BSM Higgs: Theory Status II

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CERN

18 June 2018

Workshop on the physics of HL-LHC,
and perspectives at HE-LHC
CERN

Outline

- Summary of Higgs related contributions in the BSM session
- ALPs at the HL-LHC and HE-LHC

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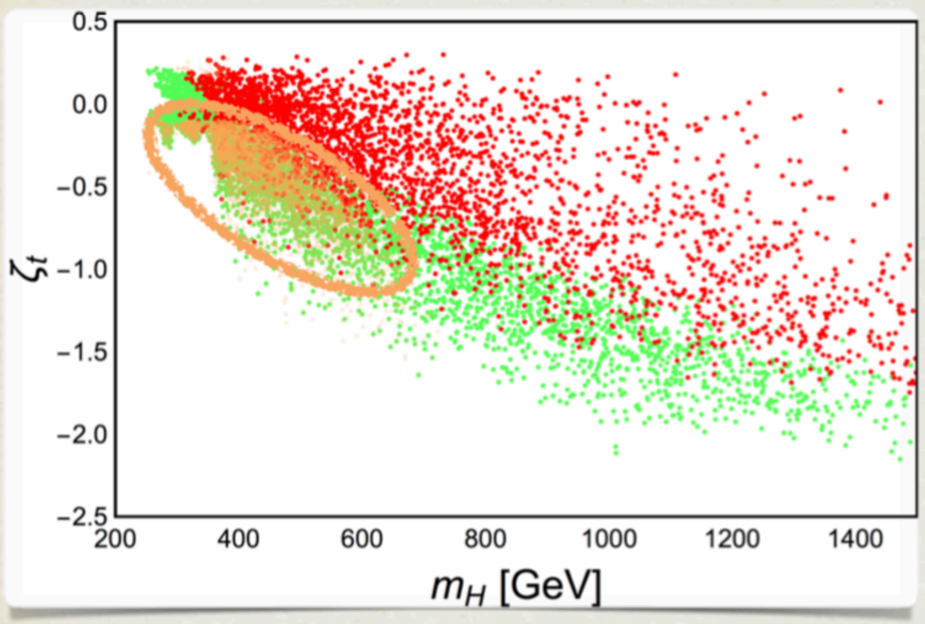
Testing compositeness of 2HDM

interplay between indirect and direct searches

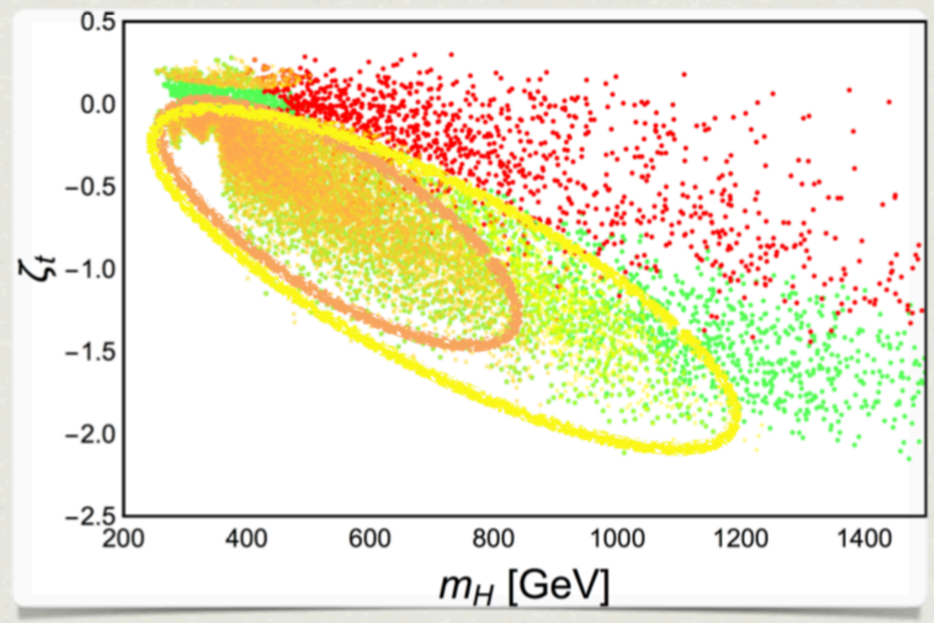
$gg \to H \to hh \to bb\gamma\gamma$

see talk by Luigi Delle Rose

end of Run 3



HL-LHC and HE-LHC



PRELIMINARY

colour legend:

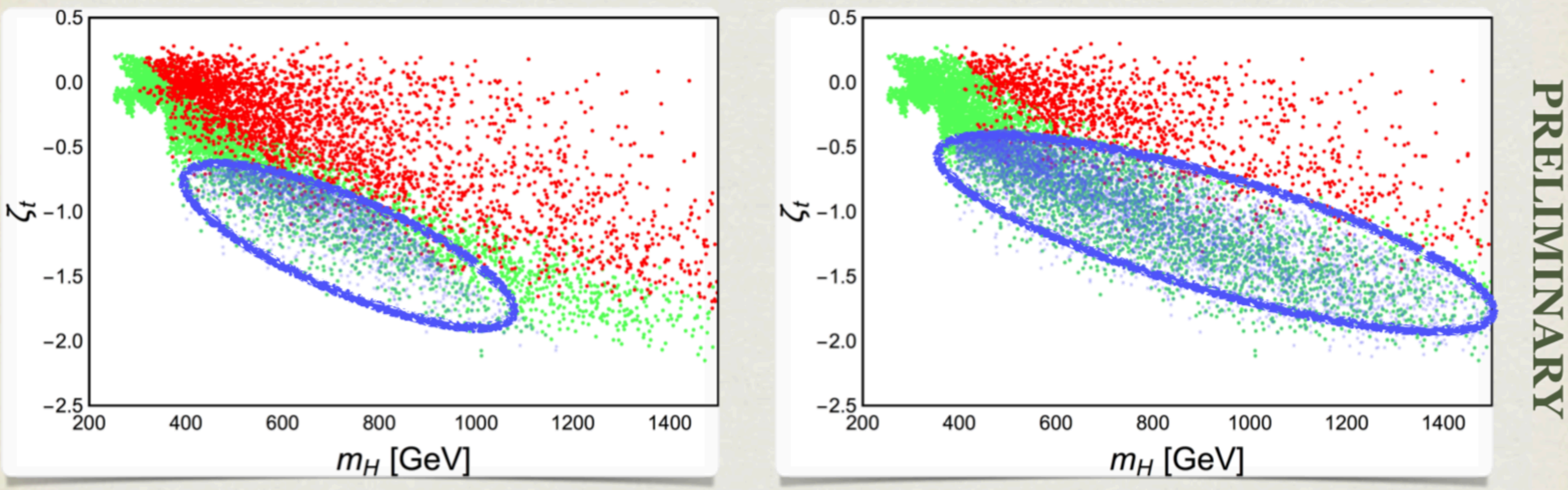
- **green**: *points that pass present constraints at 13 TeV*
- **red**: *points that have κ_V, κ_γ and κ_g within 95% CL projected uncertainty at L = 300 fb⁻¹ (left) and L = 3000 fb⁻¹ (right) (arXiv:1307.7135)*
- ***orange****: points that are 95% CL excluded by direct search at L = 300 fb⁻¹ (left) and L = 3000 fb⁻¹ (right) (CMS PAS HIG-17-008)*
- ***yellow****: points hat are 95% CL excluded by direct search at the HE-LHC (right)*

Testing compositeness of 2HDM

interplay between indirect and direct searches
gg → H → tt (*semileptonic*)

see talk by Luigi Delle Rose

end of Run 3 | *HL-LHC*



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- **red**: *points that have κ_V, κ_γ and κ_g within 95% CL projected uncertainty at $L = 300\ fb^{-1}$ (left) and $L = 3000\ fb^{-1}$ (right) (arXiv:1307.7135)*
- ***blue***: *points that are 95% CL excluded by direct search at $L = 300\ fb^{-1}$ (left) and $L = 3000\ fb^{-1}$ (right) (arXiv:1804.10823)*

2HDM with U(1) gauge symmetries

- Sensitivity in di-lepton searches

Model	13 TeV, 36 fb^{-1}	13 TeV, 300 fb^{-1}	13 TeV, 3000 fb^{-1}	27 TeV, 300 fb^{-1}	27 TeV, 3000 fb^{-1}
$U(1)_A$	2.2 TeV	3.07 TeV	4.09 TeV	5.02 TeV	7.03 TeV
$U(1)_B$	2.2 TeV	3.07 TeV	4.09 TeV	5.02 TeV	7.03 TeV
$U(1)_C$	1.6 TeV	2.37 TeV	3.34 TeV	3.73 TeV	5.54 TeV
$U(1)_D$	3.5 TeV	4.45 TeV	5.46 TeV	7.76 TeV	9.89 TeV
$U(1)_E$	2.3 TeV	3.18 TeV	4.21 TeV	5.24 TeV	7.27 TeV
$U(1)_F$	3.6 TeV	4.55 TeV	5.56 TeV	7.97 TeV	10.09 TeV
$U(1)_G$	1.1 TeV	1.73 TeV	2.60 TeV	2.62 TeV	4.16 TeV
$U(1)_{B-L}$	2 TeV	2.84 TeV	3.85 TeV	4.60 TeV	6.55 TeV

Table 18: HL-LHC and HE-LHC projected sensitivities for all $U(1)_X$ models studied in this work using dilepton data at 13 TeV and 27 TeV of CM energy and for $\mathcal{L} = 36$, 300 and 3000 fb^{-1}. Here, $g_X = 0.1$.

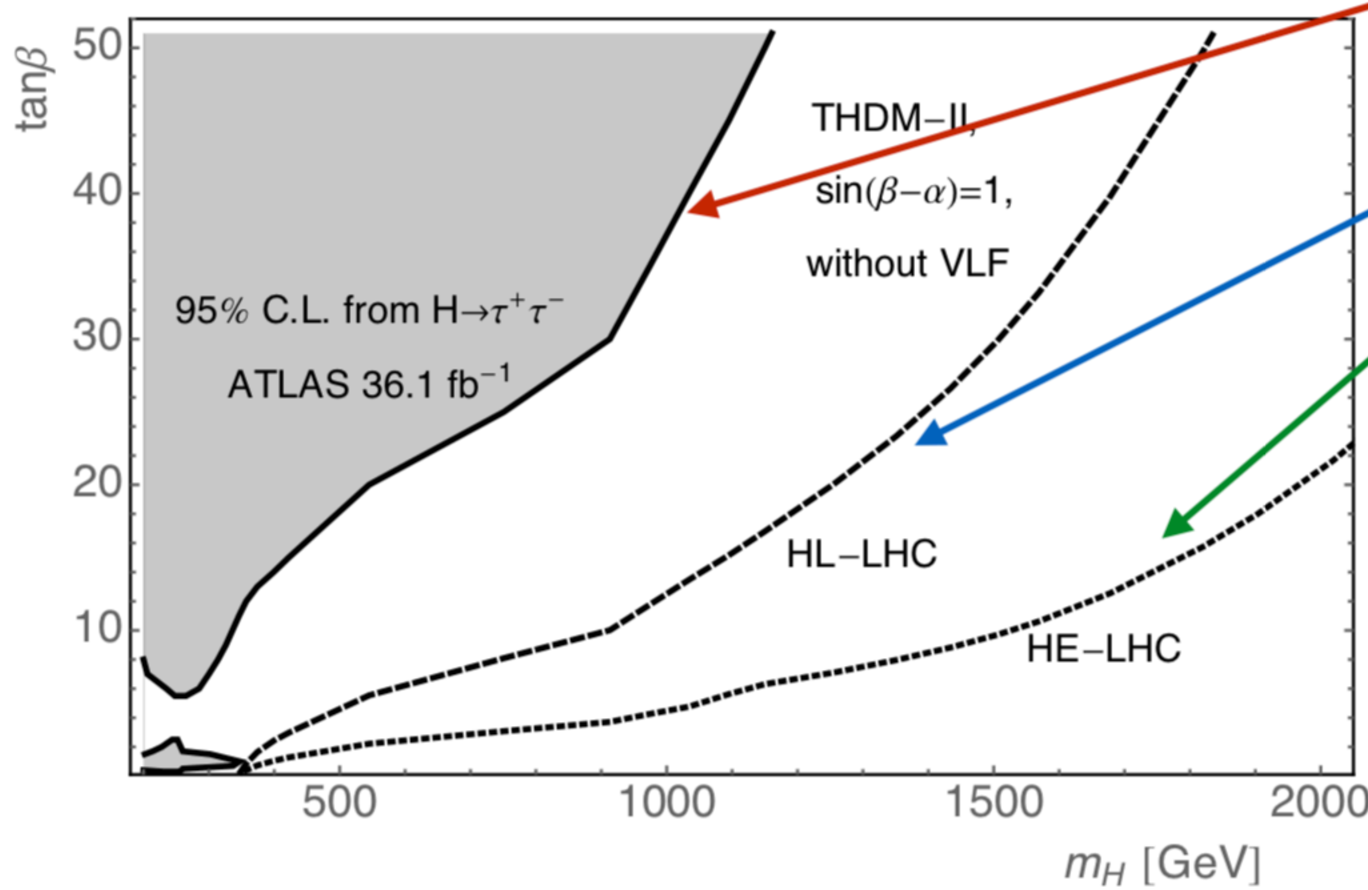
work by D. Camargo, L. Delle Rose, S. Moretti, F. Queiroz

Extended Higgs and matter sector

see talk by Radovan Dermisek

Heavy Higgses

- fairly large production rates
- hard to search for final states $H \to t\bar{t},\ b\bar{b},\ \tau\tau,\ \gamma\gamma$



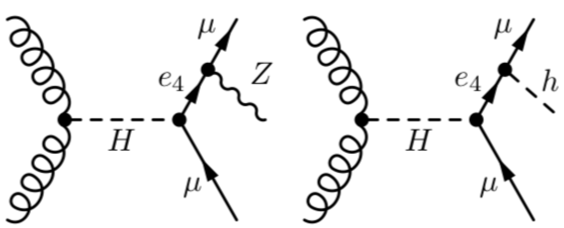
projected limits at **HL-LHC** and **HE-LHC** obtained by simple rescaling of luminosities and production cross sections (assuming signal and background scales the same) and everything else as in the current ATLAS analysis

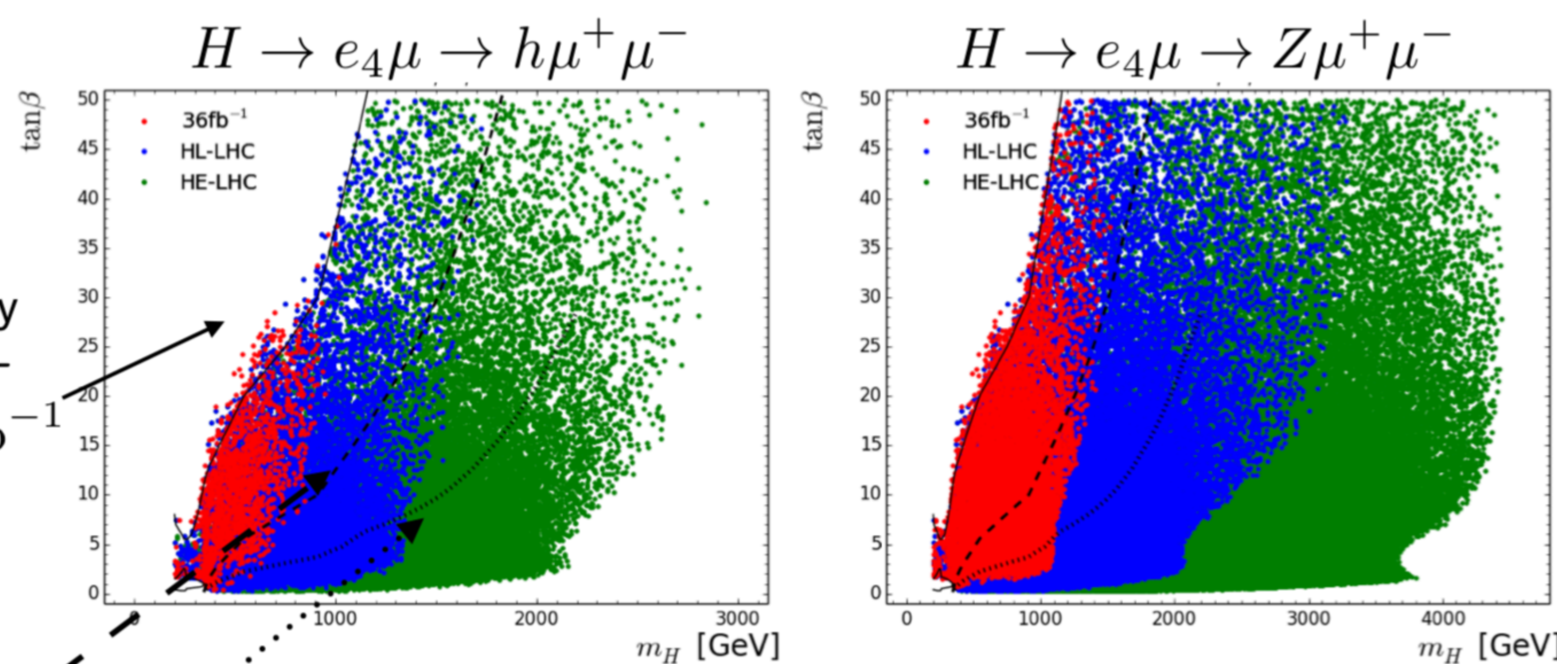
Extended Higgs and matter sector

Sensitivity to $H \to h\mu\mu,\ Z\mu\mu$ at HL/HE-LHC

see talk by Radovan Dermisek

Scenarios satisfying all the limits that can be seen at 95% C.L.:





excluded by $H \to \tau\tau$ with $36\ \mathrm{fb}^{-1}$

projected $H \to \tau\tau$ at HL-LHC and at HE-LHC

HL(HE)-LHC sensitive to heavy Higgses up to ~3(4.5) TeV

Dark photons via Higgs bosons

$$gg \to H \to \gamma\bar{\gamma}$$

- Discovery and exclusion reach

$\text{BR}_{\gamma\bar{\gamma}}$ (%)	3 ab^{-1}@14 TeV		15 ab^{-1}@27 TeV	
significance	2σ	5σ	2σ	5σ
CMS inspired	0.012	0.030	0.0052	0.013
jet veto in $\lvert\eta^j\rvert < 4.5$	0.020	0.051	0.021	0.053

work by S. Biswas, E. Gabrielli, M. Heikinheimo, B. Mele

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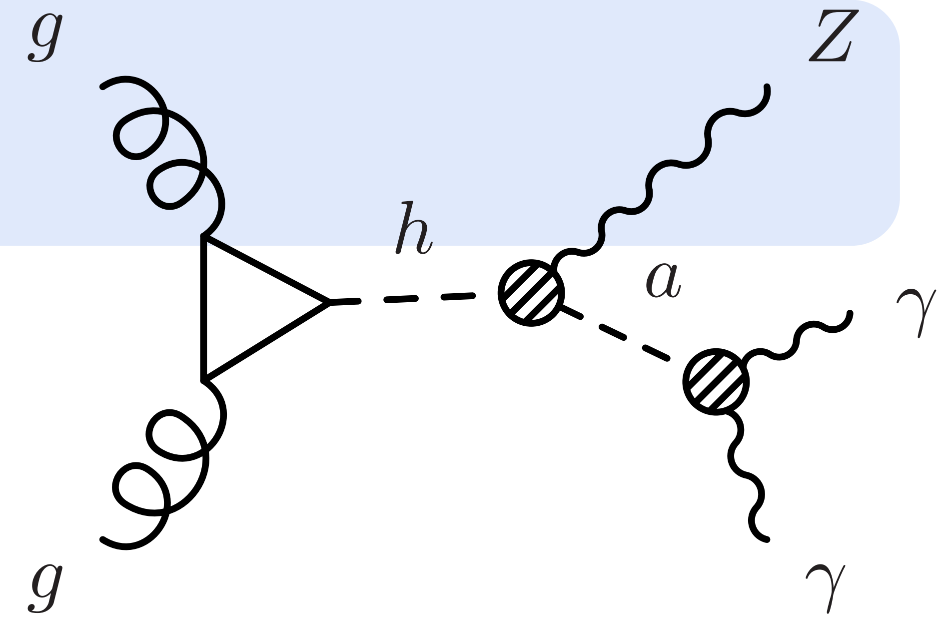

- Summary of Higgs related contributions in the BSM session
- ALPs at the HL-LHC and HE-LHC

with Martin Bauer and Matthias Neubert

based on arXiv:1610.00009, 1704.08207, 1708.00443
and work in progress

Motivation

- Pseudo-scalars in many extensions of the SM
  - QCD axion - solution to strong CP-problem
  - Nambu-Goldstone bosons of a broken symmetry
  - mediators to the dark sector
  - explanations of various anomalies
- Good reason to study them!
- Large regions of parameter space already probed by many different experiments
- We add a region that can be probed through exotic Higgs decays in run 2 of LHC and at future colliders

Effective Lagrangian

- Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f + g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A}$$
$$+ e^2\,C_{\gamma\gamma}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\,C_{\gamma Z}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\,C_{ZZ}\,\frac{a}{\Lambda}\,Z_{\mu\nu}\,\tilde{Z}^{\mu\nu}$$

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$$\Lambda = 4\pi f$$
$$C_{VV} = \bar C_{VV}/4\pi$$
$$f = -2\bar C_{GG} f_a$$

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- Higgs interactions at dimension-6 and 7

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$h \to aa$

[Dobrescu, Landsberg, Matchev: 0005308]
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$h \to Za$

[Bauer, Neubert, Thamm: 1607.01016]

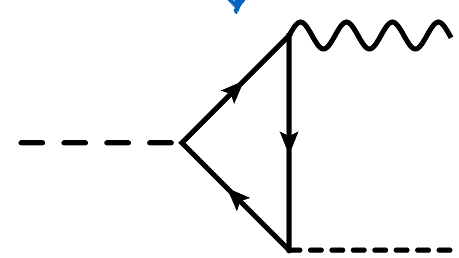
Exotic Higgs Decays $h \to Za$

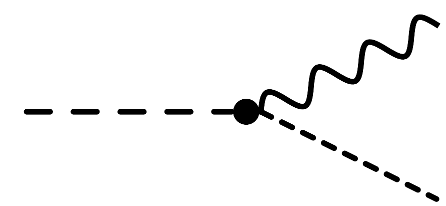
- Contributions

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left| C_{Zh}^{(5)} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \right|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$

$$\frac{(\partial^\mu a)}{\Lambda} \left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right)$$

Vanishes through EOM





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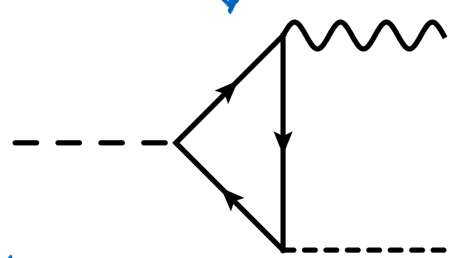

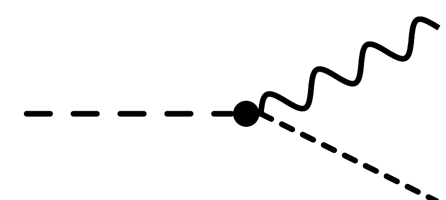

Non-polynomial operator for models with new heavy particles whose mass arises from EWSB

$$\frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right) \ln \frac{\phi^\dagger \phi}{\mu^2}$$

[Pierce, Thaler, Wang: 0609049]
[Bauer, Neubert, Thamm: 1607.01016]
[Bauer, Neubert, Thamm: 1610.00009]

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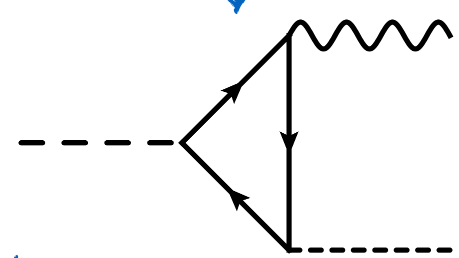

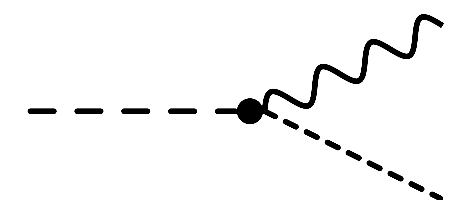

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- Numerically

$$C_{Zh}^{\text{eff}} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

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- For $\mathrm{Br}(h \to Za) = 0.1$ need $|C_{Zh}|/\Lambda \approx 0.34\,\mathrm{TeV}^{-1}$
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  - $h \to Za \to Zll$
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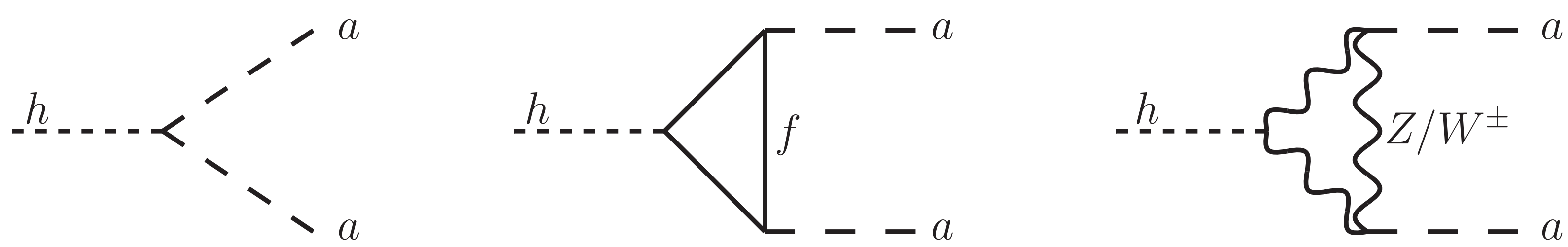
- All these modes can be reconstructed at run II

Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]
[Chang, Fox, Weiner: 0608310]



$$C_{ah}^{\text{eff}} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln\frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] - \frac{3\alpha}{2\pi s_w^2}\left(g^2 C_{WW}\right)^2 \left[\ln\frac{\mu^2}{m_W^2} + \delta_1 - g_2(\tau_{W/h})\right] - \frac{3\alpha}{4\pi s_w^2 c_w^2}\left(\frac{g^2}{c_w^2}\, C_{ZZ}\right)^2 \left[\ln\frac{\mu^2}{m_Z^2} + \delta_1 - g_2(\tau_{Z/h})\right]$$

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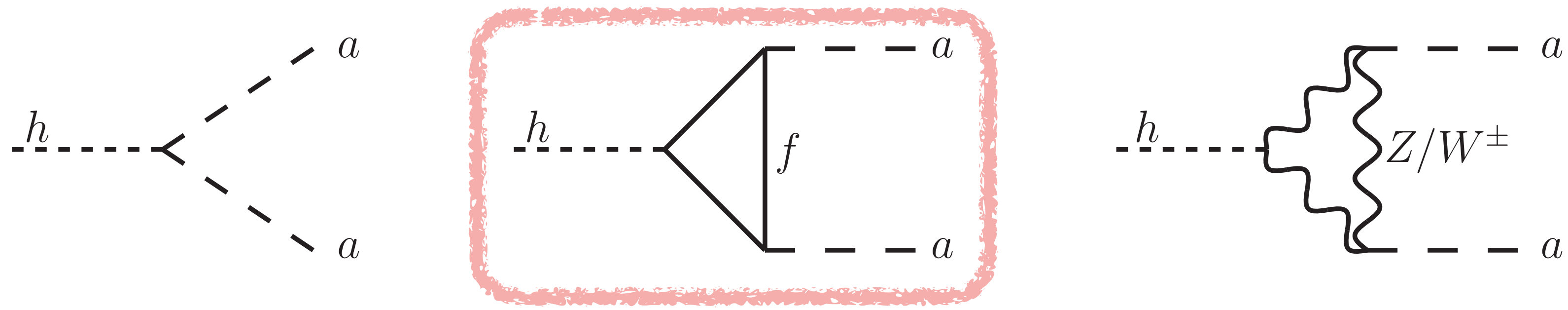

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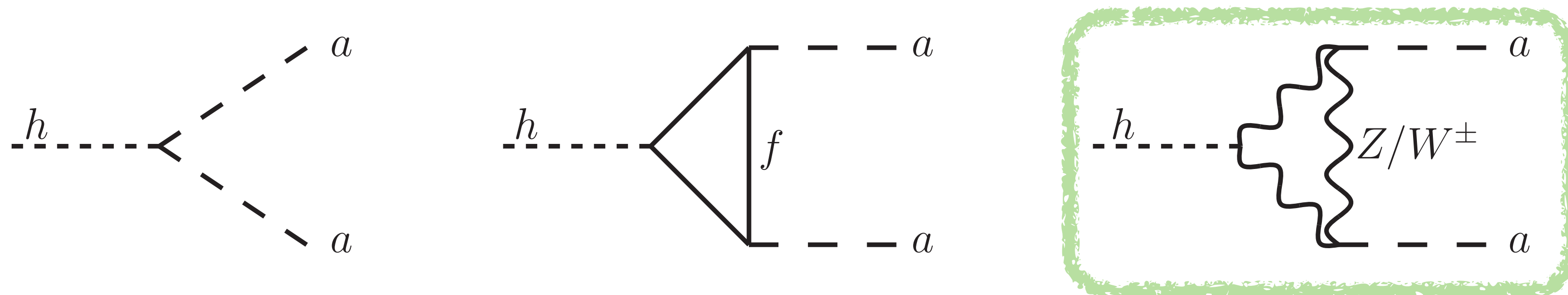

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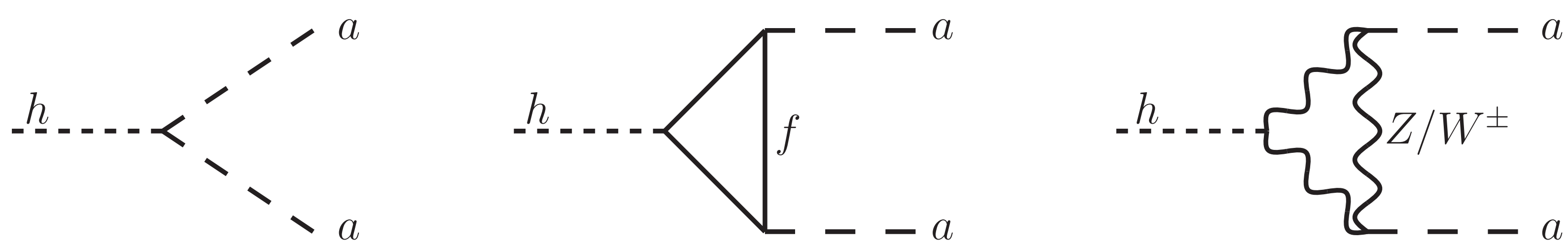

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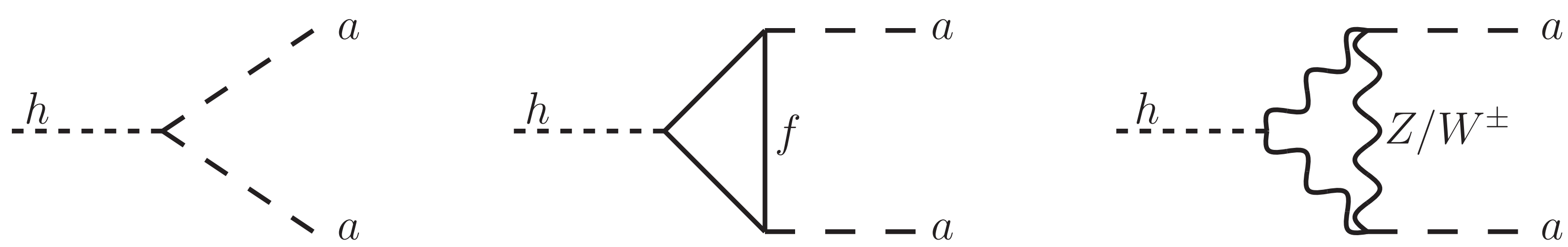
$$C_{ah}^{\text{eff}} \approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\left(C_{WW}^2 + C_{ZZ}^2\right)$$

Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]
[Chang, Fox, Weiner: 0608310]



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- Interesting final states
  - $h \to aa \to \gamma\gamma\gamma\gamma$
  - $h \to aa \to l^+l^-l^+l^-$
  - $h \to aa \to 4\text{jets}$
  - $h \to aa \to \text{invisible}$

- All these modes can be reconstructed at run II

Detecting ALPs in $h \to Za$

- Average decay length perpendicular to beam axis

$$L_a^\perp(\theta) = \sin\theta \, \frac{\beta_a \gamma_a}{\Gamma_a} = \sin\theta \sqrt{\gamma_a^2 - 1} \, \frac{\text{Br}(a \to X\bar{X})}{\Gamma(a \to X\bar{X})}$$

- Fraction of ALPs decaying before travelling a certain distance

$$f_{\text{det}} = \int_0^{\pi/2} d\theta \, \sin\theta \left(1 - e^{-L_{\text{det}}/L_a^\perp(\theta)}\right)$$

Decay into photons before EM calorimeter

$L_{\text{det}} = 1.5\,\text{m}$

Decay into electrons before inner tracker

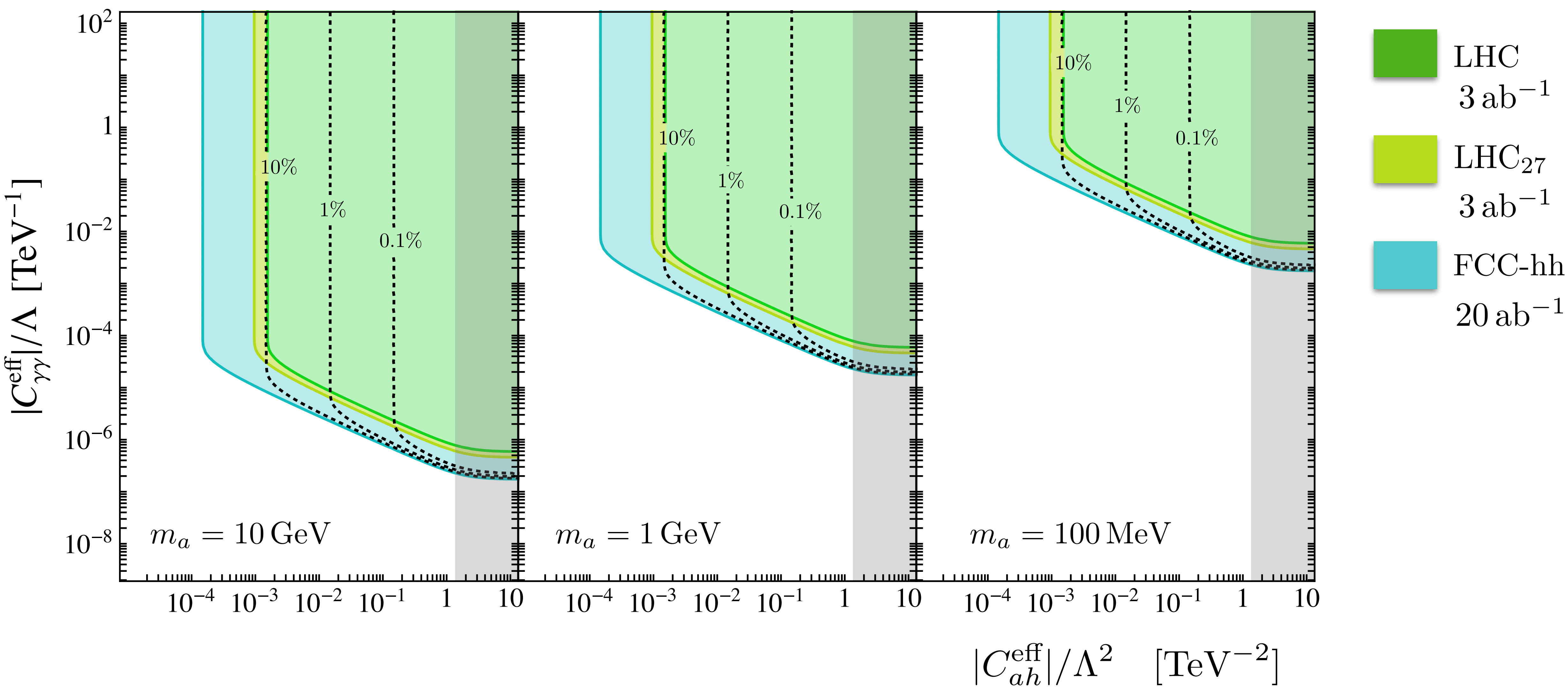
$L_{\text{det}} = 2\,\text{cm}$

- Effective branching ratios

$$\text{Br}(h \to Za \to \ell^+\ell^- X\bar{X})\big|_{\text{eff}} = \text{Br}(h \to Za) \times \text{Br}(a \to X\bar{X}) \, f_{\text{dec}} \, \text{Br}(Z \to \ell^+\ell^-)$$

Exclusion at future colliders

- Current bounds on $h \to aa$



[Bauer, Neubert, Thamm: to appear]

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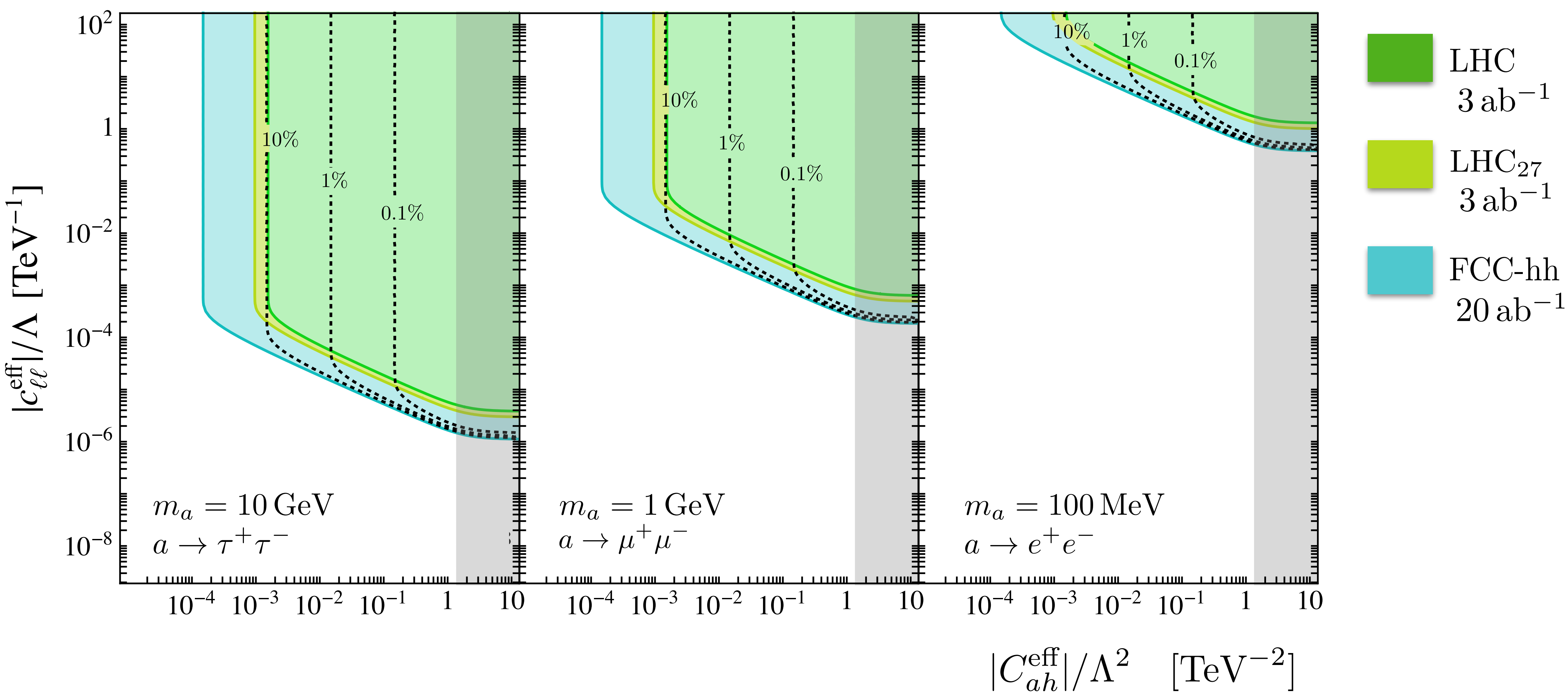
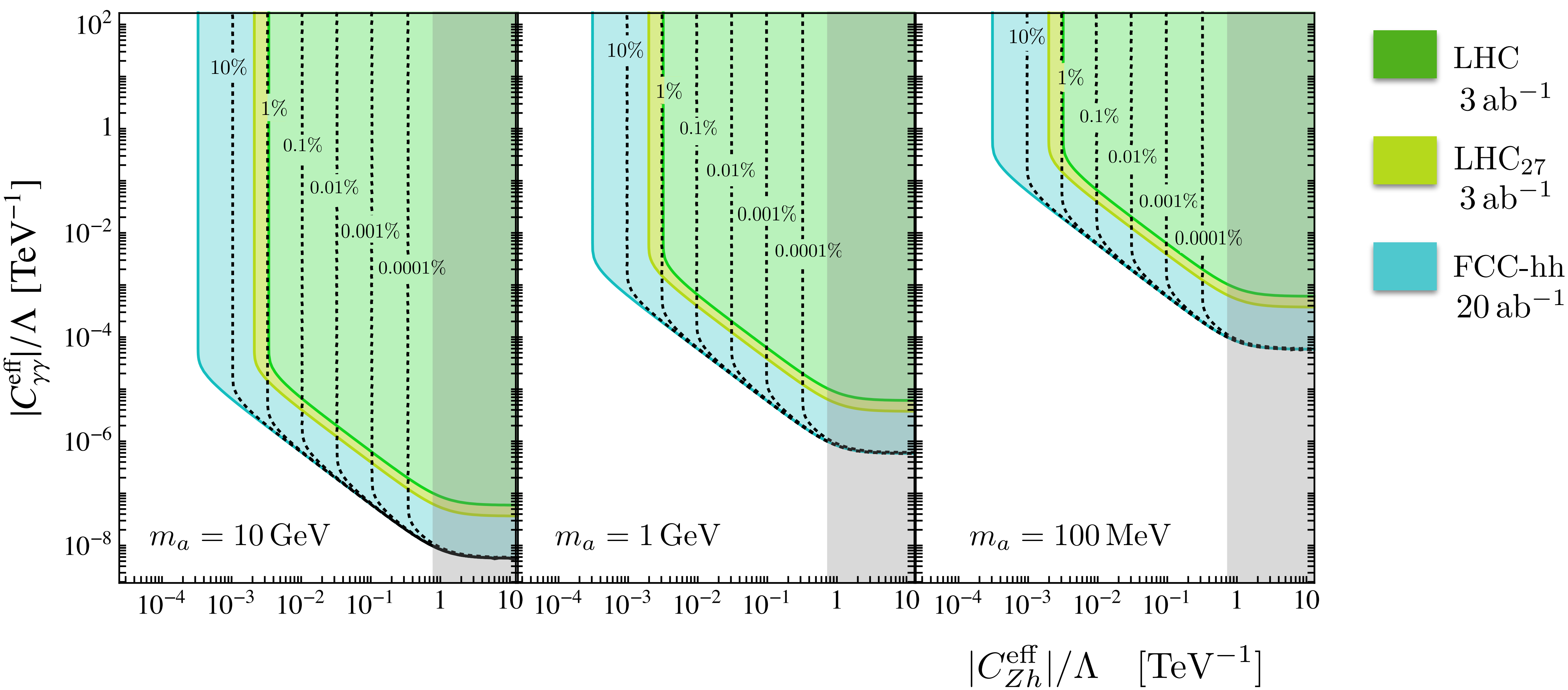


[Bauer, Neubert, Thamm: to appear]

Exclusion at future colliders

- Current bounds on $h \to Za$
- Leptonic Z decays



[Bauer, Neubert, Thamm: to appear]

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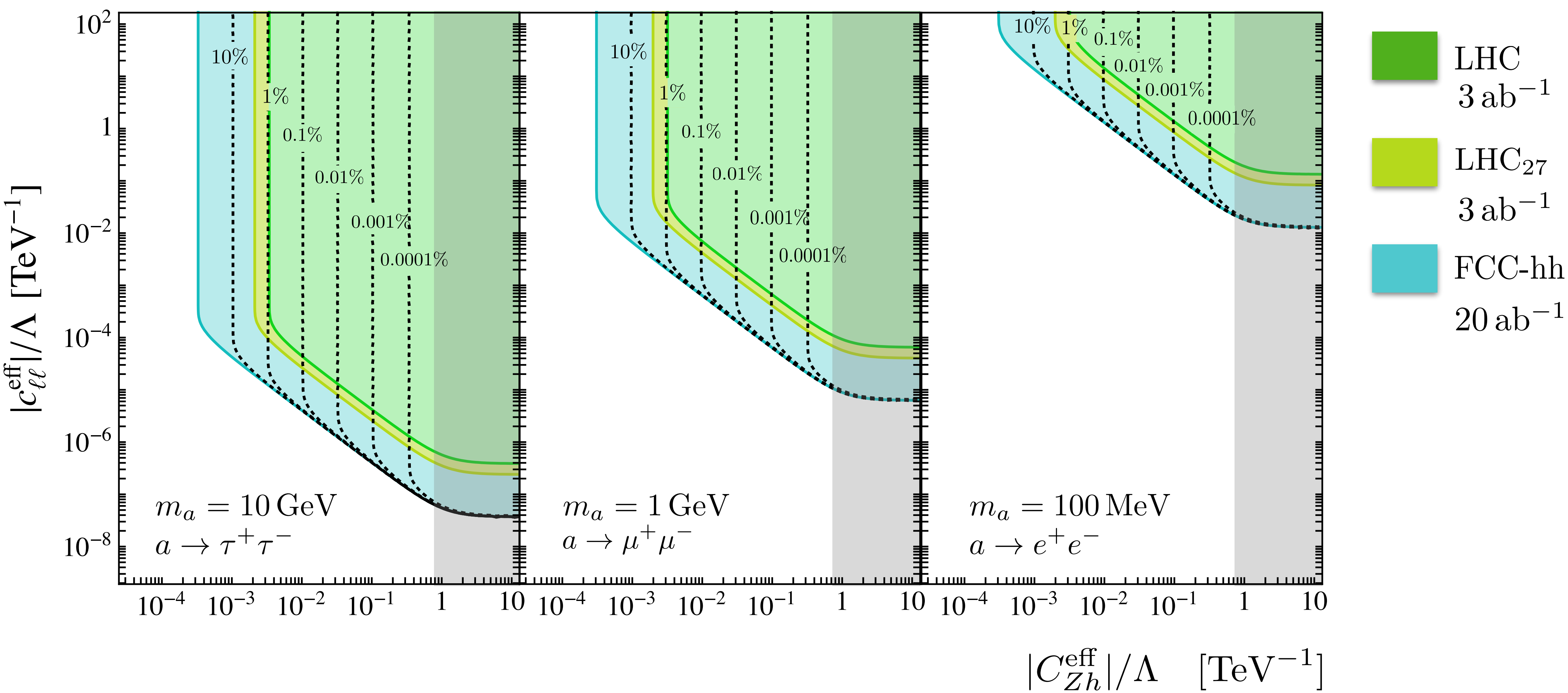
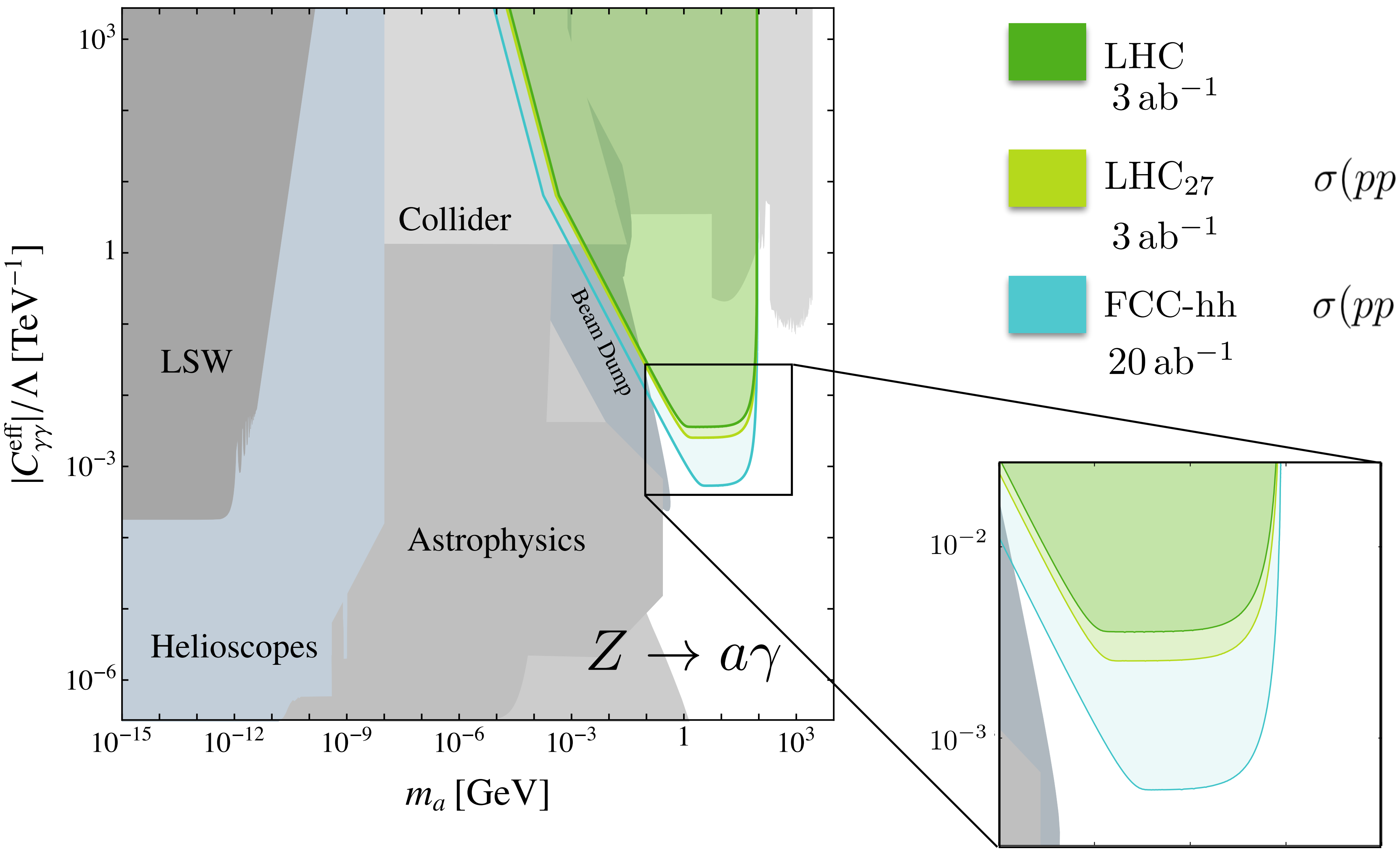


[Bauer, Neubert, Thamm: to appear]

Exclusion at future colliders

- Current bounds on $Z \to \gamma a$
- Improvement by factor 1.5



$\sigma(pp \to Z) = 118.76\,\rm nb$

$\sigma(pp \to Z) = 0.4\,\mu\rm b$

Andrea Thamm

[Bauer, Neubert, Thamm: to appear]

Conclusions

- Rare Higgs decays provide a powerful way to probe the existence of ALPs with masses between 30 MeV and 60 GeV
- Future colliders very promising!