Search for heavy axion-like particles in light-by-light scattering at the FCC-hh

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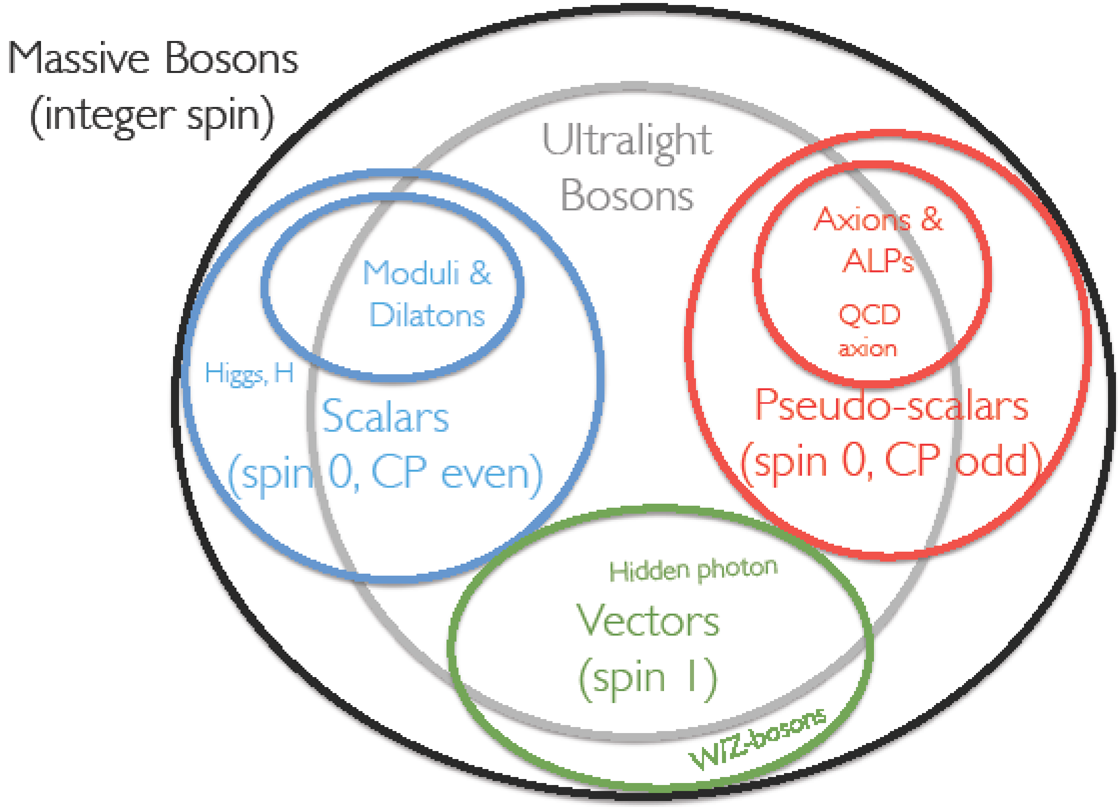
Plan of the talk

- Axion and axion-like particles (ALPs).
- ALPs in light-by-light (LbL) process in p-p, p-Pb and Pb-Pb collisions at the FCC-hh.
- Bounds on ALP-photon coupling depending on ALP mass.
- Comparison with current LHC limits.
- Conclusions.



(F.Chadha-Day et al., 2022)

Many extensions of SM predict additional massive bosons, beyond W, Z, and Higgs bosons. They might be scalar, pseudo-scalar, or vector particles. Other proposals include pseudo-scalar ALPs, hidden photons, and scalar particles such as moduli and dilatons.

Strong CP problem and QCD axion

QCD Lagrangian: global symmetry

$$U(3)_V \times U(3)_A = SU(3)_V \times SU(3)_A \times U(1)_V \times U(1)_A$$

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

→ NG massless boson should appear

Absence of NG boson is known as U(1) problem

U(1) problem

→ axial anomaly → θ-vacuum

→ strong CP problem → QCD axion

(R.Peccei & H.Quinn, 1977)

Axion phenomenology:

stellar evolution

axion mediated forces

axion decays

axion-photon conversion

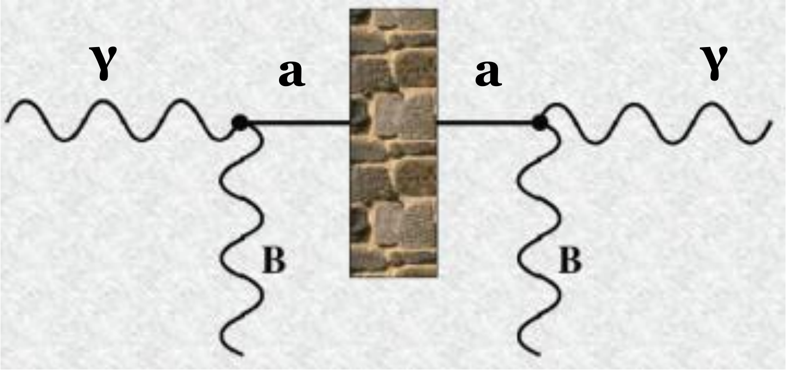
light shining through the wall

solar axions

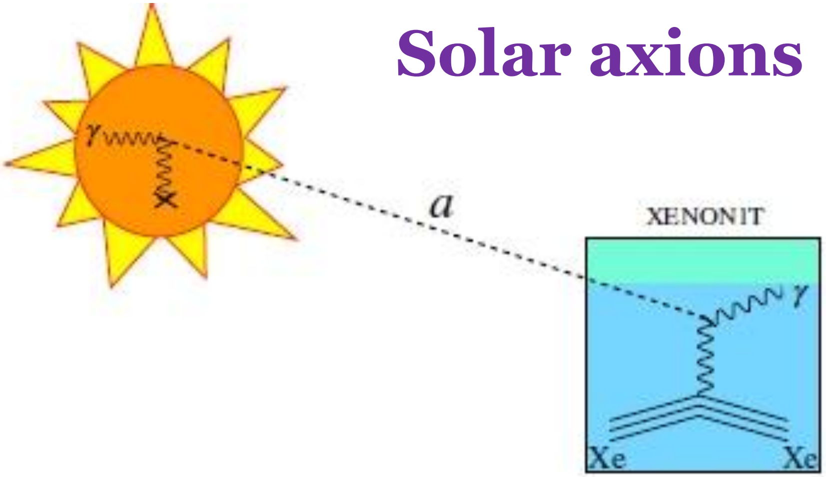
dark matter detection

Axion is a leading DM candidate

Light shining through the wall



Solar axions



Axion-like particles (ALPs)

ALP mass is treated independently of its coupling

As a result, ALPs can be significantly heavier than QCD axions, with masses extending into GeV or even TeV range

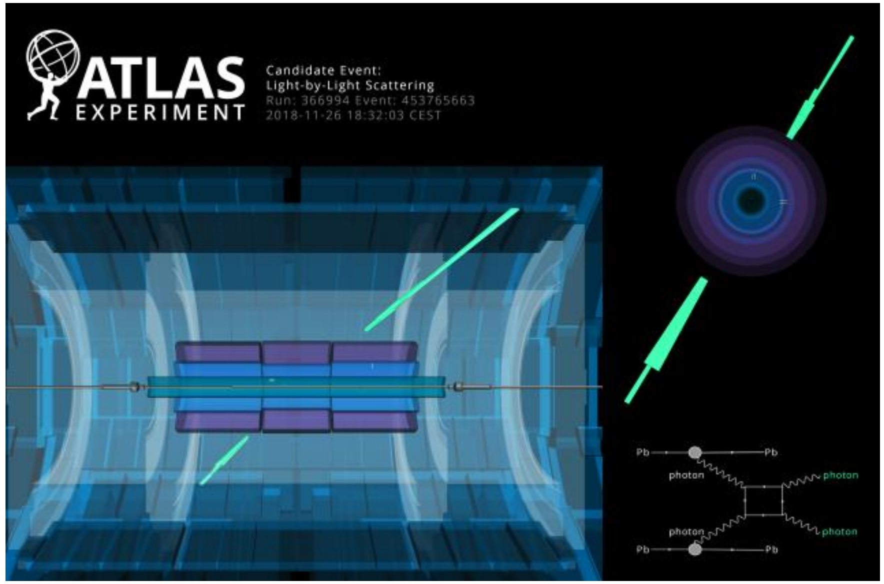
Nonzero coupling to gluons, photons & fermions
→ ALPs may be detected at colliders in γγ-scattering

ALP-photon Lagrangian

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

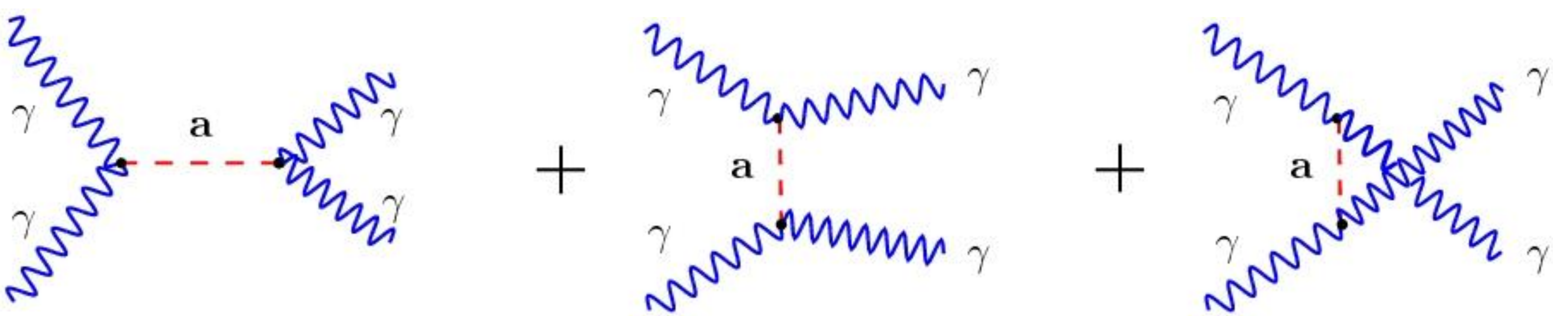
$$\longrightarrow \quad \Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi f_a^2}$$

LbL process in Pb-Pb collisions at the LHC

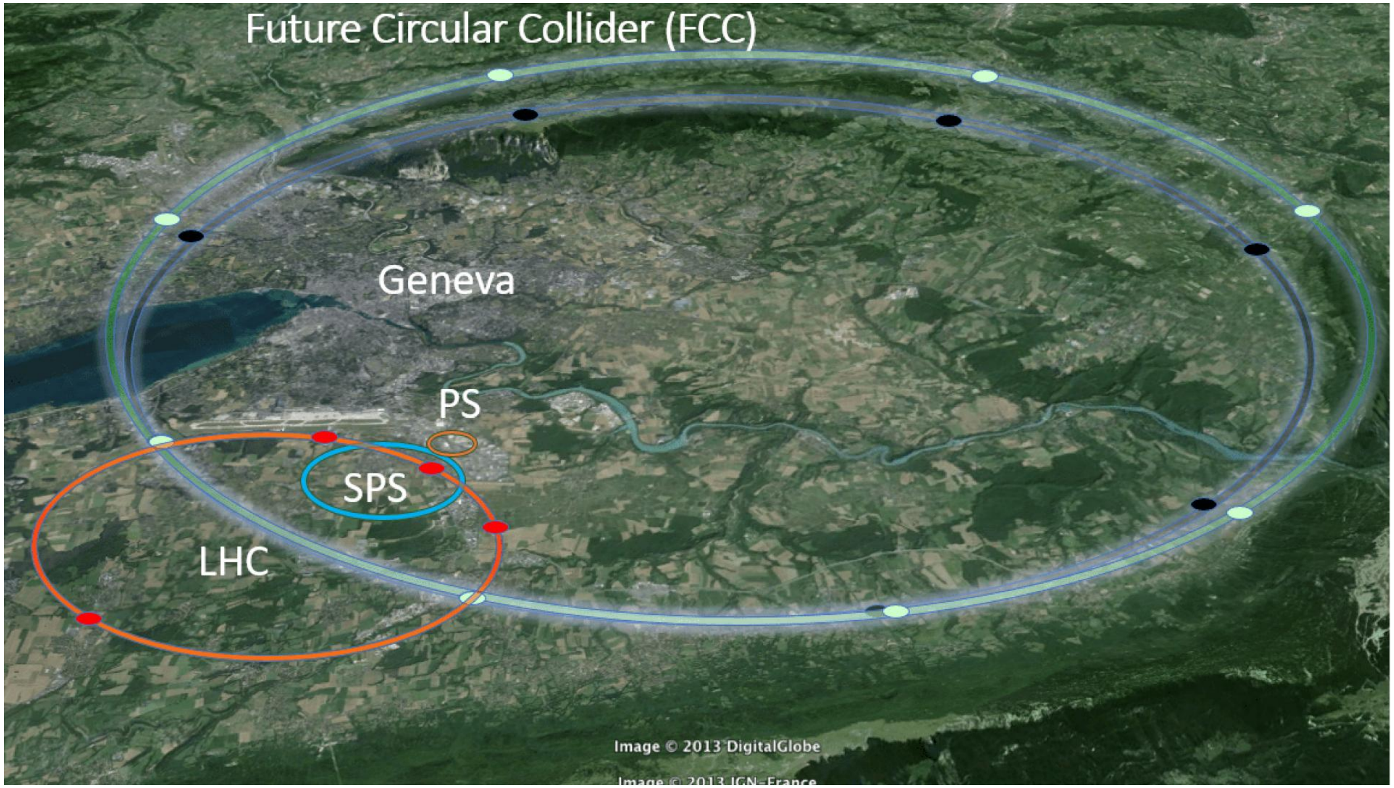


(ATLAS, 2019)

ALP contribution to the LbL process



Hadron collider parameters (*pp*)



	LHC / HL-LHC	HE-LHC (tentative)	FCC-hh Initial	FCC-hh Ultimate
Cms energy [TeV]	14	27	100	100
Luminosity [$10^{34} cm^{-2} s^{-1}$]	1 / 5	28	5	20-30

LbL process in collisions at the FCC-hh

$$pp \to p\,(\gamma\gamma \to \gamma\gamma)\,p\,,$$
$$pPb \to p\,(\gamma\gamma \to \gamma\gamma)\,Pb\,,$$
$$PbPb \to Pb\,(\gamma\gamma \to \gamma\gamma)\,Pb$$

System	$\sqrt{s_{\rm NN}}$ (TeV)	$\mathcal{L}_{\rm AB}\cdot\Delta t$ (per year)	$\gamma_{\rm L}$ ($\times 10^3$)	$\omega_{\rm max}$ (TeV)	$\sqrt{s_{\gamma\gamma}^{\rm max}}$ (TeV)
pp	100	1 fb^{-1}	53.0	17.6	35.2
p–Pb	63	8 pb^{-1}	33.5	0.95	1.9
Pb–Pb	39	33 nb^{-1}	21.0	0.60	1.2

Numerical analysis

Differential cross section

$$d\sigma_{AB} = \int\limits_{W_{\min}}^{W_{\max}} \frac{dL_{\gamma\gamma}}{dW}\, d\hat{\sigma}_{\gamma\gamma\to\gamma\gamma}(W)\, dW$$

A,B = p or Pb

$$\frac{dL_{\gamma\gamma}}{dW} = \frac{W}{2} \int\limits_{\omega_{\min}}^{\omega_{\max}} f_{\gamma/A}\left(\frac{W^2}{4\omega}\right) f_{\gamma/B}(\omega)\, \frac{d\omega}{\omega}$$

$f_{\gamma/A}(\omega)$ is photon distribution in proton or nuclear in energy fraction $\omega = E_\gamma/E_A$

Photon flux in proton

$$f_{\gamma/p}(\omega) = \frac{\alpha}{\pi\omega}\left(1 - \frac{\omega}{E_B}\right)\left[\phi\left(\frac{Q^2_{\mathrm{max}}}{Q^2_0}\right) - \phi\left(\frac{Q^2_{\mathrm{min}}}{Q^2_0}\right)\right],$$

$$\phi(x) = (1+ay)\left[-\ln\left(1+\frac{1}{x}\right) + \sum_{k=1}^{3}\frac{1}{k(1+x)^k}\right] + \frac{y(1-b)}{4x(1+x)^3}$$
$$+ c\left(1+\frac{y}{4}\right)\left[\ln\left(\frac{1-b+x}{1+x}\right) + \sum_{k=1}^{3}\frac{b^k}{k(1+x)^k}\right],$$

with $Q^2_{\mathrm{min}} = 0.71\ \mathrm{GeV}^2$ and $Q^2_{\mathrm{max}} = 2\ \mathrm{GeV}^2$

$$y = \frac{\omega^2}{E_B(E_B - \omega)},$$

with the parameters a, b, c given by

(O.Kepka & C.Royon, PRD, 2008)

$$a = 1 + \frac{\mu_p^2}{4} + \frac{4m_p^2}{Q_0^2} \approx 7.16,$$
$$b = 1 - \frac{4m_p^2}{Q_0^2} \approx -3.96,$$
$$c = \frac{\mu_p^2 - 1}{b^4} \approx 0.028,$$

Photon flux in lead ion

(Z = 82, A =208, R_A = 1.2 $A^{1/3}$ = 7.1 fm)

$$f_{\gamma/N}(\omega) = \frac{2Z^2\alpha}{\pi\omega}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}(K_1^2(\xi) - K_0^2(\xi))\right]$$

$$\xi = \omega/E_R,\ E_R = E_N/(m_N R_A) = \sqrt{s_{NN}}/(2m_p R_A)$$

(G.Baur et al., Phys. Rep., 2002)

Beam momentum (√s/2)(Z/A): 19.7 TeV
Beam energy (√s/2)Z: 4100 TeV
Energy per nucleon: √s(Z/A): 39.4. TeV

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

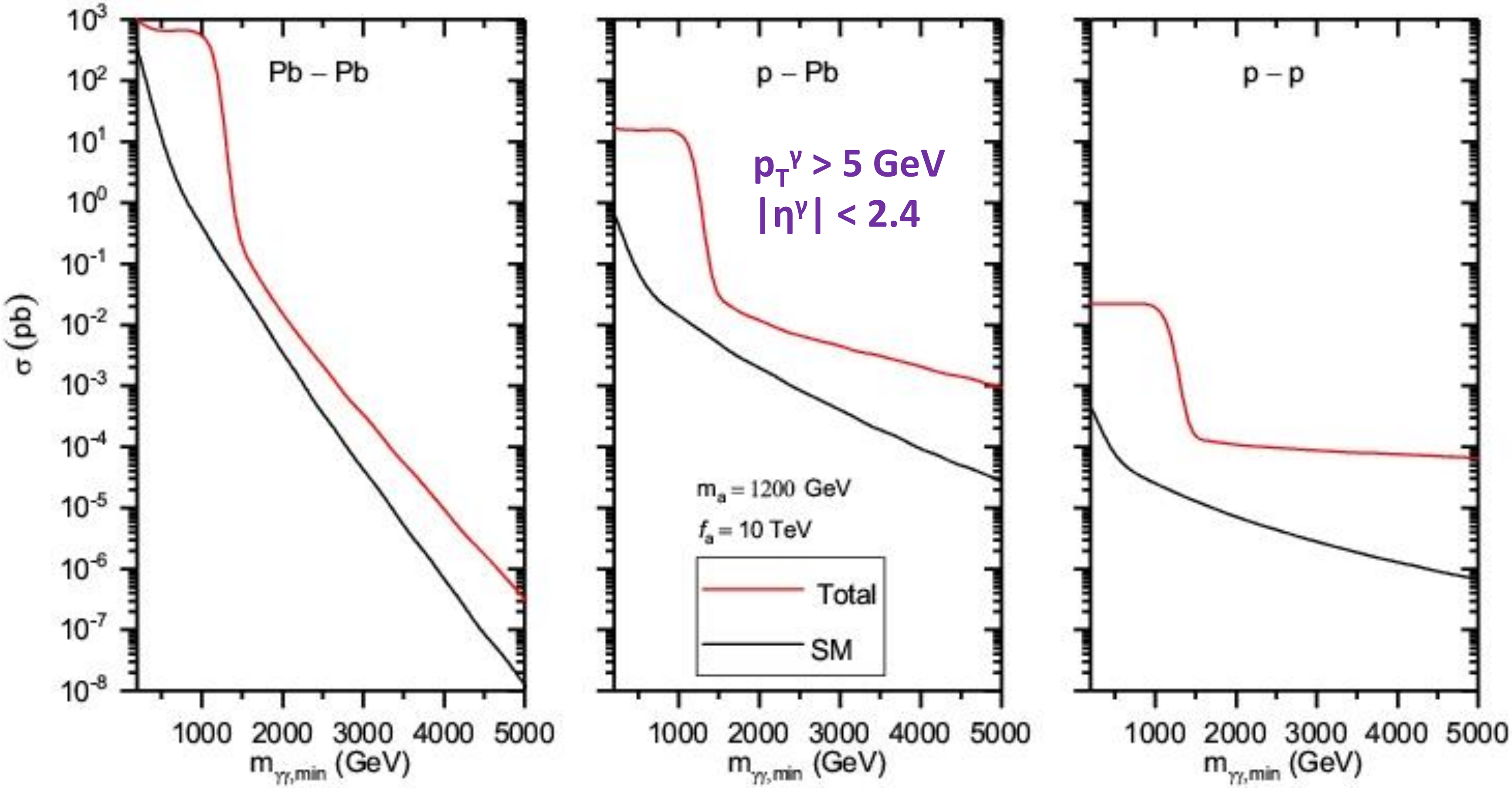
ALP helicity amplitudes squared

$$M^{(a)}_{++++} = -\frac{4}{f_a^2}\frac{s^2}{s - m_a^2 + i m_a \Gamma_a},$$

$$M^{(a)}_{+-+-} = -\frac{4}{f_a^2}\frac{u^2}{u - m_a^2 + i m_a \Gamma_a},$$

$$M^{(a)}_{+--+} = -\frac{4}{f_a^2}\frac{t^2}{t - m_a^2 + i m_a \Gamma_a},$$

$$M^{(a)}_{++--} = \frac{4}{f_a^2}\left(\frac{s^2}{s - m_a^2 + i m_a \Gamma_a} + \frac{t^2}{t - m_a^2 + i m_a \Gamma_a} + \frac{u^2}{u - m_a^2 + i m_a \Gamma_a}\right).$$



Total cross sections of two photon production at the FCC-hh versus invariant mass of outgoing photons. The parameters of the ALP are: m_a = 1200 GeV, f_a = 10 TeV

Exclusion significance (δ = percentage systematic error)

(Y.Zhang & J.Shen, EPJC, 2020)

$$S_{\mathrm{excl}} = \sqrt{2}\left[s - b\ln\left(\frac{b+s+x}{2b}\right) - \frac{1}{\delta^2}\ln\left(\frac{b-s+x}{2b}\right) - (b+s-x)\left(1+\frac{1}{\delta^2 b}\right)\right]^{1/2}$$

s (b) = number of signal (background) events

$$x = \sqrt{(s+b)^2 - 4\delta^2 s b^2/(1+\delta^2 b)}$$

In the limit δ = 0

$$S_{\mathrm{excl}} = \sqrt{2\left[s - b\ln\left(1+\frac{s}{b}\right)\right]}$$

s << b →

$$S_{\mathrm{excl}} = \frac{s}{\sqrt{b}}$$

$S_{\mathrm{excl}} \geq 1.645$ is the region that can be excluded at 95% C.L.

Discovery significance (δ = percentage systematic error)

$$S_{\text{dis}} = \sqrt{2}\left[(s+b)\ln\left(\frac{(s+b)(1+\delta^2 b)}{b+\delta^2 b(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\frac{\delta^2 s}{1+\delta^2 b}\right)\right]^{1/2}$$

In the limit δ = 0

$$S_{\text{dis}} = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]}$$

s << b

$$S_{\text{dis}} = \frac{s}{\sqrt{b}}$$

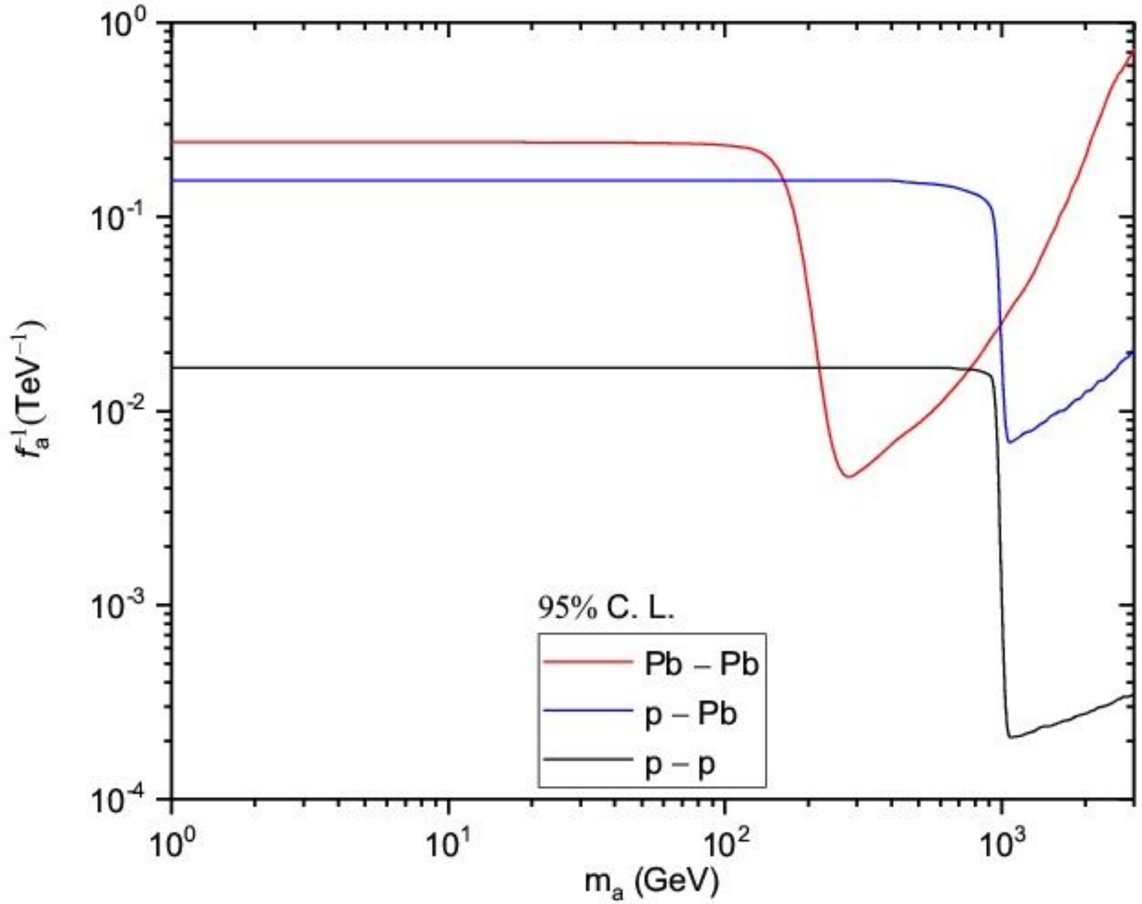
S_{dis} ≥ 5 as discovery region

Integrated luminosities:

$\mathscr{L}_{pp} = 30\ ab^{-1}$

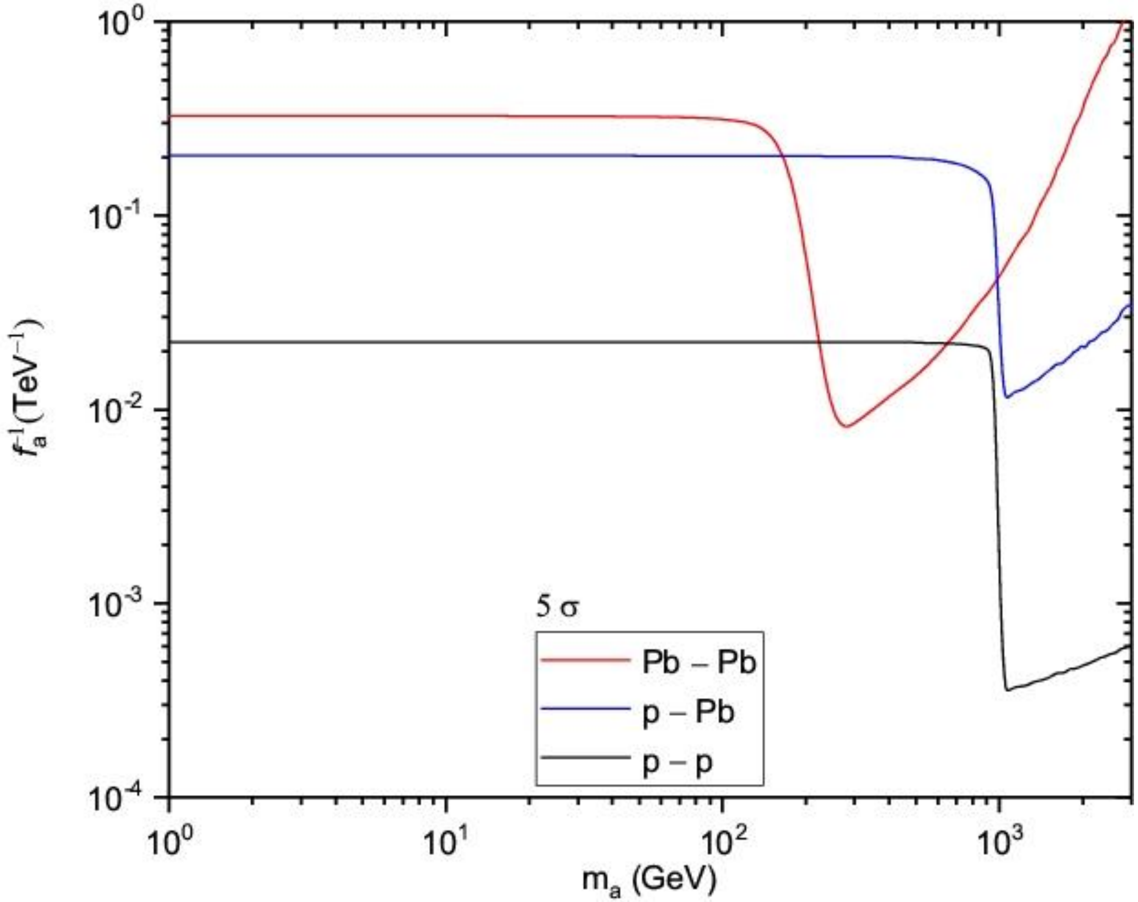
$\mathscr{L}_{pPb} = 27\ pb^{-1}$

$\mathscr{L}_{PbPb} = 110\ nb^{-1}$



$m_{\gamma\gamma}$ > 1 TeV

The 95% CL limits on the ALP coupling constant depending on the ALP mass from p-p, p-Pb and Pb-Pb collisions at the FCC-hh *(S.Inan & A.K., JHEP, 2026)*



$m_{\gamma\gamma} > 1$ TeV

The 5σ discovery limits on the ALP coupling constant depending on the ALP mass from p-p, p-Pb and Pb-Pb collisions at the FCC-hh *(S.Inan & A.K., JHEP, 2026)*

Current LHC limits

ATLAS (*JHEP, 2023*)
p-p collisions at 13 TeV

$1/f_a = 0.04 - 0.09\ \mathrm{TeV}^{-1}$ ($m_a = 150 - 1600$ GeV)

CMS + TOTEM (*Phys. Rev. D, 2024)*
p-p collisions at 13 TeV

$1/f_a = 0.03 - 1\ \mathrm{TeV}^{-1}$ ($m_a = 500 - 2000$ GeV)

Low mass region, ATLAS (*JHEP, 2021*)
Pb-Pb collisions at 5.02 TeV

$1/f_a = 0.06 - 0.3\ \mathrm{TeV}^{-1}$ ($m_a = 6 - 100$ GeV)

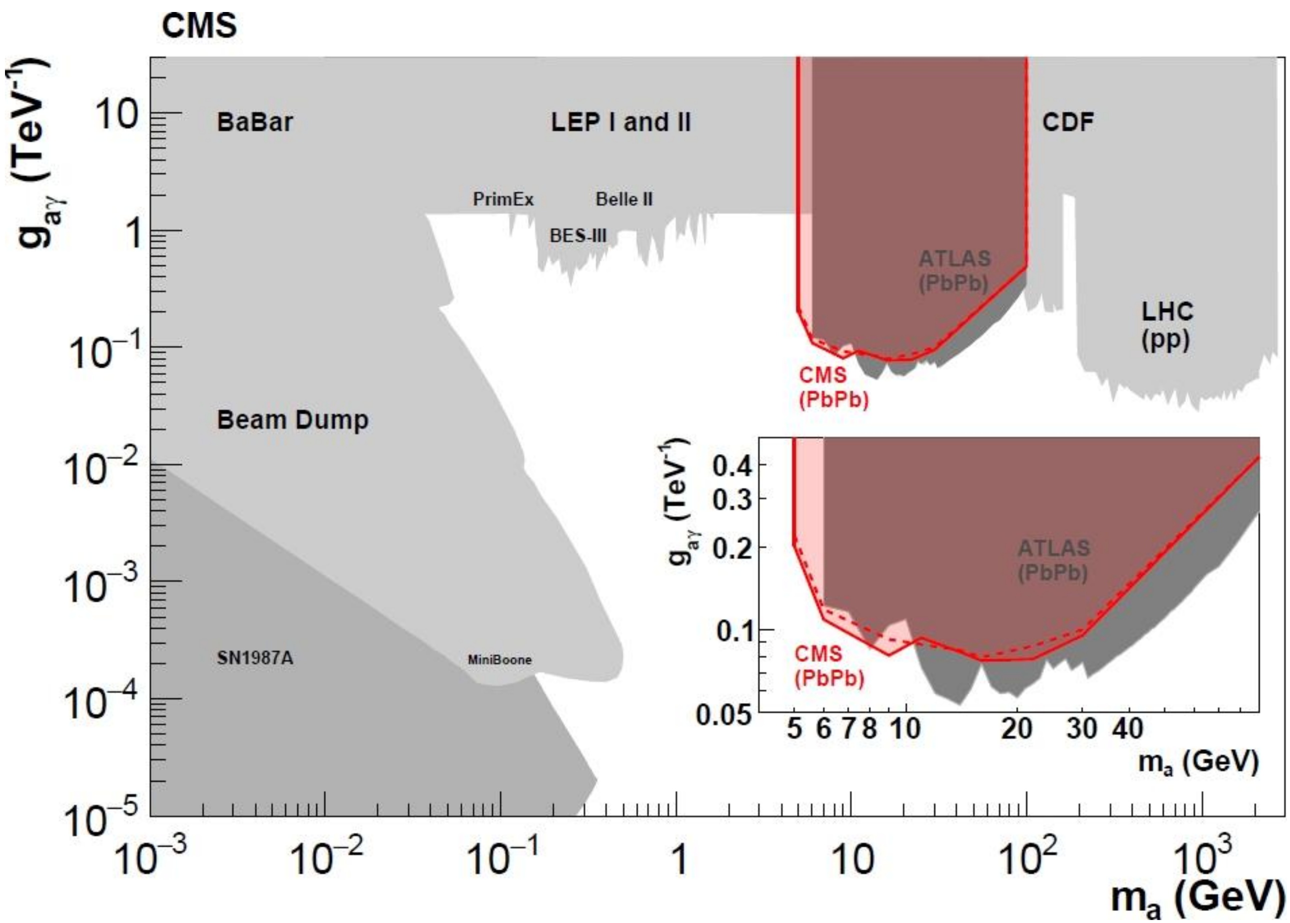
3 TeV collider CLIC with $\mathcal{L}_{pp} = 5\ ab^{-1}$

$$e^+ e^- \rightarrow e^+ \gamma\gamma e^-$$

$1/f_a \approx 0.06\ TeV^{-1}$ (m_a = 10 GeV – 1 TeV)

$1/f_a \approx 0.001\ TeV^{-1}$ (m_a = 1 – 2 TeV)

(S.Inan & A.K., JHEP, 2020)



The exclusion limits at 95% CL on the ALP-photon coupling versus ALP mass plane, assuming ALPs coupled only to photons *(CMS, JHEP, 2025)*

Conclusions

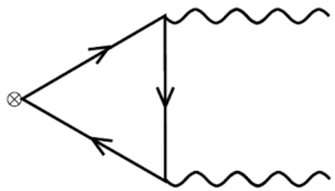
- Coupling of axion-like particles (ALPs) to photons $1/f_a$ in LbL process is studied in p-p, p-Pb and Pb-Pb collisions at the FCC-hh.
- Both 95% CL exclusion limits and 5σ discovery limits on the coupling $1/f_a$ depending on the ALP mass are obtained.
- Our best 95% CL bounds are at least one magnitude stronger than the current LHC bounds on $1/f_a$.

Thank you for attention!

Backup

Possible solution of U(1) problem: ABJ chiral anomaly

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



This term is a total divergency

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

Chiral anomaly introduces a pure surface integral to QCD action

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

Gluon field is a pure gauge at spatial infinity

$$A_\mu\big|_{r\to\infty} \to -\frac{i}{g}\,\partial_\mu\omega\omega^{-1}$$

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

→ θ-vacuum (eigenstate of “large” gauge transformations)

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

As a result, QCD action acquires θ-term

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

Exp. limit on neutron electric dipole moments, $|d_n| < 1.8 \times 10^{-13}$ e fm, requires $\theta_{phys} < 10^{-9}$

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

Solution of strong CP problem: Peccei-Quinn (PQ) mechanism with a new, spontaneously broken, global $U(1)_{PQ}$ symmetry

(R.Peccei & H.Quinn, 1977)

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

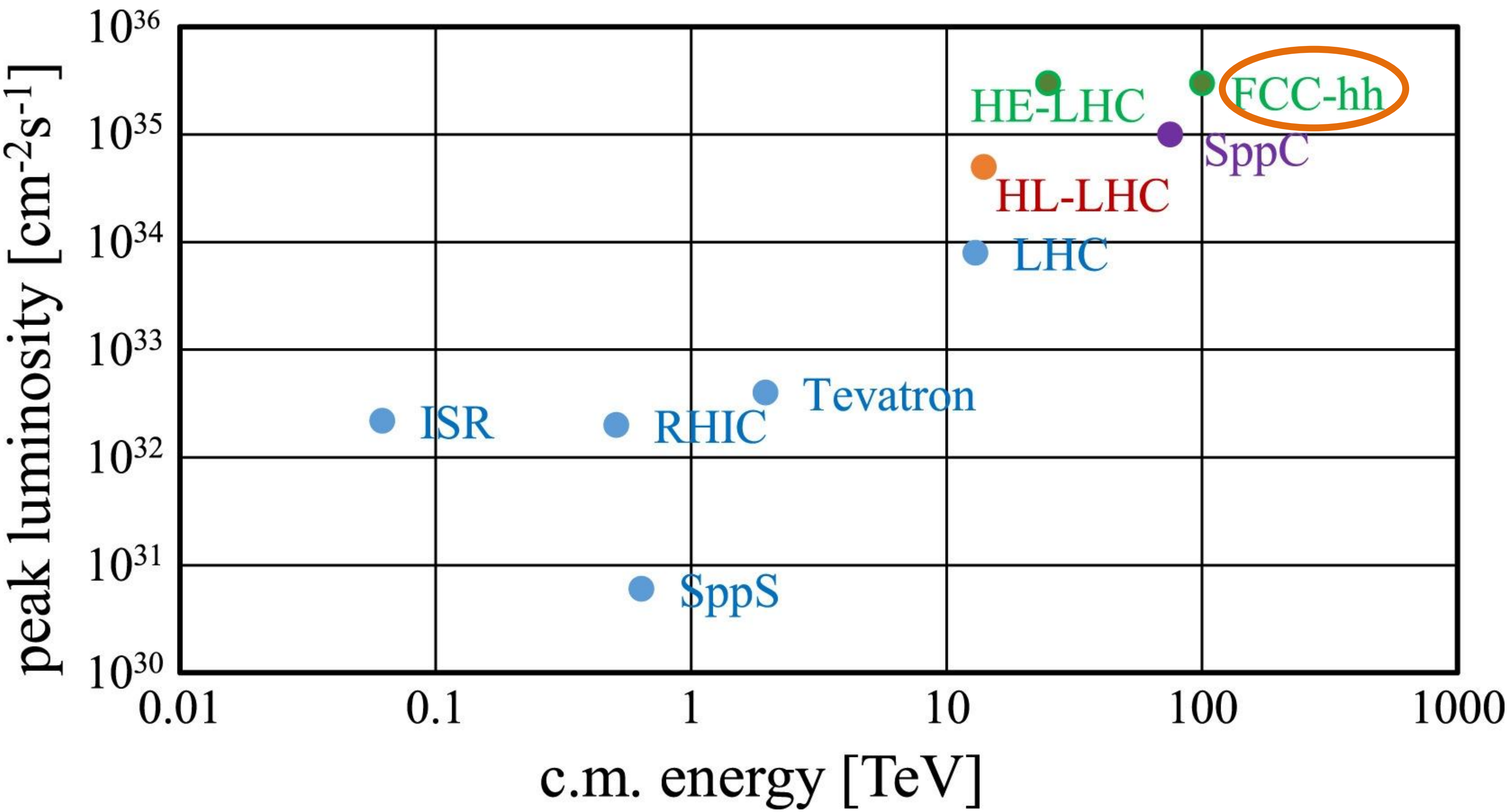
$$\mathcal{L}_a = \xi \frac{g^2}{32\pi^2} \frac{a}{f_a} G_{a\mu\nu} \tilde{G}_a^{\mu\nu}$$

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

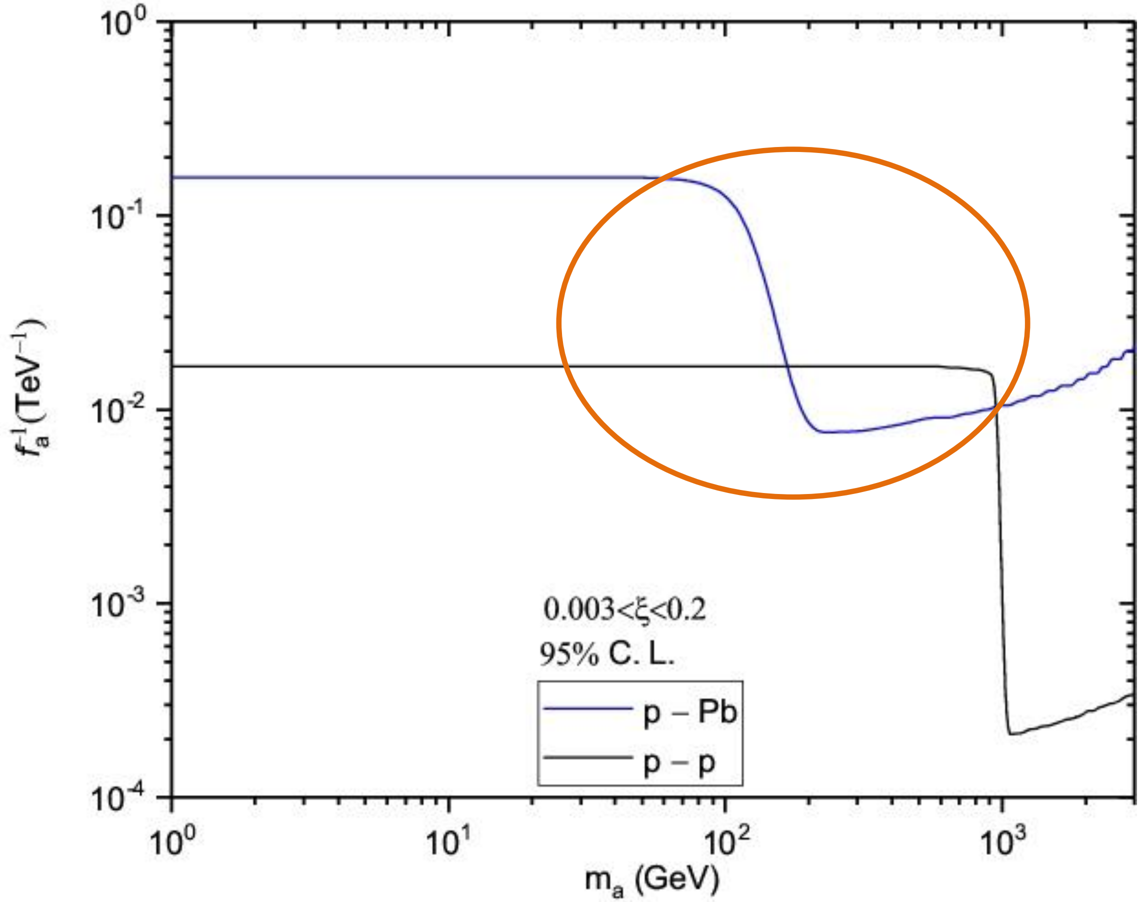
New symmetry effectively replaces static CP-violating angle θ with dynamically CP-conserving field, axion *a*

(S.Weinberg, F.Wilczek, 1978)

Luminosity vs. center-of-mass energy for past and present (blue), upcoming (red), and future hadron colliders (green and purple) around the world



(M. Benedikt & F. Zimmermann, 2018)



$m_{\gamma\gamma} > 1$ TeV

$\xi = \Delta p/p$

The 95% CL limits on the ALP coupling constant in p-Pb and p-p collisions at the FCC-hh, with proton tagging

Unitarity bounds on anomalous couplings

Partial-wave expansion in c.m.s.

(Jacob & Wick Ann. Phys. 7, 404 (1959))

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\theta,\varphi) = 16\pi \sum_J (2J+1)\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})}$$
$$\times\; e^{i(\lambda-\mu)\phi}\, d^J_{\lambda\mu}(\theta)\, T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)\;,$$

$$\lambda = \lambda_1 - \lambda_2,\;\; \mu = \lambda_3 - \lambda_4$$

Partial-wave amplitude

$$T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s) = \frac{1}{32\pi}\frac{1}{\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})}}\int_{-1}^{1} M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,z)\, d^J_{\lambda\mu}(z)\, dz$$

Partial-wave expansion of helicity amplitude

(M.Jacob & G. Wick, Ann. Phys. 7, 404, 1959; ibid 281, 774 2000)

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\theta,\varphi) = 16\pi \sum_J (2J+1)\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})} \times e^{i(\lambda-\mu)\phi}\, d^J_{\lambda\mu}(\theta)\, T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)$$

$d^J_{\lambda\mu}$ = Wigner's (small) d-function

$$T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s) = \frac{1}{32\pi}\frac{1}{\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})}}\int_{-1}^{1} M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,z)\, d^J_{\lambda\mu}(z)\, dz$$

Partial-wave unitary bound

$$\left|T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)\right| \le 1$$

(C.Baldenegro et al., JHEP, 2017)