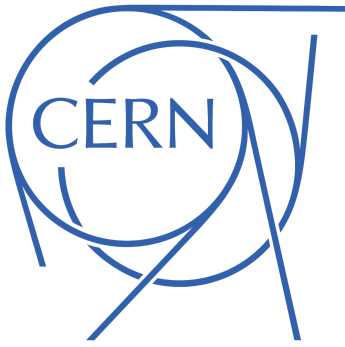




# **CERN SUMMER STUDENT PROGRAMME 2023 REPORT**

## **Chasing the axion-like particles using the proton tagging with the CMS experiment**

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### **Abstract**

Various theories beyond the SM predict axion-like particles (ALPs) to address the longstanding questions in particle physics: the strong CP problem and the nature of dark matter. In particular, ALPs can be produced via photon fusion and decay back to a pair of photons, and their production can be identified in proton-proton collisions by tagging the surviving protons using the CMS detector. In the project, we explore the sensitivity to discover ALPs, within the mass range between 50 GeV to 5 TeV. We aim at including events with only one tagged proton into analysis; we look for different ways to distinguish signal protons from those coming from background, and estimate the efficiency of chosen selection methods; we determine how much our sensitivity will improve with better detector time resolution; and finally, we compare the results to existing and future experiments.

## Introduction

It is possible to observe the production of Axion-Like Particles through a photonic portal: two colliding photons can produce an ALP, which later decays in a di-photon mode. Sometimes, LHC may act as a photon collider: when protons, which are electrically charged, emit photons, the production of ALPs can occur in the collision vertex. We will consider 2 possible scenarios of such events: the first, called “elastic” (or “exclusive”) scattering, occurs when two colliding protons remain intact, scattering at very small angles; the second, called “semi-elastic” (or “semi-exclusive”), occurs when a single proton dissociates, and the other one gets scattered. Those two scenarios are represented at **Fig. 1**.

Such events can be identified by using special proton detectors: in our study, it is the CMS Precision Proton Spectrometer, or PPS, which had been installed during LHC-Run 2 and served to measure various beyond-SM processes possibly occurring during photon collisions. PPS includes tracking (3D Si pixels) and timing (diamonds) detectors.

Tracking detectors allow us to reconstruct the kinematic properties of the protons, [1].

Timing detectors allow us to distinguish signal protons from background ones, which come from different collision vertices in the same bunch crossing – pileup (PU) interactions, which can number up to  $\sim 200$  of them at HL-LHC. The correlation of detection times is represented at **Fig. 2**.

At HL-LHC, the central part of CMS will not only reconstruct the z-coordinate of a vertex, but it will also have precise timing measurement from the CMS ECAL (Electromagnetic Calorimeter), which will allow us to correlate the proton detection times with time of interaction in a vertex. As a result, we will be able to employ the correlations for protons, to distinguish them from pileup ones, which do not have such correlations: see [2].

There is also a range of acceptance which

characterises PPS detector: it is sensitive to those protons which have fractional momentum loss in between 0.0147 and 0.1967, as shown in [3].

To study the sensitivity of CMS experiment at HL-LHC to ALP production, we will apply our analysis to simulated signal and background samples, generated by SuperChic 4 [4], and by Madgraph5 [5] respectively. To model the CMS detector performance, we will apply Delphes fast simulation tool. Signal samples include 50000 events at  $\sqrt{s} = 14\text{TeV}$  with 200 PU interactions, in diphoton mass range from 50 to 5000 GeV.

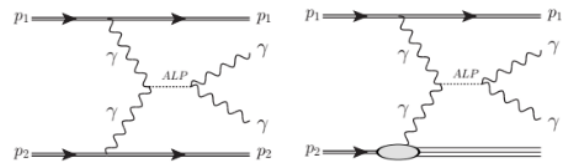


Figure 1: Elastic (left) and Semi-elastic (right) processes of ALP production and decay

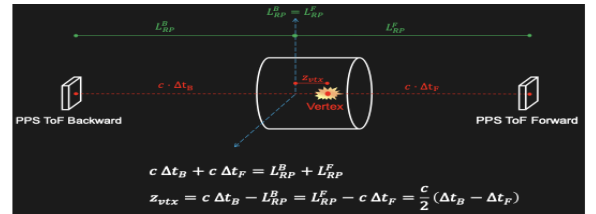


Figure 2: Time correlations for tagged protons employed at LHC-Run 2

## The basic approach

A process of ALP production can be described by Poisson distribution:  $P(k, \lambda) = \lambda^k e^{-\lambda} / k!$ , where  $k$  is observed number of events, and  $\lambda$  is the expected number. If after certain time we see zero events, then with confidence level  $\alpha$  we can state that the real number of events was no more than  $\lambda$ :  $P(0, \lambda) = 1 - \alpha$ . Setting confidence level to  $\alpha = 95\%$ , we find the expected maximum number of events  $\lambda$ :  $P(0, \lambda) = \lambda^0 e^{-\lambda} / 0! = e^{-\lambda} = 0,05 \Rightarrow \lambda \approx 3$ . Introducing integrated luminosity over the time of observation ( $L_{int} = 3000 fb^{-1}$  for HL-LHC), we can estimate the largest possible cross-section of ALP production:

$$L_{int} = \int L dt = \int \frac{1}{\sigma} \frac{dN}{dt} dt = \frac{1}{\sigma} N, \quad \sigma_{95} = N_{95} / L_{int} = 3 / 3000 fb^{-1} = 10^{-3} fb = 10^{-6} pb = 1 ab$$

Now, given that cross-section is related to coupling constant as  $\sigma \propto g^2$ , we can find the coupling constant under which the cross-section reaches the value of  $\sigma_{95}$ :

$$\sigma_{95} = const \cdot g_{ax}^2, \quad \sigma_{g=10^{-4} GeV^{-1}} = const \cdot (10^{-4} GeV^{-1})^2, \quad g_{ax} = \sqrt{\frac{\sigma_{95}}{\sigma_{g=10^{-4} GeV^{-1}}}} \cdot 10^{-4} GeV^{-1}$$

These calculated values of  $g_{ax}$  make up an exclusion diagram: the New Physics particles (in our case, ALPs) are expected to be produced on the condition that the true value of coupling constant is higher then the calculated value of  $g_{ax}$  corresponding to the same diphoton mass.

In the simplest case, we consider those events to be signal ones, which have exactly two reconstructed photons and which have at least one proton inside the PPS acceptance range; in this case background is not considered. Such events are categorised into 1-tag and 2-tag categories, depending on the number of tagged protons.

In practice, the values of coupling constant for exclusion diagram were calculated as:

$$g_{ax} = \sqrt{\frac{\sigma_{95}}{\sigma_{g=10^{-4} GeV^{-1}} \cdot a_{el} + \sigma_{g=10^{-4} GeV^{-1}} \cdot a_{Semiel}}} \cdot 10^{-4} GeV^{-1}, \quad a = \frac{N_{1tag} + N_{2tag}}{N_{events}}, \quad a_{Semiel} = \frac{\frac{1}{2} N_{1tag} + N_{2tag}}{N_{events}}$$

Here  $a$  and  $a_{Semiel}$  are acceptances to elastic and semi-elastic events, shown at **Fig. 3**. The obtained exclusion diagram is shown at **Fig. 6**.

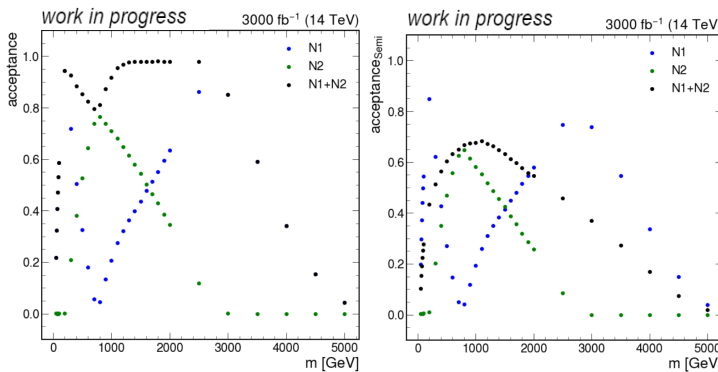


Figure 3: Acceptance for elastic (left) and semi-elastic (right) events calculated as a function of the ALP mass.

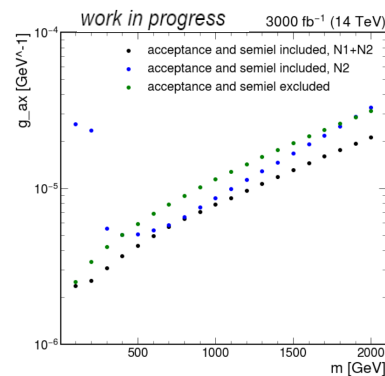


Figure 4: comparison of exclusion diagrams for three possible scenarios: only elastic process is considered, acceptance is set to 1; acceptances and semi-elastic processes are also considered, but only 2-tag event category is taken into account; and both processes and categories are included.

## Background introduction

We included background by considering it to also have Poisson distribution of occurrence probability. Expected numbers of signal and background events are defined as  $N_s = \sigma_s \cdot L_{int} \cdot a_s$  and  $N_b = \sigma_b \cdot L_{int} \cdot a_b$ . We can use the following logic to relate them:

Let us have the expected number of events assuming null hypothesis ( $H_0$ ):  $N_0 = N_b$ , and expected number of events assuming alternative hypothesis ( $H_1$ ):  $N_1 = N_s + N_b$ . Then, if the null hypothesis is correct, we can set a maximum value for  $N_s$  with 95% confidence level:  $P(N_s + N_b) = 0.05$ . Now, for a random variable  $n$ :  $P(n \leq X) = \Phi(X)$ , where  $\Phi(X)$  is a cumulative distribution function. If we consider the number of events to have a Poisson distribution  $P(n, \lambda) = \frac{\lambda^n}{n!} e^{-\lambda}$ , then:  $\Phi(X) = \frac{\Gamma(X, \lambda)}{X!} = 0.05$ ,  $\Gamma(X, \lambda) = \int_{\lambda}^{\infty} e^{-t} t^X dt$ , where  $X = N_b$ ,  $\lambda = N_s + N_b$ . After some calculations, we come up with an expression relating  $N_s$  and  $N_b$ :

$N_s = \epsilon^2 + \epsilon \sqrt{\epsilon^2 + 2N_b}$ , where  $\epsilon = \text{erf}^{-1}(0.9)$ . The expected numbers of signal and background events are shown at **Fig. 5**, and updated exclusion diagram (with  $\sigma_{95} = N_s/L_{int}$ ) is represented at **Fig. 6**.

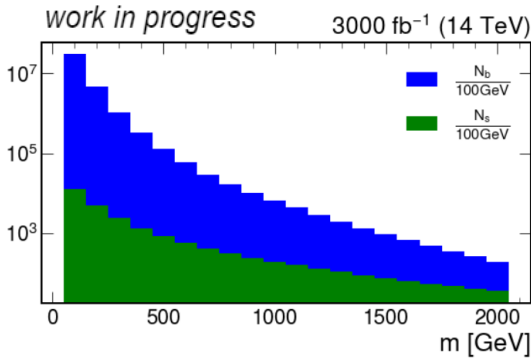


Figure 5: expected numbers of signal and background events

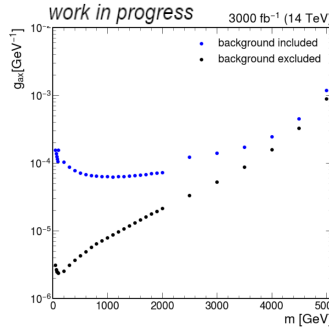


Figure 6: updated exclusion diagram with background excluded and background included

## Event selection

We introduce event selection by choosing the following physical variables as criteria to distinguish signal events from background ones: the scalar sum of transverse momentum, carried out by particles from a vertex (SHT); the angle between two photons coming out of the vertex; and measured diphoton mass.

The normalised distributions of SHT,  $1 - \frac{\Delta\phi}{\pi} \equiv \Phi$  and mass for  $m_{\gamma\gamma} = 300\text{GeV}$  samples are shown in **Fig. 7**.

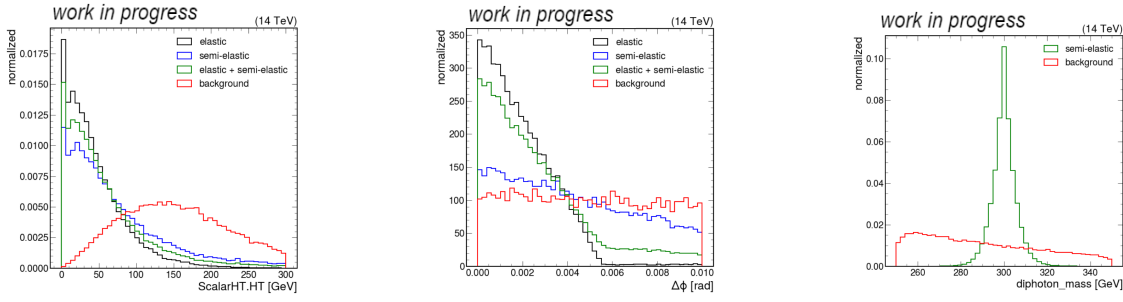


Figure 7: distribution of discriminating variables used in event selection. Left: SHT (scalar sum of transverse momentum carried out from the vertex), Middle:  $\Phi$  (a function of angle between two outgoing photons), Right: measured Invariant Mass. All plots shown for signal of  $m = 300$  GeV

We set event cuts to the values of SHT and  $\Phi$  which correspond to the crossing of three histograms: the ones corresponding to signal, and one corresponding to background. Those events, which are characterised by values smaller than the cut value, will be considered signal events, and the other ones will be considered background. Mass windows, on the other hand, are required to include 95% of signal events, and do not depend on background distribution. All events inside the mass window are considered signal. Dependences of SHT and  $\Phi$  cuts from mass turned out to be flat, and they can be averaged out to single values: mean SHT cut is 79.5 GeV, mean  $\Phi$  cut is  $\approx 0.0038$ . Mass window depends on the mass value as shown at **Fig. 8**.

In order to numerically represent the advantages of different event selection methods, we will introduce such values as: signal efficiency  $\epsilon^s$ ; background efficiency  $\epsilon^{bg}$ ; relative significance  $\epsilon^s / \sqrt{\epsilon^{bg}}$ . Signal and background efficiencies represent the fraction of events which underwent detector cut and a selected optimization cut, with regard to number of events which underwent only the detector cut. Relative significance represents the efficiency of a selected optimization cut: the better cut is selected, the higher it is. At **Fig. 9** and **10** one can see signal and background efficiencies of a combined “SHT+ $\Phi$ +mass” cut, and on **Fig. 11** is the comparison of it’s relative significance to the ones from “SHT” and “SHT+ $\Phi$ ” cuts.

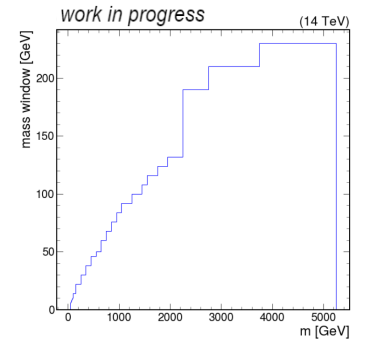


Figure 8: The dependence of mass window from diphoton invariant mass value in a corresponding sample. The obvious discontinuity is caused by a technical issue in event reconstruction.

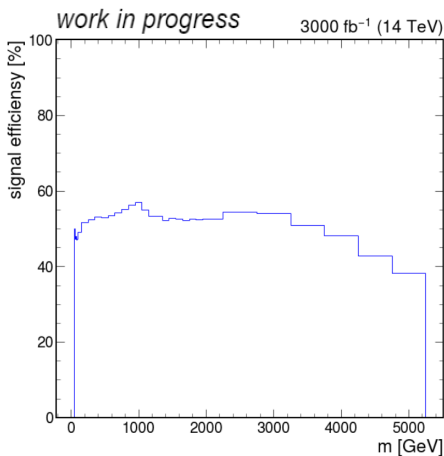


Figure 9: signal efficiency for “SHT+ $\Phi$ +m” cut

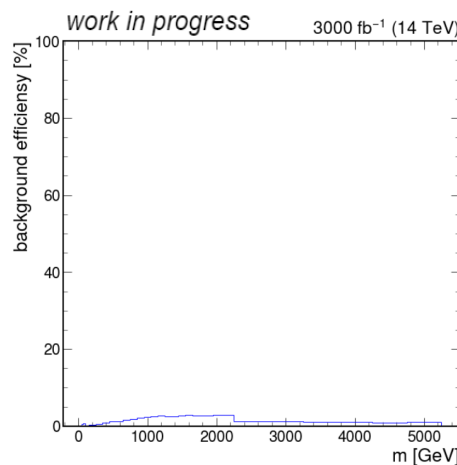


Figure 10: background efficiency for “SHT+ $\Phi$ +m” cut

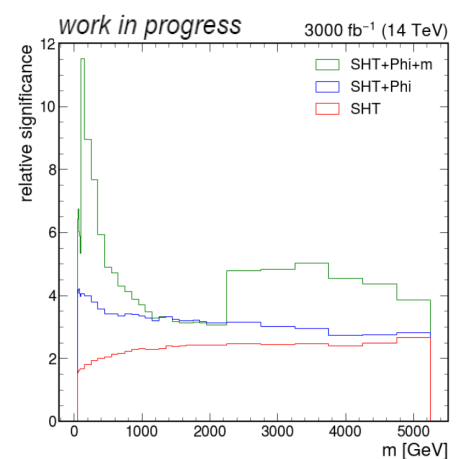


Figure 11: relative significance comparison for different event selections

Now we can update exclusion diagram:

$$g_{ax} = \sqrt{\frac{\sigma_{95}}{\sigma_{g=10^{-4}GeV^{-1}}^{el} \cdot a^{el} + \sigma_{g=10^{-4}GeV^{-1}}^{Semiel} \cdot a^{Semiel}}} \cdot 10^{-4} GeV^{-1}$$

$$\sigma_{95} = \frac{N_s}{L_{int}} \quad N_s \cdot \epsilon_s = \epsilon^2 + \epsilon \sqrt{\epsilon^2 + 2N_{bg} \cdot \epsilon_{bg}} \quad N_{bg} = \sigma_{bg} \cdot a_{bg} \cdot L_{int}$$

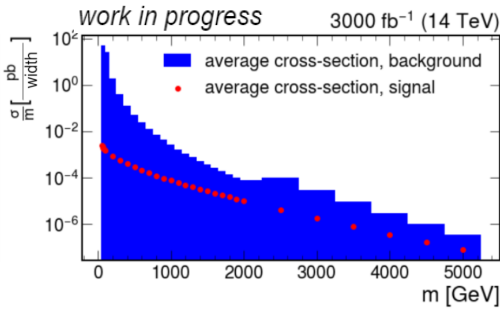


Figure 12: average values of cross-section per sample width after "SHT+Φ+m" selection

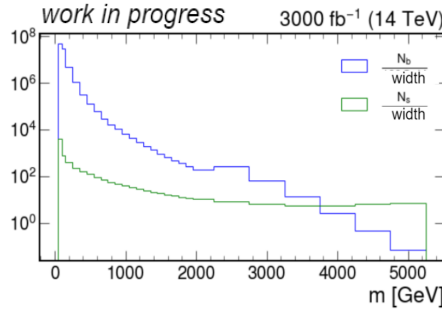


Figure 13: expected numbers of signal and background events per sample width after "SHT+Φ+m" selection

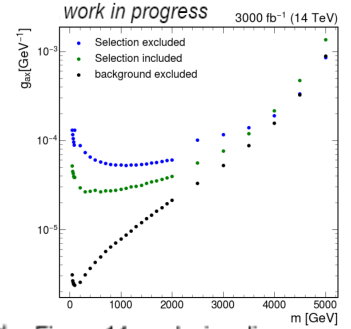


Figure 14: exclusion diagram after "SHT+Φ+m" selection

## Including proton kinematics

We introduced yet another way of separating signal from background, this time – by looking at proton kinematics. We use the following variables, which show the difference between signal and background:  $\Delta\xi/\xi = (\xi_{CMS}^{\pm} - \xi_{PPS}^{pr})/\xi_{CMS}^{\pm}$  ("delxi"), where  $\xi_{CMS}^{\pm} = 1/\sqrt{s}(p_{T,2}e^{\pm\eta_2} + p_{T,1}e^{\pm\eta_1})$  is expected proton momentum loss reconstructed from photons, and  $\xi_{PPS}^{pr} = 1 - |p_z|/7000$  is proton momentum loss;  $\Delta t = t_{CMS} - t_{PPS} + L_{PPS}/c$ , where  $t_{CMS}$  is the time when interaction occurred in a vertex,  $t_{PPS}$  is the time of proton detection, and  $L_{PPS}$  is distance from a vertex to PPS detector. After extracting values of  $t_{PPS}$ , we apply Gaussian smearing to them, to model two values of detector resolution: 50 ps and 20 ps.

In **Fig. 15** one can see the  $\Delta t$  distribution for 1-tag elastic event category; in **Fig. 17** is  $\Delta t$  distribution for 2-tag elastic category (there is no signal data at low and high masses, as can be seen from **Fig. 3**). We determine  $\Delta t$  windows from the requirement that they include 95% of signal events; the results are shown at **Fig. 17** and **18**.

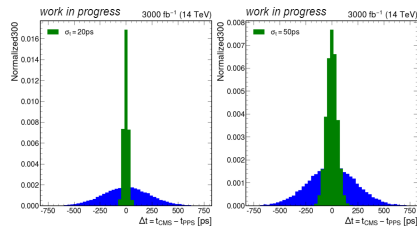


Figure 15: delta t distribution for 1-tag elastic category at 300 GeV for two considered values of PPS time resolution: 20 ps (left) and 50 ps (right)

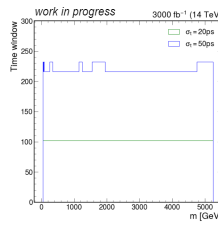


Figure 16: delta t cut values which include 95% of signal events

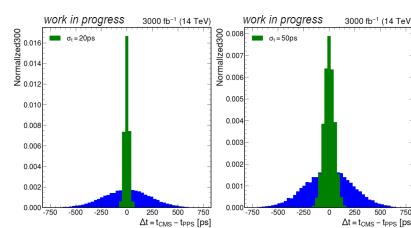


Figure 17: delta t distribution for 2-tag elastic category at 300 GeV for two considered values of PPS time resolution: 20 ps (left) and 50 ps (right)

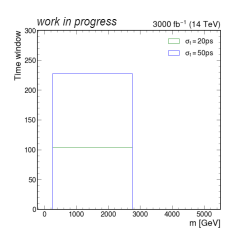


Figure 18: delta t cut values which include 95% of signal events

In **Fig. 19** is the delxi distribution for 1-tag elastic event category and in **Fig. 21** – the distribution for 2-tag elastic category; delxi windows including 95% of signal events are shown at **Fig. 20** and **22**.

We consider only elastic event categories because they give us a tighter selection.

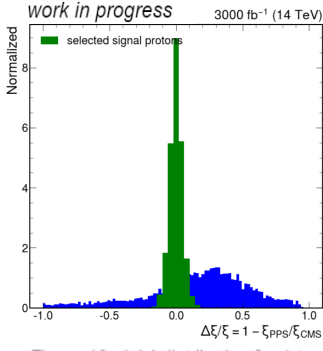


Figure 19: delxi distribution for 1-tag elastic category at 300 GeV

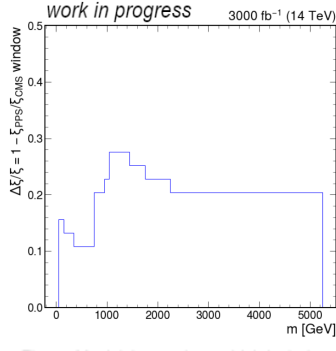


Figure 20: delxi cut values which include 95% of signal events from the category

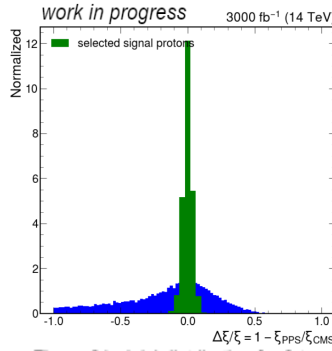


Figure 21: delxi distribution for 2-tag elastic category at 300 GeV

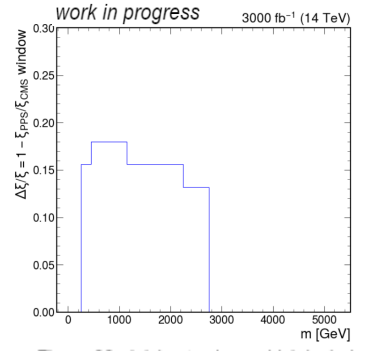


Figure 22: delxi cut values which include 95% of signal events from the category

## Applying combined event selection

Finally, we applied two possible combined event selections to our samples:

“SHT+ $\Phi$ +mass+ $\Delta\xi/\xi$ +T20” and “SHT+ $\Phi$ +mass+ $\Delta\xi/\xi$ +T50”. The comparison of signal and background efficiencies is shown at **Fig. 23, 24**, and relative significances – at **Fig. 25**.

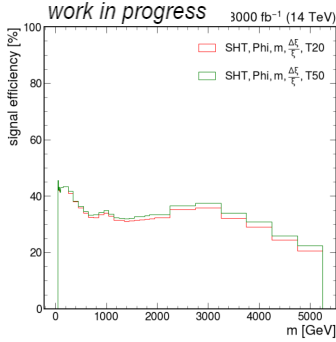


Figure 23: comparison of signal efficiencies for two considered event selections

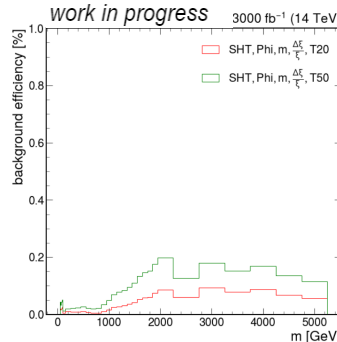


Figure 24: comparison of background efficiencies for two considered event selections

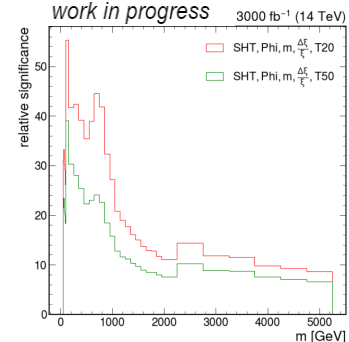


Figure 25: comparison of relative significance values for two considered event selections

Final exclusion diagrams are displayed at **Fig. 26**, and **Fig. 27** presents the comparison of obtained results to ALP sensitivities of current and future collider projects. We can see that at high masses ( $> 3500$  GeV) the “Selection included” options show worse behaviour than “Selection excluded”: at high masses the theory we applied is irrelevant.

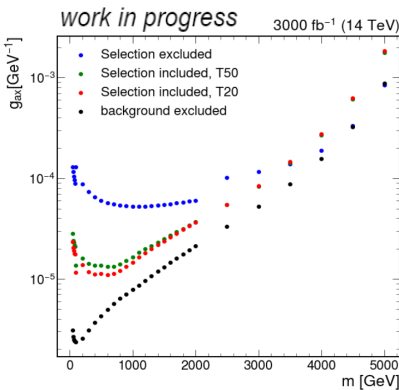


Figure 26: final exclusion diagrams for event selections which differ by chosen values of time resolution of PPS detector. The only unsmoothness at 100-200 GeV is caused by a change of binning, which leads to a sudden drop in background sensitivity.

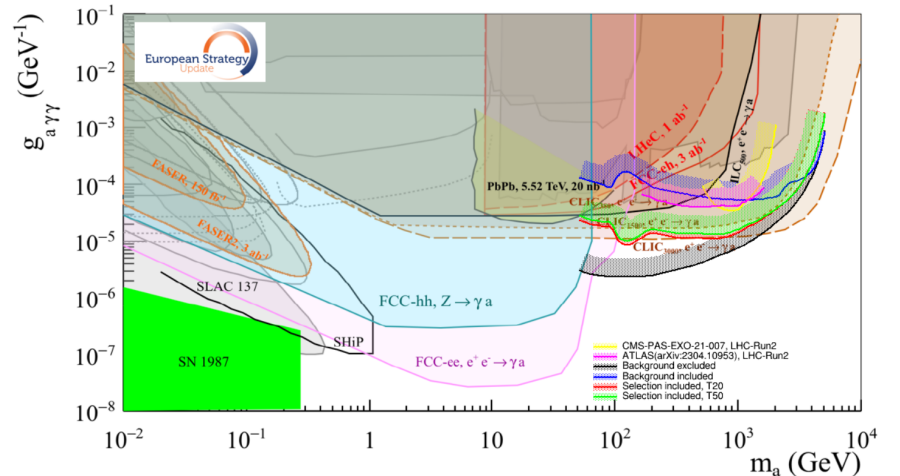


Figure 27: comparison of obtained results to current and future collider projects from the European Strategy, see [6]

## Conclusions

We have obtained a possible sensitivity of the CMS experiment at HL-LHC to ALP production at 14 TeV. We have discovered that adding 1-tag event category to analysis significantly improves our sensitivity, and does not lead to uncontrolled background growth: on the contrary, we can efficiently suppress it. 200 pileup events in samples do not prevent us from obtaining clear correlations, which distinguish signal from background. It was also determined that sensitivity given by detectors with 50 ps resolution is almost as good as the one for 20 ps resolution, and those obtained sensitivities are very similar to the sensitivity of CLIC at high masses.

The results, however, can still be improved: we can look for a still more efficient event selection (in terms of chosen cut and window values), we can look for a smoother event selection for proton kinematics variables, and we can try working with larger background samples to determine more clear correlations and avoid having statistical errors [7].

## Acknowledgement

I would like to express my gratitude to my supervisors for providing me with a set of excellent Jupyter Notebooks, which introduced the main physical concepts later applied for analysis, and for the effort they have put into a thorough investigation and explanation of the analysis results emerging during my work on the project.

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- [7] A more explicit version of the report, written during the course of a workflow: <https://docs.google.com/document/d/1mwWYbjCYbtraIVBiYN3kRuox5De2XLHepHwAVaobnK0/edit?usp=sharing>

## Appendix: Efficiency of vertex reconstruction

During the course of work, we needed to measure a correlation between the real vertex  $z$  coordinate and the reconstructed vertex  $z$ , determined from generator-level information. The result for background is shown at **Fig. 28**, and it is clear that correlation is present. For signal of elastic type, as shown on **Fig. 29**, there is no correlation. And for semi-elastic type, surprisingly, the correlation is present too, as shown on **Fig. 30**.

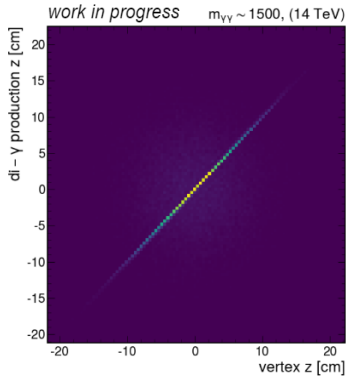


Figure 28: there is clear correlation between real and reconstructed  $z$ -coordinates of a vertex for background, as show the example of 1500 GeV sample

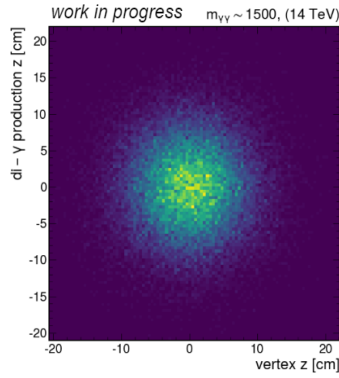


Figure 29: there is no correlation between real and reconstructed vertex  $z$ -coordinates for events in elastic sample

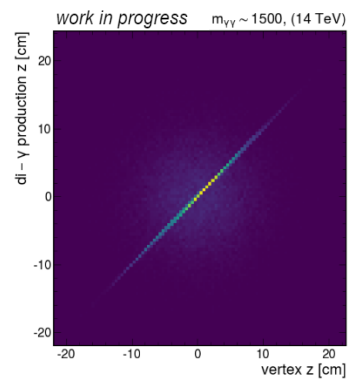


Figure 30: as it turns out, there is a good correlation between real and reconstructed vertex  $z$ -coordinates for events in semi-elastic sample