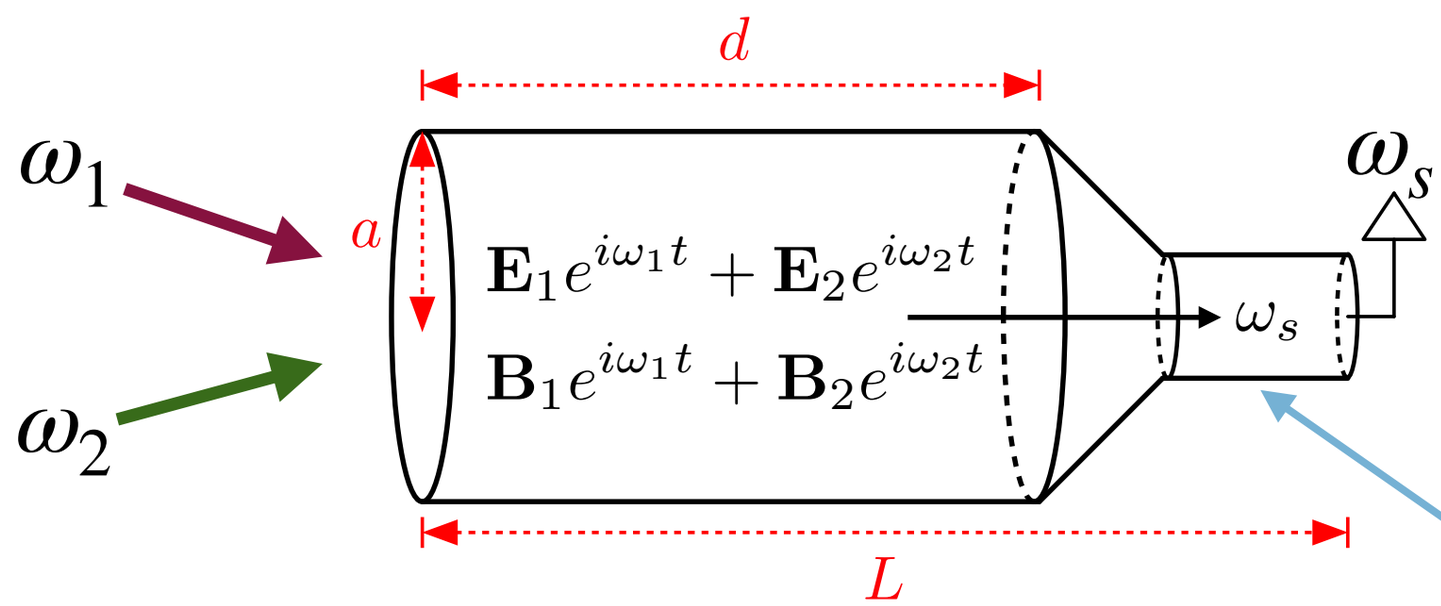
$E \ll m_e$

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

Sensitivity to ALPs

the number of signal photons

quality factor

cavity volume

pump field strength

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

electric field of the induced ALP current

modes overlap

Sensitivity to ALPs

the number of signal photons

quality factor

cavity volume

pump field strength

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

electric field of the induced ALP current

modes overlap

signal-to-noise ratio (SNR)

(Dicke radiometer equation)

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

time

signal bandwidth

thermal noise photons

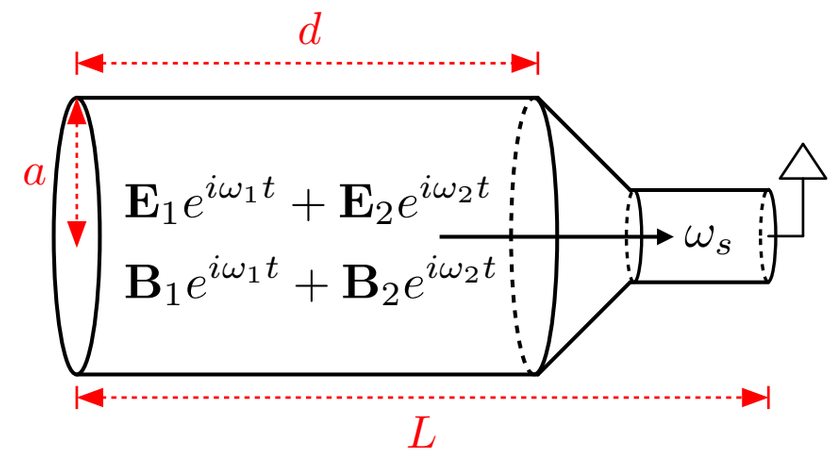
$\mathrm{Temperature}/\omega_s$

cavity's length

Sensitivity to ALPs

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

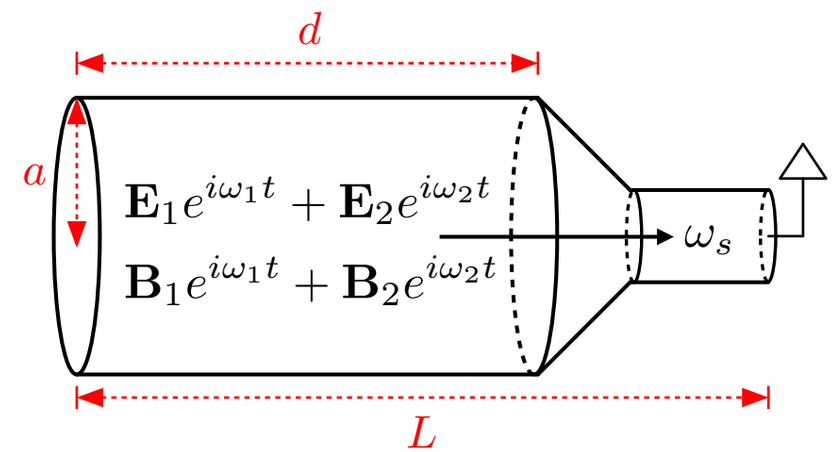
SNR = 5



Sensitivity to ALPs

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

$\mathrm{SNR} = 5$



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

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

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

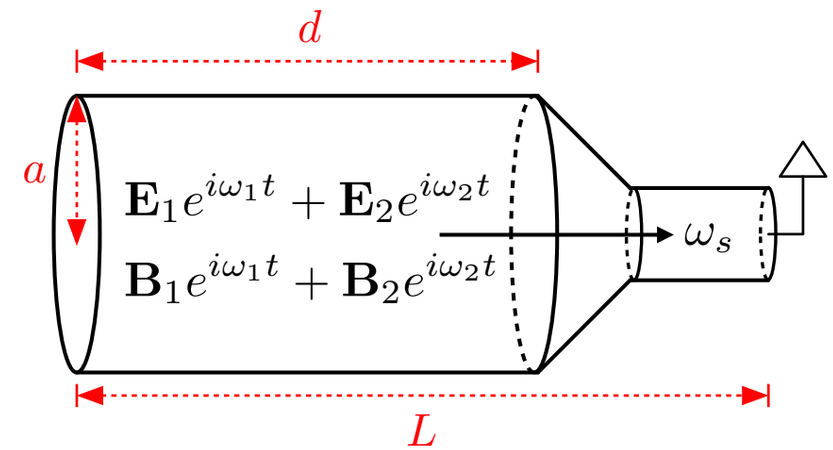
$K_0 = 0.4\,,\ K_\infty = 0.18$

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

Sensitivity to ALPs

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

$\mathrm{SNR} = 5$



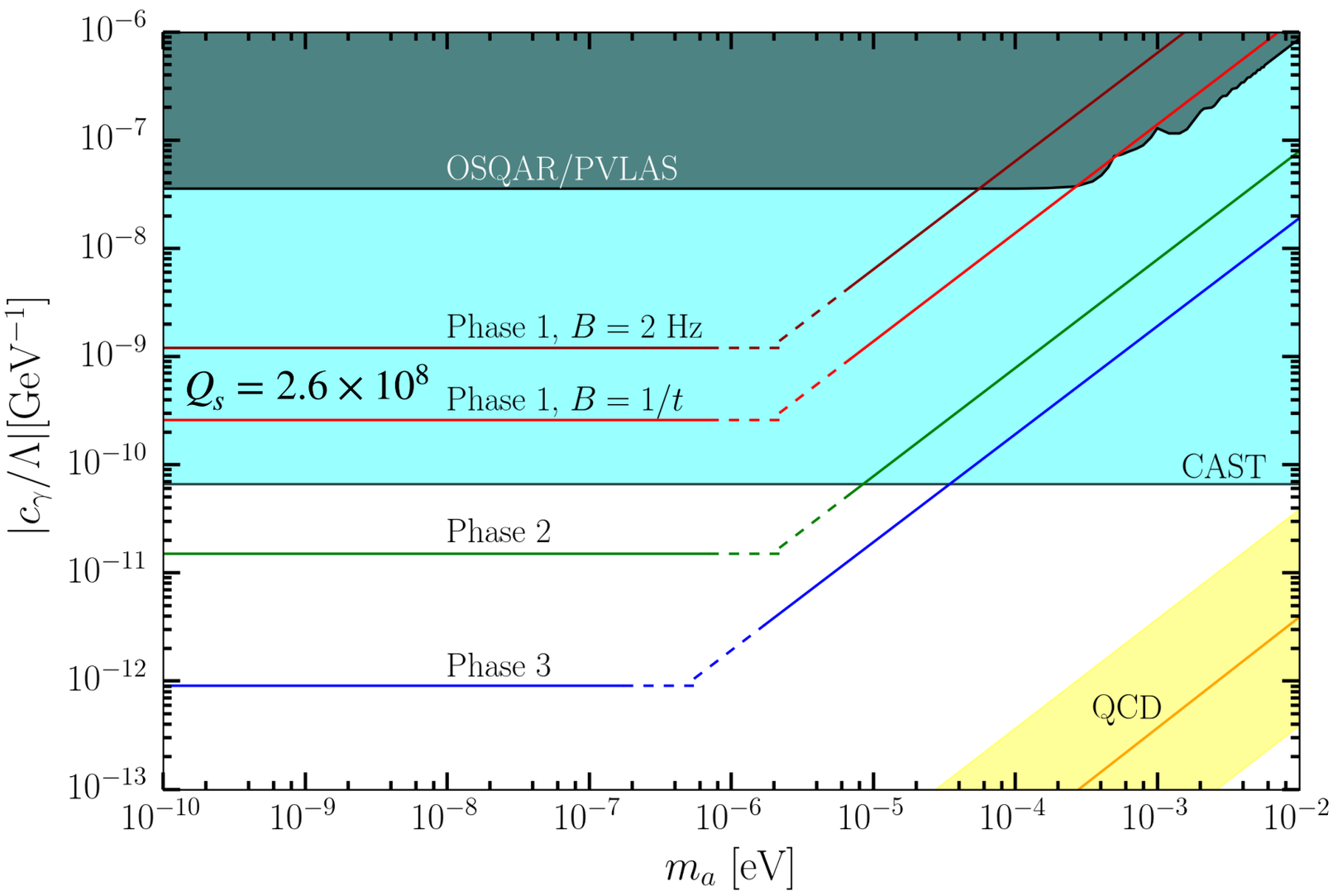
$a = 0.5\,\mathrm{m}$, $d = 1.56\,\mathrm{m}$, $V = 1.23\,\mathrm{m}^3$

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

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

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

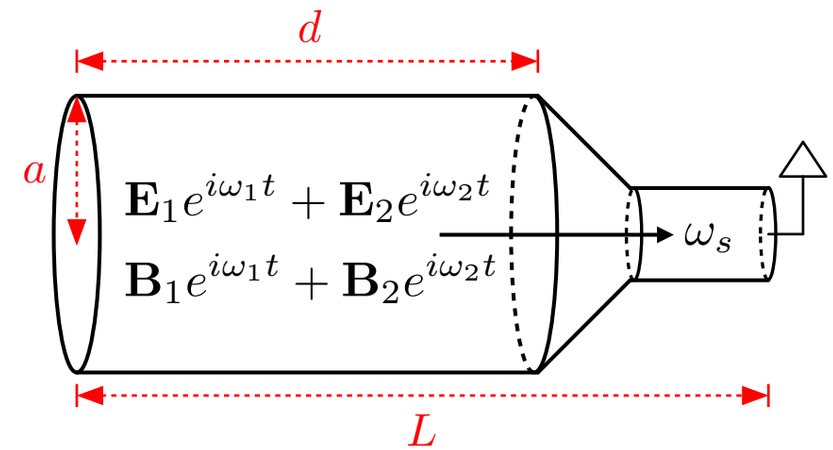
$E_0 = 45\,\mathrm{MV/m}$ $T = 1.5\,\mathrm{K}$



Sensitivity to ALPs

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

$\mathrm{SNR} = 5$



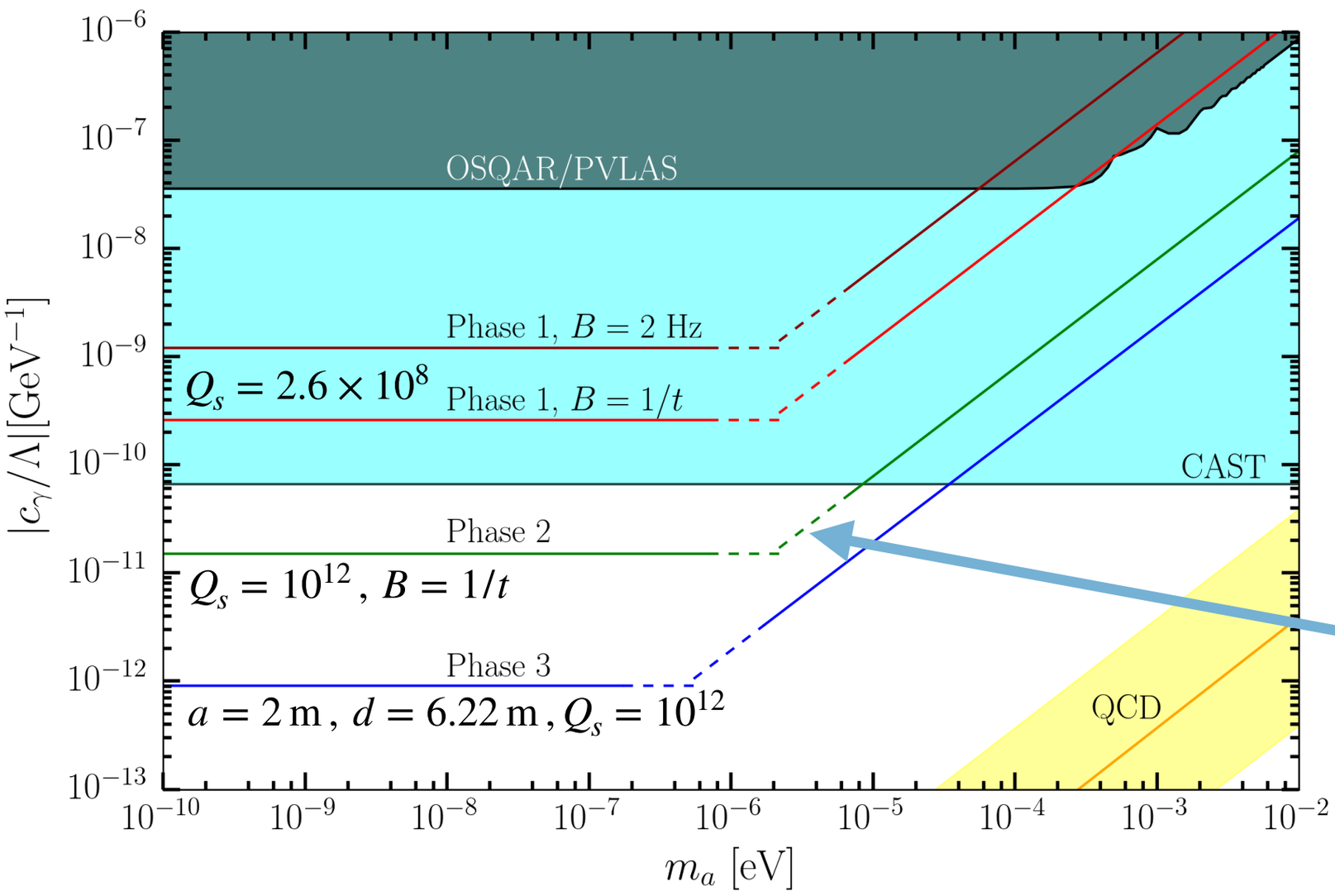
$a = 0.5\,\mathrm{m}$, $d = 1.56\,\mathrm{m}$, $V = 1.23\,\mathrm{m}^3$

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

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

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

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



20 days run to detect EH!

ALPs at the MeV to the GeV scale

Aloni, YS, Soreq - 1811.03474
Aloni, Fanelli,YS, Soreq - 1903.03586

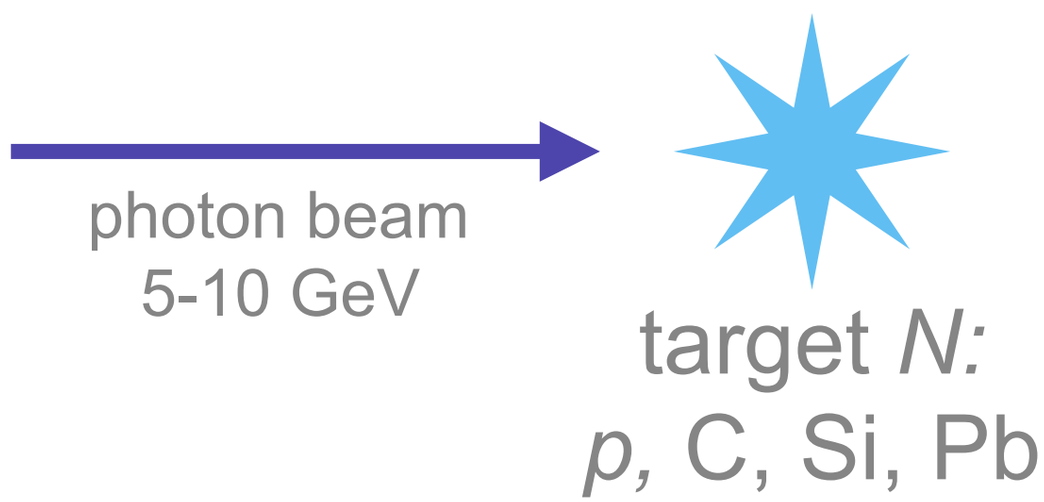
ALPs at the MeV to the GeV scale

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

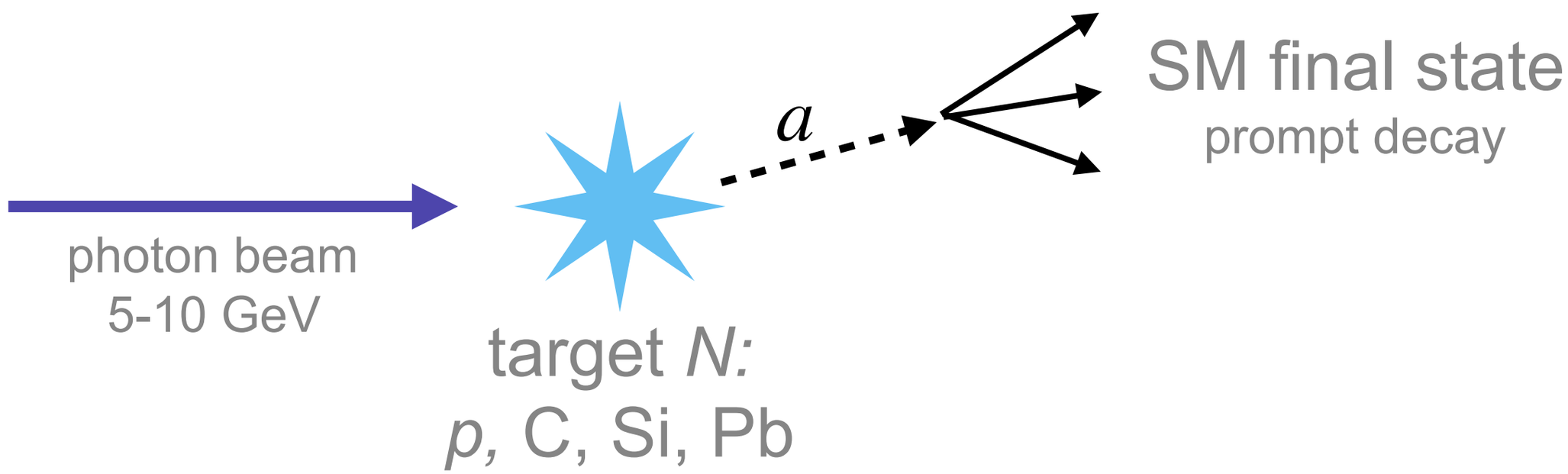
$$c_g \neq 0 \text{ or } c_\gamma \neq 0$$

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

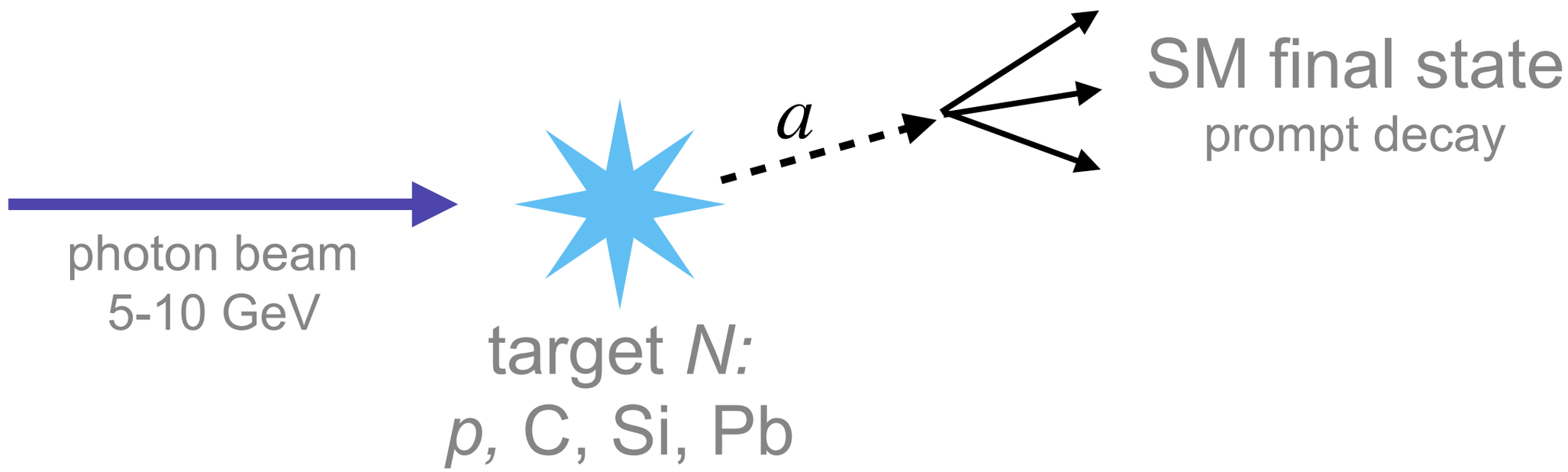
ALPs at Primakoff like experiments

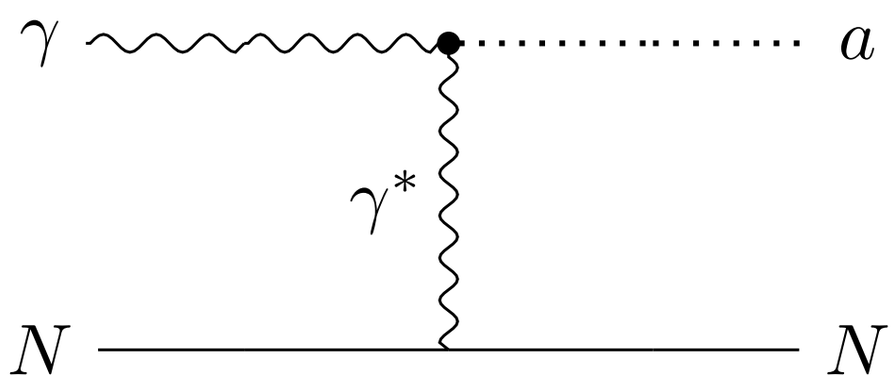


ALPs at Primakoff like experiments

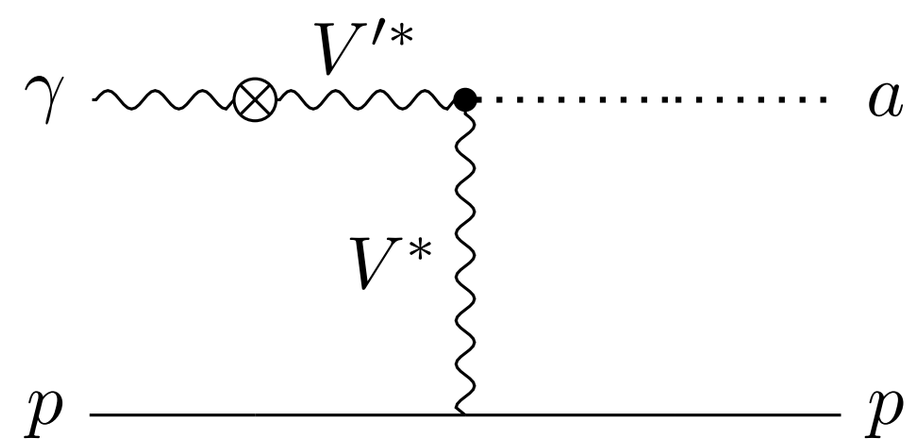


ALPs at Primakoff like experiments

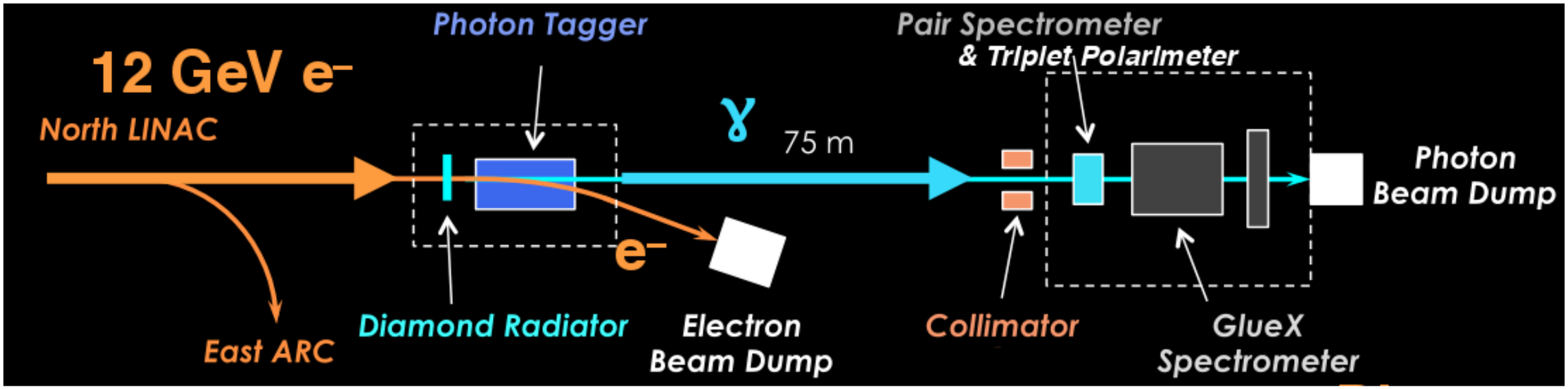


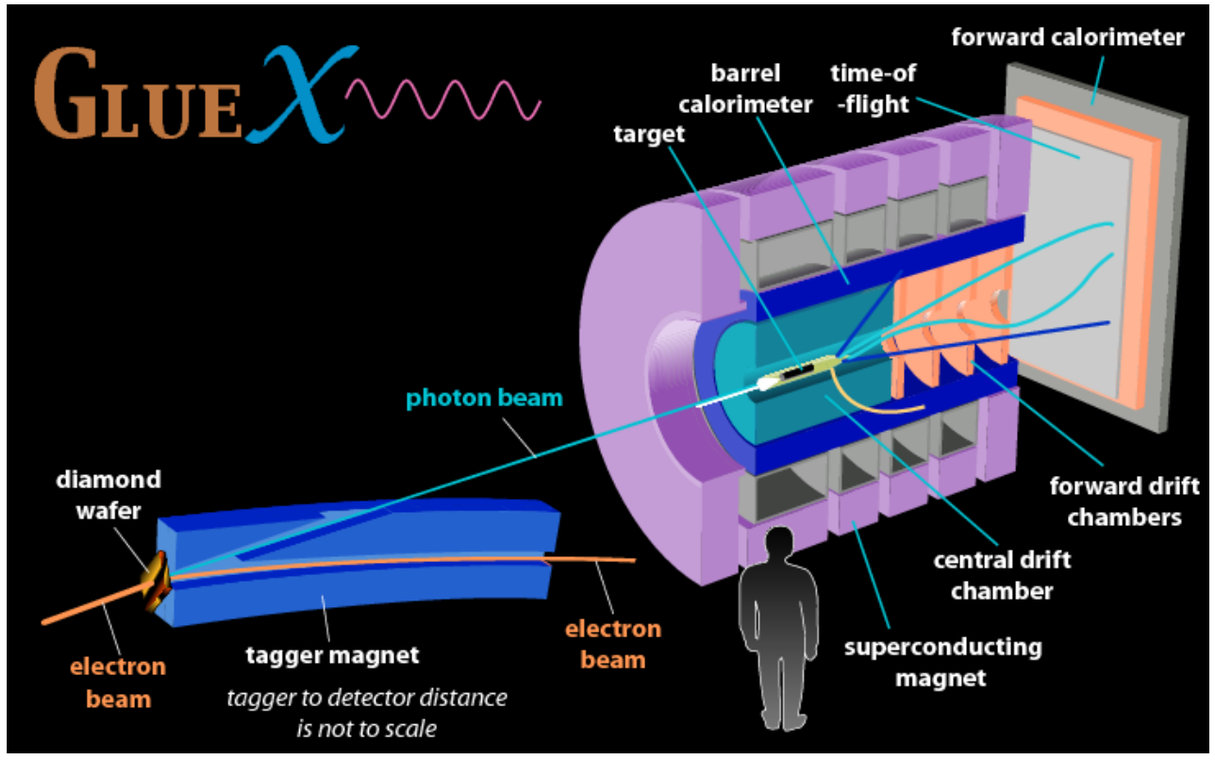


$$\frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

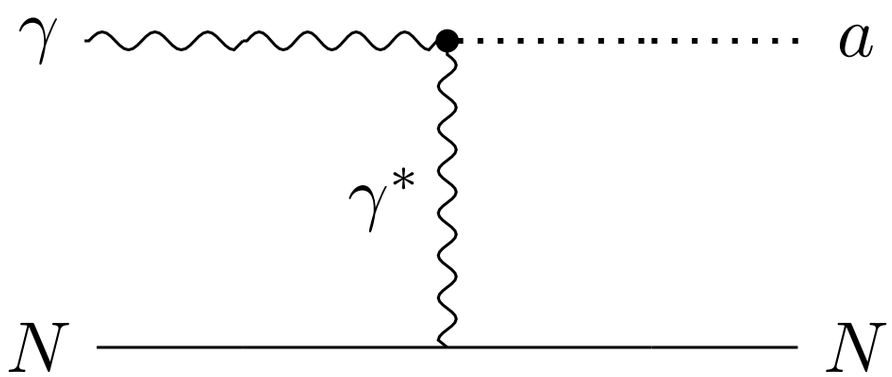


$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$


12 GeV e⁻
North LINAC
East ARC
Photon Tagger
Diamond Radiator
e⁻
γ
75 m
Electron
Beam Dump
Pair Spectrometer
& Triplet Polarimeter
Collimator
GlueX
Spectrometer
Photon
Beam Dump

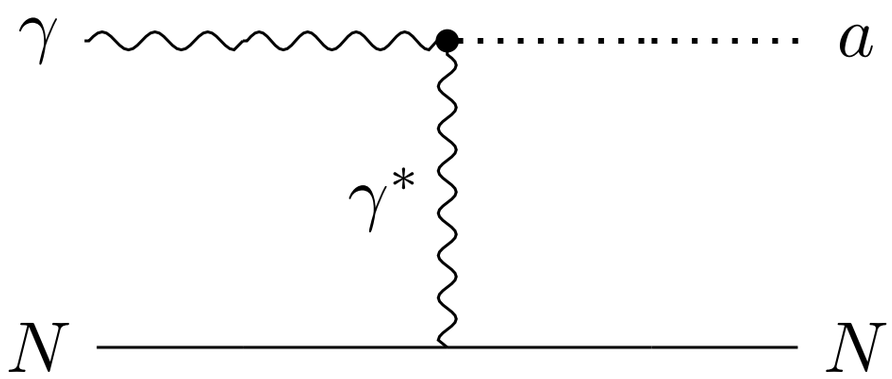

GlueX
forward calorimeter
barrel
calorimeter
time-of
-flight
target
photon beam
diamond
wafer
electron
beam
tagger magnet
tagger to detector distance
is not to scale
electron
beam
forward drift
chambers
central drift
chamber
superconducting
magnet

ALP photons coupling



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

ALP photons coupling



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

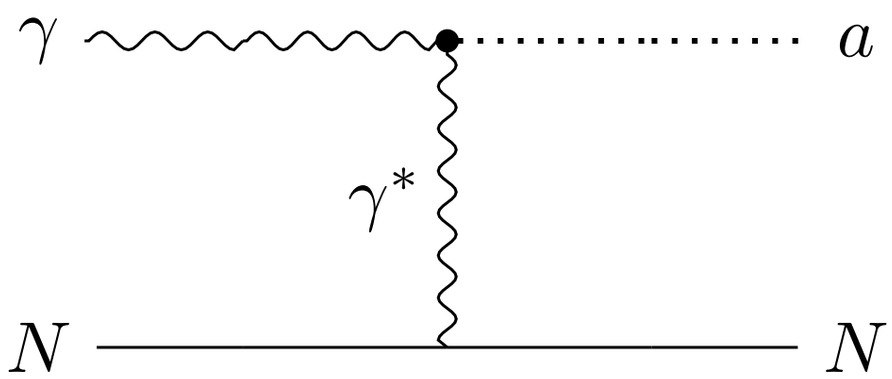
$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \alpha\, Z_N^2 F_N^2(t)\Gamma_{a\to\gamma\gamma}\,\mathscr{H}(m_N, m_a, s, t)$$

target charge

form factor

kinematical function

ALP photons coupling



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

$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \alpha Z_N^2 F_N^2(t)\Gamma_{a\to\gamma\gamma}\mathscr{H}(m_N, m_a, s, t)$$

target charge

form factor

kinematical function

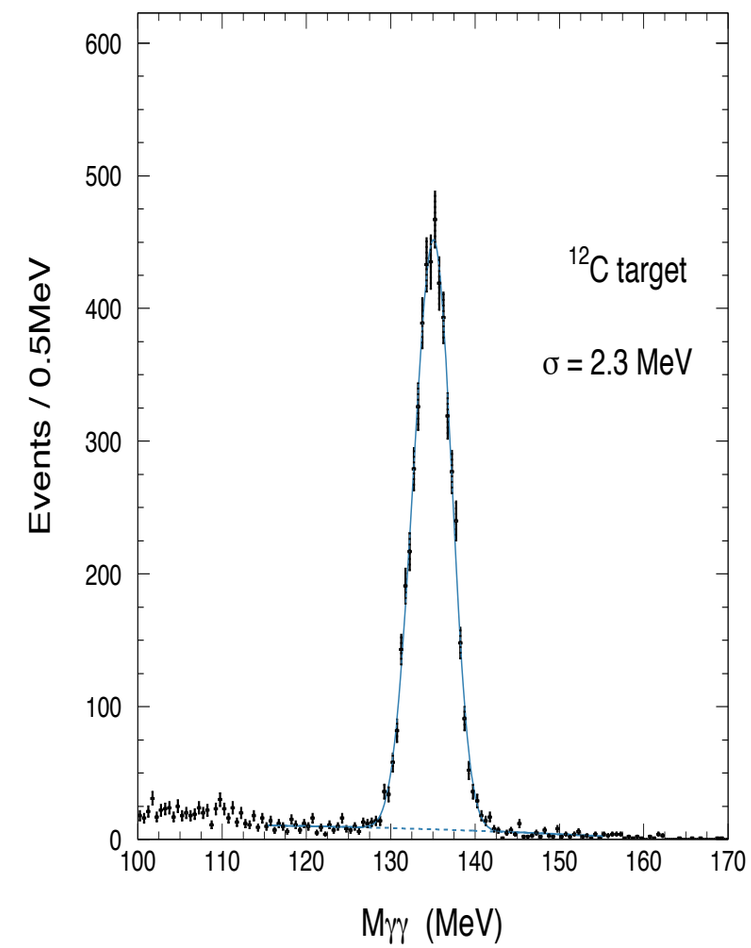
Primakoff production of ALPs and pion/eta are similar

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

Data-driven signal normalisation

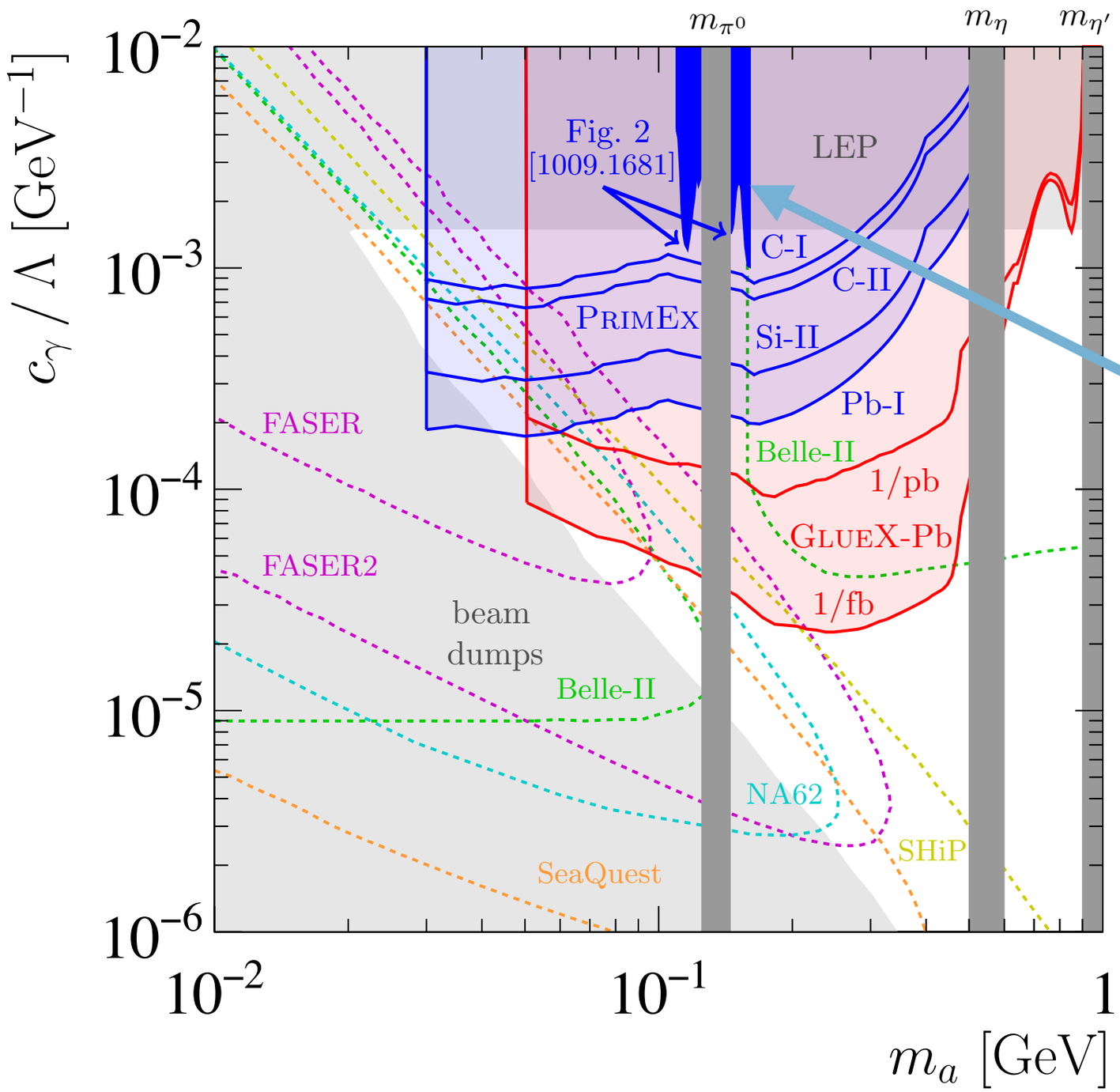
(cancel form factor and flux dependence)

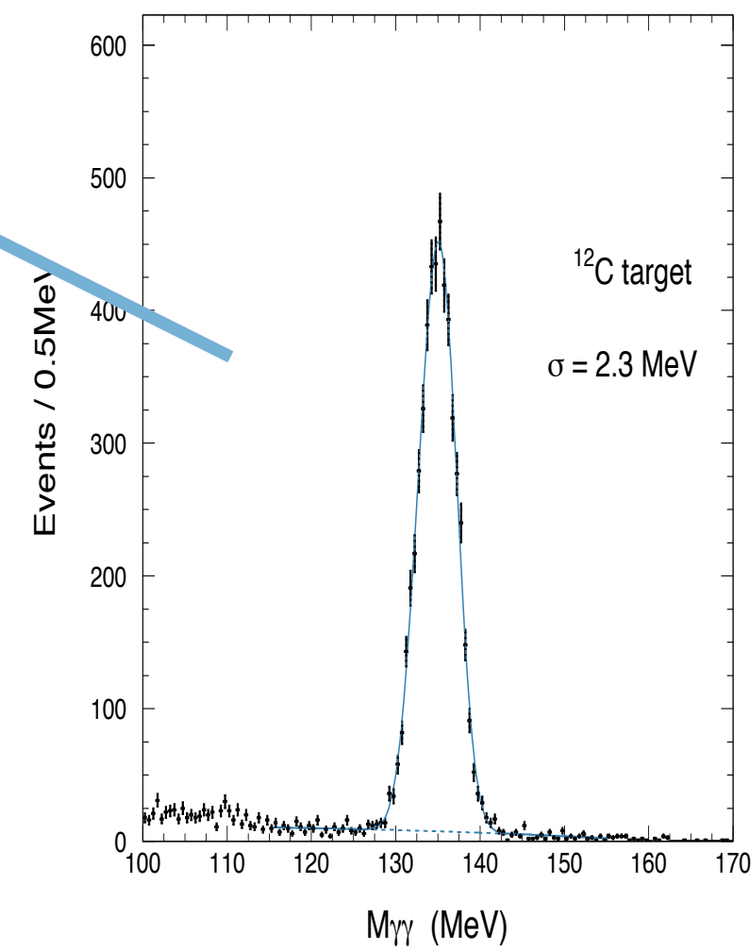
ALP photons coupling



PrimEx - 1009.1681

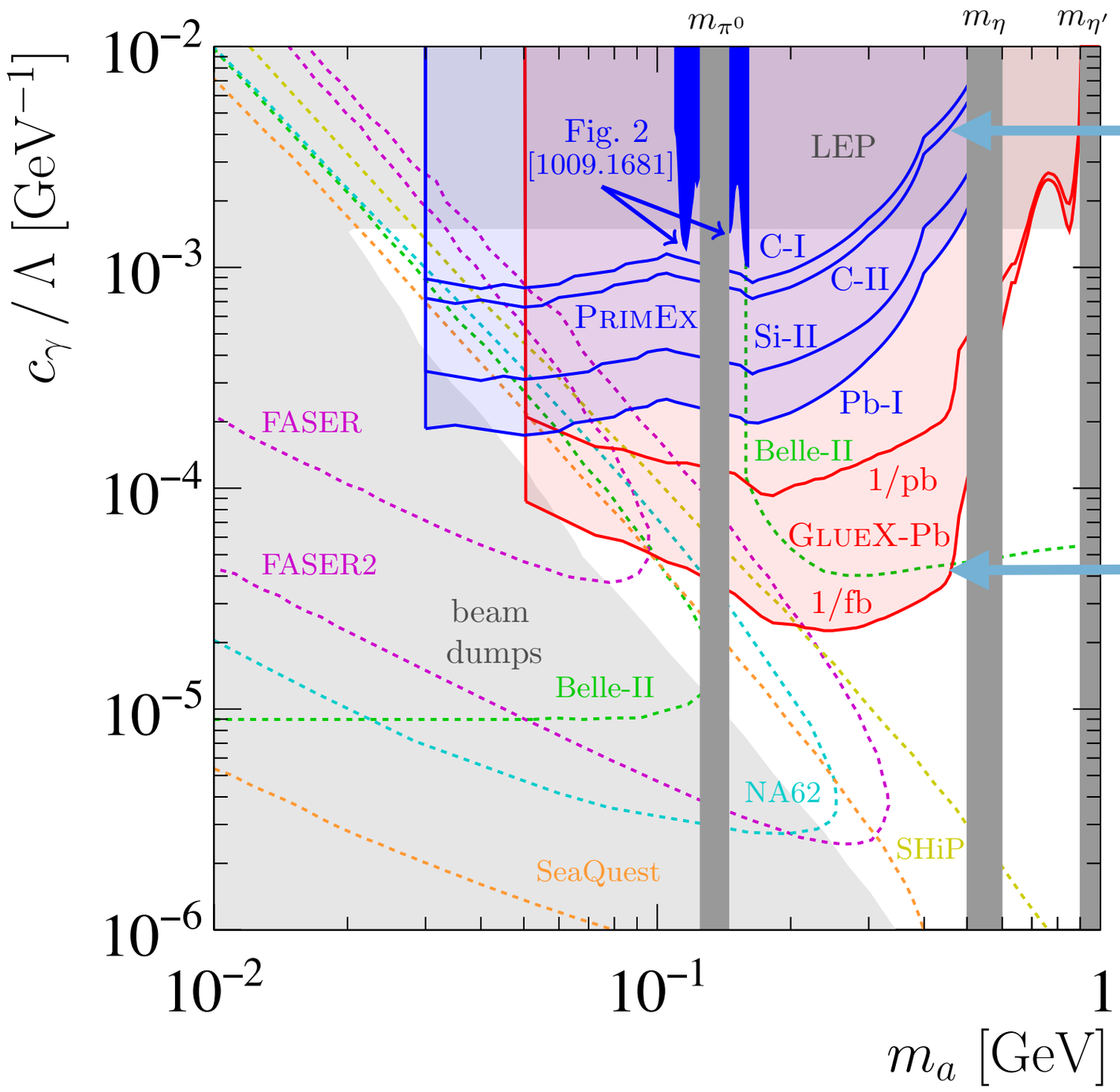
ALP photons coupling





PrimEx - 1009.1681

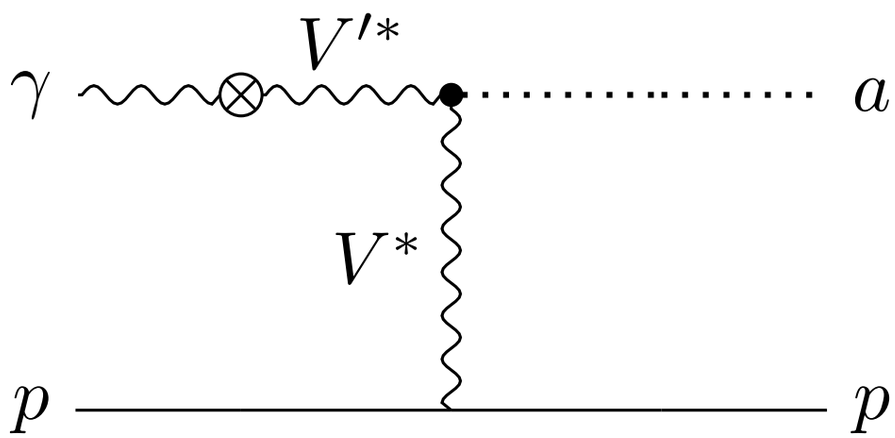
ALP photons coupling



on tape PrimEx data

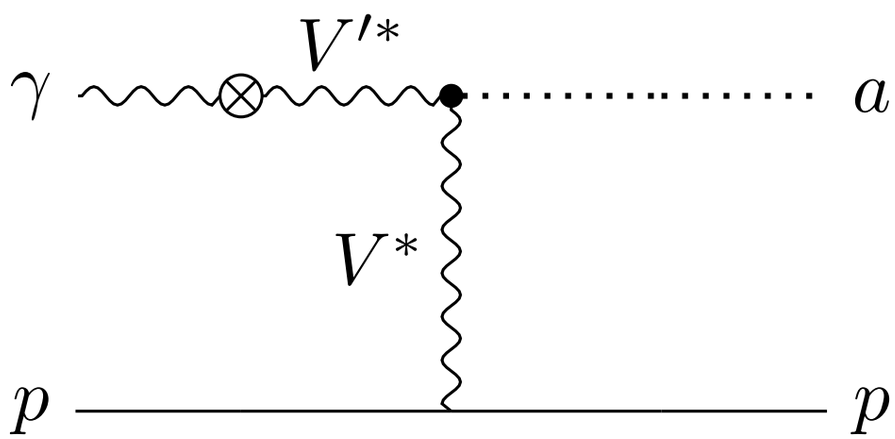
projection for GlueX

ALP gluons coupling

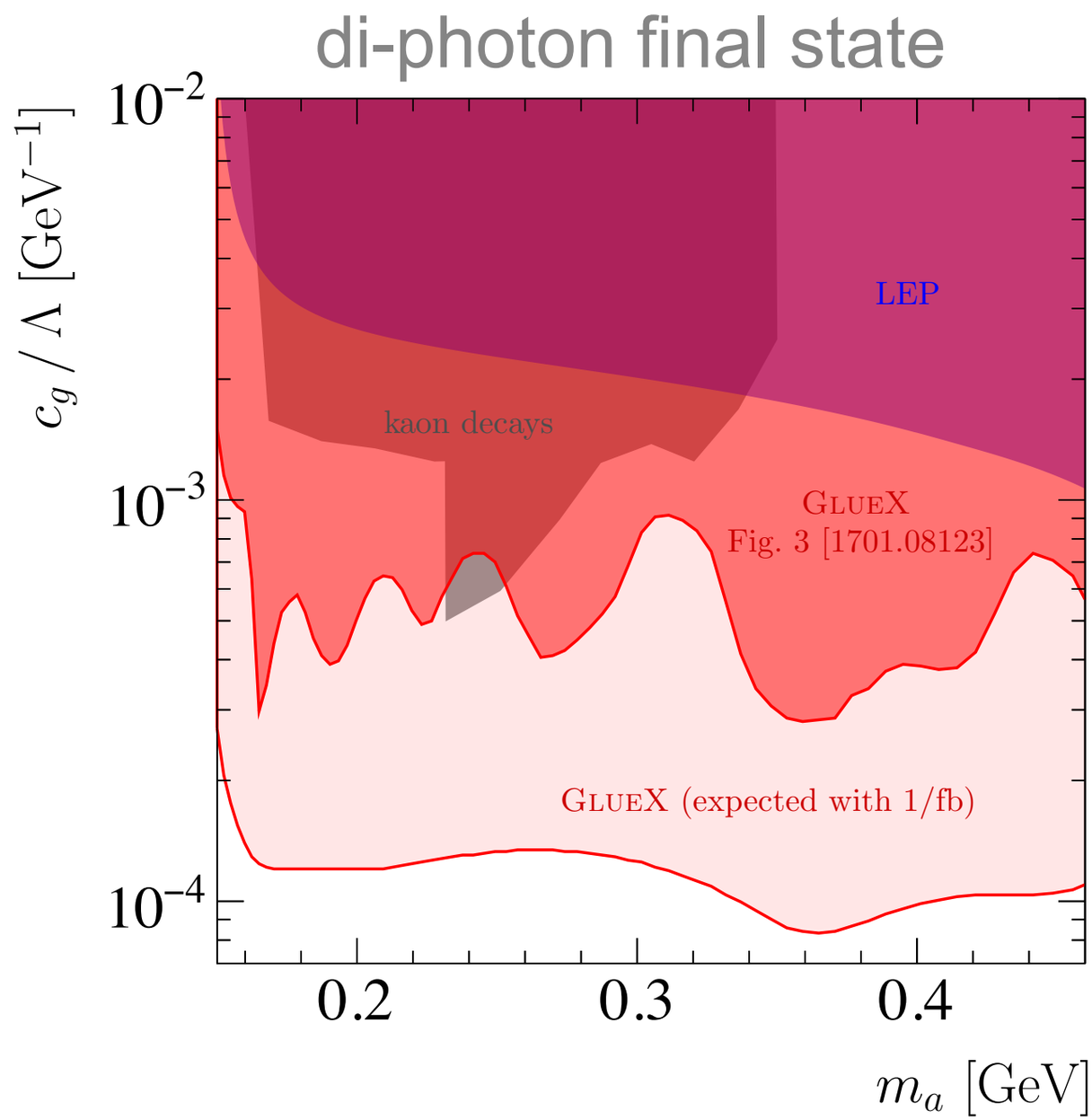


$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

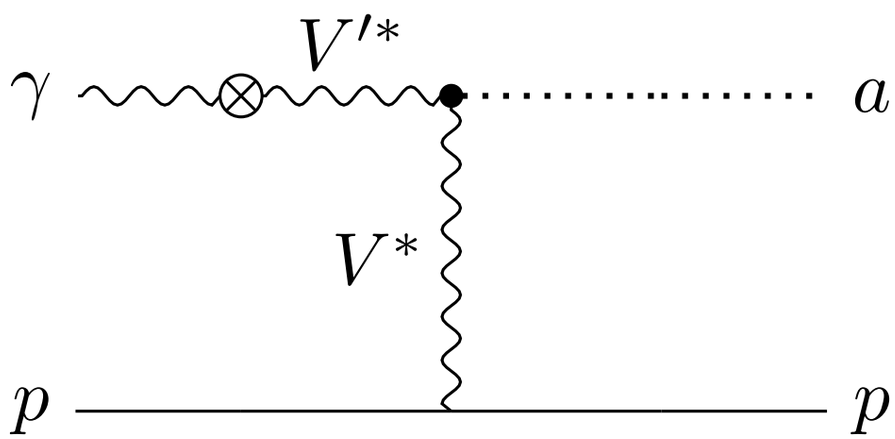
ALP gluons coupling



$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

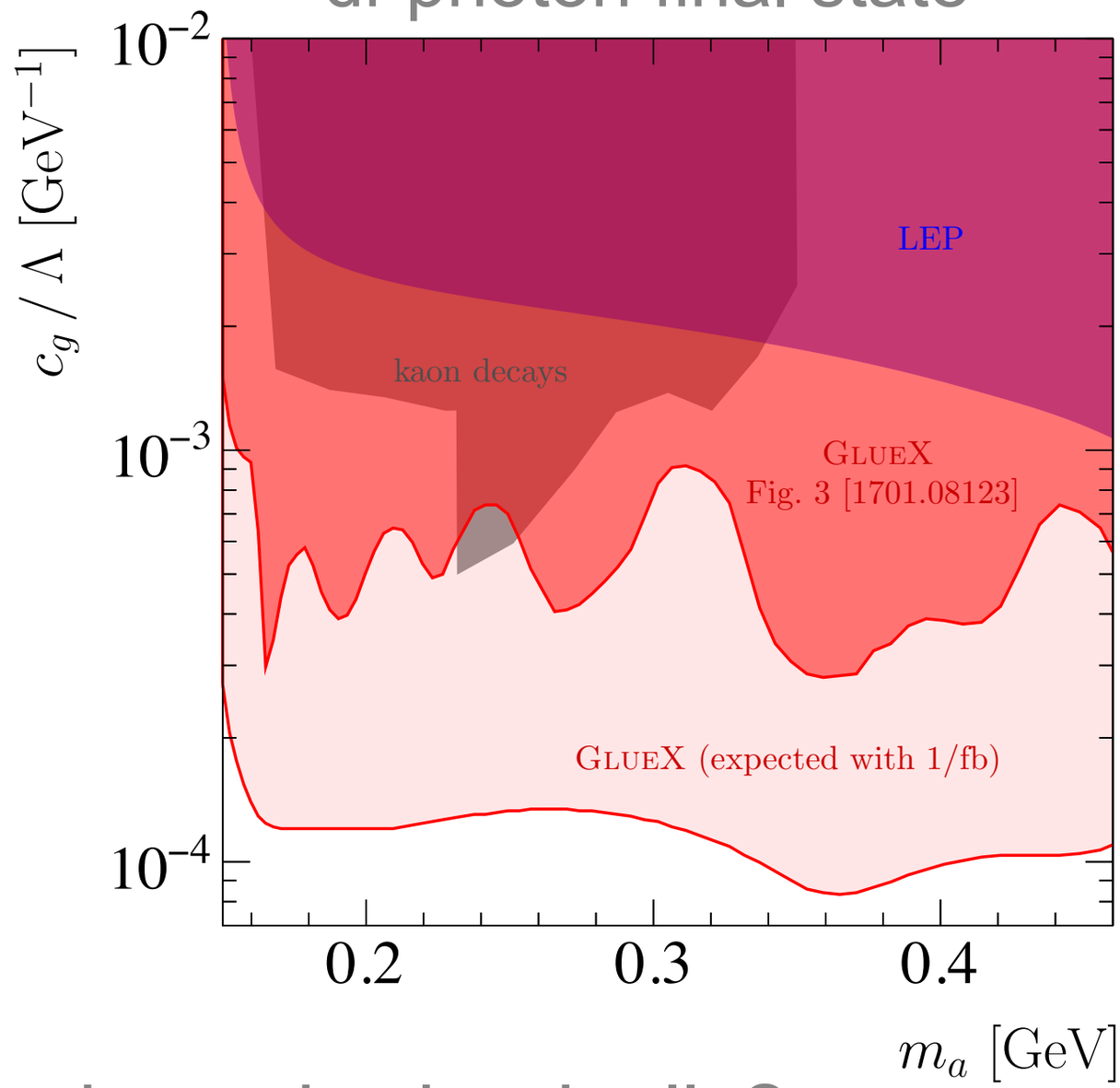


ALP gluons coupling



$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

di-photon final state



what if ALP can decay hadronically?
(above 3 pion mass)

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

$m_a \lesssim \mathrm{GeV}$

chiral PT

?????

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

pQCD

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

$m_a \lesssim \mathrm{GeV}$

chiral PT

?????

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

pQCD

use data!!

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

$m_a \lesssim \mathrm{GeV}$ — chiral PT

?????

$m_a \gtrsim 2\,\mathrm{GeV}$ — pQCD

use data!!

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

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

$m_a \lesssim \mathrm{GeV}$ — chiral PT

?????

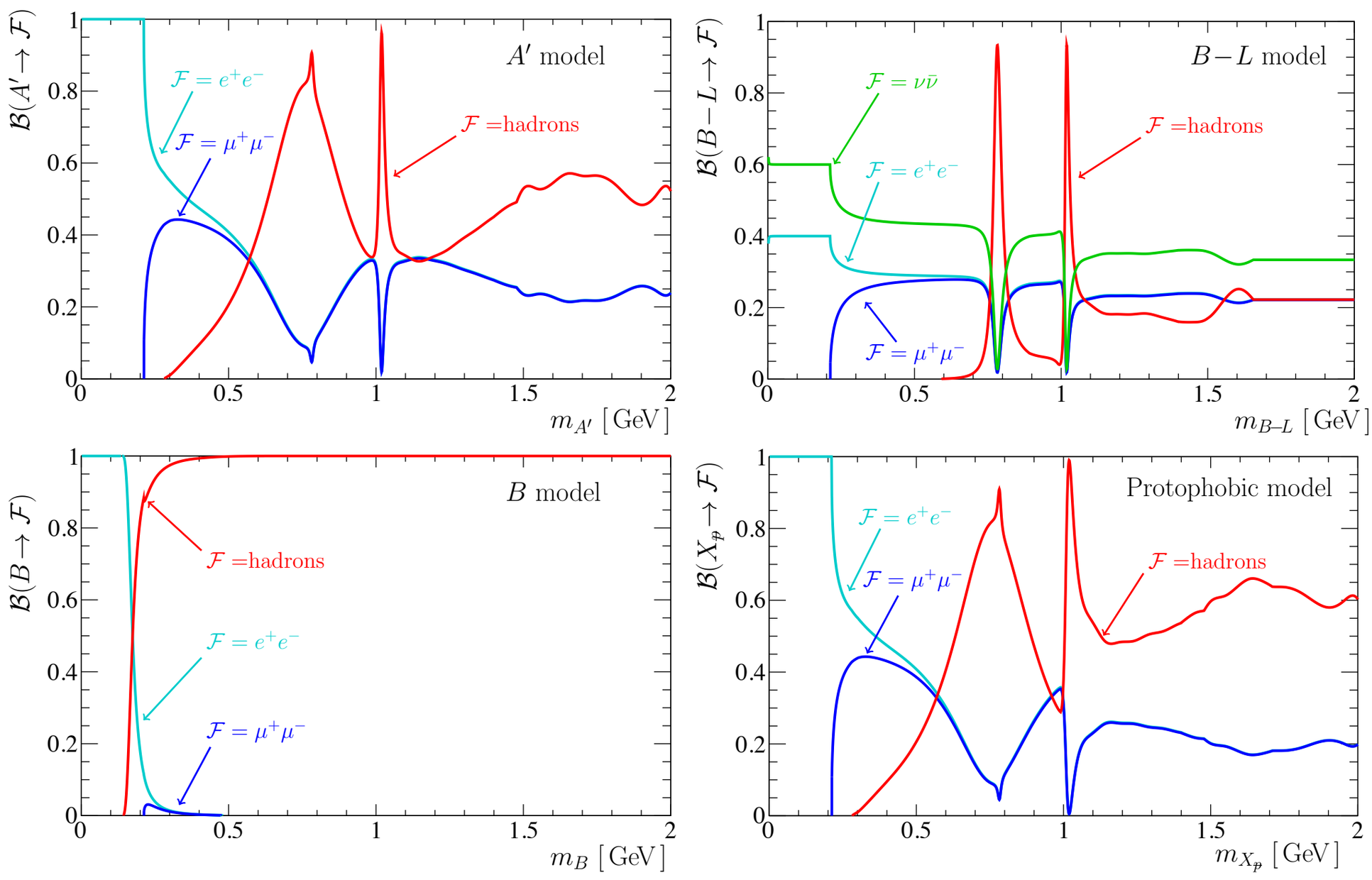
$m_a \gtrsim 2\,\mathrm{GeV}$ — pQCD

use data!!

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

directly deduce the hadronic rates of vectors

ALP gluons coupling



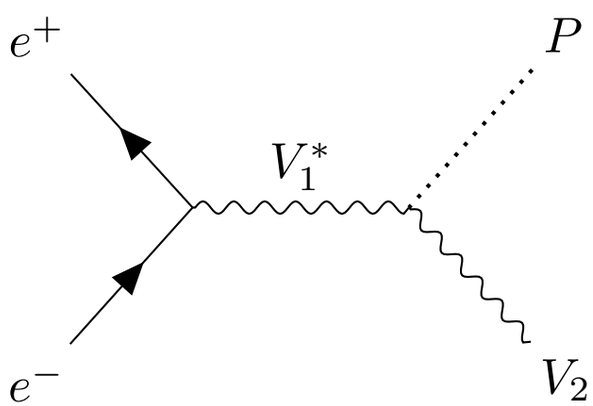
Ilten, YS, Williams, Xue, 1801.04847

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

ALPs hadronic rates?

$$e^+e^- \to V_1^* \to V_2 P$$

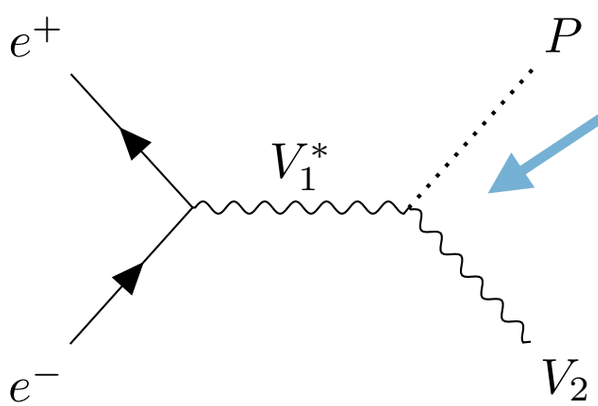


ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

ALPs hadronic rates?

$$e^+e^- \to V_1^* \to V_2 P$$



$$\mathscr{A}(V_1 \to V_2 P) = \epsilon_{\mu\nu\alpha\beta}\epsilon_1^{\mu}\epsilon_2^{*\nu} p_1^{\alpha} p_2^{\beta}\, \mathscr{F}\left(p_1^2, p_2^2, q^2\right) \times \frac{3g^2}{4\pi^2 f_\pi}\langle \boldsymbol{V_1 V_2 P}\rangle$$

one Lorentz structure

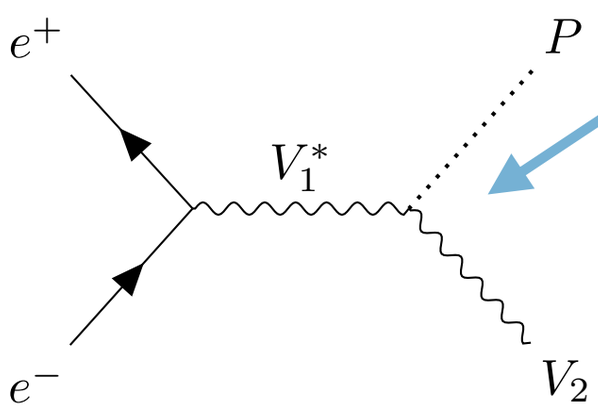
modified VMD

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

ALPs hadronic rates?

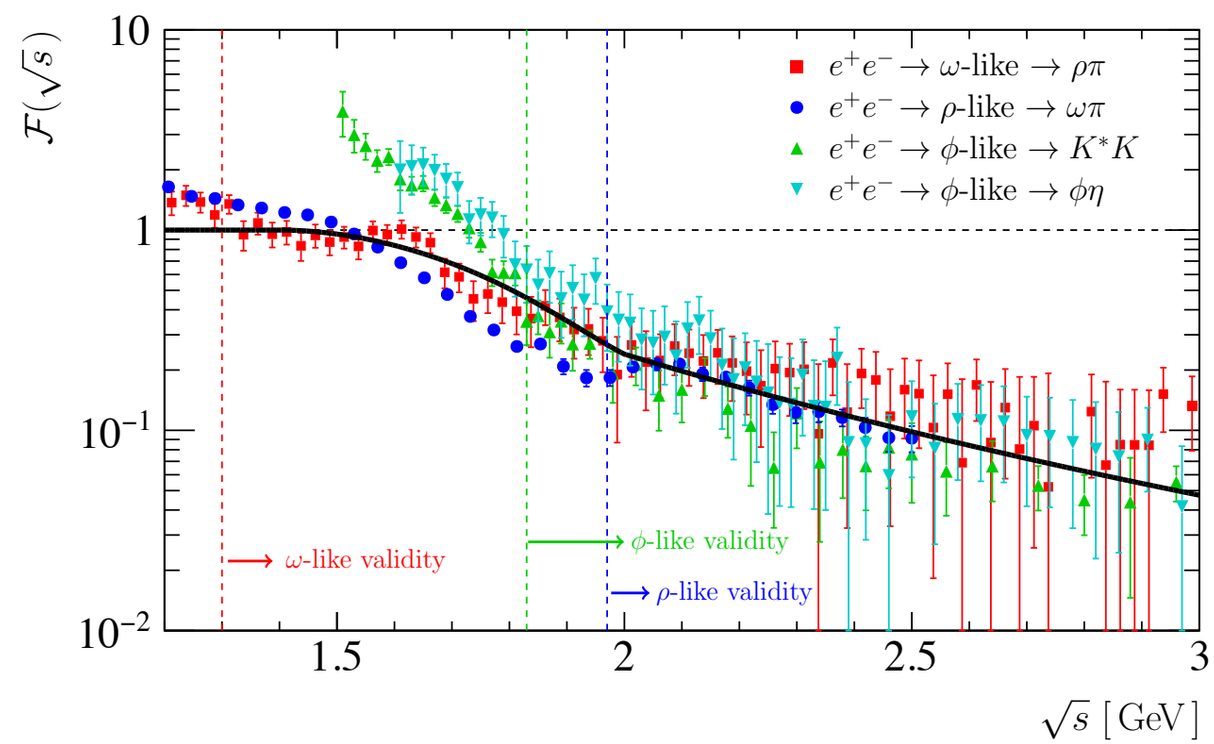
$$e^+e^- \to V_1^* \to V_2 P$$



$$\mathscr{A}(V_1 \to V_2 P) = \epsilon_{\mu\nu\alpha\beta}\epsilon_1^{\mu}\epsilon_2^{*\nu} p_1^{\alpha} p_2^{\beta}\, \mathscr{F}\left(p_1^2, p_2^2, q^2\right) \times \frac{3g^2}{4\pi^2 f_\pi}\langle \boldsymbol{V_1 V_2 P}\rangle$$

one Lorentz structure

modified VMD



from data

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

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

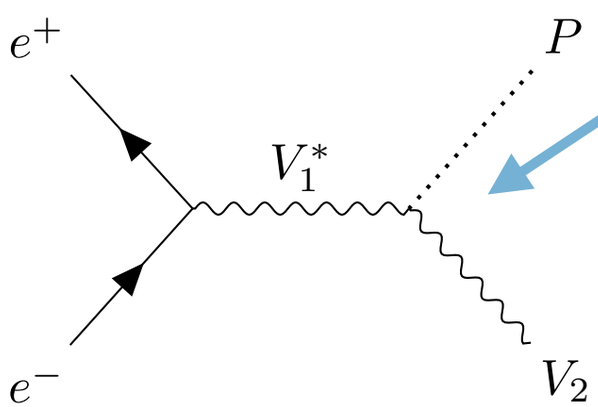
ALPs hadronic rates?

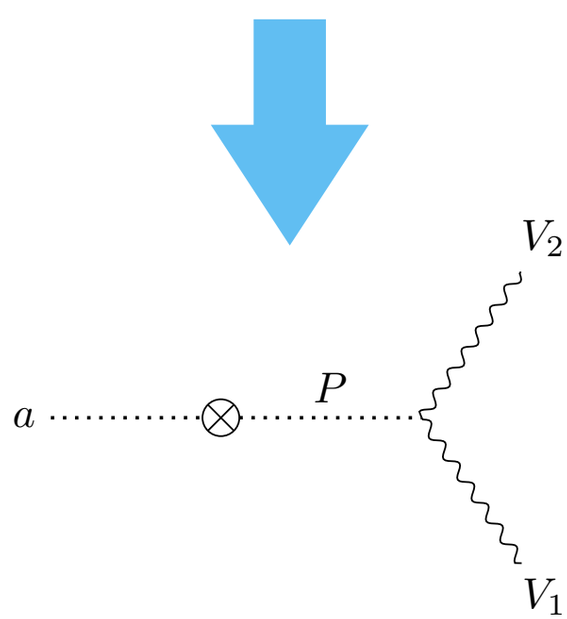
$$e^+e^- \to V_1^* \to V_2 P$$

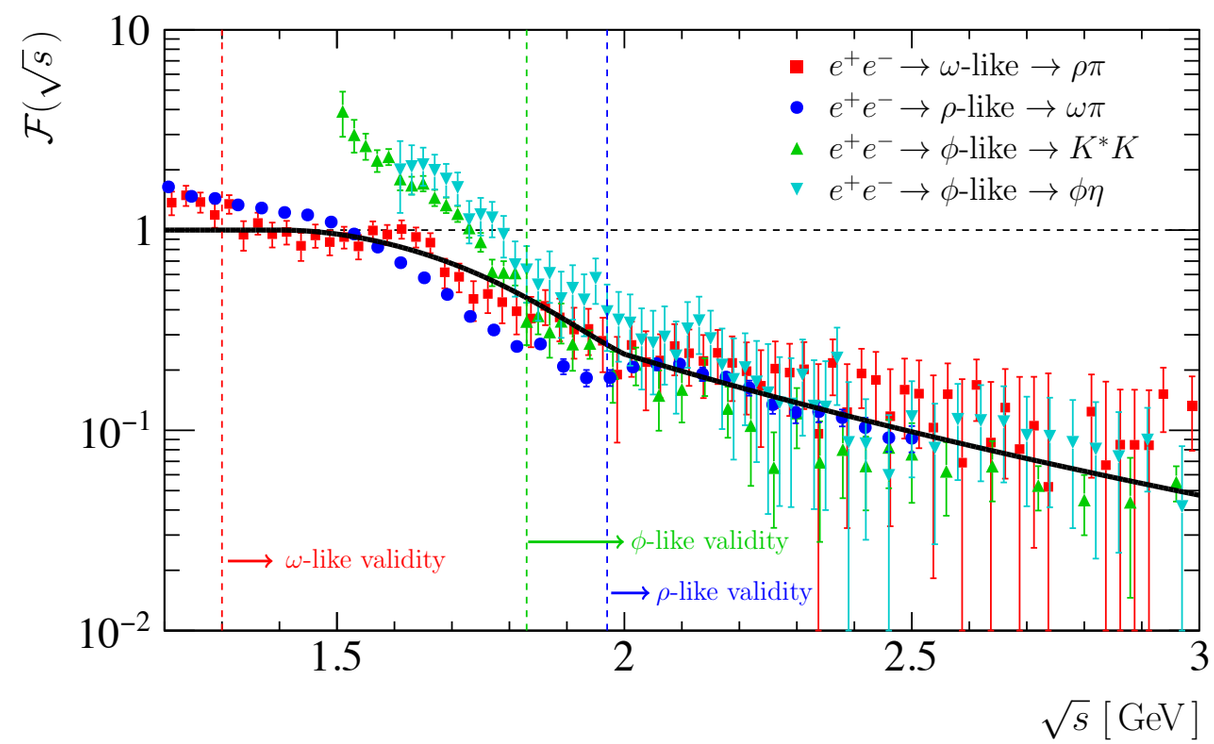
$$\mathscr{A}(V_1 \to V_2 P) = \epsilon_{\mu\nu\alpha\beta}\epsilon_1^{\mu}\epsilon_2^{*\nu} p_1^{\alpha} p_2^{\beta}\, \mathscr{F}\left(p_1^2, p_2^2, q^2\right) \times \frac{3g^2}{4\pi^2 f_\pi}\langle \boldsymbol{V_1 V_2 P}\rangle$$

one Lorentz structure

modified VMD







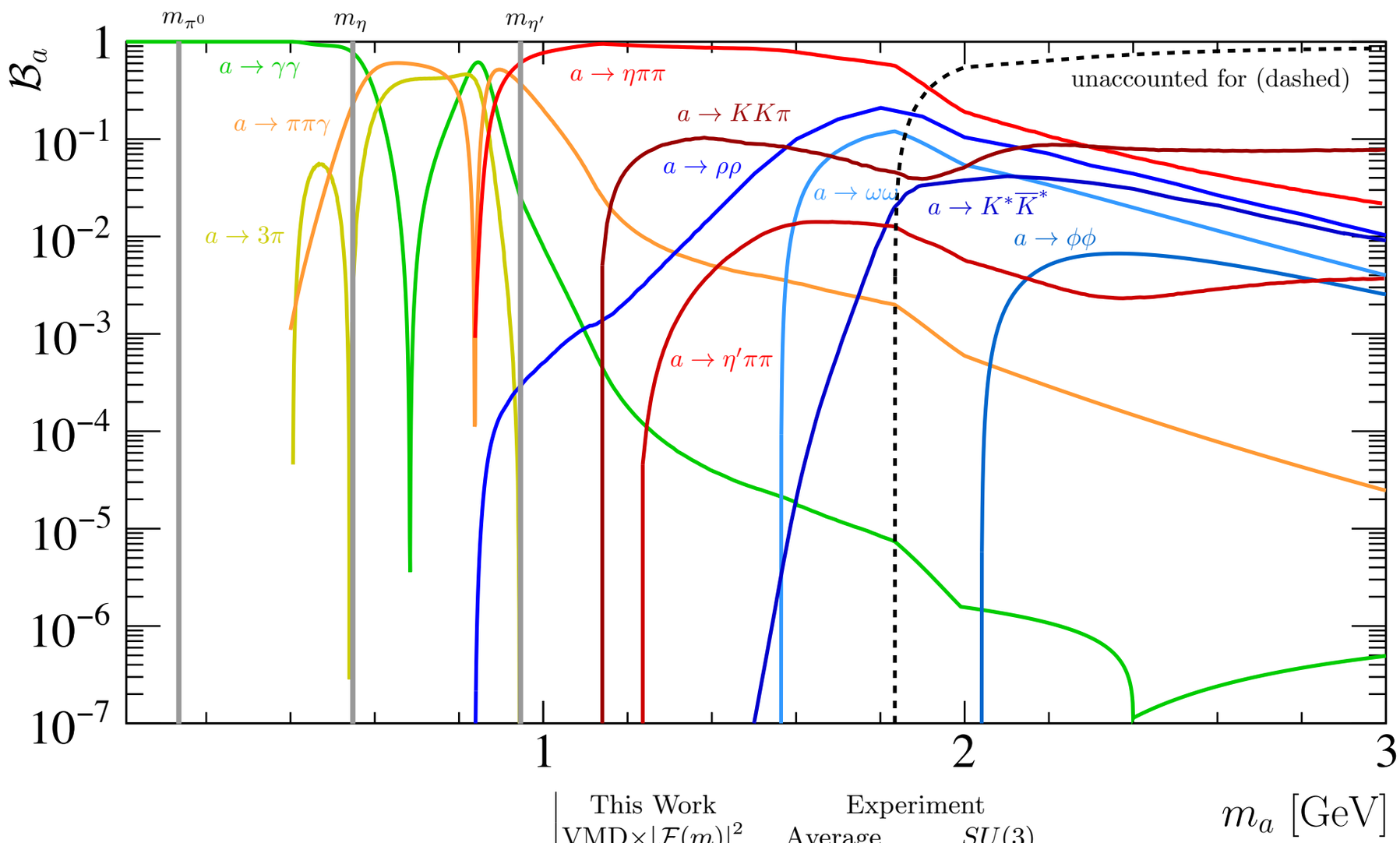
from data

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

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

replace *P* by *P*-ALP mixing

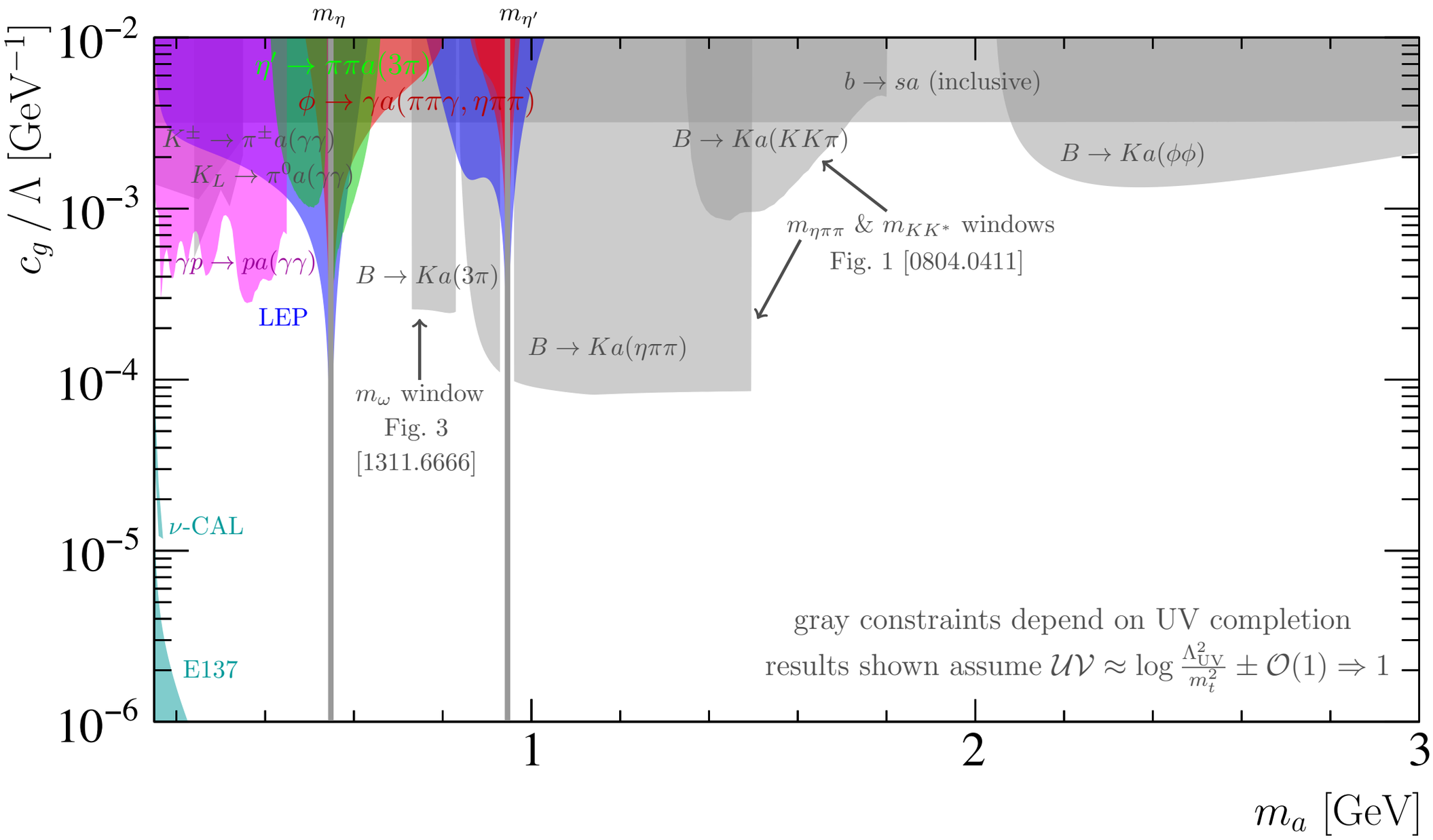


η_c – cross check

	This Work VMD$\times|\mathcal{F}(m)|^2$	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%	$0.91 \pm 0.26\%$	$1.00 \pm 0.13\%$

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda} a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

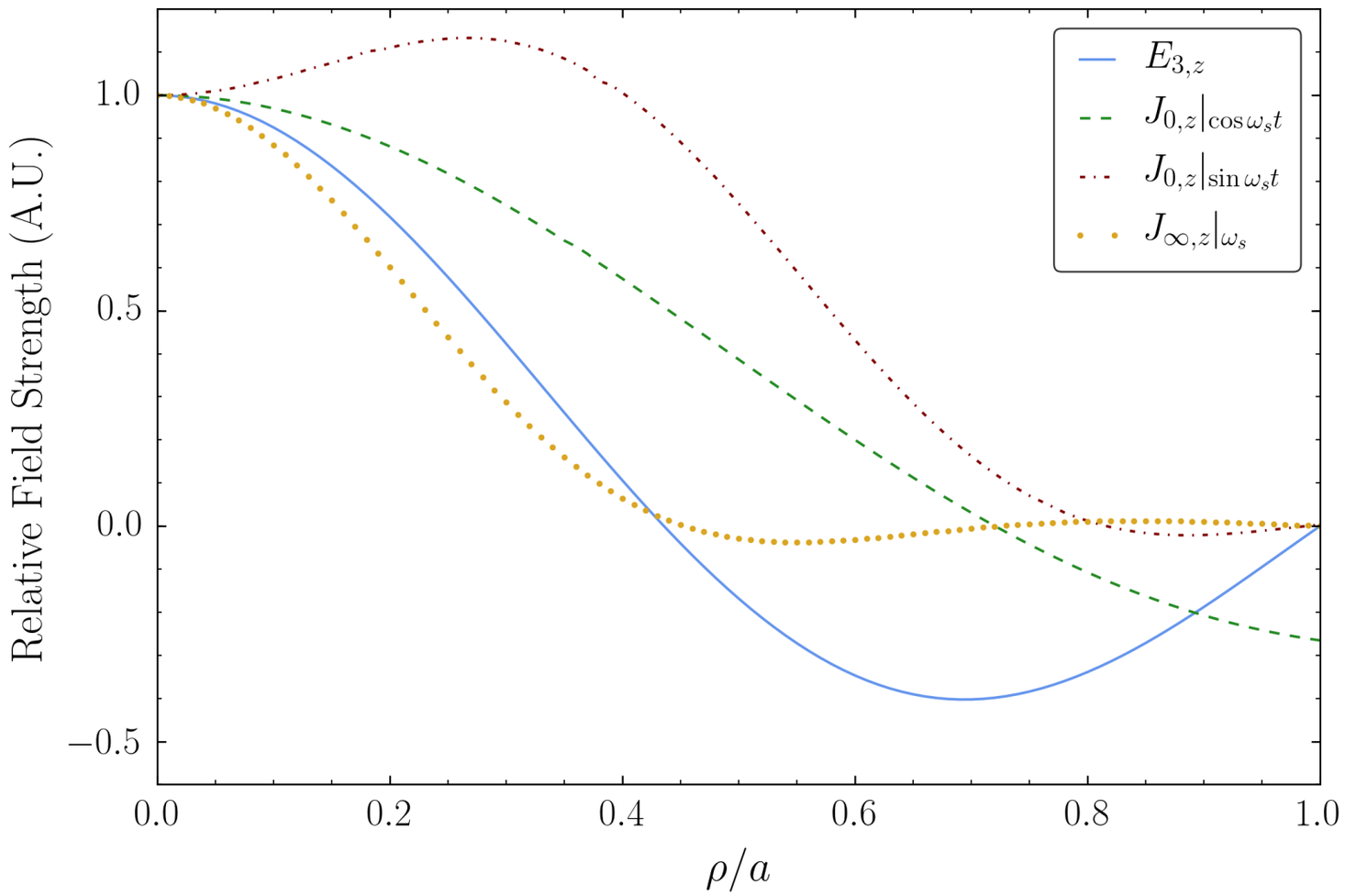


Outlook

* superconducting radiofrequency cavities can be the most powerful to probe ALPs in the lab
* the Euler Heisenberg effect (QED light by light scattering) can be probed, for the first time, in the same experimental setup
* On tape PrimEx data can improve the sensitive to ALP with QCD mass scale, future GlueX data will improve it by order of magnitude
* ALP hadronic rates for, mass around the GeV, can be estimated using data-driven method

Backups

Overlap


$E_{3,z}$
$J_{0,z}|_{\cos\omega_s t}$
$J_{0,z}|_{\sin\omega_s t}$
$J_{\infty,z}|_{\omega_s}$
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

Cavity vs LSW

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

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

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 couling

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