Electroweak precision test of axion-like particles

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Based on [hep-ph] 2302.11377

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Introduction

Standard Model

We have problems that cannot be explained within the SM.

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

SM must be extended to solve these problems.

Axion-like particles

- Pseudo-scalar particles (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.

$$\mathcal{L}_{\mathrm{ALP}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

Electroweak symmetry breaking

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

$$\left\{\begin{aligned} g_{a\gamma\gamma} &= \frac{4}{f_a}(s_W^2 c_{WW} + c_W^2 c_{BB}),\\ g_{aZ\gamma} &= \frac{2}{f_a}(c_{WW} - c_{BB})s_{2W},\\ g_{aZZ} &= \frac{4}{f_a}(c_W^2 c_{WW} + s_W^2 c_{BB}),\\ g_{aWW} &= \frac{4}{f_a}c_{WW},\end{aligned}\right.$$

The ALP couplings are controlled by two independent parameters.

We study the ALP model by the electroweak precision test (EWPT).

Electroweak precision test

Z-pole observables are precisely measured at the LEP.

SM is consistent with EWPT except for the recent CDF measurement. CDF, Science 376 (2022)

PDG values w/o CDF

Recent CDF result

	Measurement
$\alpha_s(m_Z^2)$	0.1177 ± 0.0010
$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$	0.02766 ± 0.00010
m_t [GeV]	172.69 ± 0.30
m_h [GeV]	125.21 ± 0.17
m_W [GeV]	80.377 ± 0.012
	80.4133 ± 0.0080
Γ_W [GeV]	2.085 ± 0.042
$\mathcal{B}(W \to \ell\nu)$	0.10860 ± 0.00090
$\mathcal{A}_\ell$ (LEP)	0.1465 ± 0.0033
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021

	Measurement
m_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4955 ± 0.0023
σ_h^0 [nb]	41.4802 ± 0.0325
R_ℓ^0	20.7666 ± 0.0247
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
R_b^0	0.21629 ± 0.00066
R_c^0	0.1721 ± 0.0030
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035
$\mathcal{A}_b$	0.923 ± 0.020
$\mathcal{A}_c$	0.670 ± 0.027

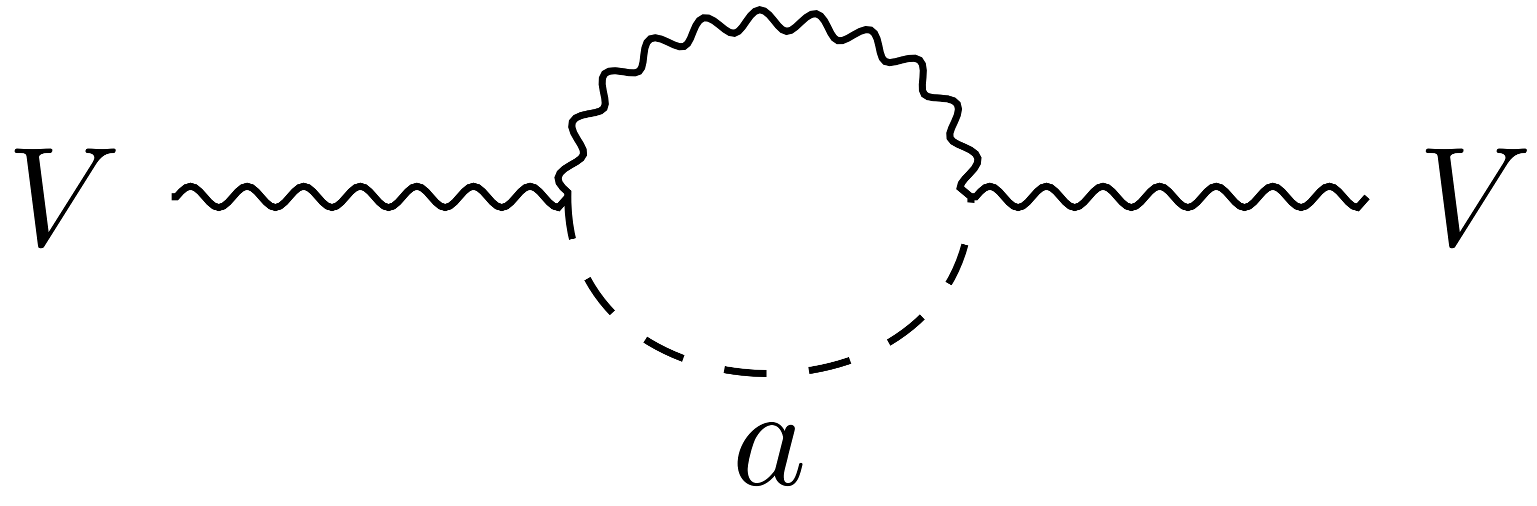
SM vs PDG: $< 2\sigma$ (consistent)

SM vs CDF: $\sim 7\sigma$

We perform EWPT both w/ and w/o CDF result.

Oblique correction

ALP contributes to the EWPOs via vacuum polarization.



New physics contributions via vacuum polarization can be parametrized by the oblique parameters, S, T and U.

Peskin, Takeuchi PRD46 (1992)

Hagiwara, Matsumoto, Haidt, Kim, Z. Phys. C64 (1994)

$$S = 16\pi \, \mathrm{Re}\left[\Pi^{3Q}_{T,\gamma}(m_Z^2) - \Pi^{33}_{T,Z}(0)\right]$$

$$T = \frac{4\sqrt{2}\,G_F}{\alpha} \mathrm{Re}\left[\Pi^{33}_T(0) - \Pi^{11}_T(0)\right]$$

$$U = 16\pi \, \mathrm{Re}\left[\Pi^{33}_{T,Z}(0) - \Pi^{11}_{T,W}(0)\right]$$

$$\Pi^{ab}_{T,V}(k^2) = \frac{\Pi^{ab}_T(k^2) - \Pi^{ab}_T(m_V^2)}{k^2 - m_V^2}$$

EWPT can be performed only by using STU parameters if other effects are negligibly small.

Previous works

ALP is assumed much lighter than Z boson

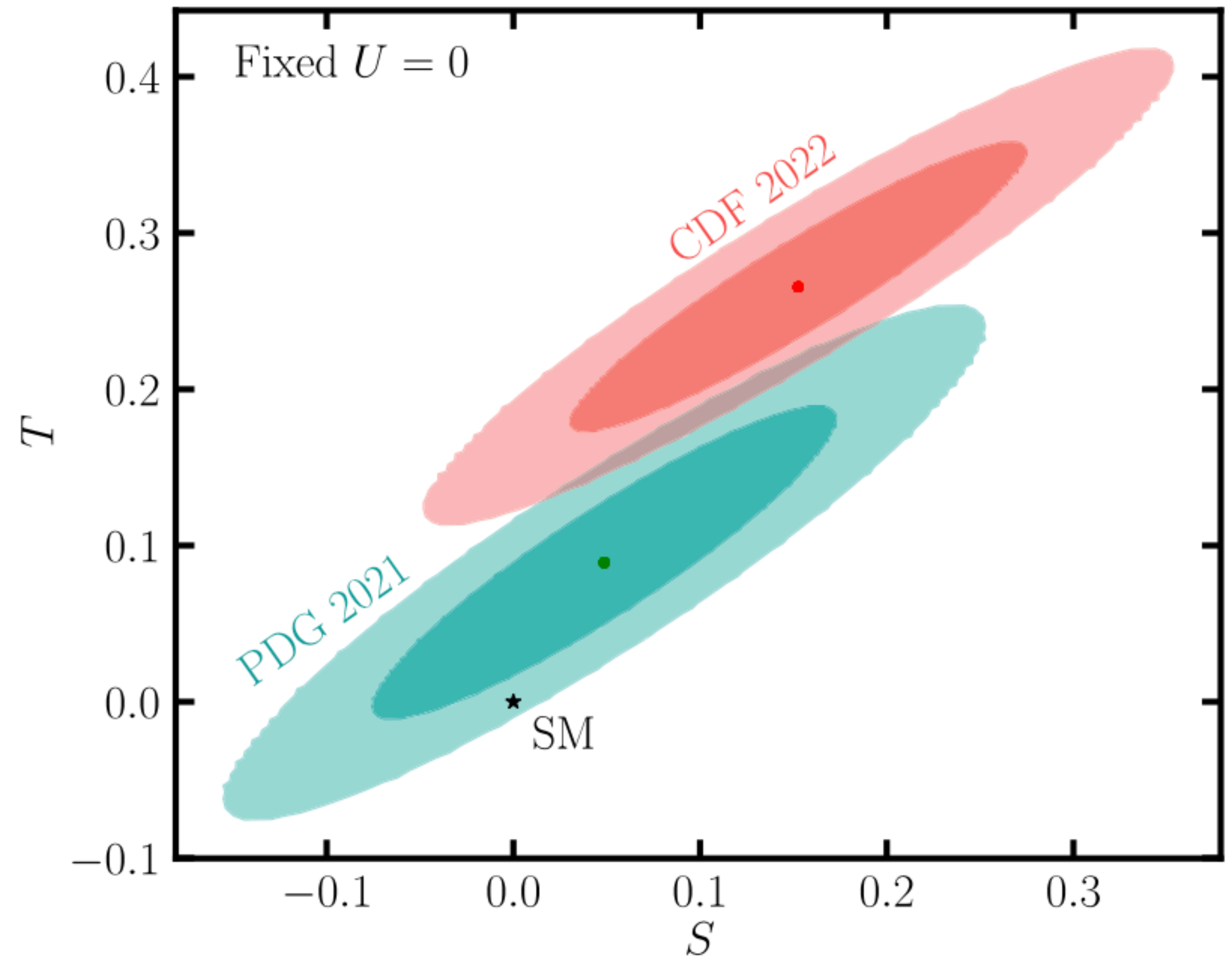
Bauer, Neubert, Thamm, JHEP12 (2017)

$$\alpha S = -\frac{2c_W^2 s_W^2 m_Z^2}{\pi^2}\frac{c_{WW}c_{BB}}{f_a^2}\left(\ln\frac{m_Z^2}{\Lambda^2}+1\right)$$

$$\alpha T = 0$$

$$\alpha U = -\frac{2s_W^4 m_Z^2}{3\pi^2}\frac{c_{WW}^2}{f_a^2}\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{1}{3}+\frac{2c_W^2}{s_W^2}\ln\frac{m_W^2}{m_Z^2}\right)$$

ALP was tested using global fit results for the STU parameters.



Lu, Wu, Wu, Zhu, PRD106 (2022)

It was concluded that **“the interpretation of the W-boson mass excess with ALP is just marginally acceptable”**

Yuan, Zu, Feng, Cai, Fan, 2204.04183

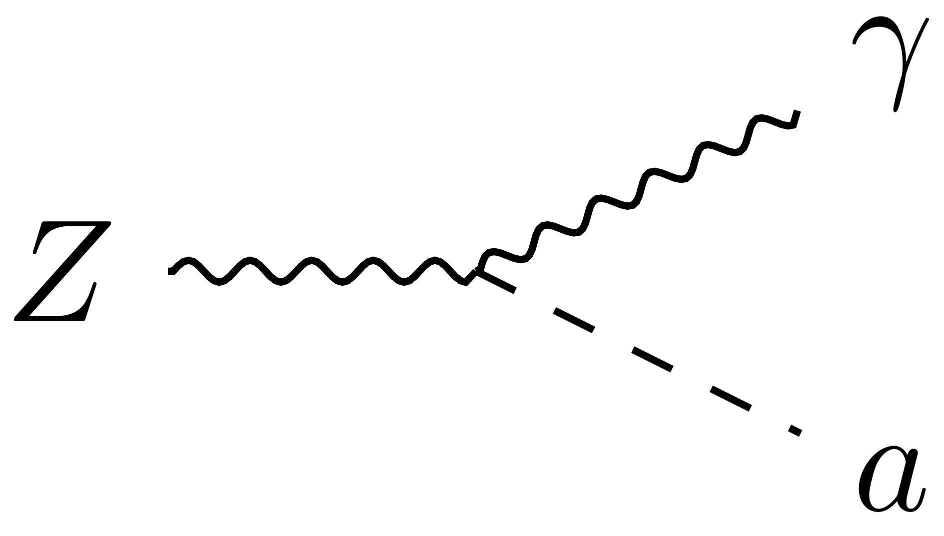
Z-boson decay

In previous works, other effects are assumed to be negligibly small.

However, this assumption is not valid in the ALP model.

$Z \to a\gamma$

$$\Gamma_{a\gamma} \equiv \Gamma(Z \to a\gamma) = \frac{m_Z^3}{96\pi} g_{aZ\gamma}^2 \left(1 - \frac{m_a^2}{m_Z^2}\right)^3$$



This decay mode contributes to the total width of Z boson.

Since this is tree level, the effect is not negligible.

Radiative corrections

Beyond STU

Radiative corrections to gauge couplings via vacuum polarization

$$\begin{aligned}
\bar{\alpha}(m_Z^2) &= \alpha \left\{1 - \mathrm{Re}\left[\Pi_{T,\gamma}^{\gamma\gamma}(m_Z^2) - \Pi_{T,\gamma}^{\gamma\gamma}(0)\right]\right\} \equiv \alpha\,(1 + \Delta\alpha) \\
\bar{g}_Z^2(m_Z^2) &= \bar{g}_Z^2(0)\left\{1 - \mathrm{Re}\left[\Pi_{T,Z}^{ZZ}(m_Z^2) - \Pi_{T,Z}^{ZZ}(0)\right]\right\} \equiv g_Z^2(0)\,(1 + \Delta_Z) \\
\bar{g}^2(m_W^2) &= \bar{g}^2(0)\left\{1 - \mathrm{Re}\left[\Pi_{T,W}^{WW}(m_W^2) - \Pi_{T,W}^{WW}(0)\right]\right\} \equiv g^2(0)\,(1 + \Delta_W)
\end{aligned}$$

Z-pole observables

* Formulae for the other EWPOs are presented in the paper.

$$\Gamma(Z \to f\bar{f}) = N_C^f \frac{G_F m_Z^3}{6\sqrt{2}\pi}\left[|g_{V,f}|^2 + |g_{A,f}|^2\right] \qquad \left\{\begin{aligned}
&g_{V,f} = \sqrt{\rho_Z}\left[I_3^f - 2\,Q_f\,\bar{s}^2(m_Z^2)\right], \quad g_{A,f} = \sqrt{\rho_Z}\,I_3^f \\
&\bar{s}^2(m_Z^2) = s_W^2\left[1 + \frac{c_W^2}{c_W^2 - s_W^2}\,(\Delta\alpha - \alpha T) + \frac{\alpha S}{4 s_W^2 (c_W^2 - s_W^2)}\right] \\
&\rho_Z = 1 + \alpha T + \Delta_Z
\end{aligned}\right.$$

Can we neglect $\Delta\alpha, \Delta_Z$ and Δ_W?

ALP contributions

Light ALP

$$\alpha S = -\frac{2c_W^2 s_W^2 m_Z^2}{\pi^2}\frac{c_{WW}c_{BB}}{f_a^2}\left(\ln\frac{m_Z^2}{\Lambda^2}+1\right)$$

$$\alpha U = -\frac{2s_W^4 m_Z^2}{3\pi^2}\frac{c_{WW}^2}{f_a^2}\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{1}{3}+\frac{2c_W^2}{s_W^2}\ln\frac{m_W^2}{m_Z^2}\right)$$

$$\left.\begin{aligned}
\Delta\alpha &= \frac{m_Z^2}{96\pi^2}\left[g_{a\gamma\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{3}\right)+g_{aZ\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{6}\right)\right]\\
\Delta_Z &= \frac{m_Z^2}{96\pi^2}\left(g_{aZ\gamma}^2+g_{aZZ}^2\right)\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{4}{3}\right)\\
\Delta_W &= \frac{m_W^2}{96\pi^2}g_{aWW}^2\left(\ln\frac{m_W^2}{\Lambda^2}+\frac{4}{3}\right)
\end{aligned}\right\}$$

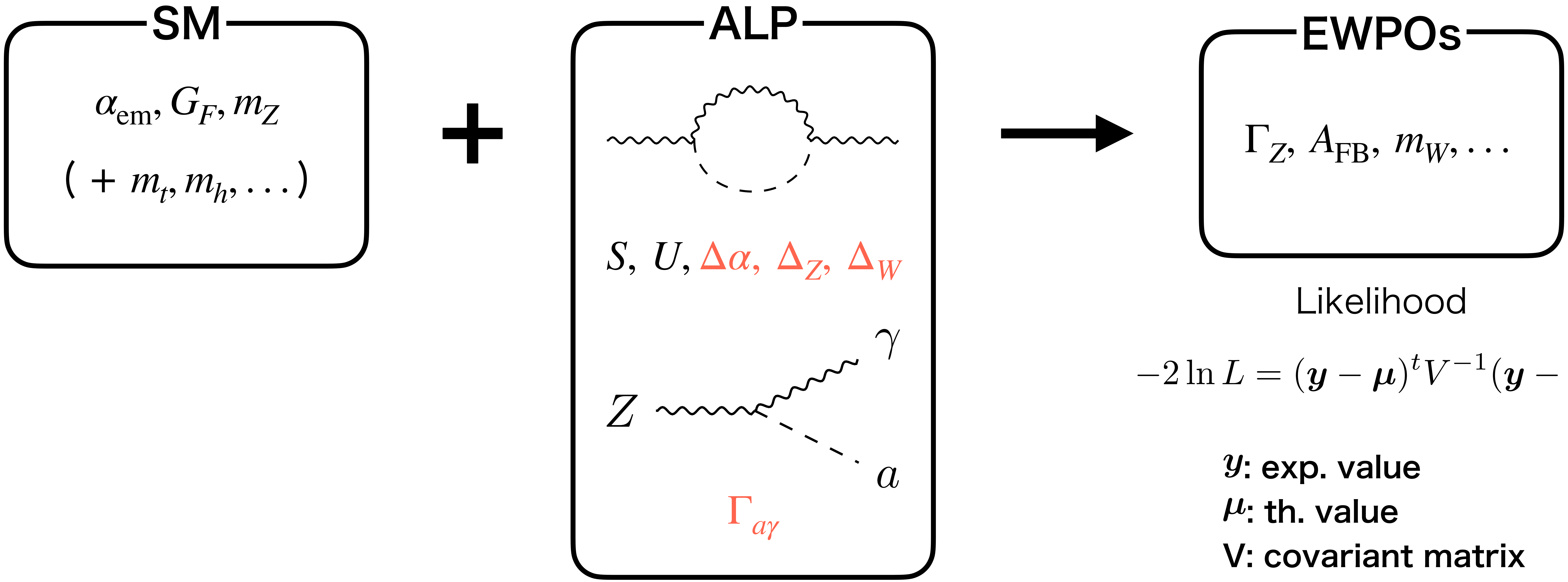
New contributions

MA, Endo, 2302.11377

* Formulae valid for any ALP mass are provided in the paper.

New contributions are comparable to S and U. → We cannot neglect them.

EWPT in ALP model



SM

$\alpha_{\text{em}}, G_F, m_Z$

$(+ m_t, m_h, \ldots)$

+

ALP

$S,\ U,\ \Delta\alpha,\ \Delta_Z,\ \Delta_W$

$\Gamma_{a\gamma}$

EWPOs

$\Gamma_Z,\ A_{\text{FB}},\ m_W, \ldots$

Likelihood

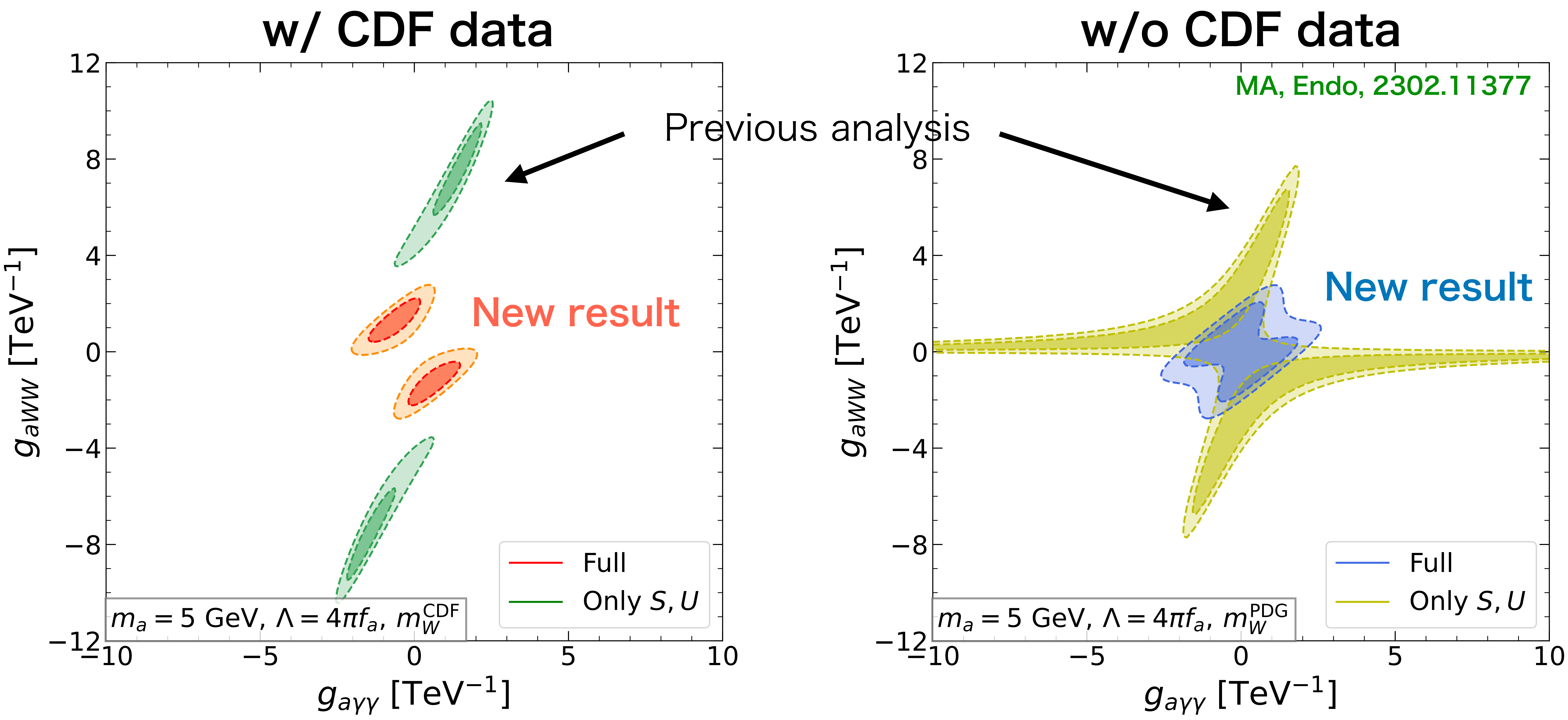
$$-2\ln L = (\boldsymbol{y} - \boldsymbol{\mu})^t V^{-1} (\boldsymbol{y} - \boldsymbol{\mu})$$

y: exp. value
μ: th. value
V: covariant matrix

1. Evaluate the probability distribution from the likelihood
2. Normalize the probability distribution on the model-parameter plane
3. Determine 68% and 95% region

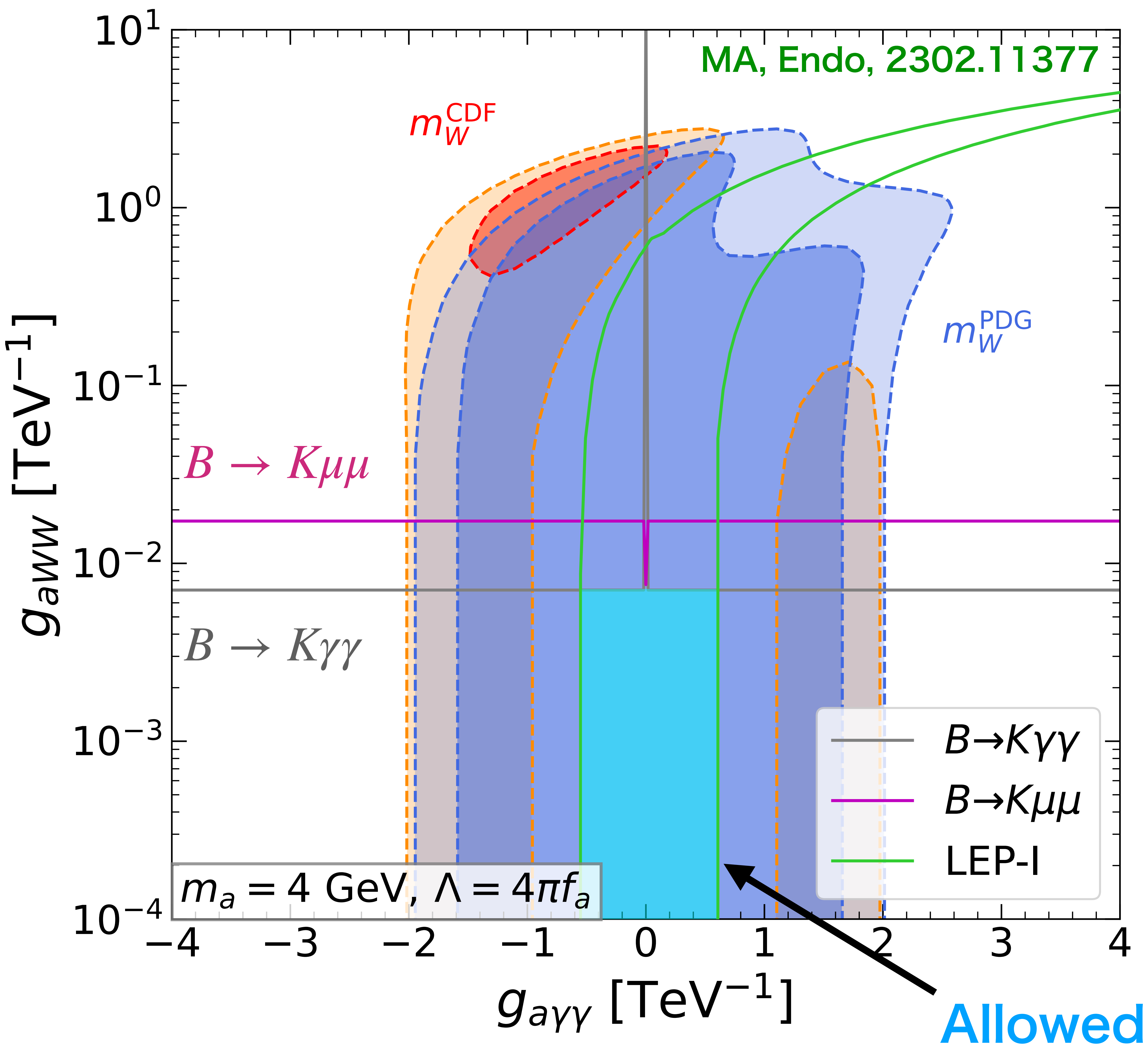
Impact of new contributions

ALP is much lighter than Z boson



New contributions, especially $\Gamma(Z \to a\gamma)$, significantly affect the results

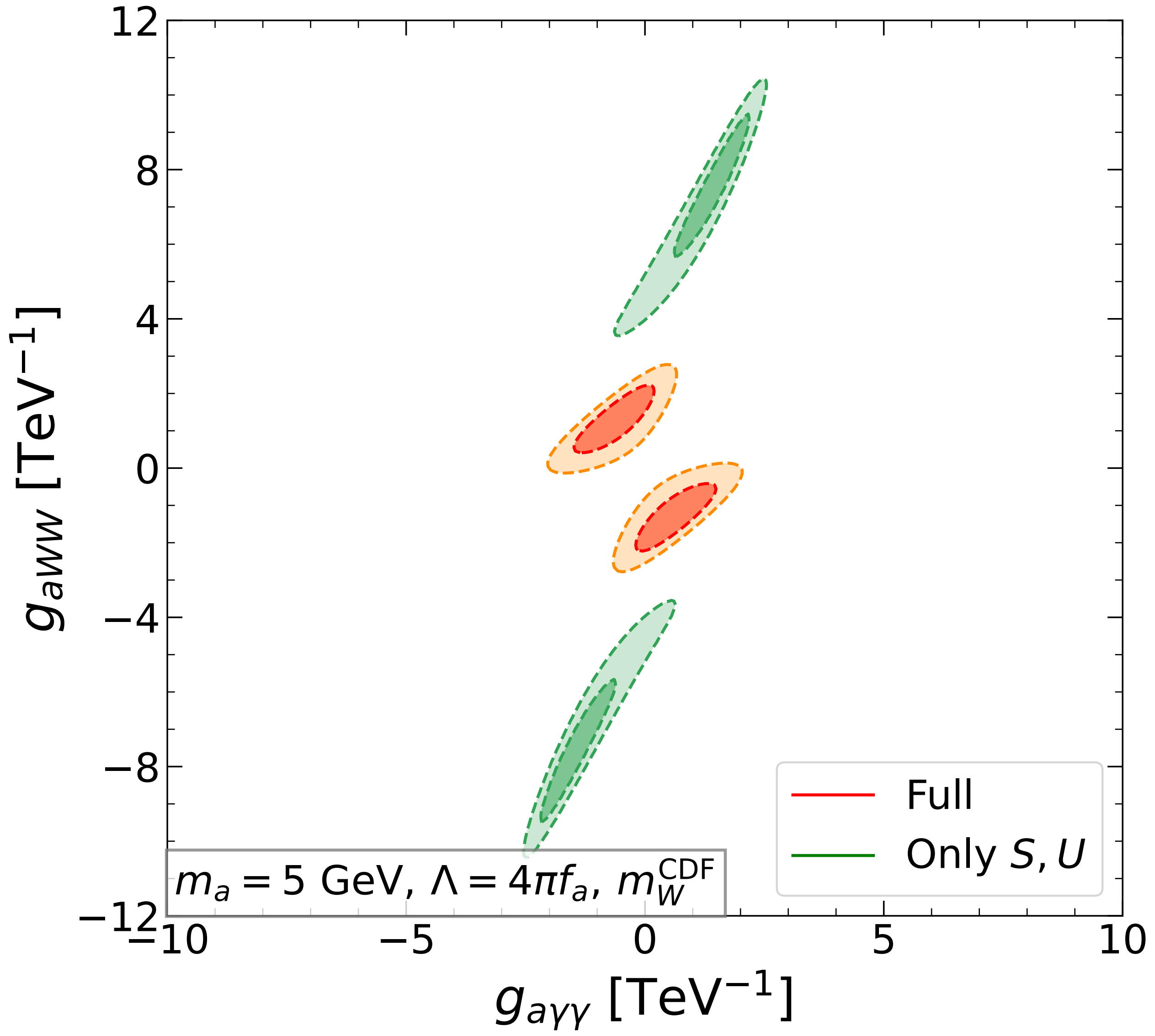
EWPT with light ALP ($m_a = 4$ GeV)



$Z \to a\gamma,\ a \to \gamma\gamma, jj$

y: logarithm

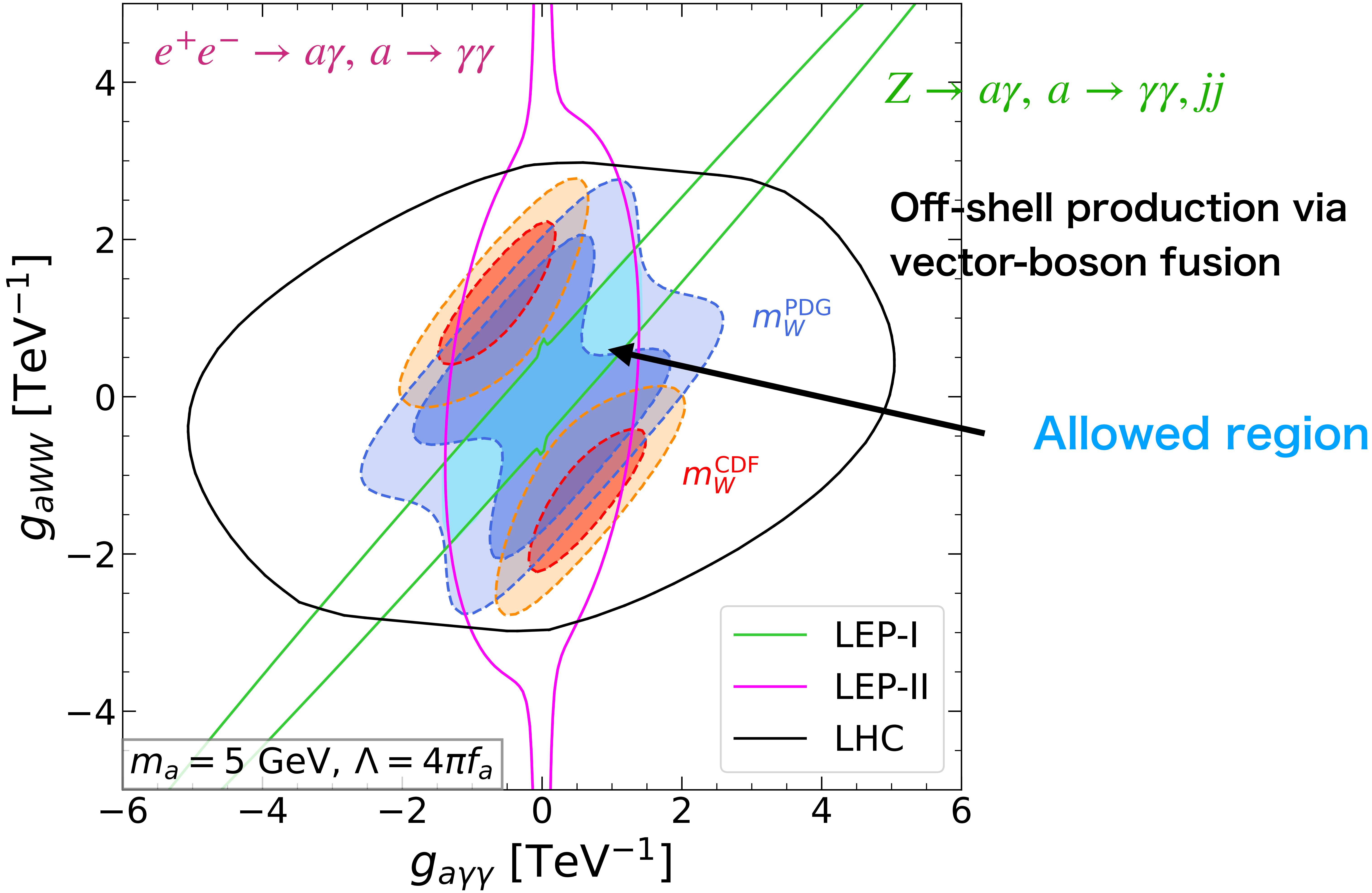
Allowed region



Flavor experiments tightly constrain for $m_a \leq 4.8$ GeV.

EWPT with light ALP (m_a = 5 GeV)

MA, Endo, 2302.11377

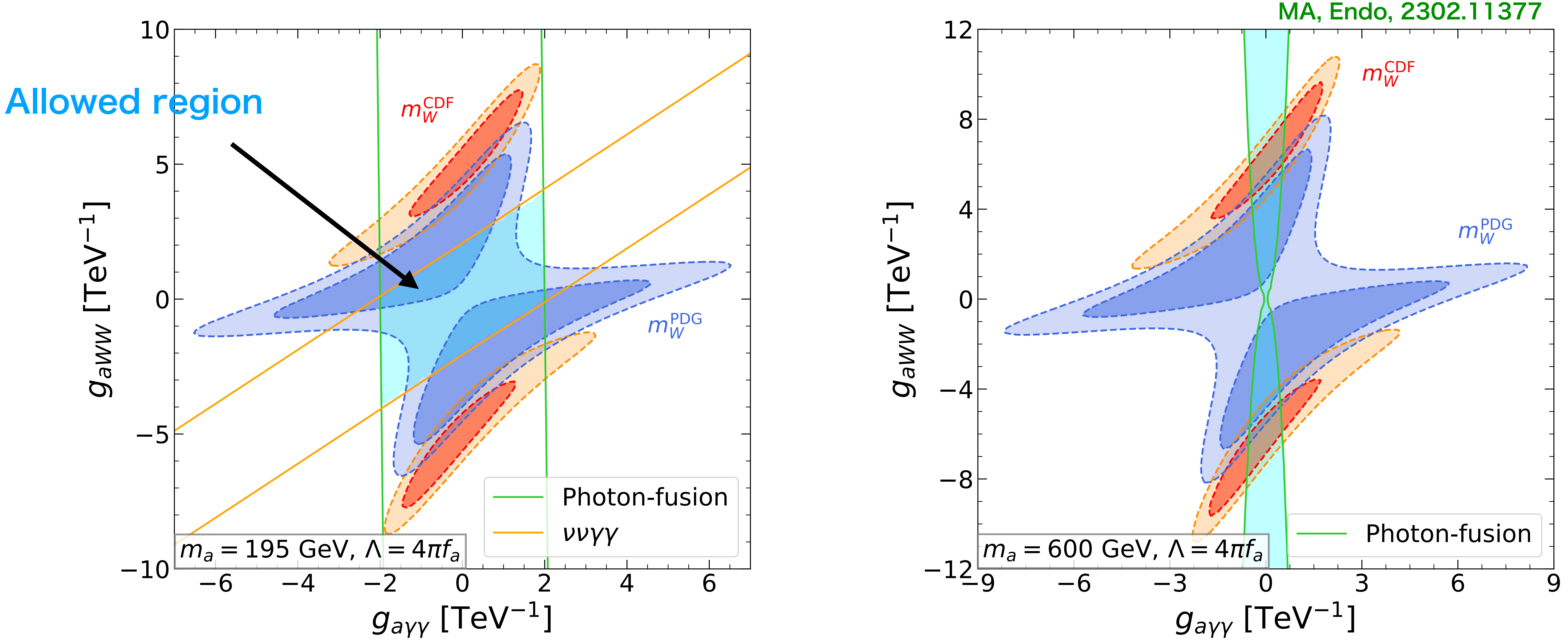


Off-shell production via vector-boson fusion

Allowed region

Light ALP can be consistent with EWPT for m_W^{PDG}, but not for m_W^{CDF}.

EWPT with $m_a > m_Z$



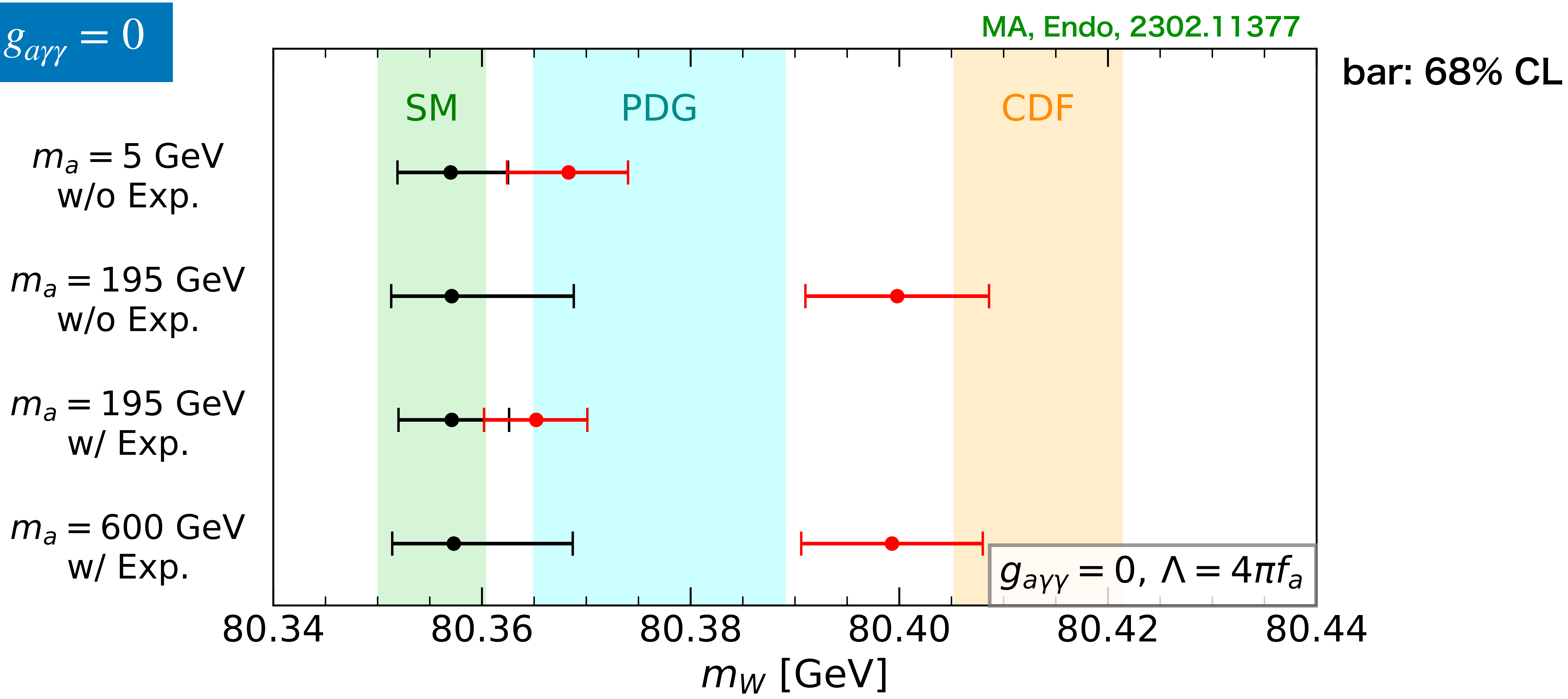
MA, Endo, 2302.11377

ALP can be consistent with EWPT both for m_W^{PDG} and m_W^{CDF}

if ALP is heavy and $g_{a\gamma\gamma} \approx 0$.

Prediction on W-boson mass

Case with $g_{a\gamma\gamma} = 0$



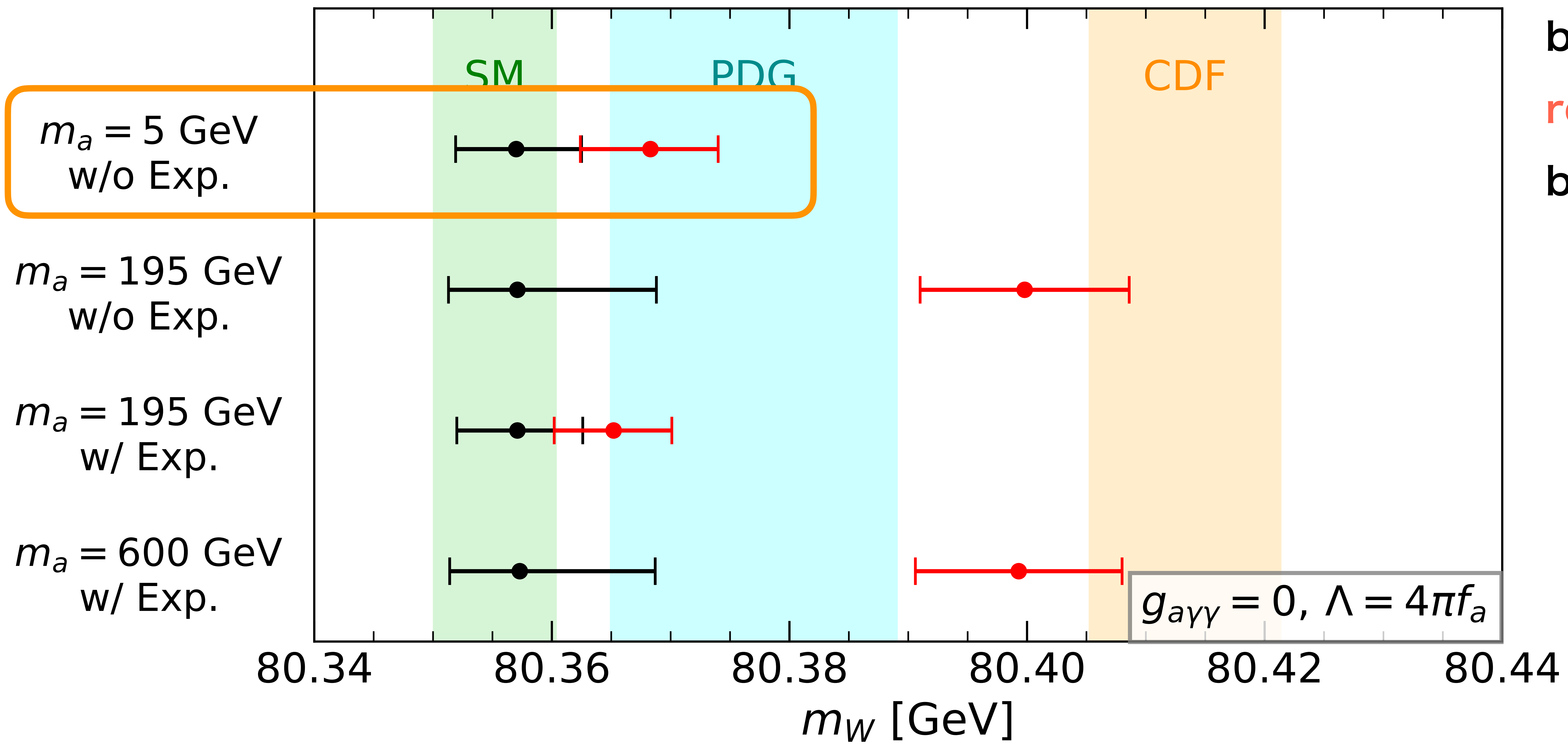
Black: indirect prediction

m_W is determined by global fits w/o including the m_W in the likelihood

Red: theoretical value for which m_W is included in the likelihood

Prediction on W-boson mass

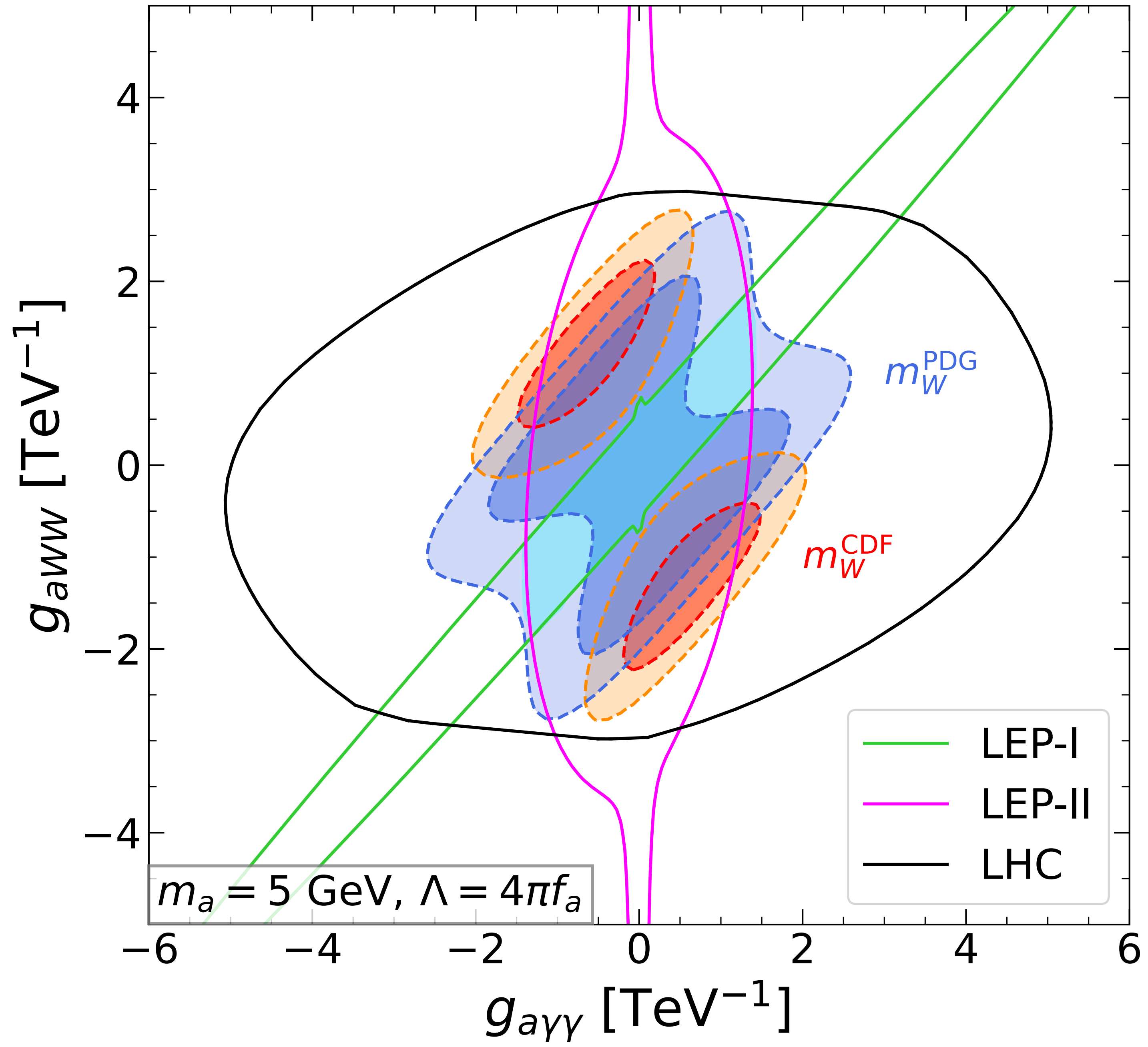
MA, Endo, 2302.11377



black: w/o m_W

red: w/ m_W

bar: 68% CL

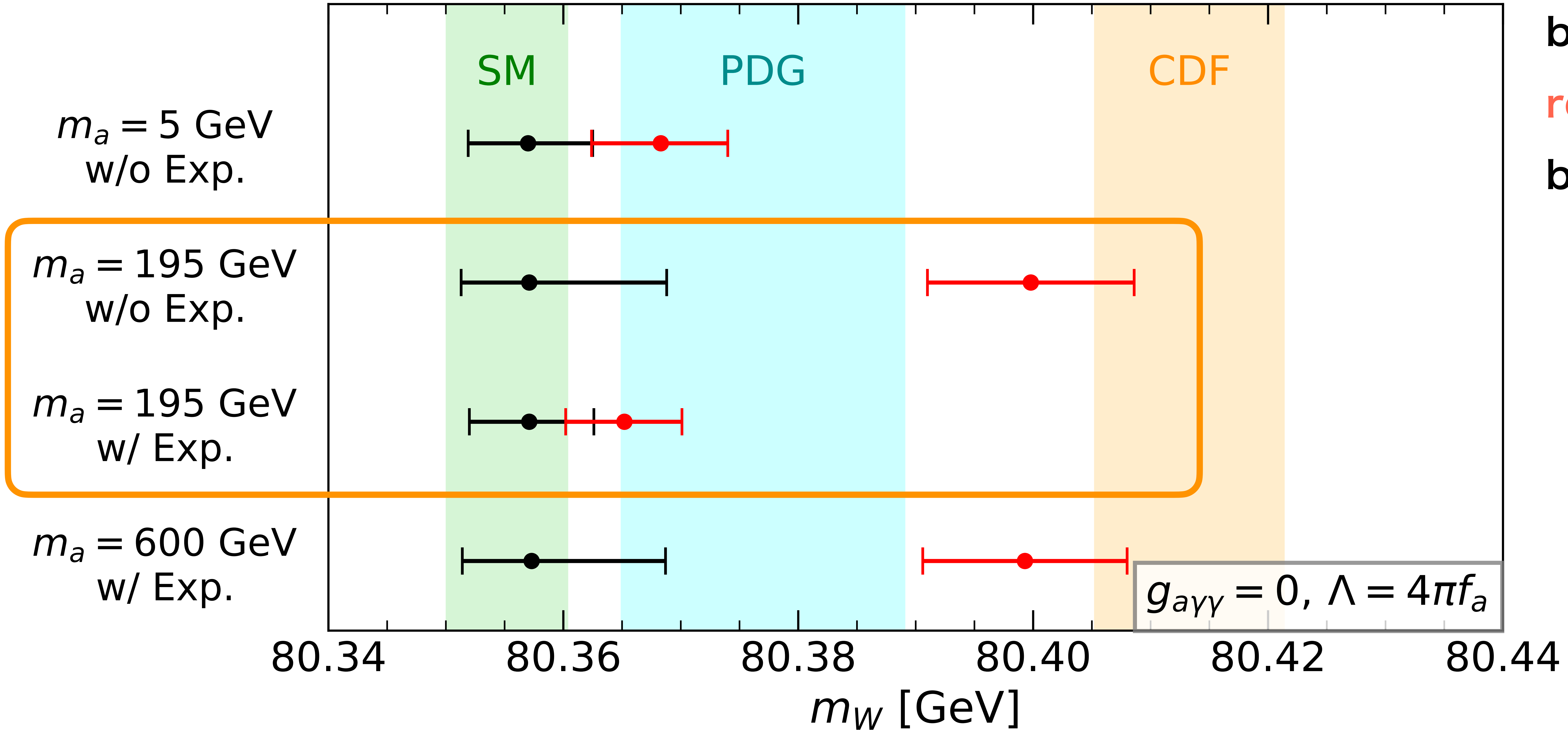


Light ALP cannot explain the CDF value even if we omit the collider constraints.

Contrary to Yuan et al 2204.04183

The fit quality cannot be improved with $\Gamma(Z \to a\gamma) \approx 0$.

Prediction on W-boson mass

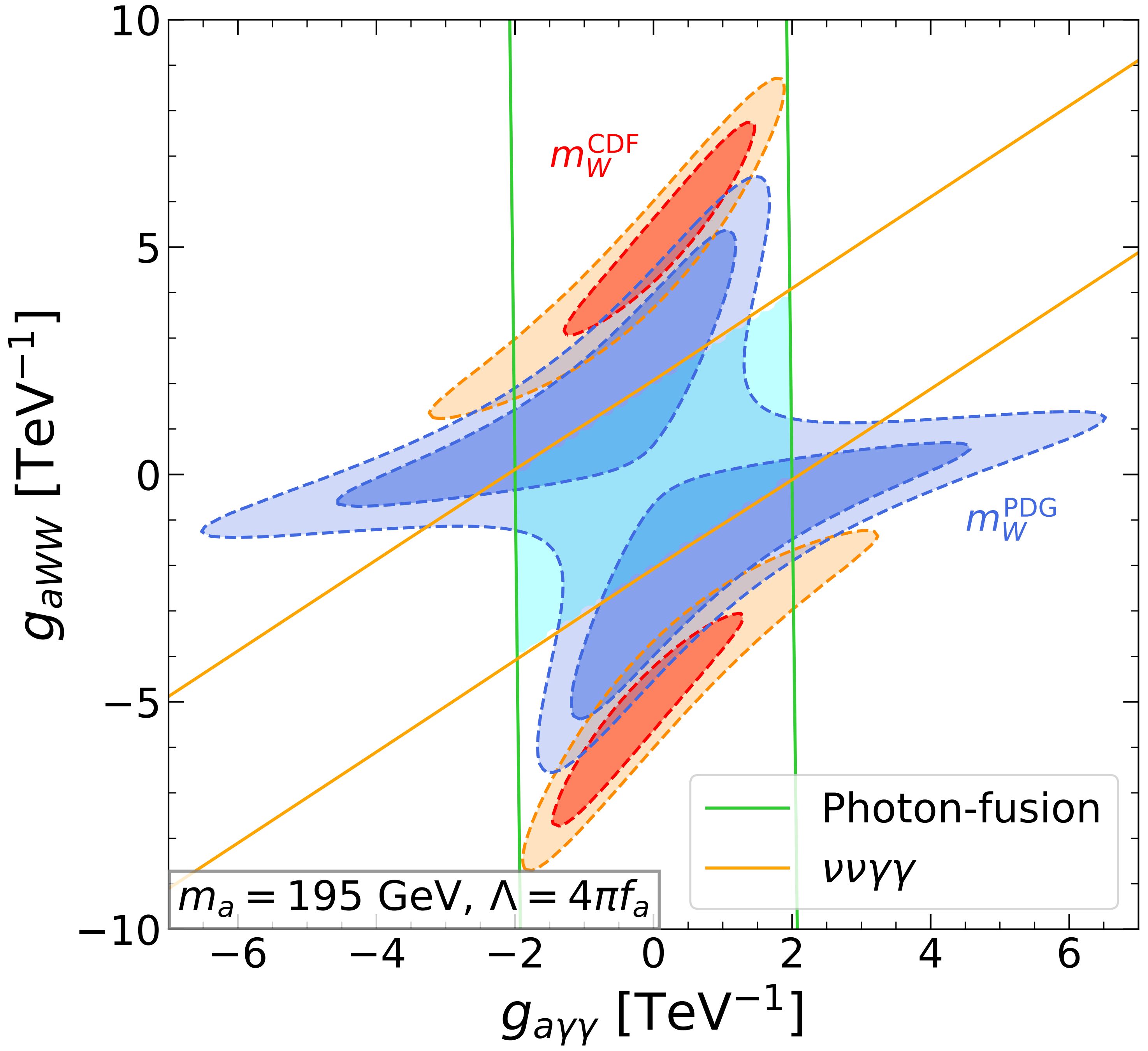


MA, Endo, 2302.11377

black: w/o m_W

red: w/ m_W

bar: 68% CL

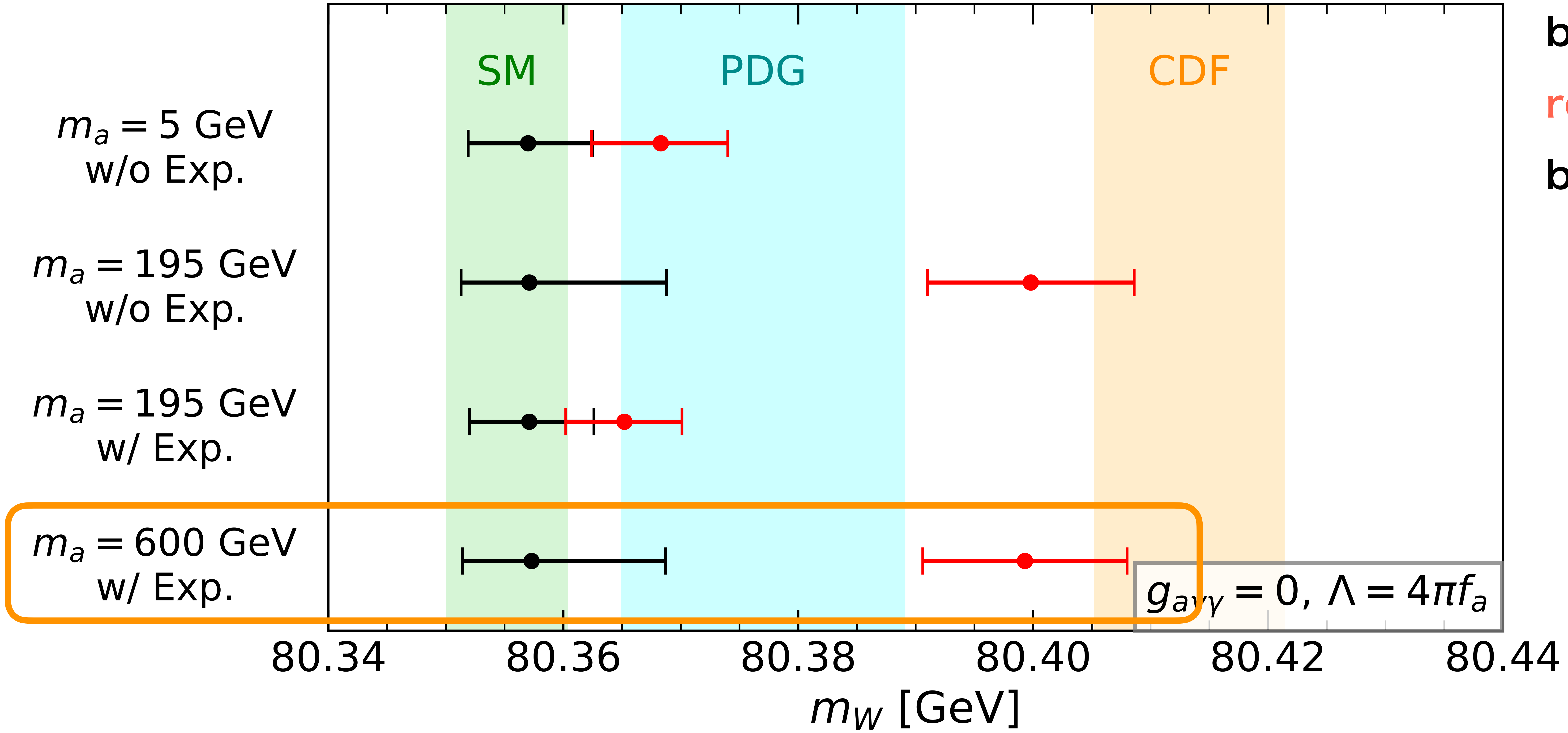


ALP potentially explains the CDF value.

Collider bounds already exclude the parameter regions.

Prediction on W-boson mass

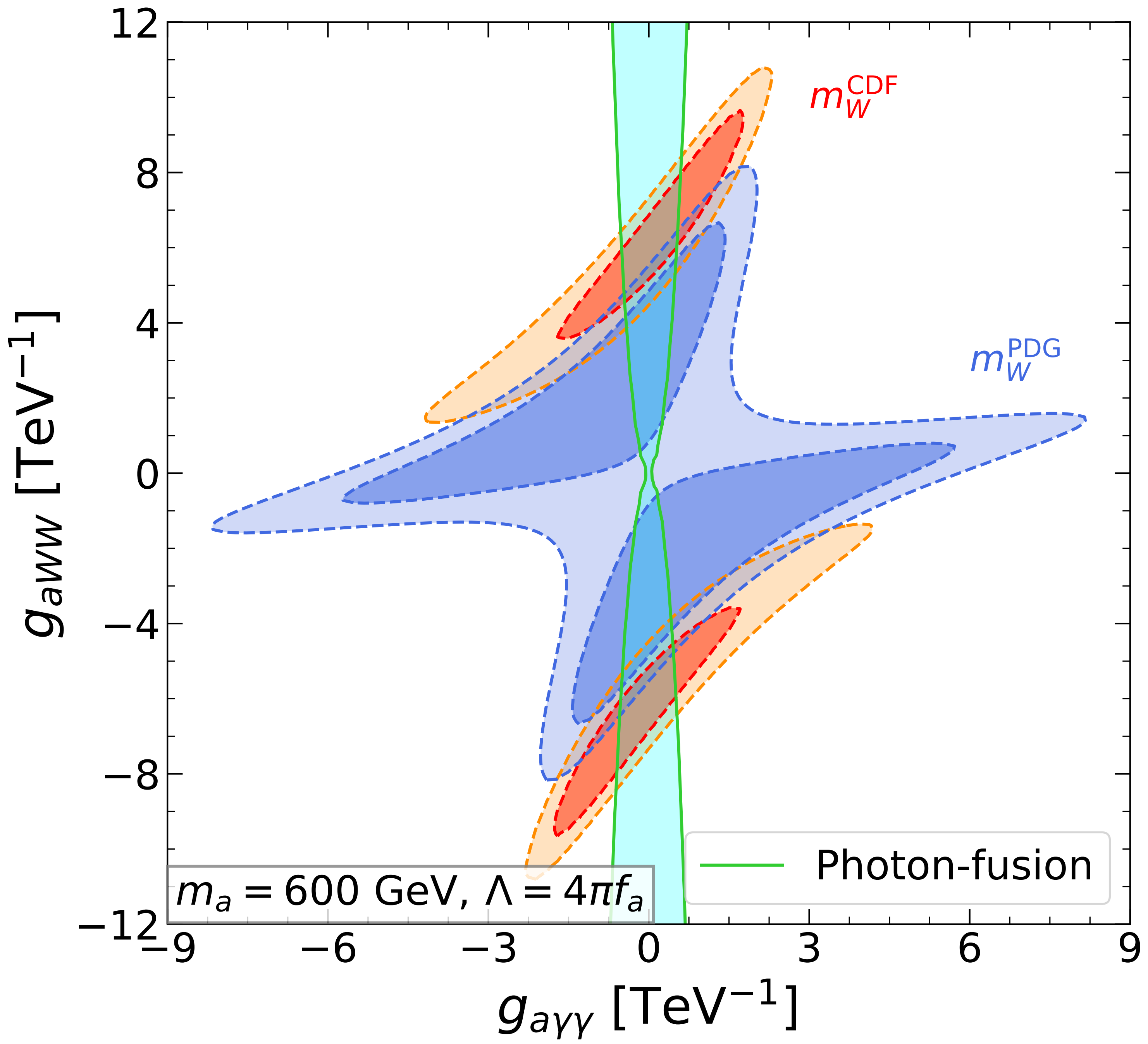
MA, Endo, 2302.11377



black: w/o m_W

red: w/ m_W

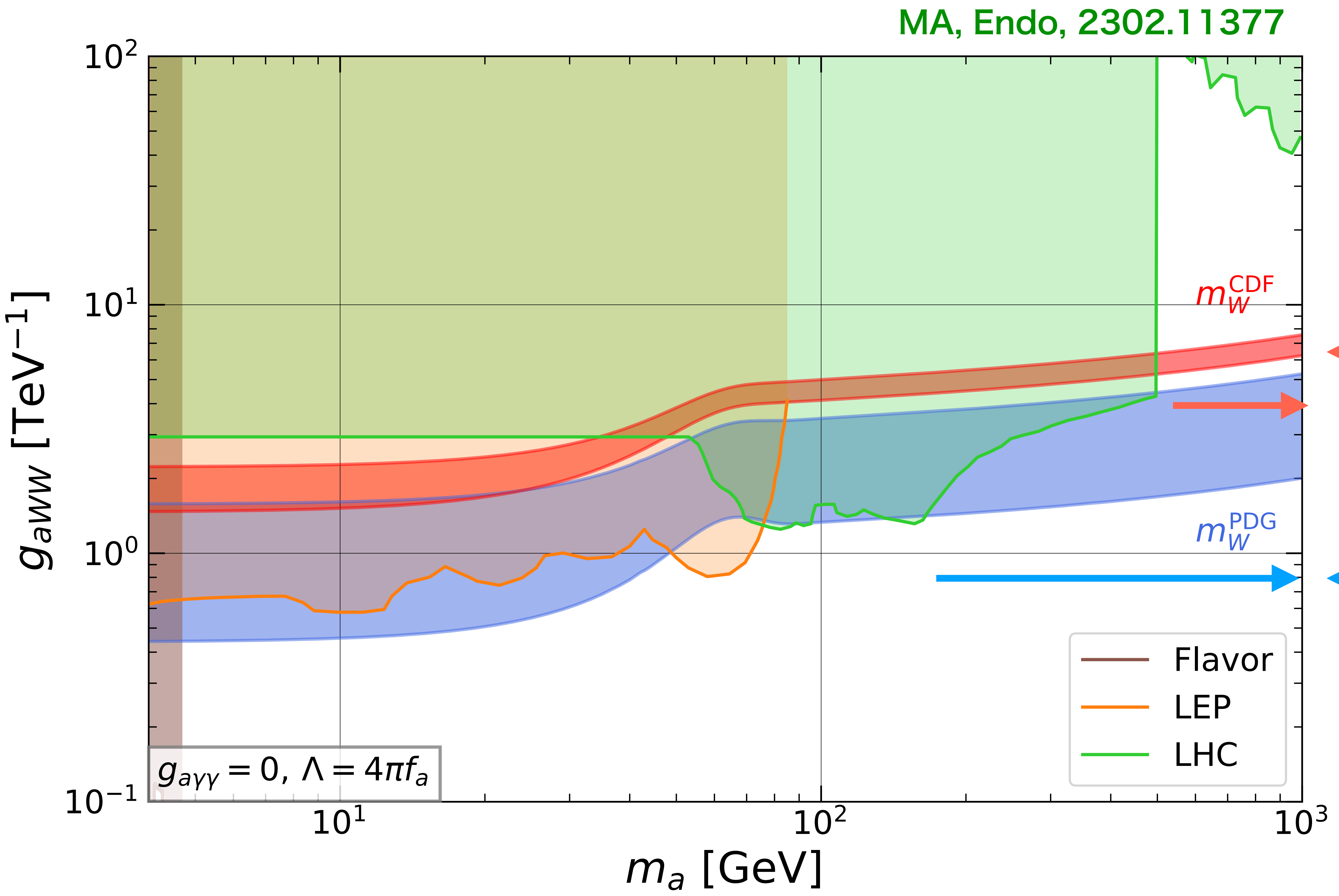
bar: 68% CL



ALP can explain the CDF value.

The fit quality can be improved both for $m_W^{\rm PDG}$ and $m_W^{\rm CDF}$.

Mass dependence of EWPOs global fit



CDF tension is solved

Fit quality is improved

ALP improves EWPOs global fit if $m_a > 160$ (500) GeV for $m_W^{\rm PDG}$ ($m_W^{\rm CDF}$).

Summary

What is new

We performed the global fit of EWPOs in the ALP model.

The following effects, which are neglected in previous works, are included

- Z-boson decays into ALP
- Corrections beyond STU parameters.

In addition, relevant flavor and collider experiments are taken into account.

What we found

Analysis only with STU parameters is not valid in the ALP model.

The EWPOs global fit can be improved against the SM if ALP is heavier than 160 GeV.

To explain the CDF result of W-boson mass, ALP should be heavier than 500 GeV.

Back up slides

CDF measurement of W-boson mass

CDF measurement of W-boson mass

SM prediction

$$m_W^{\mathrm{SM}} = 80.3552 \pm 0.0055 \ \mathrm{GeV}$$

World Average w/o CDF

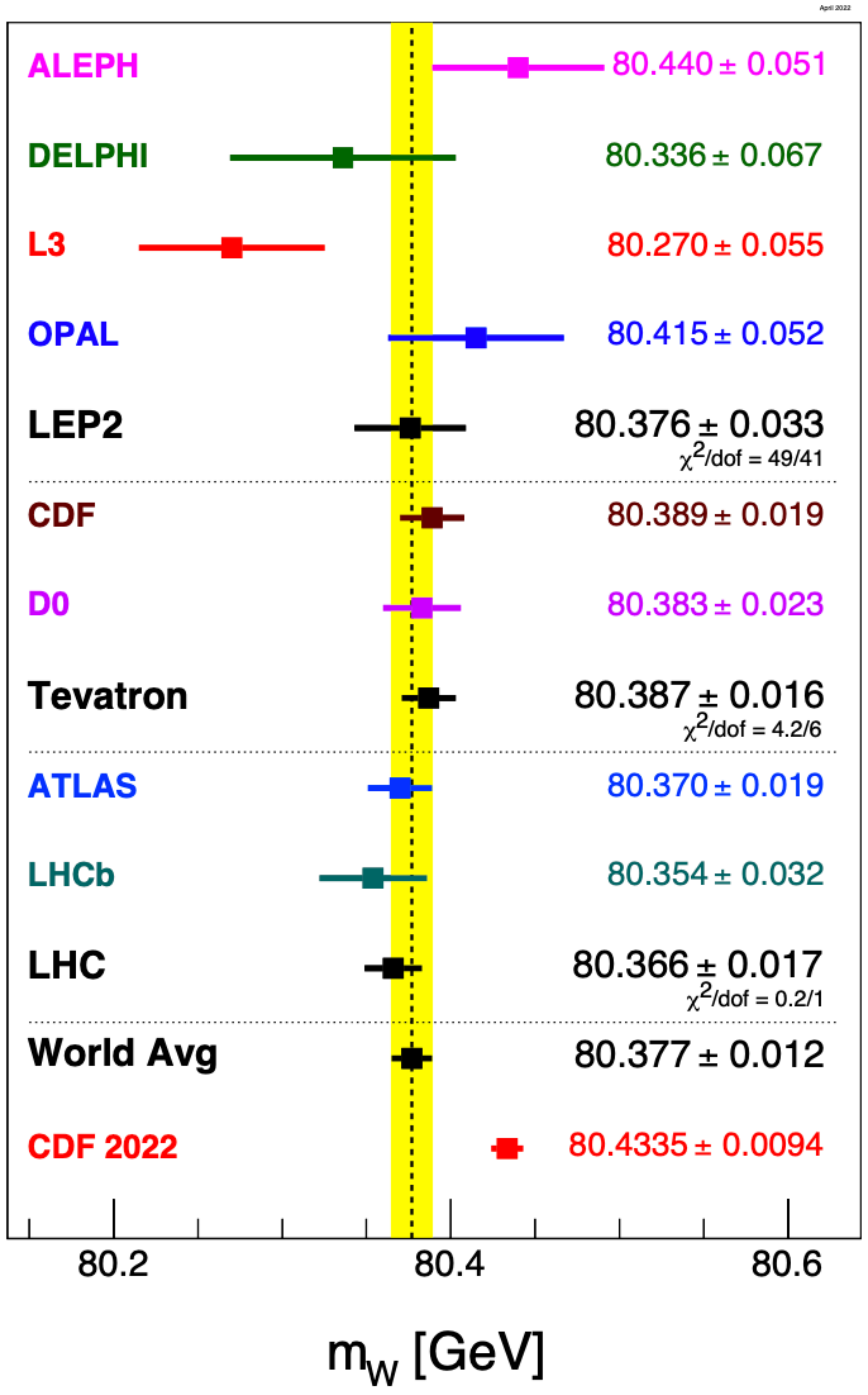
$$m_W^{\mathrm{PDG}} = 80.377 \pm 0.012 \ \mathrm{GeV}$$

$< 2\sigma$

CDF 2022

$$m_W^{\mathrm{CDF}} = 80.4335 \pm 0.0094 \ \mathrm{GeV}$$

$\sim 7\sigma$



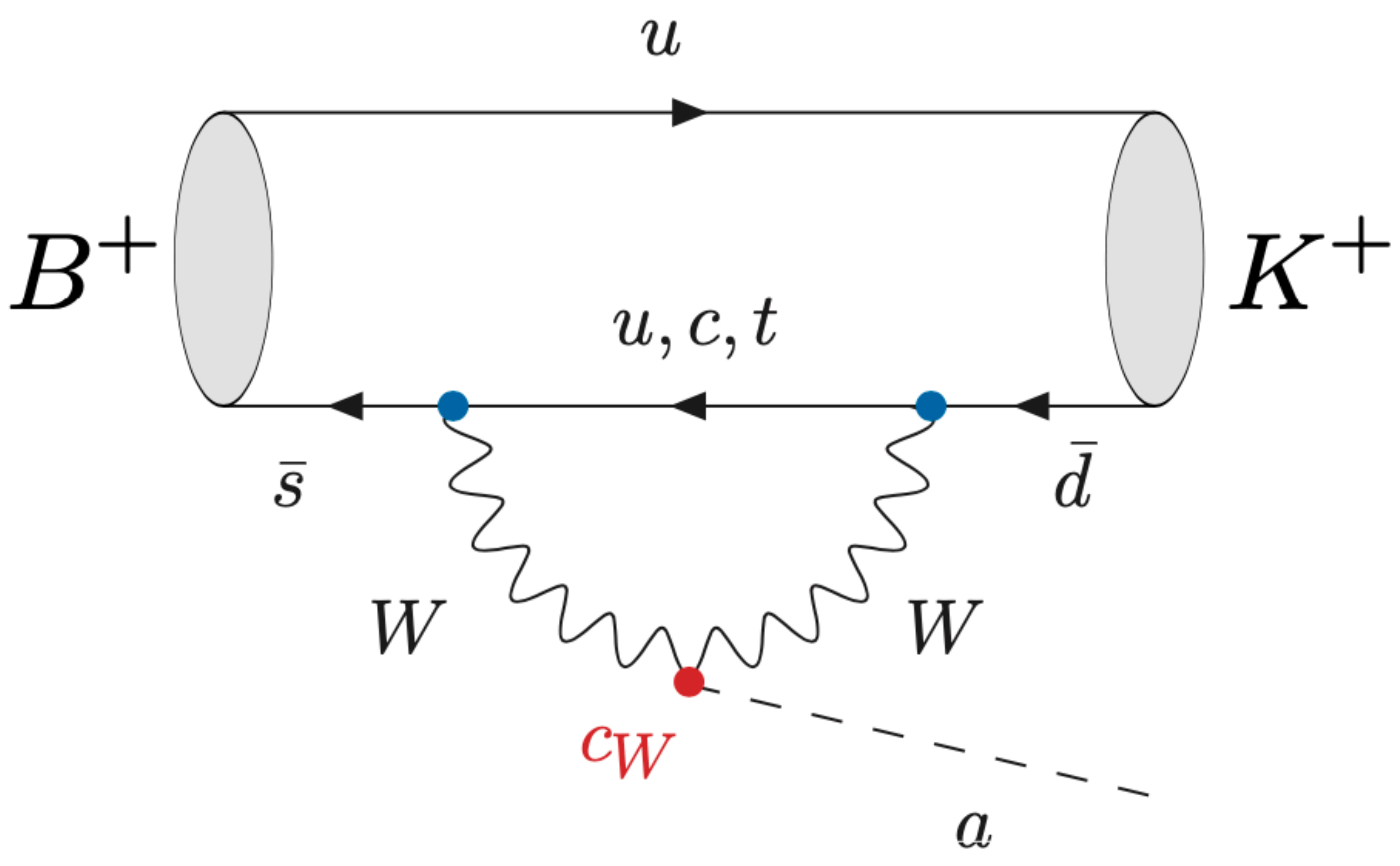
Flavor constraints

B-meson decay

$B \to Ka$

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

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



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

Collider constraints

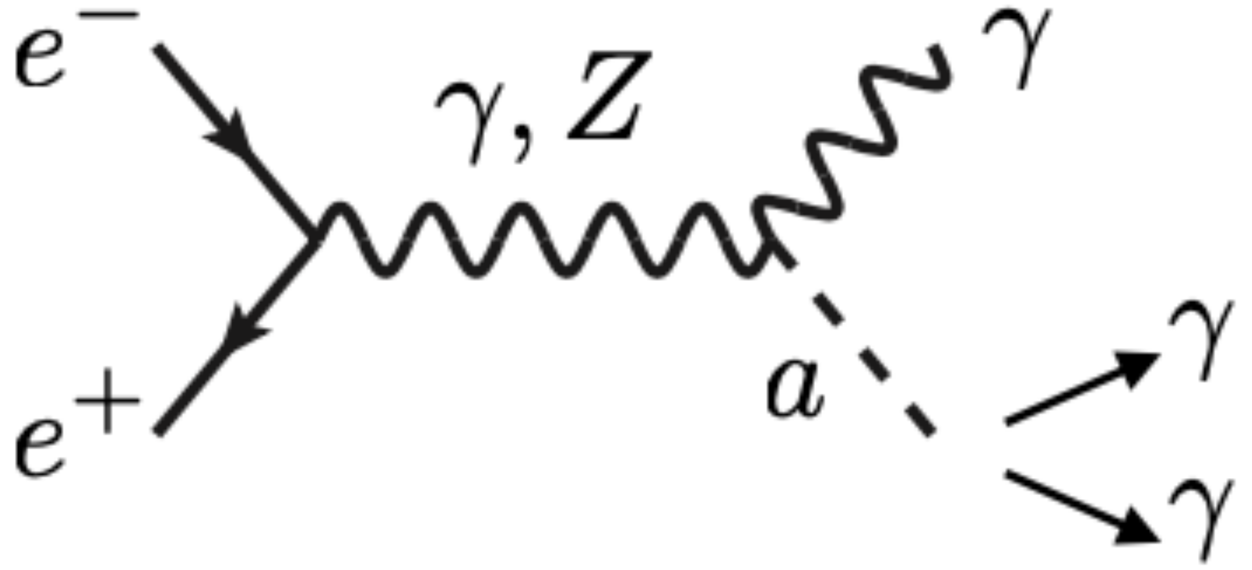
ALP lighter than Z boson

$a \to \gamma\gamma$

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

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

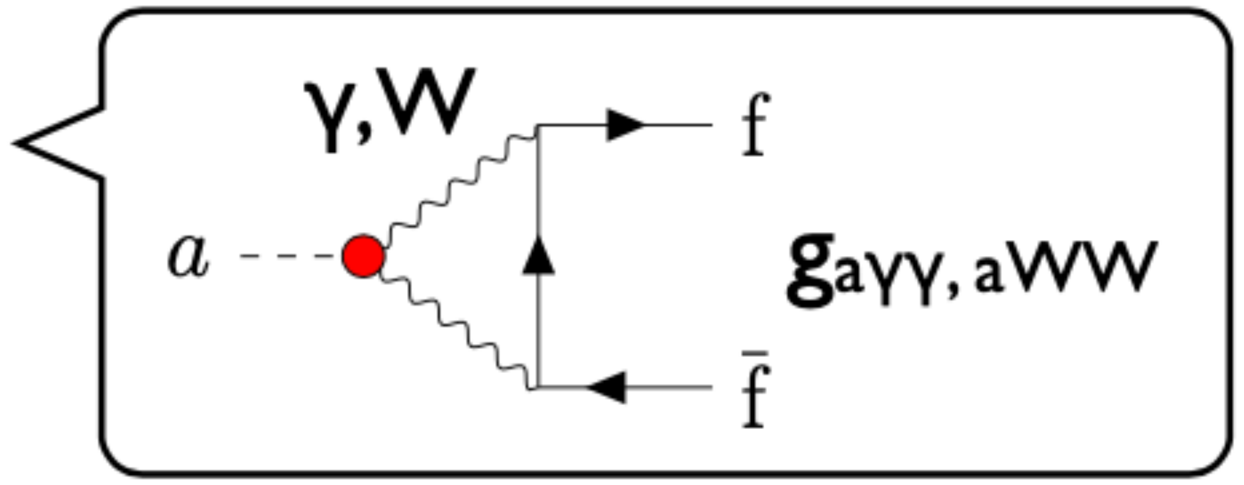
Off-shell γ, Z exchange: $aZ\gamma$ and $a\gamma\gamma$ couplings



$a \to jj$

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

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

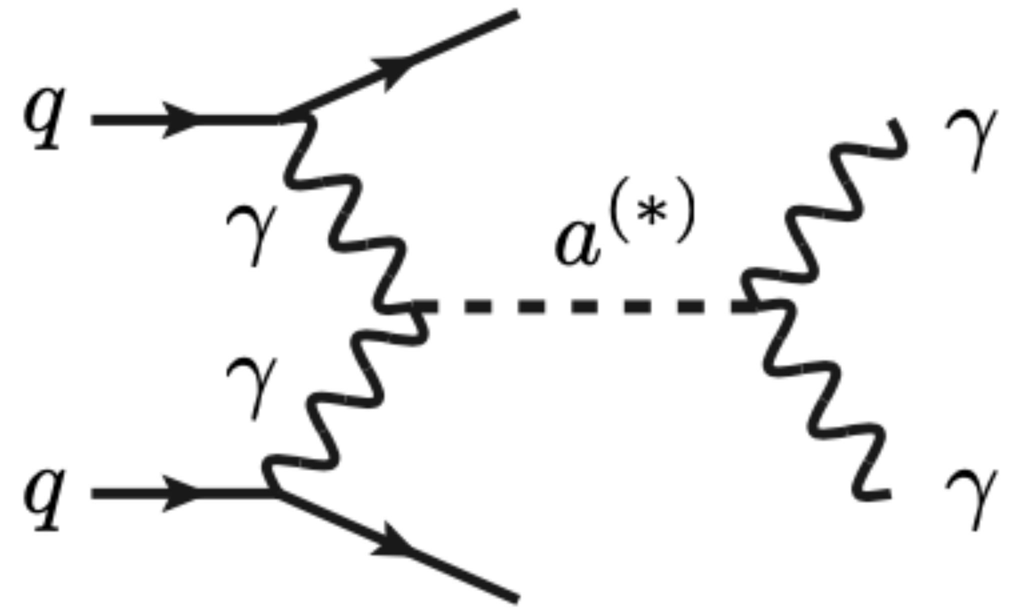


ALP heavier than Z boson

$a \to \gamma\gamma$

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

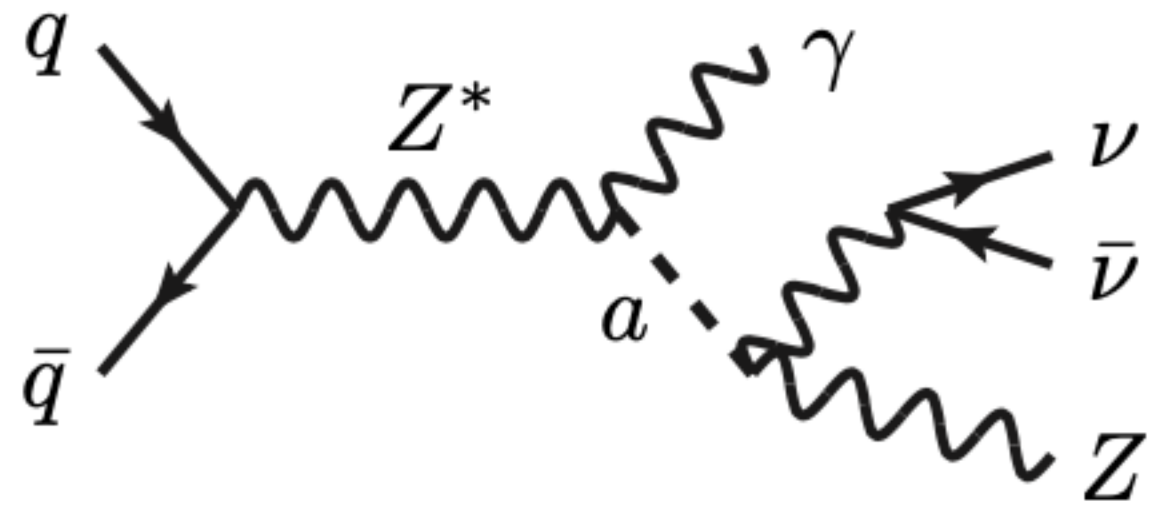
$g_{a\gamma\gamma}$ is tightly constrained.



$a \to Z\gamma$

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



Global fit results

Cutoff dependence

$\Lambda = f_a$