Axion-like Particles via γ-fusion @ILC

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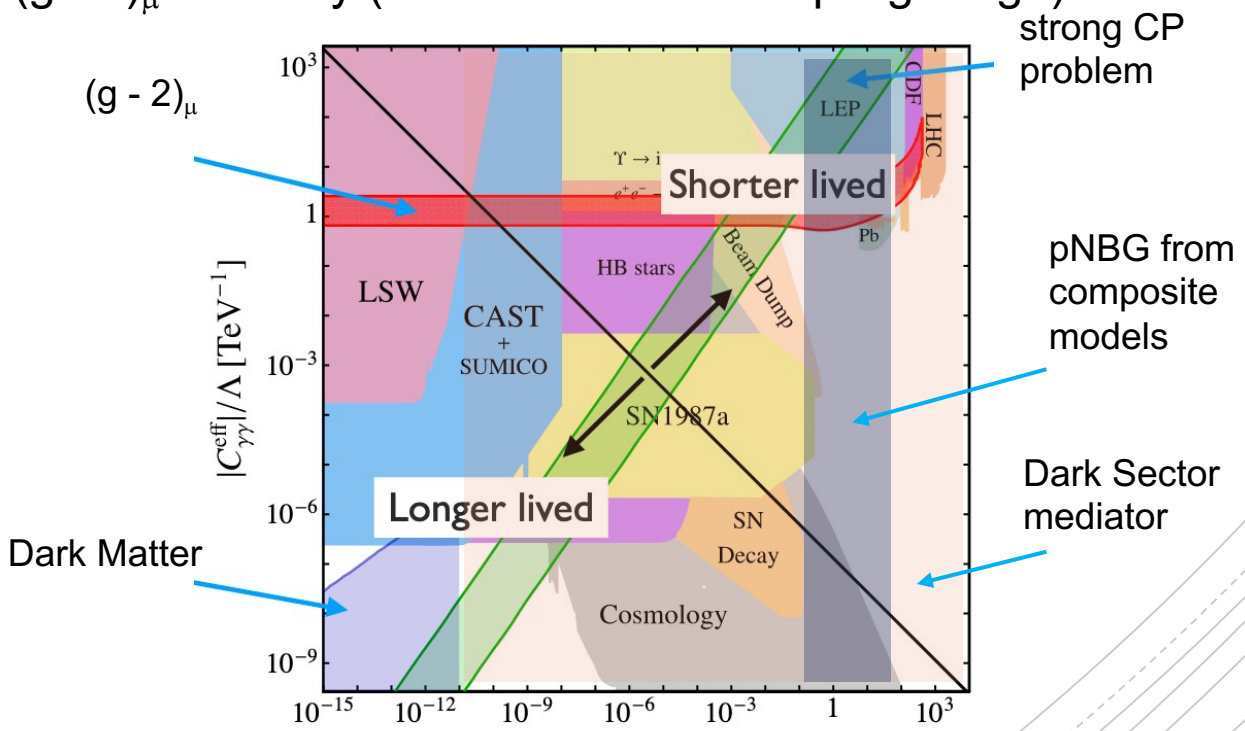
Axion-like particles (ALPs) are "versatile" pseudoscalars suggested in many SM extensions:

Motivations

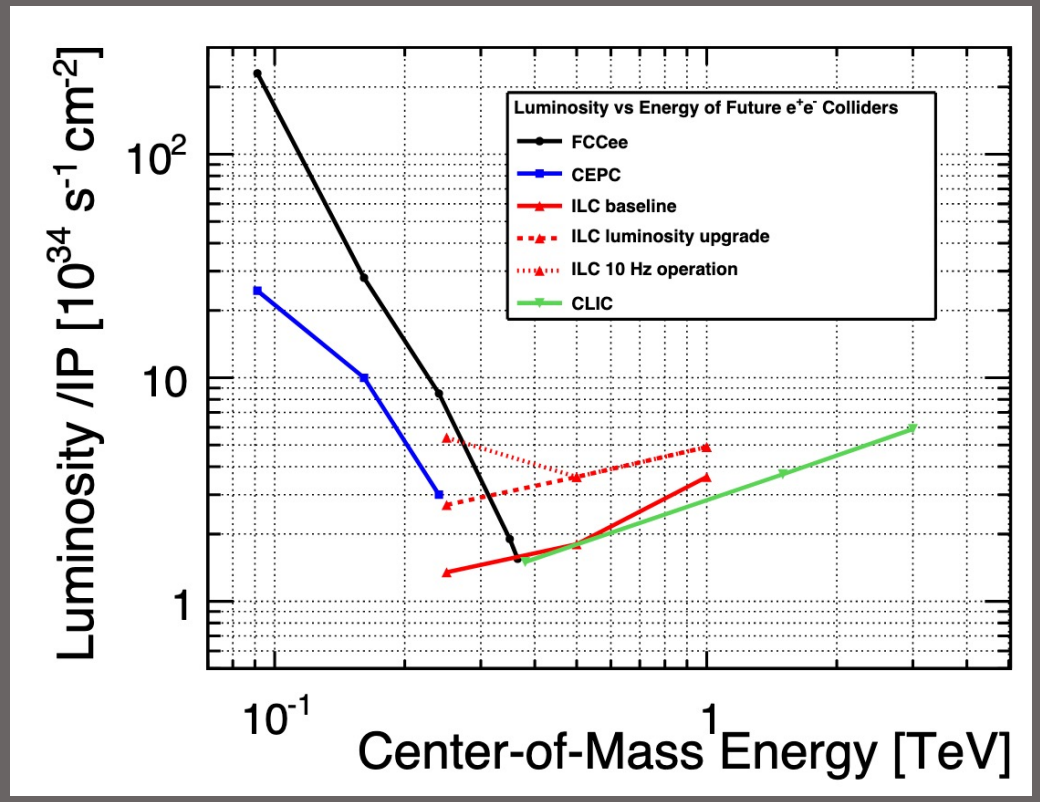
See WIN2021 P. Teles talk for FCC-ee studies

1. Solve strong CP problem (with explicit m_a vs. SM-couplings proportionality).
2. Dark Matter candidate (for stable very light m_a), or dark sector mediator (higher mass values)
3. Pseudo Nambu-Goldstone boson of new spontaneously broken global symmetries (π^0-like) in high-energy SM extensions (for $m_a \sim$ GeV)
4. Solve $(g - 2)_\mu$ anomaly (over narrow SM coupling range)



[Figure adapted from Andrea Thamm link]

Future e^+e^- colliders under discussion



Collision energy(GeV)	Lum.(/cm^{2}s)
250 (baseline)	1.35
250 (Nbunchx2)	2.7
250 (above + 10 Hz)	5.4
500 (baseline)	1.8
500 (Nbunchx2)	3.6
1000 (baseline)	3.6
1000 (high L)	4.9

- Data samples expected at $\sqrt{s}$ = 250 (1.35nb^{-1}), 500 (1.8nb^{-1}), 1000 GeV (3.6 nb^{-1}), at different luminosities, useable for ALP searches.

https://indico.fnal.gov/event/20759/contributions/58924/attachments/36900/44905/Lum-Energy-doc-preliminary.pdf

See WIN2021 P. Teles talk for FCC-ee studies

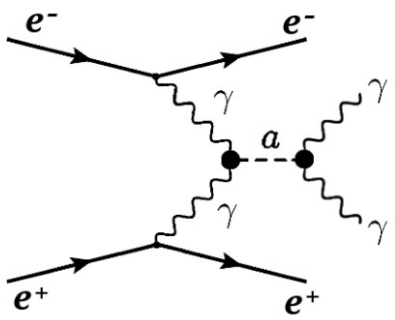
$$\mathcal{L} = \frac{1}{2}\partial^{\mu}a\partial_{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{1}{4}g_aaF^{\mu\nu}\tilde{F}_{\mu\nu}$$

Production of an Axion–like particle (ALP) via the two–body photon decay channel

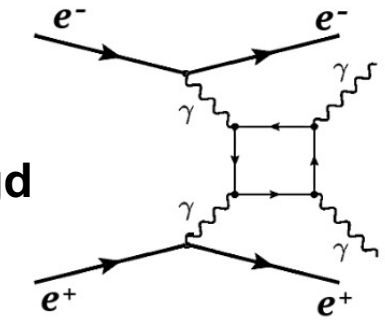
SuperChic v4.X MC to generate ALP signal & irreducible light-by-light background link

$$\Gamma = \frac{g_{a\gamma}^2\, m_a^3}{64\pi}$$

ALP signal



LbyL backgd

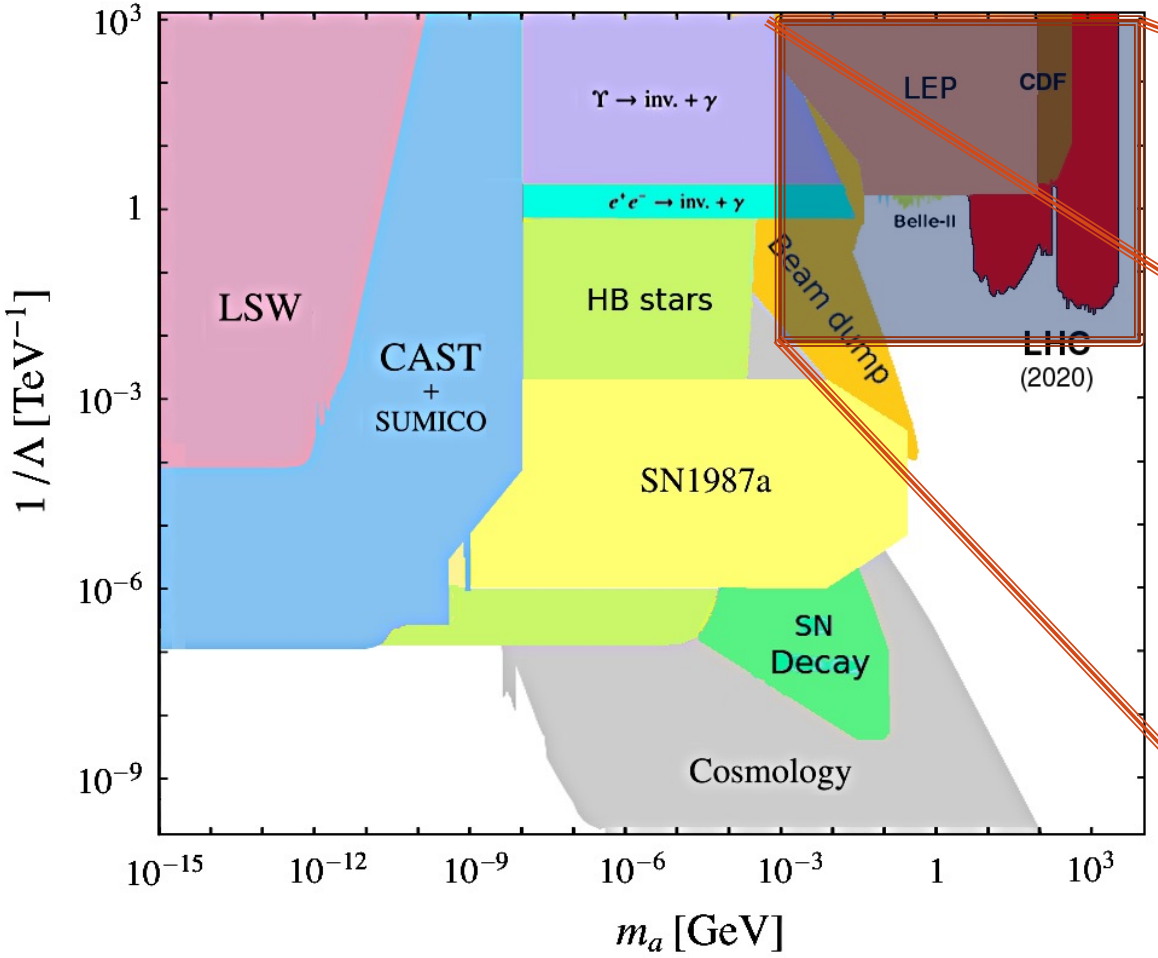


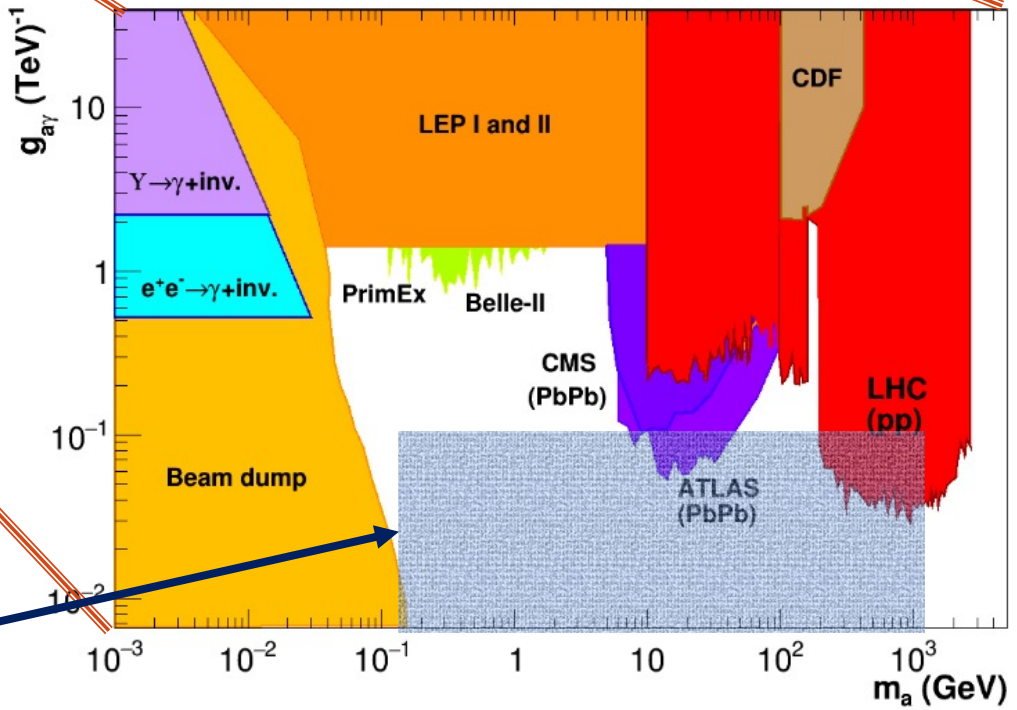
95%CL upper limits on the cross-section σ ($\gamma\,\gamma \rightarrow a \rightarrow \gamma\,\gamma$) and on the ALP-photon coupling $g_{a\gamma}$ (assuming BR($a \rightarrow \gamma\,\gamma$) = 100%) over the mass range m_a = 0.1 -- 1000 GeV (working points on next slide)*.

SuperChic does not allow beam polarization (link for beam polarization effects in ILC)

*** Results from ILC parametrized detector effects being worked out. Showing now here parton-level only results.**

What can be achieved, via γγ-fusion at ILC, in the heavy-ALP region ($m_a \gtrsim 0.1$ GeV)?





[Figure from David d'Enterria, arXiv:2102.08971]

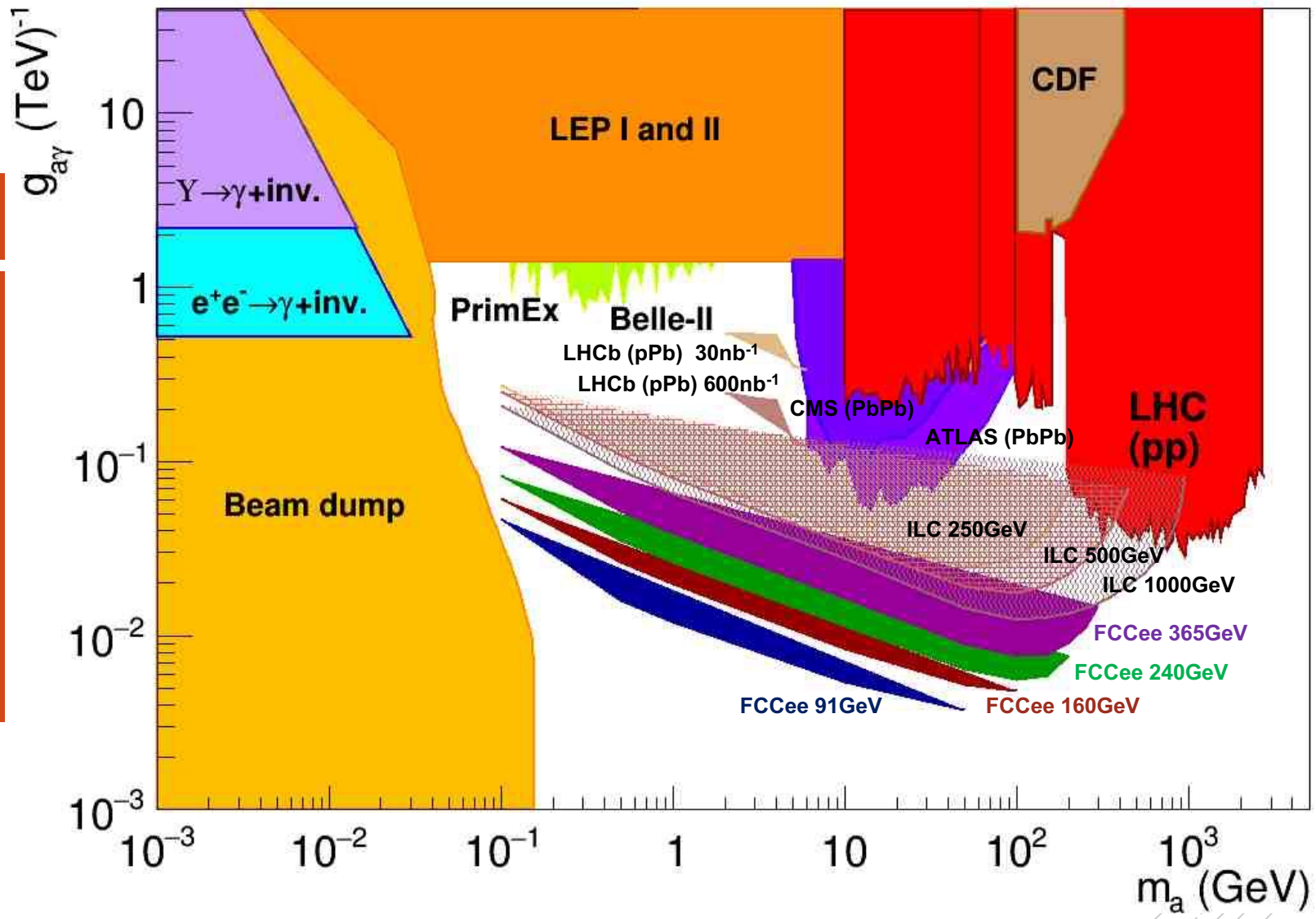
Benchmark coupling at $g_{a\gamma} \sim 0.1$ TeV^{-1} for the following working points:

√s=250 GeV (1.35nb^{-1}) : m_a = 0.1, 0.5, 1, 10, 50, 100, 200 GeV

√s=500 GeV (1.8nb^{-1}): plus m_a = 250, 300, 350, 400, 450 GeV

√s=1000 GeV (3.6nb^{-1}): plus m_a = 500, 550, 600, 650, 700, 750, 800, 850, 900, 950 GeV

Sensitivity of experiments @95% CL



Competitive 95%CL upper limits, covering regions not sensitive to other experiments.

Proposals & improvements

- **Polarization effects**: Madgraph enabled in run_card

  # Beam polarization from -100 (left-handed) to 100 (right-handed)

  0.0 = polbeam1 ! beam polarization for beam 1

  0.0 = polbeam2 ! beam polarization for beam 2

- **Beyond a > $\gamma\gamma$ decay** => more general lagrangian implemented in Madgraph (http://feynrules.irmp.ucl.ac.be/raw-attachment/wiki/ALPsEFT)
  - the most generic ALP coupling to electroweak bosons includes couplings to γ, Z, and $W^{\pm}$. Then, any experimental searches for $a\gamma\gamma$ decay can be interpreted assuming γ-ALP-only ($g_{a\gamma}$) or γ,Z-ALP (g_{aB}) couplings (leaving the W case aside). For m_a > 91GeV that opens the decay channel a > $Z\gamma$ and so the BR(a > $\gamma\gamma$) = 100% would not be valid anymore (because it ignores a > $Z\gamma$ decays that now is possible). It is discussed in D. d'Enterria, 2102.08971 [hep-ex] and references.
  - Photon-Jet channel to probe ALPs as proposed by D.Wang et al, 2102.01532 [hep-ph]: highly collimated photons => detected as single photon events ("photon-jet")
  - New lagrangian proposed by Helayel et al (in progress) : could be implemented via Feynrules in Madgraph for future phenomenology approach.
- **Detector simulation**: Pythia8 + Delphes available at https://github.com/iLCSoft/ILCDelphes (updated tutorial to be checked)

Looking ahead (training and projects)

Julia Ceddia and **Pedro Alipio**, started working with the CBPF researcher José Helayël Netto in September 2018. Patricia Teles also joined the team as collaborator with the phenomenology and experimental approaches.

In order to come up and understand Particle Physics, they had classes every Sunday on Electromagnetism, Maxwell's Equations, Non Linear Electrodynamics, Calculus 1 and 2, Particle Physics, Relativity, and the role of the physicist in society.

After submitting their project on Non-Linear Electrodynamics (NLE) for the CERN's competition BEAMLINE FOR SCHOOLS 2019, which proposed to improve the understanding of electromagnetism and the Standard Model (link to Youtube), they were invited to give a speech on the First International Masterclasses Hands on Particle Physics in CBPF in May 2019. Recently, Pedro (UFRJ physics student) presented his work on Axions in PROVOC 2020-2021 Seminar. Julia will start her undergraduation in physics in 2022.

After building solid knowledge in NLE, they are now preparing **a review about Axions** aiming to be published in portuguese to widely reach Brazilian teachers and students.

Key references
(not exhaustive)

- “Searches of axion-like particles via photon fusion at the FCC-ee”, WIN2021 presentation link, Patricia Rebello Teles and David d’Enterria, paper in progress; “Collider constraints on axion-like particles”, Workshop on Feebly Interacting Particles, David d’Enterria, 2102.08971 [hep-ex]; “A search for axion-like particles in light-by-light scattering at the CLIC”, Inan, S. C. and Kisselev, A. V., JHEP06(2020)183; “Searching for axion-like particles at future electron-positron colliders”, Zhang et al, 2103.05218 [hep-ph].
- ILC TDR links and Fermilab ILC Workshop
- “Searching for axionlike particles with low masses in pPb and PbPb collisions”, V. Goncalves, D. Martins, M. Rangel, Eur.Phys.J.C 81 (2021) 6, 522; “Production of axionlike particles in PbPb collisions at the LHC, HE-LHC and FCC: A phenomenological analysis”, R. Coelho, V. Goncalves, D. Martins and M. Rangel, Phys.Lett.B 806 (2020) 135512; “Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at 5.02 TeV”, CMS Collaboration, Phys. Lett. B 797 (2019) 134826; Photon-Jet as a probe of axion-like particle at LHC, D.Wang et al, 2102.01532 [hep-ph]
- “Recent progress in physics of axions and ALPs”, K. Choi et al, 2012.05029; Axionic non-linear Electrodynamics”, J. A. Helayël-Neto, M. J. Neves, L. P. R. Ospedal, J. M. A. Paixão (Work in progress); PROVOC 2020-2021 (CBPF), XXIII Seminário de Vocação científica, “Teorias e fenômenos não-lineares na busca por Áxions” , P. Alipio and J.A. Helayel-Neto; “Axions: teoria, fenomenologia e experimento” (title TBC), Julia Ceddia, Pedro Alipio, J.A.Helayel Netto, Patricia Rebello Teles (work in progress)

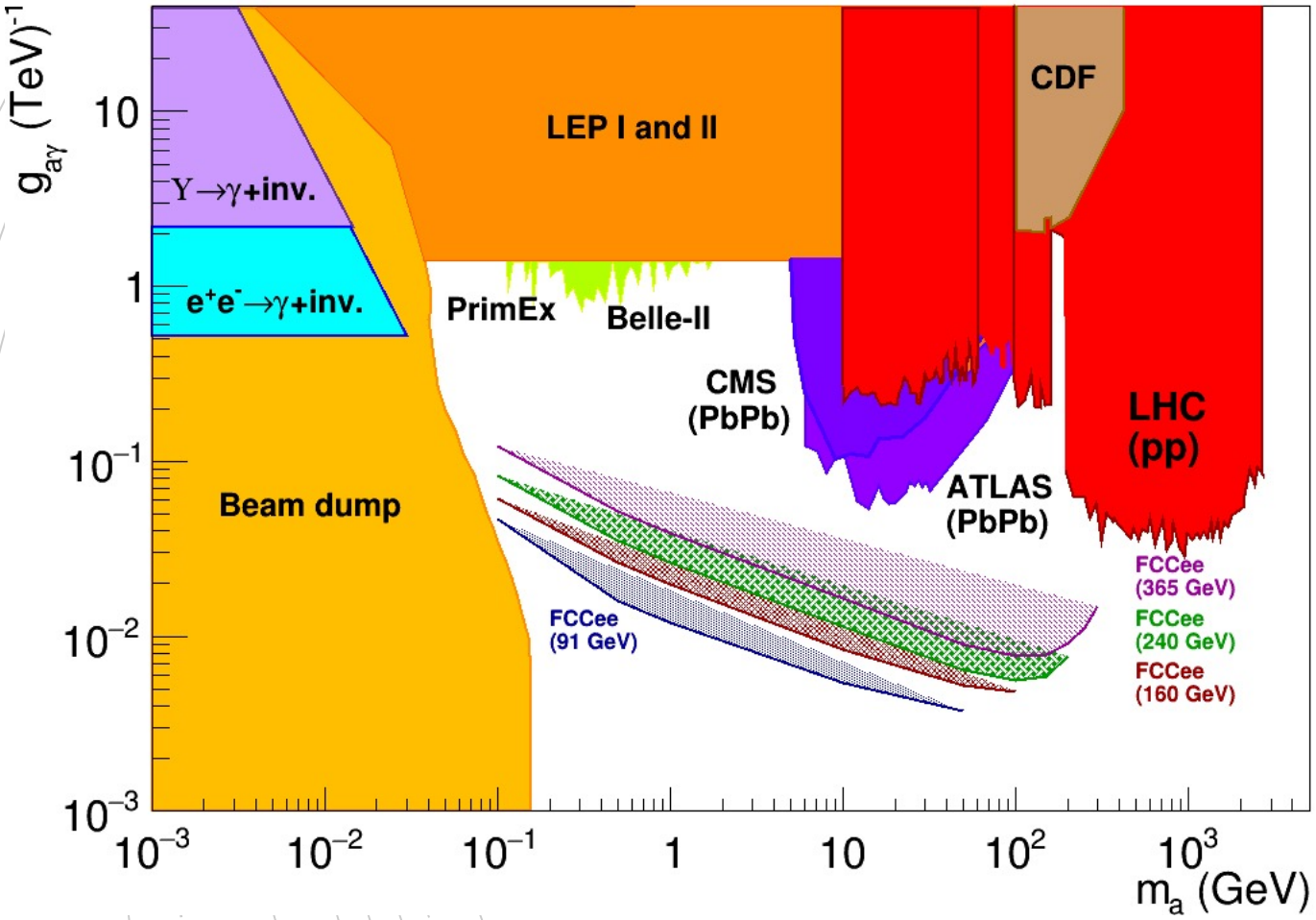
Conclusions

- Axion-like particles (ALP) are well-supported candidates for many extensions of the SM, motivating many experimental searches over a very broad range of masses, covered by collider, astrophysics, cosmology, low-energy precision.. measurements.
- The International Linear Collider as $\gamma\gamma$-collider, strongly enables the search for new physics. Here, in particular, we presented 95%CL upper limits for the axion-photon $g_{a\gamma}$ couplings down to $O(10^{-2})$ TeV^{-1}, covering regions not sensible to other future lepton beam experiments.
- Detector simulation, beam polarization effects and other important channels feasibility are being worked out.
- ALPs join efforts among theorists, phenomenologists and experimentalists worldwide.
- Training students and researches in the field will enable outstanding Brazilian presence in the future experiments, in particular at ILC collaboration, among others.

Thank you 🙂

Backup slides

BACKUP



- "Searches of axion-like particles via photon fusion at the FCC-ee", WIN2021 presentation, Patricia Teles & David d'Enterria, paper with the detector simulation in progress
- Very prominent upper limits @95% CL for ALPs searches in the mass range 0.1 GeV $\leq m_a \leq$ 300 GeV, with couplings to photons $g_{a\gamma}$ in the order of $O(10^{-2} - 10^{-3})$ TeV $^{-1}$.
- FCC-ee coverage is 10 - 50 better than any other current experiment.