Axion-like particles searches in low-energy precision experiments

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Marc Vanderhaeghen

EINN 2025

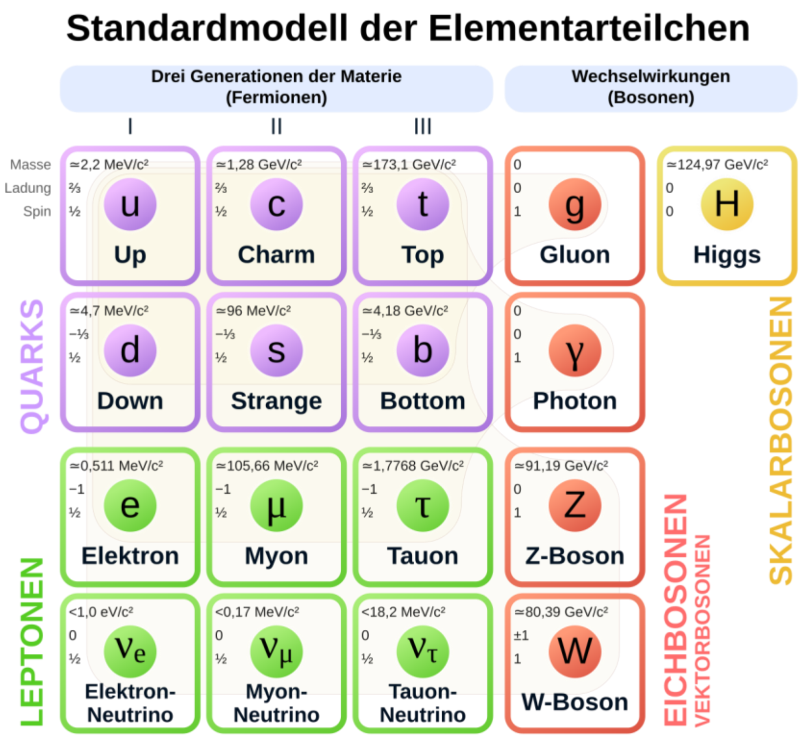
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

October 28, 2025

Research Unit FOR 5327 Photon-photon interactions in the Standard Model and beyond
Exploiting the discovery potential from MESA to the LHC

Motivation

We have an incredible theory to describe ¾ of what is observable with (almost) no flaws



$$\mathcal{L}_{QCD} \propto \frac{\theta}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

Still, some shameful stains persist…

Probably the most unpleasant ones are the **strong CP problem** and dark matter

Let's focus on the **first one** for a second. $\theta \neq 0$ naturally gives rise to a relatively large neutron Electric Dipole Moment. Meanwhile:

As if the only contribution to nEDM is from CKM matrix (marked as **Standard Model calculations**)

This also implies $\theta \lesssim 10^{-10}$ – finely tuned?

Numerous experiments to further improve this by reaching 10^{-27}e · cm bound (red dot on the plot)

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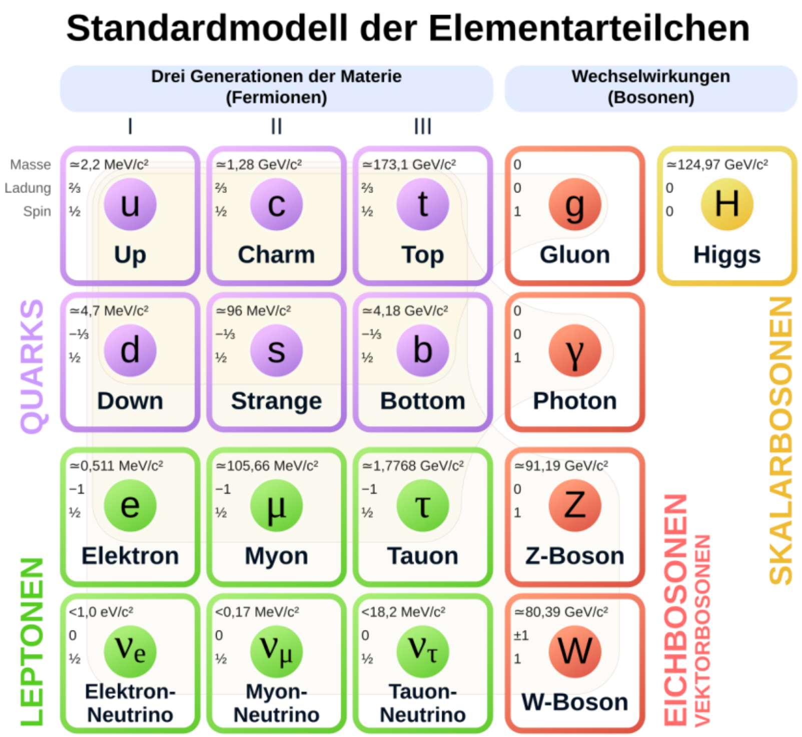

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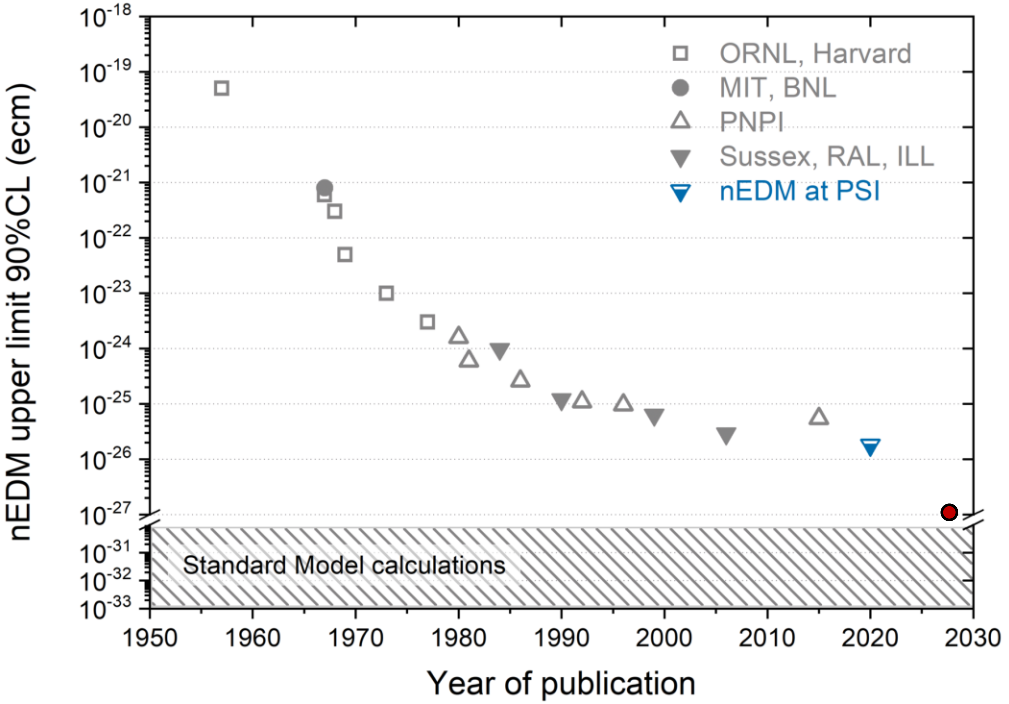


Acknowledgments

The **idea is very simple** (to "clean up" the strong CP-problem):

1) Postulate a **new $U(1)$ symmetry** (Peccei-Quinn)
2) Spontaneously **break it** at some scale Λ
3) The **(pseudo)-Goldstone boson** cancelling θ is called axion:

$$\mathcal{L}_{total} \rightarrow \mathcal{L}_{SM} + \frac{a}{\Lambda} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

The exact mechanism of axion-gluon coupling is model-dependent, but typically through **quark triangle** or **mixing with pion**

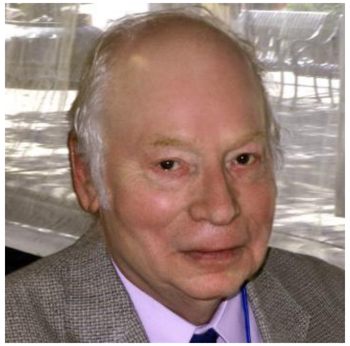
Two "benchmark" models (along with their variations) are widely used:

KSVZ: **heavy, electrically neutral quarks** carrying PQ charge

DFSZ: SM quarks carry PQ charge, **additional Higgs doublet**

Roberto Peccei

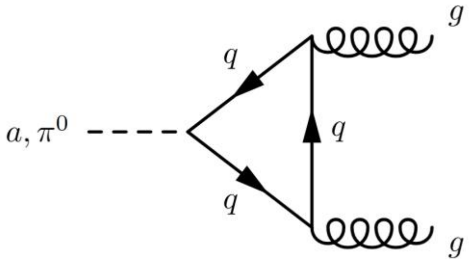
Helen Quinn



Steven Weinberg

Frank Wilczek

In both models scale Λ **is the only dimensonfull parameter**, $m_a \propto \Lambda$, coupling to SM particles $\propto 1/\Lambda$



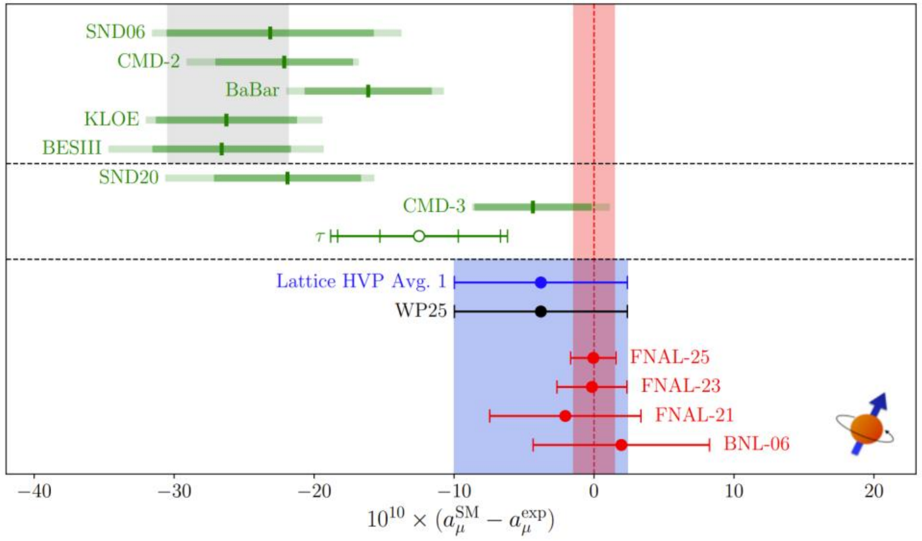
Axion-Like Particles

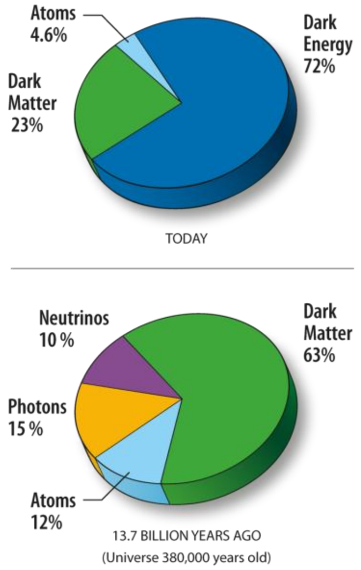
Beyond QCD-motivated benchmark models ⇒
Axion-Like Particles – broader theory framework!

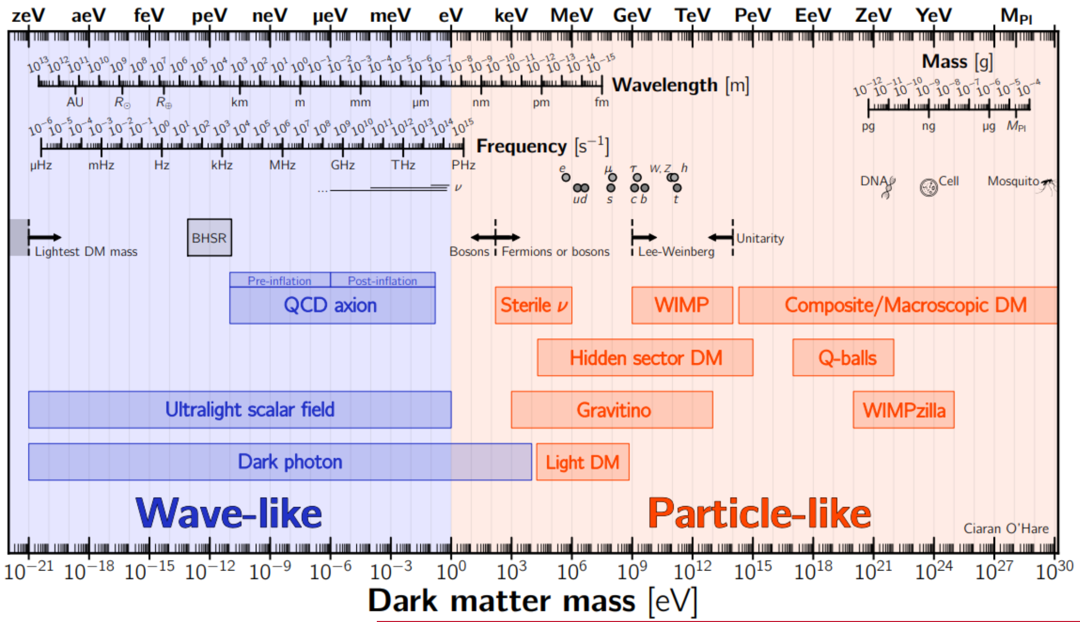
Mass and coupling are generally independent

Relevant to **variety of problems**:

1) Initial motivation is to **cancel QCD $\boldsymbol{\theta}$**
2) Some are potentially **dark matter**
3) May explain anomalous **star cooling**
4) Could fix **TeV transparency of Universe**
5) Contributes to $(g-2)_\mu$ without spoiling $(g-2)_e$?
6) General feature of ***string theories***
7) ...

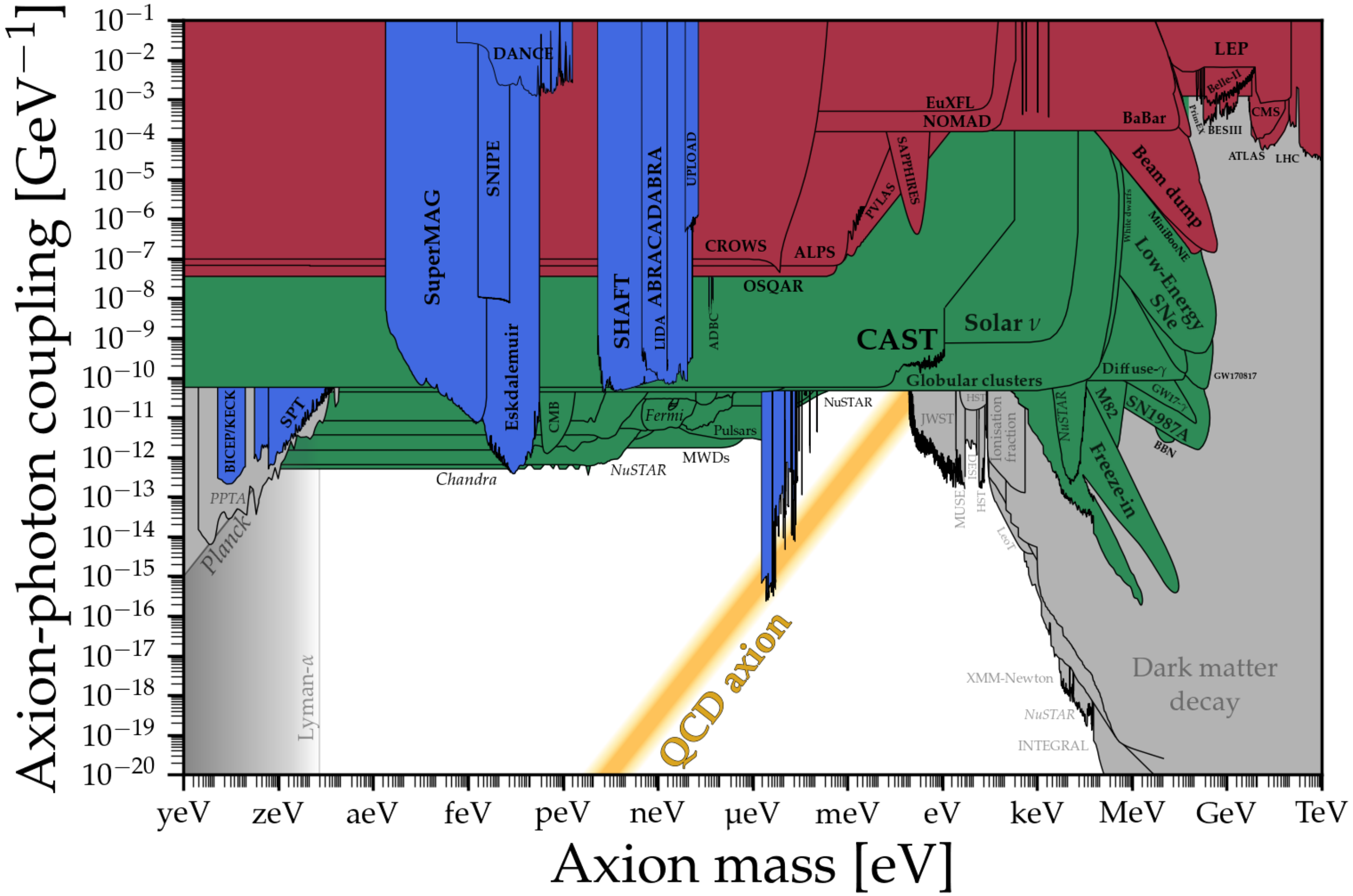






Many thanks to Fred Jegerlehner, Vladimir Pascalutsa and Simone Bacchio for their extremely comprehensive reviews on this subject

Where Do We Look for ALPs



Strong astrophysical bounds (model-independence from low to moderate) in the low-mass region are in contrast with the high-mass region
QCD axion stands for original KSVZ/DFSZ models

Credits for the figure to https://cajohare.github.io/

A “striking” **gap – few hundred MeV to GeV** mass

This domain almost entirely relies on e^+e^- colliders.
A lot of attention during the past few years!

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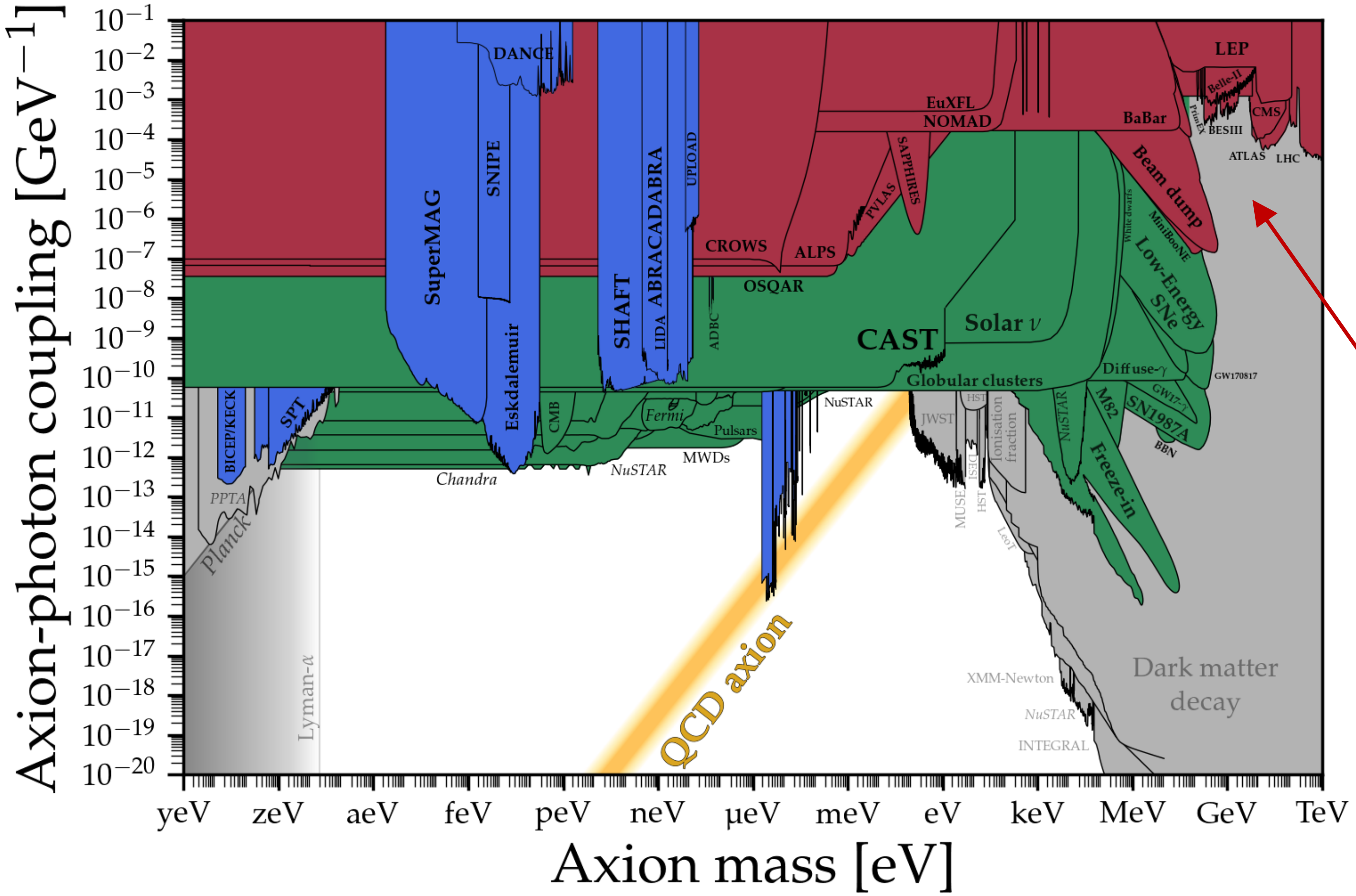

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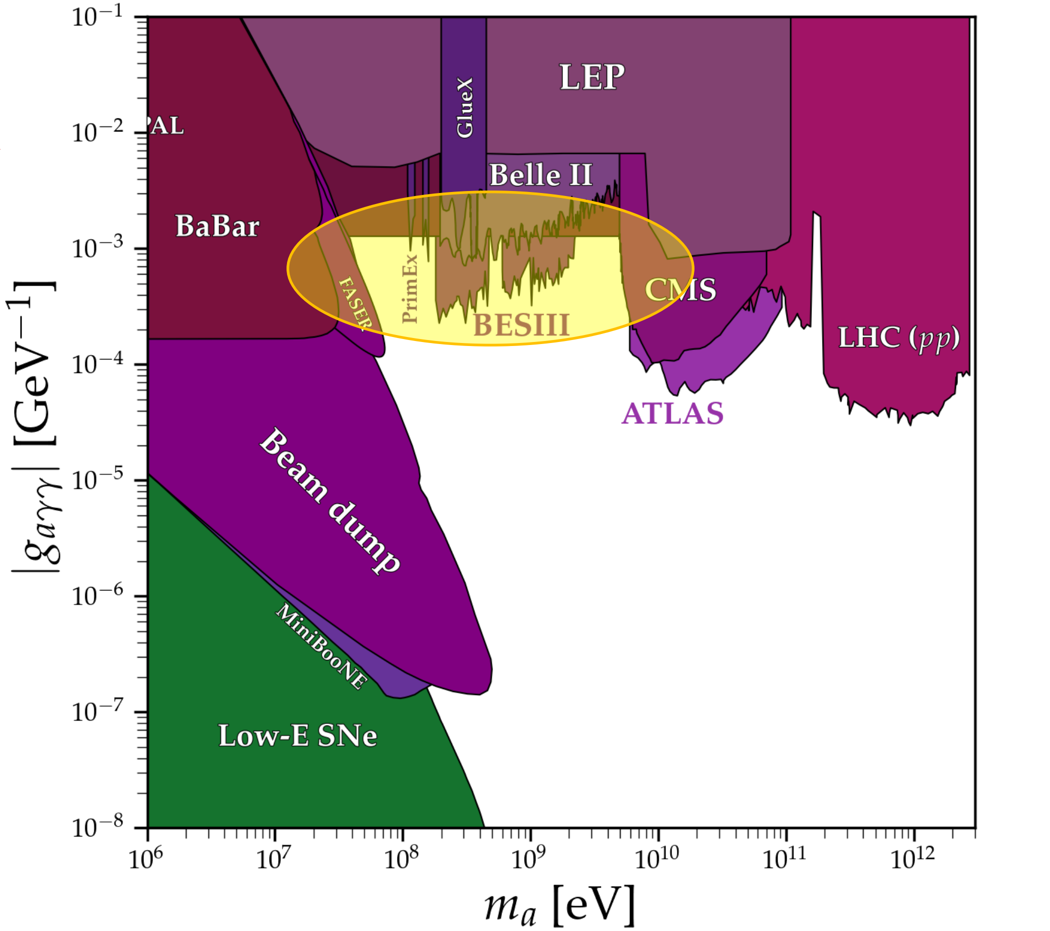

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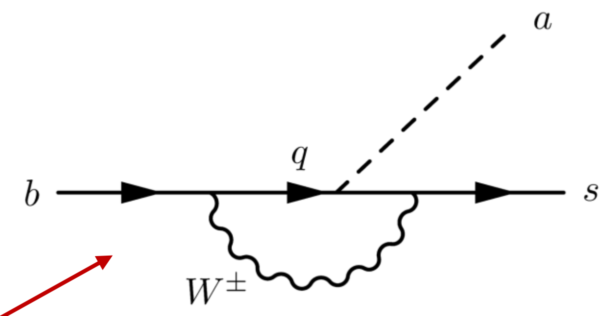
Existing Constraints

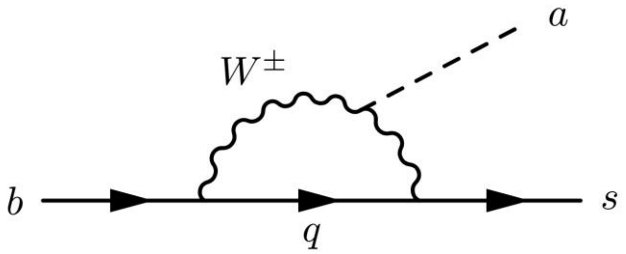
Our objective is to systematically search for ALP signals at e^+e^- colliders. **Generic CP-even coupling to fermions**:

$$\mathcal{L} = -\frac{g_{aff}}{2m_f}\partial_\mu a \cdot \bar{\psi}\gamma^5\gamma^\mu\psi$$

In the domain of interest **QCD couplings** typically lead to severely constrained flavour-changing processes – they can only be **subdominant**

M. Dolan et al. JHEP 171 (2015)





Lepton coupling is much less constrained and **must be taken into account**, but off-diagonal couplings seem to be ruled out

M. Bauer et al. JHEP 44 (2017)

Lowest-order coupling to **Electroweak sector**:

$$\mathcal{L} = -\frac{g_{aBB}}{4}aB_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{g_{aWW}}{4}a\boldsymbol{W}_{\mu\nu}\widetilde{\boldsymbol{W}}^{\mu\nu}$$

Where $\tilde{T}^{\mu\nu} = \varepsilon^{\alpha\beta\mu\nu}T_{\alpha\beta}$

$$\mathcal{L} \subset -\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{2}aF_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$g_{a\gamma\gamma} = g_{aBB}\cos^2\theta_w + g_{aWW}\sin^2\theta_w$$

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θ_w – Weinberg angle. **Flavour constraints** also require

$$g_{aWW} \ll g_{aBB}$$

E. Izaguirre et al.
Phys. Rev. Lett. 118 (2017)

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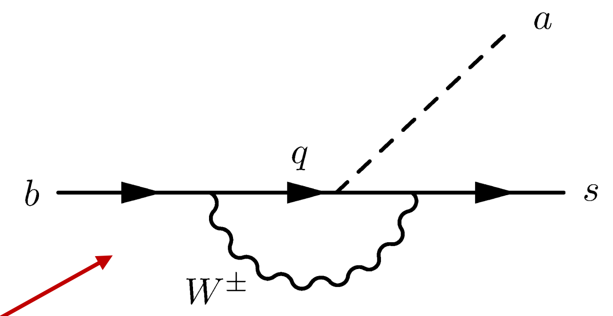

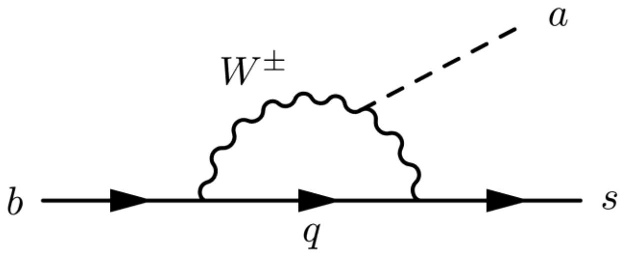

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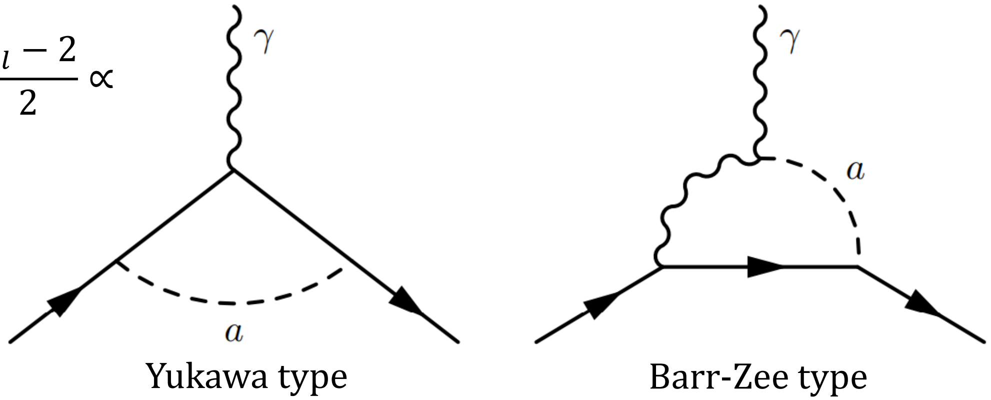

Other vital **constraints** are **from lepton dipole moments: tight bounds on CP-odd couplings**

Lepton universality ⇒ derivative coupling (**Goldstone theorem**) ⇒ **enhanced ALP-muon coupling**

$$g_{a\mu\mu} \approx \frac{m_\mu}{m_e} g_{aee}$$

⇒ resolving $(\boldsymbol{g-2})_{\boldsymbol{\mu}}$ without spoiling $(\boldsymbol{g-2})_{\boldsymbol{e}}$

The left (Yukawa-like) diagram from leptonic coupling gives a negative contribution to the $(g-2)_l$:

$$\Delta a_l^Y = -\frac{g_{all}^2}{8\pi^2}\frac{m_l^2}{m_a^2}\int_0^1 \frac{(1-z)^3}{z + m_l^2 m_a^{-2}(1-z)^2} dz < 0$$

The right diagram is proportional to $g_{all} g_{a\gamma\gamma}$ and its positive contribution can dominate:

$$\Delta a_l^{BZ} \simeq \frac{g_{all} m_l}{8\pi^2} \ln \Lambda^2 \left(g_{a\gamma\gamma} - \frac{4\sin^2\theta_W - 1}{4\sin\theta_W \cos\theta_W} g_{a\gamma Z} \right)$$

Λ requires UV-complete theory. However, large Λ means bigger effects and more stringent bounds

We set **Λ = 1 TeV – conservative estimate**

W. J. Marciano et al., Phys. Rev. D 94 (2016)
A. Pustyntsev and M. Vanderhaeghen, Phys. Rev. D 110 (2024)

Constraints from Lepton Magnetic Moments

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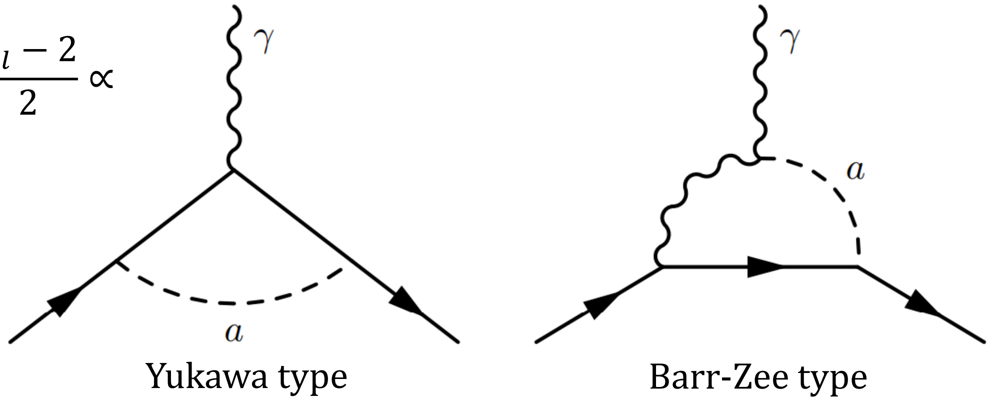

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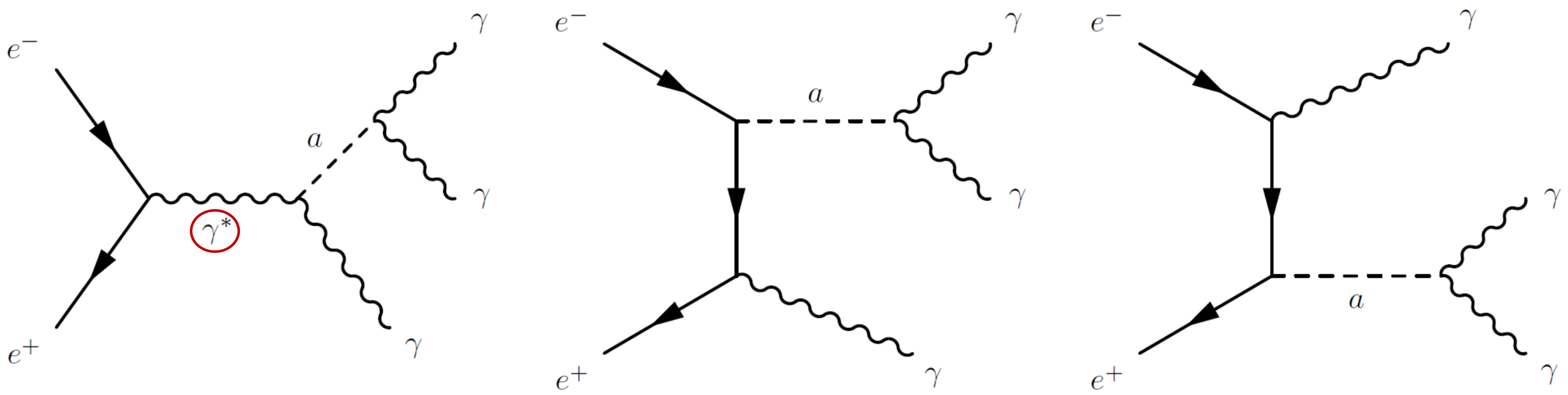
Searches at e^+e^- Colliders



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  narrow width approximation shrinks the phase space
- We look for a narrow spike in $m_{\gamma\gamma}$ or a recoil photon
- Different scaling of two couplings $\Rightarrow$ the **left** diagram is **less important** when $m_a^2 \ll s$

More contributions $\neq$ better constraints, they are weakened by the branching ratio!

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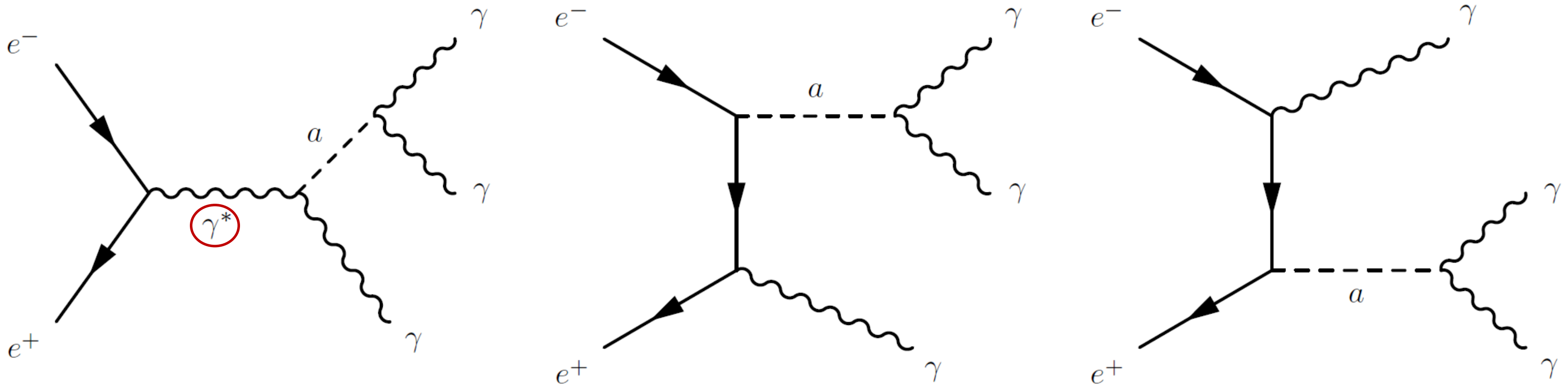

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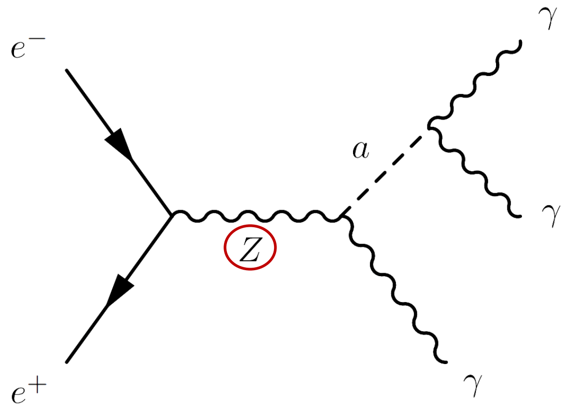
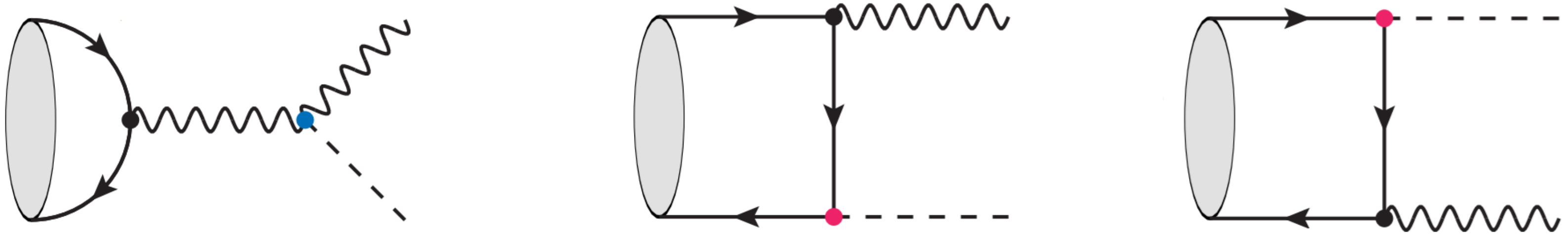


Searches at Vector Meson Decays



L. Merlo et al. JHEP 91 (2019)

BESIII applies a different search strategy, relying on $J/\psi \to 3\gamma$ decays, which produces a comparable signal strength to the non-resonant searches:

Advantages:

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- This type of search **could exploit** the large luminosity collected at $\sqrt{s} = m_{\Upsilon(4S)}$ at **Belle II** and potentially provide one of most stringent limit of a photon coupling

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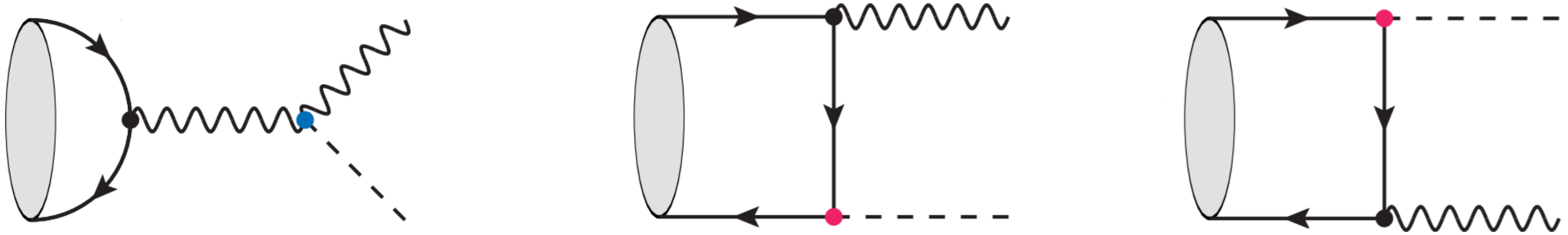

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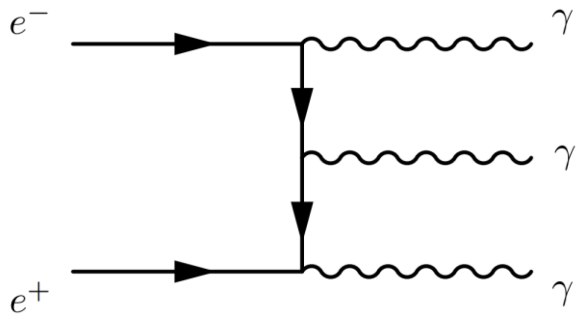

The 95% c.l. signal over background ratio

$$\frac{\sigma_{ALP}}{\sigma_{QED}} = \frac{2}{\sqrt{L \cdot \sigma_{QED}}}$$

Reach$[g_{a\gamma\gamma}] \propto \sqrt[4]{L}$ – **huge luminosity** L to get a signal and an **optimized event selection** procedure

- **A small portion** of background also arises from $e^+e^- \to e^+e^-\gamma$, etc.

- The search is additionaly complicated by **peaking backgrounds** from pseudoscalar mesons $\boldsymbol{\pi^0, \eta}$, …

- **Low-mass ALPs** are highly boosted, the decay photons merge into one – **very challenging**. The main obstacle in accessing the low-mass ALP region

The strongest limit in this region so far is from **LEP** constraints for $Z \to 2\gamma$

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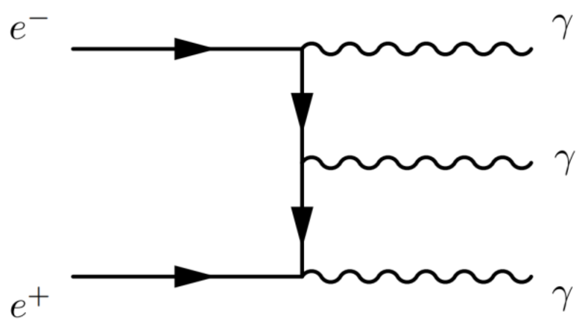

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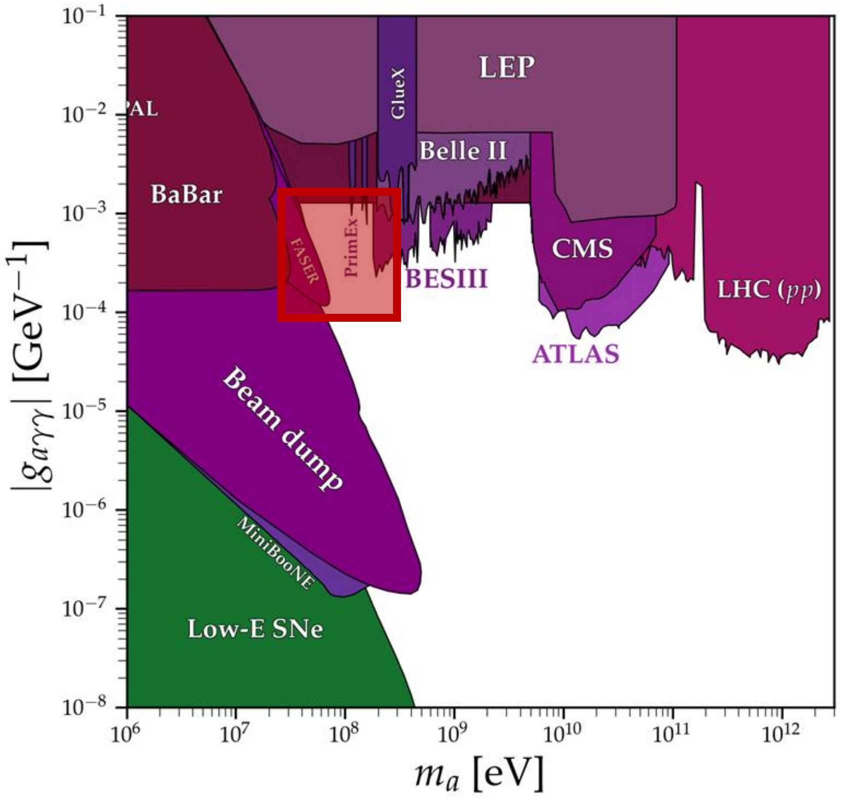

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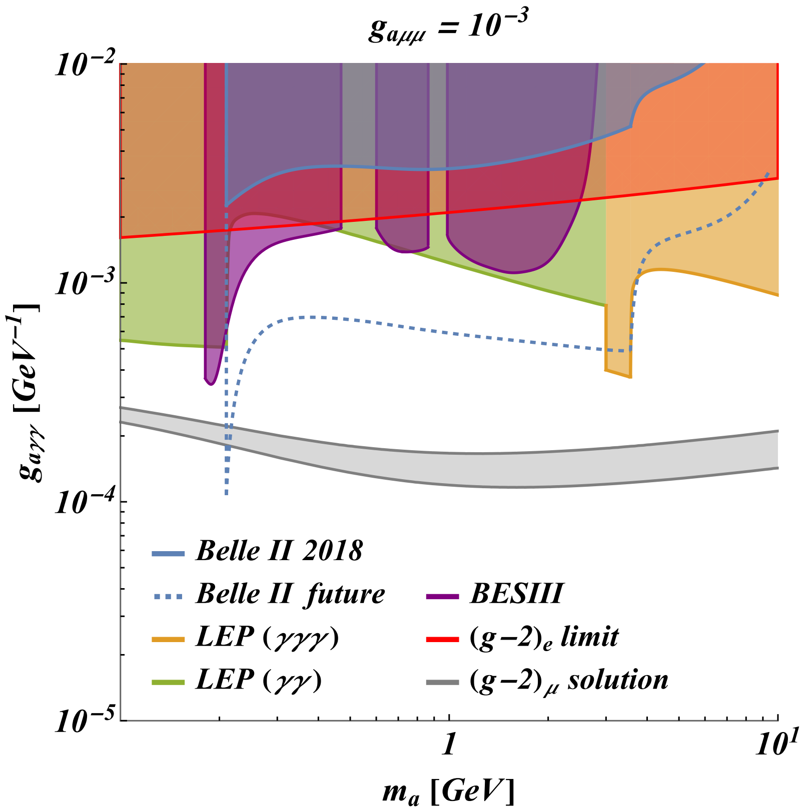
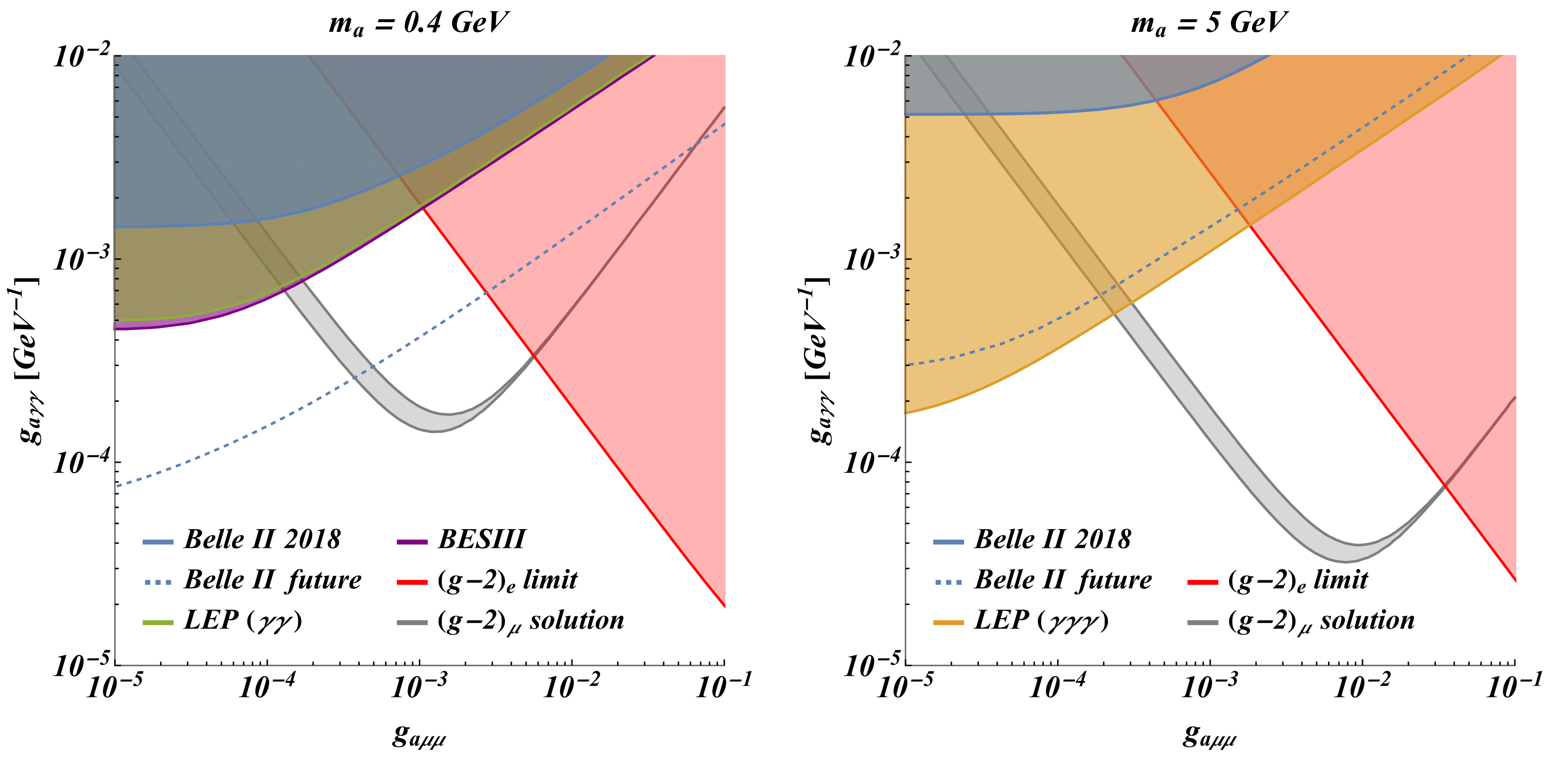
Results for Pseudoscalar – before 2025 $(g-2)_\mu$

Projection onto the $(m_a, g_{a\gamma\gamma})$ plane



Projection onto the $(g_{a\mu\mu}, g_{a\gamma\gamma})$ plane



1. Despite a significant improvement in the near future, still **no full access** $(g-2)_\mu$-relevant parameter space
2. BESIII and Belle II access to the **lower mass region is limited by the spatial resolution** of a di-photon pair
3. Lepton universality is assumed for collider bounds and $(g-2)_e$
4. **LEP data at Z-pole are still highly competitive**

A. Pustyntsev and M. Vanderhaeghen, Phys. Rev. D 110 (2024)

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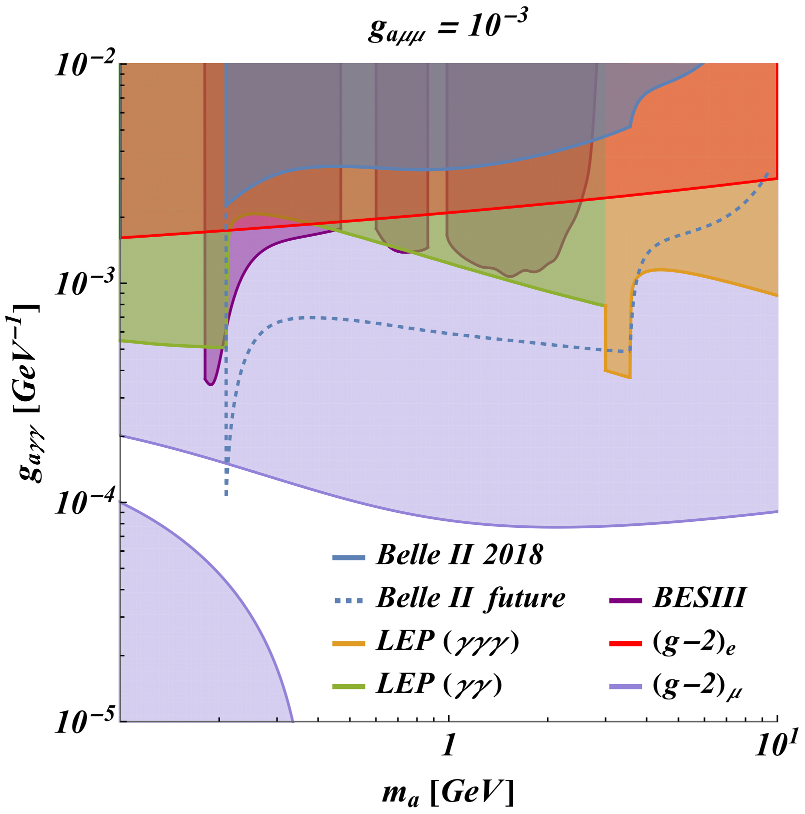

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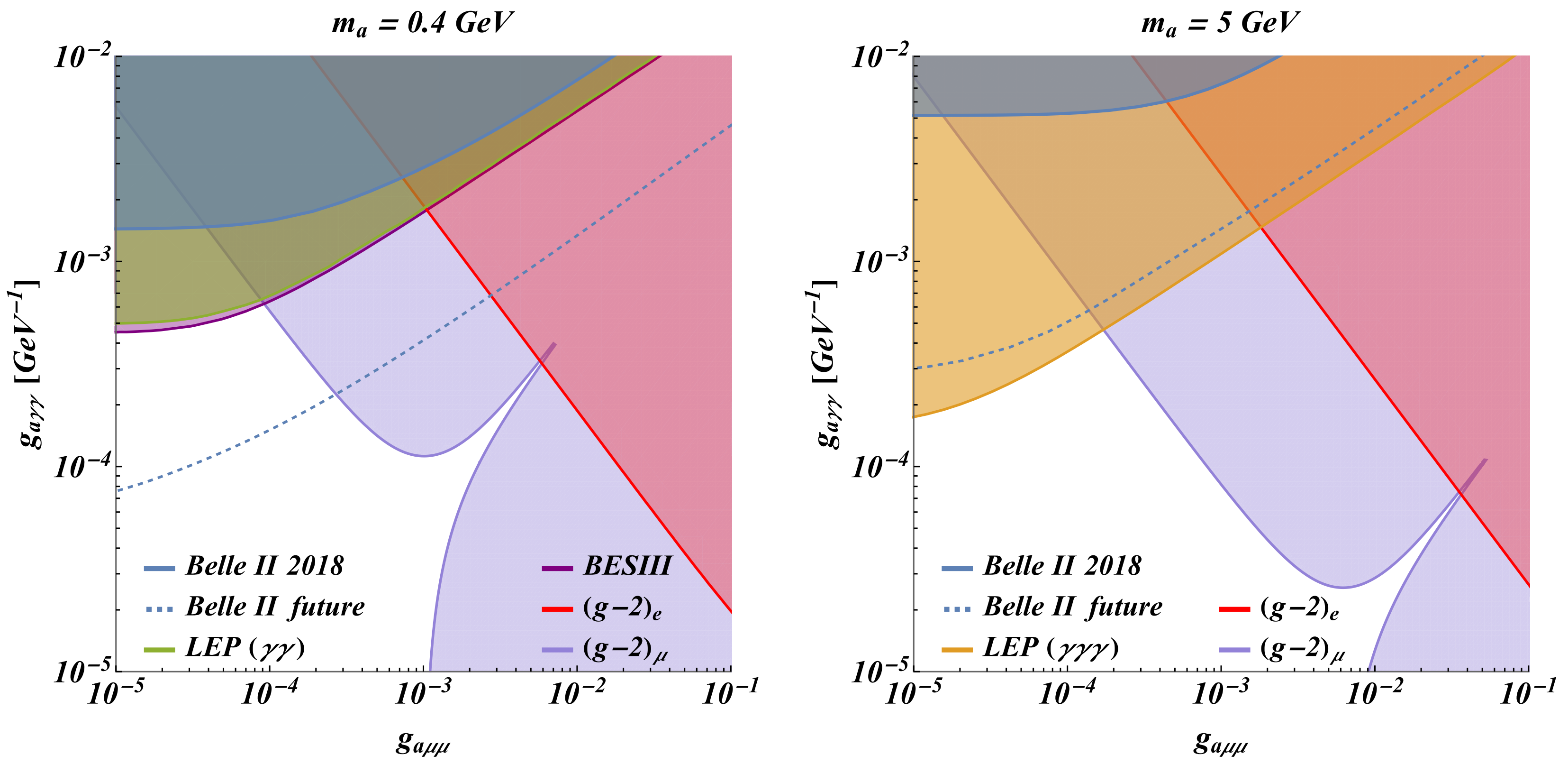


1. If $(g-2)_\mu$ discrepancy is solved within the SM ⇒ **one of the most stringent constraints** on the BSM parameter space
2. **No specific model assumption** to derive these bounds
3. Error $\Delta a = 63.7 \times 10^{-11}$ is **dominated by the theory uncertainity**
4. **Similar strength constraints can be found for a scalar particle**

arXiv:2506.17750 (accepted for publication in PRD)

A Note on Dark Photons

Dark photons, mediating **gauge forces within the dark sector**, are another commonly discussed BSM scenario

$$\mathcal{L} = \varepsilon e \cdot \bar{\psi}(\gamma A')\psi$$

M. Fabbrichesi et al., arXiv:2005.01515

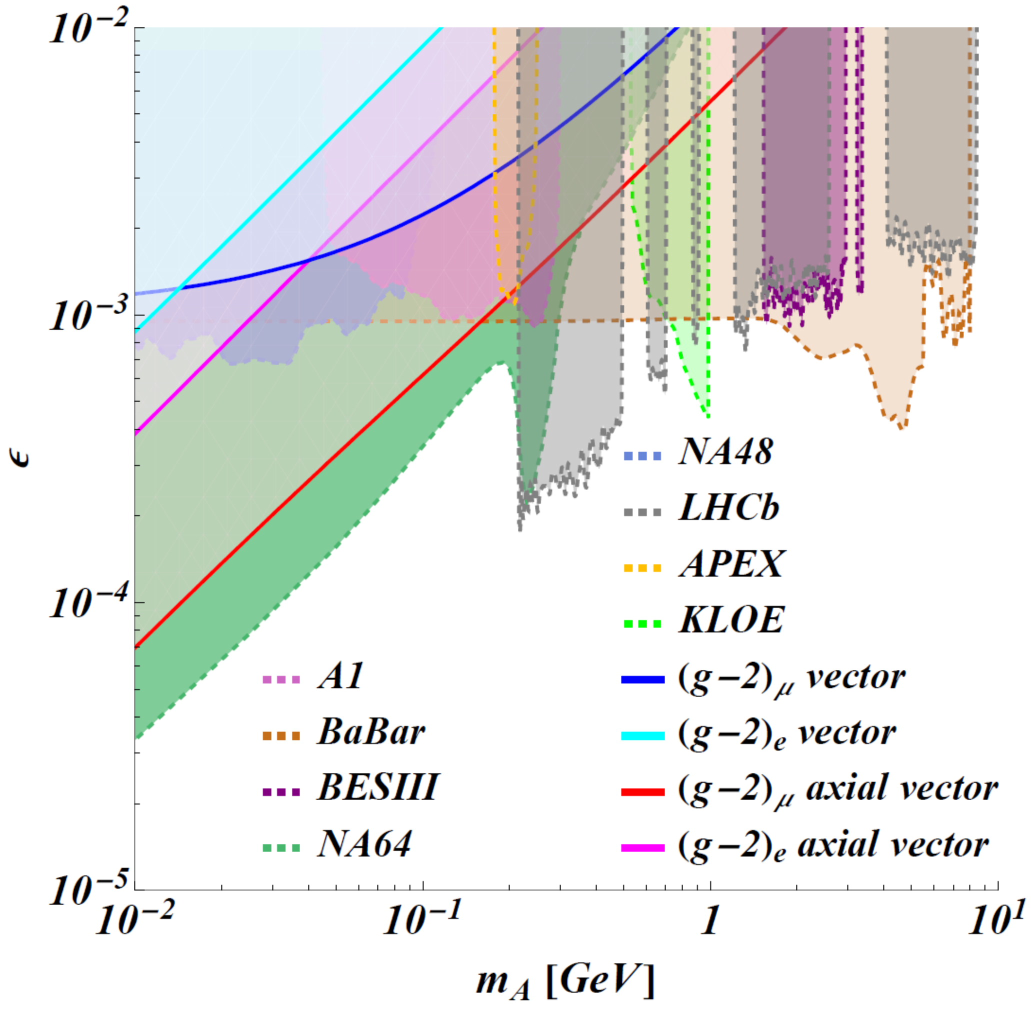
$$\Delta a = \frac{\alpha \varepsilon^2 m_l^2}{\pi} \int_0^1 \frac{z^2(1-z)}{m_l^2 z^2 + m_A^2(1-z)} dz > 0$$

ε is a mixing parameter between dark and SM photons

Pseudovectors are also of interest in many models (Δa enhanced by the axial anomaly)

$$\mathcal{L} = \varepsilon e \cdot \bar{\psi}\gamma^5(\gamma A')\psi$$

$$\Delta a = -\frac{\alpha \varepsilon^2 m_l^2}{\pi} \int_0^1 \frac{z(1-z)(4-z) + 2\frac{m_l^2}{m_A^2} z^3}{m_l^2 z^2 + m_A^2(1-z)} dz < 0$$



While beam dump and collider bounds often rely on specific model assumptions, $(g-2)_l$ **constraints are assupmtion-free**

BSM Searches at MESA

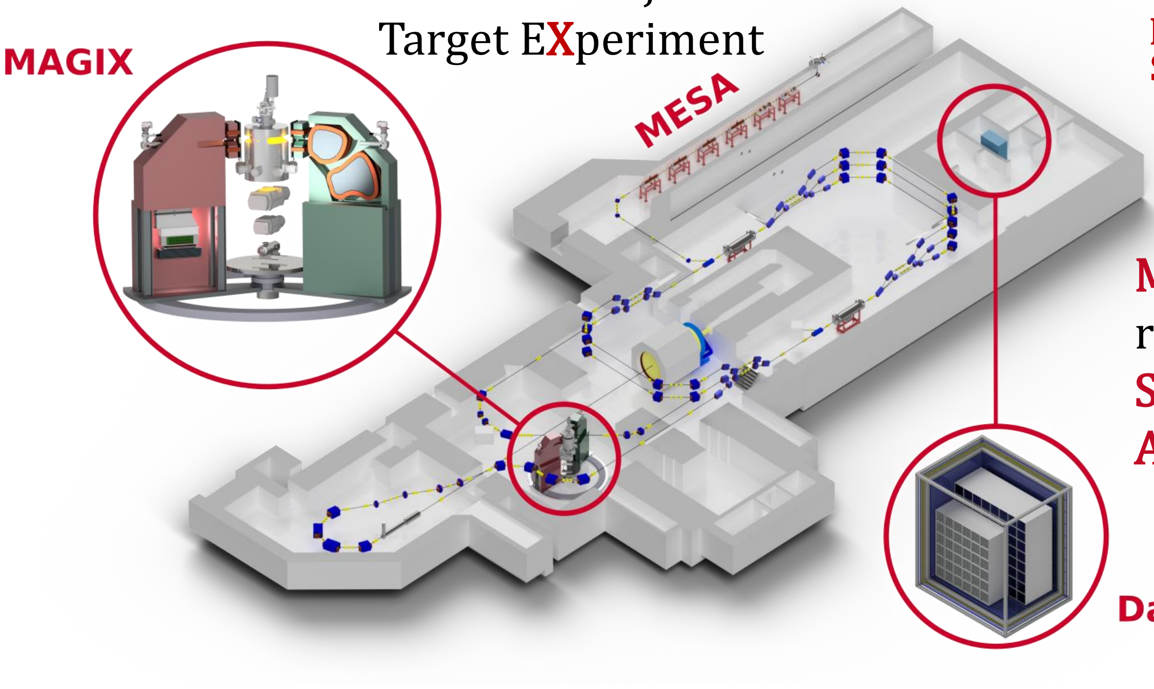
MESA beam dump setup **is perfect** for scanning the low-energy range for the New Physics:

1) Very high **intensity**
2) State-of-the-art **precision**
3) **Uncertainties** are under **control**

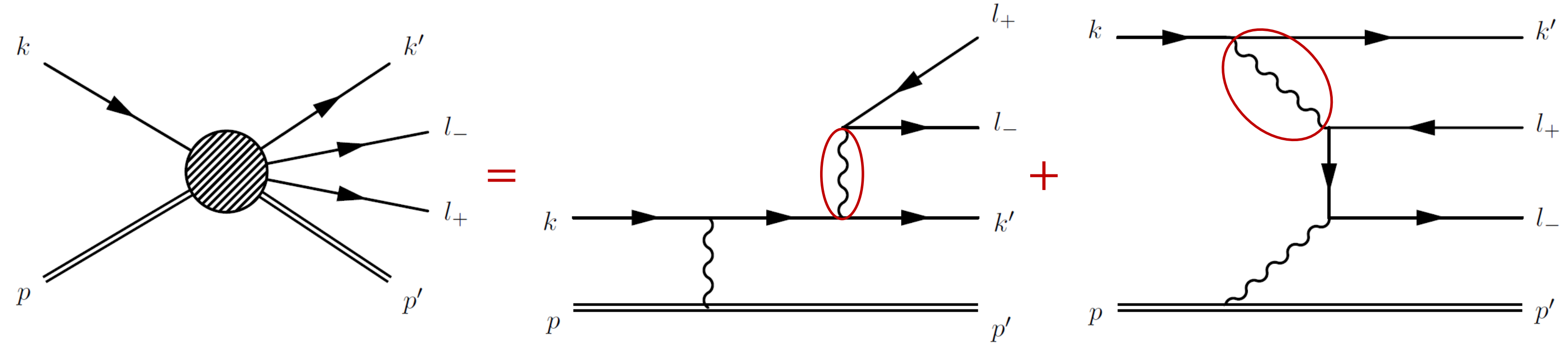
Ubiquitous way to **probe various quantum numbers**, an insight < 100 MeV mass range

MAinz Gas Injection Target EXperiment

For more details – please see the talk of Sebastian Stengel



Mainz Energy-recovery Superconducting Accelerator



Timelike production

Spacelike production

can be (pseudo)scalar, (pseudo)vector, …

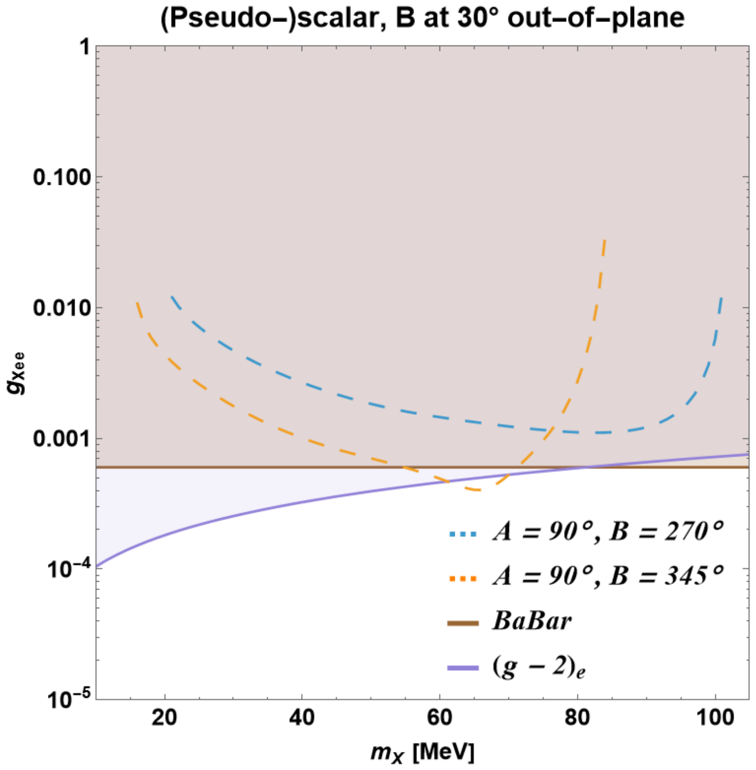
Weak interacting ⇒ stable ⇒ tiny decay width, **bump search** in the invariant mass distribution

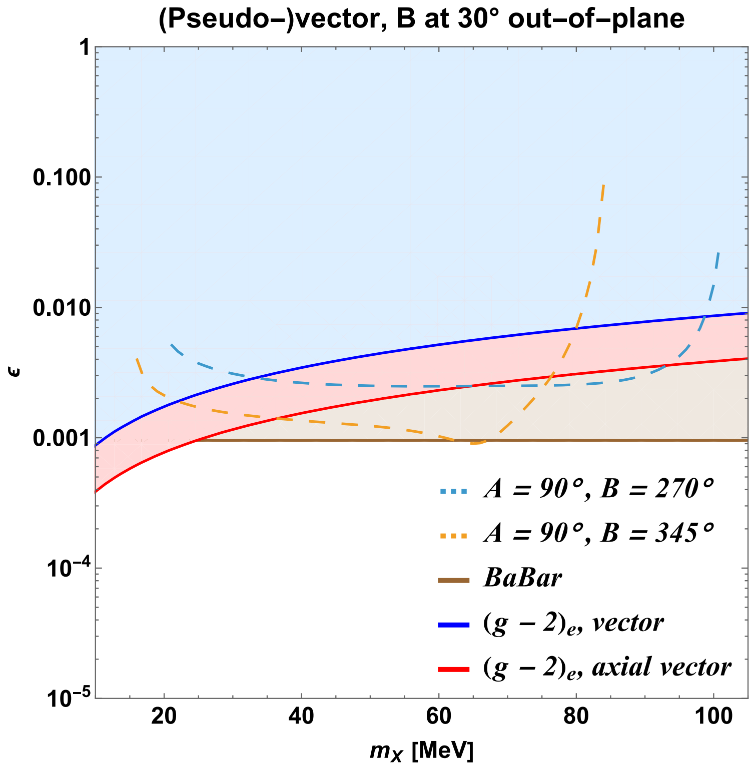
Spectrometers A and B are positioned to minimize the background, but…

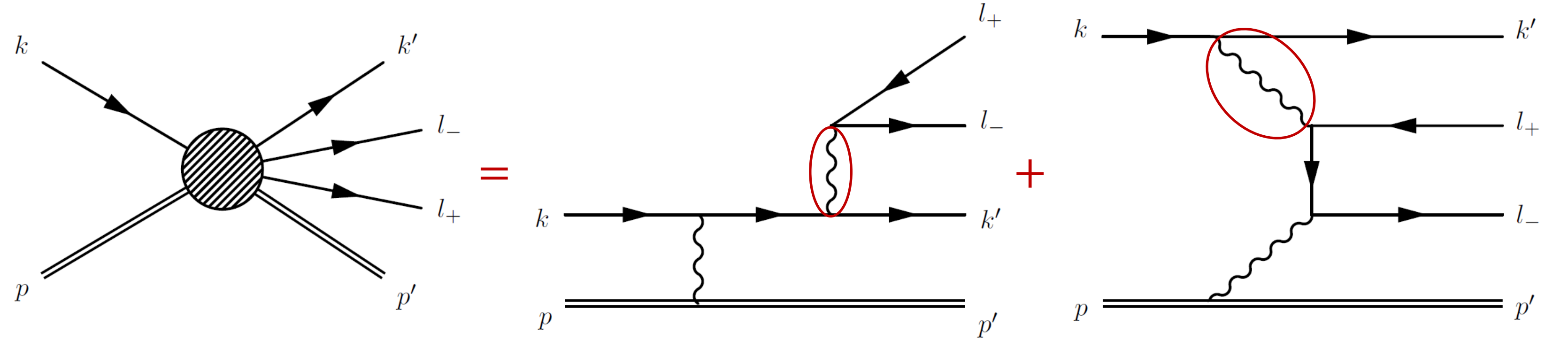
1) **Bottlenecked by luminosity** (factor of two improvement = sixteen times more collected data)

2) **Out-of-plane kinematics** for best signal-over-background ratio

3) **Challenging to improve** upon the BaBar bounds on missing energy and $(g-2)_e$





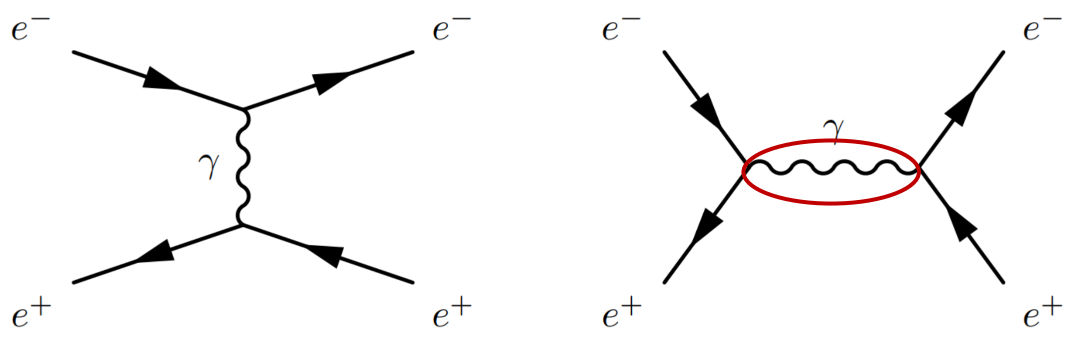


100 days of beam time for all projections (preliminary results)

^{181}Ta target ($Z = 73$), similar to A1 analysis Phys. Rev. Lett. 112 (2014)

Searches in Bhabha Scattering

JLab is to launch the high-energy polarized **positron beam**



- Scattering against **atomic electrons**, $\sqrt{s} \approx 80$ MeV
- **BSM** particles can be **exchanged**
- Allows for **much more efficient** and **less luminosity**-dependent strategy via measuring spin asymmetries
- Utilizing C, P and T invariance, we parameterize:

$$M = \sum_{i=S,P,V,A,T} A_i(s,t) \cdot \bar{v}' \Gamma_i \, v \cdot \bar{u} \, \Gamma_i \, u'$$

Only 5 independent amplitudes entering this process!

$$\Gamma_S = \mathbb{1}, \qquad \Gamma_P = \gamma^5, \qquad \Gamma_V = \gamma^\mu, \qquad \Gamma_A = \gamma^5\gamma^\mu, \qquad \Gamma_T = \sigma^{\mu\nu}$$

A single spin asymmetry:

No contribution from a pseudoscalar (?)

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{\sqrt{stu}}{4\pi s \sigma_0} \mathrm{Im}[(A_S - A_A)(A_V^* + 2A_T^*)]$$

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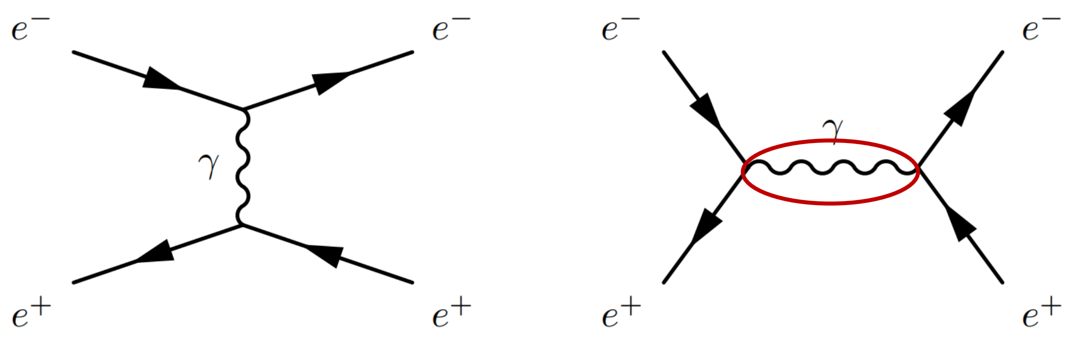

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Searches in Bhabha Scattering

Master student project:
Muthubharathi Subbulakshmi

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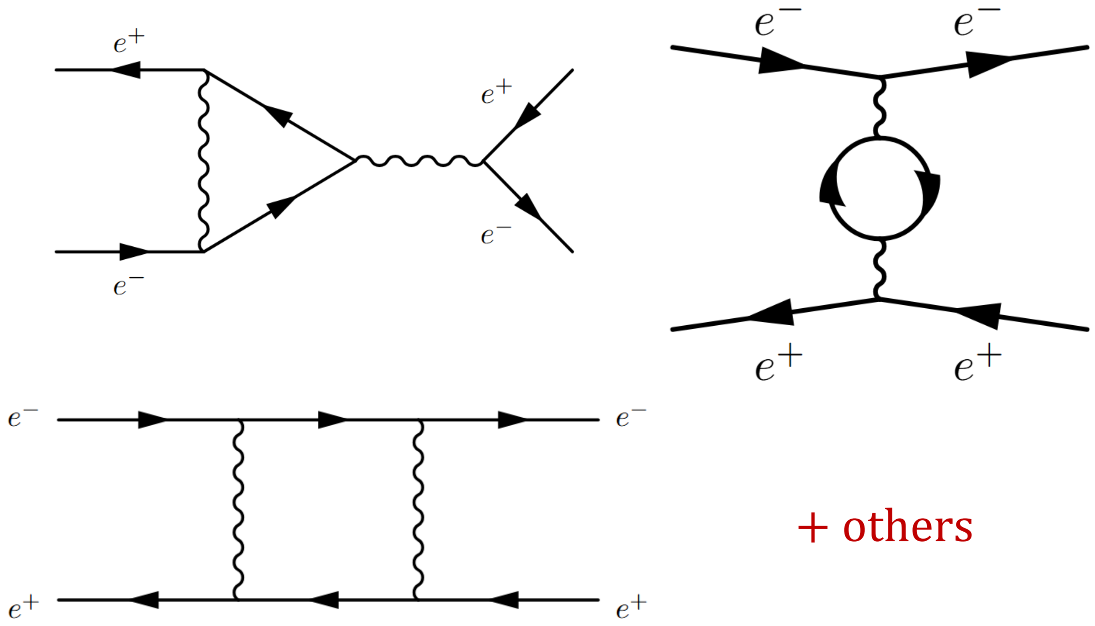
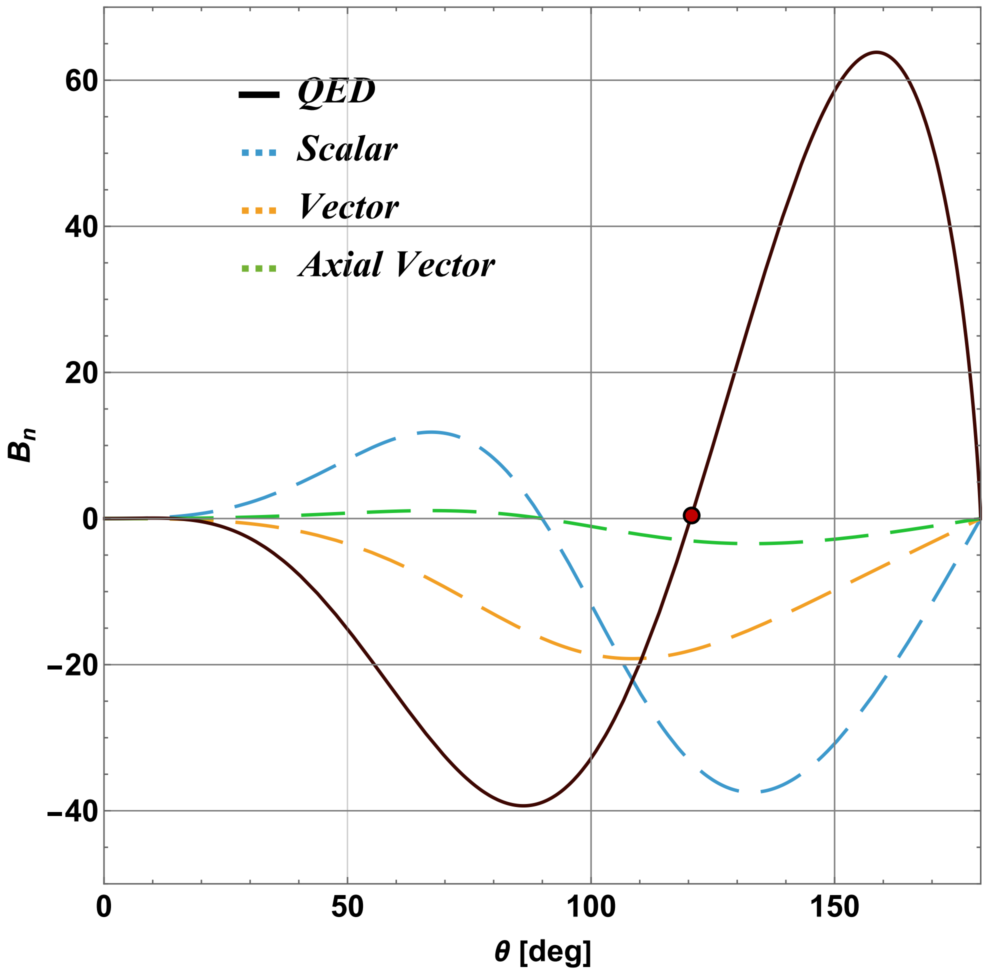
Requires at least **full one-loop calculation**



+ others



$g_{see} = 10^{-4}, \quad \varepsilon = 10^{-4}, \quad \sqrt{s} = 78.3$ MeV

QED contribution: C. Fronsdal and B. Jakšić, Phys. Rev. 121, 916 (1961)

Conclusions

- Axions and ALPs in the **MeV-GeV mass range are viable** BSM candidates, with current constraints leaving open a lot of parameter space

- **Further improvements anticipated** from both theory and experiment perspectives

- Measurements of $(\boldsymbol{g-2})_{\boldsymbol{l}}$ **remains a key benchmark** for any potential BSM scenario

A lot of possible directions for further analyses:

- **BSM search at MESA** from $e^- Z \to e^- Z e^- e^+$: ubiquitous way to probe mediators with various quantum numbers

- **JLab polarized positrons program** – setting tighter bounds via beam asymmetry measurements

Σας ευχαριστώ πολύ για την προσοχή σας!

Vielen Dank für Ihre Aufmerksamkeit!

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

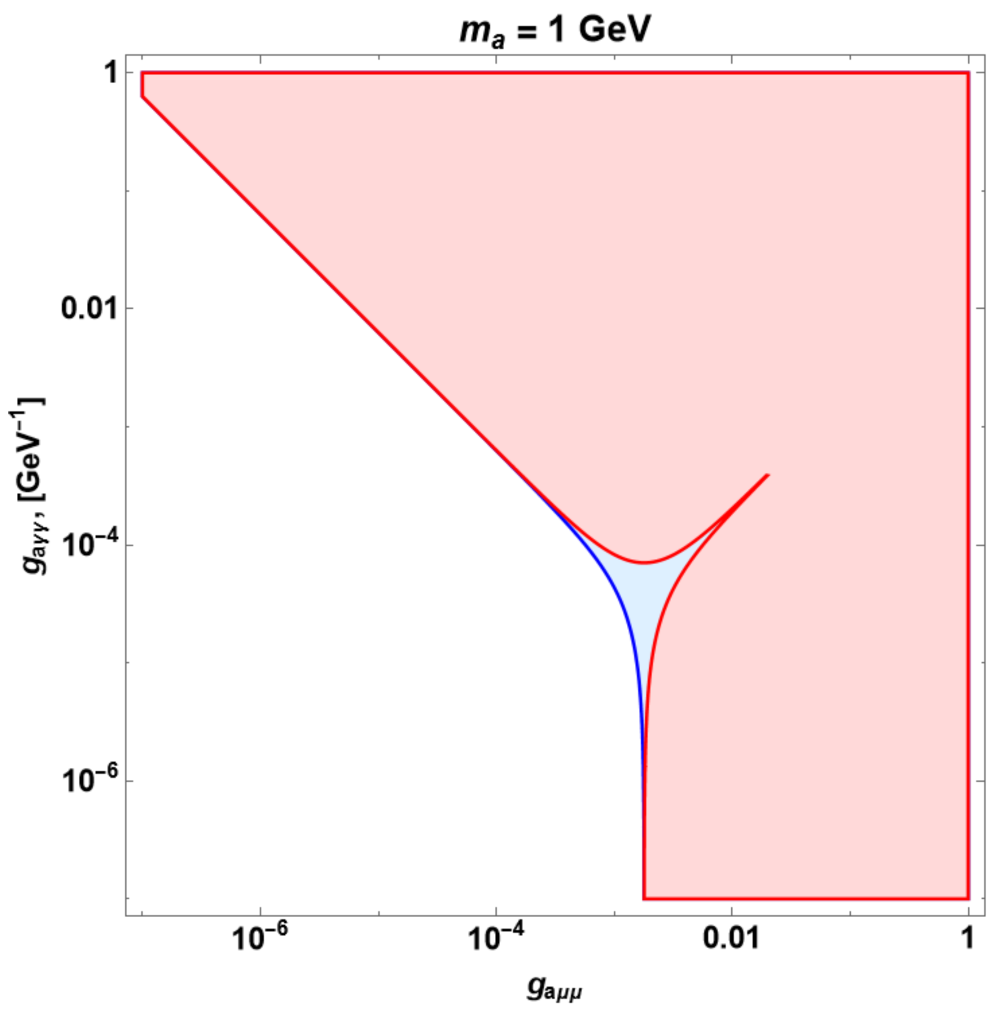
October 28, 2025

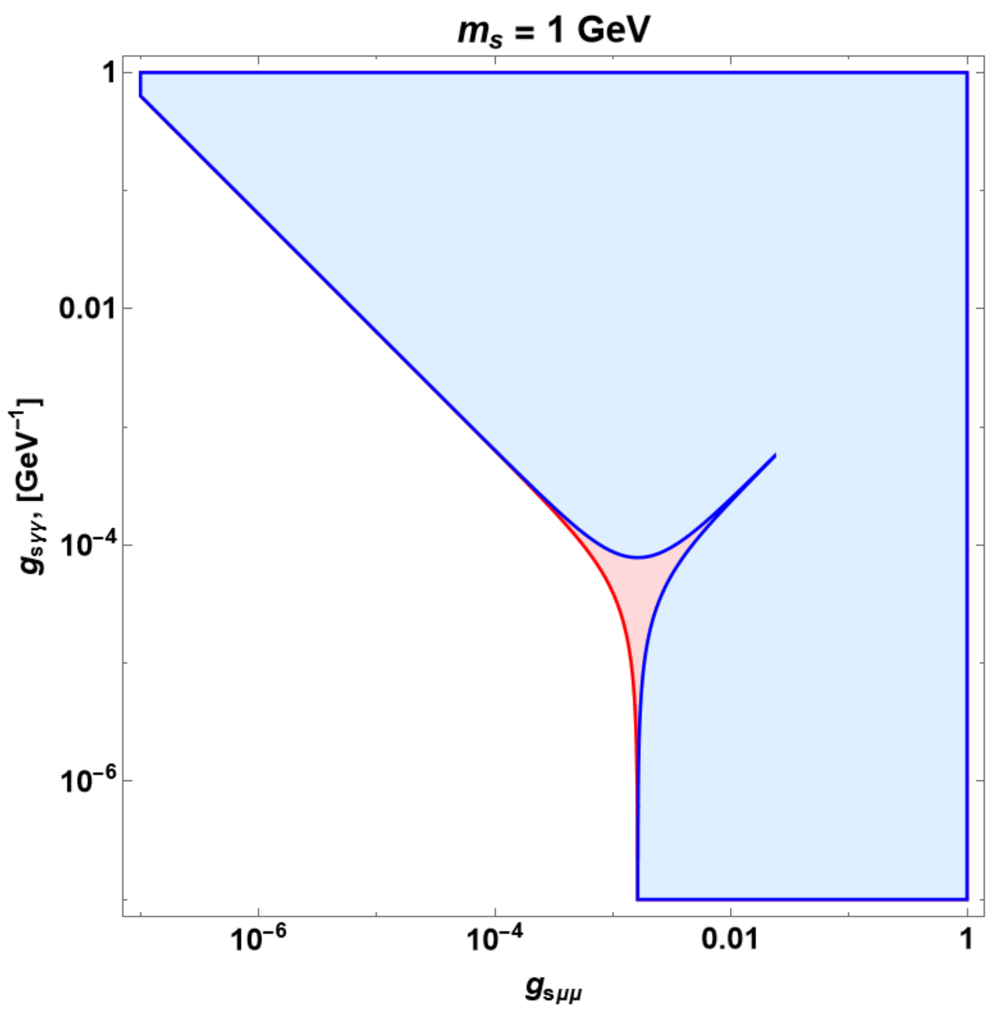
Research Unit FOR 5327

Photon-photon interactions in the Standard Model and beyond

Exploiting the discovery potential from MESA to the LHC

Cancellation vs Enahcement





Red refers to $g_{X\mu\mu}g_{X\gamma\gamma} > 0$ scenario, blue stands for to $g_{X\mu\mu}g_{X\gamma\gamma} > 0$. The visible thin line represents the situation where the two contributions cancel each other out. Cancellation provides weaker constraints

Why So Heavy?

MeV-GeV mass range is typically not associated with axions, but this is **just a question of a clever model-building**:

1) A viable **strong CP problem** solution is not only **possible** with MeV mass axion
2) … But also can simultaneously **generate enough baryon asymmetry**
3) Just a **right amount of dark matter** is included
4) Interesting **interplays with Higgs physics** for even heavier ALPs

ABSTRACT: We demonstrate that the observed cosmological excess of matter over anti-matter may originate from a heavy QCD axion that solves the strong CP problem but has a mass much larger than that given by the Standard Model QCD strong dynamics. We investigate a rotation of the heavy QCD axion in field space, which is transferred into a baryon asymmetry through weak and strong sphaleron processes. This provides a strong cosmological motivation for heavy QCD axions, which are of high experimental interest. The viable parameter space has an axion mass m_a between 1 MeV and 10 GeV and a decay constant $f_a < 10^5$ GeV, which can be probed by accelerator-based direct axion searches and observations of the cosmic microwave background.

Dark Matter through the Axion Portal

Yasunori Nomura and Jesse Thaler
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720 and Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

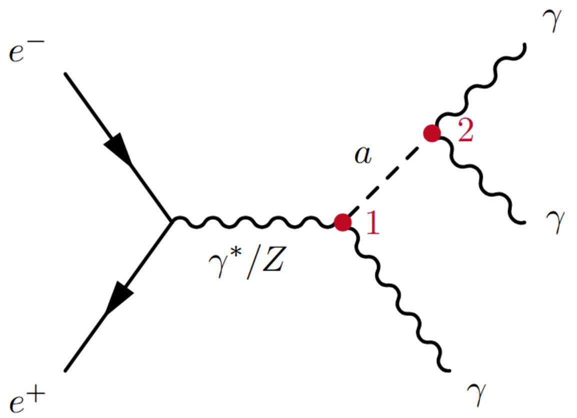
Motivated by the galactic positron excess seen by PAMELA and ATIC/PPB-BETS, we propose that dark matter is a TeV-scale particle that annihilates into a pseudoscalar "axion." The positron excess and the absence of an anti-proton or gamma ray excess constrain the axion mass and branching ratios. In the simplest realization, the axion is associated with a Peccei-Quinn symmetry, in which case it has a mass around 360 – 800 MeV and decays into muons. We present a simple and predictive supersymmetric model implementing this scenario, where both the Higgsino and dark matter obtain masses from the same source of TeV-scale spontaneous symmetry breaking.

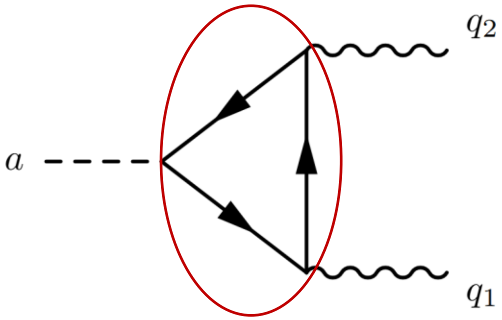
A viable QCD axion in the MeV mass range

Daniele S. M. Alves[1,2,3,*] and Neal Weiner[1,†]
[1]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2]*Department of Physics, Princeton University, Princeton, NJ 08544*
[3]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
(Dated: September 15, 2020)

"Give me an axion, and I'll find a model for it"

Loop-Induced Effects





This has **important implications** for the physics of ALPs **in hot and dense environments**, such as supernovae

At e^+e^- collider energies the effect, however, **becomes negligible** – the correction is too small

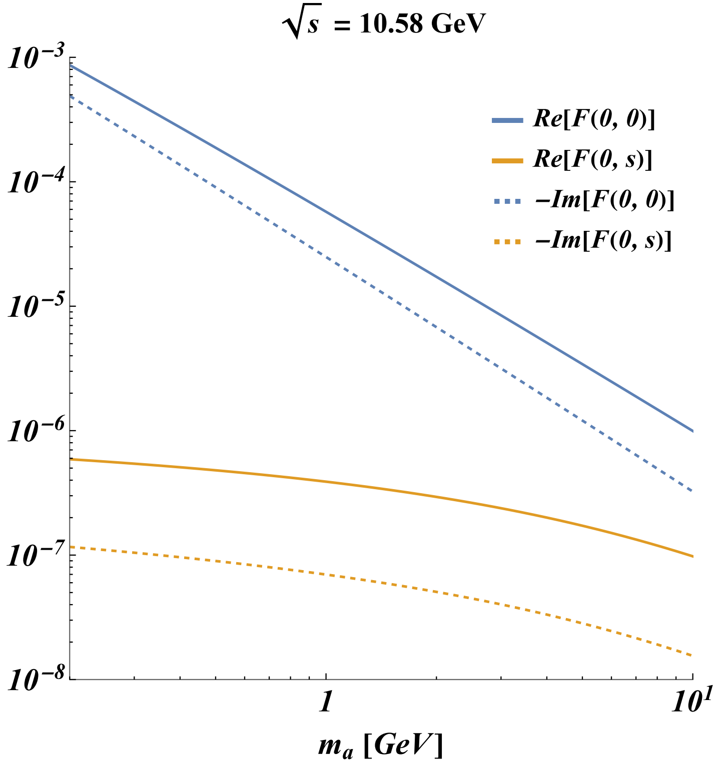
An important observation is that **couplings** at 1 and 2 are **essentially different** couplings, as the correction to $g_{a\gamma\gamma}$ induced by the electron triangle is

$$\delta g_{a\gamma\gamma} = \frac{\alpha g_{aee}}{\pi m_e}\left[1 + F(q_1^2, q_2^2)\right]$$

Related to the Passarino-Veltman triangle function C_0

Is significantly different depending on whether a **Primakoff-like process** occurs, involving an off-shell photon, $q_1^2 = 0, q_2^2 \neq 0$, or the **ALP decays into a photon pair** with $q_1^2 = q_2^2 = 0$

Ricardo Z. Ferreira et. al JCAP11(2022)057

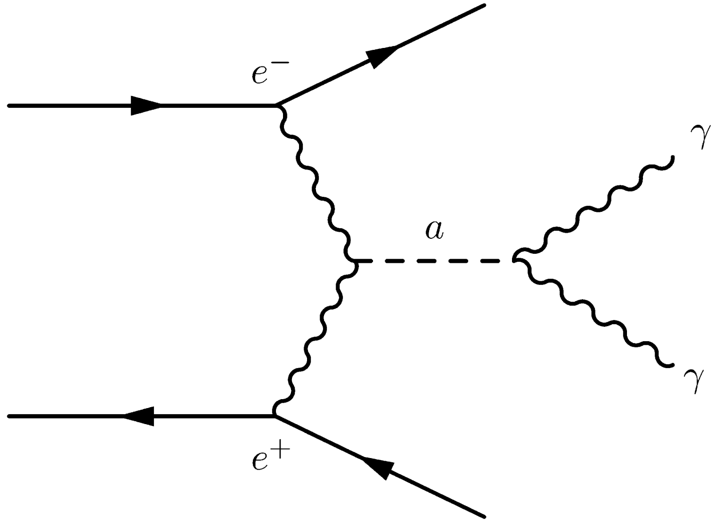


...Nevertheless, it reminds us that **we only have sensitivity to effective couplings**!

$1/m_e$ enhancement in $\delta g_{a\gamma\gamma}$ is also **meaningless** unless the tree-level $g^0_{a\gamma\gamma}$ coupling is fixed

A. Pustyntsev and M. Vanderhaeghen, EPJ C 84, 546 (2024)

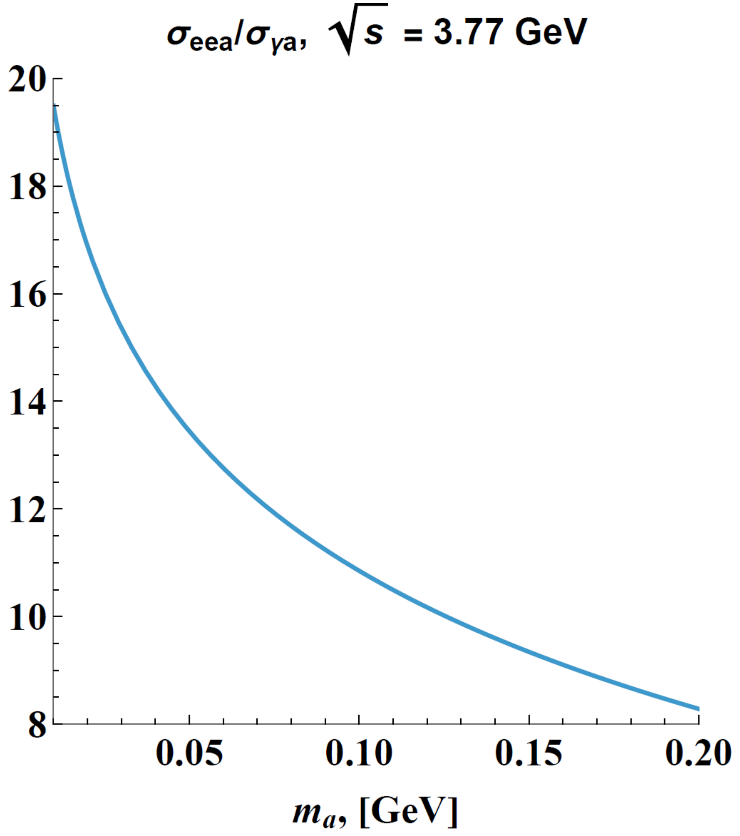
Photon Fusion



Another potential search channel is **photon fusion**:

1) ALPs production at rest is enhanced – two photons are back-to-back
2) Most photons end up in the electromagnetic calorimeter
3) And, most importantly, at low m_a it dominates over the other ALP production contributions

W. J. Marciano et al., Phys. Rev. D 94 (2016)



Despite all of that, **not investigated so far** – extremely complicated event selection and large backgrounds, but at the same time very promising

Same challenges as before:

M. Dolan et al. JHEP 94 (2017)

1) Charged tracks reconstruction – to be improved, multiple challenges
2) Irreducible peaking backgrounds from π_0 production

Addressing these issues could significantly **tighten bounds on ALP-photon coupling** in the region where the existing constraints are especially loose