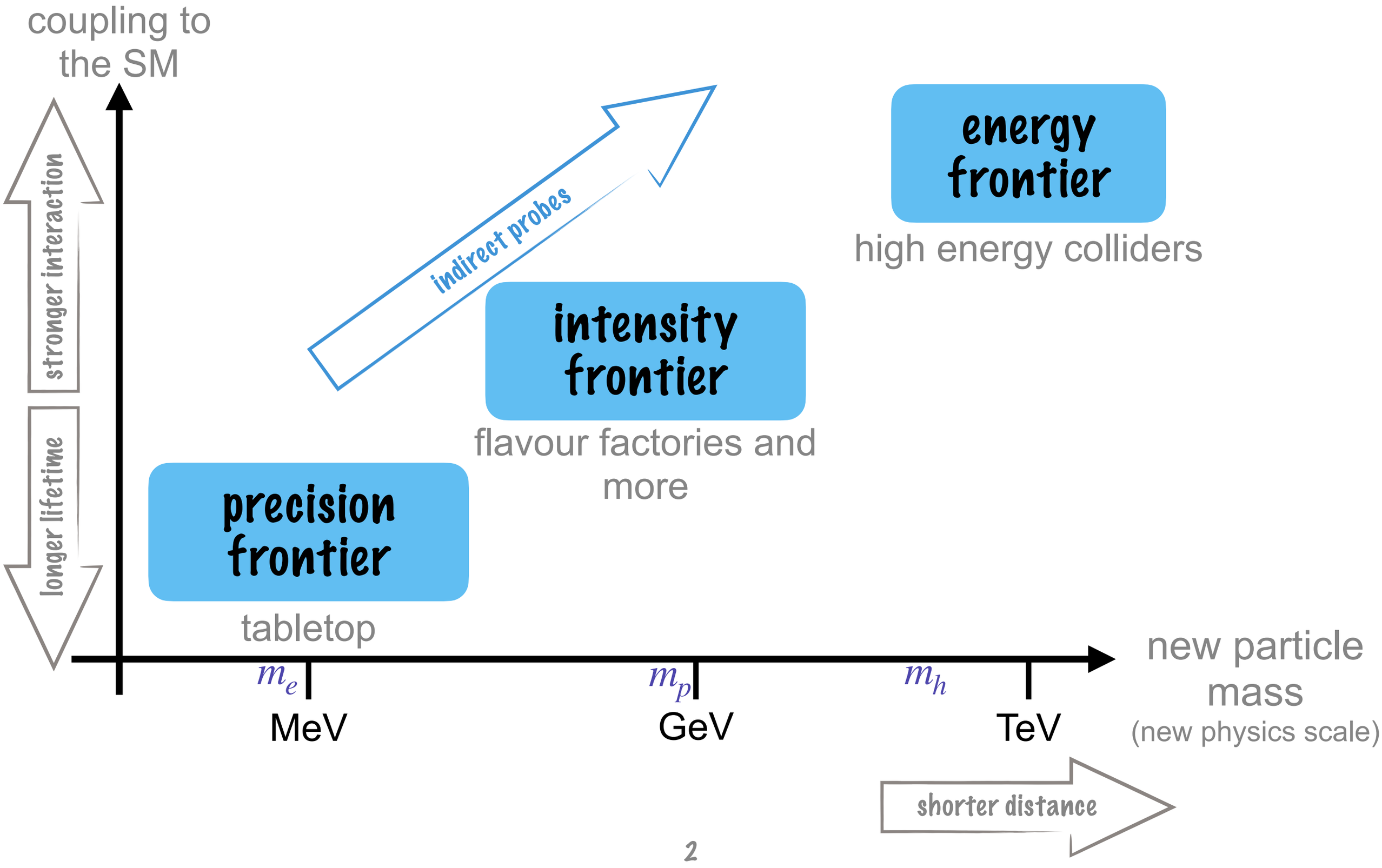
photoproduction of axion-like-particles

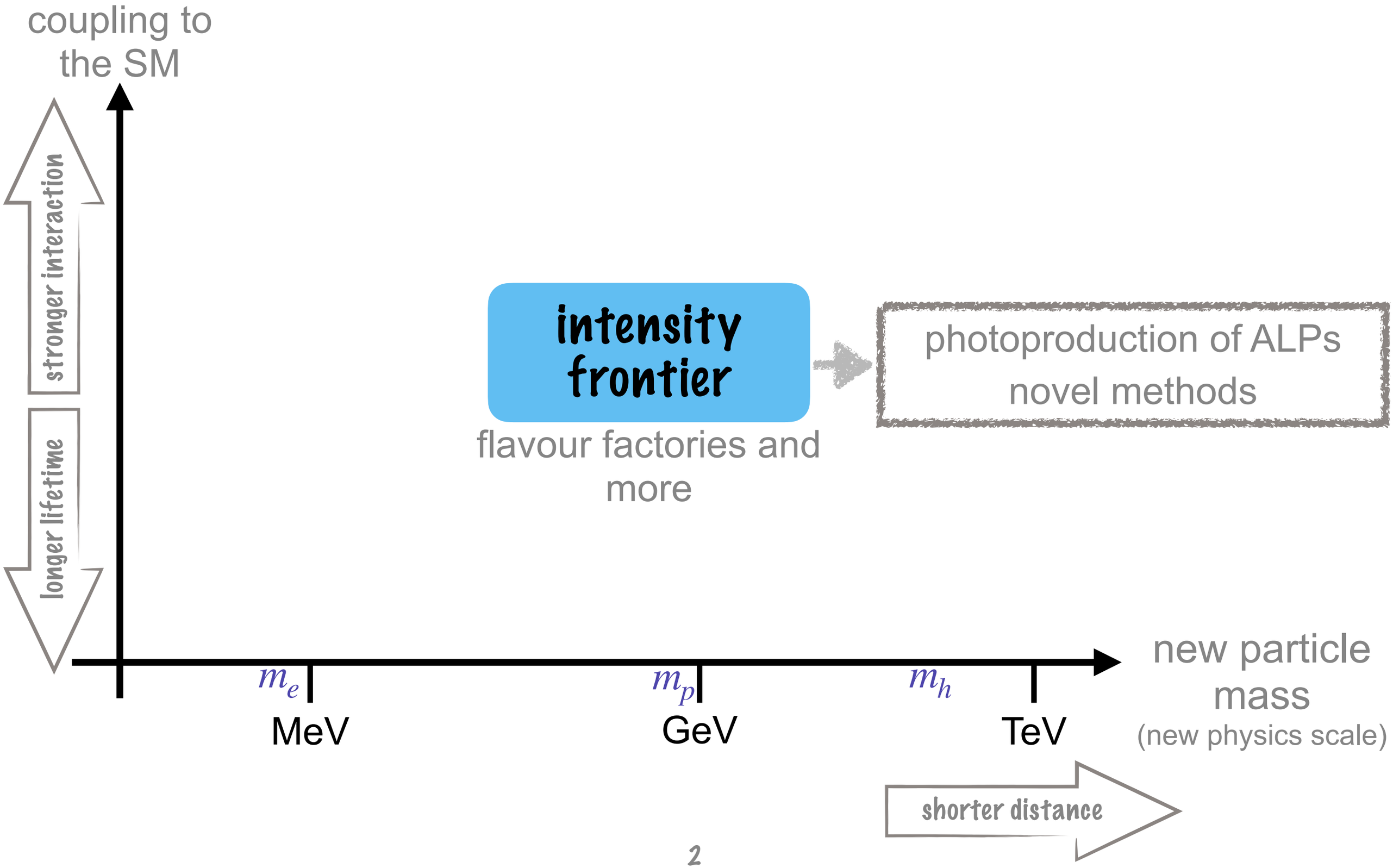
Yotam Soreq

20 Lomonosov conference, Aug 25, 2021

the quest for new physics



the quest for new physics



axion like particles - ALPs

* originally - the Axion, part of a solution to the strong CP problem (PC)
* pseudo-Goladstone mode
* portal to dark matter and/or dark sector
* if very light, it is a dark matter candidate
* predicted by string theory

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focus the effective ALP photon interaction

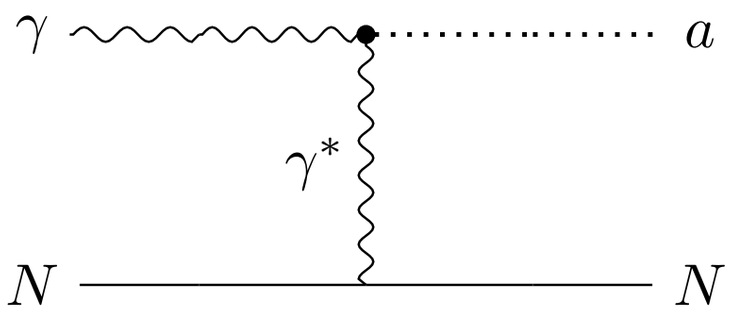
$$\mathscr{L}_{\text{eff}} = \frac{a}{4\Lambda} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$m_a \in [\text{MeV, GeV}] \quad \Lambda \gg m_a$$

well motivated BSM scenario

ALPs photoproduction

a photon beam
O(few GeV)



target *N:*
C, Si, Pb, W

prompt/displaced
decay to $\gamma\gamma$

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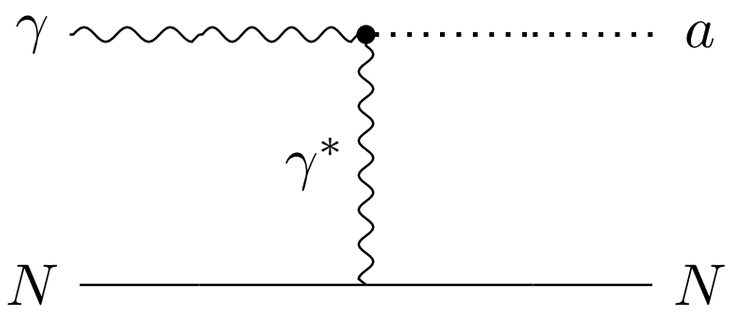

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PrimEx/GlueX
@ J-Lab

Aloni, Fanelli, YS, Williams
1903.03586

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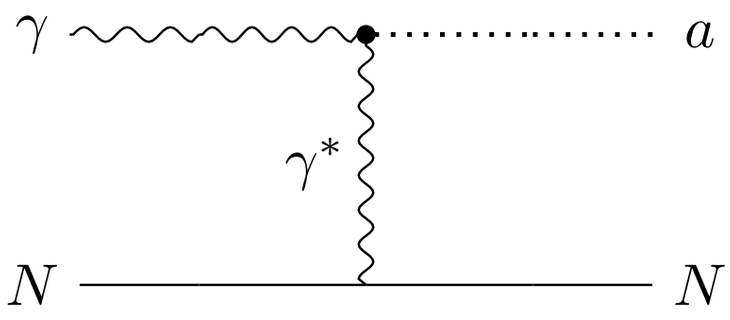

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LUXE-NPOD
@ DESY

Bai, Blackburn, Borysov, Davidi, Hartin,
Heinemann, Ma, Perez, Santra, YS, Tal Hod,
2107.13554

LUXE

ALPs photoproduction

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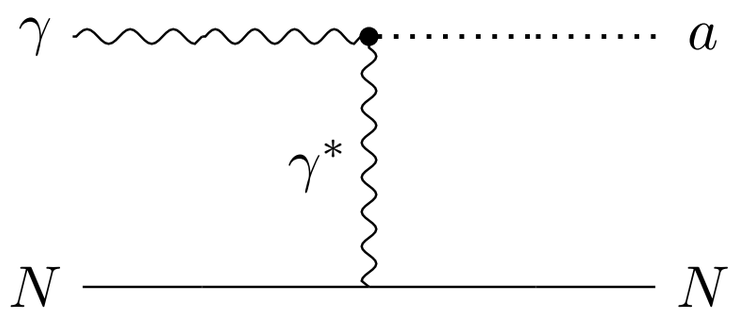

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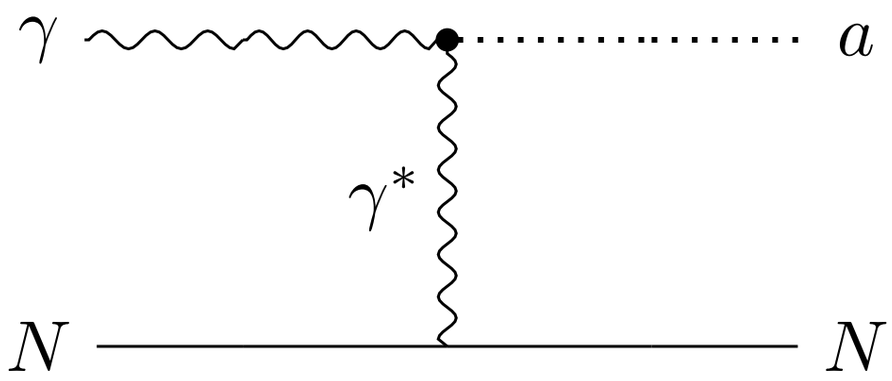
2107.13554

LUXE

Gamma-Factory @ CERN

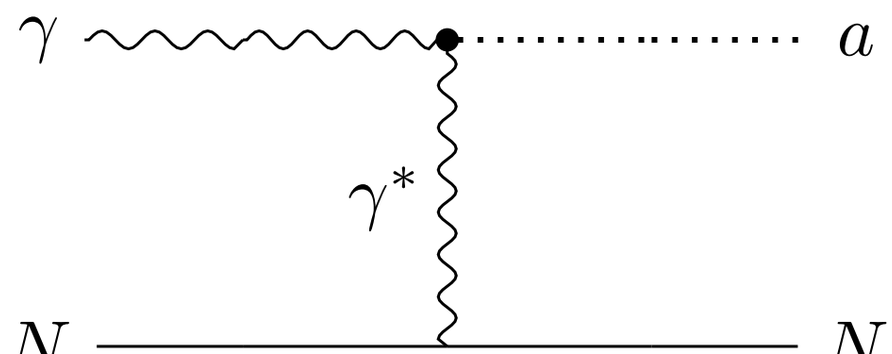
Balkin, Krasny, Ma, Safdi, YS
2105.15072

ALPs photoproduction



$$\frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

ALPs photoproduction



$$\frac{c_\gamma}{4\Lambda}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

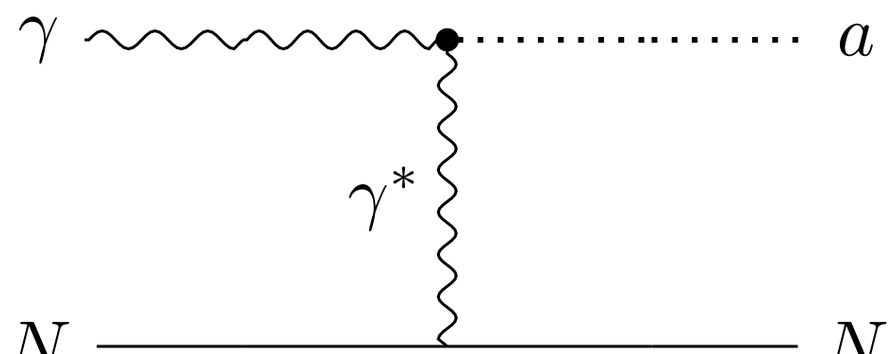
$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \alpha\, Z_N^2 F_N^2(t)\Gamma_{a\to\gamma\gamma}\,\mathscr{H}(m_N, m_a, s, t)$$

target charge

form factor

kinematical function

ALPs photoproduction



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target charge

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kinematical function

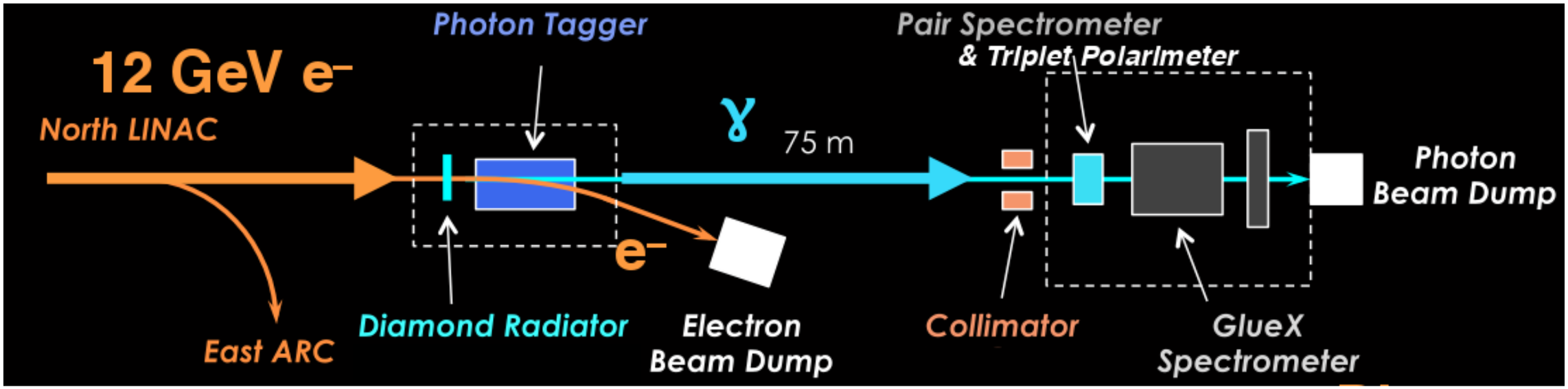
Primakoff production of ALPs and $P = \pi^0, \eta$ are similar

$$\frac{d\sigma^{\text{elastic}}_{\gamma N\to aN}}{dt} = \frac{\Gamma_{a\to\gamma\gamma}}{\Gamma_{P\to\gamma\gamma}}\frac{\mathscr{H}(m_N, m_a, s, t)}{\mathscr{H}(m_N, m_p, s, t)}\frac{d\sigma^{\text{elastic}}_{\gamma N\to PN}}{dt}$$

at the forward region

data-driven signal normalization

(cancel form-factor and flux dependence)


12 GeV e⁻
North LINAC
Photon Tagger
γ
75 m
Pair Spectrometer
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Photon
Beam Dump
e⁻
East ARC
Diamond Radiator
Electron
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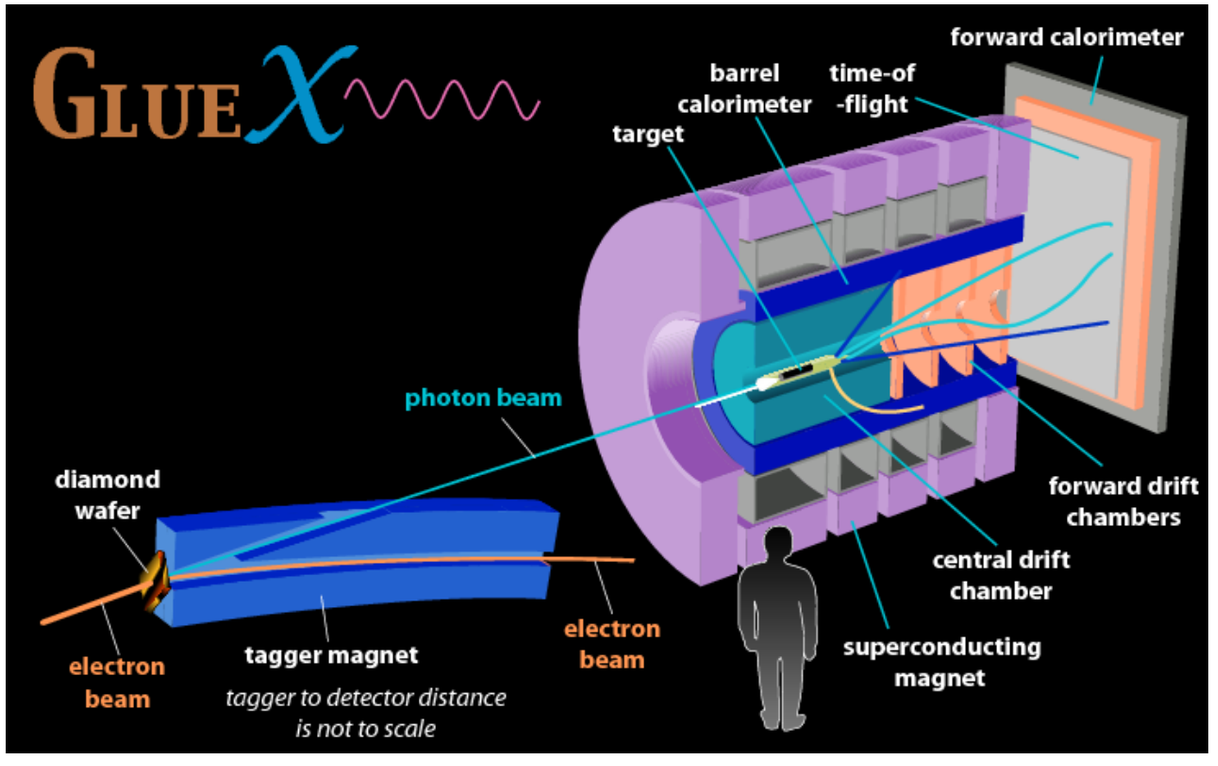
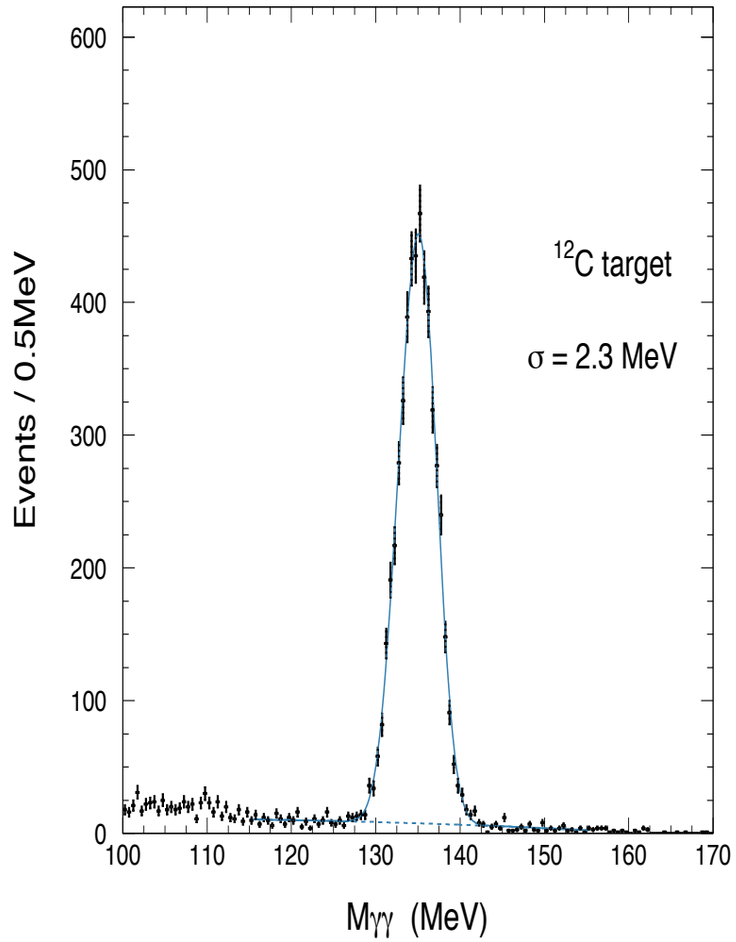
Collimator
GlueX
Spectrometer

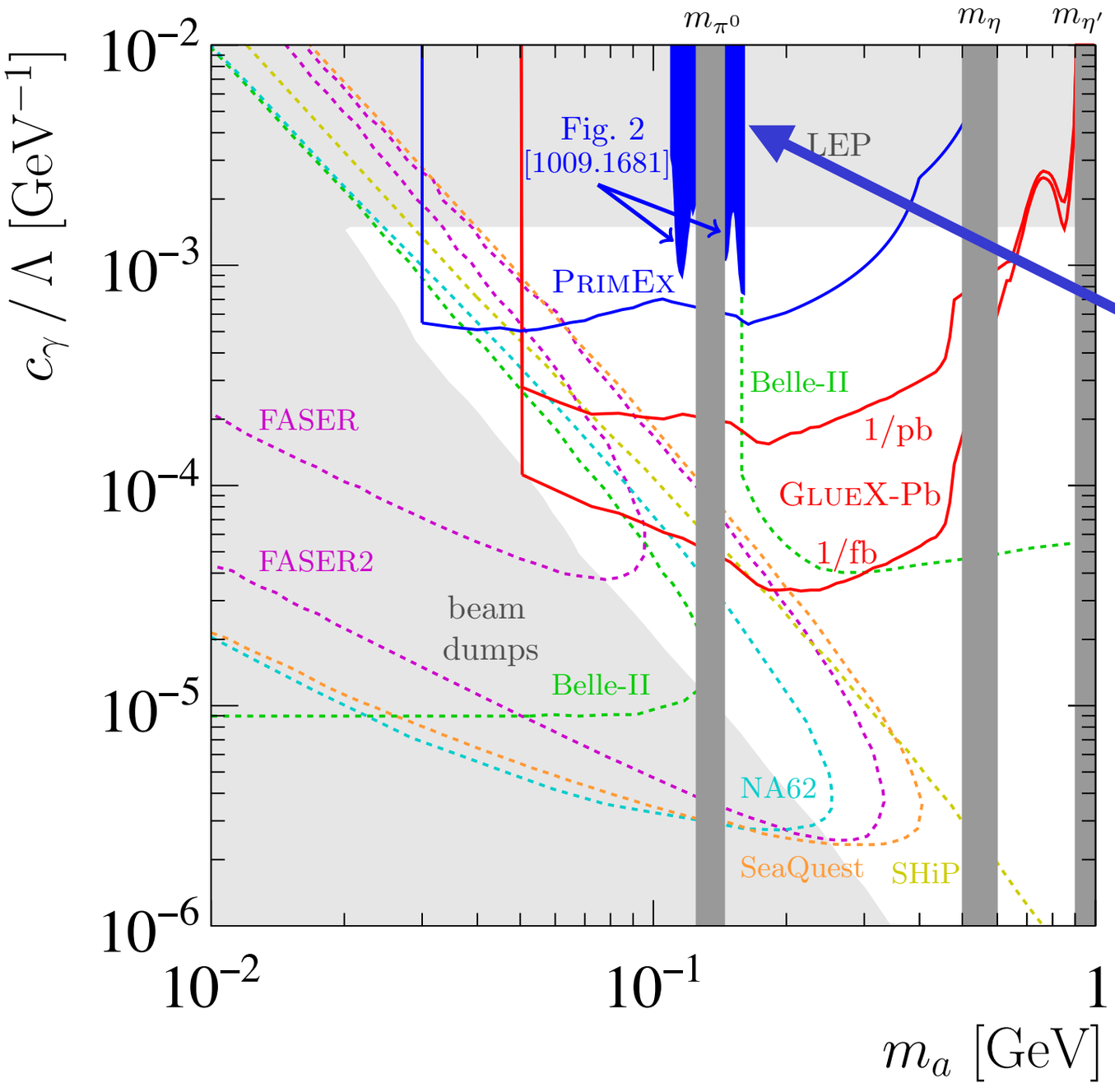

GLUEX
forward calorimeter
barrel
calorimeter
time-of
-flight
target
photon beam
diamond
wafer
forward drift
chambers
central drift
chamber
electron
beam
tagger magnet
tagger to detector distance
is not to scale
electron
beam
superconducting
magnet

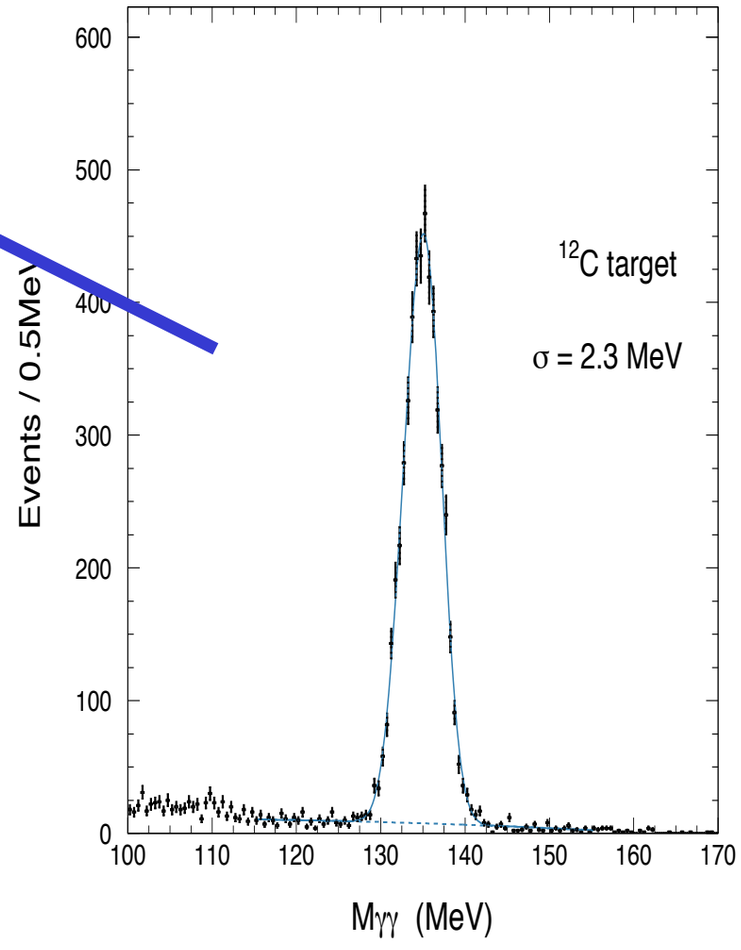
ALP photons coupling



PrimEx - 1009.1681

ALP photons coupling





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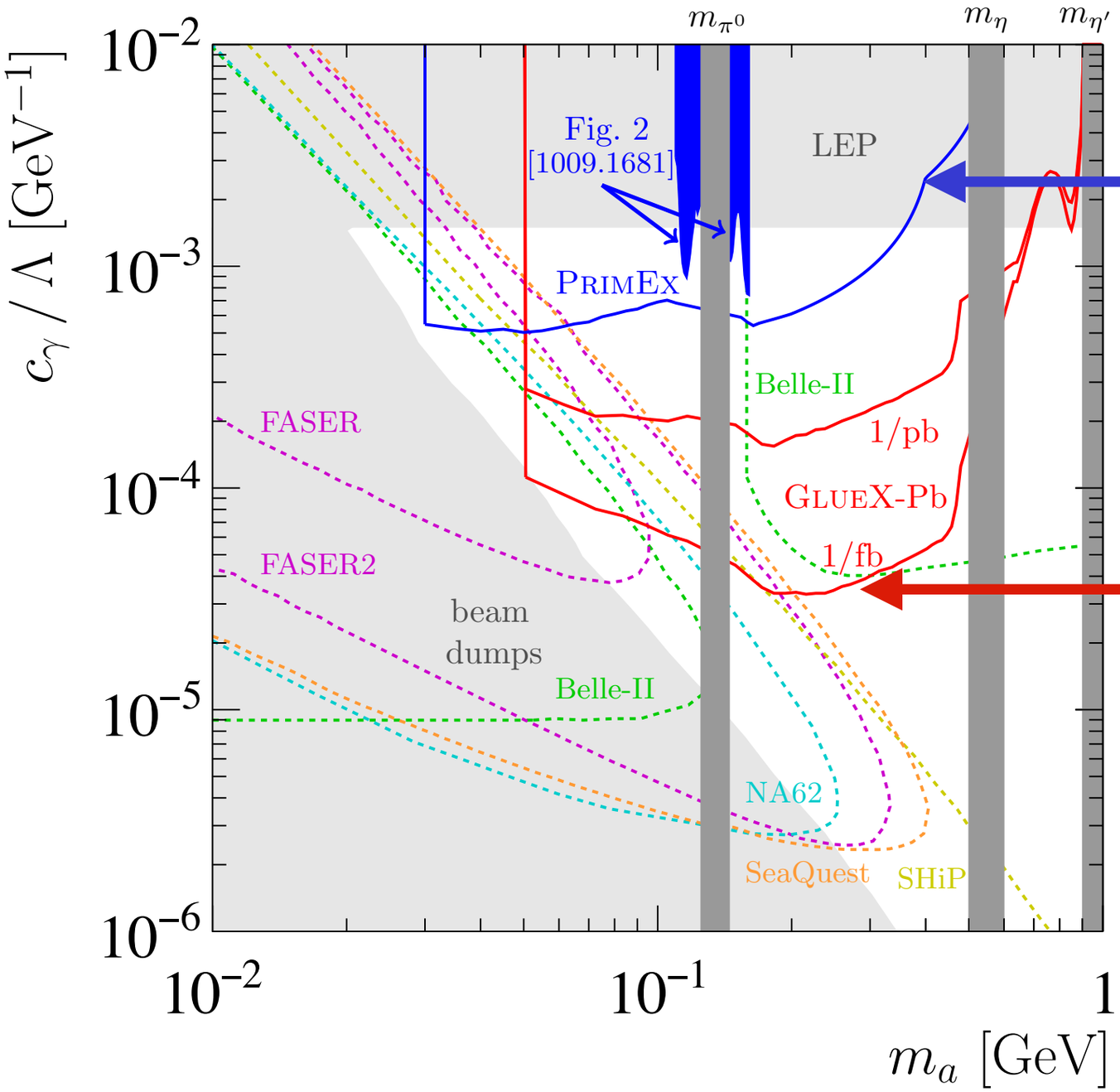


on tape PrimEx data

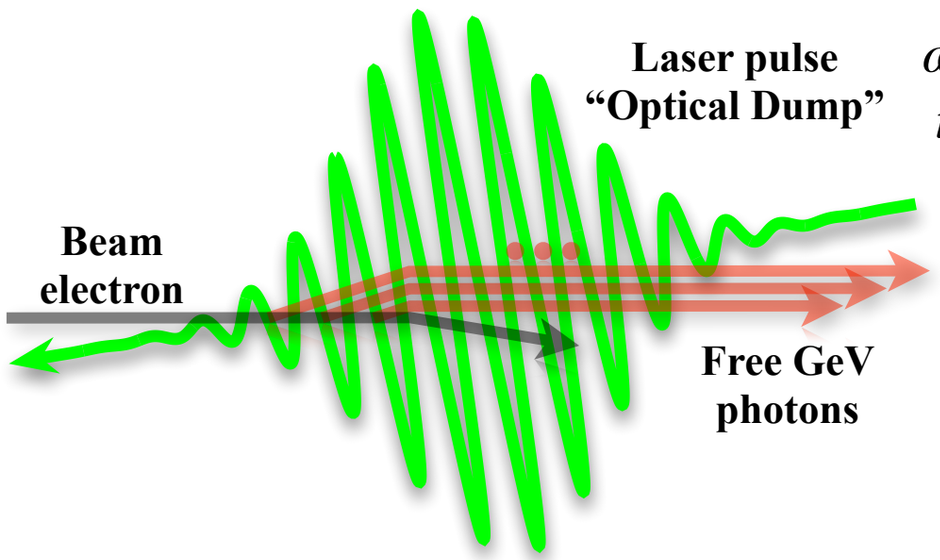
projection for GlueX

Aloni, Fanelli, YS, Williams
1903.03586

LUXE-NPOD: new physics searches with an optical dump at LUXE

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, Santra, YS, Tal Hod, 2107.13554

the LUXE setup



$E_e \approx 16.5\,\mathrm{GeV}$

$\omega_\mathrm{L} \approx 1.5\,\mathrm{eV}$

$t_\mathrm{L} \sim \mathcal{O}(10-100)\,\mathrm{fs}$

Ritus, 1985
LUXE, 1909.00860, 2102.02032

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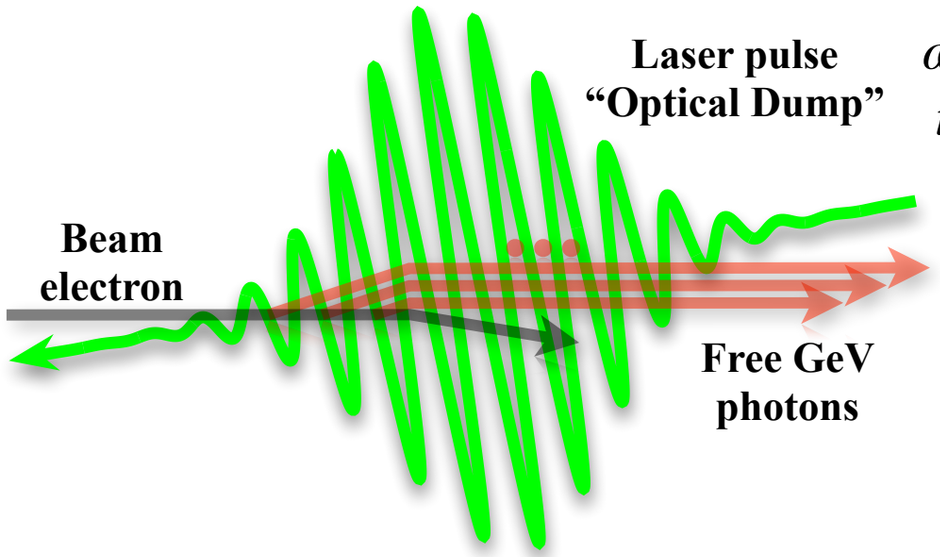

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$e^-_\mathrm{V} \to e^-_\mathrm{V}\ \gamma,\ \tau_\gamma \sim \mathcal{O}(10)\mathrm{fs}$

$\gamma \to e^+_V\ e^-_V, \tau_{ee} \sim \mathcal{O}(10^4 - 10^6)\mathrm{fs}$

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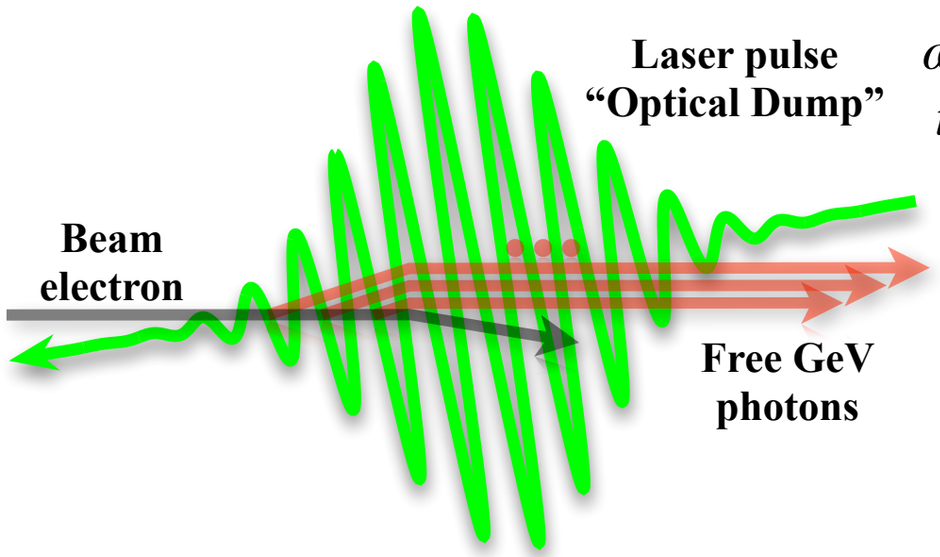

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emitted photons per pulse per e^-

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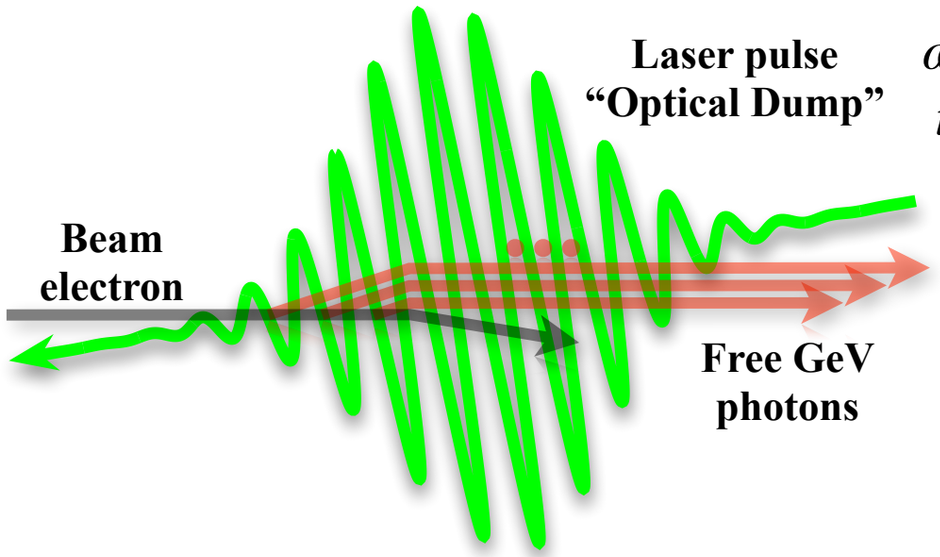

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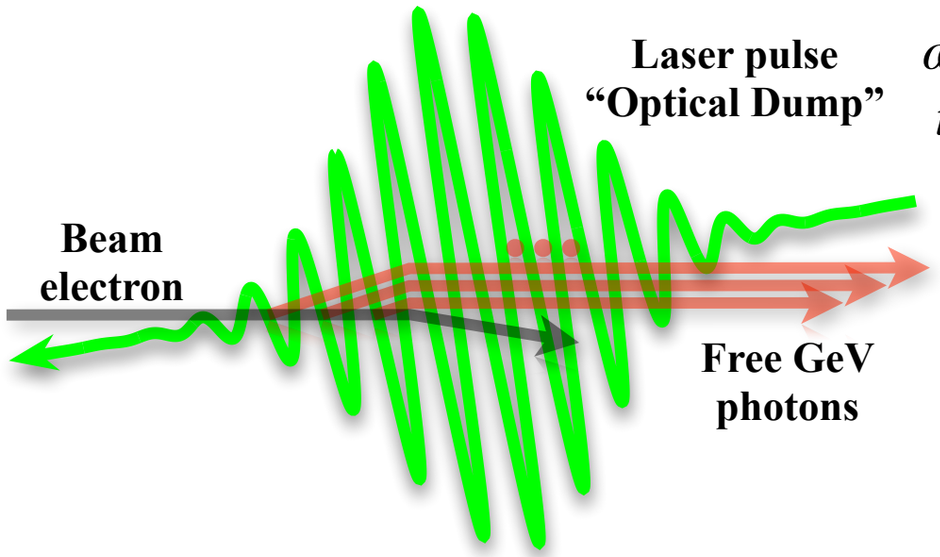
pair production is suppressed

the LUXE setup



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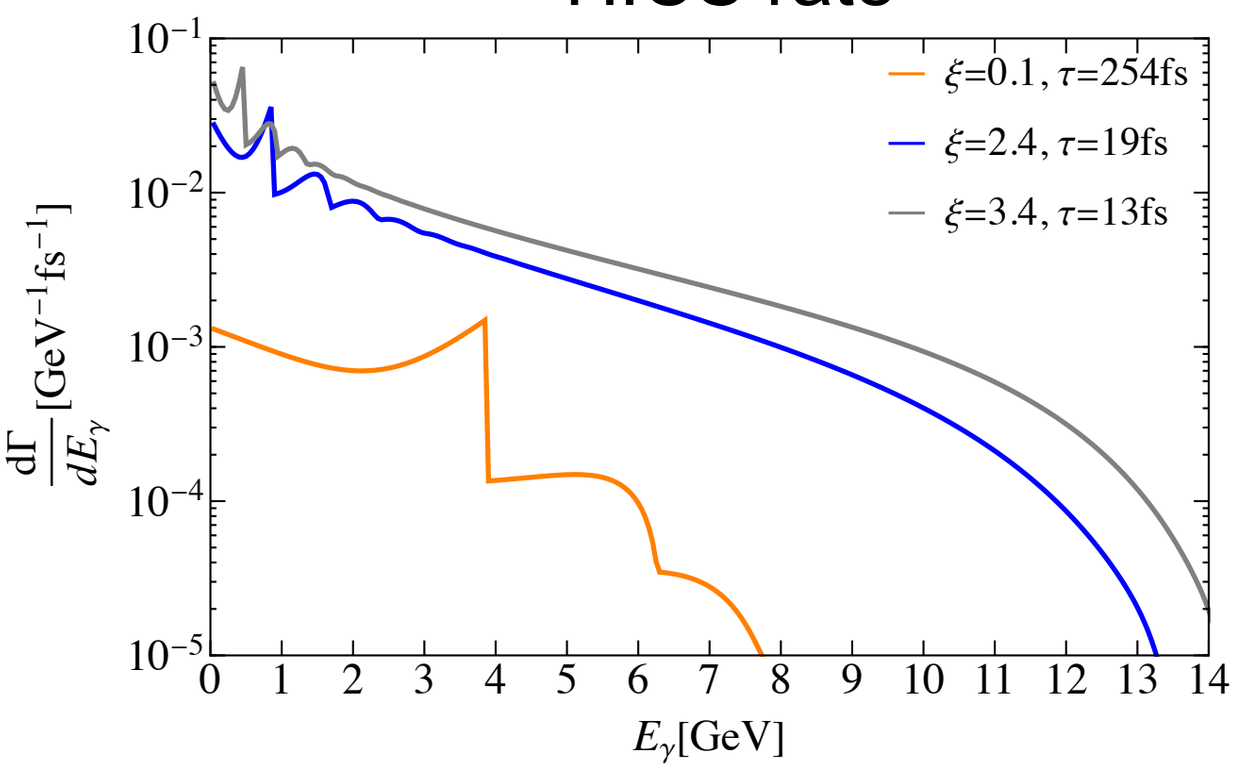
pair production is suppressed

excellent source of
GeV scale photons

the photon spectrum



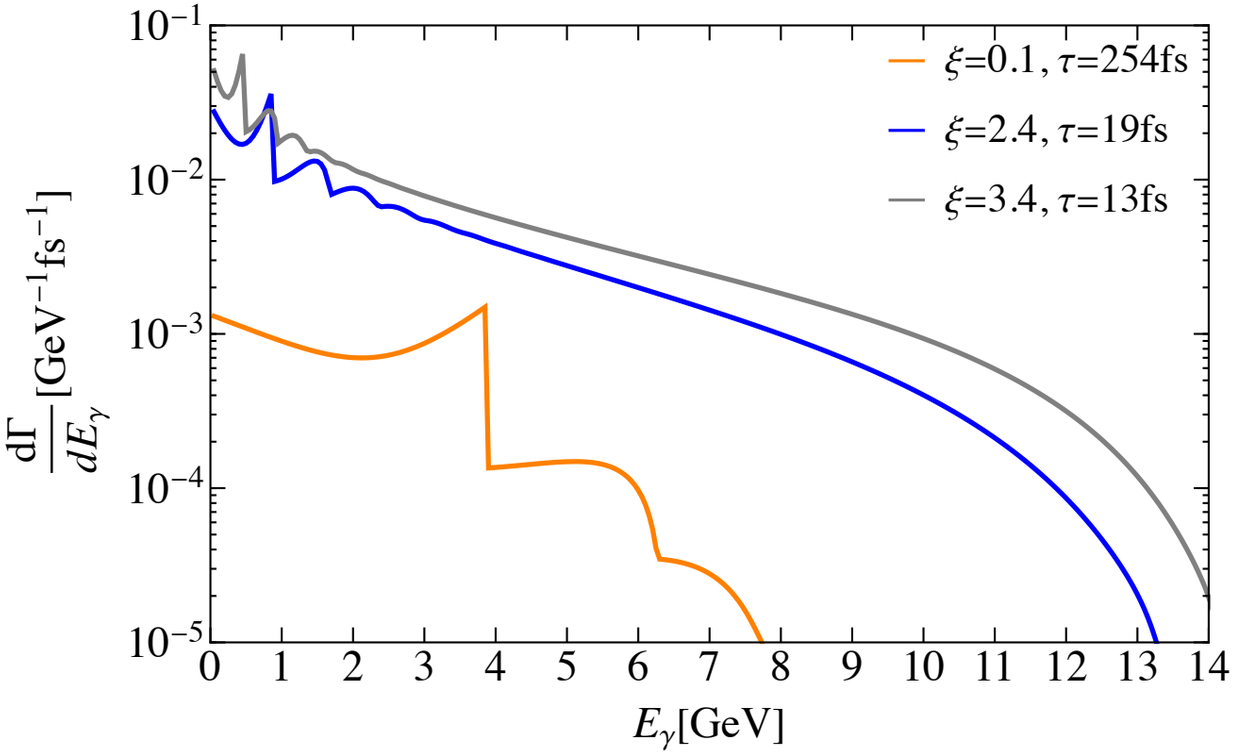
$$\chi\,\xi^2 > 1$$

for non perturbative region

$$\chi = \frac{eE_e}{m_e^3}\mathscr{E}_L\left(1+\beta_e\cos\theta\right),\quad \xi = \frac{e\mathscr{E}_{\mathrm{L}}}{m_e\omega_{\mathrm{L}}}$$

the photon spectrum

HICS rate



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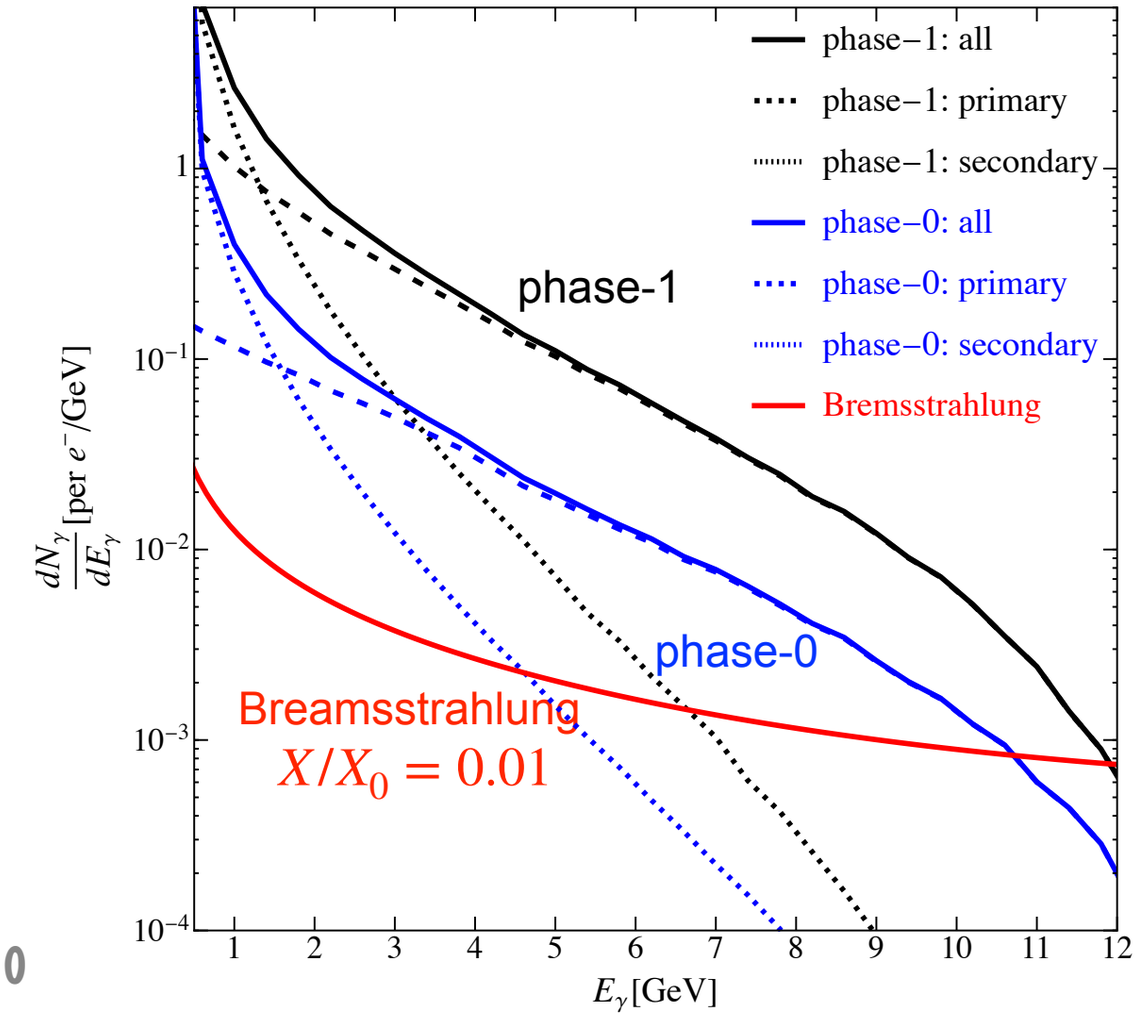
outgoing Compton photon spectrum



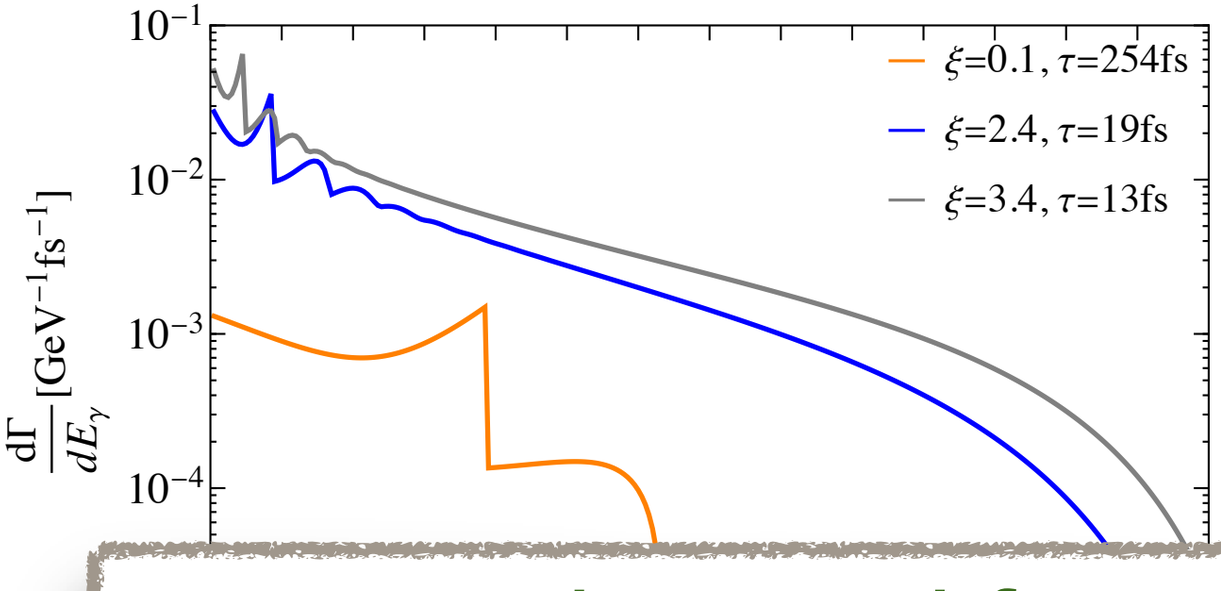
convolution with the laser

phase-0:
$\tau_\mathrm{L} = 25$ fs
$w_0 = 6.5\,\mu$m
$\xi = 3.2$
$N_{\gamma/e} < 1$

phase-1:
$\tau_\mathrm{L} = 120$ fs
$w_0 = 10\,\mu$m
$\xi = 3.4$
$N_{\gamma/e} = 3.5\,(1.7),\ E_\gamma > 0\,(1)$ GeV

the photon spectrum

HICS rate



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outgoing Compton photon spectrum

can be used for new physics searches in particular with photon and/or electron coupling

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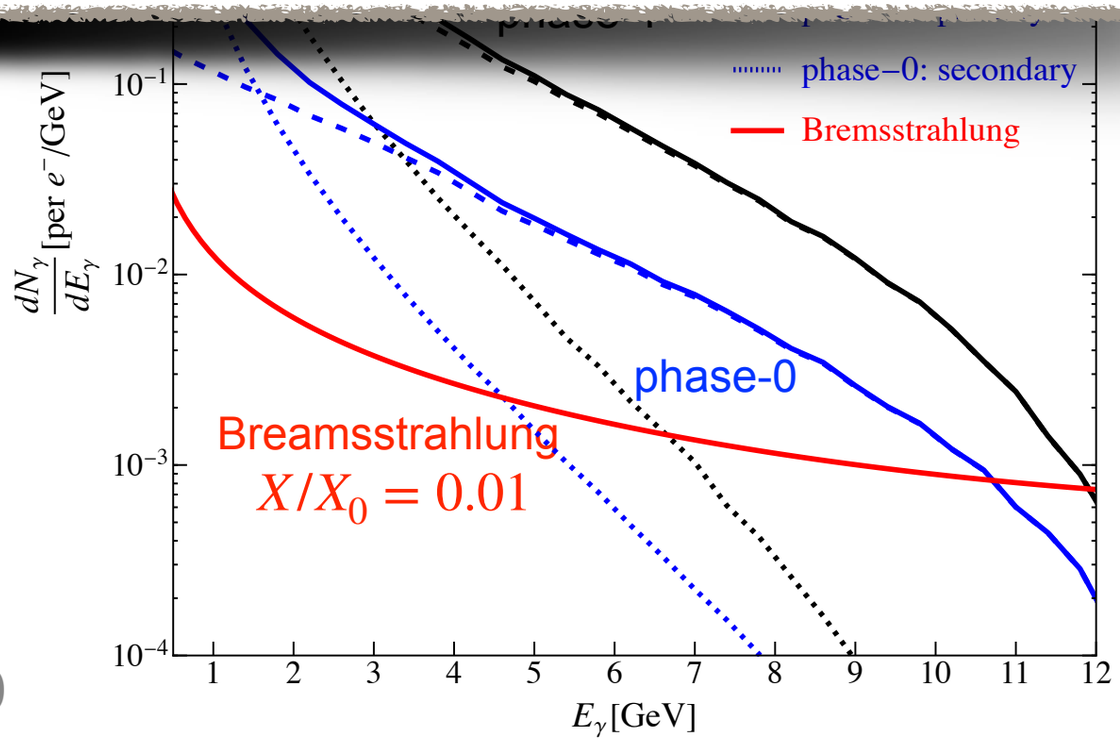
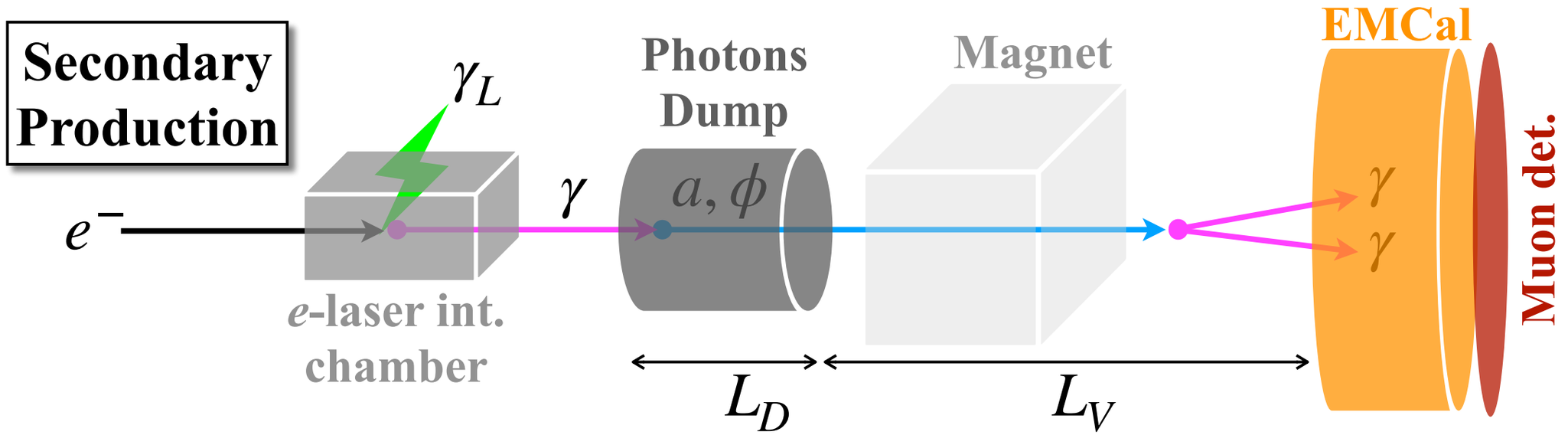
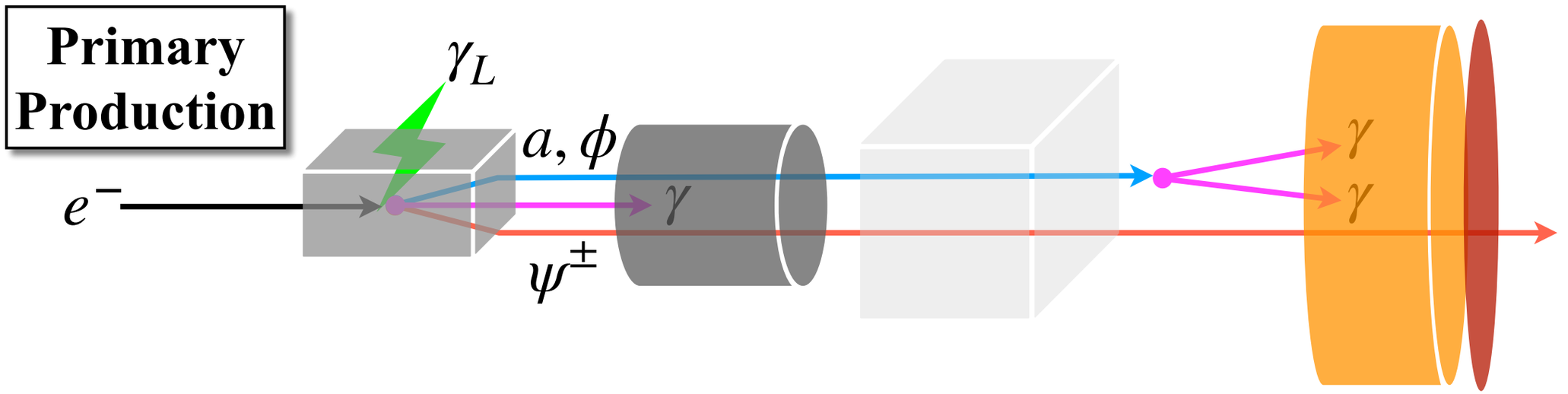
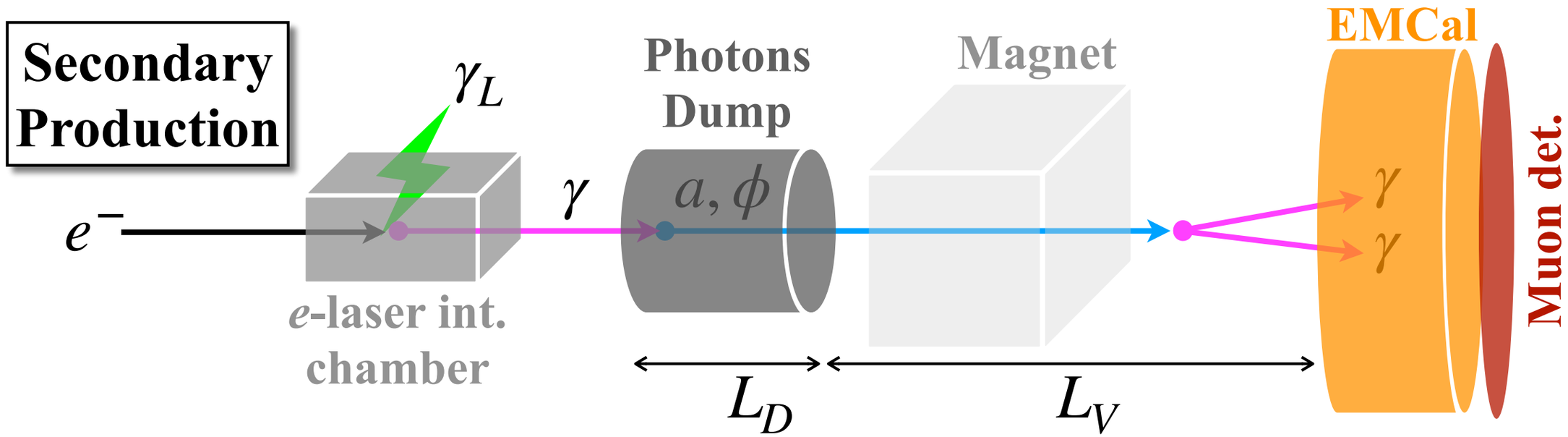


new physics production at LUXE





secondary ALPs production



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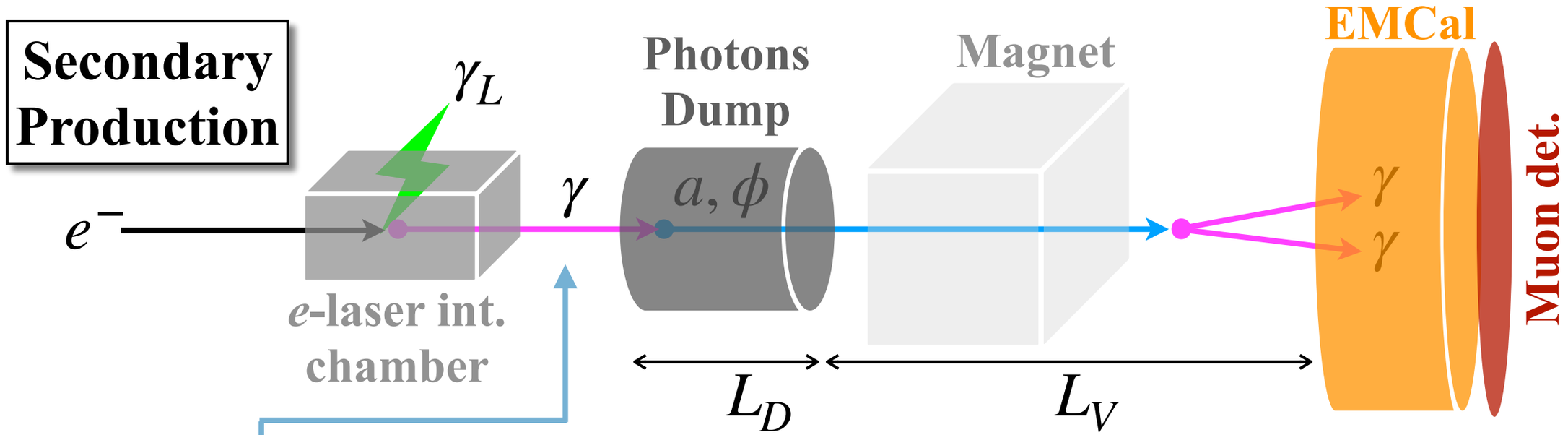
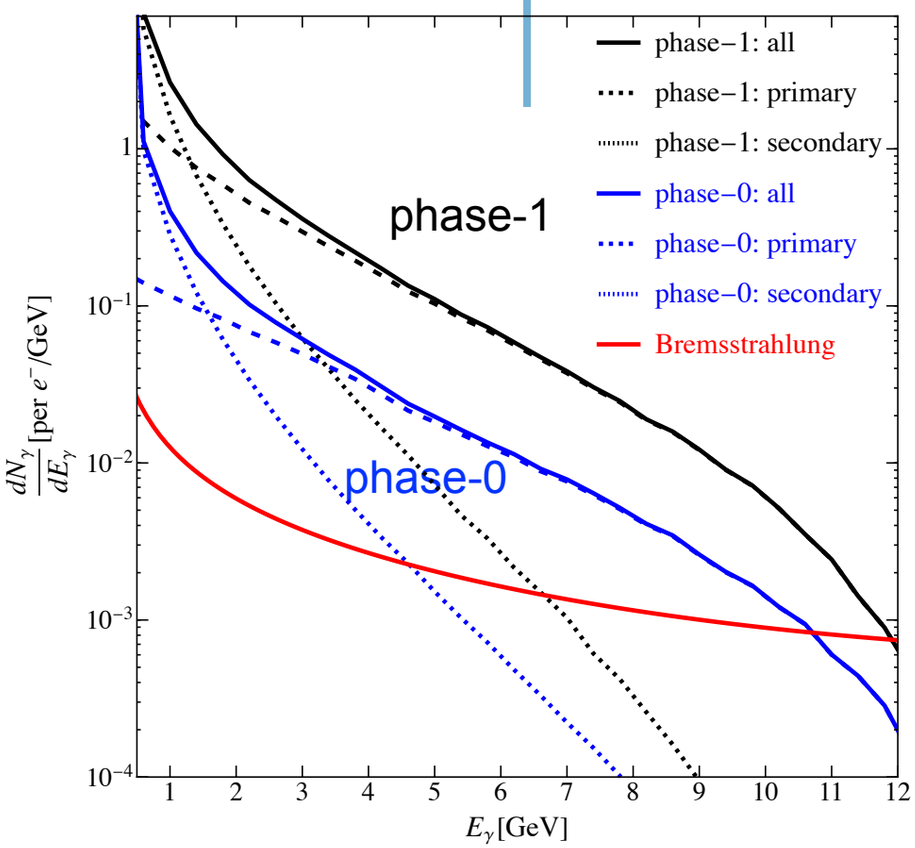
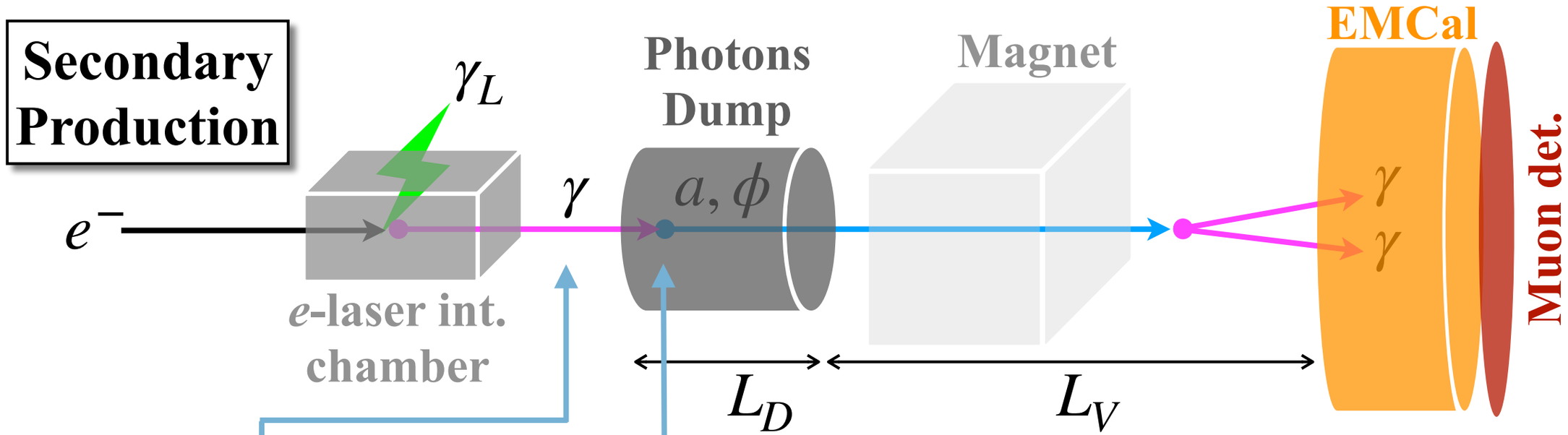
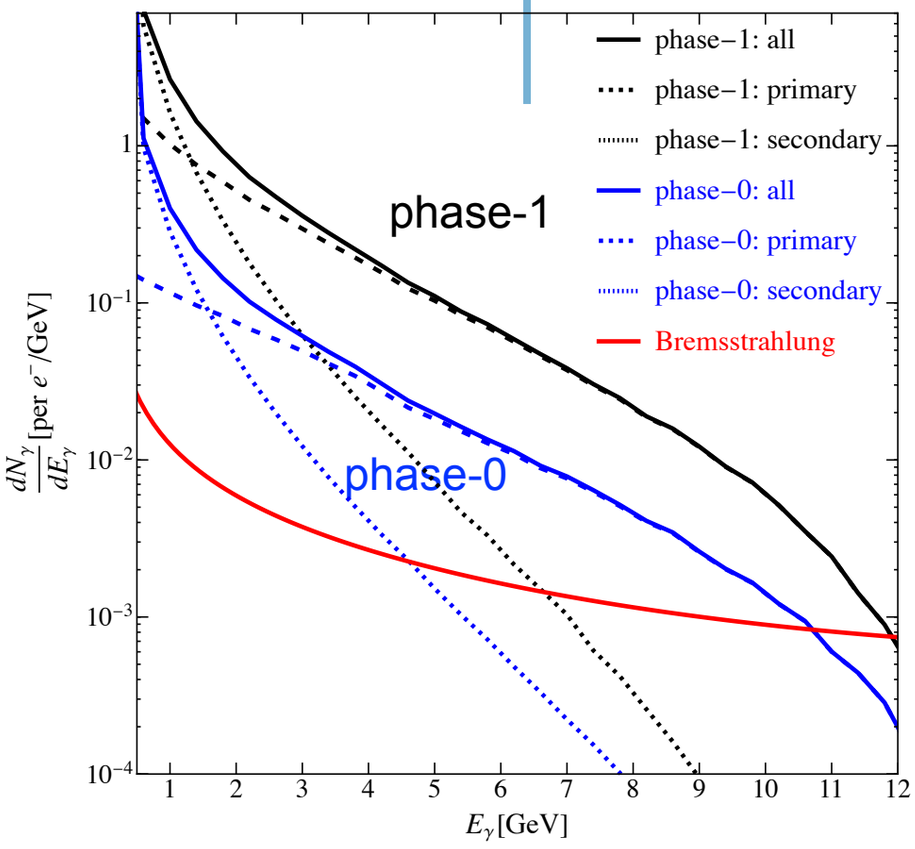


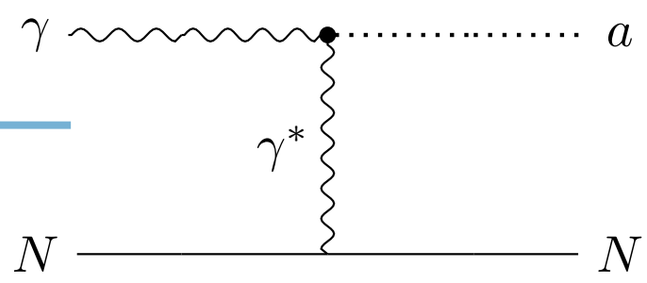


source	# photons, E>1 GeV	backgrounds
LUXE-0/1	0.4 / 2.5	effectively free
e-beam thin	0.03	effectively free
e-beam thick	6.7	O(100) larger

secondary ALPs production







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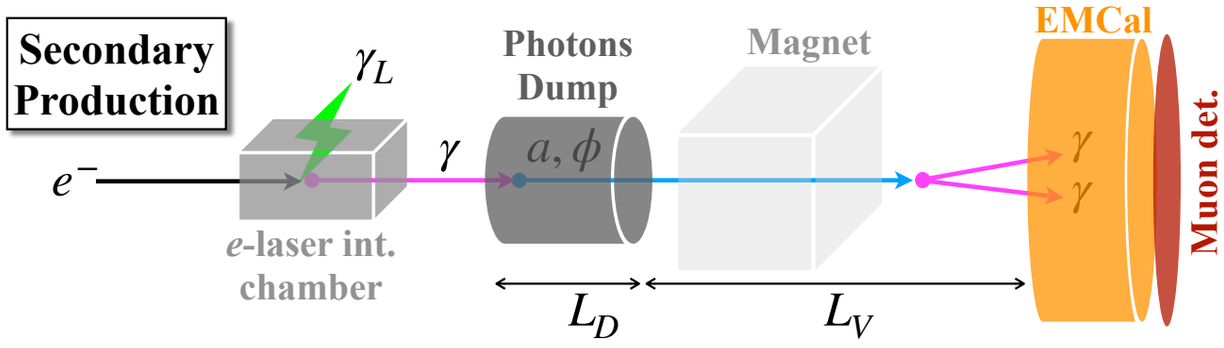
ALP signal estimation



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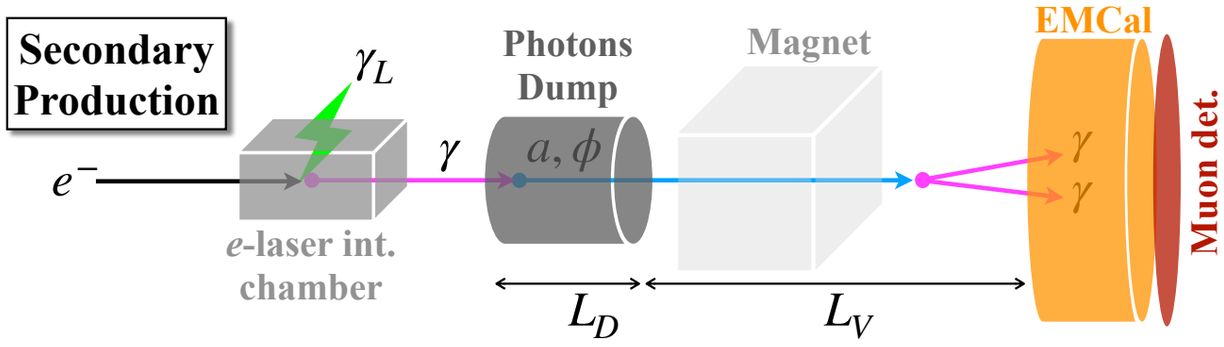


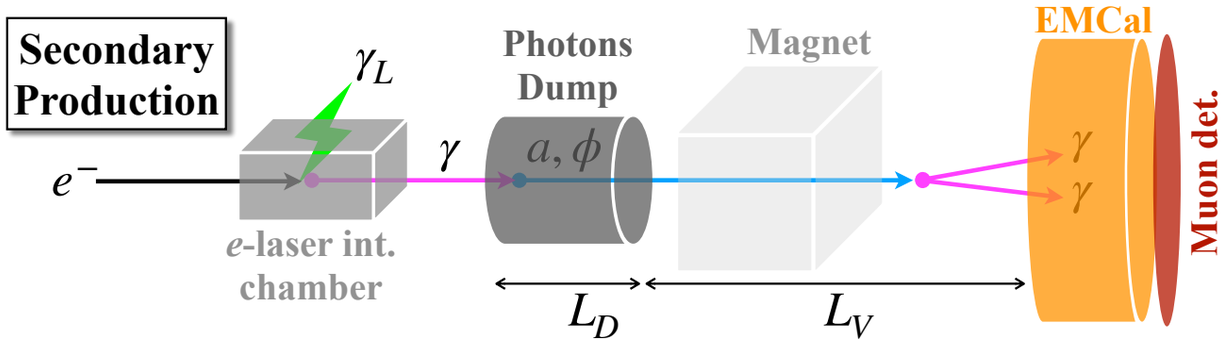
number of ALPs

$$N_a\Big|_{E_a \approx E_\gamma} \approx \mathscr{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathscr{A}$$

$$\frac{9}{7} N_e N_{\text{BX}} \frac{\rho_W X_0}{A_W m_0}$$

$$L_a \equiv \frac{\sqrt{E_a^2 - m_a^2}}{m_a \Gamma_a}$$

ALP signal estimation



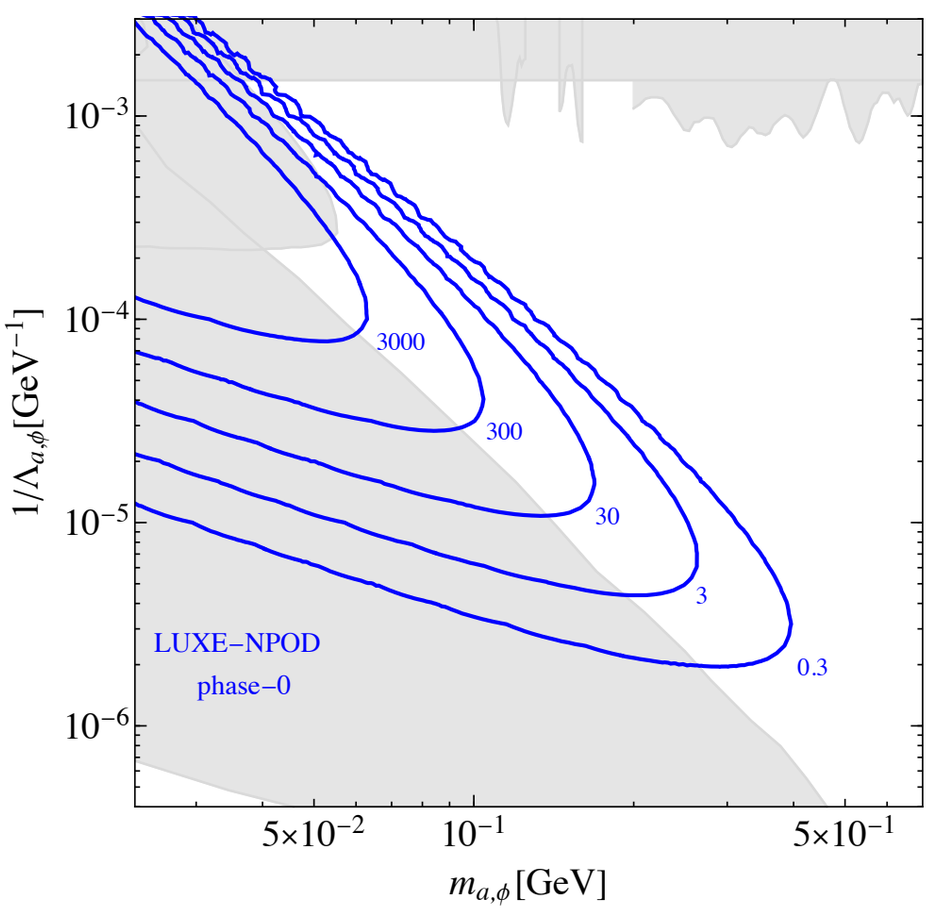
number of ALPs

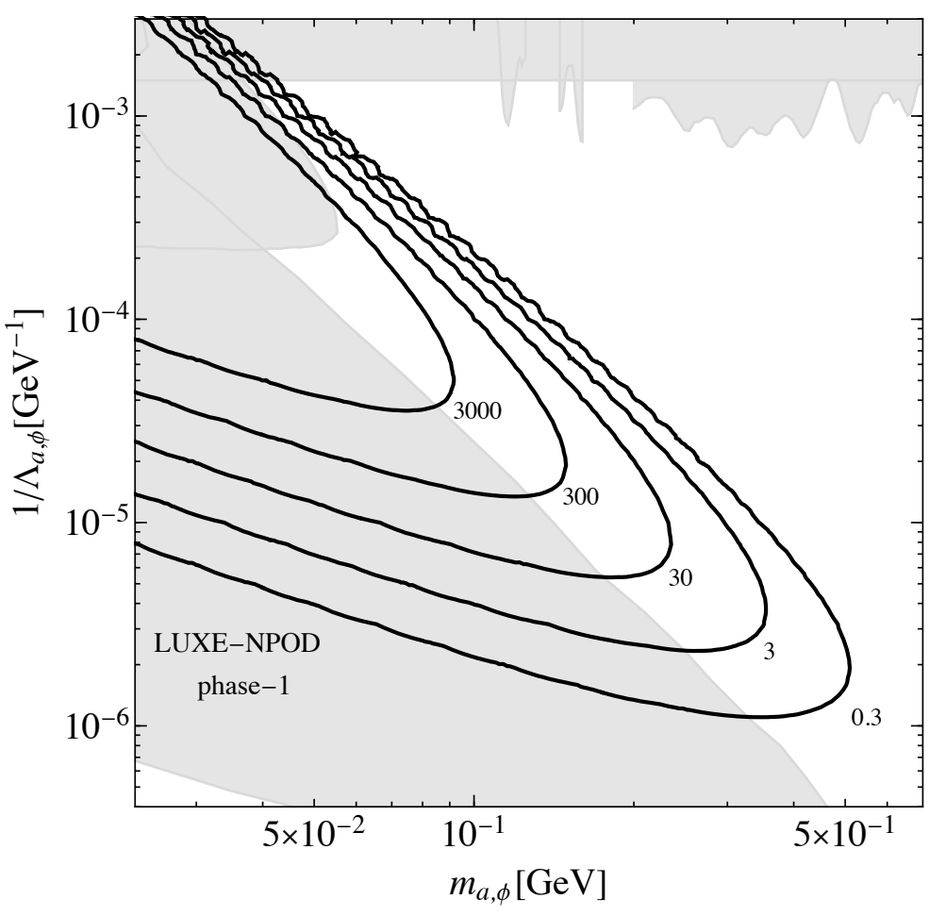
$$N_a\Big|_{E_a \approx E_\gamma} \approx \mathscr{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathscr{A}$$

$$\frac{9}{7} N_e N_{\text{BX}} \frac{\rho_W X_0}{A_W m_0}$$

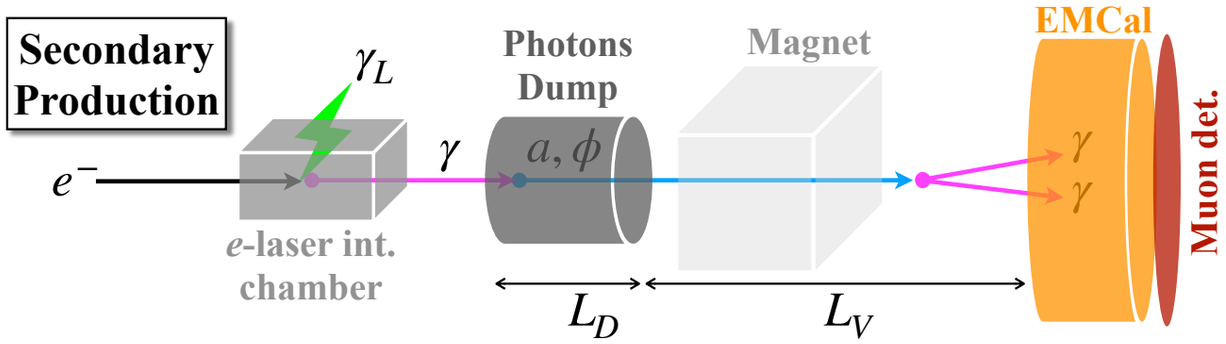
$$L_a \equiv \frac{\sqrt{E_a^2 - m_a^2}}{m_a \Gamma_a}$$

$E_e = 16.5\,\text{GeV}$ $N_e = 1.5 \times 10^9$ $N_{\text{BX}} = 10^7$ $L_S = 1.0\,\text{m}$ $L_D = 2.5\,\text{m}$ $R_D = 1.0\,\text{m}$ $E_{\gamma,\text{min}} = 0.5\,\text{GeV}$





ALP signal estimation



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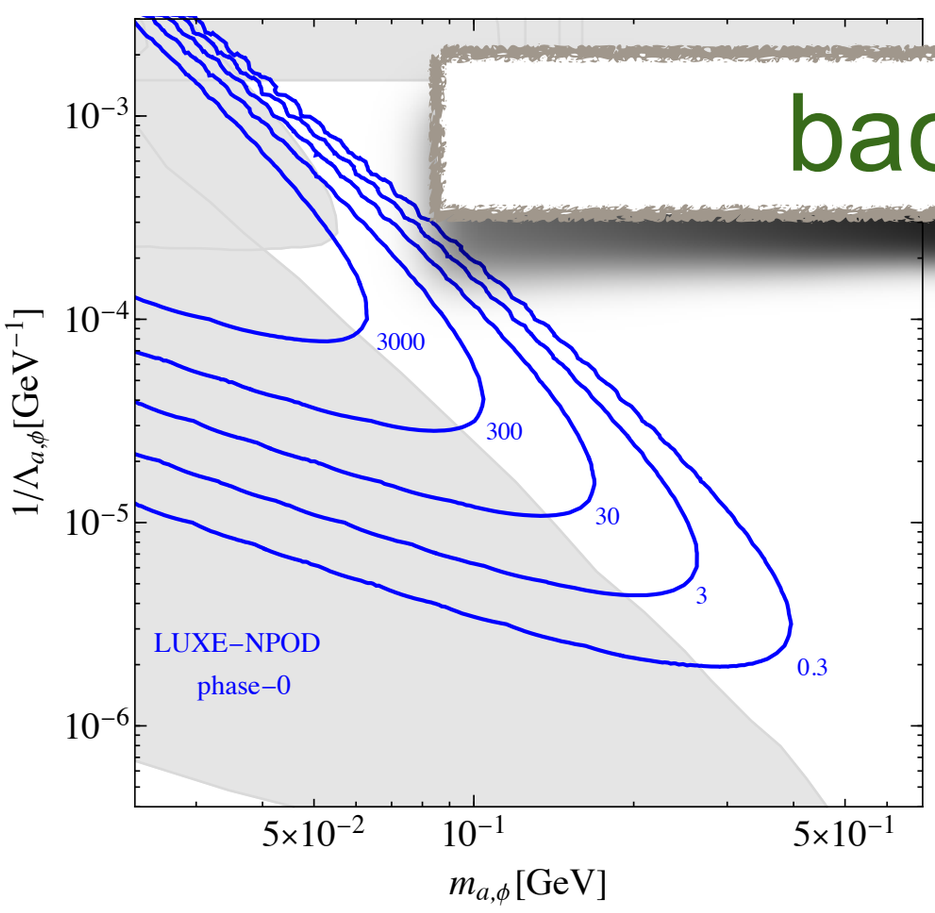
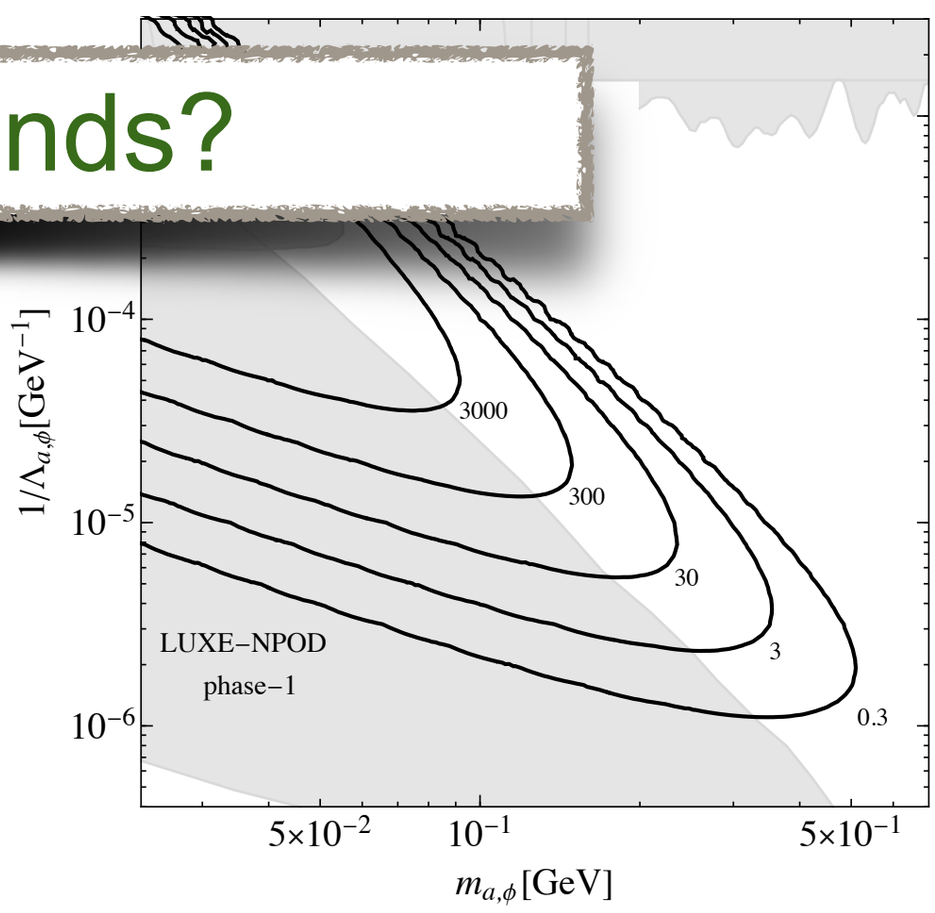
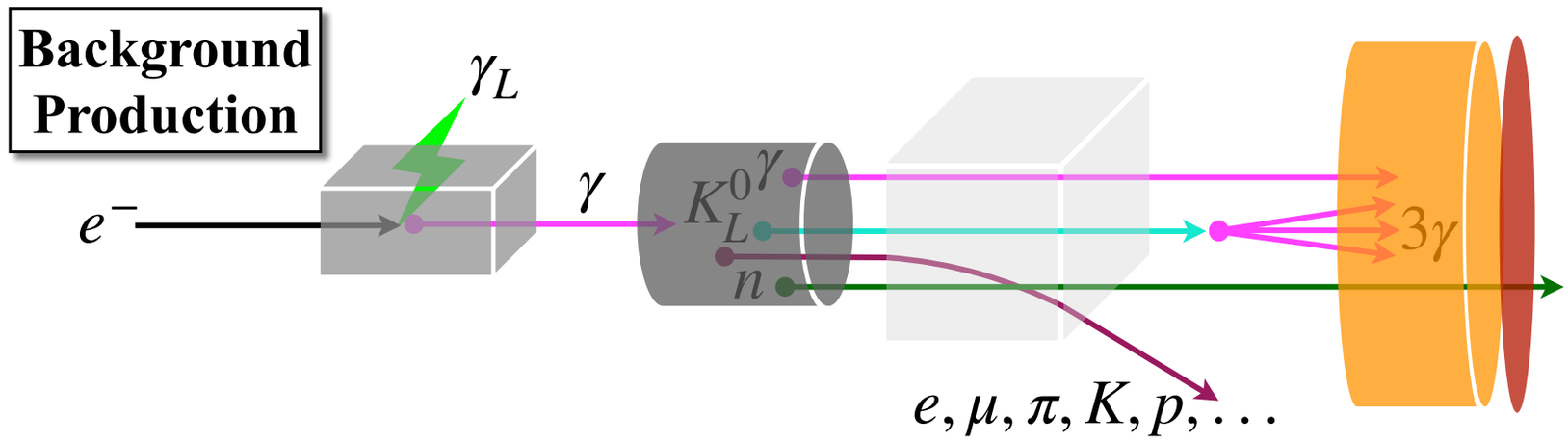
backgrounds?

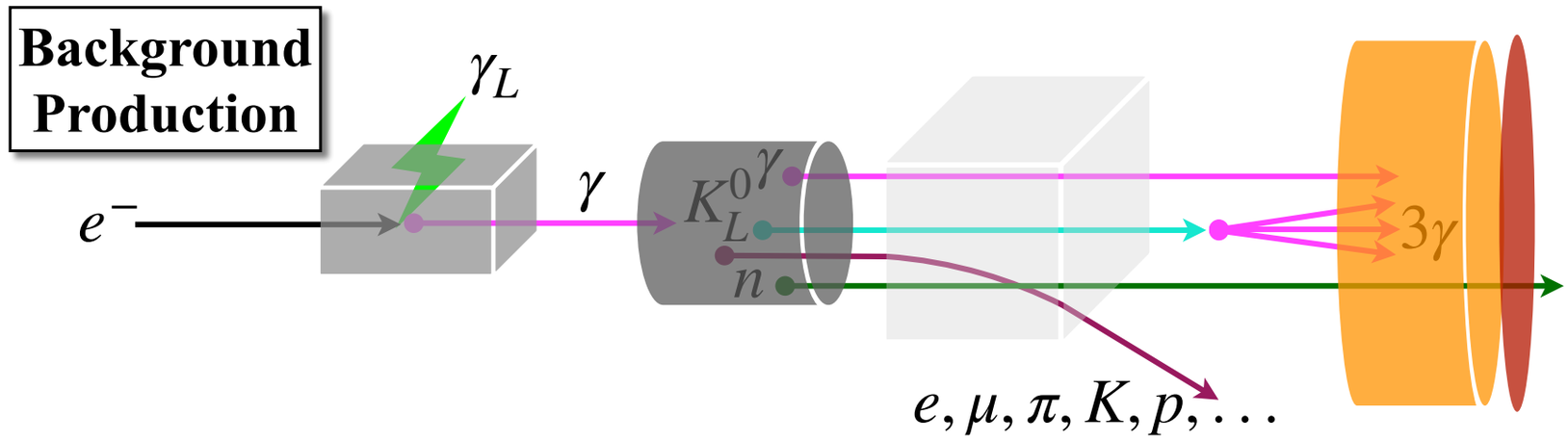




background estimation



background estimation



backgrounds (based on GEANT 4 simulation):

1. **charged particles** - bended by a magnetic field (1.5T of 1m)
2. **fake photons** - $N_{2n\to 2\gamma} \approx 5\times 10^{8} f_{n\to\gamma}^{2} e^{-10 f_{n\to\gamma}} R_{\mathrm{sel}}$

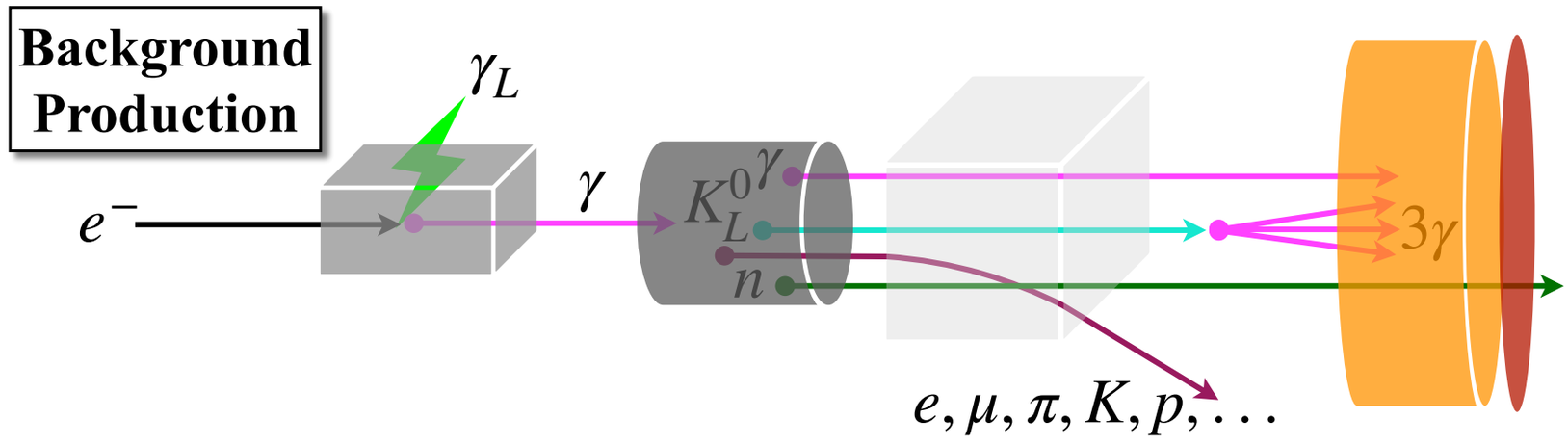
   $N_{n\gamma\to 2\gamma} \approx 1\times 10^{6} f_{n\to\gamma} e^{-10 f_{n\to\gamma}} R_{\mathrm{sel}}$
3. **real photons** - $N_{2\gamma} \approx 8\times 10^{2} R_{\mathrm{sel}}$ dominant

R_{sel} - event selection rejection

$f_{n\to\gamma}$ - neutron fake rate

depend on detector technology
(energy, pointing and timing resolutions)

background estimation



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3. **real photons** - $N_{2\gamma} \approx 8\times 10^2 R_{\text{sel}}$ dominant

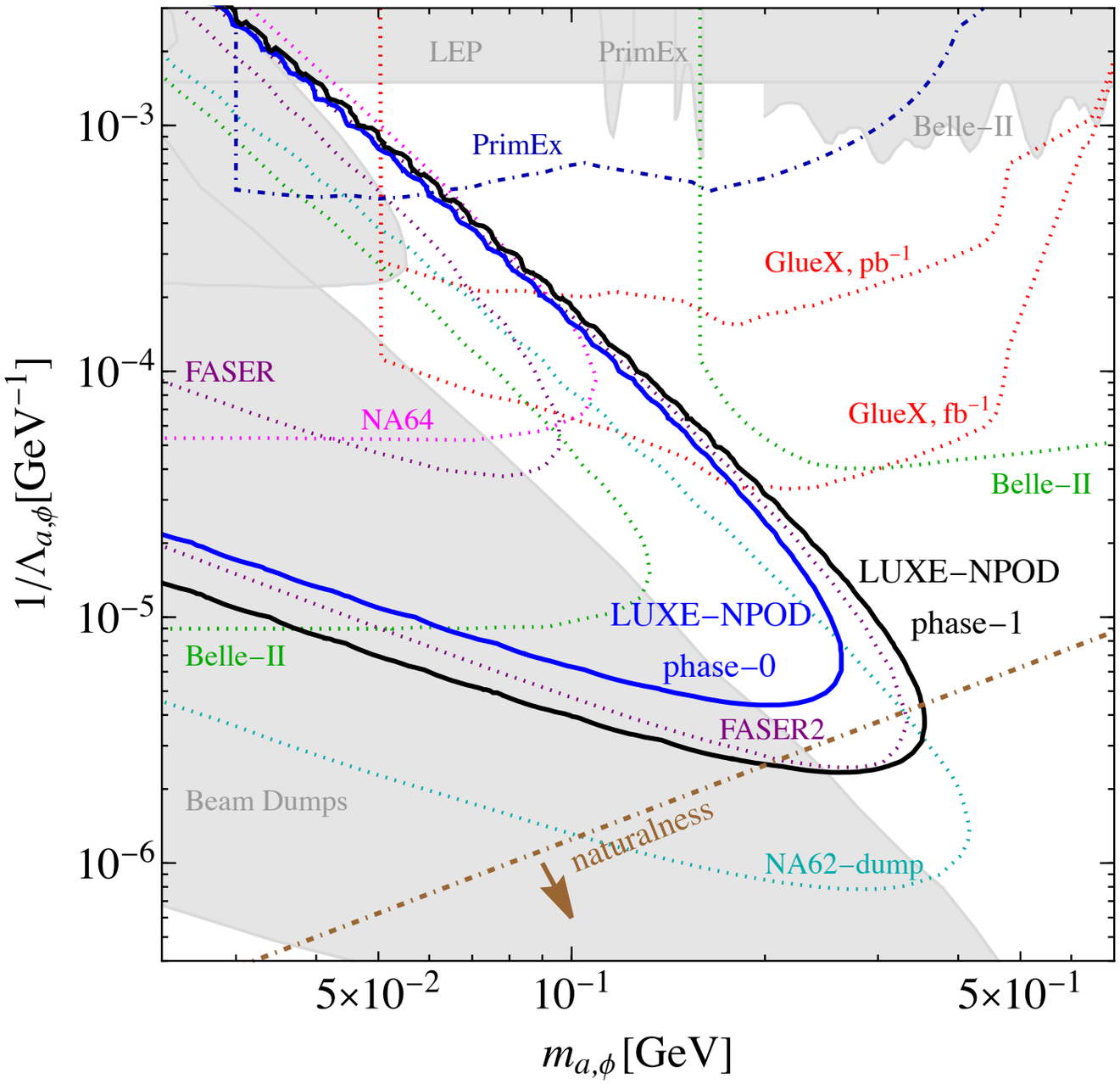
$R_{\text{sel}}, f_{n\to\gamma} \lesssim 10^{-3}$
for background free
achievable with current technologies
(CMS/LHCb/SHiP)

R_{sel} - event selection rejection
$f_{n\to\gamma}$ - neutron fake rate

depend on detector technology
(energy, pointing and timing resolutions)

ALP reach estimation

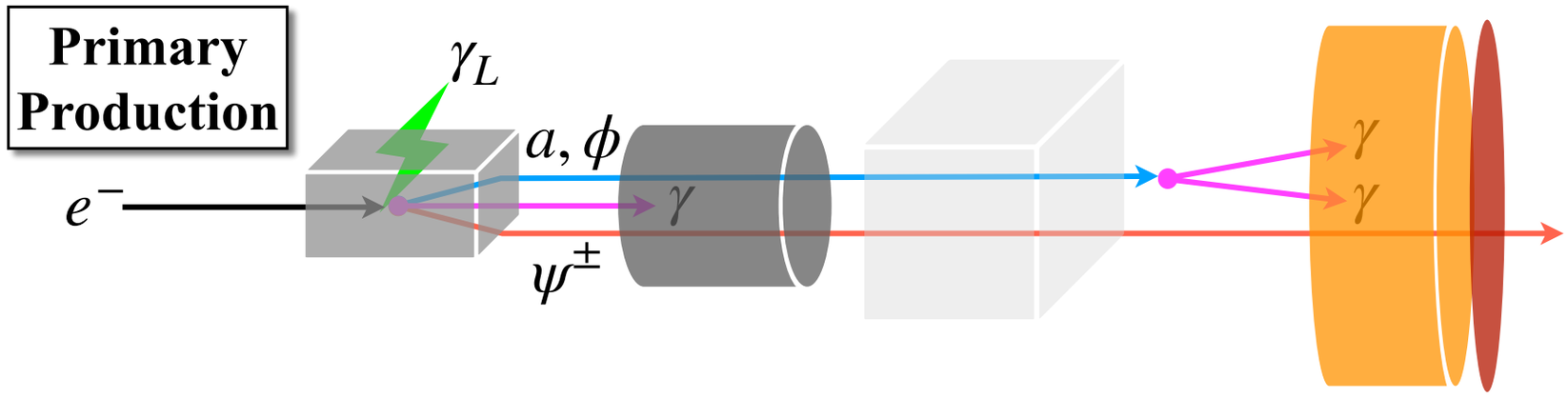
$E_e = 16.5\,\text{GeV}$ $N_e = 1.5 \times 10^9$ $N_{\text{BX}} = 10^7$ $L_S = 1.0\,\text{m}$ $L_D = 2.5\,\text{m}$ $R_D = 1.0\,\text{m}$ $E_{\gamma,\text{min}} = 0.5\,\text{GeV}$



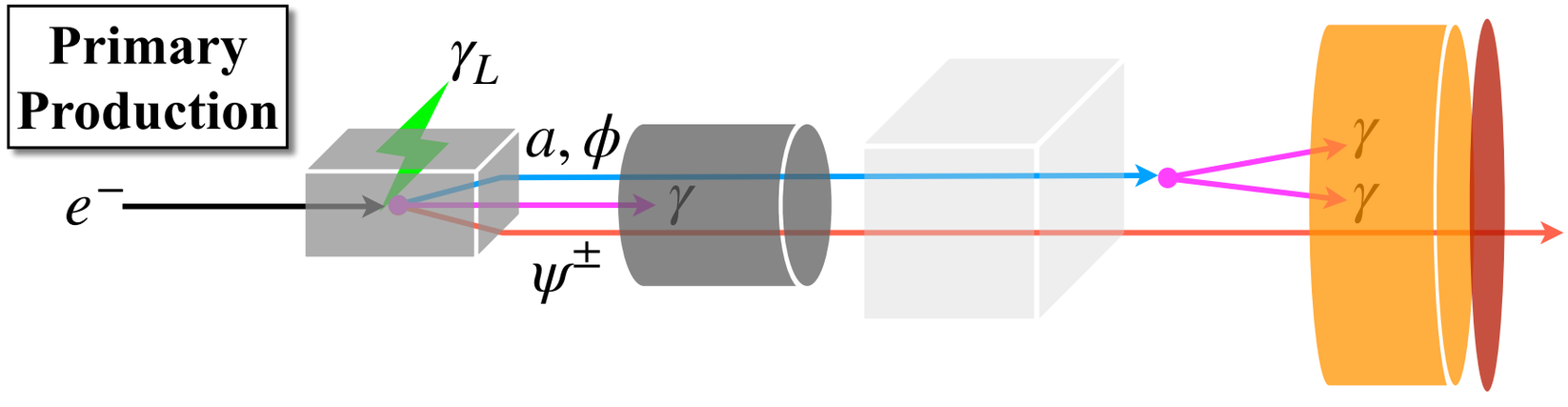
LUXE-NPOD
new Physics optical dump

assuming background free

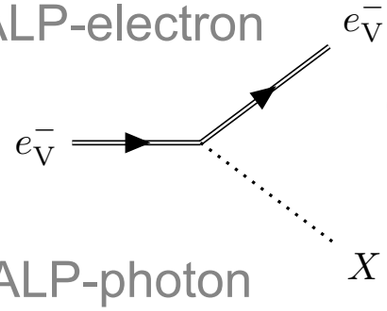
primary ALP production



primary ALP production

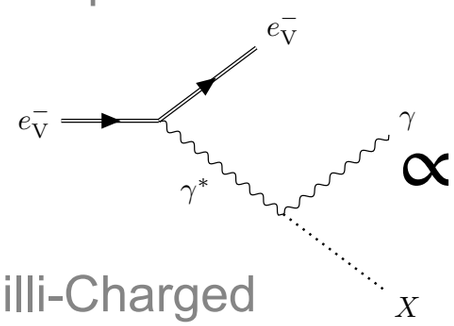


ALP-electron



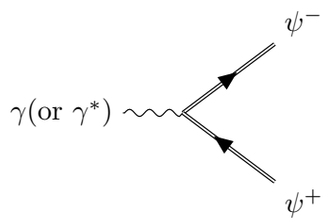
$\propto g_{ae}^2$

ALP-photon



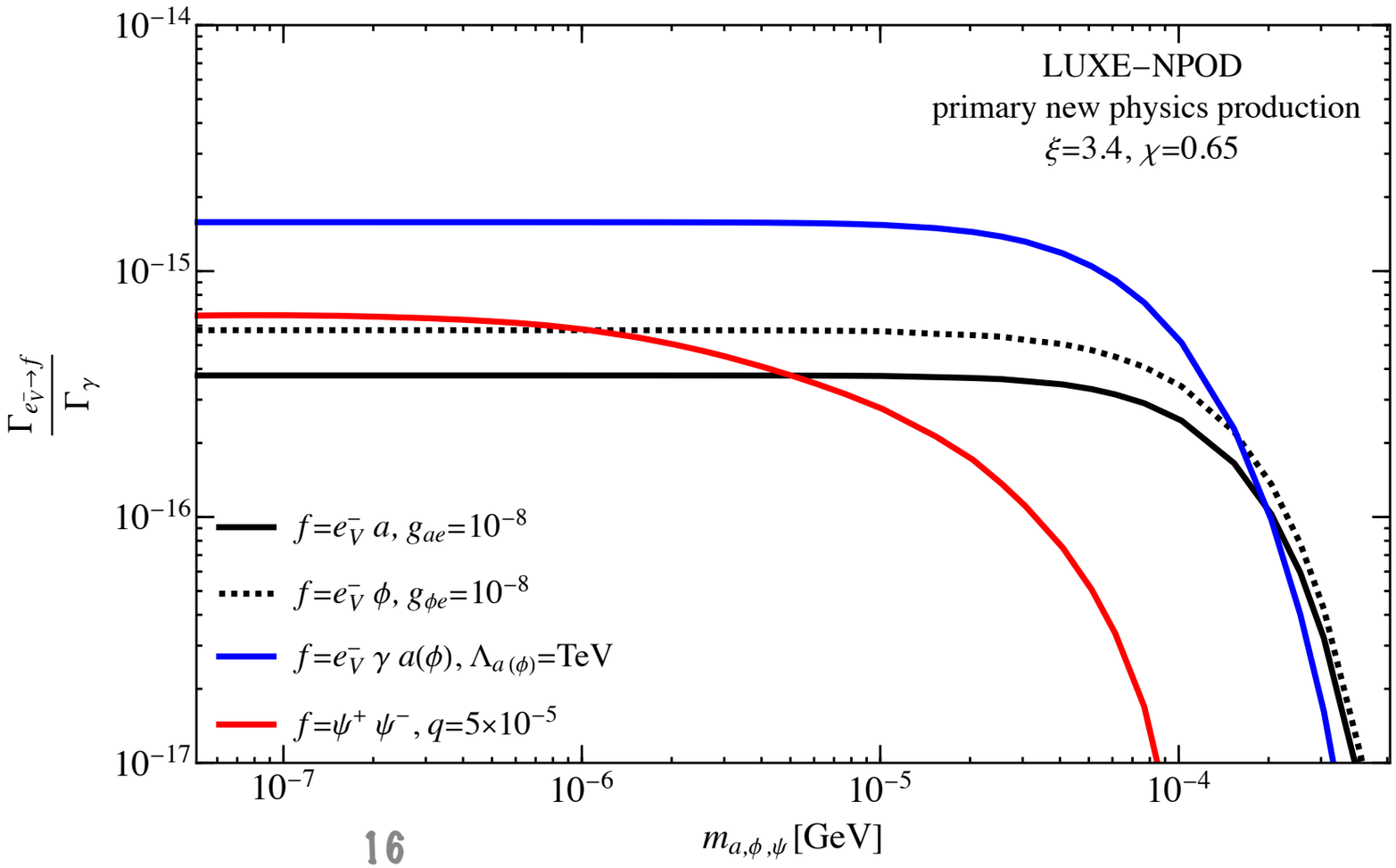
$\propto 1/\Lambda_{a,\phi}^2$

milli-Charged



$\propto q^4$

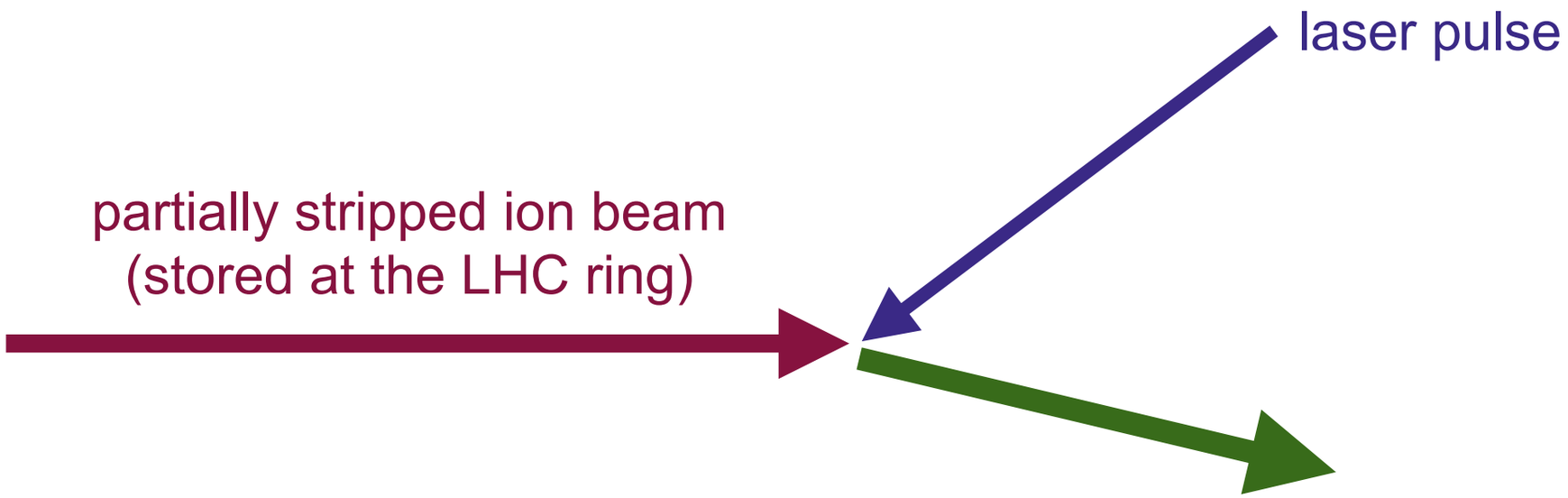
$\mathscr{L}_\psi = eq\bar{\psi}A_\mu\gamma^\mu\psi$



Probing ALPs at the CERN Gamma Factory

Balkin, Krasny, Ma, Safdi, YS
2105.15072

the Gamma-Factory



$$E_\gamma \sim \mathcal{O}(1-400)\,\mathrm{MeV}, \quad \frac{dN_\gamma}{dt} \approx (10^{16}-10^{18})\,\mathrm{sec}^{-1}$$

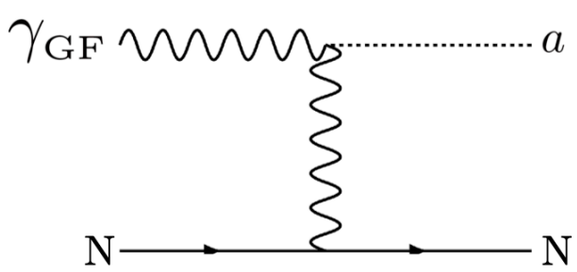
factor of $\mathcal{O}(10^7)$ larger than present sources

Krasny et al. 1511.07794

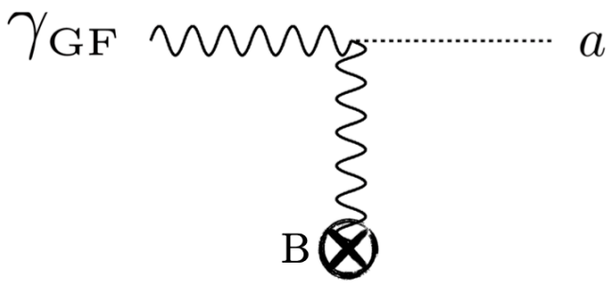
use this huge photon flux for BSM

probing ALP at the Gamma-Factory

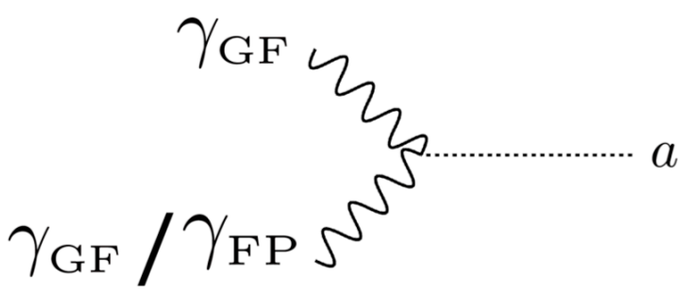
production



(1), (4)



(2)



(3)

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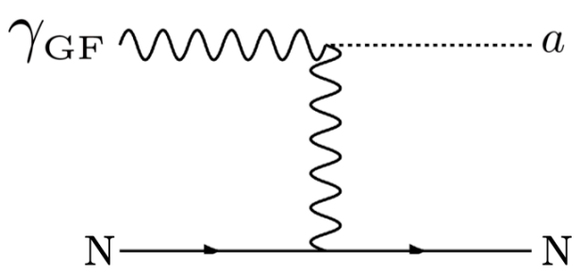
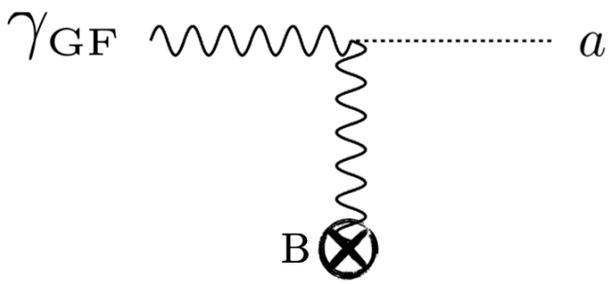
probing ALP at the Gamma-Factory

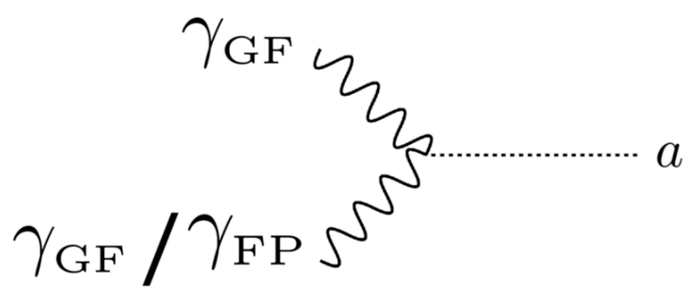
production



(1), (4)

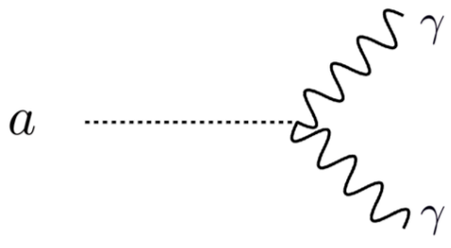


(2)

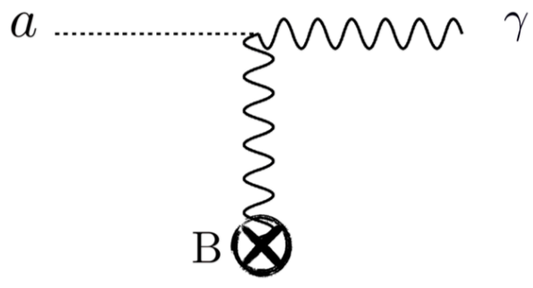


(3)

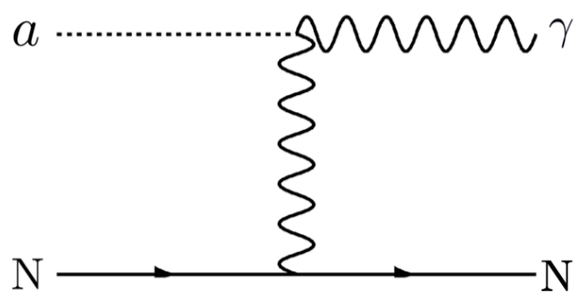
detection



(a)



(b)



(c)

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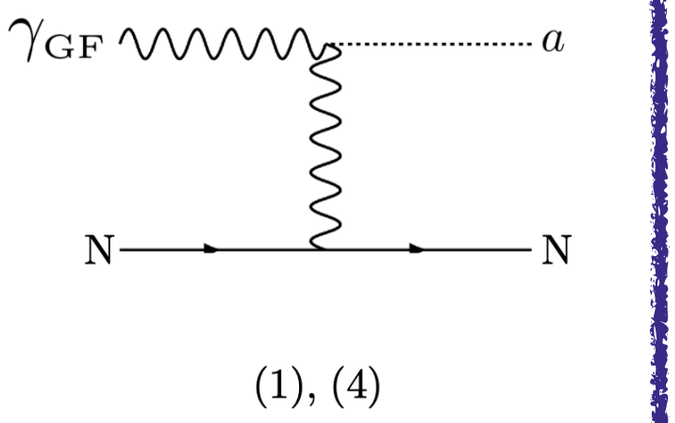
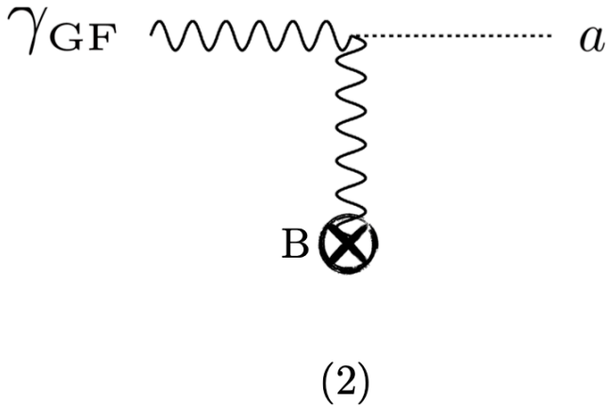
probing ALP at the Gamma-Factory

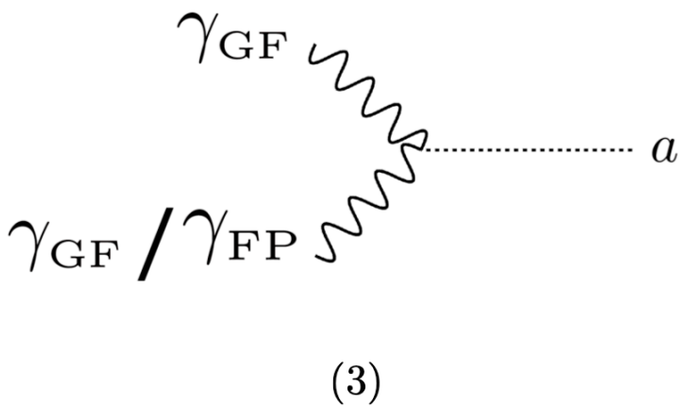
production



(1), (4)

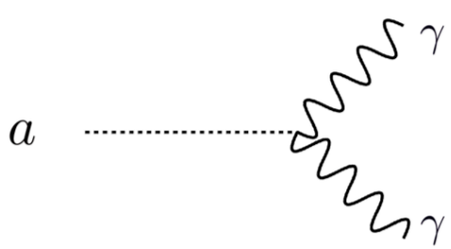


(2)

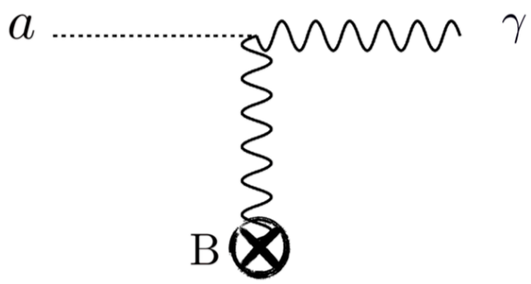


(3)

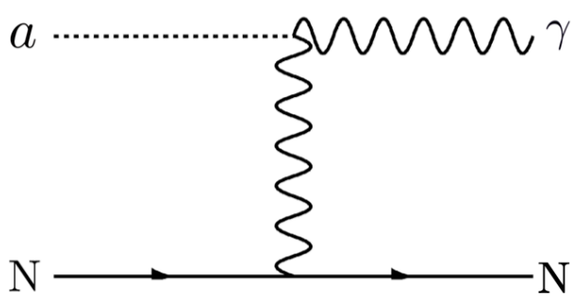
detection



(a)



(b)



(c)

focus today

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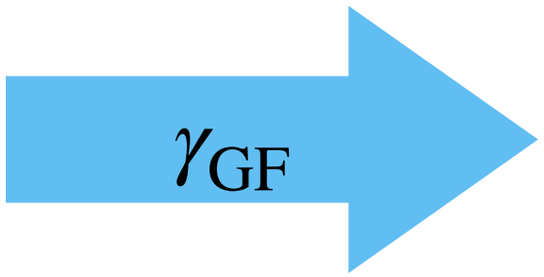
probing ALP at the Gamma-Factory



$$\frac{dN_\gamma}{dt} \sim \frac{10^{17}}{\rm sec}$$

$$E_\gamma \lesssim 400\,{\rm MeV}$$

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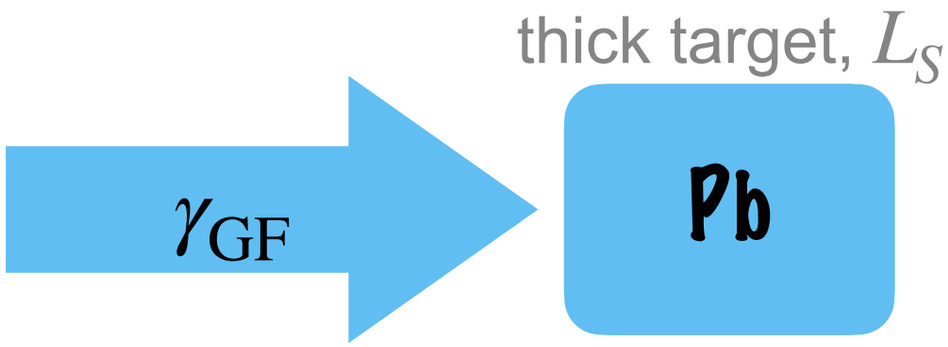
probing ALP at the Gamma-Factory



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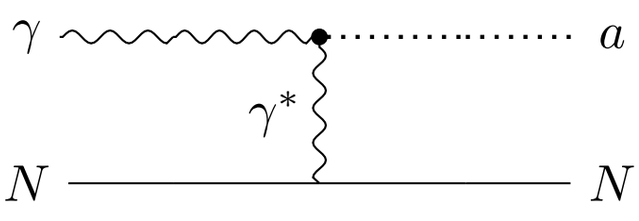

$$N_a^{\rm prod} = N_\gamma \frac{\rho_N X_0}{A m_0}\,\sigma_a$$

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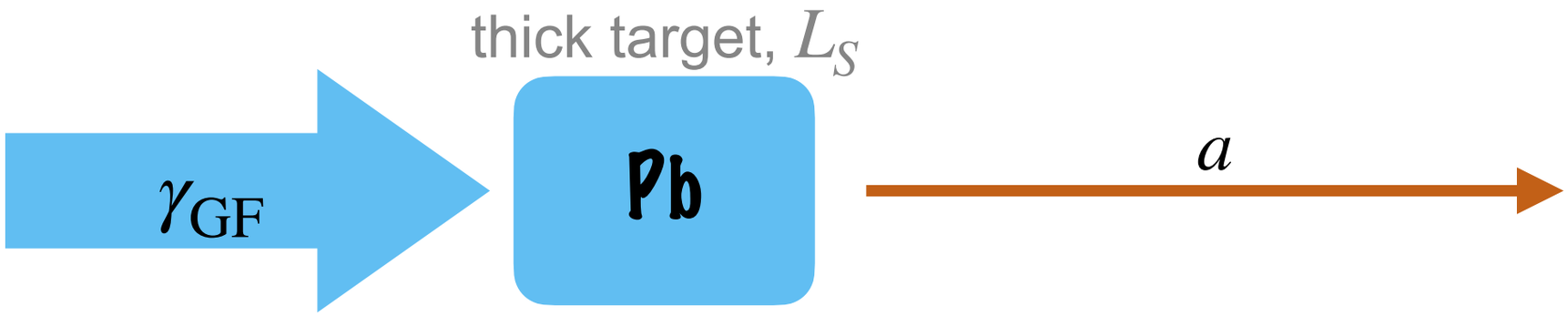
probing ALP at the Gamma-Factory



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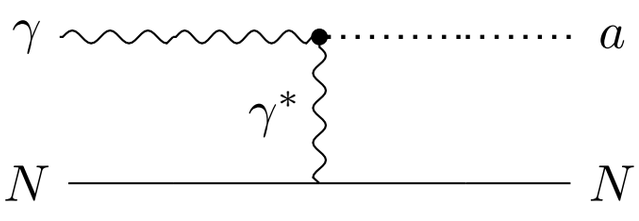

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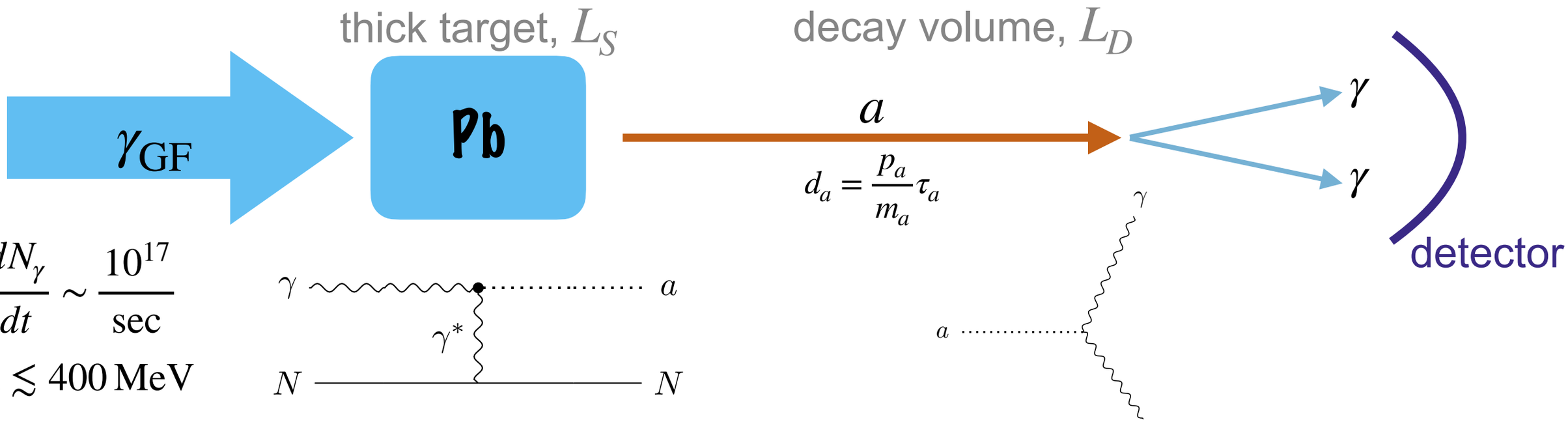
probing ALP at the Gamma-Factory



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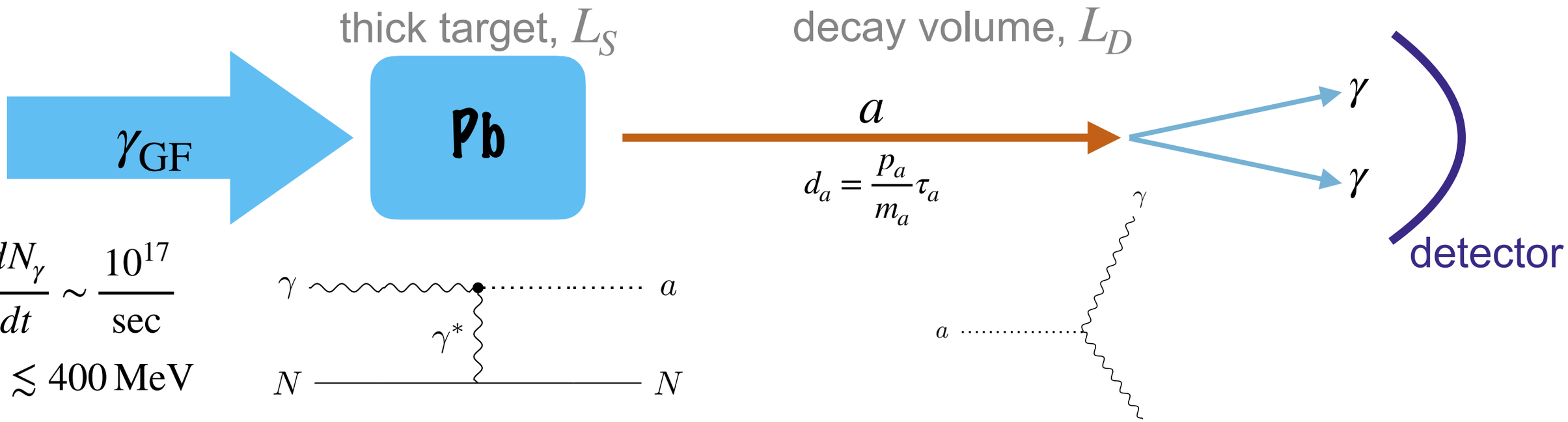
probing ALP at the Gamma-Factory



$$N_a^{\rm prod} = N_\gamma \frac{\rho_N X_0}{A m_0}\,\sigma_a$$

$$e^{-L_S/d_a}\left(1-e^{-L_D/d_a}\right)\overset{\gamma}{\mathscr{A}} \approx \frac{L_D}{d_a}$$

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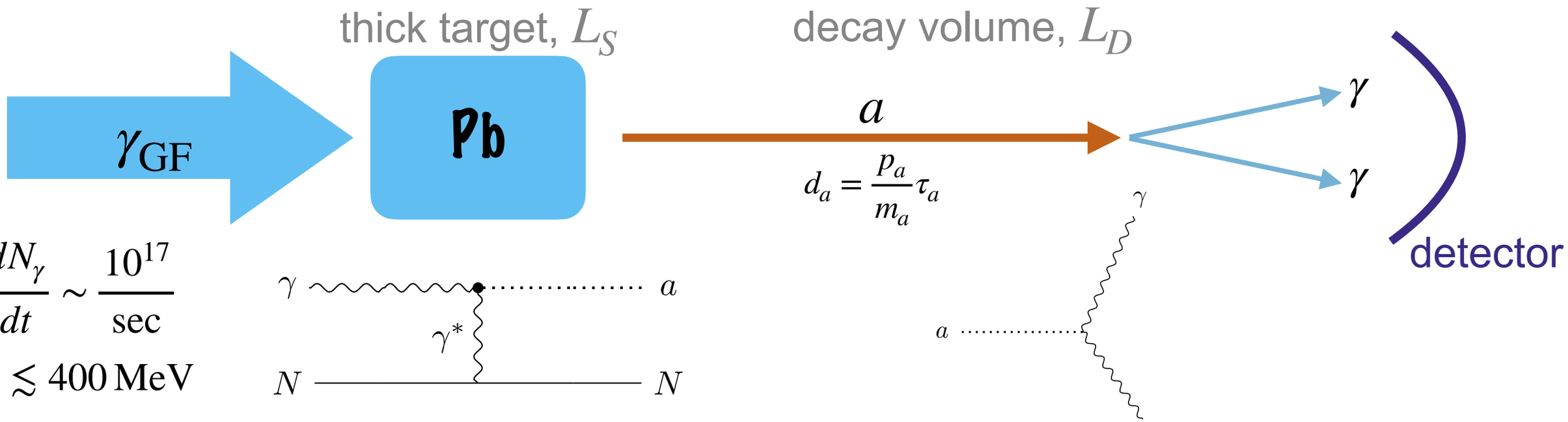
probing ALP at the Gamma-Factory



$$N_a^{\rm prod} = N_\gamma \frac{\rho_N X_0}{A m_0}\,\sigma_a \qquad e^{-L_S/d_a}\left(1-e^{-L_D/d_a}\right)\mathscr{A}^{\gamma} \approx \frac{L_D}{d_a}$$

$$N_a^{\rm tot} \approx 6\times 10^8 \left(\frac{N_\gamma}{10^{24}}\right)\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^2 \frac{L_D}{8\times 10^9{\rm m}}\left(\frac{0.2\,{\rm GeV}}{E_\gamma}\right)\left(\frac{m_a}{\rm MeV}\right)^4\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^2 \approx 3\frac{L_D}{40\,{\rm m}}\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^4$$

$k_\gamma = 200\,{\rm MeV}$
$m_a = 1\,{\rm MeV}$

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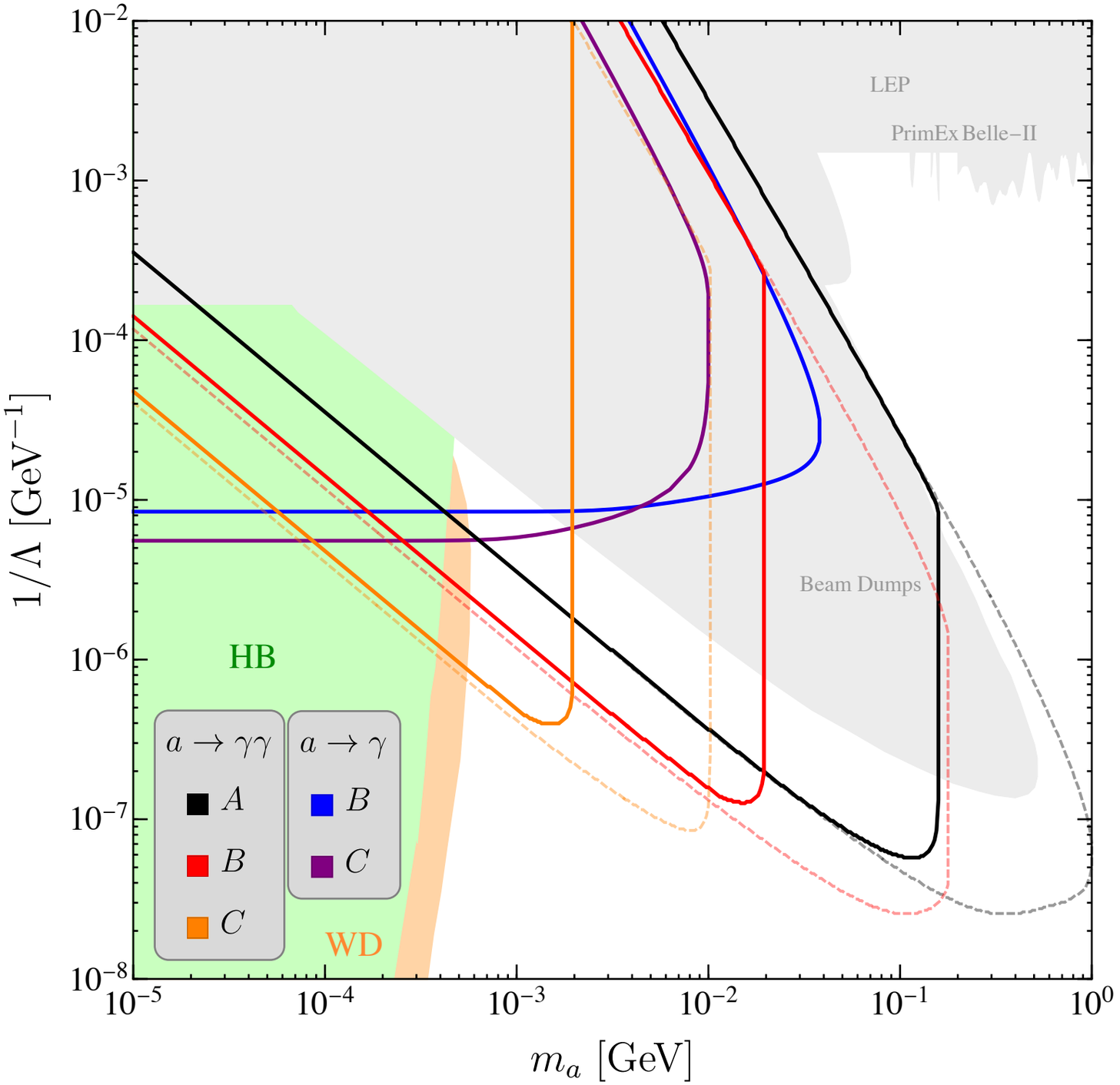
probing ALP at the Gamma-Factory



(A): $E_{\gamma_{\rm GF}} = 1.6\,{\rm GeV}$ $\quad \frac{dN_\gamma}{dt} = 10^{16}\,{\rm sec}^{-1}$

(B): $E_{\gamma_{\rm GF}} = 0.2\,{\rm GeV}$ $\quad \frac{dN_\gamma}{dt} = 10^{17}\,{\rm sec}^{-1}$

(A): $E_{\gamma_{\rm GF}} = 0.02\,{\rm GeV}$ $\quad \frac{dN_\gamma}{dt} = 10^{18}\,{\rm sec}^{-1}$

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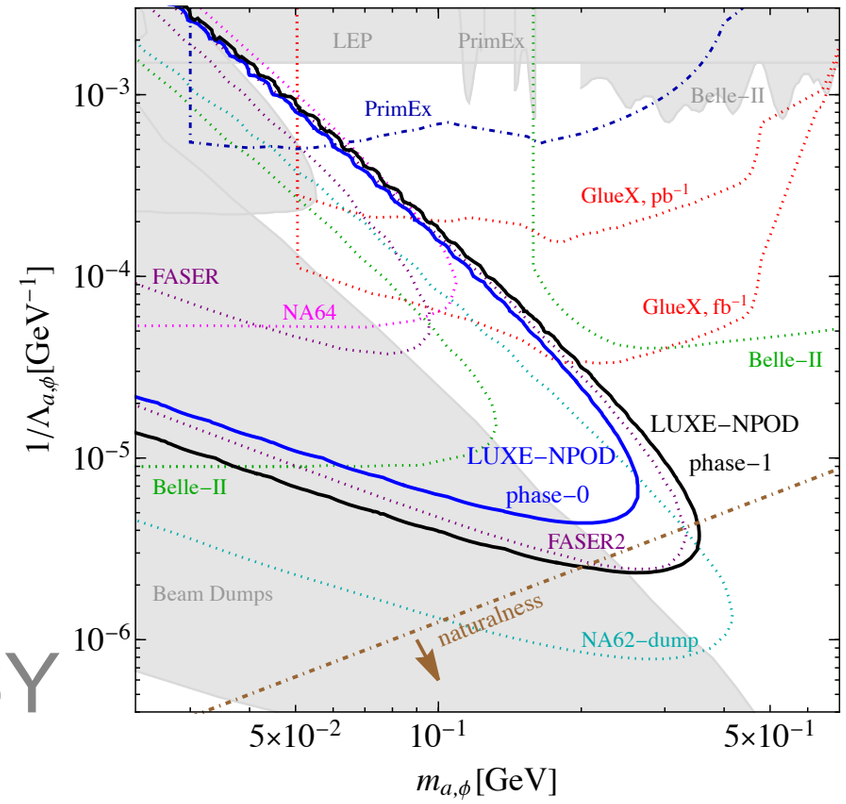
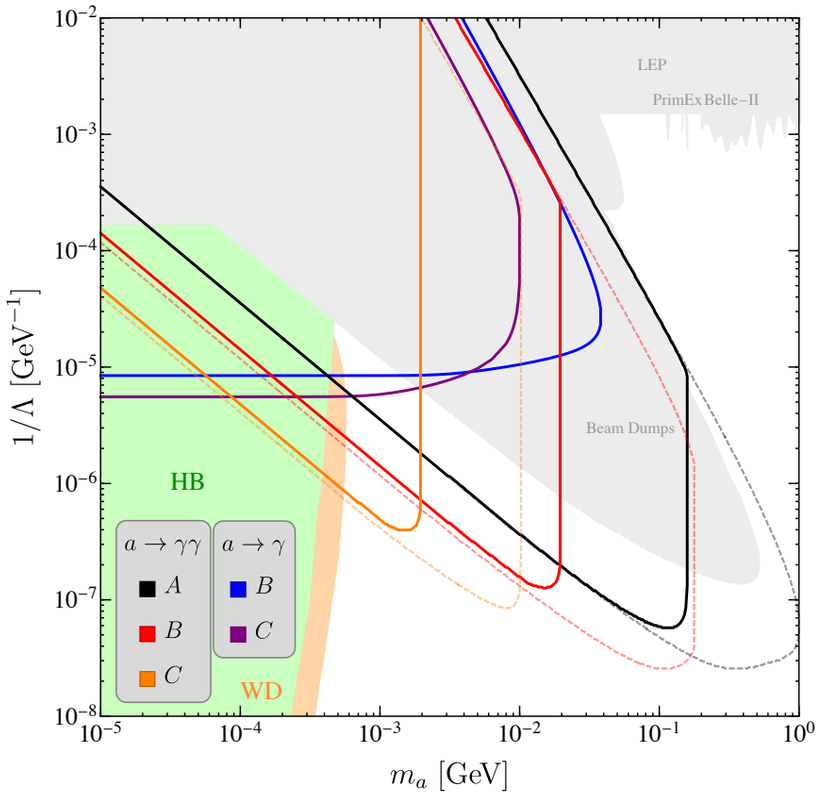
Outlook

* primEx/GlueX - prompt search
* LUXE-NPOD: open the door to novel type of beam dump experiments, connect BSM and high intense QED LUXE is proposed experiment at DESY and Eu.XFEL (pass CD0 stage)
* the CERN Gamma-Factory

all probe different and unexplored ALP (and scalar) parameter space





Backups

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

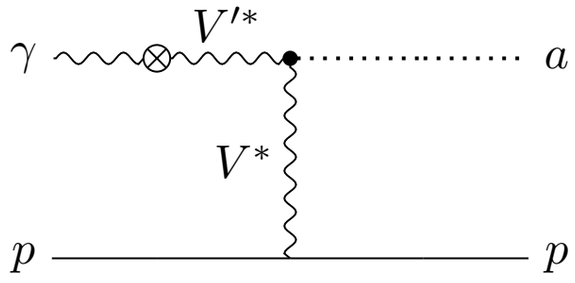
$$F_a = |\Lambda/(32\pi^2 c_g)|$$

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$F_a = |\Lambda/(32\pi^2 c_g)|$$

GlueX
p traget



$$\frac{d\sigma_{\gamma p\to ap}}{dt} \approx \left(\frac{f_\pi}{F_a}\right)^2 \left[|\langle a\pi^0\rangle|^2 \frac{d\sigma_{\gamma p\to \pi^0 p}}{dt} + |\langle a\eta\rangle|^2 \frac{d\sigma_{\gamma p\to \eta p}}{dt} \right]$$

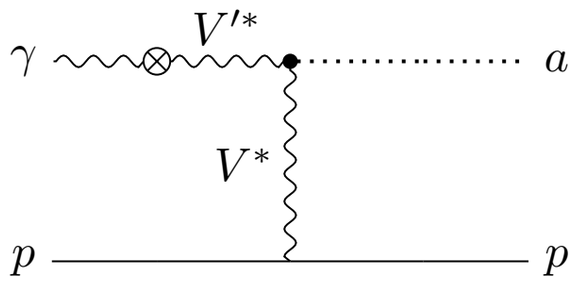
$a-\pi^0,\eta$ mixing

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

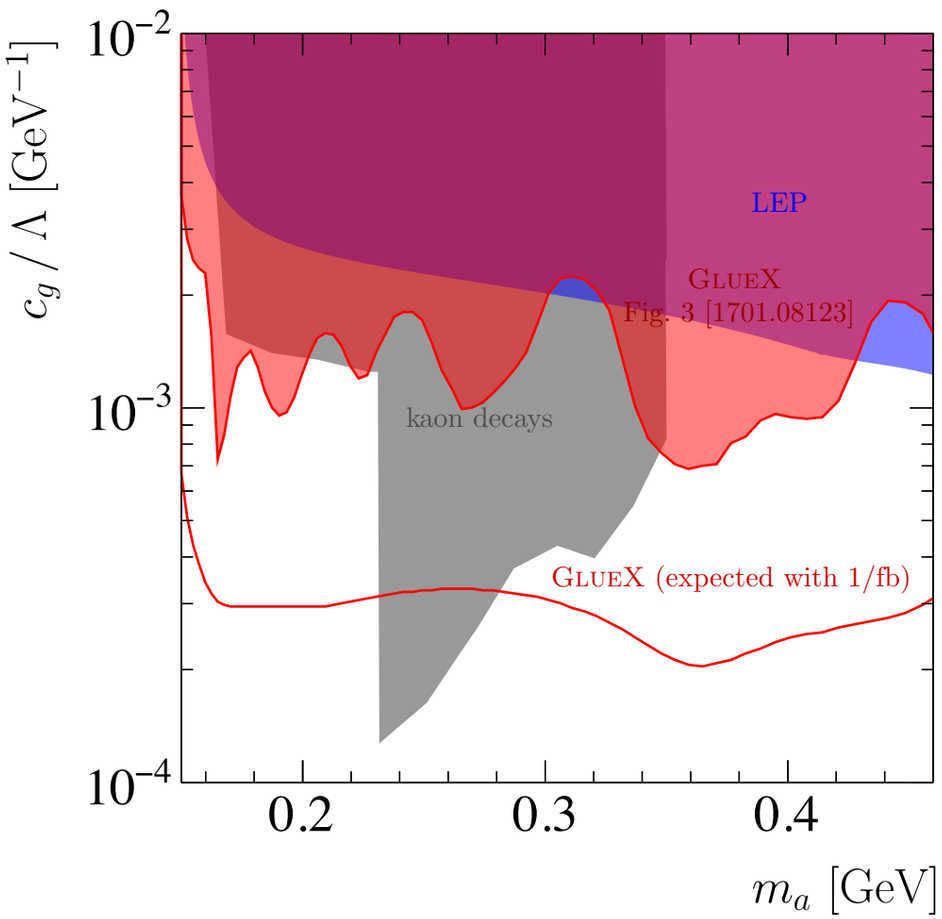
$$F_a = |\Lambda/(32\pi^2 c_g)|$$

GlueX
p traget



$$\frac{d\sigma_{\gamma p\to ap}}{dt} \approx \left(\frac{f_\pi}{F_a}\right)^2 \left[|\langle a\pi^0\rangle|^2 \frac{d\sigma_{\gamma p\to \pi^0 p}}{dt} + |\langle a\eta\rangle|^2 \frac{d\sigma_{\gamma p\to \eta p}}{dt} \right]$$

$a - \pi^0, \eta$ mixing



$\gamma\gamma$ final state

ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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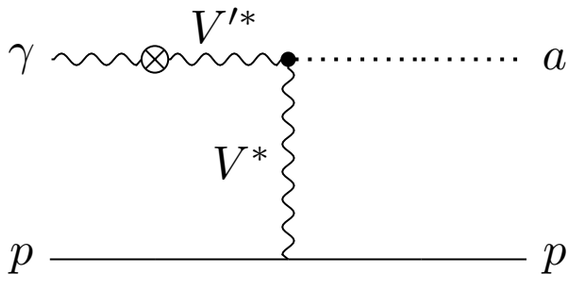
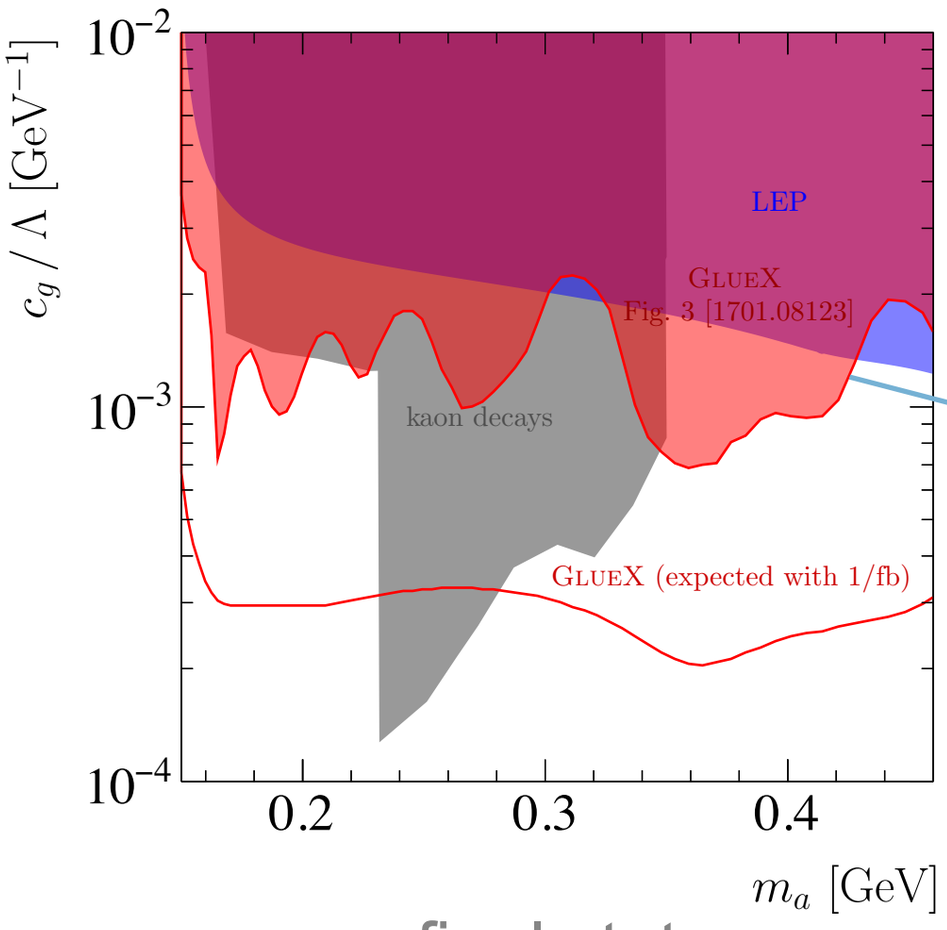
GlueX

p traget

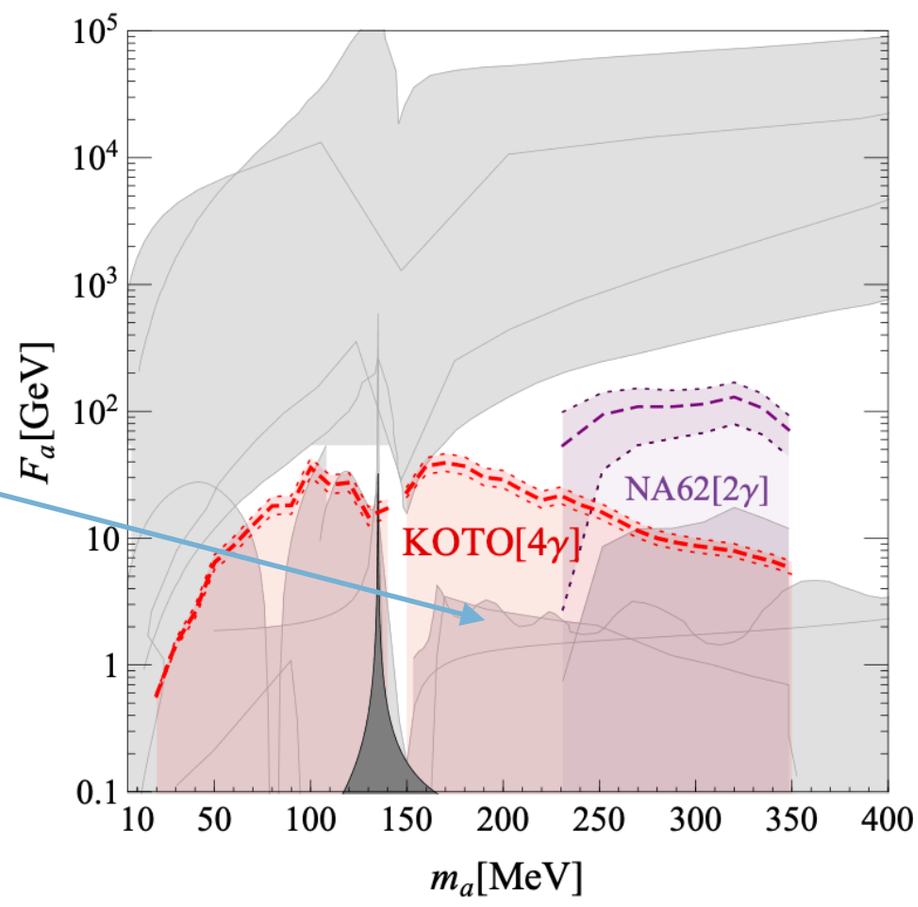


KOTO

$K_L \to \pi^0 a \to 4\gamma$



$\gamma\gamma$ final state



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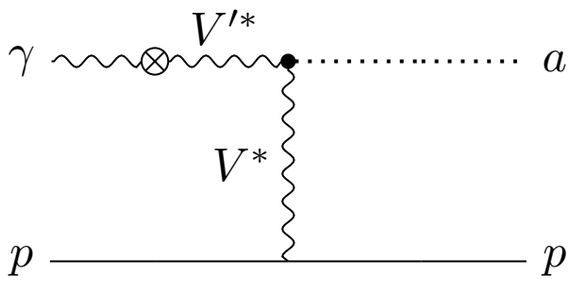
ALP gluons coupling

$$-\frac{4\pi\alpha_s c_g}{\Lambda}\, a\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$$F_a = |\Lambda/(32\pi^2 c_g)|$$

GlueX

p traget

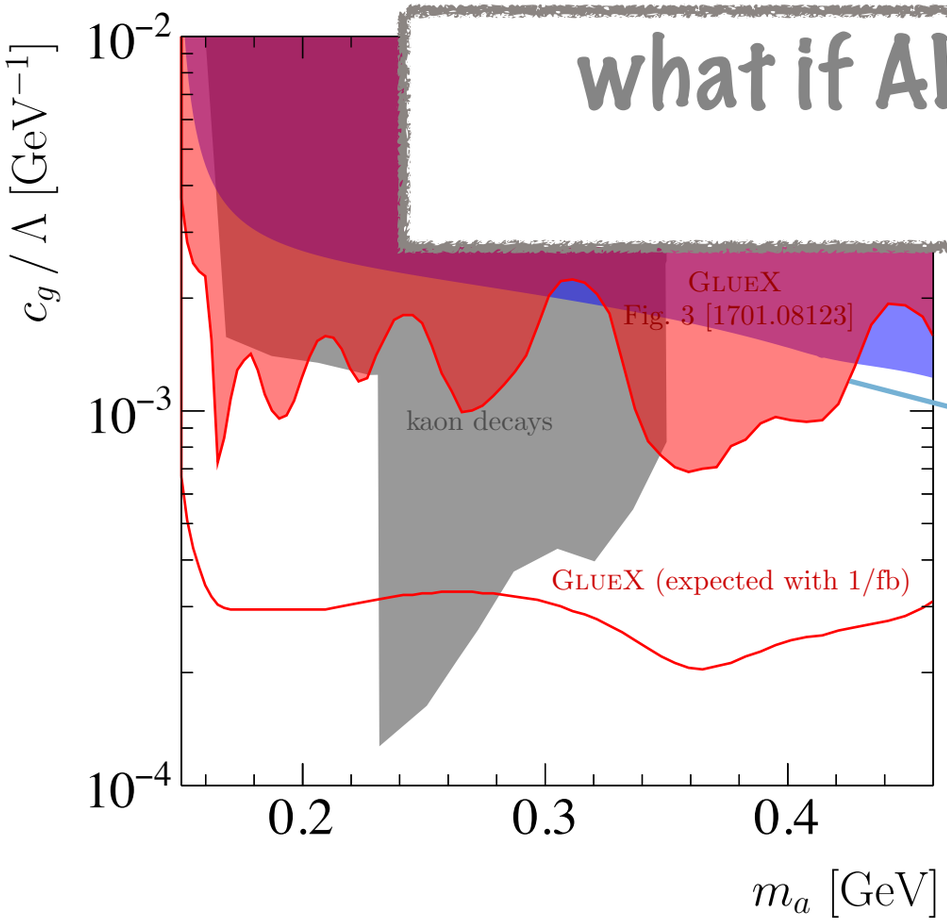


KOTO

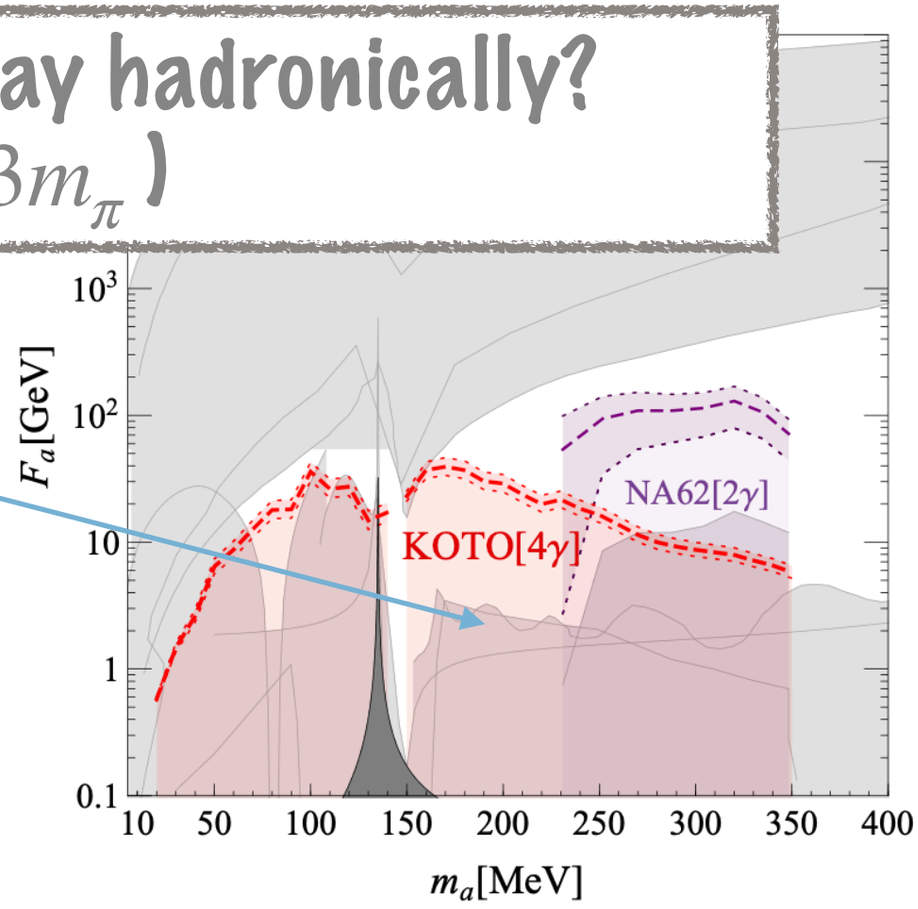
$K_L \to \pi^0 a \to 4\gamma$

what if ALP can decay hadronically?

$(m_a > 3m_\pi)$



$\gamma\gamma$ final state



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LUXE-NPOD backgrounds