Expect the unexpected: future directions in LLP searches

Tien-Tien Yu (CERN/UOregon)

based on work in progress with
Matthew McCullough and Wei Xue

DM@LHC — UHeidelberg/KIP — April 6, 2018

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axion-like particles (ALPs)

QCD axion

$$\mathcal{L} \supset \left(\frac{a}{f_a} - \bar{\Theta}\right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}^{a}_{\mu\nu}$$

$$\mathcal{L} \supset -g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

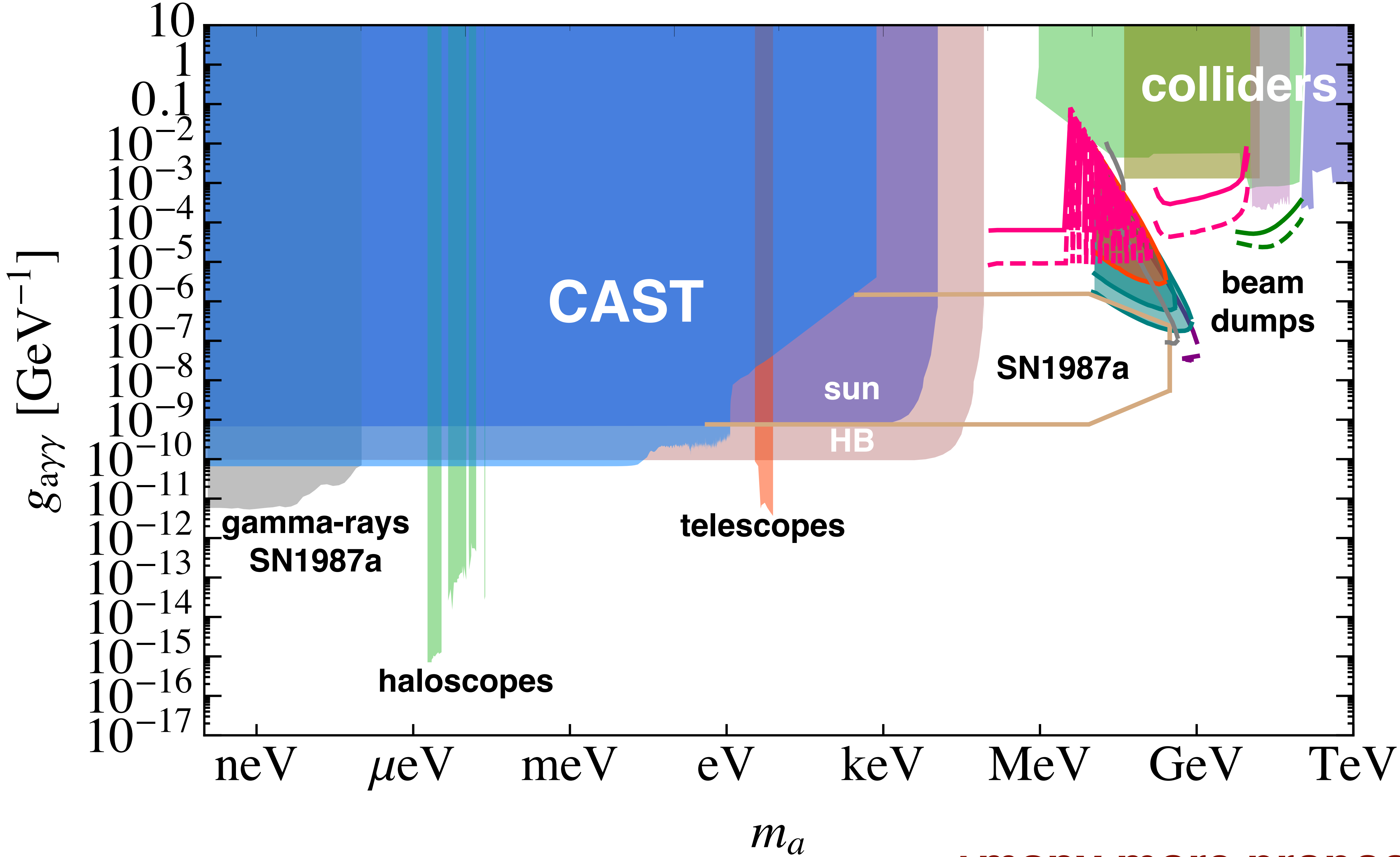
AXION

photon coupling and mass related by properties of pion

ALP

photon coupling and mass are independent parameters

many searches for ALPs



+many more proposed!

photon coupling

EM anomaly

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a/C}\left(\frac{E}{C} - \frac{2}{3}\frac{4+z}{1+z}\right)$$

color anomaly

$$z = \frac{m_u m_d}{(m_u + m_d)^2}$$

but what if the underlying theory is anomaly-free?

photon coupling

$$\mathcal{L}_{aff} \supset \frac{2m_f}{f_a} \partial_\mu a \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

$$\tilde{g}_{a\gamma\gamma} \sim \frac{\alpha}{2\pi f_a} \frac{m_a^2}{m_f^2} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

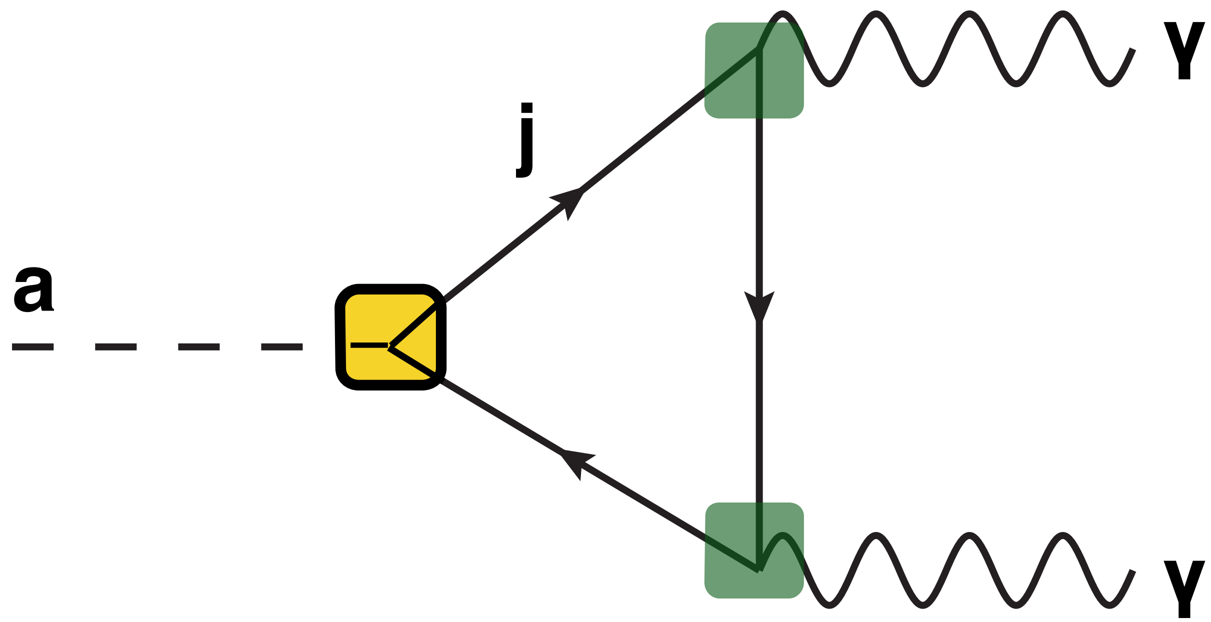
photon coupling

$$\mathcal{L}_{aff} \supset \frac{2m_f}{f_a} \partial_\mu a \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

$$\tilde{g}_{a\gamma\gamma} \sim \frac{\alpha}{2\pi f_a} \frac{m_a^2}{m_f^2} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

can we tell the difference?

ALP-photon coupling

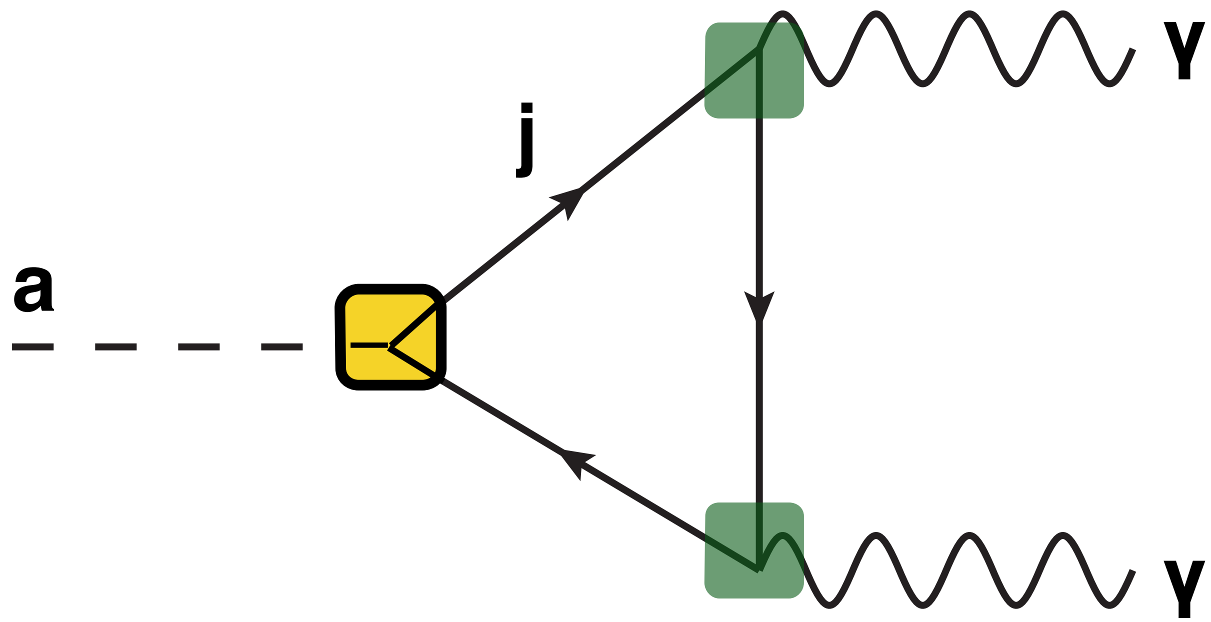


ALP charge

$$\mathcal{L} \supset \frac{\alpha}{2\pi f_a} a F^{\mu\nu} \widetilde{F}_{\mu\nu} \times \sum_j q_j^2 \tilde{q}_j F\left(\frac{m_a^2}{4m_j^2}\right)$$

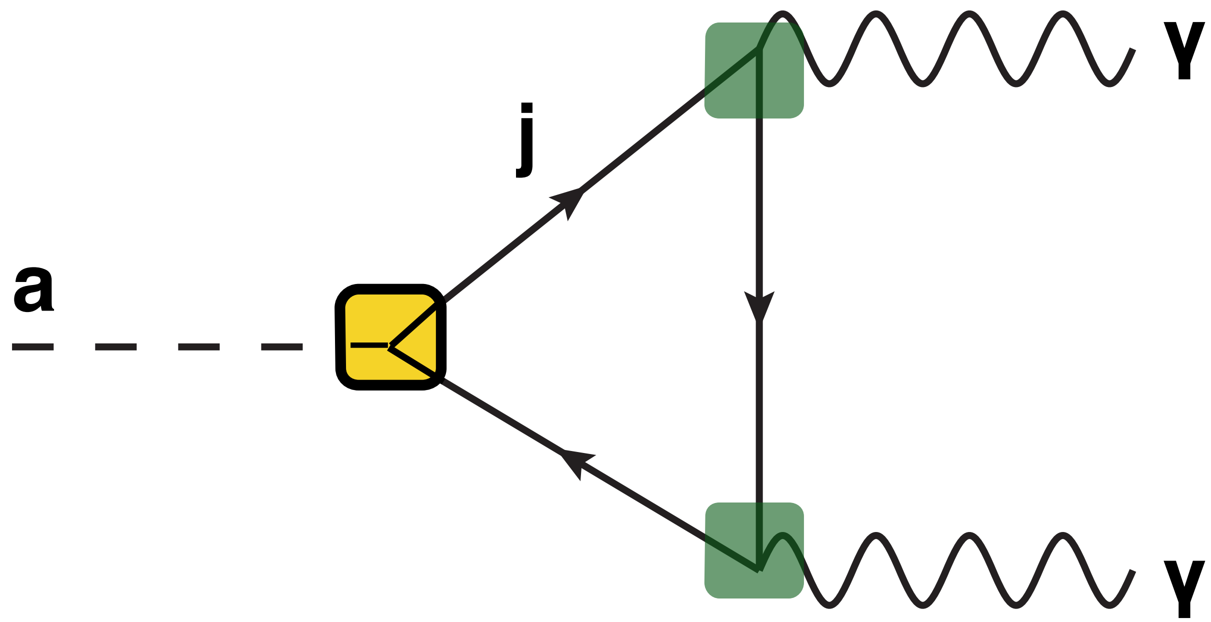
$$F(x) = \frac{1}{2x}\mathrm{Arctan}^2\left(\sqrt{\frac{x}{1-x}}\right)$$ "form factor"

ALP-photon coupling



$$m_a \ll m_j \qquad \mathcal{L} \sim \frac{\alpha}{2\pi f_a} a F^{\mu\nu} \widetilde{F}_{\mu\nu} \times \sum_j q_j^2 \tilde{q}_j \left(1 + \frac{1}{12}\frac{m_a^2}{m_j^2}\right)$$

ALP-photon coupling



$$m_a \ll m_j \qquad \mathcal{L} \sim \frac{\alpha}{2\pi f_a} a F^{\mu\nu} \widetilde{F}_{\mu\nu} \times \sum_j q_j^2 \tilde{q}_j \left(1 + \frac{1}{12} \frac{m_a^2}{m_j^2} \right)$$

cancels for non-anomalous models

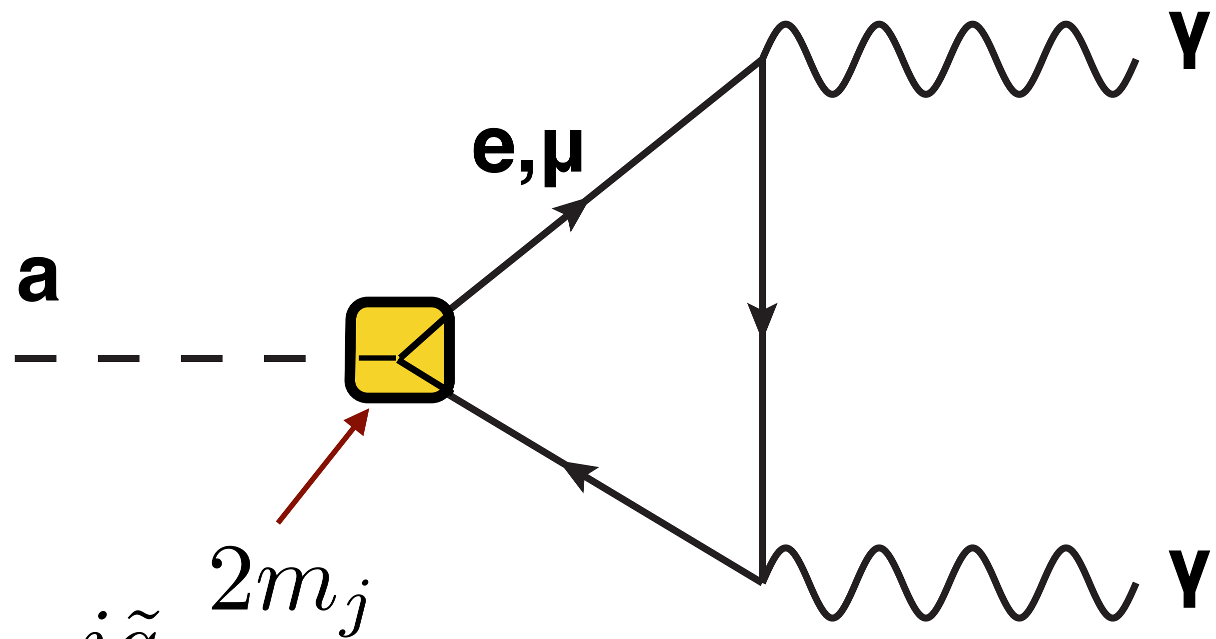
Coupling to Leptons

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \left(\tilde{q}_e \overline{e} \gamma^\mu \gamma^5 e + q_\mu \overline{\mu} \gamma^\mu \gamma^5 \mu \right)$$

$$-i \frac{2}{f_a} (\tilde{q}_e m_e \overline{e} \gamma^5 e + \tilde{q}_\mu m_\mu \overline{\mu} \gamma^5 \mu)$$

$$g^j_{aff} = -i \tilde{q}_j \frac{2 m_j}{f_a}$$

ALP-photon coupling

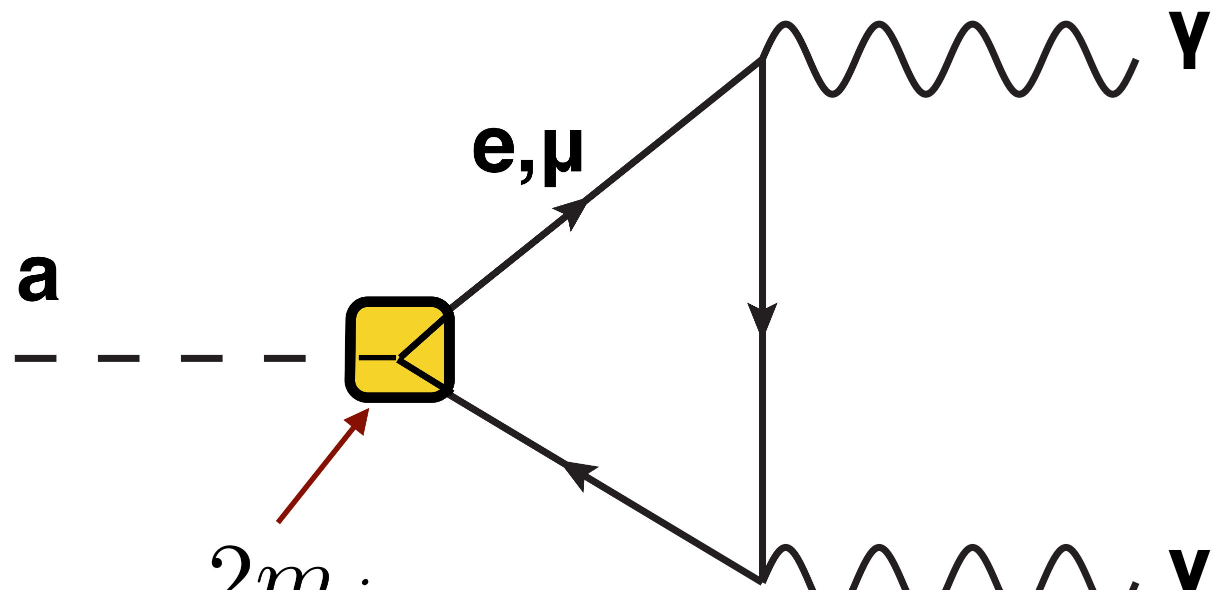


$$g^{j}_{aff} = -i\tilde{q}_j \frac{2m_j}{f_a}$$

with anomaly $\tilde{q}_e = 1$, $\tilde{q}_\mu = 1$

without anomaly $\tilde{q}_e = 1$, $\tilde{q}_\mu = -1$

ALP-photon coupling



$$g^j_{aff} = -i\tilde{q}_j \frac{2m_j}{f_a}$$

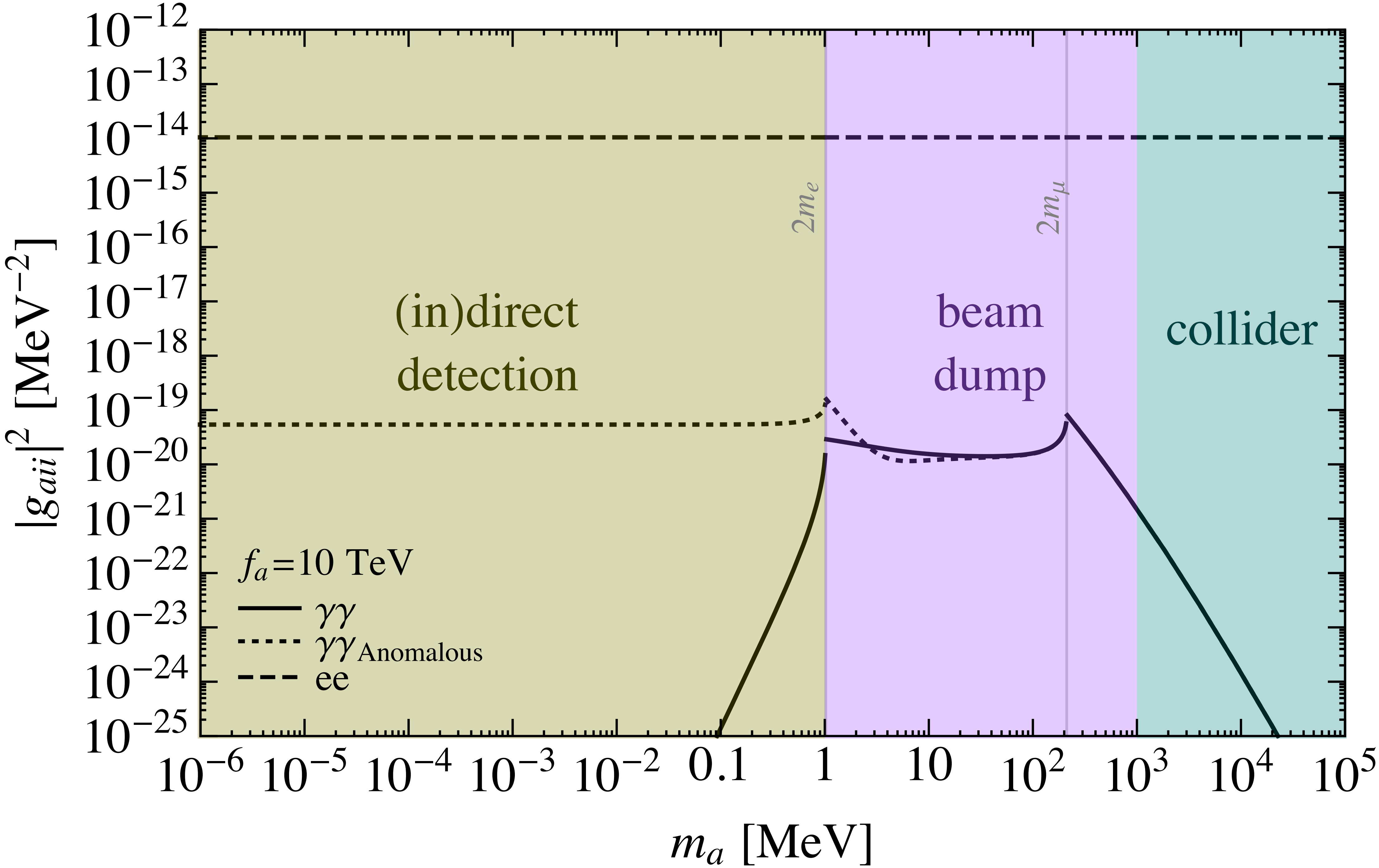
with anomaly $\tilde{q}_e = 1$ $\tilde{q}_\mu = 1$

ALP

without anomaly $\tilde{q}_e = 1$ $\tilde{q}_\mu = -1$

nALP

nALP couplings



decay widths

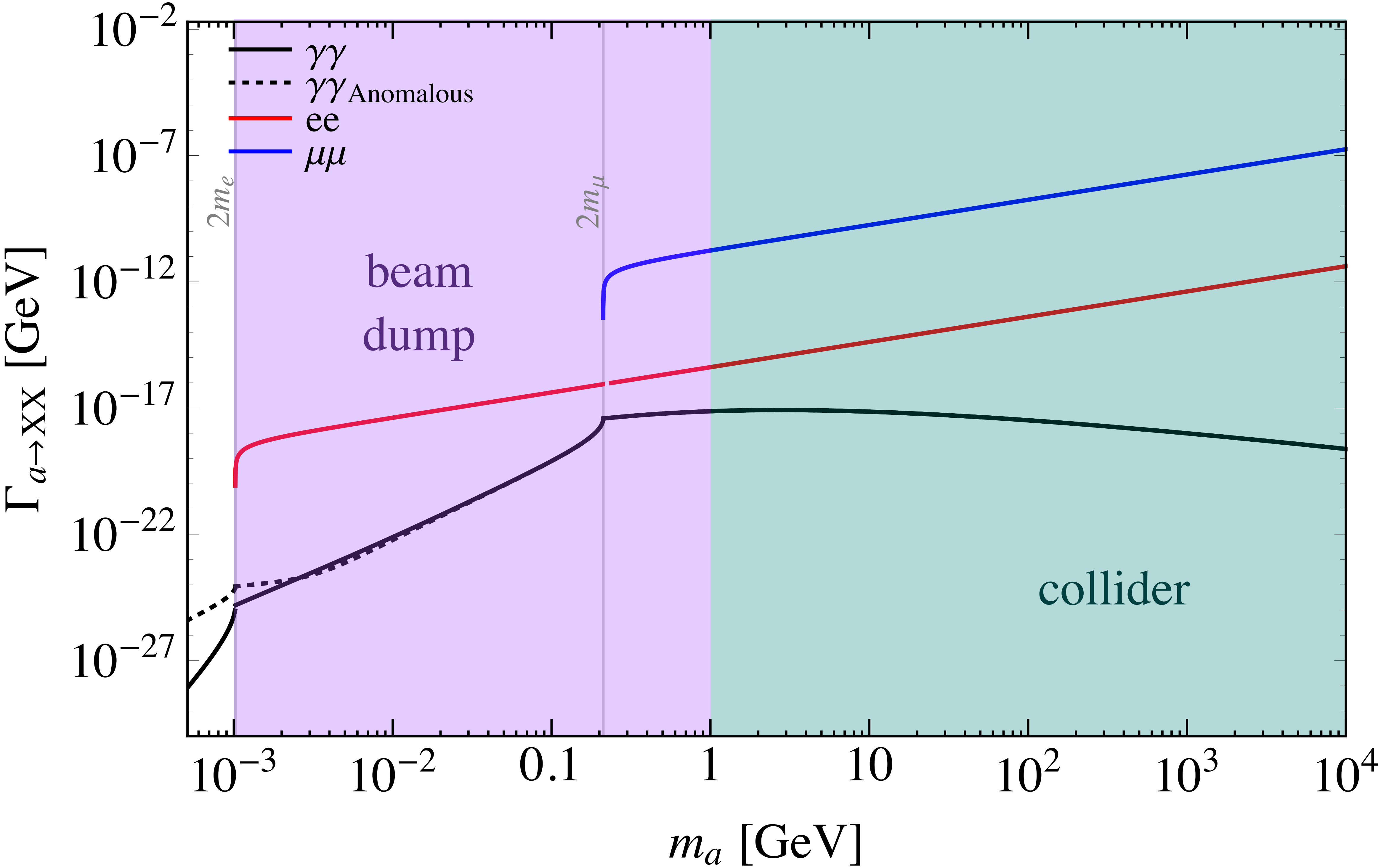
$$\Gamma_{aff} = \frac{|g_{aff}|^2}{8\pi} m_a \sqrt{1 - \frac{4m_f^2}{m_a^2}}$$

$$\Gamma_{a\gamma\gamma} = \frac{|g_{a\gamma\gamma}|^2}{64\pi} m_a^3$$

with anomaly $$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a} \left[F\left(\frac{m_a^2}{4m_e^2}\right) + F\left(\frac{m_a^2}{4m_\mu^2}\right) \right]$$

without anomaly $$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a} \left[F\left(\frac{m_a^2}{4m_e^2}\right) - F\left(\frac{m_a^2}{4m_\mu^2}\right) \right]$$

decay widths



goodness of fit

$$R \equiv N_{ee}/N_{\gamma\gamma} = \Gamma_{ee}/\Gamma_{\gamma\gamma}$$

$$\chi^2 = \frac{(R_{ab} - R_{non-ab})^2}{\Delta R^2}$$

$$\Delta R = \sqrt{\Delta R^2_{stat} + \Delta R^2_{syst}}$$

goodness of fit

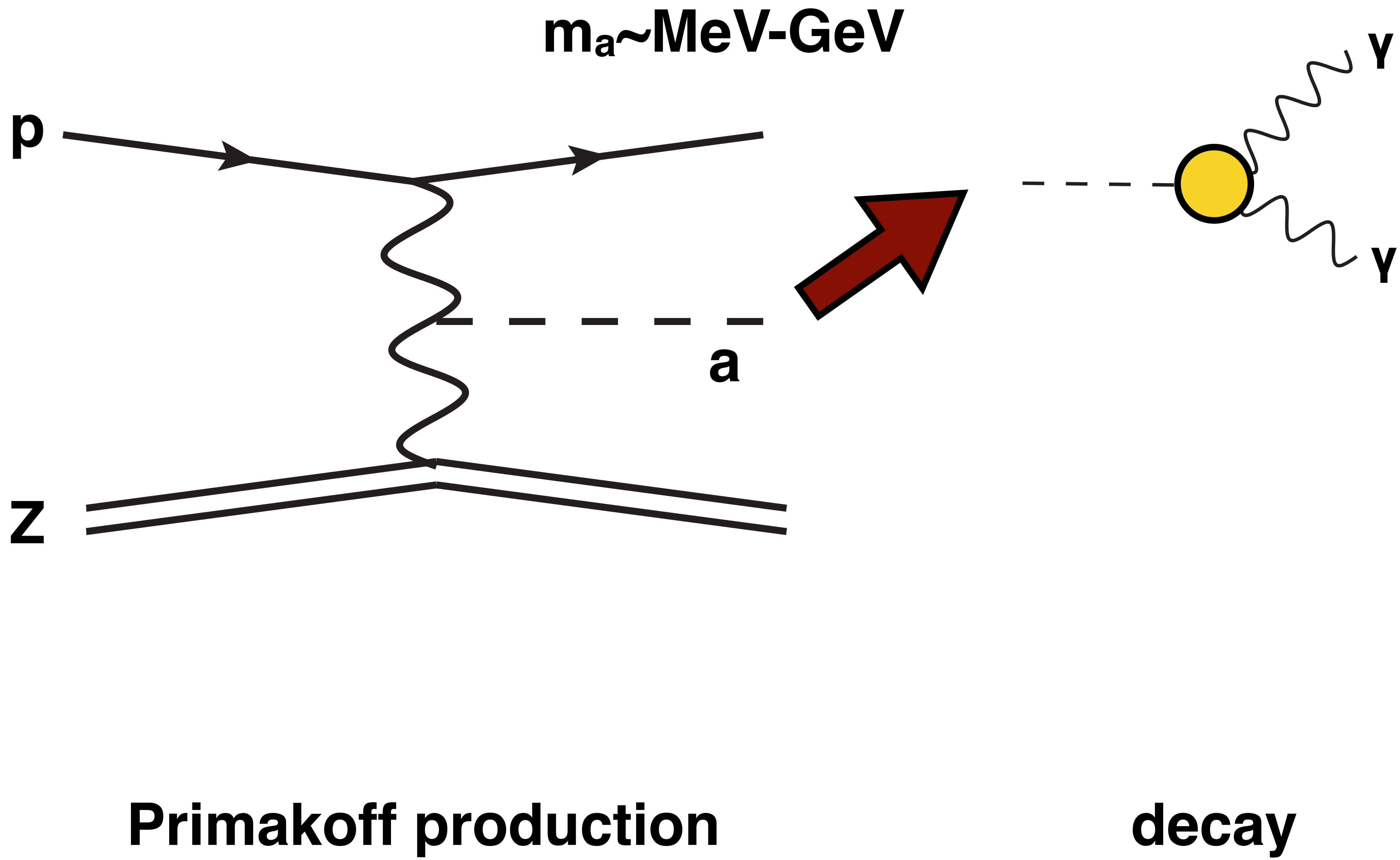
$$\Delta R = \sqrt{\Delta R_{stat}^2 + \Delta R_{syst}^2}$$

statistical uncertainty $\Delta N_i = 1/\sqrt{N_i}$

$$\begin{aligned}\Delta R_{stat}^2 &= \left(\Delta N_{ee}/N_{\gamma\gamma}\right)^2 + \left(R\Delta N_{\gamma\gamma}/N_{\gamma\gamma}\right)^2 \\ &= 1/N_{\gamma\gamma}^2 \left(1/N_{ee} + R^2/N_{\gamma\gamma}\right)\end{aligned}$$

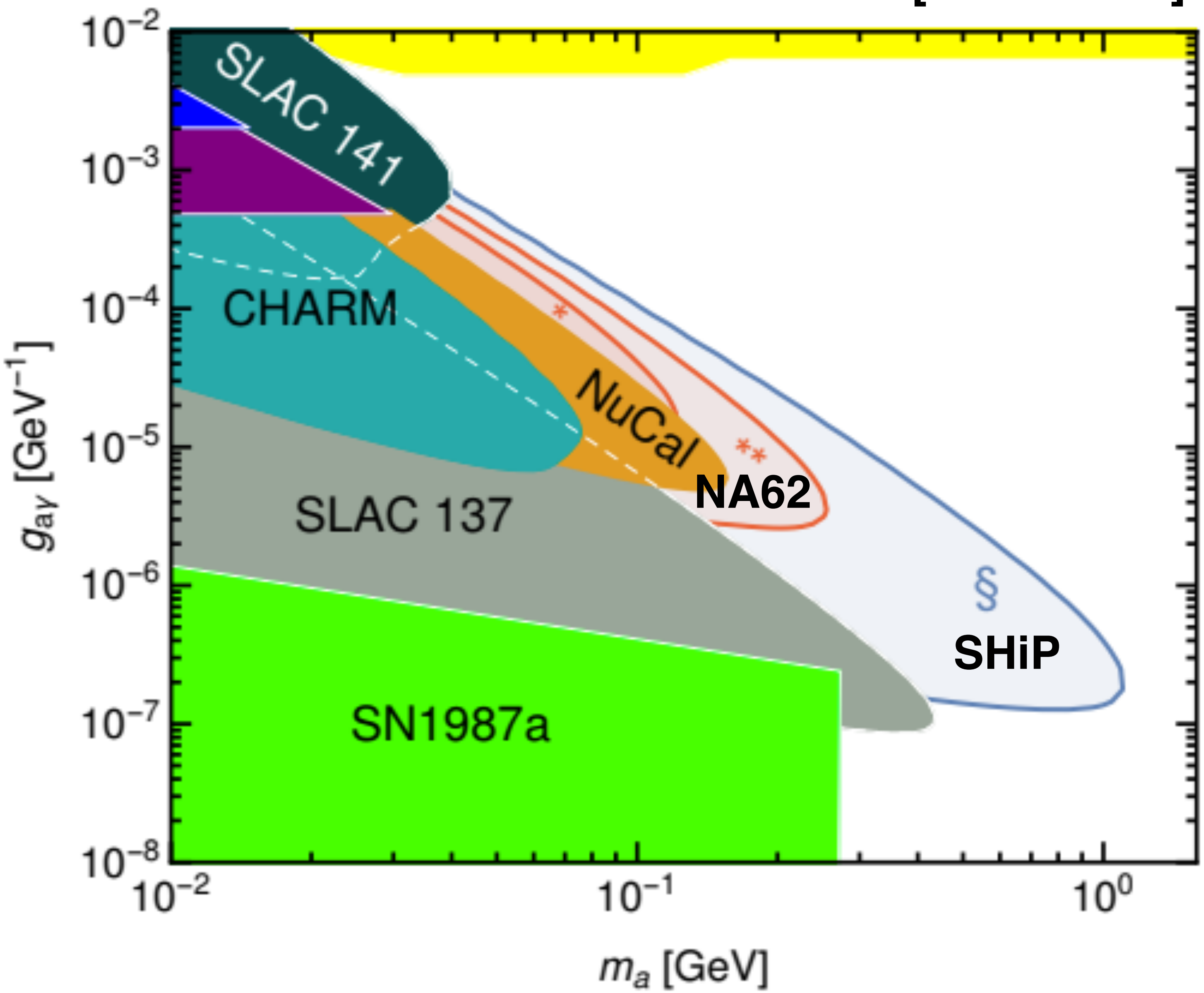
$$\Delta R(R, N_{\gamma\gamma})_{stat}^2 = 1/N_{\gamma\gamma}^3 \left(1/R + R^2\right)$$

beam dump

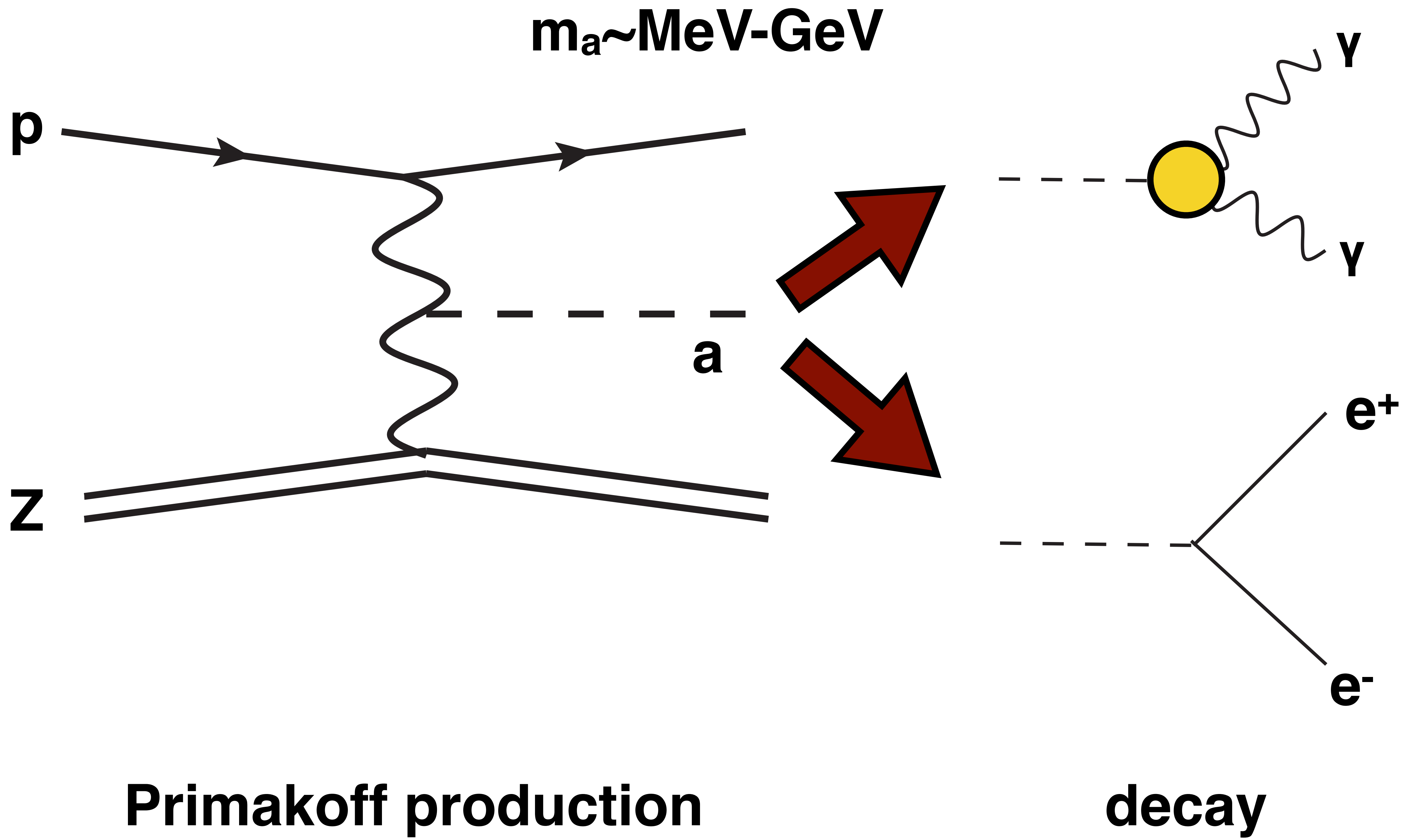


beam dump

[1512.03069]

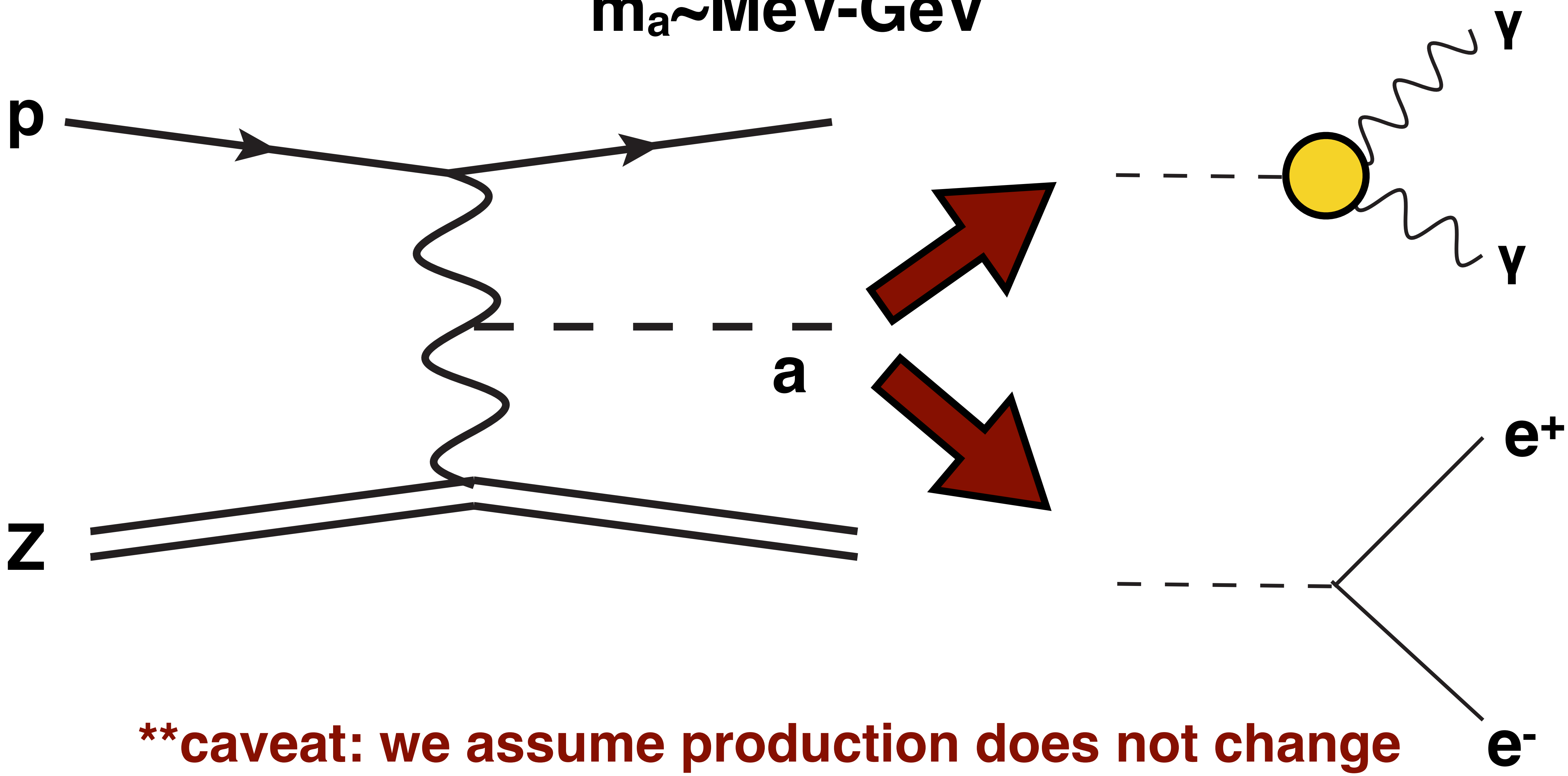


beam dump



beam dump

m_a~MeV-GeV

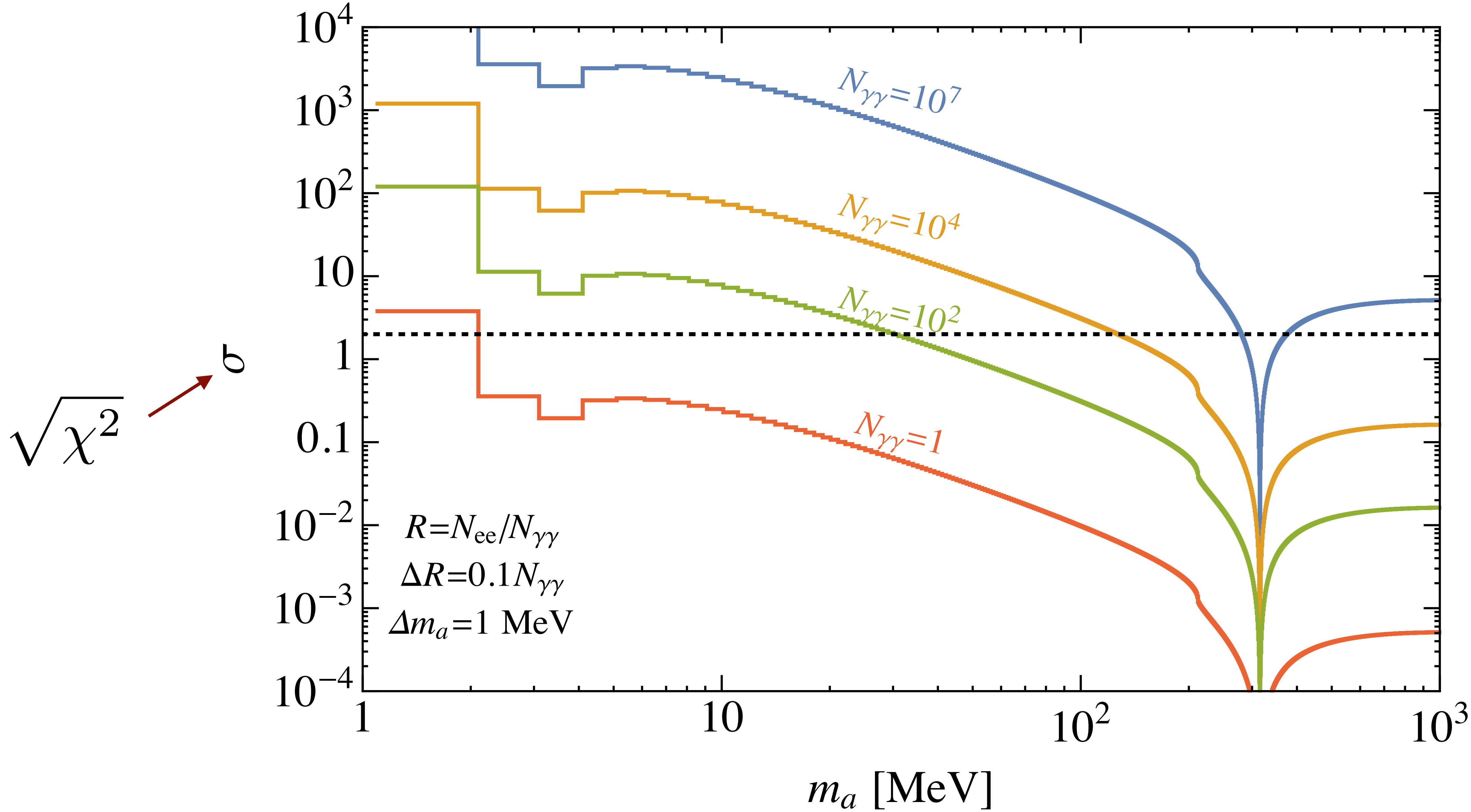


**caveat: we assume production does not change

Primakoff production

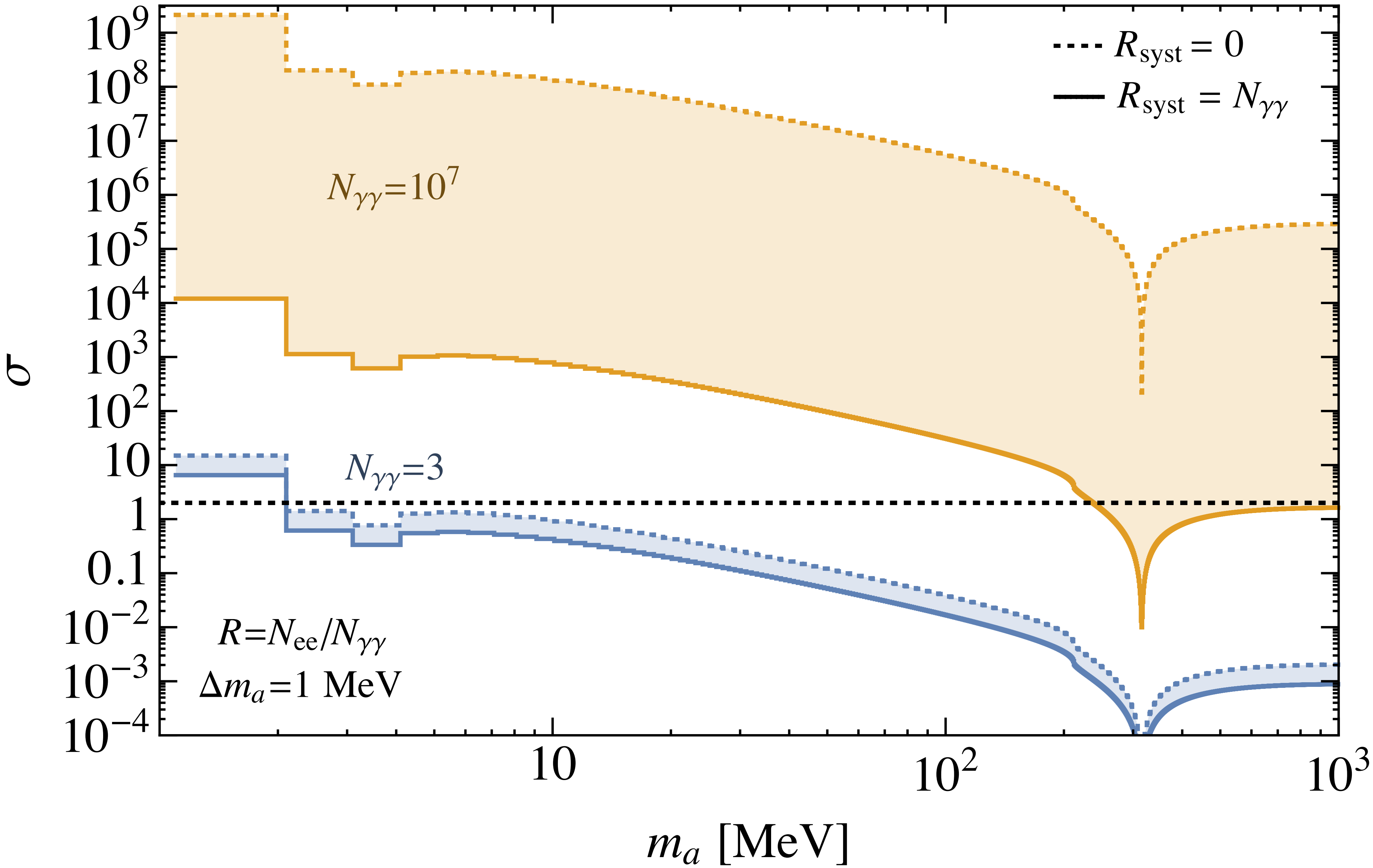
decay

beam dump



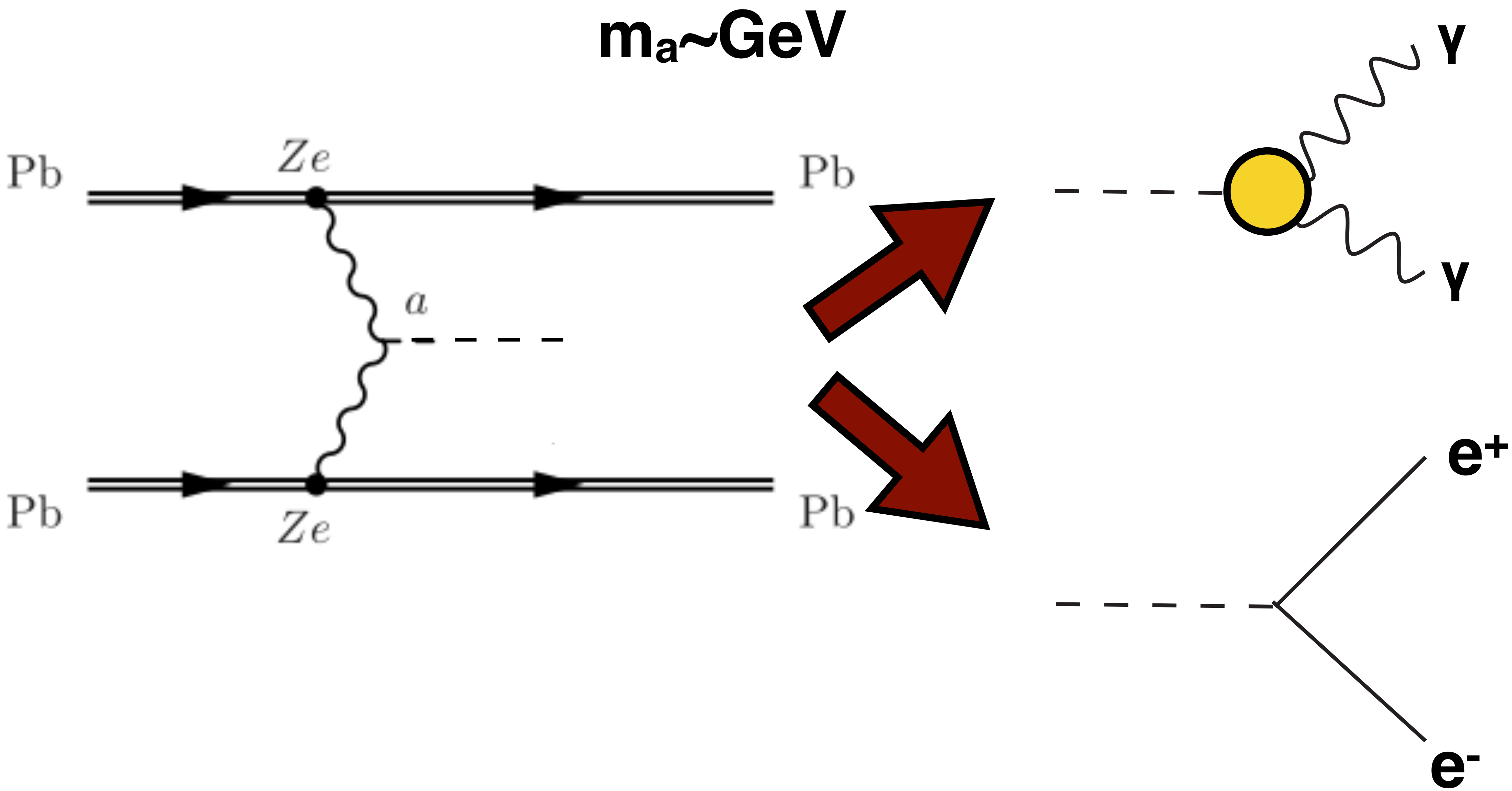
$\sqrt{\chi^2}$
σ
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
$N_{\gamma\gamma}=10^7$
$N_{\gamma\gamma}=10^4$
$N_{\gamma\gamma}=10^2$
$N_{\gamma\gamma}=1$
$R=N_{ee}/N_{\gamma\gamma}$
$\Delta R=0.1 N_{\gamma\gamma}$
$\Delta m_a=1$ MeV
1
10
10^2
10^3
m_a [MeV]

beam dump



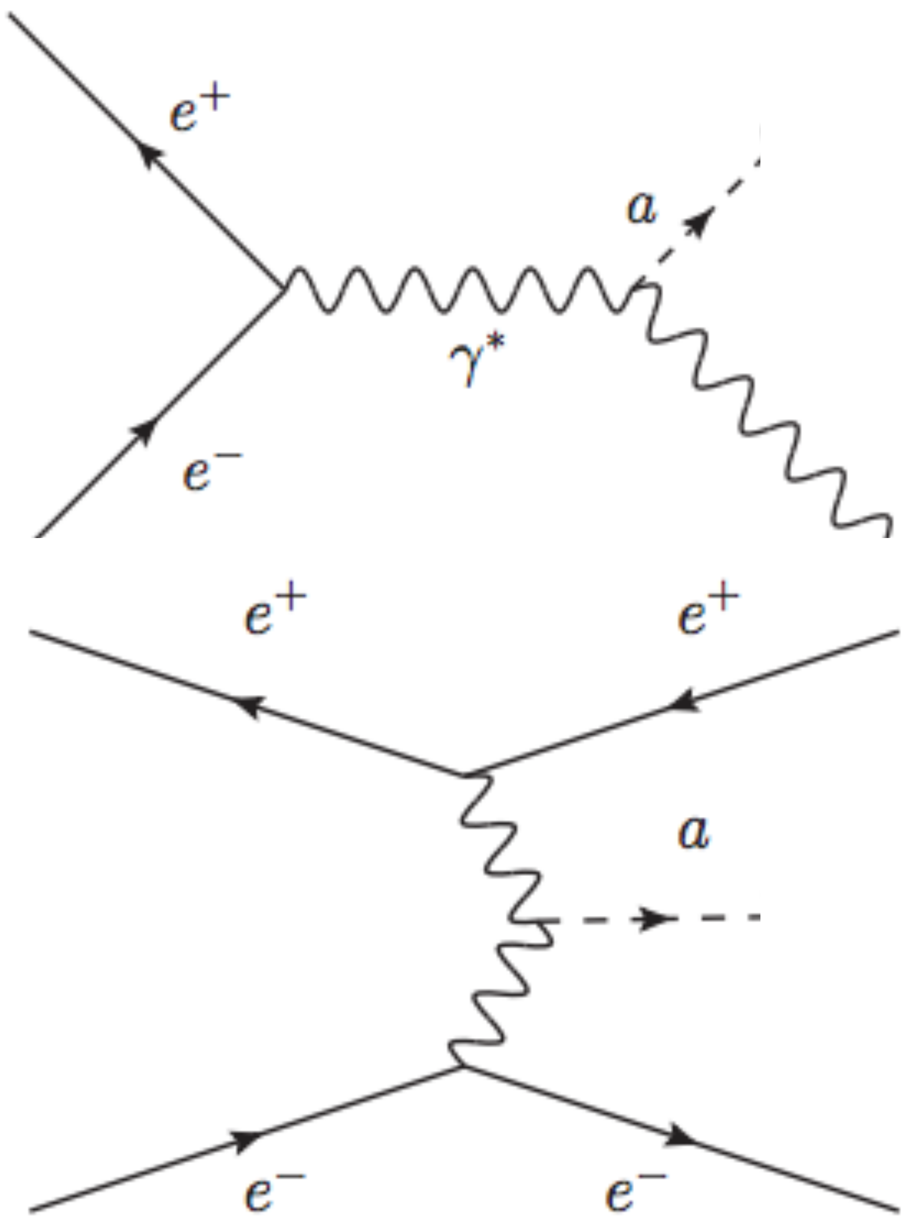
$R_{\rm syst} = 0$
$R_{\rm syst} = N_{\gamma\gamma}$
$N_{\gamma\gamma}$=10^7
$N_{\gamma\gamma}$=3
R=$N_{\rm ee}/N_{\gamma\gamma}$
Δm_a=1 MeV
σ
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10
10^2
10^3
m_a [MeV]

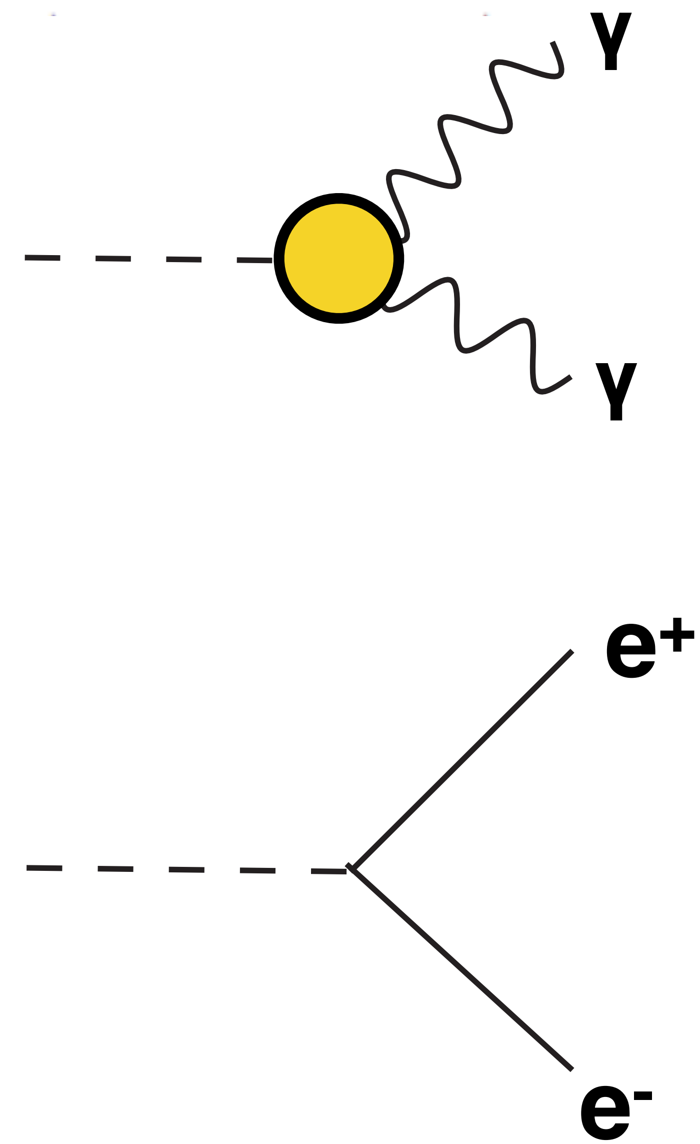
collider

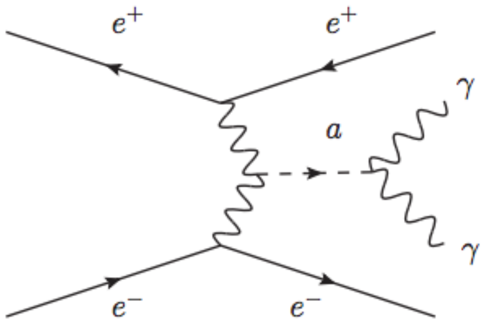


collider

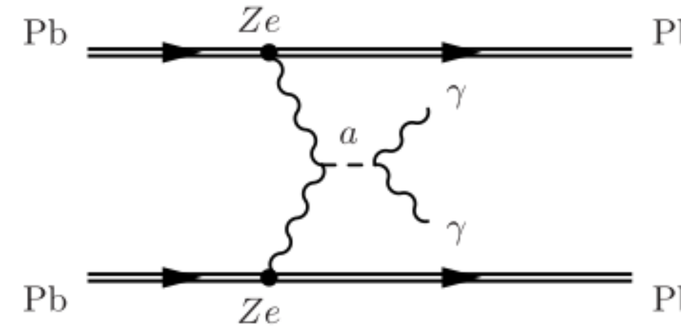
m_a~GeV





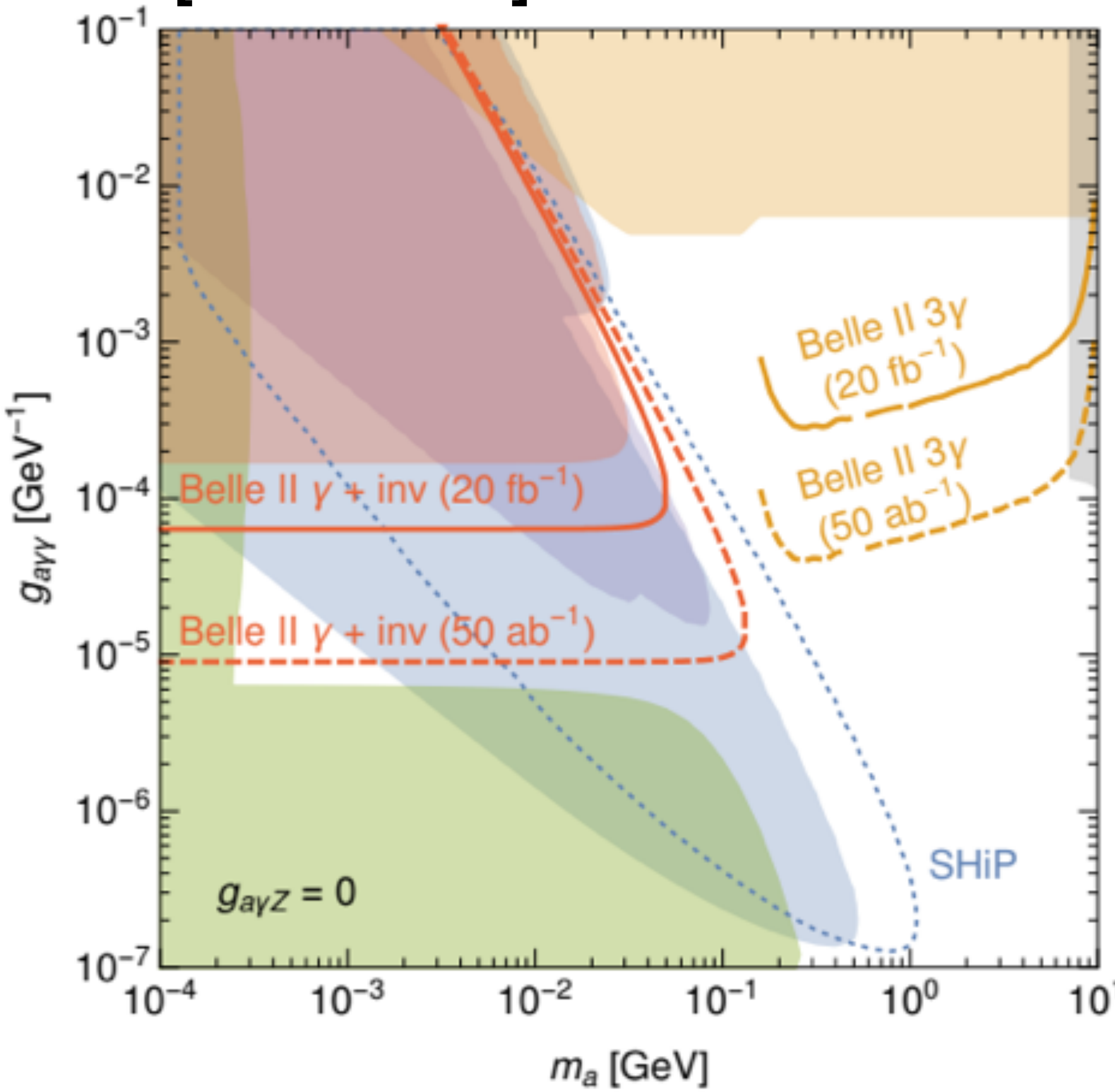


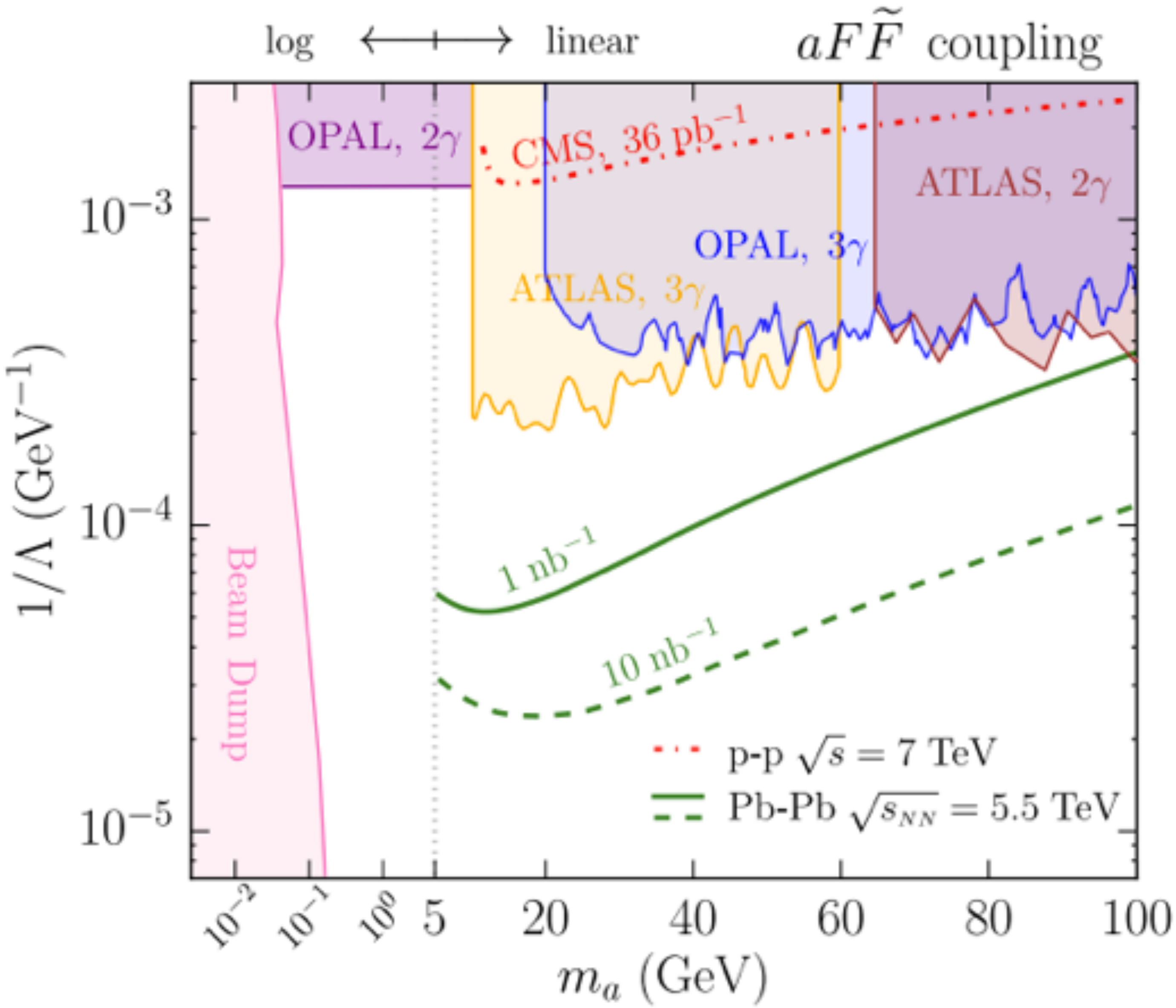
collider



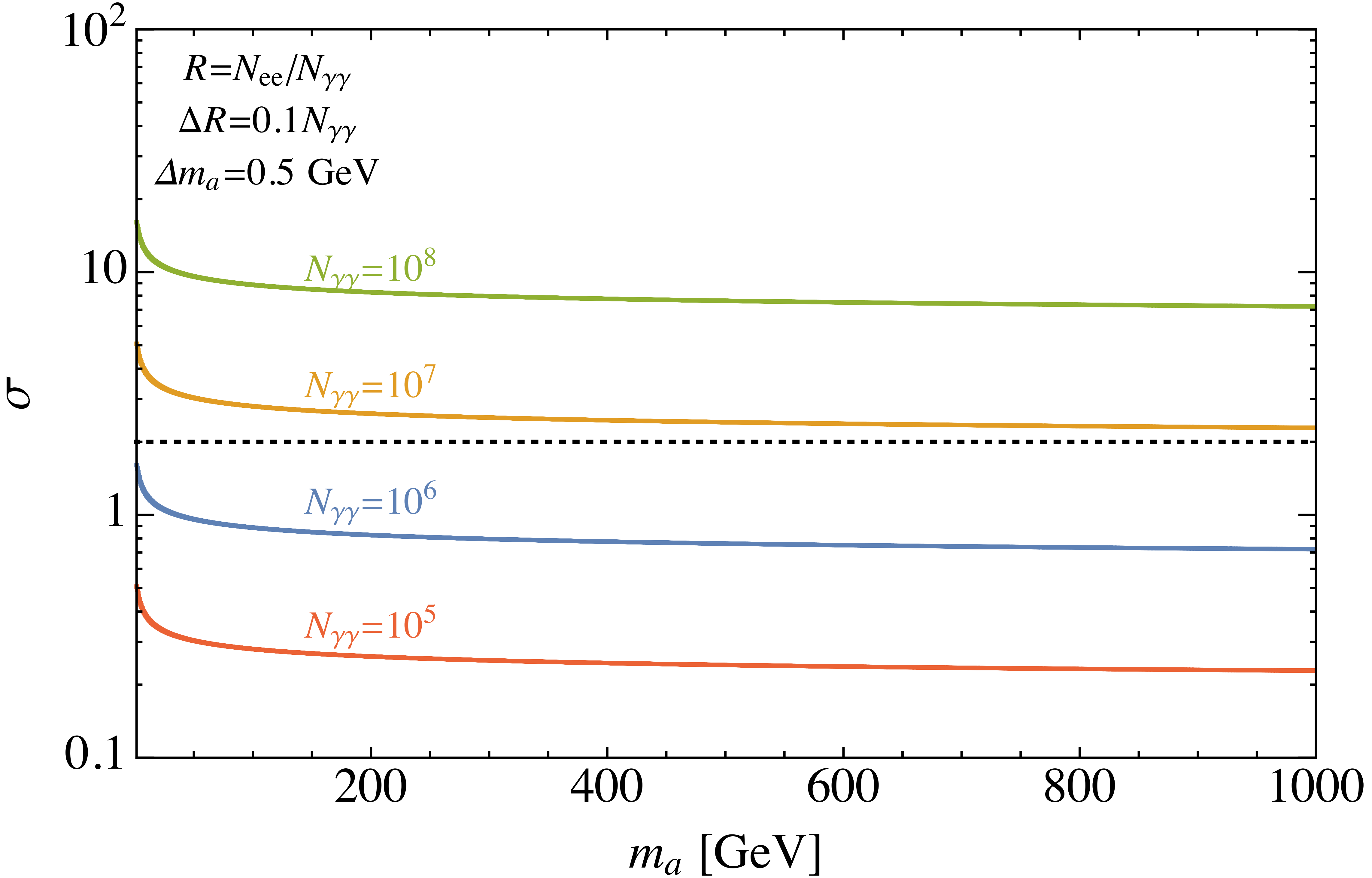
[1607.06083], see also [1509.00476]

[1709.00009]



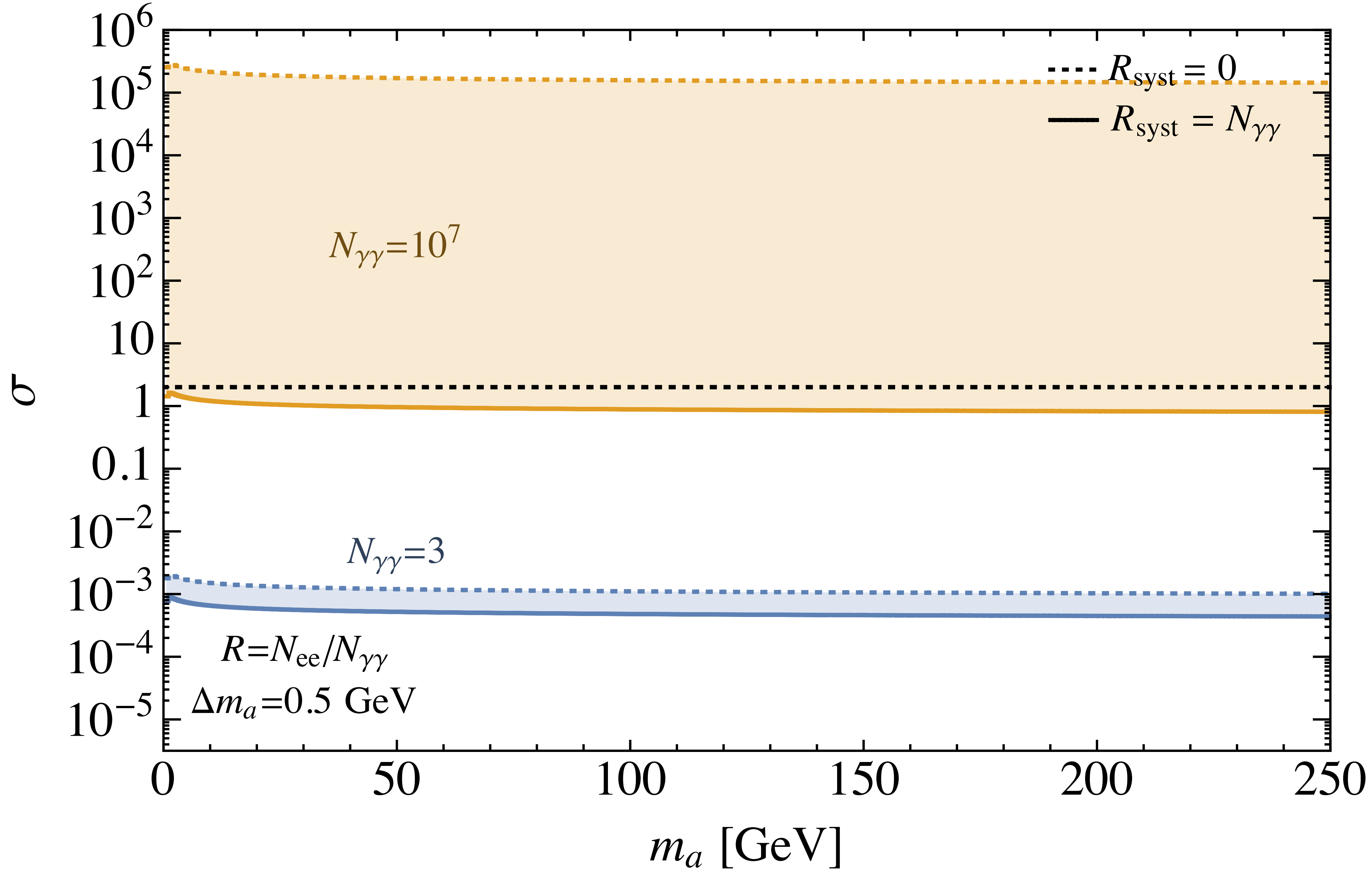


collider



$R=N_{ee}/N_{\gamma\gamma}$
$\Delta R=0.1N_{\gamma\gamma}$
$\Delta m_a=0.5$ GeV
$N_{\gamma\gamma}=10^8$
$N_{\gamma\gamma}=10^7$
$N_{\gamma\gamma}=10^6$
$N_{\gamma\gamma}=10^5$
10^2
10
1
0.1
σ
200
400
600
800
1000
m_a [GeV]

collider



10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ
0
50
100
150
200
250
m_a [GeV]
$R_{\rm syst} = 0$
$R_{\rm syst} = N_{\gamma\gamma}$
$N_{\gamma\gamma}=10^7$
$N_{\gamma\gamma}=3$
$R=N_{\rm ee}/N_{\gamma\gamma}$
Δm_a=0.5 GeV

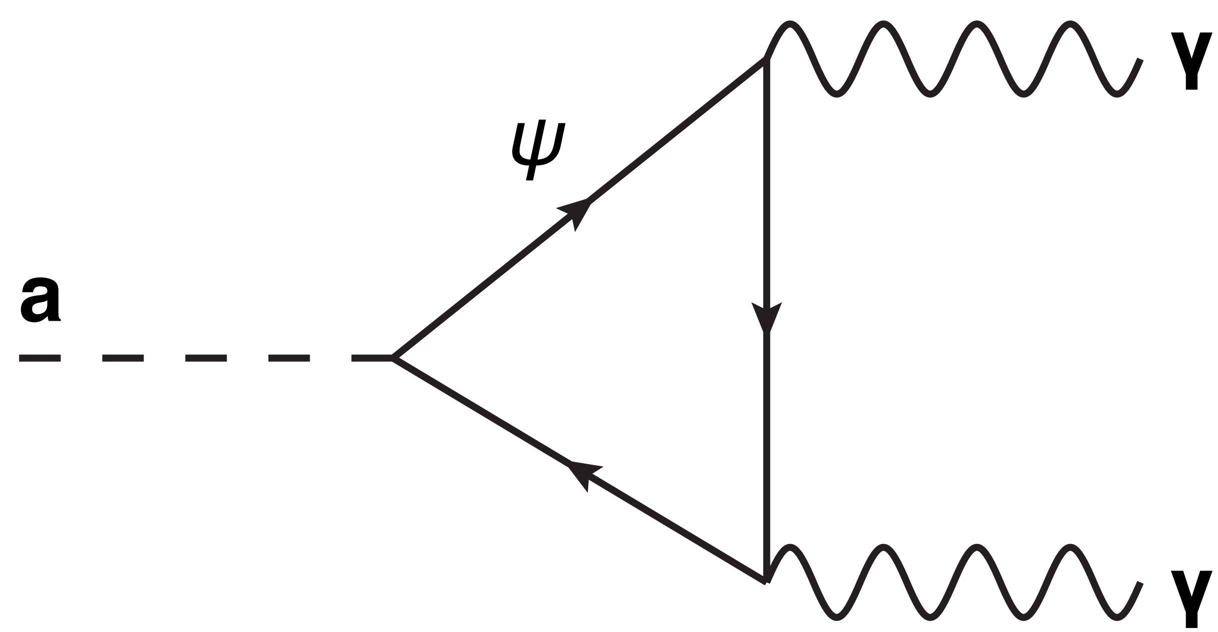
conclusions

- anomalous vs. non-anomalous theories will give different predictions for the ratio of the photon and fermion couplings
- beam dump searches can start to differentiate with $N>10^2$ events for MeV-GeV masses
- collider searches can differentiate with $N>10^{6-7}$ for masses above a few GeV
- systematics are experiment dependent, but the lower the better

another example

new heavy fermions

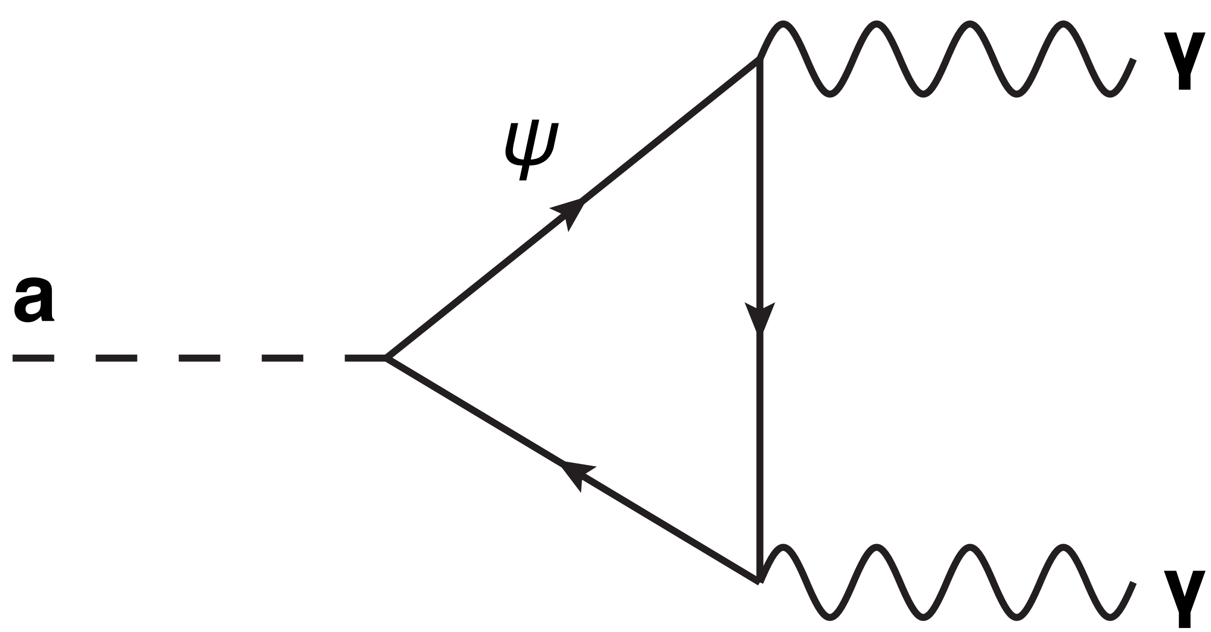
no coupling to SM fermions
coupling to heavy fermions ψ



$$\mathcal{L}_{nALP} \supset \frac{\alpha_{EM}}{2\pi f_a} \sum_{\psi} F\left(\frac{m_a^2}{4m_\psi^2}\right) aF^{\mu\nu}\tilde{F}_{\mu\nu} \quad \mathcal{L}_{ALP} \supset g_{a\gamma\gamma} aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

new heavy fermions

no coupling to SM fermions
coupling to heavy fermions ψ

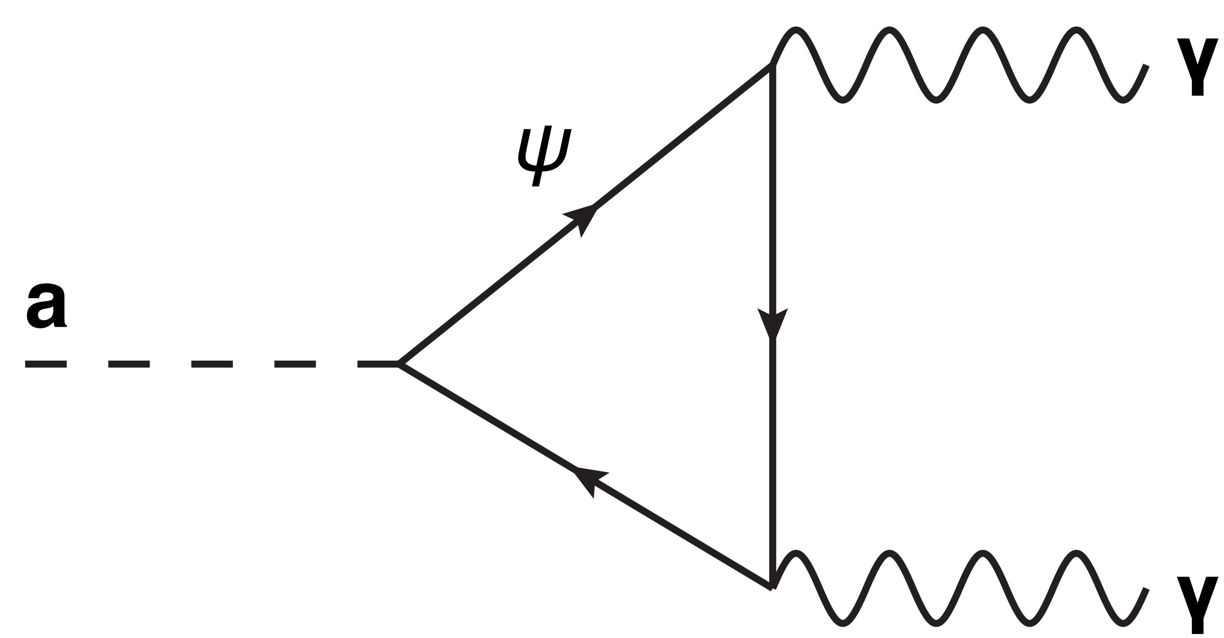


$$\mathcal{L}_{nALP} \supset \frac{\alpha_{EM}}{2\pi f_a} \sum_\psi F\left(\frac{m_a^2}{4m_\psi^2}\right) aF^{\mu\nu}\tilde{F}_{\mu\nu} \qquad \mathcal{L}_{ALP} \supset g_{a\gamma\gamma} aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$m_\psi = \lambda_\psi f$$

new heavy fermions

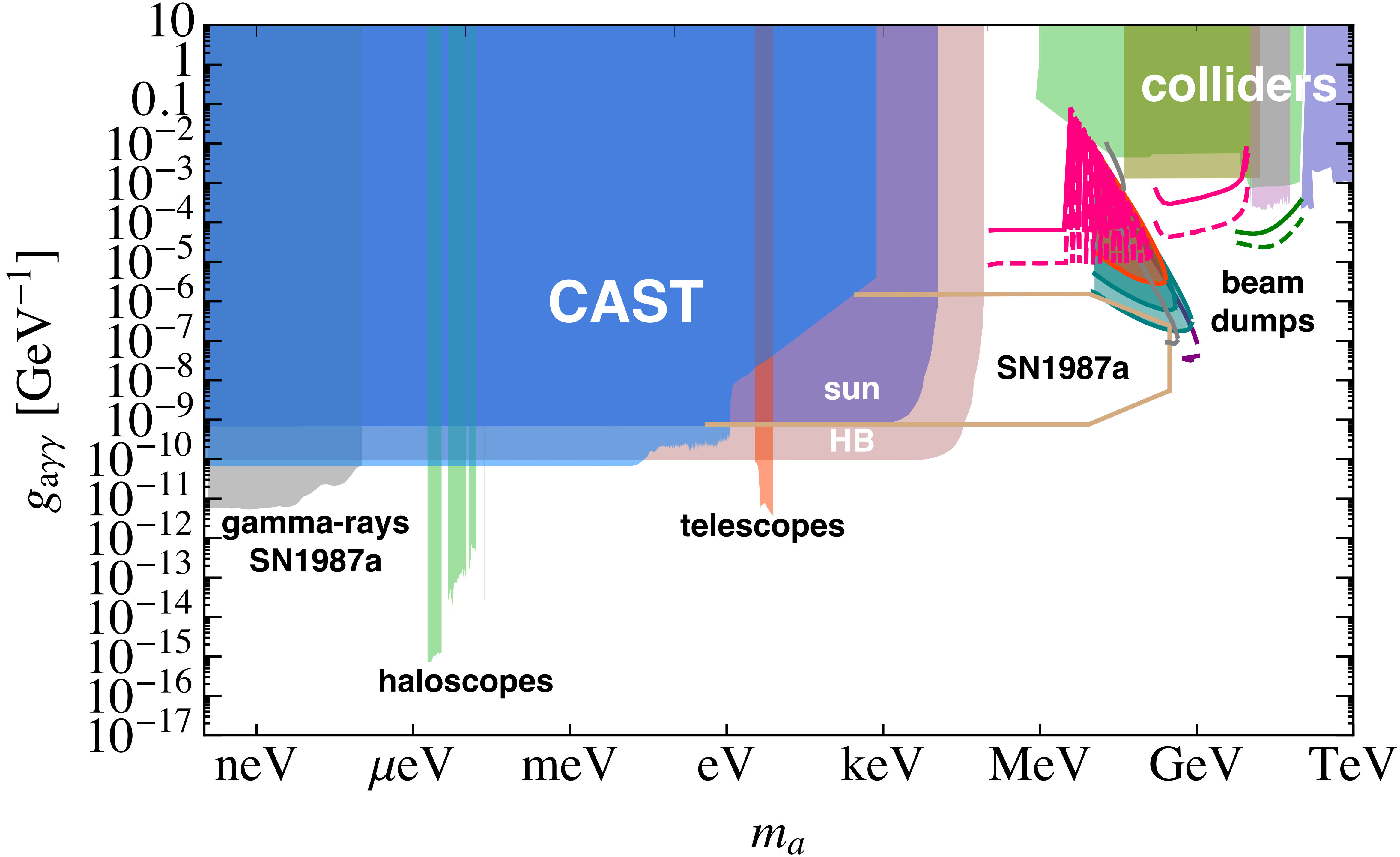
no coupling to SM fermions
coupling to heavy fermions ψ



$$\mathcal{L}_{nALP} \supset \frac{\alpha_{EM}}{2\pi f_a} \sum_{\psi} F\left(\frac{m_a^2}{4m_\psi^2}\right) aF^{\mu\nu}\tilde{F}_{\mu\nu} \qquad \mathcal{L}_{ALP} \supset g_{a\gamma\gamma} aF^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$m_\psi = \lambda_\psi f \qquad f_{\text{eff}} = \frac{12\pi m_\psi^3}{\lambda \alpha m_a^2}$$

searches for ALPs



new heavy fermions