Electroweak precision test of axion-like particles

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Electroweak precision test

EW theory is predictive.

Input of SM prediction: α, G_F, M_Z at tree level (+ α_s, … for rad.)

Test of SM and hypothetical models.

Two experimental data for W-boson mass.

		Measurement	Ref.
SM rad	$\alpha_s(m_Z^2)$	0.1177 ± 0.0010	[40]
	$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$	0.02766 ± 0.00010	[40]
	m_t [GeV]	172.69 ± 0.30	[5]
	m_h [GeV]	125.21 ± 0.17	[5]
	m_W [GeV]	80.377 ± 0.012	[5]
		80.4133 ± 0.0080	[40]
	Γ_W [GeV]	2.085 ± 0.042	[5]
	$\mathcal{B}(W \to \ell\nu)$	0.10860 ± 0.00090	[44]
	$\mathcal{A}_\ell$ (LEP)	0.1465 ± 0.0033	[42]
	$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	[42]

	Measurement	Ref.
m_Z [GeV]	91.1875 ± 0.0021	[41]
Γ_Z [GeV]	2.4955 ± 0.0023	
σ_h^0 [nb]	41.4802 ± 0.0325	
R_ℓ^0	20.7666 ± 0.0247	
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	
R_b^0	0.21629 ± 0.00066	[42, 43]
R_c^0	0.1721 ± 0.0030	
$A_{\text{FB}}^{0,b}$	0.0996 ± 0.0016	
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	
$\mathcal{A}_b$	0.923 ± 0.020	
$\mathcal{A}_c$	0.670 ± 0.027	

Recent W-boson mass result at CDF

PDG: W-boson mass w/o new CDF

$M_W = 80.377 \pm 0.012$ GeV

tension

Recent CDF result

$M_W = 80.4335 \pm 0.0094$ GeV

tension

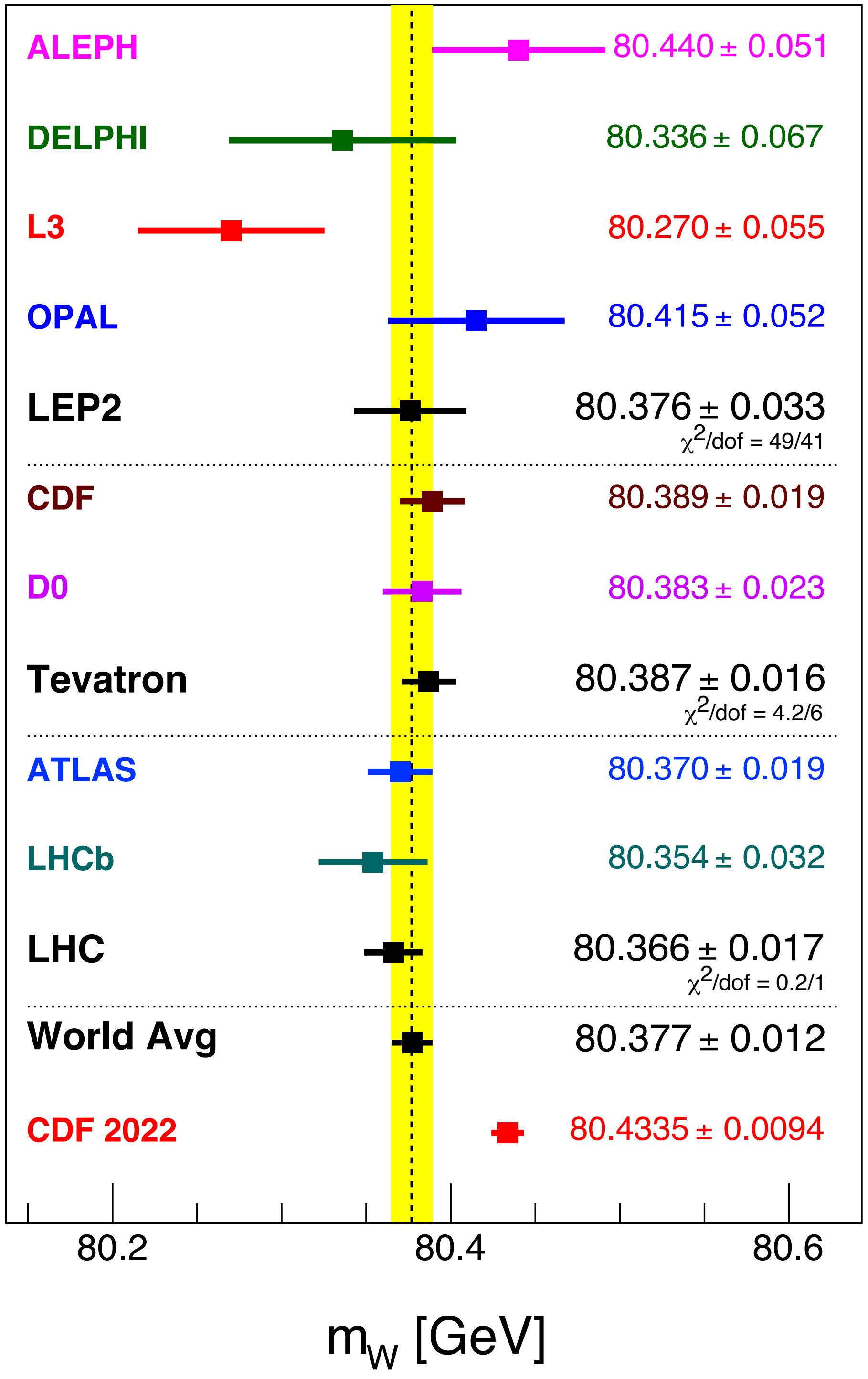
SM prediction

$M_W = 80.3552 \pm 0.0055$ GeV

SM vs PDG → $<2\sigma$ (consistent)

SM vs CDF → $\sim 7\sigma$ → New physics?

[PDG'22]



Axion-like particle (ALP)

Pseudo NG bosons associated to (approximate) global symmetry

Interactions are invariant under shifts a → a + c

Consider interactions with SM SU(2) and U(1) gauge bosons

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

We revisit EWPOs in ALP model both w/ and w/o CDF result.

Contents

ALP contribution to EWPO

Previous studies have missed three points:
[Bauer, Neubert, Thamm'17; …]

1. Radiative corrections beyond S, T, U
2. Z boson decay into axion
3. Experimental constraints

W-boson mass and goodness of fit

Summary

ALP contribution to EWPO

Two ALP couplings

$$\mathcal{L}_{\rm ALP} = -c_{WW}\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - c_{BB}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

EWSB

$$= -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{2}g_{a\gamma Z}aZ_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}g_{aZZ}aZ_{\mu\nu}\widetilde{Z}^{\mu\nu} - \frac{1}{2}g_{aWW}aW^+_{\mu\nu}\widetilde{W}^{-\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_W^2 c_{WW} + c_W^2 c_{BB})$$

$$g_{aZ\gamma} = \frac{2}{f_a}(c_{WW} - c_{BB})s_{2W}$$

$$g_{aZZ} = \frac{4}{f_a}(c_W^2 c_{WW} + s_W^2 c_{BB})$$

$$g_{aWW} = \frac{4}{f_a}c_{WW}$$

Contribute to EWPOs via vacuum polarizations

→ oblique parameters

Oblique corrections

New physics contributions via vacuum polarization are parametrized in many models by oblique parameters, S, T and U [Peskin, Takeuchi'92]

$$
\begin{aligned}
S &= 16\pi \,\mathrm{Re}\Big[\Pi^{3Q}_{T,\gamma}(M_Z^2) - \Pi^{33}_{T,Z}(0)\Big] \\
T &= \frac{4\sqrt{2}\,G_F}{\alpha}\,\mathrm{Re}\big[\Pi^{33}_{T}(0) - \Pi^{11}_{T}(0)\big] \\
U &= 16\pi \,\mathrm{Re}\big[\Pi^{33}_{T,Z}(0) - \Pi^{11}_{T,W}(0)\big]
\end{aligned}
$$

def.

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

Contribution to EWPOs

e.g., W-boson mass

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

↖

new physics

Previous analysis [Bauer, Neubert, Thamm'17]

ALP is assumed to be much lighter than Z boson

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

$$T = 0$$

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

They focused only on S, T, U and supposed that other effects are negligible.

New CDF result was analyzed in the same approach:

"… (light) ALP is just marginally acceptable." [Yuan, Zu, Feng, Cai, Fan'22]

We address two additional types of contributions.

1. Radiative corrections beyond S, T, U

Radiative corrections to gauge couplings via vacuum polarizations

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

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

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

Z-pole observables: $\Gamma(Z \to f\bar{f}) = N_C \dfrac{G_F M_Z^3}{6\sqrt{2}\pi}\left[|g_{V,f}|^2 + |g_{A,f}|^2\right]$

$$\begin{cases} g_{V,f} = \sqrt{\rho_Z}\left(I_{3,f} - 2\,Q_f\,\bar{s}_W^2\right), \quad g_{A,f} = \sqrt{\rho_Z}\,I_{3,f} \\ \bar{s}_W^2(M_Z^2) = s_W^2 + \dfrac{1}{c_W^2 - s_W^2}\left[c_W^2 s_W^2\left[\Delta\alpha - \alpha T\right] + \dfrac{\alpha S}{4}\right] \\ \rho_Z = 1 + \alpha T + \Delta_Z \end{cases}$$

W-boson mass: $M_W^2 = (M_W^2)_{\mathrm{SM}} + \dfrac{c_W^2 M_Z^2}{c_W^2 - s_W^2}\left[-s_W^2\Delta\alpha - \dfrac{\alpha S}{2} + c_W^2\alpha T + \dfrac{c_W^2 - s_W^2}{4 s_W^2}\alpha U\right]$

cf. Δ_W contributes to Γ_W

ALP contributions

Formulae for ALP much lighter than Z boson [Aiko, ME]

Consistent w/ prev.

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

New

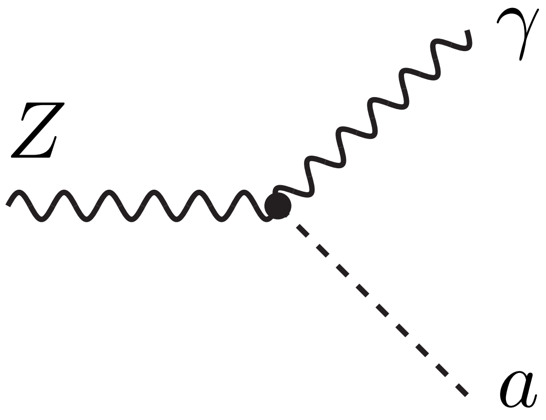
$$\left\{\begin{aligned} \Delta\alpha &= \frac{m_Z^2}{96\pi^2}\left[g_{a\gamma\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{3}\right)+g_{aZ\gamma}^2\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{11}{6}\right)\right] \\ \Delta_Z &= \frac{m_Z^2}{96\pi^2}\left(g_{aZ\gamma}^2+g_{aZZ}^2\right)\left(\ln\frac{m_Z^2}{\Lambda^2}+\frac{4}{3}\right)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

New contributions are comparable to S and U → affect EWPOs

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

2. Z boson decay into ALP

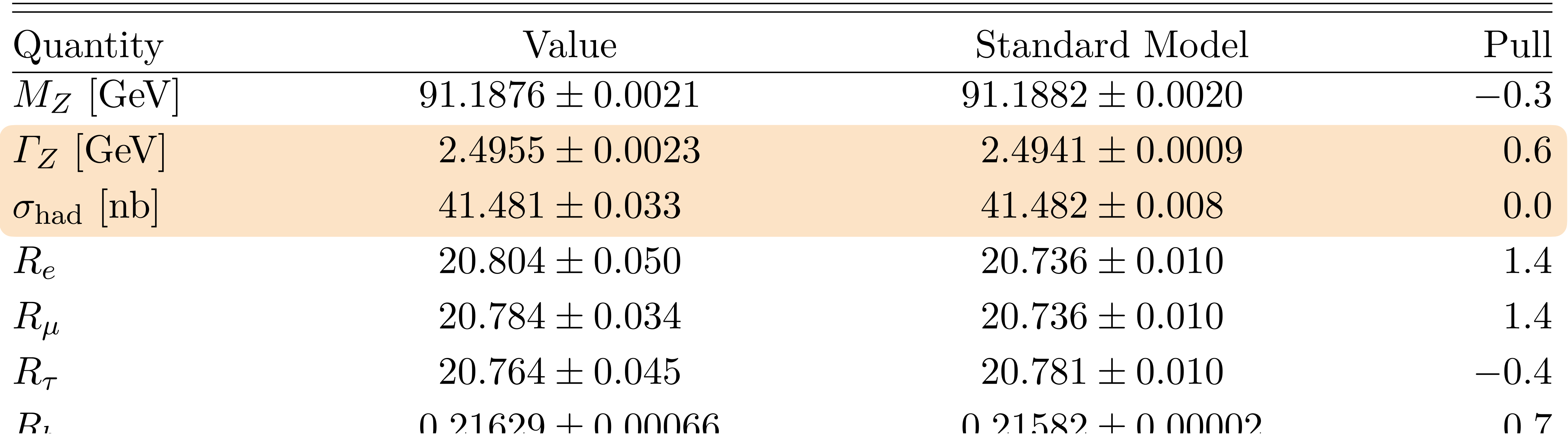
Z boson decays into light ALP w/ photon



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

Contribute to total width of Z-boson decay (and had. xsec σ_{had} via Γ_Z)

Stronger than vac. polarization because the decay is at tree level.



Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.4941 ± 0.0009	0.6
σ_{had} [nb]	41.481 ± 0.033	41.482 ± 0.008	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.736 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7

$\vdots$

EW precision test in ALP model

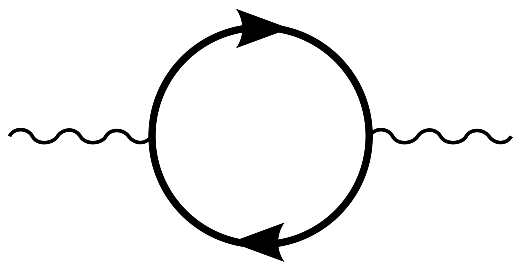
SM

α, G_F, M_Z

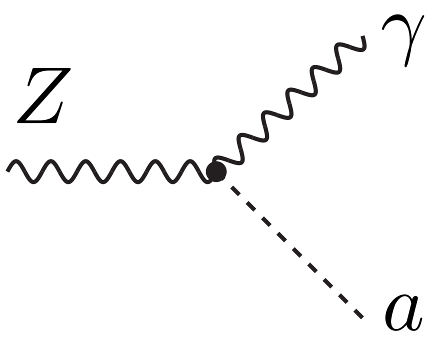
(+ m_t, … for rad.)

+

ALP



S, U + $\underline{\Delta\alpha, \Delta_V, \Delta_W}$



$\underline{\Gamma_{a\gamma}}$

→

EWPO

Γ_Z, A_{FB}, M_W, etc

Compared with experimental data (global fit analysis)

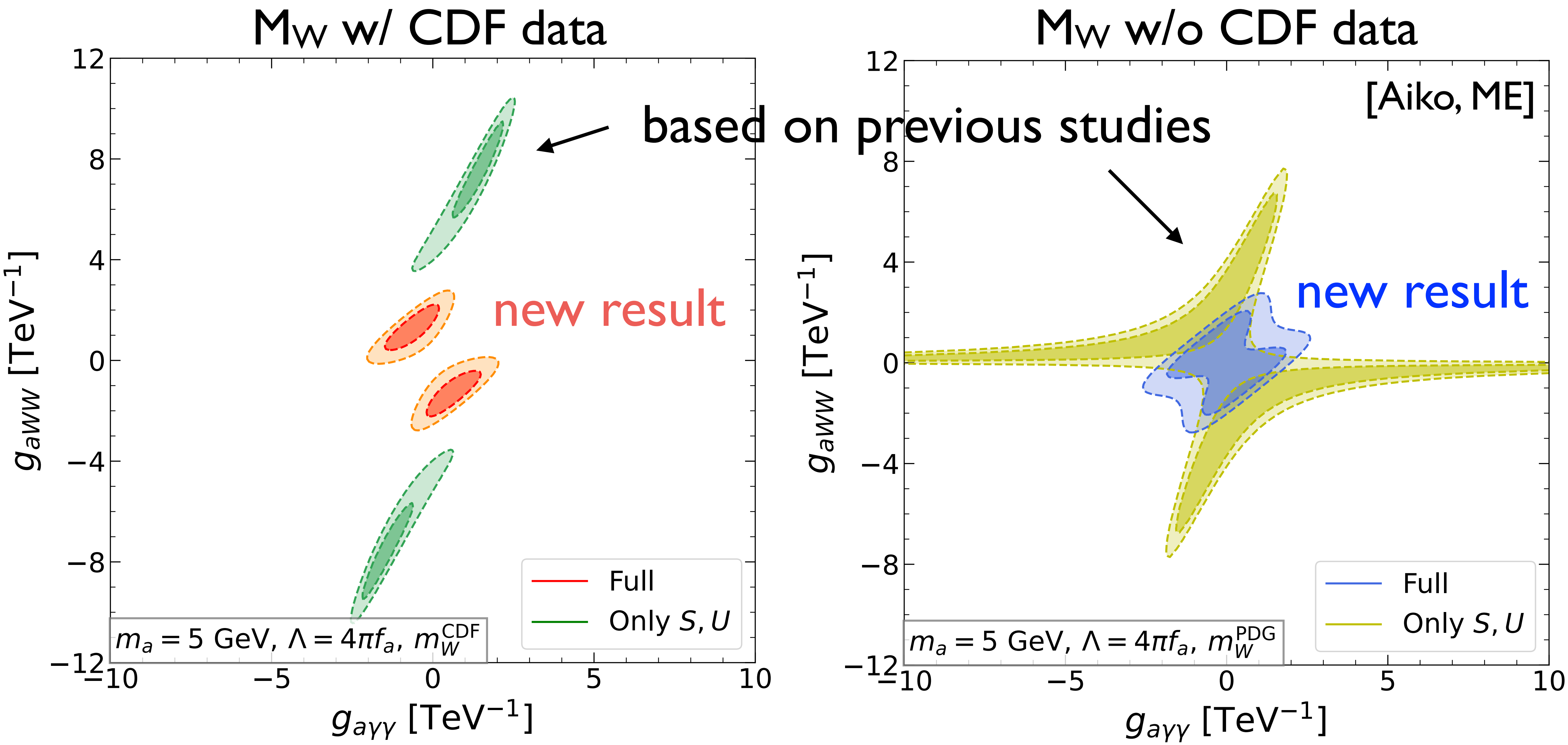
New contributions affect same observables as S, T, U.

They must be analyzed in the global fit *simultaneously*.

Impact of new contributions

ALP is much lighter than Z boson → insensitive to ALP mass.

EWPO global fit results are affected significantly, especially by $\Gamma(Z \to a\gamma)$.



M_W w/ CDF data

M_W w/o CDF data

based on previous studies

new result

new result

[Aiko, ME]

color: 68, 95%

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Summary

Flavor constraint

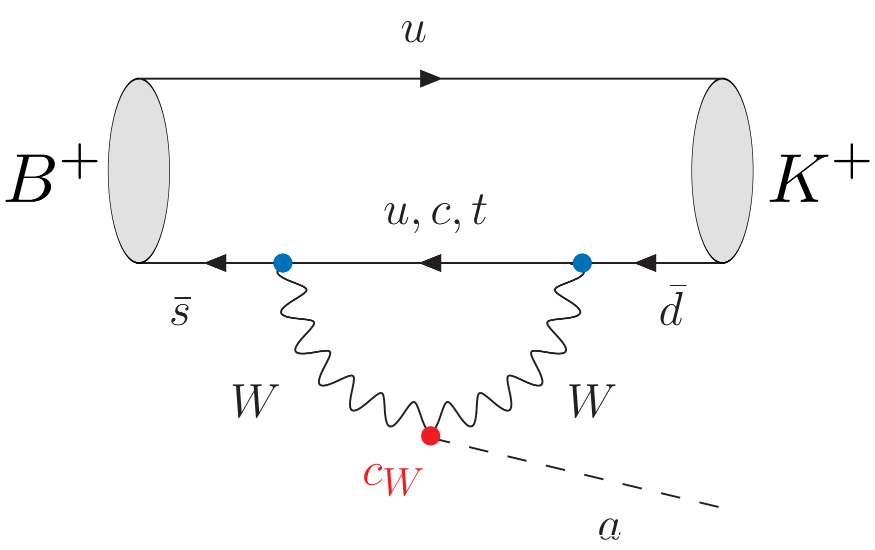
Sensitive to ALP coupling with W boson.

Quark flavor is violated due to CKM by exchanging W-boson.

B meson decays into ALP with K meson:

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

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



[Izaguirre,Lin,Shuve'17;
Gavela,Houtz,Quilez,Del Rey,Sumensari'19;
Bauer,Neubert,Renner,Schnubel,Thamm'22]

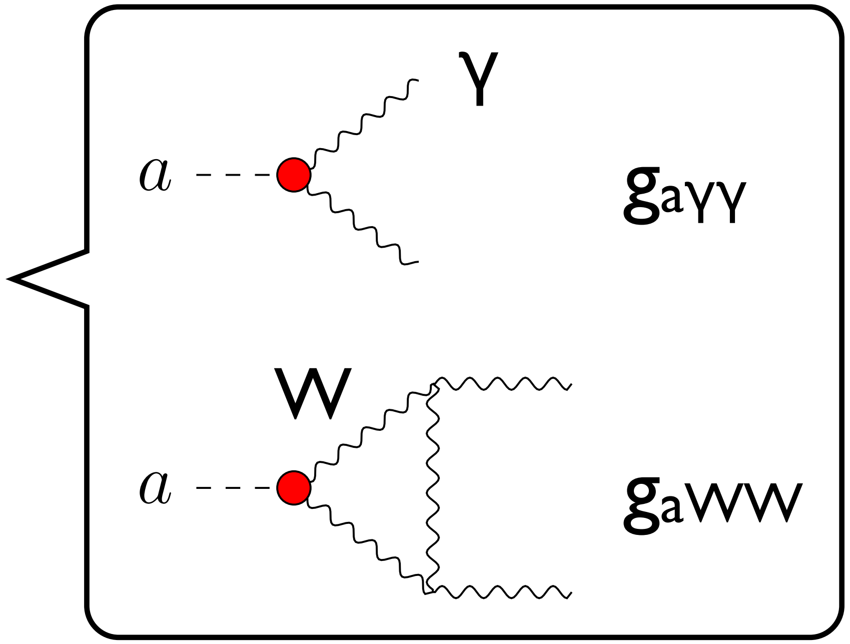
Flavor constraint … contd

ALP is subject to tight flavor constraint for m_a<~4.8GeV.

- $B \to K\, a,\ a \to \gamma\gamma$

  BaBar studied prompt and displaced decays

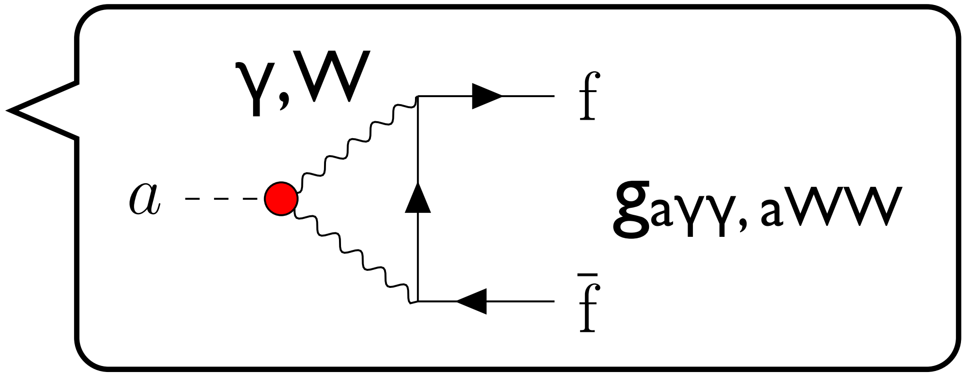
  Constraint for $0.175 < m_a < 4.78$ GeV



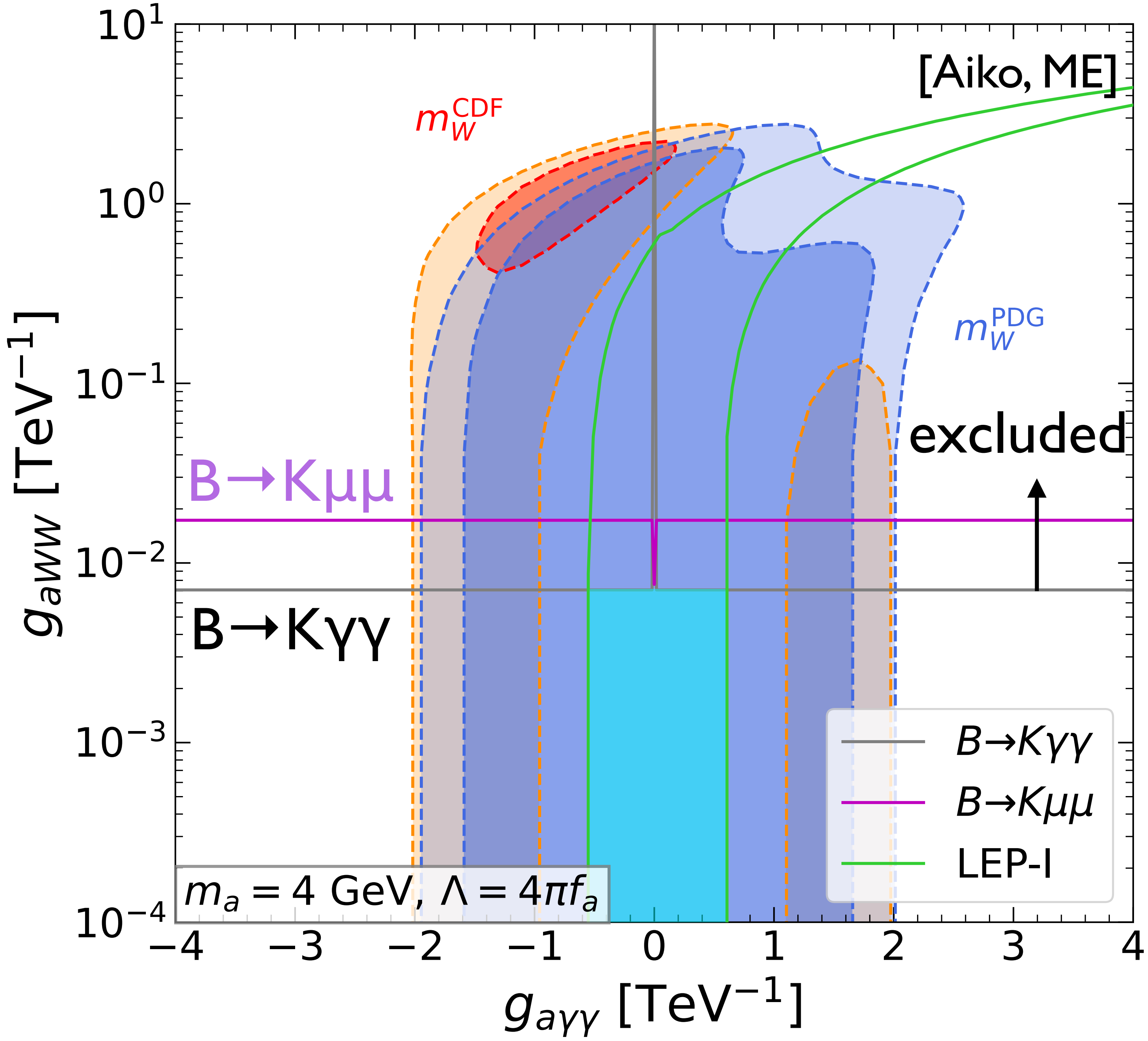
- $B \to K\, a,\ a \to \mu^+\mu^-$

  LHCb studied prompt and displaced decays

  Constraint for $0.250 < m_a < 4.70$ GeV



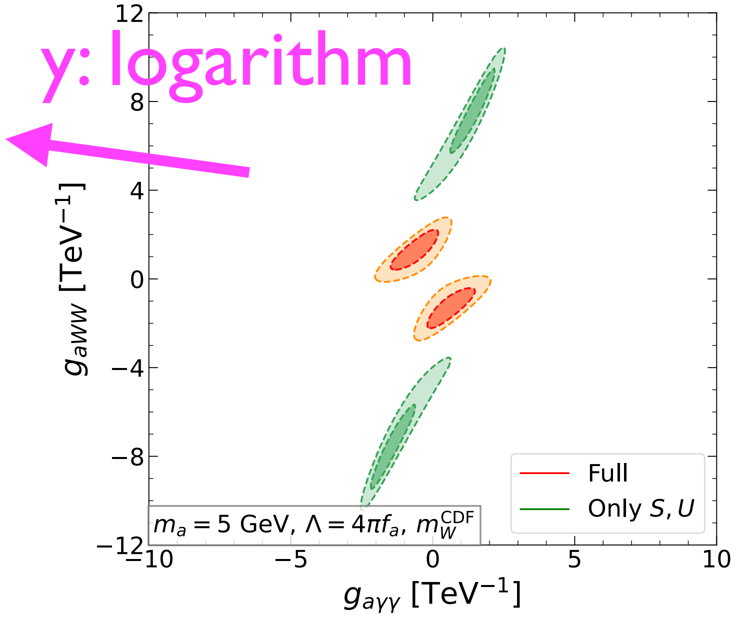
EWPT results vs flavor constraint



Collider bound

→ next

y: logarithm



Almost entire regions are excluded for $m_a < 4.8$ GeV.

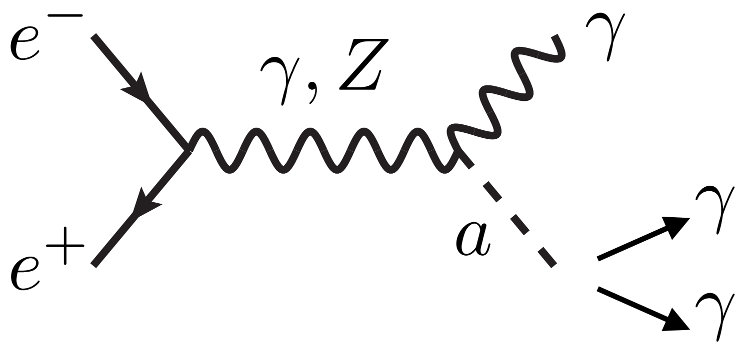
→ Consider heavier ALP to avoid flavor constraints.

Collider constraints

ALP is lighter than Z boson.

<u>Br(a→γγ)~1</u>

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



LEP data

On-shell Z exchange: a-Z-γ coupling

Off-shell γ, Z exchange: a-γ-γ as well as a-Z-γ

} complementary

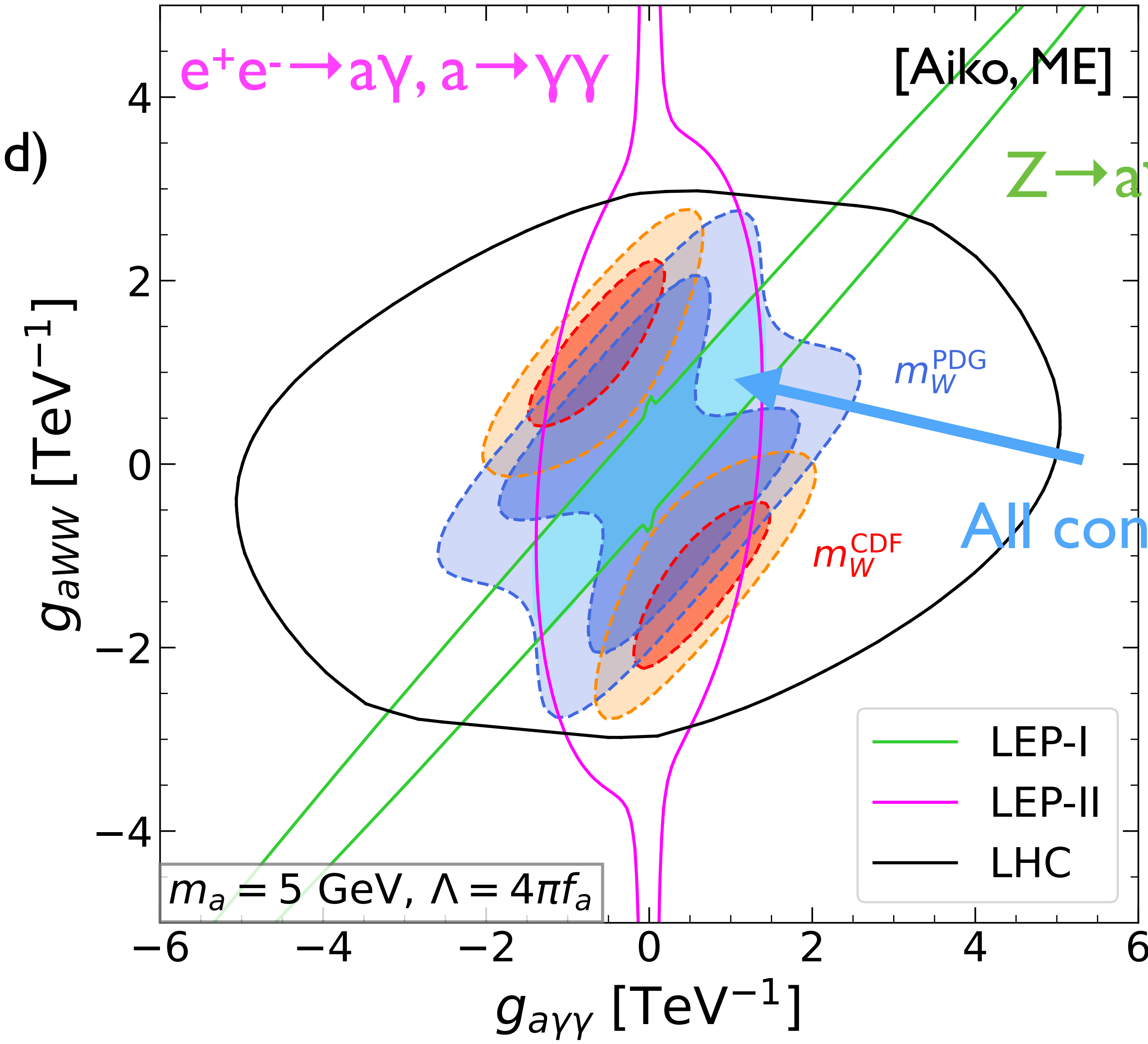
<u>Br(a→γγ)~0</u>

Bound from $e^+e^- \to$ on-shell $Z \to a\gamma$, $a \to jj$ (j=c, b, …)

Light ALP case

m_a=5GeV

(avoid flavor bound)



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

[Aiko, ME]

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

All constraints are satisfied

* LHC: off-shell ALP production via VBF

ALP is consistent with EWPOs with m_W(PDG), but not with m_W(CDF).

→ CDF tension cannot be solved by light ALP. (cf. contrary to Yuan et.al.)

Heavier ALP case

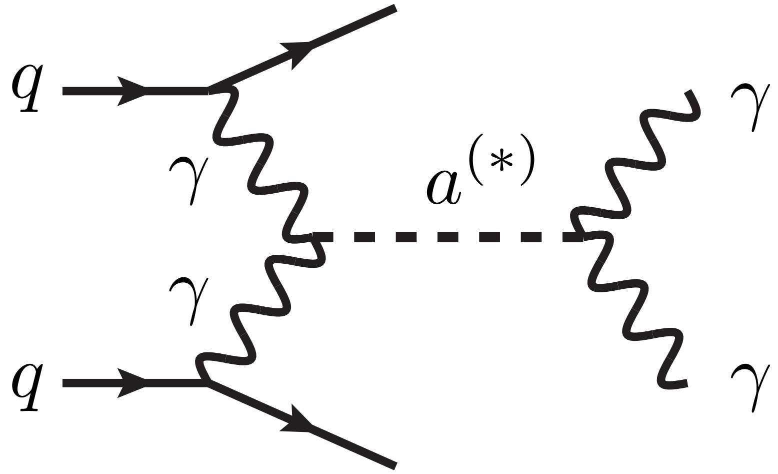
EWPO formulae for any ALP mass are provided in the paper [Aiko, ME].

Z→aγ is blocked, but Δ_α, Δ_Z, Δ_W as well as U are comparable to S.

Many collider constraints from LHC

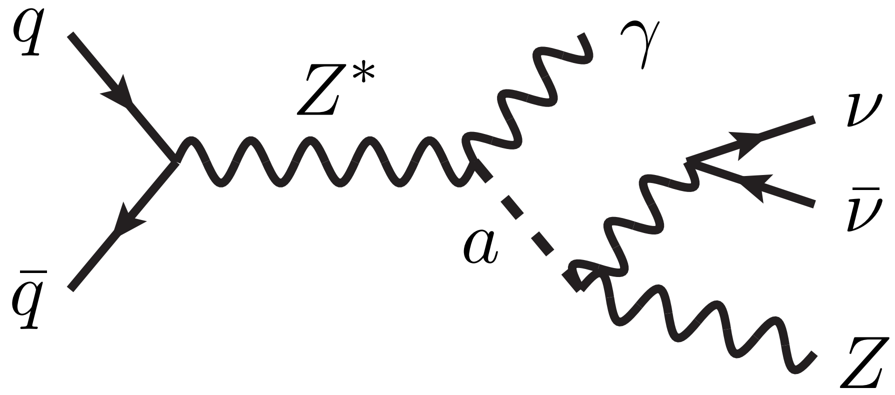
a-γ-γ

$$(pp, \mathrm{PbPb} \to)\ \gamma\gamma \to a^{(*)} \to \gamma\gamma$$



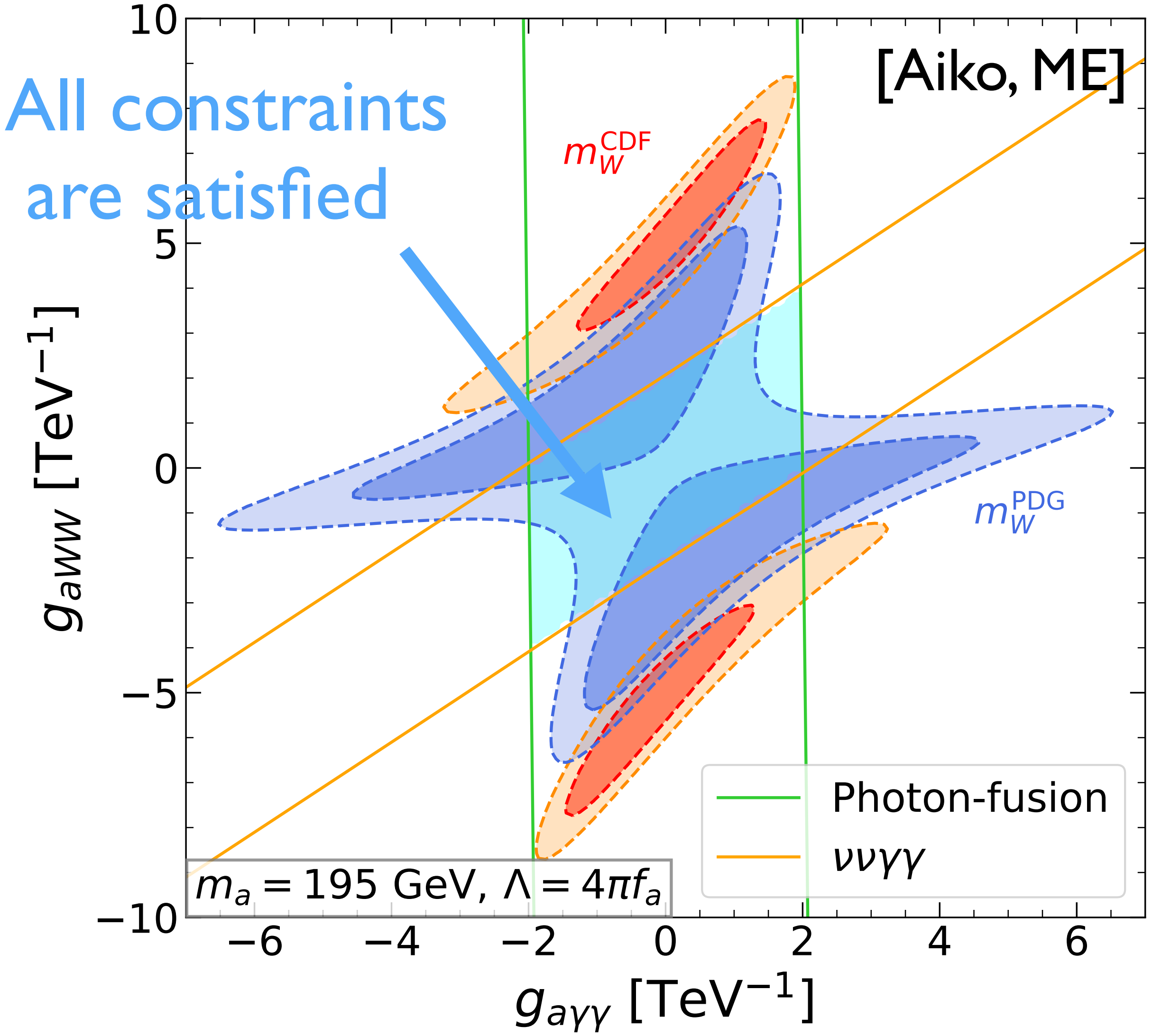
a-Z-γ

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



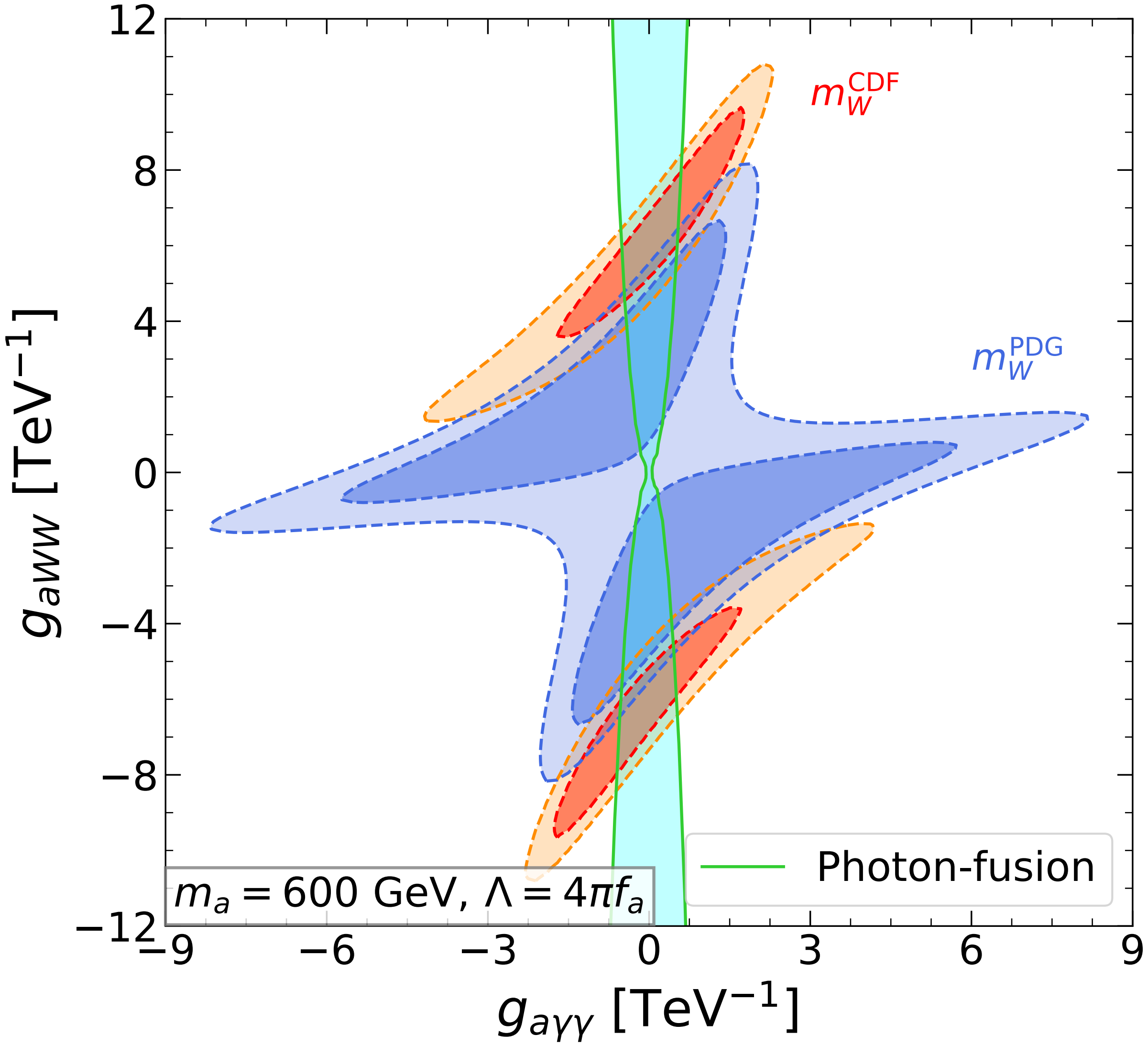
Heavier ALP case

m_a=195GeV



All constraints are satisfied

m_a=600GeV



ALP can be consistent with EWPOs both for m_W(PDG) & m_W(CDF) if ALP is heavy and its coupling to di-photon is suppressed.

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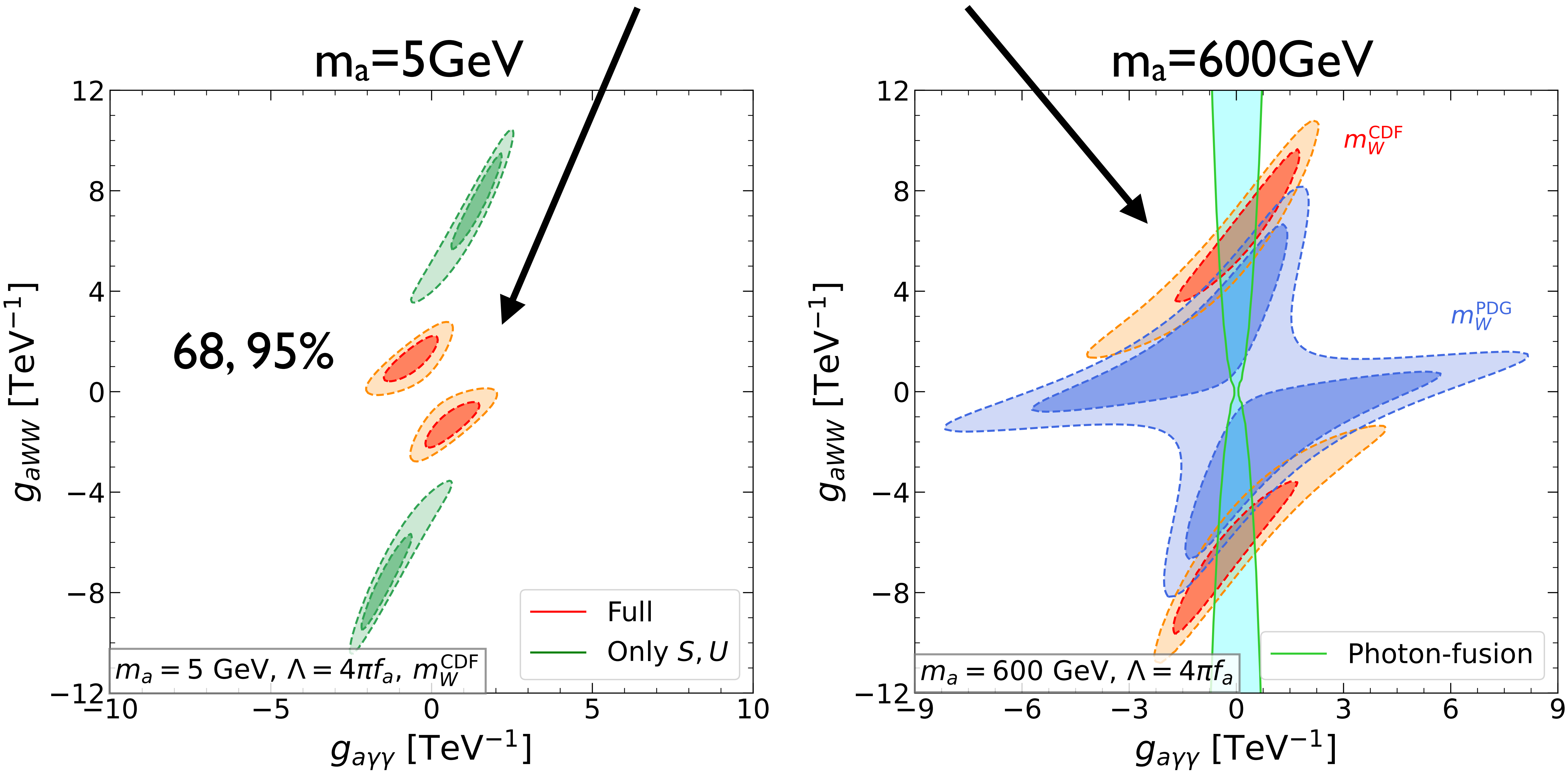
Summary

Goodness of fit

Is CDF tension solved in both masses?



Global fit analysis

1. Probability distribution from likelihood

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

y: exp., μ: th. value, V: cov.

2. Normalize probability distribution on model-parameter plane.

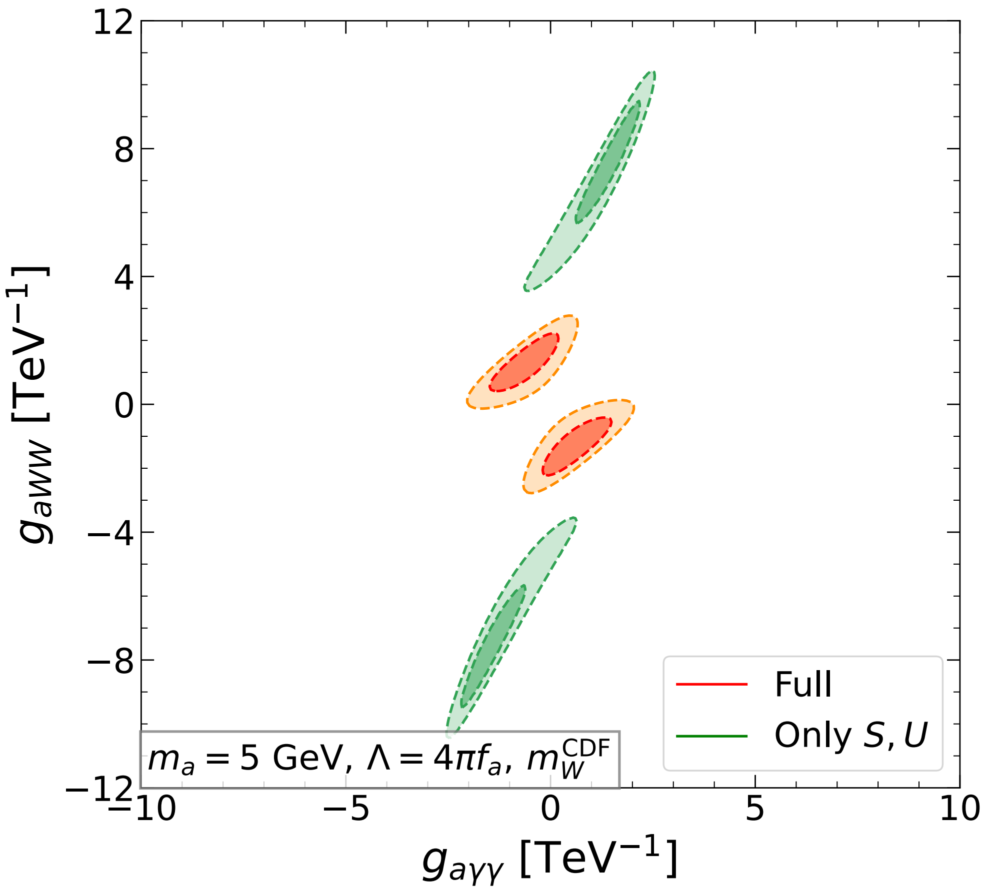
3. Determine 68% and 95% region.

Then, "68%" does *not* always mean

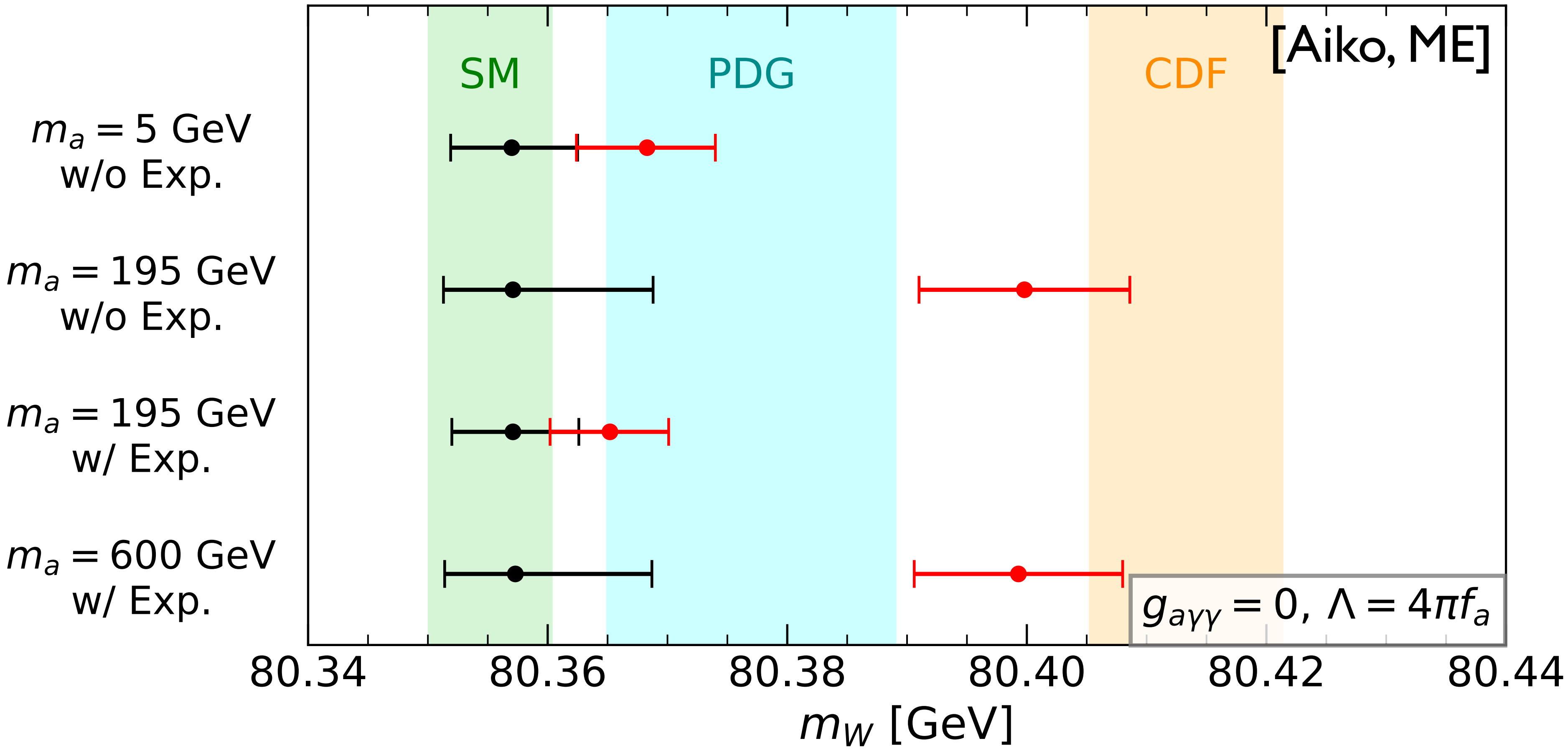
"all tensions are solved"

but

"fit is better than outside"



W-boson mass for M_W(CDF)



black: w/o M_w

red: w/ M_w

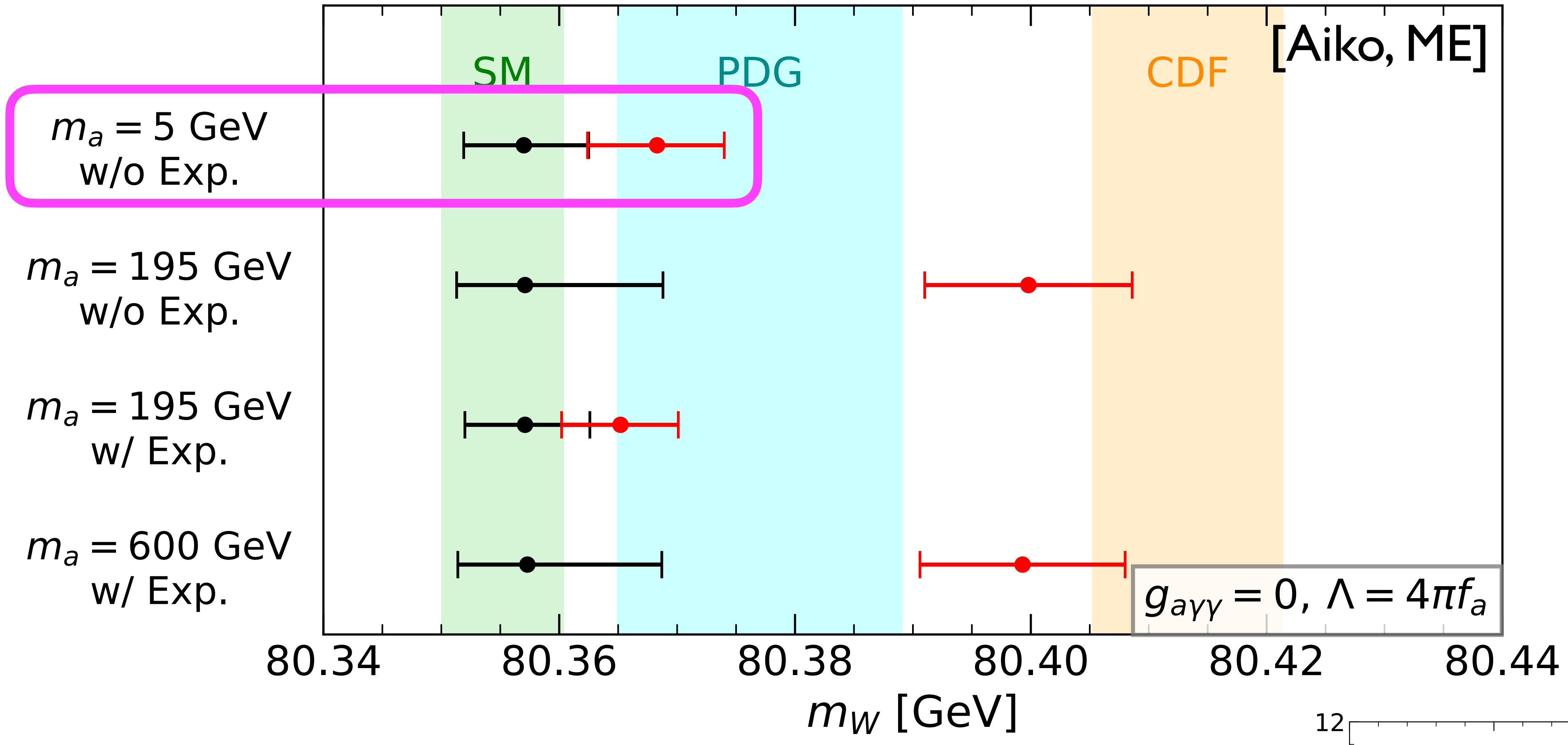
bar: 68%

(black) indirect prediction

M_w determined by global fit w/o including M_w in likelihood

(red) theoretical value for which M_w is included in likelihood

W-boson mass for M_W(CDF)



black: w/o M_W

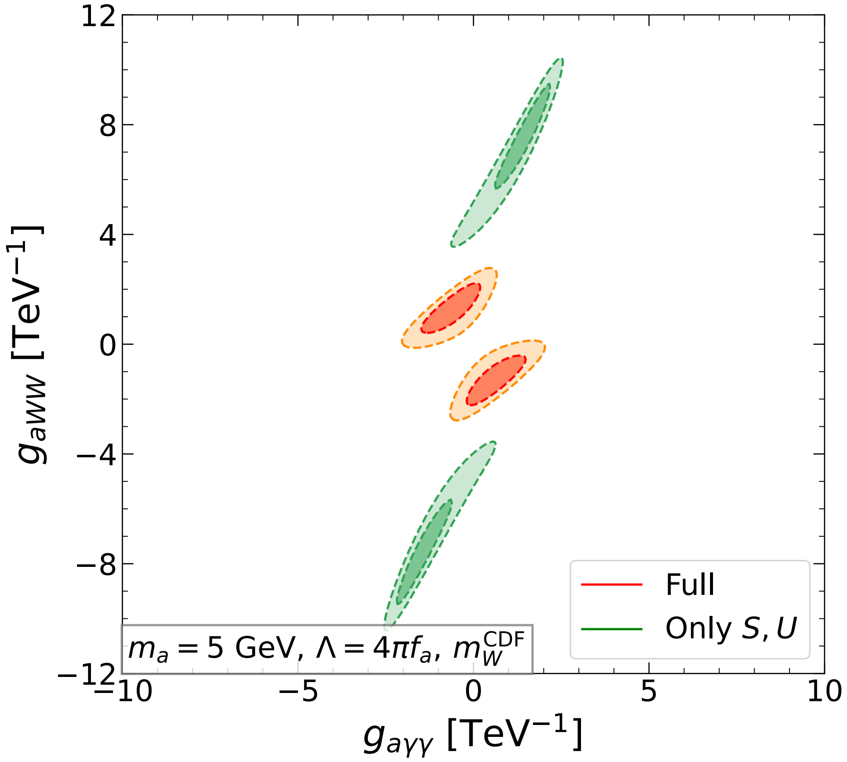
red: w/ M_W

bar: 68%

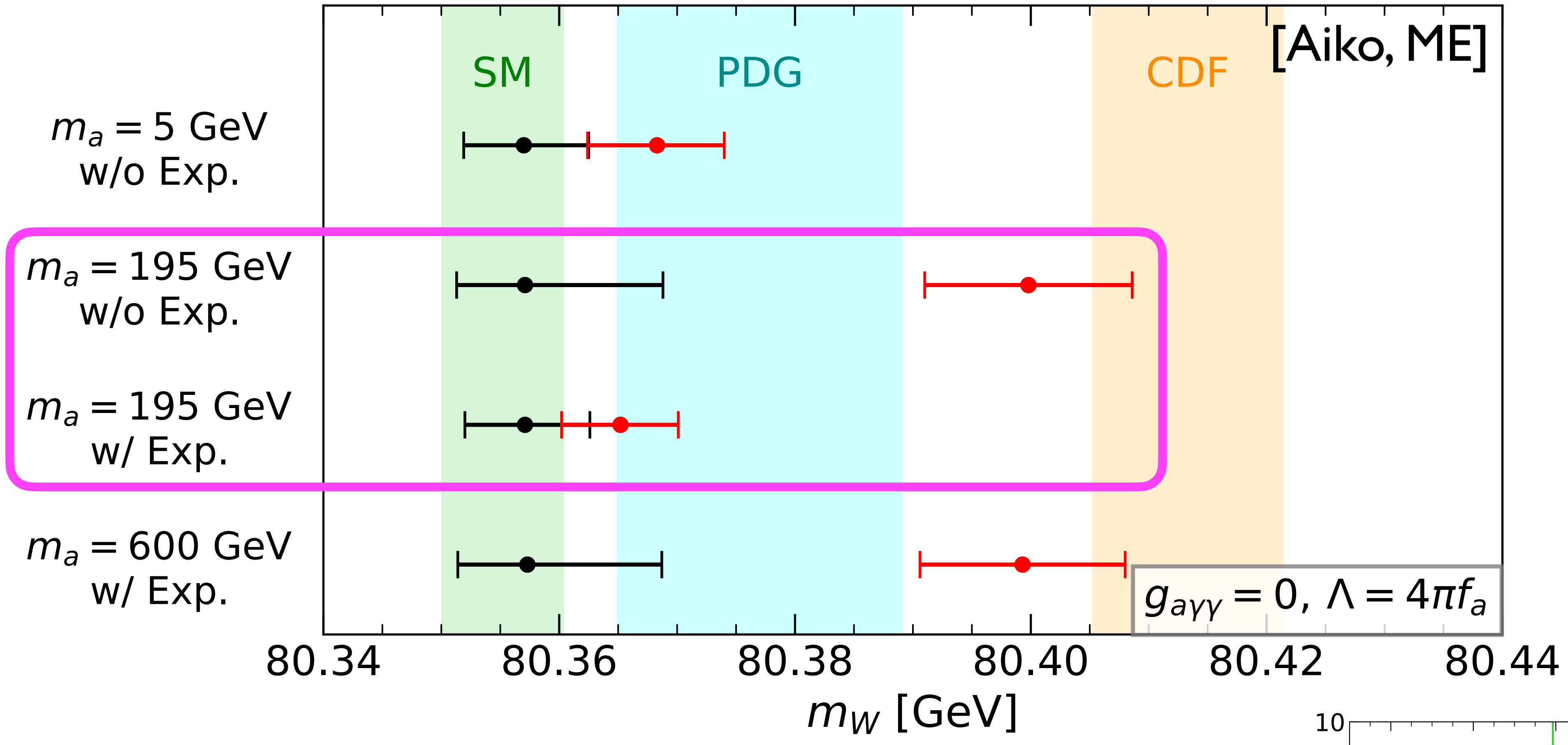
Black and red bars are away from CDF value.

→ The fit quality is poor even for "68%."

Same conclusion holds as long as Z→aγ contributes.



W-boson mass for M_W(CDF)



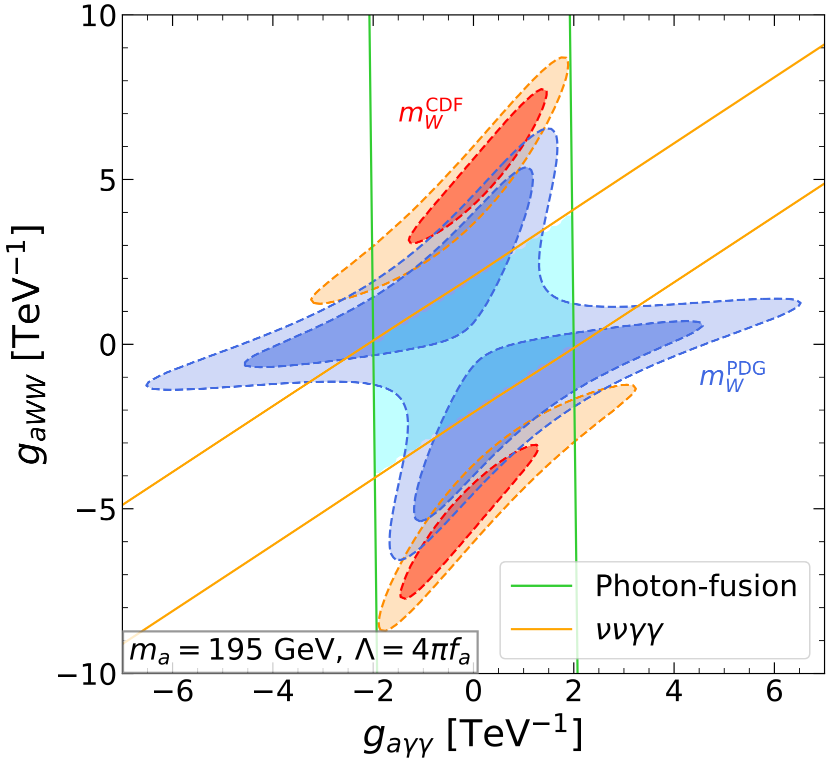
black: w/o M_w

red: w/ M_w

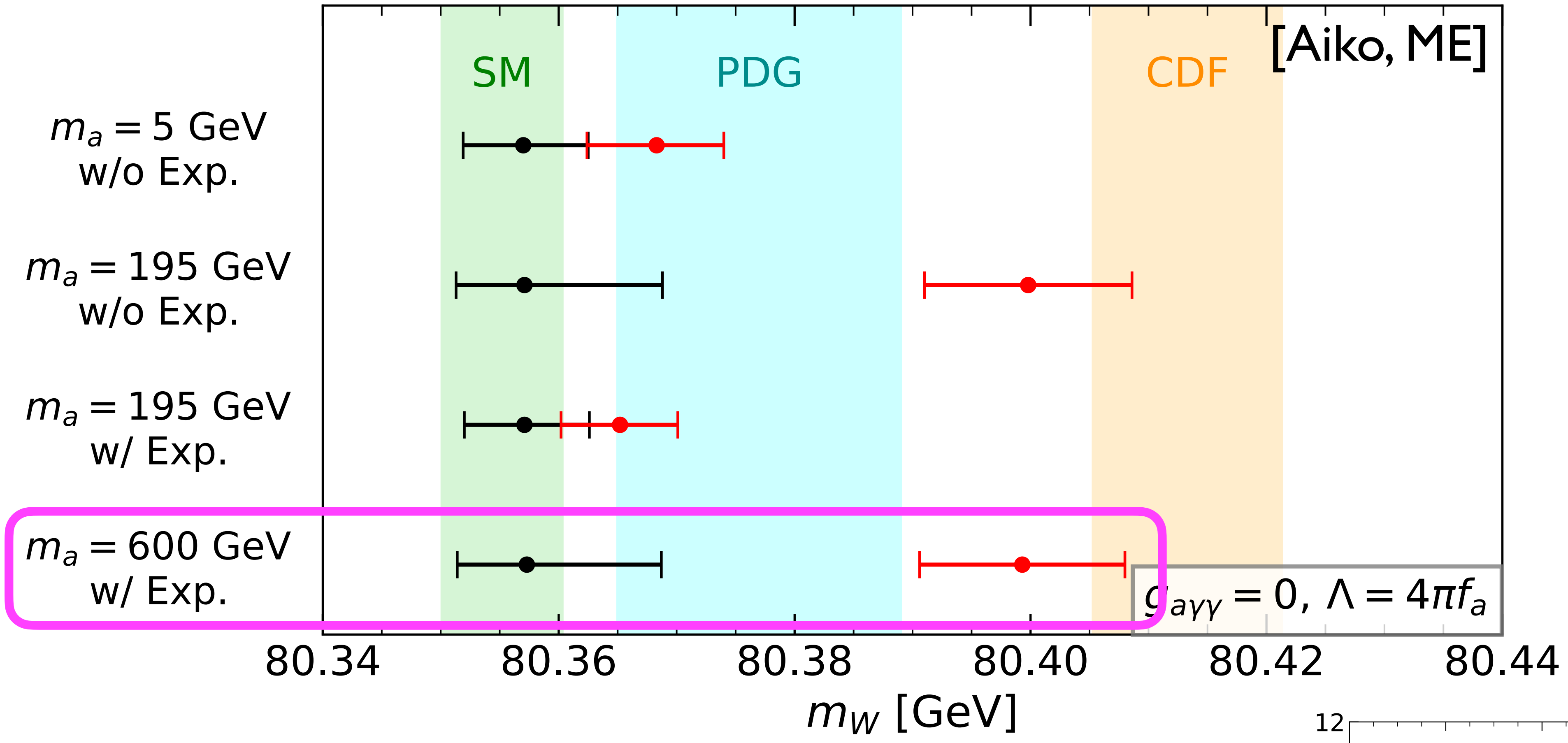
bar: 68%

Prob. distribution for indirect prediction (black) has a long tail toward large Mw.

The fit quality is good if collider bounds are ignored. → poor if bounds are included.



W-boson mass for M_W(CDF)



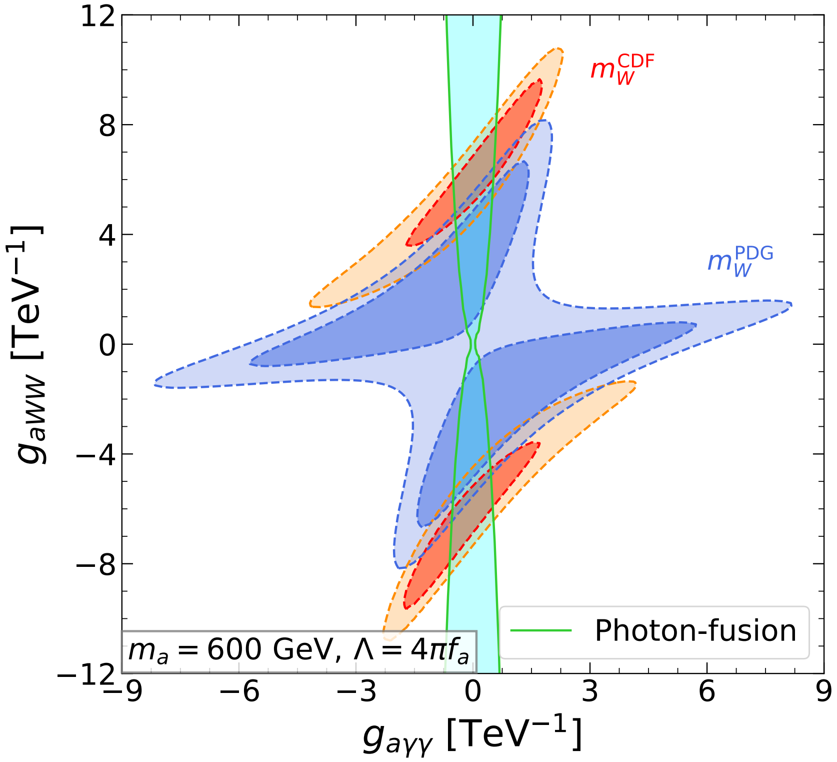
black: w/o M_W

red: w/ M_W

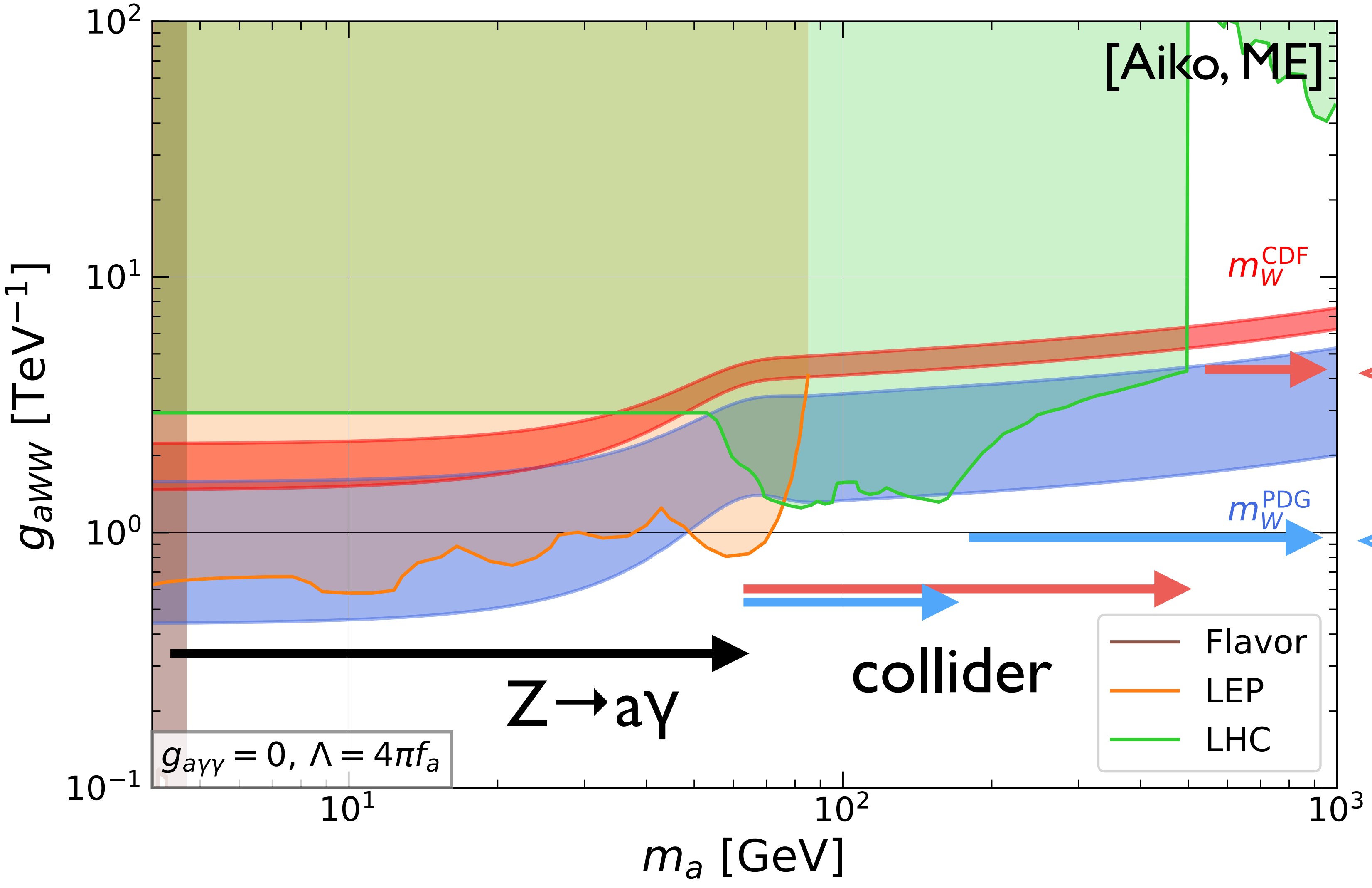
bar: 68%

Collider bounds are greatly relaxed when ALP is heavy enough and g(aγγ) = 0.

The fit quality is good & M_W tension is solved.



ALP mass dependence of EWPO global fit



CDF tension is solved

Global fit is improved

ALP coupling to di-photon is suppressed, i.e., g(aγγ) = 0.

Probability distributions are normalized for each ALP mass.

ALP improves global fit well if m_a>160 (500)GeV for M_w(PDG) [M_w(CDF)].

Summary

We revisited ALP contributions to EWPO.

We pointed out three missing effects in the previous works:

1. Corrections beyond S, T, U via vac. polarizations are sizable.
2. Z boson decaying into ALP affects EWPOs significantly.
3. Flavor and collider constraints are considered appropriately.

It was shown that the EWPO global fit can be improved much against SM if ALP is heavy and its coupling to di-photon, g(aγγ), is suppressed.

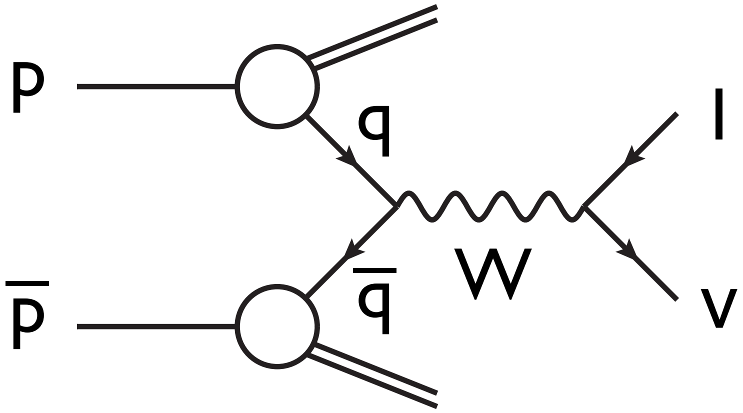
The tension between SM and CDF values of W-boson mass can be solved if ALP is heavier than 500GeV with g(aγγ)=0.

Tevatron collider at Fermilab

Proton-anti-proton collision at $\sqrt{s}$ = 1.96TeV

- cf. LHC: pp collision at $\sqrt{s}$ = 13TeV [CERN]
- Two detectors: CDF and D0
- Data taking finished in 2011

New result from CDF w/. $\int L = 8.8\mathrm{fb}^{-1}$ (full)

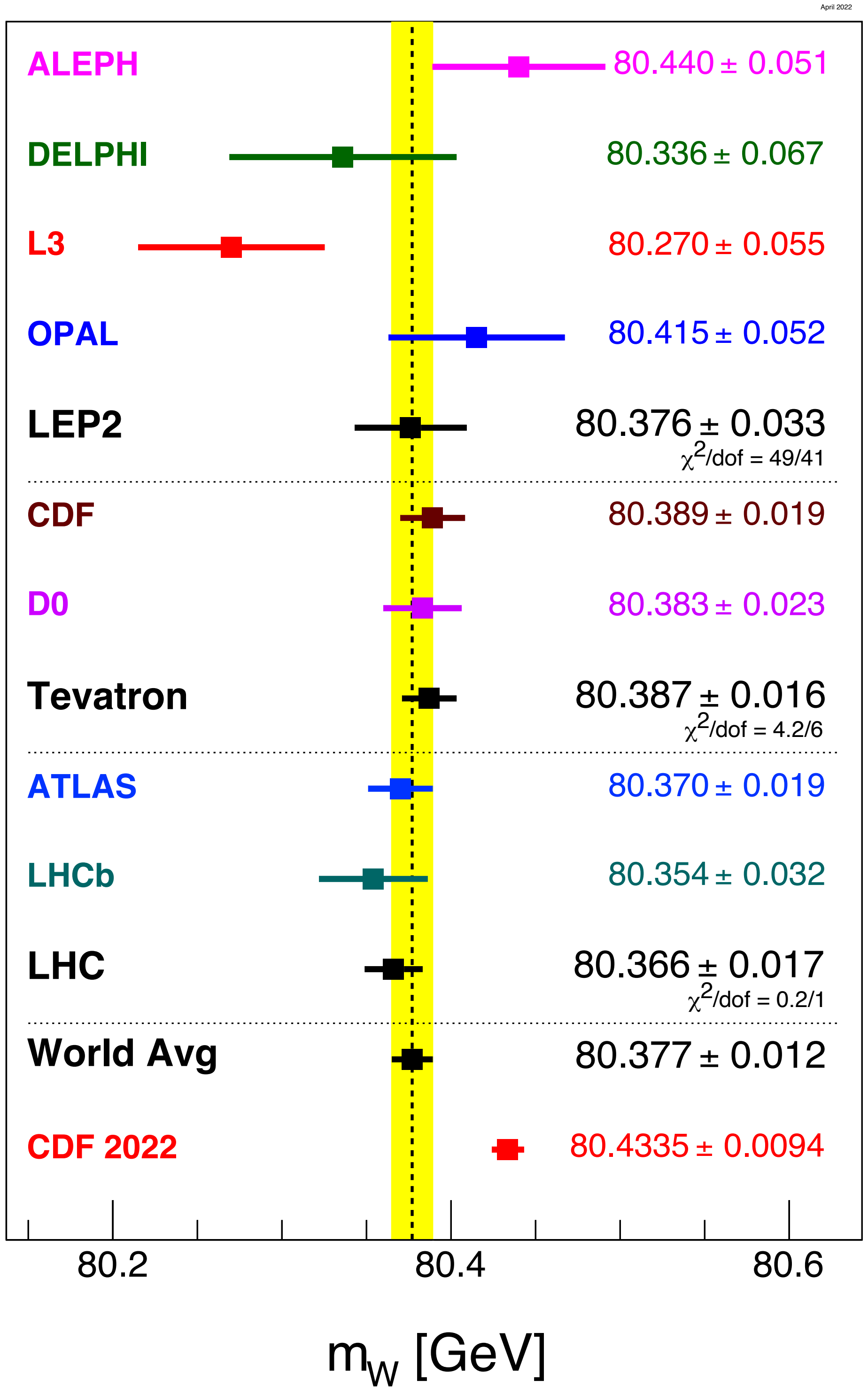


→ M_W

Inconsistent w/. other results → syst.

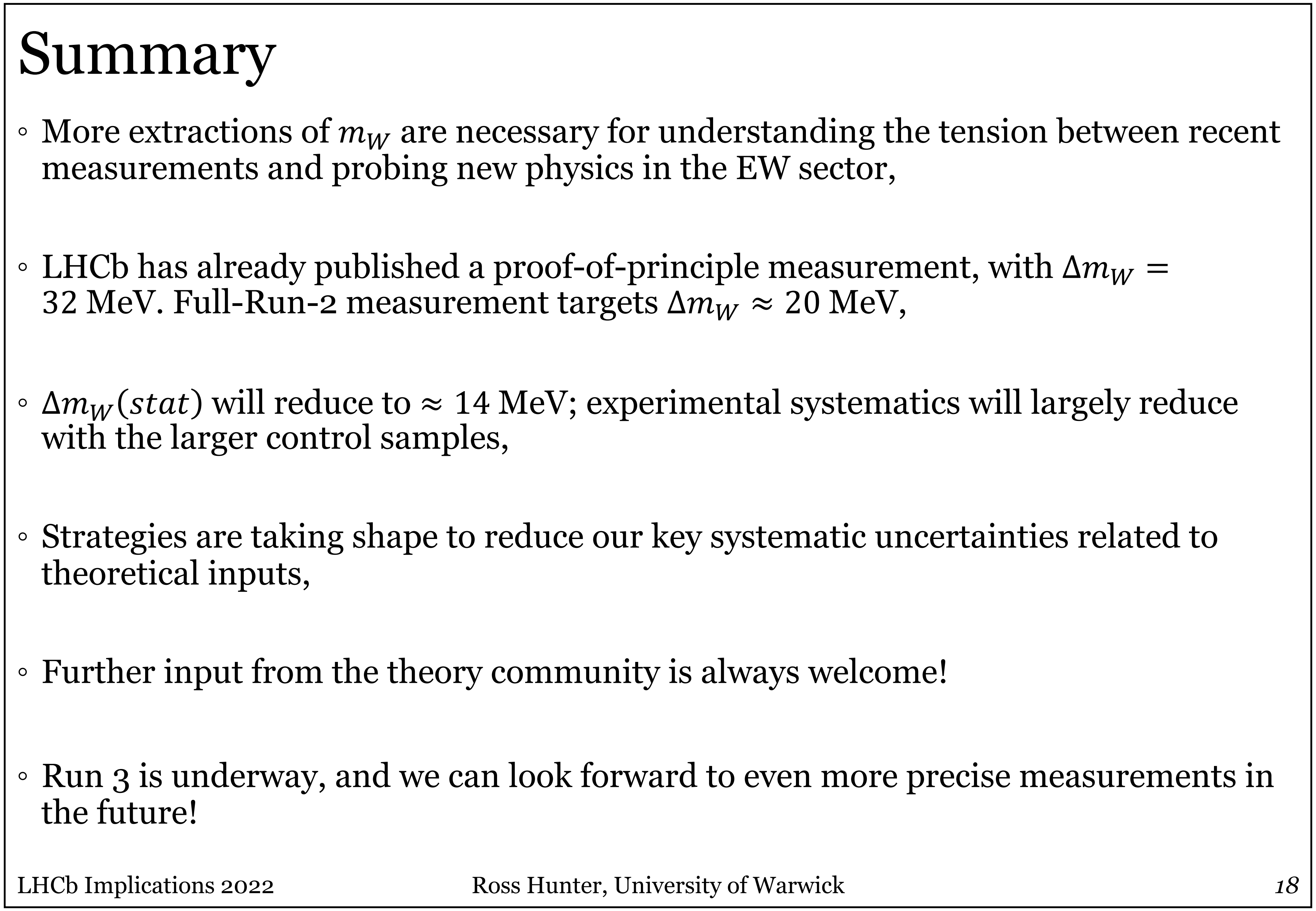
- cf. D0 result w/. $\int L = 5.3\mathrm{fb}^{-1}$

[PDG 2022]



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!

LHCb Implications 2022 Ross Hunter, University of Warwick *18*

Standard Model prediction

$$M_W = 80.3552 \pm 0.0055\,\mathrm{GeV}$$

[7.2σ smaller than CDF]

	data
$\alpha_s(M_Z)$	0.1177 ± 0.0010
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z)$	0.02766 ± 0.00010
M_Z [GeV]	91.1876 ± 0.0021
m_t [GeV]	172.69 ± 0.30
m_H [GeV]	125.25 ± 0.17

[PDG 2022]

Uncertainty is dominated by M_Z

Issue on definition of measured m_t

→ Inflate uncertainty as $\delta m_t = 1.0$GeV

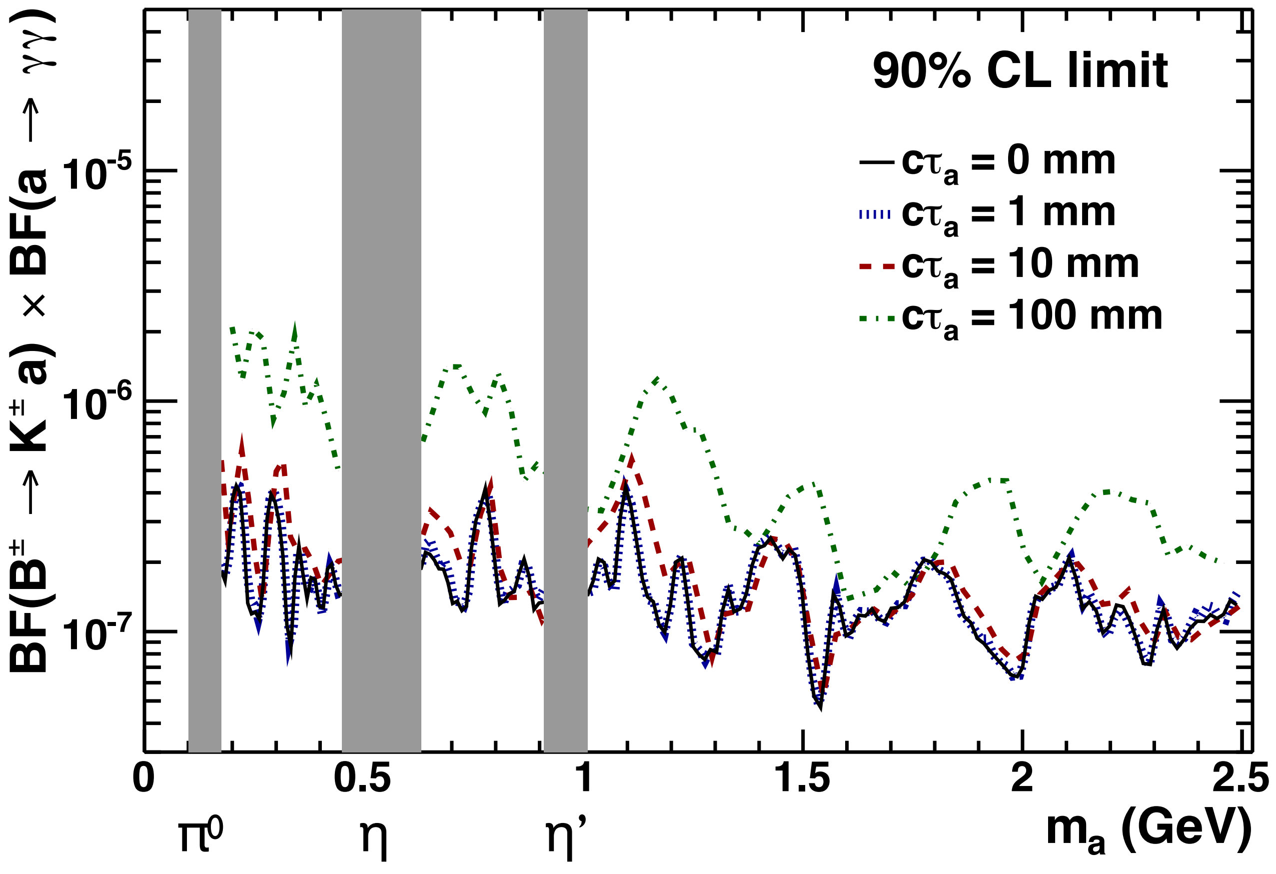
$$M_W = 80.3552 \pm 0.0079\,\mathrm{GeV}$$ [6.4σ]

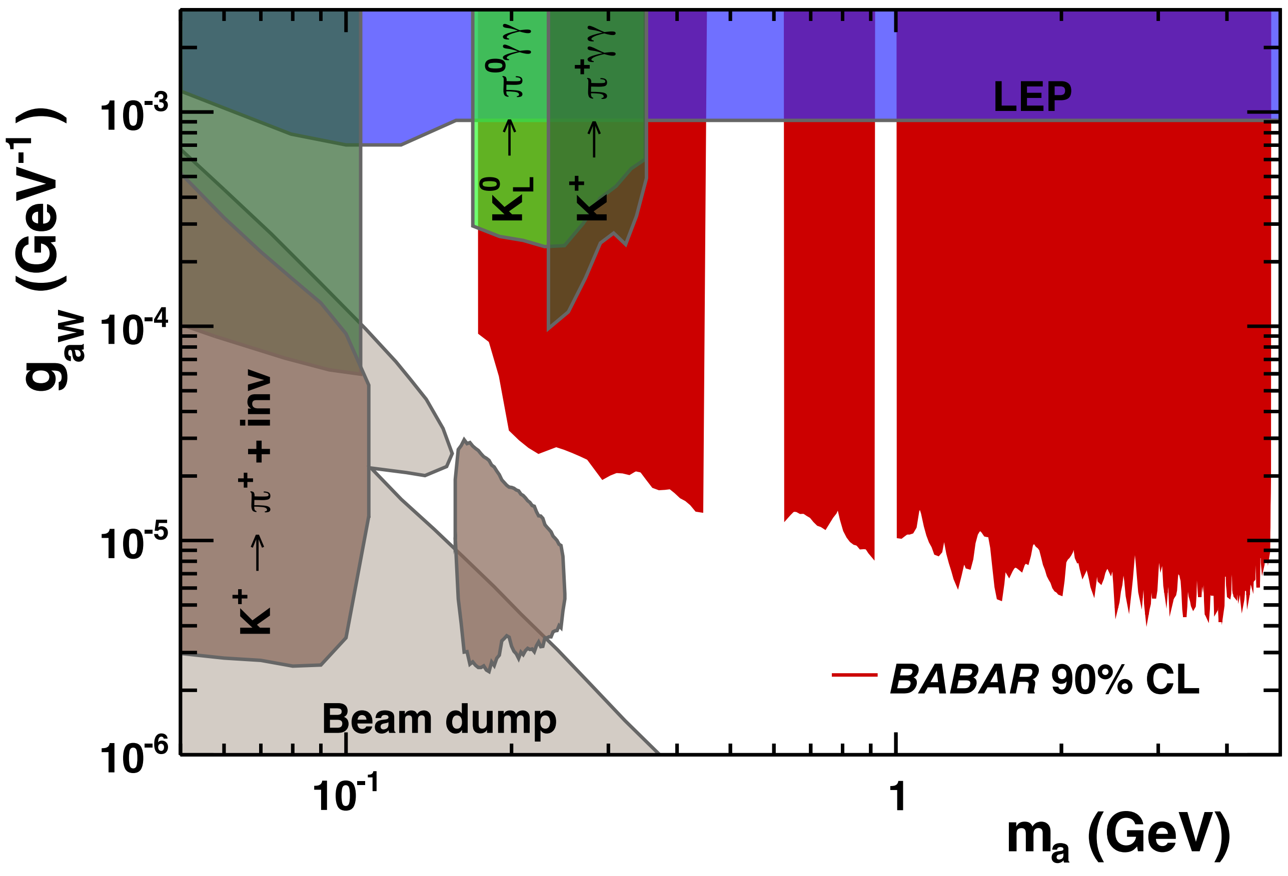
	$\alpha_s(M_Z)$	$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z)$	M_Z	m_t	m_H	higher	Total
δM_W [GeV]	0.0007	0.0018	0.0026	0.0018	0.0001	0.004	0.0055
				0.0060			0.0079

Experimental data

$B \to K\,a,\ a \to \gamma\gamma$: BaBar, prompt + displaced decay

Constraint for $0.175 < m_a < 4.78$ GeV



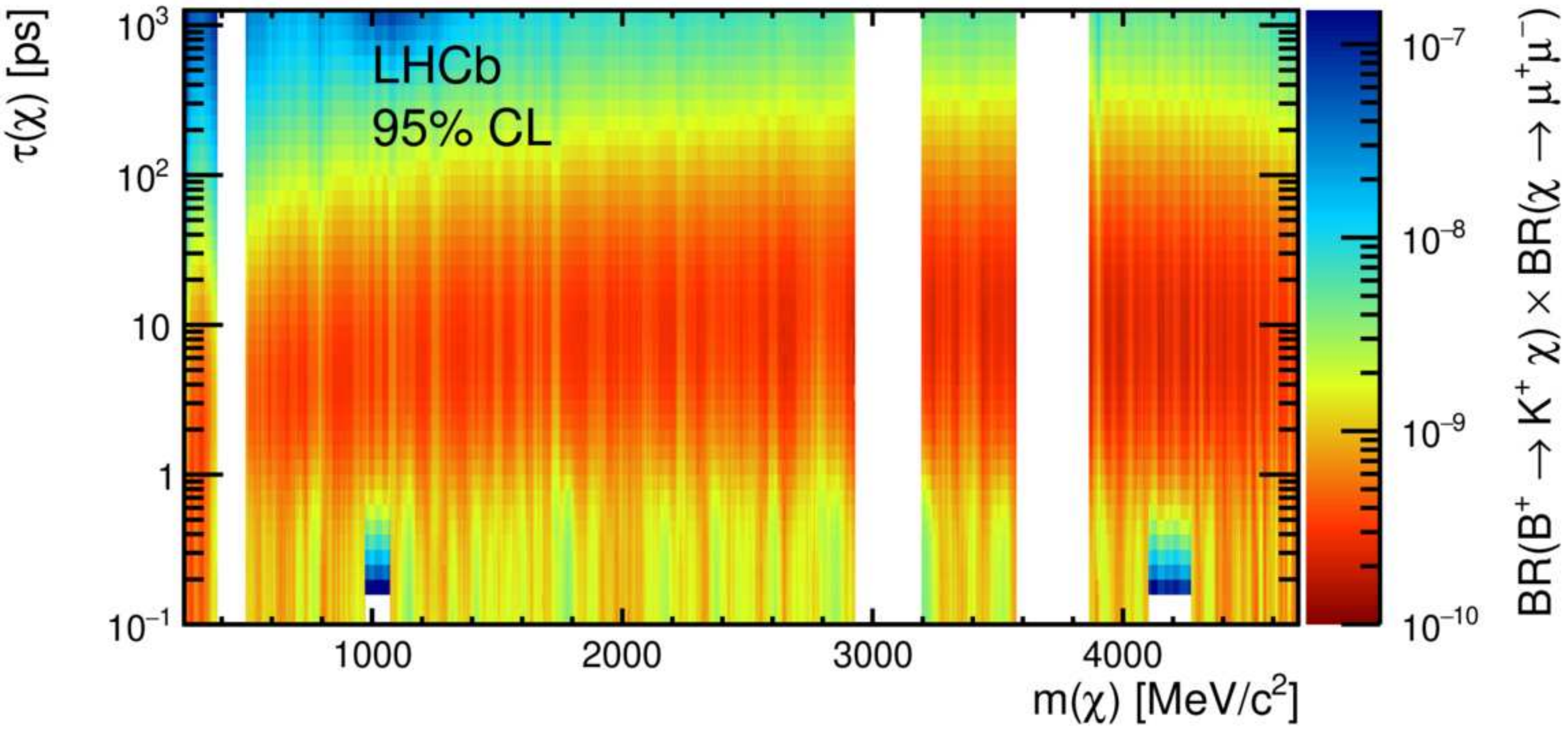


$$\mathrm{Br}(a \to \gamma\gamma) \simeq 1$$

Experimental data

B→K a, a→μμ: LHCb, prompt + displaced decay

Constraint for $0.250 < m_a < 4.70$ GeV



Empty regions: K_S, J/ψ, ψ(2S), ψ(3770) for all, and ϕ, ψ(4160) for prompt

Collider constraints for Br(a→γγ)=1