Axion-like particles at MuC

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PittPACC MuC workshop
Nov 17, 2023

Introduction

- QCD axion & strong CP

$$m_a \approx 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

- Axion-like particles (m_a, f_a)

- sub-eV to TeV

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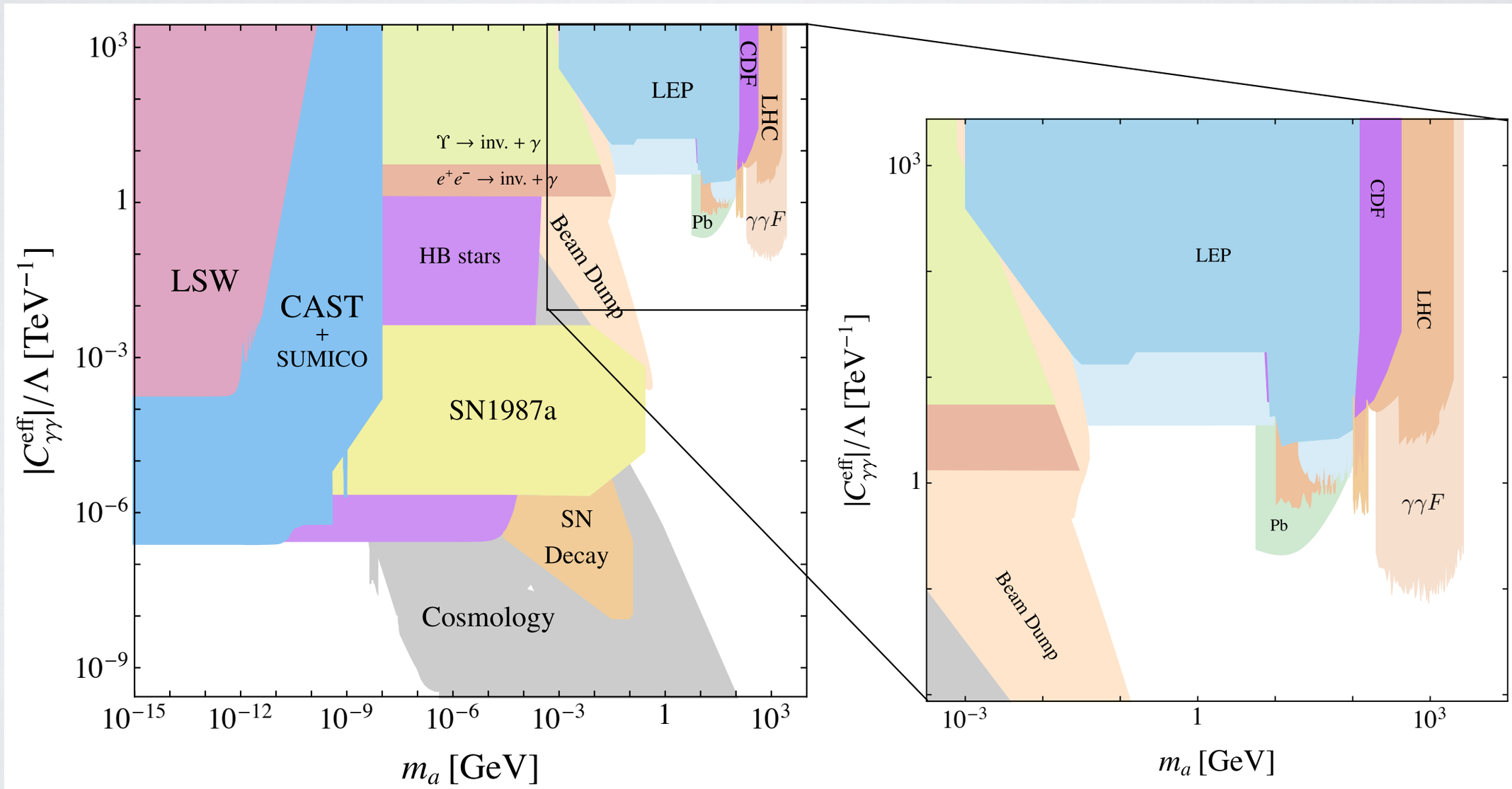
Motivation

- Current constraints



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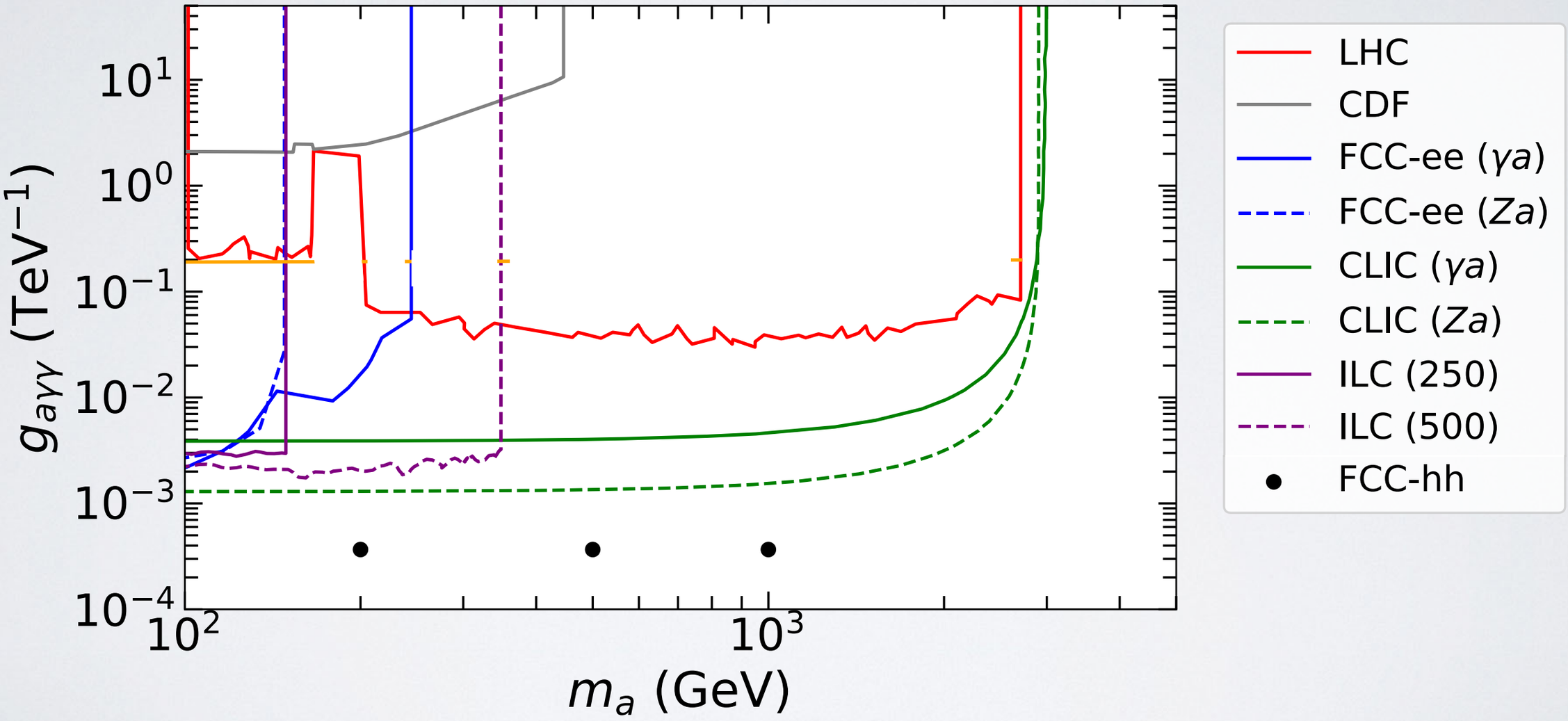
arXiv: 1808.10323

Motivation

- Future projections



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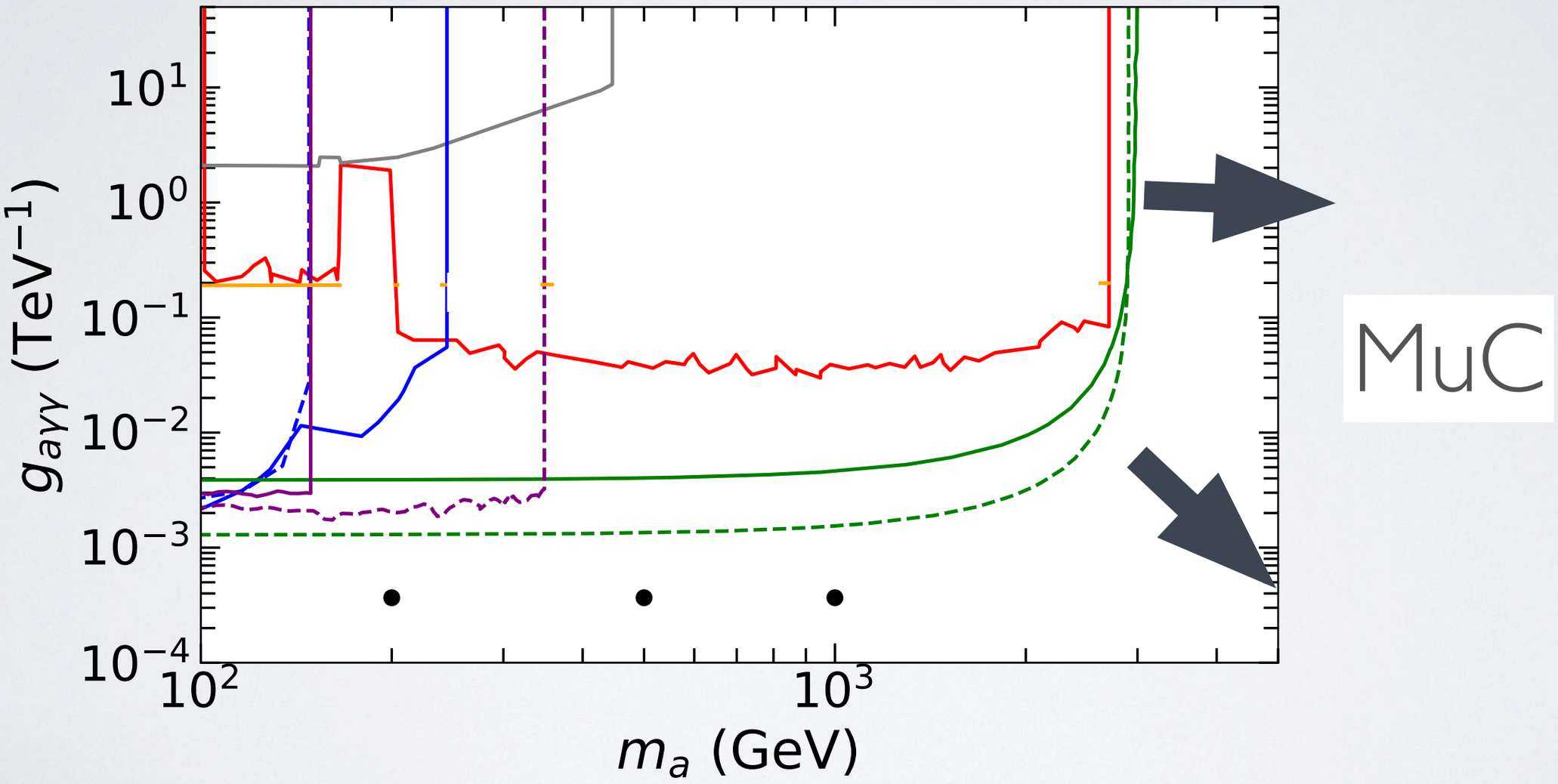
Motivation

- Future projections



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ALP Couplings

- Axion interactions via dim-5 operators

$$\mathcal{L}_{eff} = C_{\tilde{G}}\mathcal{O}_{\tilde{G}} + C_{\tilde{B}}\mathcal{O}_{\tilde{B}} + C_{\tilde{W}}\mathcal{O}_{\tilde{W}} + C_{a\Phi}\mathcal{O}_{a\Phi}$$

$$\mathcal{O}_{\tilde{G}} \equiv -\frac{a}{f_a}G^i_{\mu\nu}\tilde{G}^{\mu\nu}_i \ , \quad \mathcal{O}_{\tilde{W}} \equiv -\frac{a}{f_a}W^j_{\mu\nu}\tilde{W}^{\mu\nu}_j \ ,$$

$$\mathcal{O}_{\tilde{B}} \equiv -\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} \ , \quad \mathcal{O}_{a\Phi} \equiv i\frac{\partial^\mu a}{f_a}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \ ,$$

- Axion couples to SM gauge bosons

$$\mathcal{L}_{eff} \supset -\frac{g_{agg}}{4}aG^a_{\mu\nu}\tilde{G}^{\mu\nu}_a - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4}aF_{\mu\nu}\tilde{Z}^{\mu\nu}$$
$$- \frac{g_{aZZ}}{4}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4}aW_{\mu\nu}\tilde{W}^{\mu\nu} \ ,$$

$$g_{agg} = \frac{4}{f_a}C_{\tilde{G}} \ , \quad g_{a\gamma\gamma} = \frac{4}{f_a}(s^2_\theta C_{\tilde{W}} + c^2_\theta C_{\tilde{B}}) \ , \quad g_{aZZ} = \frac{4}{f_a}(c^2_\theta C_{\tilde{W}} + s^2_\theta C_{\tilde{B}}) \ ,$$
$$g_{a\gamma Z} = \frac{8}{f_a}s_\theta c_\theta (C_{\tilde{W}} - C_{\tilde{B}}) \ , \quad g_{aWW} = \frac{4}{f_a}C_{\tilde{W}} \ ,$$

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ALP Production

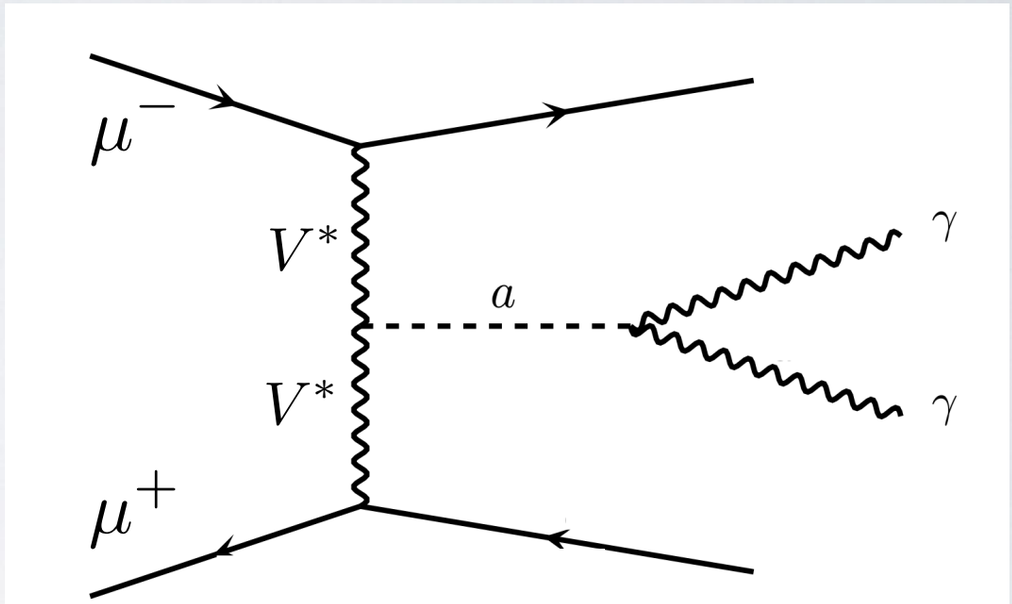
- Vector-boson-fusion (VBF)

$$\gamma\gamma \to a$$

$$ZZ \to a$$

$$\gamma Z \to a$$

$$W^+W^- \to a$$



(a) Parton description (inclusive)

$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^1 d\tau \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau} \hat{\sigma}(V_i V_j \to F) \,,$$

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_\tau^1 \frac{d\xi}{\xi} \Big[f_i(\xi, Q^2) f_j(\frac{\tau}{\xi}, Q^2) + (i \leftrightarrow j) \Big]$$

(b) Final state muons tagged (exclusive di-muon)

$$10^\circ < \theta_{\mu^\pm} < 170^\circ \qquad m_{\mu^+\mu^-} > 200 \text{ GeV}$$

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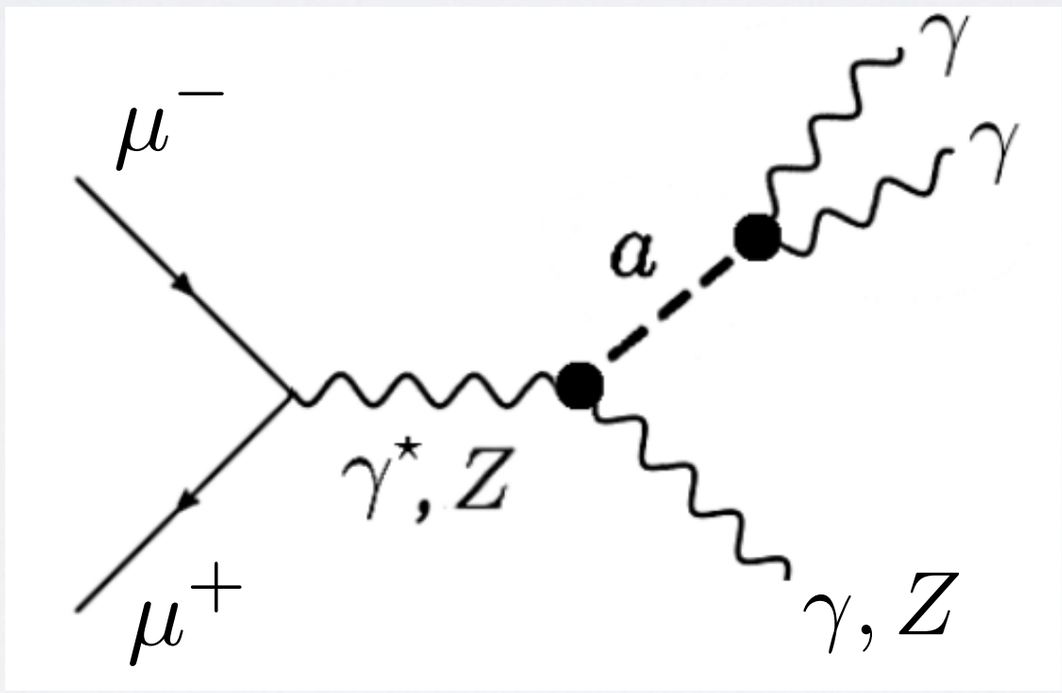
ALP Production

- Associated production

$$\mu^+\mu^- \to Va, \quad V = \gamma, Z$$



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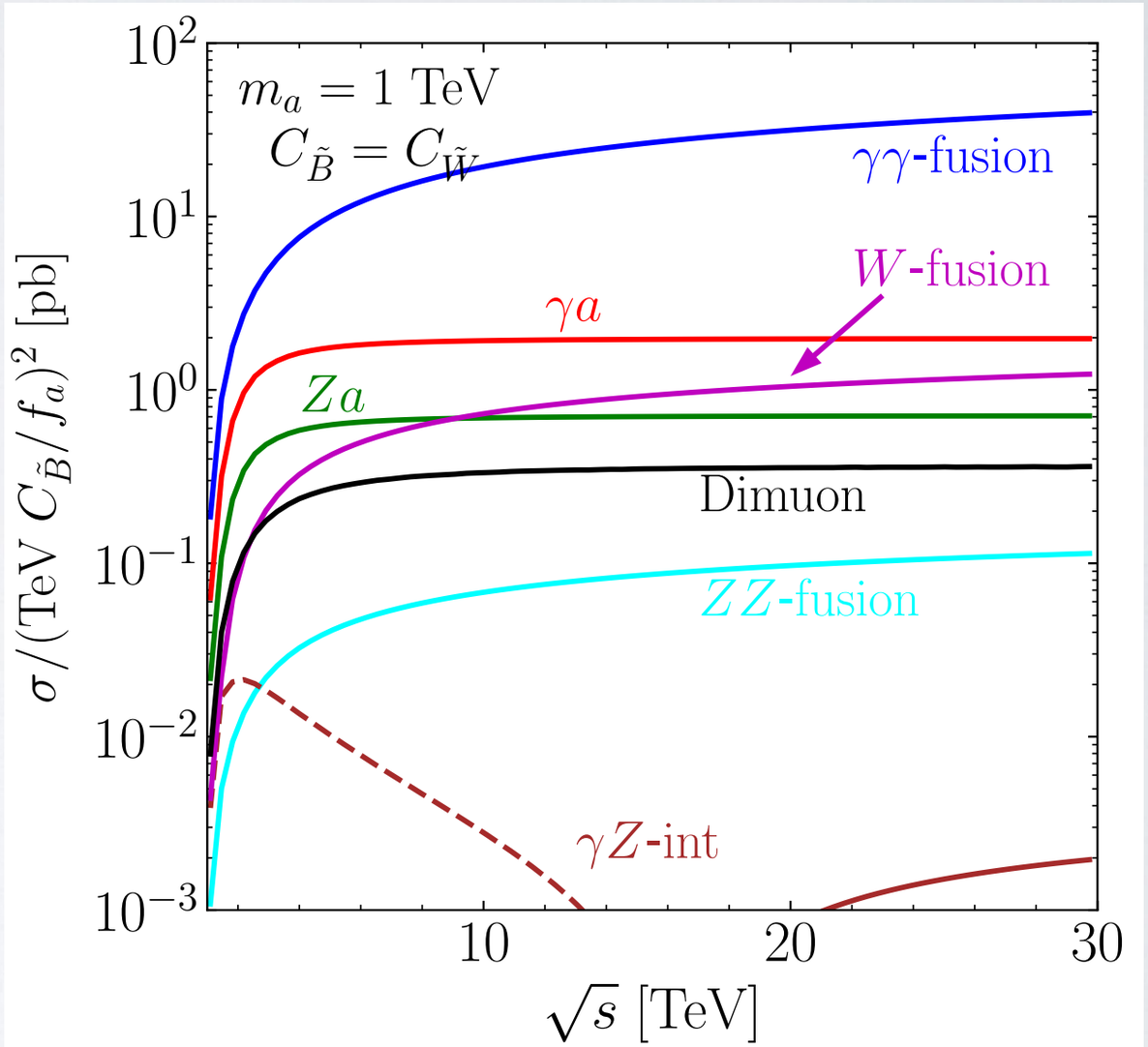
ALP Production

- At high energies,
  - Associated production goes flat
  - VBF has log-enhanced
  - Di-muon limited by angular cuts



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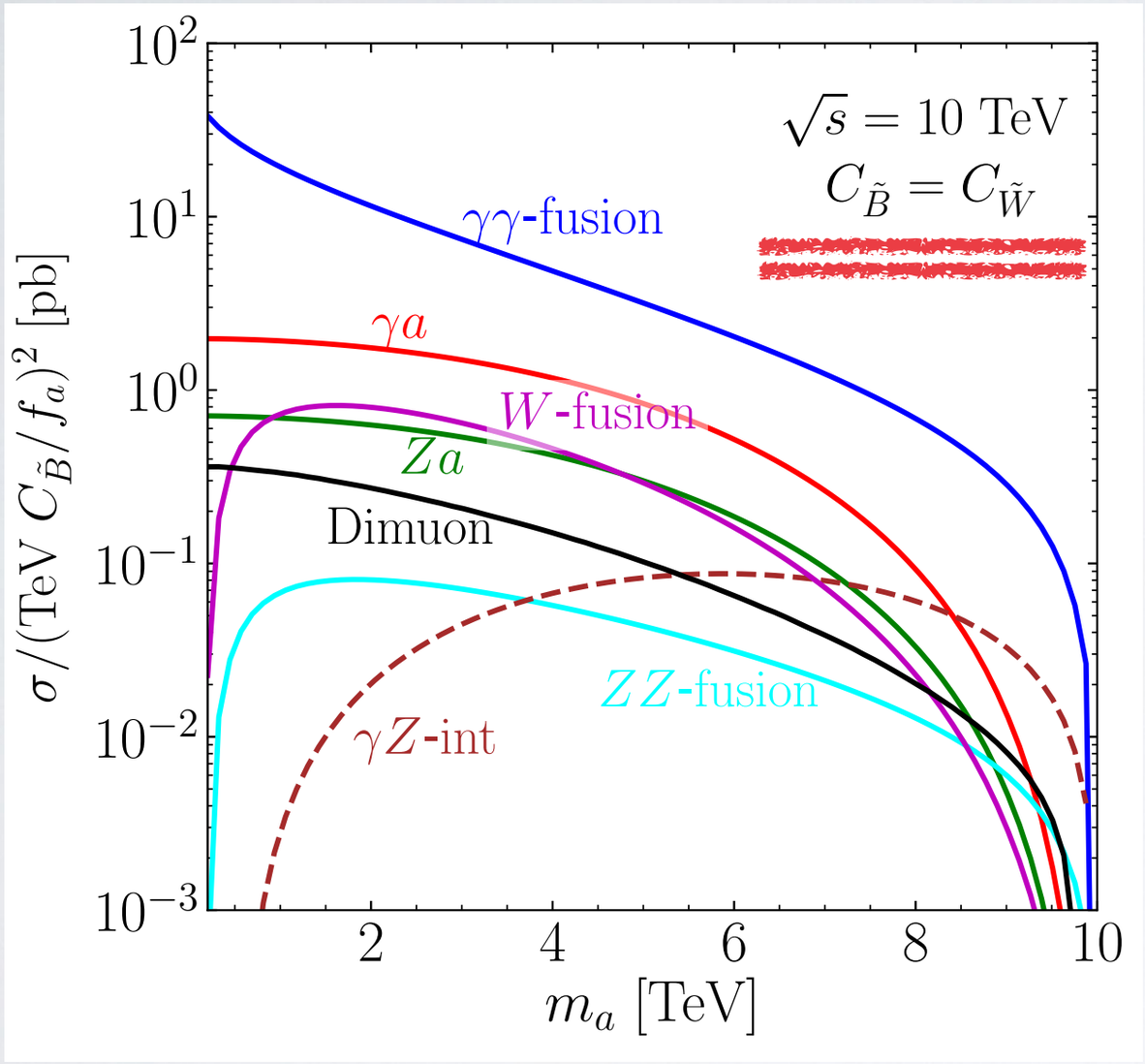
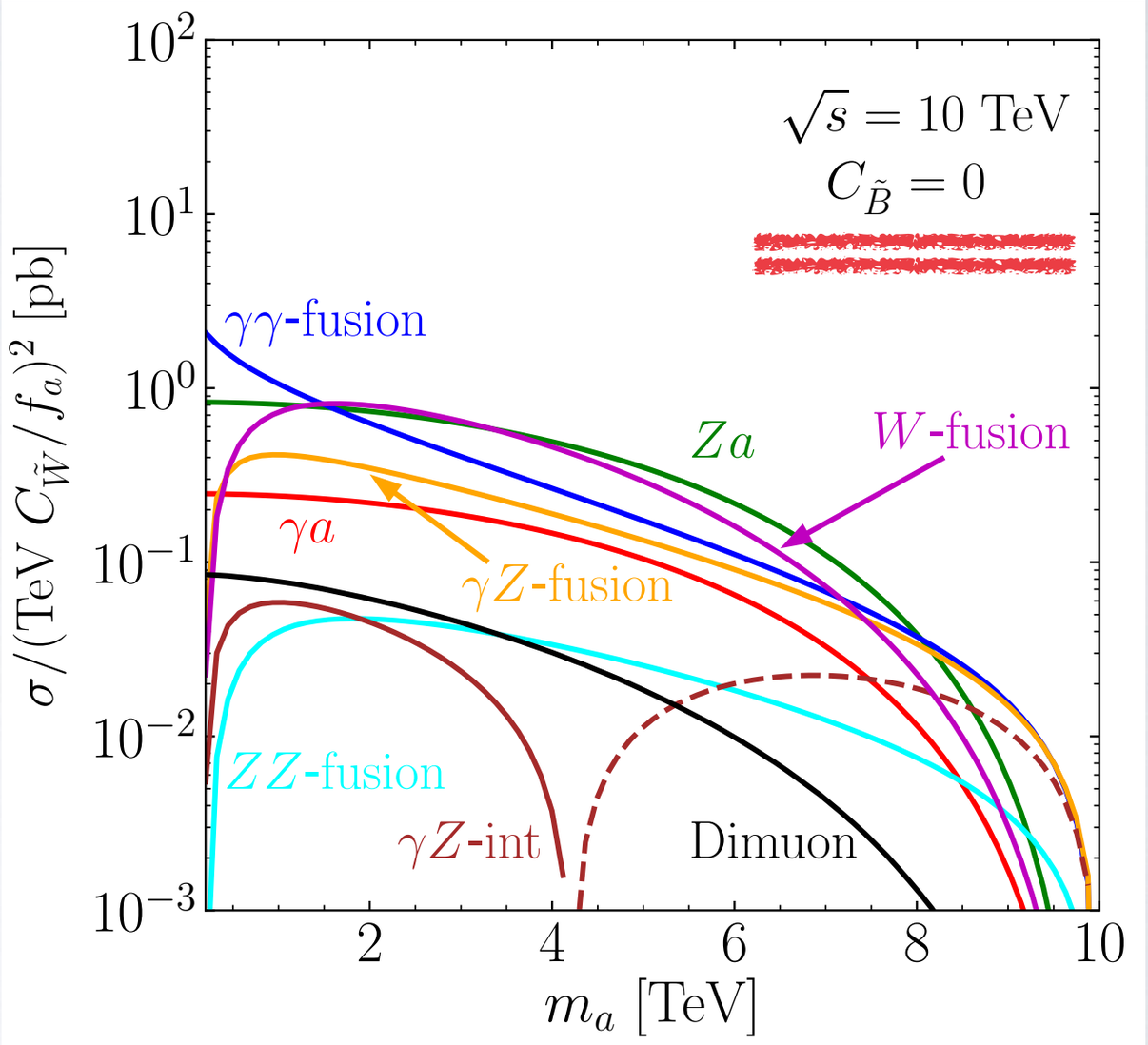
ALP Production





$$g_{agg} = \frac{4}{f_a} C_{\tilde{G}} \,, \quad g_{a\gamma\gamma} = \frac{4}{f_a}(s_\theta^2 C_{\tilde{W}} + c_\theta^2 C_{\tilde{B}}) \,, \quad g_{aZZ} = \frac{4}{f_a}(c_\theta^2 C_{\tilde{W}} + s_\theta^2 C_{\tilde{B}}) \,,$$
$$g_{a\gamma Z} = \frac{8}{f_a} s_\theta c_\theta (C_{\tilde{W}} - C_{\tilde{B}}) \,, \quad g_{aWW} = \frac{4}{f_a} C_{\tilde{W}} \,,$$

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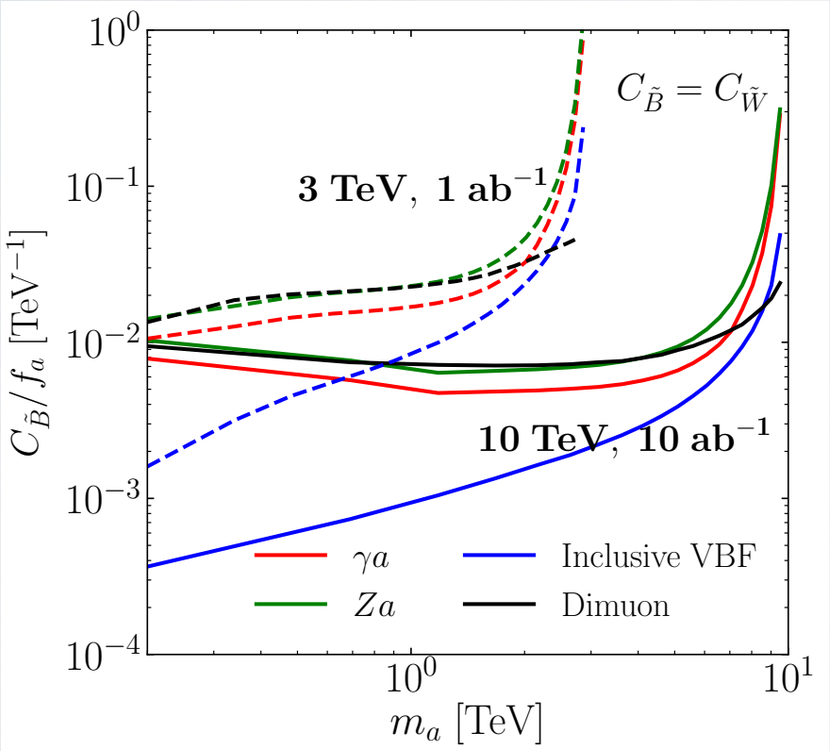
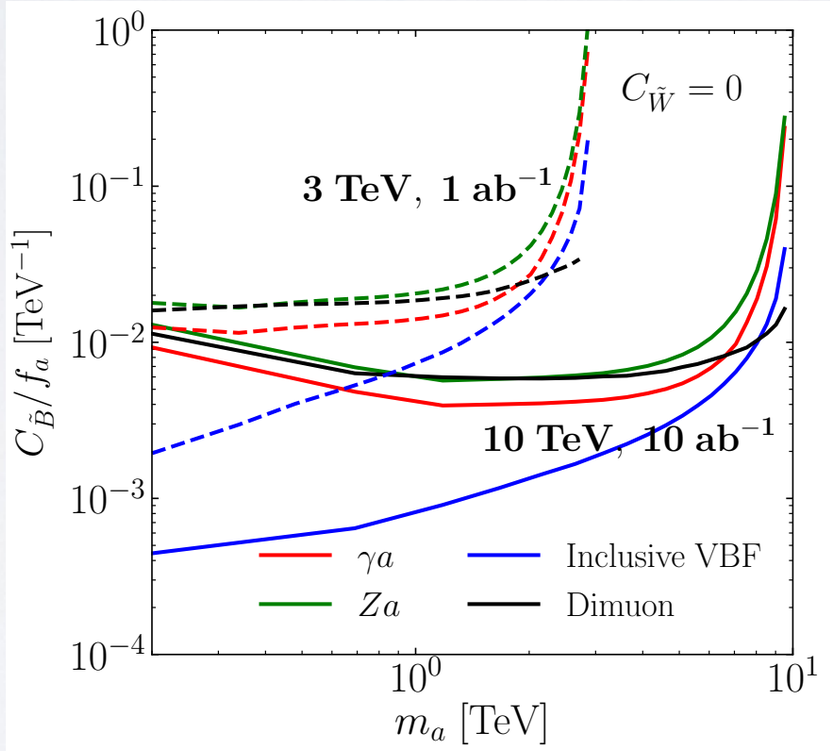
Bounds from $a \to \gamma\gamma$

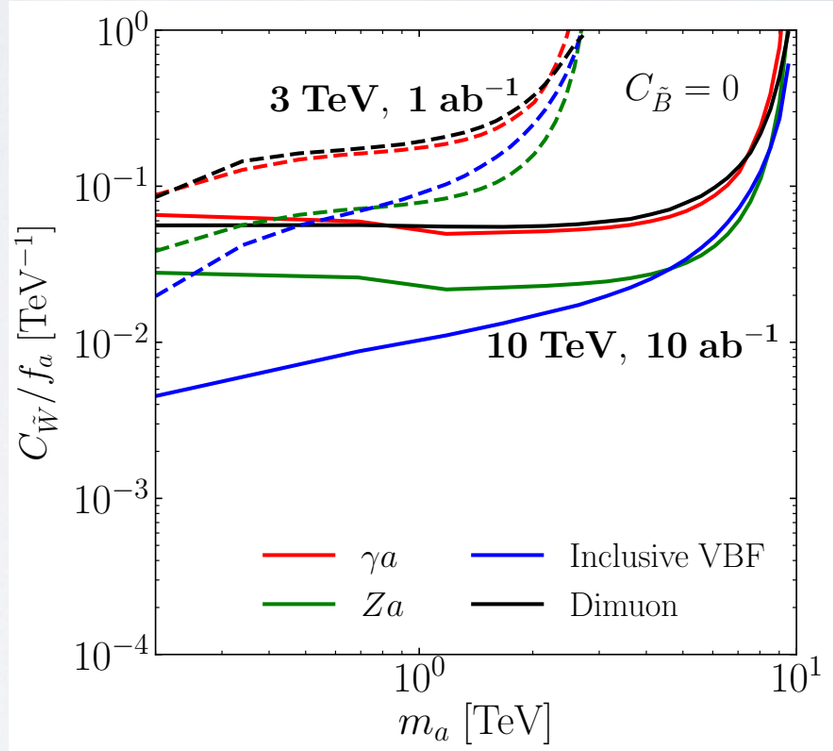
- Discovery limits

arXiv: 2203.05484

$$N_{\rm SD} = \frac{S}{\sqrt{S+B}} = 5$$







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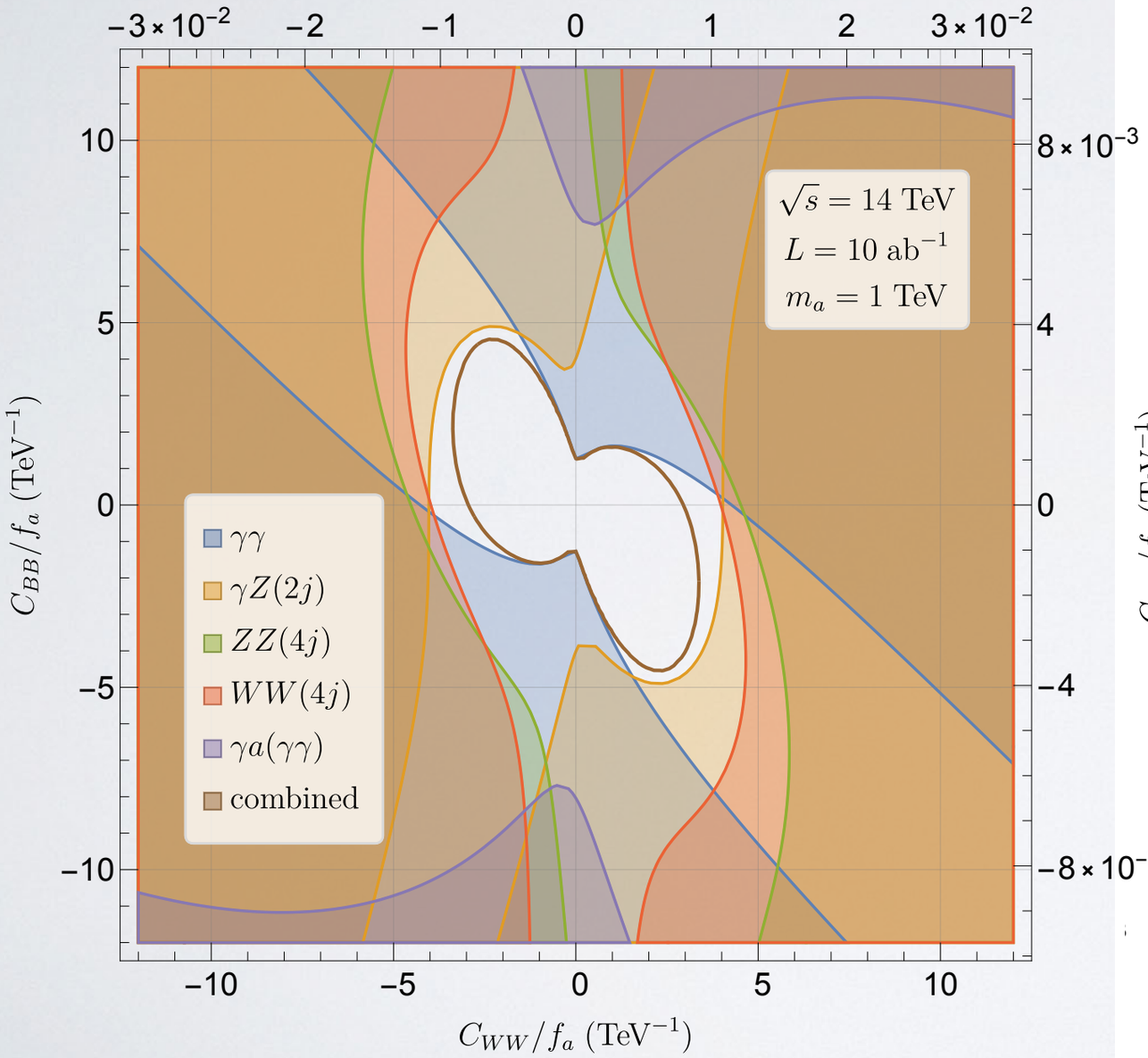
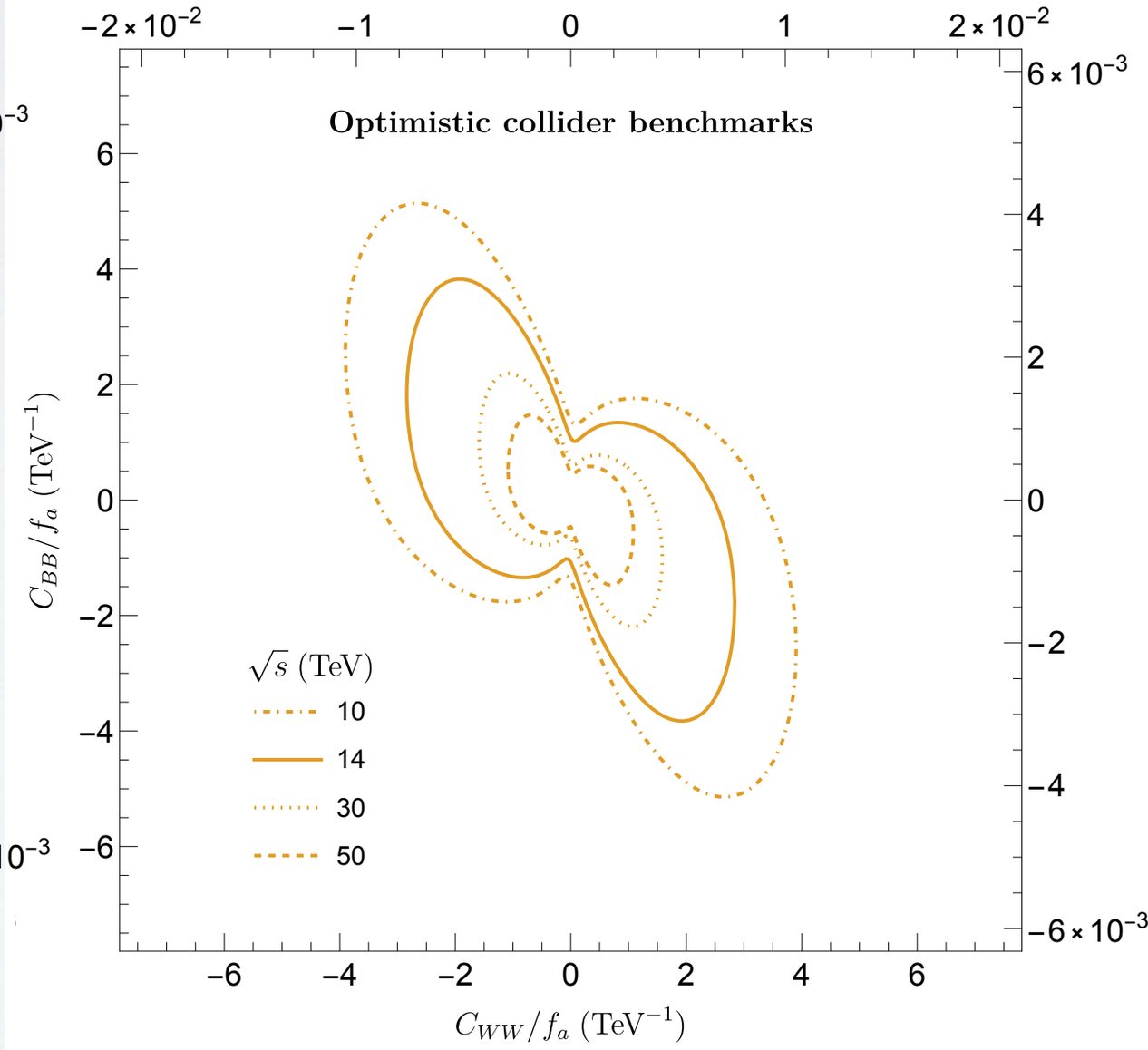
Complementary Channels

arXiv: 2203.04328





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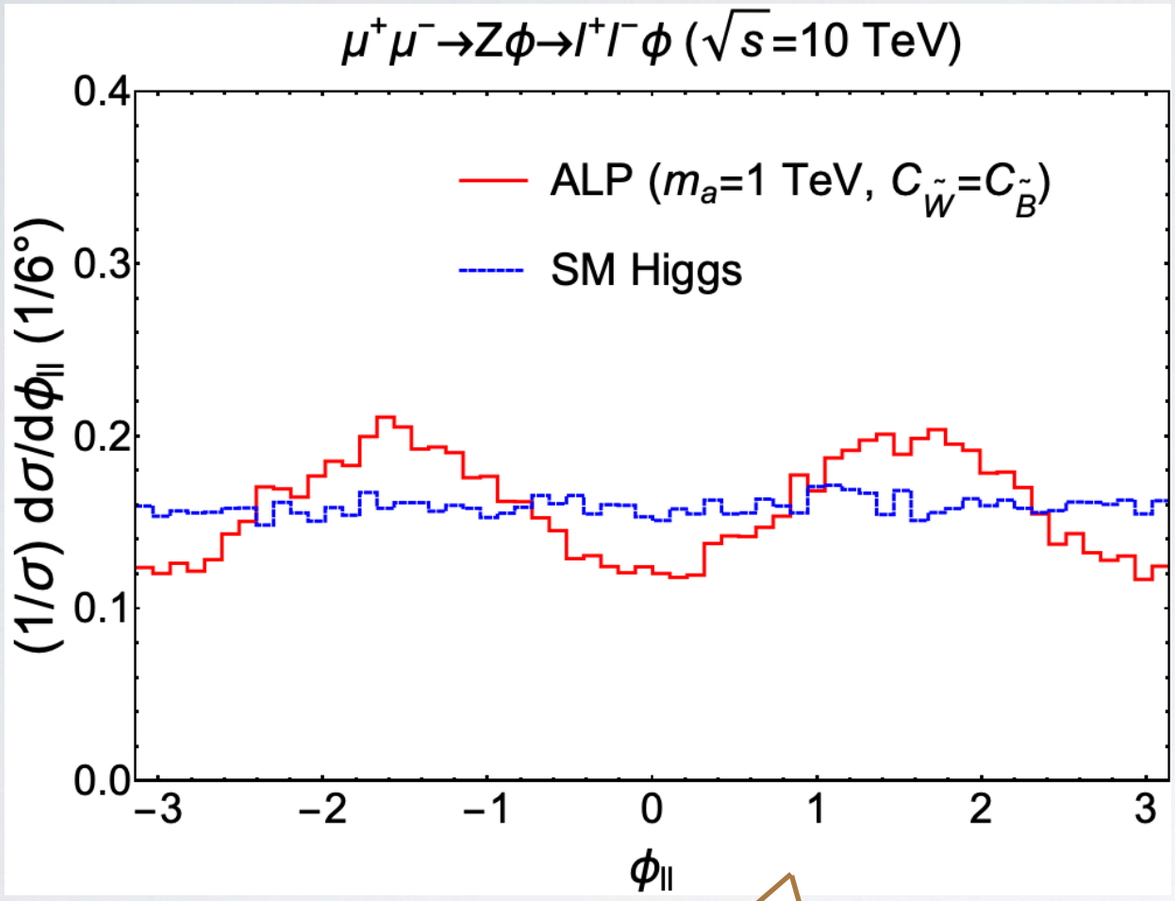
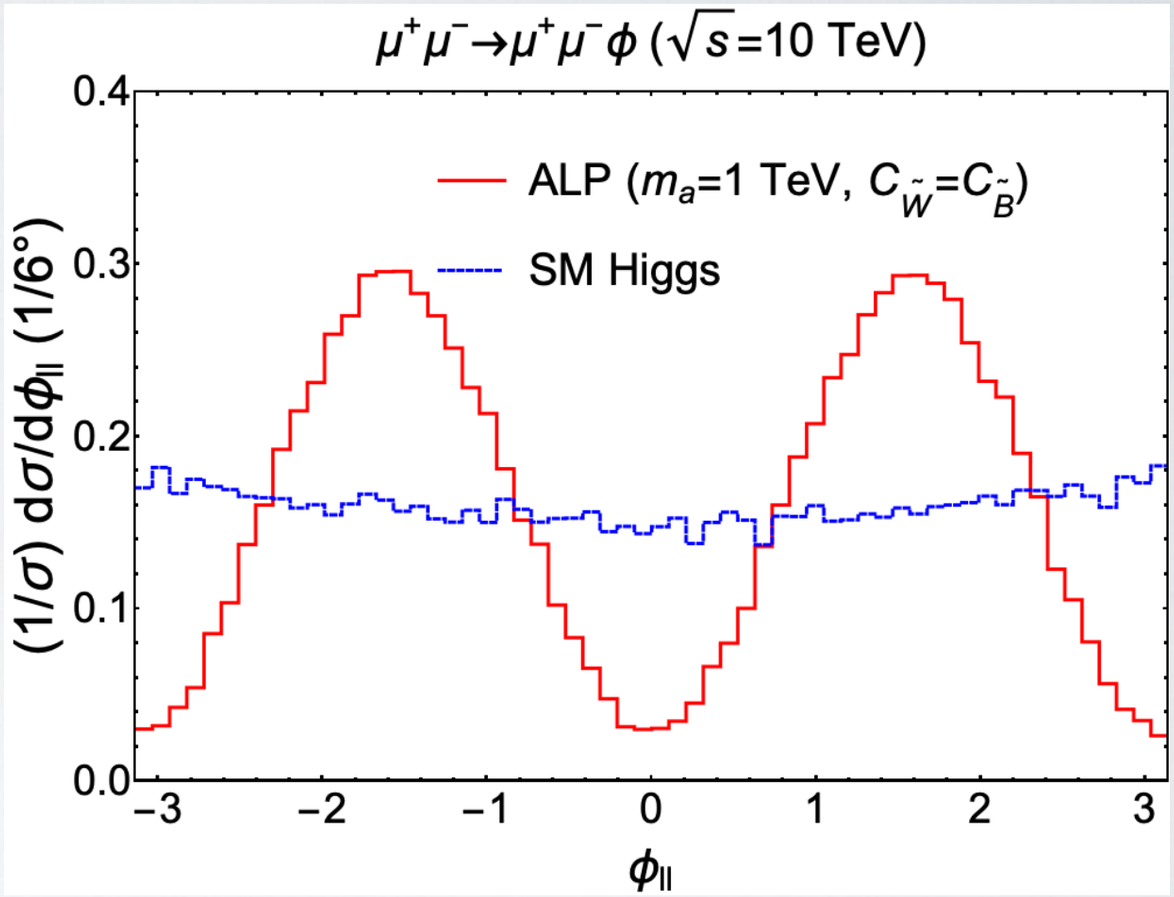
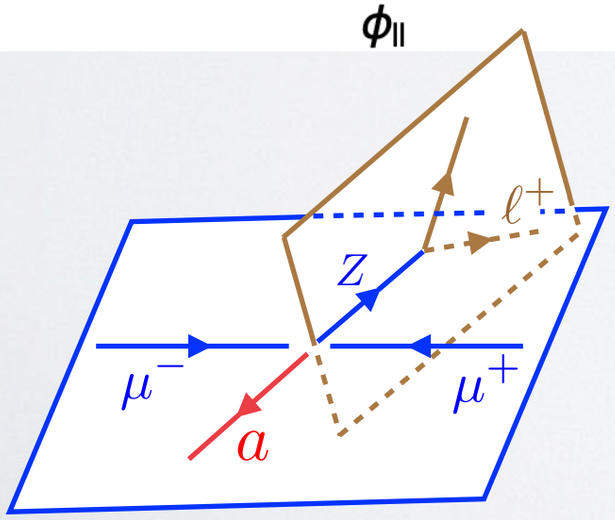
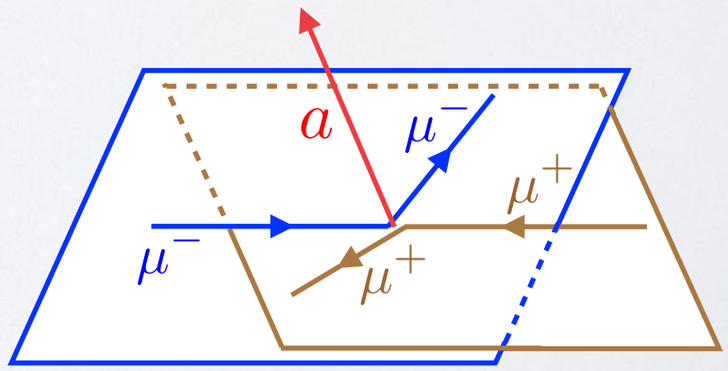
ALPs vs. Higgs









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Conclusion

- Muon colliders have great physics potential
- Search for Heavy ALPs
  - $\gamma\gamma$-fusion dominates ALP production
  - Complementary channels
  - Angular correlations can reveal the CP property

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Back-ups

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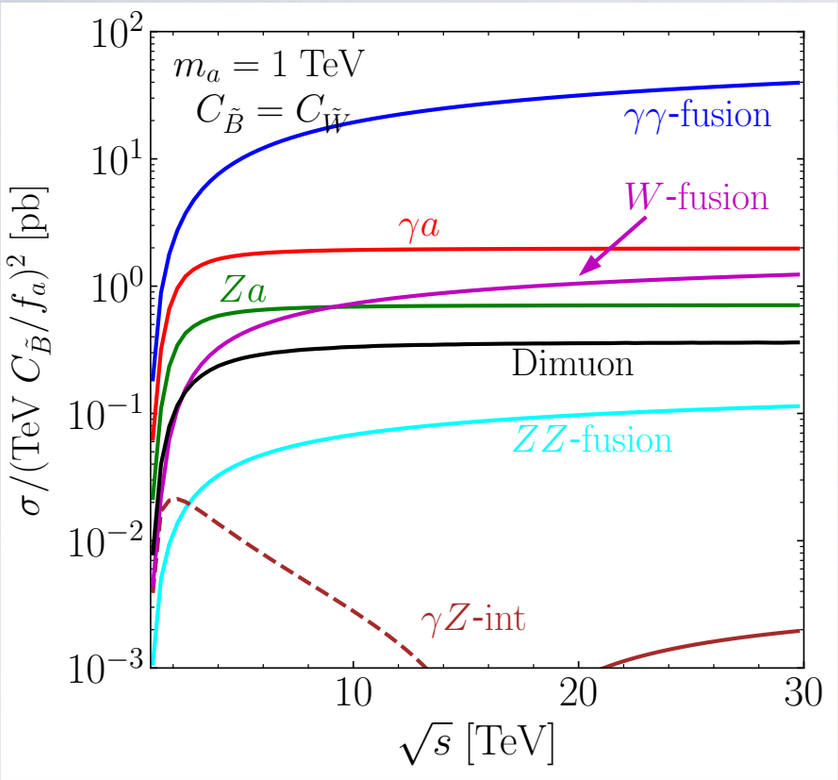

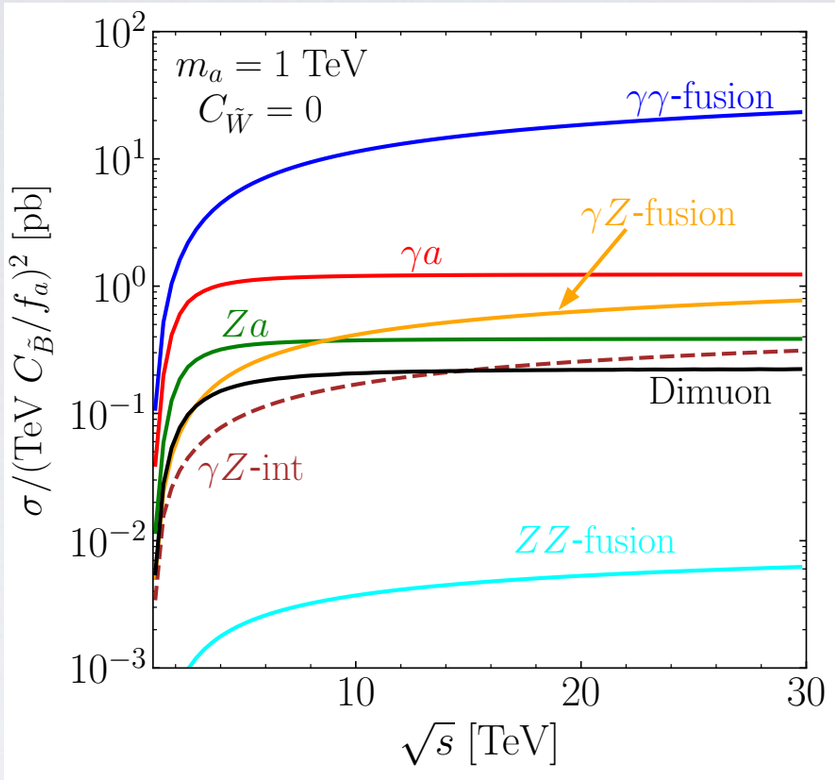

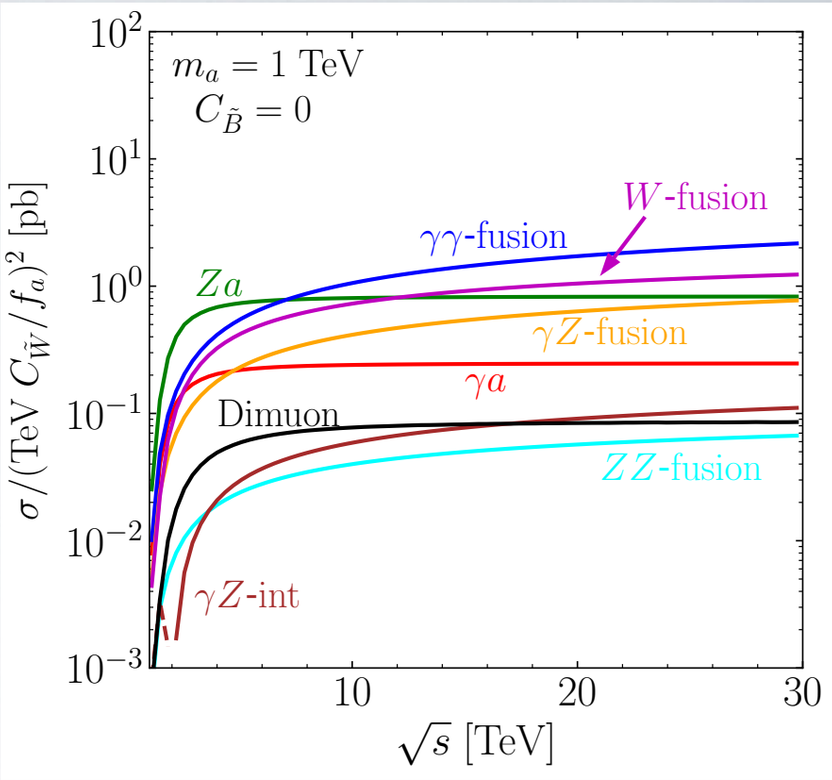

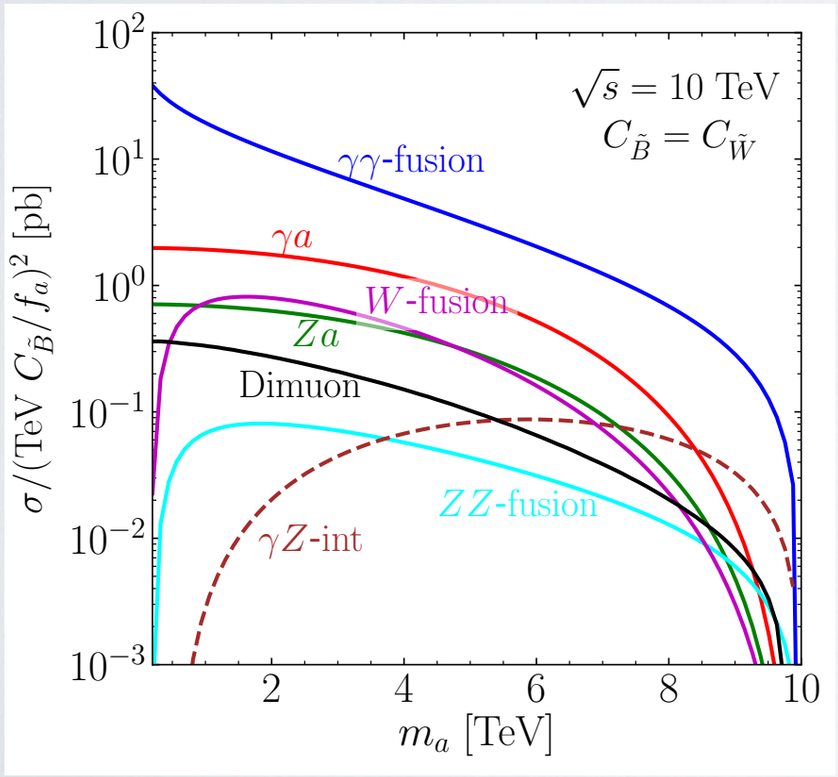

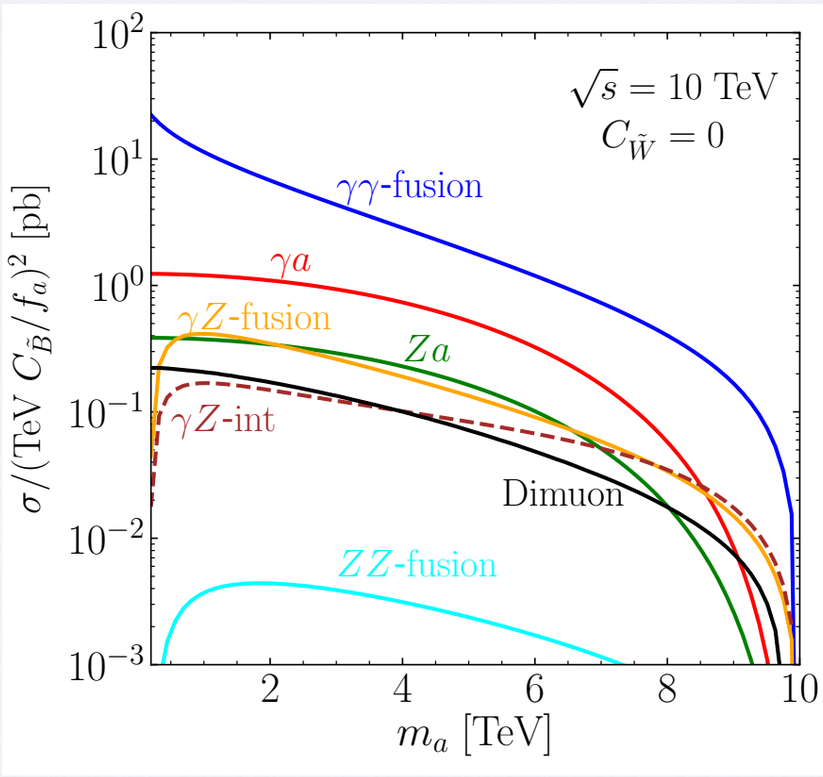

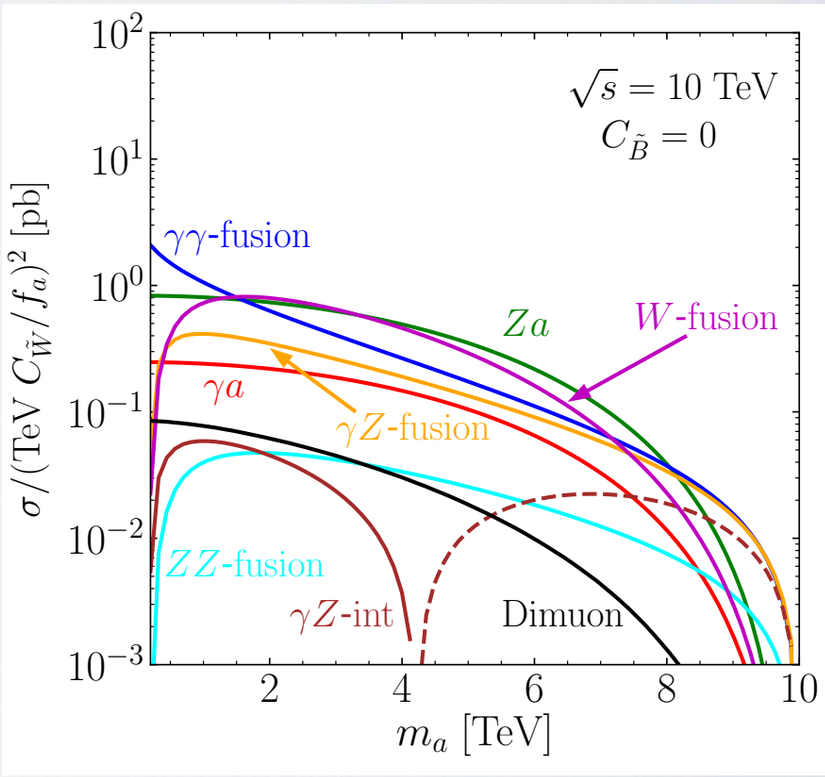

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Bounds @ MuC

- Consider decay channel $a \to \gamma\gamma$
- Leading backgrounds for
  - Associated production

$$\mu^+\mu^- \to V\gamma\gamma, \quad V = \gamma, Z$$

  - Inclusive VBF

$$\mu^+\mu^- \to \gamma\gamma \ \text{ with ISR}$$

  - Exclusive di-muon

$$\mu^+\mu^- \to \mu^+\mu^-\gamma\gamma$$

- Basic cuts

$$p_T(\gamma) > 10 \text{ GeV}, \quad |\eta(\gamma)| < 2.5, \quad \Delta R_{\gamma\gamma} > 0.4$$

$$\frac{|m_{\gamma\gamma} - m_a|}{m_a} < 0.05$$

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