# SEARCHES FOR AXIONS IN PROTON-PROTON AND LEAD-LEAD COLLISIONS AT ENERGIES OF 5.02 TEV AND 13 TEV

Serhii Chernyshenko, Tatiana Obikhod

Institute for Nuclear Research

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# Motivation

- A large number of (in)direct hints at new physics: ν-oscillations, $(g\text{-}2)_\mu$, dark matter, etc.
- Light and weakly bound (pseudo)scalar particles are an interesting alternative to heavy new physics.
- There are many models for axion-like particles (ALPs): QCD axion, flavon, familon, composite Higgs.
- ALP were postulated in 1977 to solve soft asymmetry problem
- The ALP are Nambu-Goldstone pseudo-bosons associated with spontaneous symmetry breaking
- The ALP can be coupled to different sectors of the SM. Different types of searches at colliders will coming soon!

# ALP Lagrangian

ALPs: the mass term

Part of Lagrangian which connected to ALP interaction with fermions

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{f} \sum_F \bar{\psi}_F \mathbf{c}_F \gamma^\mu \psi_F$$

$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W^A_{\mu\nu} \tilde{W}^{\mu\nu,A} + c_{BB} \frac{\alpha_1}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

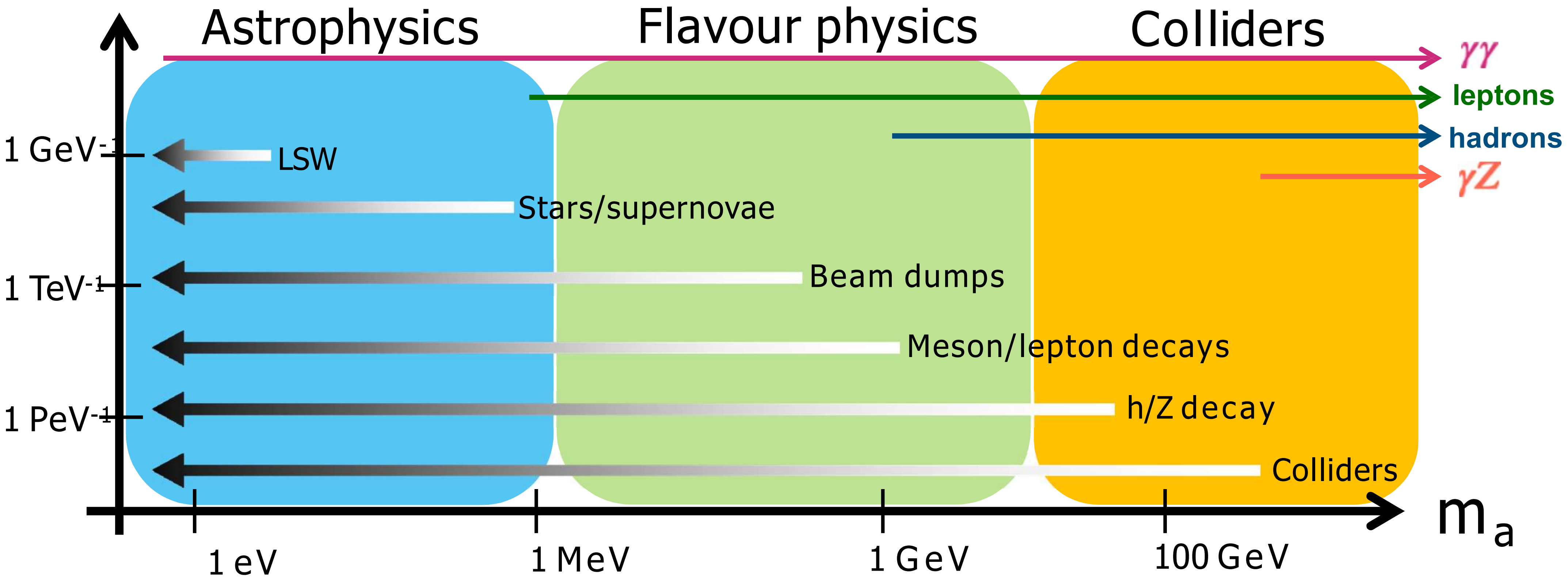
A scale-independent part of the Lagrangian that reflects the interaction of axions with gauge particles

$$\tilde{V}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} V_{\alpha\beta}$$

# Energy limits of axion searches

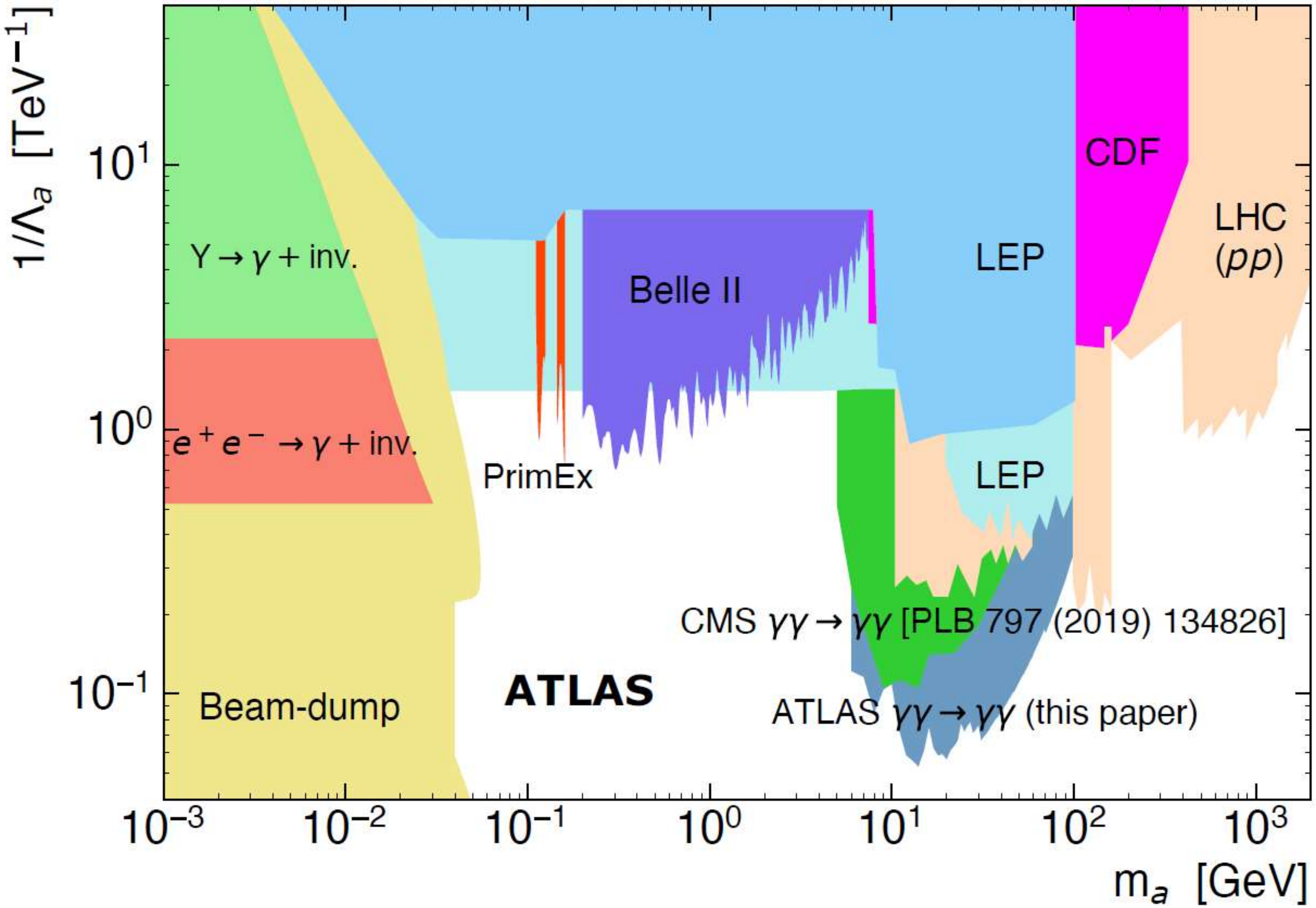
ALP mass region is very wide from eV to GeV

The mass about 1 eV is connected to Astrophysics, from 1 MeV to 10 GeV is connected to Flavour physics, and over 10 GeV is Collider physics




Source: M. Schnubel - Overview for Axions and ALPs

# Benchmark scenarios

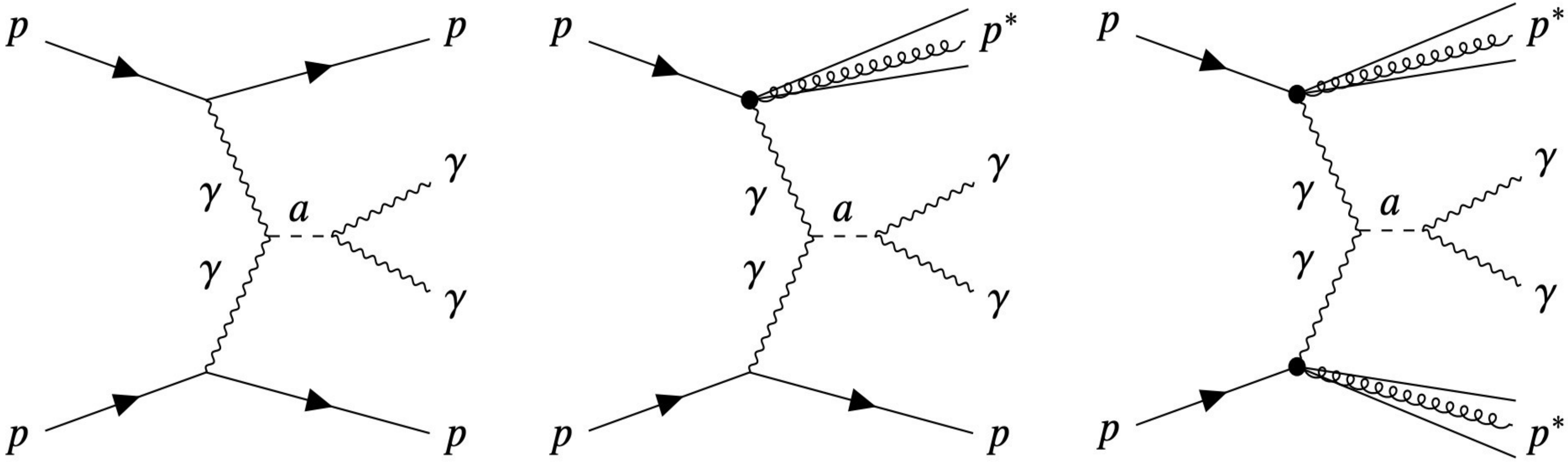



Compilation of exclusion limits at 95% Confidence Levels (CL) in the ALP-photon coupling (1/Λa) versus ALP mass (ma) plane obtained by different experiments.

The exclusion limits labelled "LHC (pp)" are based on pp collision data from ATLAS and CMS.

All measurements assume a 100% ALP decay branching fraction into photons.

# Feynman diagrams for the production of an axion in pp collisions with decay to 2 γ




- Strict selection requirements :
  - $E_T > 22$ GeV, $|\eta| < 2.37$
  - $p_T > 40$ GeV
  - $|\Delta\xi| = |\xi_{AFP} - \xi_{\gamma\gamma}| < 0.004 + 0.1\xi_{\gamma\gamma}$, where $\xi = 1 - E_{scattered}/E_{beam}$
  - **The interaction constant ALP coupling was used**: $1/\Lambda \sim 4*10^{-3}$ GeV (arXiv: 2304.10953)
  - In the simulations, the ALP was set as a pseudoscalar particle

# 4 models in SuperChic v4.2 simulations of ALP production processes

In the Goode-Walker formalism in QCD, the cross section for the pomeron exchange between two dipoles is the following:

$$\sigma_{ab} = \int \frac{dk_T^2}{k_T^4} \alpha_s^2 \left[1 - F_a(4k_T^2)\right] \left[1 - F_b(4k_T^2)\right].$$

There is the description of the models using a two-channel eikonal and parameterisation of the form factor of each state in the form:

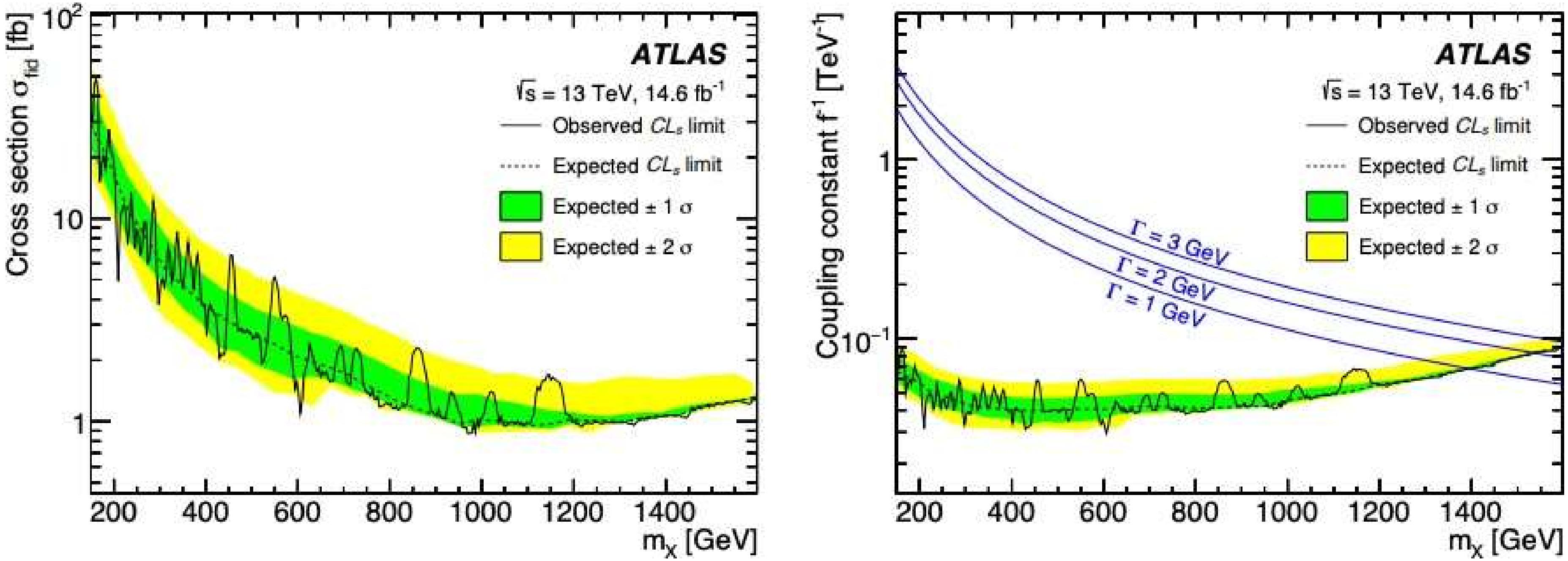
$$F_i(t) = \exp(-(b_i(c_i - t))^{d_i} + (b_i c_i)^{d_i}),$$

The total diffractive cross section with elastic component, SD - the single dissociation and DD – diffractive dissociation components, has a form (used in MC simulations):

$$\sigma_{el+SD+DD} = \int d^2b \sum_{i,k} |a_i|^2 |a_k|^2 |(1 - e^{-\Omega_{ik}(b)/2})|^2,$$

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $\Delta$ | 0.13 | 0.115 | 0.093 | 0.11 |
| $\alpha'_P$ (GeV$^{-2}$) | 0.08 | 0.11 | 0.075 | 0.06 |
| $\sigma_0$ (mb) | 23 | 33 | 60 | 50 |
| $\lambda$(1.8 TeV) | 0.2 | 0.17 | 0.19 | 0.19 |
| $\gamma$ | 0.55 | 0.4 | - | - |
| $k_1/k$(1.8 TeV) | - | - | 1.03 | 1.3 |
| $k_2/k$(1.8 TeV) | - | - | 4.8 | 6.0 |
| $\lvert a_1\rvert^2$ | 0.46 | 0.25 | 0.24 | 0.25 |
| $b_1$ (GeV$^{-2}$) | 8.5 | 8.0 | 5.3 | 7.2 |
| $c_1$ (GeV$^2$) | 0.18 | 0.18 | 0.35 | 0.53 |
| $d_1$ | 0.45 | 0.63 | 0.55 | 0.6 |
| $b_2$ (GeV$^{-2}$) | 4.5 | 6.0 | 3.8 | 4.2 |
| $c_2$ (GeV$^2$) | 0.58 | 0.58 | 0.18 | 0.24 |
| $d_2$ | 0.45 | 0.47 | 0.48 | 0.48 |

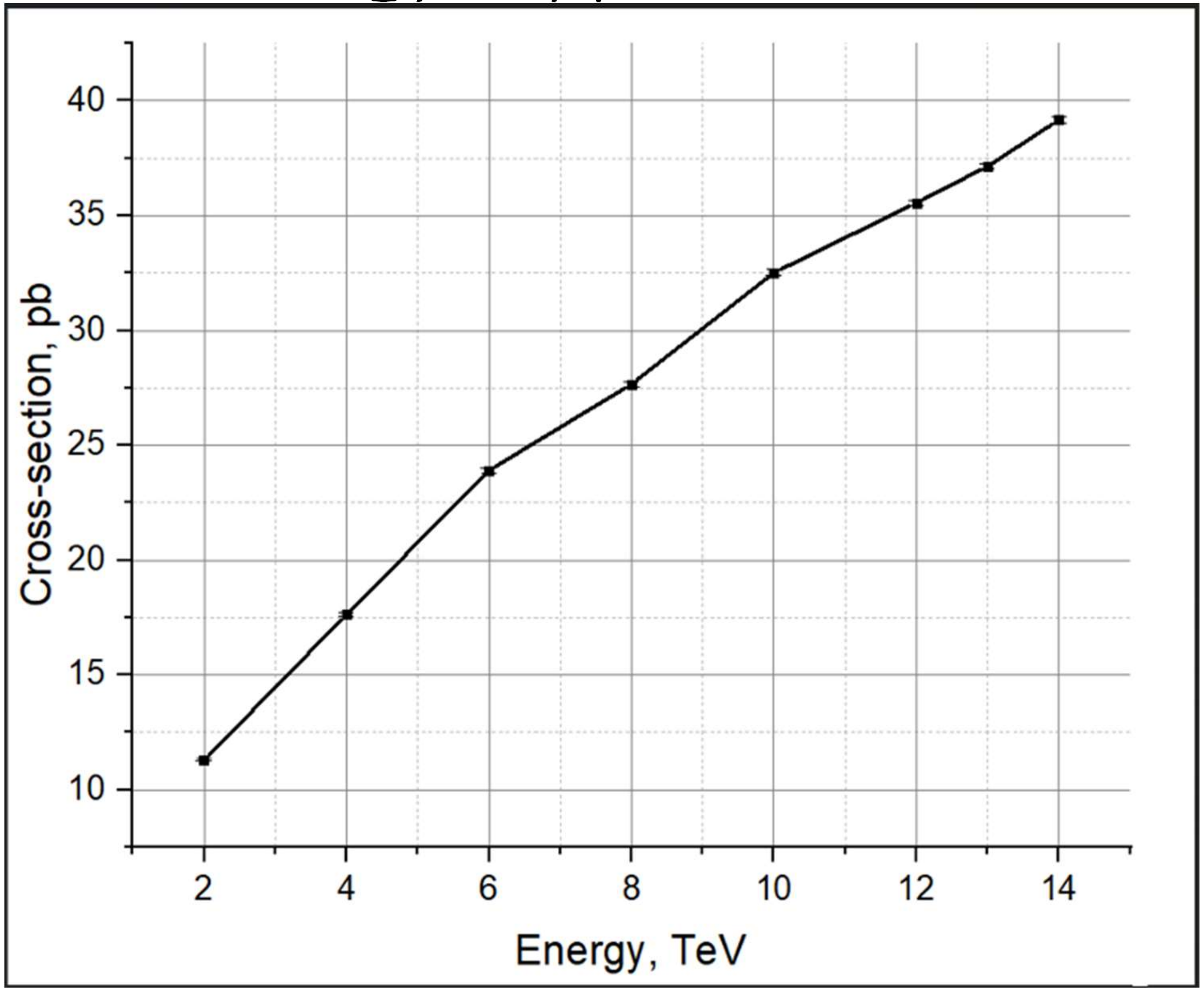
# Experimental data for pp -> yy at ATLAS




Expected and observed 95% CL upper limits on (a) the signal fiducial cross section $\sigma$fid and (b) the ALP coupling constant, assuming 100% branching ratio for ALP decay into two photons, as functions of the hypothetical ALP mass $mX$. The $1\sigma$ and $2\sigma$ confidence intervals are shown by the coloured bands. Contours of the ALP natural width Γ are illustrated by the smooth blue solid lines.

2304.10953

# Cross-section of ALP production dependency on energy in pp collisions



# Cross sections of ALPs production for energy 5.02 TeV (first row at the table) and 13 TeV (second row in the table) (1 and 2 models)

| $SD1$ | $DD1$ | $SD2$ | $DD2$ |
|---|---|---|---|
| $20.908+/-0.081$ | $9.167+/-0.079$ | $20.926+/-0.081$ | $9.219+/-0.079$ |
| $0.461\times10^{-4}\pm 0.31\times10^{-6}$ | $0.176\times10^{-4}\pm 0.18\times10^{-6}$ | $0.461\times10^{-4}\pm 0.31\times10^{-6}$ | $0.171\times10^{-4}\pm 0.165\times10^{-6}$ |

Single dissociation is an order of magnitude larger than diffraction dissociation at 5.02 TeV.
For 5.02 TeV ALP mass region amounts to 5-30 GeV, for 13 TeV is 5-1400 GeV.
The ALP cross-section of second region drops by 6 orders of magnitude with increasing in energy to 13 TeV.

# Cross sections of ALPs production for energy 5.02 TeV (first row at the table) and 13 TeV (second row in the table) (3 and 4 models)

| $SD3$ | $DD3$ | $SD4$ | $DD4$ |
|---|---|---|---|
| $20.922+/-0.081$ | $9.161+/-0.079$ | $20.905+/-0.081$ | $9.086+/-0.079$ |
| $0.416\times10^{-4}\pm 0.26\times10^{-6}$ | $0.173\times10^{-4}\pm 0.183\times10^{-6}$ | $0.419\times10^{-4}\pm 0.27\times10^{-6}$ | $0.173\times10^{-4}\pm 0.183\times10^{-6}$ |

Single dissociation is an order of magnitude larger than diffraction dissociation at 5.02 TeV.
For 5.02 TeV ALP mass region amounts to 5-30 GeV, for 13 TeV is 5-1400 GeV.
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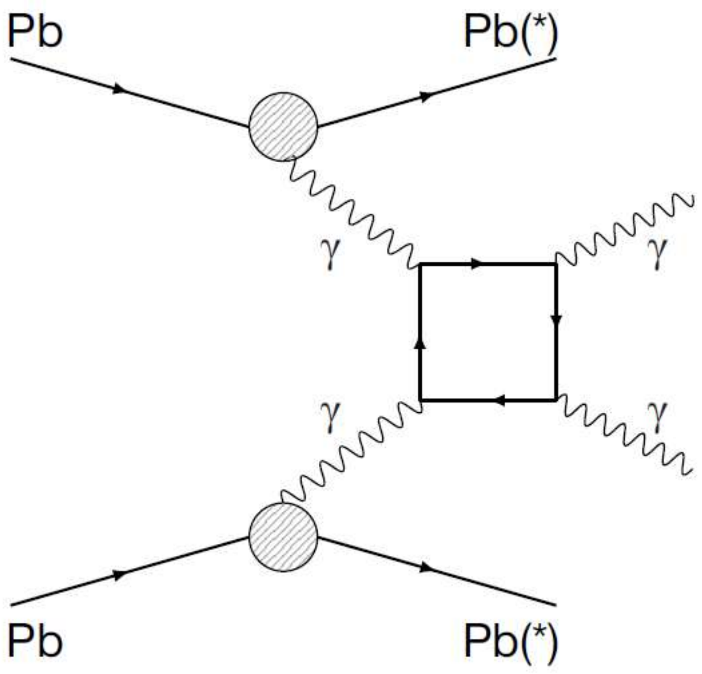
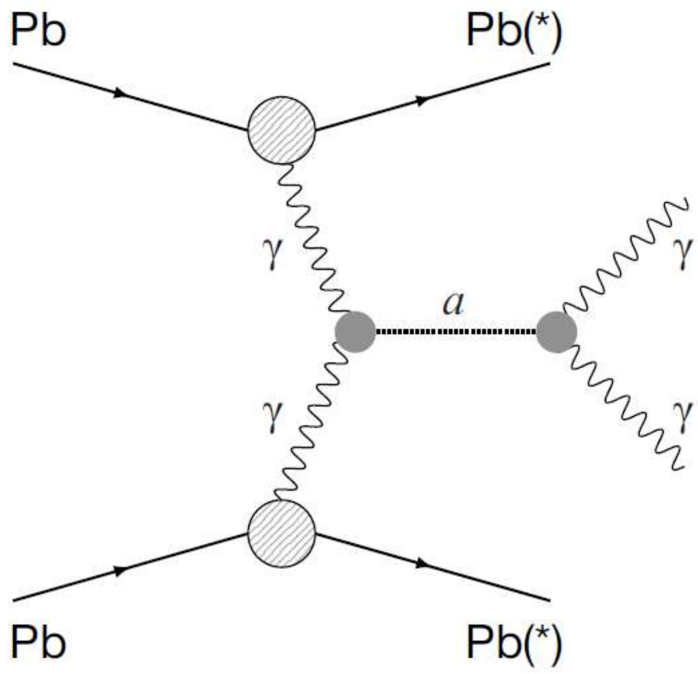
# Feynman diagrams for axion production in Pb-Pb collisions with decay to 2 γ



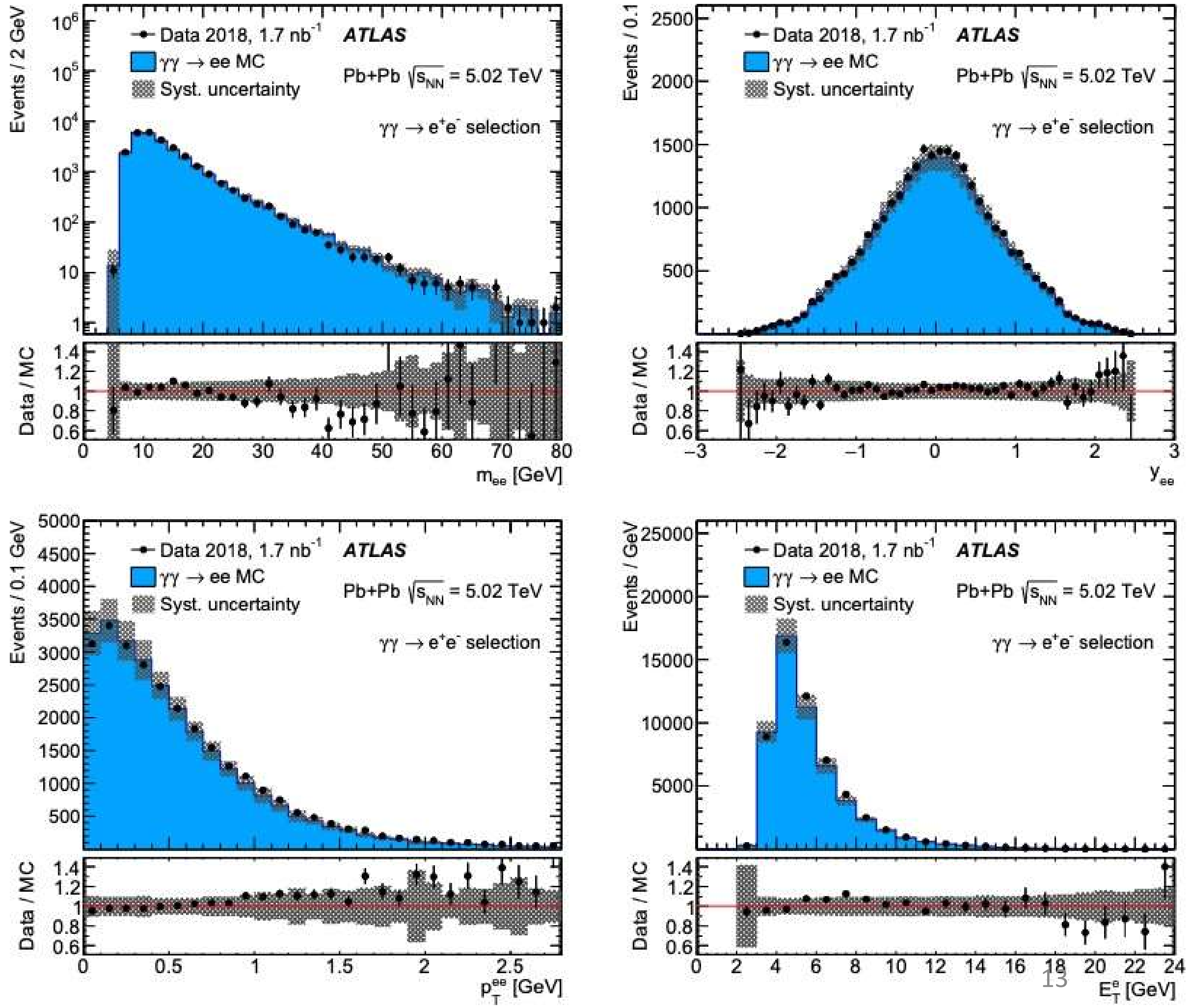



# Experimental data for Pb –Pb -> yy

- mass range of ALP:

$6\ \mathrm{GeV} < m_a < 100\,\mathrm{GeV}$

- Requirements for two outgoing photons:
  - $E_{\mathrm{T}} > 2\,\mathrm{GeV}, |\eta| < 2.37$
  - mγγ > 5 GeV, pγγ < 1 GeV



# Experimental data for ATLAS searches of dependence Confidence Levels / ALPs mass

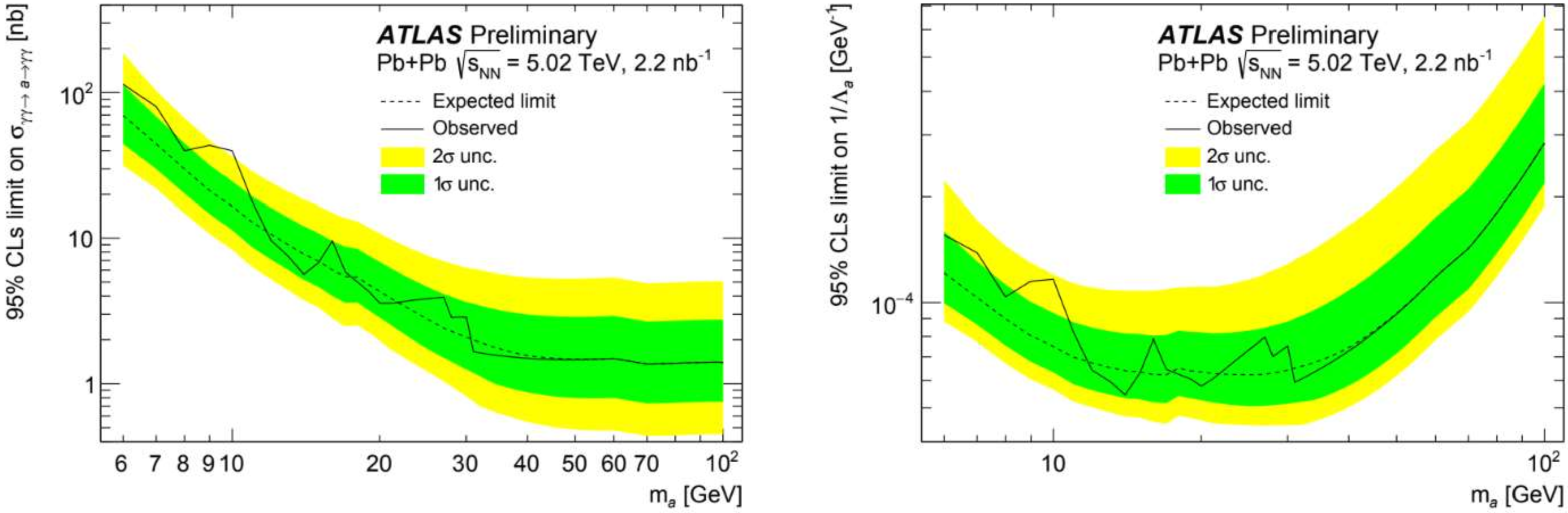
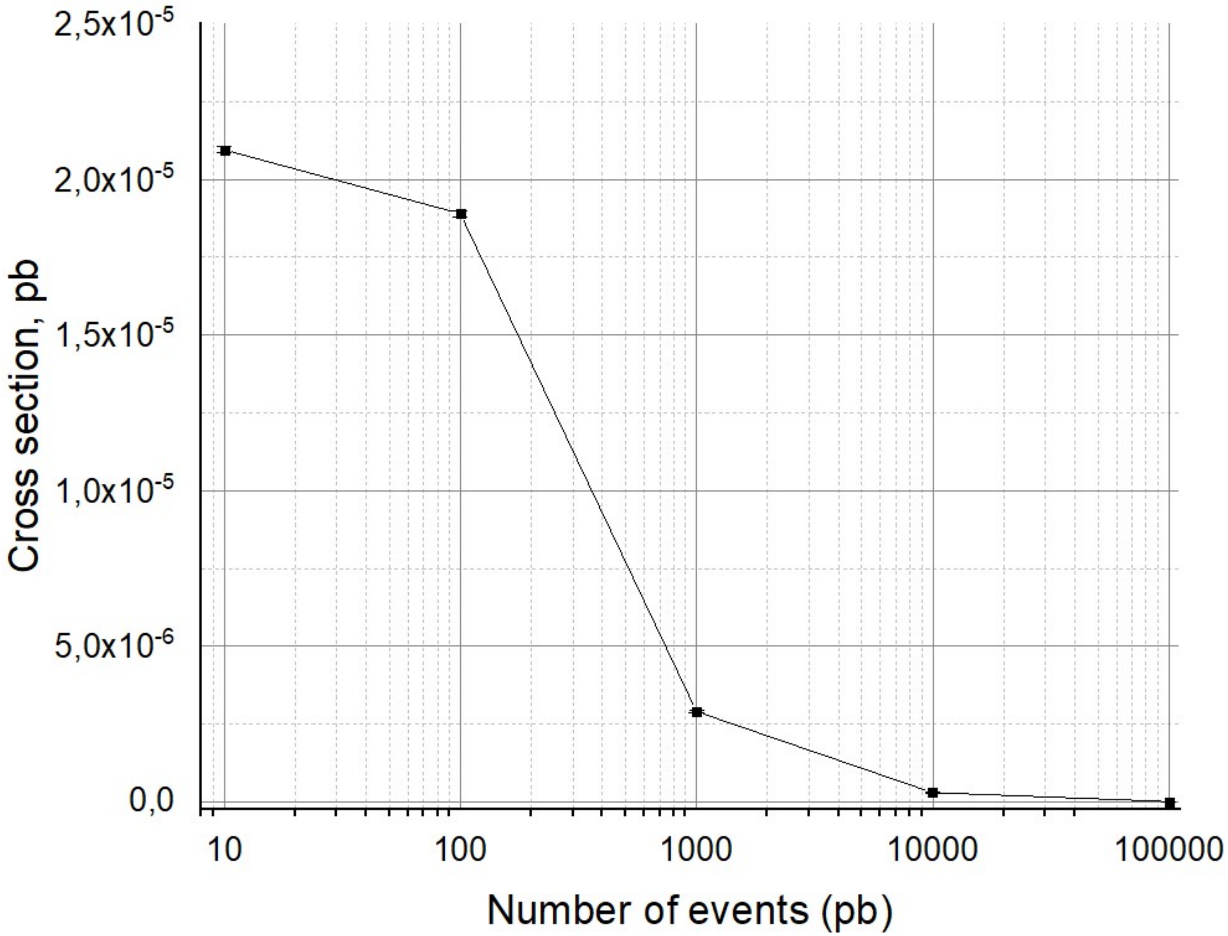
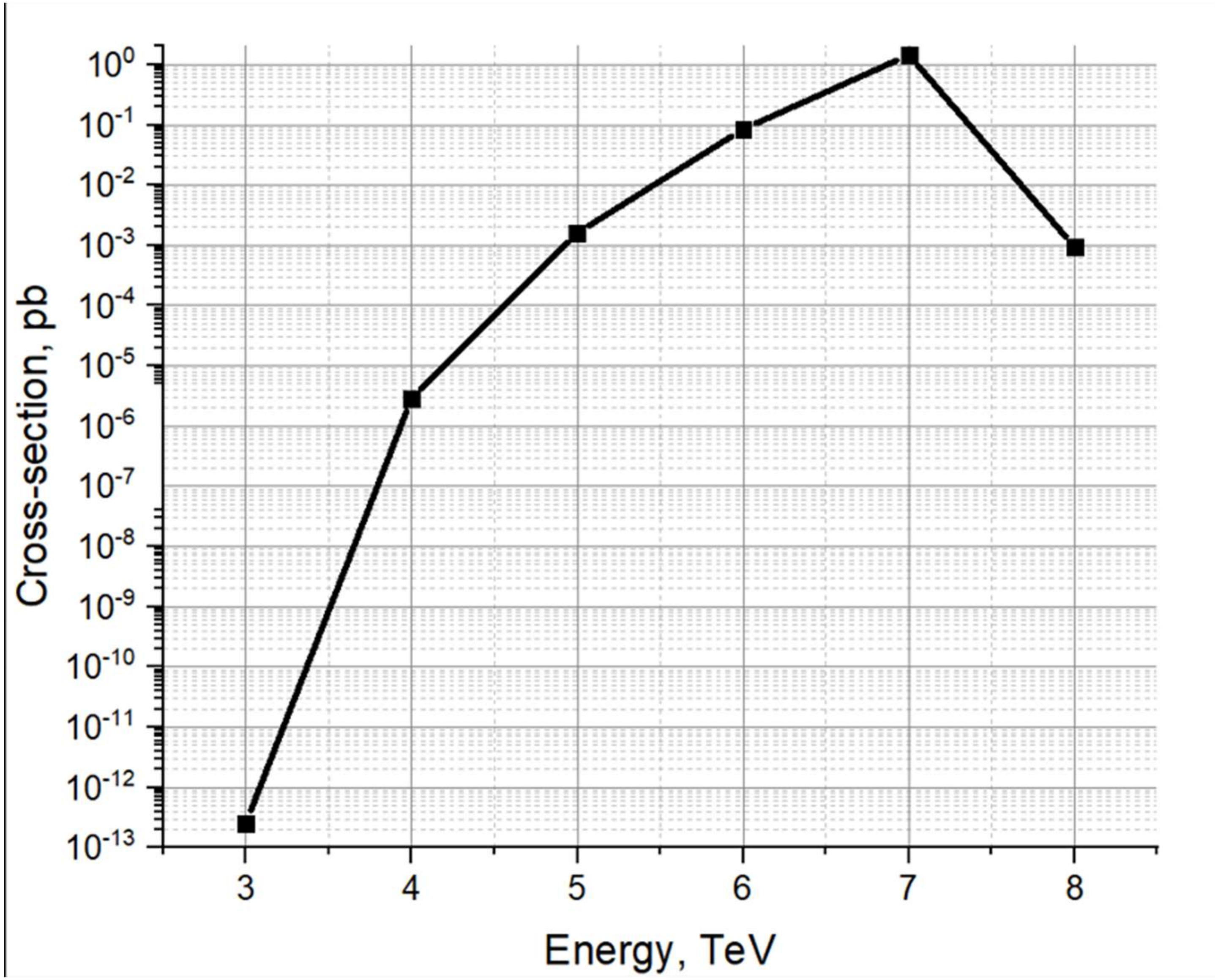



Figure 9: The 95% CL upper limit on the ALP cross section $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ (left) and ALP coupling $1/\Lambda_a$ (right) for the $\gamma\gamma \to a \to \gamma\gamma$ process as a function of ALP mass $m_a$. The observed upper limit is shown as a solid black line and the expected upper limit is shown by the dashed black line, with a green $\pm 1\sigma$ and a yellow $\pm 2\sigma$ band.

# Dependence of the cross section as the N axion number at 5.02 TeV for Pb-Pb






Dependence of the axion production cross section for Pb-Pb collisions at different TeV energies. With increasing energy, the cross section begins to decrease due to the large number of produced particles.

# Conclusions

- Simulations for pp and Pb-Pb collisions were performed to search for axion-like particles.
- The simulations were carried out using the modern computer program SuperChic v4.2. Using four experimental models we calculated the ALP production cross-sections.
- The results of calculations of the cross sections for the ALP production for proton-proton and Pb-Pb collisions showed its different behavior with increasing energy in the center of mass system, and if in the first case it grows, then, for lead, the cross section begins to fall in the energy region from 7 to 8 TeV.
- The highest ALP production cross-section is associated for number of axions from 10 to 100 in Pb-Pb collisions for 5.02 TeV.
- For pp collisions, the cross section of ALP production for single dissociation is an order of magnitude larger than for double dissociation.
- The cross section of the ALP production decreases due to the increasing of the mass region of the ALP.
- The ALP production cross section in pp collisions depend on the type of model, however  Pb-Pb collisions does not depend on the type of model