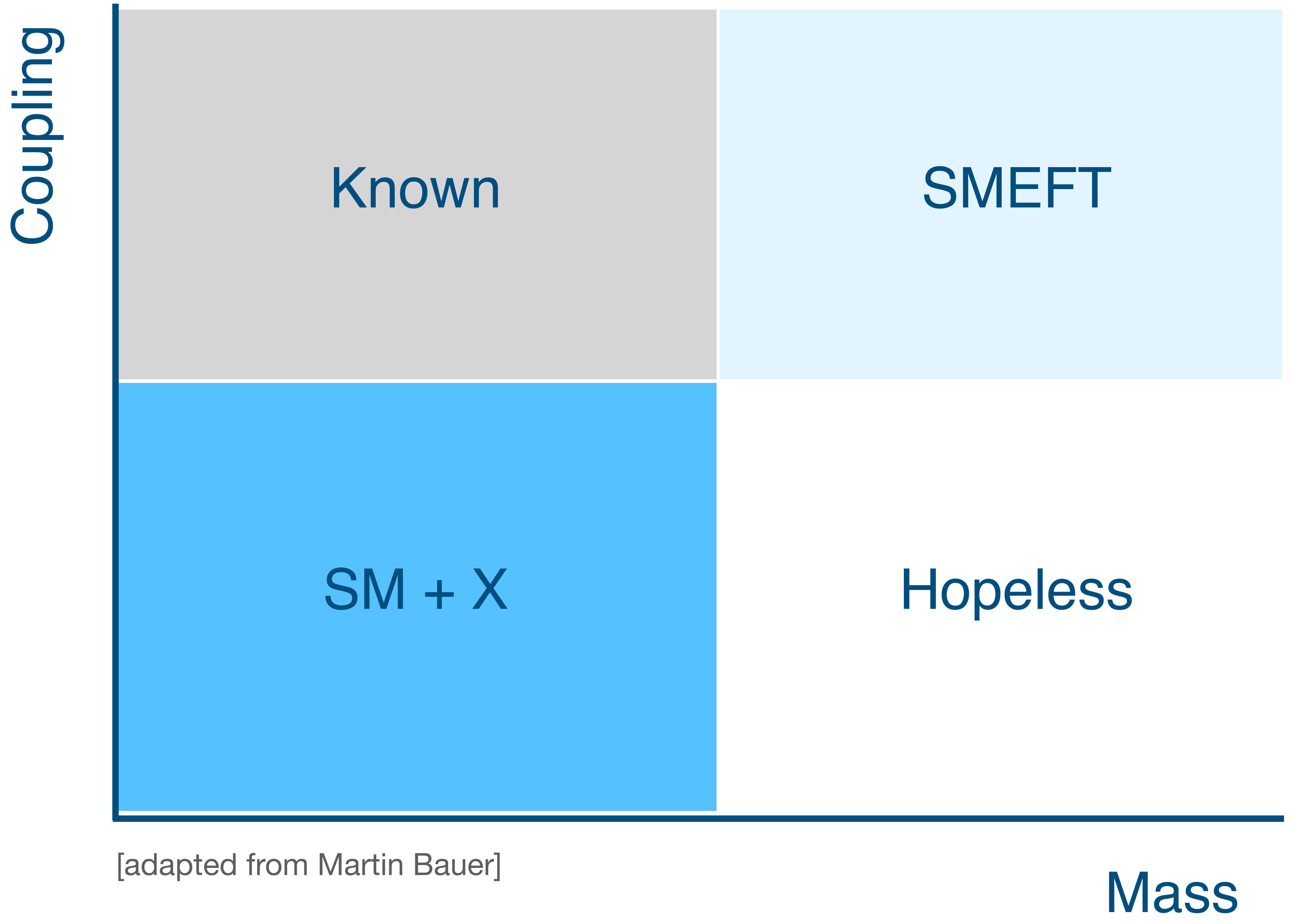
A global view on dark sector searches

Anke Biekötter - JGU Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Belle II Physics Week, Tsukuba, Oct 16, 2024

Feebly-interacting particles



[adapted from Martin Bauer]

Light new physics?

- Spin-0: scalars, axion-like particles
- Spin-1/2: heavy neutral leptons
- Spin-1: dark photons

[Robert's talk]

Outline

- Light (pseudo-)scalars
- Belle II phenomenology
- Global analyses

Interplay between experiments

Reinterpretability

HepData

Fast simulation

How can we test this model?

⬇

Which models can we test?

Light scalars - motivation

Does Dark Matter (DM) receive its mass via a coupling to a scalar particle?

Is there a whole Dark Sector?

Dark Higgs and SM Higgs could mix

$$V(\Phi,\,H) \subset \lambda_{h\phi}|\Phi|^2|H|^2$$

$$h \to \cos\theta\, h + \sin\theta\,\phi$$
$$\phi \to -\sin\theta\, h + \cos\theta\,\phi$$

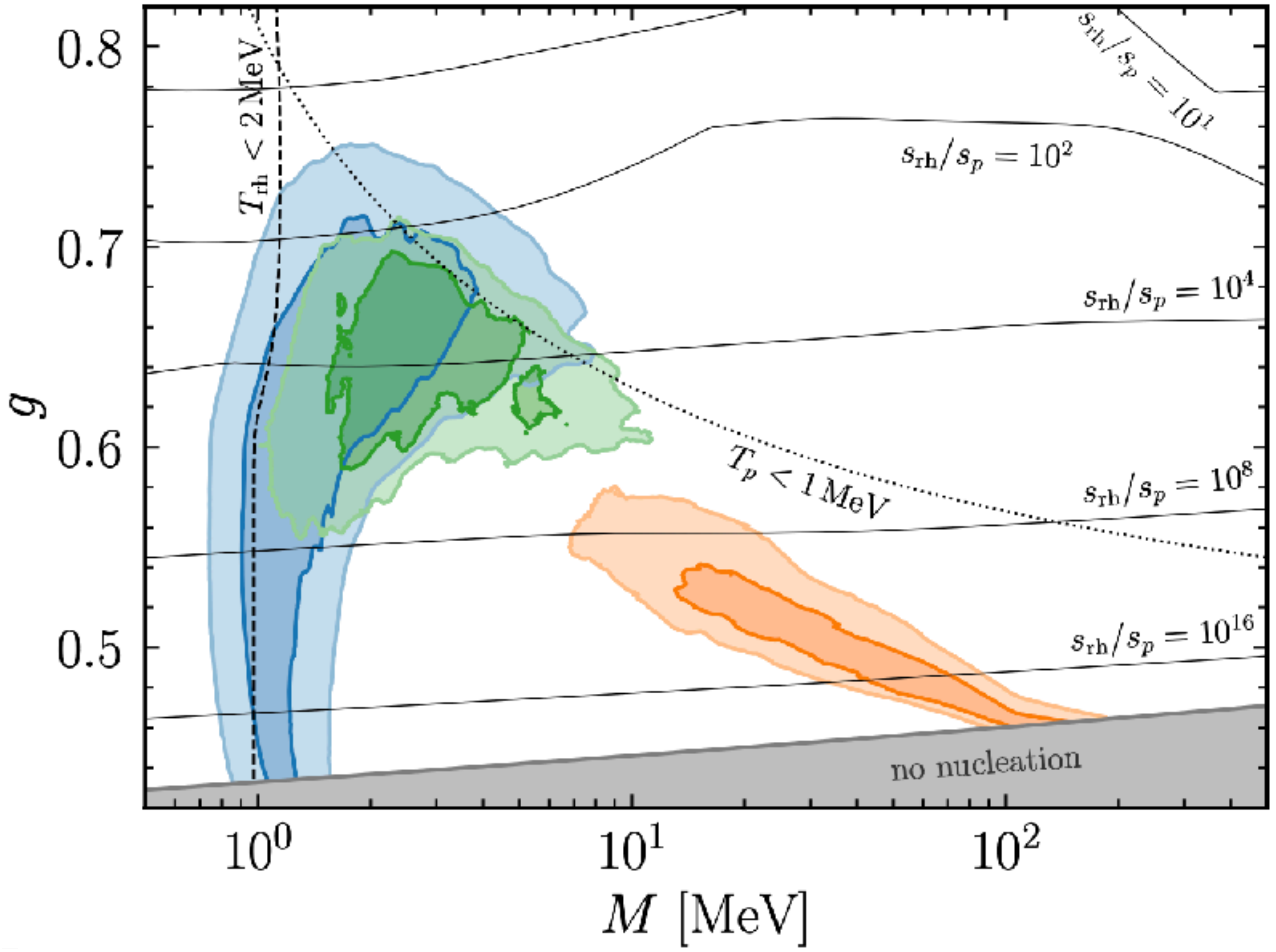
Pulsar Timing Array (PTA) data compatible with a light scalar

$(0.92 - 6.9)$ MeV NANOGrav

$(11.5 - 124)$ MeV IPTA

T_{rh} reheating temperature
T_p percolation temperature

[Madge et al. (2306.14856)]

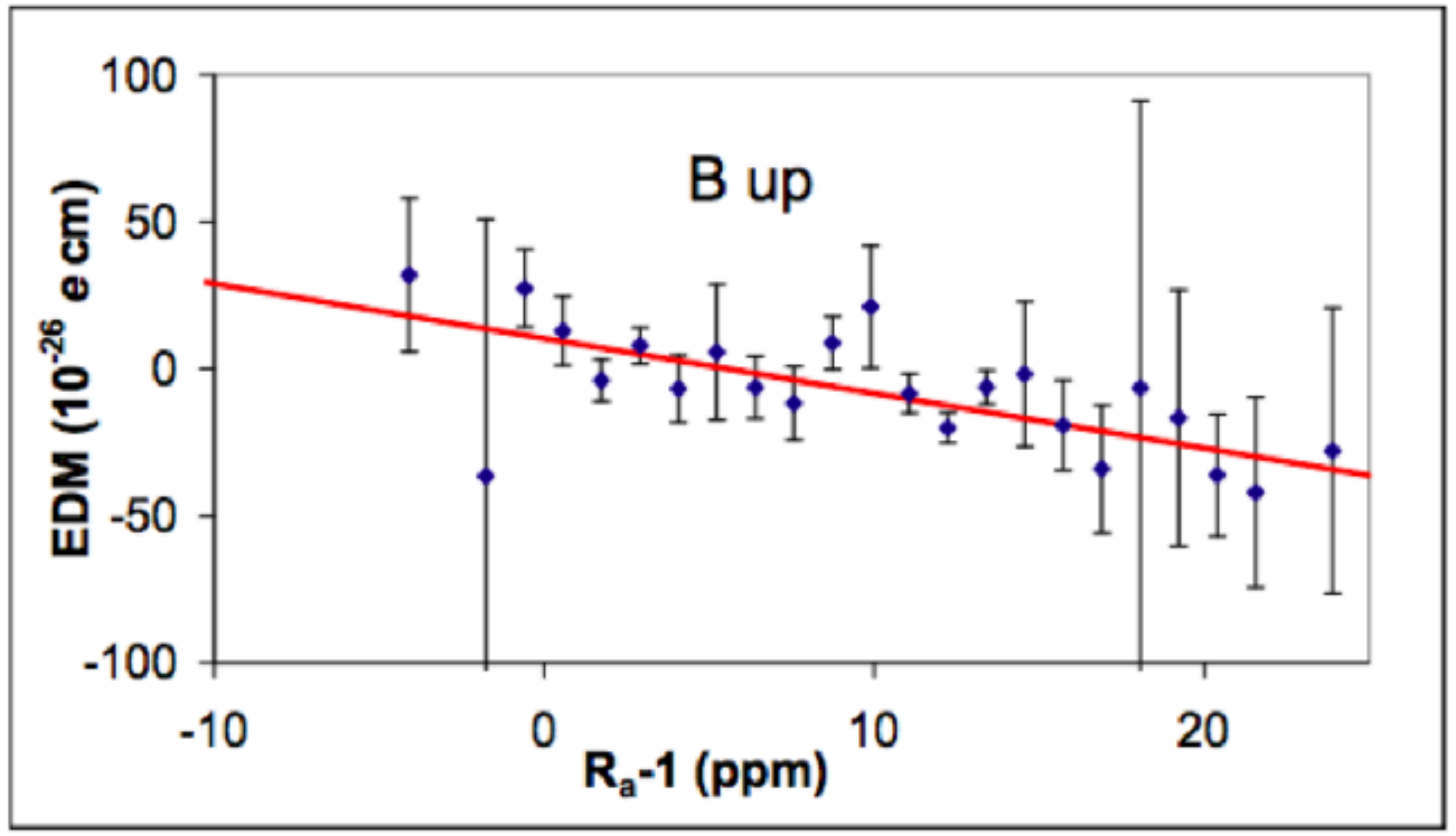


Axions

$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Why is the theta term so small?

[Baker et al. (hep-ex/0602020)]



Electric dipole moment of the neutron

$$\mathcal{L} = \left(\theta - \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Dynamical solution to the strong CP problem

[Peccei, Quinn (ref1, ref2)]
[Weinberg] [Wilczek]

$$m_a f_a = \text{const.}$$

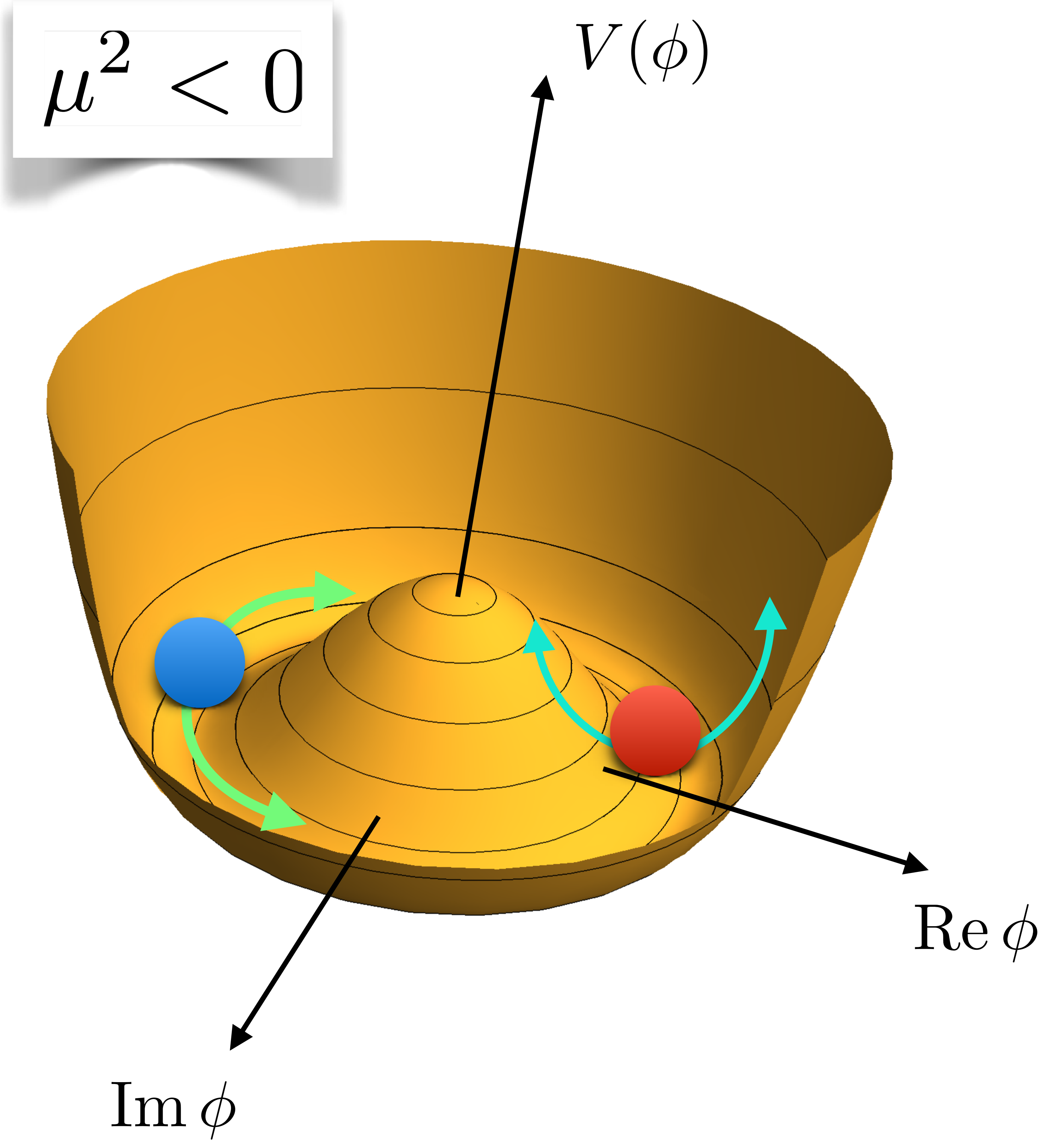
Axion-like particles - motivation

A spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$\phi = (f + s)e^{ia/f}$$

Shift symmetry
$$a \to a + a_0$$

$$m_s^2 = 4\lambda f^2 = |\mu|^2$$
$$m_a^2 = 0$$



[Bauer (PADUA23)]

Axion-like particles

EFT with an additional light d.o.f. and at dimension 5

- Featured in many BSM scenarios: "Higgs portal" dark matter, composite Higgs models, …
- Consider a generic ALP with effective Lagrangian
- Shift symmetry $a \to a + a_0$, Lagrangian terms: $\frac{\partial_\mu a}{f_a} (\mathrm{SM})^\mu$

[Peccei, Quinn (ref1, ref2)]
[Weinberg] [Wilczek]

[Brivio et al. (1701.05379)]
[Bauer et al. (1708.00443)]

[Stefania's talks]

$$\mathcal{L}_{\mathrm{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{f} \sum_F \bar{\psi}_F c_F \gamma_\mu \psi_F + c_\phi \frac{\partial^\mu a}{f} (\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi)$$
$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu} .$$

Light BSM particles at the LHC

[Thamm (LHCP24)]

Example: axion-like-particles

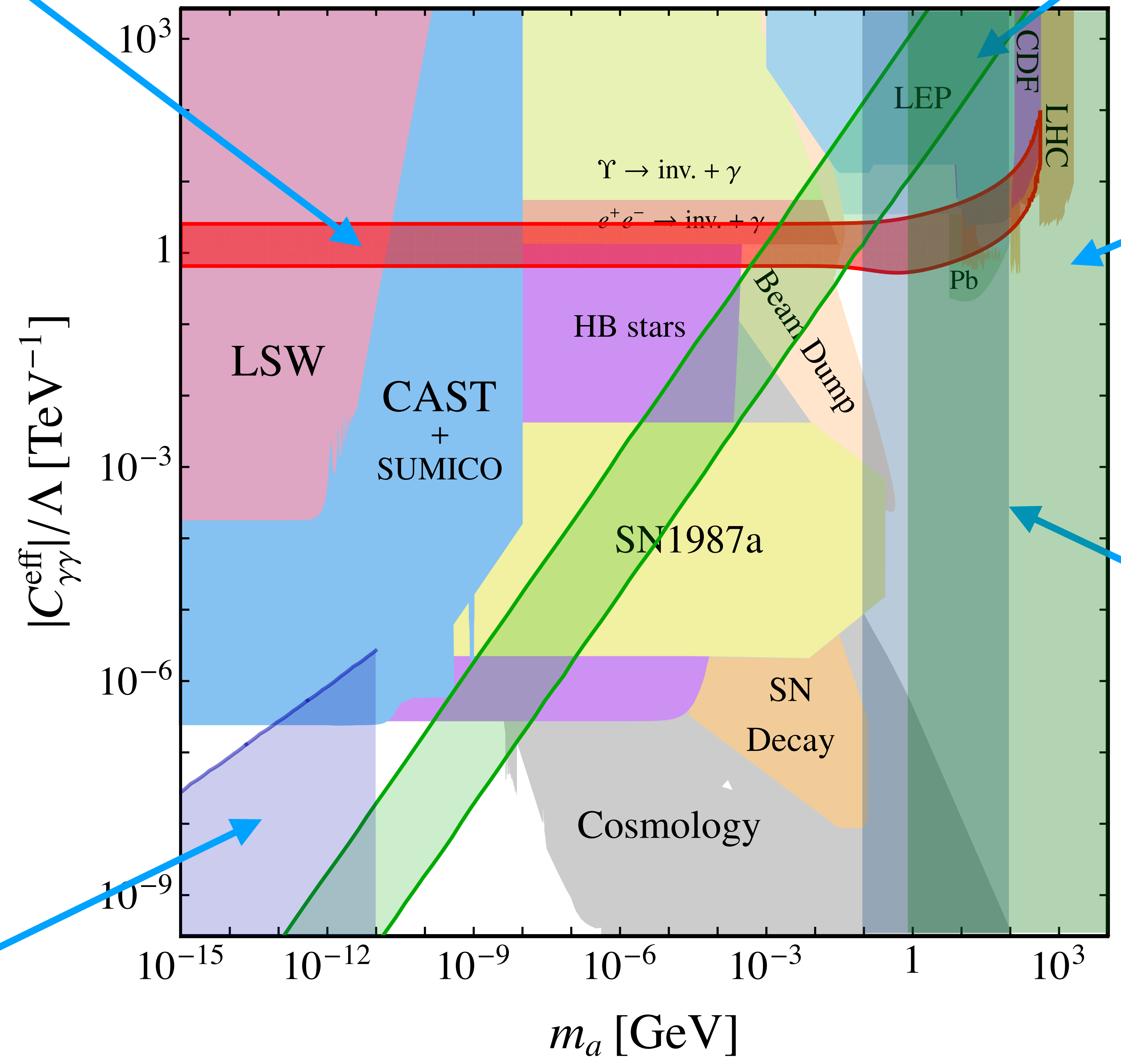
Solves $(g-2)_\mu$ anomaly

1708.00443, 1908.00008

QCD axion

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Heavy axion



pNGB in supersymmetric or composite models

0902.1483, 1312.5330, 1702.02152, 2104.11064

DM candidate

Andrea Thamm

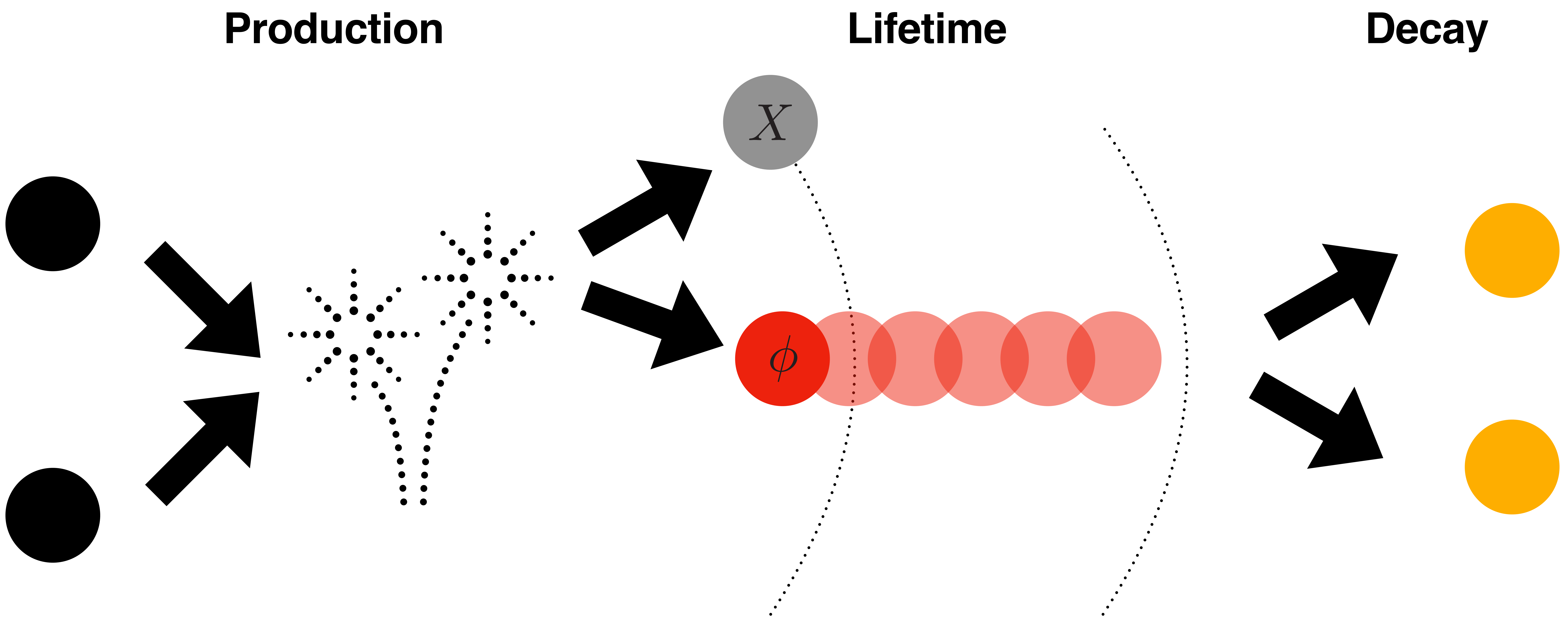
18

ALP mass range covered by **Belle II** interesting in the context of

- Heavy axions
- Pseudo Nambu Goldstone bosons from SUSY, composite Higgs
- g-2

Interplay of experiments/ observations crucial

Phenomenology of (pseudo-)scalars



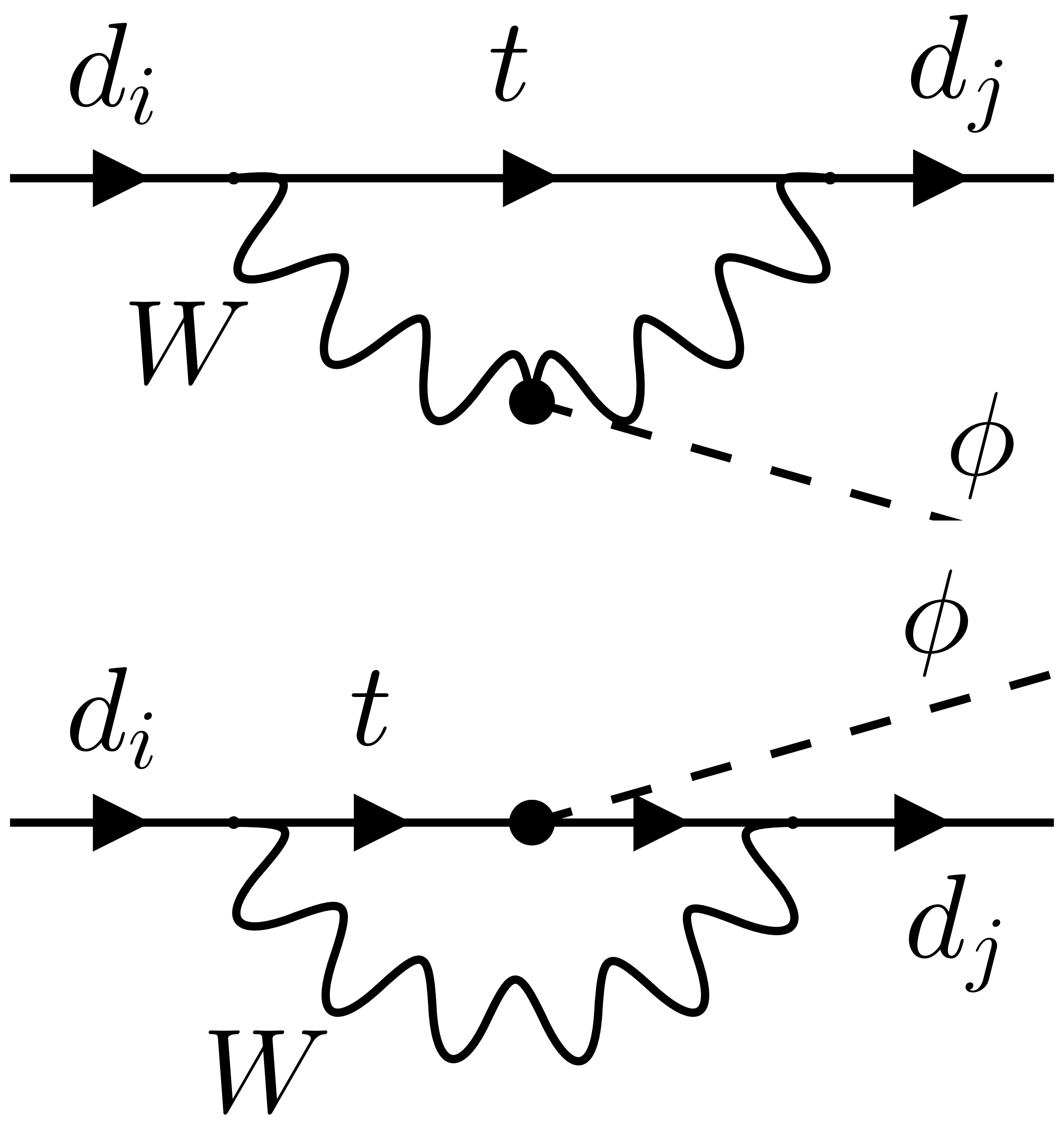
(Pseudo-)scalar production at Belle II

Rare meson decays

Sizeable top/W couplings lead to loop-induced decays

$K^+ \to \pi^+ \phi$

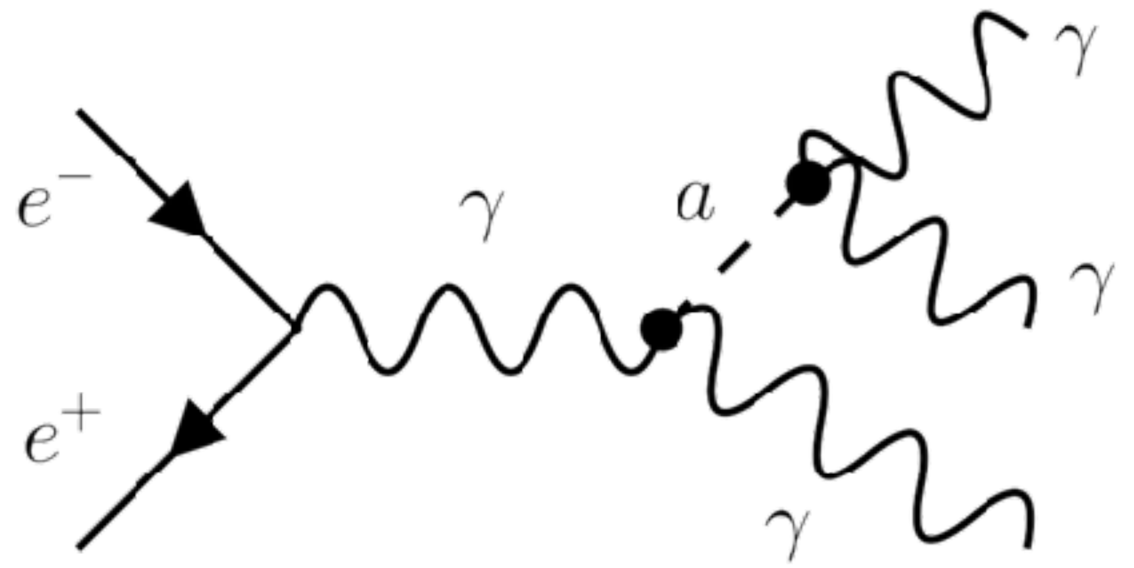
$B^+ \to K^+ \phi$



Mixing with SM particles

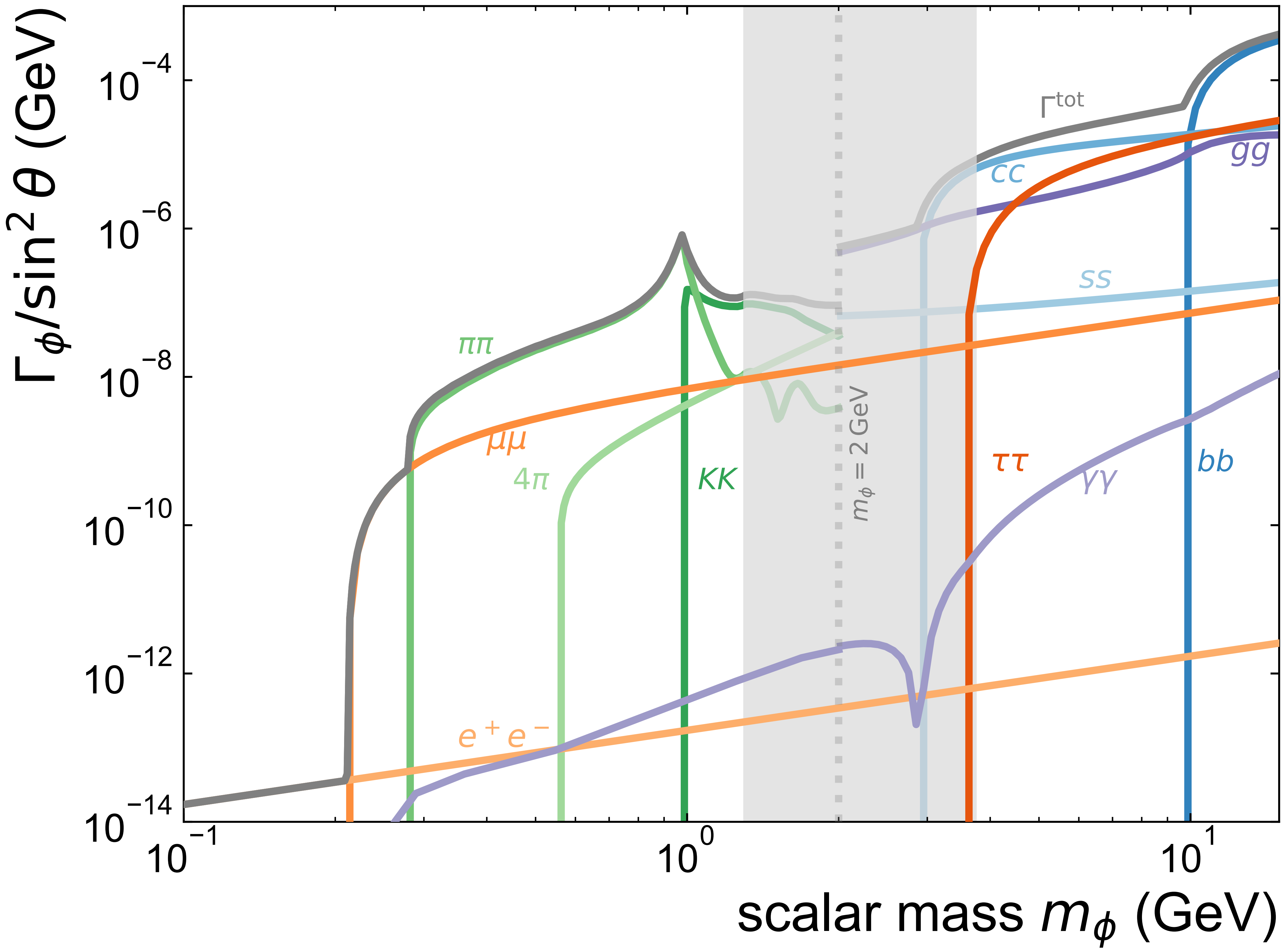
$\pi^0 \leftrightarrow a$

Photon coupling



(Pseudo-)scalar decays

[Ferber, Grohsjean, Kahlhöfer (2305.16169)]



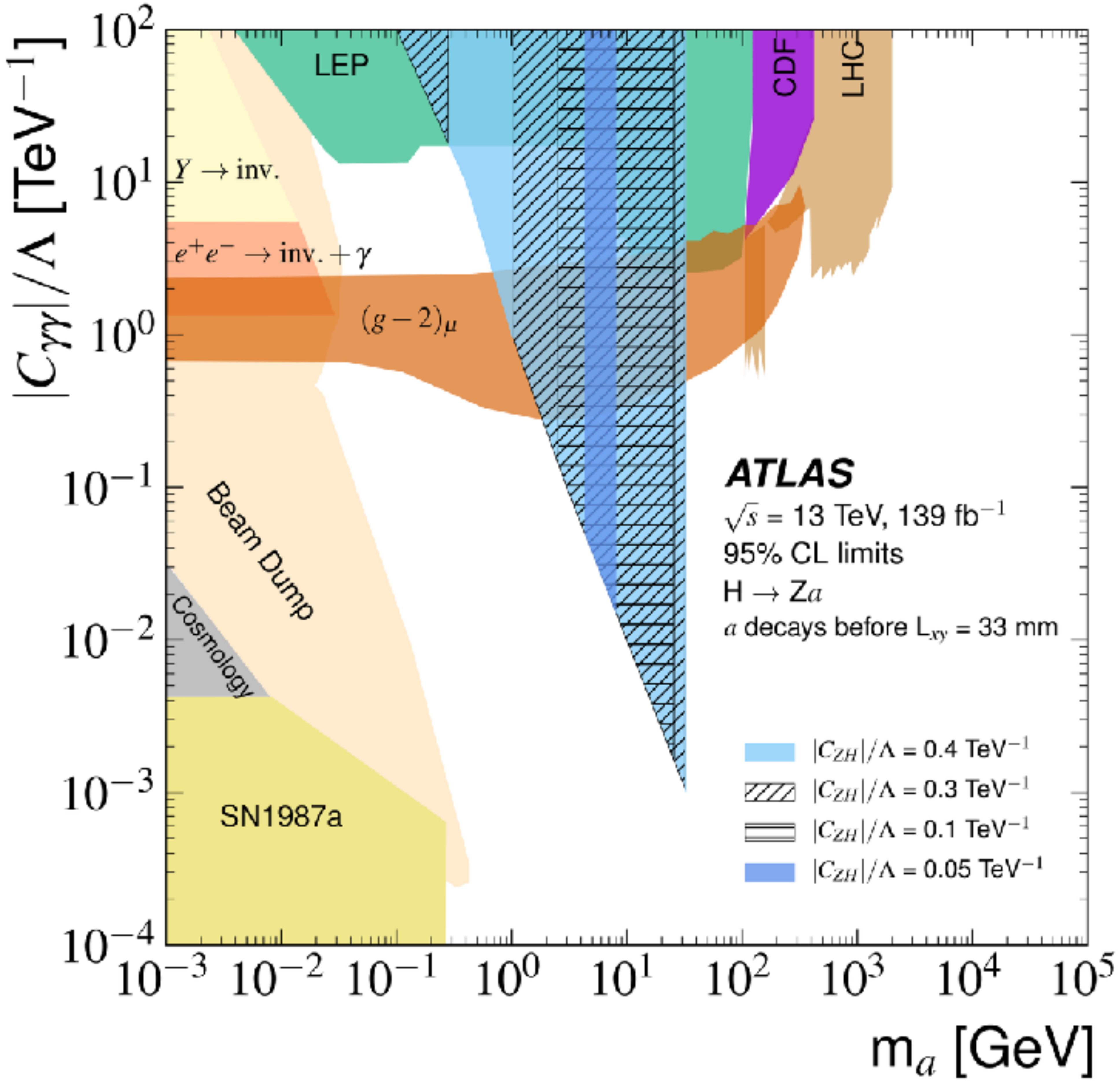
Photons, leptons, hadrons

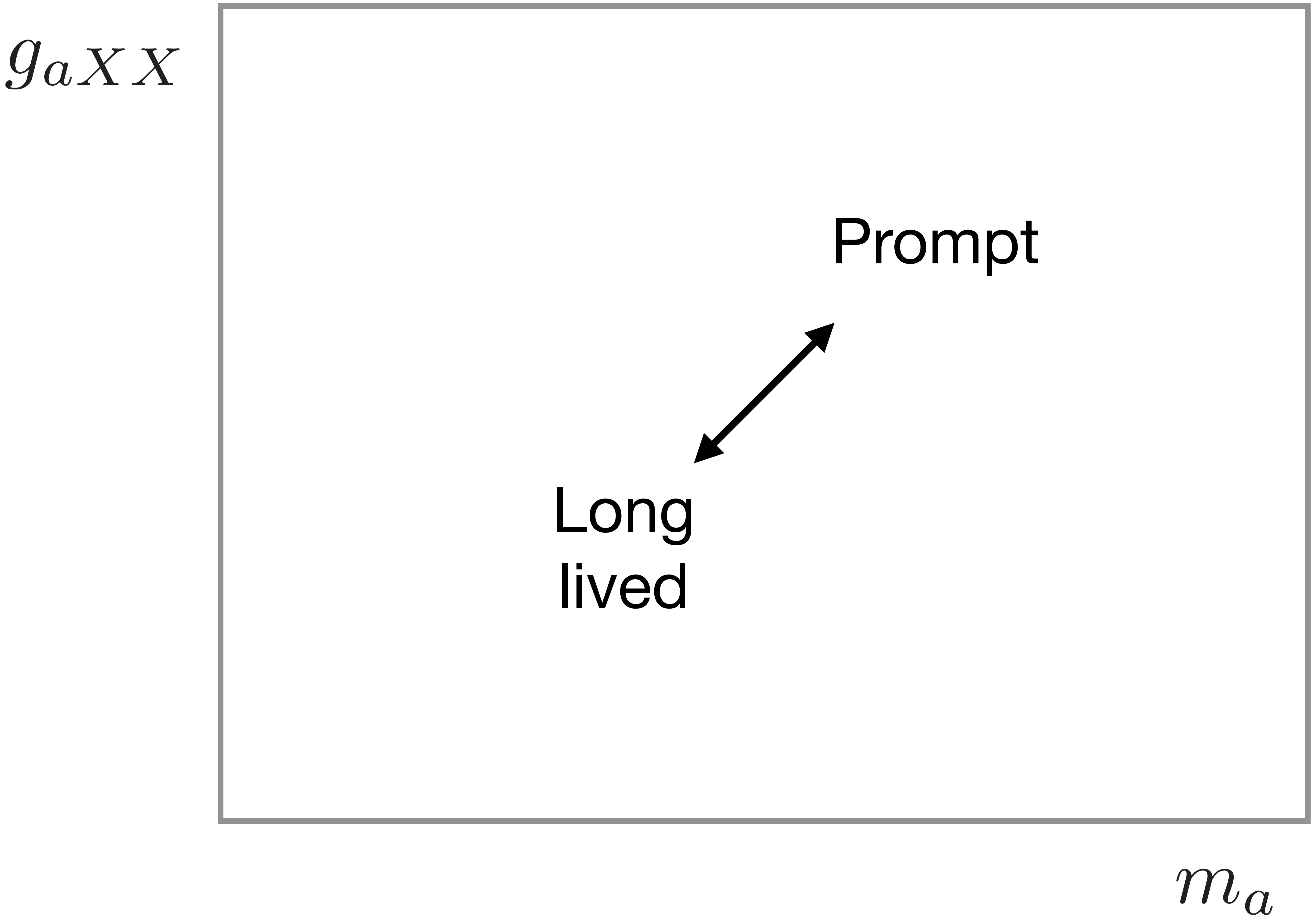
Known hierarchy for a scalar mixing with the SM Higgs

For a general (pseudo)scalar, the hierarchy of the various decay channels might be different

What if we are not in a minimal scenario?

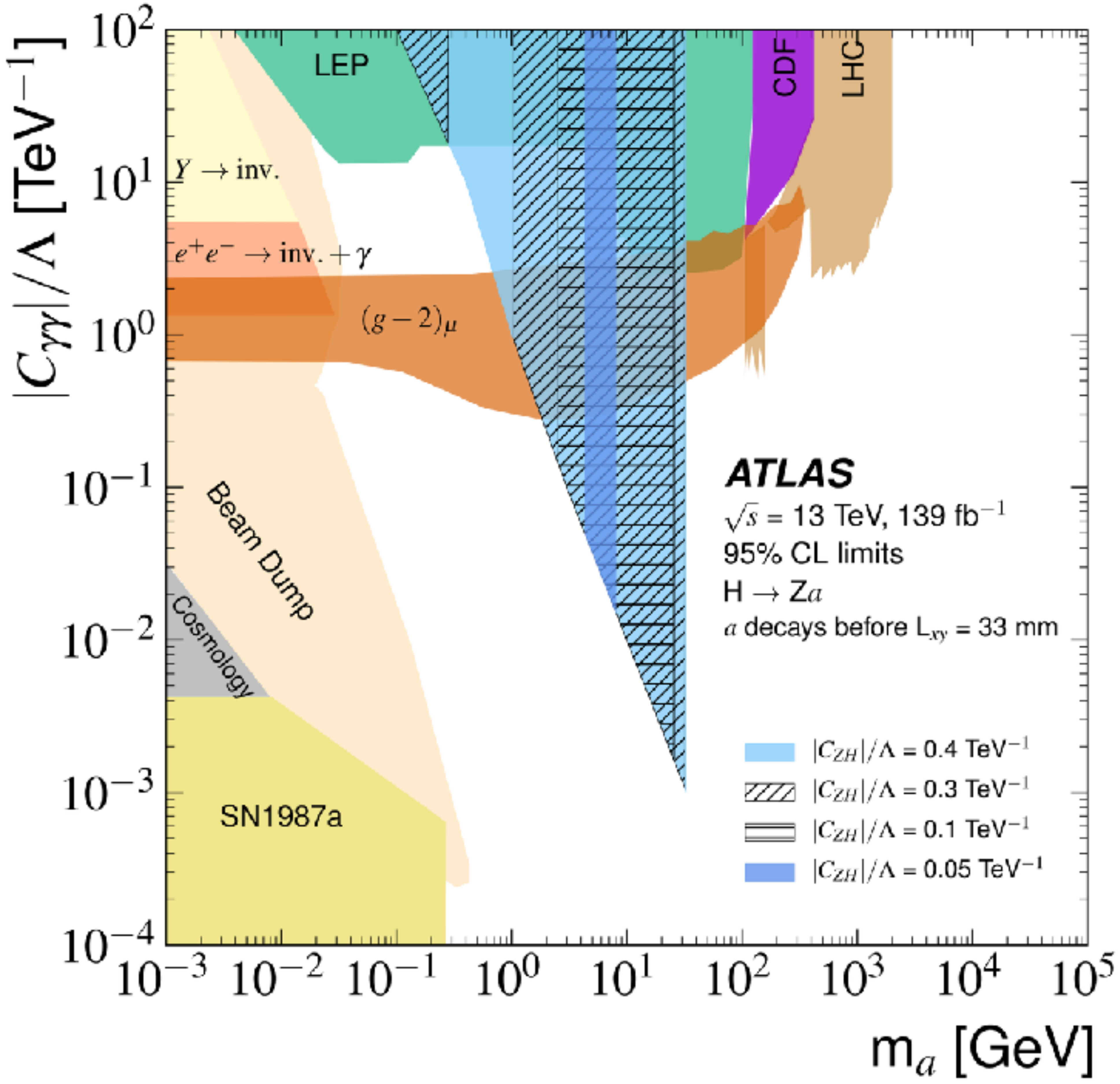
ALPs at colliders



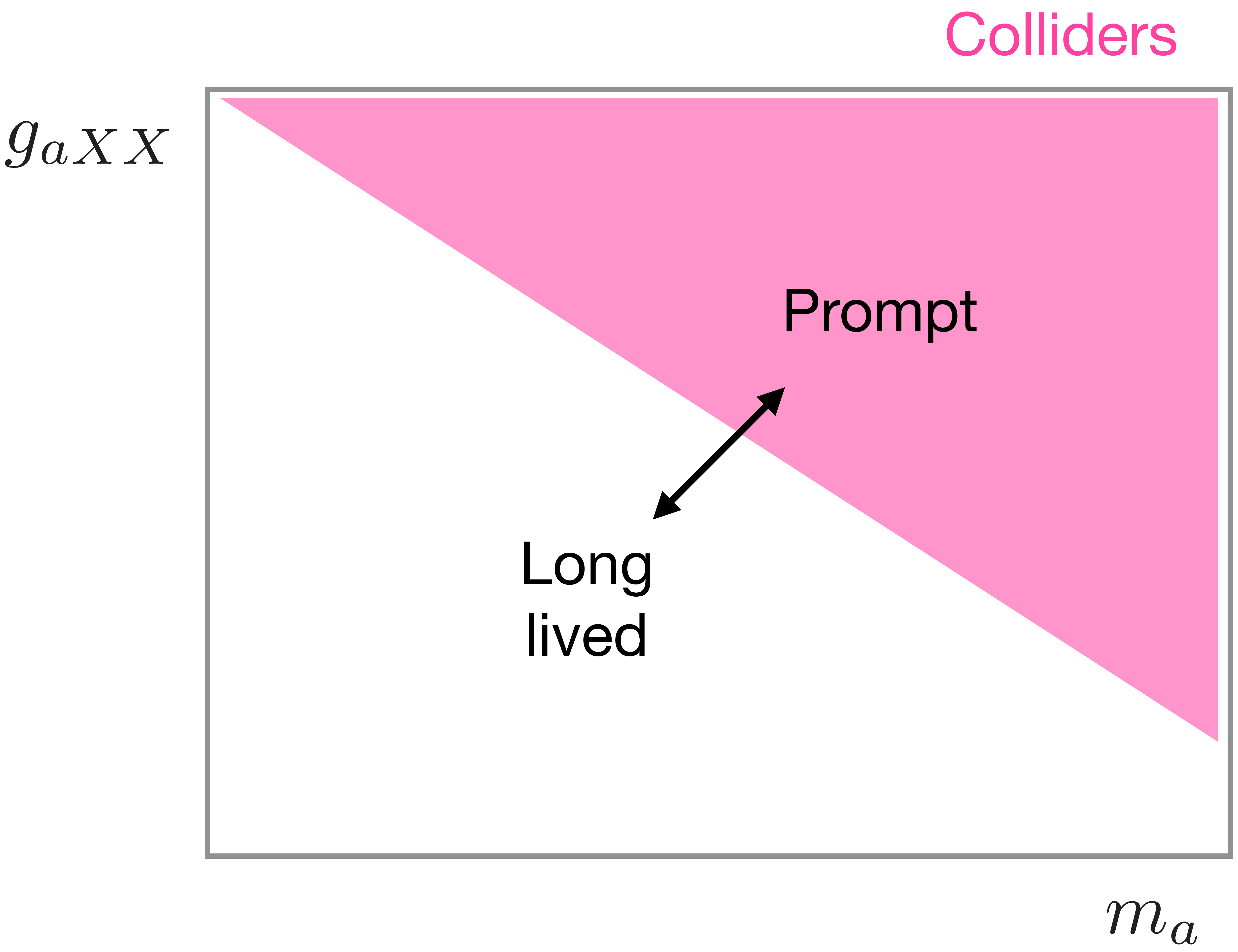


[ATLAS (2312.01942)]

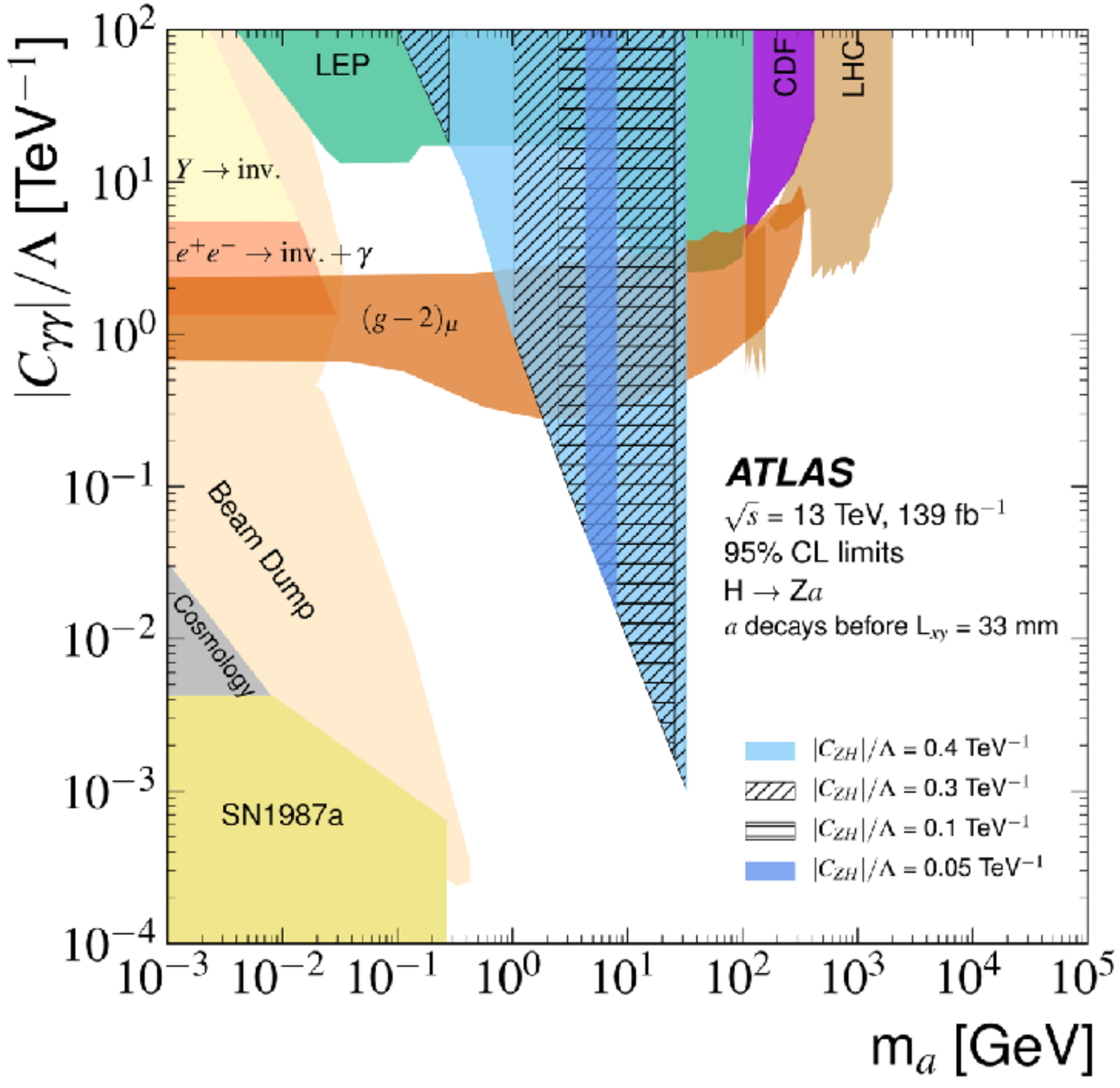
ALPs at colliders

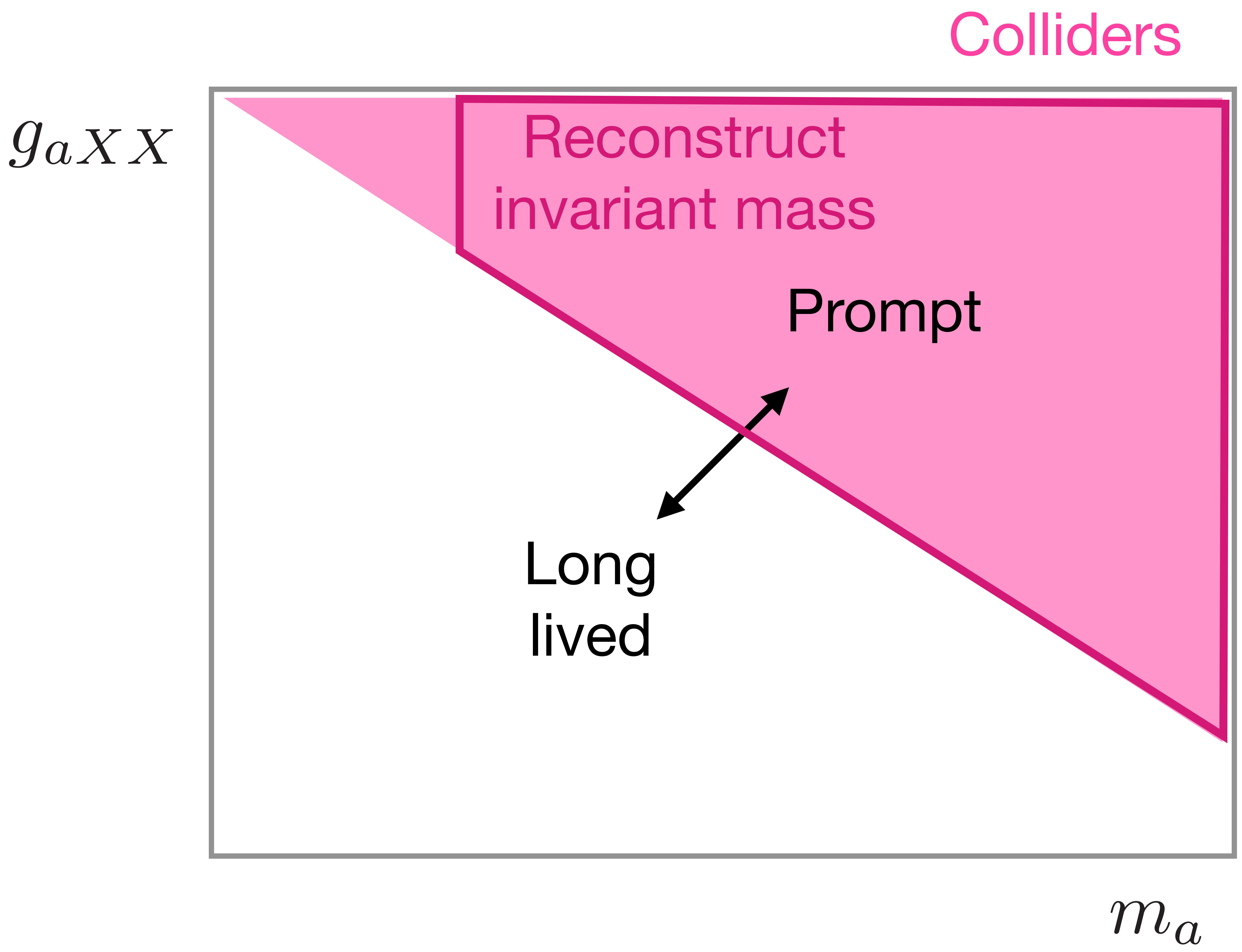


[ATLAS (2312.01942)]



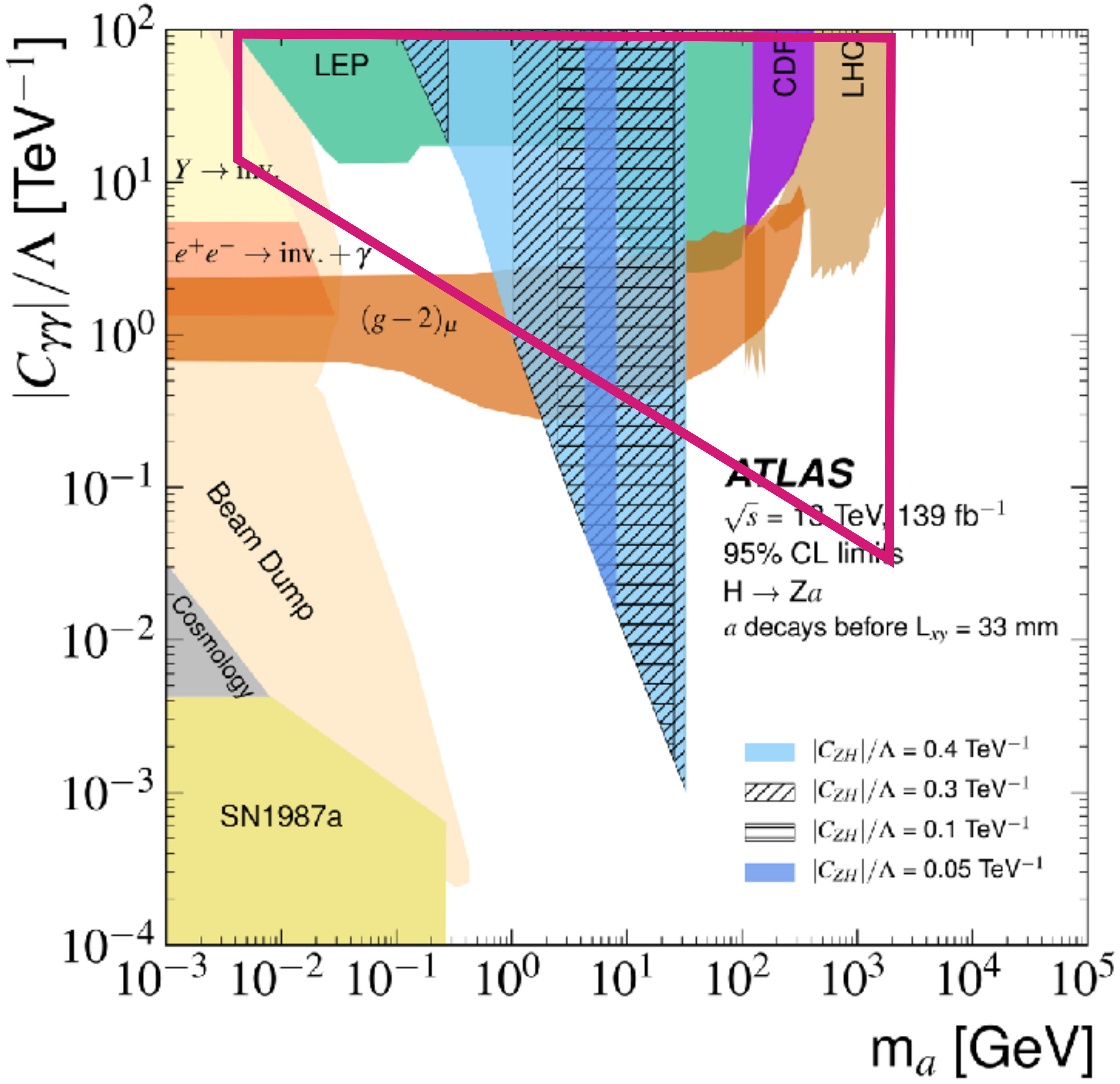
ALPs at colliders

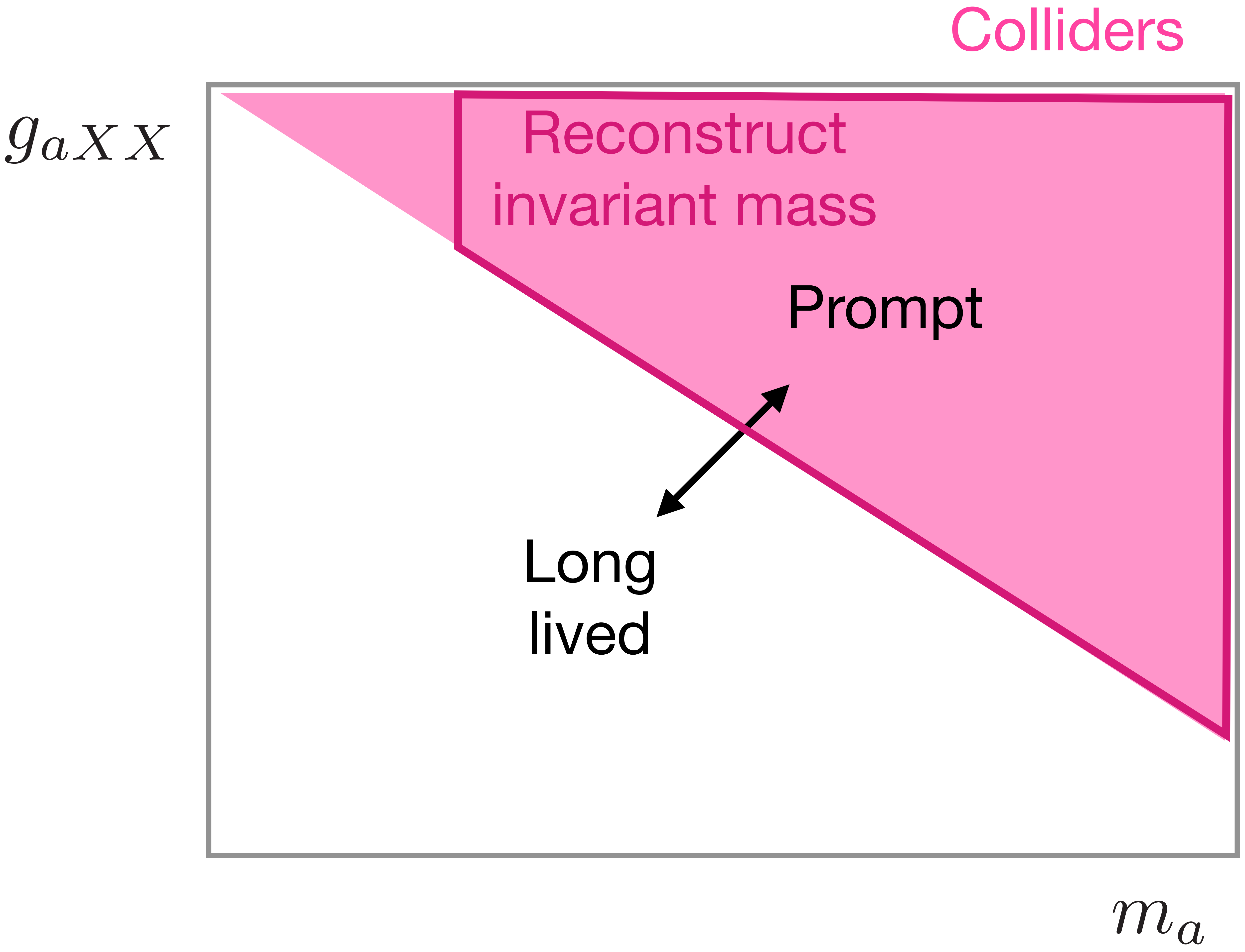




[ATLAS (2312.01942)]

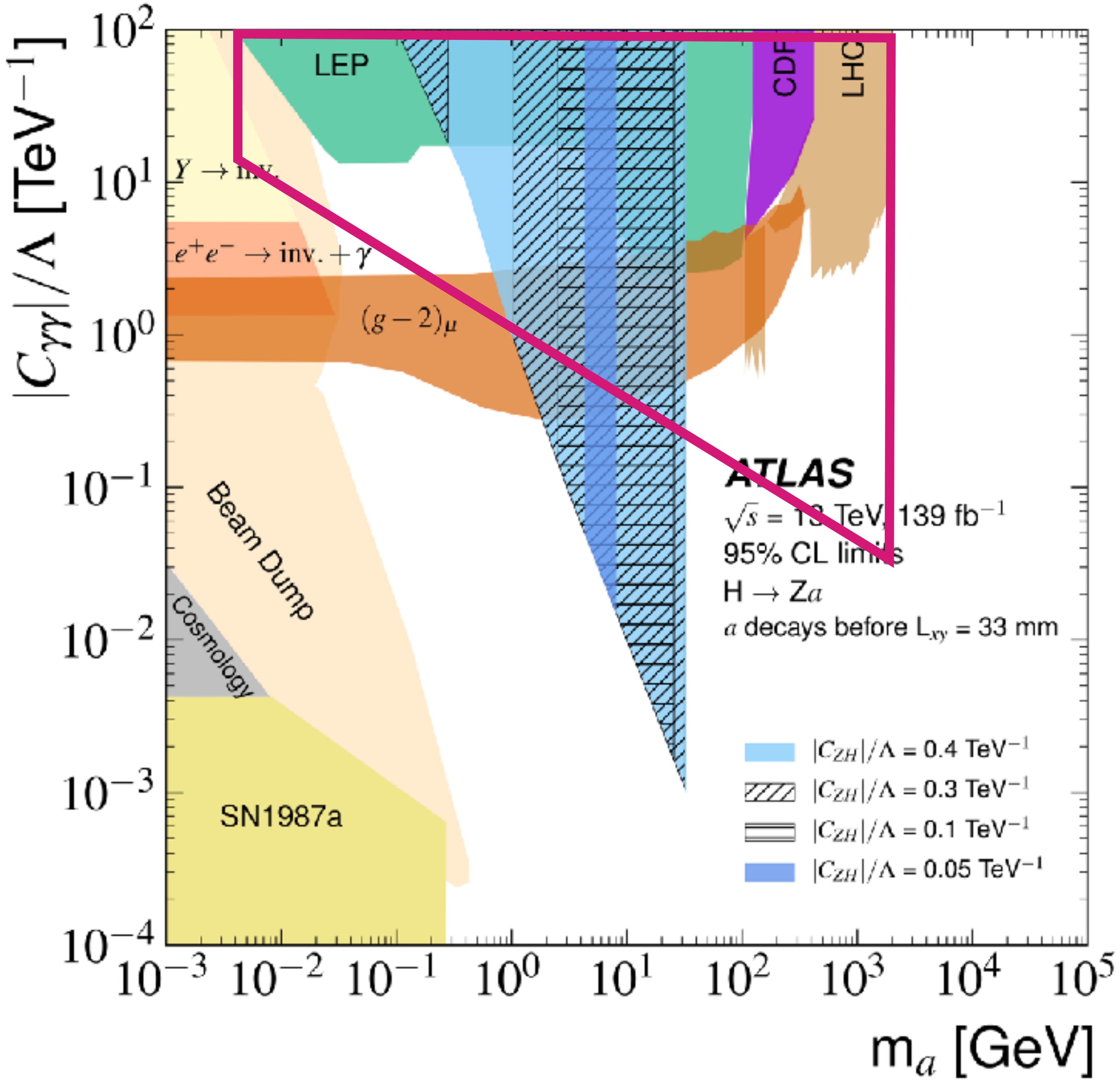
ALPs at colliders



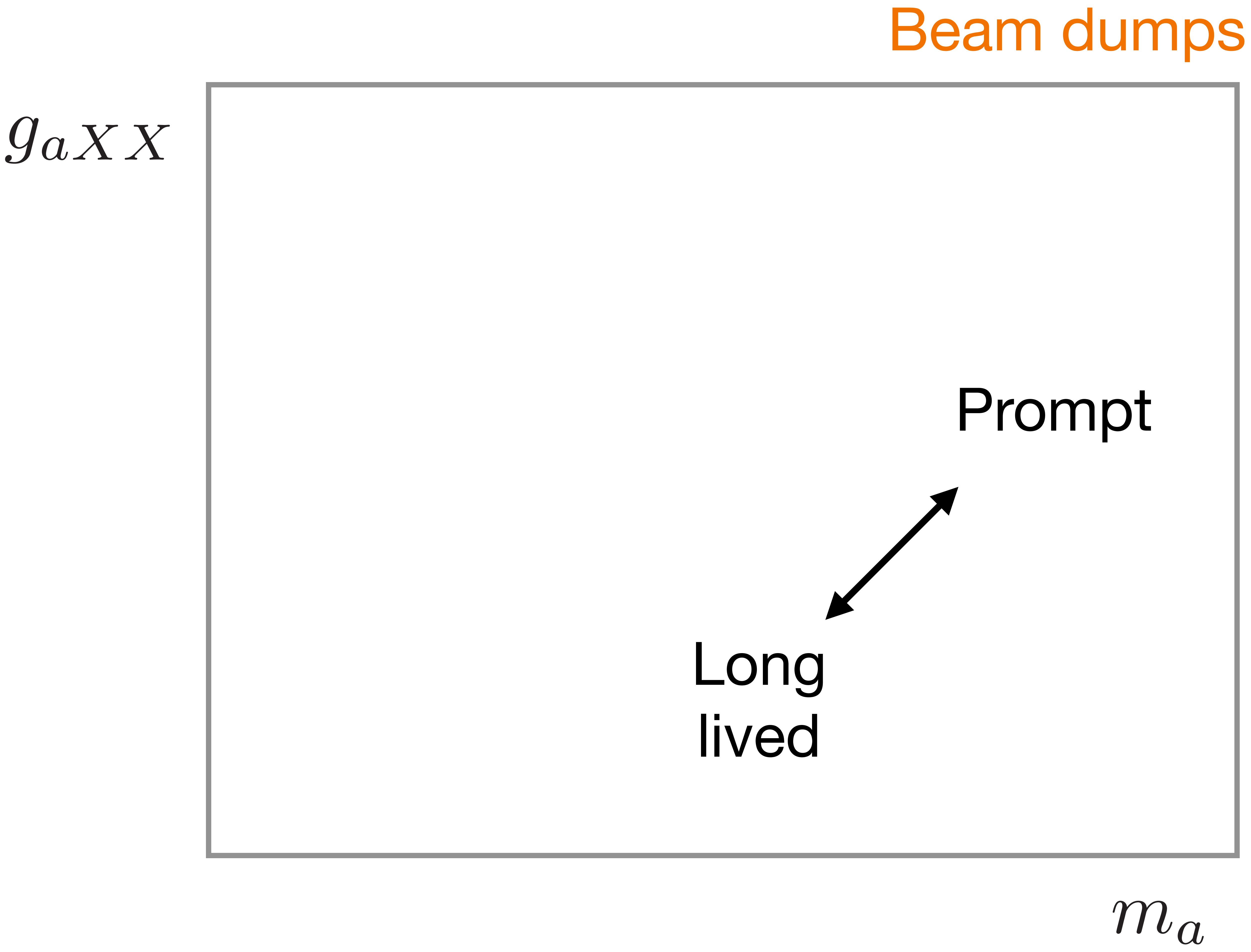


[ATLAS (2312.01942)]

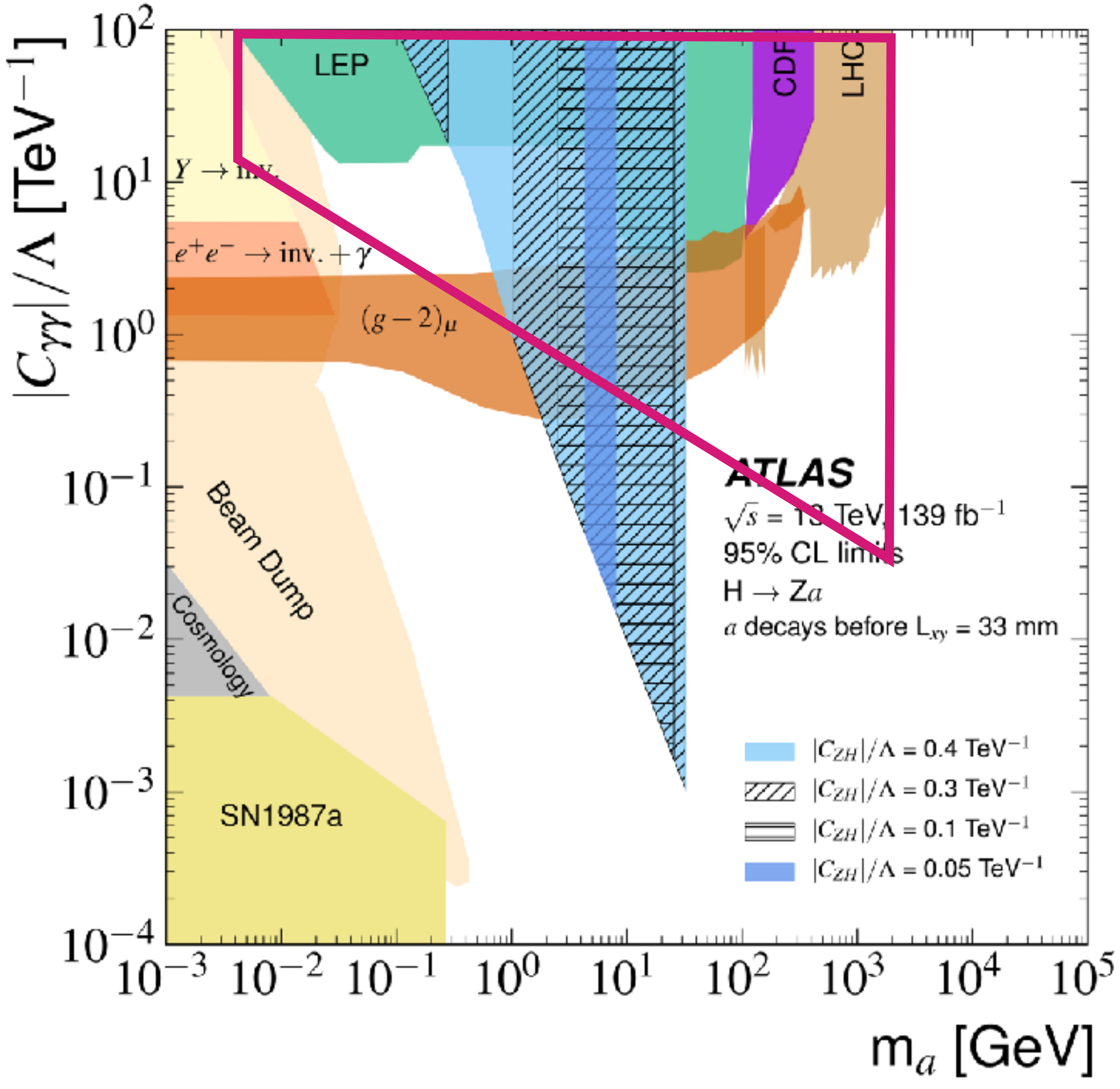
ALPs at colliders



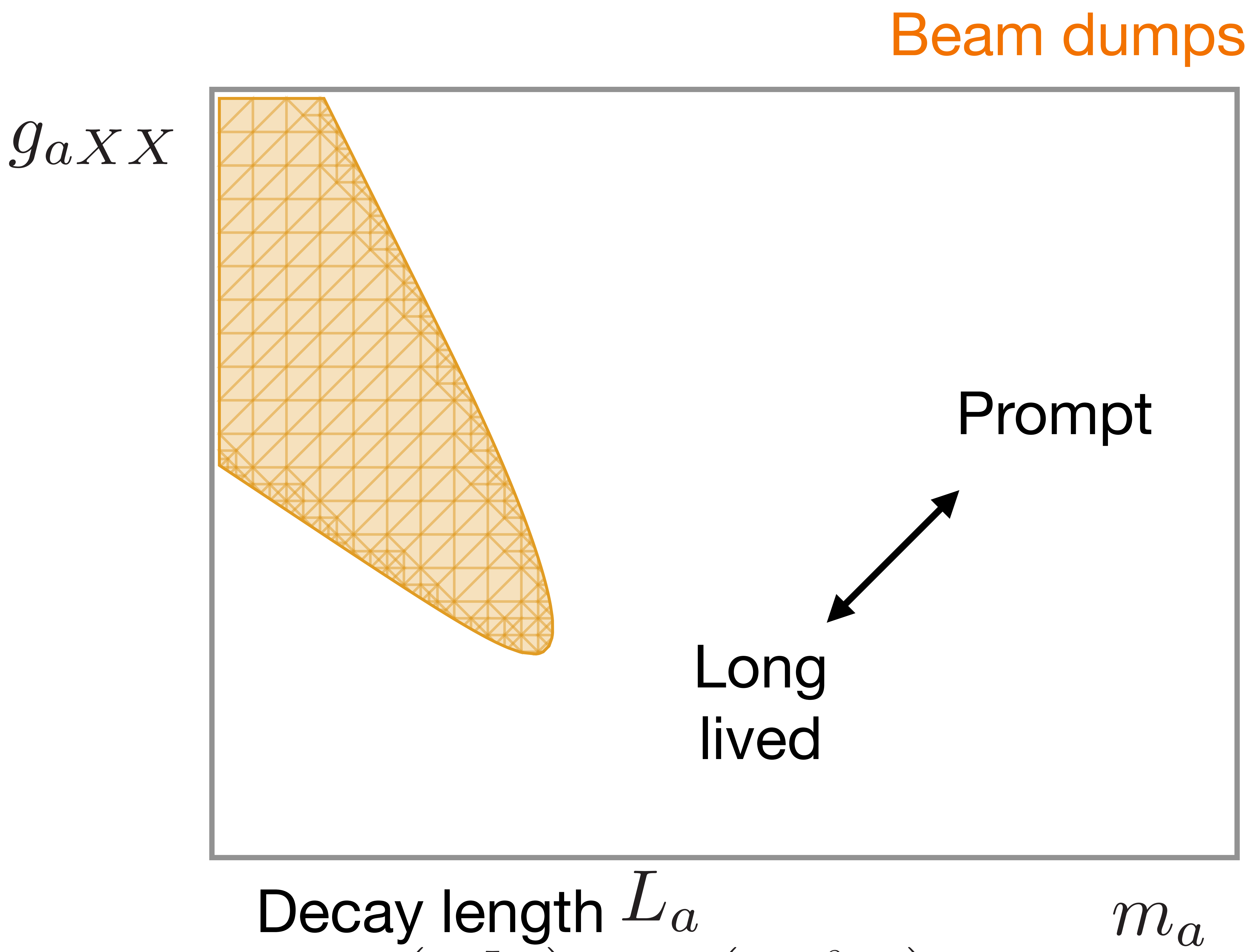
[ATLAS (2312.01942)]



ALPs at colliders

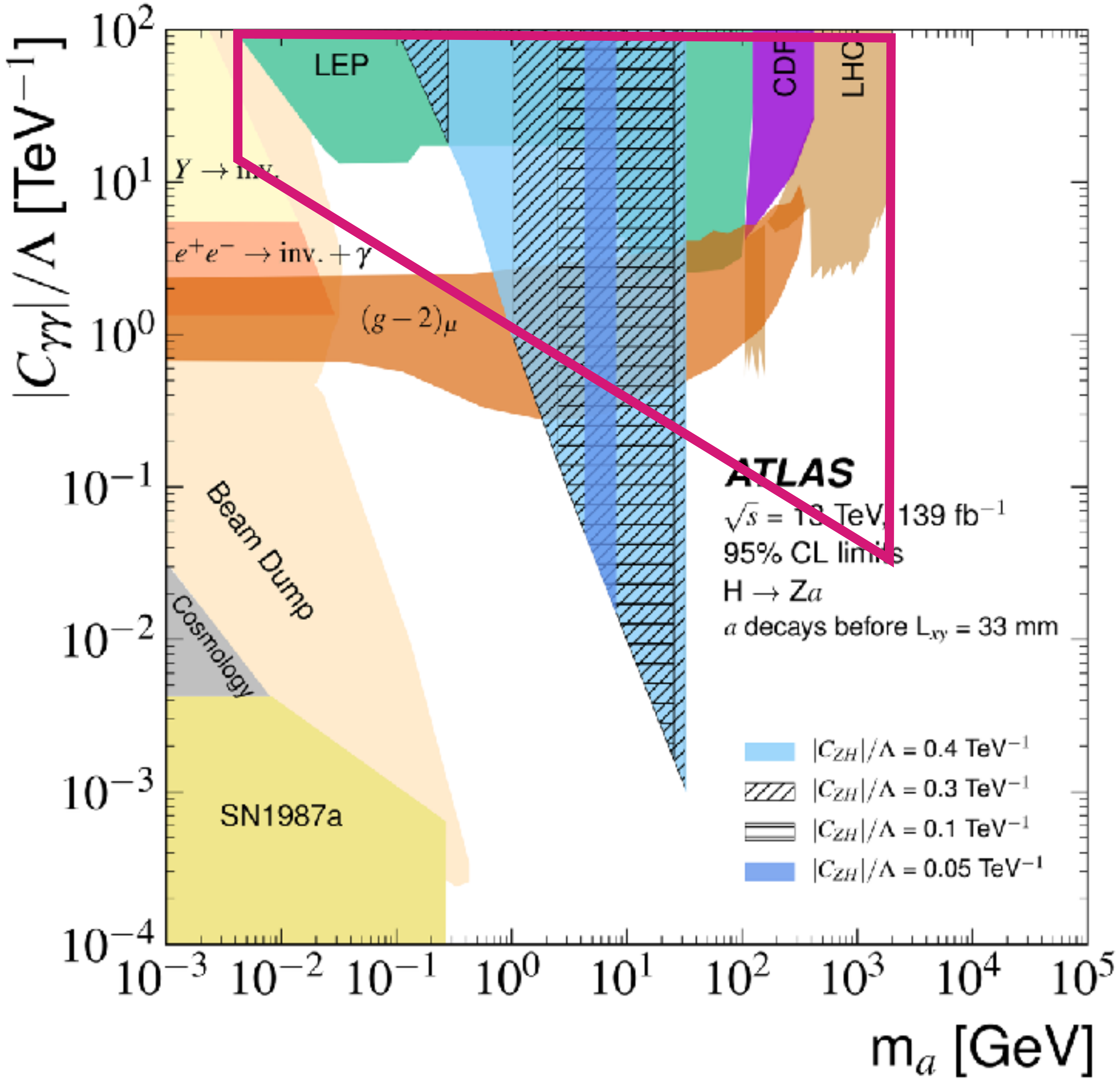


[ATLAS (2312.01942)]

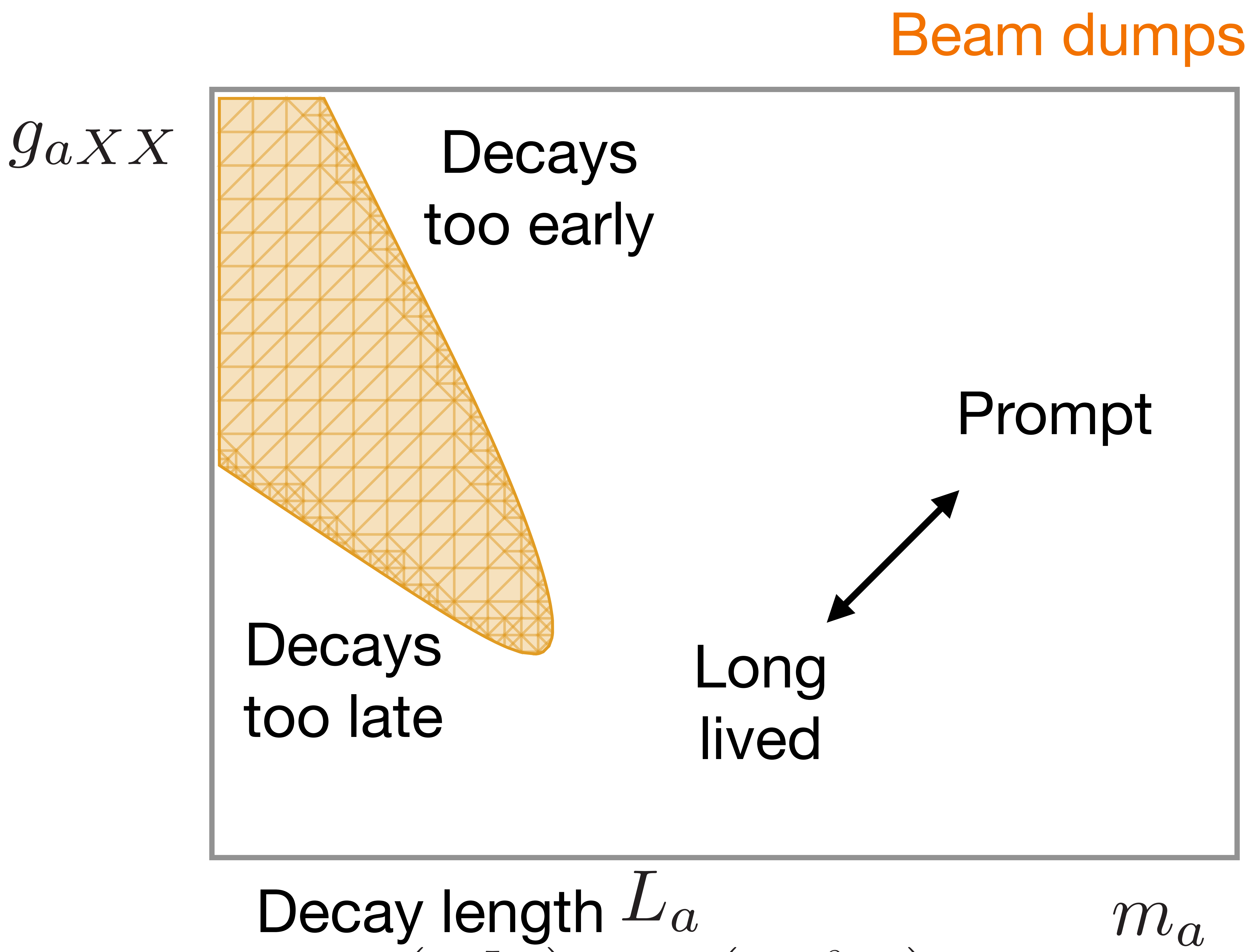


$$\exp\left(-\frac{L_a}{L_{\rm det}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\rm det}}\right)$$

ALPs at colliders

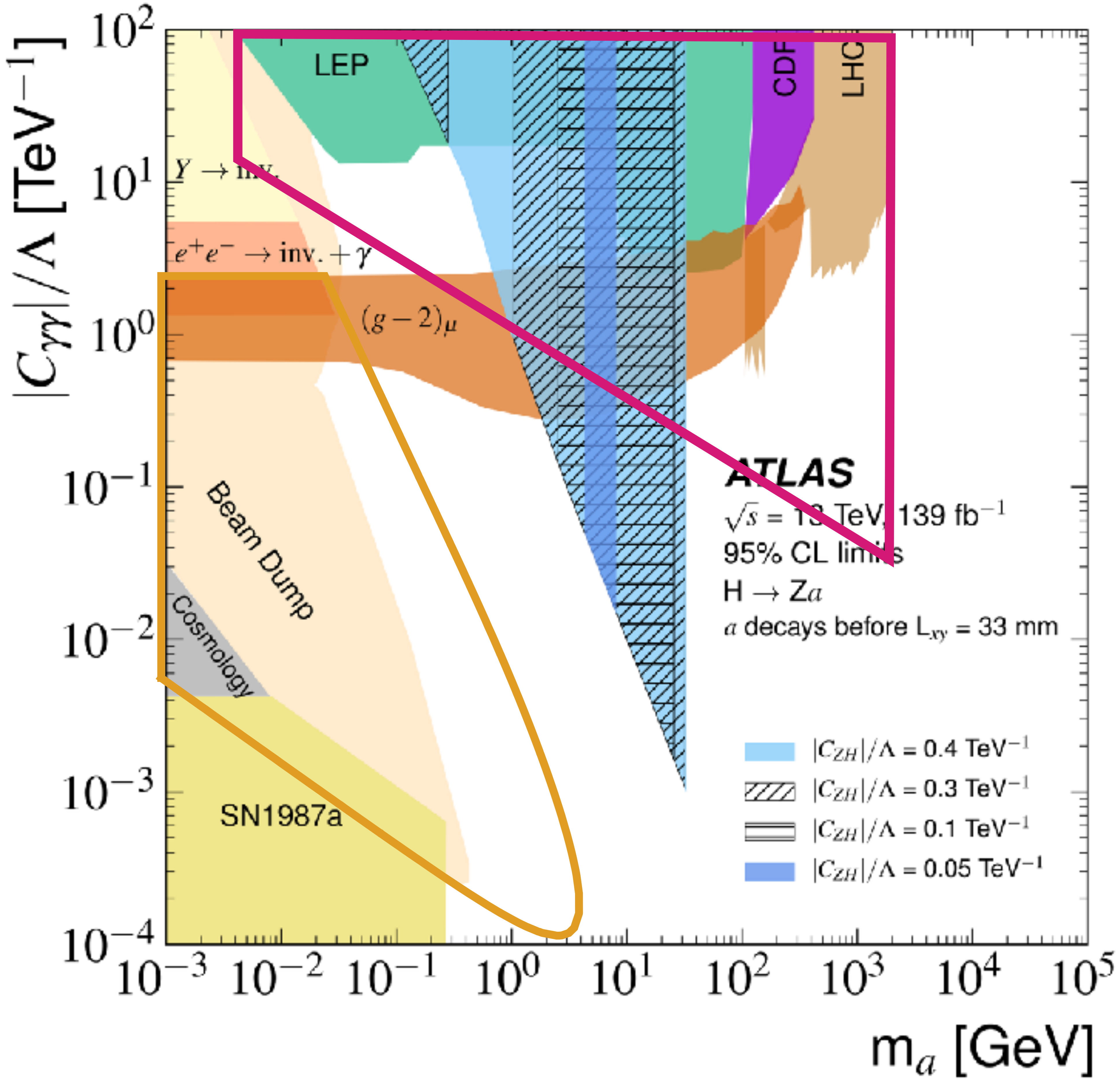


[ATLAS (2312.01942)]

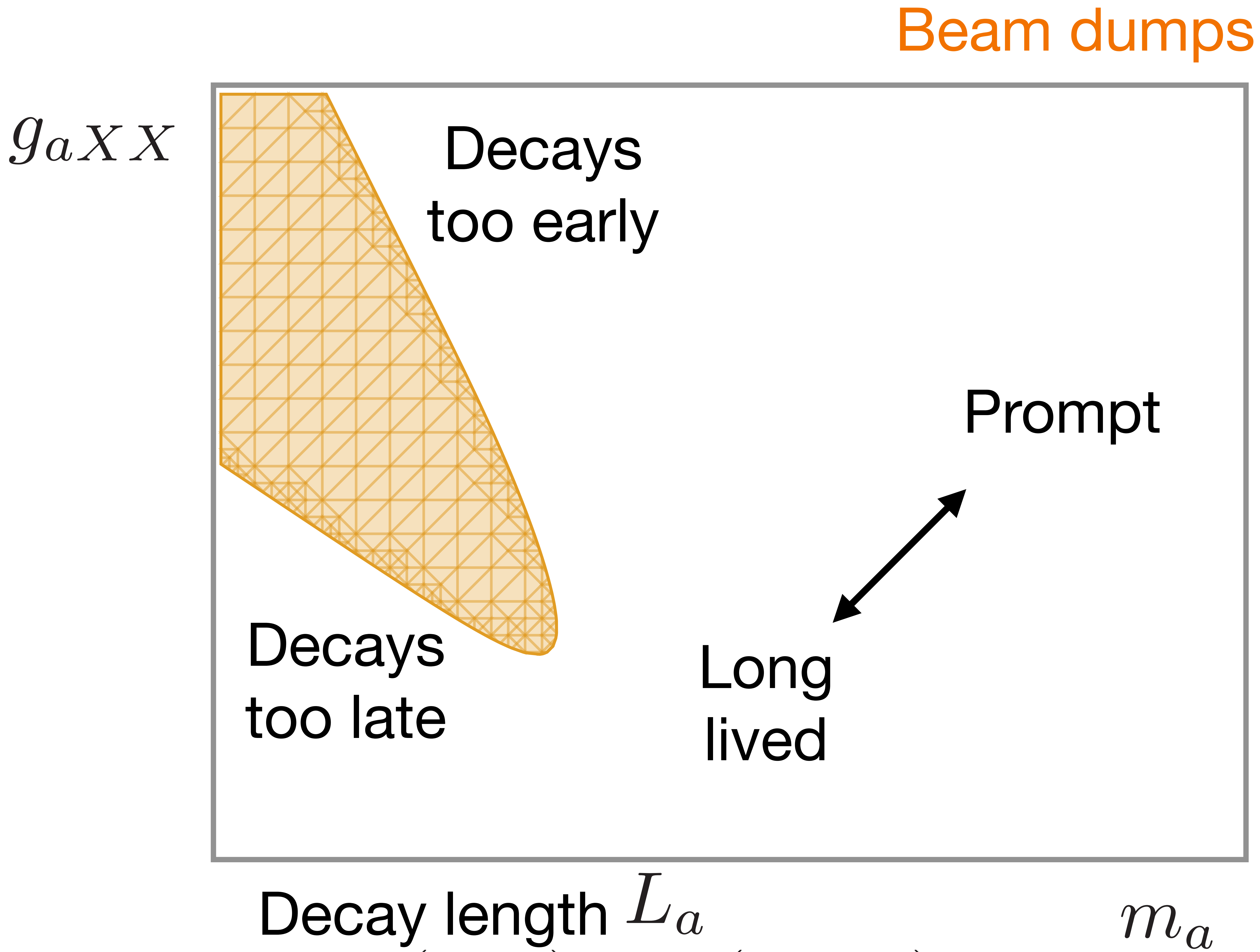


$$\exp\left(-\frac{L_a}{L_{\text{det}}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\text{det}}}\right)$$

ALPs at colliders

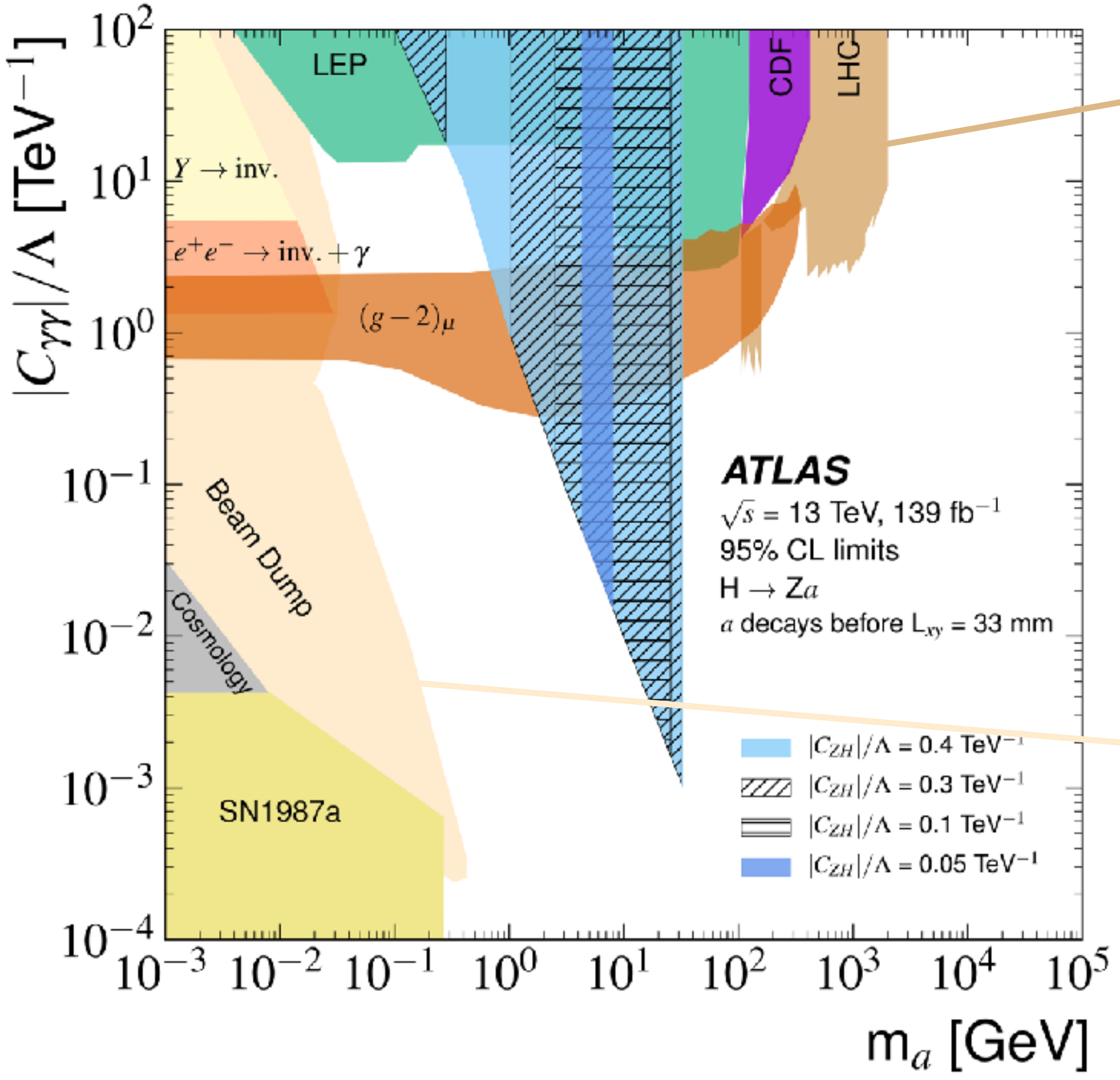


[ATLAS (2312.01942)]



$$\exp\left(-\frac{L_a}{L_{\rm det}}\right) = \exp\left(-\frac{\beta c}{\Gamma_a L_{\rm det}}\right)$$

2D bounds



[ATLAS (2312.01942)]

LHC limits

$pp \to a \to \gamma\gamma$

Mass-dependent (resonance search)

Assuming $\mathrm{BR}(a \to \gamma\gamma) = 100\,\%$

$\mathrm{BR}(a \to ZZ)$?

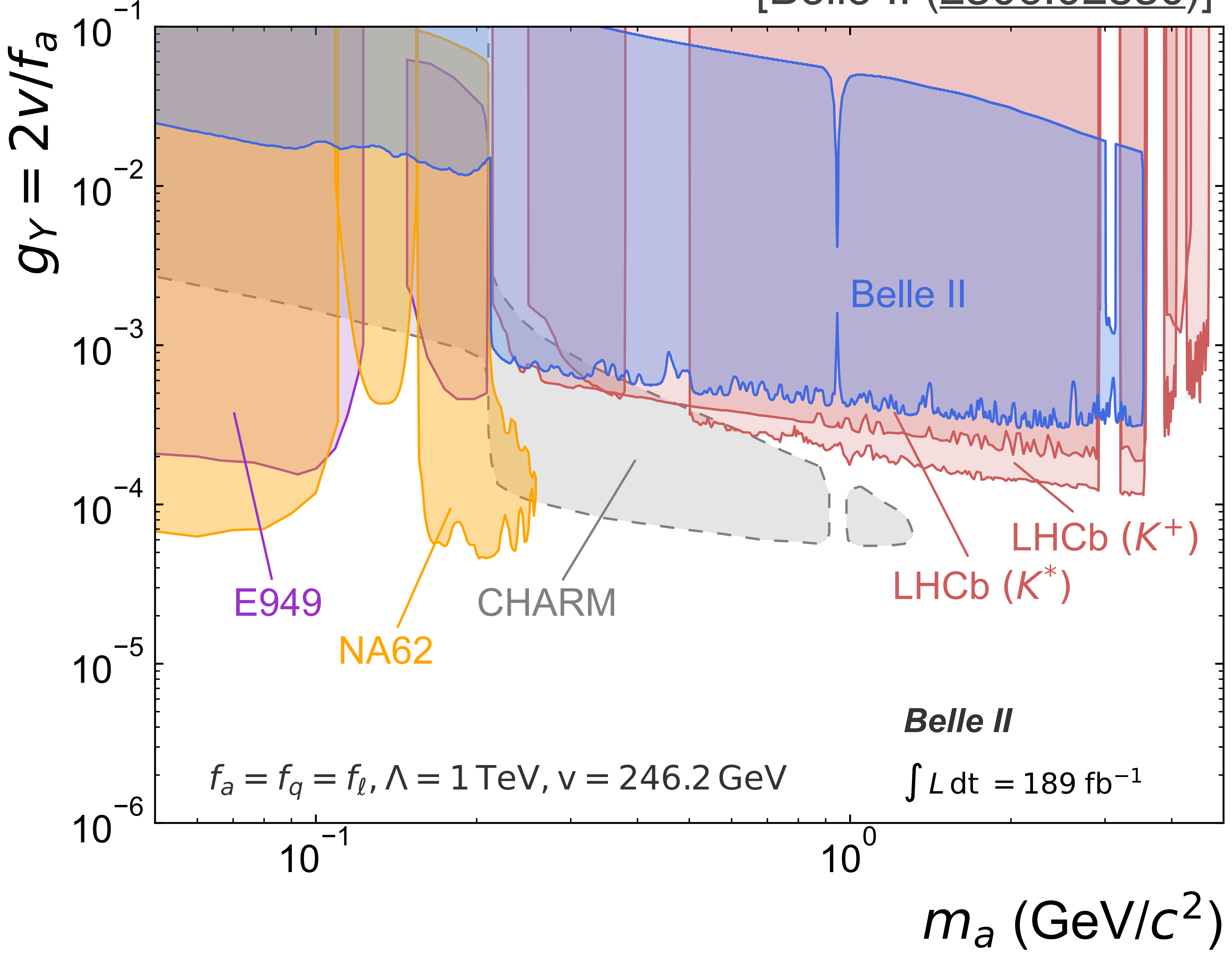
$\mathrm{BR}(a \to Z\gamma)$?

Beam dump limits

Can be changed (or invalidated) if $a \to e^+e^-$ decay possible

Limits on ALPs

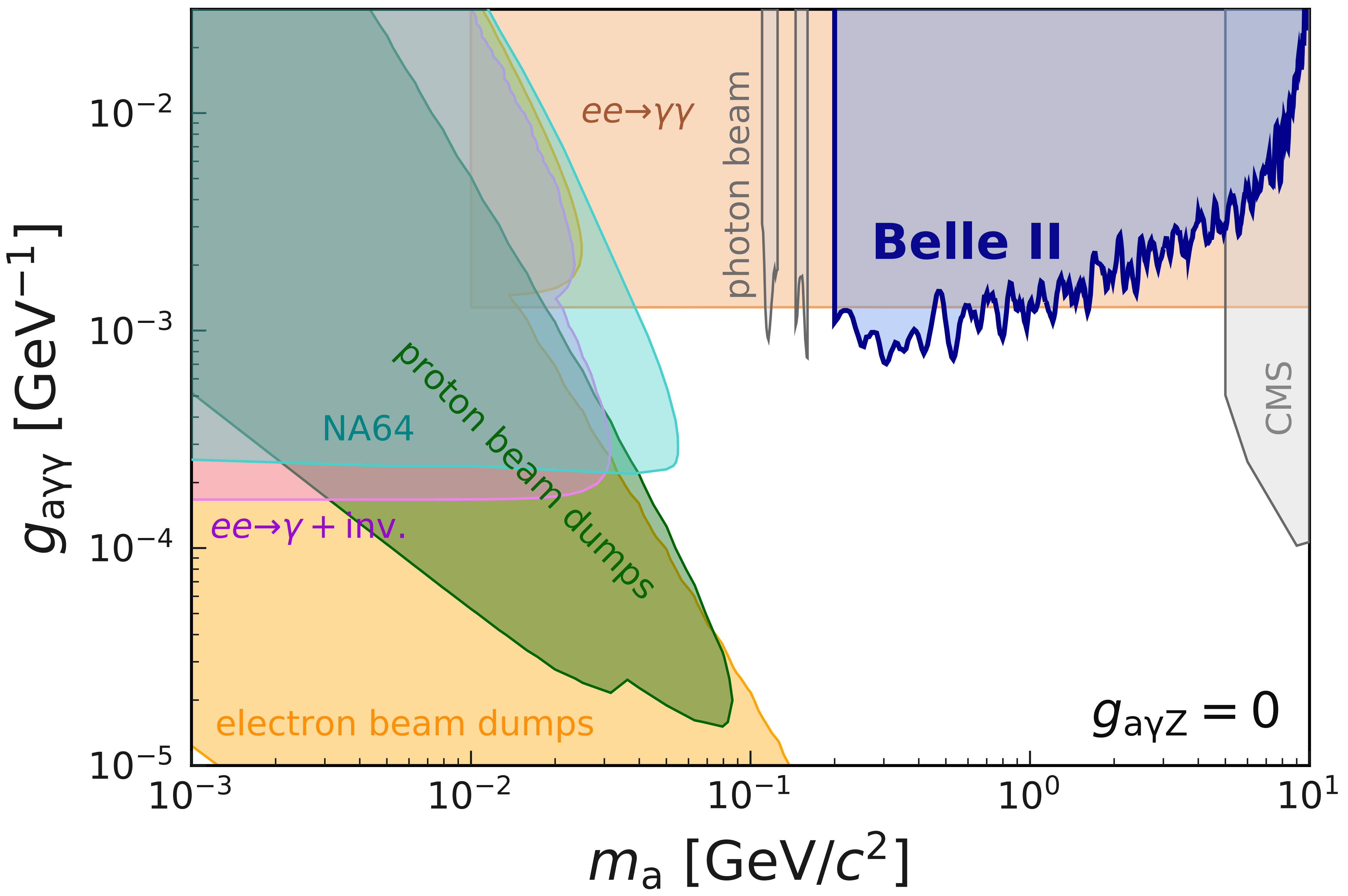
[Belle II (2306.02830)]



Universal couplings to fermions

$$\mathcal{L} = \sum_\psi \frac{\partial_\mu a}{f_\psi} \bar{\psi}\gamma_\mu\gamma^5\psi$$

[Belle II (2007.13071)]



Coupling to photons

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

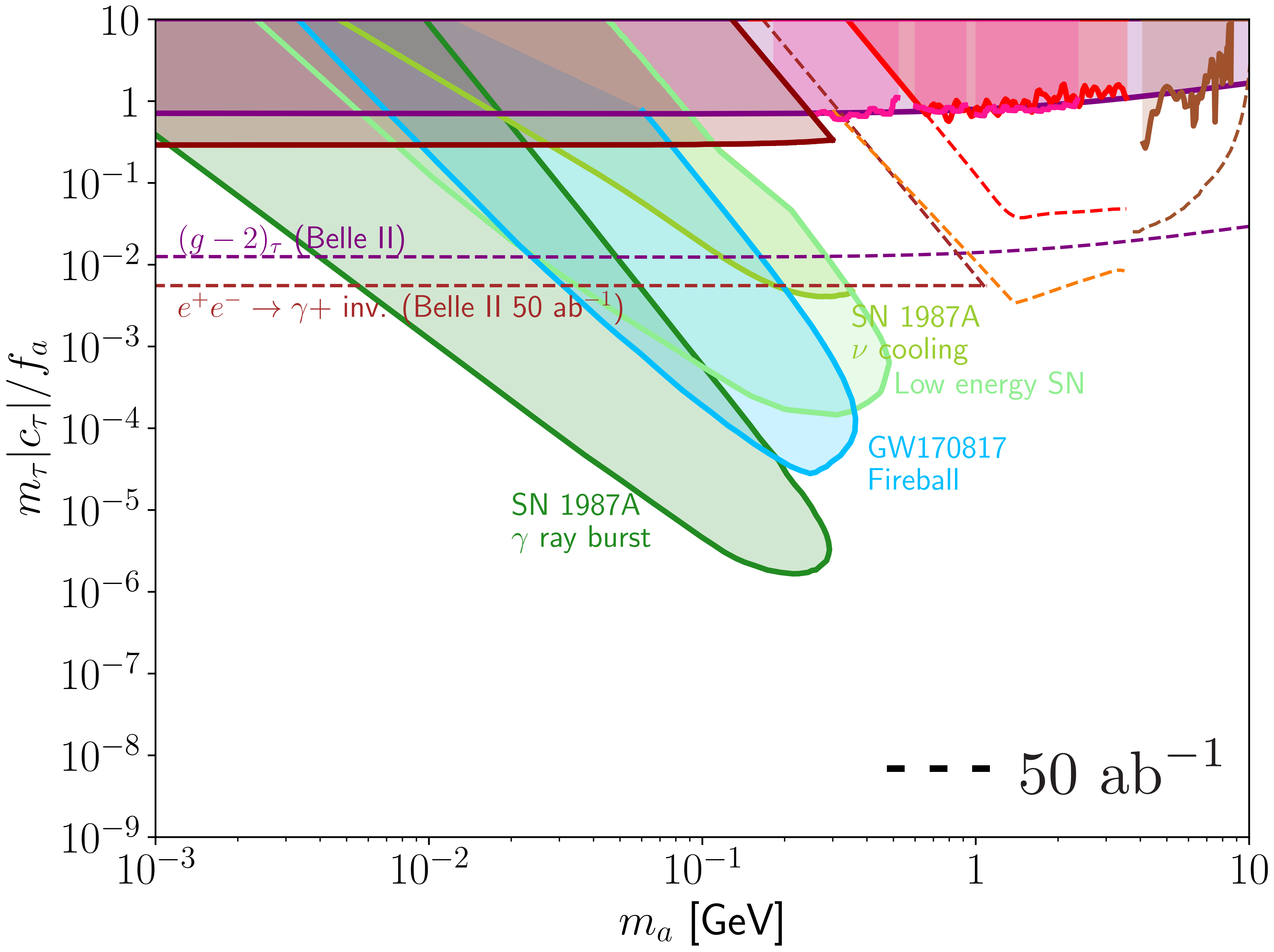
[Alda, Levati, Paradisi, Rigolin, Selimovic (2407.18296)]

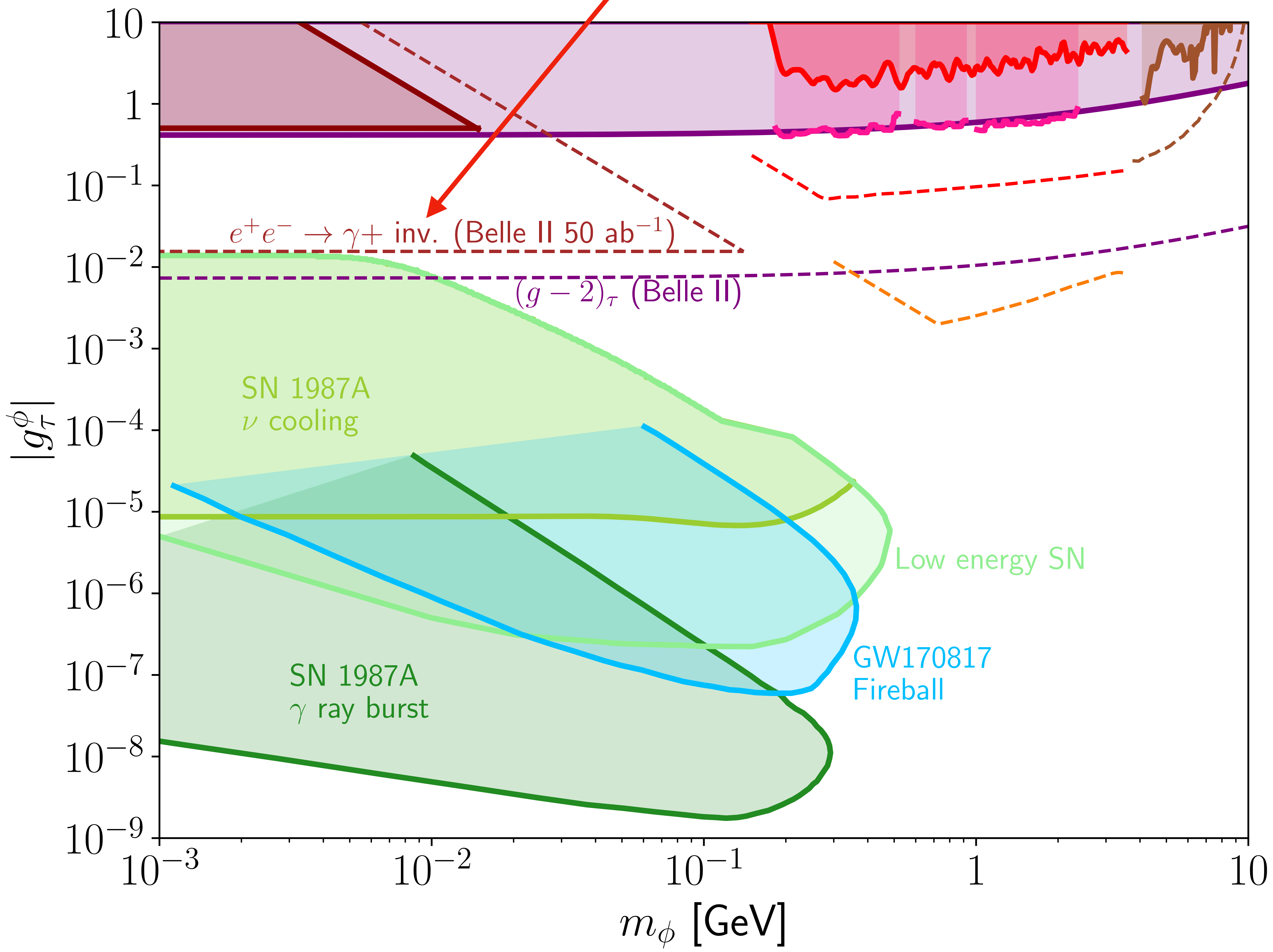
ALPs and scalars couplings to tau leptons

$e^+e^- \to 3\gamma$ (Belle II)

$(g-2)_\tau$ (CMS) $J/\psi \to 3\gamma$ (BESIII) $e^+e^- \to \gamma\tau^+\tau^-$ (Belle II)

Remarkable complementarity



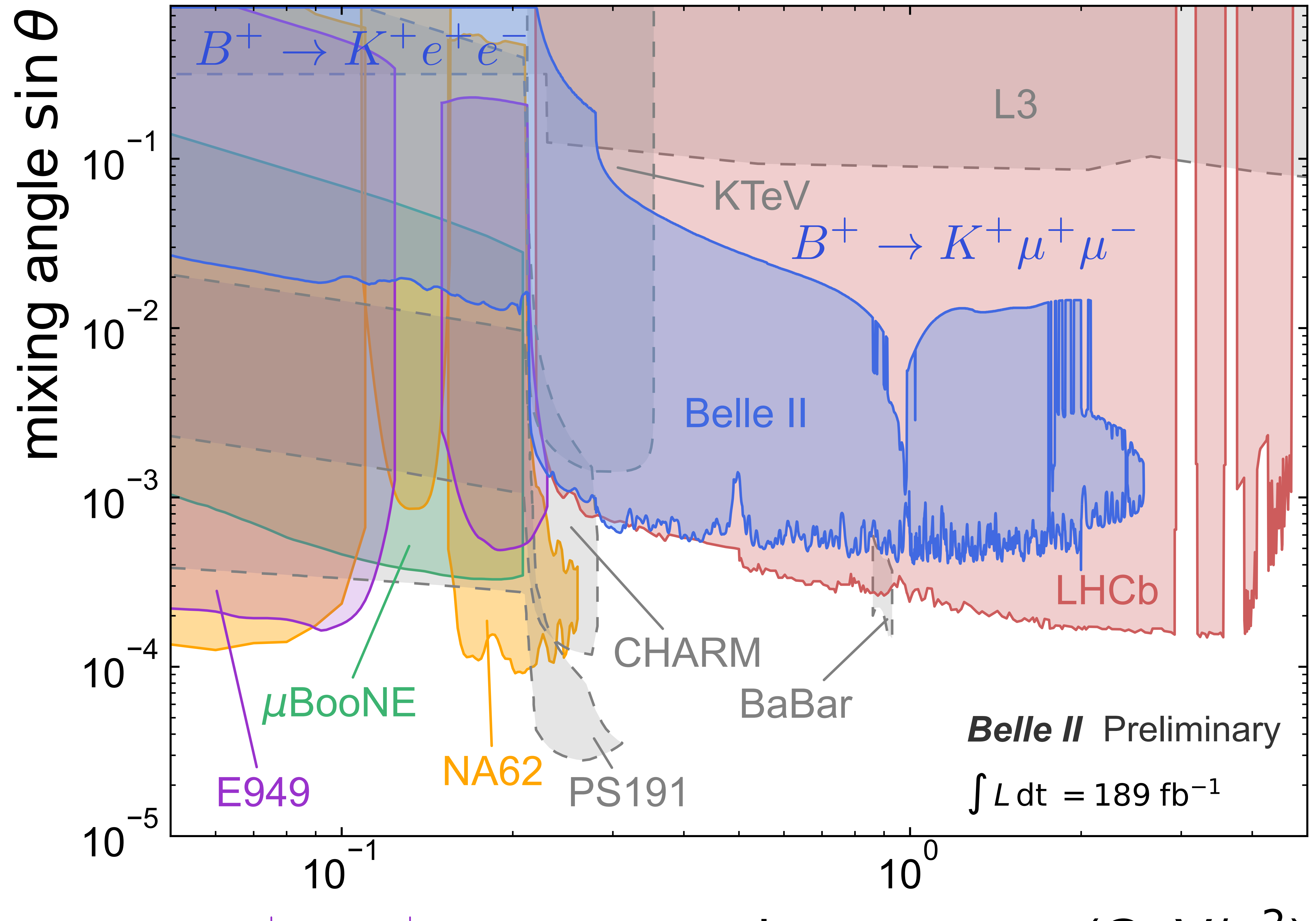


Constant L^a_{lab} for $|c_\tau| m_\tau f_a \propto m_a^{-4}$

Constant L^ϕ_{lab} for $|g^\phi_\tau| \propto m_a^{-2}$

Light scalar mixing with the SM Higgs

[Ferber, Grohsjean, Kahlhöfer (2305.16169)]

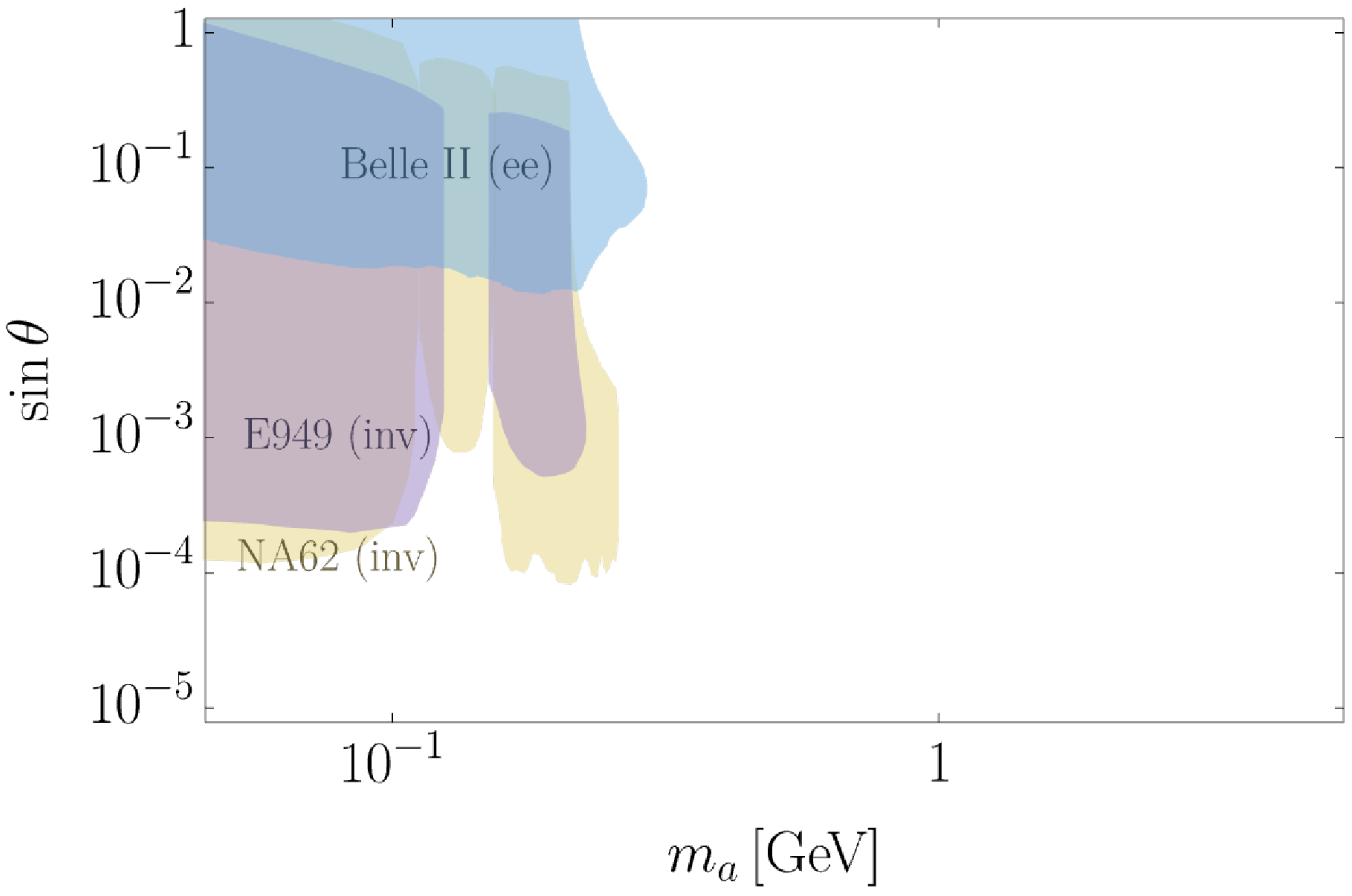


$K^+ \to \pi^+ + E_{\text{miss}}$

$K^+ \to \pi^+ + E_{\text{miss}}$

$B^+ \to K^+\ell^+\ell^-$

[AB, Díaz Carmona, Schwaller (WIP)]

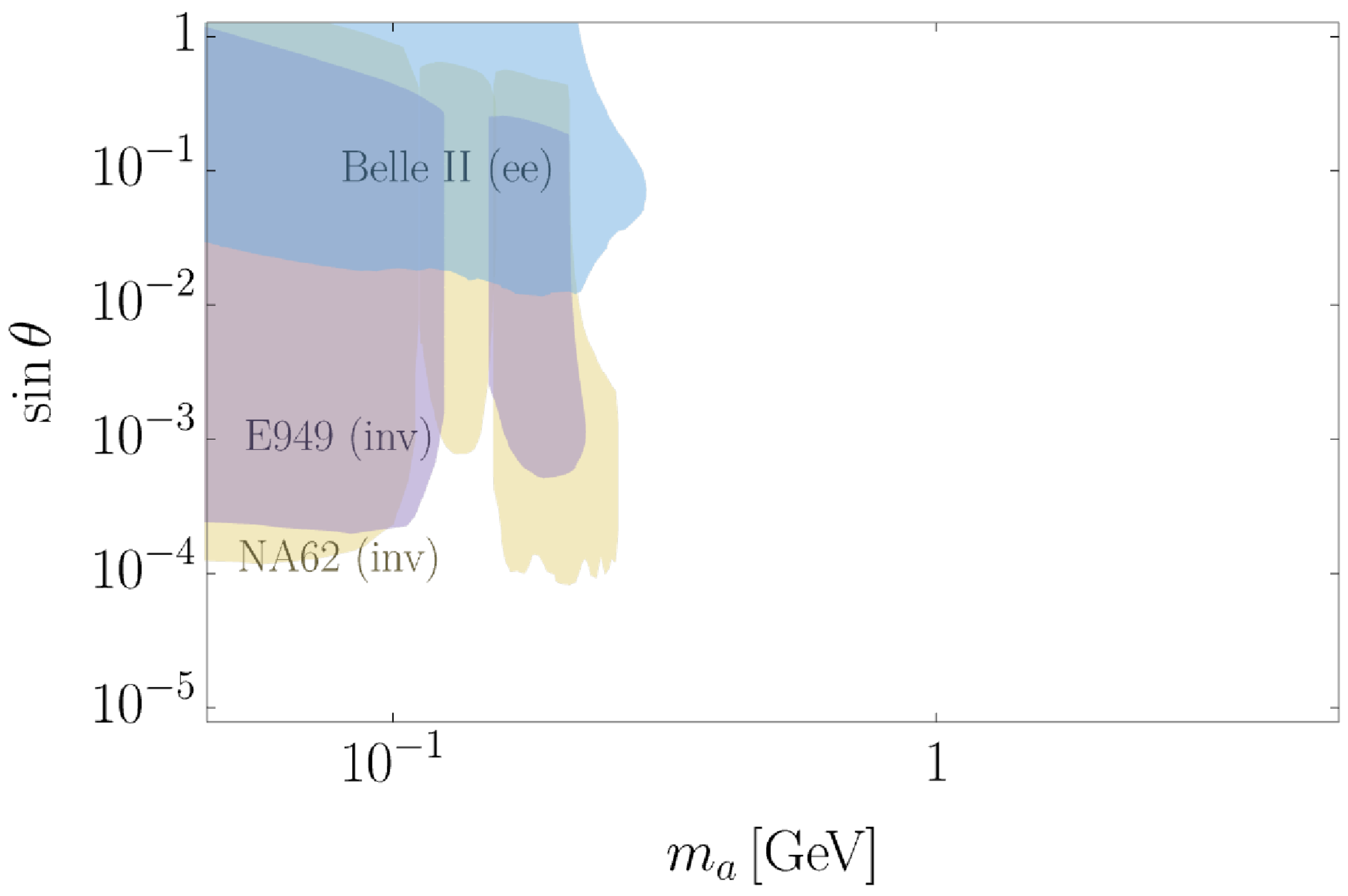


Light scalars

[AB, Díaz Carmona, Schwaller (WIP)]

$$\mathcal{L}_{\rm mix} = \sin\theta \sum_f \frac{m_f}{v} \phi \bar{f} f + \sin\theta \, \frac{2M_W^2}{v} \phi W_\mu^+ W^{-,\mu}$$

$$\mathcal{L} = C_f \, \phi \bar{f} f + C_W \, M_W \phi W_\mu^+ W^{-,\mu}$$

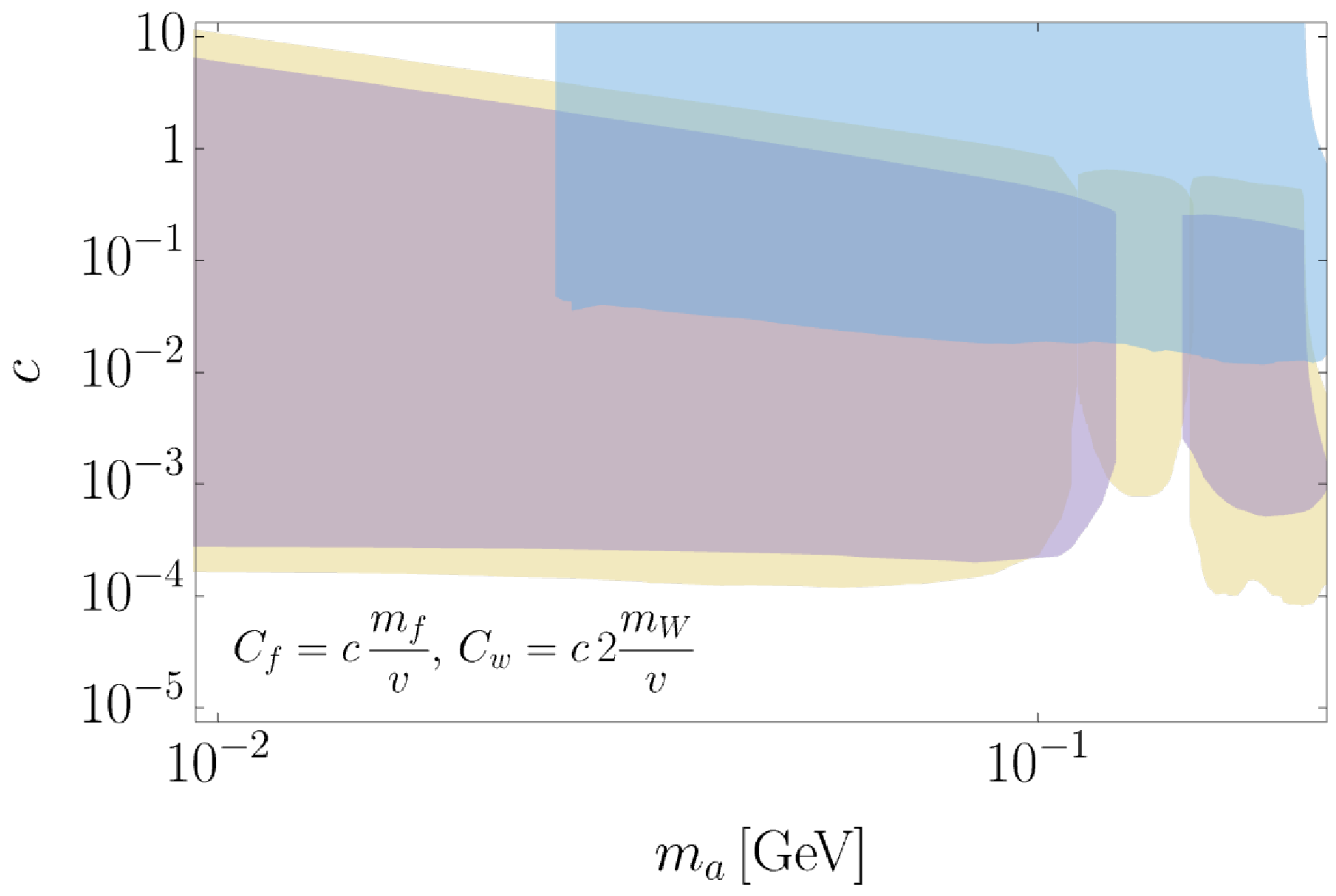


Light scalars

$$\mathcal{L}_{\text{mix}} = \sin\theta \sum_f \frac{m_f}{v}\phi\bar{f}f + \sin\theta\,\frac{2M_W^2}{v}\phi W_\mu^+ W^{-,\mu}$$

$$\mathcal{L} = C_f\,\phi\bar{f}f + C_W\,M_W\phi W_\mu^+ W^{-,\mu}$$

[AB, Díaz Carmona, Schwaller (WIP)]



Light scalars

[AB, Díaz Carmona, Schwaller (WIP)]

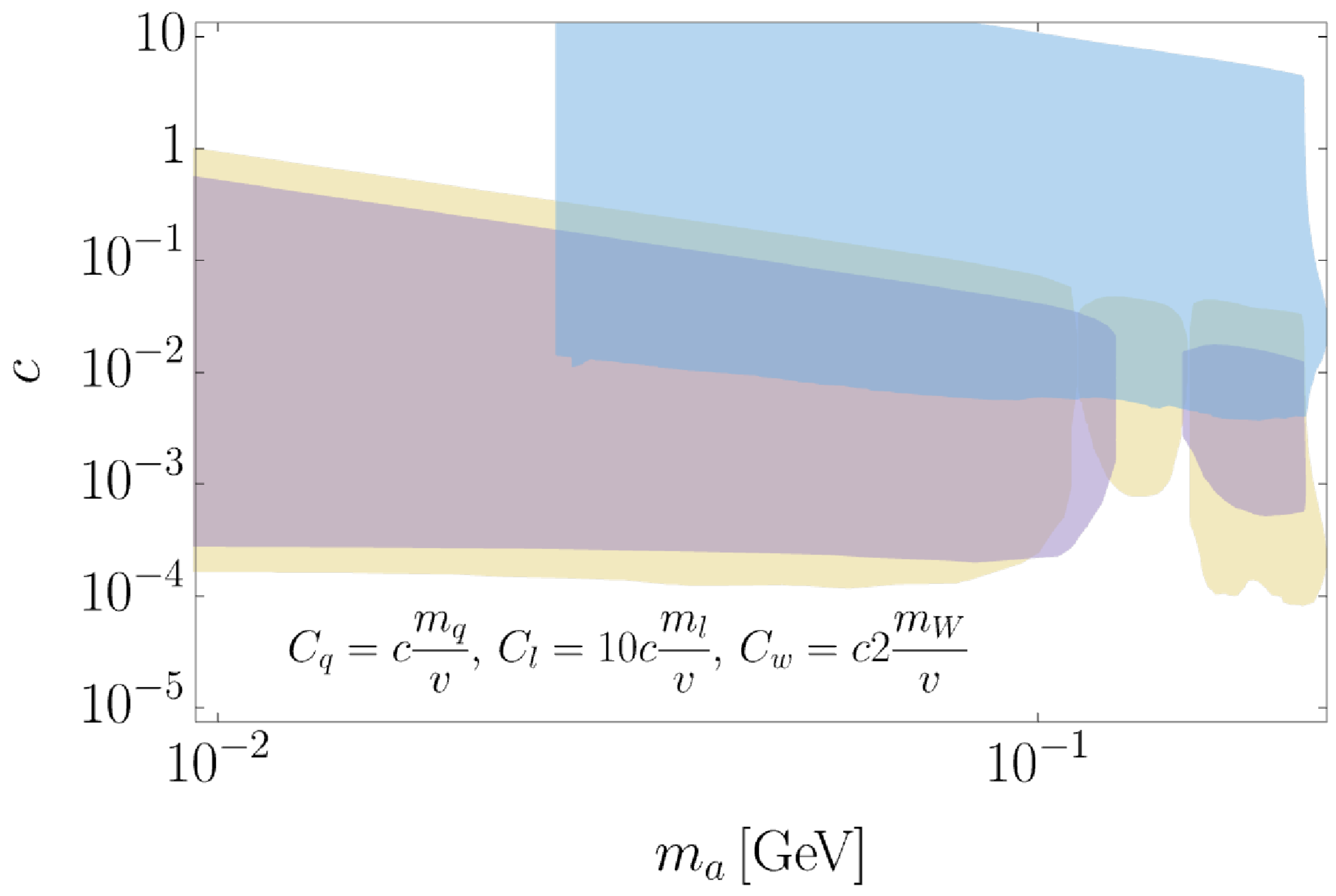
$$\mathcal{L}_{\rm mix} = \sin\theta \sum_f \frac{m_f}{v} \phi \bar{f} f + \sin\theta \, \frac{2M_W^2}{v} \phi W_\mu^+ W^{-,\mu}$$

$$\mathcal{L} = C_f \, \phi \bar{f} f + C_W \, M_W \phi W_\mu^+ W^{-,\mu}$$

Same production cross section,

Different decay rate

Lepton couplings increased by factor 10



Light scalars

$$\mathcal{L}_{\rm mix} = \sin\theta \sum_f \frac{m_f}{v}\phi \bar{f} f + \sin\theta\,\frac{2M_W^2}{v}\phi W_\mu^+ W^{-,\mu}$$

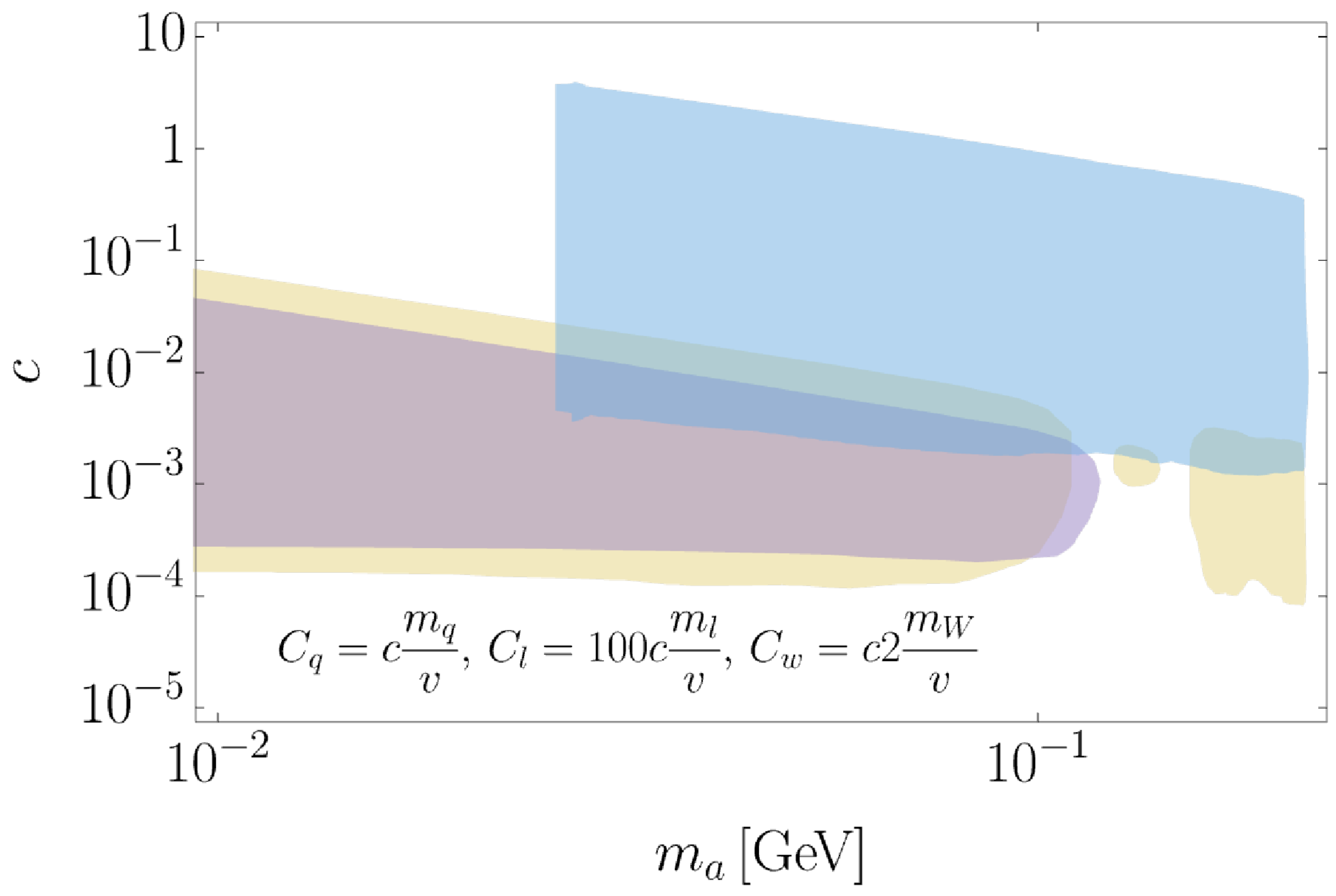
$$\mathcal{L} = C_f\,\phi\bar{f}f + C_W\,M_W \phi W_\mu^+ W^{-,\mu}$$

Same production cross section,

Different decay rate

Lepton couplings increased by factor 100

[AB, Díaz Carmona, Schwaller (WIP)]



Light scalars

$$\mathcal{L}_{\text{mix}} = \sin\theta \sum_f \frac{m_f}{v}\phi\bar{f}f + \sin\theta\,\frac{2M_W^2}{v}\phi W_\mu^+ W^{-,\mu}$$

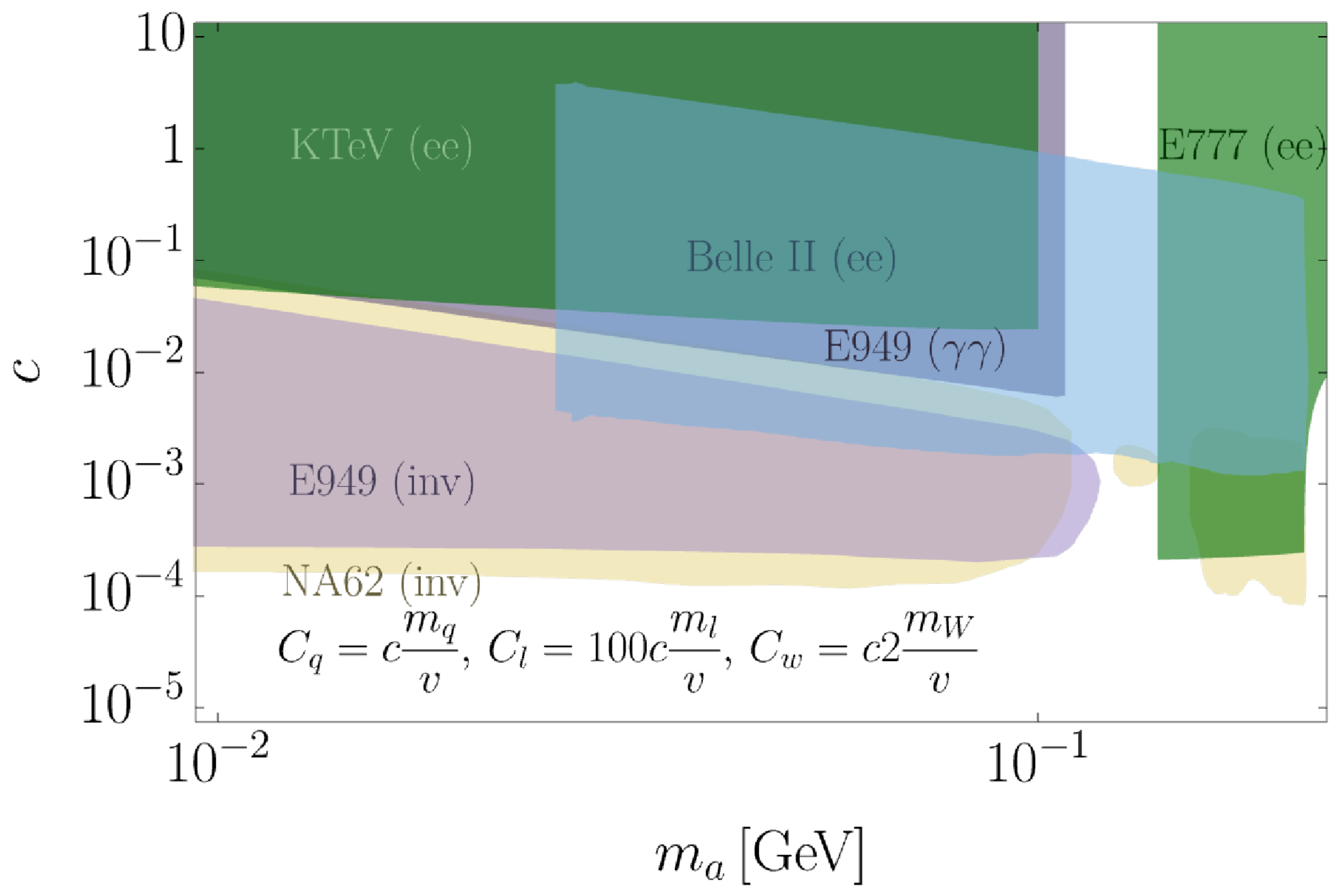
$$\mathcal{L} = C_f\,\phi\bar{f}f + C_W\,M_W\phi W_\mu^+ W^{-,\mu}$$

Same production cross section,

Different decay rate

Lepton couplings increased by factor 100

[AB, Díaz Carmona, Schwaller (WIP)]



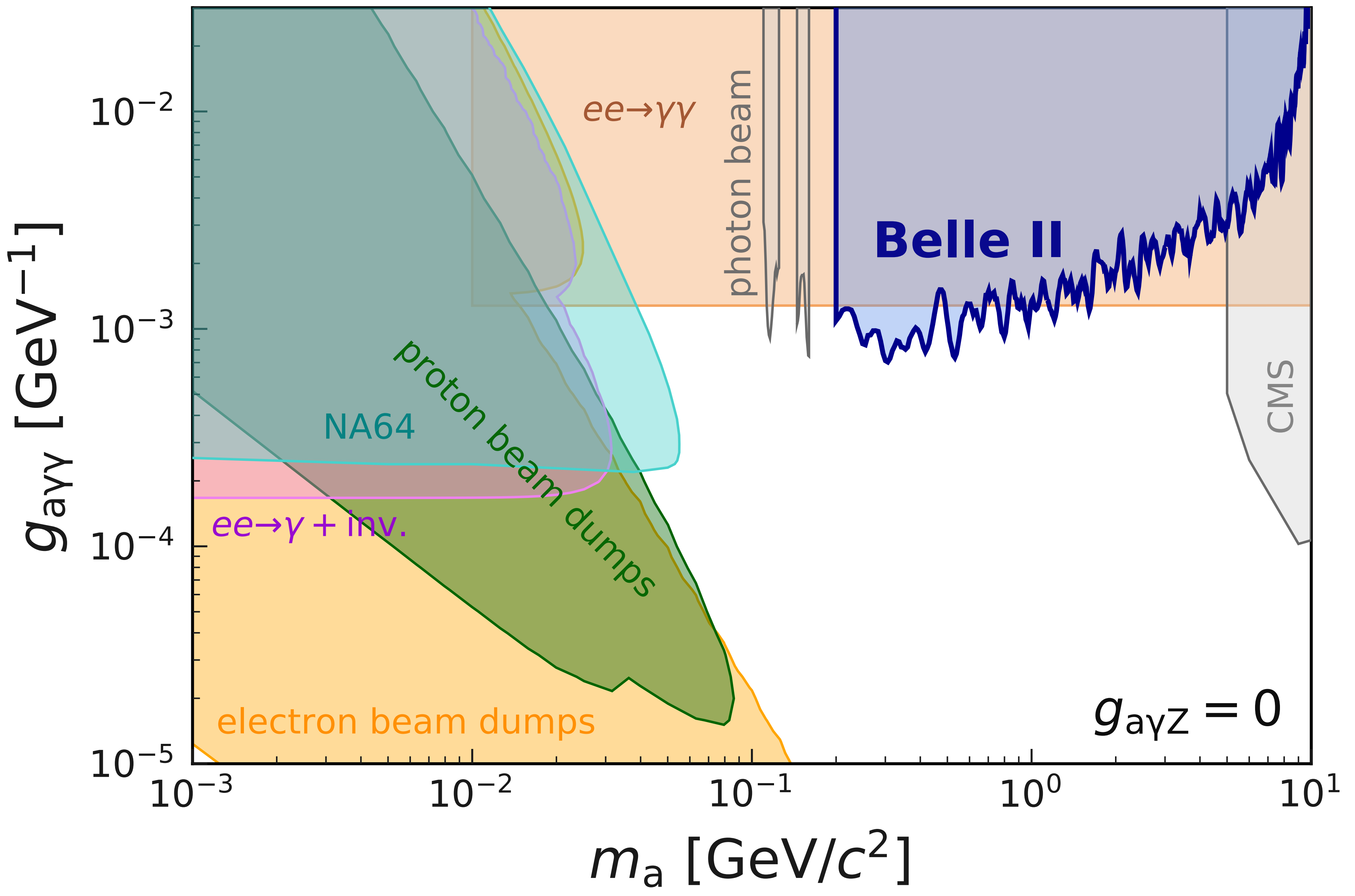
Likelihoods and statistics

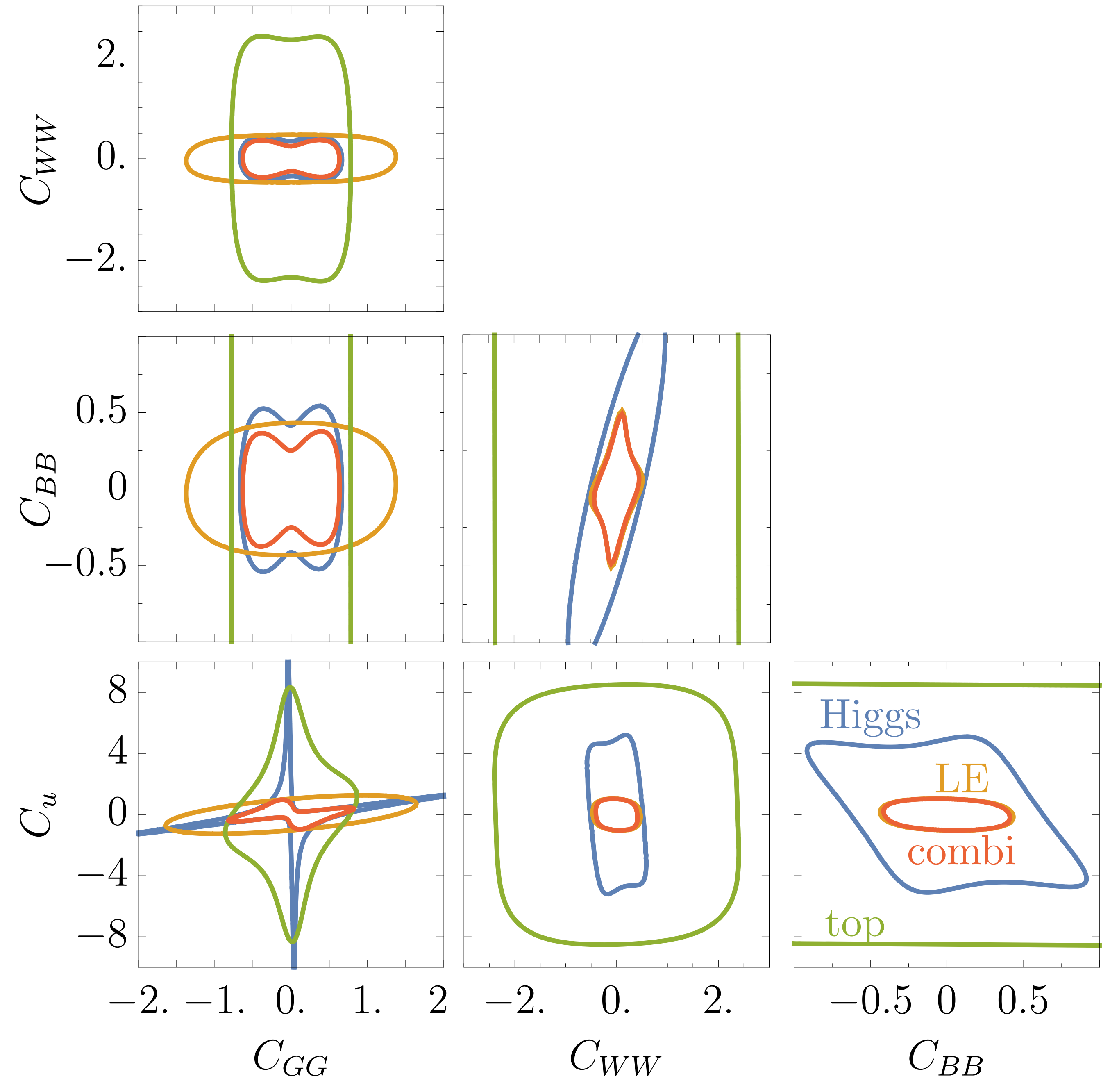
Global analysis: Combination of results from different observables/experiments

Correlations (also between experiments)

Publishing **likelihoods** would be a big help for phenomenologists! [Lorenz' talk]

[Belle II (2007.13071)]





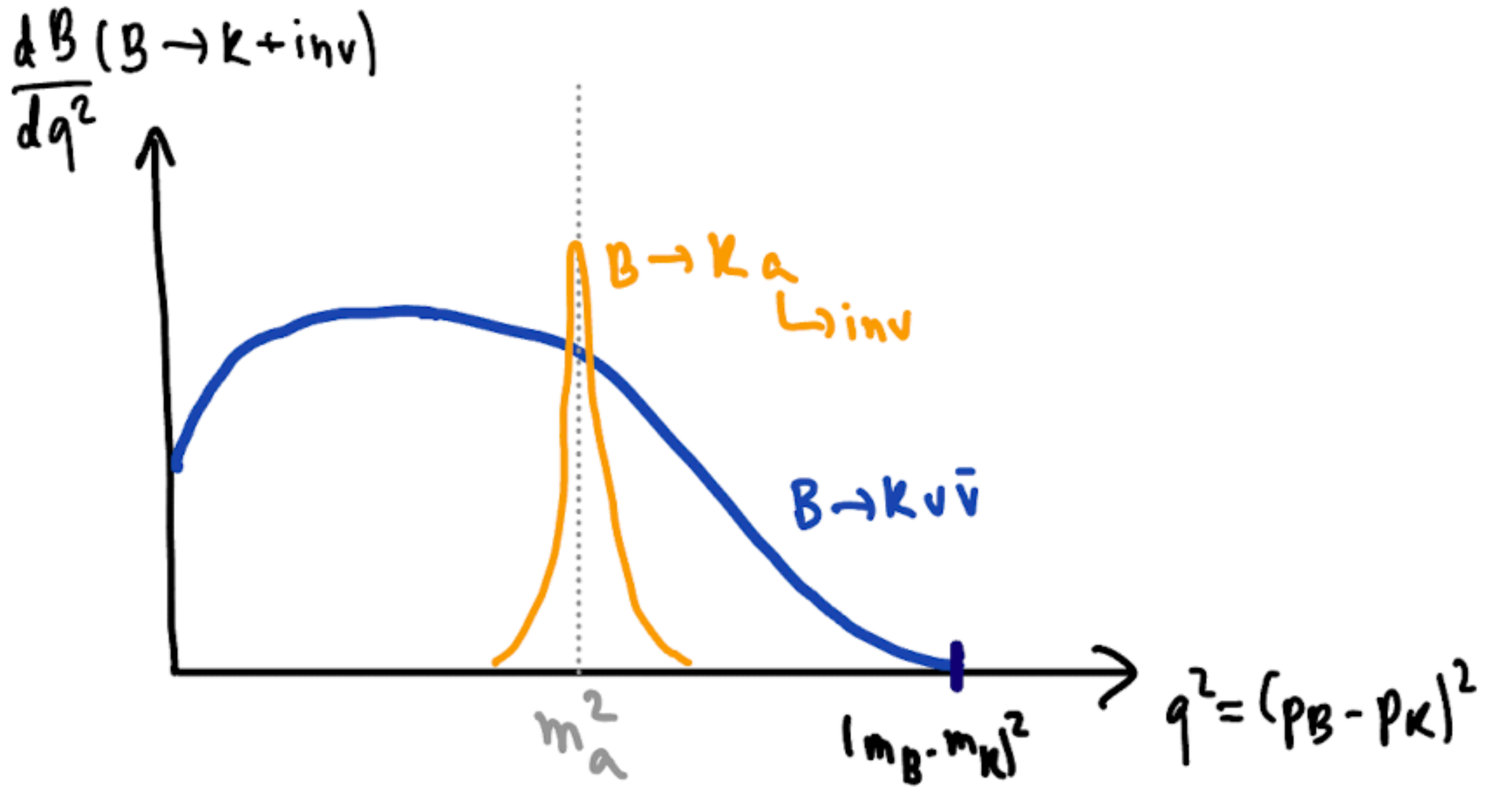
Reinterpretation

- **Different kinematics** compared to SM processes: *two vs three-body decay*

e.g., for the invisible ALP

Assumption:

$$\mathscr{B}(a \to \text{inv}) = 1$$



[Intermezzo] $B \to K^{(*)}a(\to \mu\mu)$ at LHCb

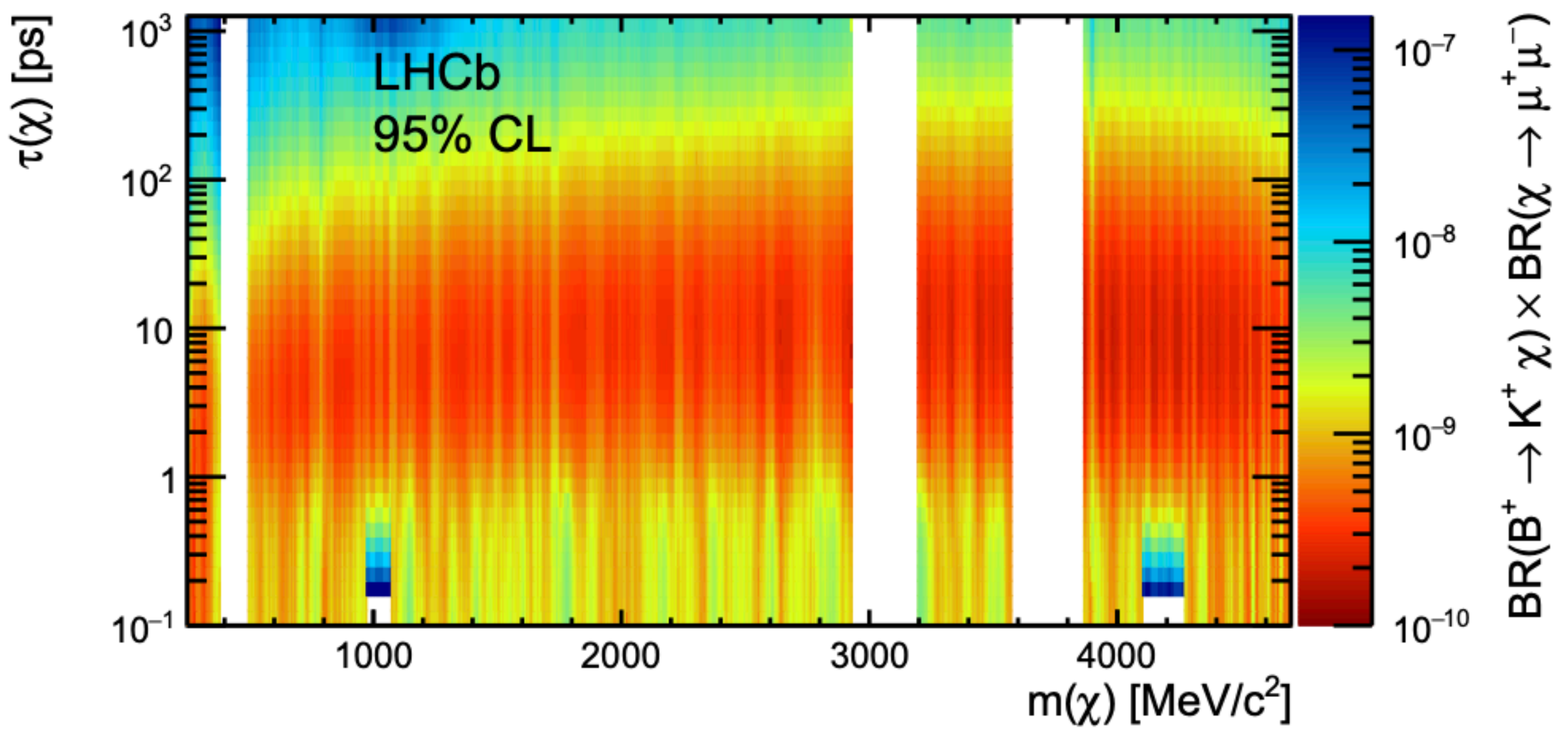
- A **caveat** of **searches** for **long-lived particles** (such as ALPs) decaying into visible final states is the **dependence** of the signal yields on the **lifetime** (very model-dependent!).

[Dobrich et al. '18]

- Good examples are the searches of $B \to K^{(*)}a(\to \mu\mu)$ by LHCb, which provide not only the limit on the branching fraction but also its **dependence on the lifetime** (τ_a):

[Olcyr's talk]

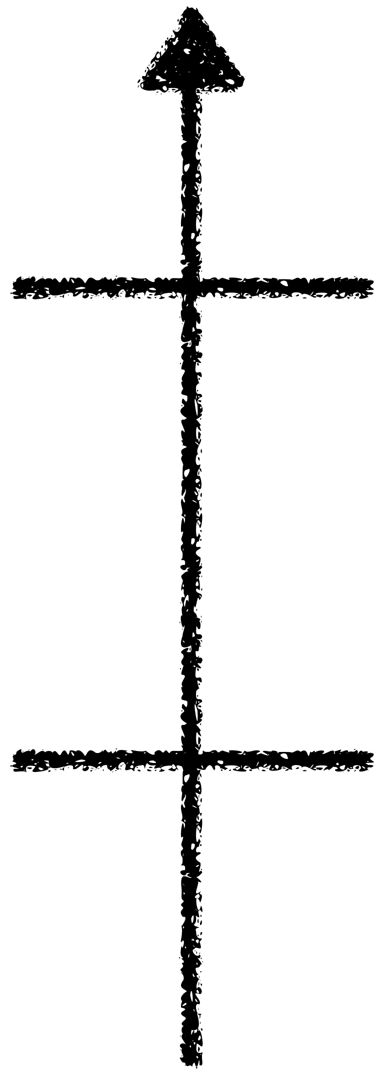
[LHCb, 1508.04094,1612.07818]



ALP-SMEFT interference

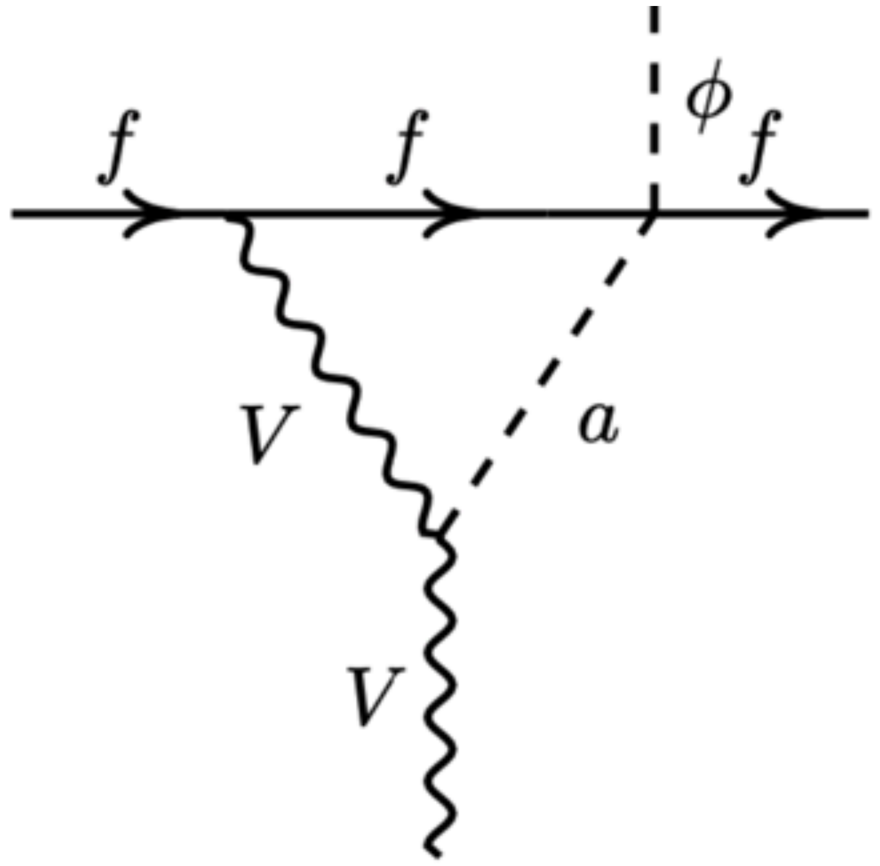
[Galda, Neubert, Renner (2105.01078)]

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \boxed{\frac{S_i}{(4\pi f)^2}}$$

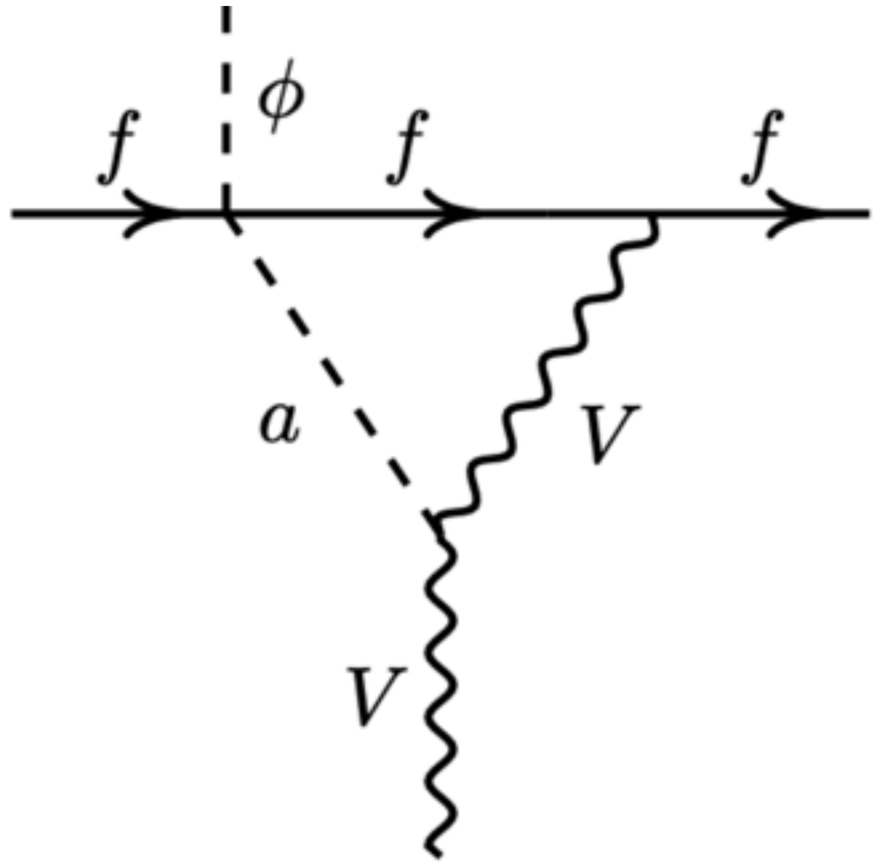


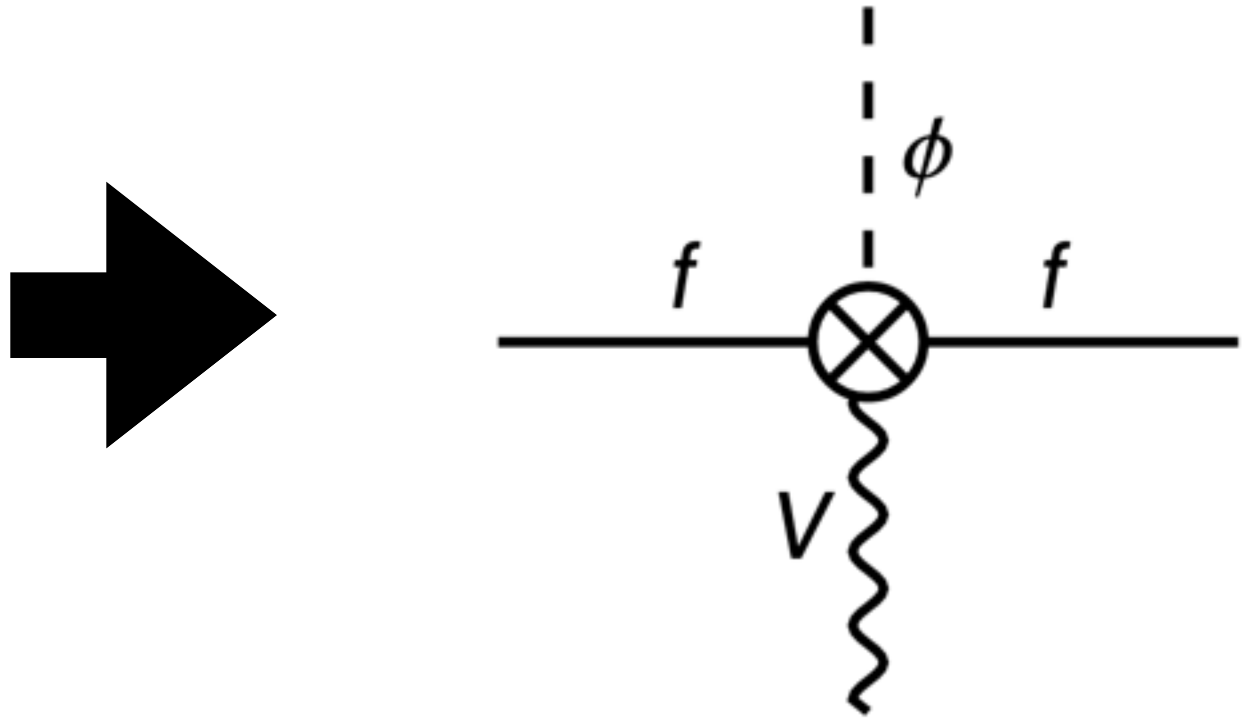
$C^{\mathrm{ALP}}(\Lambda) \neq 0,$
$C^{\mathrm{SMEFT}}(\Lambda) = 0$

$C^{\mathrm{ALP}}(\mu) \neq 0$
$C^{\mathrm{SMEFT}}(\mu) \neq 0$



$\sim 1/\epsilon$

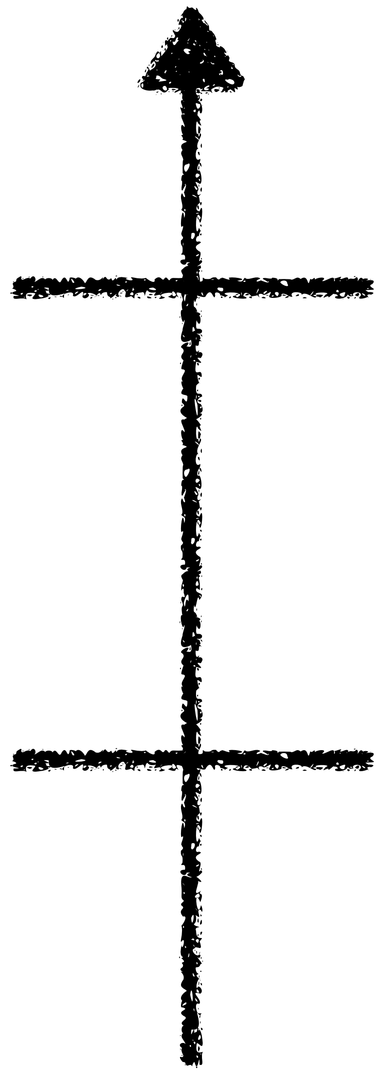




ALP-SMEFT interference

[Galda, Neubert, Renner (2105.01078)]

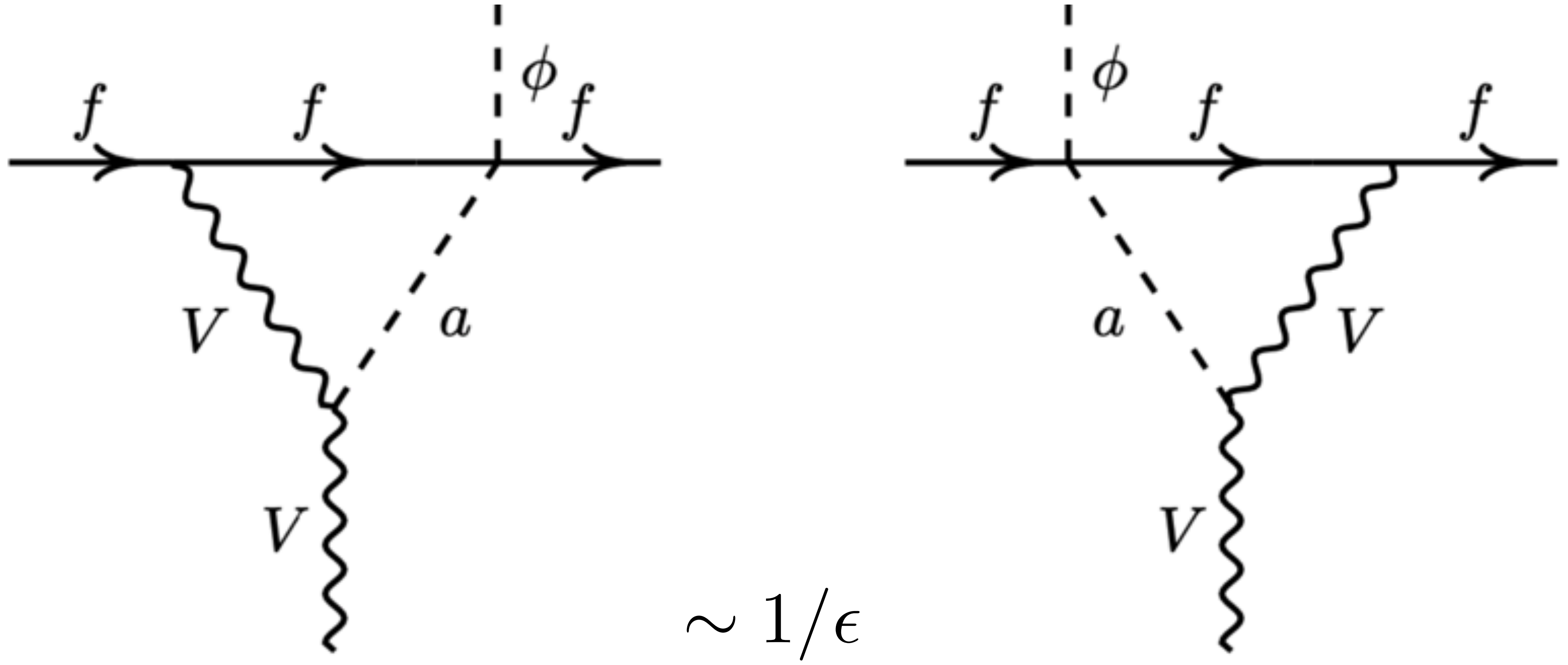
$$\frac{\mathrm{d}}{\mathrm{d}\log\mu}C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}}C_j^{\mathrm{SMEFT}} = \boxed{\frac{S_i}{(4\pi f)^2}}$$



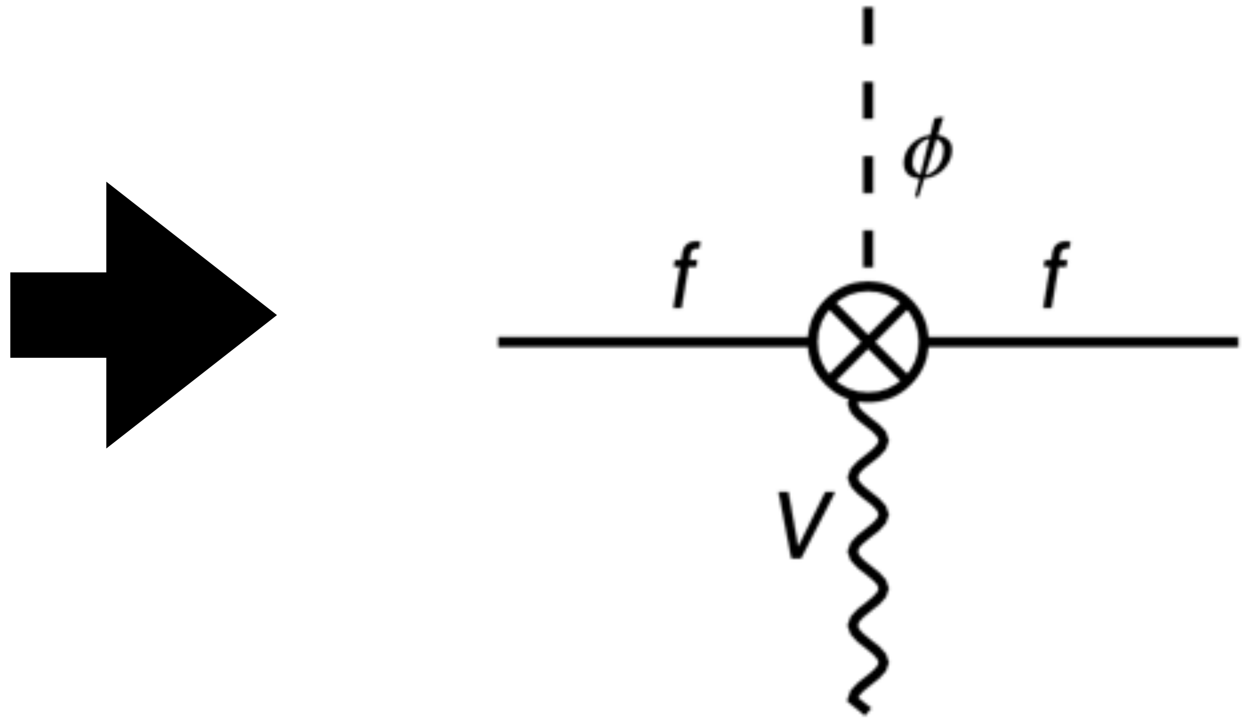
$C^{\mathrm{ALP}}(\Lambda) \neq 0,$
$C^{\mathrm{SMEFT}}(\Lambda) = 0$

$C^{\mathrm{ALP}}(\mu) \neq 0$
$C^{\mathrm{SMEFT}}(\mu) \neq 0$

ALP running induces non-zero SMEFT coefficients!



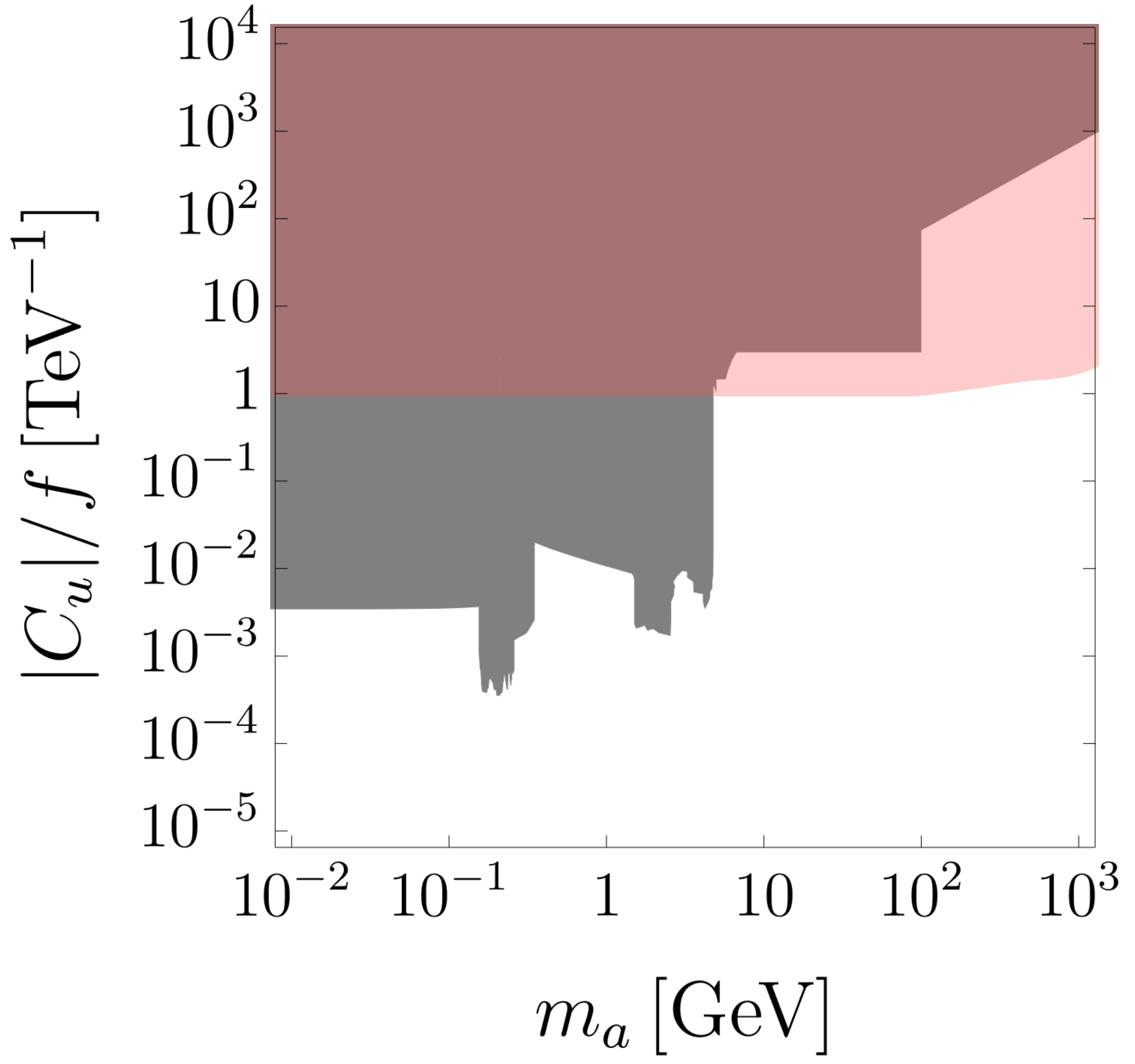
$\sim 1/\epsilon$

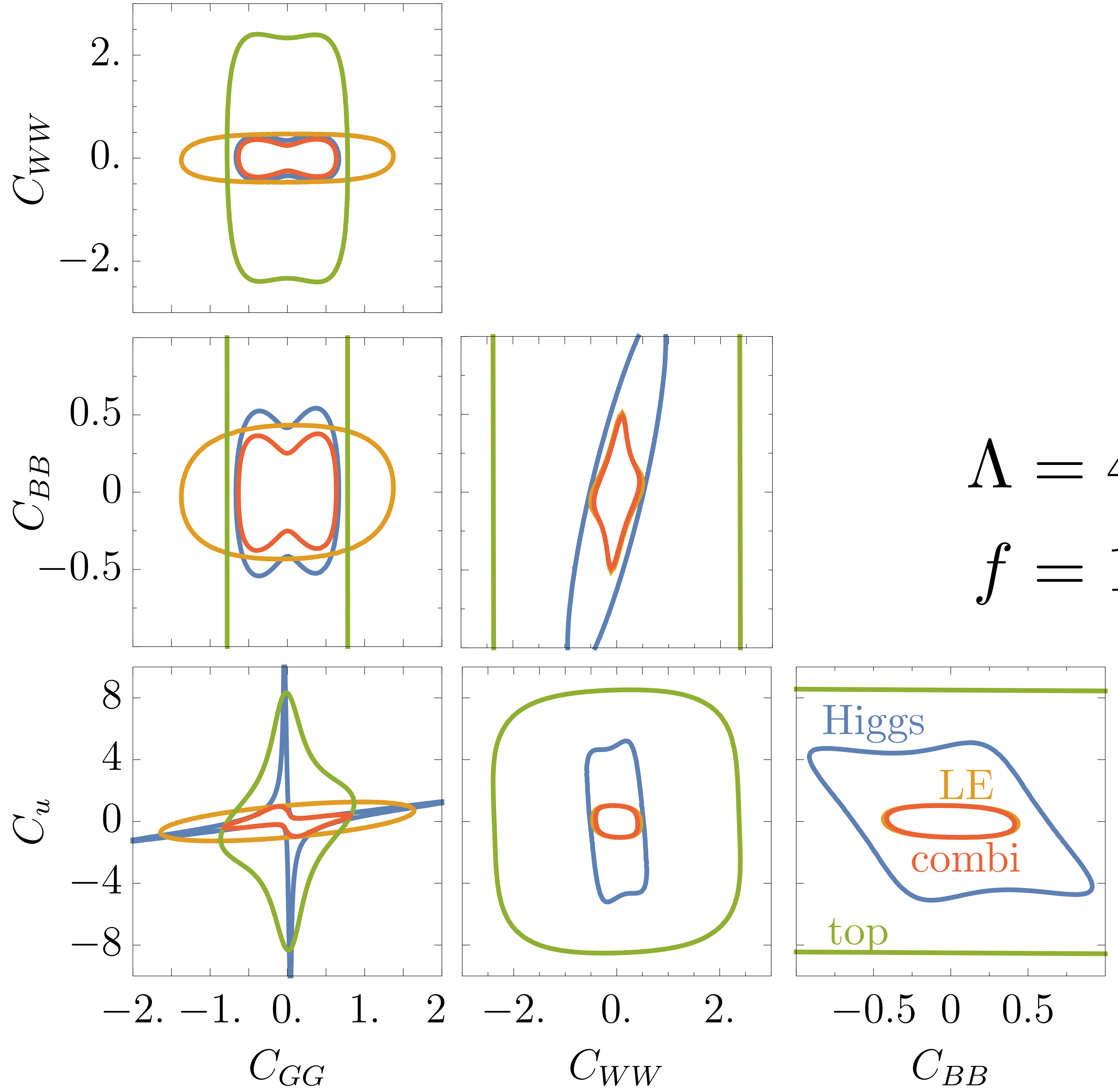


2D ALP limits

Limits from **ALP-SMEFT interference**

[Galda, Neubert, Renner (2105.01078)]



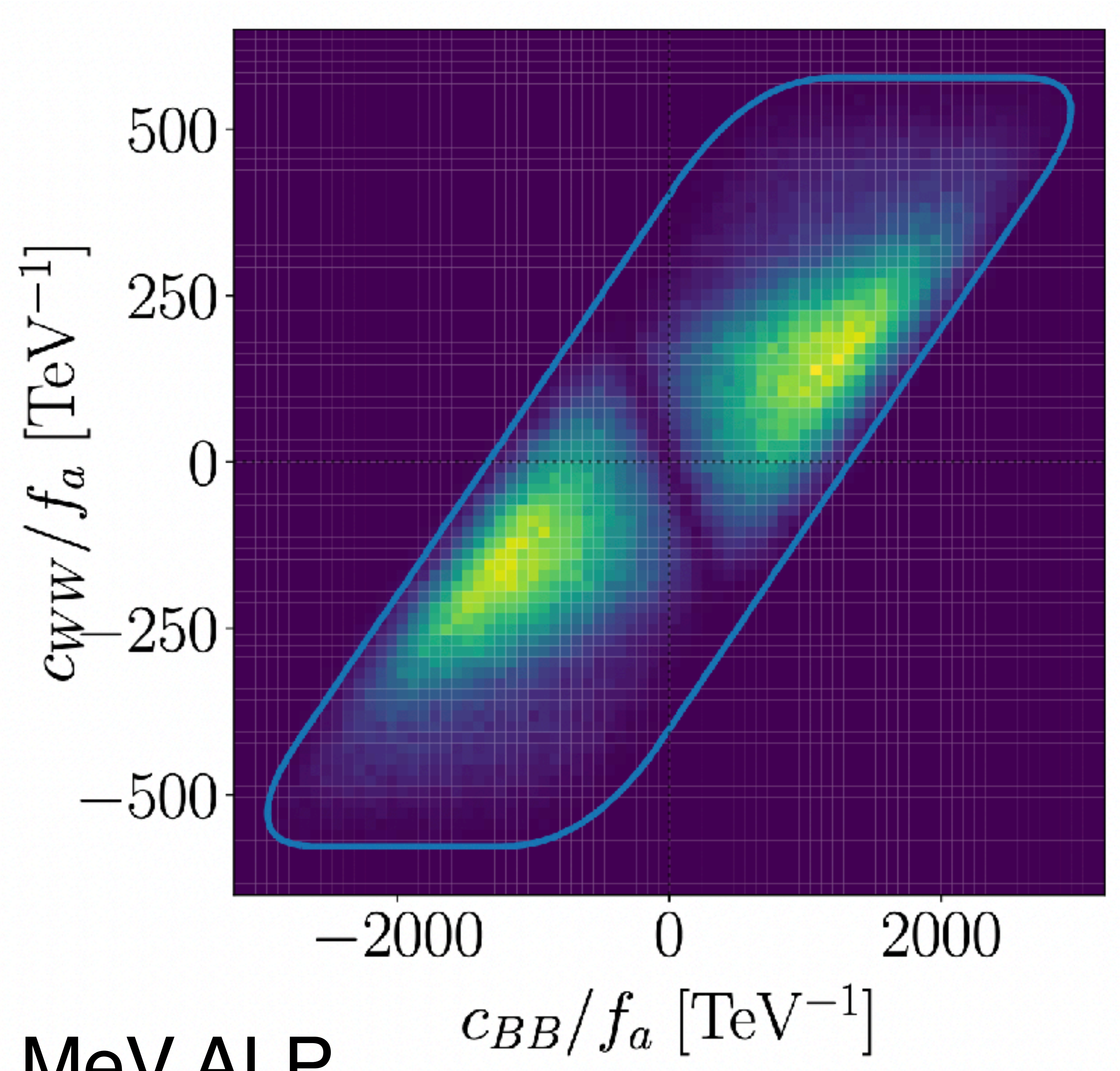


$$\Lambda = 4\pi f$$

$$f = 1\ \mathrm{TeV}$$

 [AB, Fuentes Martín, Galda, Neubert (2307.10372)]

Global fits - LHC + flavor



300 MeV ALP

LHC

Same-sign diboson

Z boson width

Flavor

[Bruggisser, Grabitz, Westhof (2308.11703)]

Reinterpreting the limits for UV axion models

KSVZ

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

Vector-like quark **+** Scalar singlet

Boson-philic ALP

DFSZ

[Dine-Fischler-Srednicki-Zhitnitsky (1980, 1981)]

2HDM **+** Scalar singlet

Fermion-philic ALP

KSVZ model

[Kim-Shifman-Vainshtein-Zakharov (1979, 1980)]

$$\mathcal{L}_{Qq} = -y_q^p\, \bar{q}_L^p H Q_R + \text{h.c.}$$

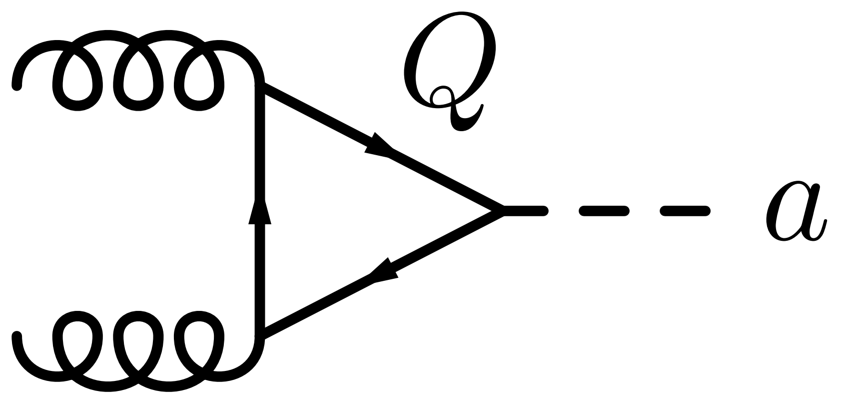
$$Q_{L,R} \sim (\mathbf{3},\mathbf{1})_{-1/3}$$

$$\mathcal{L}_{\rm KSVZ} = \mathcal{L}_{\rm SM} + |\partial_\mu S|^2 + \bar{Q}\, i\not{D}\, Q - y_Q \left(S\, \bar{Q}_L Q_R + \text{h.c.}\right) + \mu_S |S|^2 - \frac{\lambda_S}{2}|S|^2 - \lambda_{SH}|S|^2 (H^\dagger H) + \mathcal{L}_{Qq}$$

VLQ decay

Vector-like quark Q

Singlet scalar S $\quad S(x) = \frac{1}{\sqrt{2}}\left[f + \rho(x)\right] e^{\frac{i a(x)}{f}}\,,$



Heavy particles Q and ρ

$M_Q = y_Q\, f/\sqrt{2},\ M_\rho^2 = \lambda_S f^2$

Integrate out

KSVZ model - EFT

$$\mathcal{L}_{Qq} = -y_q^p \, \bar{q}_L^p H Q_R + \text{h.c.}$$

$$\mathcal{L}_{\text{EFT}} \supset +\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 \, a^2 \boxed{-\frac{\alpha_s}{8\pi}} \frac{a}{f} \, G^A_{\mu\nu} \widetilde{G}^{\mu\nu\, A} \boxed{-\frac{1}{3}\frac{\alpha_Y}{4\pi}} \frac{a}{f} \, B_{\mu\nu} \widetilde{B}^{\mu\nu}$$
$$\boxed{-\frac{\lambda_{SH}^2 f^2}{2M_\rho^4} Q_{H\Box}} + \boxed{\frac{y_q^p y_q^{r\,*}}{2M_Q^2} \left(\boldsymbol{Y}_d^{rs} \, [Q_{dH}]^{ps} - \frac{1}{2} \, [Q_{Hq}^{(1)}]^{pr} - \frac{1}{2} \, [Q_{Hq}^{(3)}]^{pr} + \text{h.c.} \right)}$$

At scale Λ: ALP couplings and SMEFT contributions

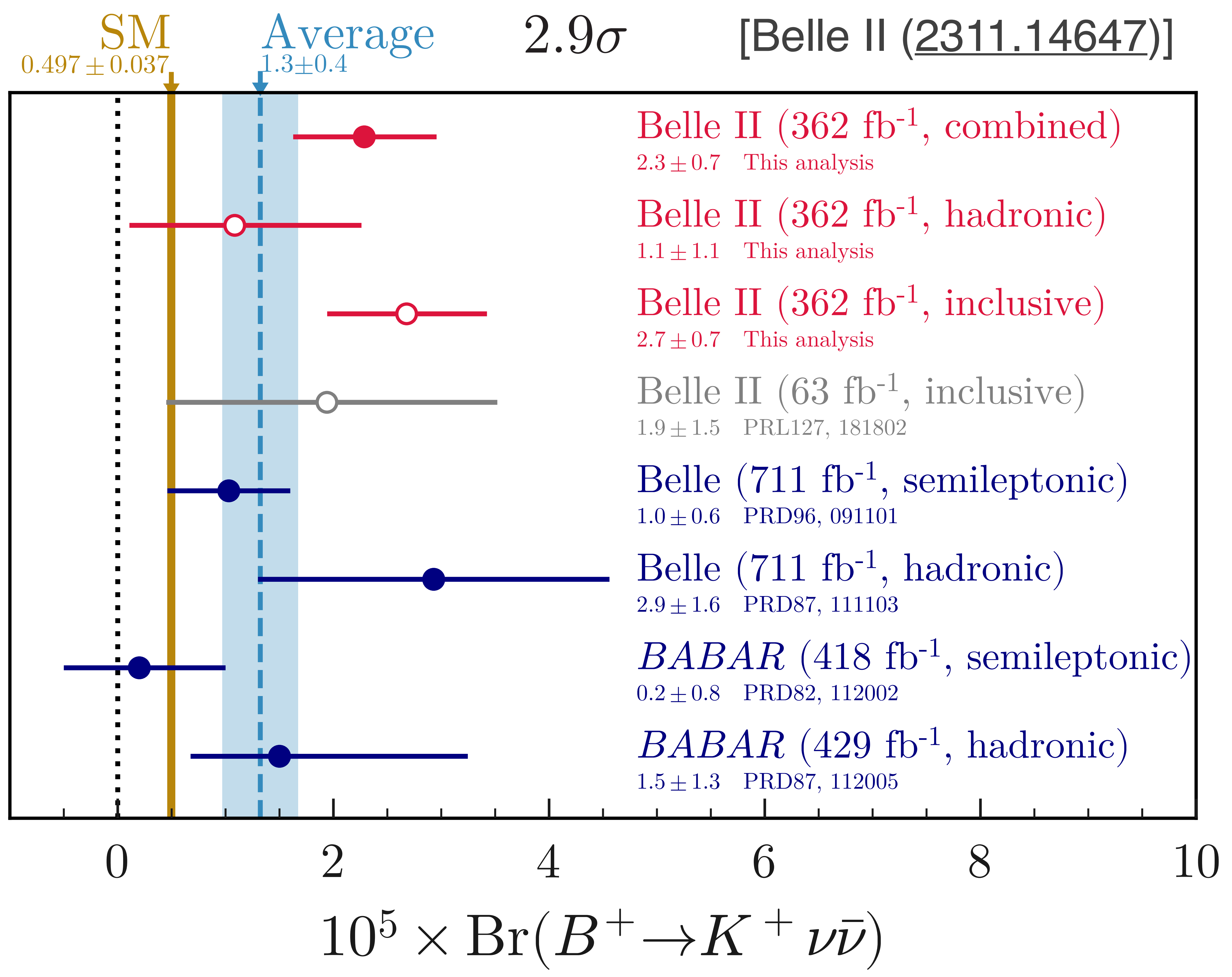
Limits on f can be obtained for fixed CGG and CBB from one-parameter ALP fit

Additional Limits on scalar parameters and portal

$$\lambda_S^2 \, f / \lambda_{SH} > 2.8 \, \text{TeV}$$
$$|y_q / M_Q| < 0.1 \text{TeV}^{-1}$$

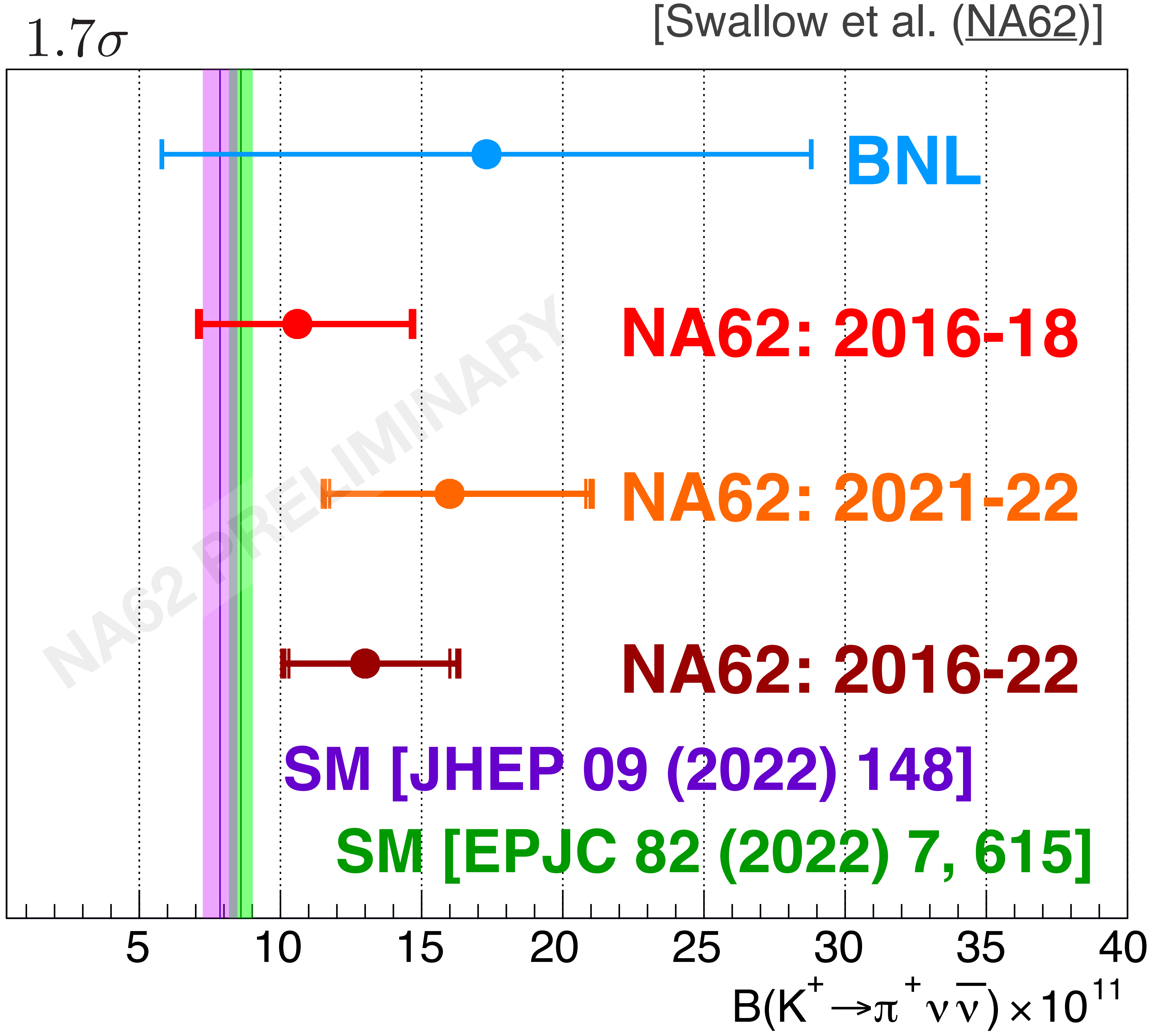
Have we seen first hints of new light scalars already?

[Tobioka's talk]



[Belle II (2311.14647)]

[Swallow et al. (NA62)]



See e.g. [Altmannshofer et al. (2311.14629)], [McKeen, Ng, Tuckler (2312.00982)], [Fridell, Ghosh, Okui, Kohsaku (2312.12507)]

Conclusions

- Belle II offers an ideal environment to test **light new physics** with a variety of couplings
- **Global analyses** could help identifying interesting scenarios and untested parameter space
- Results could easily be **re-interpreted** in UV complete scenarios
- Publication of **likelihoods** and **details on kinematics** would be a big help

Conclusions

- Belle II offers an ideal environment to test **light new physics** with a variety of couplings
- **Global analyses** could help identifying interesting scenarios and untested parameter space
- Results could easily be **re-interpreted** in UV complete scenarios
- Publication of **likelihoods** and **details on kinematics** would be a big help

Thank you for your attention!

Backup

DFSZ model

Two-Higgs doublet model + scalar singlet

$$S(x) = \frac{1}{\sqrt{2}}\left[f + \rho(x)\right] e^{\frac{i a(x)}{f}} \,,$$

Two options for relation to SM Yukawas

$$\begin{aligned}\mathcal{L}_{\text{DFSZ}} \supset\ & |D_\mu H_1|^2 + |D_\mu H_2|^2 + |\partial_\mu S|^2 - \left(\bar{q}\,\tilde{H}_1\,\mathbf{\Gamma}_u\,u_R + \bar{q}\,H_2\,\mathbf{\Gamma}_d\,d_R + \boxed{\bar{\ell}\,H_i\,\mathbf{\Gamma}_e\,e_R} + \text{h.c.}\right) \\ & - m_1^2\,|H_1|^2 - m_2^2\,|H_2|^2 - \frac{\lambda_1}{2}\,|H_1|^4 - \frac{\lambda_2}{2}\,|H_2|^4 - \lambda_3\,|H_1|^2|H_2|^2 - \lambda_4\,|H_1^\dagger H_2|^2 \\ & + \mu_S\,|S|^2 - \frac{\lambda_S}{2}\,|S|^4 - \lambda_{SH_1}\,|S|^2|H_1|^2 - \lambda_{SH_2}\,|S|^2|H_2|^2 - \lambda_{SH_{12}}\left[(H_1^\dagger H_2)S^2 + \text{h.c.}\right]\end{aligned}$$

Heavy particles Φ and ρ

DFSZ model - EFT

Mixing angle α

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$C_u = -2s_\alpha^2$ $\quad$ $C_d = -2c_\alpha^2$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$

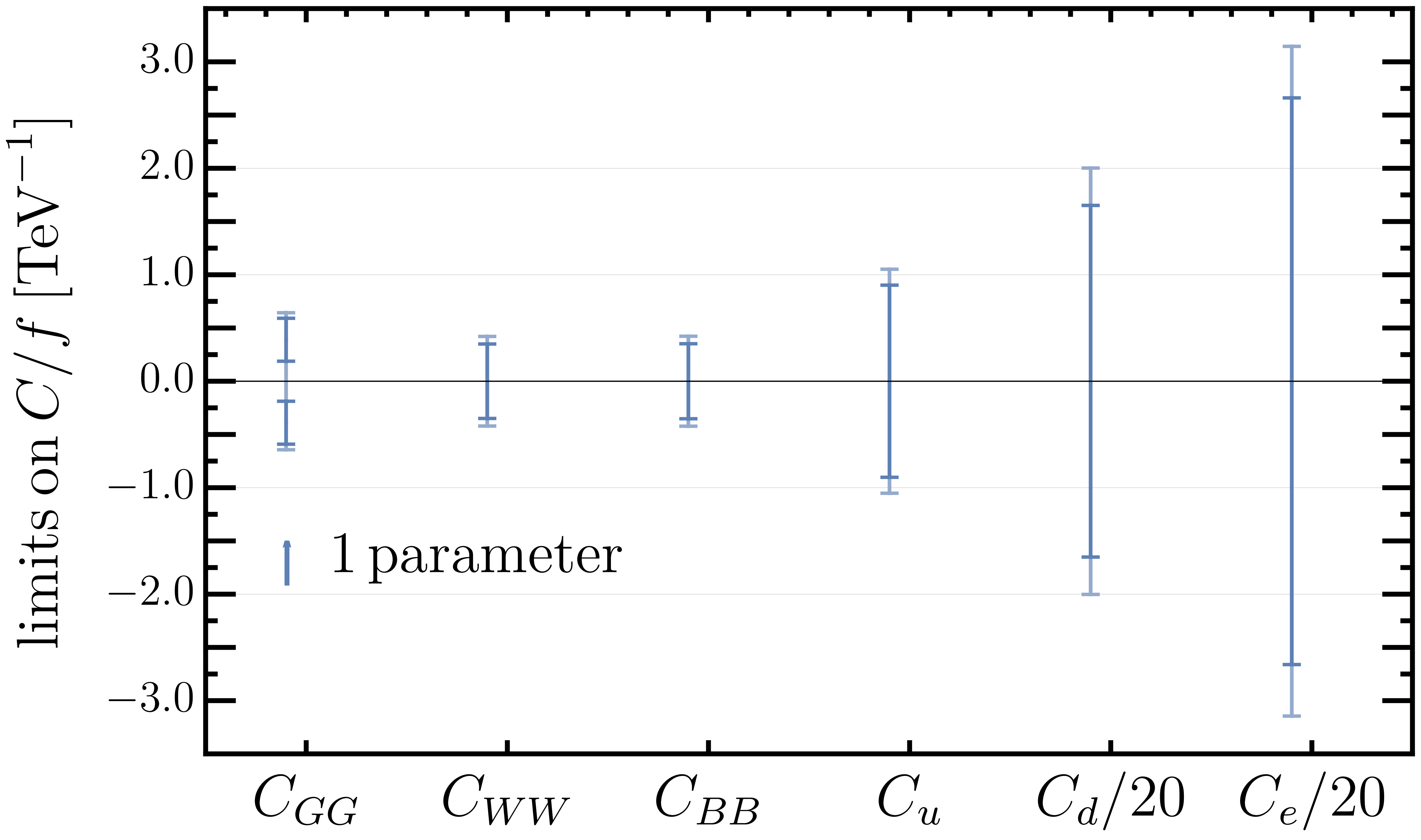
DFSZ model - EFT

$|C_u|/f < 1/\text{TeV}$

$\boxed{C_u = -2s_\alpha^2}$ $\quad C_d = -2c_\alpha^2$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$



Mixing angle α

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

DFSZ model - EFT

Mixing angle α

$$|C_u|/f < 1/\text{TeV}$$

$$\boxed{C_u = -2s_\alpha^2} \qquad C_d = -2c_\alpha^2$$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$$\begin{aligned}
\mathcal{L}_{\text{EFT}} \supset & -\frac{C_{\psi H}}{M_\Phi^2}\left(\boxed{t_\alpha}\,[\boldsymbol{Y}_u]^{pr}\,[Q_{uH}]^{pr} - t_\alpha^{-1}\,[\boldsymbol{Y}_d]^{pr}\,[Q_{dH}]^{pr} - \eta_\alpha\,[\boldsymbol{Y}_e]^{pr}\,[Q_{eH}]^{pr} + \text{h.c.}\right) \\
& - \frac{[\boldsymbol{Y}_u^*]^{sr}\,[\boldsymbol{Y}_u]^{pt}\,\boxed{t_\alpha^2}}{M_\Phi^2}\left(\frac{1}{6}\,[Q_{qu}^{(1)}]^{prst} + [Q_{qu}^{(8)}]^{prst}\right) - \frac{[\boldsymbol{Y}_d^*]^{sr}\,[\boldsymbol{Y}_d]^{pt}\,t_\alpha^{-2}}{M_\Phi^2}\left(\frac{1}{6}\,[Q_{qd}^{(1)}]^{prst} + [Q_{qd}^{(8)}]^{prst}\right) \\
& - \frac{[\boldsymbol{Y}_e^*]^{sr}\,[\boldsymbol{Y}_e]^{pt}\,\eta_\alpha^2}{2M_\Phi^2}\,[Q_{le}]^{prst} - \frac{1}{M_\Phi^2}\left([\boldsymbol{Y}_u]^{pr}\,[\boldsymbol{Y}_d]^{st}\,[Q_{quqd}^{(1)}]^{prst} - [\boldsymbol{Y}_u]^{st}\,[\boldsymbol{Y}_e]^{pr}\,t_\alpha\eta_\alpha\,[Q_{lequ}^{(1)}]^{prst}\right. \\
& \left. -[\boldsymbol{Y}_d^*]^{st}\,[\boldsymbol{Y}_e]^{pr}\,t_\alpha^{-1}\eta_\alpha\,[Q_{ledq}]^{prst} + \text{h.c.}\right) + \frac{C_H}{M_\Phi^2}\,Q_H - \frac{\lambda_{SH}^2 f^2}{2M_\rho^4}\,Q_{H\Box}\,,
\end{aligned}$$

Yukawa suppressed

DFSZ model - EFT

Mixing angle α

$|C_u|/f < 1/\text{TeV}$

$$\boxed{C_u = -2s_\alpha^2} \qquad C_d = -2c_\alpha^2$$

DFSZ I $\quad C_e = -2s_\alpha^2$

DFSZ II $\quad C_e = -2c_\alpha^2$

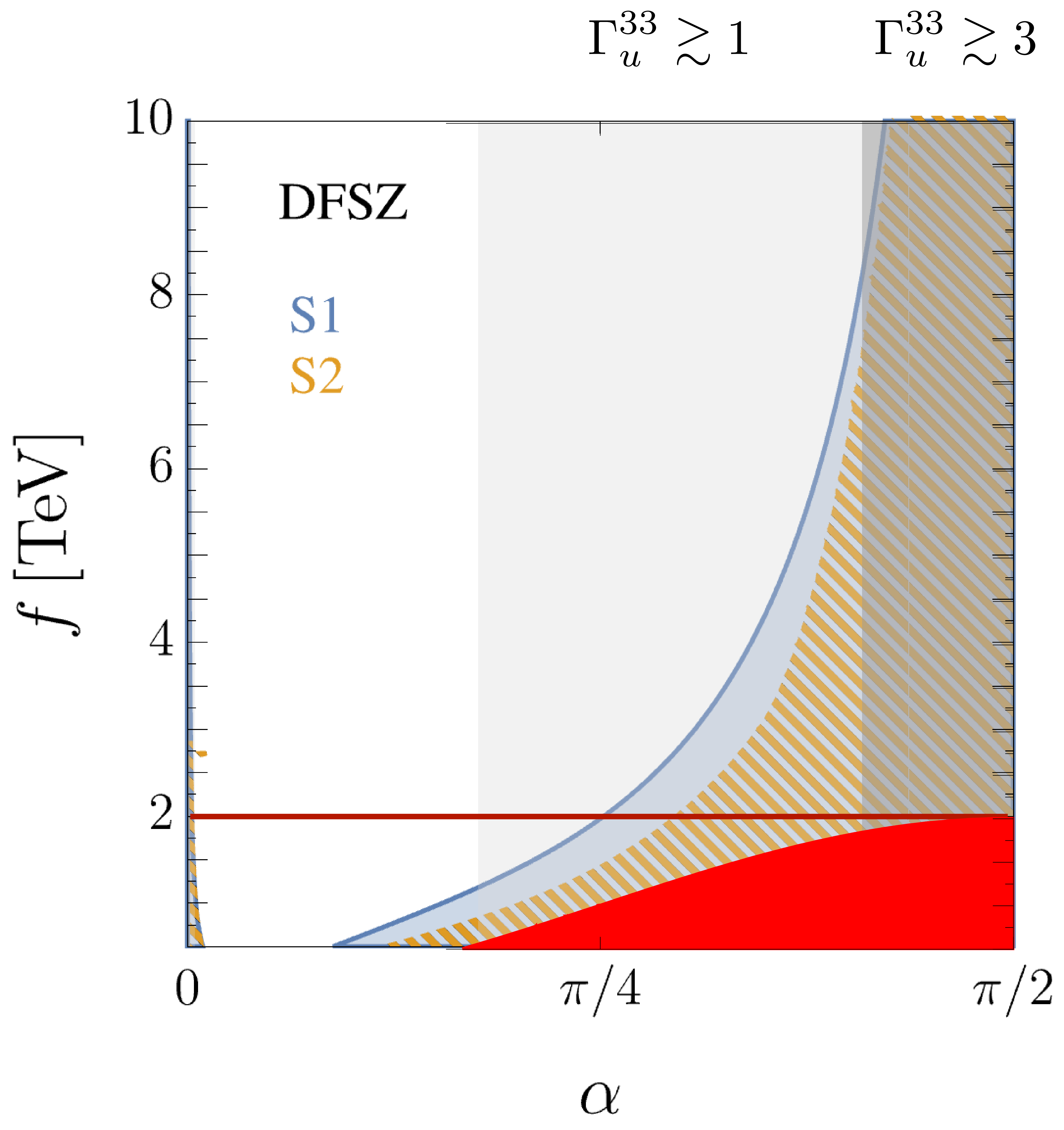
$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

$$\begin{aligned}\mathcal{L}_{\text{EFT}} \supset & -\frac{C_{\psi H}}{M_\Phi^2}\left(\boxed{t_\alpha}[\mathbf{Y}_u]^{pr}[Q_{uH}]^{pr} - t_\alpha^{-1}[\mathbf{Y}_d]^{pr}[Q_{dH}]^{pr} - \eta_\alpha[\mathbf{Y}_e]^{pr}[Q_{eH}]^{pr} + \text{h.c.}\right) \\ & - \frac{[\mathbf{Y}_u^*]^{sr}[\mathbf{Y}_u]^{pt}\,\boxed{t_\alpha^2}}{M_\Phi^2}\left(\frac{1}{6}[Q_{qu}^{(1)}]^{prst} + [Q_{qu}^{(8)}]^{prst}\right) - \frac{[\mathbf{Y}_d^*]^{sr}[\mathbf{Y}_d]^{pt}\,t_\alpha^{-2}}{M_\Phi^2}\left(\frac{1}{6}[Q_{qd}^{(1)}]^{prst} + [Q_{qd}^{(8)}]^{prst}\right) \\ & - \frac{[\mathbf{Y}_e^*]^{sr}[\mathbf{Y}_e]^{pt}\,\eta_\alpha^2}{2M_\Phi^2}[Q_{le}]^{prst} - \frac{1}{M_\Phi^2}\left([\mathbf{Y}_u]^{pr}[\mathbf{Y}_d]^{st}[Q_{quqd}^{(1)}]^{prst} - [\mathbf{Y}_u]^{st}[\mathbf{Y}_e]^{pr}\,t_\alpha\eta_\alpha[Q_{lequ}^{(1)}]^{prst}\right. \\ & \left. - [\mathbf{Y}_d^*]^{st}[\mathbf{Y}_e]^{pr}\,t_\alpha^{-1}\eta_\alpha[Q_{ledq}]^{prst} + \text{h.c.}\right) + \frac{C_H}{M_\Phi^2}Q_H - \frac{\lambda_{SH}^2 f^2}{2M_\rho^4}Q_{H\Box}\,,\end{aligned}$$

Yukawa suppressed

ALP couplings and SMEFT operators depend on same parameters α and f

DFSZ models - results



$$C_u = -2s_\alpha^2$$

$$|C_u|/f < 1/\mathrm{TeV}$$

S1: negligible scalar parameters

S2: profiling of scalar parameters

Limits on f dominated by SMEFT contributions

ALP Lagrangian

derivative
basis

$$\mathcal{L}^{D\leq 5}_{\text{SM+ALP}} = c_{GG}\frac{a}{f}G^{a}_{\mu\nu}\tilde{G}^{a,\mu\nu} + c_{WW}\frac{a}{f}W^{A}_{\mu\nu}\tilde{W}^{A,\mu\nu} + c_{BB}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial^{\mu}a}{f}\sum_{F}\bar{\psi}_{F}\,\mathbf{c}_{F}\,\gamma_{\mu}\psi_{F}$$

$$\Downarrow$$

$$\psi_F \to \psi_F + i\,\frac{a}{f}\,\mathbf{c}_F\,\psi_F$$

ALP Lagrangian

derivative basis

$$\mathcal{L}^{D\leq 5}_{\mathrm{SM+ALP}} = c_{GG}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + c_{WW}\frac{a}{f}W^A_{\mu\nu}\tilde{W}^{A,\mu\nu} + c_{BB}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\mathbf{c}_F\,\gamma_\mu\psi_F$$

$$\psi_F \to \psi_F + i\,\frac{a}{f}\,\mathbf{c}_F\,\psi_F$$

pseudoscalar basis

$$\mathcal{L}^{D\leq 5}_{\mathrm{SM+ALP}} = C_{GG}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\underline{\tilde{Y}_u}\,u_R + \bar{Q}\,H\,\underline{\tilde{Y}_d}\,d_R + \bar{L}\,H\,\underline{\tilde{Y}_e}\,e_R + \mathrm{h.c.}\right)$$

$$\underline{\tilde{Y}_u = i(Y_u\,c_u - c_Q\,Y_u)},\quad \underline{\tilde{Y}_d = i(Y_d\,c_d - c_Q\,Y_d)},\quad \underline{\tilde{Y}_e = i(Y_e\,c_e - c_L\,Y_e)}$$

ALP Lagrangian

derivative basis

$$\mathcal{L}_{\text{SM+ALP}}^{D\leq 5} = c_{GG}\frac{a}{f}G_{\mu\nu}^{a}\tilde{G}^{a,\mu\nu} + c_{WW}\frac{a}{f}W_{\mu\nu}^{A}\tilde{W}^{A,\mu\nu} + c_{BB}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\mathbf{c}_F\,\gamma_\mu\psi_F$$

$$\psi_F \to \psi_F + i\,\frac{a}{f}\,\mathbf{c}_F\,\psi_F$$

pseudoscalar basis

$$\mathcal{L}_{\text{SM+ALP}}^{D\leq 5} = C_{GG}\,\frac{a}{f}\,G_{\mu\nu}^{a}\,\tilde{G}^{\mu\nu,a} + C_{WW}\,\frac{a}{f}\,W_{\mu\nu}^{A}\,\tilde{W}^{\mu\nu,A} + C_{BB}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu} - \frac{a}{f}\left(\bar{Q}\,\tilde{H}\,\underline{\tilde{Y}_u}\,u_R + \bar{Q}\,H\,\underline{\tilde{Y}_d}\,d_R + \bar{L}\,H\,\underline{\tilde{Y}_e}\,e_R + \text{h.c.}\right)$$

$$\underline{\tilde{Y}_u = i(Y_u\,c_u - c_Q\,Y_u)},\quad \underline{\tilde{Y}_d = i(Y_d\,c_d - c_Q\,Y_d)},\quad \underline{\tilde{Y}_e = i(Y_e\,c_e - c_L\,Y_e)}$$

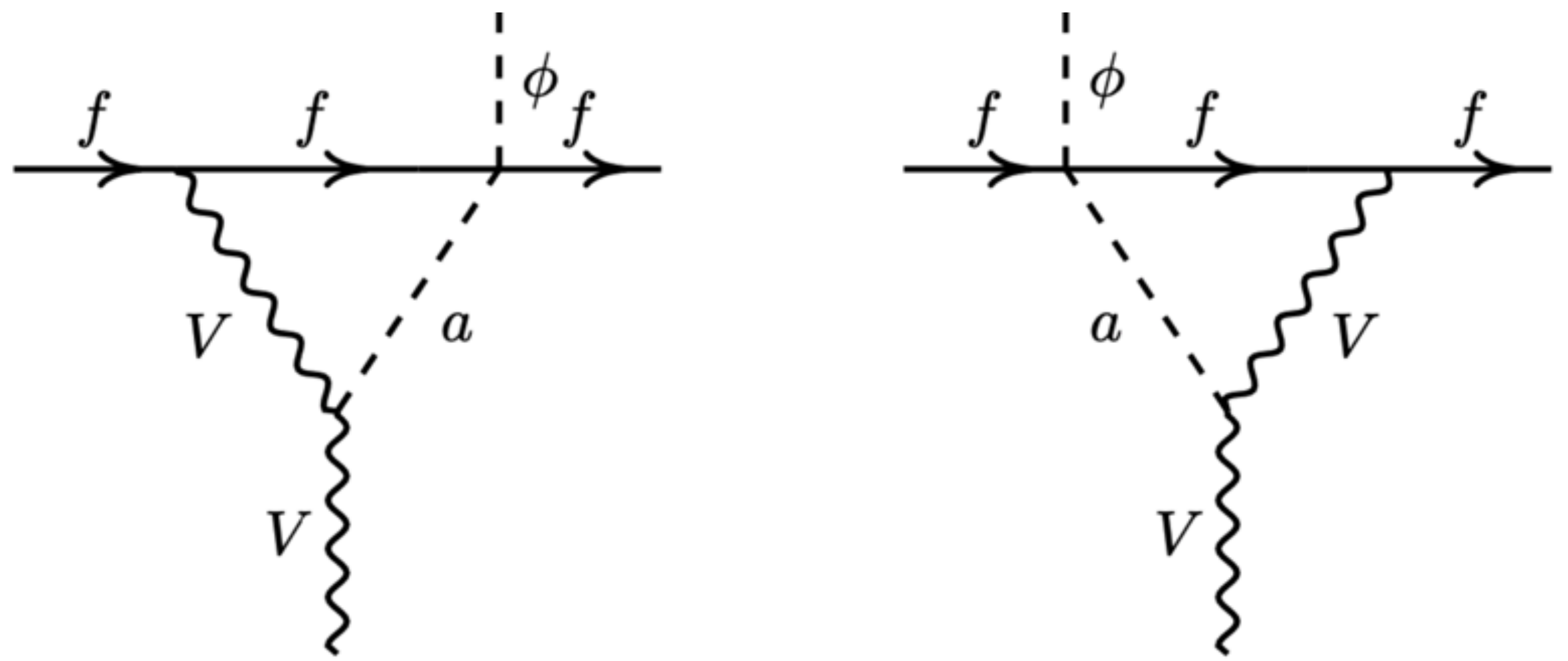
$\tilde{c}_X = c_X \mathbb{1}_3$ Flavor universal

$$\tilde{Y}_u = i(c_u - c_Q)Y_u = -iC_uY_u,\quad \tilde{Y}_d = i(c_d - c_Q)Y_d = -iC_dY_d,\quad \tilde{Y}_e = i(c_e - c_L)Y_e = -iC_eY_e$$

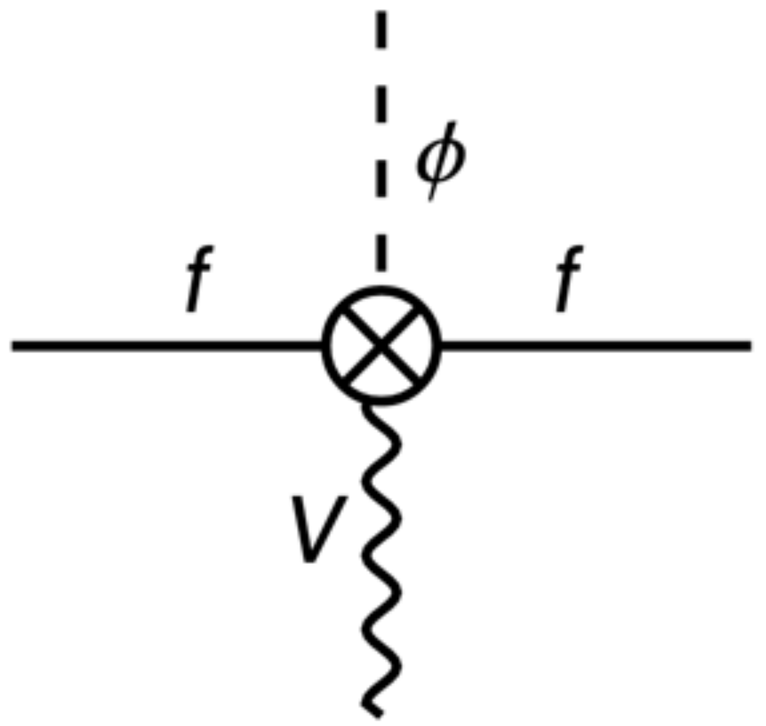
Indirect ALP effects

[Marciano, Masiero, Paradisi, Passera (1607.01022)]
[Bauer, Neubert, Thamm (1704.08207)]

- Virtual ALP exchange induces UV-divergent one-loop graphs
- Dimension-6 operators required as counterterms



$\sim 1/\epsilon$



ALP as a solution for g - 2 discrepancy

Requires D6 operator as counterterm

SMEFT!

Exploiting the ALP-SMEFT interference

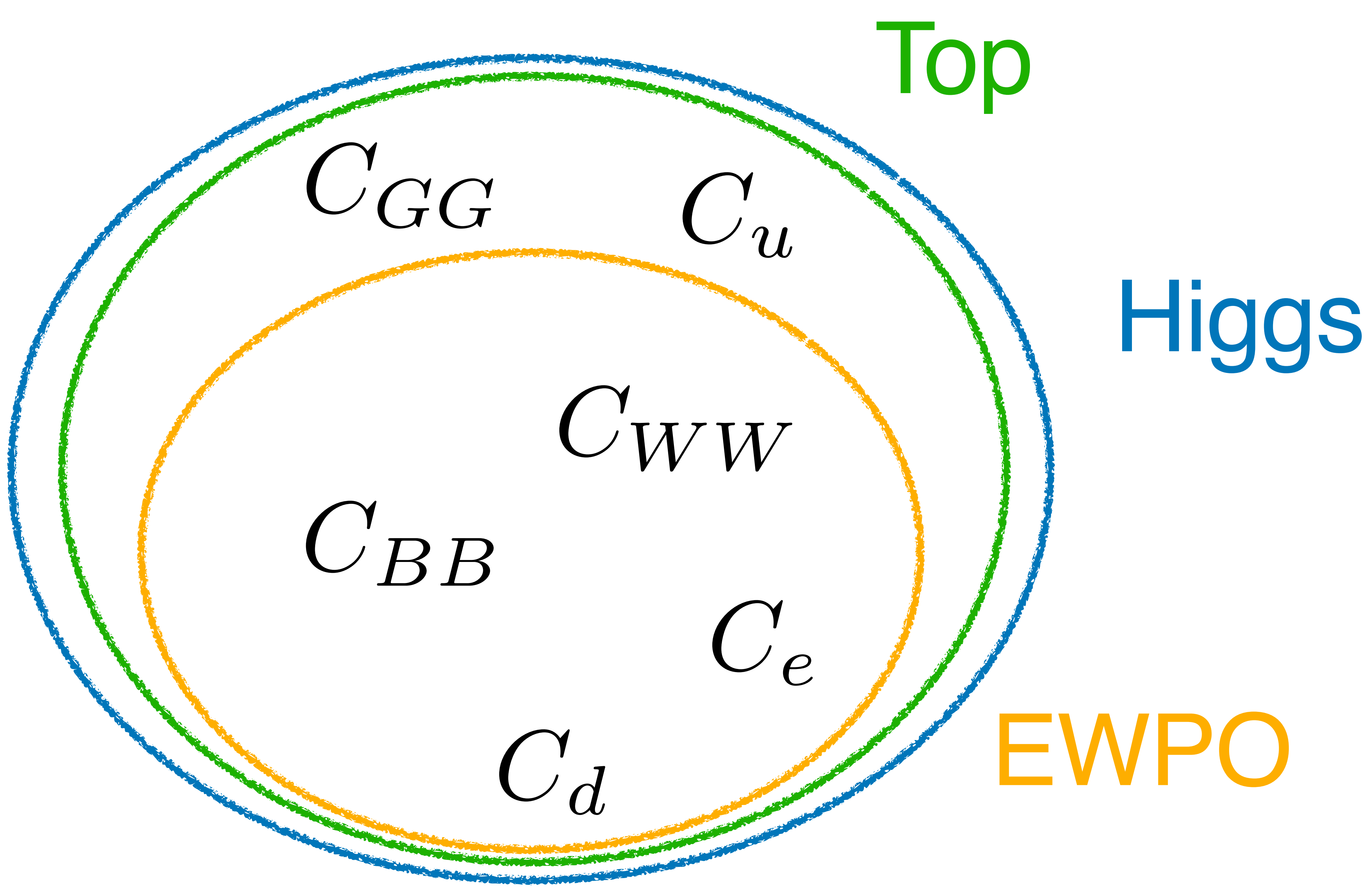
Observables used

- Low energy:
  - Electroweak precision observables (EWPO)
  - Parity violation experiments
  - Lepton scattering

  [Falkowski et al. (1706.03783)]
- Higgs
- Top [Ellis et al. (2012.02779)]

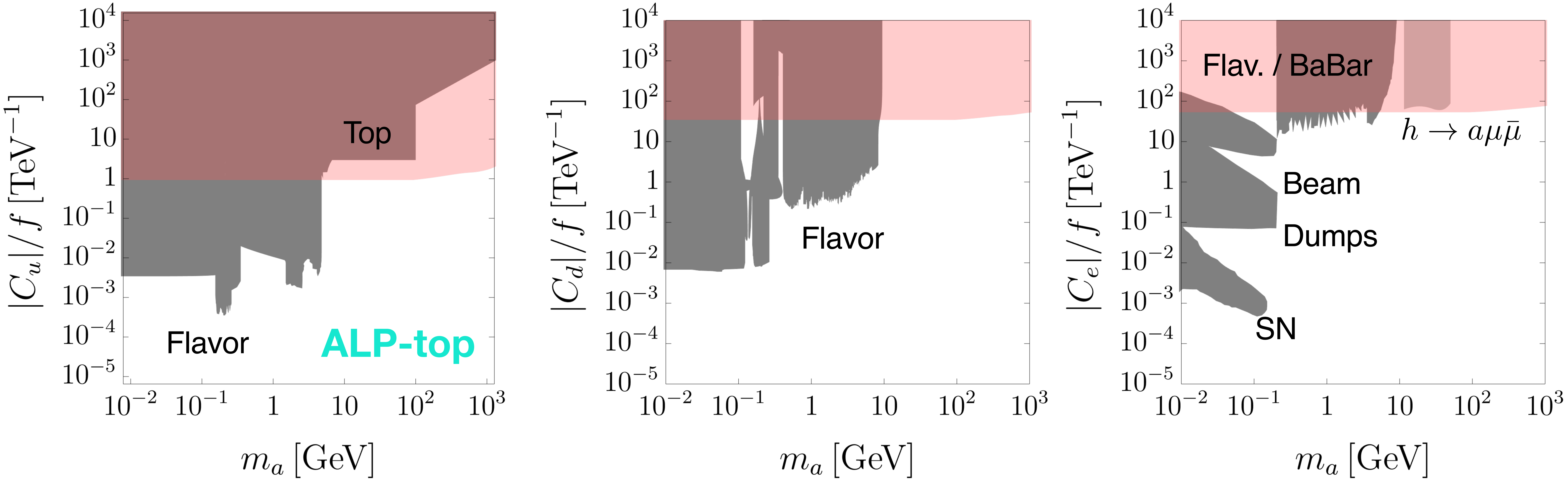
Six free parameters

$$C_{GG},\, C_{WW},\, C_{BB},\, C_u,\, C_d,\, C_e$$



Comparison with direct bounds - fermions

[AB, Fuentes Martín, Galda, Neubert (2307.10372)]



[BaBar (1406.2980)]

[Esser, Madigan, Sanz, Ubiali (2303.17634)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

[AB, Chala, Spannowski (2203.14984)]

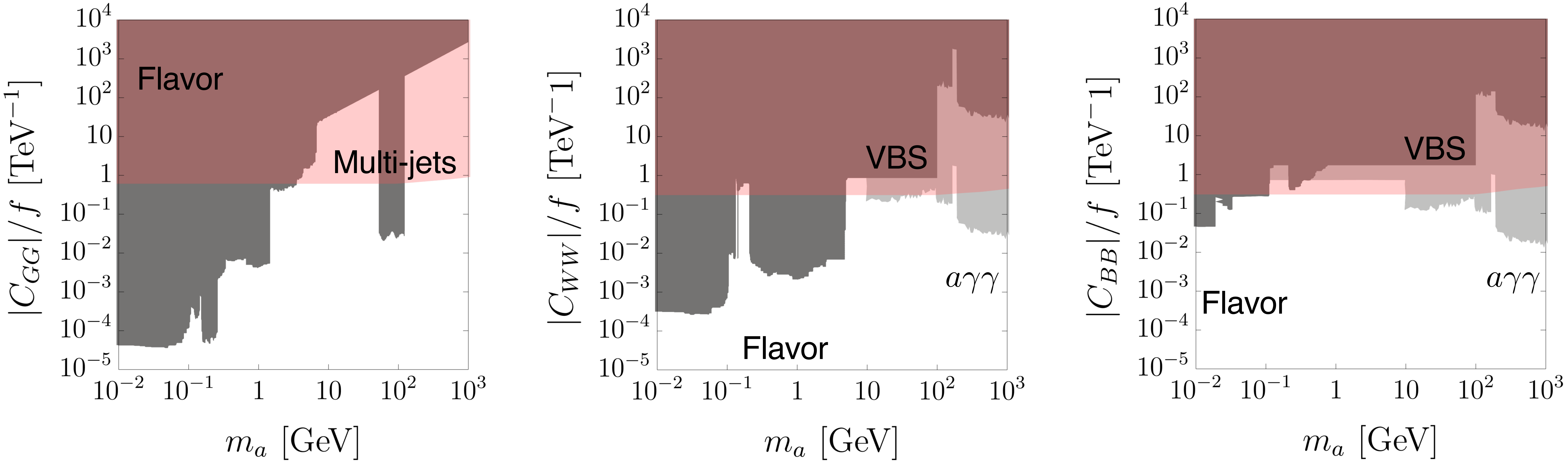
[Lucente, Carenza (2107.12393)]

[Essig, Harnik, Kaplan, Toro (1008.0636)]

Comparison with direct bounds

Light gray bounds with additional assumptions

[AB, Fuentes Martín, Galda, Neubert (2307.10372)]



[Mariotti, Redigolo, Sala, Tobiok (1710.01743)]

[Bonilla, Brivio, Machado-Rodríguez, de Trocóniz (2202.03450)]

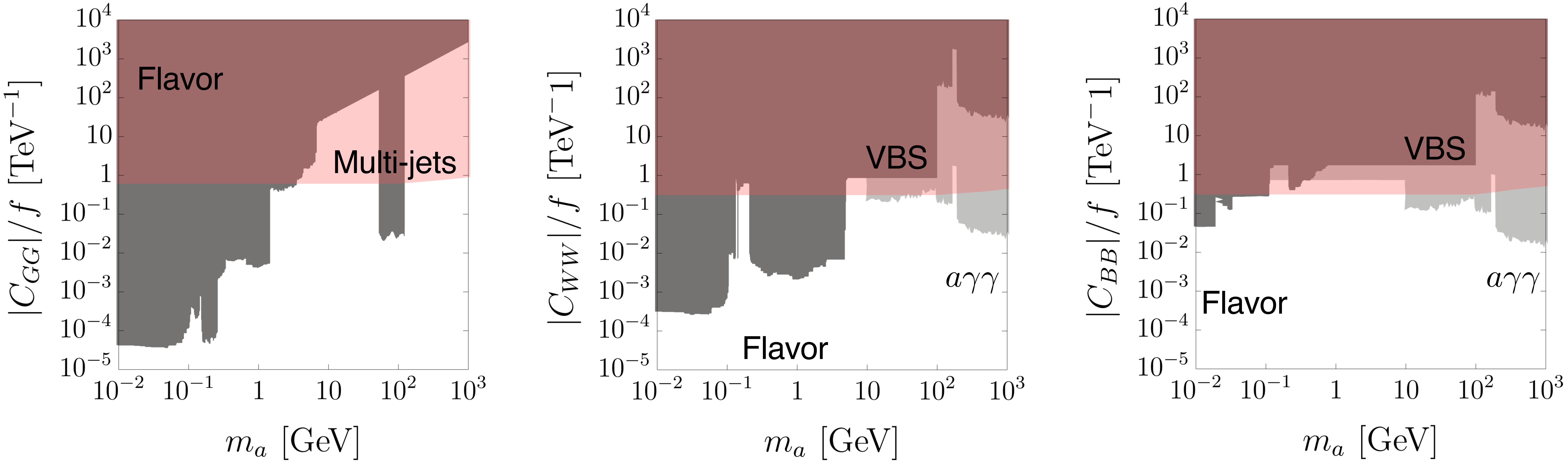
[Bauer, Neubert, Thamm (1708.00443)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

Comparison with direct bounds

[AB, Fuentes Martín, Galda, Neubert (2307.10372)]

Light gray bounds with additional assumptions



[Mariotti, Redigolo, Sala, Tobiok (1710.01743)]

[Bonilla, Brivio, Machado-Rodríguez, de Trocóniz (2202.03450)]

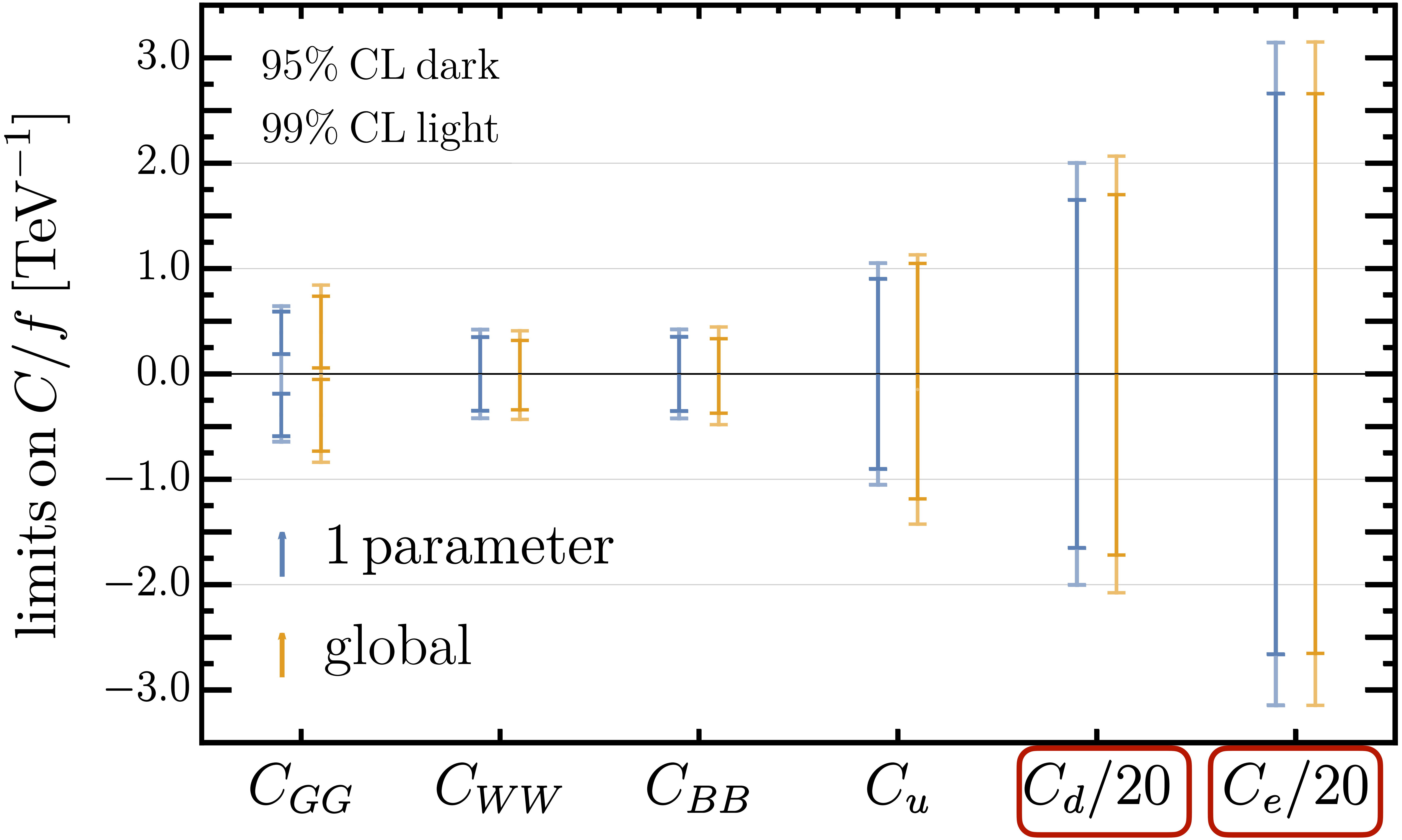
[Bauer, Neubert, Thamm (1708.00443)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

ALP-SMEFT interference tests unconstrained parameter space

A global analysis

[AB, Fuentes Martín, Galda, Neubert (2307.10372)]



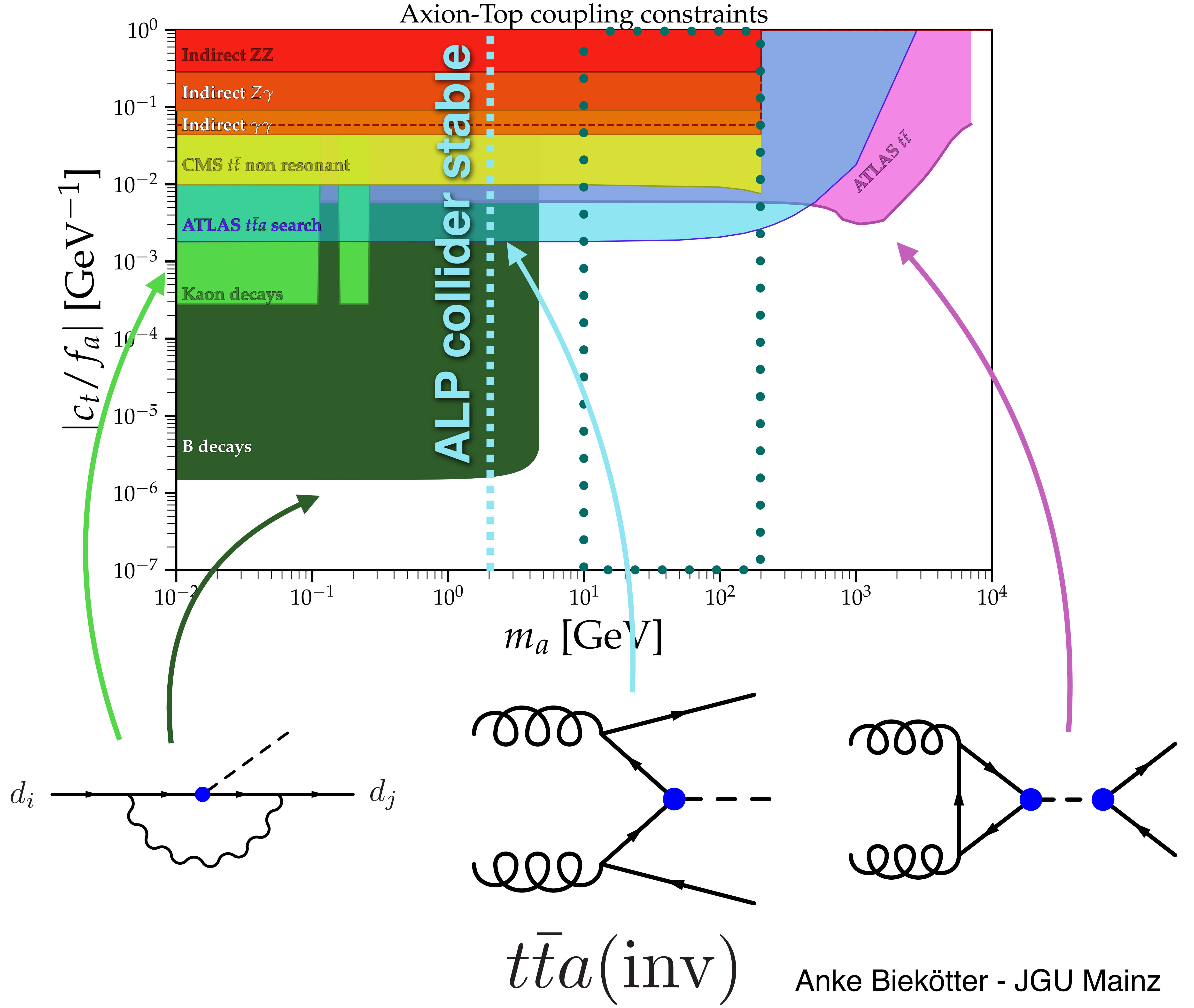
$\Lambda = 4\pi f$

$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

Interplay between couplings is relatively small

ALPs and tops @ colliders

[Esser, Madigan, Sanz, Ubiali (2303.17634)]



see also

[Phan, Westhoff (2312.00872)]

[Blasi, Maltoni, Mariotti, Mimasu, Pagani, Tentori (2311.16048)]

$t\bar{t}$ most relevant at high ALP masses