Leptophilic Axion-like Particles at Forward Detectors
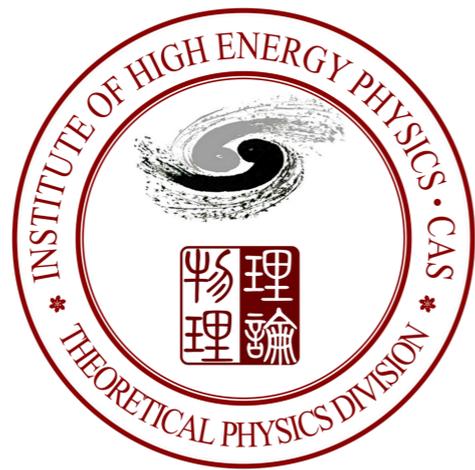
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For IAS Program FP2025

ꙮ Axions in General

- A broad mass range: rich pheno

QCD axion · EW bosons

$$10^{-31} \qquad 10^{0} \qquad 10^{10} \quad [\text{GeV}]$$

$$10^{-15} \qquad m_a \qquad 10^{2}$$

Fuzzy dark matter · Dark hadrons? · Heavy dofs

[PDG Review]

- Flavor decays!

  FCNC processes

- At colliders

  [Cheng et al.]
  [Cheng, **Jiang** et al.]
  [Cheng, **Jiang** and Li]

Many searches for light ones; heavier ones?
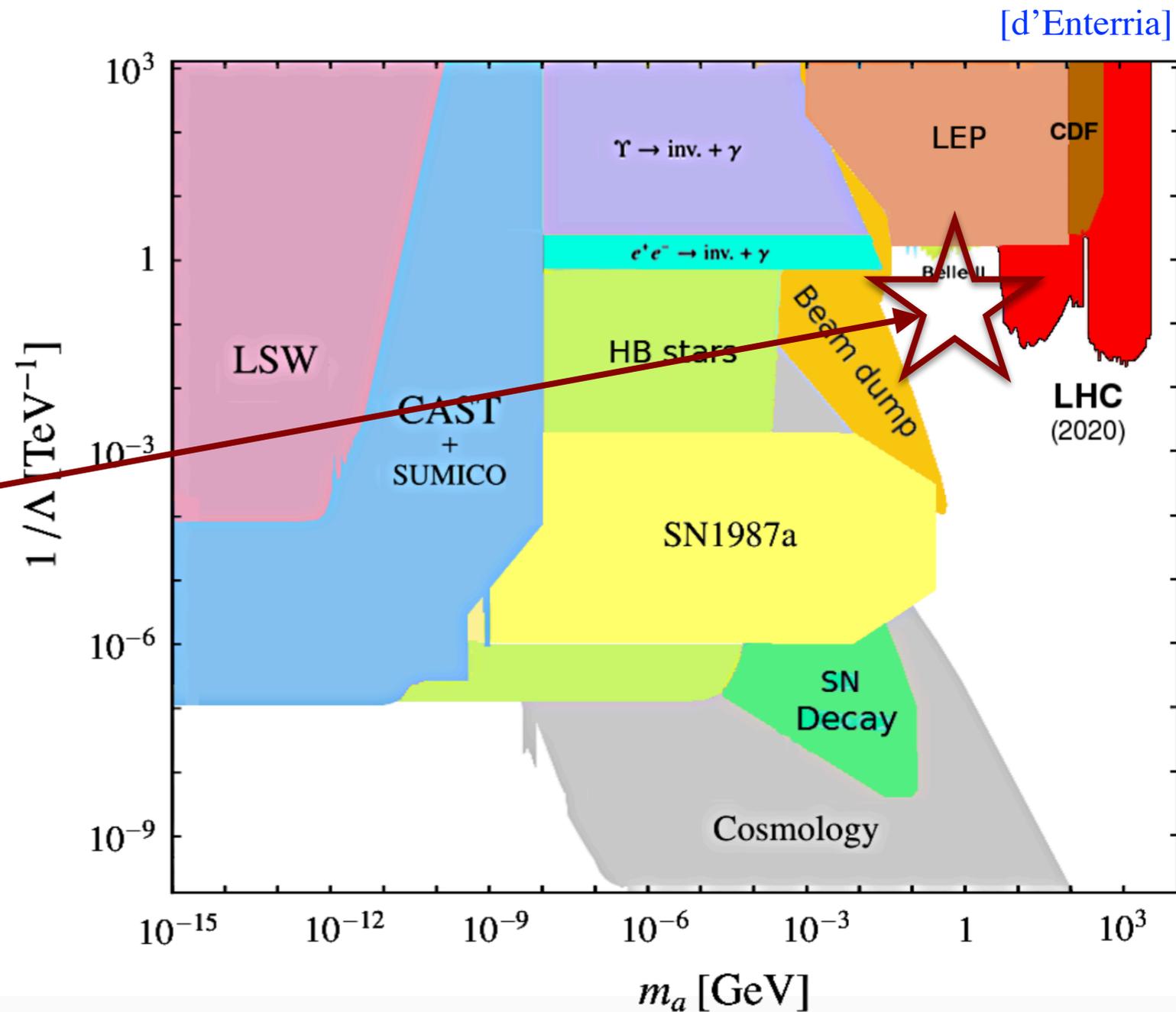
Axions at Colliders

- Current bounds

  Many regions probed

- Unexplored parts!

$$m_a \sim \mathcal{O}(1) \text{ GeV}$$

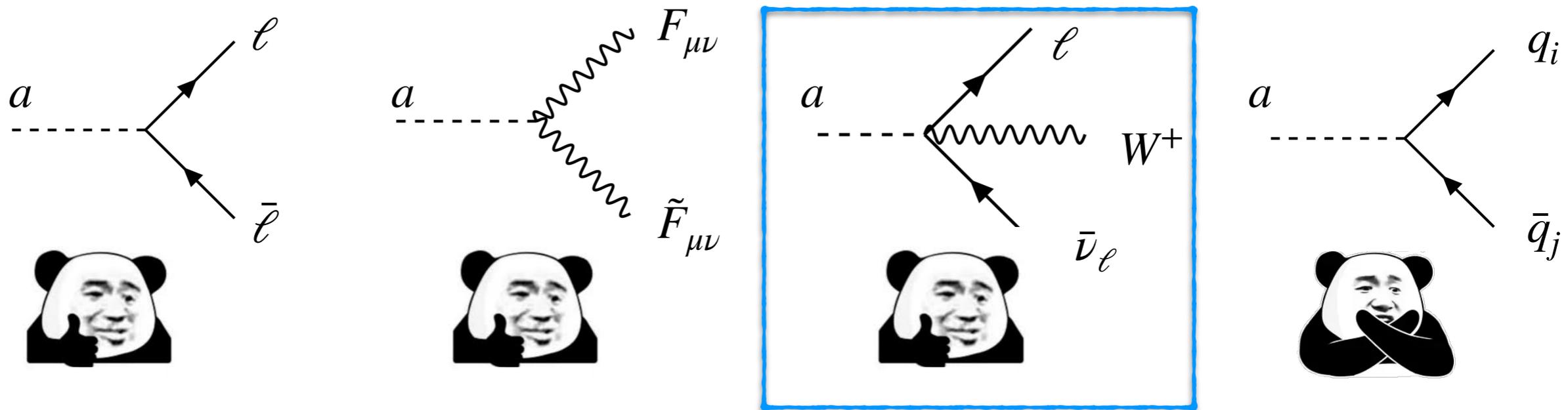$$\frac{g_{a\gamma}}{\Lambda} \lesssim 1 \text{ TeV}^{-1}$$

[d'Enterria]

- Flavors matter.

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➤ Leptophilic ALPs

- Couplings with leptons/gauges only

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

- Interactions, considering $a\partial_{\mu}J^{\mu}_{\mathrm{PQ}}$:
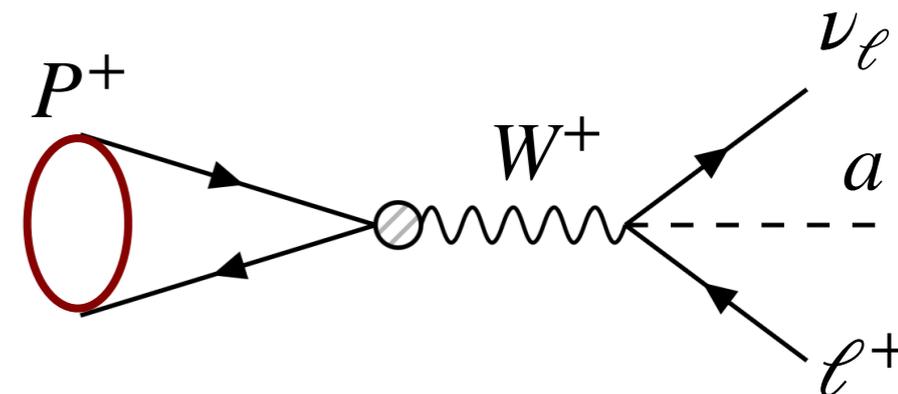
  A 4-point interaction, usually being ignored
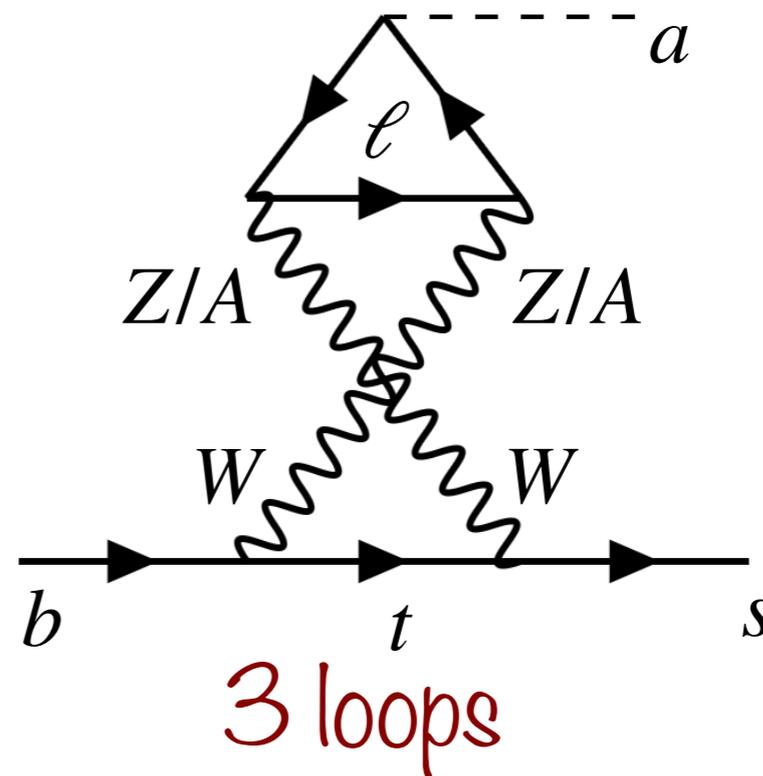

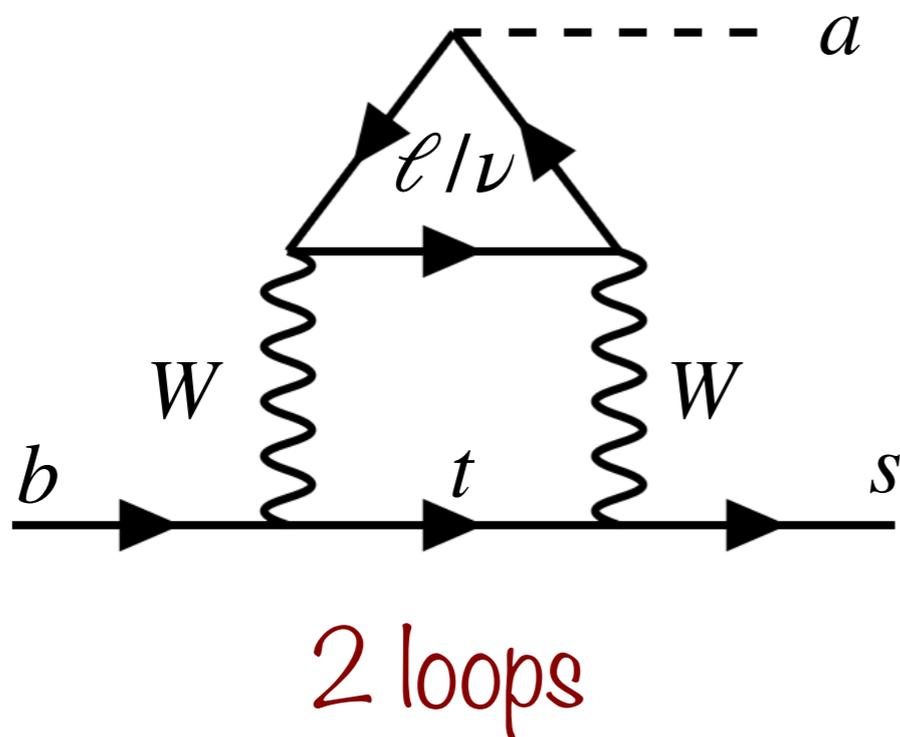No direct hadronic currents involved!

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

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

- 2-body decays: $M_1 \to D_1 a$

2 loops

3 loops

Leading contributions from loops

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❧ Scenarios

B decays for instance:

$$\mathrm{BR}(B^0 \to K^* a) = \frac{|g_{bs}|^2}{64\pi} \frac{m_B^3}{\Lambda^2} |A_0^{B \to K^*}(m_a^2)|^2 \lambda^{\frac{3}{2}} \left(\frac{m_{K^*}^2}{m_B^2}, \frac{m_a^2}{m_B^2} \right)$$

with:

- EW Violating: $c_\nu = c_\ell^V = 0$ $\qquad J_{\mathrm{PQ}}^\mu \sim \bar{\ell}\gamma^\mu\gamma^5\ell$

$$g_{d_i d_j} = -\frac{g^2}{16\pi^2} V_{ti}^* V_{tj} \left[\boxed{\frac{g^2}{16\pi^2} \frac{3}{8}(c_\ell^A - c_\ell^V - c_\nu) F(x_t)} + \frac{g'^4}{(16\pi^2)^2} \frac{17}{96}(c_\ell^A + c_\ell^V) x_t \log^2(\frac{\Lambda^2}{m_t^2}) \right]$$

2-loop: leading $\qquad\qquad$ 3-loop

- EW Preserving: $c_\ell^A = c_\ell^V, \; c_\nu = 0$ $\qquad J_{\mathrm{PQ}}^\mu \sim \bar{\ell}\gamma^\mu P_R \ell$

$$g_{d_i d_j} = -\frac{g^2}{16\pi^2} V_{ti}^* V_{tj} \left[\frac{g^2}{16\pi^2} \frac{3}{8}(c_\ell^A - c_\ell^V - c_\nu) F(x_t) + \frac{g'^4}{(16\pi^2)^2} \frac{17}{96}(c_\ell^A + c_\ell^V) x_t \log^2(\frac{\Lambda^2}{m_t^2}) \right]$$

LRSA and ALP Decays

- Left-Right Softly Asymmetry (LRSA): $c_L \approx c_R$

$$\Delta \equiv \left| \frac{c_L - c_R}{c_L + c_R} \right| = \left| \frac{c_\ell^A}{c_\ell^V} \right| \quad \text{To consider } \Delta = 0.1$$

  - Enhancement of production due to $c_\ell^V \neq 0$
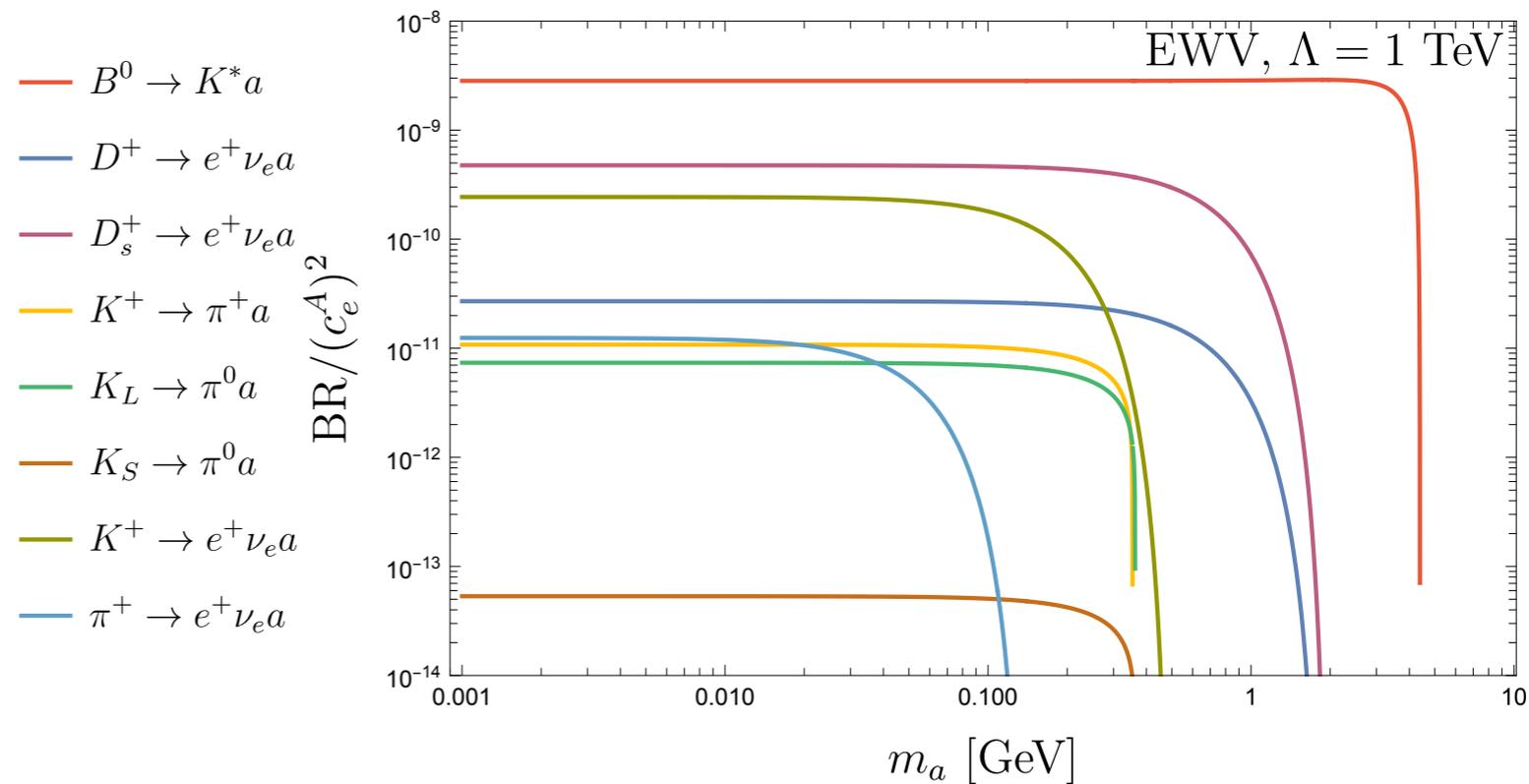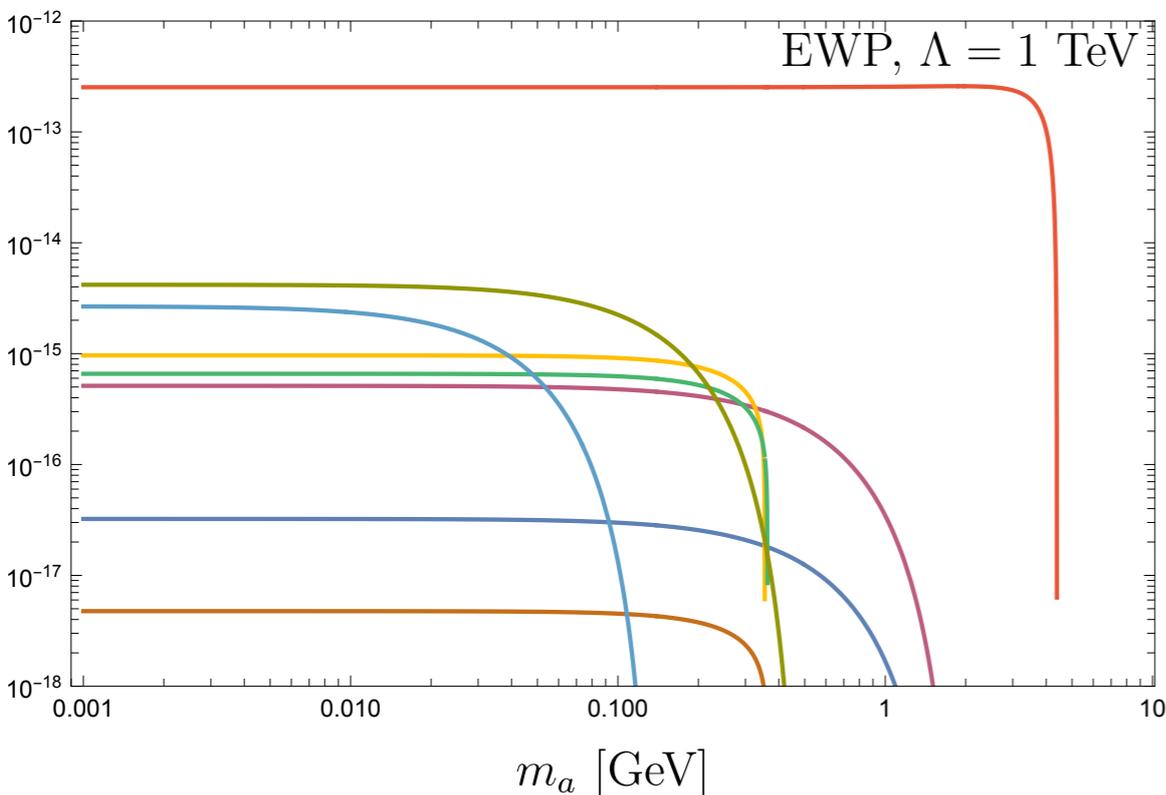
  - No influence on ALP decays

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

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

c_ℓ^A only!

Electrophilic ALP Production

- ● Exotic flavor decays

- ■ EWP: more loops, more suppressed

- ■ From $\mathcal{O}(1)$ MeV to $\mathcal{O}(1)$ GeV

- ■ Opportunities at forward detectors

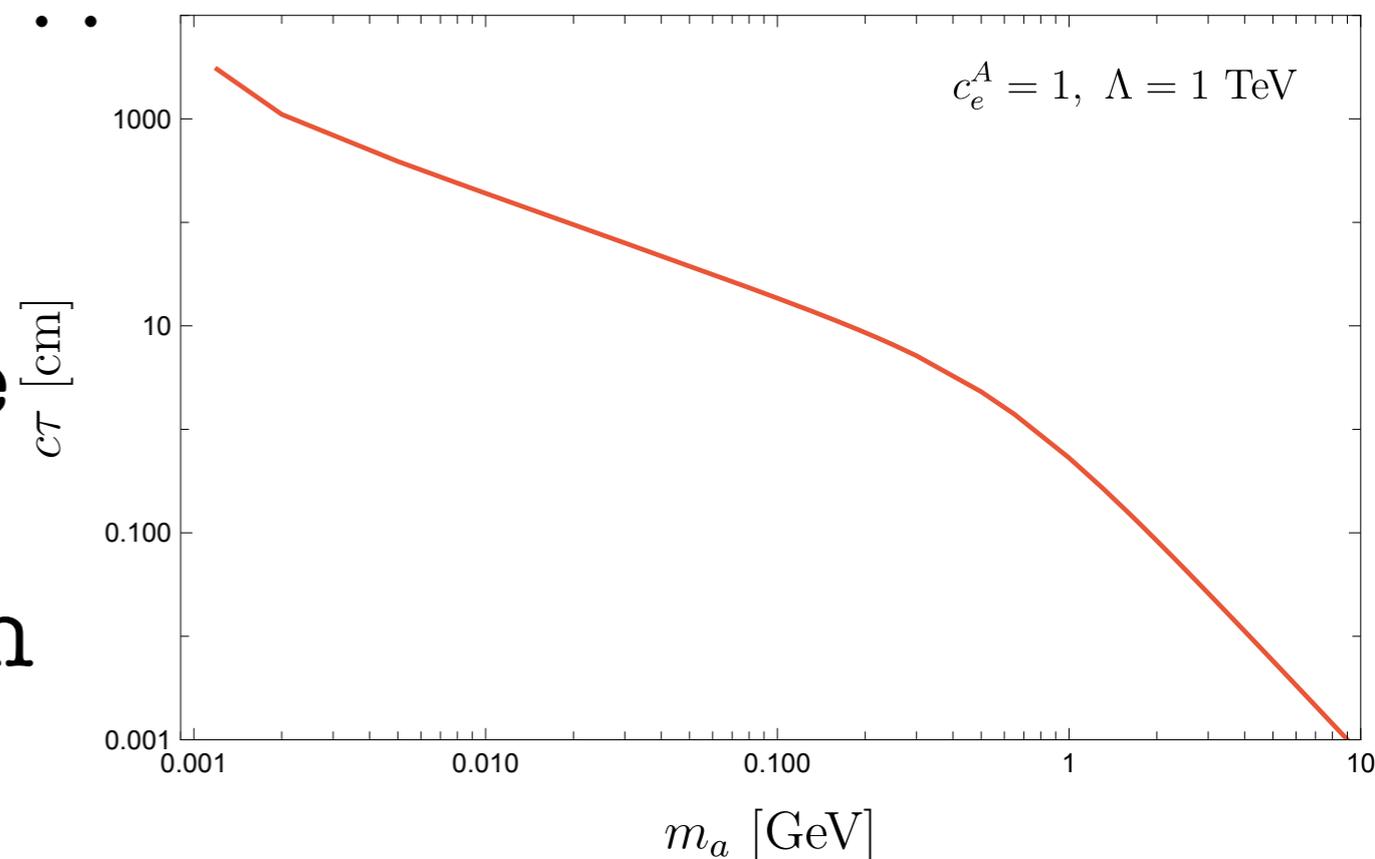# Electrophilic ALPs
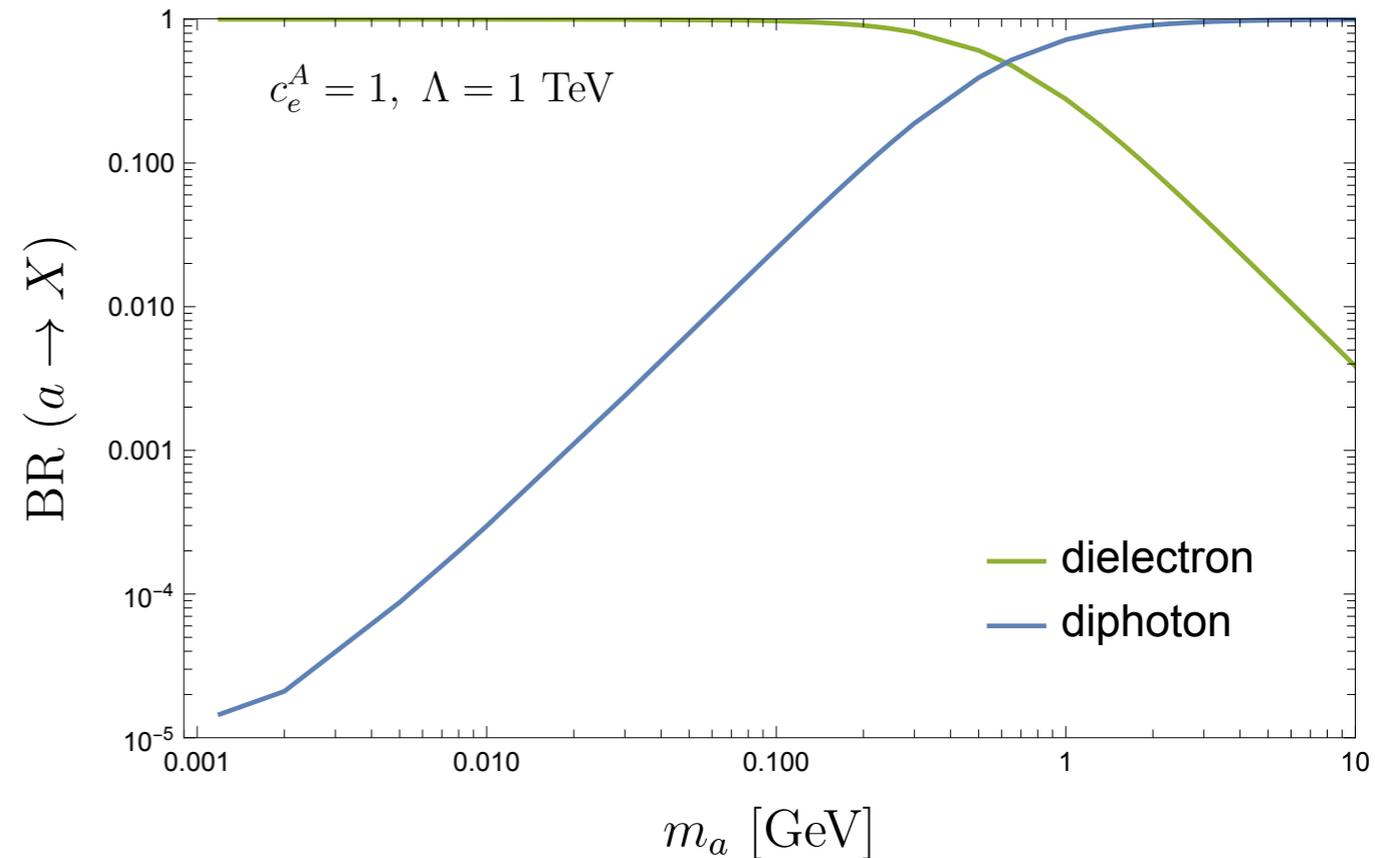
- **Decay channels**

  dielectron vs. diphoton:

  balance around 0.6 GeV

- **ALP lifetime:** $\tau_a \sim \dfrac{1}{(c_e^A)^2} \cdots$

  - Balance between production and lifetime
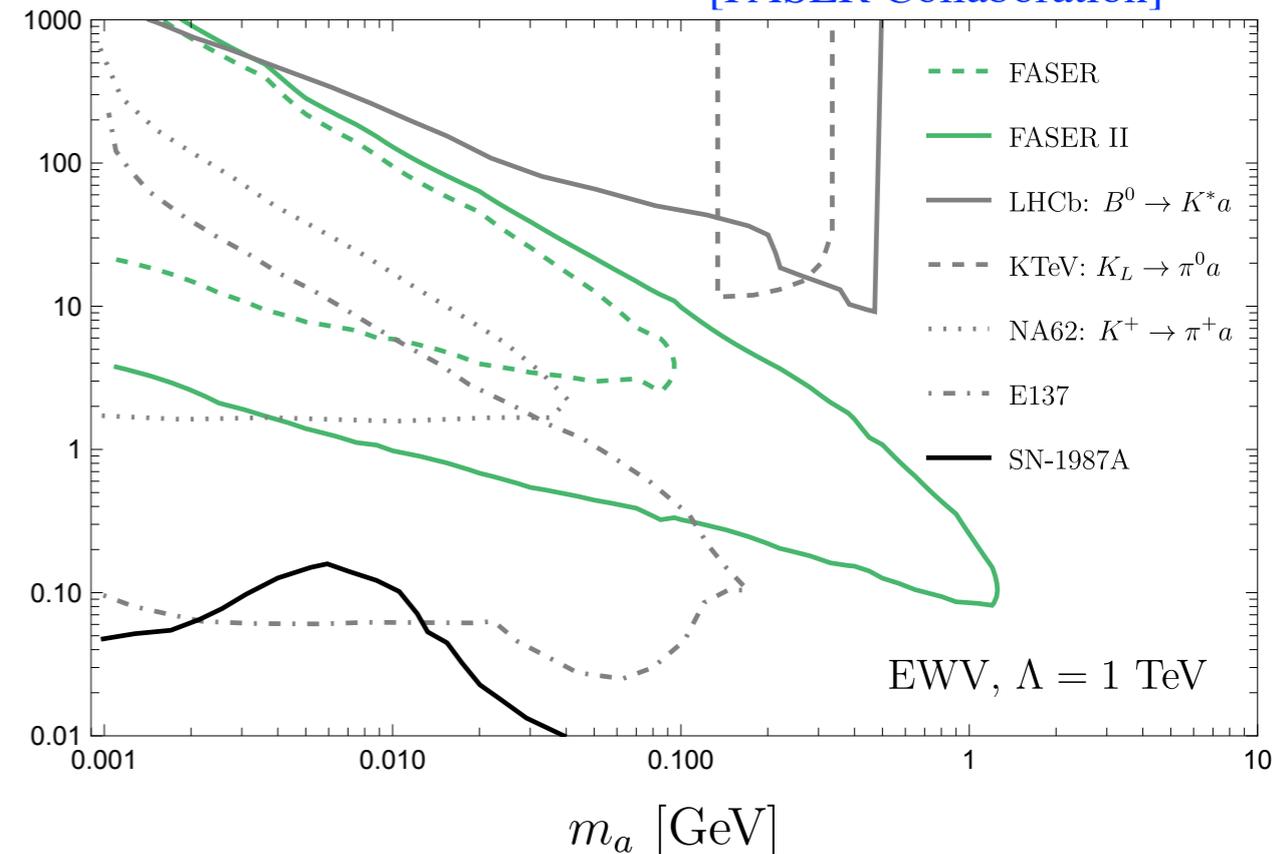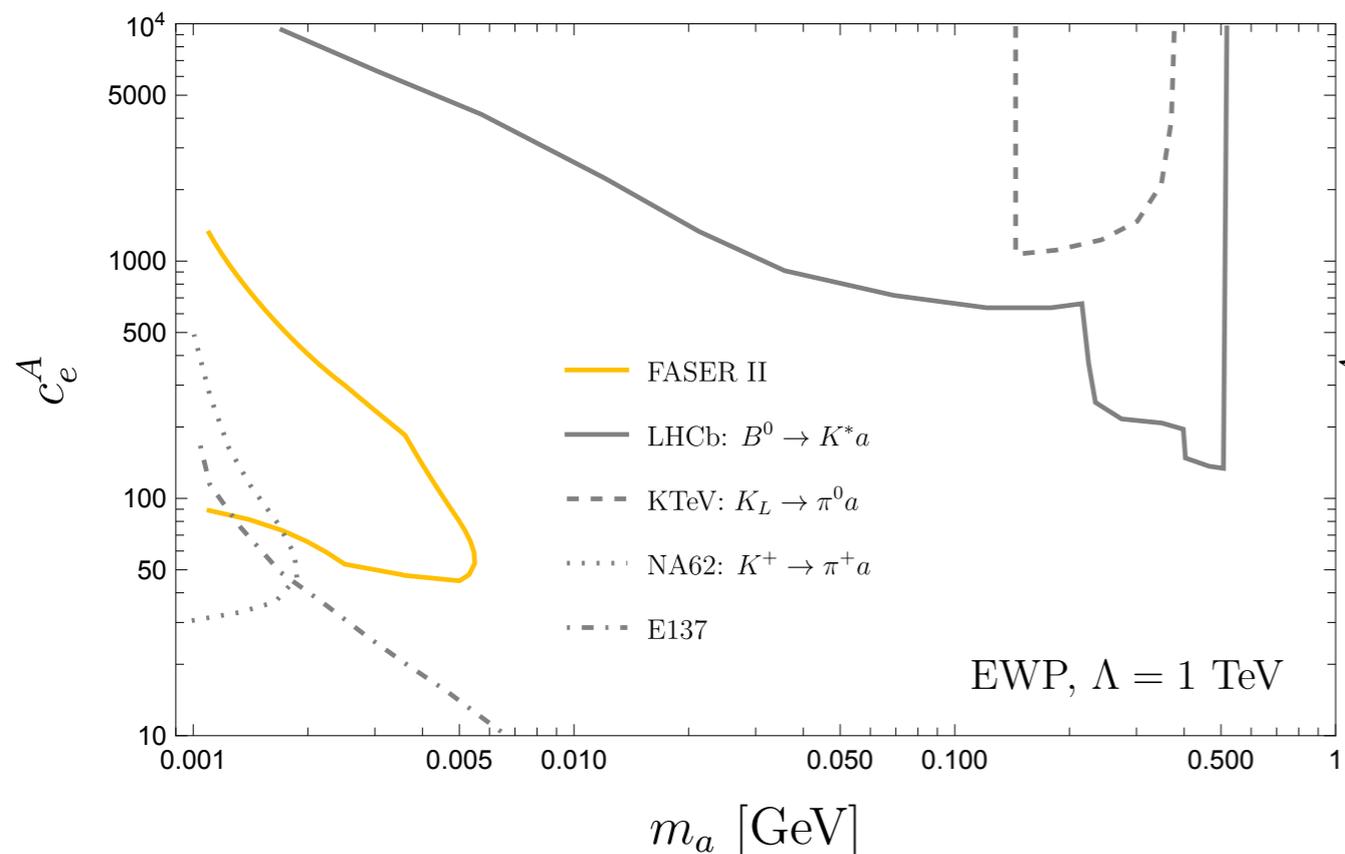
  - Far or prompt detection

- Far detectors   At forward regions [FASER Collaboration]

Detector	Geometry	Displacement (m)	Volume (m)	Luminosity (fb^{-1})
FASER [30]	Cylinder	0, 0, 480	0.2, 1.5	300
FASER 2 [30]	Cylinder	0, 0, 480	2, 5	3000

- A clean environment   Requiring $E > 500$ GeV

[FASER Collaboration]

- To probe new regions: EWP narrower

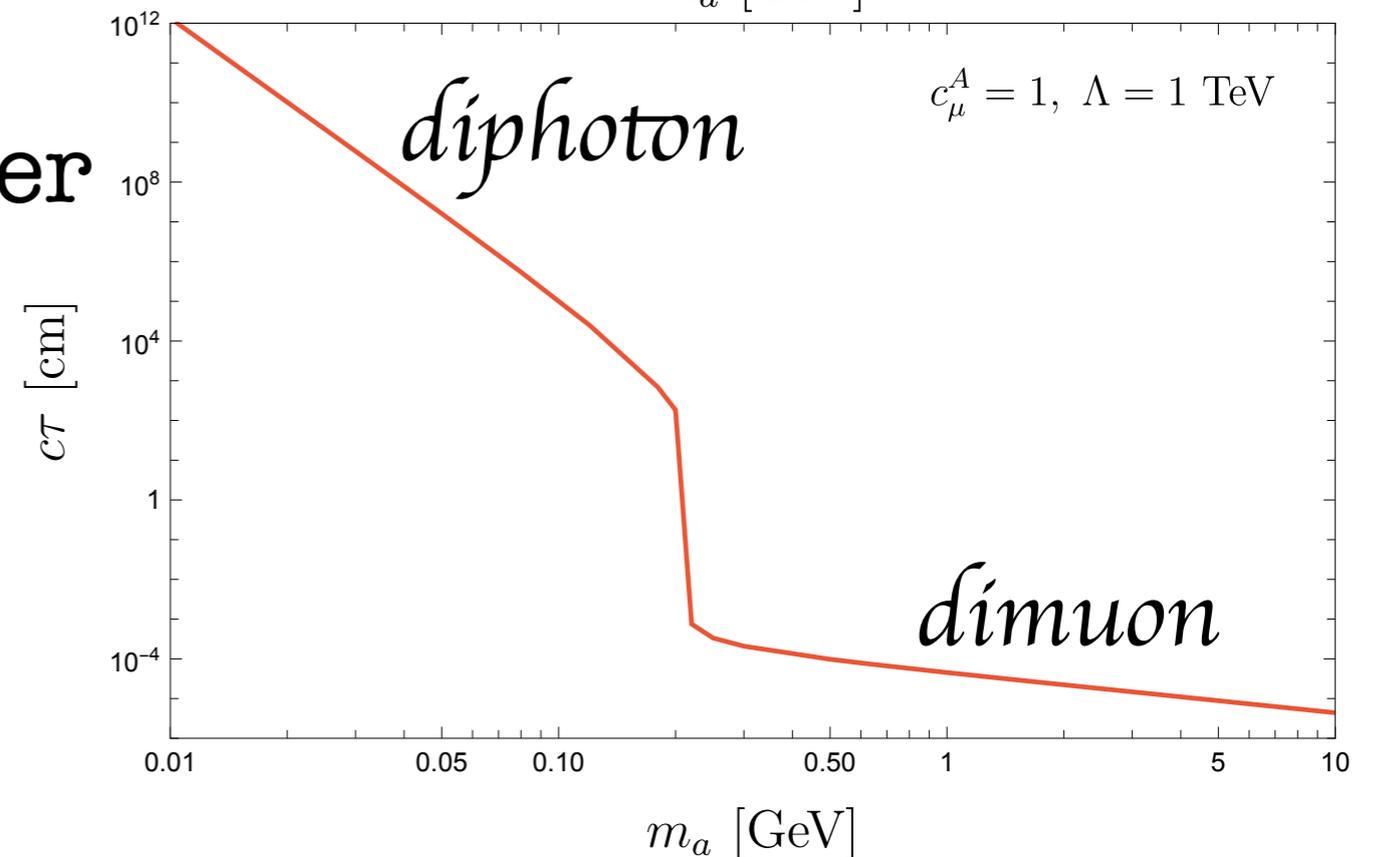EWV: Dielectron at FASER; diphoton at FASER II
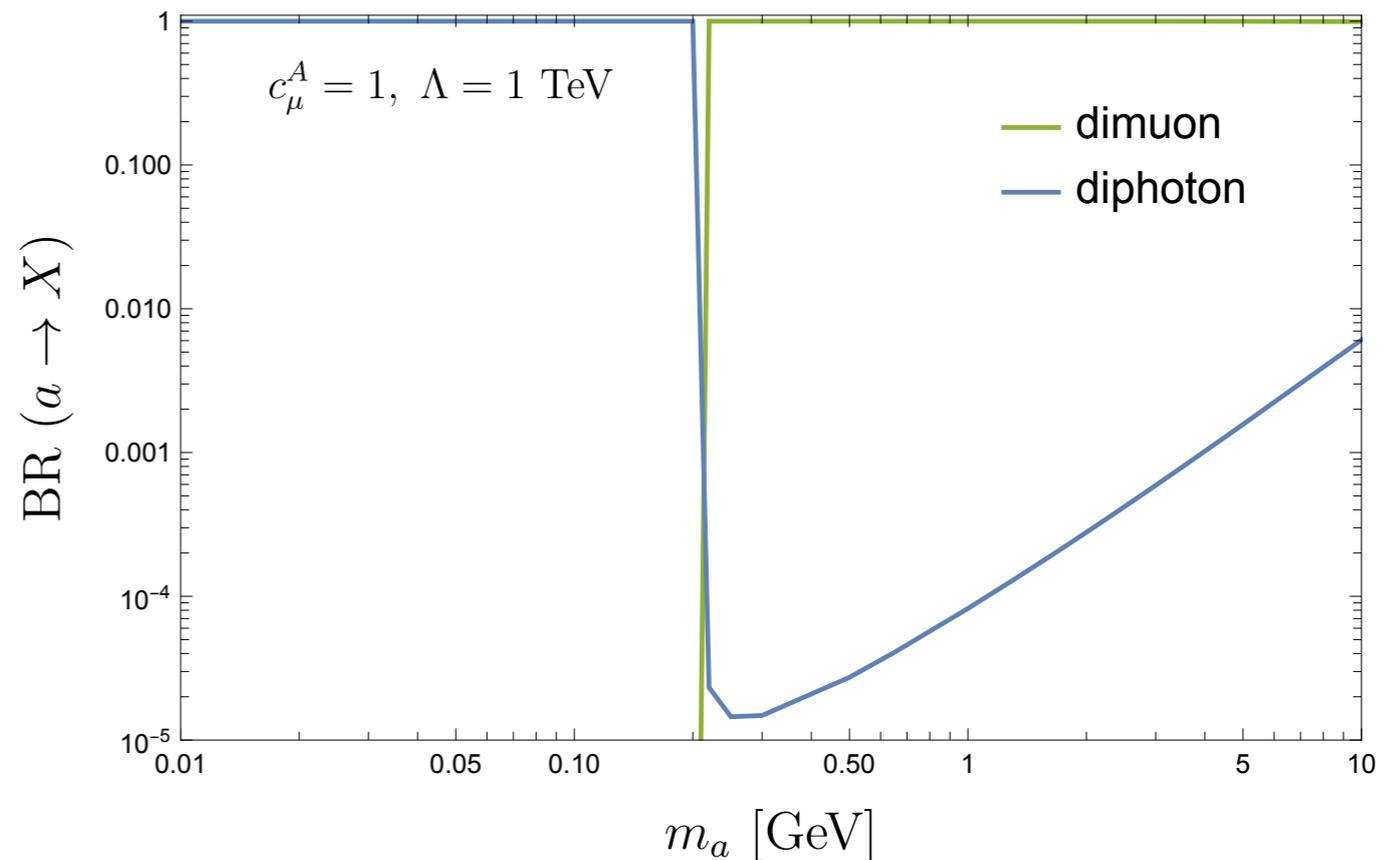
- Decay channels

  dimuon or diphoton:

  threshold at $2m_\mu$

- ALP lifetime:

  - Diphoton, much longer

  - A sharp drop at $2m_\mu$
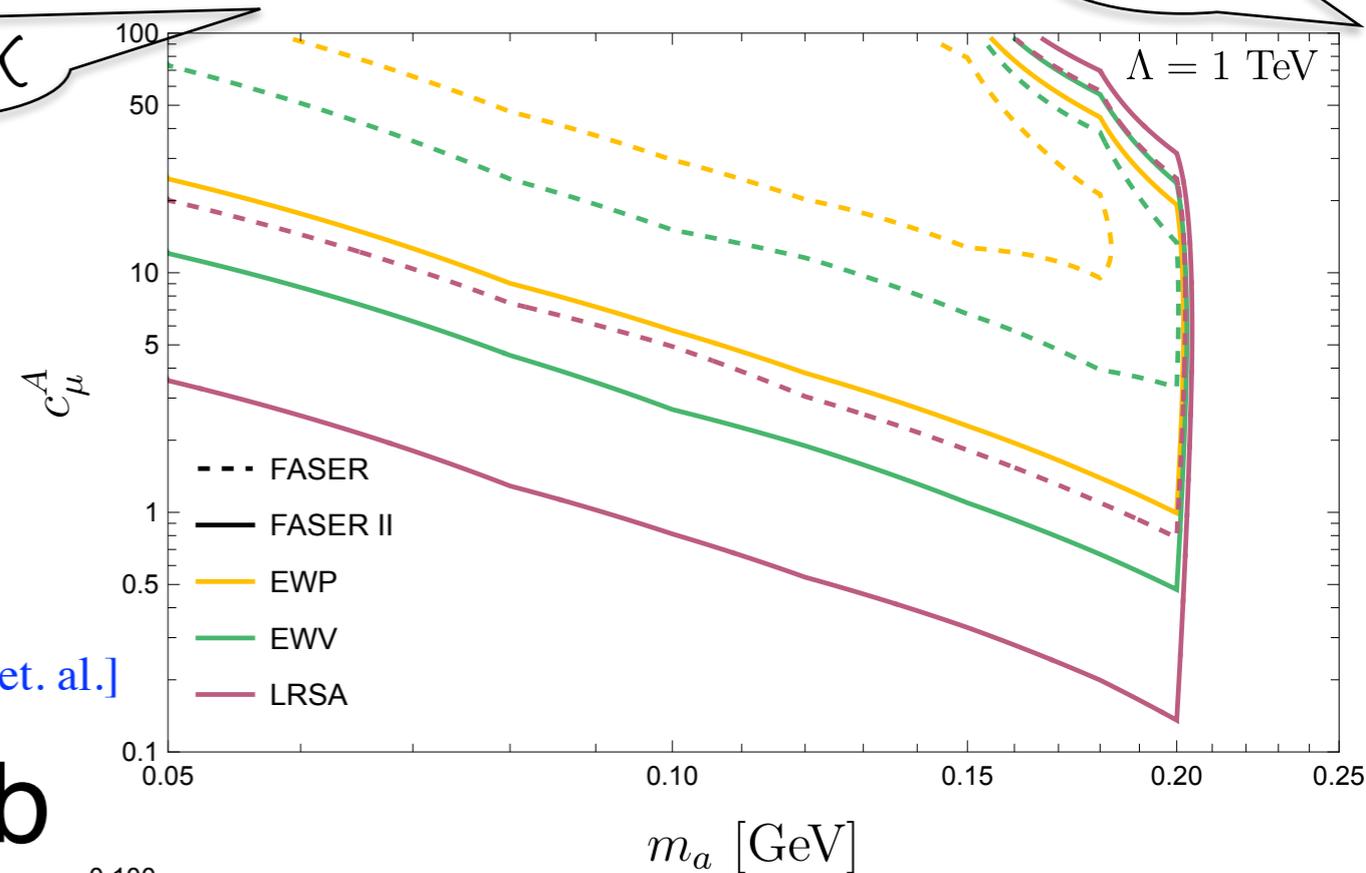
  - Diphoton: far; dimuon: prompt?

$c_\mu^A = 1,\ \Lambda = 1$ TeV

BR $(a \to X)$ vs m_a [GeV] — dimuon, diphoton

$c_\mu^A = 1,\ \Lambda = 1$ TeV

diphoton

dimuon

$c\tau$ [cm] vs m_a [GeV]

- ## FASER (II)
  - Only when below $2m_\mu$
  - An unexplored region
  - To complement others (BaBar, SuperK...) [Cheung et. al.]

- ## Low resonance at LHCb

SuperK

Barbar

$\Lambda = 1$ TeV

c_μ^A

- - - FASER
—— FASER II
—— EWP
—— EWV
—— LRSA

m_a [GeV]

[LHCb Collaboration]

$\mathrm{BR}(B \to K\hat{\pi}) \times \mathrm{BR}(\hat{\pi} \to \mu^+\mu^-)$

- - - 5.1 fb^{-1}, 650 MeV
- - - 5.1 fb^{-1}, 2 GeV
—— 300 fb^{-1}, 650 MeV
—— 300 fb^{-1}, 2 GeV

FCNC, LHCb

$c\tau$ [cm]

[Cheng, **Jiang** and Li]

$\Lambda = 1$ TeV, 300 fb^{-1}
$c_\mu^A = -0.1 c_\mu^V$
$c_\nu = 0$

c_μ^A

—— LRSA at LHCb

m_a [GeV]

Muonphilic ALPs

- FASER (II)
  - Only when below $2m_\mu$
  - An unexplored region
  - To complement others (BaBar, SuperK...) [Cheung et. al.]

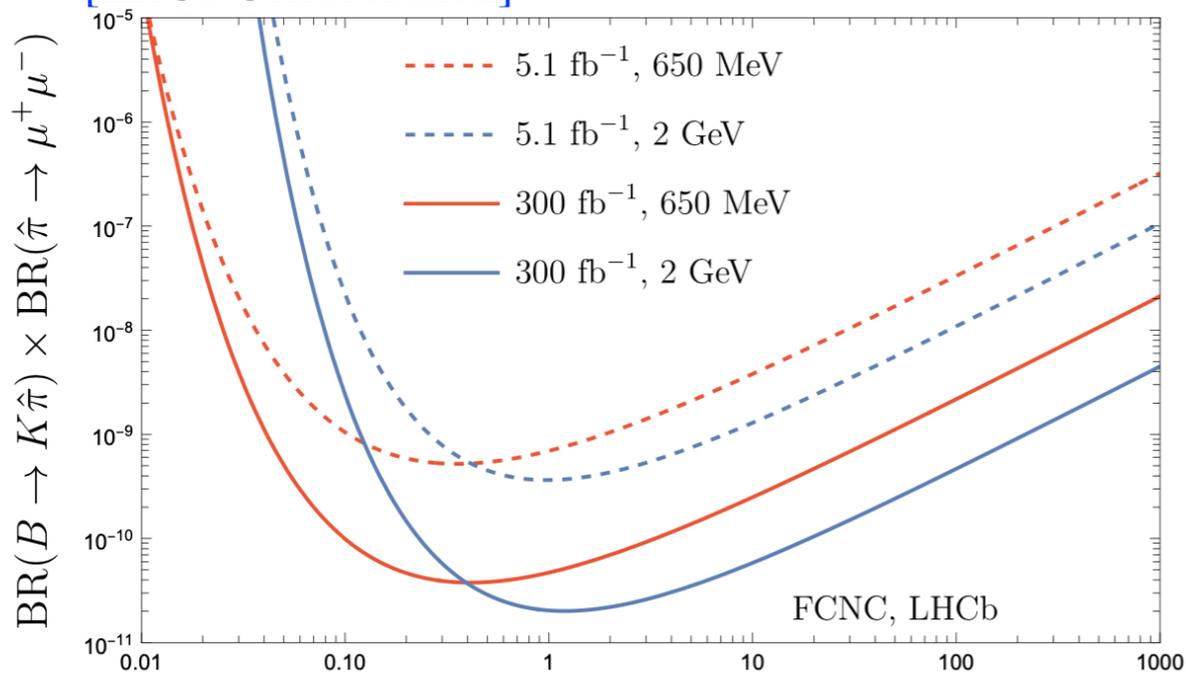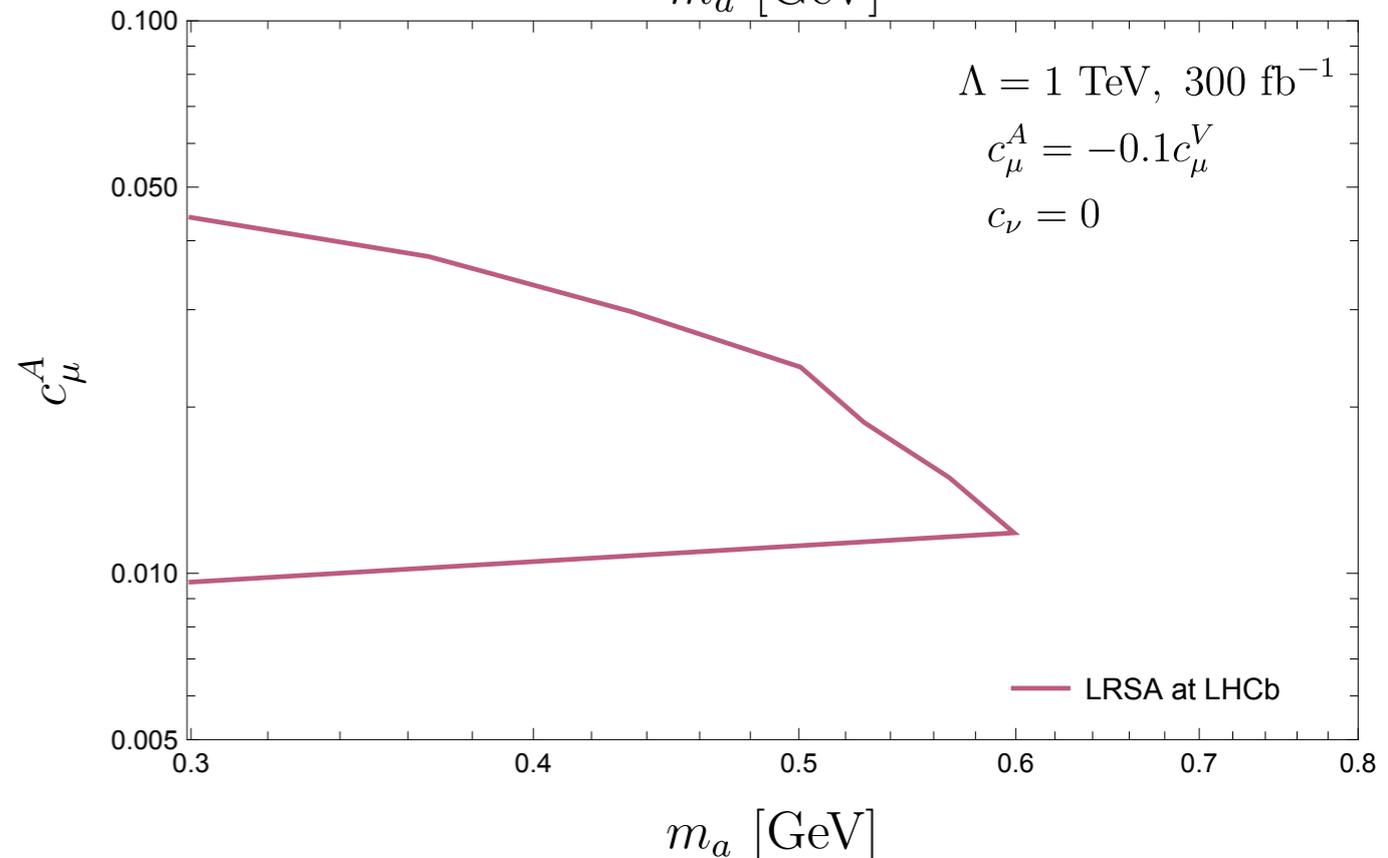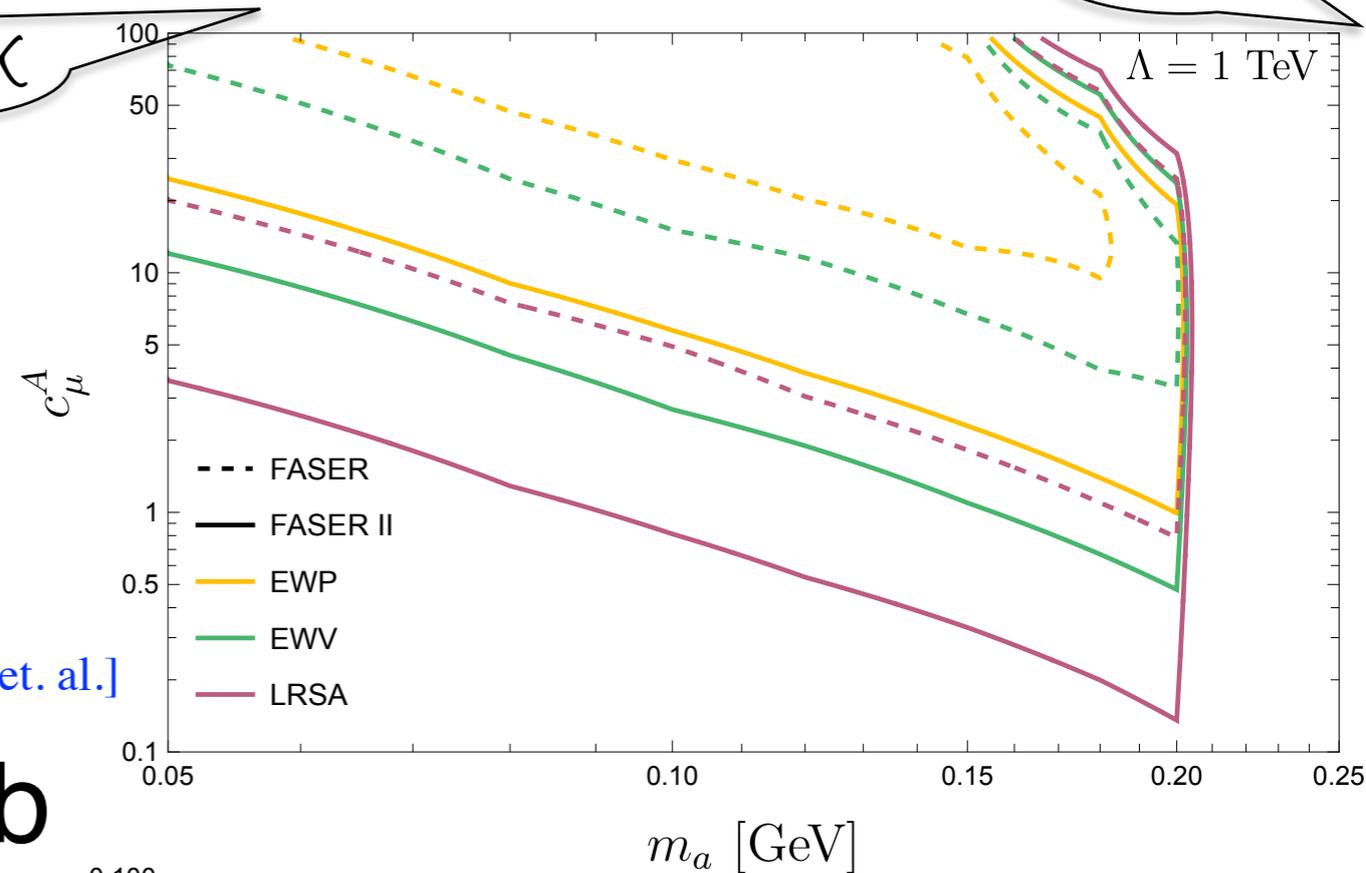- Low resonance at LHCb

[LHCb Collaboration]

SuperK

Barbar

$\Lambda = 1$ TeV

- - - FASER
—— FASER II
—— EWP
—— EWV
—— LRSA

m_a [GeV]

5.1 fb^{-1}, 650 MeV
5.1 fb^{-1}, 2 GeV
300 fb^{-1}, 650 MeV
300 fb^{-1}, 2 GeV

FCNC, LHCb

$c\tau$ [cm]

[Cheng, **Jiang** and Li]

$\Lambda = 1$ TeV, 300 fb^{-1}
$c_\mu^A = -0.1 c_\mu^V$
$c_\nu = 0$

Only LRSA scenario would be probed!

LRSA at LHCb

m_a [GeV]

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Conclusions and Outlooks

- Leptophilic ALPs: exotic flavor decays

- Opportunities at forward detectors (FASER, LHCb…): unexplored regions

  - UV completion? Concrete models?

  - Tau-philic ALPs: any opportunities?

Back-Up

❧ Interactions

[Altmannshofer et. al.]

With integral by parts,

$$a \; \partial_\mu J^\mu_{\mathrm{PQ},\ell} = ic^A_\ell \frac{m_\ell}{\Lambda} \; a\bar{\ell}\gamma_5\ell$$

$$+ \frac{\alpha_{\mathrm{em}}}{4\pi\Lambda}\left[\frac{c^V_\ell - c^A_\ell + c_\nu}{4s^2_W} \; aW^+_{\mu\nu}\tilde{W}^{-,\mu\nu} \right.$$

$$+ \frac{c^V_\ell - c^A_\ell(1 - 4s^2_W)}{2s_W c_W} \; aF_{\mu\nu}\tilde{Z}^{\mu\nu} - c^A_\ell \; aF_{\mu\nu}\tilde{F}^{\mu\nu} +$$

$$\left. \frac{c^V_\ell(1 - 4s^2_W) - c^A_\ell(1 - 4s^2_W + 8s^4_W) + c_\nu}{8s^2_W c^2_W} \; aZ_{\mu\nu}\tilde{Z}^{\mu\nu} \right]$$

$$- \frac{ig}{2\sqrt{2}\Lambda}(c^A_\ell - c^V_\ell + c_\nu) \; a(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu \; + \; \mathrm{h.c.}.$$

ALP-Leptons

Anomalies   A 4-point interaction, usually being ignored

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3-body Decays

$$\frac{\mathrm{BR}(P^+ \to \ell^+ \nu_\ell a)}{\mathrm{BR}(P^+ \to \mu^+ \nu_\mu)} = \frac{m_P^4}{1536\pi^2 m_\mu^2 \Lambda^2} \left(1 - \frac{m_\mu^2}{m_P^2}\right)^{-2} \left[(c_\ell^A - c_\ell^V + c_\nu)^2 f_0(x_P) + \frac{16 m_\ell^2}{m_P^2} c_\ell^{A2} f_1(x_P)\right]$$

- ● Hadronic effects cancellation

- ● EWV: both 2 terms;
  EWP: only the 2nd term.

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