Leptophilic axionlike particles at forward detectors

卢致廷 Chih-Ting Lu *ctlu@njnu.edu.cn*

NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

中国精确检验与新物理合作组

Collaborator: Xu-Hui Jiang（蒋旭辉）;

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TeV物理前沿专题研讨会暨第31届LHC Mini-Workshop

4 W + 1 H questions for axion-like particles (ALPs)

1. **What** does an ALP come from ?

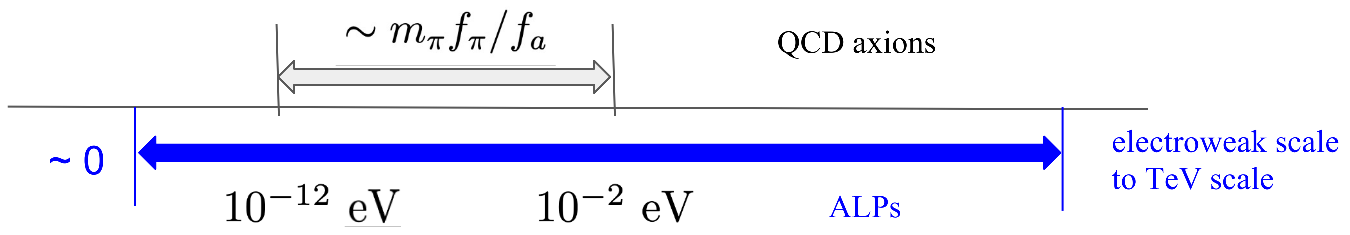
   → An ALP is a light pseudoscalar with approximate shift symmetry.

2. **Why** we need ALPs ?

   → (1) Strong CP problem, (2) DM candidates, (3) Hierarchy problem of the Higgs boson mass, (4) A hint of some string theories, … etc.

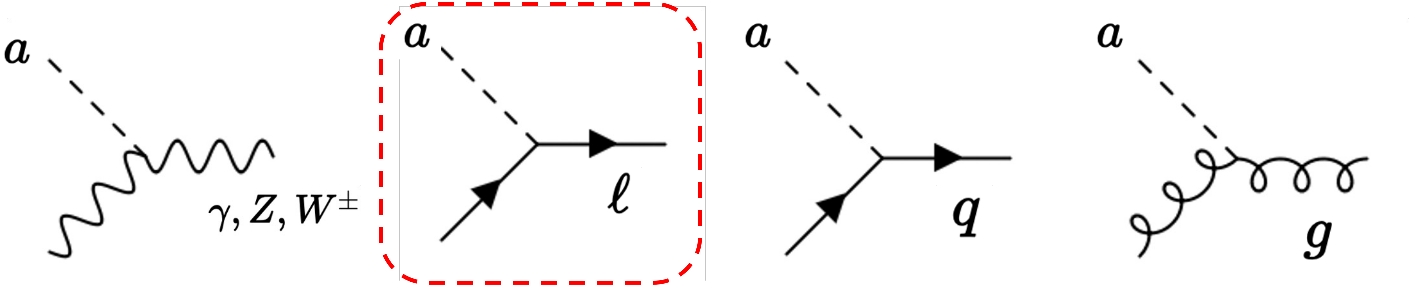
3. **Which** is the mass range of ALPs ?

   →

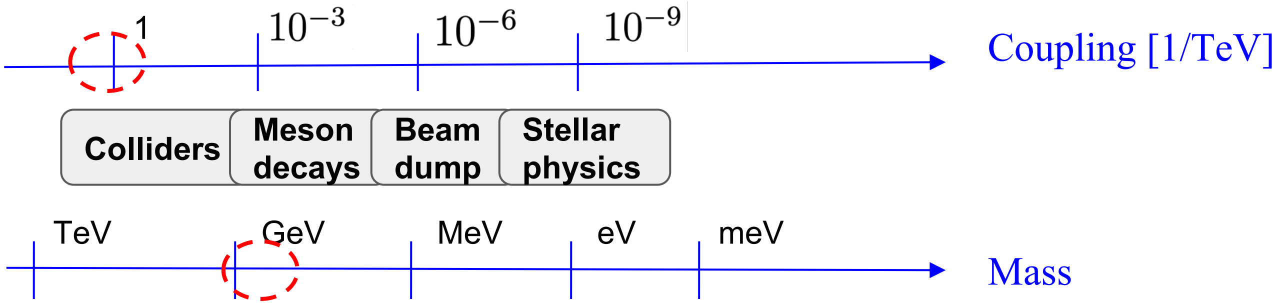


4 W + 1 H questions for axion-like particles (ALPs)

4. **Who** can interact with ALPs (SM particles only) ?



5. **How** to search for ALPs ?



ALP-lepton interactions

The global ~~$U(1)_{\rm PQ}$~~ ⇒ pseudo Nambu-Goldstone bosons

(ALPs)

shift symmetry ⇓

$$a(x) \rightarrow a(x) + \text{const.}$$

⇓

$$\mathcal{L}_{\ell \rm ALP} = \partial_\mu a \; J^\mu_{{\rm PQ},\ell}$$

ALP-lepton interactions

$$\mathcal{L}_{\ell \mathrm{ALP}} = \partial_\mu a \, J^\mu_{\mathrm{PQ},\ell}$$

dimensionless coupling

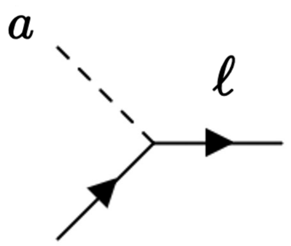
$$J^\mu_{\mathrm{PQ},\ell} = \frac{c_\ell^V}{2\Lambda}\bar{\ell}\gamma^\mu \ell + \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma^\mu\gamma_5 \ell + \frac{c_\nu}{2\Lambda}\overline{\nu_\ell}\gamma^\mu P_L \nu_\ell$$

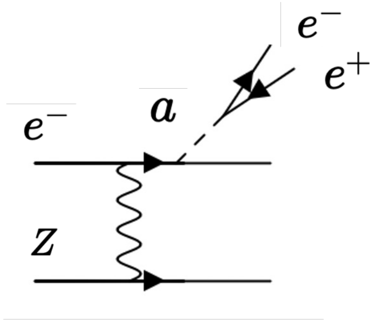
~~$U(1)_{\mathrm{PQ}}$~~ new physics scale

ALP-lepton interactions

After integration by parts of $\partial_\mu a\, J^\mu_{\mathrm{PQ},\ell}$, the $\mathcal{L}_{\ell\mathrm{ALP}}$ can be represented as

$$
\begin{aligned}
a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} =\; & i c_\ell^A \frac{m_\ell}{\Lambda}\, a\bar{\ell}\gamma_5\ell \\
& + \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\left[\frac{c_\ell^V - c_\ell^A + c_\nu}{4s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\right. \\
& + \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} + \\
& \left.\frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8s_W^2 c_W^2}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\
& + \frac{ig_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\, a(\bar{\ell}\gamma^\mu P_L \nu)W^-_\mu \;+\; \mathrm{h.c.}\,,
\end{aligned}
$$

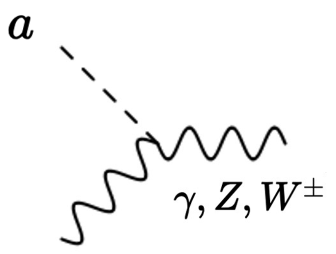


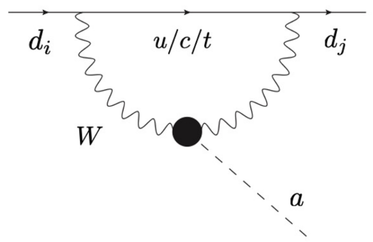


ALP-lepton interactions

After integration by parts of $\partial_\mu a\, J^\mu_{\mathrm{PQ},\ell}$, the $\mathcal{L}_{\ell \mathrm{ALP}}$ can be represented as

$$
\begin{aligned}
a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} &= i c_\ell^A \frac{m_\ell}{\Lambda}\, a\bar{\ell}\gamma_5\ell \\
&+ \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\Bigg[\frac{c_\ell^V - c_\ell^A + c_\nu}{4 s_W^2}\, aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu} \\
&+ \frac{c_\ell^V - c_\ell^A(1-4s_W^2)}{2 s_W c_W}\, aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c_\ell^A\, aF_{\mu\nu}\tilde{F}^{\mu\nu} + \\
&\frac{c_\ell^V(1-4s_W^2) - c_\ell^A(1-4s_W^2+8s_W^4) + c_\nu}{8 s_W^2 c_W^2}\, aZ_{\mu\nu}\tilde{Z}^{\mu\nu}\Bigg] \\
&+ \frac{i g_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\, a(\bar{\ell}\gamma^\mu P_L \nu)W^-_\mu \;+\; \text{h.c.}\,,
\end{aligned}
$$





ALP-lepton interactions

After integration by parts of $\partial_\mu a\, J^\mu_{\mathrm{PQ},\ell}$, the $\mathcal{L}_{\ell\mathrm{ALP}}$ can be represented as

$$
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a\,\partial_\mu J^\mu_{\mathrm{PQ},\ell} = {} & i c_\ell^A \frac{m_\ell}{\Lambda}\; a\bar{\ell}\gamma_5\ell \\
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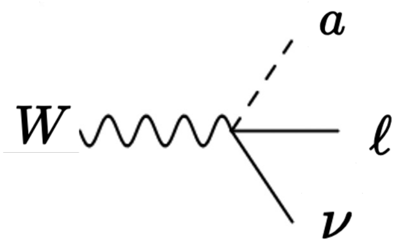
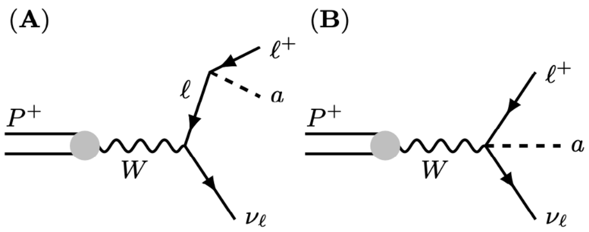
& + \frac{i g_W}{2\sqrt{2}\Lambda}(c_\ell^A - c_\ell^V + c_\nu)\; a(\bar{\ell}\gamma^\mu P_L \nu)W^-_\mu \;+\; \mathrm{h.c.},
\end{aligned}
$$





Three benchmark scenarios

$$J^{\mu}_{\mathrm{PQ},\ell} = \frac{c_\ell^V}{2\Lambda}\bar{\ell}\gamma^\mu \ell + \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma^\mu\gamma_5 \ell + \frac{c_\nu}{2\Lambda}\overline{\nu_\ell}\gamma^\mu P_L \nu_\ell$$

$$\text{Electroweak Violating } (\mathbf{EWV}) : c_\ell^V = c_\nu = 0, c_\ell^A \neq 0,$$

$$\text{Electroweak Preserving } (\mathbf{EWP}) : c_\nu = 0, c_\ell^V = c_\ell^A \neq 0$$

EWV: The lepton current is pure axial-vector current $J^{\mu}_{\mathrm{PQ},\ell} = \frac{c_\ell^A}{2\Lambda}\bar{\ell}\gamma_\mu\gamma_5\ell$

EWP: The lepton current is pure right-handed coupling current $J^{\mu}_{\mathrm{PQ},\ell} = \frac{c_\ell^A}{\Lambda}\bar{\ell}\gamma_\mu P_R\ell$

Left-Right Softly Asymmetric (LRSA) scenario:

$$\Delta \equiv \left|\frac{c_L - c_R}{c_L + c_R}\right| = \left|\frac{c_\ell^A}{c_\ell^V}\right|$$

$c_L \approx c_R$

A nearly non-chiral UV completion corresponds to $\boldsymbol{\Delta \ll 1}$.
In this study, we adopt $\boldsymbol{\Delta = 0.1}$ as a benchmark, which corresponds to $\boldsymbol{c_\ell^A = -0.1 c_\ell^V}$ **and** $\boldsymbol{c_\nu = 0}$.

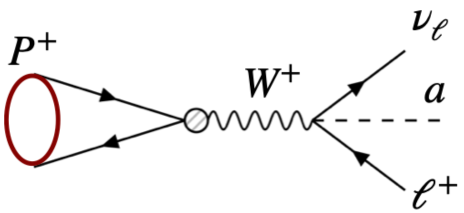
Productions and decays of ALPs

Scenario	Electrophilic	Muonphilic
4-body	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu a$ $a \to \gamma\gamma, e^+e^-$	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu a$ $a \to \gamma\gamma$
3-body	$P^+ \to e^+ \nu_e a$ $a \to \gamma\gamma, e^+e^-$	$P^+ \to \mu^+ \nu_\mu a$ $a \to \gamma\gamma, \mu^+\mu^-$
2-body	$M_1 \to M_2 a$ $a \to \gamma\gamma, e^+e^-$	$M_1 \to M_2 a$ $a \to \gamma\gamma, \mu^+\mu^-$

$P = \pi, K, D, D_s$,
$\ell = e, \mu$,
$(M_1, M_2) = (B, K^*), (K^+, \pi^+), (K_{L,S}, \pi^0)$.

- 3-body decays: $P^+ \to \ell^+ \nu_\ell a$

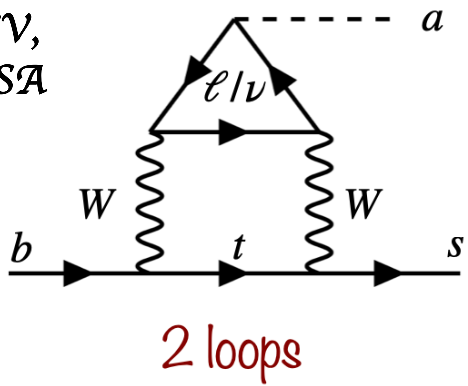
$P \in \{\pi, K, D, D_s\}$

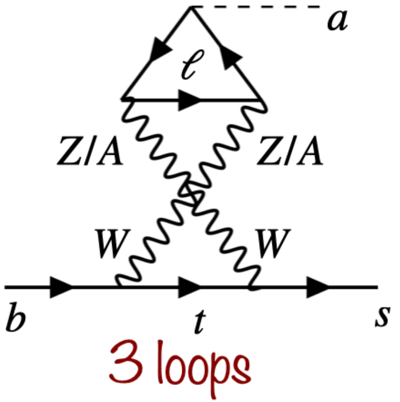


EWV, LRSA

- 2-body decays: $M_1 \to M_2 a$

EWV, LRSA

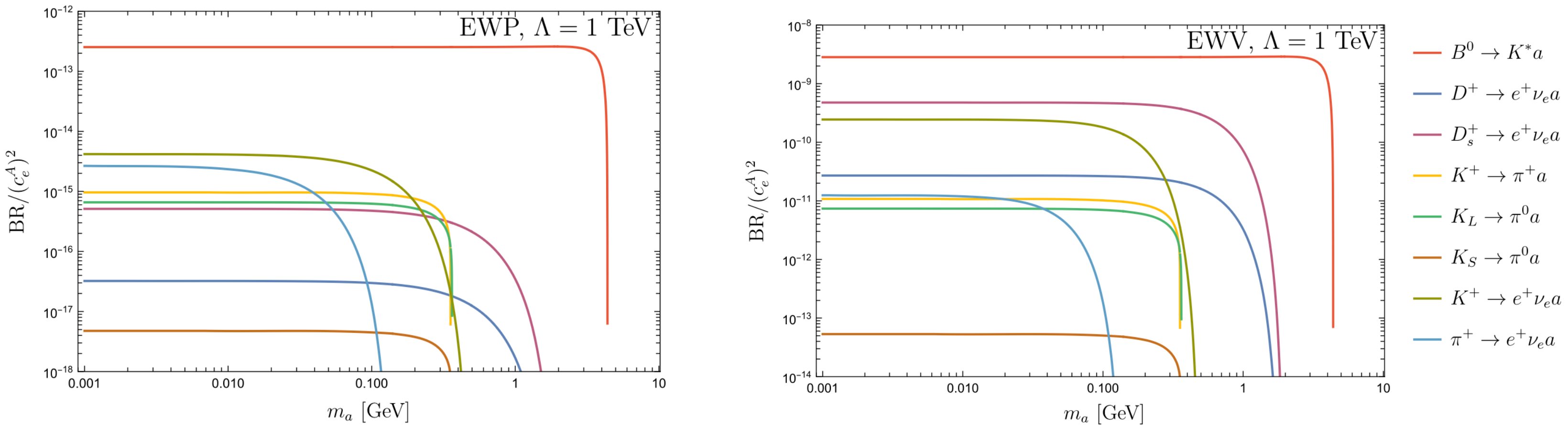




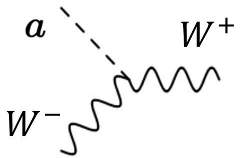
For **LRSA scenario**, enhancement of production due to $c_\ell^V \neq 0$, but no influence on ALP decays.

Leading contributions from loops

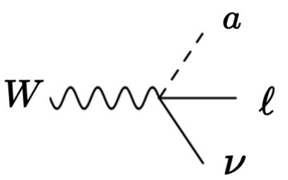
2-body and 3-body exotic meson decays



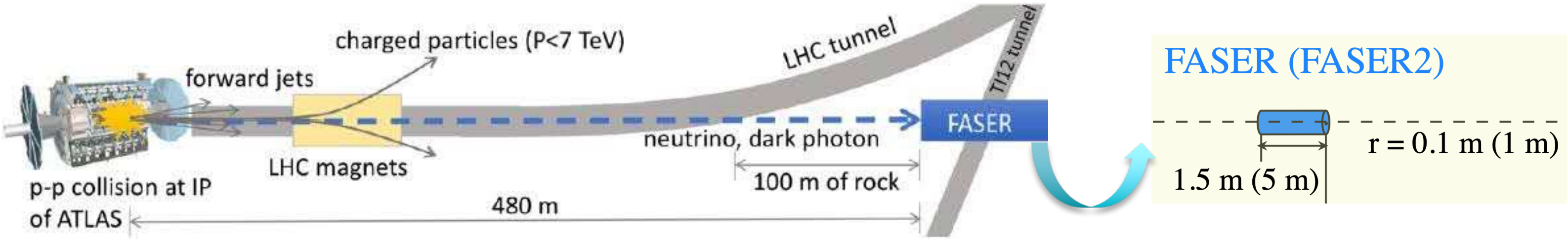
For 2-body exotic meson decays, the branching ratios between EWP and EWV scenarios are ***about 4 orders of magnitude.***

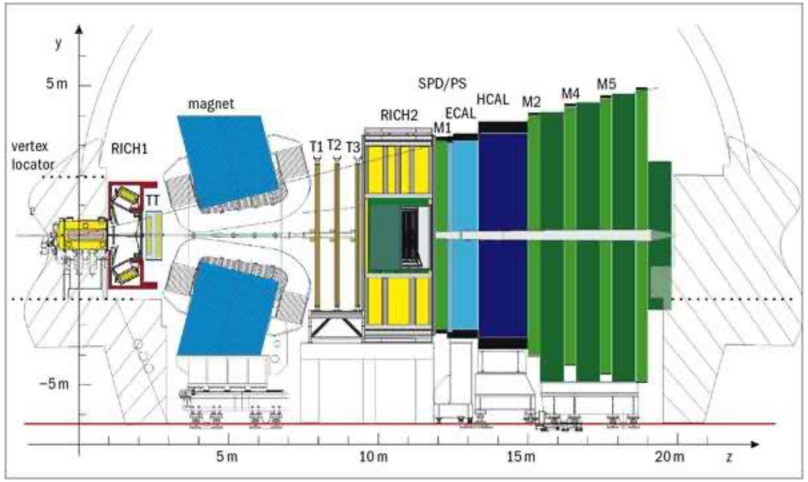


For 3-body exotic meson decays, the branching ratios between EWP and EWV scenarios can be **up to 6 orders of magnitude**!



Forward detectors (FASER, FASER II, LHCb)



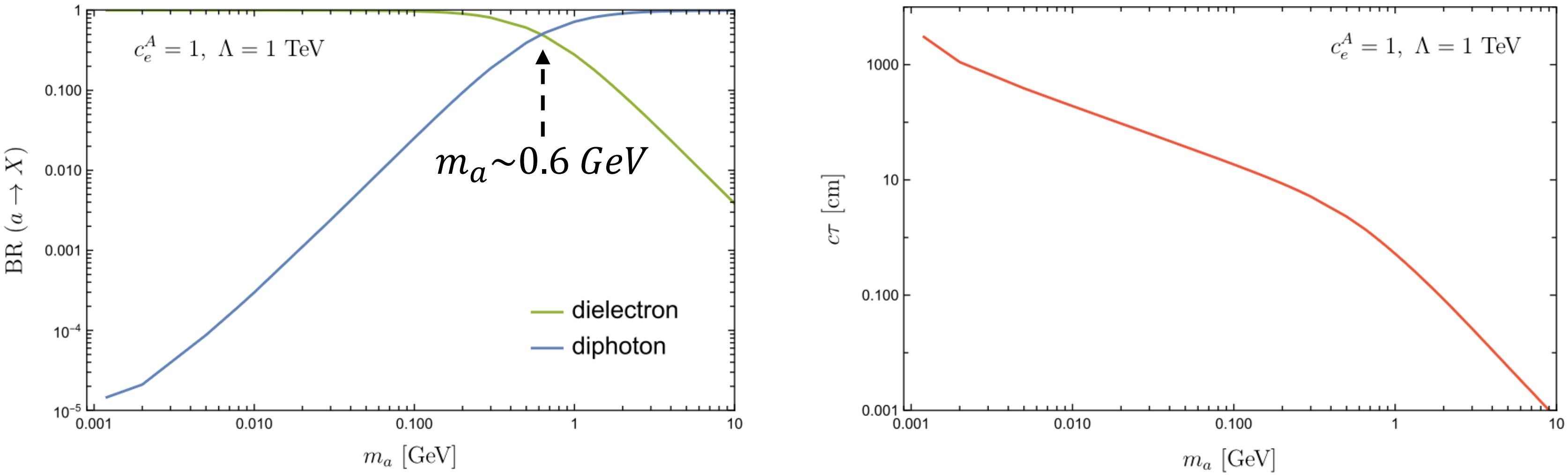


LHCb:
A forward spectrometer and plannar detectors, 21 m long, 13 m wide, and 10 m high.

Advantages for detecting LLPs:
Precise vertex reconstruction capabilities and flexible trigger system.

The B meson is required to reside in the forward region, satisfying $\eta \in [2, 5]$.

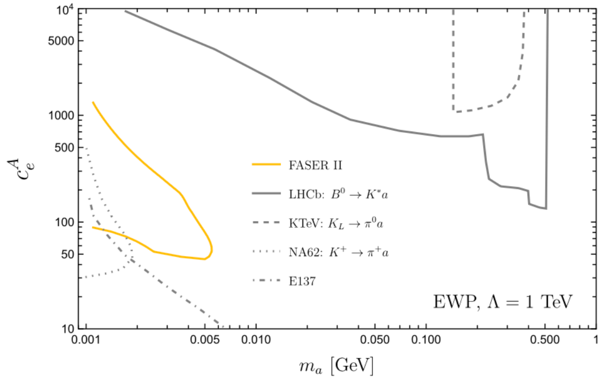
Electrophilic ALPs

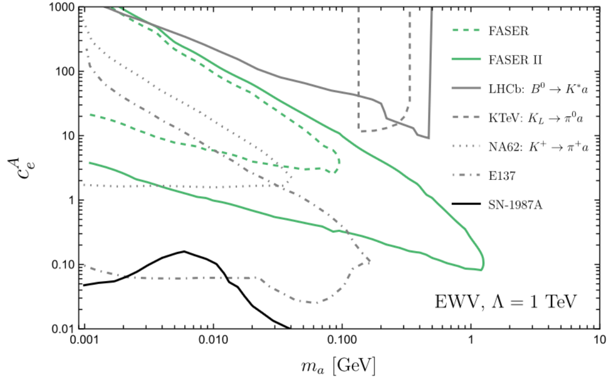


$$\Gamma_{a\to\ell^+\ell^-} = \frac{(c_\ell^A)^2 m_\ell^2 m_a}{8\pi\Lambda^2}\sqrt{1-\frac{4m_\ell^2}{m_a^2}},$$

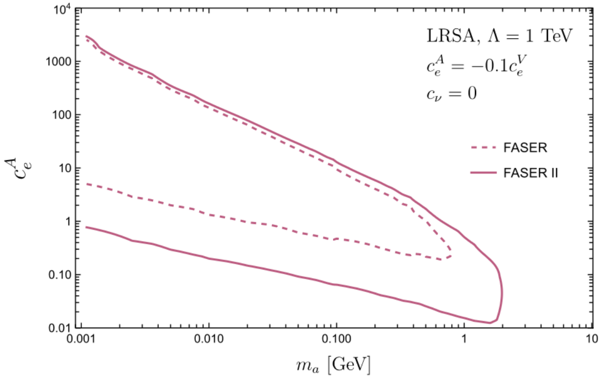
$$\Gamma_{a\to\gamma\gamma} = \frac{m_a^3}{64\pi}\left(\frac{\alpha_{\rm em}}{\pi}\frac{c_\ell^A}{\Lambda}\left|1-\mathcal{F}\left(\frac{m_a^2}{4m_\ell^2}\right)\right|\right)^2,$$

Electrophilic ALPs



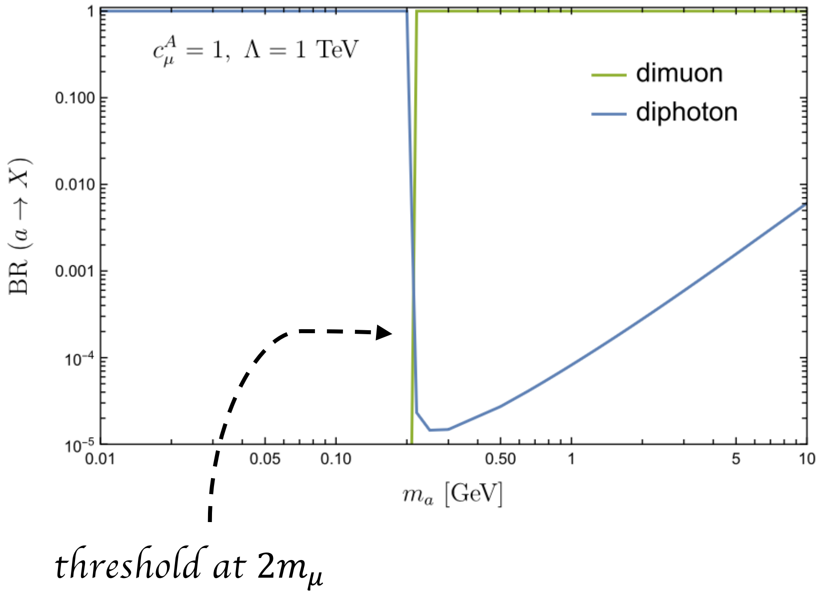


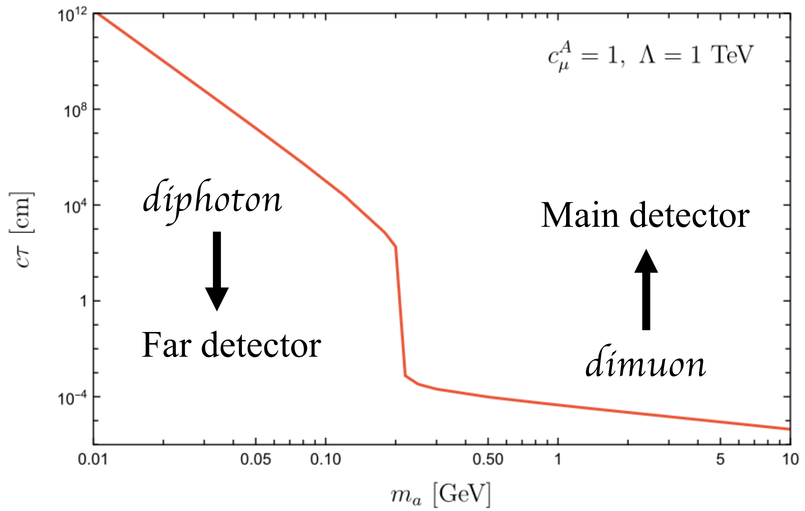
Tight cut:
Requiring $E_{tot} > 500$ GeV



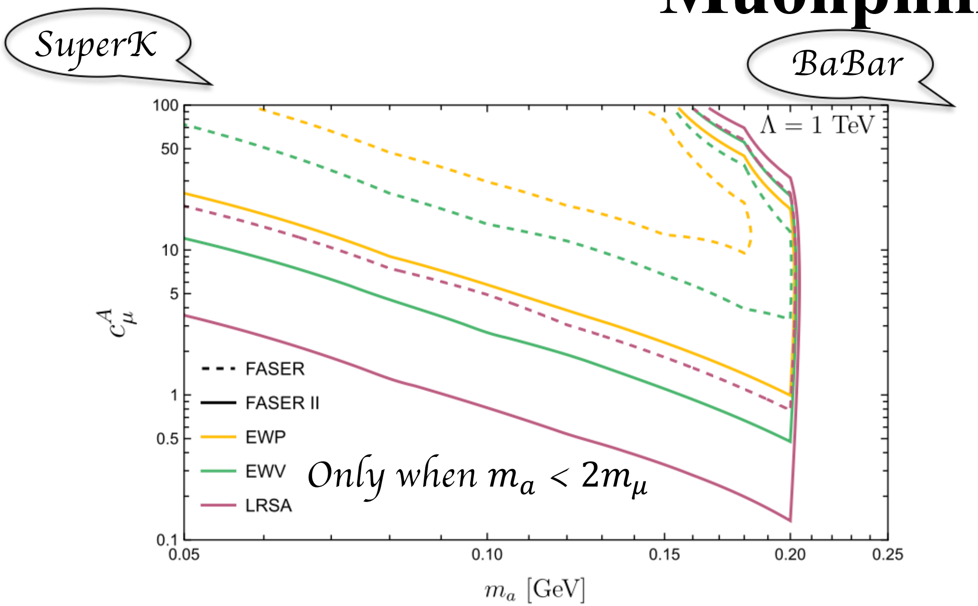
Dielectron at FASER;
Diphoton at FASER II

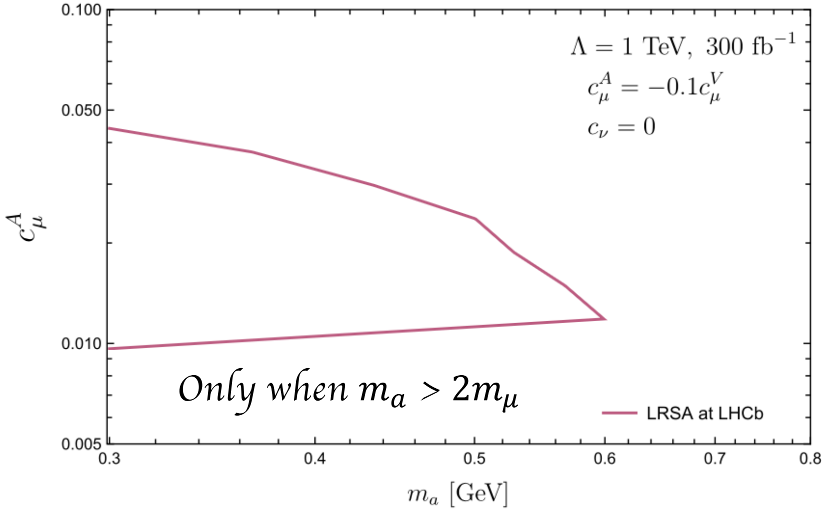
Muonphilic ALPs





Muonphilic ALPs





Far detectors excel in searching for long-lived ALPs with small masses and large couplings!

LHCb is better suited for heavier ALPs with feeble couplings!

*We focus exclusively on the $B \to Ka$ process to avoid overwhelming SM background events.

Conclusion

- Searching for **leptophilic** (both electrophilic and muonphilic) ALPs from 2-body and 3-body exotic meson decays at **forward detectors** (FASER, FASER II, and LHCb).

- For the **electrophilic ALPs**, **FASER II** enables sensitivity to ALPs with *masses up to 1 GeV* and *couplings as small as* $\mathcal{O}(1)$ from the combination of dielectron and diphoton channels.

- For the **muonphilic ALPs**, **FASER** and **FASER II** remain sensitive to *diphoton* signals for *lighter ALPs*, while **LHCb** excels in probing *heavier ALPs* that decay into *dimuons*. Particularly, LHCb's high-luminosity phase will allow for robust constraints in the LRSA scenario.

Thank you
for your attention

Back-up Slides

Simulations

- The hadron producitons and decays are simulated using ***PYTHIA8*** for heavy mesons ($B^0, D^{\pm}, D_s^{\pm}$) and ***EPOS LHC*** for light mesons ($\pi^{\pm}, K^{\pm}, K_{L,S}$).
- The FASER and FASER II enviroment is simulated using the ***FORESEE*** package.
- For selection cuts in the LHCb analysis, we require both muon tracks to sastify $p_T > 0.5\ GeV$, $|p| > 10\ GeV$, and $\eta \in [2, 5]$. Additionally, the reconstructed ALP must meet the criteria $p_T > 0.5\ GeV$ and transverse displacement $\ell_{xy} \in [6,22]\ mm$. To account for potential imporvements in the $m_{\mu\mu}$ resolution, the mass window width is set to 16 MeV for $m_{\mu\mu} < 1\ GeV$, or $0.016 m_{\mu\mu}$ for $m_{\mu\mu} \geq 1\ GeV$. Finally, a global detector efficiency of 0.7 is universally applied as a benchmark.