Поиск аксионо-подобных частиц в фотон-фотонном рассеянии на коллайдере CLIC

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arXiv:2007.01693 v1 (часть II)

Семинар ОТФ, 13 октября 2020 года

План доклада

- Нарушение CP-инвариантности и КХД аксион. Аксионо-подобные частицы (ALPs).
- Вклад аксионо-подобных частиц в рождение пары фотонов на лептонном коллайдере CLIC в e^+e^- моде.
- ALPs и образование пары фотонов в столкновении реальных комптоновских фотонов ($\gamma\gamma$ мода CLIC).
- Процесс $\gamma\gamma \to \gamma\gamma$ с поляризованными начальными фотонами, индуцированный ALP.
- Заключение

Strong CP problem and QCD axion

U(1) problem

→ axial anomaly → θ-vacuum

→ strong CP problem → QCD axion

QCD Lagrangian: global symmetry

$$U(3)_V \bullet U(3)_A = SU(2)_V \bullet SU(2)_A \bullet U(1)_V \bullet U(1)_A$$

Quark condensates → spontaneously broken $U(1)_A$

→ NG massless boson should appear

Absence of NG boson is known as

U(1) problem

One possible solution – ABJ chiral anomaly

$$\partial^\mu J_\mu^5 = \frac{g^2 N_f}{16\pi^2} G_{a\mu\nu} \tilde{G}_a^{\mu\nu}$$

This term is a total divergency

$$G_{a\mu\nu} \tilde{G}_a^{\mu\nu} = \partial^\mu K_\mu$$

Chiral anomaly introduces a pure surface integral to QCD action

$$\Delta S_{\text{QCD}} = \frac{g^2 N_f}{16\pi^2} \int ds_\mu K^\mu$$

Gluon field is a pure gauge at spatial infinity

$$A_\mu\big|_{r\to\infty} \to -\frac{i}{g}\partial_\mu \omega\omega^{-1} \qquad \omega_n \to e^{i2\pi n} \text{ as } r \to \infty$$

Winding number

$$n = \frac{g^2}{32\pi^2}\int ds_\mu K^\mu$$

SU(2): map of 3-dimensional sphere S^3 on sphere S^3 of SU(2) group

True or θ-vacuum

$$|\theta\rangle = \sum_n e^{-in\theta}|n\rangle$$

As a result, QCD action acquires θ-term

$$S_{\rm eff} = S_{\rm QCD} + \theta \frac{g^2}{32\pi^2} \int dx\, G_{a\mu\nu} \tilde{G}_a^{\mu\nu}$$

After diagonalization of mass matrix : $\theta \to \theta_{\rm phys} = \theta + \arg\det M_q$

Exp. limit on neutron electric dipole moments,

$d_n < 0.021 \cdot 10^{-23}$ **e cm, requires $\theta_{phys} < 10^{-9}$**

Smallness of θ_{phys} is known
as *strong CP problem*

Elegant solution: Peccei-Quinn mechanism with a new, spontaneously broken, global $U(1)_{PQ}$ symmetry

(Peccei & Quinn, 1977)

$$< \varphi >= f_a \exp(ia/f_a)$$

It results in light neutral pseudoscalar particle, axion, which is a NG boson of broken $U(1)_{PQ}$ symmetry

(Weinberg, Wilczek, 1978)

$U(1)_{PQ}$ invariant total Lagrangian acquires the term

$$\mathcal{L}_a = \xi \frac{g^2}{32\pi^2} \frac{a}{f_a} G_{a\mu\nu} \tilde{G}_a^{\mu\nu}$$

Lagrangian written in terms of $a_{phys} = a + \langle a \rangle$, where $\langle a \rangle = -f_a \theta_{phys}/\xi$, no longer has CP violating term

Axion mass and its coupling are related, $m_a \approx m_\pi f_\pi / f_a$

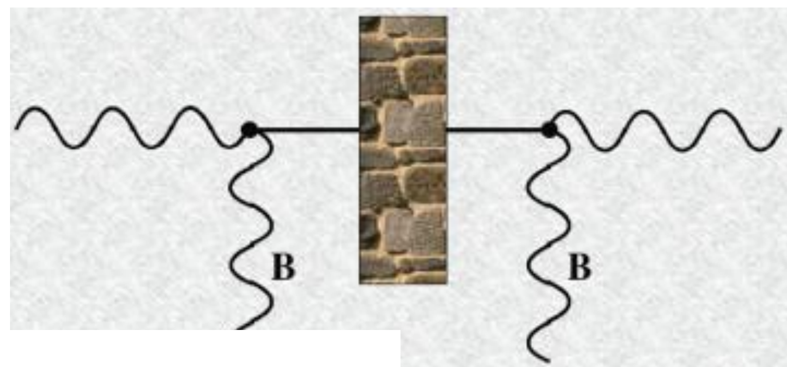
New symmetry effectively replaces static CP-violating angle θ with dynamically CP-conserving field, the axion

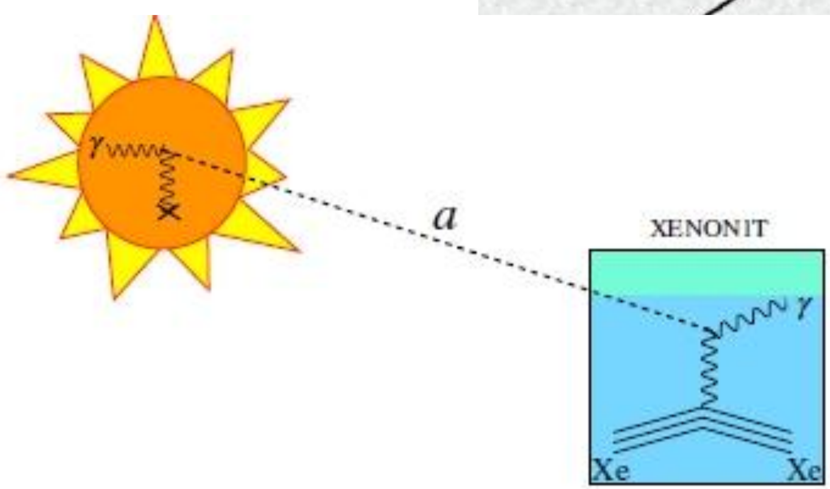
Axion is a leading DM candidates

Axion phenomenology:

stellar evolution, axion mediated forces, DM detection, axion decays, axion-photon conversion, "light shining through the wall", solar axions, *etc*.

Light shining through the wall





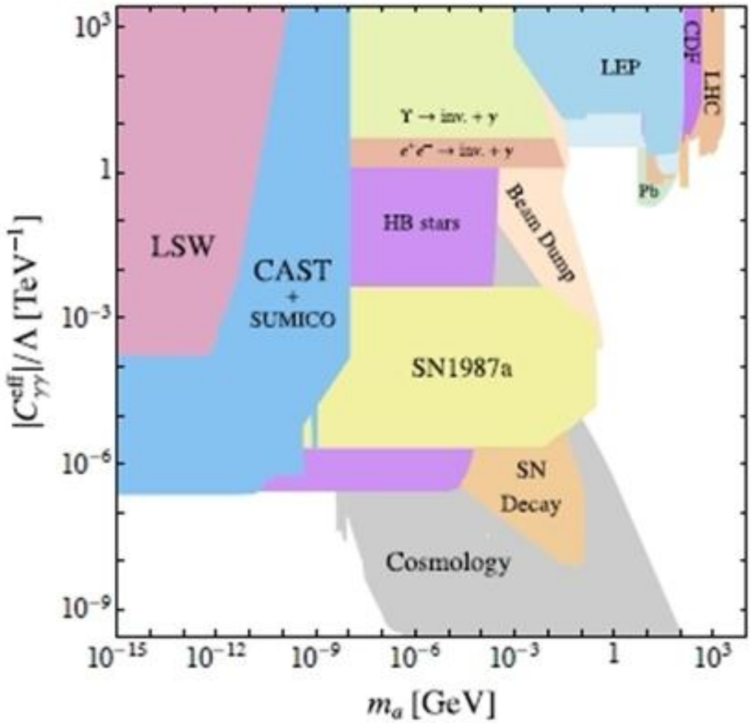
XENON1T excess

Axion-like particles (ALPs):

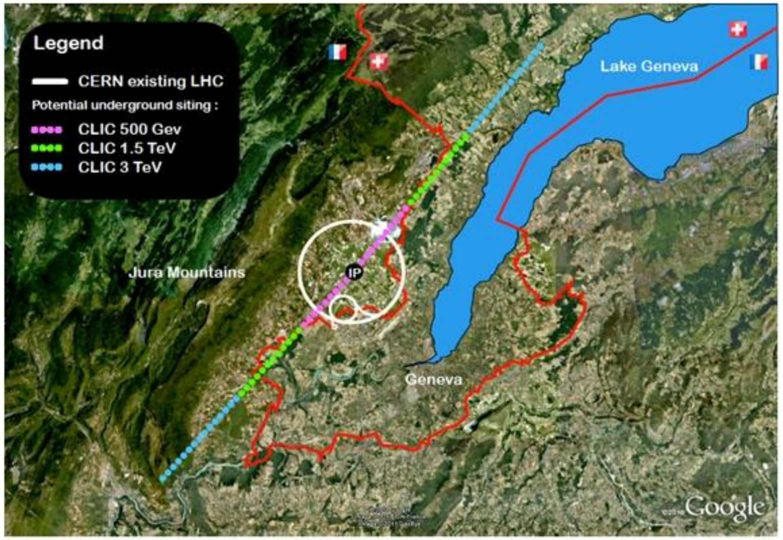
no coupling to gluons, but nonzero coupling to photons
→ may be detected at colliders in light-by-light scattering

$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \vec{B}$$

ALP mass can be treated independently of its coupling



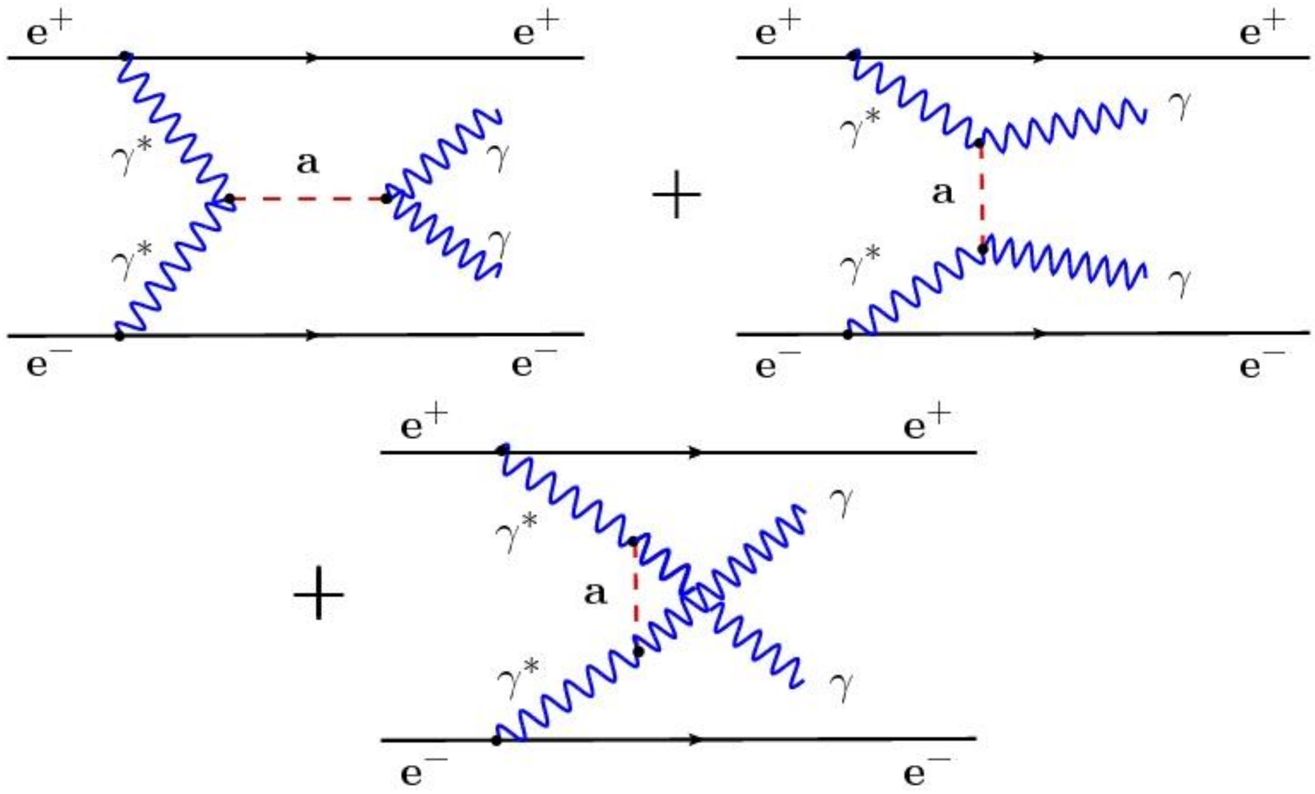
e^+e^- Compact Linear Collider (CLIC)



	Beam energy	Integrated luminosity
1-st stage	190 GeV	1000 fb^{-1}
2-nd stage	750 GeV	2500 fb^{-1}
3-rd stage	1.5 TeV	5000 fb^{-1}

PART I
(unpolarized scattering)

Photon-induced diphoton production at the CLIC (e^+e^- mode)



Diagrams for reaction $e^+e^- \to e^+ \gamma\gamma e^- \to e^{+\prime} \gamma\gamma e^{-\prime}$ mediated by axion-like particle a

The goal is to estimate a contribution of ALP to LBL process at the CLIC

Pseudoscalar ALP Lagrangian

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Differential cross section for subprocess γγ→γγ (after P invariance,T invariance and Bose symmetry taken into account)

$$\frac{d\sigma}{d\Omega} = \frac{1}{128\pi^2 s}\left(|M_{++++}|^2 + |M_{+-+-}|^2 + |M_{+--+}|^2 + |M_{++--}|^2\right)$$

Each of helicity amplitudes is a sum of ALP and SM ones

$$M = M_a + M_{\mathrm{ew}}$$

In its turn, SM (electroweak) amplitude is a sum of fermion and W boson one-loop amplitudes

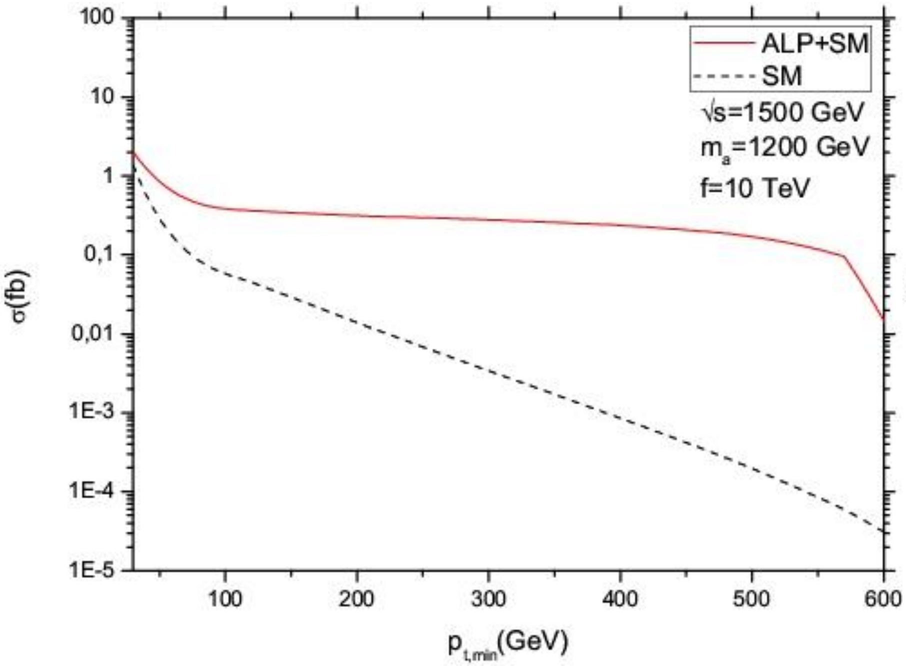
$$M_{\mathrm{ew}} = M^f + M^W$$

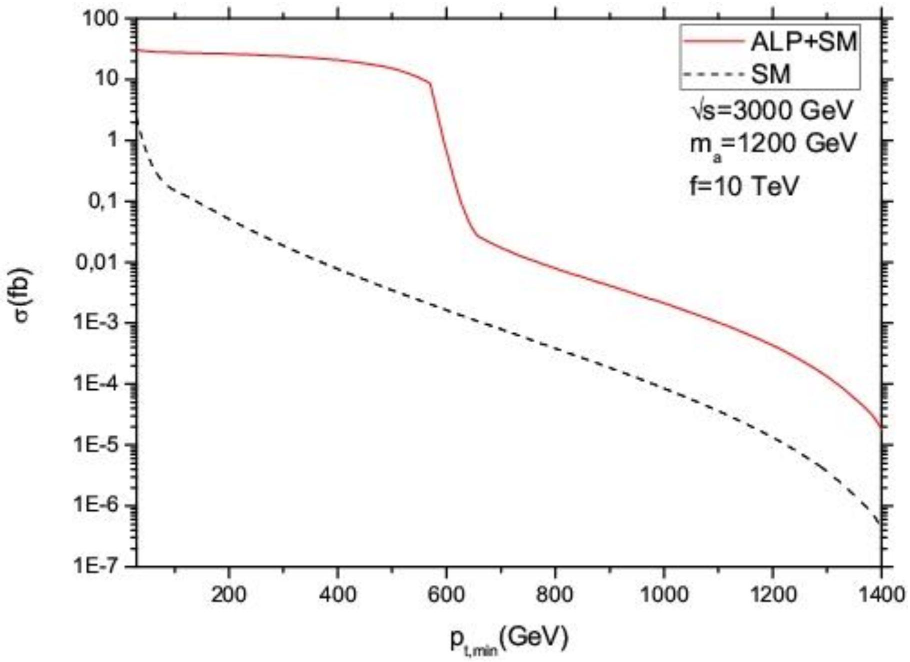
Total ALP width

$$\Gamma_a = \frac{\Gamma(a \to \gamma\gamma)}{\mathrm{Br}(a \to \gamma\gamma)}$$

ALP decay width into two photons

$$\Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi f^2}$$



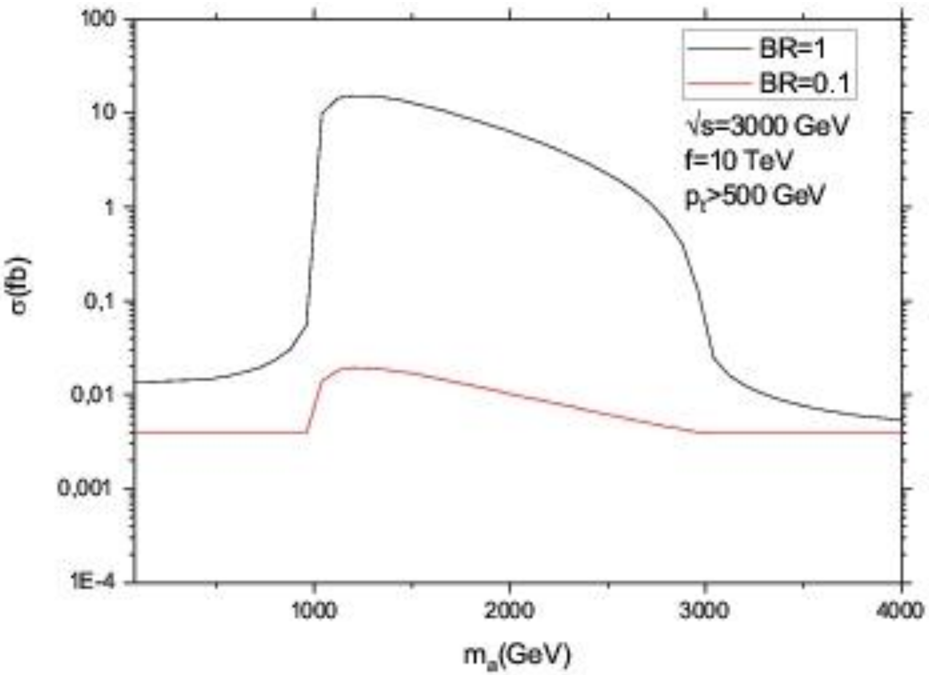


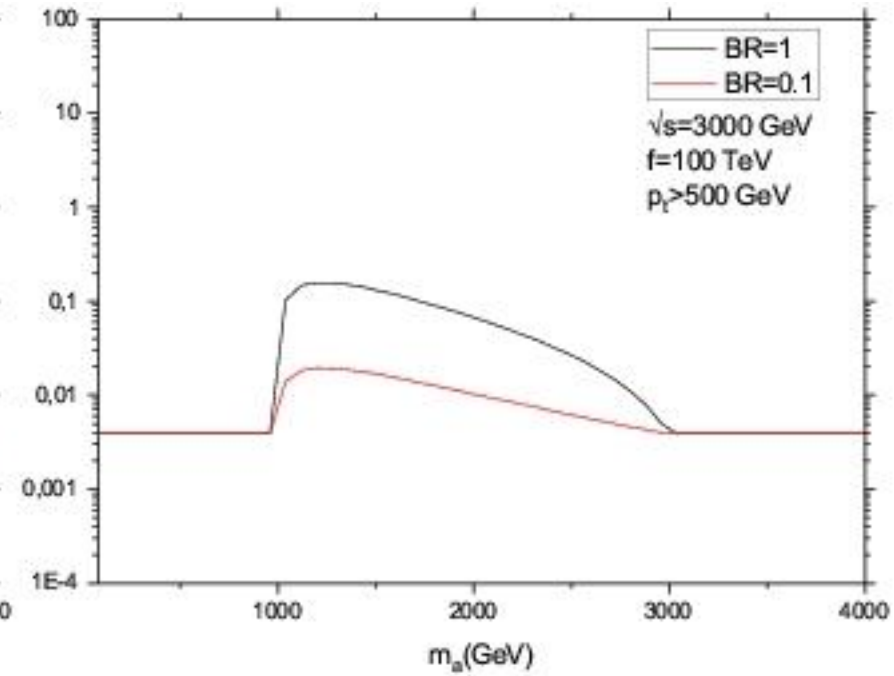
Total cross sections for the process

$e^+e^- \to e^+ \gamma\gamma\, e^- \to e^+\, a\, e^- \to e^+ \gamma\gamma\, e^-$

as functions of transverse momentum cutoff imposed on outgoing photons.

Dashed curve – SM prediction.





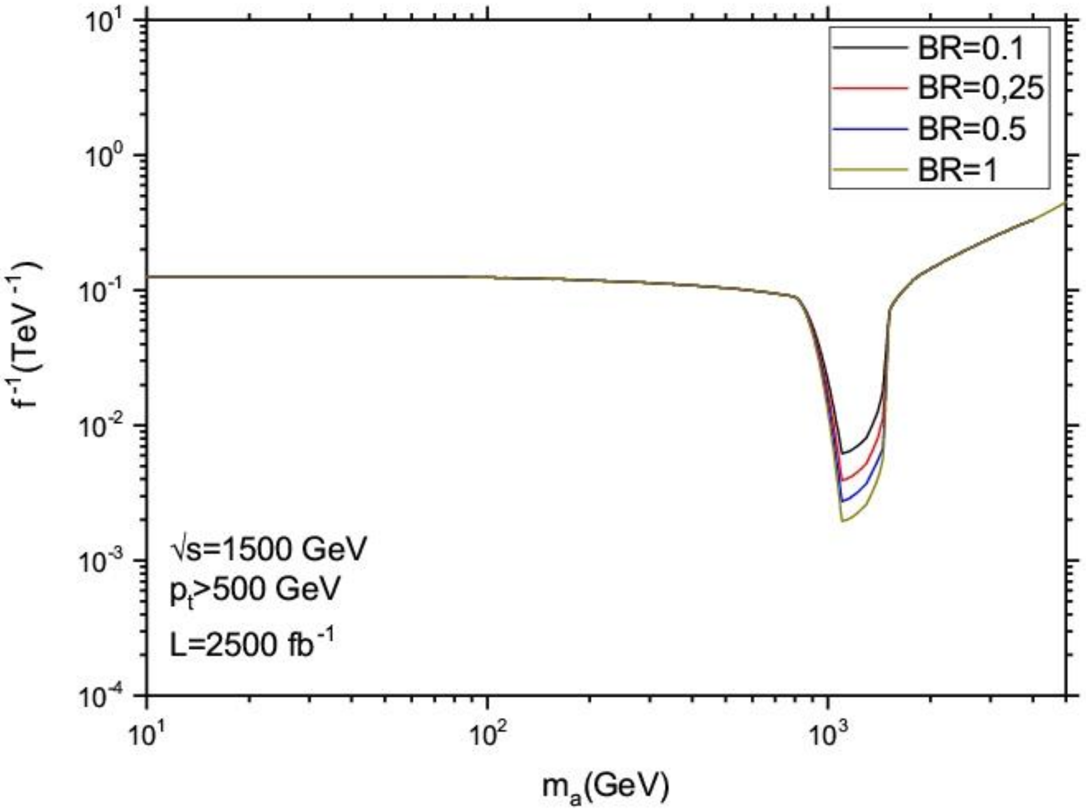
Total cross sections for the process
$e^+e^- \to e^+ \gamma\gamma\, e^- \to e^+ a\, e^- \to e^+ \gamma\gamma\, e^-$
as functions of ALP mass for two values
of ALP coupling f and Br($a \to \gamma\gamma$)

Total cross section dependence seen in mass region m_a = 1000-2500 GeV

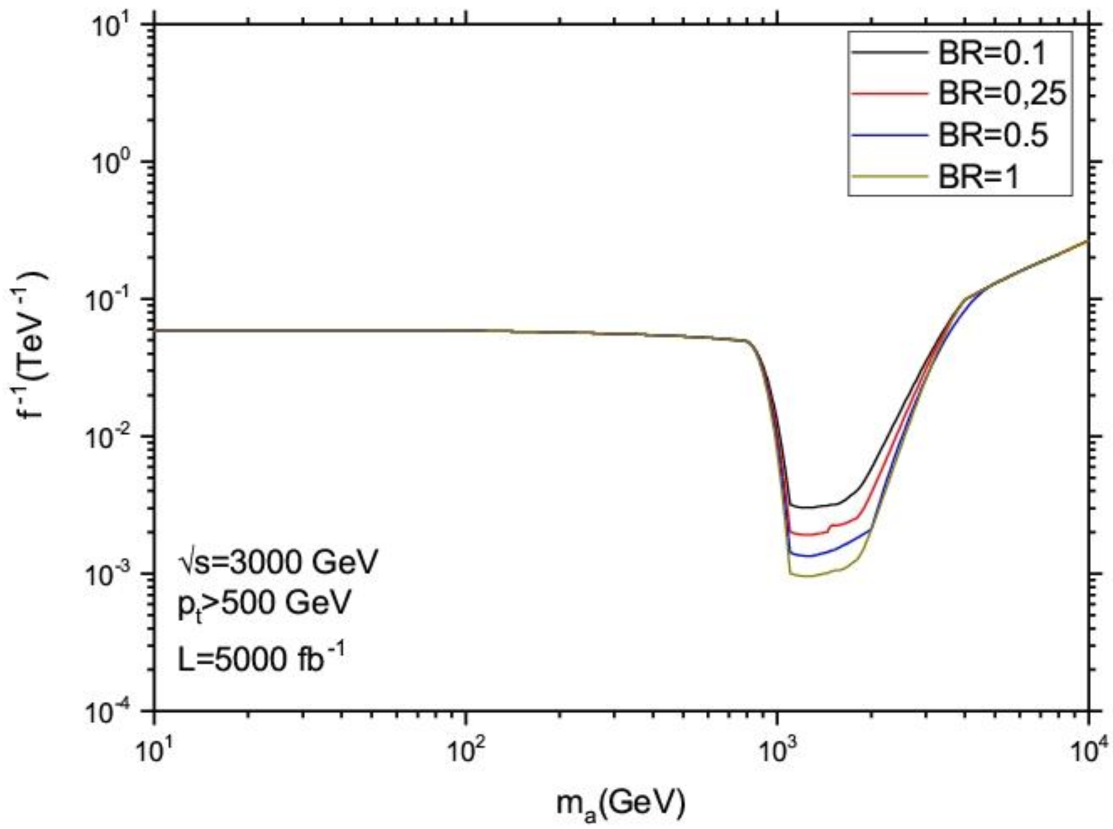
$$\sigma \sim \frac{1}{f^2}\,\mathrm{Br}(\gamma\gamma \to \mathrm{a})$$

Expectation from simple dimensional arguments

$$\sigma \approx \frac{1}{f^4}$$

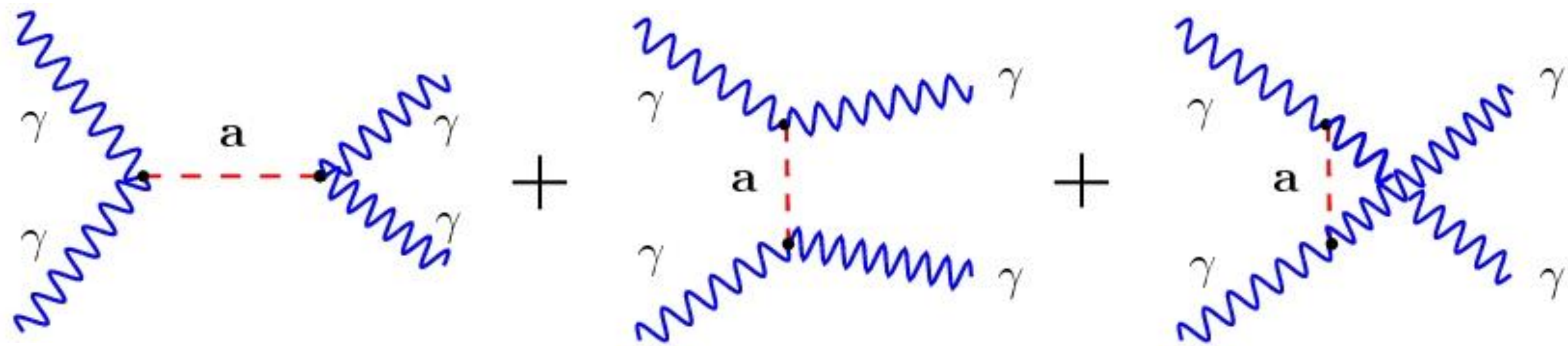


The 95% C.L. CLIC exclusion region for energy $\sqrt{s}$ = 1500 GeV, transverse momentum cut on final photons p_t = 500 GeV, Integrated luminosity L = 2500 fb^{-1}, and different Br($a \rightarrow \gamma\gamma$)

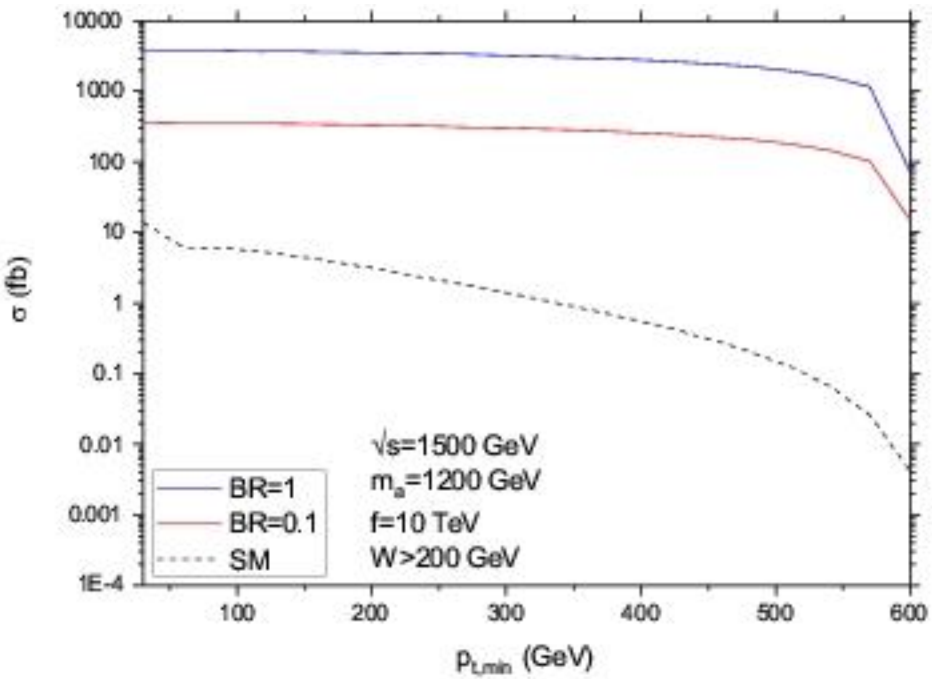


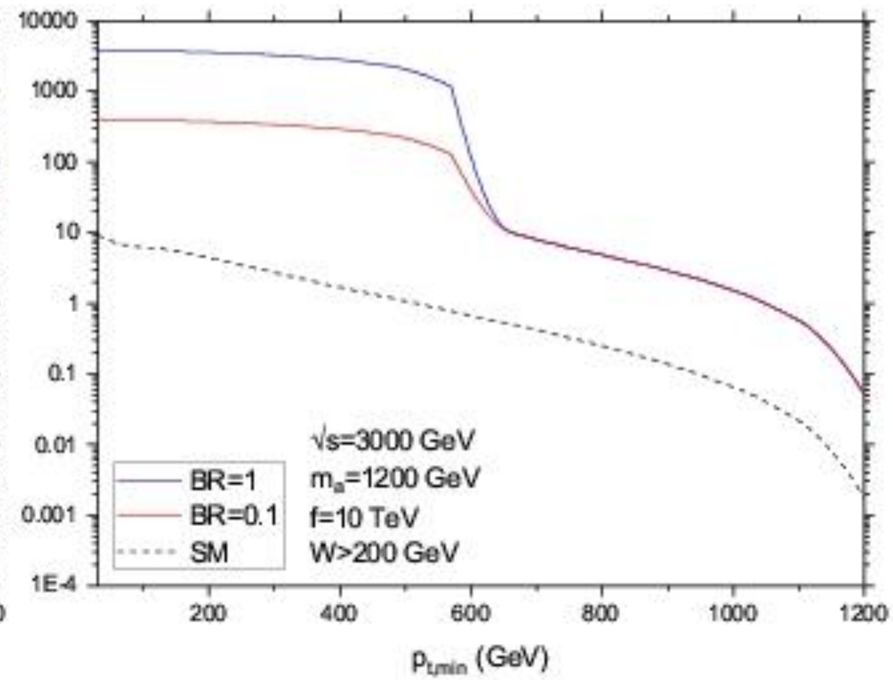
The same as in a previous figure, but for $\sqrt{s}$ = 3000 GeV and L = 5000 fb^{-1}

Photon-induced diphoton production at the CLIC (γγ mode)

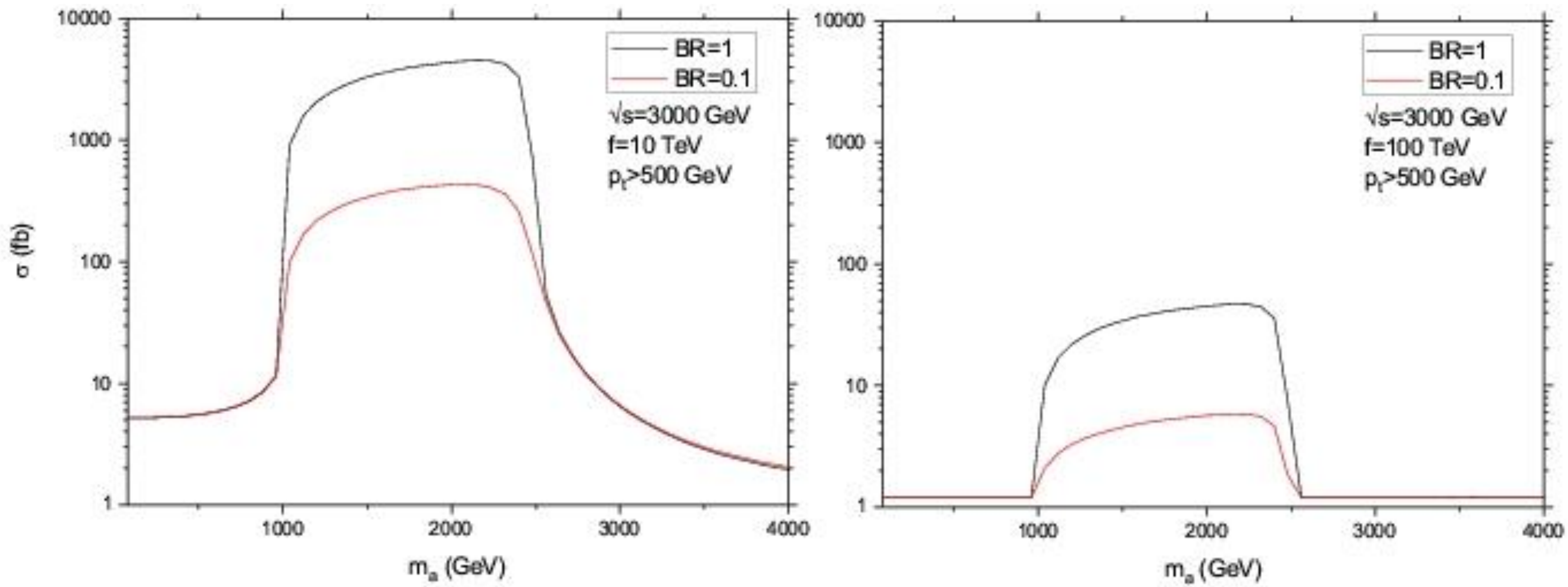


Diagrams for collision of Compton backscattered (CB) photons, $\gamma\gamma \to \gamma\gamma$, mediated by ALP a

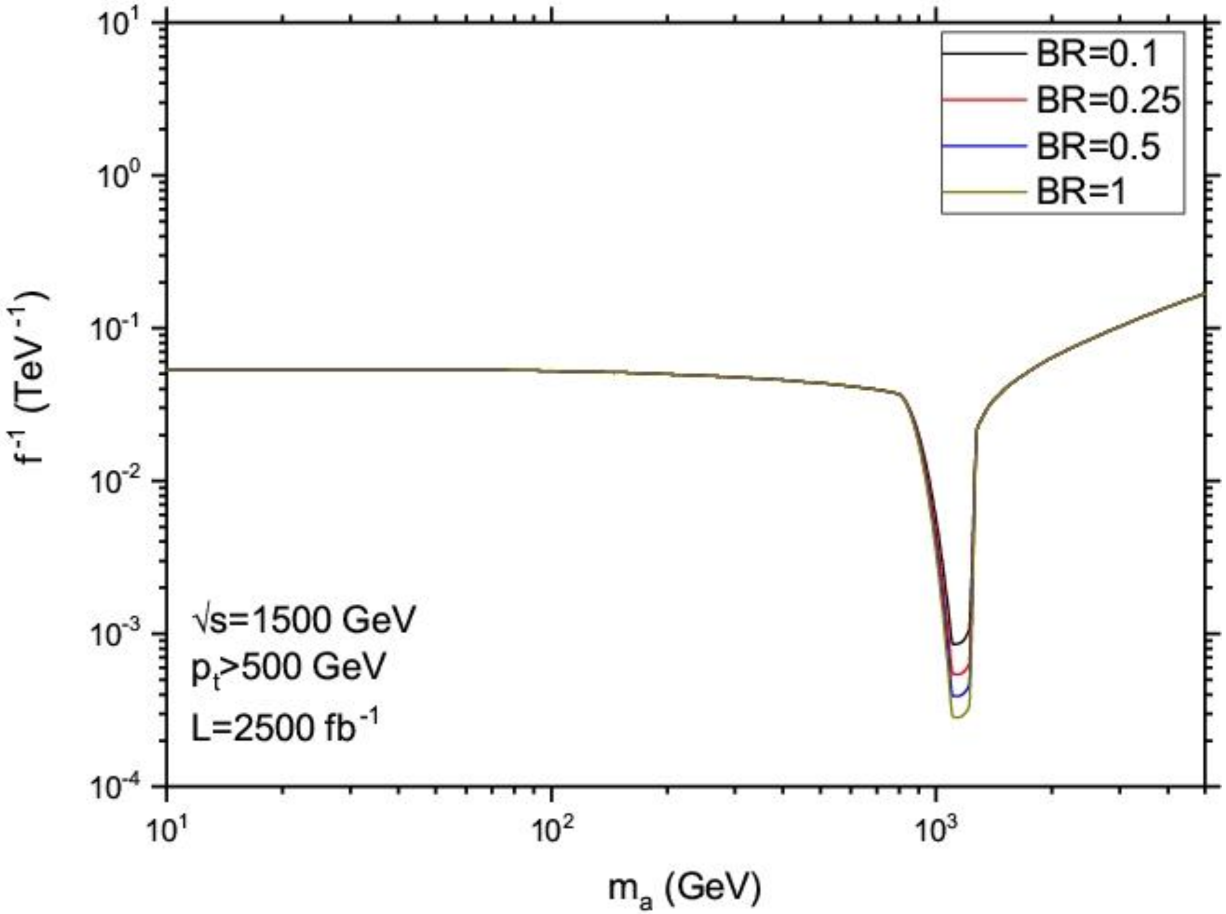




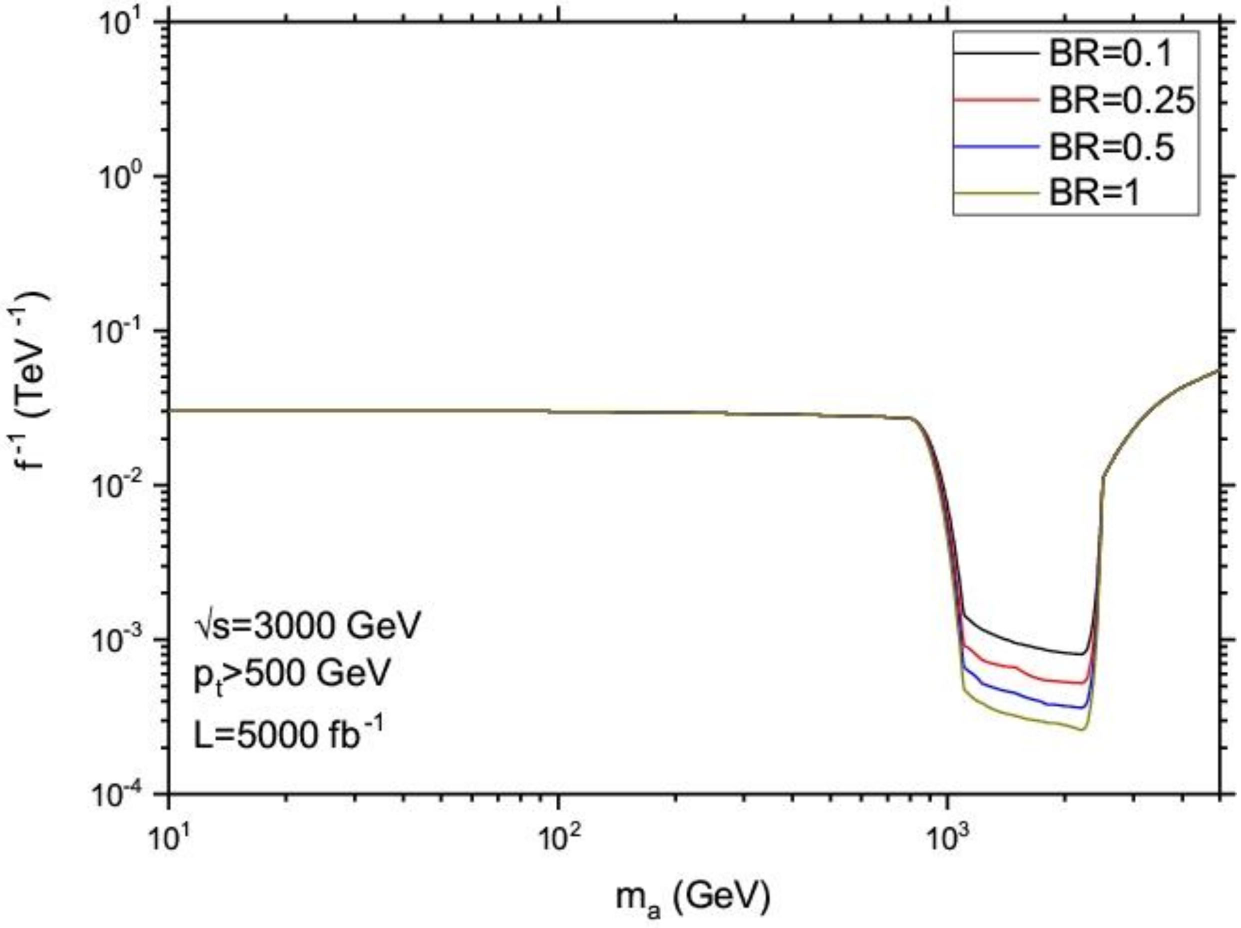
Total cross sections for the process γγ → γγ as functions of transverse momentum cutoff imposed on outgoing photons



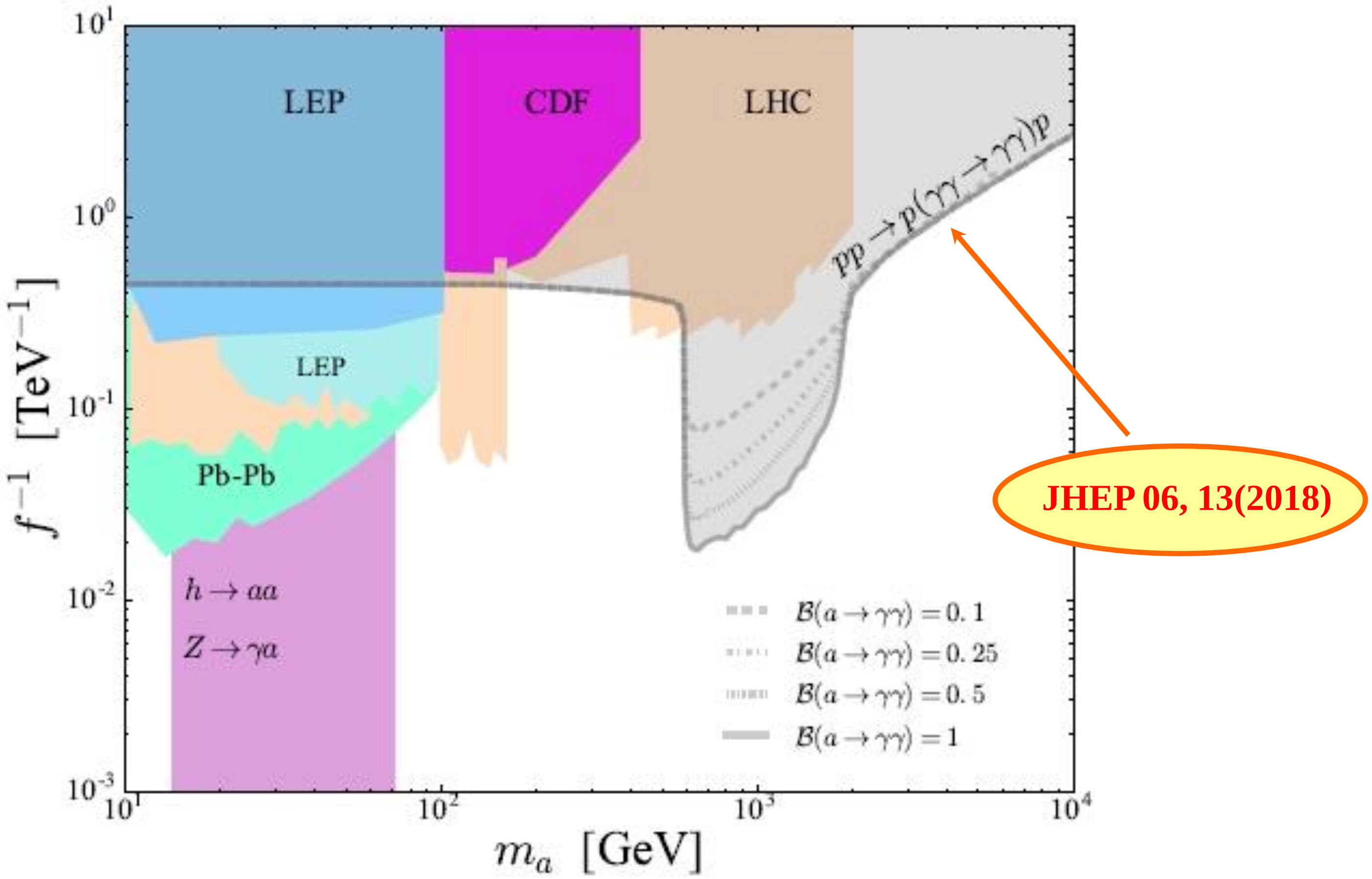
Total cross sections for the process γγ→ γγ as functions of ALP mass m_a for two values of ALP coupling f and Br(a→γγ)



The 95% C.L. CLIC exclusion regions for energy $\sqrt{s}$ = 1500 GeV, cut $m_{\gamma\gamma}$ > 200 GeV on photon invariant mass, Integrated luminosity L = 2500 fb^{-1}, and different Br($a \rightarrow \gamma\gamma$)



The same as in a previous figure,
but for $\sqrt{s}$ = 3000 GeV and L = 5000 fb^{-1}



The 95% C.L. current exclusion regions for different values of Br(a→γγ)

PART II
(polarized scattering)

Compton backscattered photons

CLIC: not only e^+e^- scattering, but also γe and $\gamma\gamma$ collisions with real photons

Photon beams are given by Compton backscattering of laser photons off linear electron beams

SM backgrounds may be reduced by a factor of 2-3, if electron beams has a polarization of 80%

λ_0 – helicity of laser photon beam
λ_e – helicity of initial electron beam

Helicities of photon and electron beams

$$(\lambda_0^{(1)}, \lambda_e^{(1)}; \lambda_0^{(2)}, \lambda_e^{(2)}) = (1, -0.8; 1, -0.8)$$
$$(\lambda_0^{(1)}, \lambda_e^{(1)}; \lambda_0^{(2)}, \lambda_e^{(2)}) = (1, +0.8; 1, +0.8)$$

CLIC energy stages and integrated luminosities

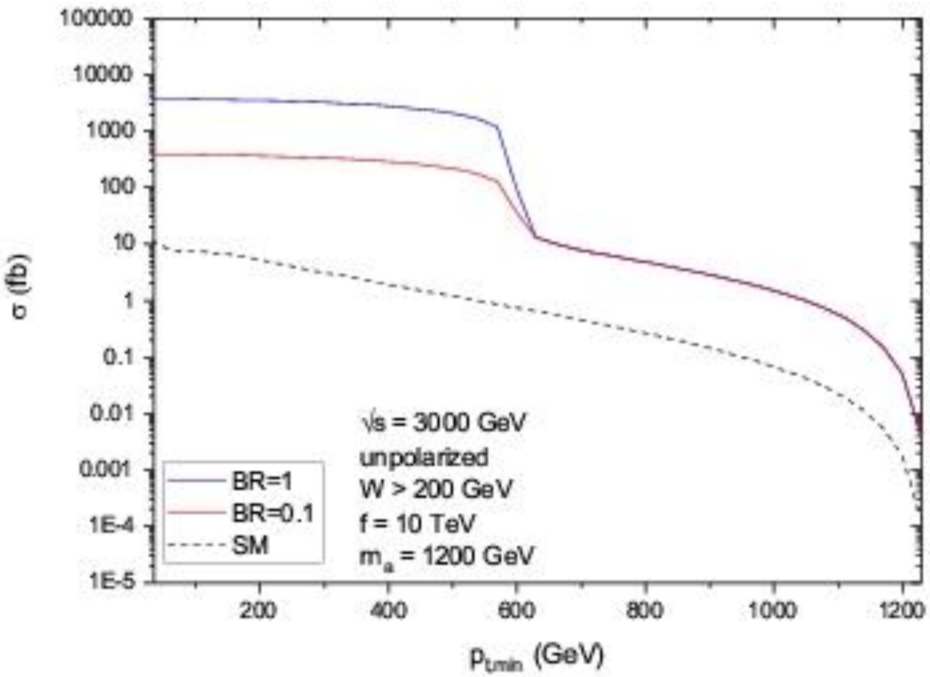
		Unpolarized	$\lambda_e = -0.8$	$\lambda_e = +0.8$
Stage	$\sqrt{s}$, GeV	$\mathcal{L}$, fb^{-1}	$\mathcal{L}$, fb^{-1}	$\mathcal{L}$, fb^{-1}
1	380	1000	500	500
2	1500	2500	2000	500
3	3000	5000	4000	1000

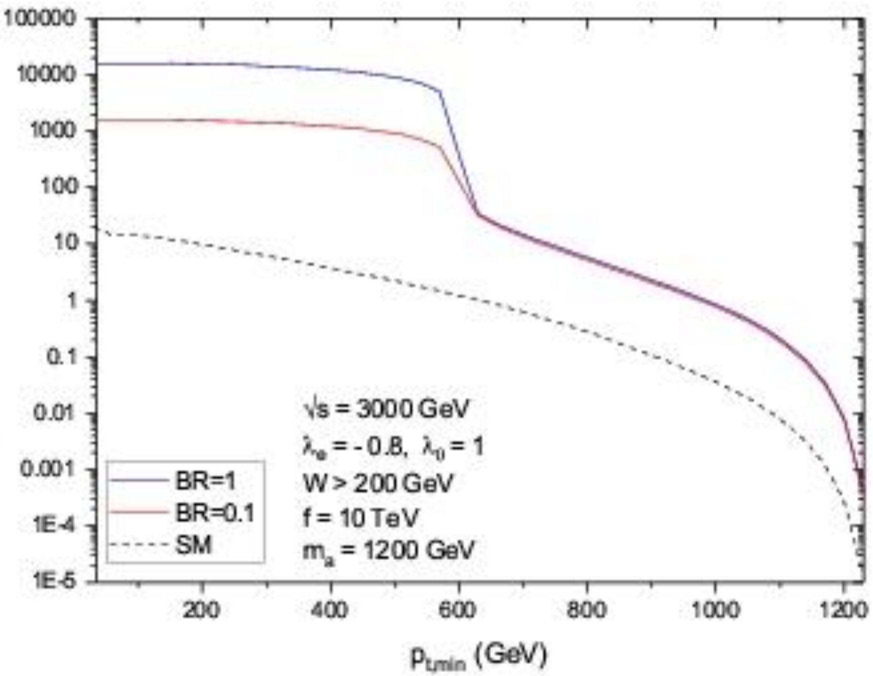
Differential cross section of diphoton production with initial polarized CB photons (summation over helicities of final photons)

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{128\pi s} \int\limits_{x_{1\,\min}}^{0.83} \frac{dx_1}{x_1} f_{\gamma/e}(x_1) \int\limits_{x_{2\,\min}}^{0.83} \frac{dx_2}{x_2} f_{\gamma/e}(x_2)$$
$$\times \left\{ \left[1 + \xi\left(E_\gamma^{(1)}, \lambda_0^{(1)}\right) \xi\left(E_\gamma^{(2)}, \lambda_0^{(2)}\right)\right] |M_{++}|^2 + \left[1 - \xi\left(E_\gamma^{(1)}, \lambda_0^{(1)}\right) \xi\left(E_\gamma^{(2)}, \lambda_0^{(2)}\right)\right] |M_{+-}|^2 \right\}$$

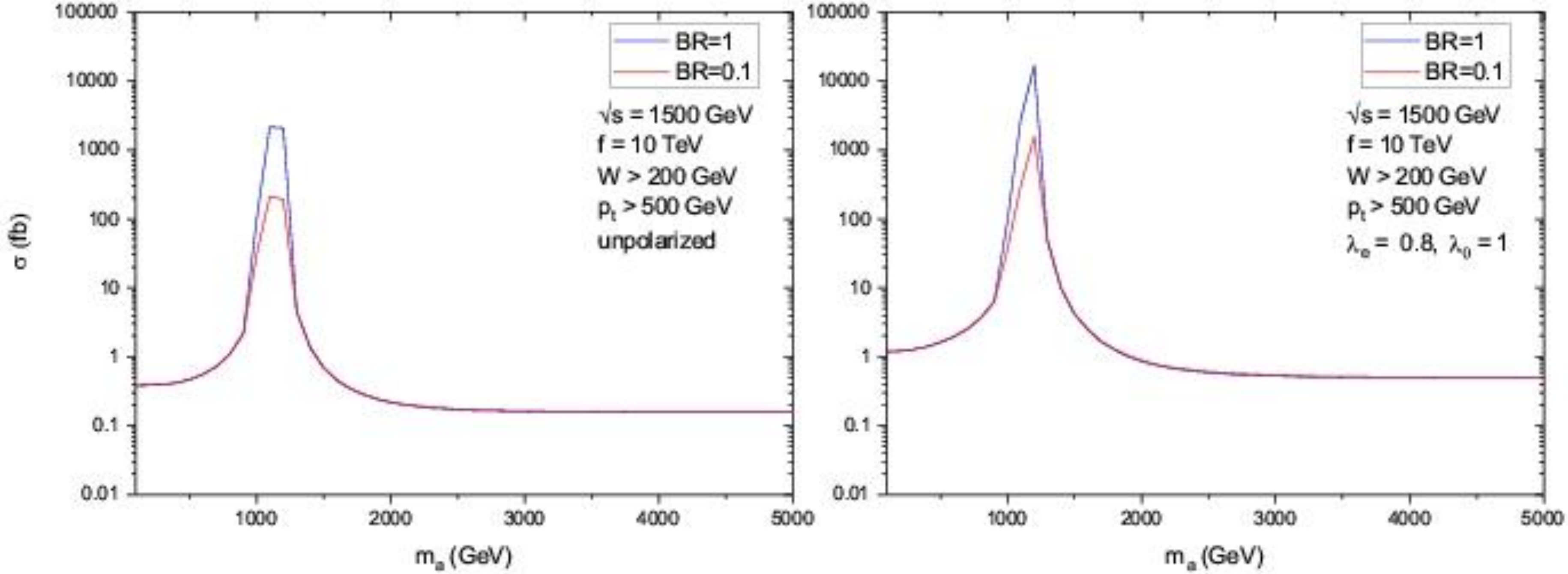
ξ – helicities of CB photons

$$|M_{++}|^2 = |M_{++++}|^2 + |M_{++--}|^2$$
$$|M_{+-}|^2 = |M_{+-+-}|^2 + |M_{+--+}|^2$$

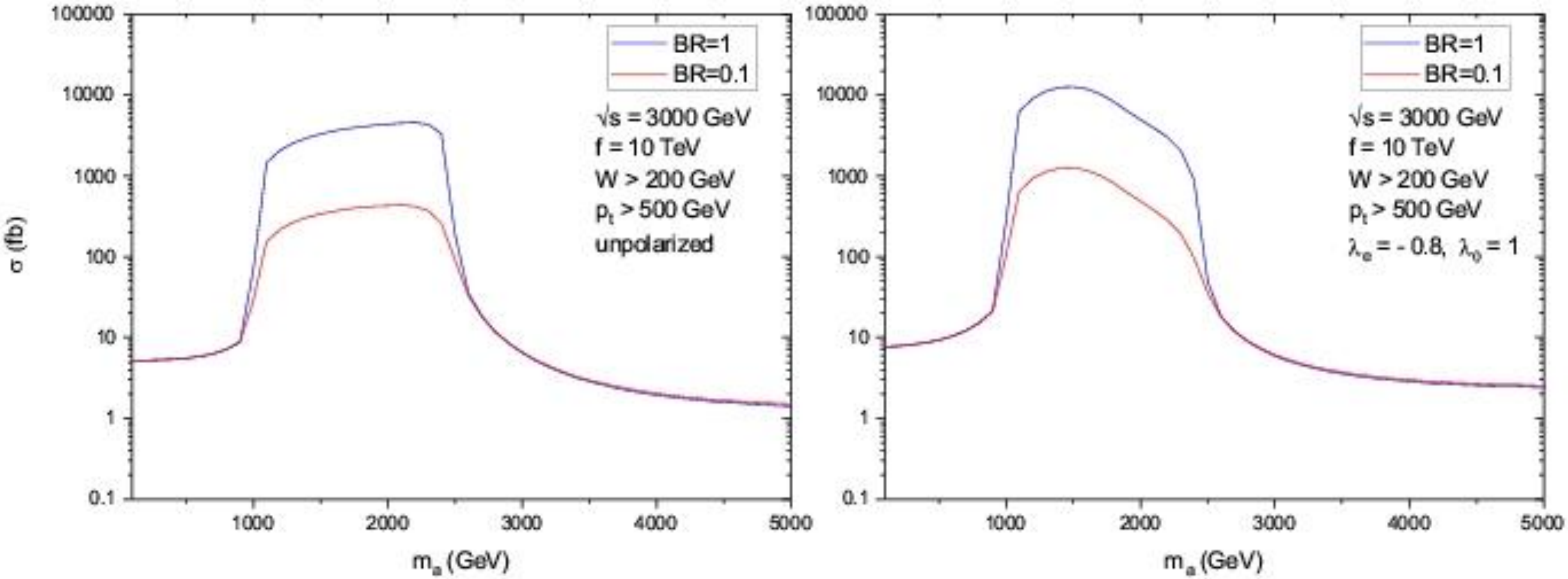




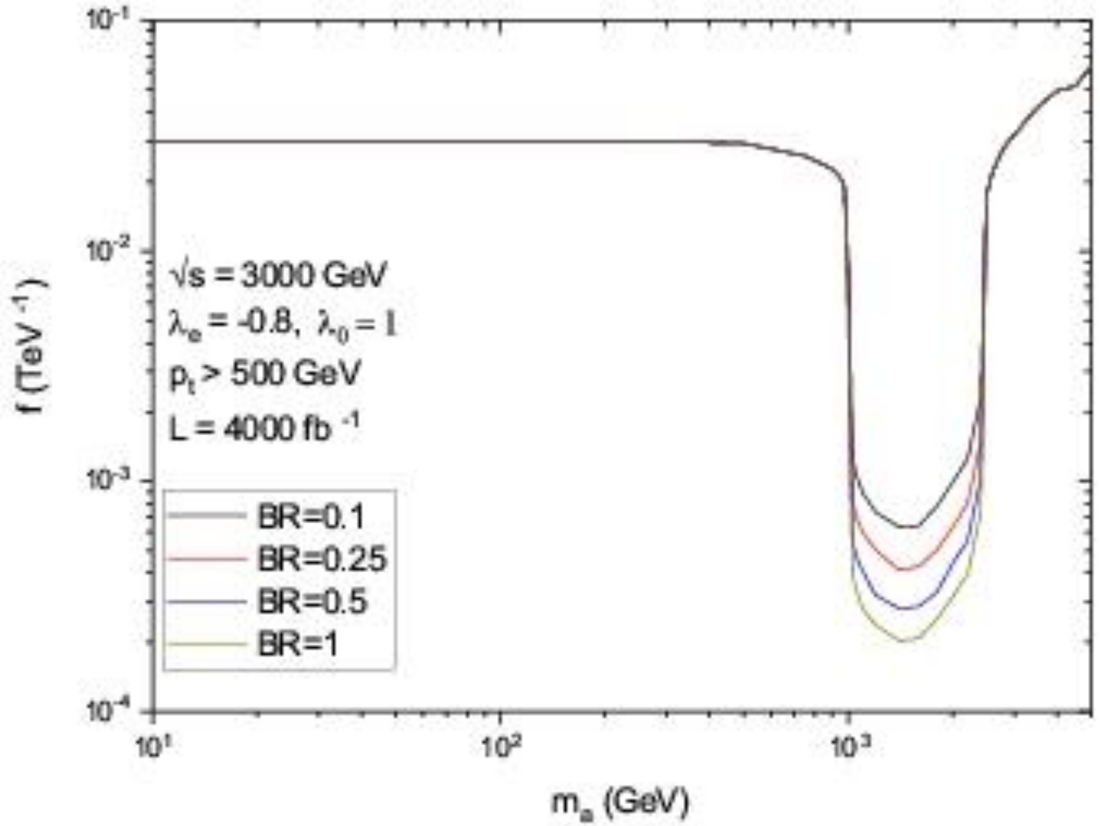
Total cross sections for the process $\gamma\gamma \to \gamma\gamma$ as functions of transverse momentum cutoff imposed on final photons for $\sqrt{s}$ = 3000 GeV. Left panel: $\lambda_e = 0$. Right panel: $\lambda_e = -0.8$.



Total cross sections for the process γγ→ γγ with CB initial photons as functions of ALP mass m_a for √s = 1500 GeV and f = 10 TeV. Left panel: unpolarized case. Right panel: λ_e = +0.8.



Total cross sections for the process $\gamma\gamma \to \gamma\gamma$ with CB initial photons as functions of ALP mass m_a for $\sqrt{s}$ = 3000 GeV and f = 10 TeV. Left panel: unpolarized case. Right panel: $\lambda_e = -0.8$.



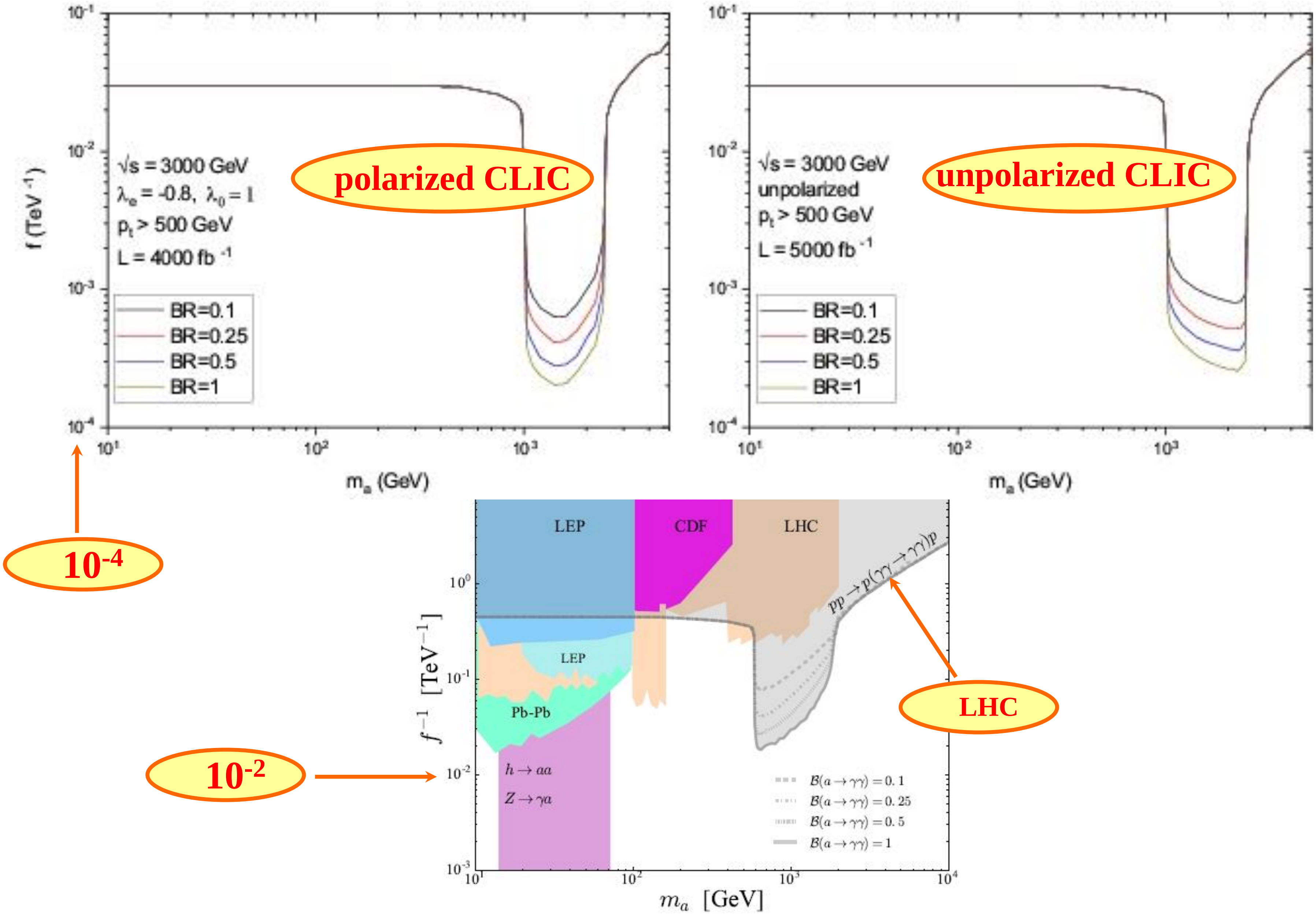
The 95% C.L. CLIC exclusion regions for the process $\gamma\gamma \rightarrow \gamma\gamma$ with CB ingoing photons. Invariant energy is $\sqrt{s}$ = 3000 GeV, electron beam helicity $\lambda_e = -0.8$, and integrated luminosity L = 4000 fb^{-1}.

Заключение

- Рассмотрено фотон-фотонное рассеяние на лептонном коллайдере CLIC, индуцированное аксионо-подобными частицами (ALPs).
- Изучено неполяризованное рассеяние в моде e^+e^- и γγ-моде с комптоновскими фотонами.
- Рассмотрен случай начальных поляризованных реальных фотонов (в γγ-моде).
- Вычислены полные сечения в зависимости от энергии столкновения и поперечного импульса конечных фотонов, а также от массы ALP и её константы связи с фотонами.

Заключение (продолжение)

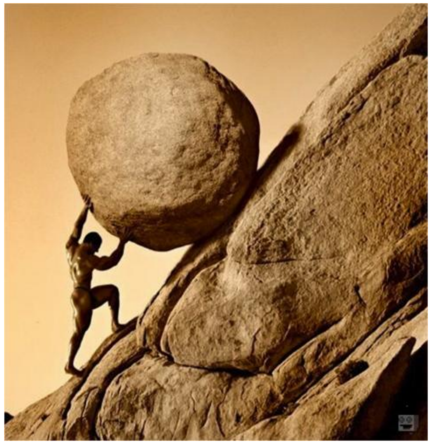
- С достоверностью 95% найдены ограничения на параметры ALP. Результаты представлены в виде кривых на плоскости (f, m_a).
- Показано, что в случае поляризованного рассеяния ограничения оказываются в 1.5 раза сильнее, чем для неполяризованного случая, в области m_a = 1-2 TeV.
- При этом они намного более сильные (на 1-2 порядка), нежели ограничения, которые могут быть достигнуты в фотон-фотонном рассеянии на LHC.

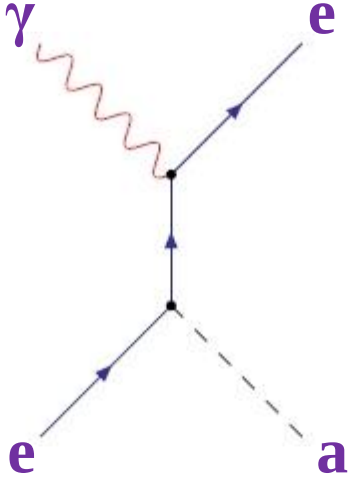


polarized CLIC
unpolarized CLIC
√s = 3000 GeV
λe = -0.8, λ0 = 1
pt > 500 GeV
L = 4000 fb -1
unpolarized
L = 5000 fb -1
BR=0.1
BR=0.25
BR=0.5
BR=1
f (TeV -1)
ma (GeV)
10-4
10-2
LHC
LEP
CDF
Pb-Pb
h → aa
Z → γa
pp → p(γγ → γγ)p
B(a → γγ) = 0.1
B(a → γγ) = 0.25
B(a → γγ) = 0.5
B(a → γγ) = 1
f-1 [TeV-1]
ma [GeV]

ПРЕДМЕТ ДАЛЬНЕЙШЕЙ РАБОТЫ

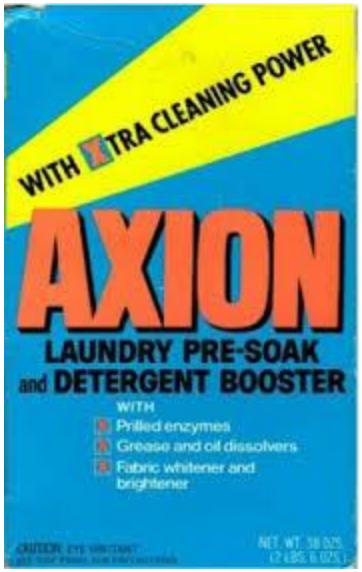
Изучение рождения аксионо-подобных частиц на коллайдере CLIC в γ-e моде в процессе $\gamma + e \rightarrow e + a$



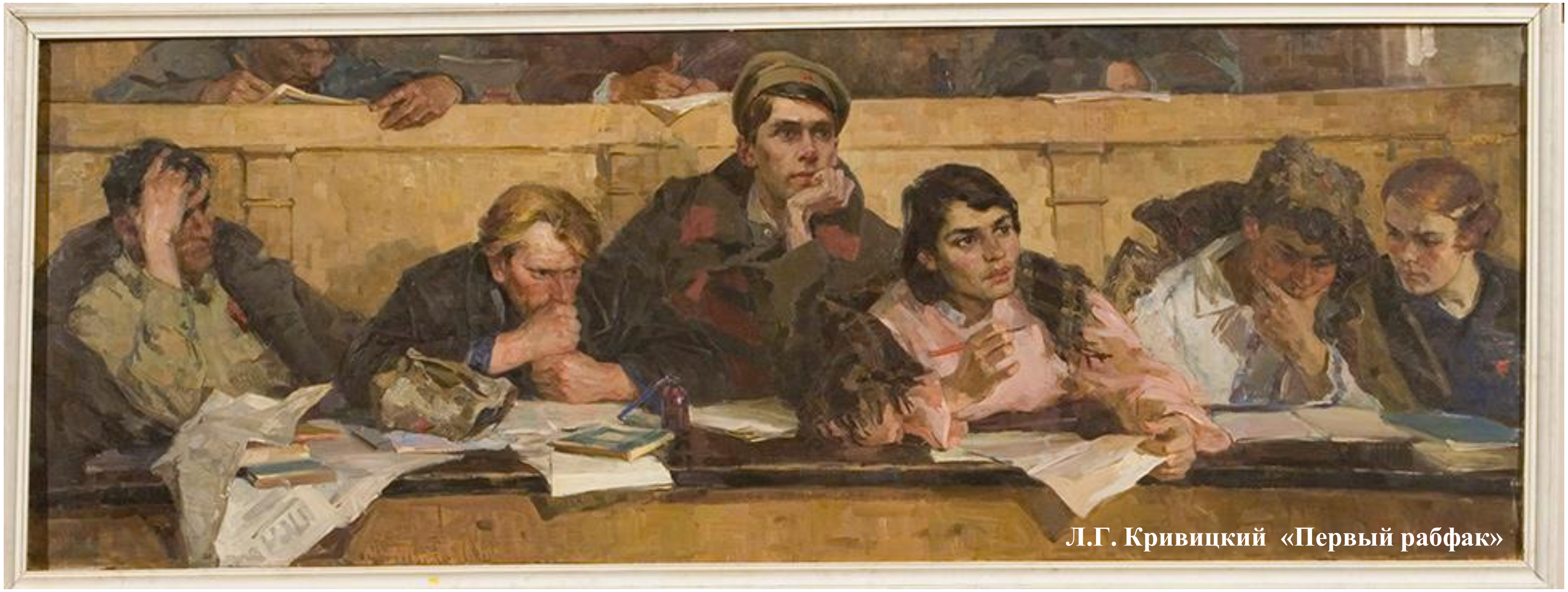


...axions. (I named them after a laundry detergent, since they clean up a problem with an axial current.)

F. Wilczek. Nobel lecture: Asymptotic freedom: from paradox to paradigm. Proceedings of the National Academy of Sciences of the United States of America. v. 102, pp. 8403-8413, 2005.



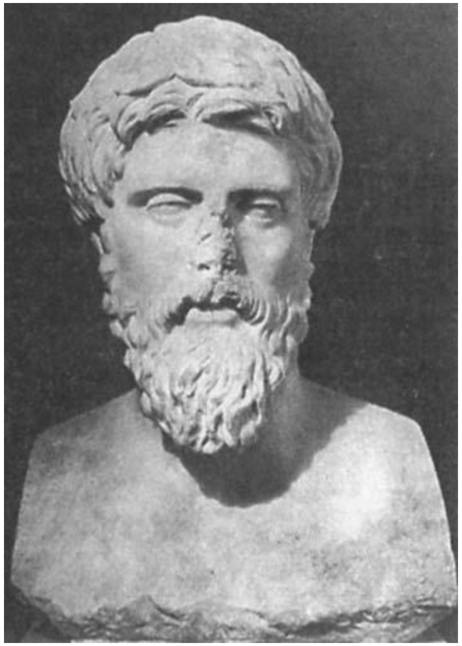
Спасибо за внимание!



Л.Г. Кривицкий «Первый рабфак»

Есть три способа отвечать на вопросы: сказать необходимое, отвечать с приветливостью и наговорить лишнего

(Πλούταρχος)



Back-up slides

$U(1)_{PQ}$ symmetry is broken due to axion's anomalous triangle coupling to gluons

$$\mathcal{L} = \left(\frac{\phi_A}{f_A} - \bar{\Theta}\right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}^a_{\mu\nu}$$

where φ_A is the axion field and f_A the axion decay constant.

Non-perturbative fluctuations of the gluon fields induce a potential for φ_A whose minimum is $\varphi_A = \theta f_A$, thereby cancelling the θ term in the QCD Lagrangian and thus restoring CP symmetry.

PQ mechanism

$$U_A(1) \xrightarrow{f_a e^{\frac{ia(x)}{f_a}}} \mathbb{I} \qquad J^\mu_{\mathrm{PQ}} = \frac{1}{f_a}\partial_\mu a + \ldots$$

$$\partial_\mu J^\mu_{\mathrm{PQ}} = \xi \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad \text{(colour anomaly)}$$

$$\Box a = \frac{\xi}{f_a} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \ldots$$

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu a)^2 + \frac{\xi}{f_a} \frac{\alpha_s}{8\pi} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \bar{\theta} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\boxed{\langle a \rangle = -\frac{f_a}{\xi}\bar{\theta}, \quad [\langle G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \rangle \neq 0]}$$

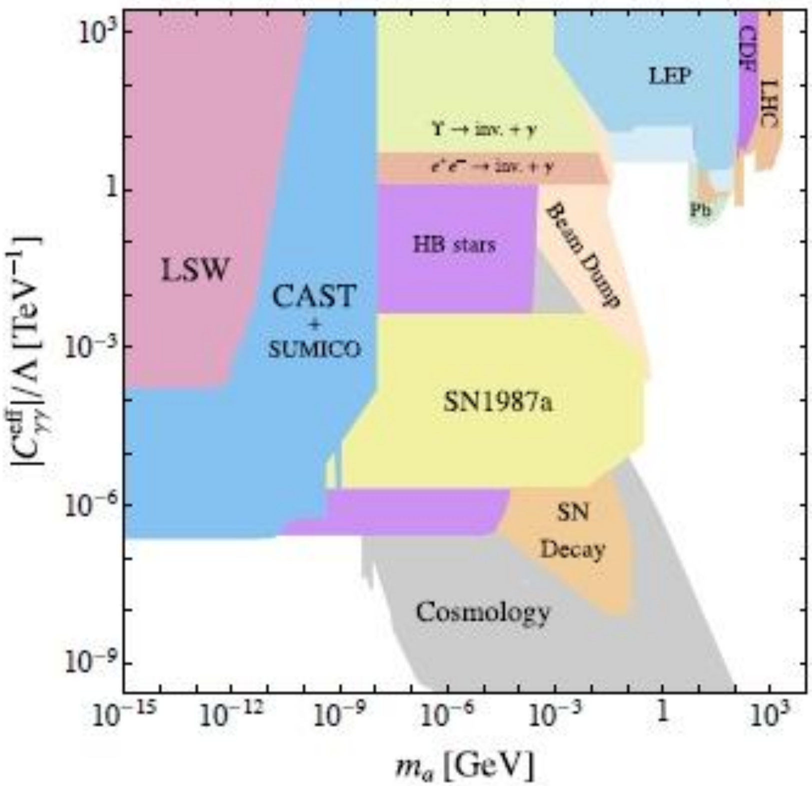
$\bar{\theta}$ is cancelled out in the vacuum!

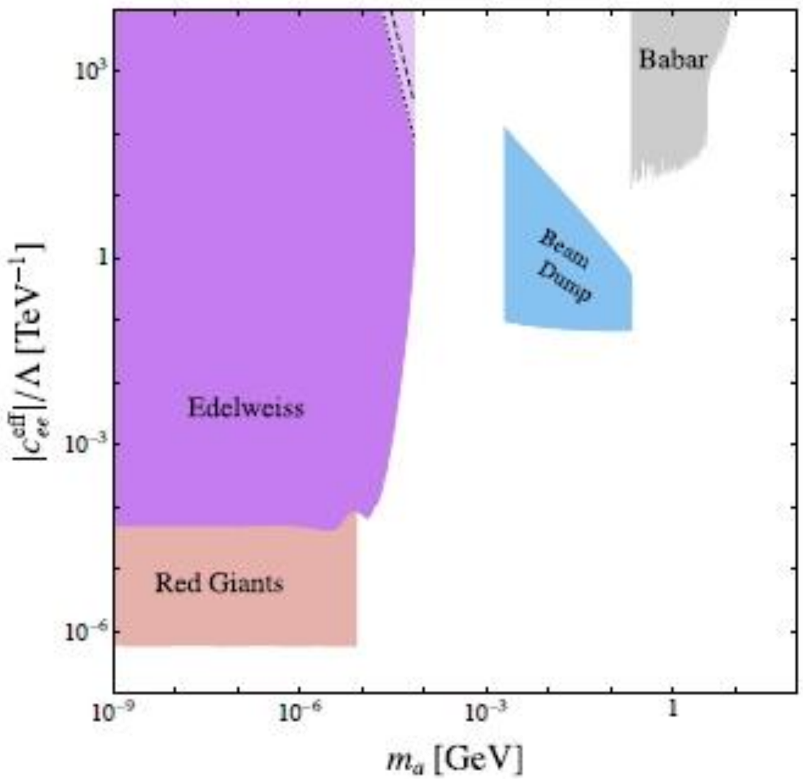
String theory: spin-zero particle must couple to photon field. It implies an existence of P-odd term in Lagrangian

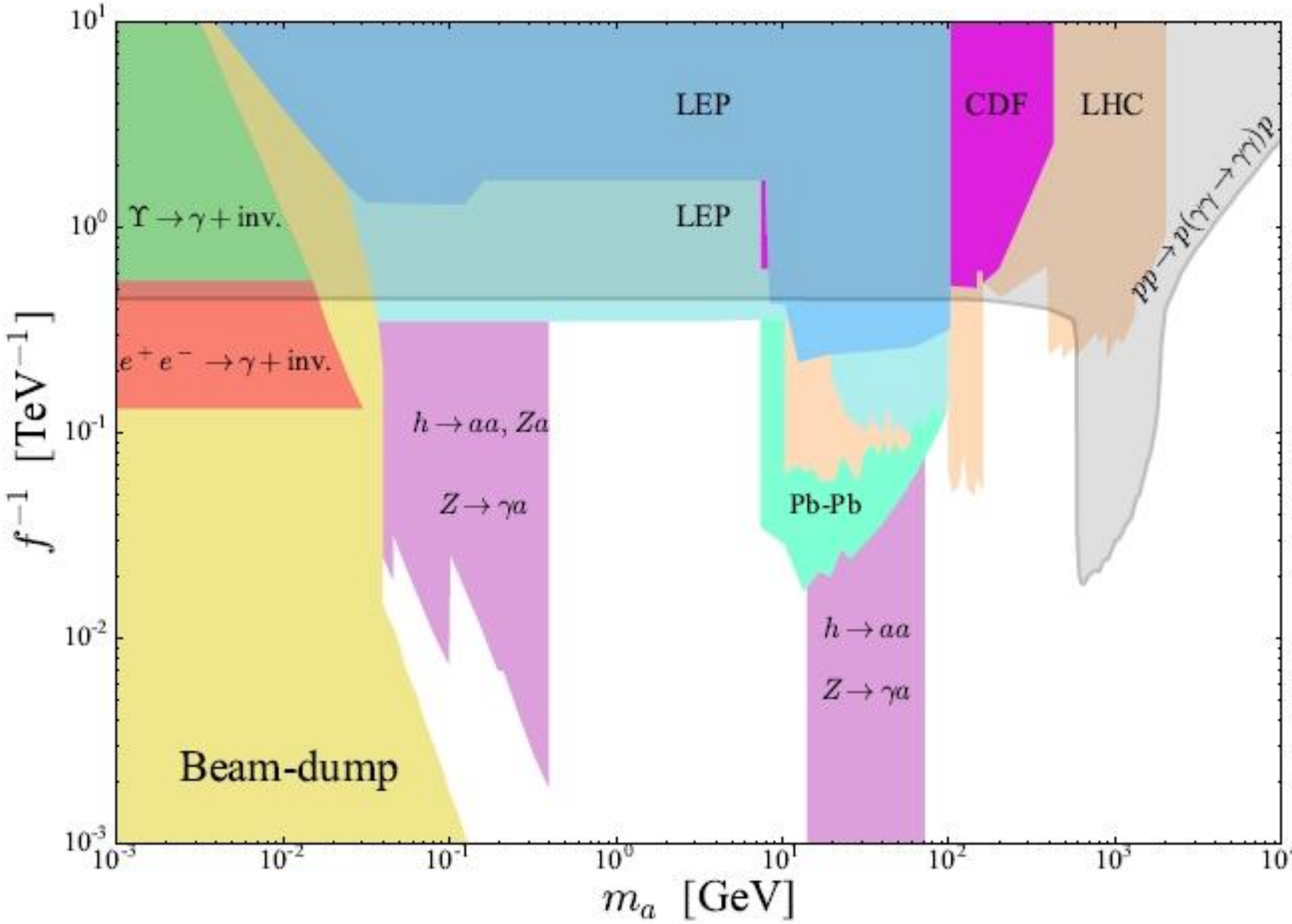
$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E}\vec{B}$$

where a denotes axion or ALP

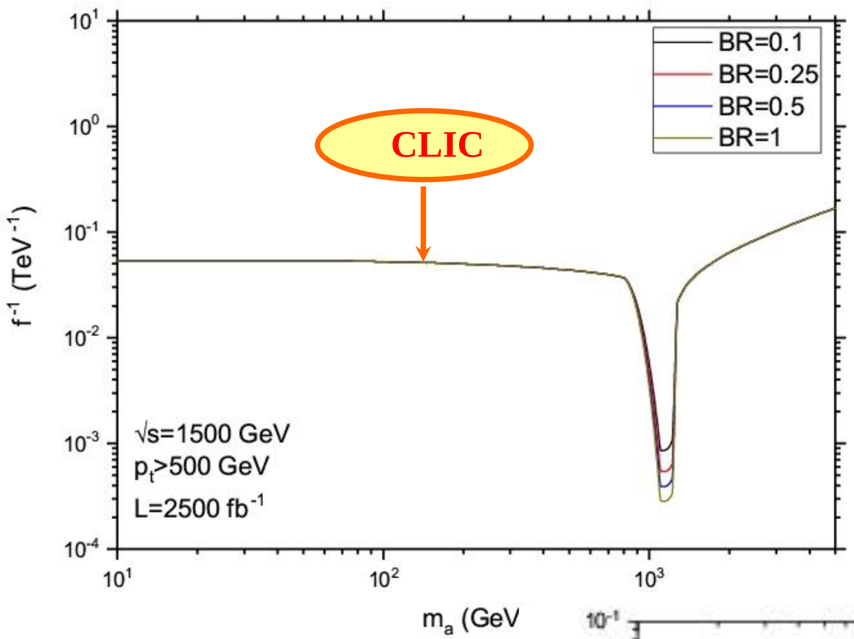
$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2 a^2 + \frac{a}{f_a^{(-)}} F_{\mu\nu} F^{\mu\nu} + \frac{a}{f_a^{(+)}} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

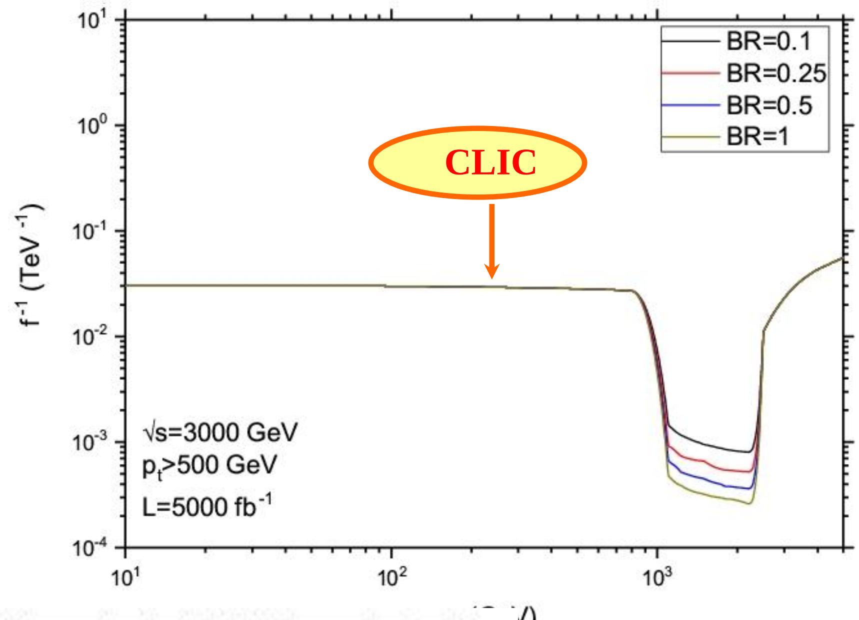

LSW
CAST
+
SUMICO
$\Upsilon \to$ inv. + γ
$e^+e^- \to$ inv. + γ
HB stars
Beam Dump
SN1987a
SN
Decay
Cosmology
LEP
CDF
LHC
Pb
$|C^{\rm eff}_{\gamma\gamma}|/\Lambda$ [TeV^{-1}]
m_a [GeV]

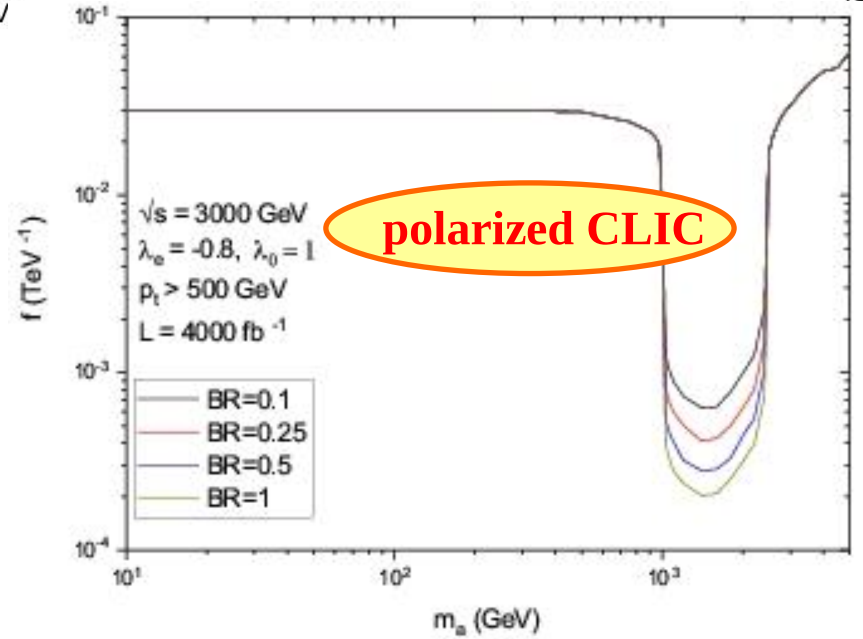

Babar
Beam
Dump
Edelweiss
Red Giants
$|c^{\rm eff}_{ee}|/\Lambda$ [TeV^{-1}]
m_a [GeV]



LEP
CDF
LHC
LEP
$\Upsilon \to \gamma + \text{inv.}$
$e^+e^- \to \gamma + \text{inv.}$
$h \to aa, Za$
$Z \to \gamma a$
Pb-Pb
$pp \to p(\gamma\gamma \to \gamma\gamma)p$
$h \to aa$
$Z \to \gamma a$
Beam-dump
f^{-1} [TeV^{-1}]
m_a [GeV]


CLIC
BR=0.1
BR=0.25
BR=0.5
BR=1
√s=1500 GeV
p_t>500 GeV
L=2500 fb^-1
f^-1 (TeV^-1)
m_a (GeV


CLIC
BR=0.1
BR=0.25
BR=0.5
BR=1
√s=3000 GeV
p_t>500 GeV
L=5000 fb^-1
f^-1 (TeV^-1)


polarized CLIC
√s = 3000 GeV
λ_e = -0.8, λ_0 = 1
p_t > 500 GeV
L = 4000 fb^-1
BR=0.1
BR=0.25
BR=0.5
BR=1
f (TeV^-1)
m_a (GeV)

Национальной науки нет, как нет национальной таблицы умножения; что же национально, то уже не наука.

А.П. Чехов, Записная книжка IV, страница 1, 17