Higgs Probes of axion-like particles

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Introduction

Standard Model

We have problems that cannot be explained within the SM.

Dark matter, Neutrino tiny mass, Baryon asymmetry of the universe etc.

SM must be extended to solve these problems.

Axion-like particles

- Pseudo-scalar particles (do not necessarily solve the strong CP problem)
- They often appear as pseudo-Nambu-Goldstone bosons associated with (approximate) global symmetry.
- Motivated as a candidate for dark matter, solution of various experimental anomalies, and so on.

ALP model

Lagrangian

ALP couples to $SU(2)_L$ and $U(1)_Y$ gauge bosons.

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu} \qquad \widetilde{X}_{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}X_{\rho\sigma}$$

Electroweak symmetry breaking

$$\begin{aligned}\mathcal{L}_{\text{ALP}} = &-\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{2}g_{a\gamma Z}aZ_{\mu\nu}\widetilde{F}^{\mu\nu} \\ &- \frac{1}{4}g_{aZZ}aZ_{\mu\nu}\widetilde{Z}^{\mu\nu} - \frac{1}{2}g_{aWW}aW^+_{\mu\nu}\widetilde{W}^{-\mu\nu} + \ldots,\end{aligned}$$

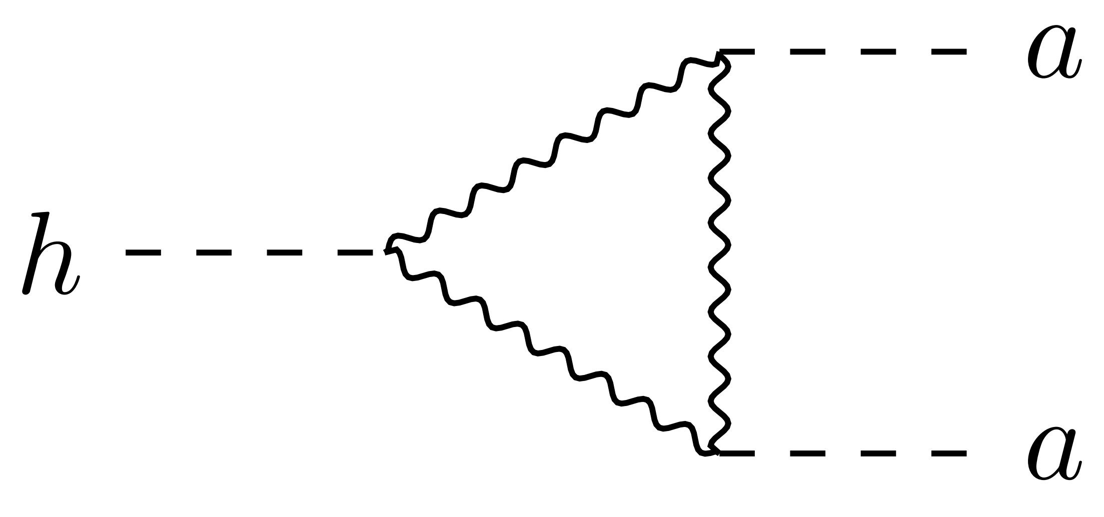
$$\begin{cases} g_{a\gamma\gamma} = \dfrac{4}{f_a}(s_W^2 c_{WW} + c_W^2 c_{BB}), \\ g_{aZ\gamma} = \dfrac{2}{f_a}(c_{WW} - c_{BB})s_{2W}, \\ g_{aZZ} = \dfrac{4}{f_a}(c_W^2 c_{WW} + s_W^2 c_{BB}), \\ g_{aWW} = \dfrac{4}{f_a}c_{WW}, \end{cases}$$

The ALP couplings are controlled by two parameters. We take g_{aWW} and $g_{a\gamma\gamma}$ as input parameters.

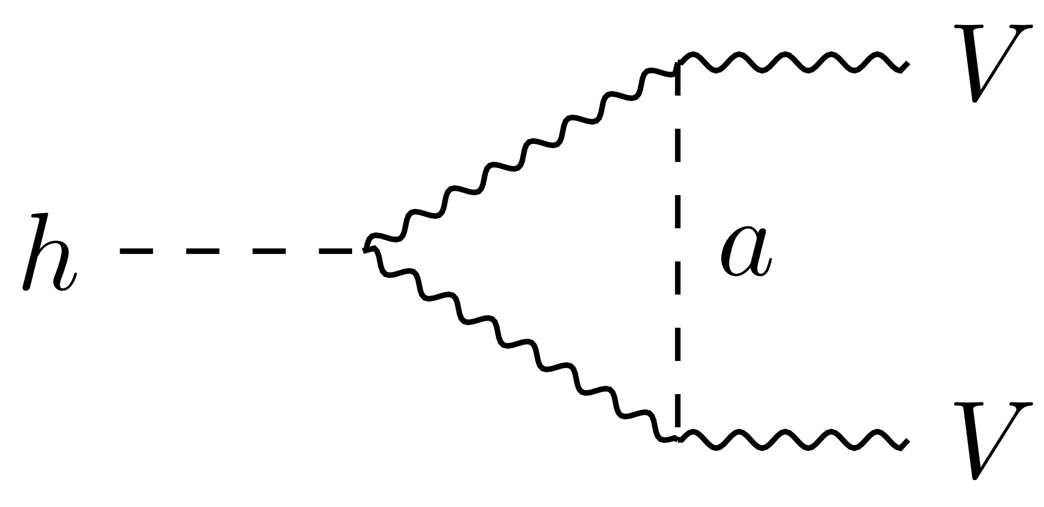
Higgs boson decay

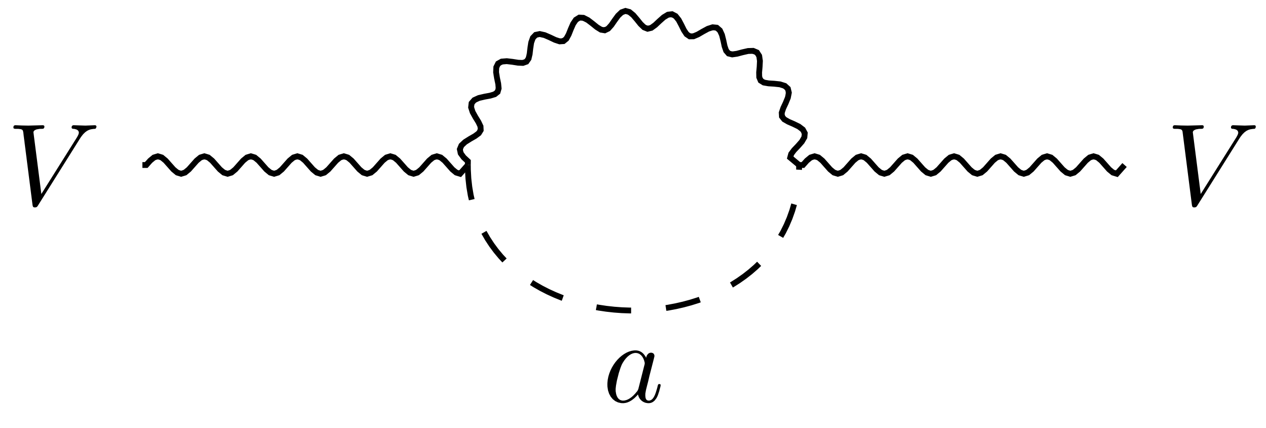
Higgs boson decays into a pair of ALPs at the one-loop level. Bauer, Neubert, Thamm, JHEP12 (2017)

* $h \to Za$ vanishes at the one-loop level.



At the same time, ALP affects the Higgs boson decays into the SM particles.





We study the testability of the ALP model via Higgs boson decays.

* At the one-loop level, $h \to Za$ vanishes, and there is no ALP contribution to $h \to gg$.

Decay modes

$$h \to f\bar{f},\ WW^*,\ ZZ^*,\ Z\gamma,\ \gamma\gamma,\ aa$$

We calculated ALP contributions to the partial decay widths of the Higgs boson based on the on-shell renormalization scheme.

Bohm, Spiesberger, Hollik, Fortsch. Phys. 34 (1986)
Hollik, Fortsch. Phys. 38 (1990)

It is found that the ALP corrections to $h \to f\bar{f}$ are canceled flavor independently. Thus, the relevant decay modes are $h \to WW^*$, ZZ^*, $Z\gamma$, $\gamma\gamma$ and aa.

To compare with the Higgs measurements, we introduce the scaling factor.

$$\kappa_{XY} = \sqrt{\frac{\Gamma(h \to XY)}{\Gamma(h \to XY)_{\rm SM}}}$$

Case with $g_{aWW} = 0$

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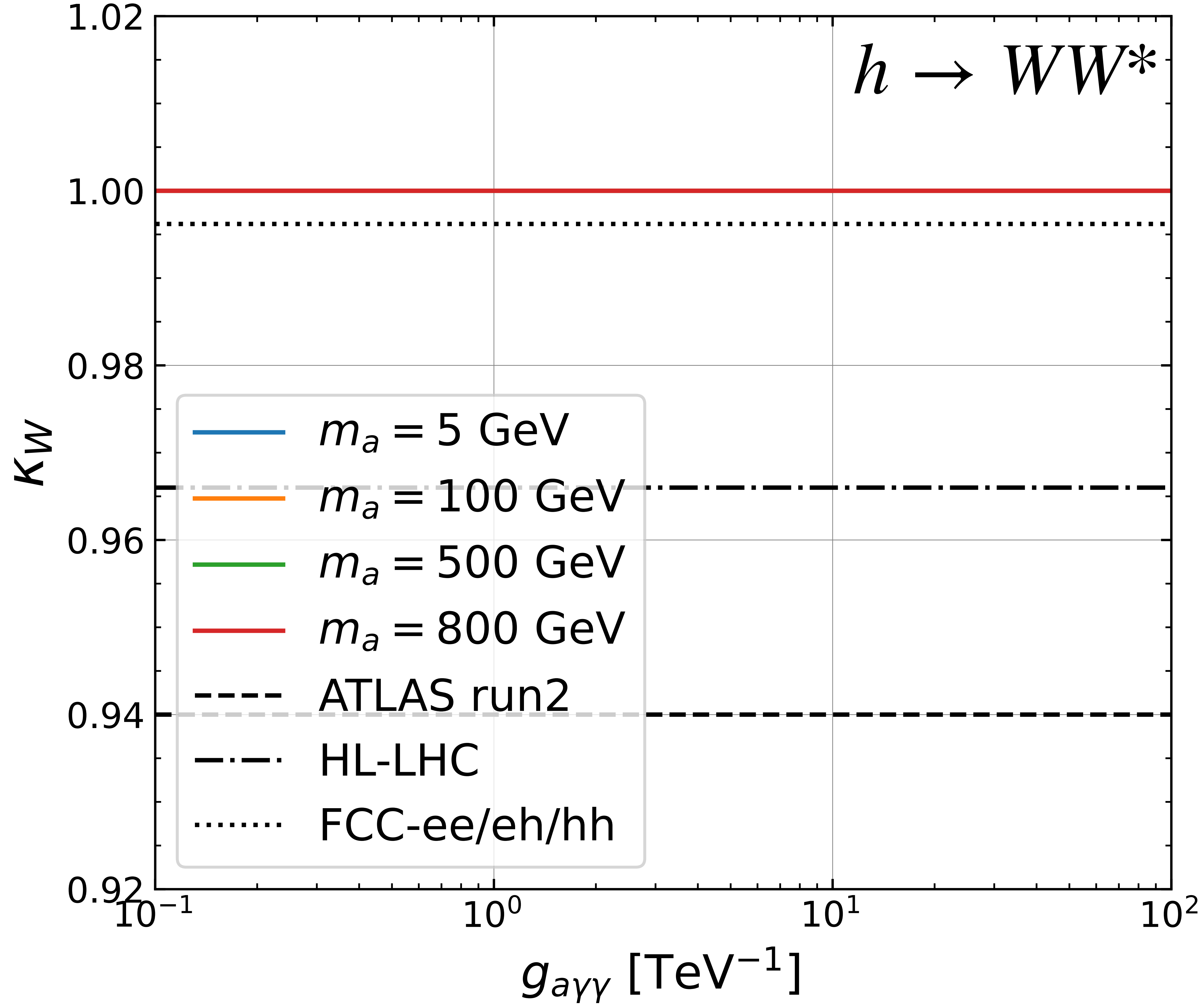

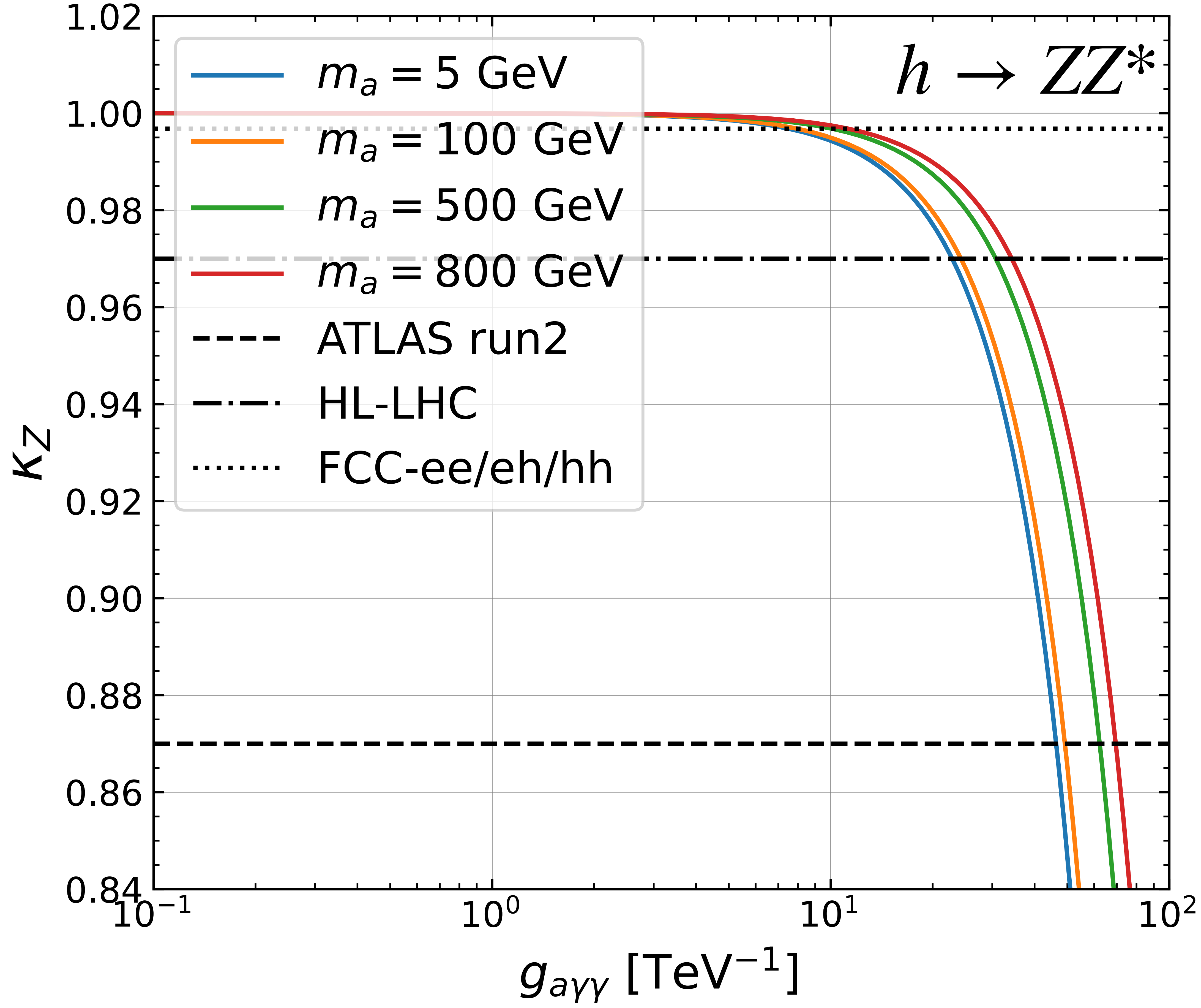

We have no ALP contributions to the $h \to WW^*$.

ALP contributions are less sensitive to m_a and become effective for $10\ \mathrm{TeV}^{-1}$.

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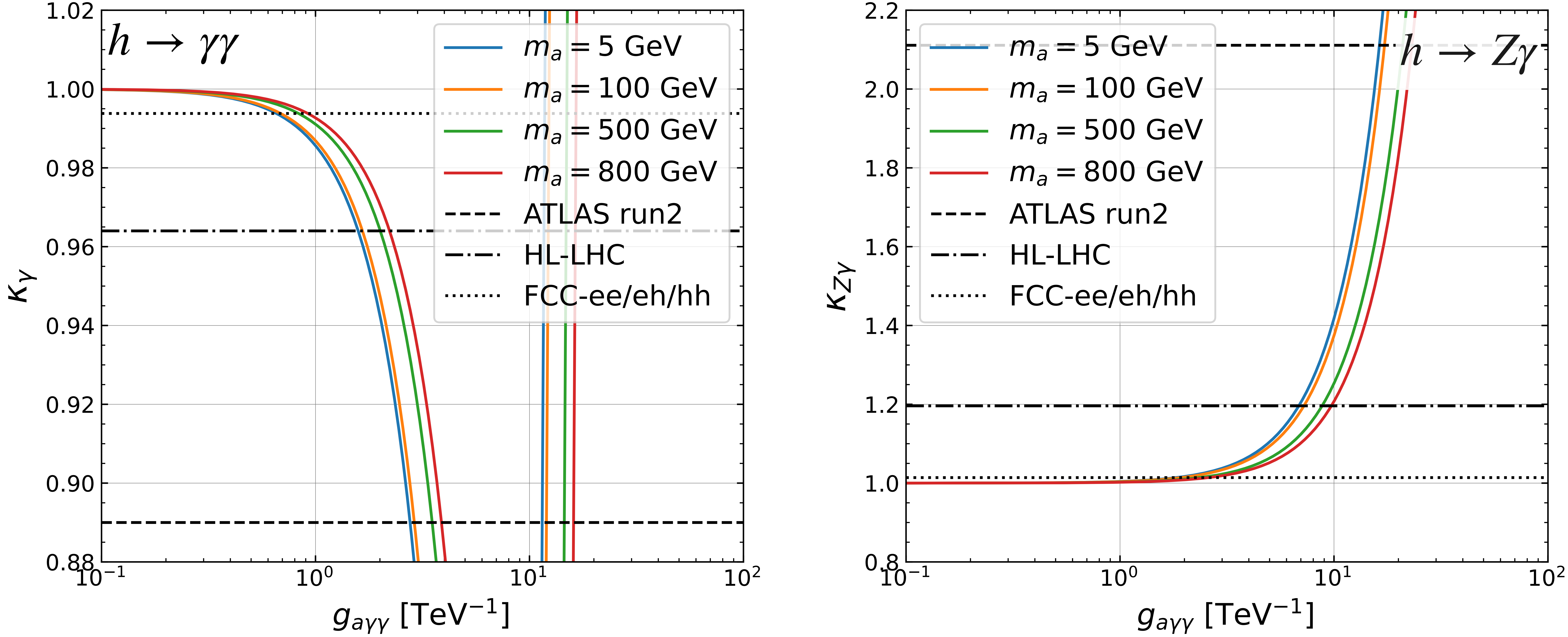

ALP contributions interfere destructively with the SM one for $h \to \gamma\gamma$. $\Gamma(h \to \gamma\gamma) \propto |\mathcal{M}_{\rm SM} + \mathcal{M}_{\rm ALP}|^2$

They become effective for $1\ \mathrm{TeV}^{-1}$, and $h \to \gamma\gamma$ is the best probe.

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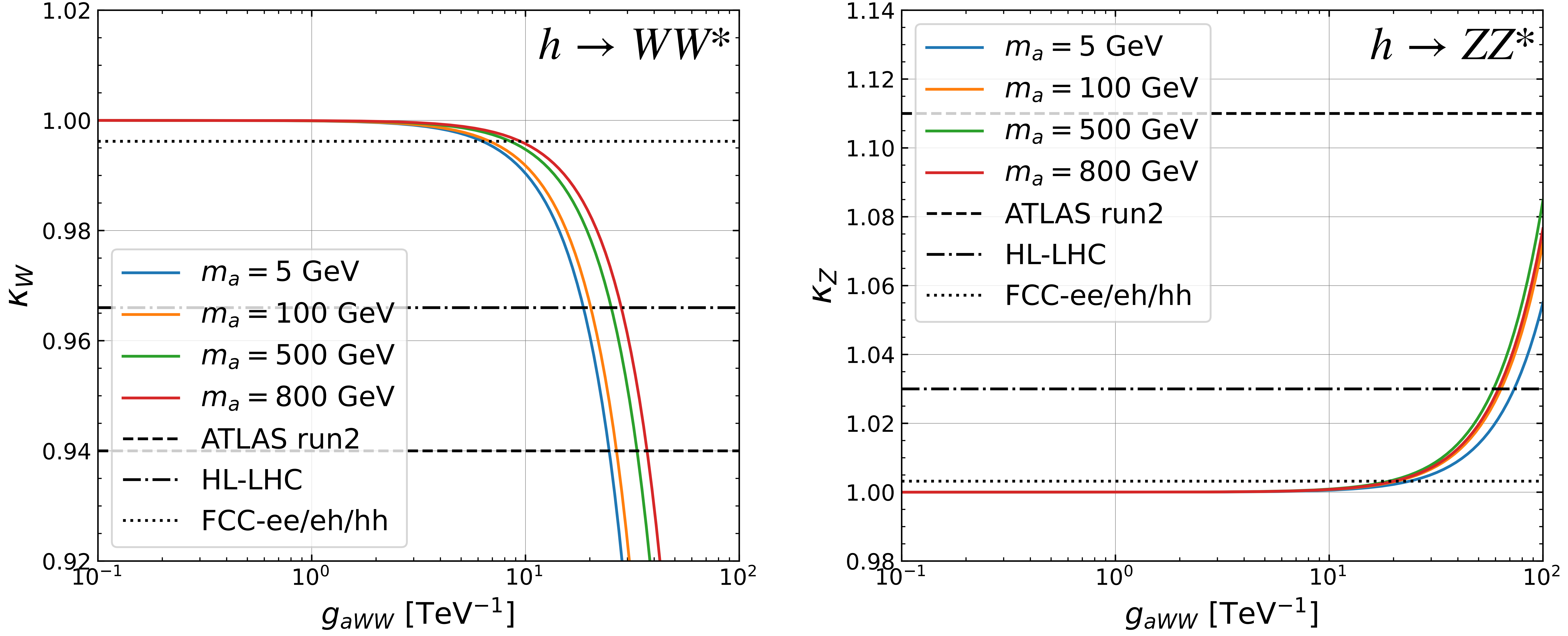
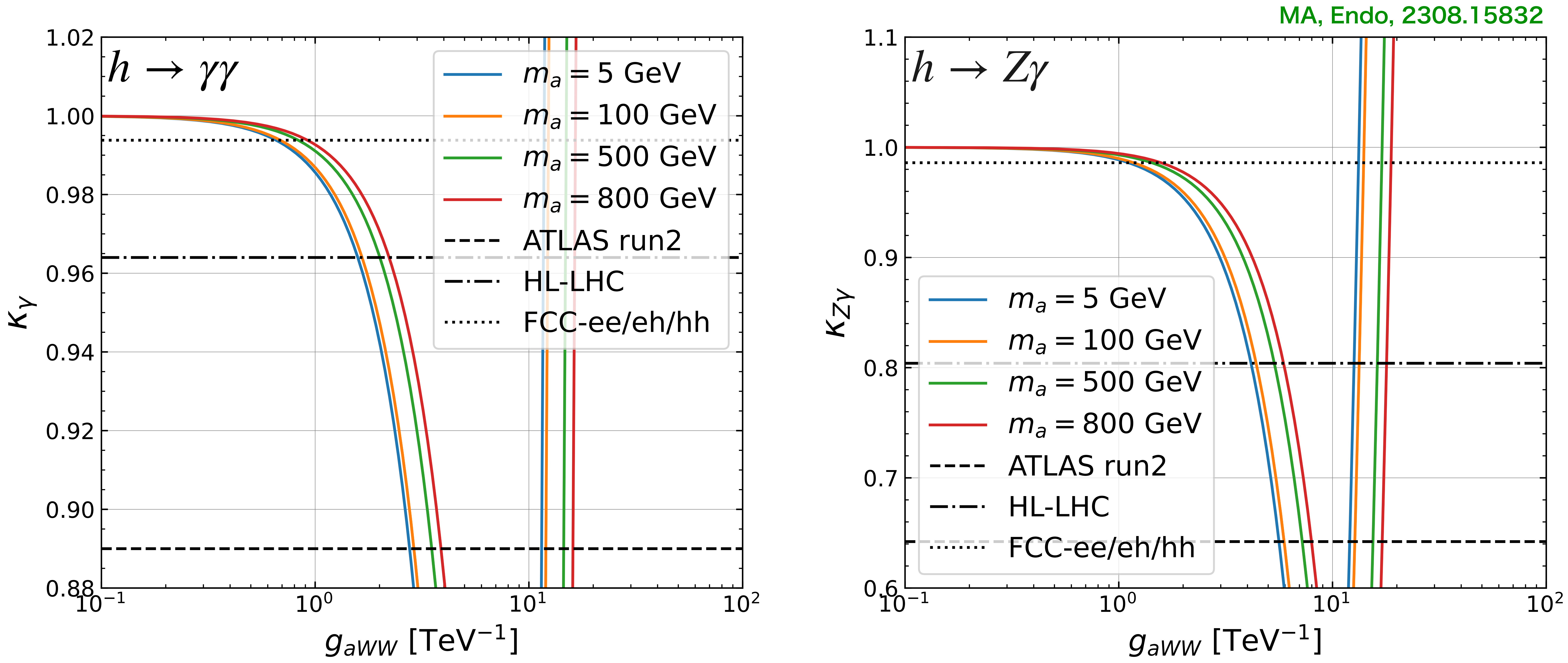


ALP contributions are less sensitive to m_a and become effective for $10\ \mathrm{TeV}^{-1}$.



ALP contributions interfere destructively with the SM one both for $h \to \gamma\gamma$ and $h \to Z\gamma$.

They become effective for $1\ \mathrm{TeV}^{-1}$, and $h \to \gamma\gamma$ is the best probe.

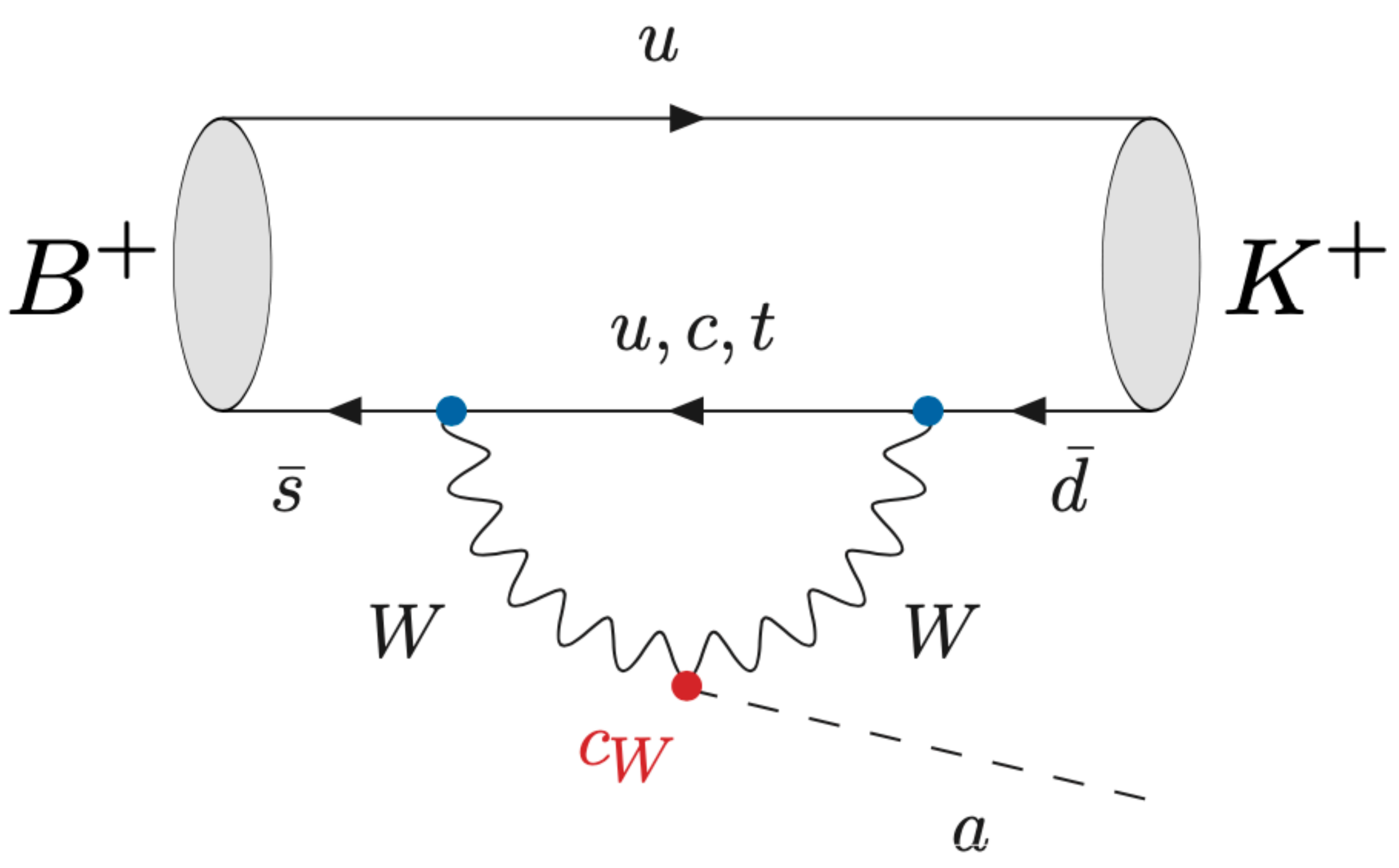
Flavor/Collider constraints

Izaguirre, Lin and Shuve PRL118 (2017)
Gavela et al. EPJC79 (2019)
Bauer et al. JHEP09 (2022)

$B \to Ka$

$$\Gamma(B^+ \to K^+ a) = \frac{m_B^3}{64\pi} \left|\Delta g^{\rm eff}_{abs}\right|^2 f_0(m_a^2) \lambda_{Ka}^{1/2} \left(1 - \frac{m_K^2}{m_B^2}\right)$$

$$g^{\rm eff}_{ad_i d_j} = -\frac{3}{4 s_W^2} \frac{\alpha}{4\pi} g_{aWW} \sum_{q=u,c,t} V_{qi} V_{qj}^* G(x_q)$$



Flavor-violating decay into ALP occurs via the W-boson exchange diagram.

- $B \to Ka$, $a \to \gamma\gamma$: constraint for $0.175 < m_a < 4.78$ GeV
- $B \to Ka$, $a \to \mu^+\mu^-$: constraint for $0.250 < m_a < 4.70$ GeV

$m_a \lesssim 5$ GeV is strongly constrained by the flavor measurements.

Light ALP ($m_a \leq m_Z$)

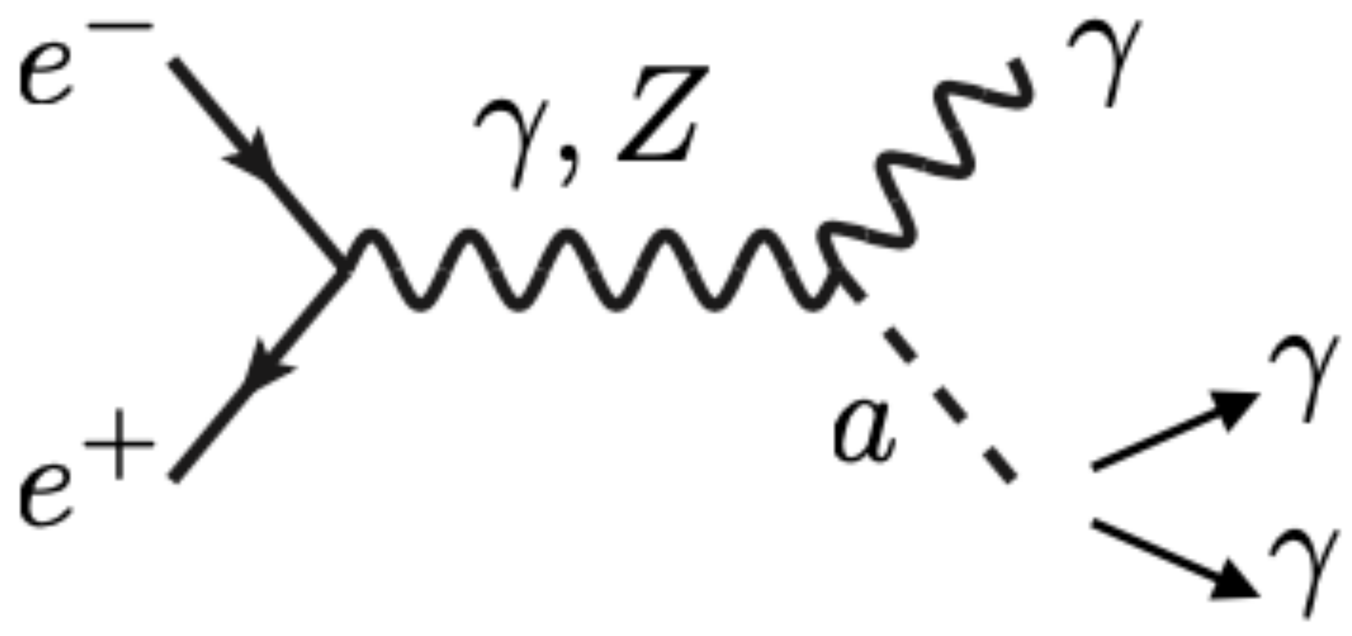
Bauer, Neubert, Thamm, JHEP12 (2017)
Craig, Hook, Kasko, JHEP09 (2018)

$a \to \gamma\gamma$

Bound from $e^+e^- \to a\gamma,\ a \to \gamma\gamma$

On-shell Z exchange (LEP-I): $aZ\gamma$ coupling

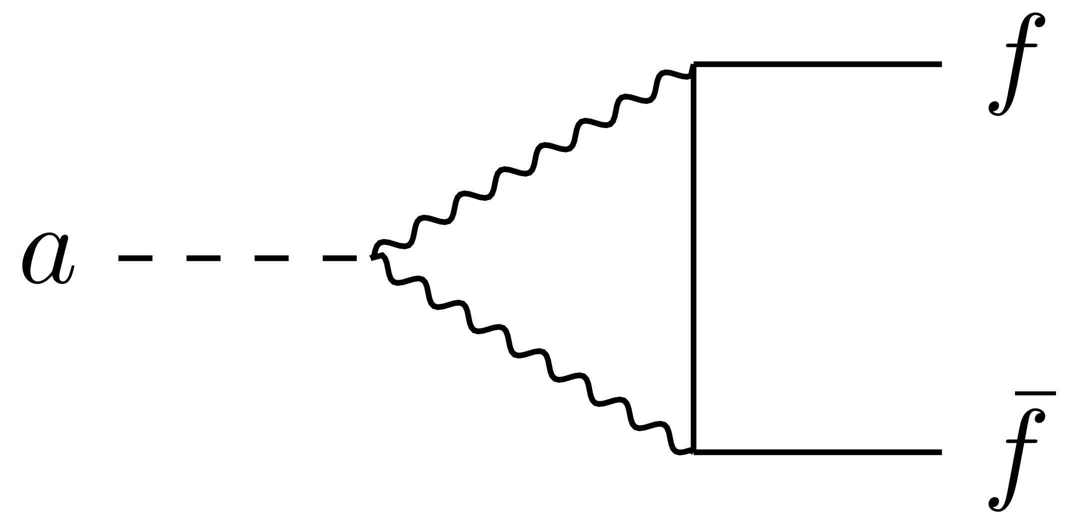
Off-shell γ, Z exchange (LEP-II): $aZ\gamma$ and $a\gamma\gamma$ couplings



$a \to jj$

On-shell Z exchange: $aZ\gamma$ coupling

Sensitive even if $g_{a\gamma\gamma} = 0$



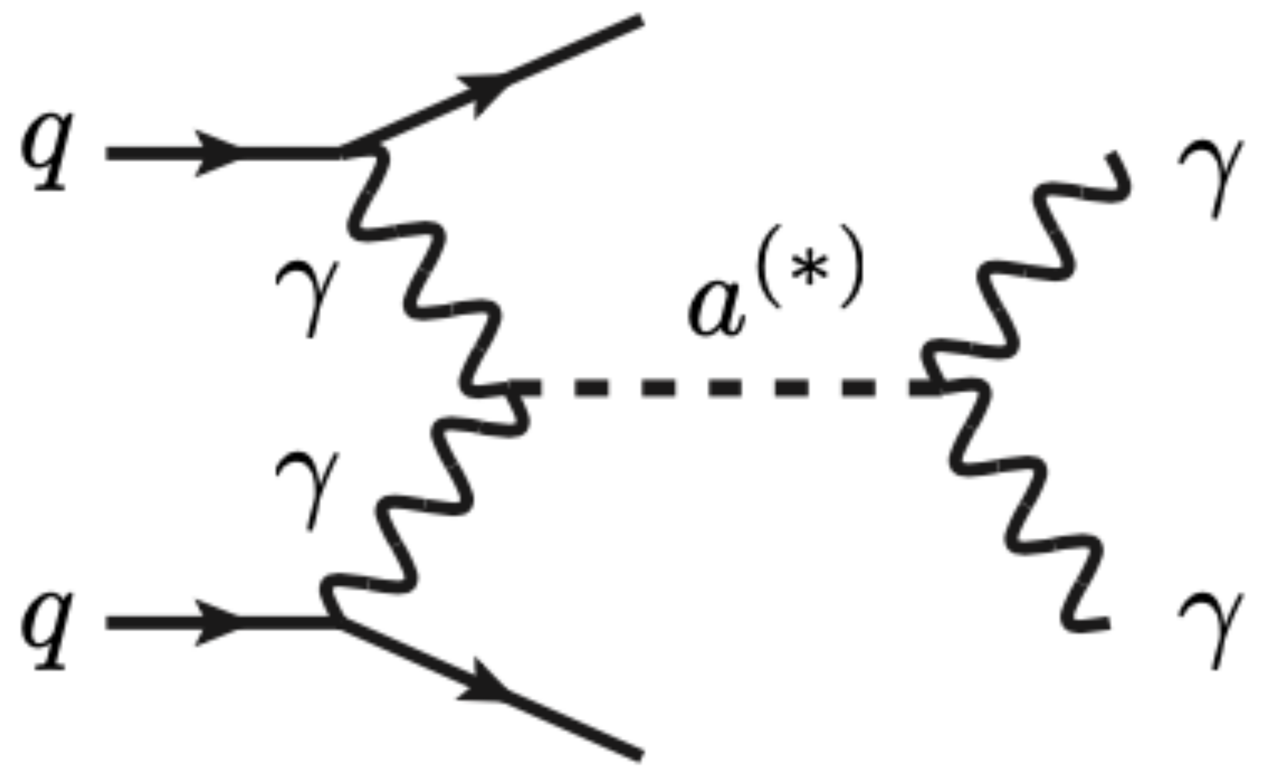
Heavy ALP ($m_a > m_Z$)

Bauer, Neubert, Thamm, JHEP12 (2017)
Craig, Hook, Kasko, JHEP09 (2018)

$a \to \gamma\gamma$

Bound from $pp, \mathrm{PbPb} \to \gamma\gamma \to a^* \to \gamma\gamma$

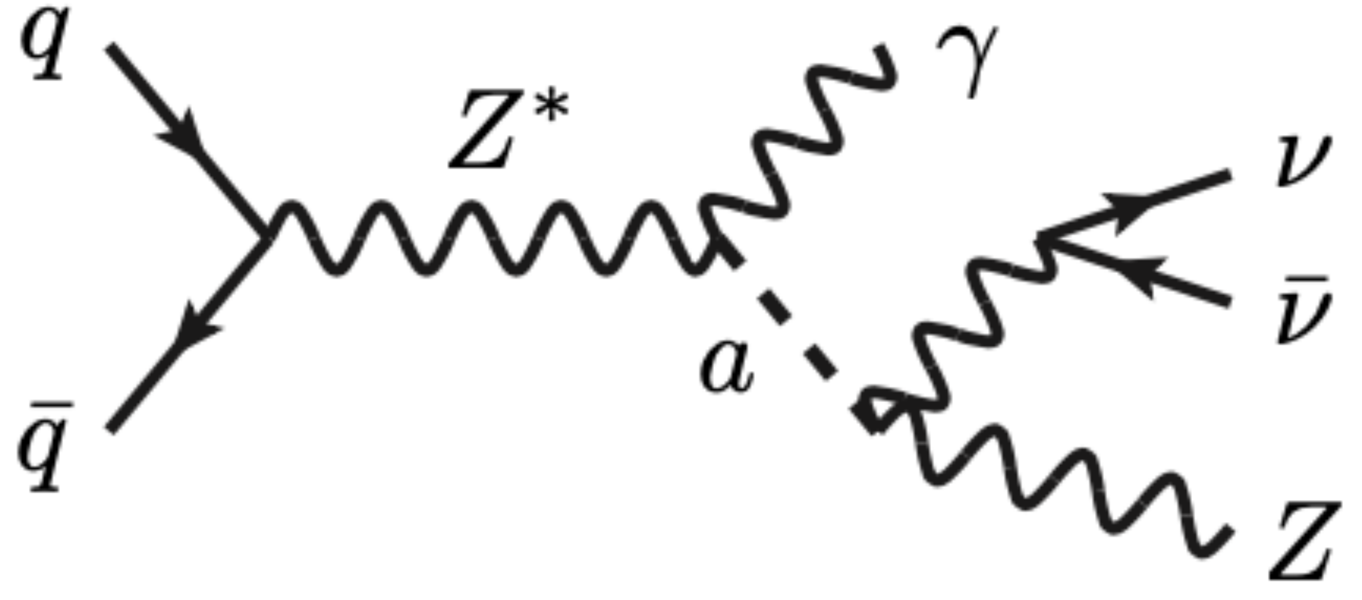
$g_{a\gamma\gamma}$ is tightly constrained.



$a \to Z\gamma$

Bound from $(pp \to)q\bar{q} \to Z^* \to a\gamma,\ a \to Z\gamma \to \nu\bar{\nu}\gamma$

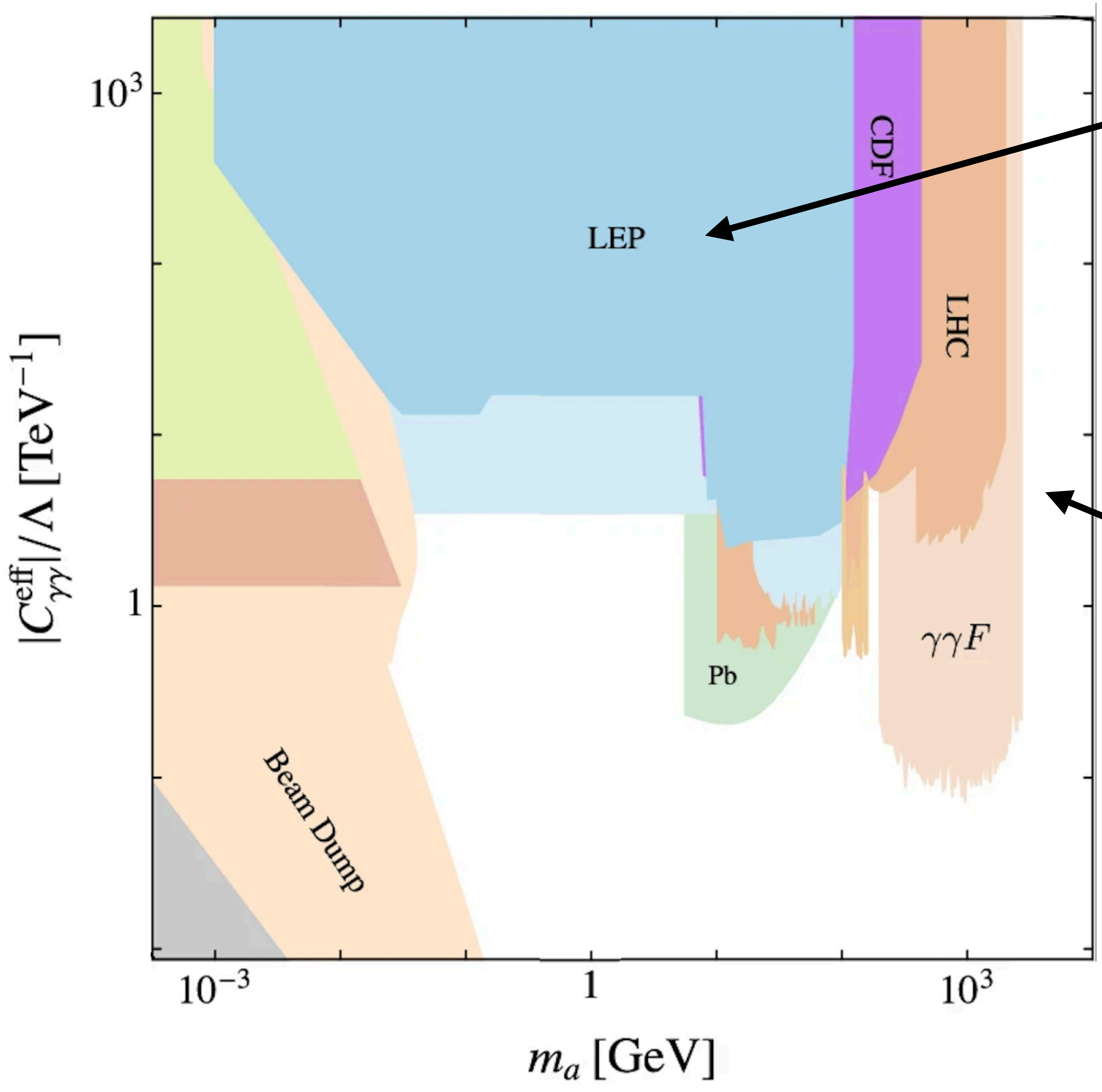
Constraint for m_a < 500 GeV



Constraint on $g_{a\gamma\gamma}$

Bauer, Neubert, Thamm, JHEP12 (2017)

$$g_{a\gamma\gamma} = 4e^2 C_{\gamma\gamma}/\Lambda$$

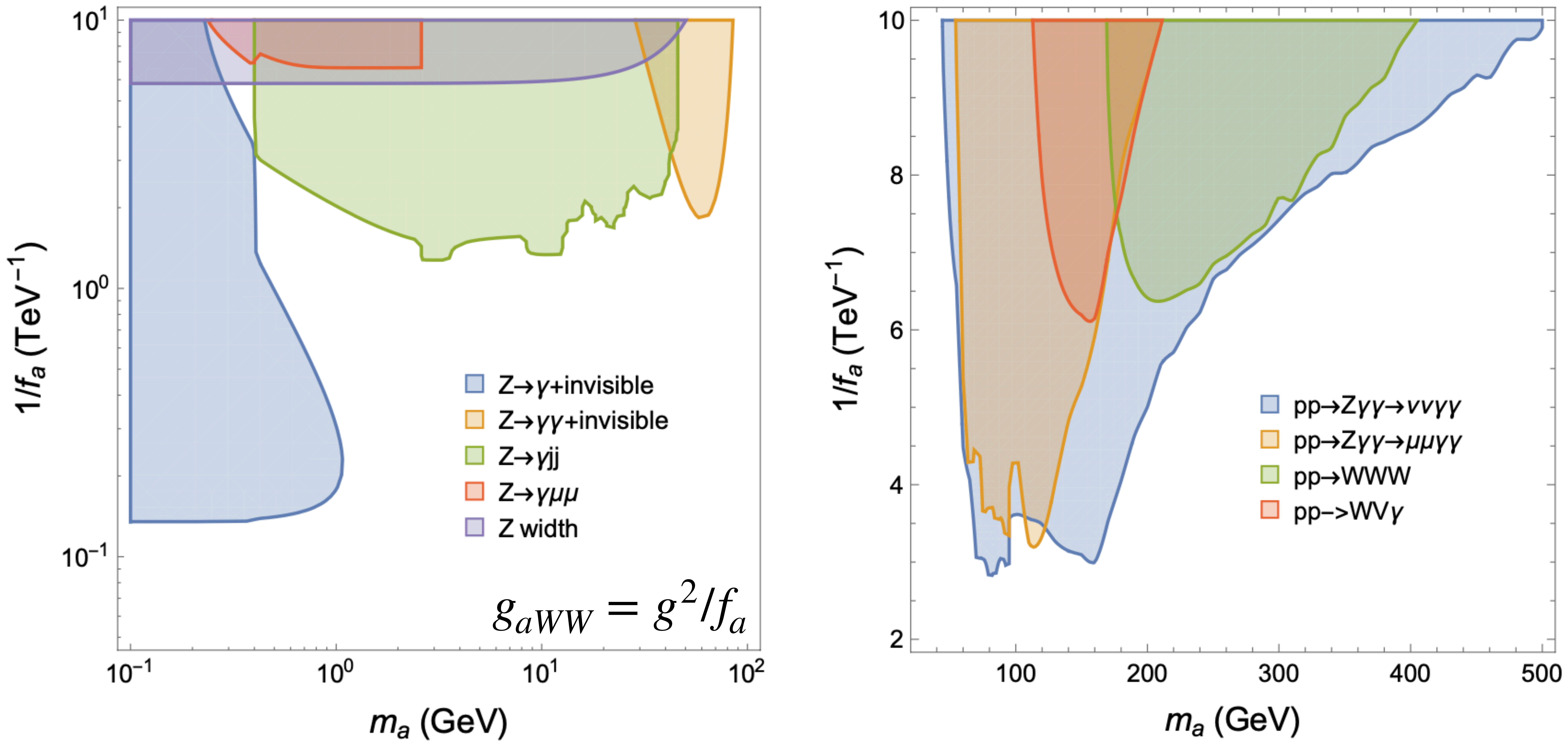


$e^+e^- \to a\gamma$

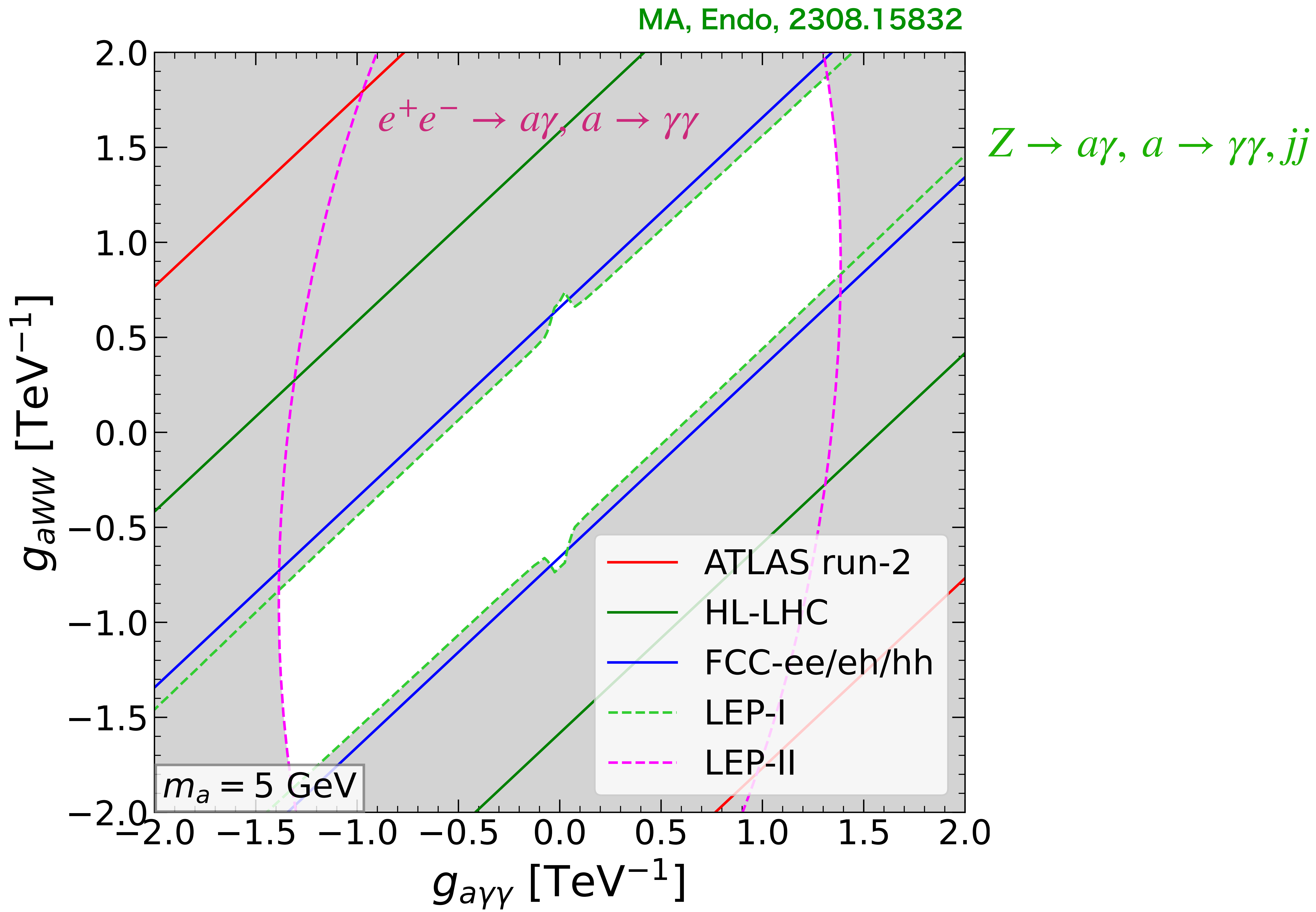
$a \to \gamma\gamma$ from pp and PbPb

Constraint on the case with $g_{a\gamma\gamma} = 0$

Craig, Hook, Kasko, JHEP09 (2018)



Light ALP case ($m_a = 5$ GeV)



LEP results give strong constraints for light ALP case ($m_a \lesssim m_Z$).

Heavy ALP case ($m_a > m_Z$)

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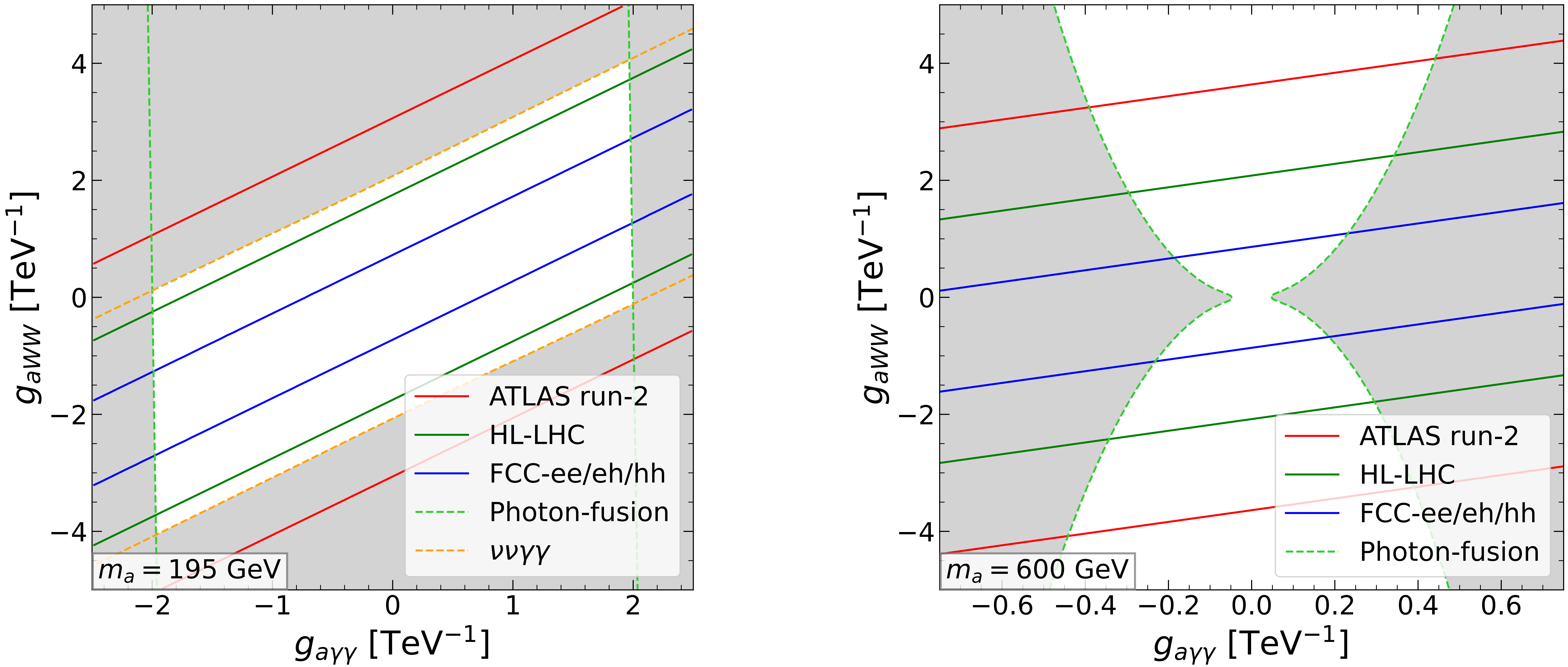

$h \to \gamma\gamma$ provides a significant probe, especially for $g_{a\gamma\gamma} \approx 0$.

ALP mass dependence

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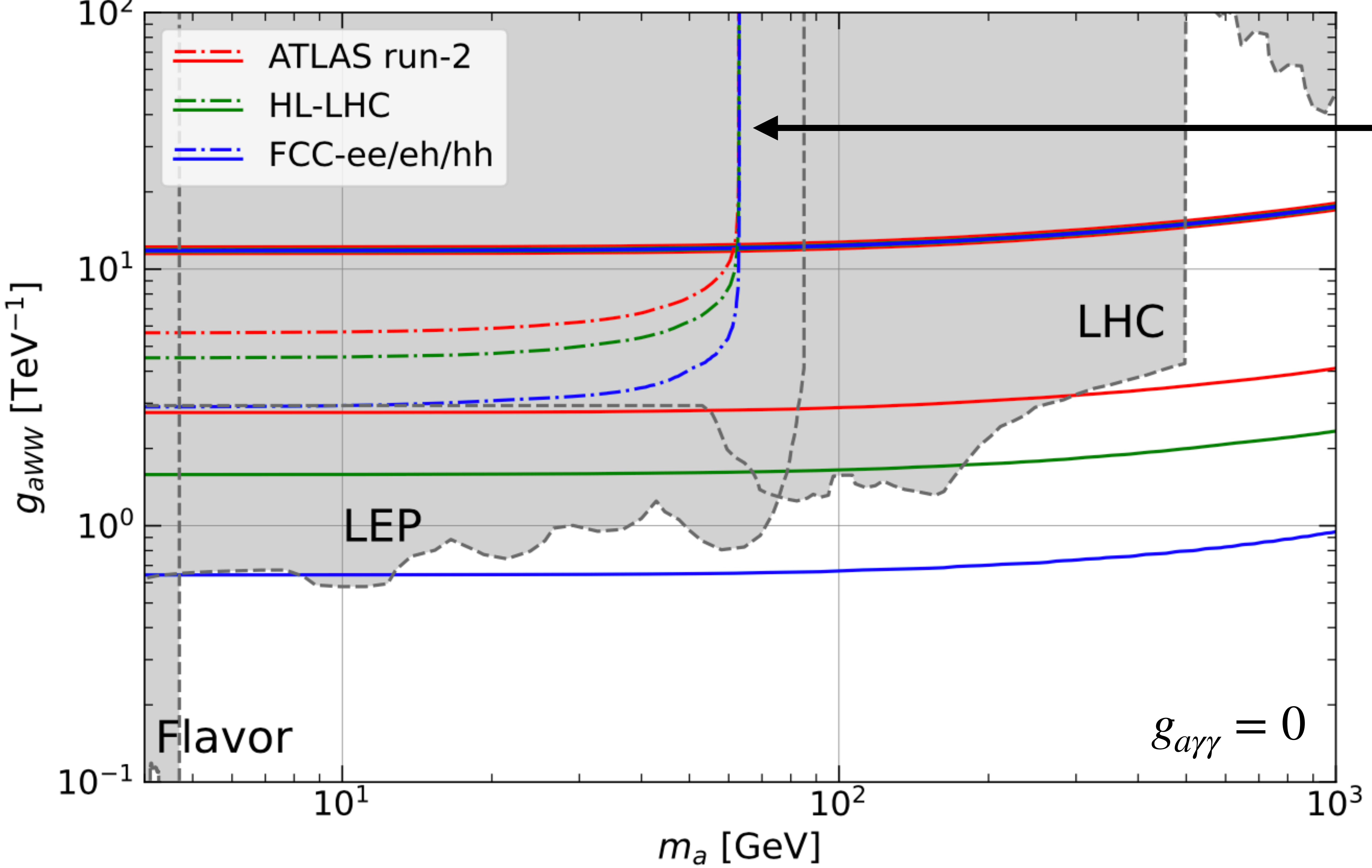
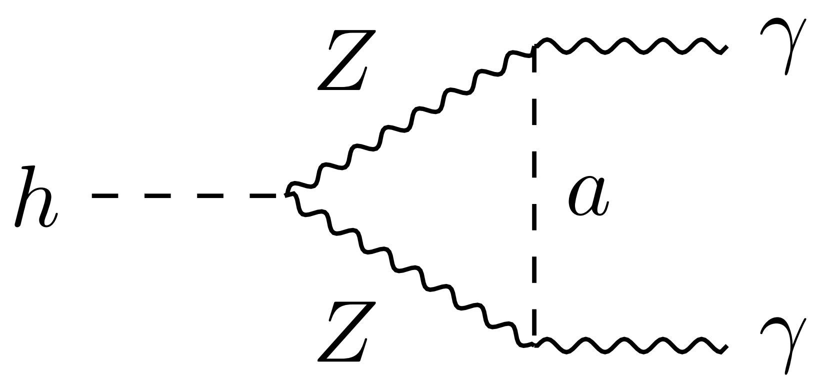


Total width $(H \to aa)$

$H \to \gamma\gamma$ decay



We obtained new contracts for heavy mass regions by the Higgs measurement.

Summary

What is new

We studied ALP contributions to the Higgs boson decays.

Full one-loop corrections are newly calculated for all Higgs decay modes,

$$h \to f\bar{f},\ WW^*,\ ZZ^*,\ Z\gamma,\ \gamma\gamma,\ aa$$

What we found

ALP contributions to $h \to f\bar{f}$ are canceled flavor independently.

Among the decay channels, $h \to \gamma\gamma$ provides the best sensitivity, and we obtained new contracts for heavy mass regions.

Back up slides