LUXE-NPOD new physics searches with an optical dump

Yotam Soreq

DESY particle and astro particle physics colloquium,
March 22, 2022

why new physics?

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experimental evidences + theoretical arguments

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➡ new interactions

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* dark matter (80% of Universe matter)

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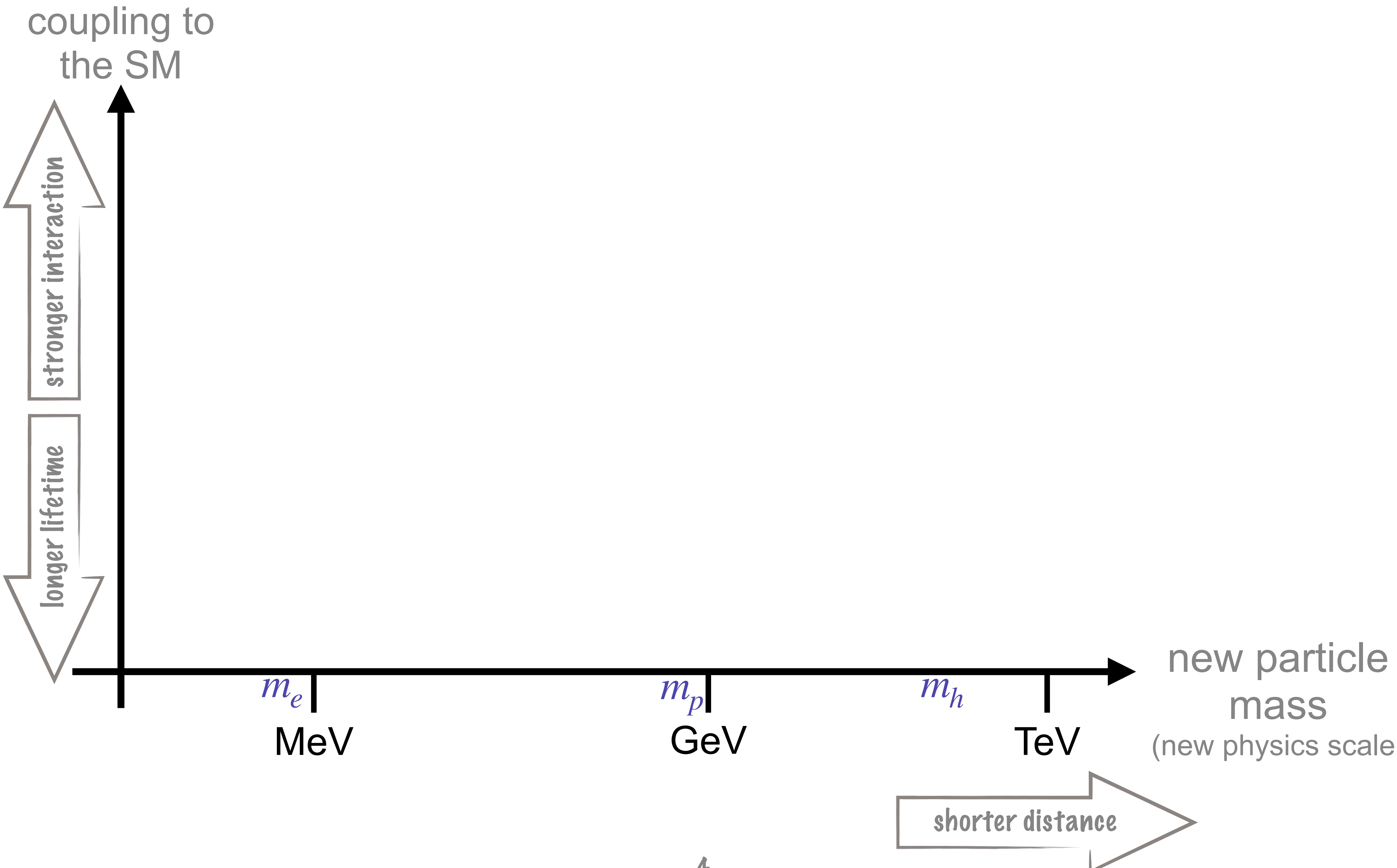
theory issues:

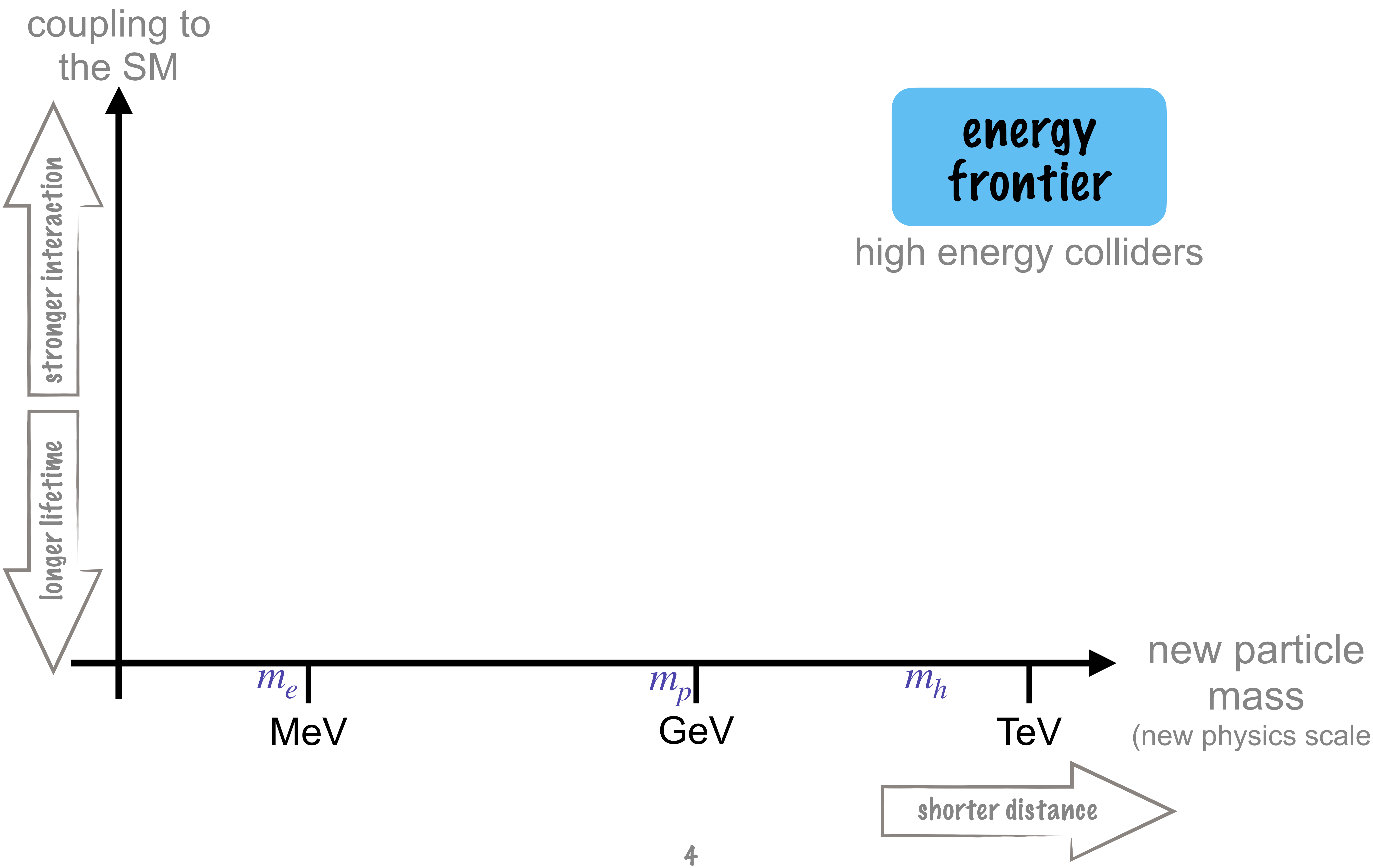
* stability of the electroweak scale
* the strong CP problem
* the flavour puzzle

→ new interactions may be related to solutions of these problems

the quest for new physics



the quest for new physics



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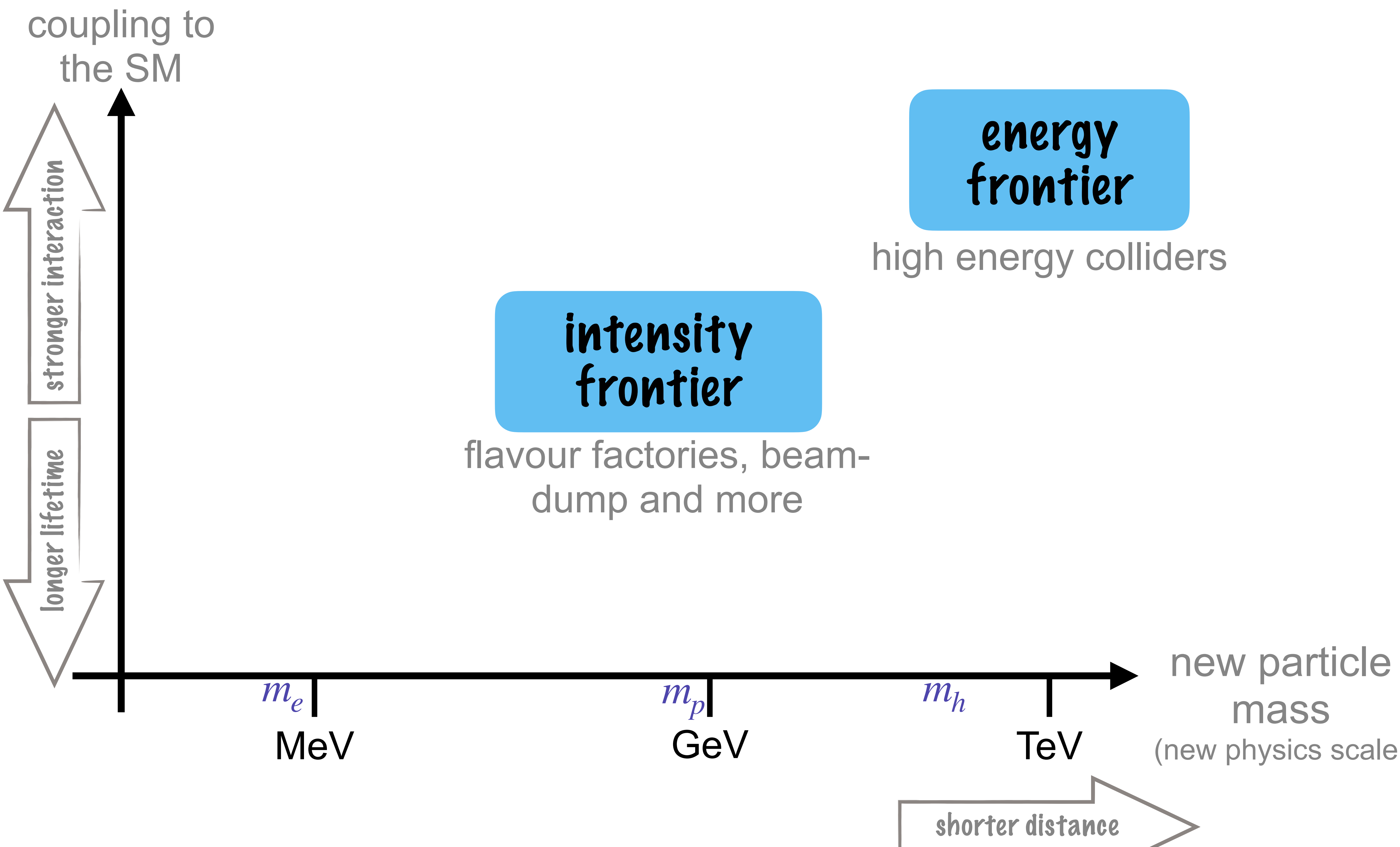

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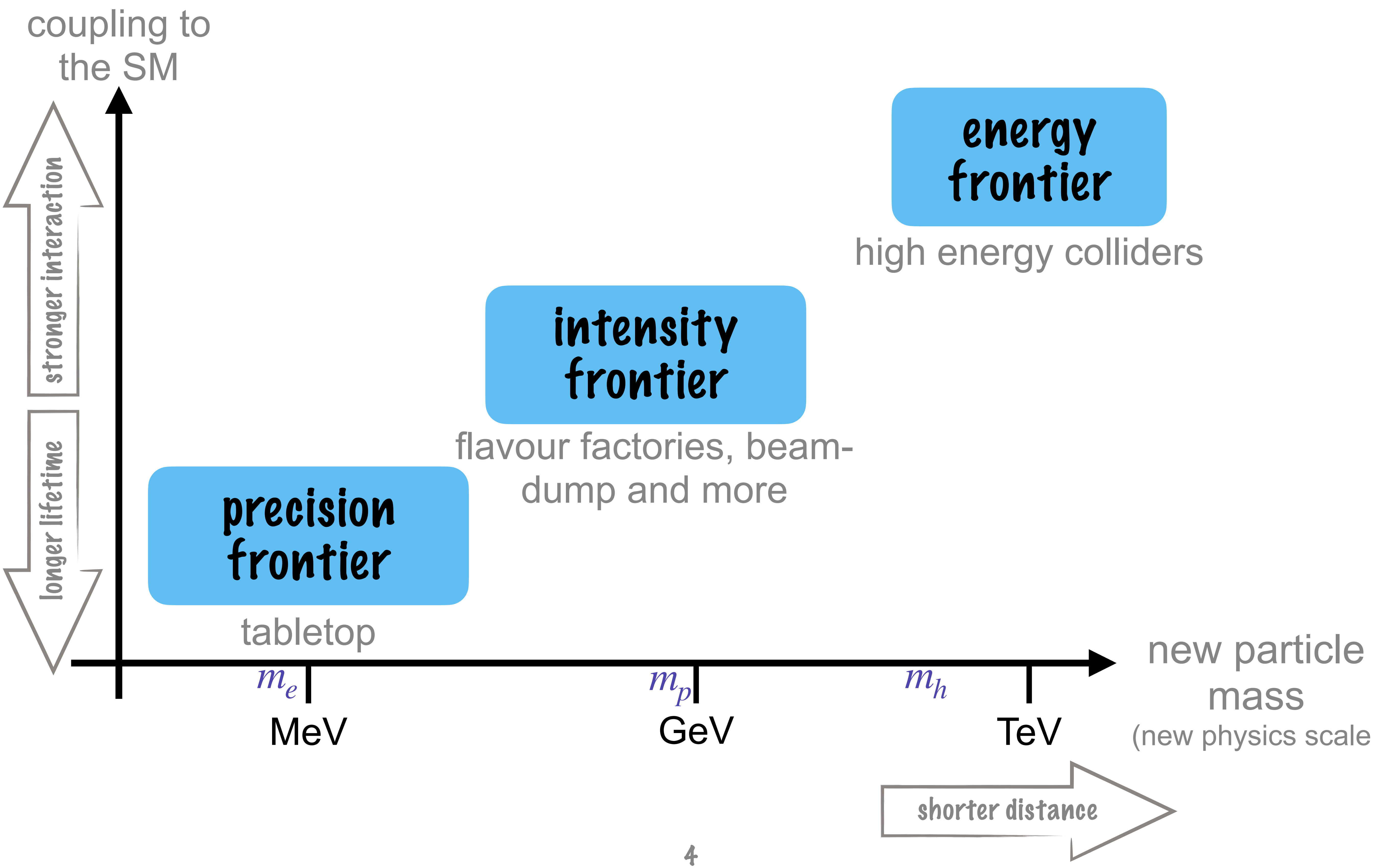

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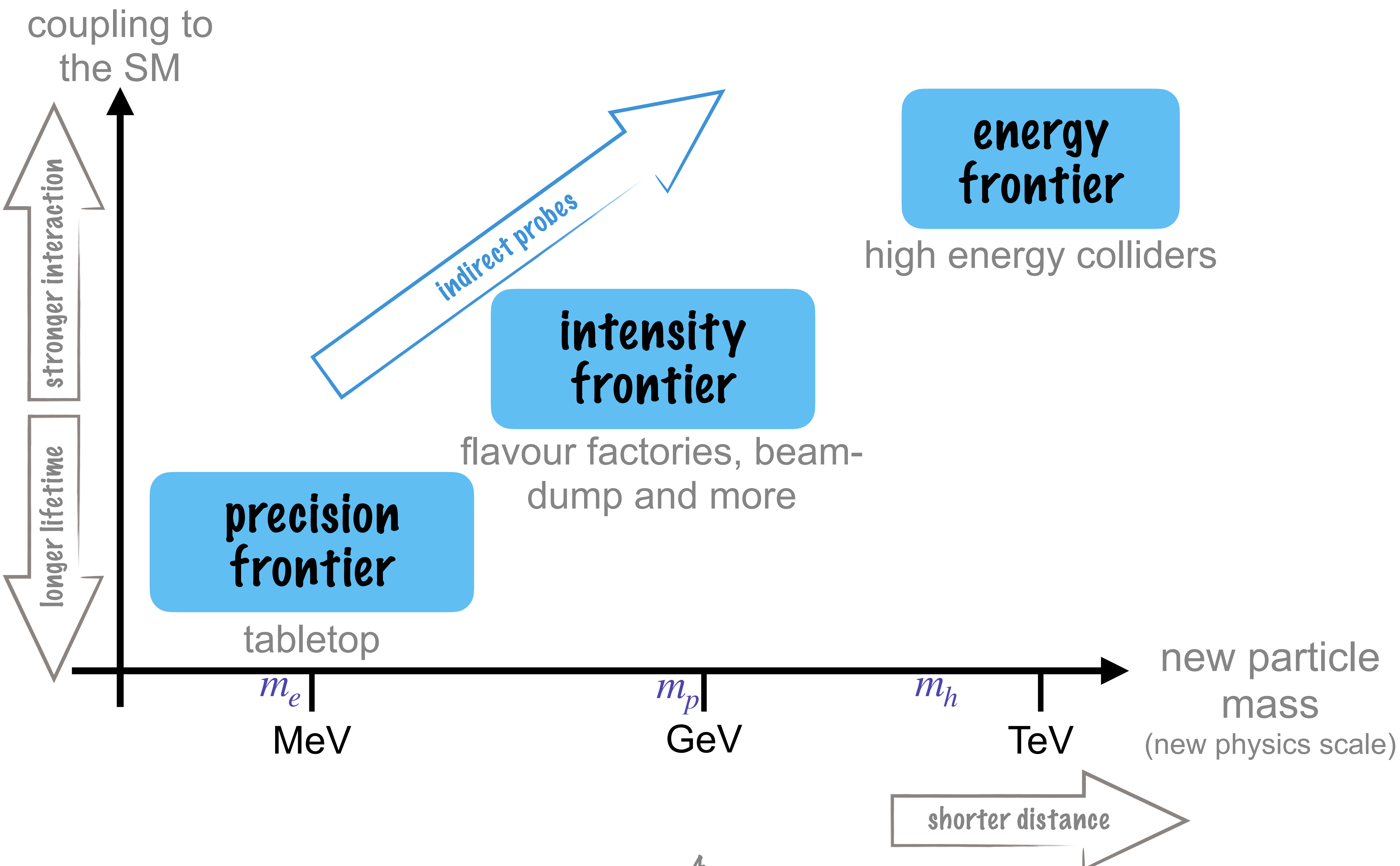

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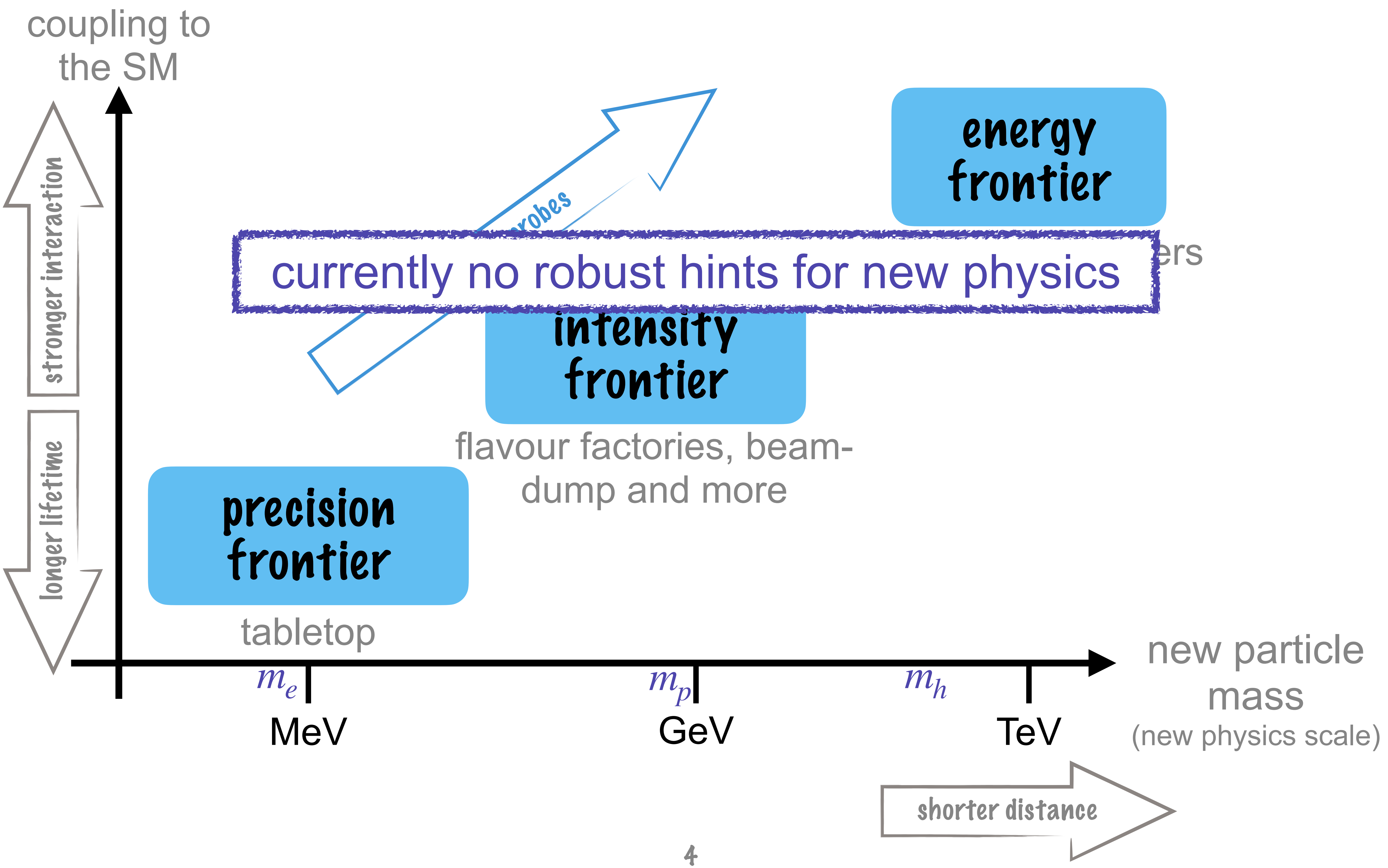

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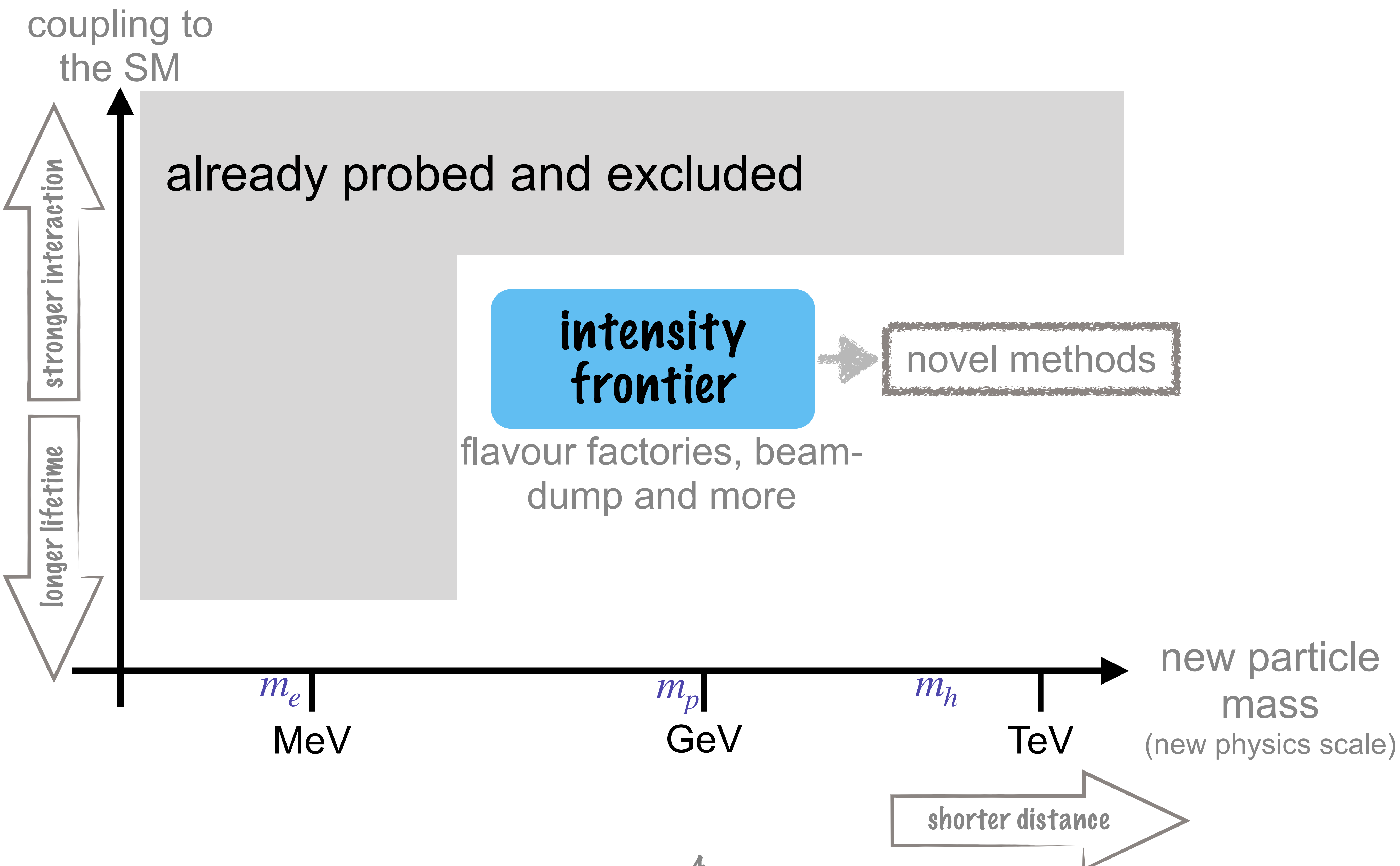

MeV-to-GeV scale new physics

well motivated
(DM portal, hierarchy problem…)

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rare SM processes ⟷ excellent BSM probes

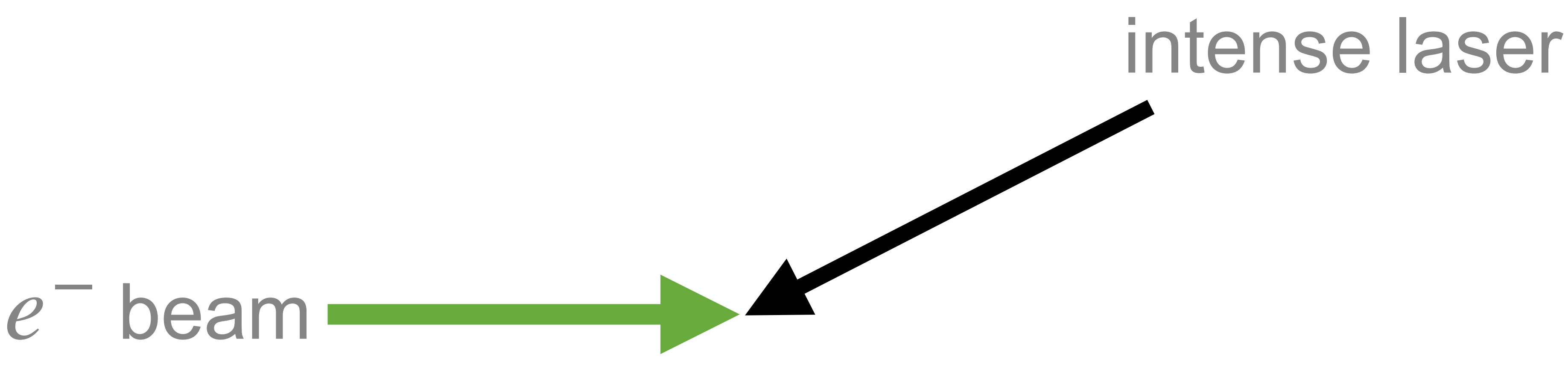
the LUXE experiment

LUXE LOI 1909.00860
LUXE CDR 2102.0232

strong field experiment

electron in strong field

e^-_{V} Volkov state, dressed electron



Ritus, 1985
SLAC 144 (96)
Hartin, Ringwald, Tapia 1807.10670

strong field experiment

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↓

non-linear & non-pert.
Compton scattering

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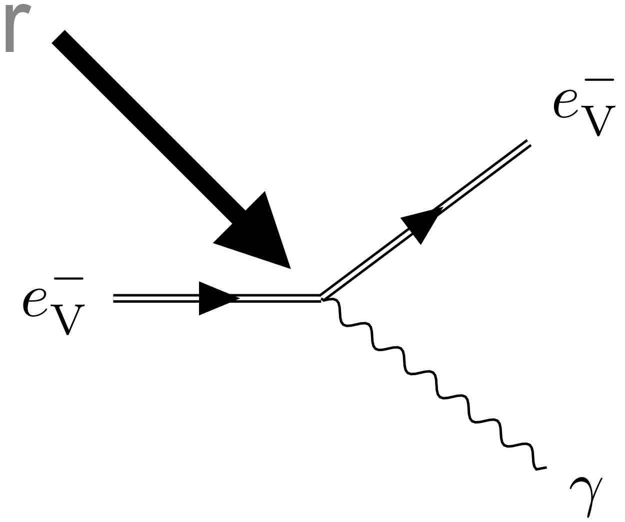
intense laser



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e^+e^- pair production (quantum tunneling)

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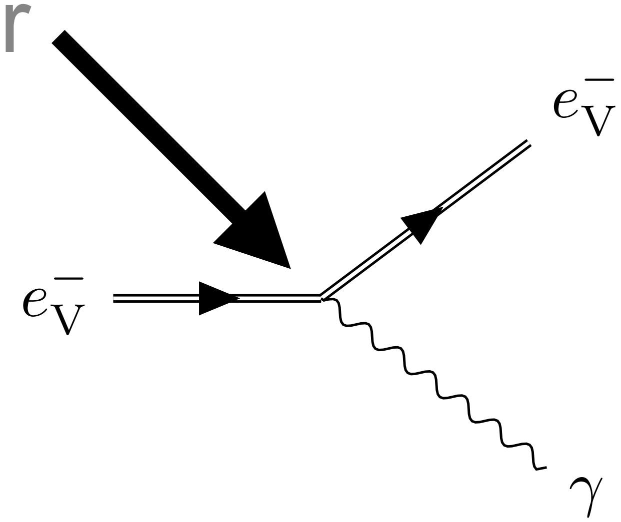

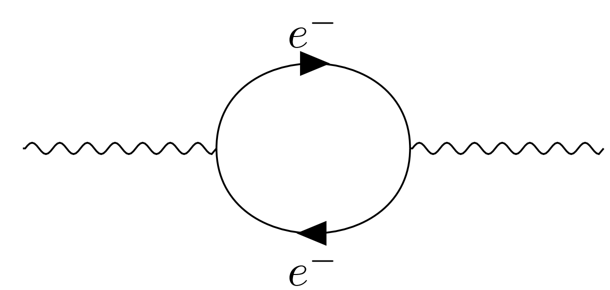

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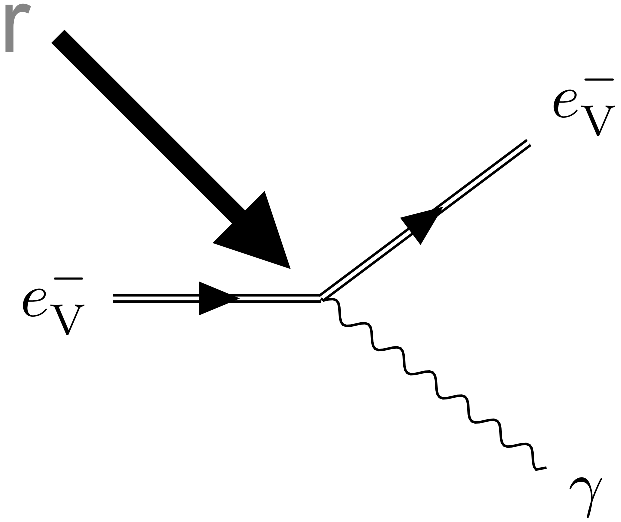

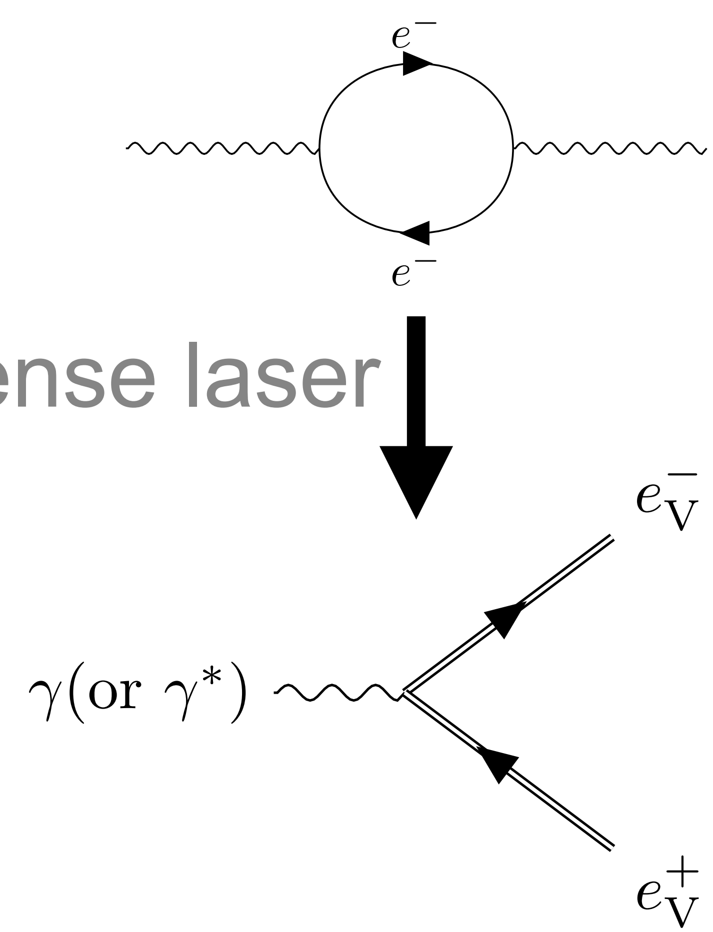

effective electric field, enhanced by a boost of E_e/m_e
is larger than Schwinger critical field of m_e^2/e

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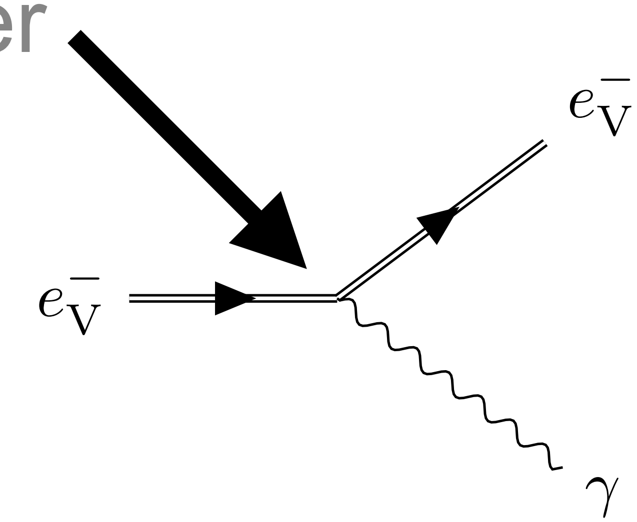
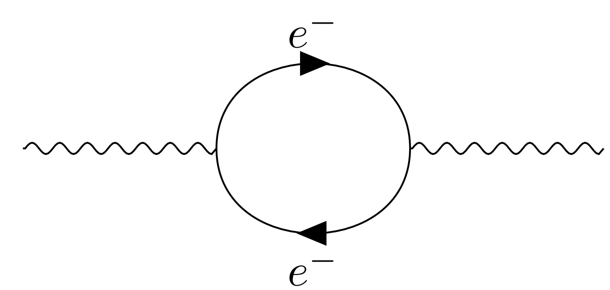
strong field experiment

hunt for unobserved SM phenomena ⟷ the quest for new physics

intense laser





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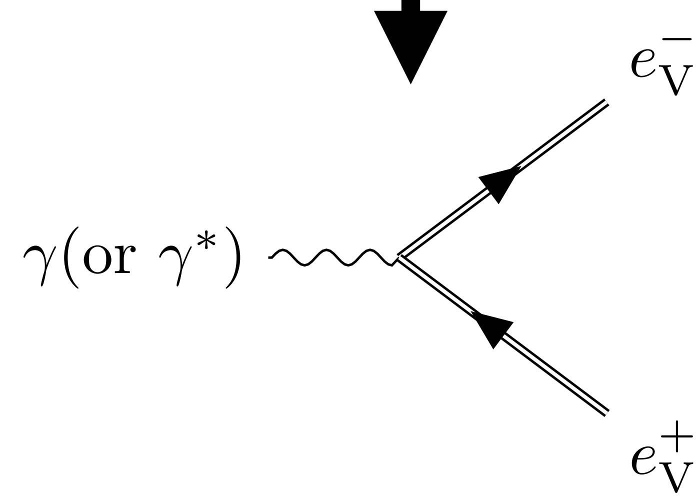

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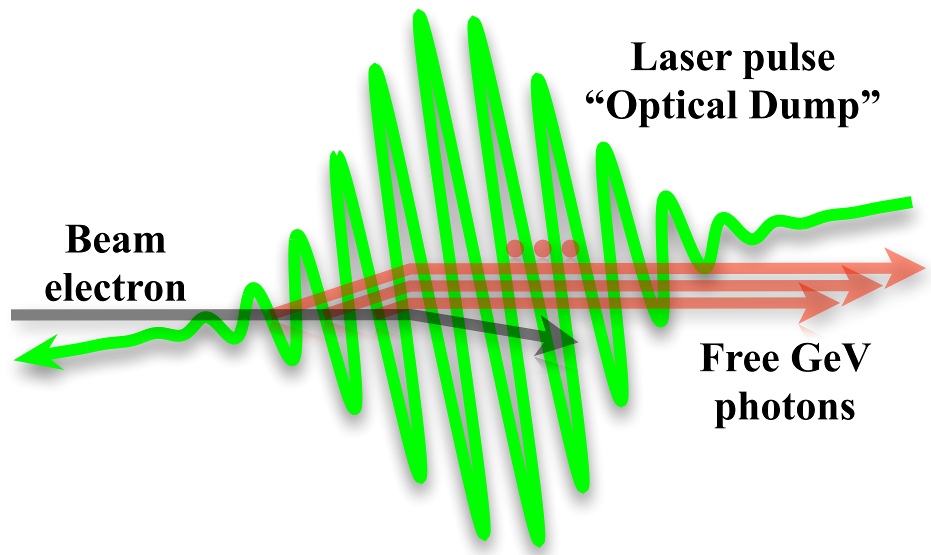
LUXE-NPOD:
new physics searches with an optical dump at LUXE

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, Santra, YS, Tal Hod, 2107.13554
LUXE CDR 2102.0232

the LUXE setup

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



$\omega_L \approx 1.5\,\mathrm{eV} \sim 1/(0.4\,\mathrm{fs})$

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

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LUXE, 1909.00860, 2102.02032

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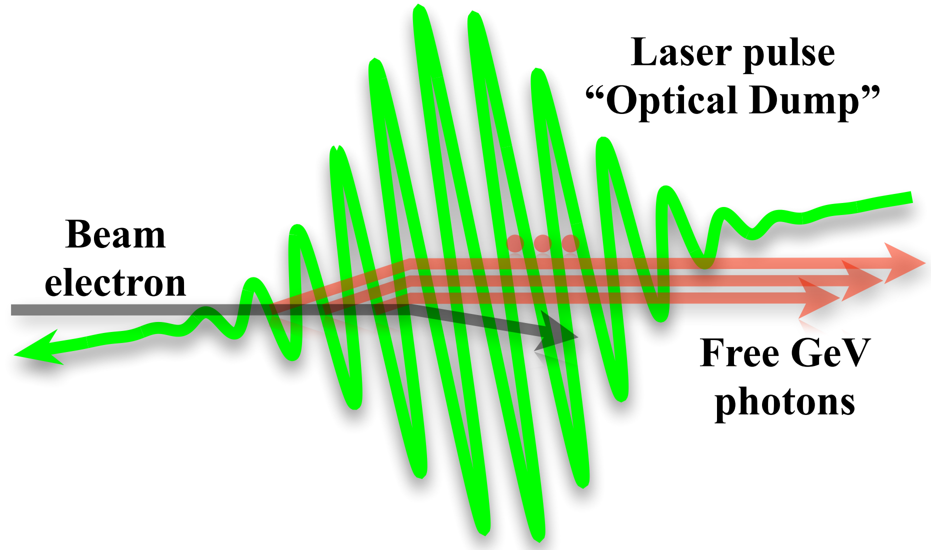

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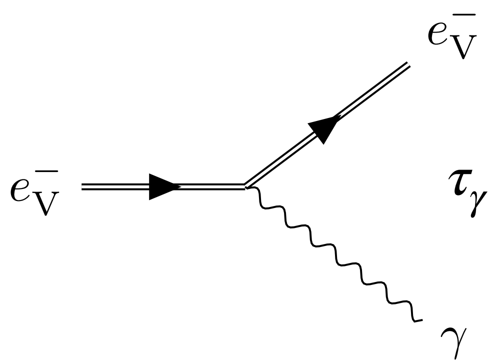
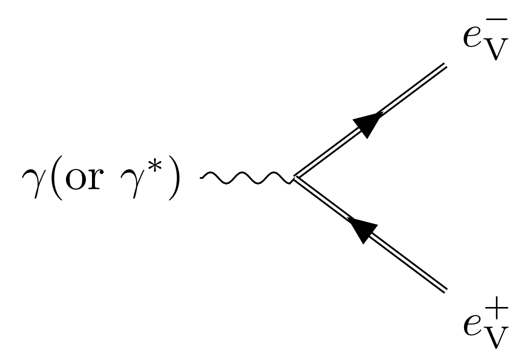


$\tau_\gamma \sim \mathcal{O}(10)\mathrm{fs}$



$\tau_{ee} \sim \mathcal{O}(10^4 - 10^6)\mathrm{fs}$

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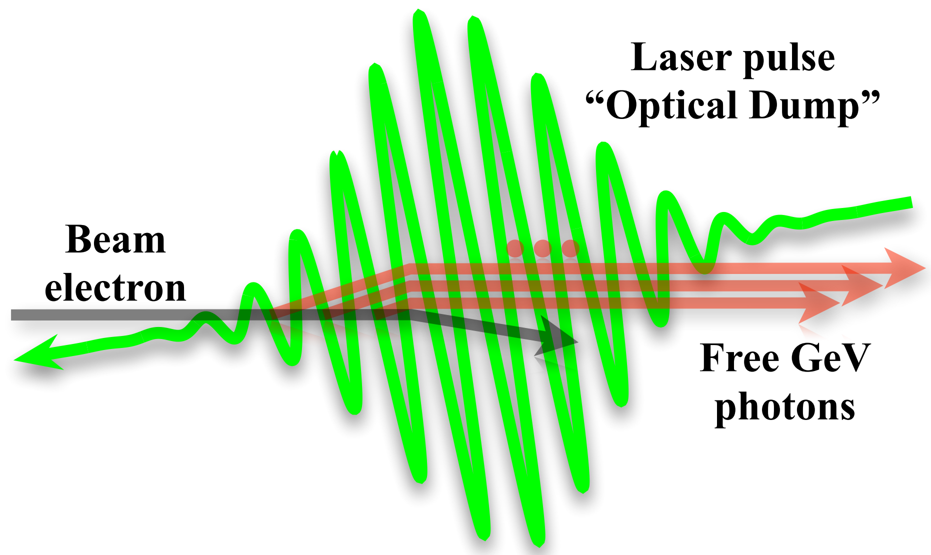

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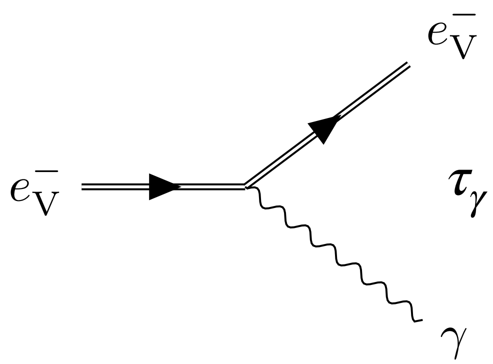

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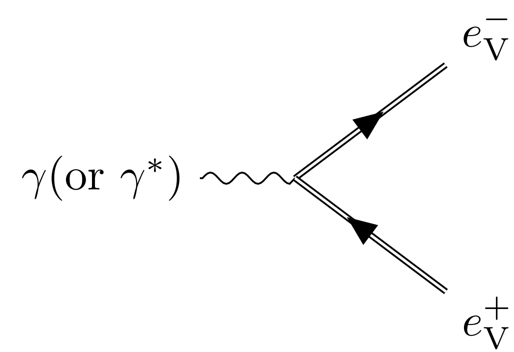

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$$1/\omega_\mathrm{L} \ll \tau_\gamma \lesssim t_\mathrm{L} \ll \tau_{ee}$$

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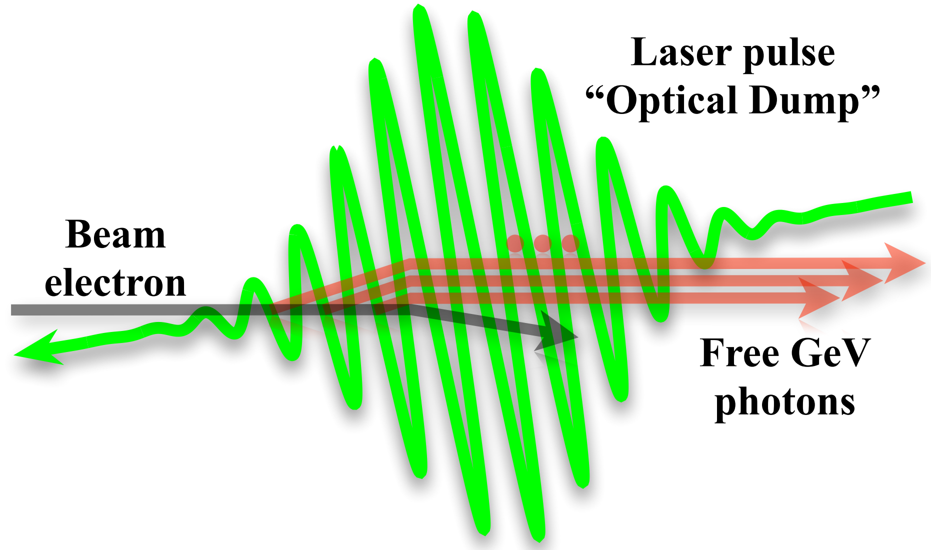

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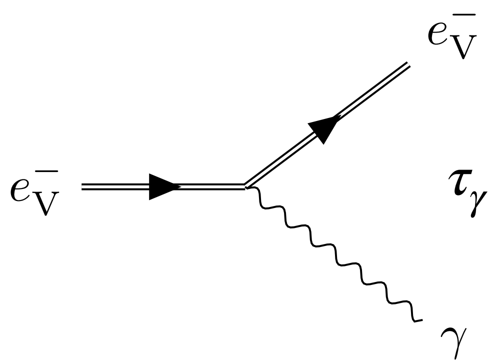

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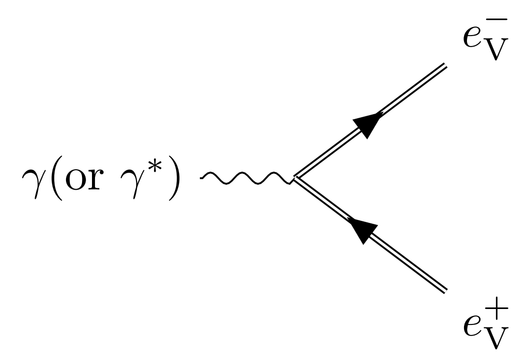

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electrons dump their energy

photons are free streaming

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LUXE, 1909.00860, 2102.02032

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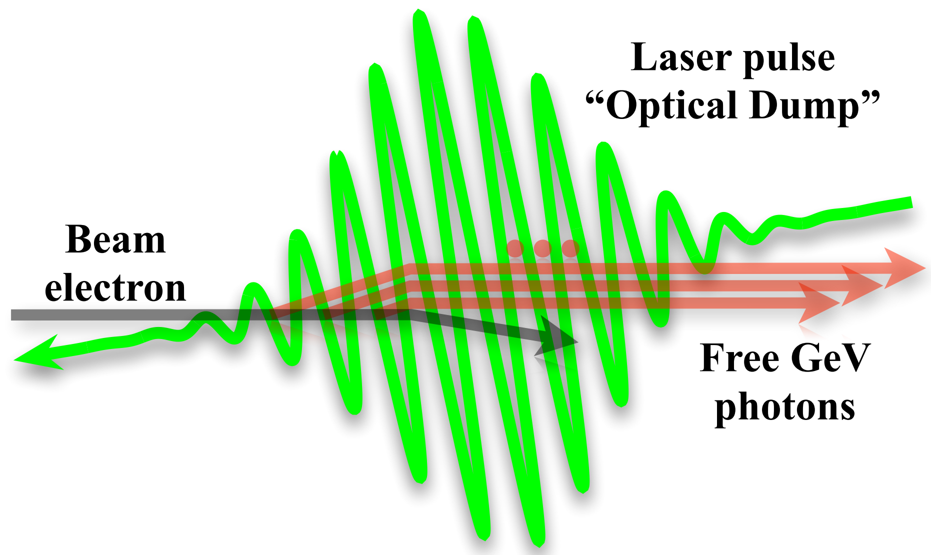

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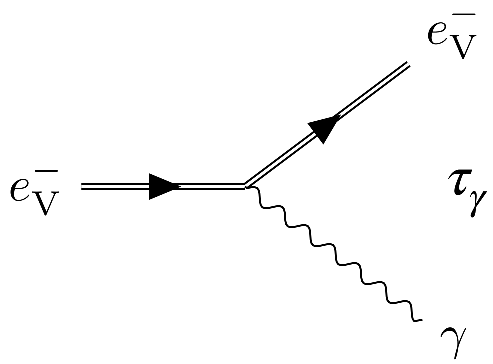

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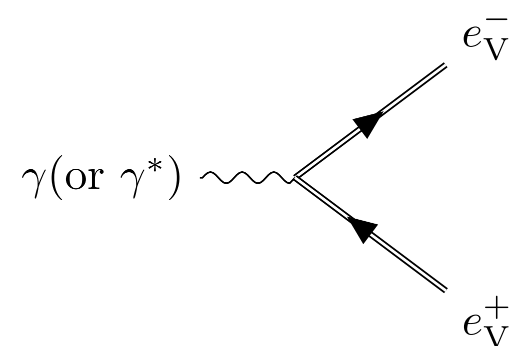

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$$1/\omega_L \ll \tau_\gamma \lesssim t_L \ll \tau_{ee}$$

electrons dump their energy

photons are free streaming

$$N_\gamma \sim \mathcal{O}(t_L/\tau_\gamma)$$

emitted photons per pulse per e^-

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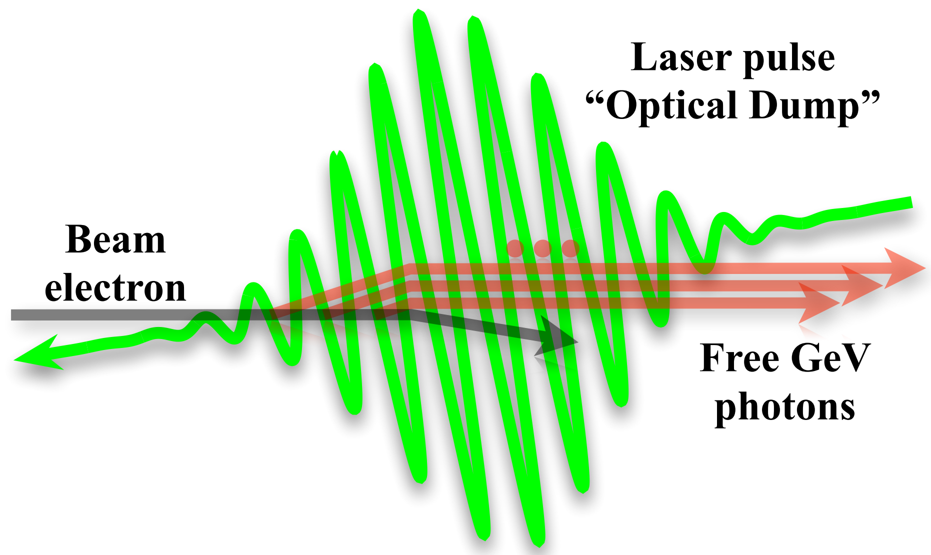

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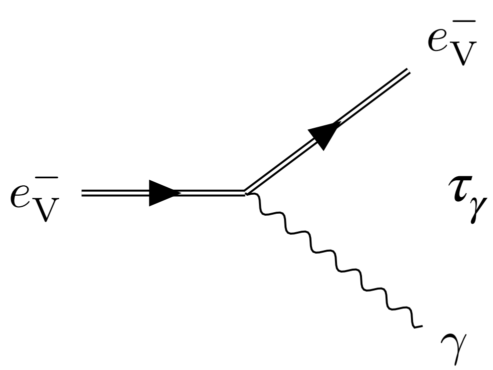

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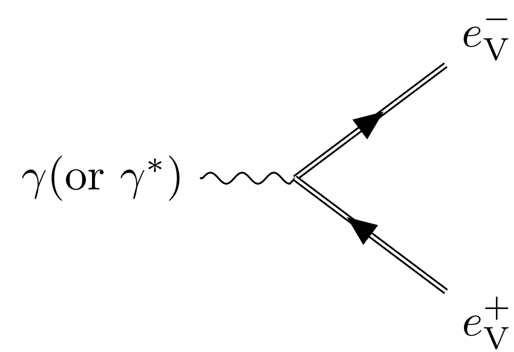

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excellent source of GeV scale photons

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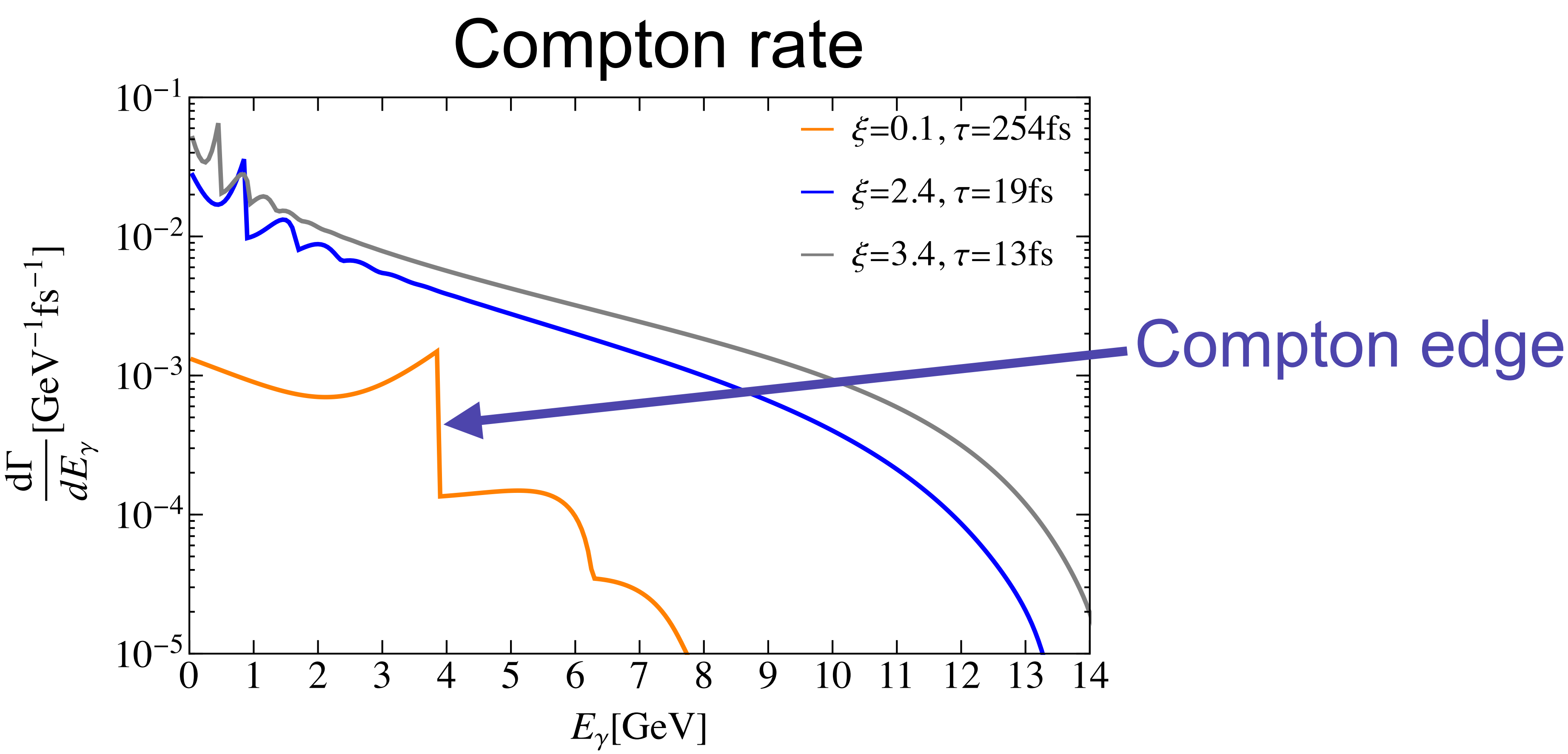
LUXE, 1909.00860, 2102.02032

the photon spectrum



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

for non perturbative region

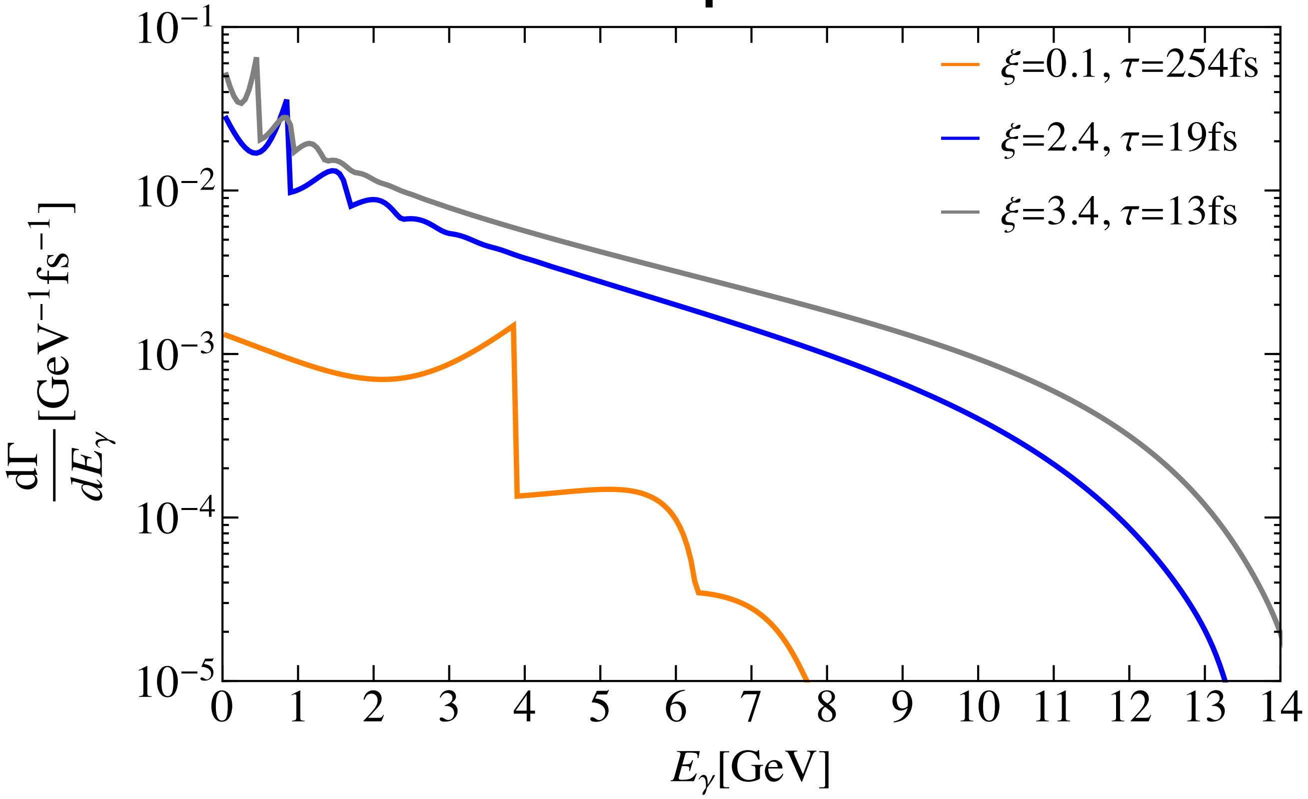
$$\chi = \frac{eE_e}{m_e^3}\mathscr{E}_L\left(1+\beta_e\cos\theta\right), \quad \xi = \frac{e\mathscr{E}_L}{m_e\omega_L}$$

$$\bar{m}_e \approx m_e(1+\xi^2)$$

e effective mass

the photon spectrum

Compton rate



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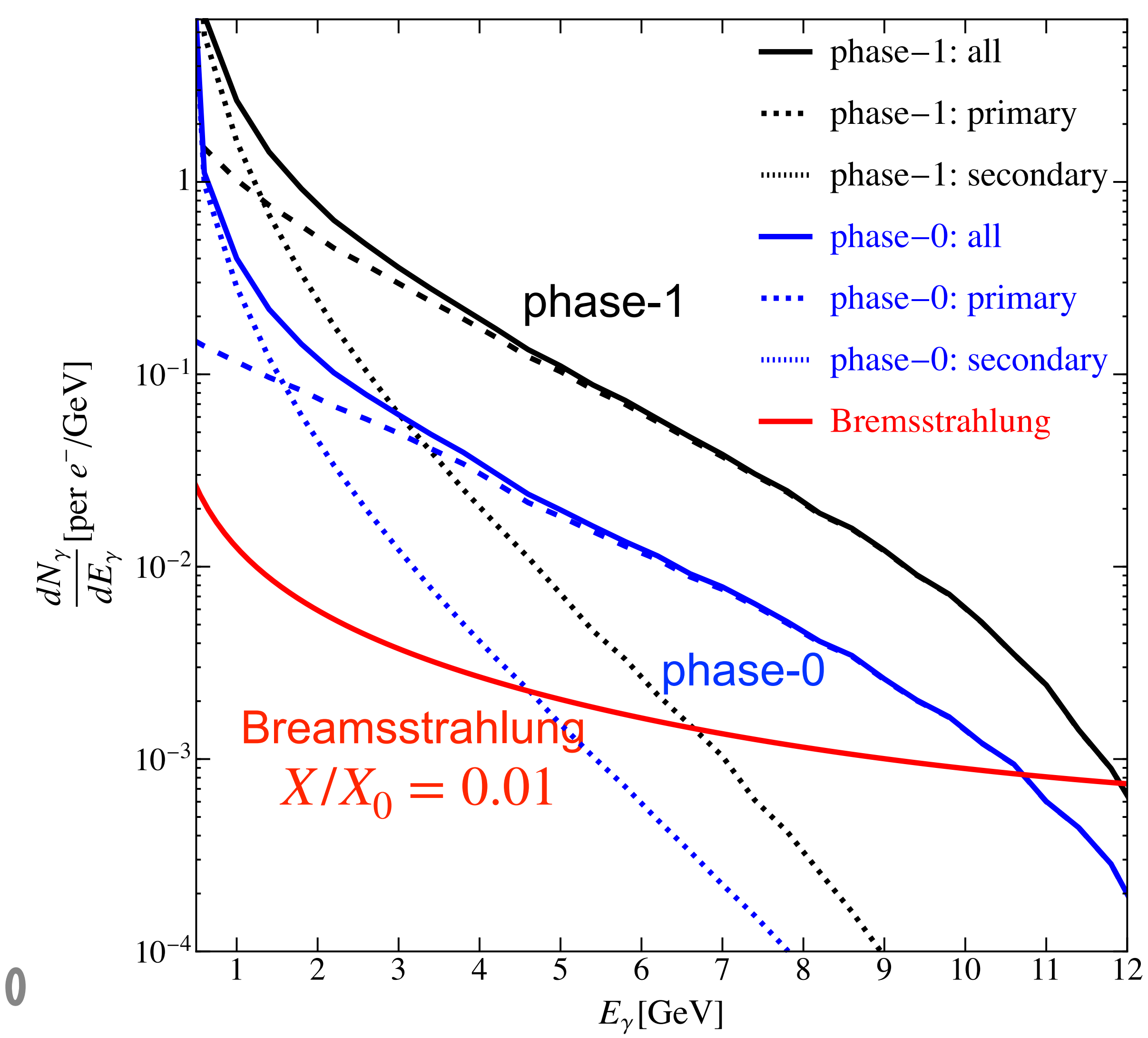
outgoing Compton photon spectrum

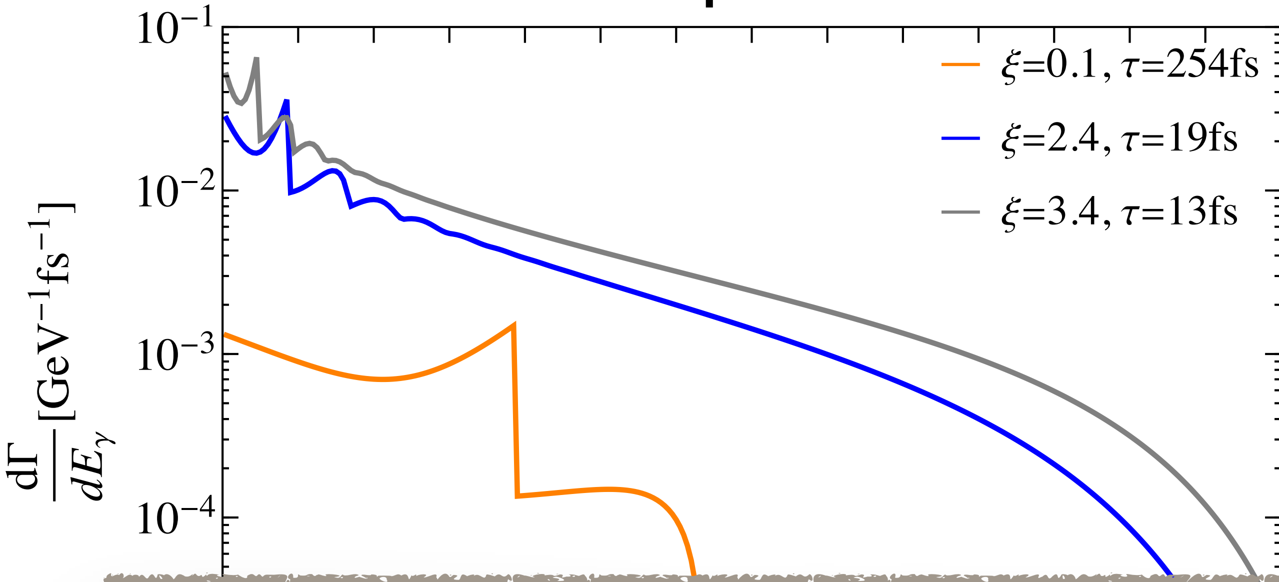


convolution with the laser

phase-0:	phase-1:
$\tau_\mathrm{L} = 25$ fs	$\tau_\mathrm{L} = 120$ fs
$w_0 = 6.5\,\mu$m	$w_0 = 10\,\mu$m
$\xi = 3.2$	$\xi = 3.4$
$N_{\gamma/e} < 1$	$N_{\gamma/e} = 3.5\,(1.7)$, $E_\gamma > 0\,(1)$ GeV

the photon spectrum

Compton rate



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outgoing Compton photon spectrum

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

convolution with the laser

phase-0:
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$w_0 = 6.5\,\mu$m
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$N_{\gamma/e} < 1$

phase-1:
$\tau_L = 120$ fs
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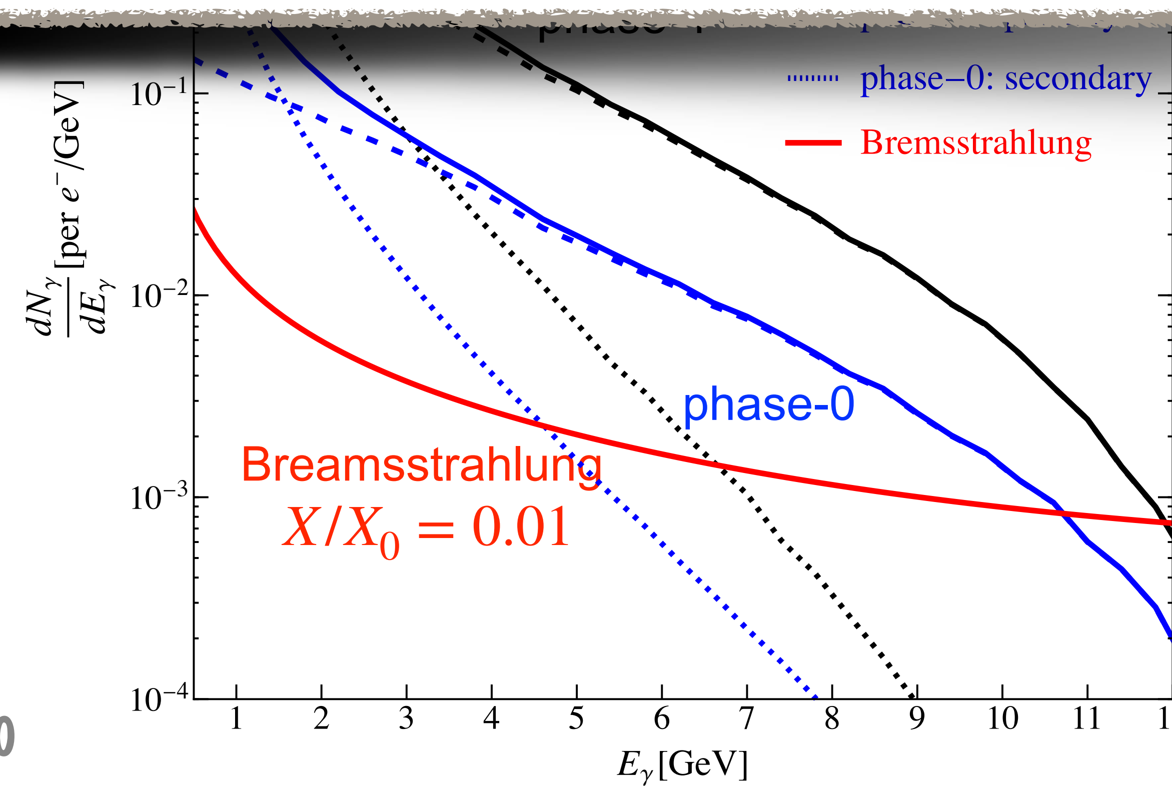
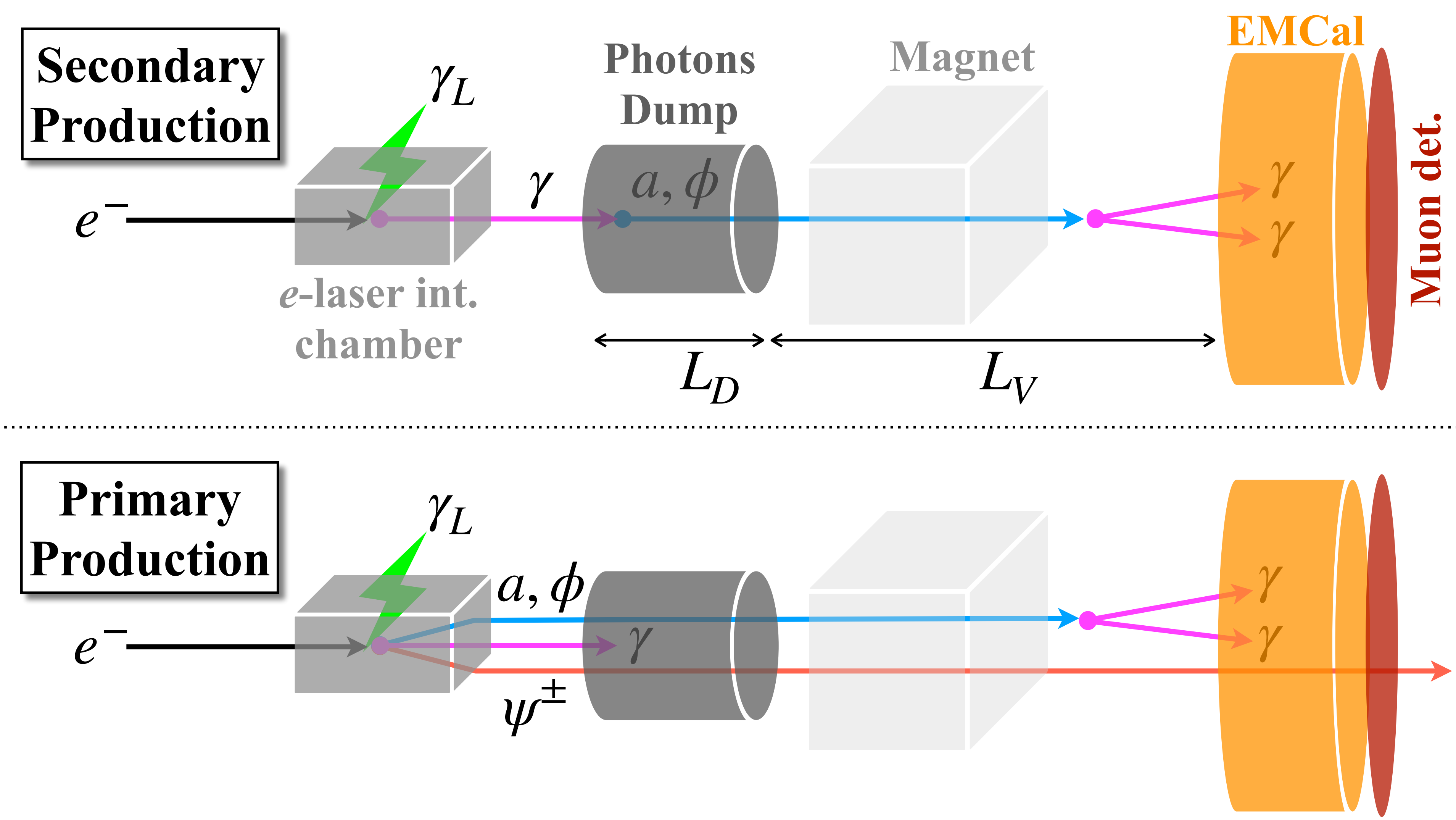
$\xi = 3.4$
$N_{\gamma/e} = 3.5\,(1.7)$, $E_\gamma > 0\,(1)$ GeV



new physics production at LUXE

mostly for new physics with photon coupling

mostly for new physics with electron coupling



relevant new physics scenarios

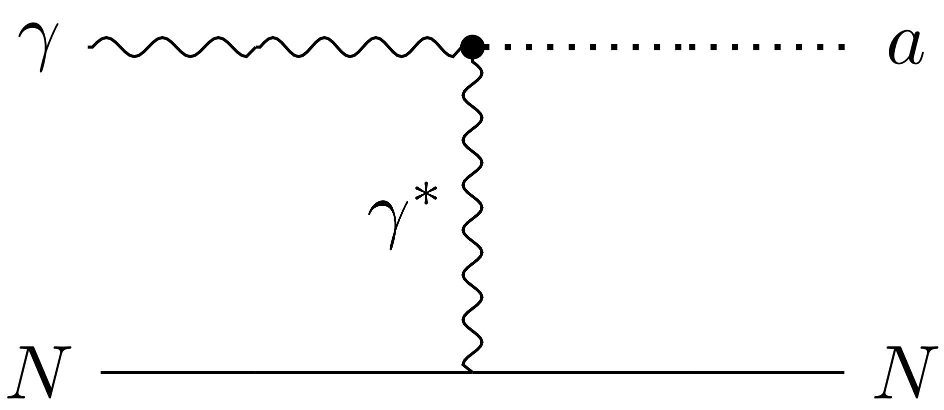
$$\mathscr{L}_{a,\phi} = \frac{a}{4\Lambda_a} F^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{\phi}{4\Lambda_\phi} F^{\mu\nu}F_{\mu\nu}$$

pseudo-scalar (ALP) scalar

$$X = a, \phi \quad m_X \in [\text{MeV}, \text{GeV}] \quad \Lambda_X \gg m_a$$

well motivated BSM scenarios

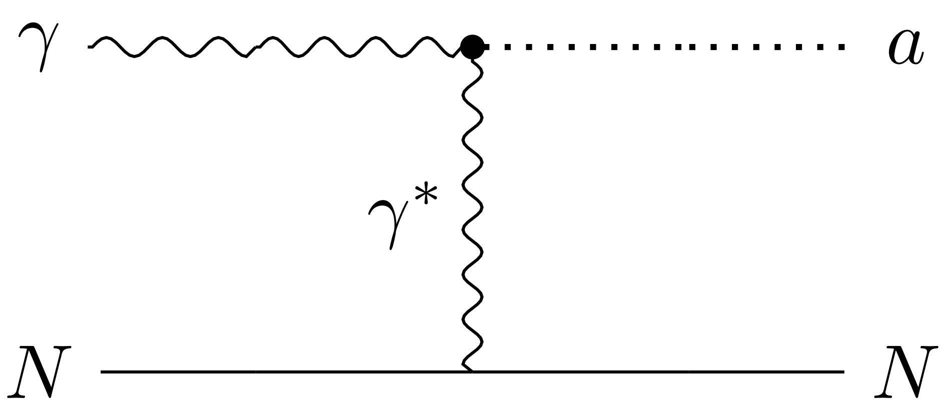
Photoproduction



$$\frac{a}{4\Lambda_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

same for scalars

Photoproduction



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same for scalars

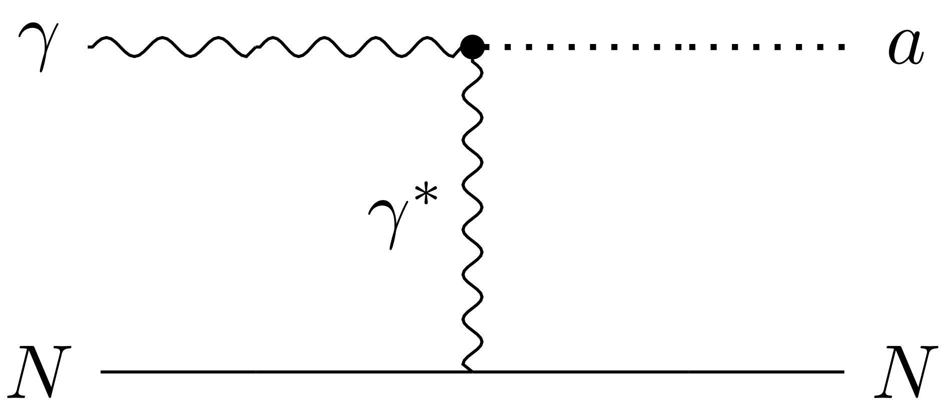
$$\frac{d\sigma^{\text{elastic}}_{\gamma N \to aN}}{dt} = \alpha\, Z_N^2 F_N^2(t) \Gamma_{a\to\gamma\gamma}\, \mathscr{H}(m_N, m_a, s, t)$$

target charge

form factor

kinematical function

Photoproduction



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Z_N^2: target charge

$F_N^2(t)$: form factor

$\mathscr{H}(m_N, m_a, s, t)$: kinematical function

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

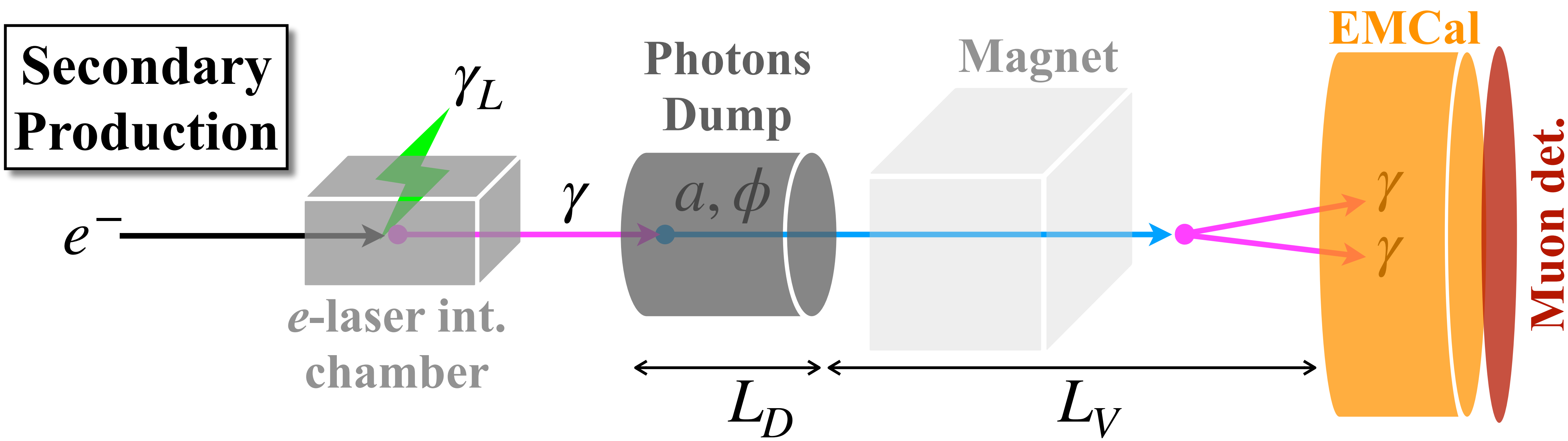
$$\frac{d\sigma^{\text{elastic}}_{\gamma N \to aN}}{dt} = \frac{\Gamma_{a\to\gamma\gamma}}{\Gamma_{P\to\gamma\gamma}} \frac{\mathscr{H}(m_N, m_a, s, t)}{\mathscr{H}(m_N, m_p, s, t)} \frac{d\sigma^{\text{elastic}}_{\gamma N \to PN}}{dt}$$

at the forward region

data-driven signal normalization

(cancel form-factor and flux dependence)

secondary ALPs production



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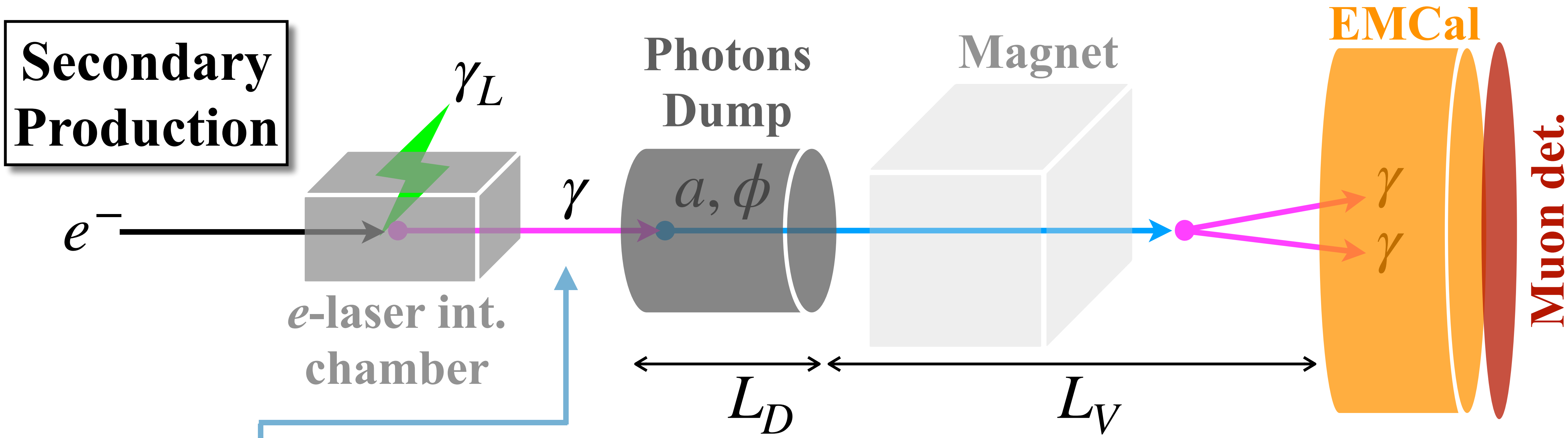
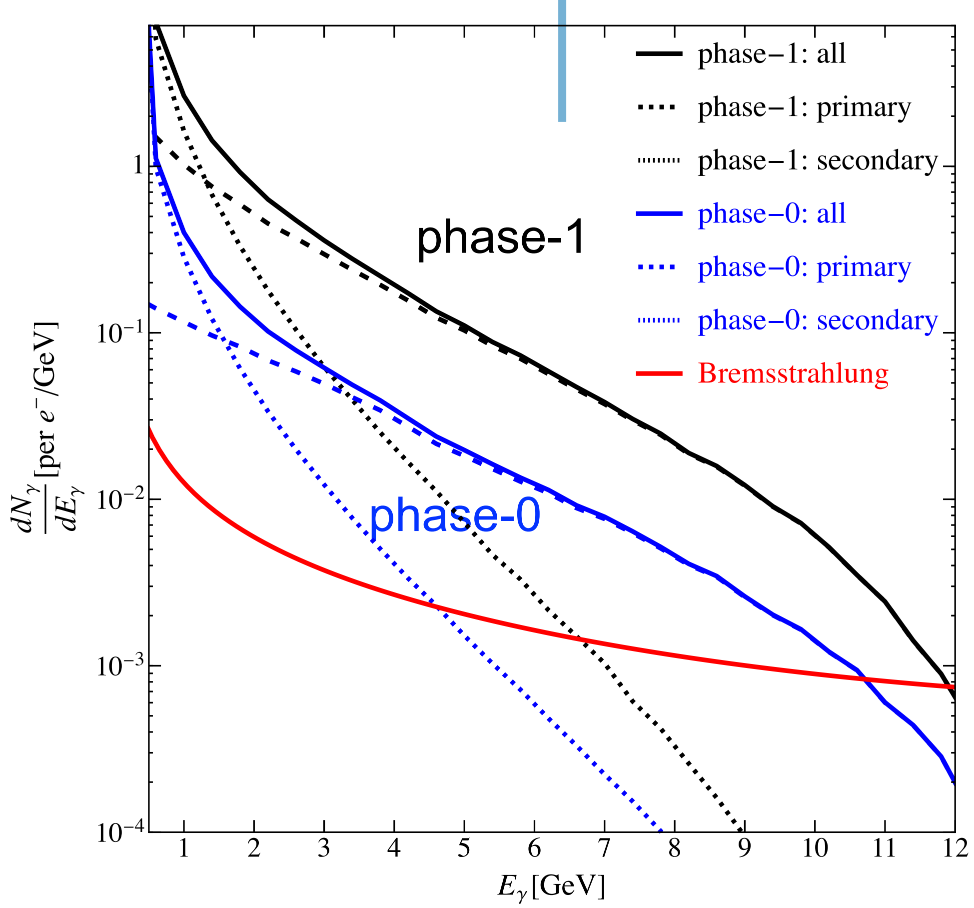
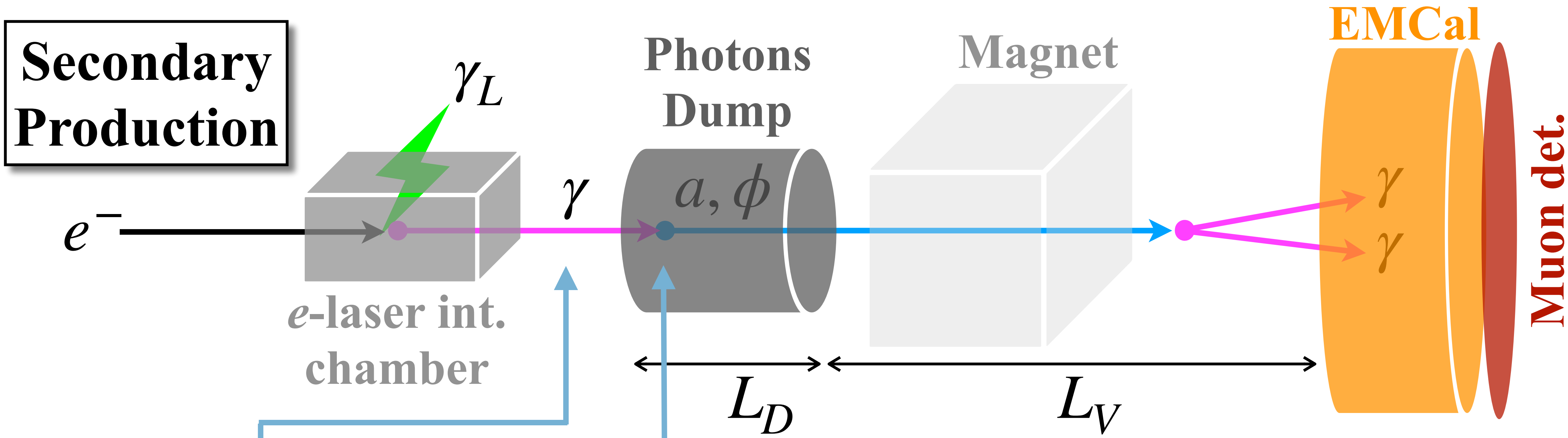
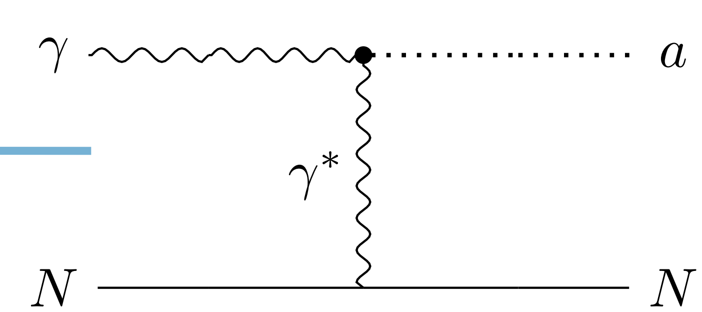


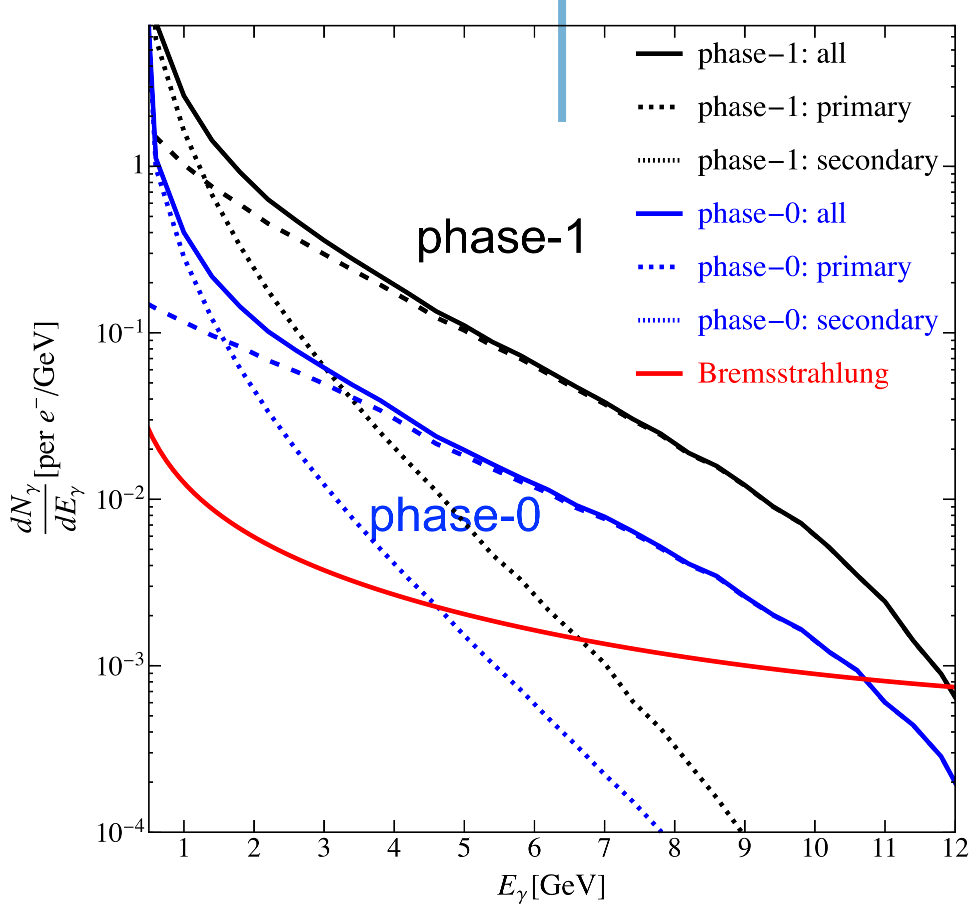


source	# photons, E>1 GeV	backgrounds
LUXE-0/1	0.4 / 2.5	effectively free
e-beam thin	0.03	effectively free
e-beam thick	6.7	O(100) larger

secondary ALPs production

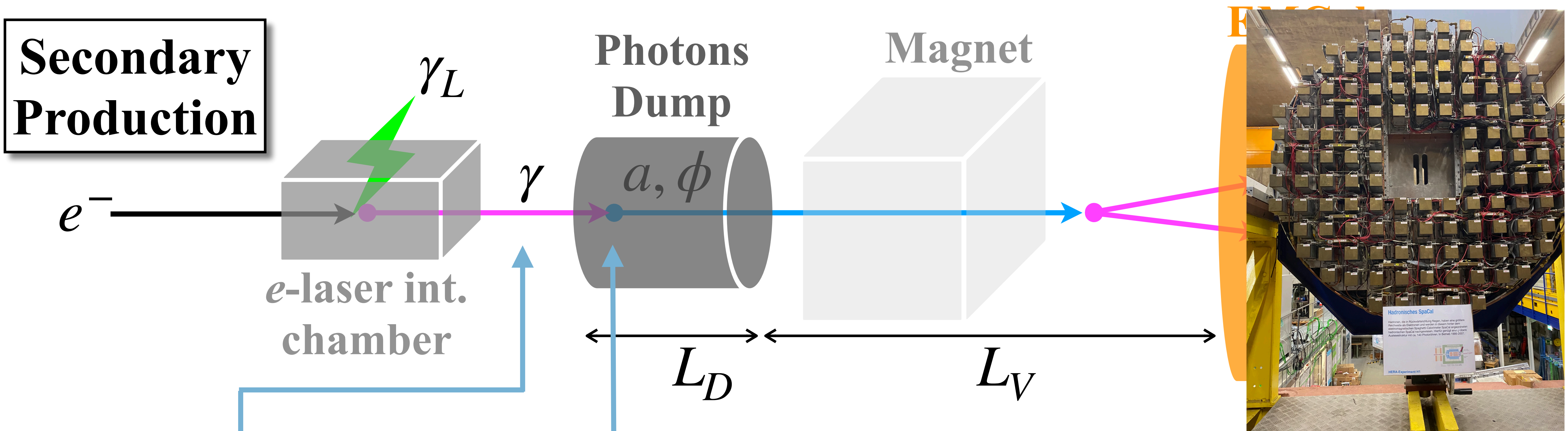


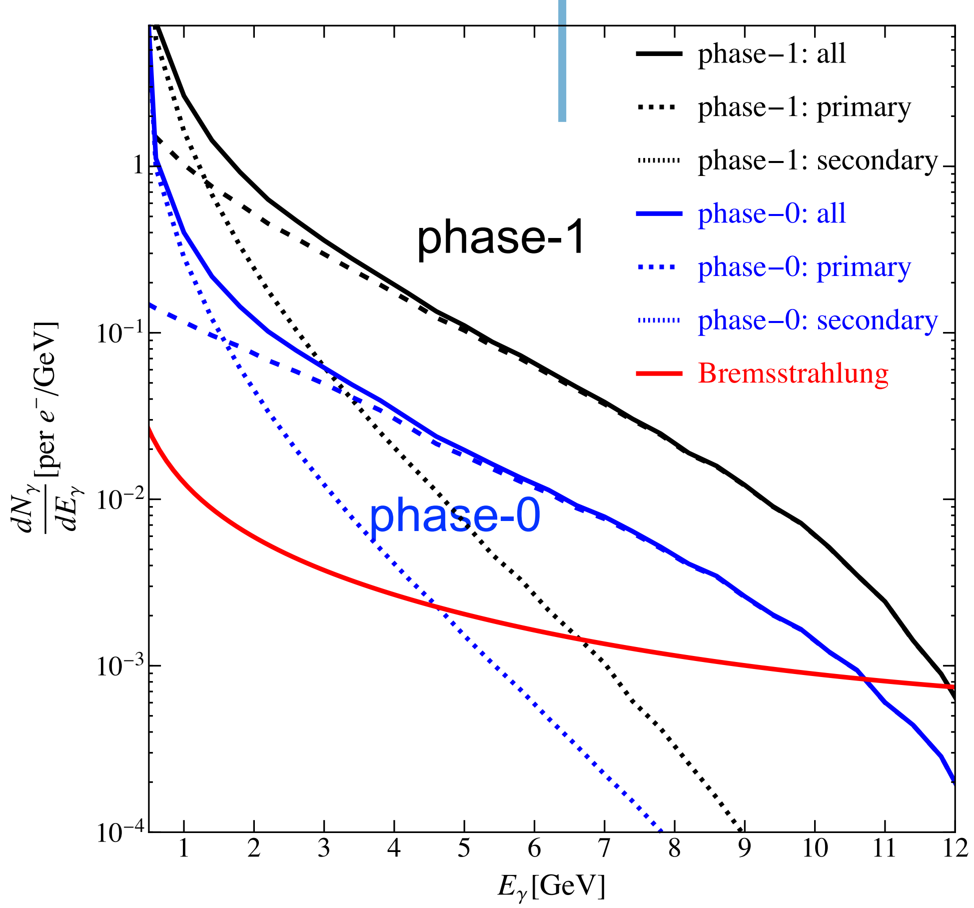


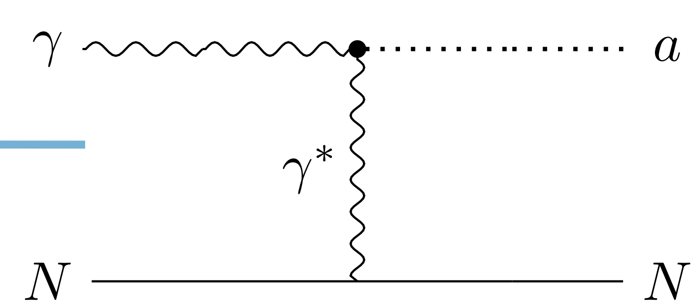


source	# photons, E>1 GeV	backgrounds
LUXE-0/1	0.4 / 2.5	effectively free
e-beam thin	0.03	effectively free
e-beam thick	6.7	O(100) larger

secondary ALPs production







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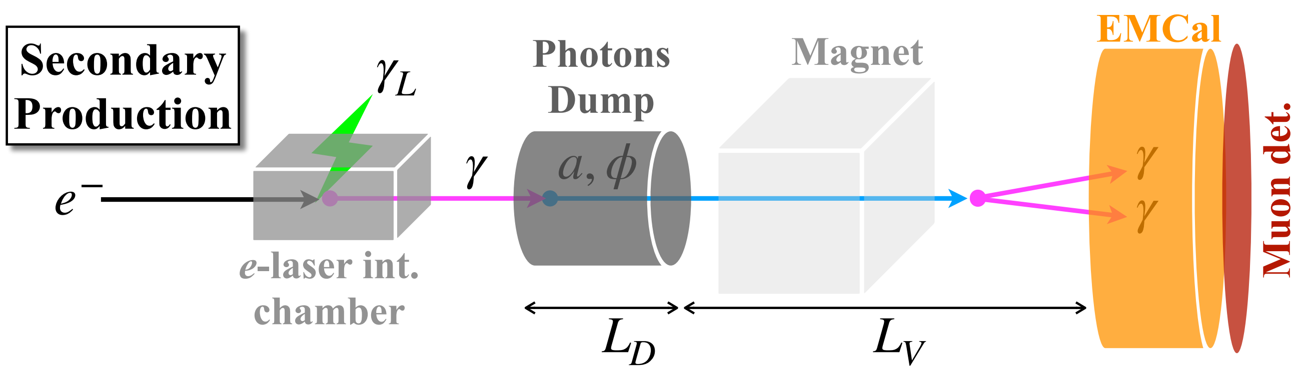
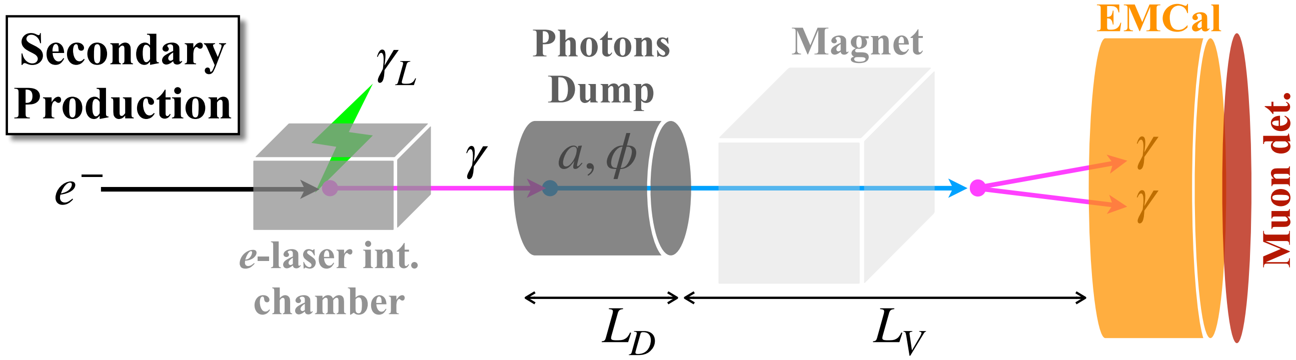
ALP signal estimation



ALP signal estimation



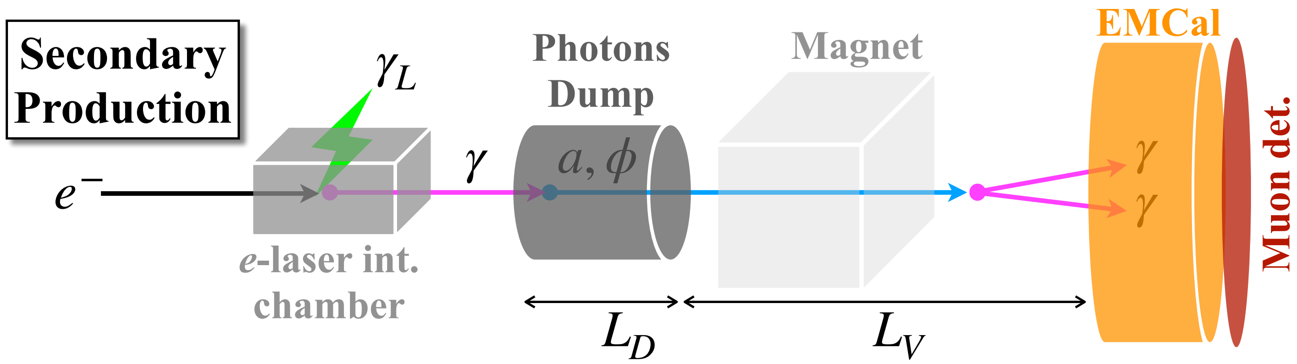
number of ALPs

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

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

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

ALP signal estimation



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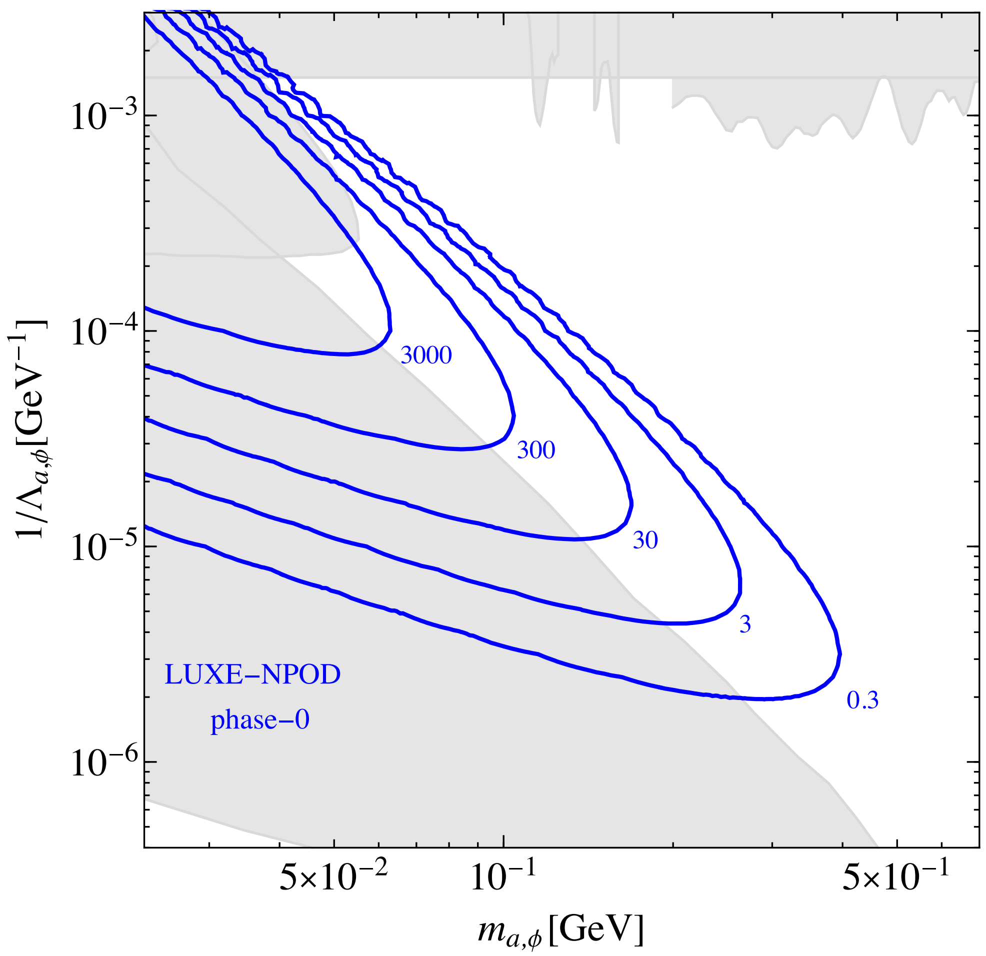
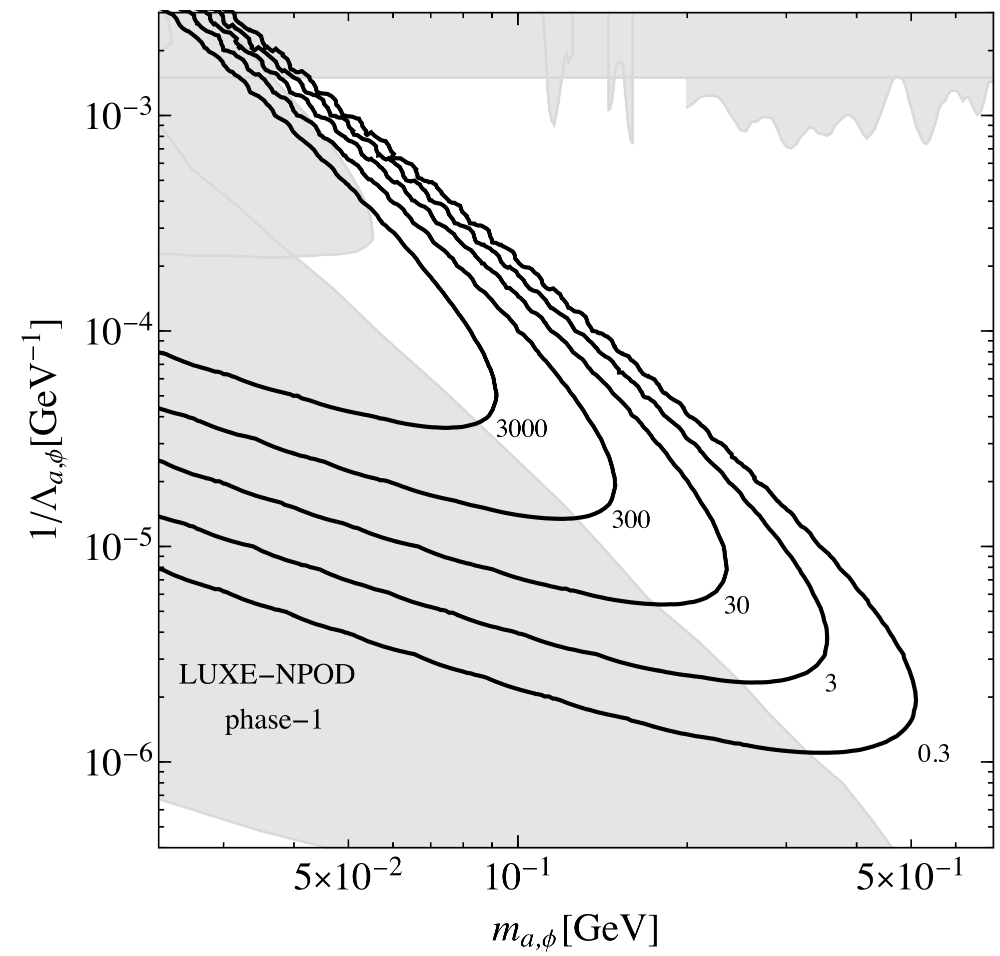
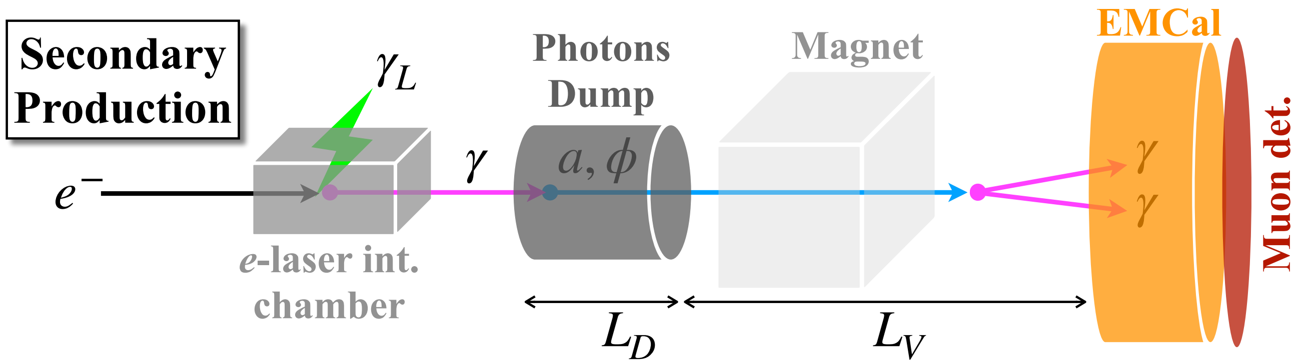
$E_e = 16.5\,\mathrm{GeV}$ $N_e = 1.5 \times 10^9$ $N_{\rm BX} = 10^7$ $L_D = 1.0\,\mathrm{m}$ $L_V = 2.5\,\mathrm{m}$ $R_D = 1.0\,\mathrm{m}$ $E_{\gamma,\rm min} = 0.5\,\mathrm{GeV}$





ALP signal estimation



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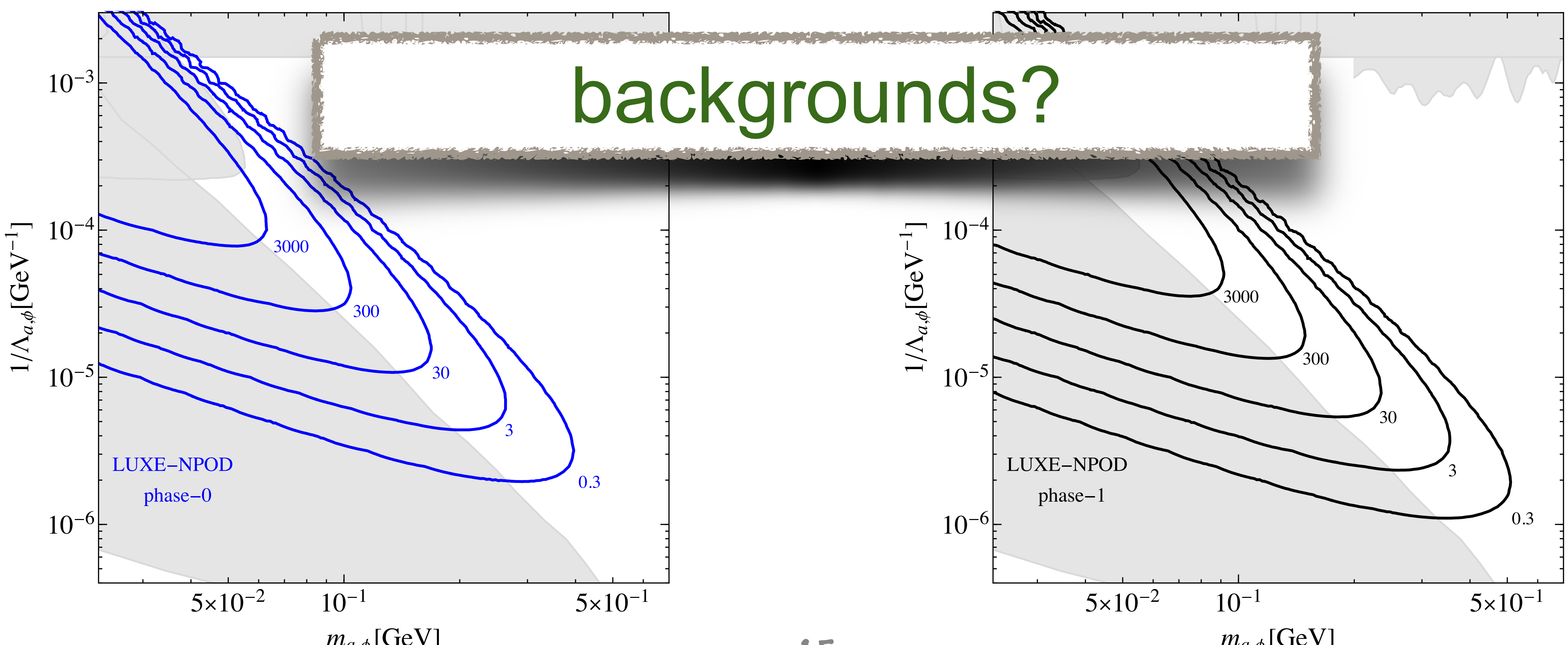
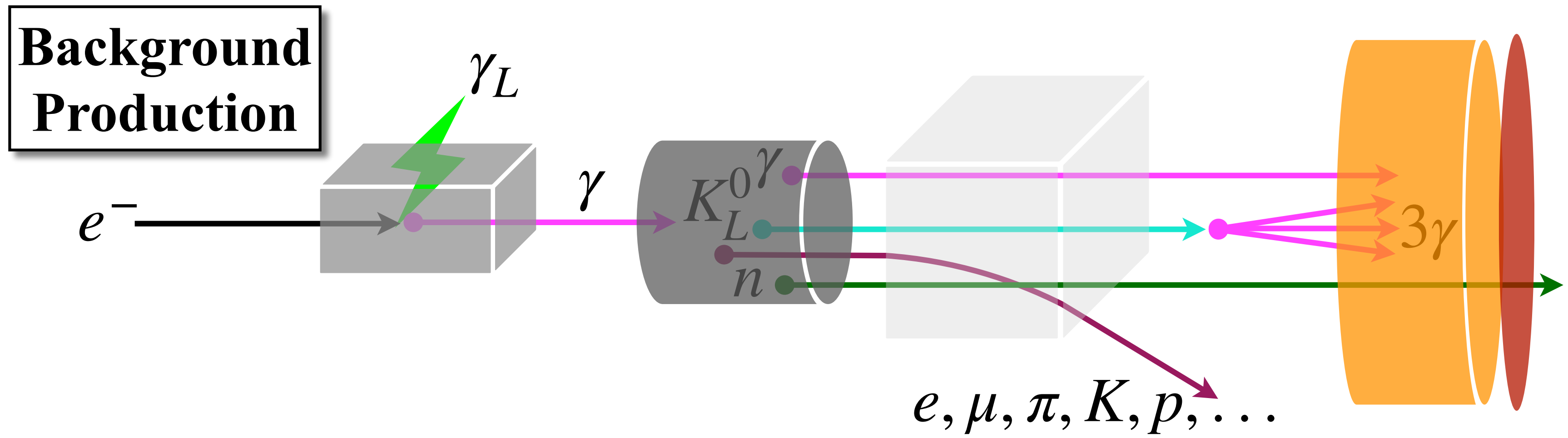
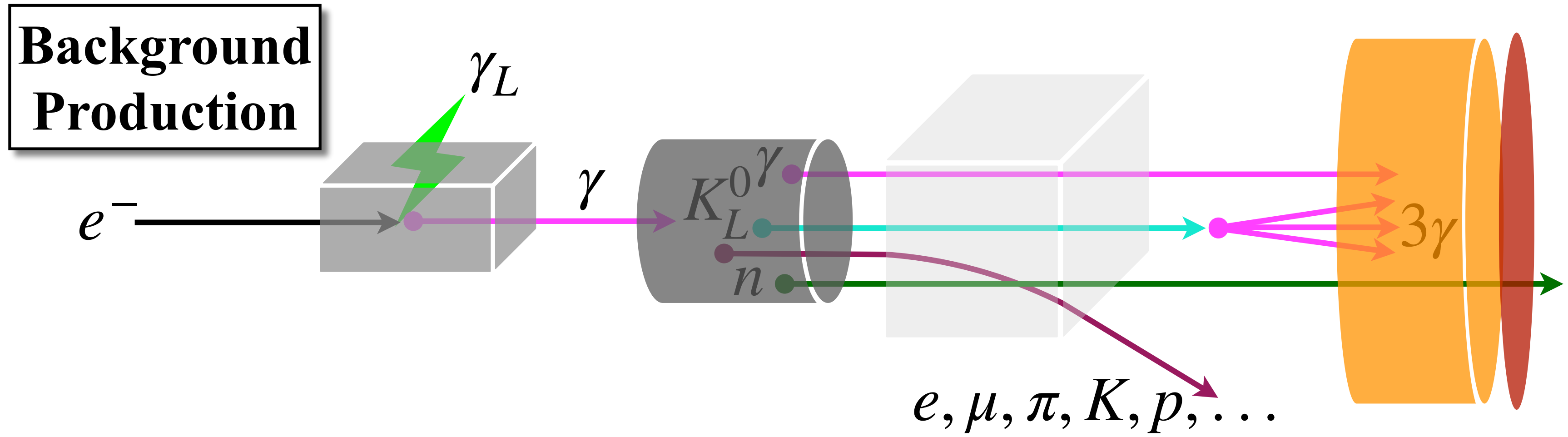


background estimation



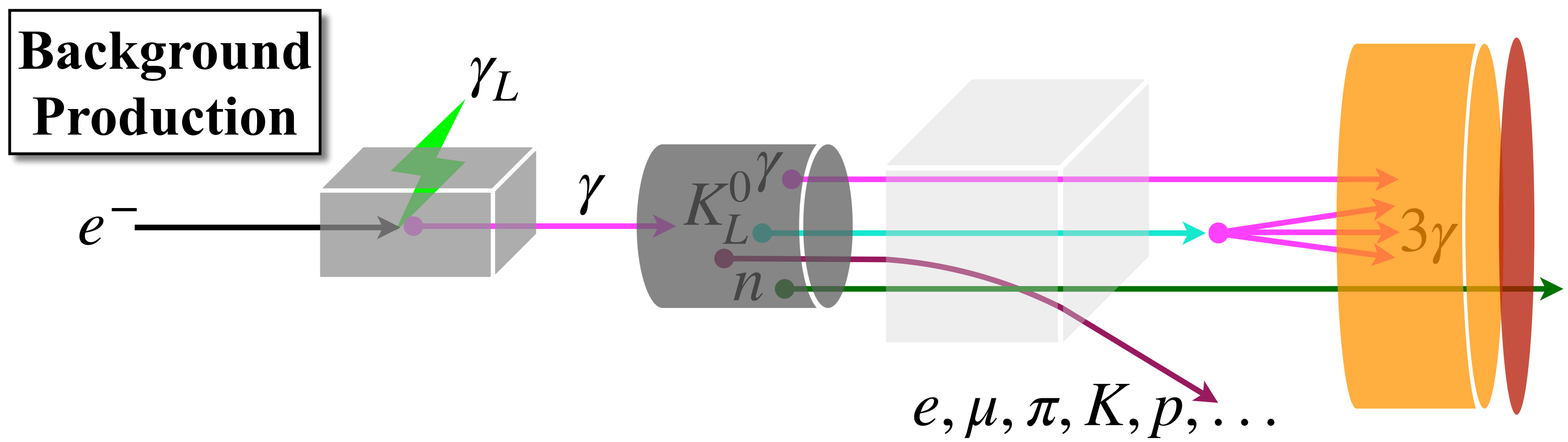
background estimation



backgrounds (based on GEANT 4 simulation):

1. **charged particles** - bended by a magnetic field
2. **fake photons**
3. **real photons - very hard to estimate** (extrapolate from a shorter dump)

background estimation



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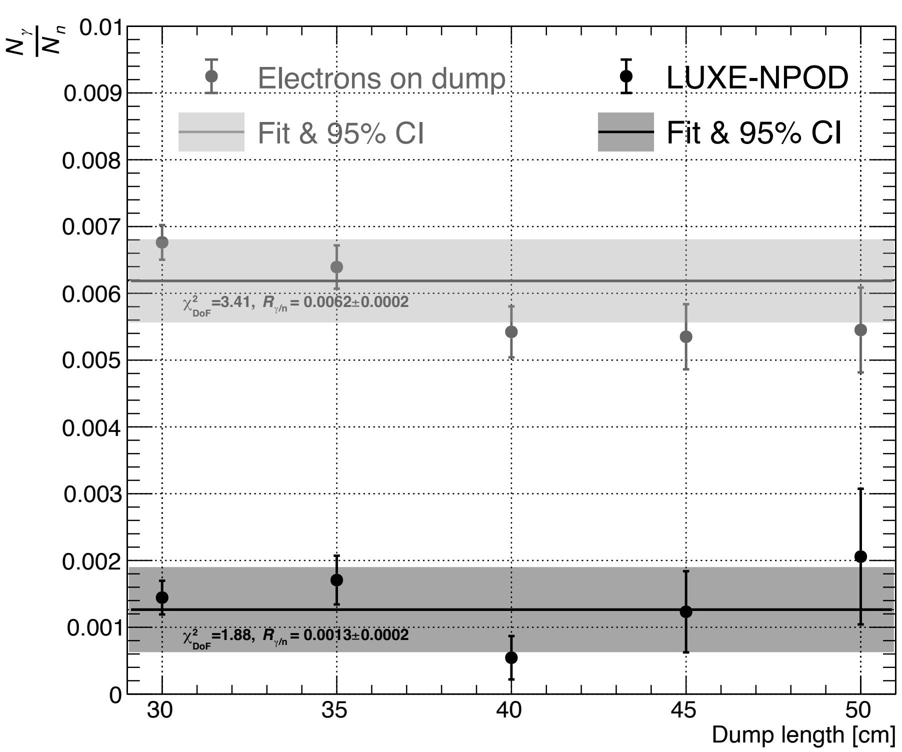
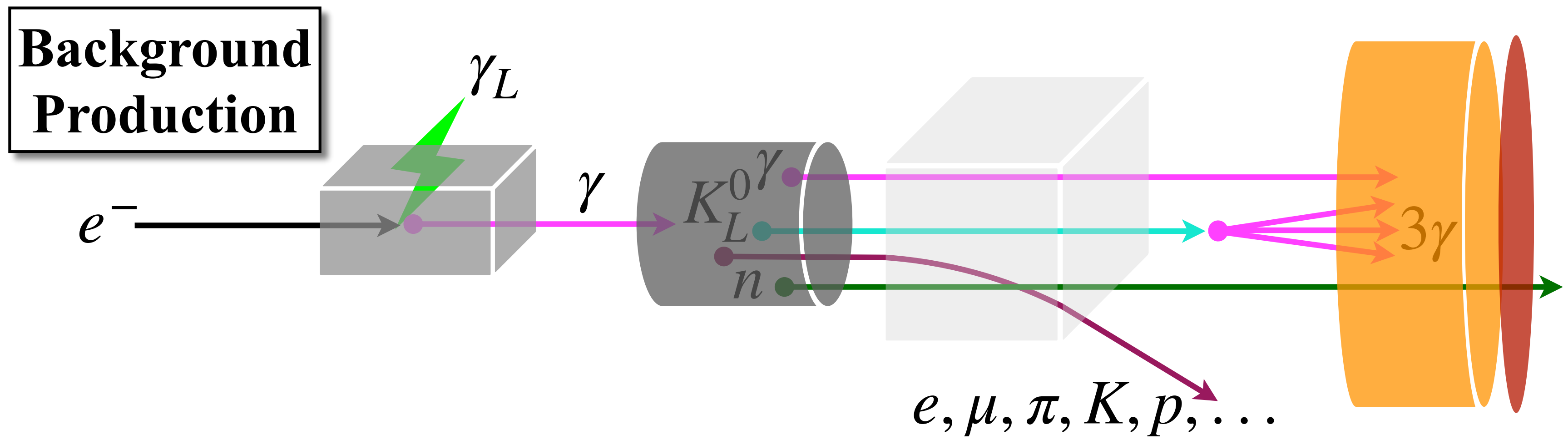


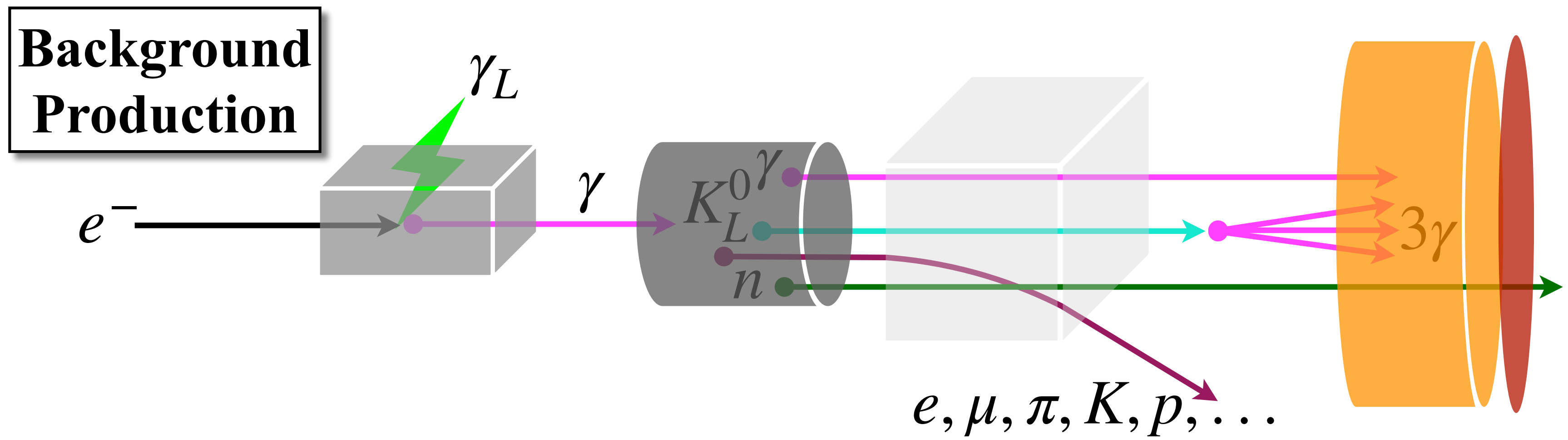
$R_{\gamma/n} = \frac{\mu_\gamma}{\mu_n} \approx 1.3 \times 10^{-3}$ almost independent of the dump length

$$\mu_\gamma(1.0\,\mathrm{m}) \approx R_{\gamma/n}\,\mu_n(1.0\,\mathrm{m}) \approx 0.013$$

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** - $N_{2n\to 2\gamma} \approx 5 \times 10^8 f_{n\to\gamma}^2 e^{-10 f_{n\to\gamma}} R_{\rm sel}$

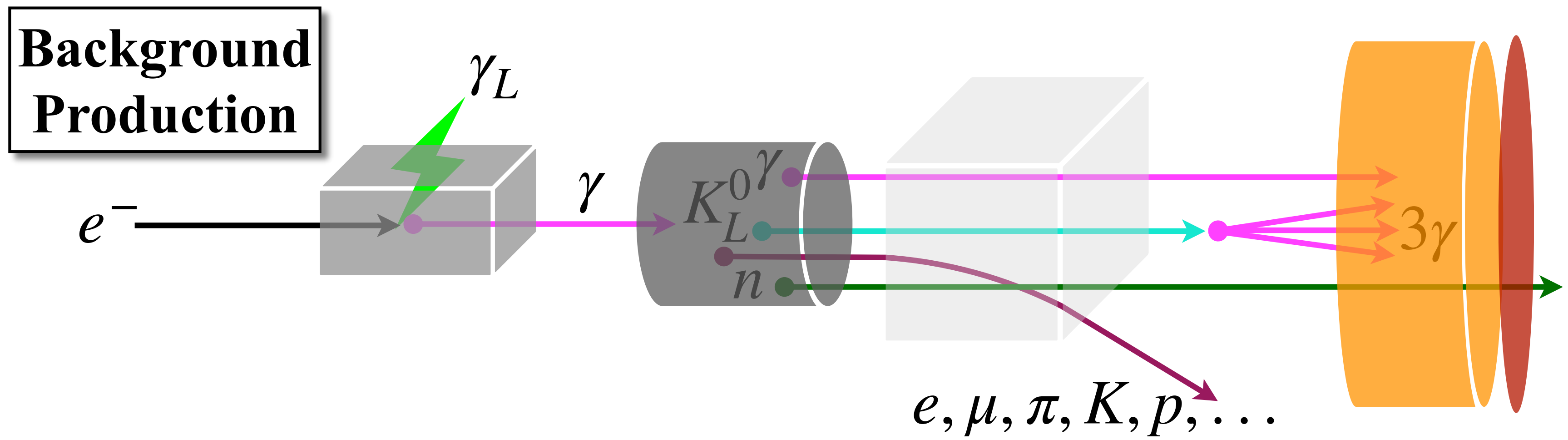
$$N_{n\gamma\to 2\gamma} \approx 1 \times 10^6 f_{n\to\gamma} e^{-10 f_{n\to\gamma}} R_{\rm sel}$$

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

$R_{\rm sel}$ - 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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$R_{\rm sel}, f_{n\to\gamma} \lesssim 10^{-3}$

for background free

achievable with current technologies (CMS/LHCb/SHiP)

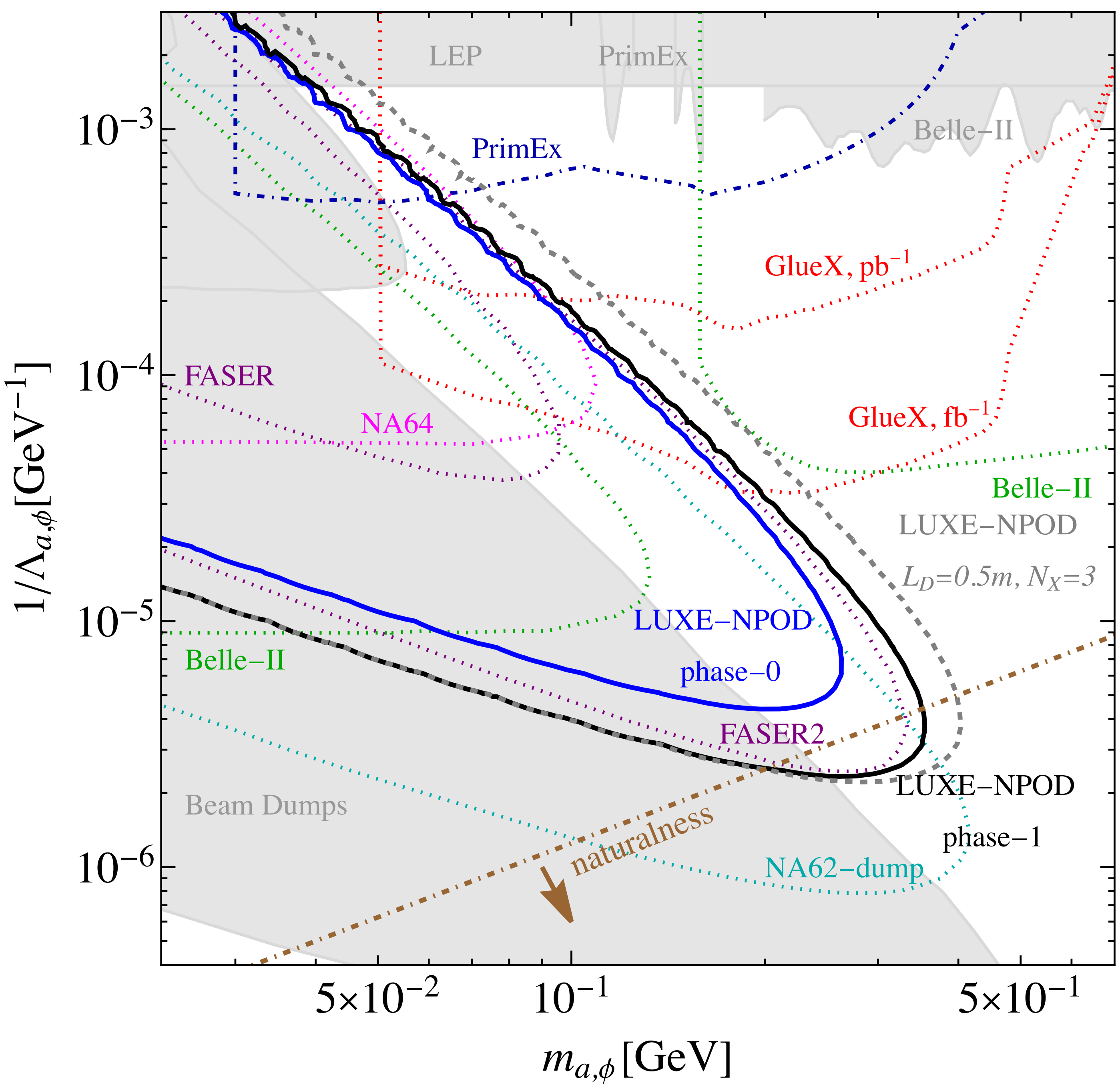
$R_{\rm sel}$ - event selection rejection

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

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

ALP reach estimation

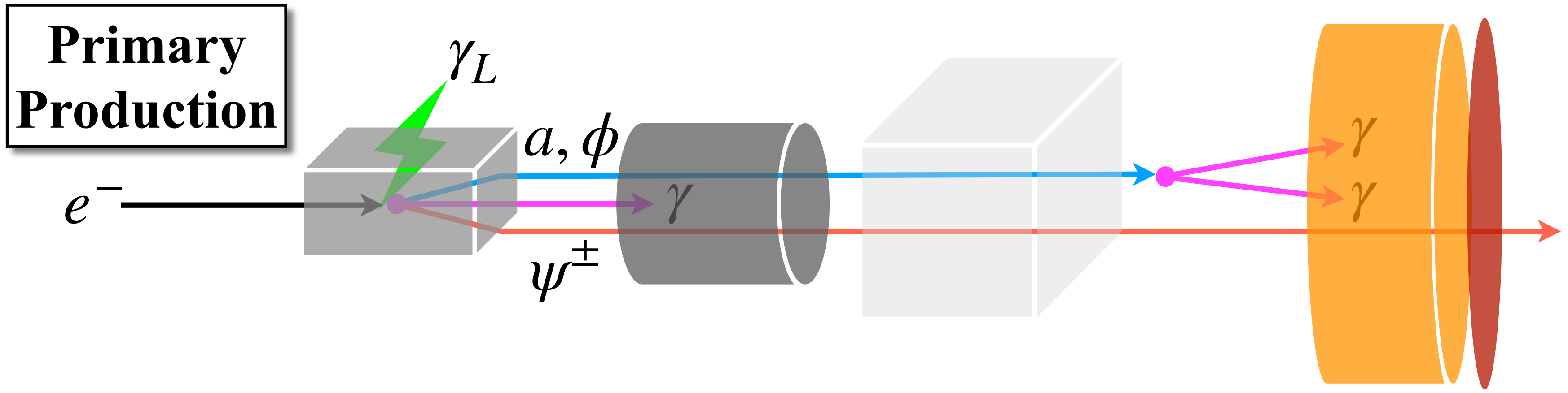
$E_e = 16.5\,\mathrm{GeV}$ $N_e = 1.5 \times 10^9$ $N_{\mathrm{BX}} = 10^7$ $L_D = 1.0\,\mathrm{m}$ $L_V = 2.5\,\mathrm{m}$ $R_D = 1.0\,\mathrm{m}$ $E_{\gamma,\mathrm{min}} = 0.5\,\mathrm{GeV}$



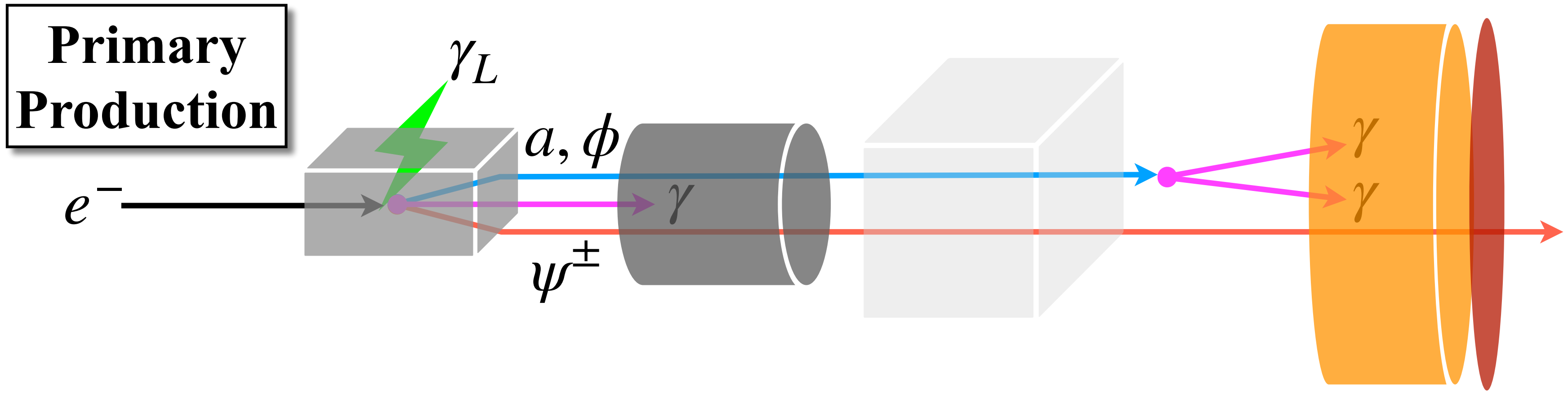
LUXE-NPOD
new Physics optical dump

assuming background free

primary ALP production

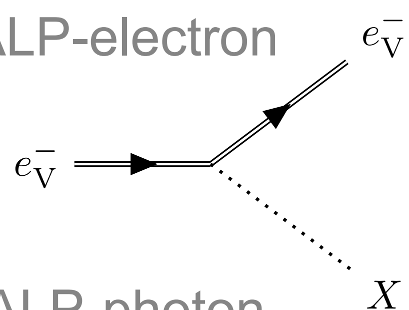


primary ALP production



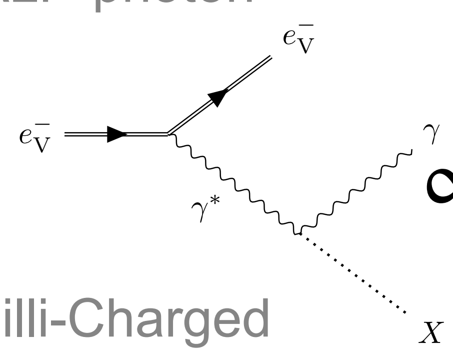
$\mathscr{L}_{e,a,\phi} = i g_{ae} a \bar{e} \gamma_5 e + g_{\phi e} a \bar{e} e$

ALP-electron



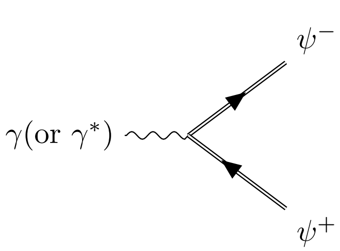
$\propto g_{ae}^2$

ALP-photon



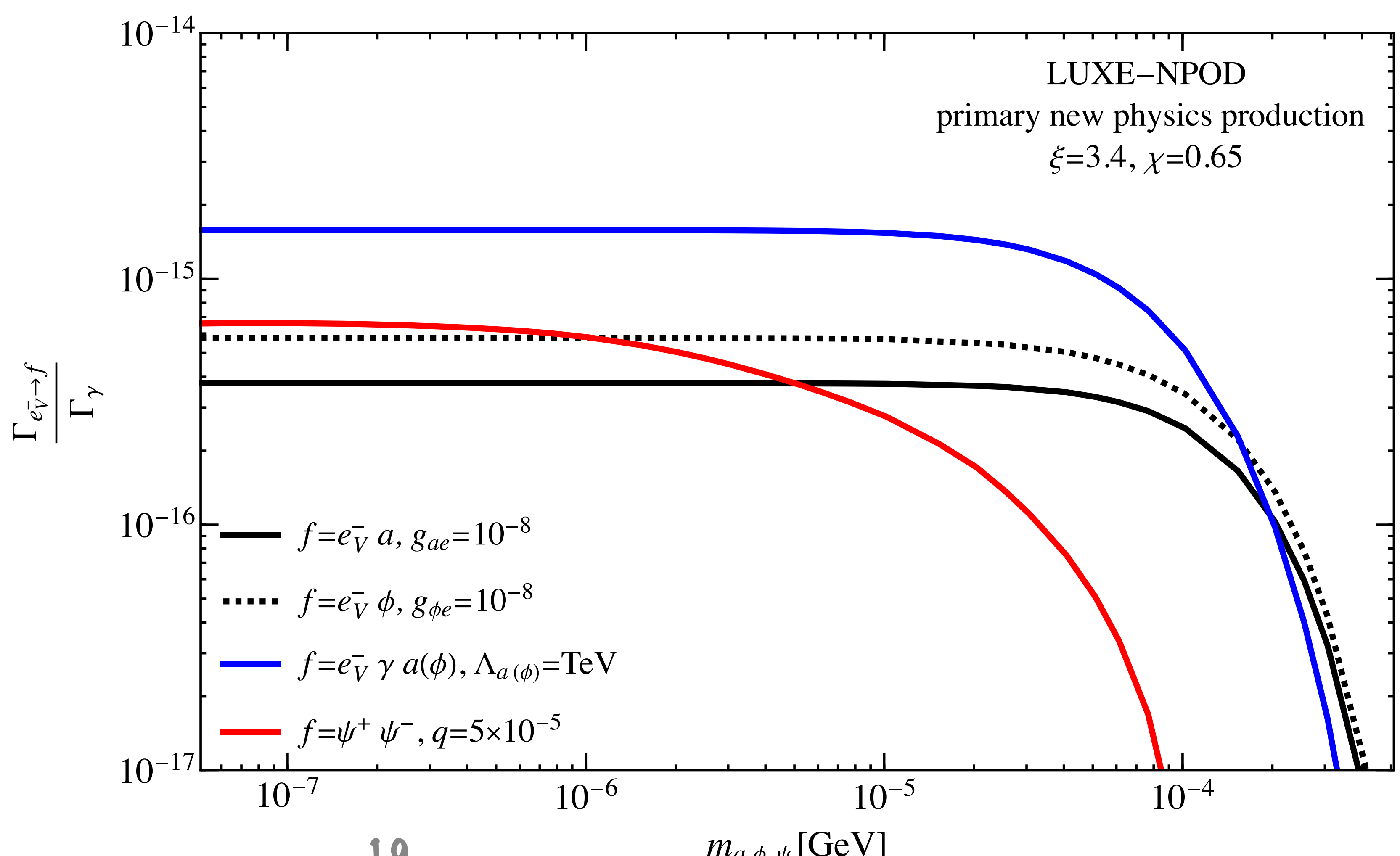
$\propto 1/\Lambda_{a,\phi}^2$

milli-Charged



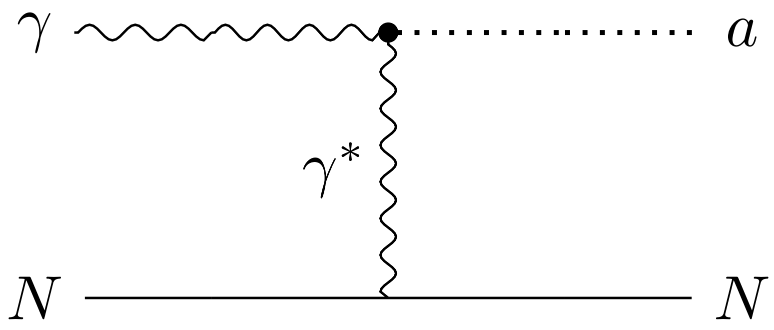
$\propto q^4$

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



back to Photoproduction

a photon beam
O(few GeV)



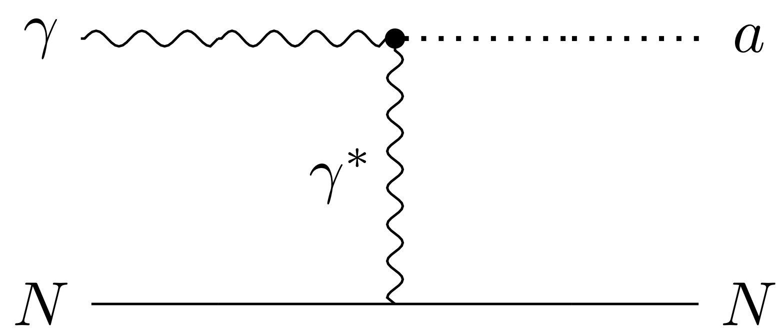
target *N:*
C, Si, Pb, W

prompt/displaced
decay to $\gamma\gamma$

$$\mathscr{L}_a = \frac{a}{4\Lambda_a} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

back to Photoproduction

a photon beam
O(few GeV)



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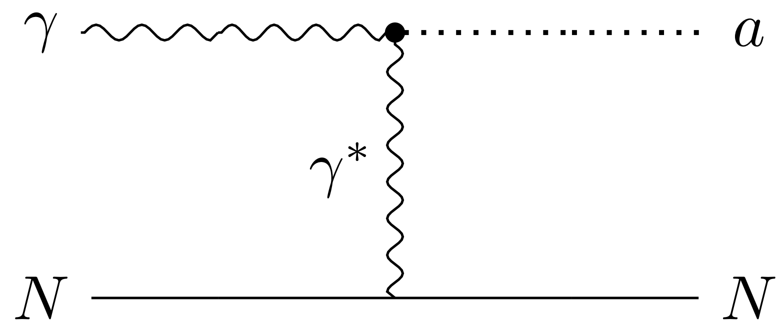
LUXE-NPOD
@ DESY

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

LUXE

back to Photoproduction

a photon beam
O(few GeV)



prompt/displaced
decay to $\gamma\gamma$

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PrimEx/GlueX
@ J-Lab

Aloni, Fanelli, YS, Williams
1903.03586

LUXE-NPOD
@ DESY

Bai, Blackburn, Borysov, Davidi, Hartin,
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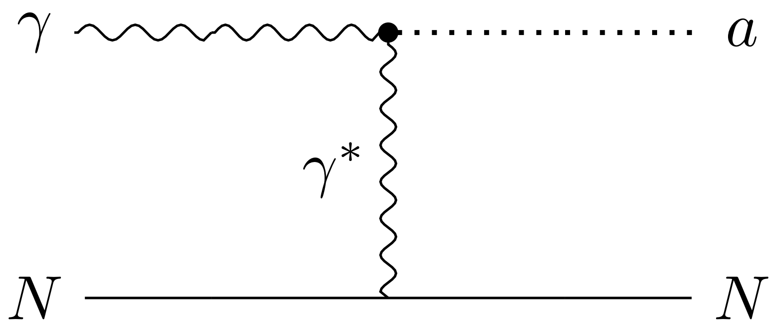
2107.13554

LUXE

back to Photoproduction

a photon beam
O(few GeV)



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PrimEx/GlueX @ J-Lab

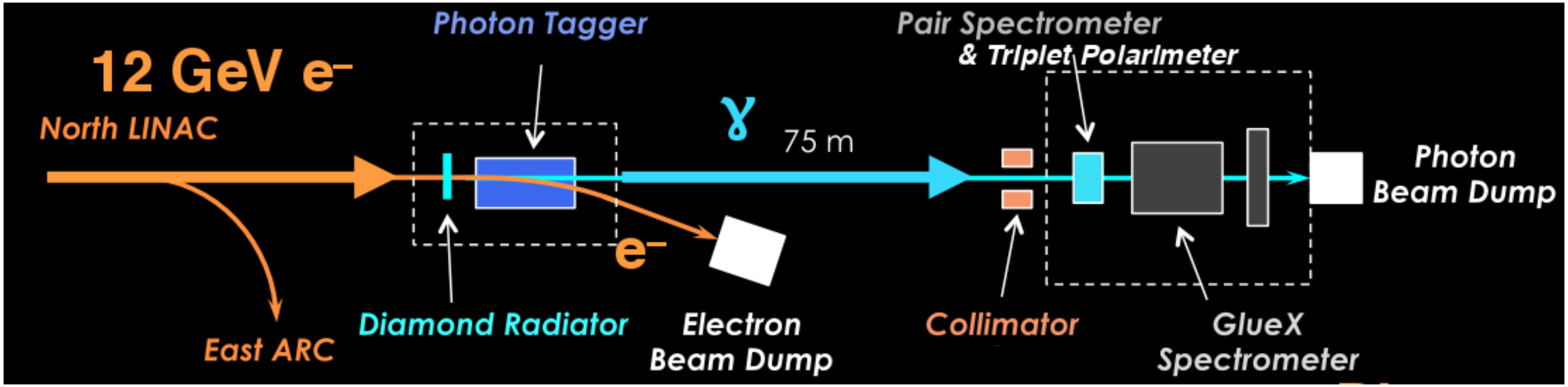
Aloni, Fanelli, YS, Williams
1903.03586

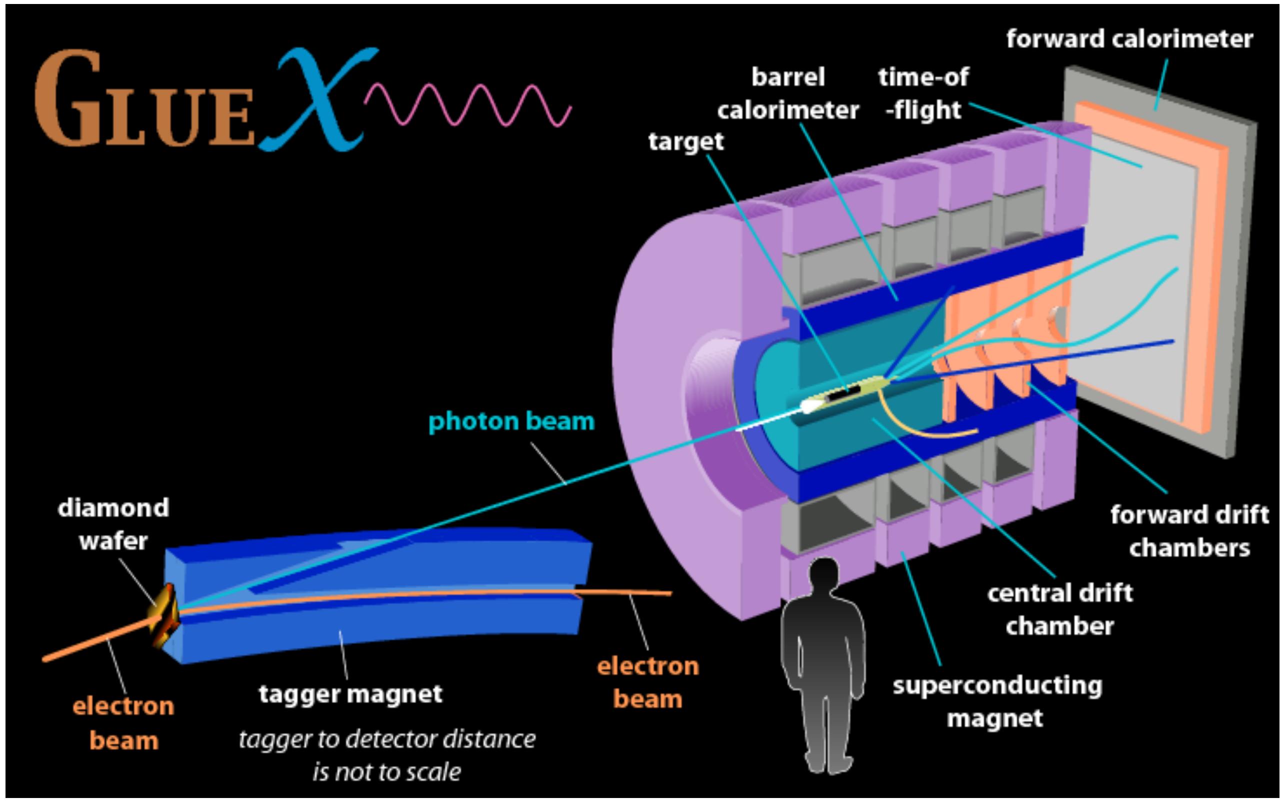
LUXE-NPOD @ DESY

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

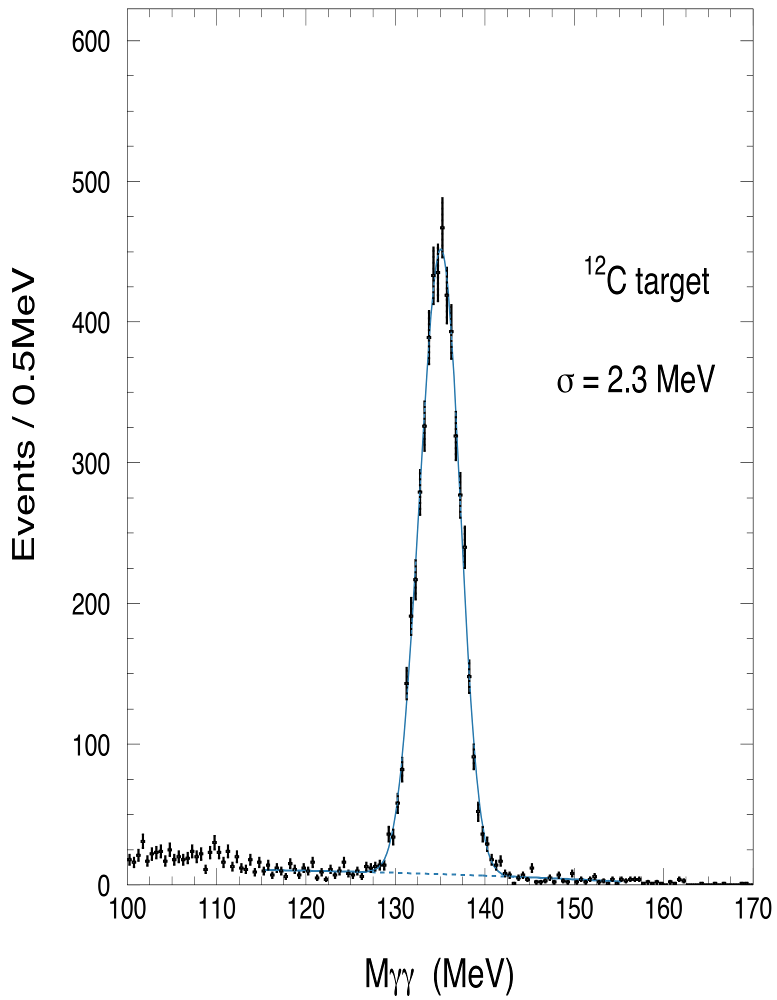
Gamma-Factory @ CERN

Balkin, Krasny, Ma, Safdi, YS
2105.15072


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

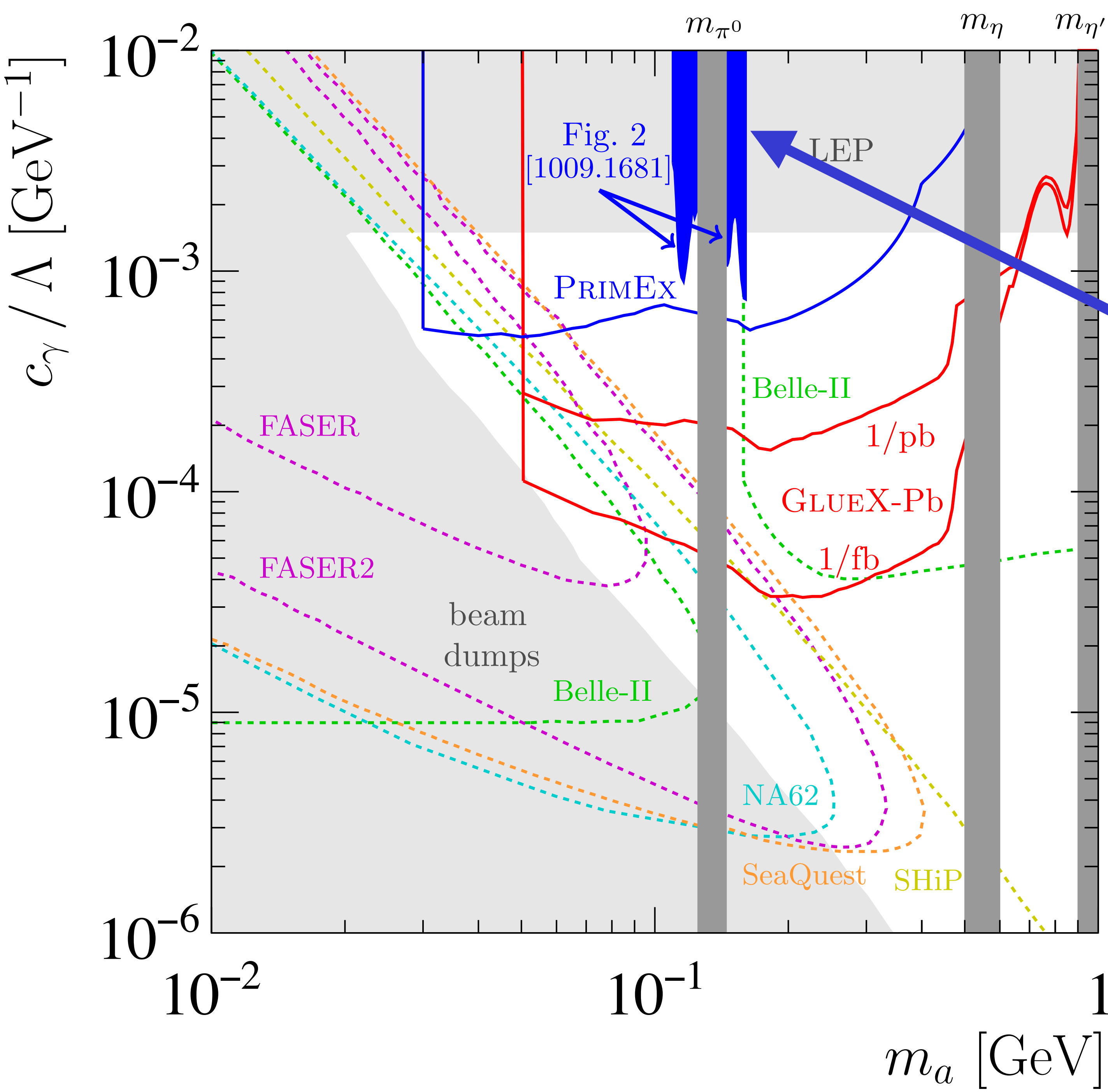

GlueX
forward calorimeter
barrel calorimeter
time-of -flight
target
photon beam
diamond wafer
electron beam
tagger magnet
electron beam
tagger to detector distance is not to scale
forward drift chambers
central drift chamber
superconducting magnet

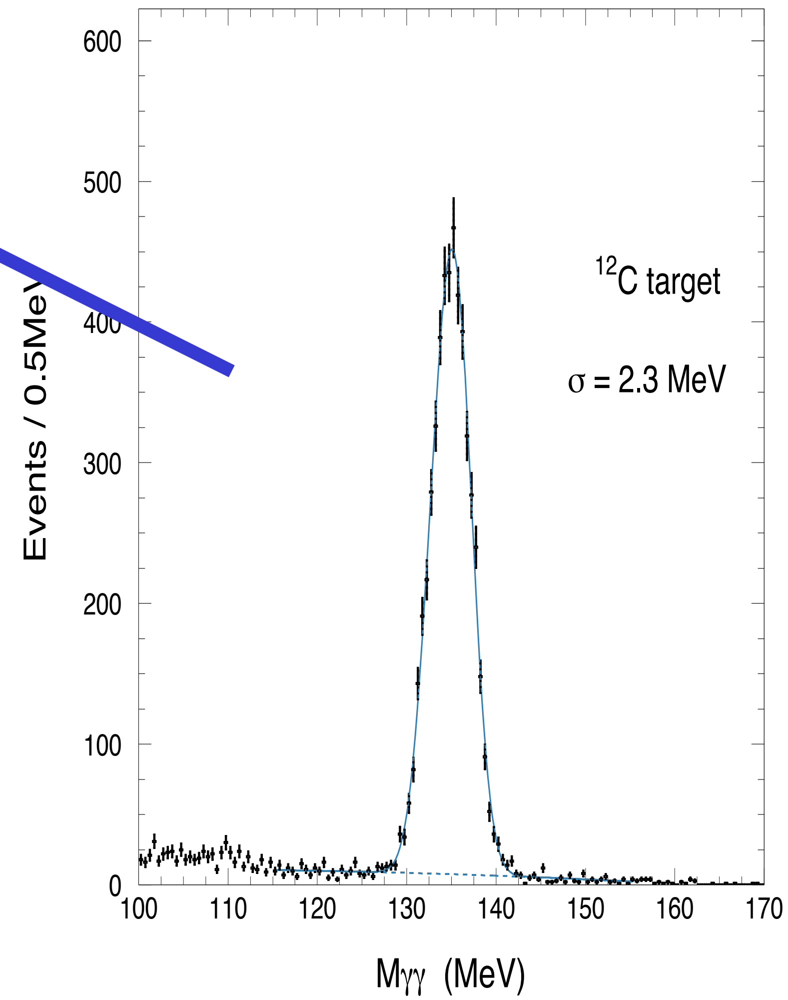
ALP photons coupling



PrimEx - 1009.1681

ALP photons coupling





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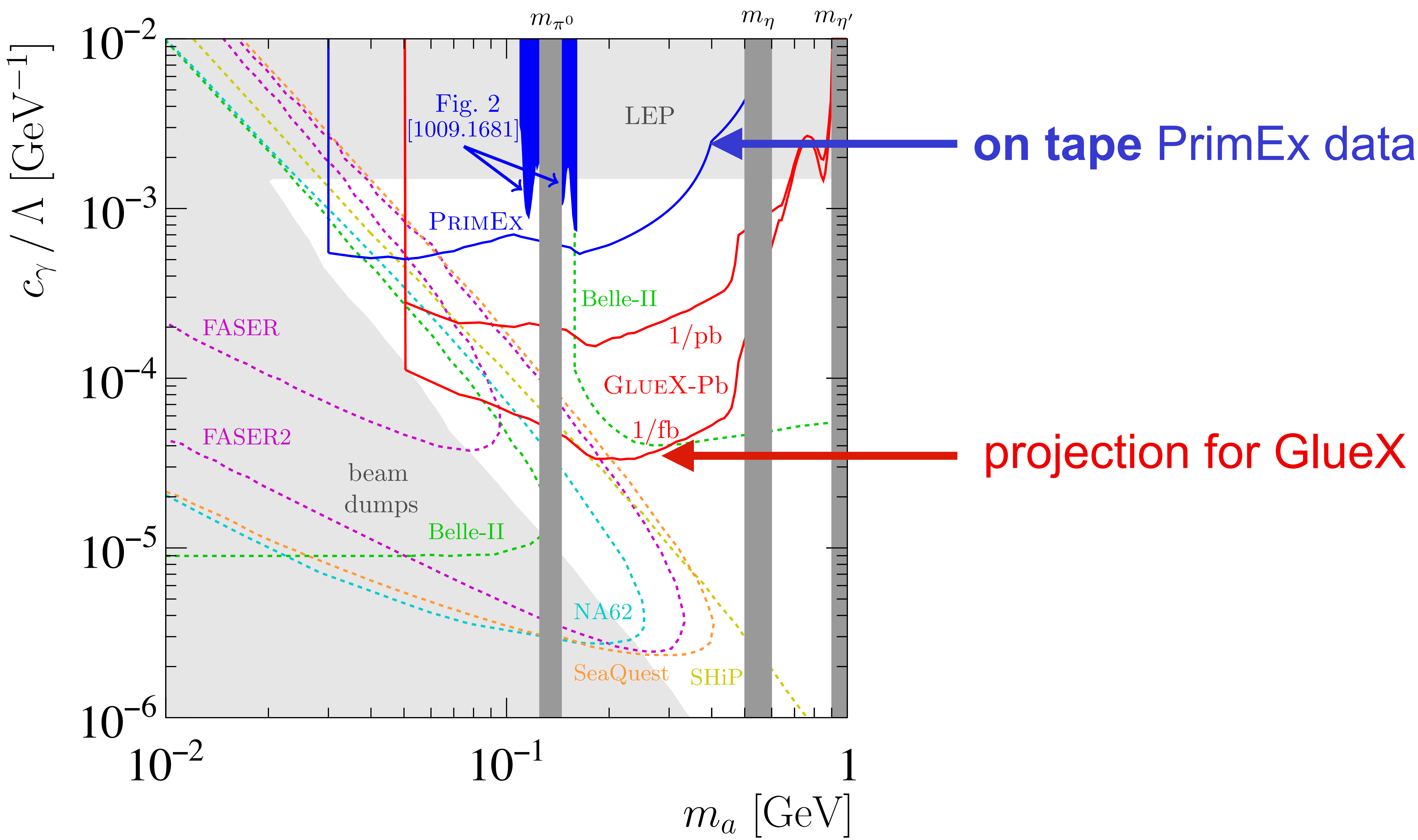
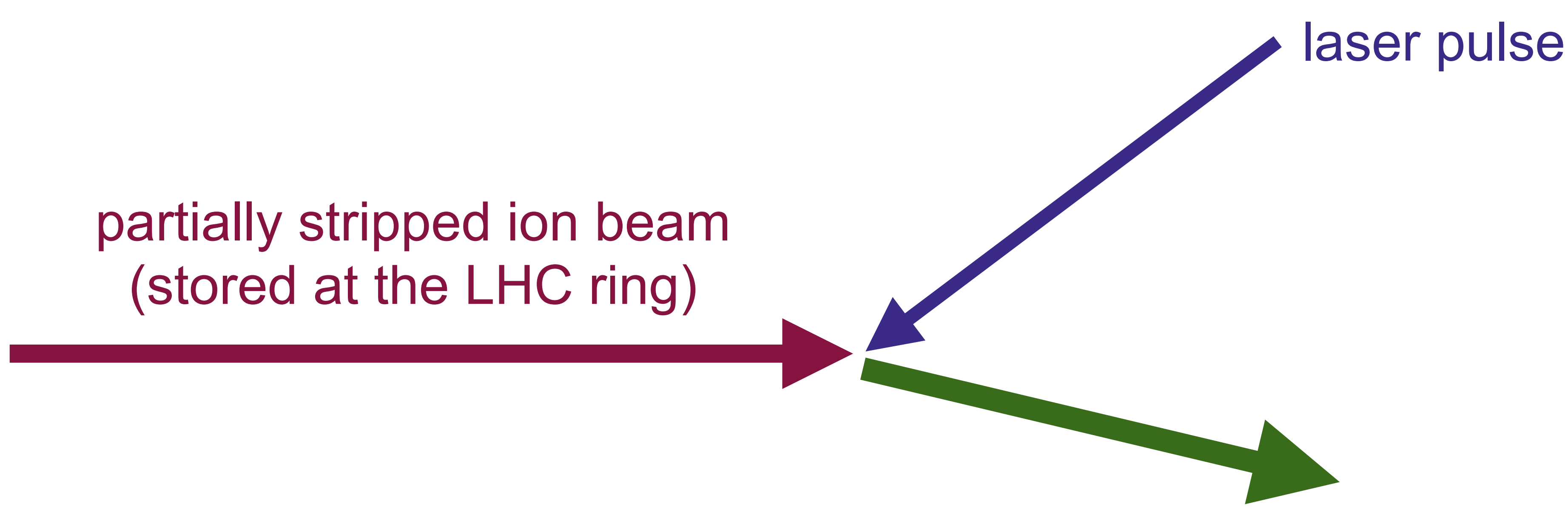


Aloni, Fanelli, YS, Williams
1903.03586

Probing ALPs at the CERN Gamma Factory

Balkin, Krasny, Ma, Safdi, YS
2105.15072

the Gamma-Factory



the outgoing photon flux:

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

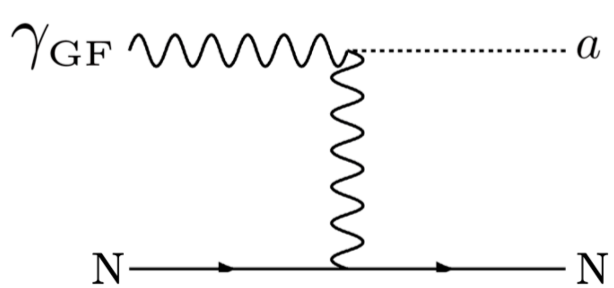
factor of $\mathcal{O}(10^7)$ larger than present sources

Krasny et al. 1511.07794

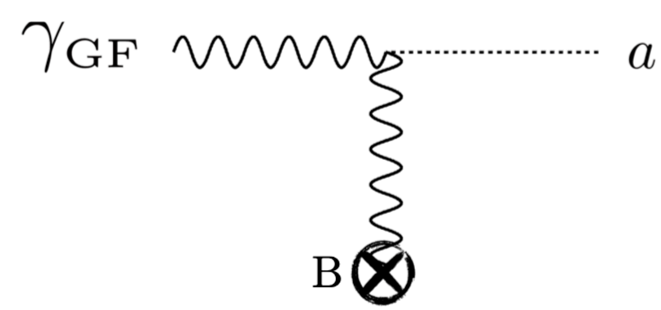
use this huge photon flux for BSM

probing ALP at the Gamma-Factory

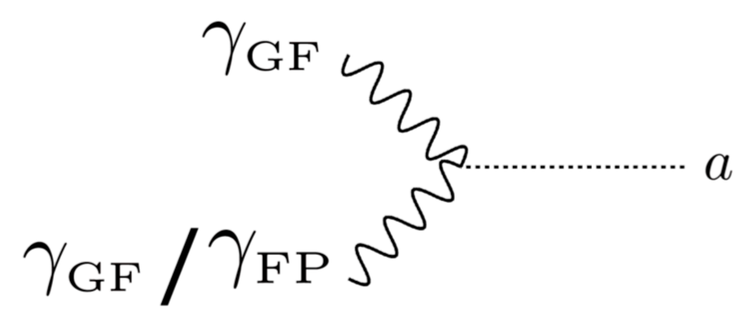
production



(1), (4)



(2)

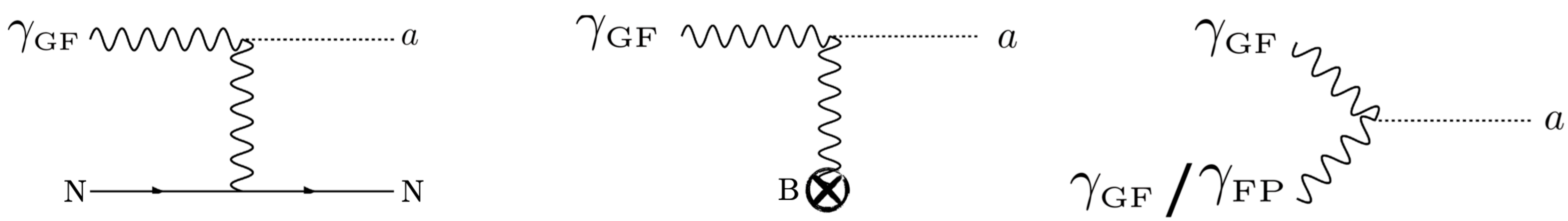


(3)

Balkin, Krasny, Ma, Safdi, YS
2105.15072

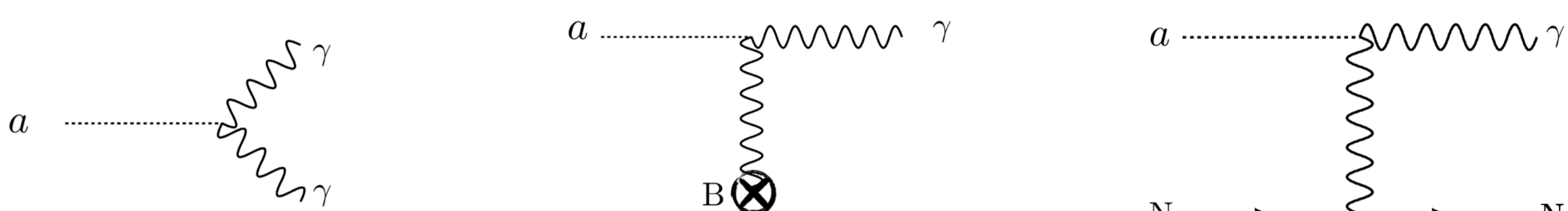
probing ALP at the Gamma-Factory

production



(1), (4) (2) (3)

detection



(a) (b) (c)

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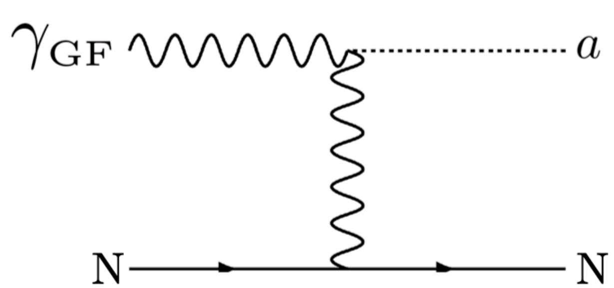
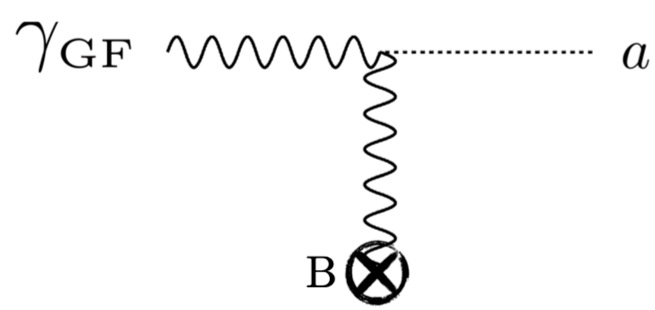
2105.15072

probing ALP at the Gamma-Factory

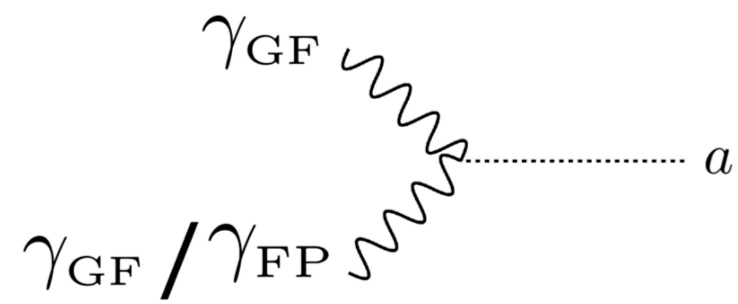
production



(1), (4)

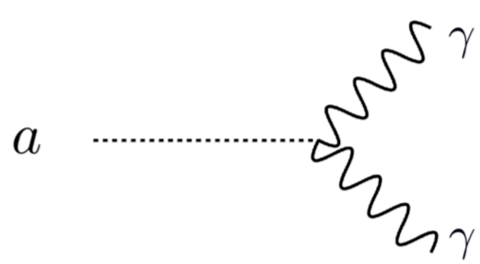


(2)

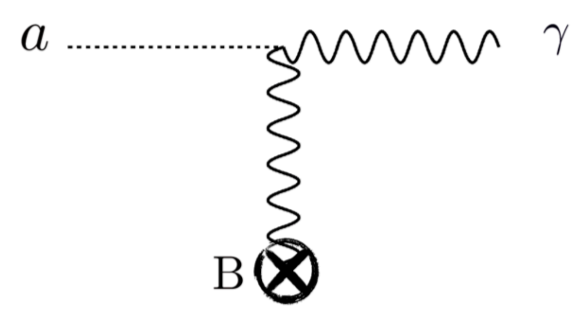


(3)

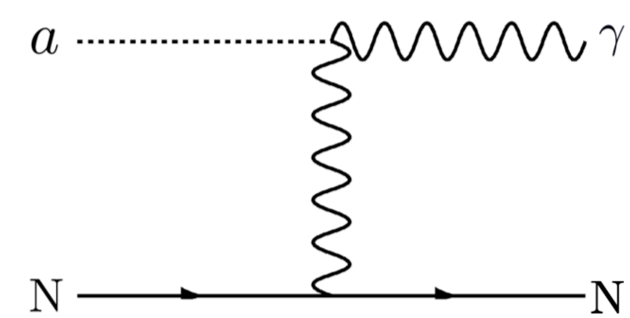
detection



(a)



(b)

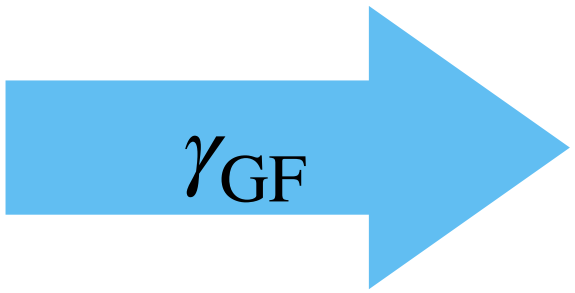


(c)

focus

Balkin, Krasny, Ma, Safdi, YS
2105.15072

probing ALP at the Gamma-Factory

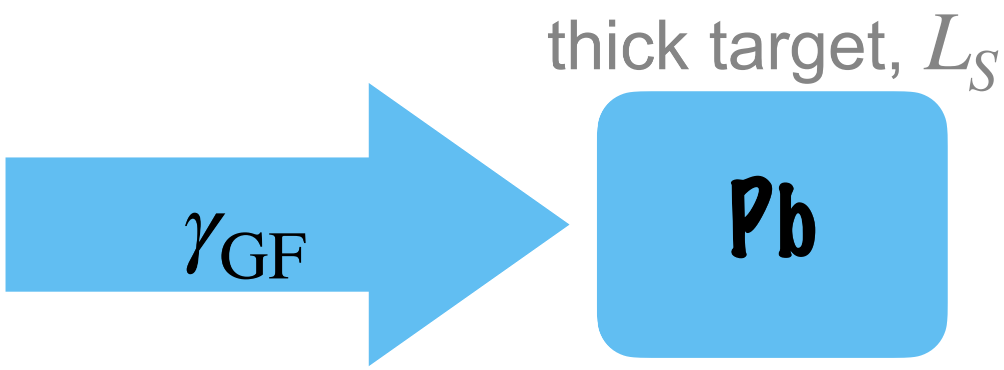


$$\frac{dN_\gamma}{dt} \sim \frac{10^{17}}{\text{sec}}$$

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

Balkin, Krasny, Ma, Safdi, YS
2105.15072

probing ALP at the Gamma-Factory



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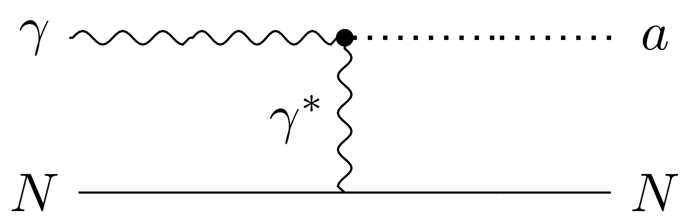

$$N_a^{\text{prod}} = N_\gamma \frac{\rho_N X_0}{A m_0} \sigma_a$$

Balkin, Krasny, Ma, Safdi, YS
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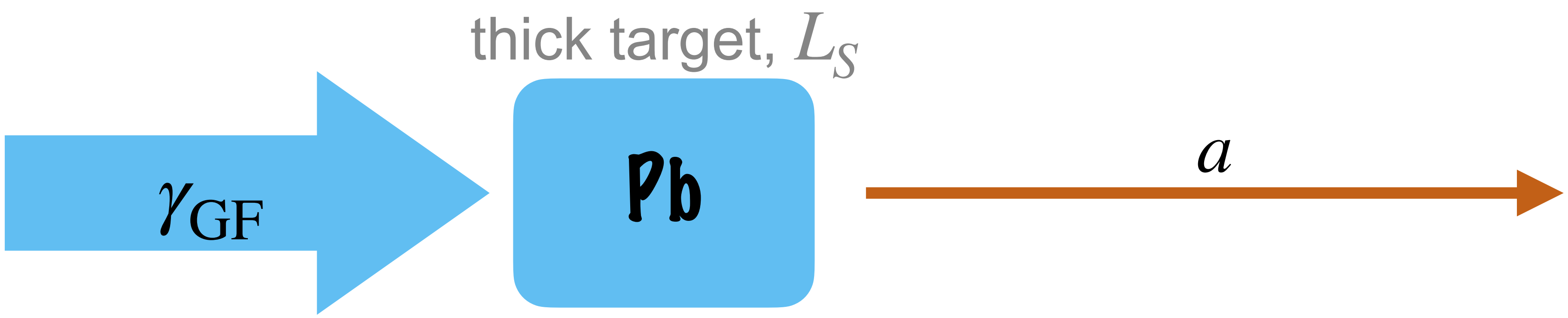

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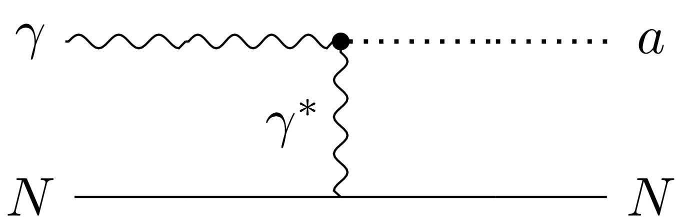

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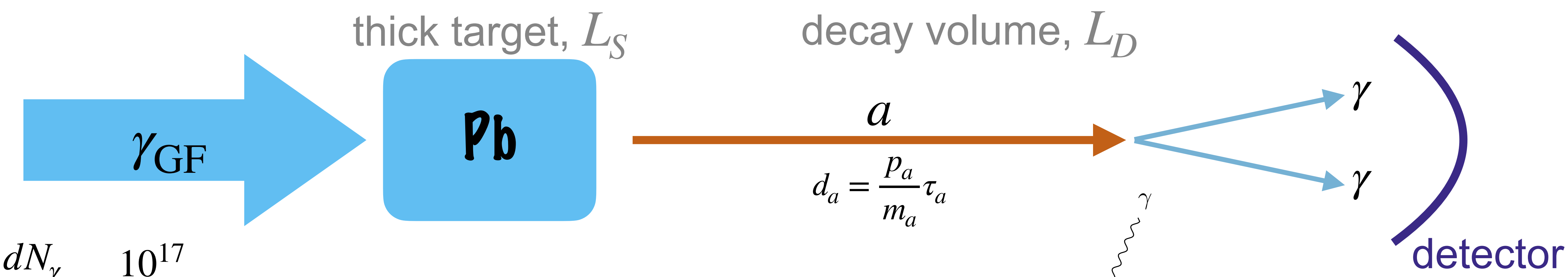

$$d_a = \frac{p_a}{m_a}\tau_a$$

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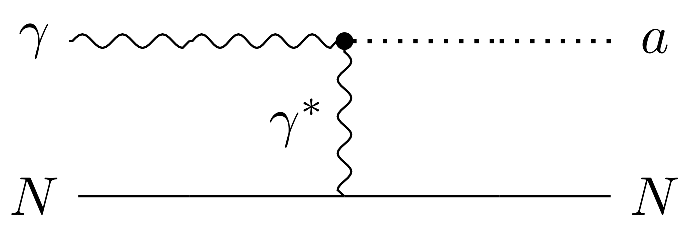

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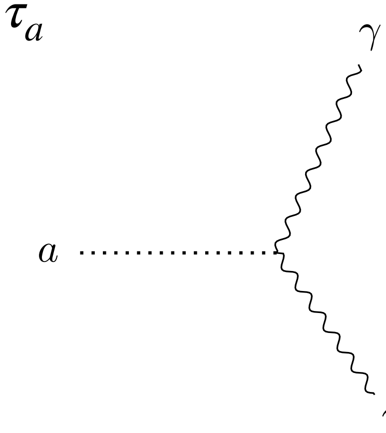

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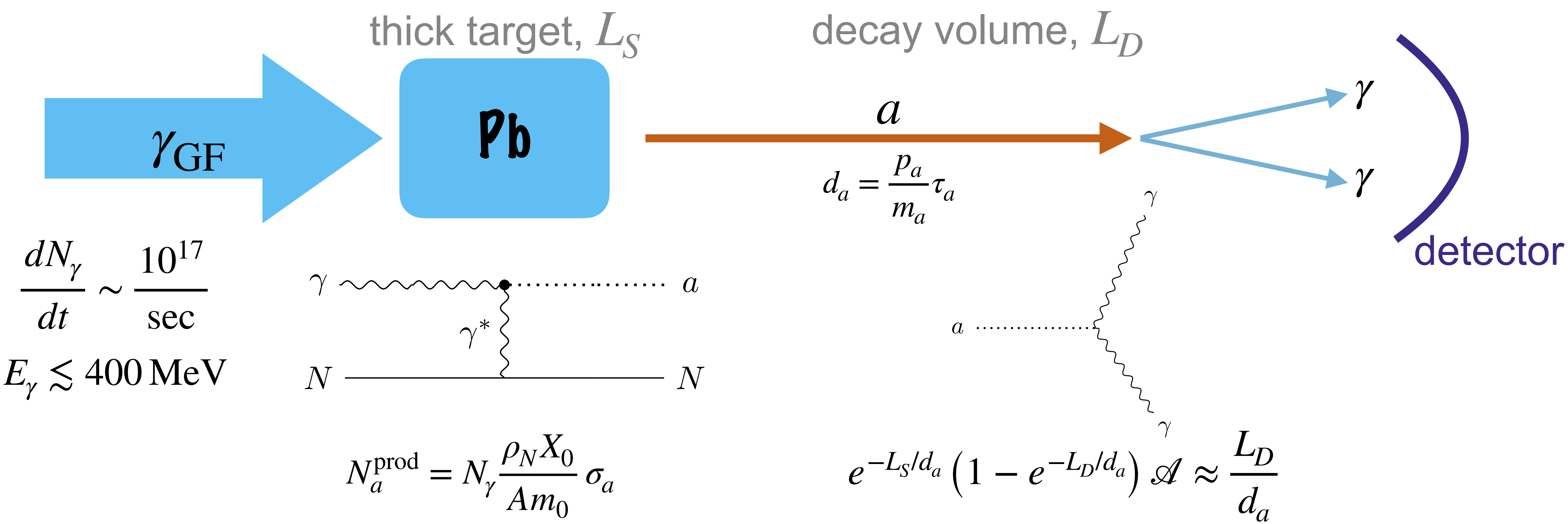

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$$e^{-L_S/d_a}\left(1 - e^{-L_D/d_a}\right)\mathscr{A} \approx \frac{L_D}{d_a}$$

Balkin, Krasny, Ma, Safdi, YS
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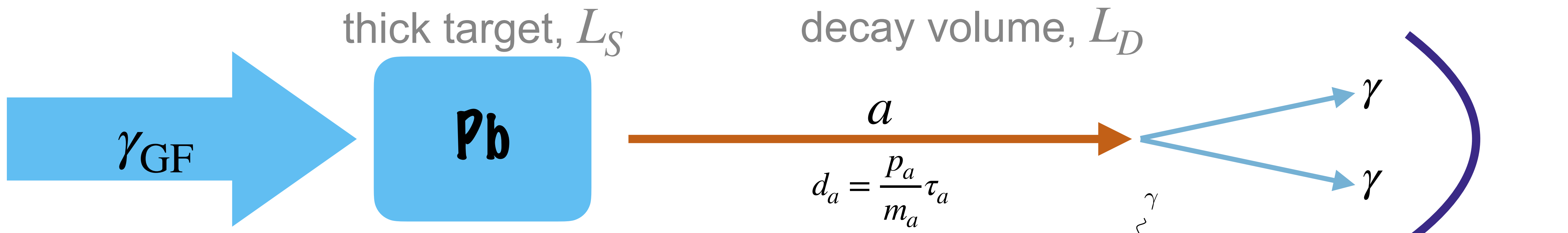

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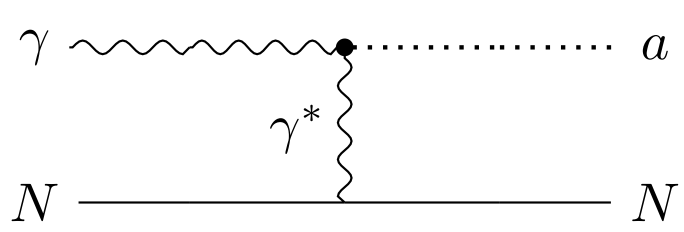
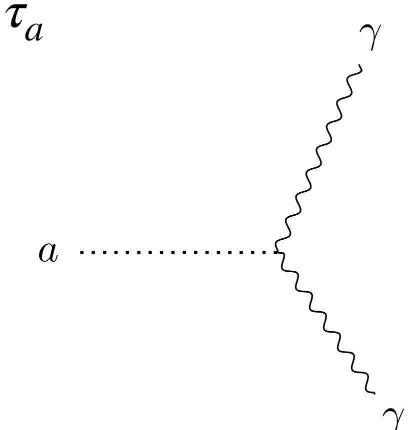




$$N_a^{\rm prod} = N_\gamma \frac{\rho_N X_0}{A m_0}\sigma_a$$

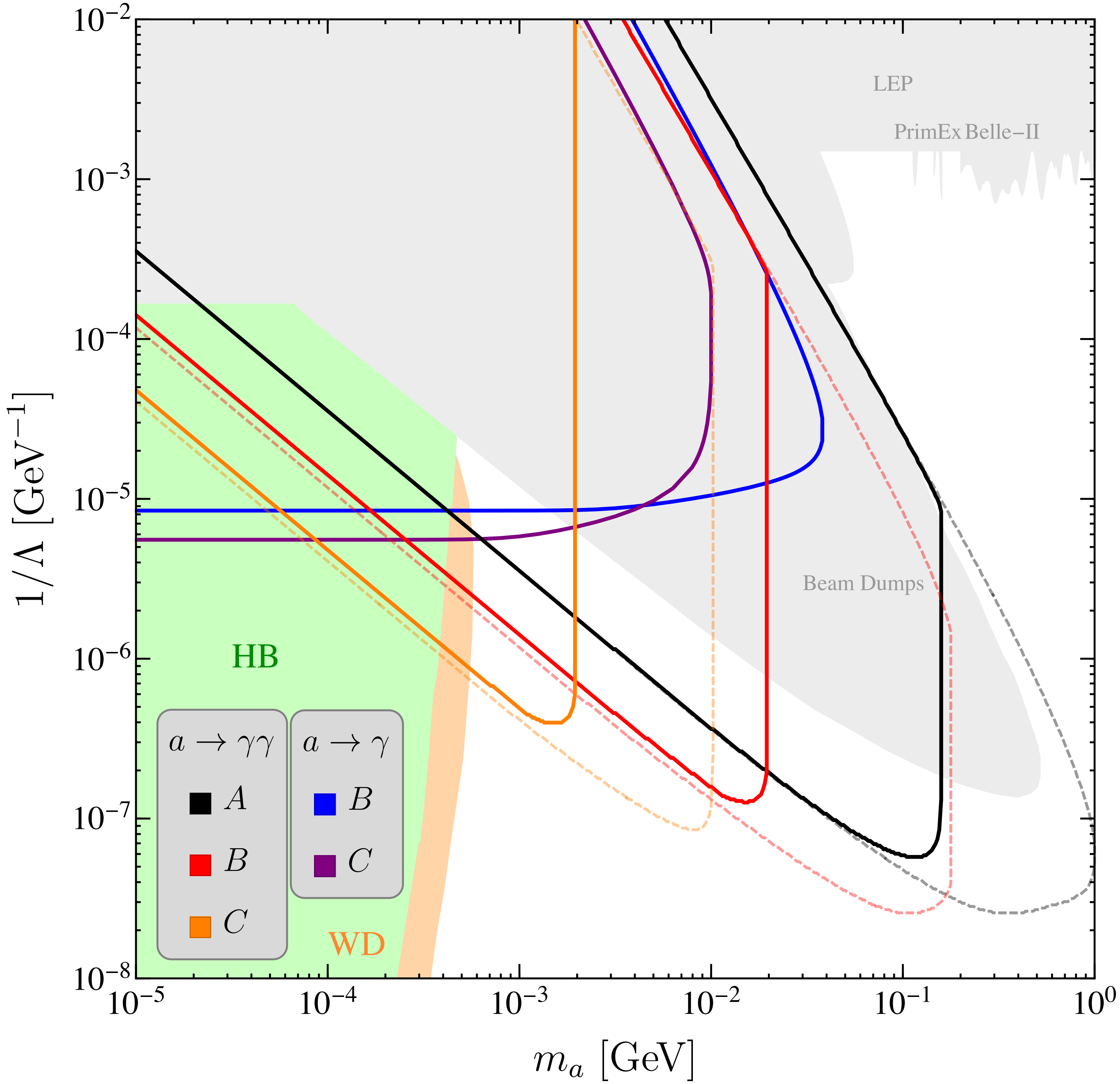
$$e^{-L_S/d_a}\left(1 - e^{-L_D/d_a}\right)\mathscr{A} \approx \frac{L_D}{d_a}$$

$$N_a^{\rm tot} \approx 6\times10^8 \left(\frac{N_\gamma}{10^{24}}\right)\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^2 \frac{L_D}{8\times10^9{\rm m}}\left(\frac{0.2\,{\rm GeV}}{E_\gamma}\right)\left(\frac{m_a}{\rm MeV}\right)^4\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^2 \approx 3\frac{L_D}{40\,{\rm m}}\left(\frac{10^6\,{\rm GeV}}{\Lambda}\right)^4$$

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

Balkin, Krasny, Ma, Safdi, YS
2105.15072

probing ALP at the Gamma-Factory



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

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

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

Balkin, Krasny, Ma, Safdi, YS
2105.15072

ALP gluons coupling

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

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

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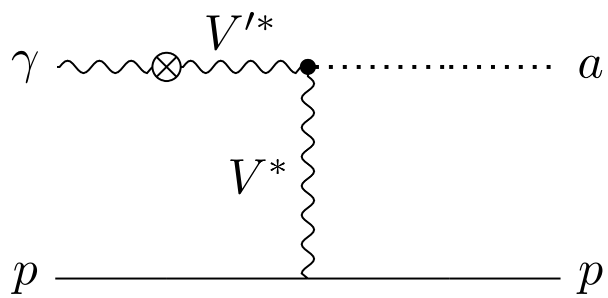
GlueX
p traget



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

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

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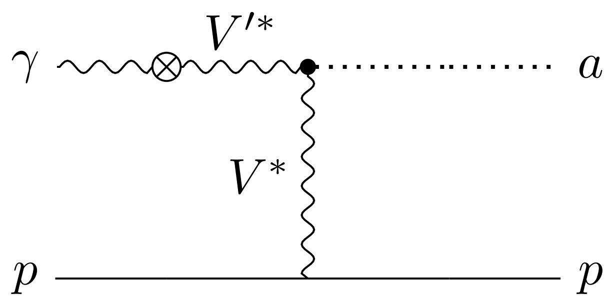

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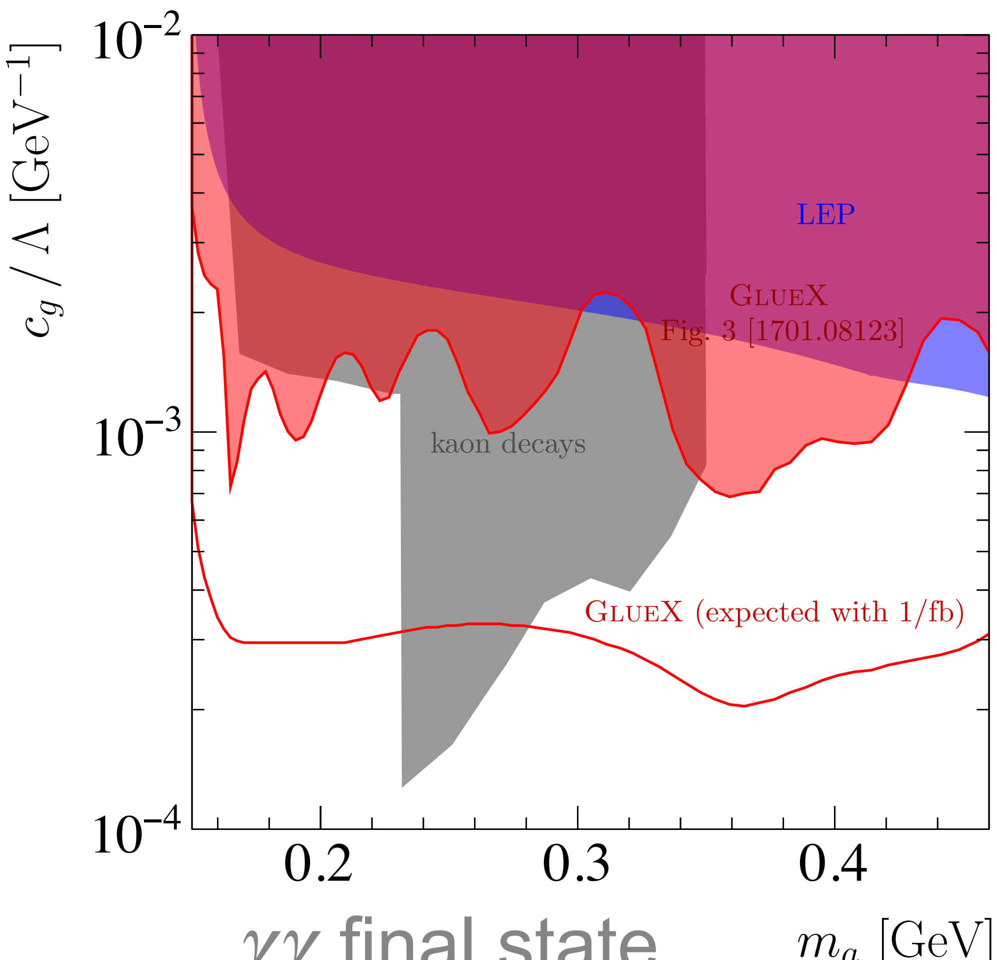

$\gamma\gamma$ final state

Aloni, Fanelli, YS, Williams 1903.03586

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GlueX
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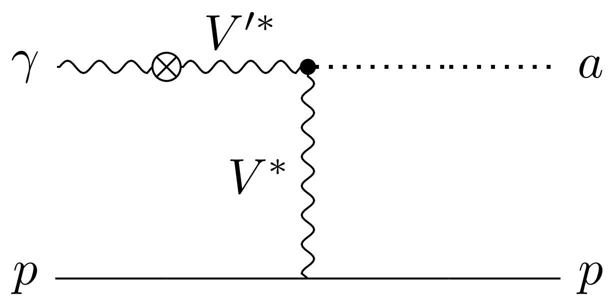
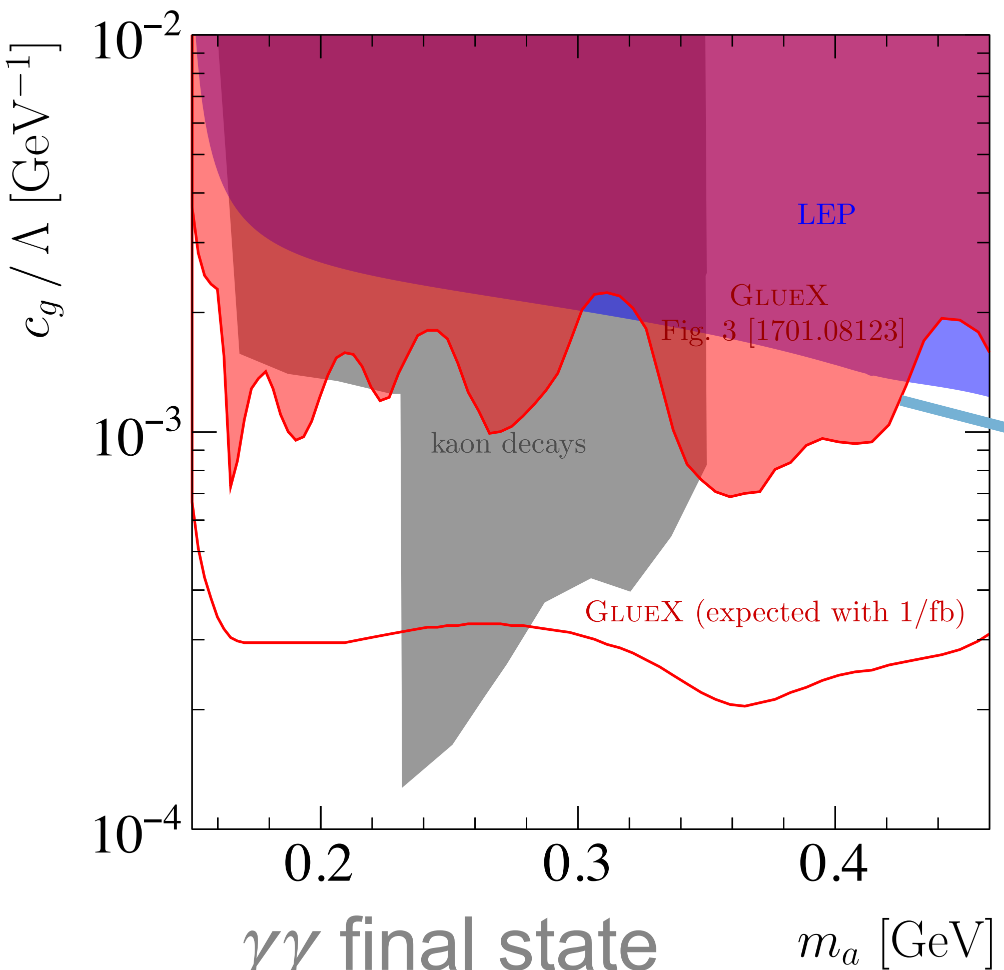
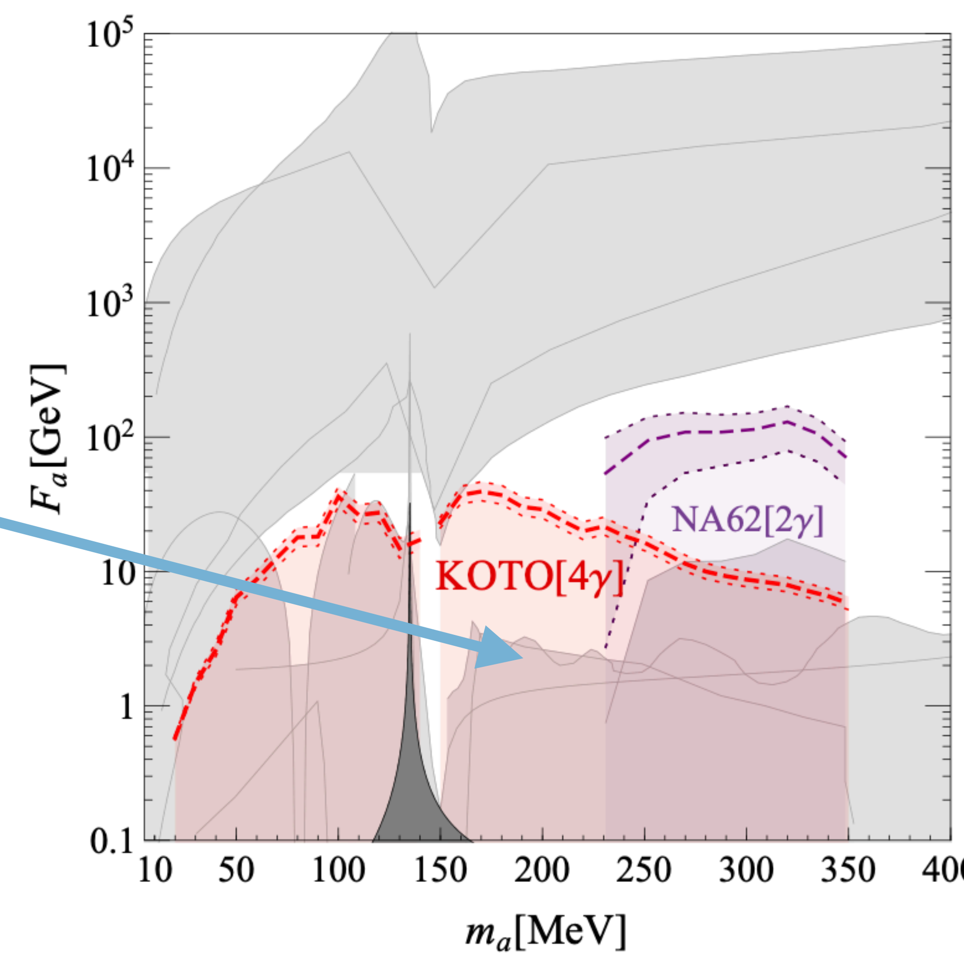


KOTO
$K_L \to \pi^0 a \to 4\gamma$





$\gamma\gamma$ final state

Gori, Perez, Tobioka - 2005.05170

Aloni, Fanelli, YS, Williams 1903.03586

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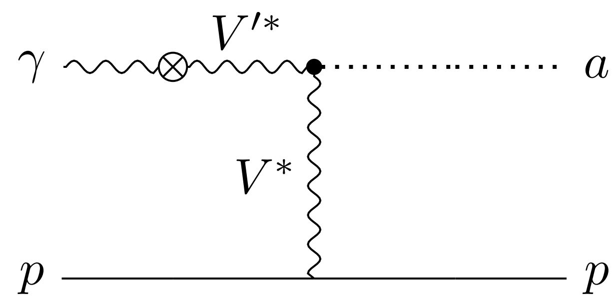

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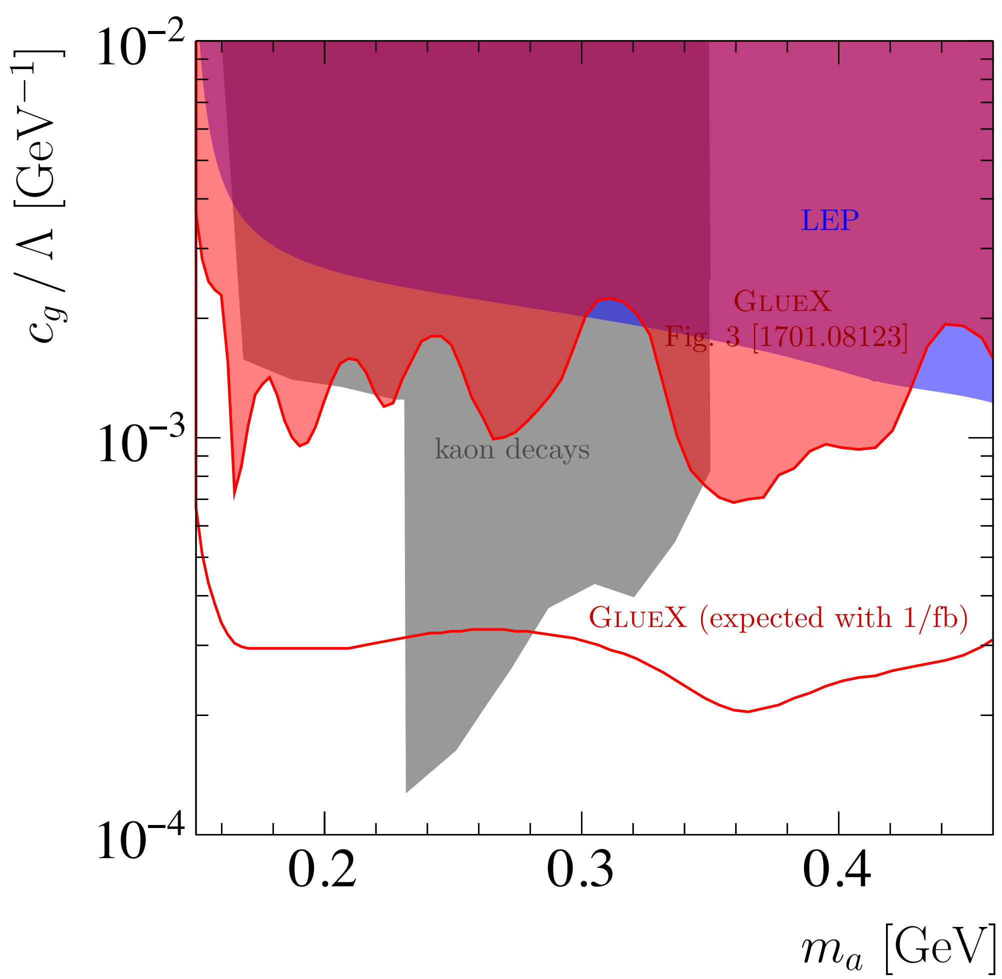
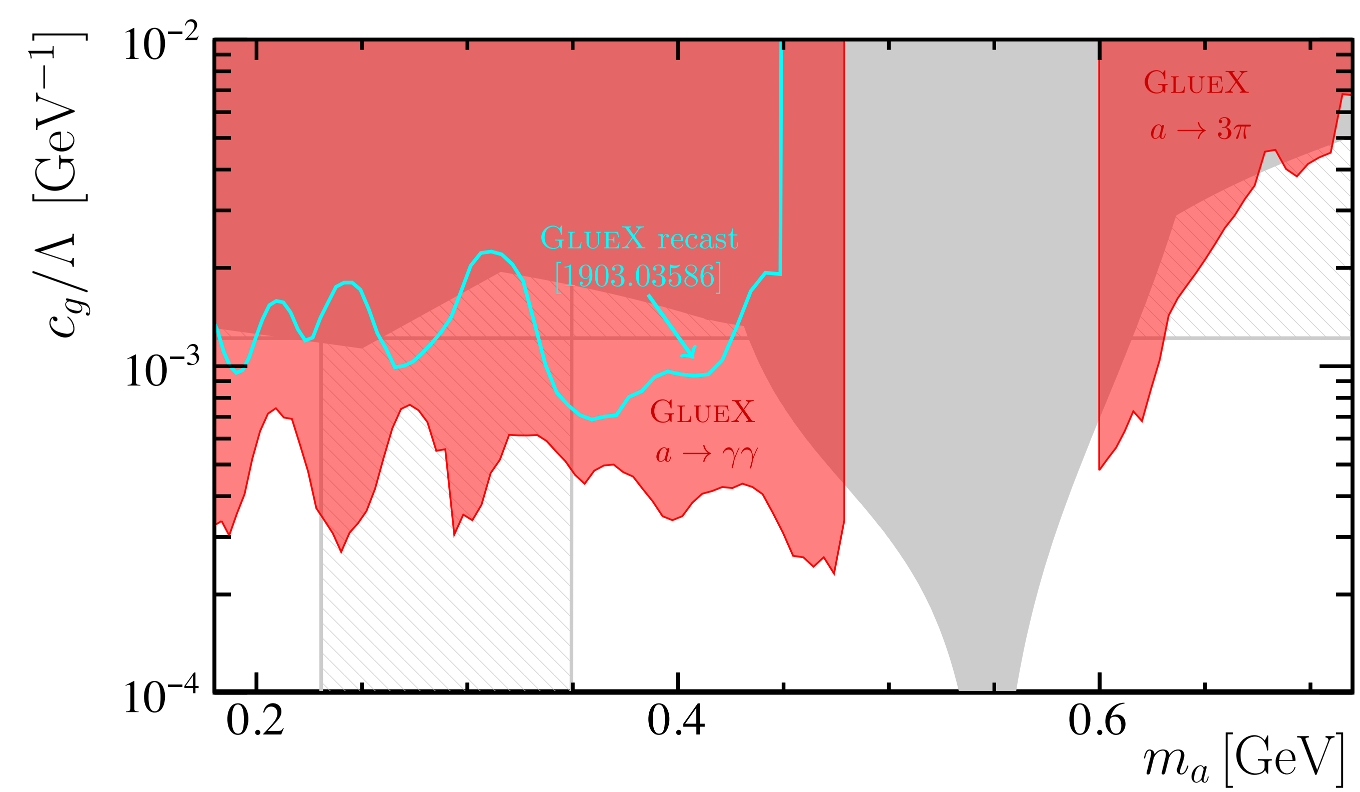
$a - \pi^0, \eta$ mixing

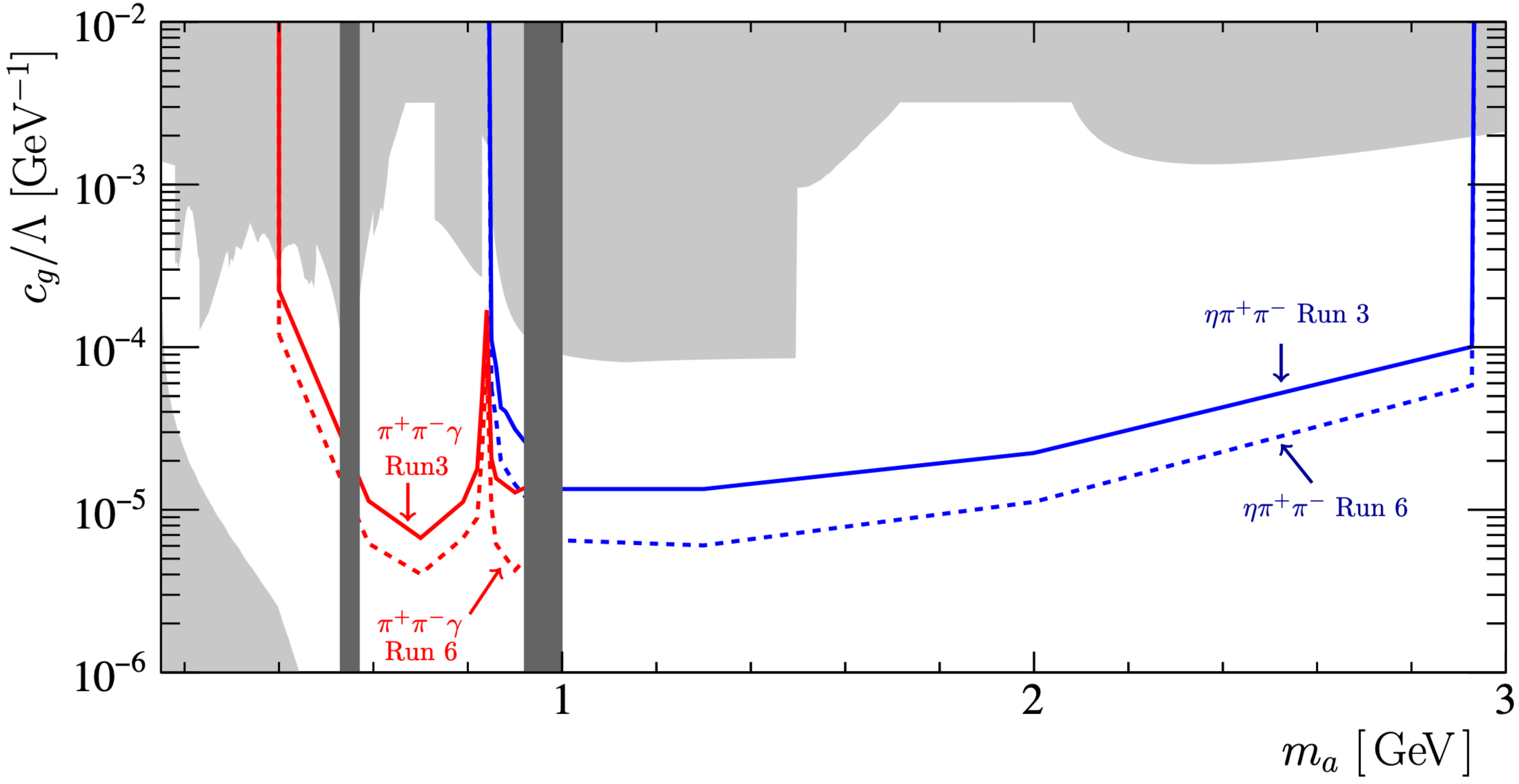




$\gamma\gamma + 3\pi$ final states

GlueX - 2109.13439

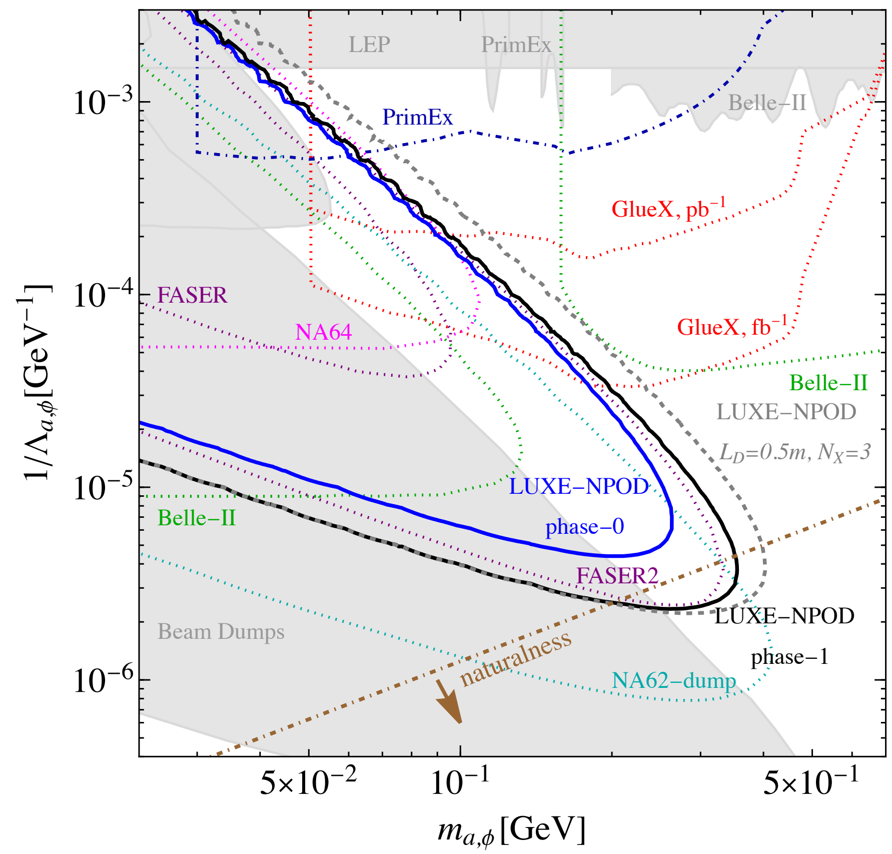
ALP gluons coupling



LHCb projections for HL - 2203.07048

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

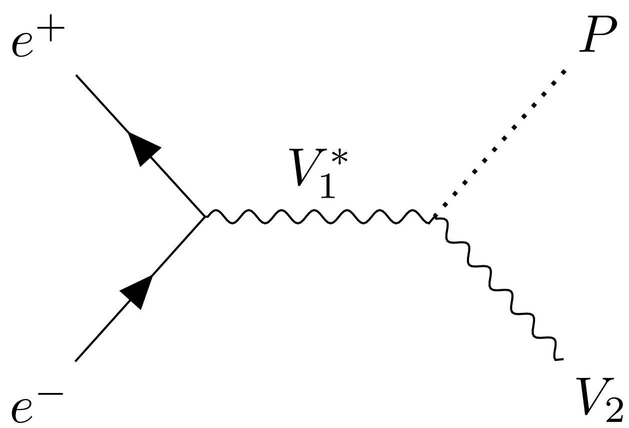
Backups

ALP gluons coupling

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

ALPs hadronic rates?

$$e^+e^- \to V_1^* \to V_2 P$$



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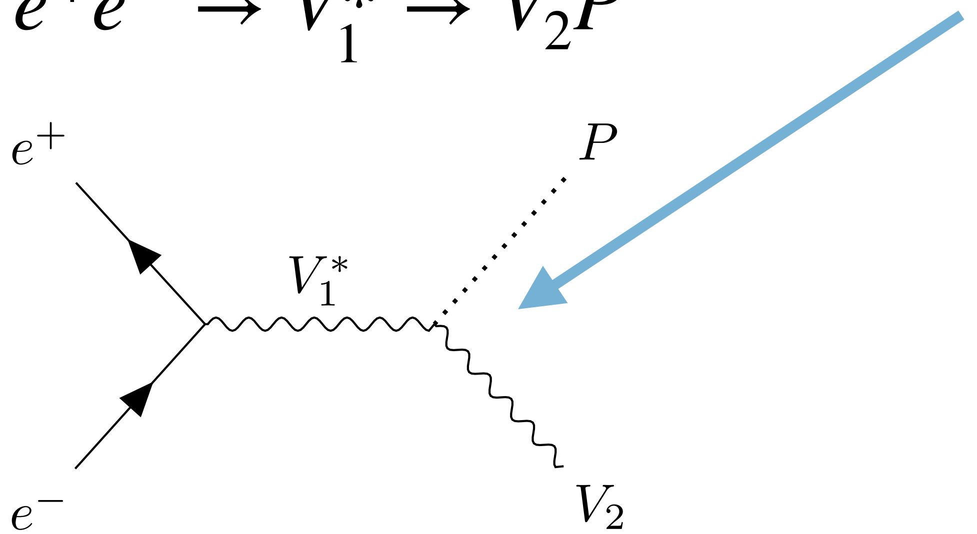

$$\mathscr{A}(V_1 \to V_2 P) = \epsilon_{\mu\nu\alpha\beta}\epsilon_1^{\mu}\epsilon_2^{*\nu}p_1^{\alpha}p_2^{\beta}\,\mathscr{F}\left(p_1^2, p_2^2, q^2\right) \times \frac{3g^2}{4\pi^2 f_\pi}\langle \boldsymbol{V_1 V_2 P}\rangle$$

one Lorentz structure   modified VMD

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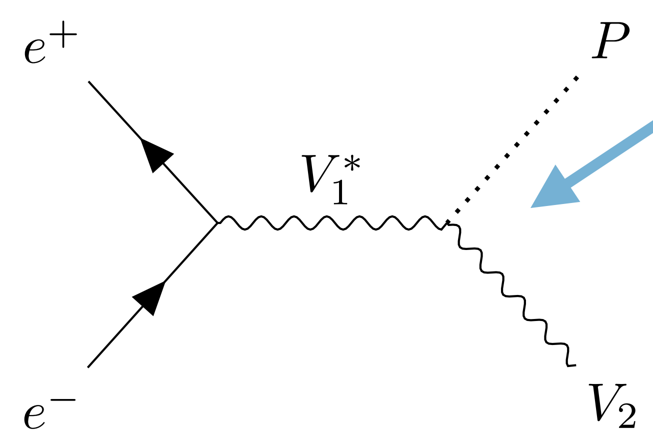

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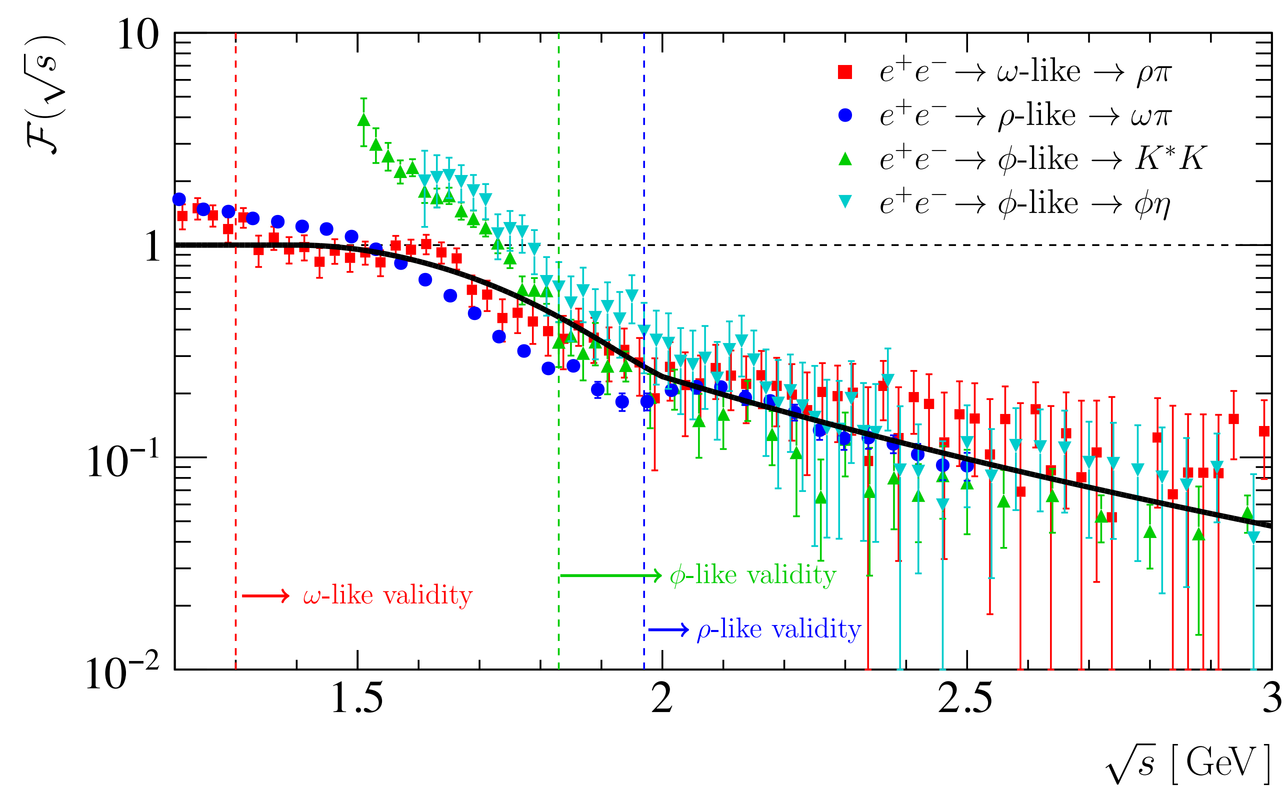

from data

$$\mathcal{F}(m) = \begin{cases} 1 & \text{for } m < 1.4\,\text{GeV} \\ \text{interpolation} & \text{for } 1.4 \le m \le 2\,\text{GeV} \\ \left[\frac{\beta_{\mathcal{F}}}{m}\right]^4 & \text{for } m > 2\,\text{GeV} \end{cases}$$

ALP gluons coupling

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ALPs hadronic rates?

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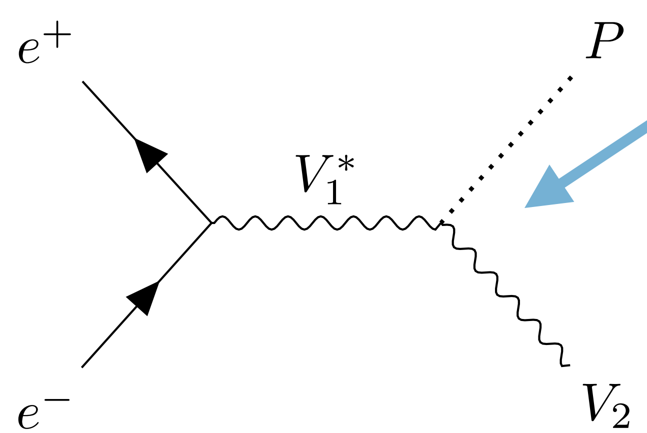

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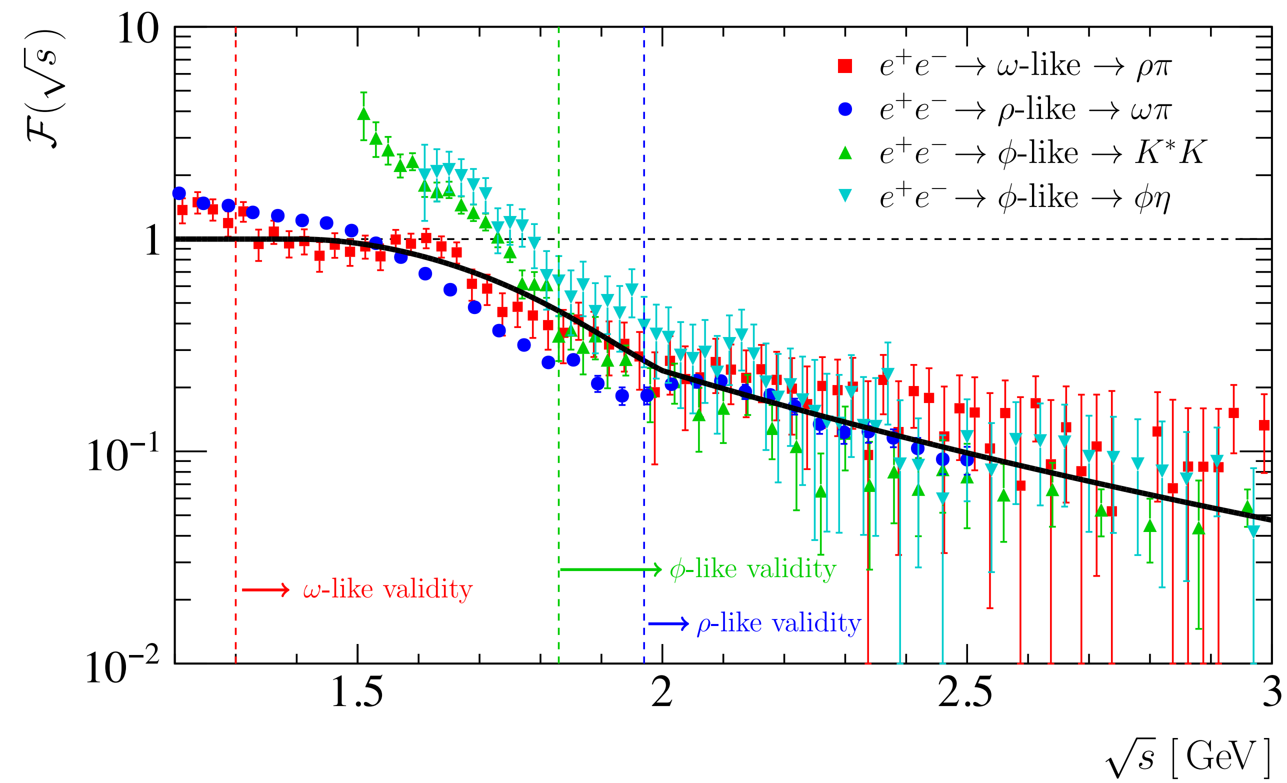
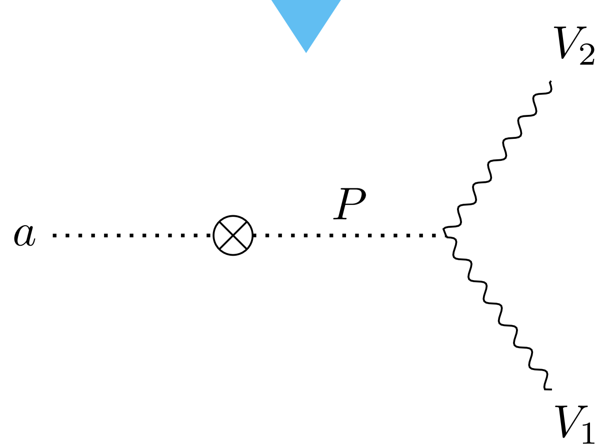
one Lorentz structure — modified VMD





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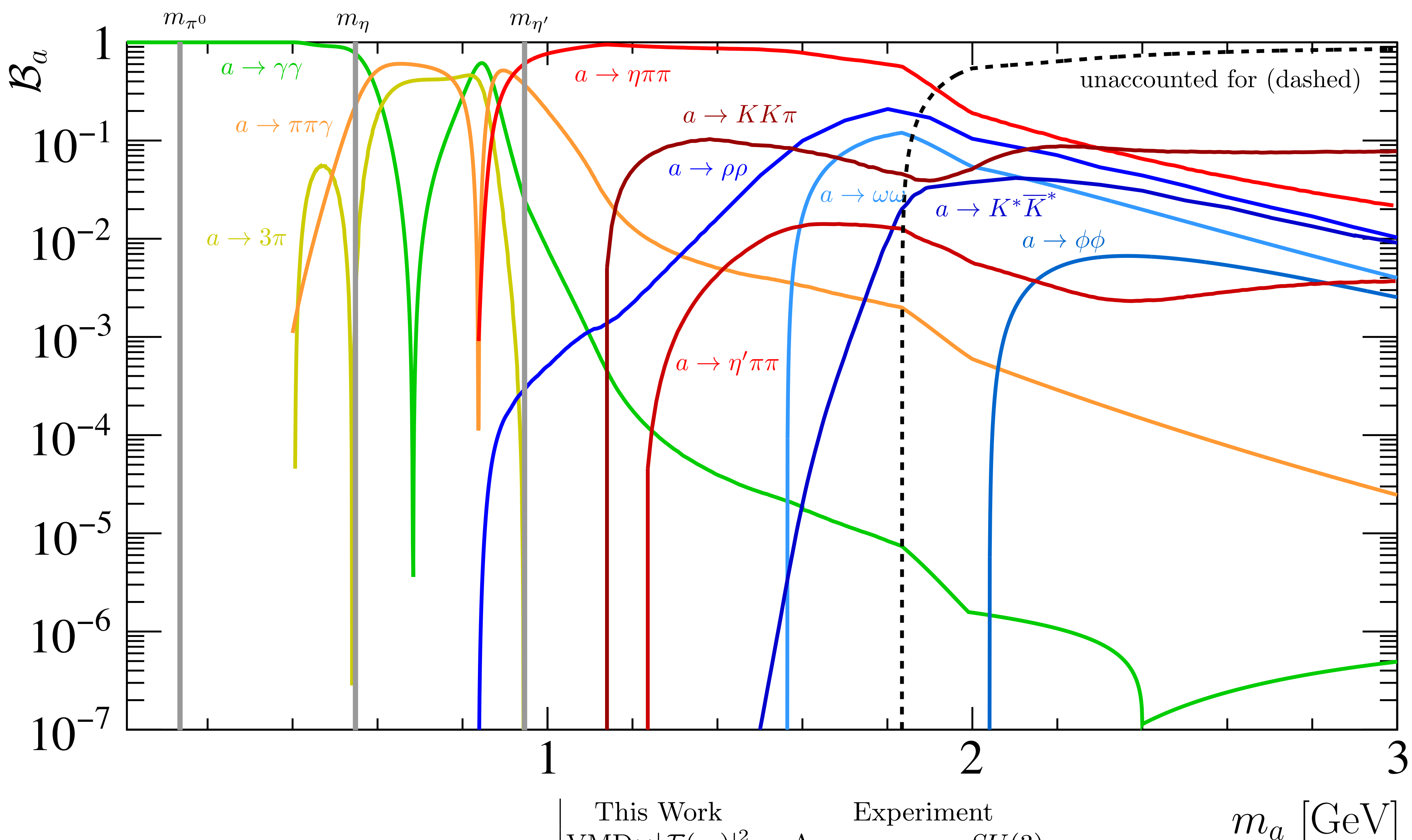
replace *P* by *P*-ALP mixing



η_c – cross check

	This Work VMD×$\lvert\mathcal{F}(m)\rvert^2$	Experiment Average	Experiment $SU(3)$
$\mathcal{B}(\eta_c \to \rho\rho)$	1.0%	$1.8 \pm 0.5\%$	$1.10 \pm 0.14\%$
$\mathcal{B}(\eta_c \to \omega\omega)$	0.40%	$0.20 \pm 0.10\%$	$0.44 \pm 0.06\%$
$\mathcal{B}(\eta_c \to \phi\phi)$	0.25%	$0.28 \pm 0.04\%$	$0.28 \pm 0.04\%$
$\mathcal{B}(\eta_c \to K^*\overline{K}^*)$	0.91%	$0.91 \pm 0.26\%$	$1.00 \pm 0.13\%$