Electroweak precision test of axion-like particles

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Based on JHEP 05 (2023) 147 [hep-ph] 2302.11377

SUSY2023（2023/07/18）

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.

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

Electroweak symmetry breaking

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

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

The ALP couplings are controlled by two independent parameters.

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

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

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

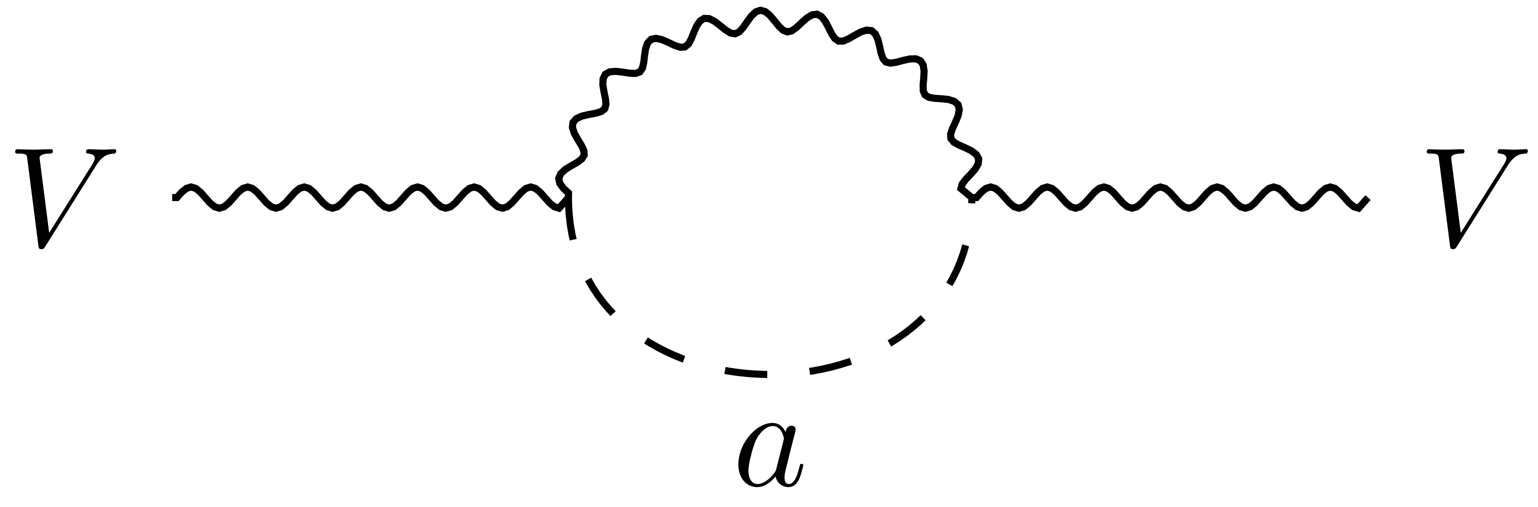
SM vs CDF: ~ 7σ

	Measurement		Measurement
$\alpha_s(m_Z^2)$	0.1177 ± 0.0010	m_Z [GeV]	91.1875 ± 0.0021
$\Delta\alpha_{\rm had}^{(5)}(m_Z^2)$	0.02766 ± 0.00010	Γ_Z [GeV]	2.4955 ± 0.0023
m_t [GeV]	172.69 ± 0.30	σ_h^0 [nb]	41.4802 ± 0.0325
m_h [GeV]	125.21 ± 0.17	R_ℓ^0	20.7666 ± 0.0247
m_W [GeV]	80.377 ± 0.012	$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
	80.4133 ± 0.0080	R_b^0	0.21629 ± 0.00066
Γ_W [GeV]	2.085 ± 0.042	R_c^0	0.1721 ± 0.0030
$\mathcal{B}(W \to \ell\nu)$	0.10860 ± 0.00090	$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016
$\mathcal{A}_\ell$ (LEP)	0.1465 ± 0.0033	$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	$\mathcal{A}_b$	0.923 ± 0.020
		$\mathcal{A}_c$	0.670 ± 0.027

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 by using STU parameters only if other effects are negligibly small.

Previous works

ALP is assumed much lighter than Z boson

Bauer, Neubert, Thamm, JHEP12 (2017)

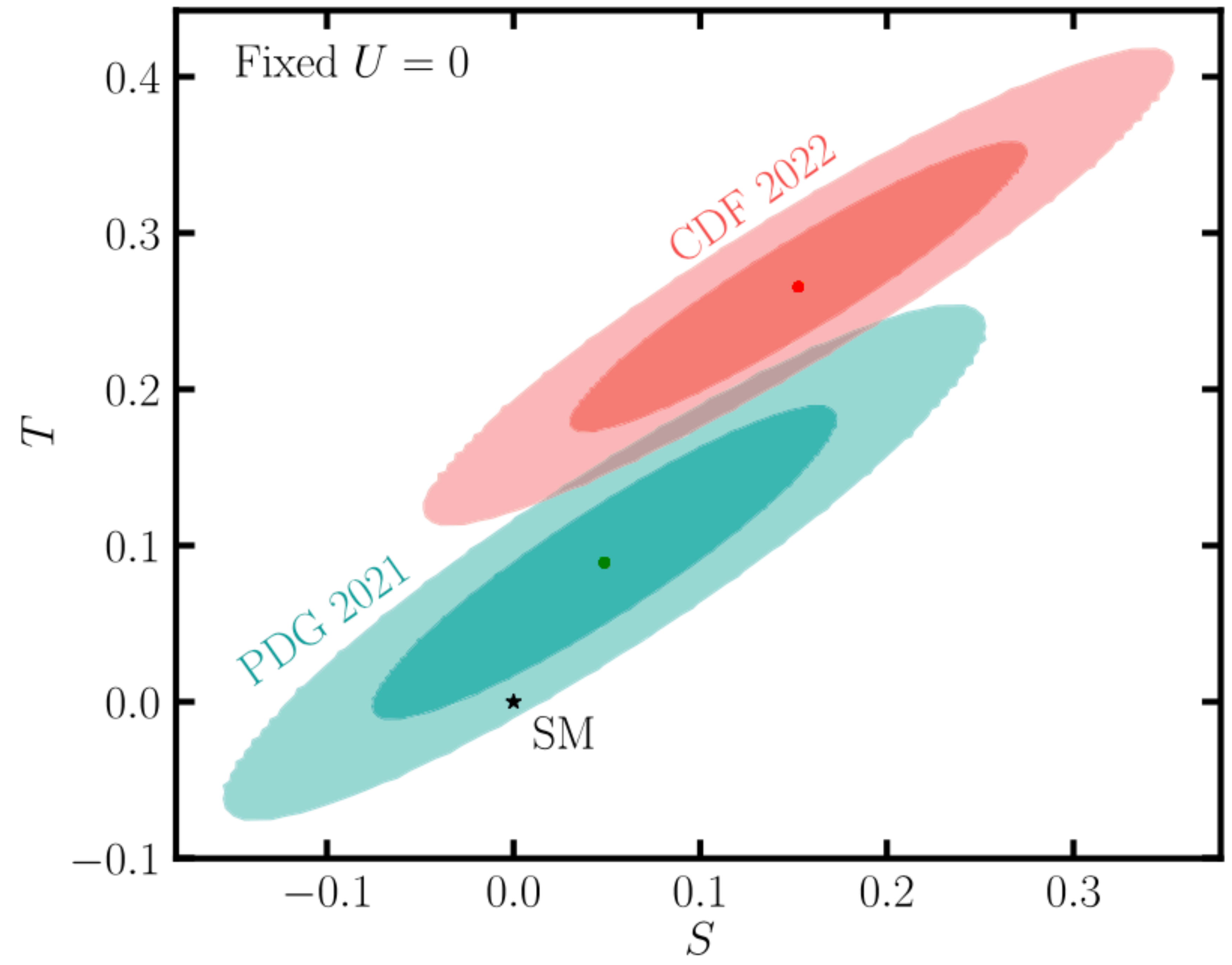
$$\alpha S = -\frac{2c_W^2 s_W^2 m_Z^2}{\pi^2}\frac{c_{WW}c_{BB}}{f_a^2}\left(\ln\frac{m_Z^2}{\Lambda^2}+1\right)$$

$$\alpha T = 0$$

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

Λ: Cutoff scale

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

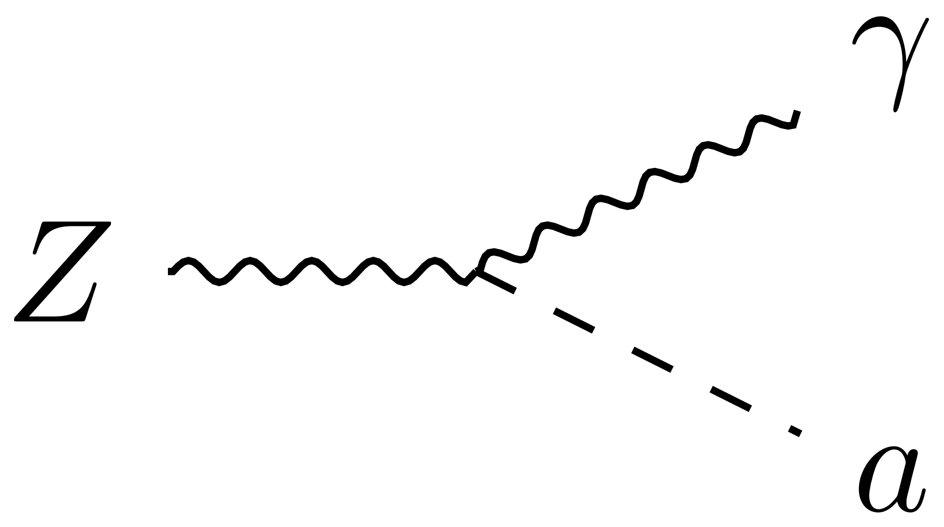
Z-boson decay

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.

Beyond STU

Radiative corrections to gauge couplings via vacuum polarization

$$\bar{\alpha}(m_Z^2) = \alpha \left\{1 - \mathrm{Re}\left[\Pi_{T,\gamma}^{\gamma\gamma}(m_Z^2) - \Pi_{T,\gamma}^{\gamma\gamma}(0)\right]\right\} \equiv \alpha\,(1 + \Delta\alpha)$$

$$\bar{g}_Z^2(m_Z^2) = \bar{g}_Z^2(0)\left\{1 - \mathrm{Re}\left[\Pi_{T,Z}^{ZZ}(m_Z^2) - \Pi_{T,Z}^{ZZ}(0)\right]\right\} \equiv g_Z^2(0)\,(1 + \Delta_Z)$$

$$\bar{g}^2(m_W^2) = \bar{g}^2(0)\left\{1 - \mathrm{Re}\left[\Pi_{T,W}^{WW}(m_W^2) - \Pi_{T,W}^{WW}(0)\right]\right\} \equiv g^2(0)\,(1 + \Delta_W)$$

EWPOs

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

$$\Gamma(Z \to f\bar{f}) = N_C^f \frac{G_F m_Z^3}{6\sqrt{2}\pi}\left[|g_{V,f}|^2 + |g_{A,f}|^2\right]$$

$$\begin{cases} g_{V,f} = \sqrt{\rho_Z}\left[I_3^f - 2\,Q_f \bar{s}^2(m_Z^2)\right], \quad g_{A,f} = \sqrt{\rho_Z}\, I_3^f \\ \bar{s}^2(m_Z^2) = s_W^2\left[1 + \dfrac{c_W^2}{c_W^2 - s_W^2}(\Delta\alpha - \alpha T) + \dfrac{\alpha S}{4 s_W^2 (c_W^2 - s_W^2)}\right] \\ \rho_Z = 1 + \alpha T + \Delta_Z \end{cases}$$

$$m_W^2 = (m_W^2)_{\mathrm{SM}} + \frac{\alpha c_W^2 m_Z^2}{c_W^2 - s_W^2}\left[-s_W^2 \frac{\Delta\alpha}{\alpha} - \frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2} U\right]$$

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

Light ALP

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

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

$$\Delta\alpha = \frac{m_Z^2}{96\pi^2}\left[g_{a\gamma\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{3}\right)+g_{aZ\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{6}\right)\right]$$

$$\Delta_Z = \frac{m_Z^2}{96\pi^2}(g_{aZ\gamma}^2+g_{aZZ}^2)\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{4}{3}\right)$$

$$\Delta_W = \frac{m_W^2}{96\pi^2}g_{aWW}^2\left(\ln\frac{m_W^2}{\Lambda^2}+\frac{4}{3}\right)$$

} New contributions

MA, Endo, JHEP 05 (2023) 147

* 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

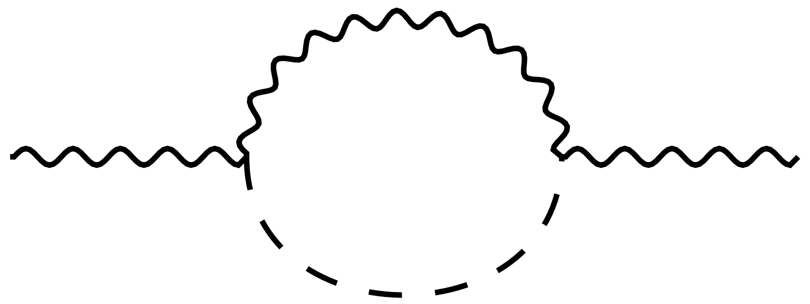
SM

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

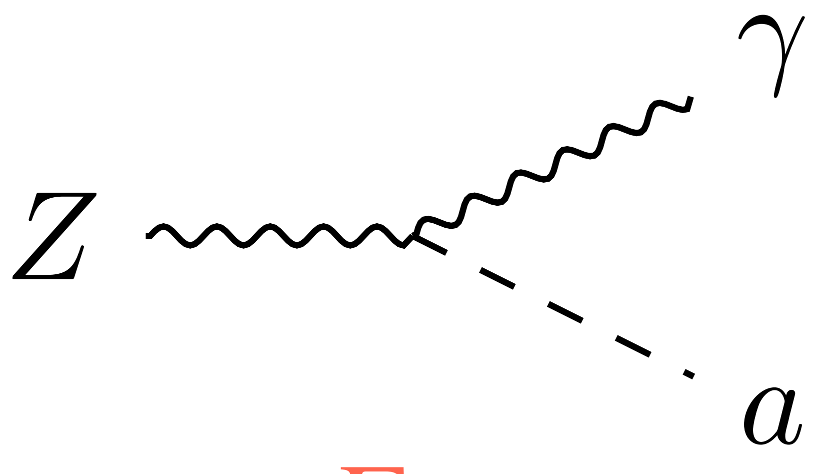
$(+ m_t, m_h, \ldots)$

+

ALP



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



$\Gamma_{a\gamma}$

→

EWPOs

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

Likelihood

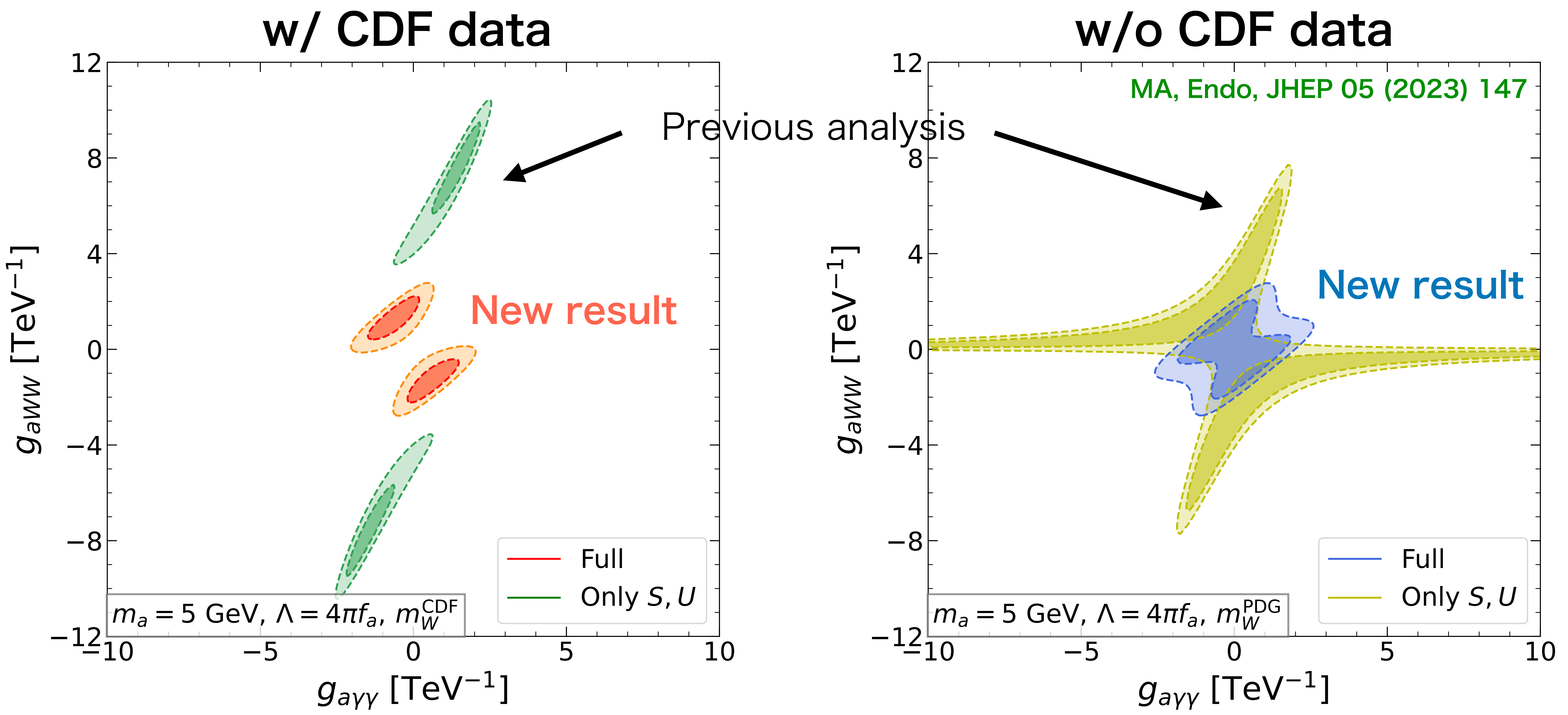
$$-2\ln L = (\boldsymbol{y}-\boldsymbol{\mu})^t V^{-1} (\boldsymbol{y}-\boldsymbol{\mu})$$

$\boldsymbol{y}$: exp. value
$\boldsymbol{\mu}$: 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

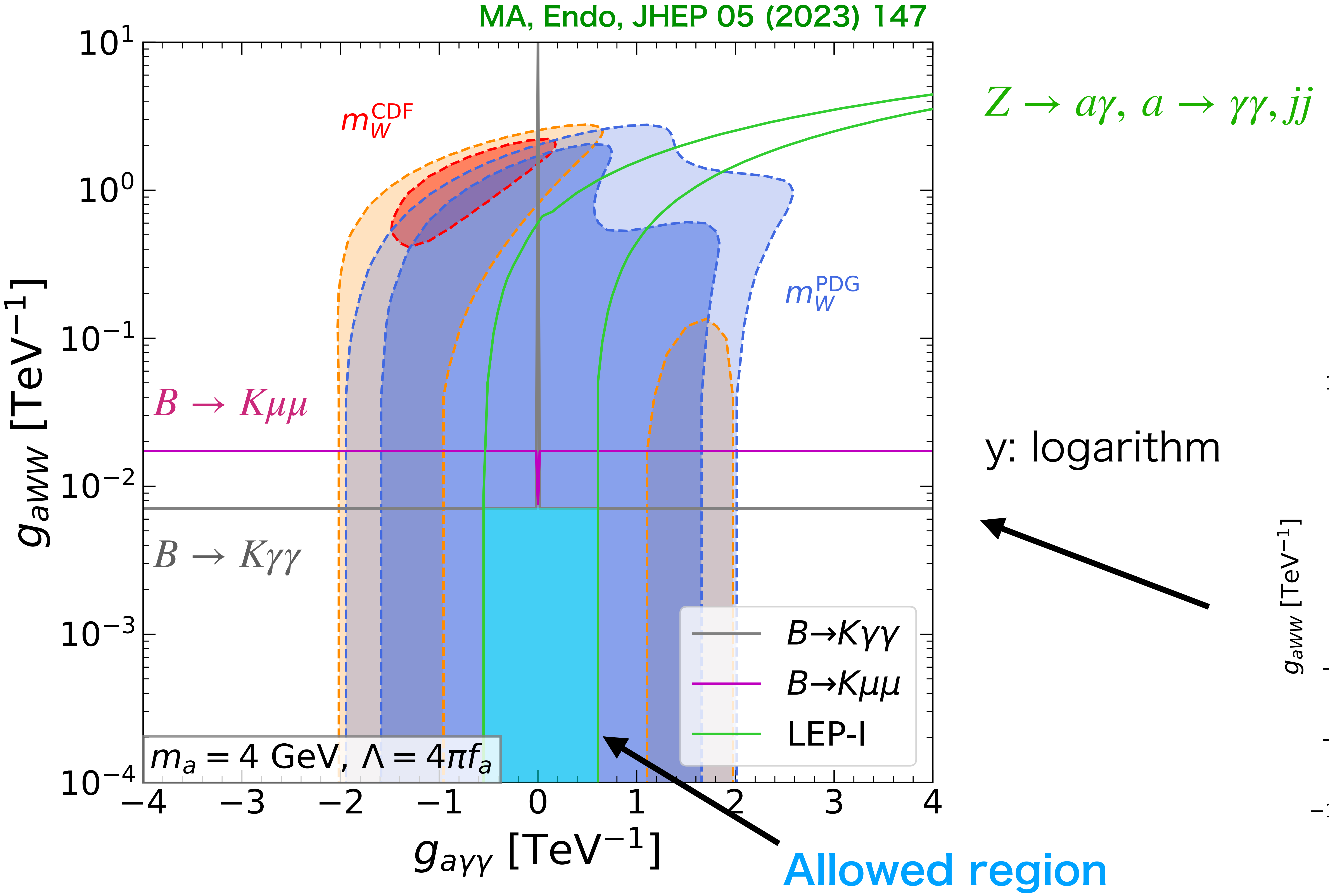
Impact of new contributions

ALP is much lighter than Z boson



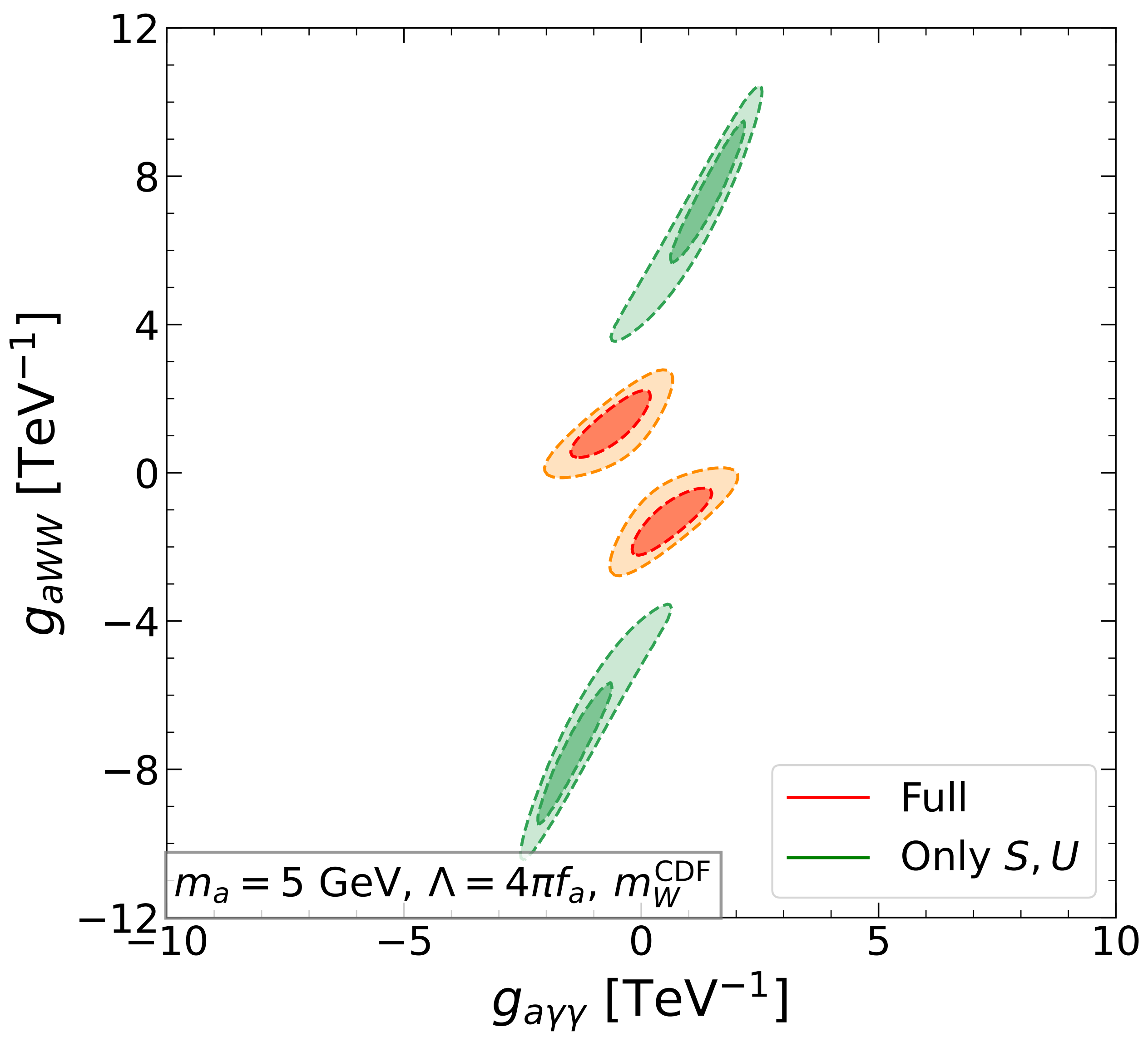
New contributions, especially $\Gamma(Z \to a\gamma)$, significantly affect the results

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



y: logarithm

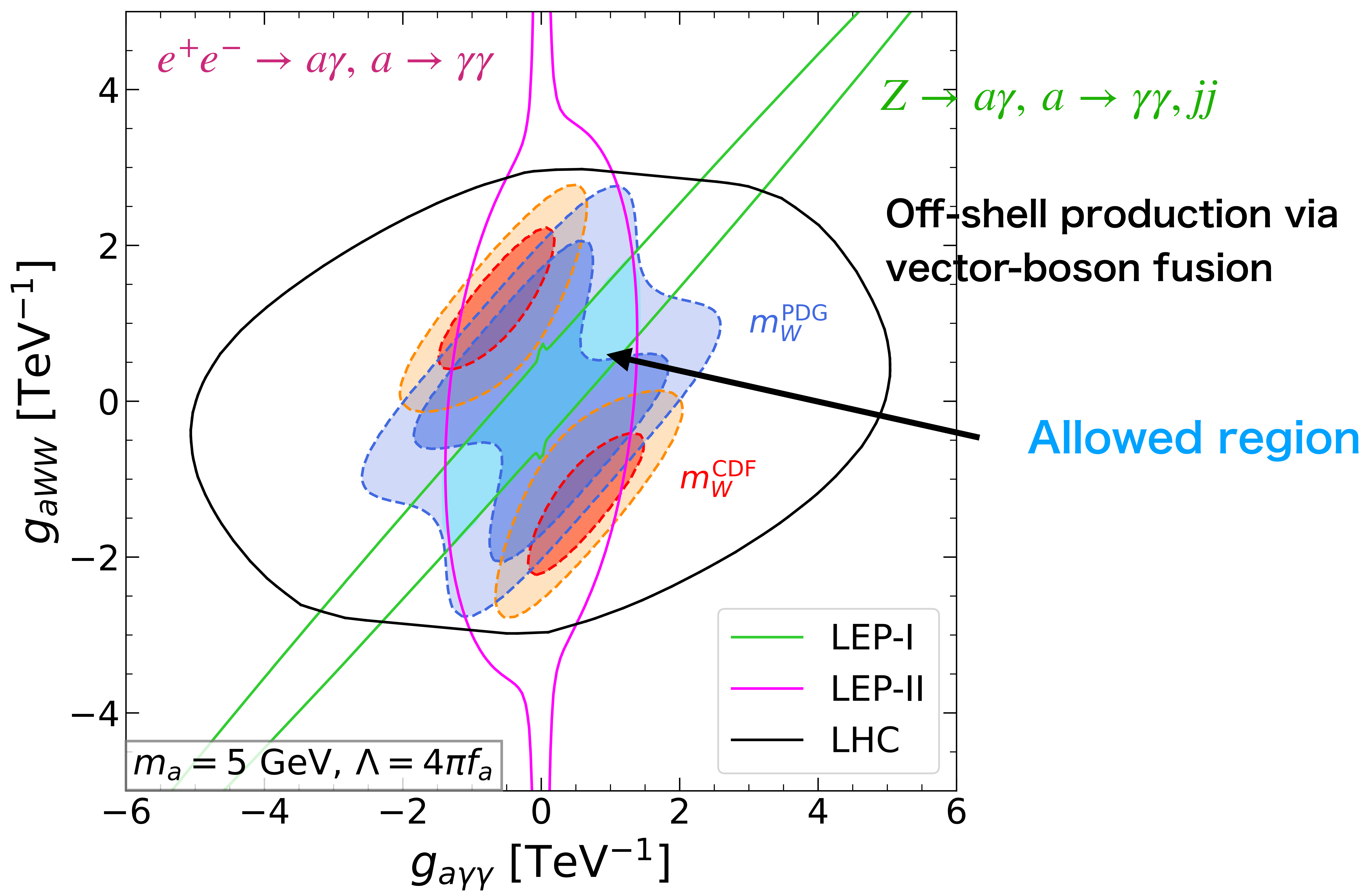
Allowed region



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

EWPT with light ALP ($m_a = 5$ GeV)

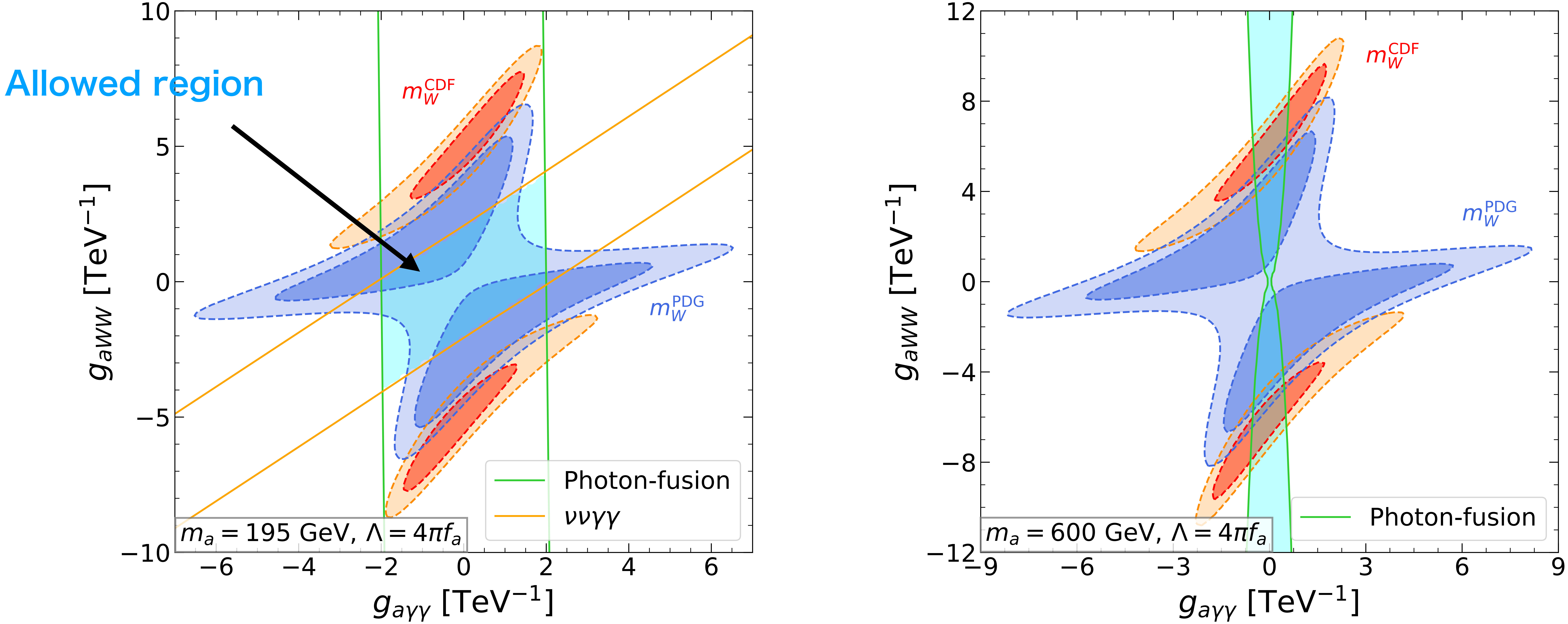
MA, Endo, JHEP 05 (2023) 147



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

EWPT with $m_a > m_Z$

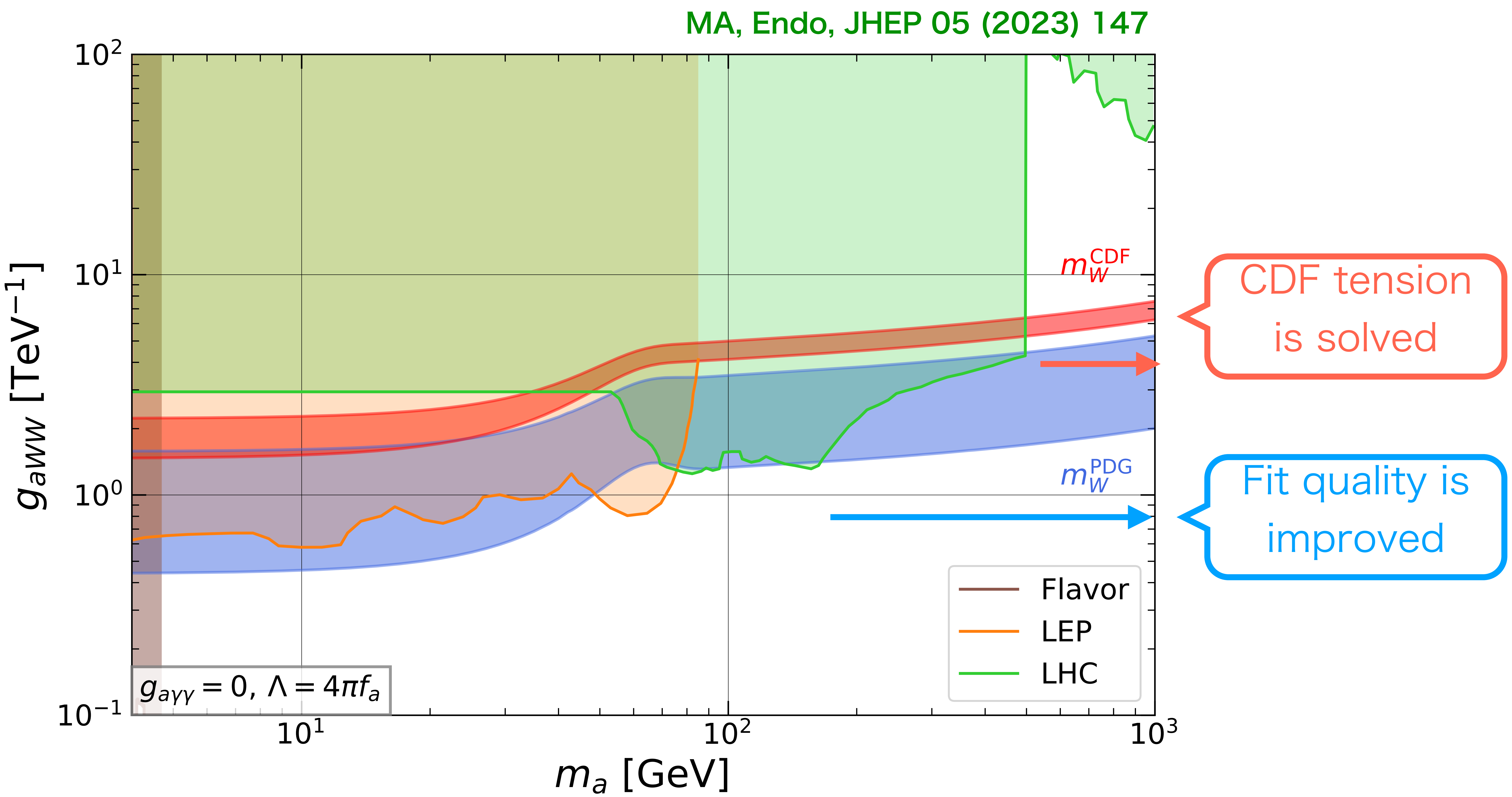
MA, Endo, JHEP 05 (2023) 147



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

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

Mass dependence of EWPOs global fit



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

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

World Average w/o CDF

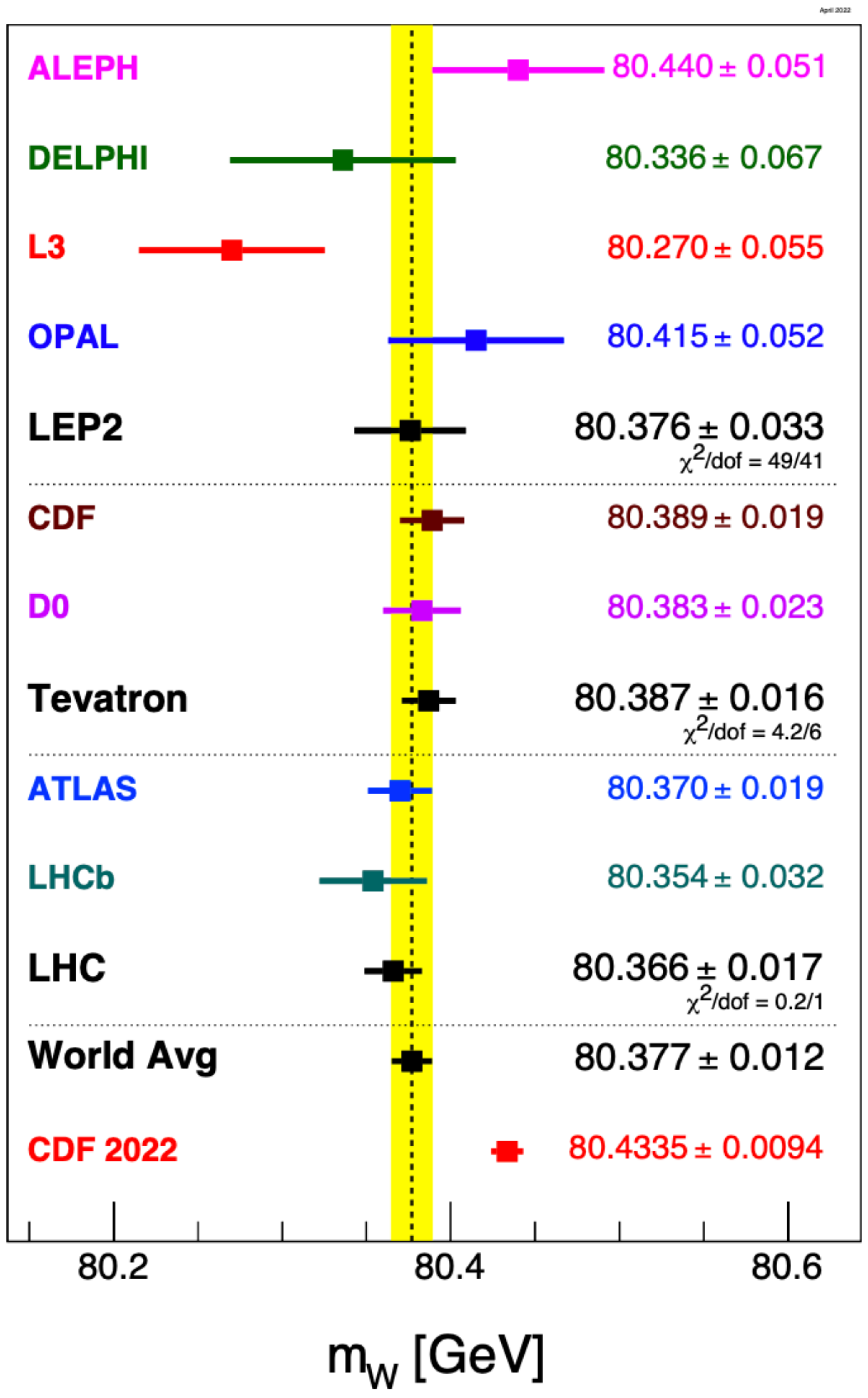
$$m_W^{PDG} = 80.377 \pm 0.012 \text{ GeV}$$

CDF 2022

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

$< 2\sigma$

$\sim 7\sigma$



Prospect

Challenging to achieve $\delta M_W \sim 10$MeV at LHC due to large PDF uncertainty, many pile-up events, …

Summary

- More extractions of m_W are necessary for understanding the tension between recent measurements and probing new physics in the EW sector,
- LHCb has already published a proof-of-principle measurement, with $\Delta m_W =$ 32 MeV. Full-Run-2 measurement targets $\Delta m_W \approx 20$ MeV,
- $\Delta m_W(stat)$ will reduce to ≈ 14 MeV; experimental systematics will largely reduce with the larger control samples,
- Strategies are taking shape to reduce our key systematic uncertainties related to theoretical inputs,
- Further input from the theory community is always welcome!
- Run 3 is underway, and we can look forward to even more precise measurements in the future!

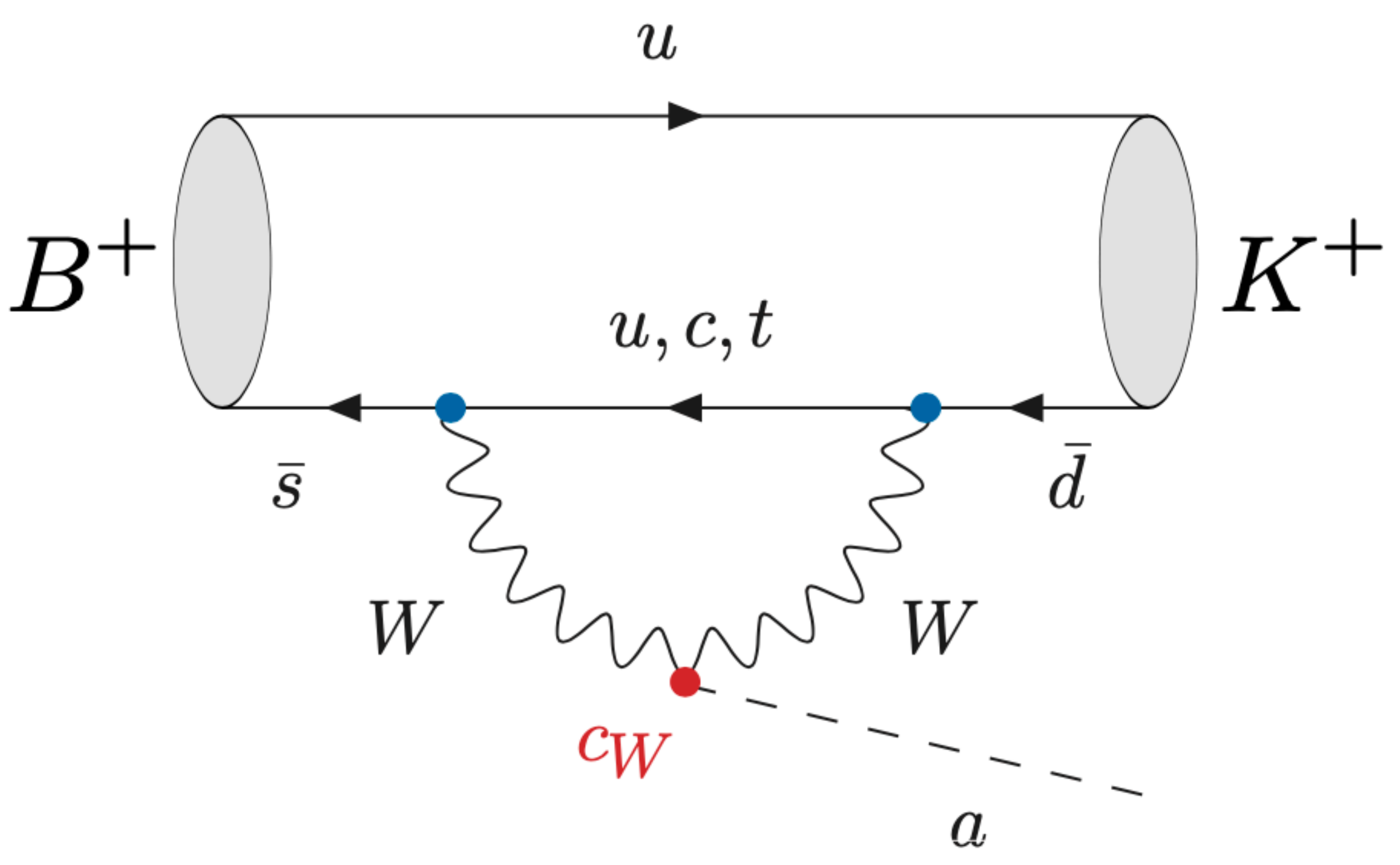
Flavor constraints

B-meson decay

$B \to Ka$

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

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



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

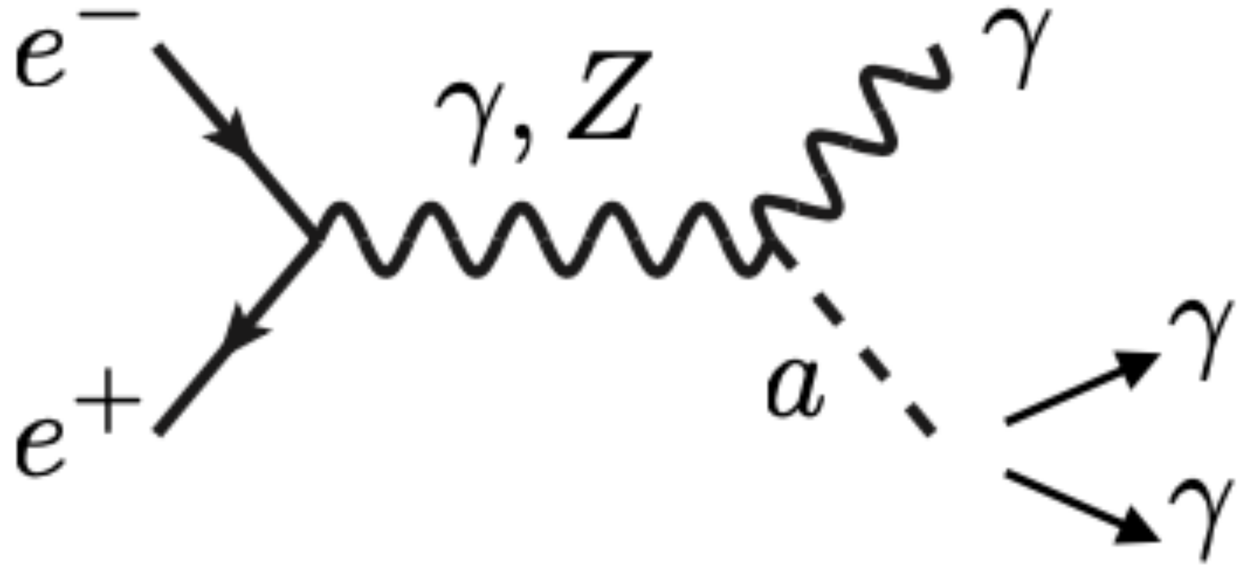
ALP lighter than Z boson

$a \to \gamma\gamma$

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

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

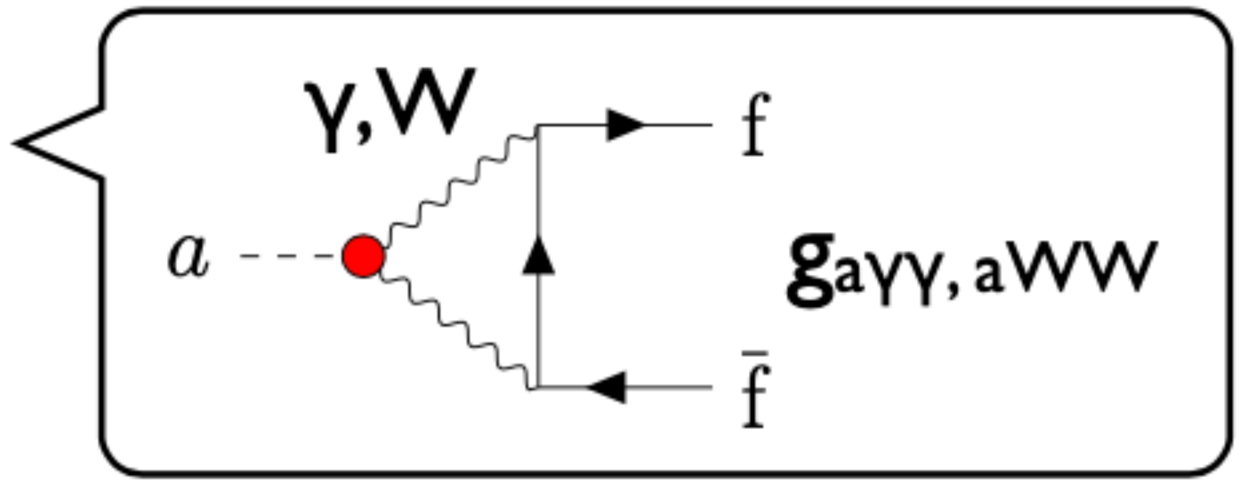
Off-shell γ, Z exchange: $aZ\gamma$ and $a\gamma\gamma$ couplings



$a \to jj$

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

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

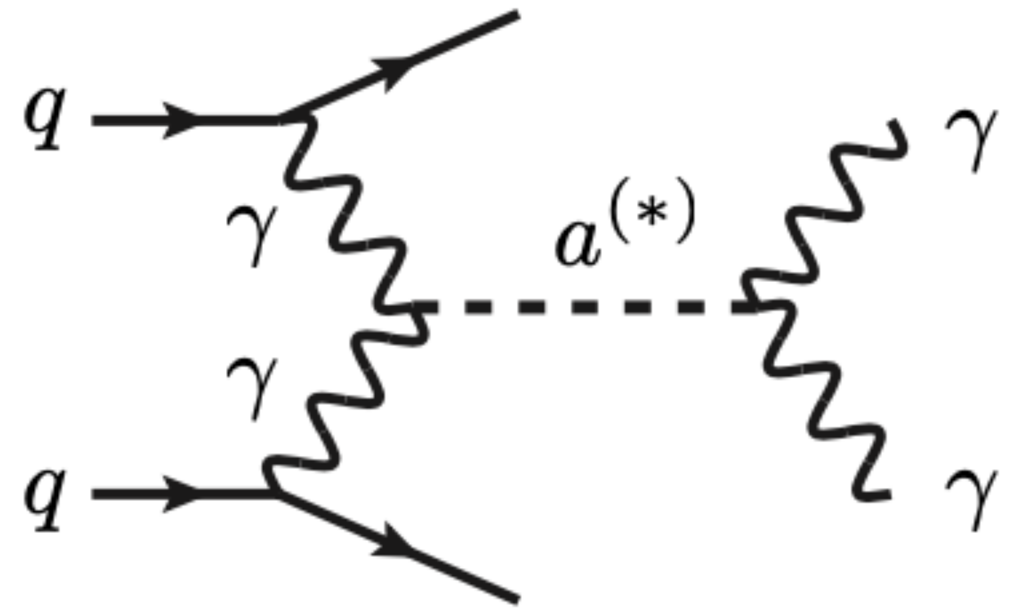


ALP heavier than Z boson

$a \to \gamma\gamma$

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

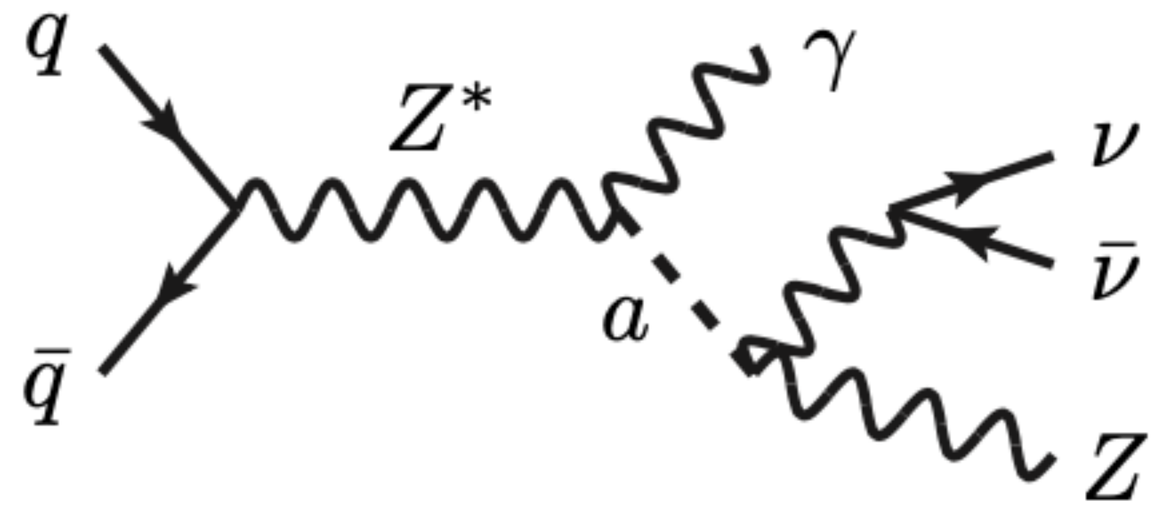
$g_{a\gamma\gamma}$ is tightly constrained.



$a \to Z\gamma$

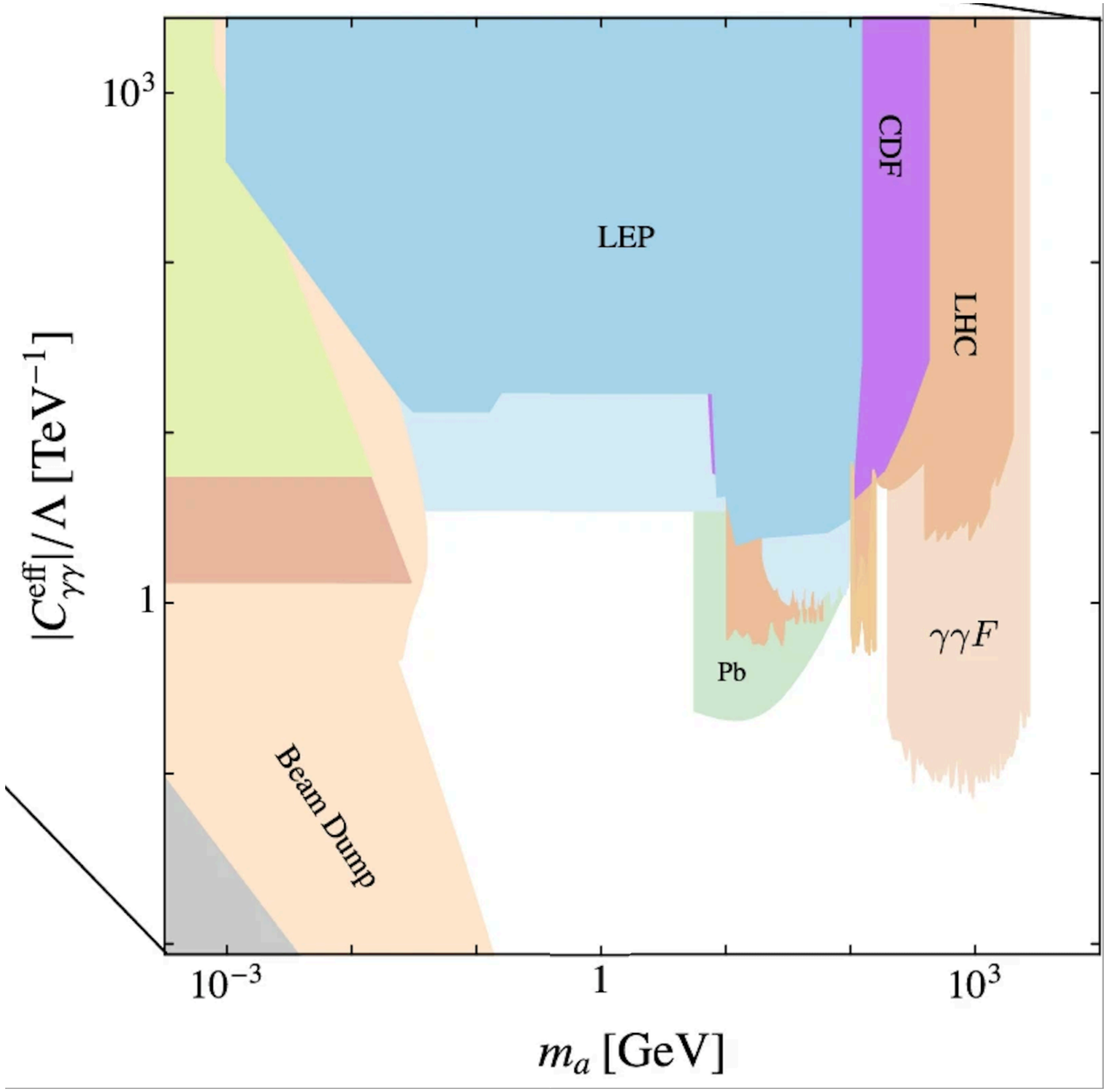
Bound from $(pp \to)q\bar{q} \to Z^* \to a\gamma,\ a \to Z\gamma \to \nu\bar{\nu}\gamma$

Constraint for $m_a < 500$ GeV



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

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

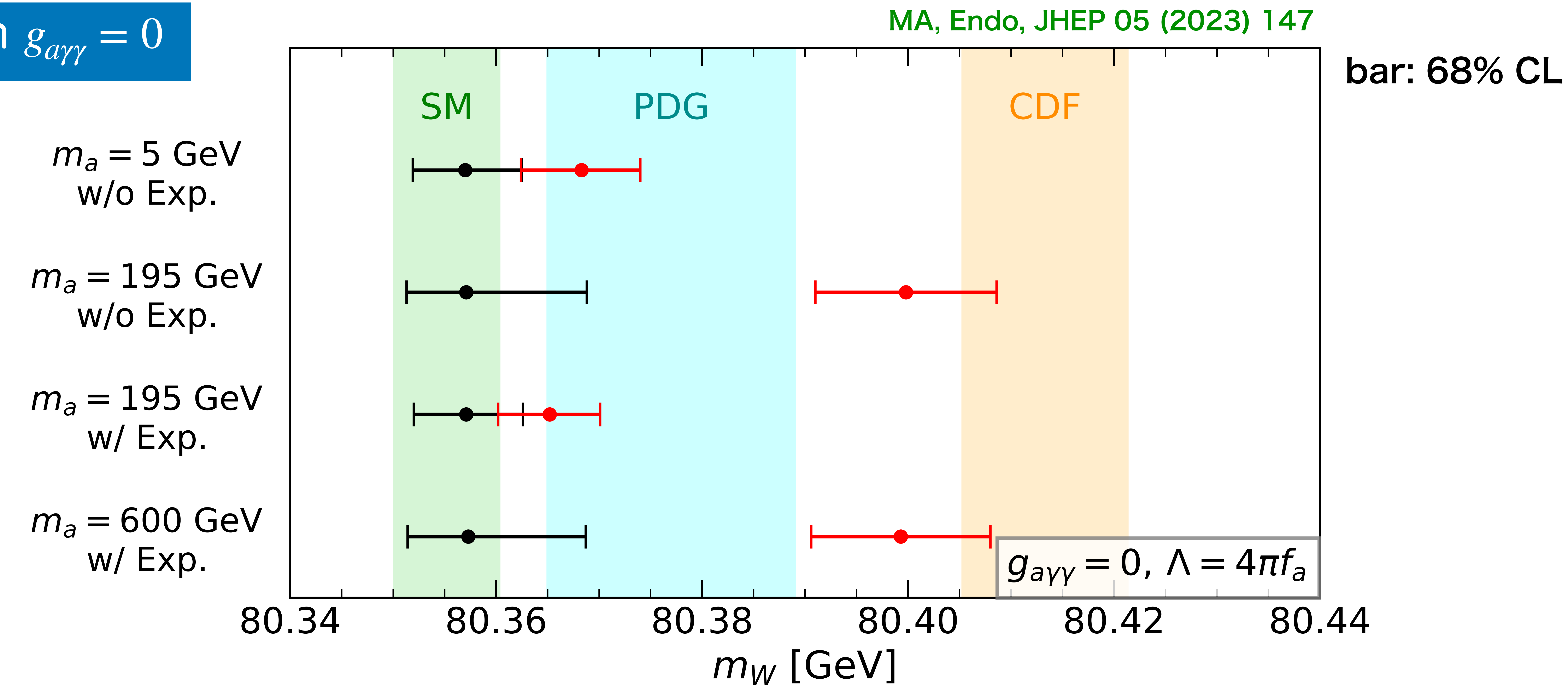


Bauer, Neubert, Thamm, JHEP12 (2017)

Global fit results

Prediction on W-boson mass

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



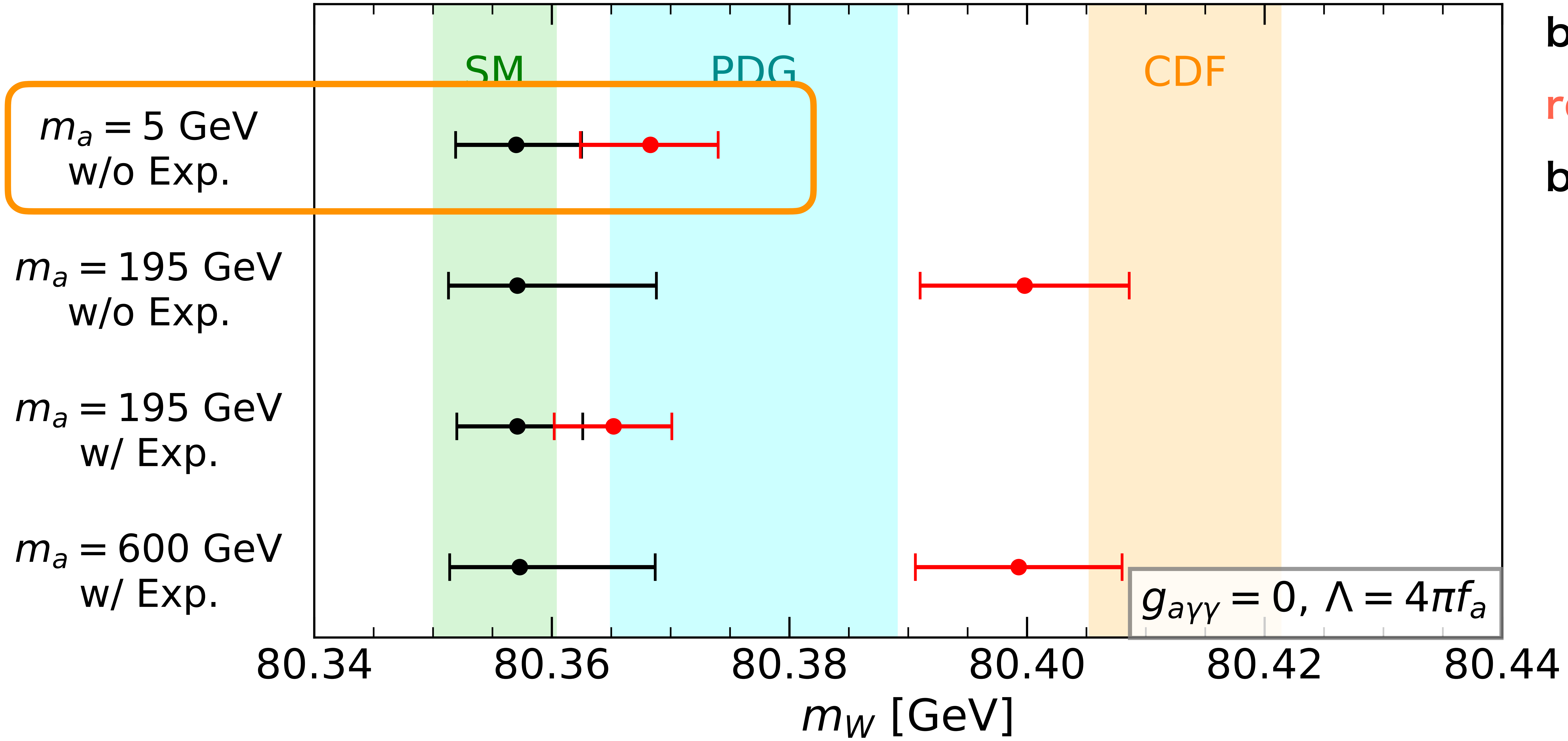
Black: indirect prediction

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

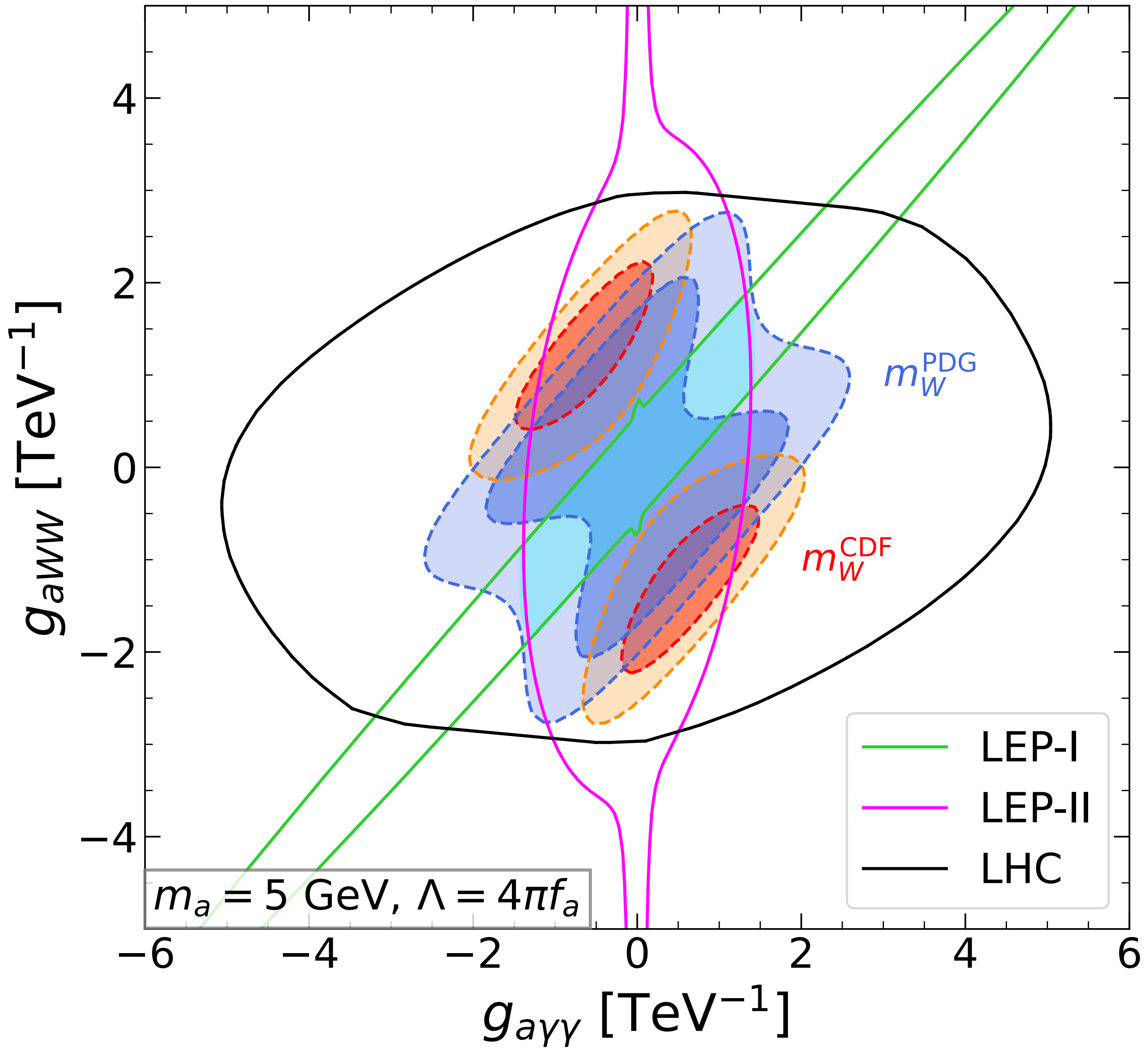
MA, Endo, JHEP 05 (2023) 147



black: w/o m_W

red: w/ m_W

bar: 68% CL



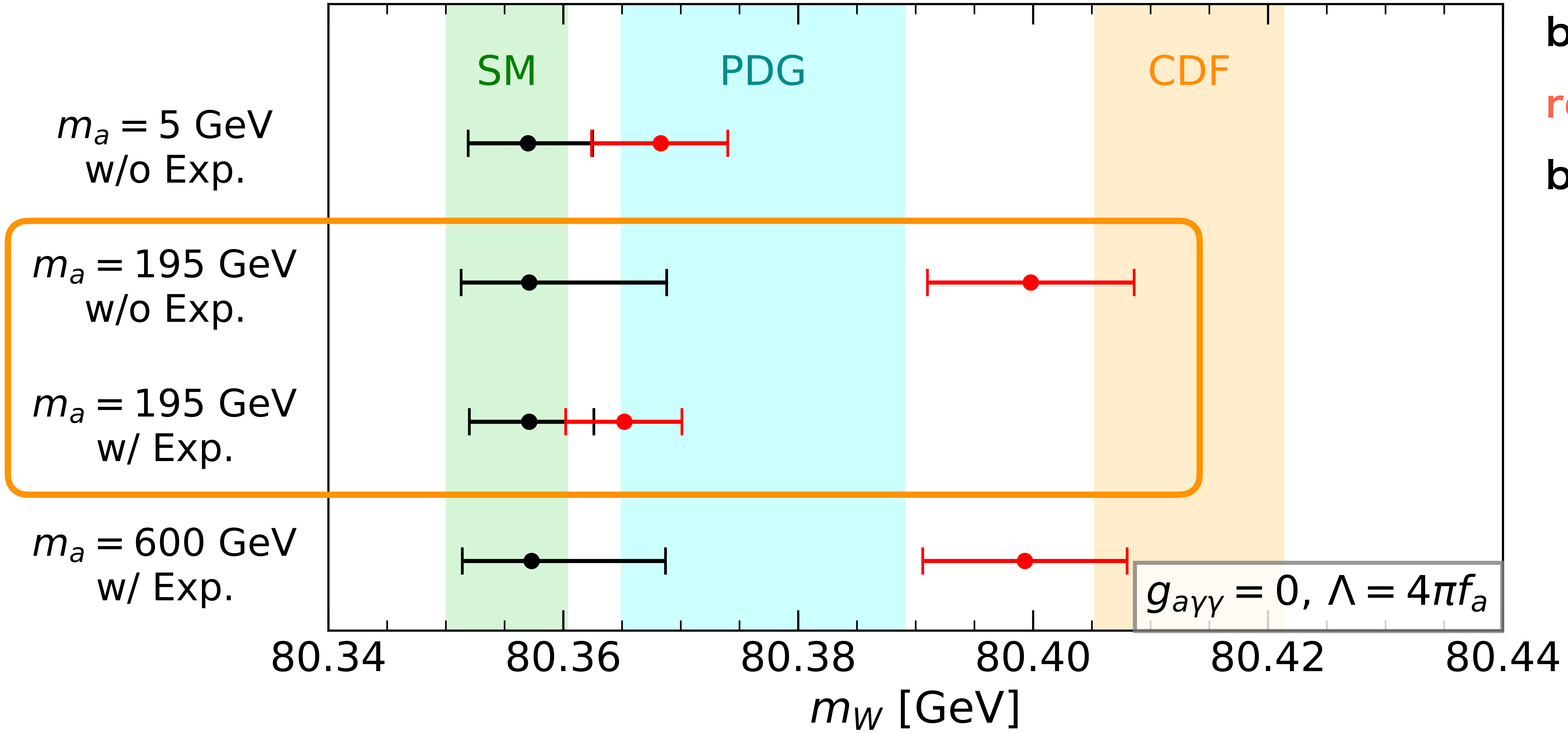
Light ALP cannot explain the CDF value even if we omit the collider constraints.

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

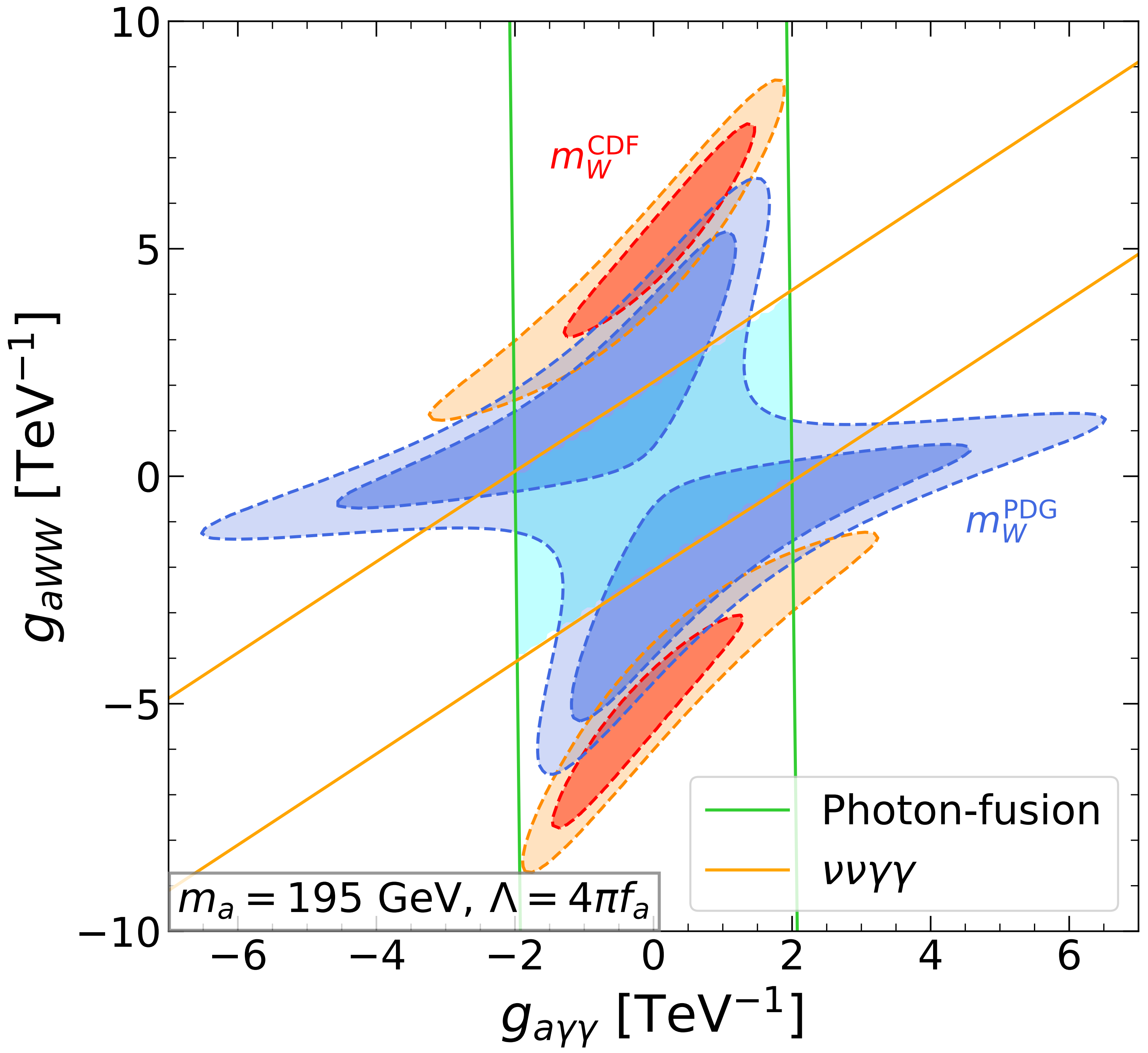
MA, Endo, JHEP 05 (2023) 147



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

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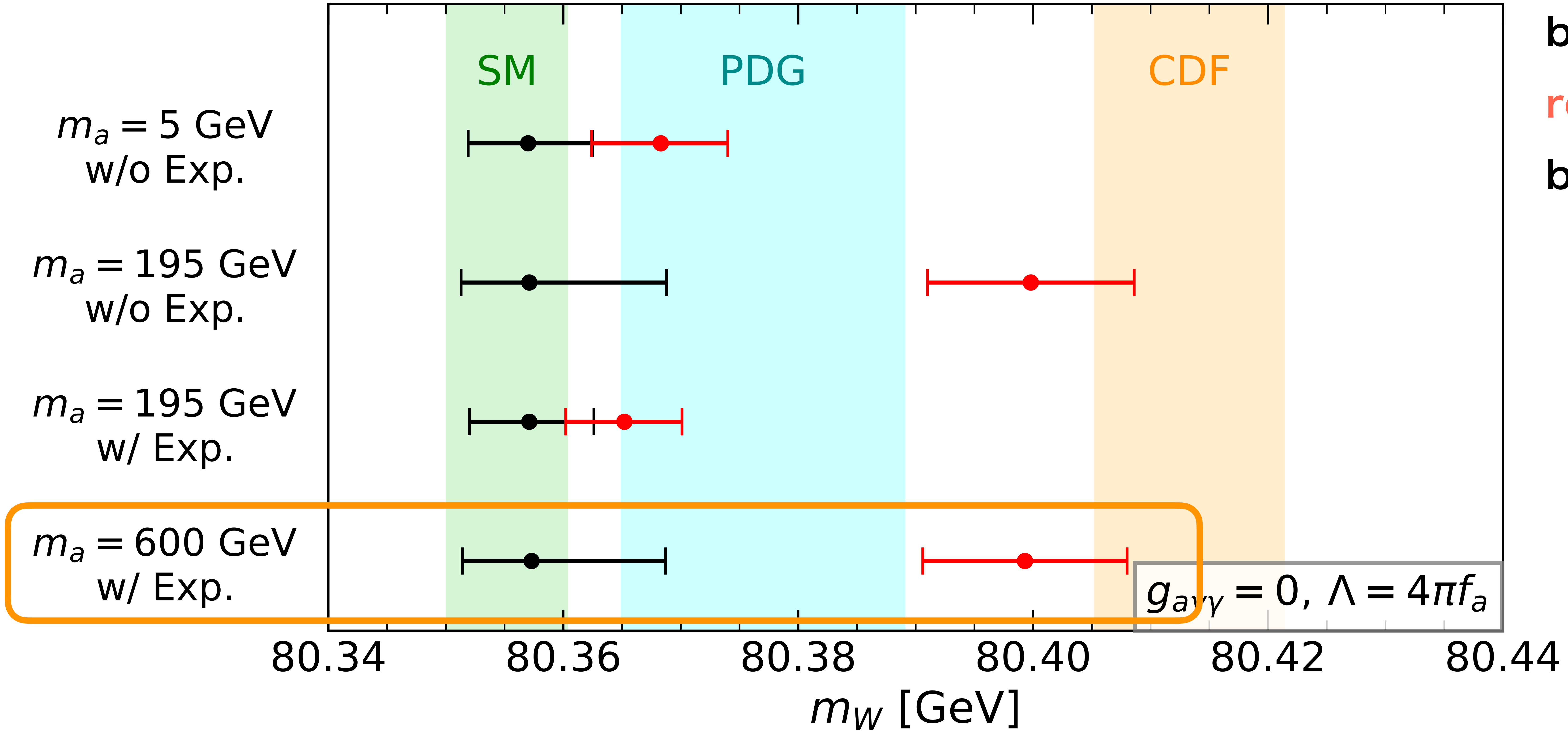
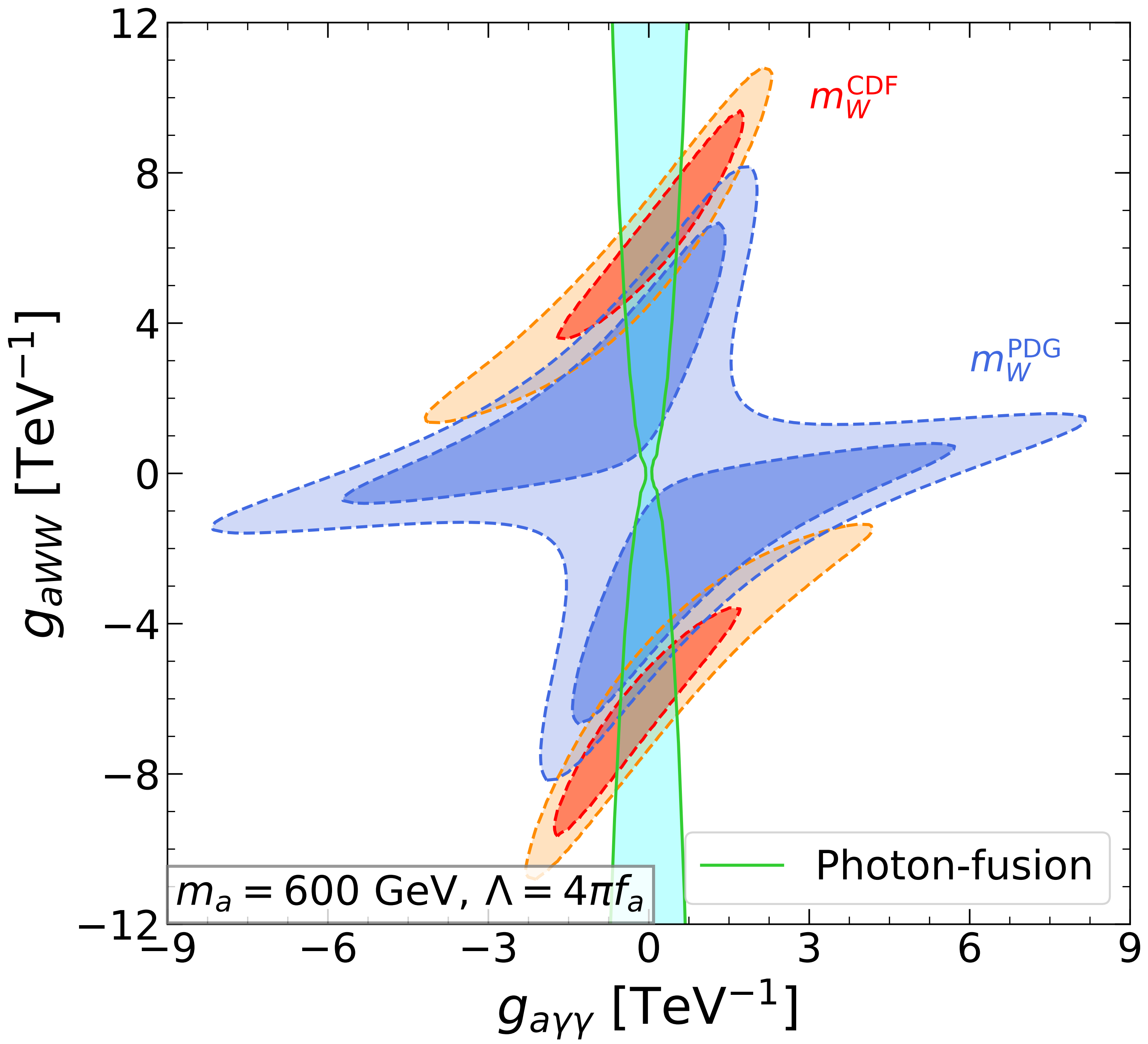


black: w/o m_W

red: w/ m_W

bar: 68% CL

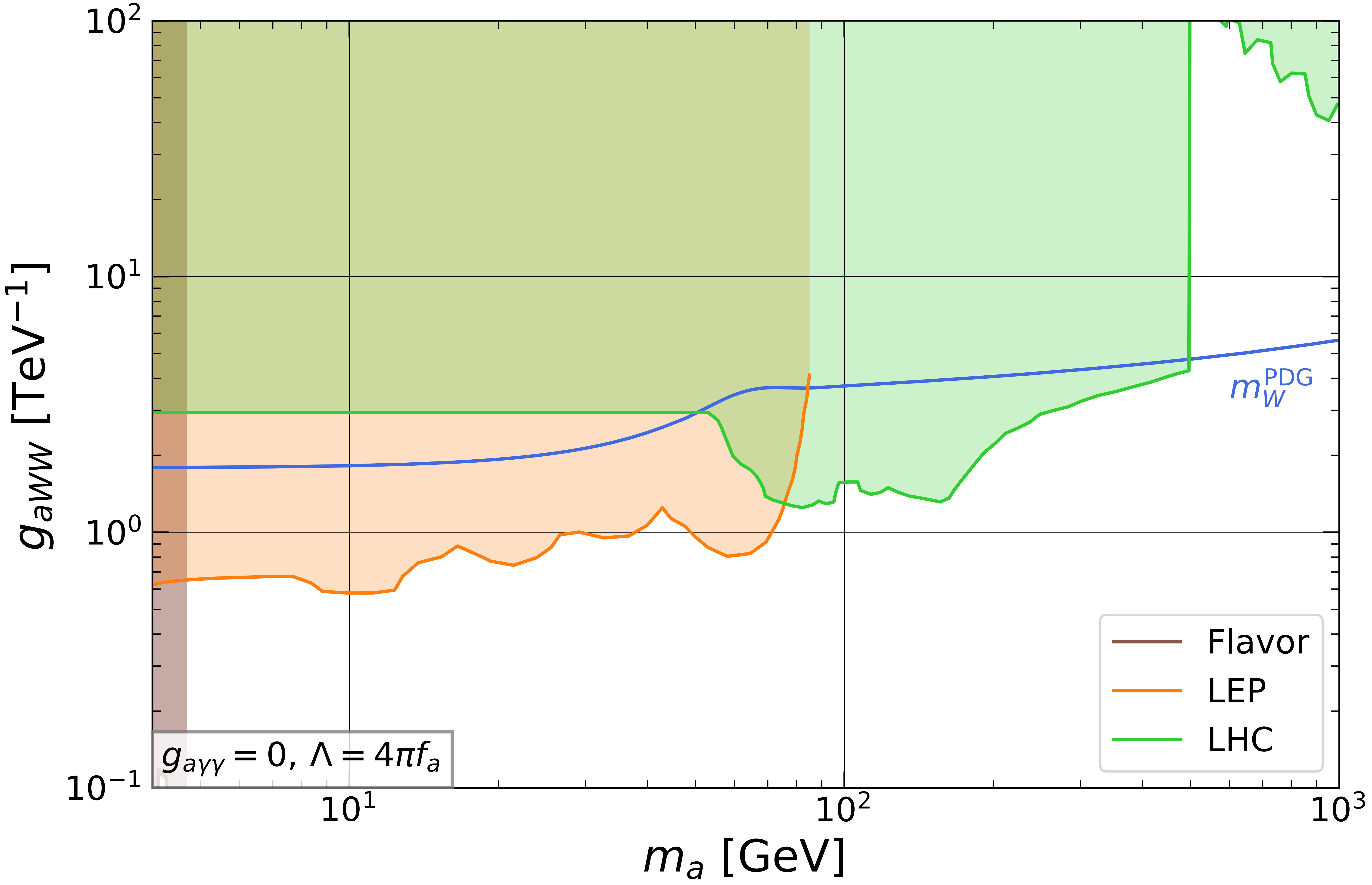


ALP can explain the CDF value.

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

Upper bound on g_{aWW}

$\Lambda = 4\pi f_a$



Cutoff dependence

$\Lambda = f_a$