Searching for ALPs
with the IDEA idea detector at FCC-ee

G. Polesello (INFN Pavia)

S. Gascon-Shotkin E. Jourd'Huy Jie Xiao

(IP2I Lyon IN2P3-CNRS/UCB Lyon 1)

G. Cacciapaglia (LPNHE Paris)

Introduction

Axion Like Particles: hypothetical pseudoscalar with similar interactions as the QCD axion, appearing naturally in many extensions of the SM

Light pseudoscalars naturally couple to photons, and their photonic final states constitute an excellent benchmark for photon performance of FCC detectors

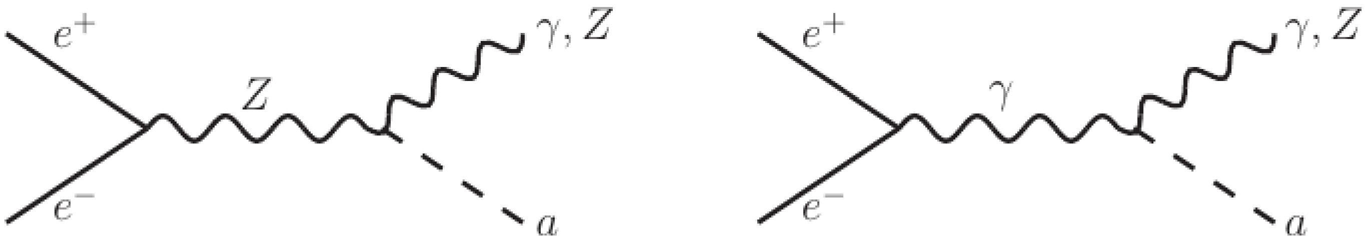
Study parameter space coverage of model for two calorimetric configurations of IDEA detector: Monolithic Dual Readout (DR) fiber calorimeter, and Crystal DR EM calorimeter.

Preliminary study based on available performance parametrisations, to get first idea of impact of performance and to be used as springboard for future work.

The model

$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}\,.$$

We are interested in the associate production of a and γ



•Assume a only couples to hypercharge and not to SU2

$$C_{\gamma Z} = -s_w^2\, C_{\gamma\gamma}$$

•Assume BR(a→ γγ)=100% → three-photon signature

Experimental reach can be represented in 2-d M_a-$C_{\gamma\gamma}$ plane

Implemented in two UFOs: Brivio et al.:arXiv: 1701.05379

Bauer et al:arXv:1808.10323

Checked that the two UFOs give the same results, use Bauer et al. for generation

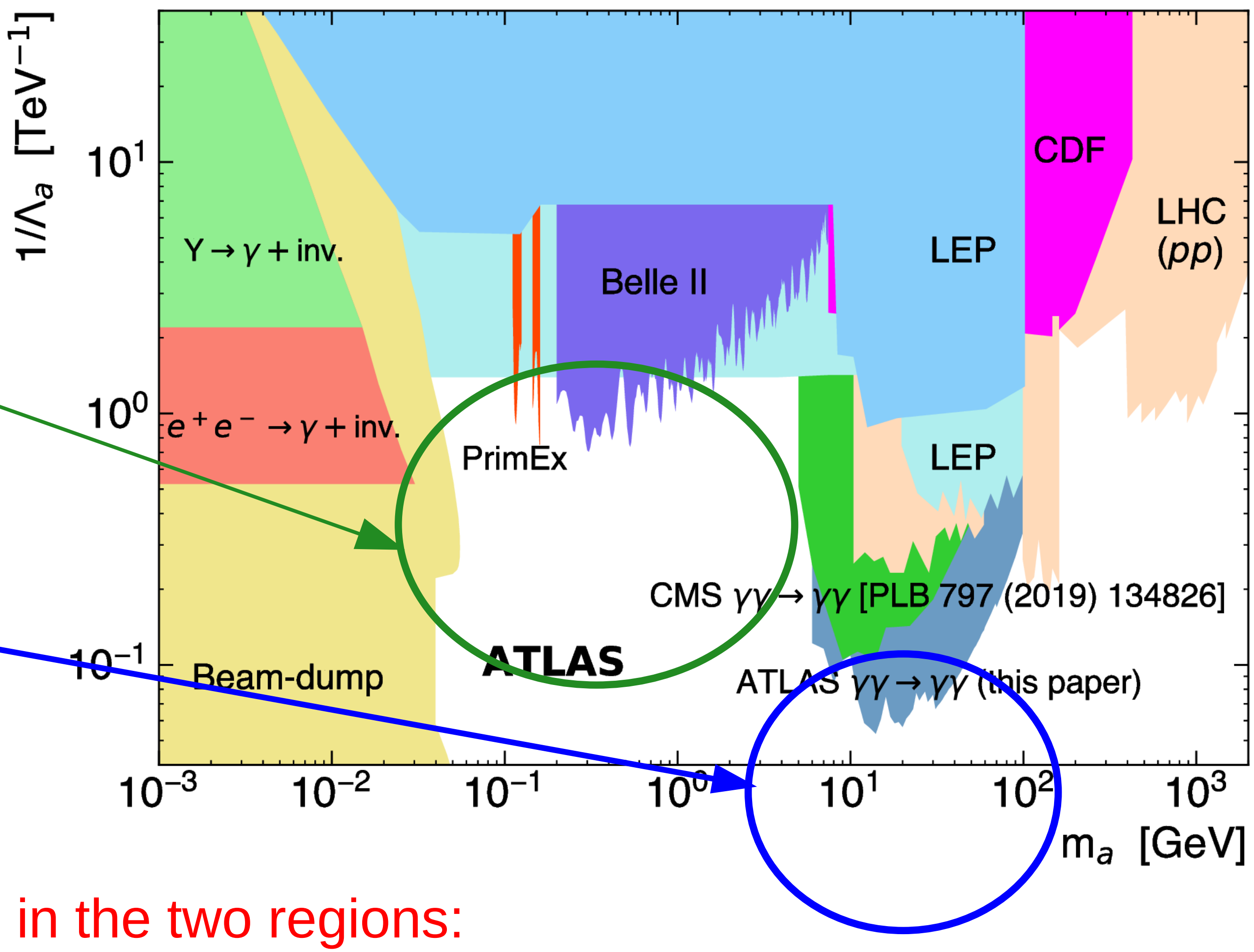
Relevant areas in parameter space

Two mass ranges:

<~100 MeV – ~5 GeV:
Can we cover this difficult region?

>~5 GeV
Are we sensitive to lower couplings than the ones explored at the LHC in photon-photon collisions?

Existing constraints from JHEP 12 (2017) 044



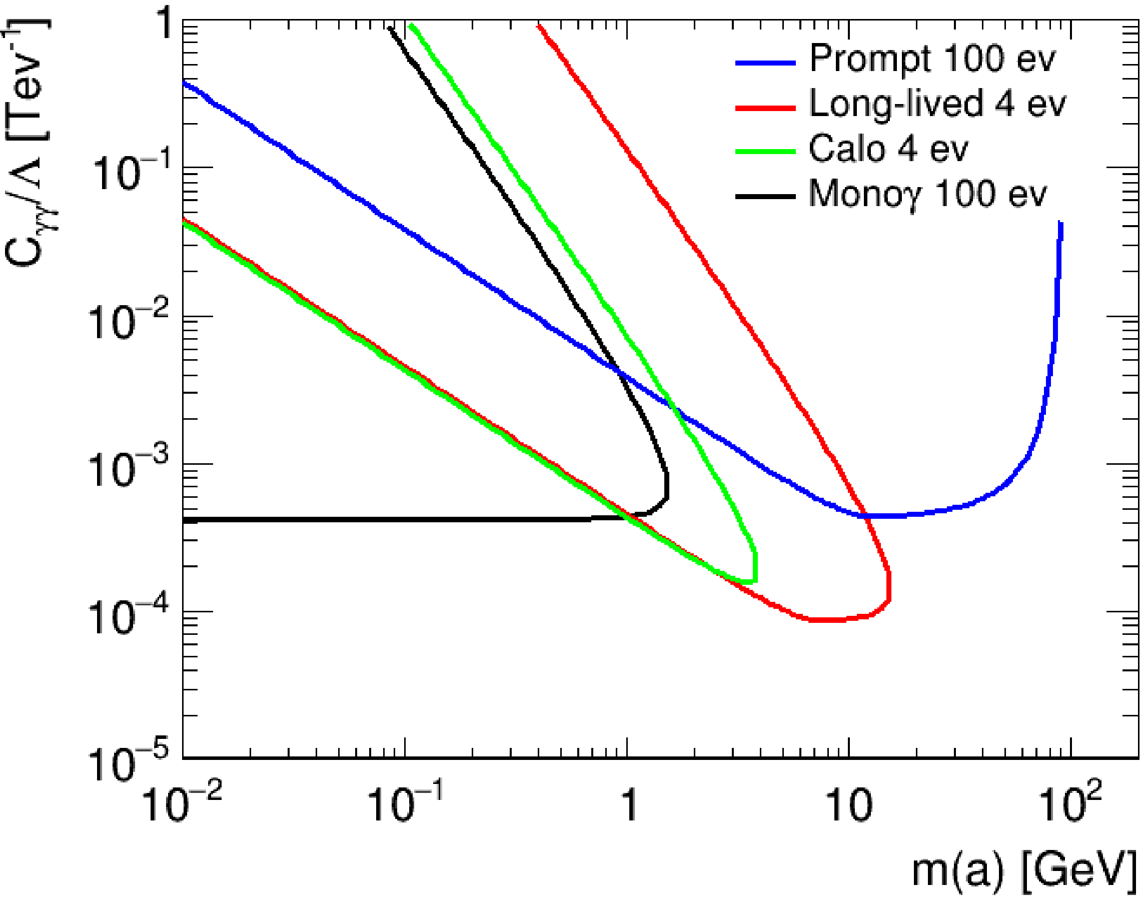
Different experimental issues in the two regions:

- >5 GeV: energy resolution
- <5 GeV: separation of two very collimated photons, resolution on position measurement

Figure from:

ATLAS:arXiv 200805355

Parameter space coverage for $e^+e^- \to \gamma a \to \gamma\gamma\gamma$



4 experimental regions depending on decay length L of ALP

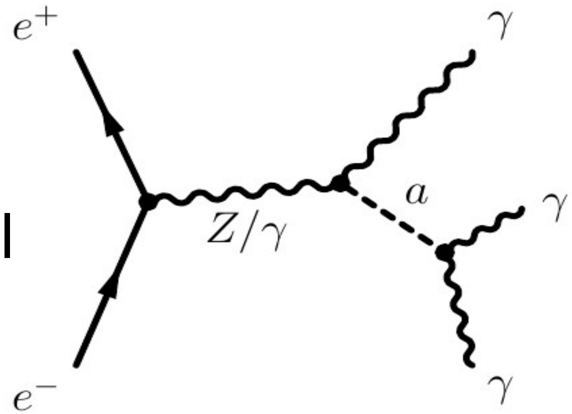
- 100 events for L<10 mm (prompt)
- 4 events for 10<L<2000 mm (Long lived) Decay in ID
- 4 events for 2000<L<4500 mm (Calo) Decay in calorimeter
- 100 events for L>4500 mm: ALP decays outside the detector, only accompanying photon detected (monophoton)

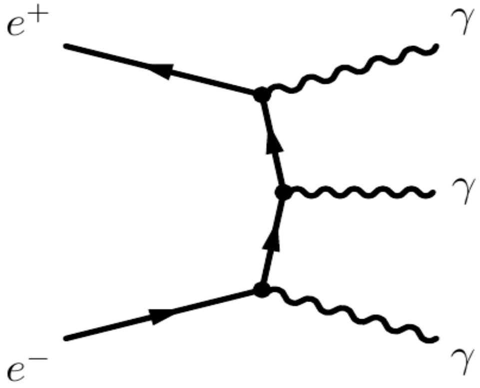
Experimental distinction of γ prompt analysis and LLP analyses depends on how well one can detect a ALP decay away from vertex → today show 3γ analysis making no assumptions on vertex detection.

In addition study very long-lived ALP resulting in a single photon recoiling against MET from undetected ALP

3γ ALP signal and backgrounds

Signal





Dominant background for 3γ analysis

Generation chain:

- LHE files produced with MG5MC@NLO
- Shower with PYTHIA8, detector simulation with DELPHES, inside FCC software
- PYTHIA and IDEA DELPHES card as for Winter23 production, output as EDM4HEP files
- Write out flat ntuple from EDM4HEP with FCC software and run analysis

Signal samples for M_a between 0.1 and 85 GeV and for the Z-pole FCC-ee run, normalise to 205 ab^{-1} as per midterm report

Calorimeter parametrisation

Take truth stable photons from PYTHIA tree in edm4hep, and smear them according to:

For DR fiber: performance figures from full simulation of testbeam prototype. Shown e.g in talk at ICHEP

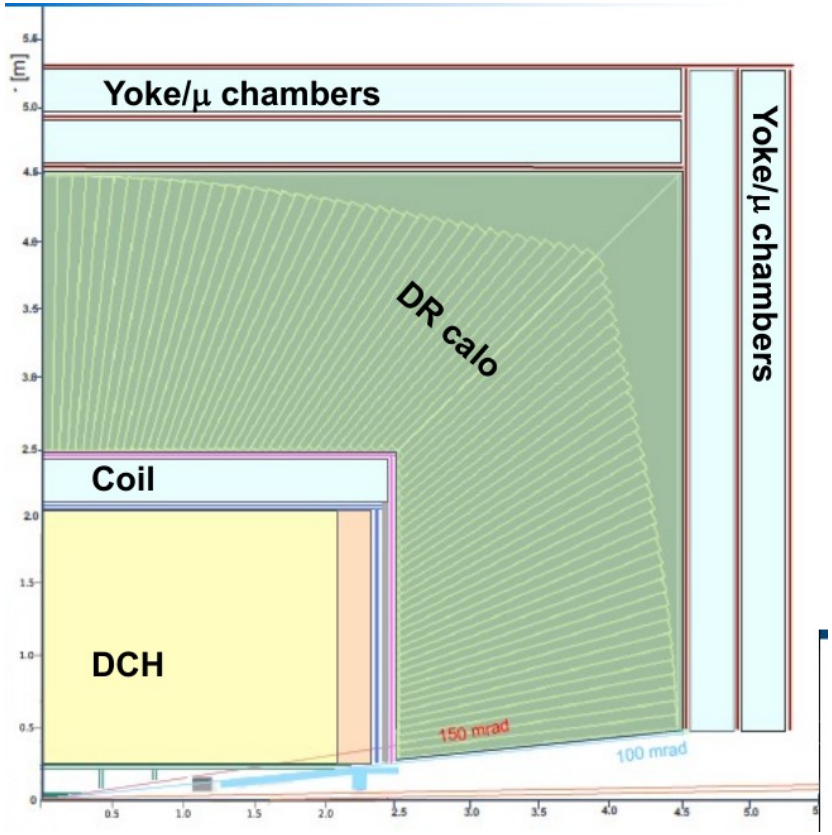
$$\frac{\sigma(E)}{E} = \frac{0.139}{\sqrt{E}} + 0.006$$

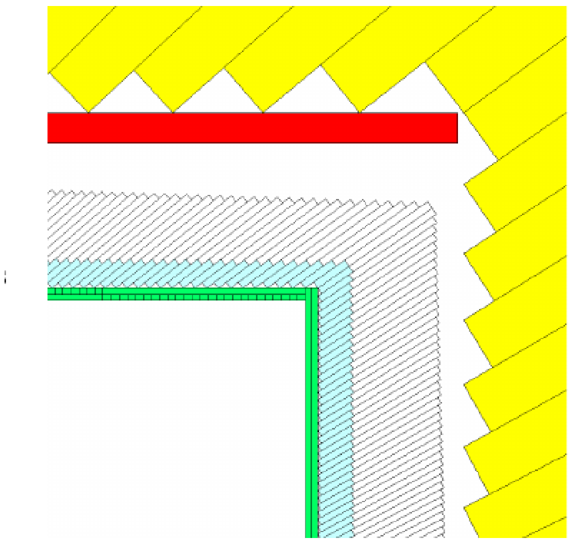
$$\sigma(x) = \frac{4.05}{\sqrt{E}} + 0.0 \qquad \sigma(y) = \frac{3.23}{\sqrt{E}} + 0.0055$$

For crystal: energy resolution as in DELPHES card, Position resolution from Lucchini et al. paper

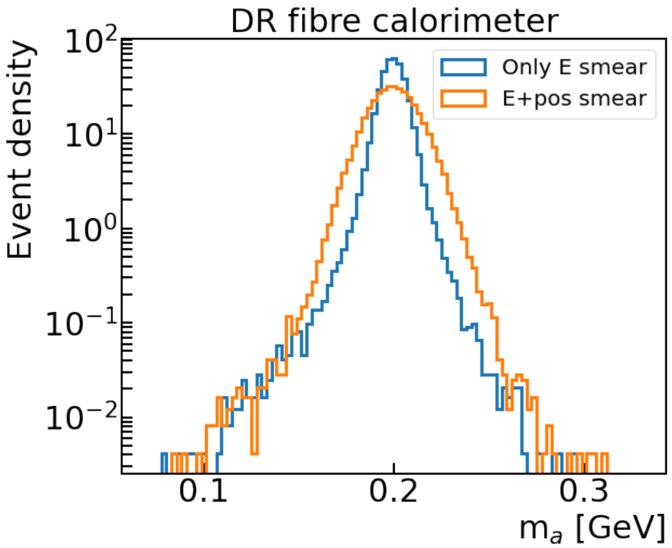
$$\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005 \oplus \frac{0.002}{E}$$

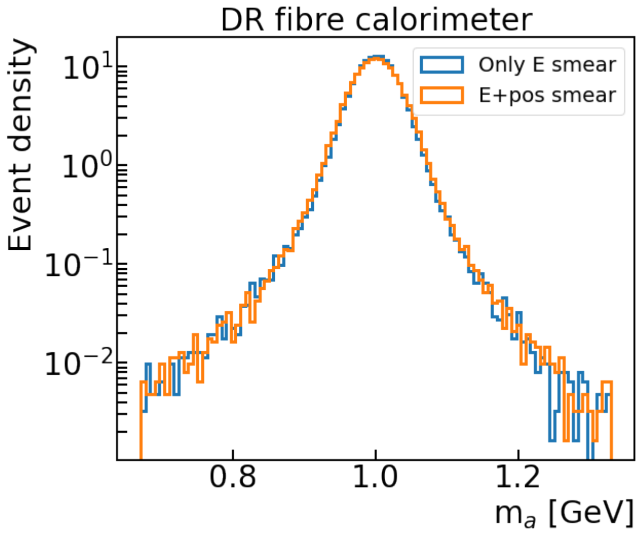
$$\sigma(\theta) = \frac{1.5}{\sqrt{E}} \oplus 0.33$$

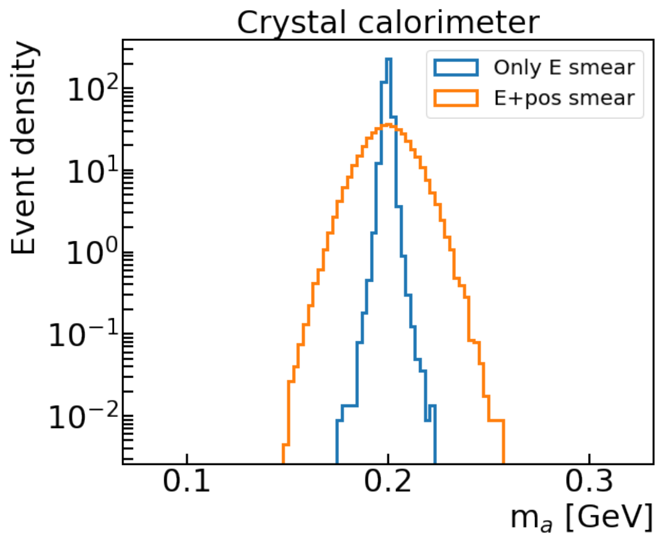


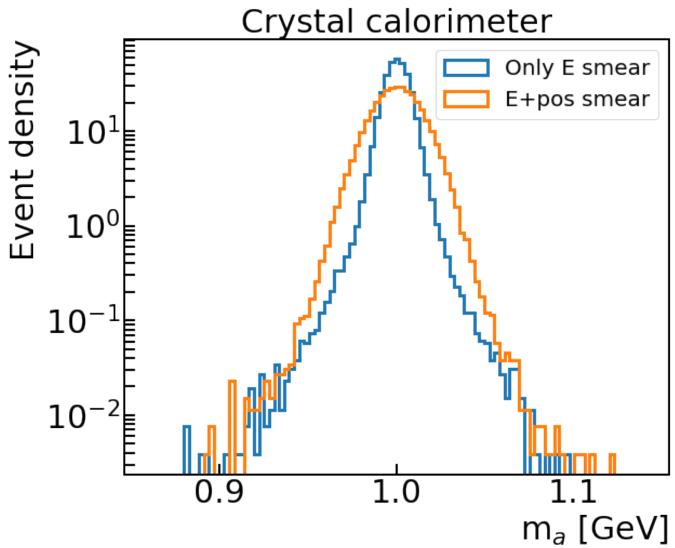


Mass resolution









Compare mass resolution for m_a=0.2, 1 GeV for the two calorimeter options, for prompt decays of ALP

Position resolution dominant effect up to ~1 GeV

3γ analysis

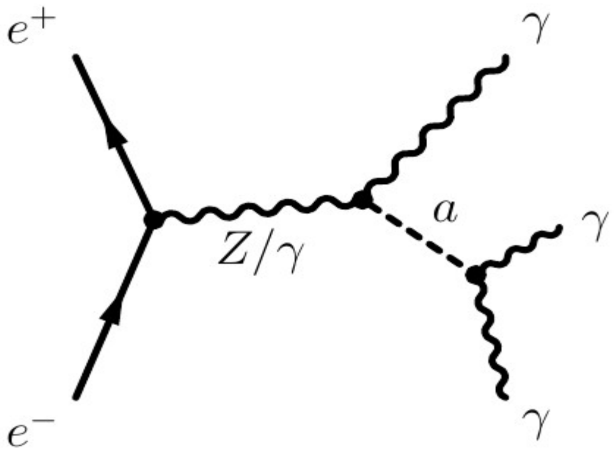
- 3 photons within detector acceptance (<2.6) and energy>1 GeV
- Scan test masses M between 0.1 and 85 GeV

For each M and E_{CM} photon produced alongside ALP has $E_\gamma = \frac{E_{CM}^2 - M^2}{2E_{CM}}$

Need to assign three photons to ALP or to Z decay

For given test mass build variable measuring compatibility of each of possible 3 assignments with expected kinematics

$$M_{cut} = \sqrt{(M_a - M)^2/\sigma^2_{M_a} + (E_{\gamma_3} - E_\gamma)^2/\sigma^2_{E_{\gamma_3}})}$$



γ_3

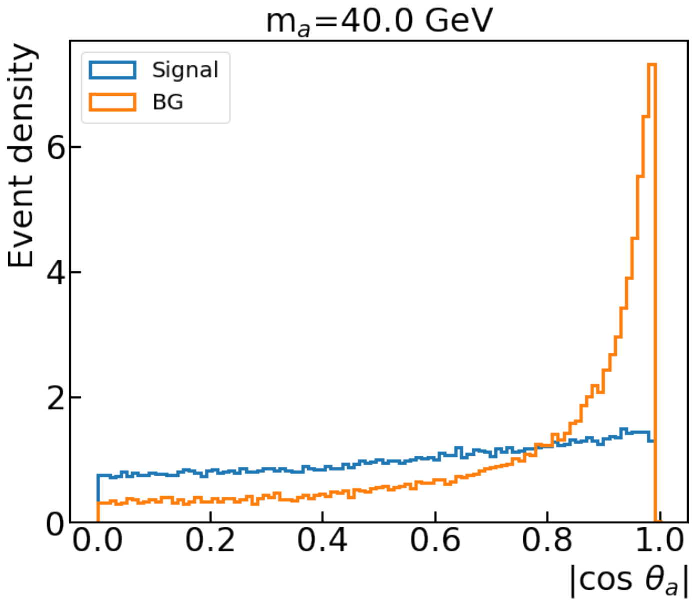
γ_1

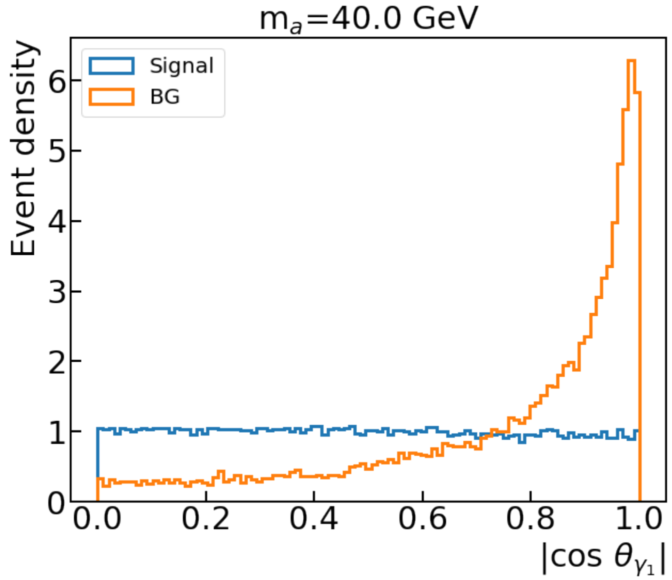
γ_2

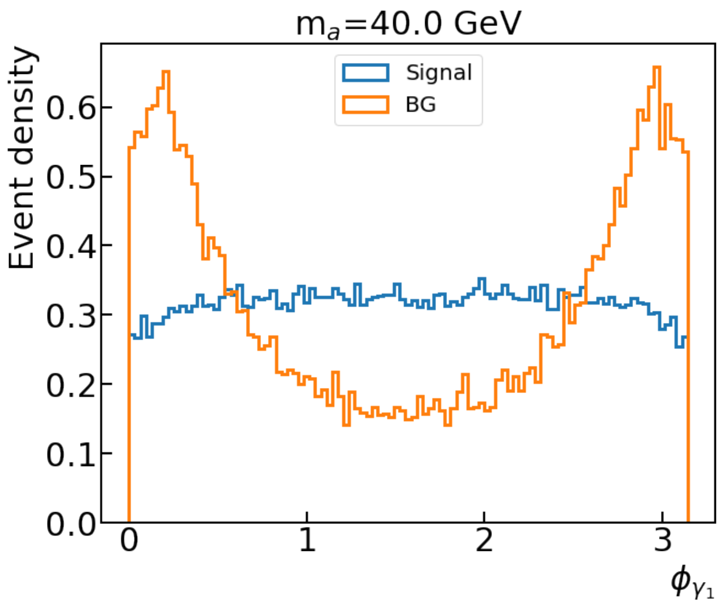
Choose assignment minimising M_{cut}

$m(\gamma 1, \gamma 2) \equiv M_a$

Discriminant variables





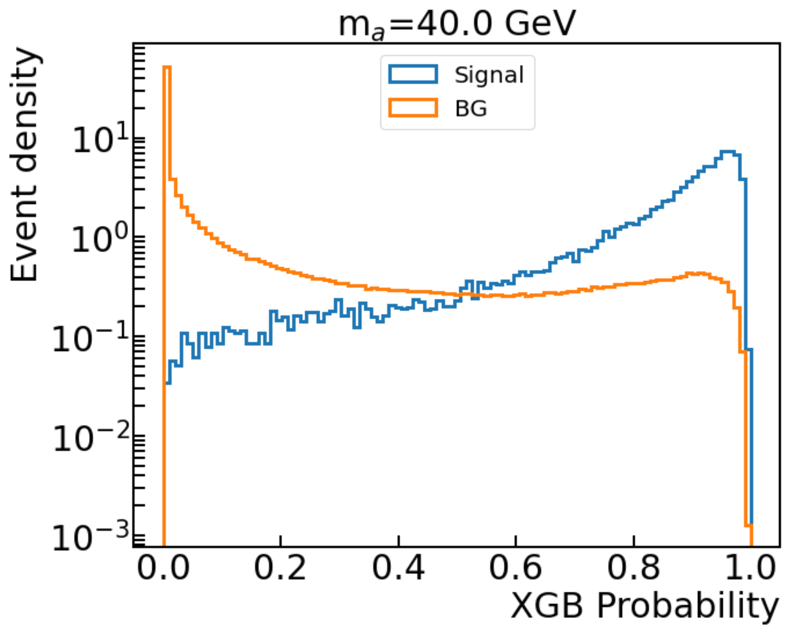


Require that event only contains three photons.

For a fixed mass, signal fully defined by three variables, after rotation such that $\varphi_{\gamma 3}=0$:

- Polar angle of ALP in lab system $|\cos\vartheta_{\alpha}|$
- Polar angle of γ_1 in ALP rest system $|\cos\vartheta_{\gamma 1}|$
- Azimuthal angle of γ_1 in ALP rest system $\varphi_{\gamma 1}$

train a boosted decision tree (XGB) on 5 variables, the three above+ $m(\gamma_1\gamma_2)$, $E_{\gamma 3}$



Experimental issues at low masses (~<5 GeV)

Signal acceptance strongly affected by width of ALP mass peak

At low masses three geometrical effects:

- Resolution of photon measured impact point in calo
  - Discussed above
- ALP decaying far from interaction point
- Two photons from ALP decay coalescing in calorimeter

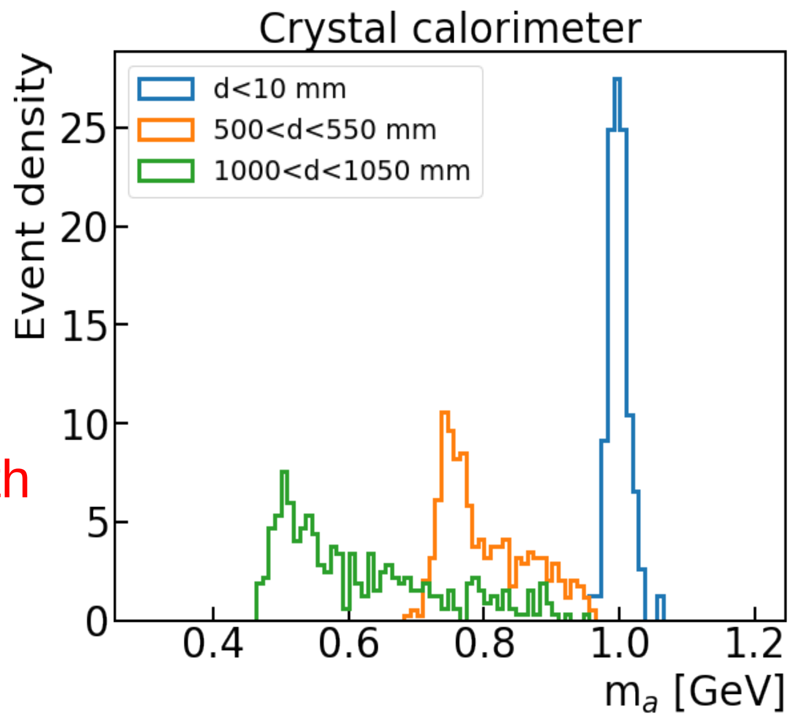
Long-lived ALP

ALP mass reconstructed assuming photons produced in center of detector. If long decay path angle between photons underestimated

Mass selection should reject ALPS with long path

For present exercise, reject manually ALPs with flight path above 1~cm. Study impact of cut at 5 and 10~cm.

Work in progress: study how mass measurement evolves with flight path of ALP (preliminary plot)



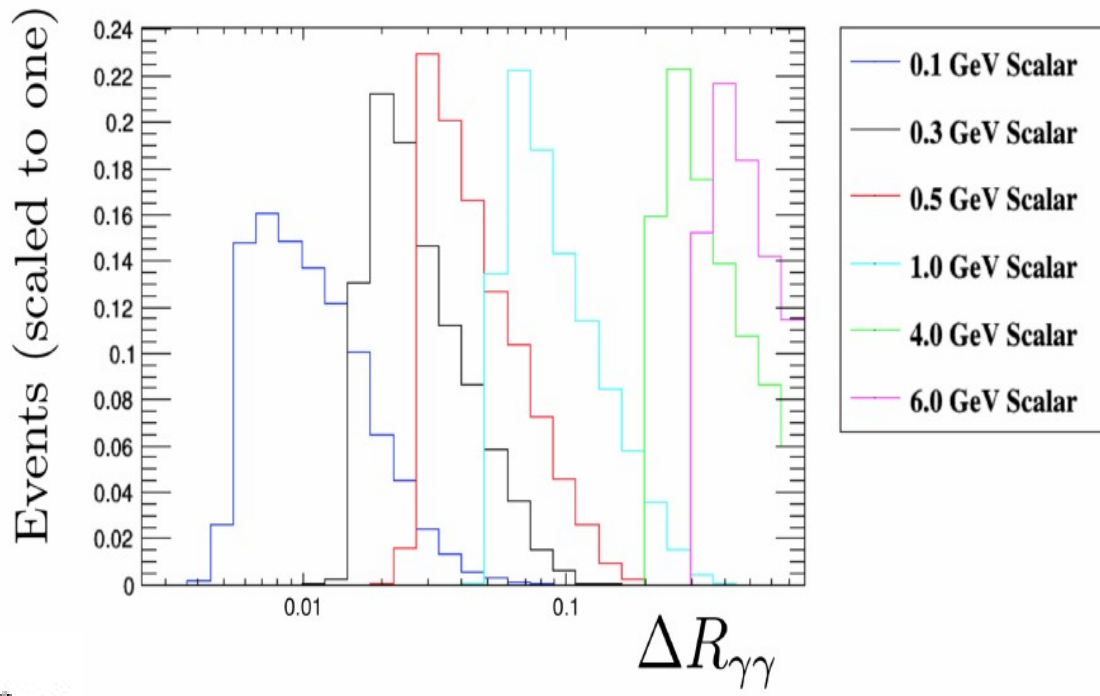
m_a=1 GeV, $C_{\gamma\gamma}$=1e-3

Coalescing Photons

Steinberg, Wells, arXiv:2101.00520

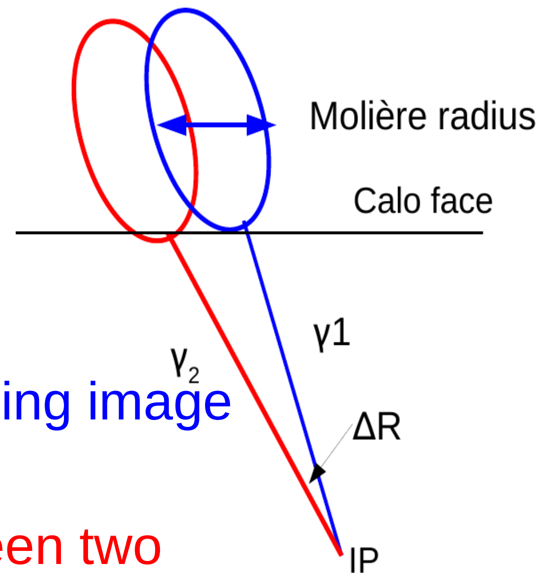
For M_a <~ 5 GeV two photons very collimated: e.g for M_a=0.5 GeV ΔR_{peak}~ 0.03

If distance from interaction point to calo face = 2 m (IDEA), two photons from 0.5 GeV ALP have distance of 6 cm.



$$\Delta R_{\rm peak} = 4m_a/m_Z$$

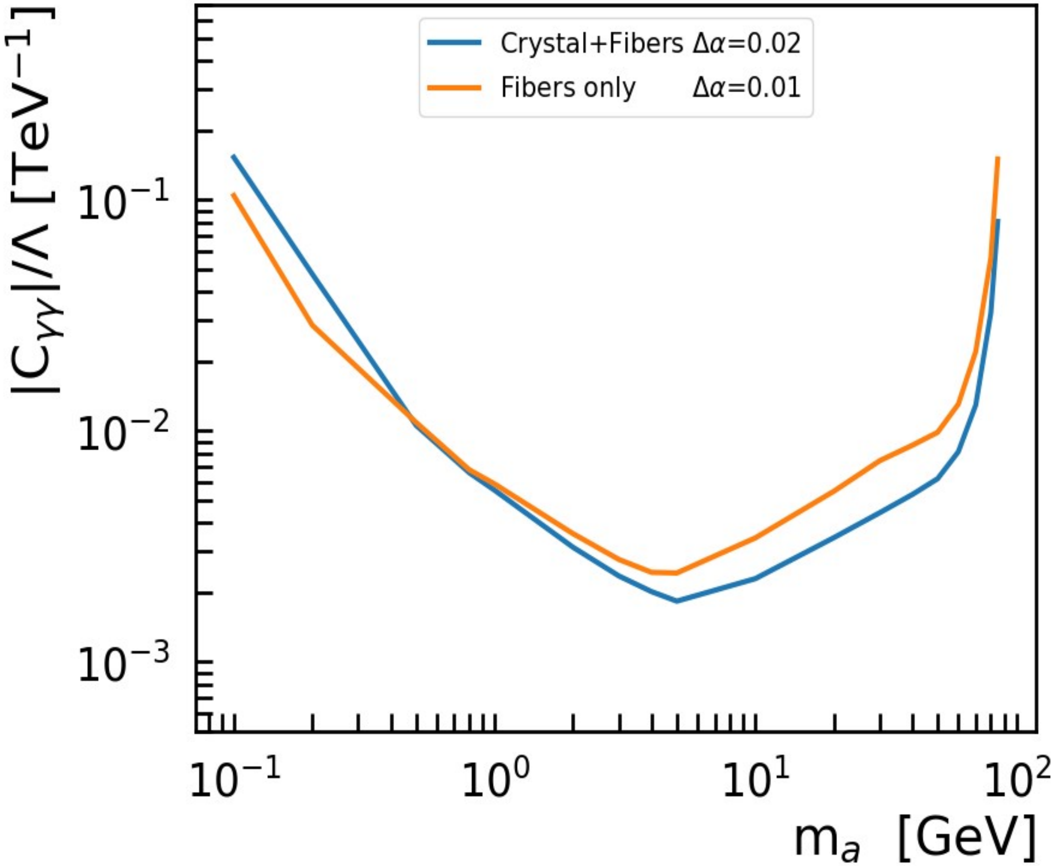
Size of photon shower in calorimeter: Molière radius, depends on material and geometry, around 2 cm for crystal calorimeter, ~2.4 cm for fibre calorimeter



Very high granularity can be exploited to measure the two clusters using image reconstruction techniques → start work soon on that

Waiting for results becoming available, reject events where Δα between two photons smaller than 0.01, 0.015, 0.02, 0.03 and study reach as a function of cut

Results



For each signal and background sample events after cuts normalised to FCC-ee lumi

s=number of signal events after cuts

b=background events after cuts

n=s+b, σ = systematic uncertainty on b

Find cut on XGB output maximising significance calculated as:

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

Significant advantage of better energy resolution at high masses

At low masses better granularity should allow better separation of close-by photons

Cross-section proportional to $C_{\gamma\gamma}^2$

For each test mass plot $C_{\gamma\gamma}$ such that Z=2

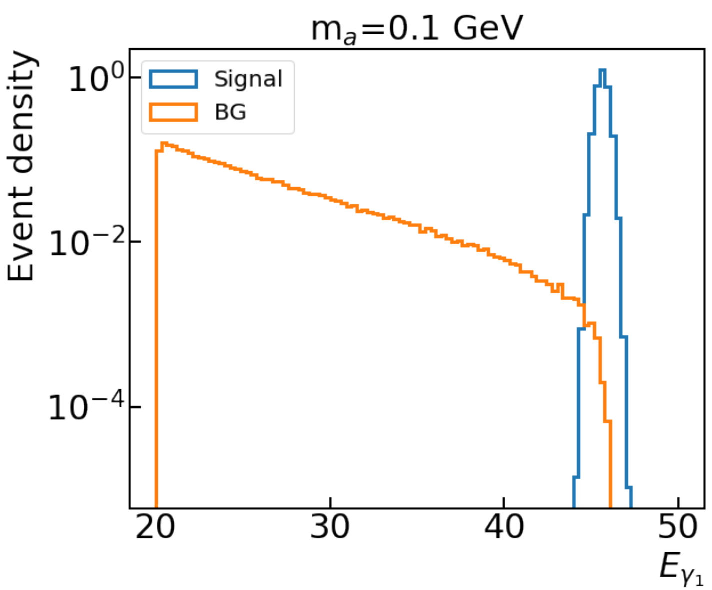
γ+MET analysis

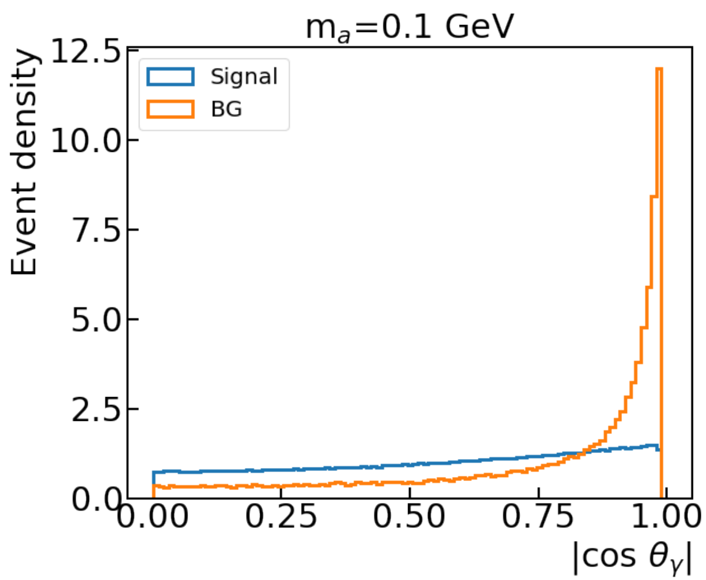
Relevant mass range below ~2~GeV → signature is a monochromatic photon of energy ~45.5 GeV and nothing else in the detector

Consider two backgrounds: irreducible: $e^+e^- \to \gamma\nu\nu$

reducible: e+e-→γe+e- where the electron and positron are outside detector acceptance (|η|>3). By requiring the photon to be within |η|<2.6 and with energy at the kinematic limit this background is reduced to very small

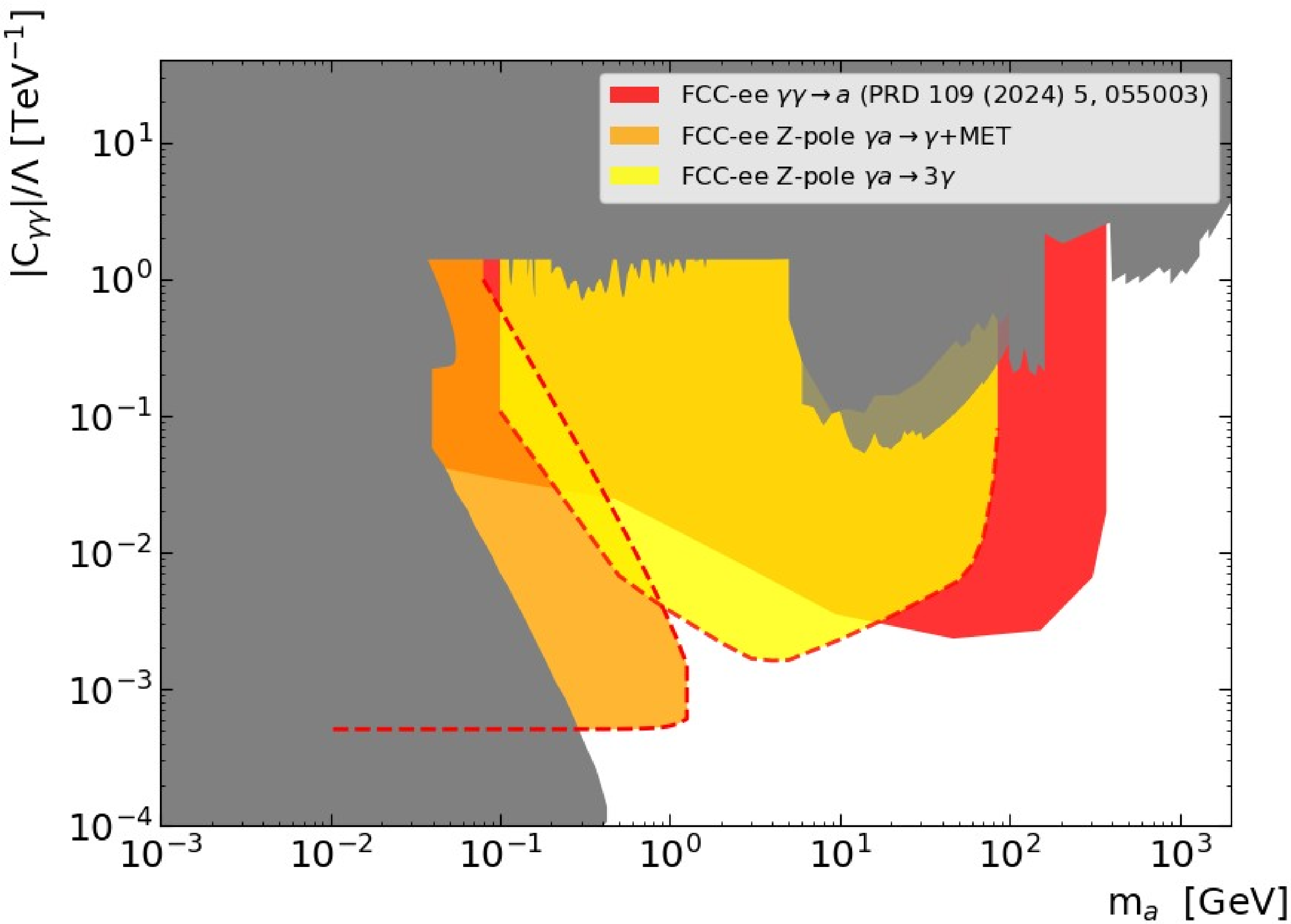
Backgrounds produced with MG5MC@NLO and passed through the usual PYTHIA-DELPHES chain





Two variables characterise the event, energy and polar angle of photon.
Combine them through XGB as for prompt analysis

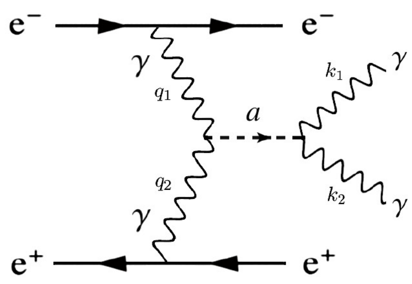
Combined plot FCC-ee



Grey areas :existing exclusions taken from ATLAS plot, to be updated with newest results

Yellow and orange areas are the two analyses of this talk

Red area is analysis of Rebello Teles et al. addressing ALP production in photon-photon fusion



Conclusion and outlook

Performed baseline exercise to evaluate reach of IDEA detector at FCC-ee for ALPS in channel $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$

Analyses for 3γ final state, and for ALP decay outside detector provide good coverage of area of parameter space not accessible to other experiments

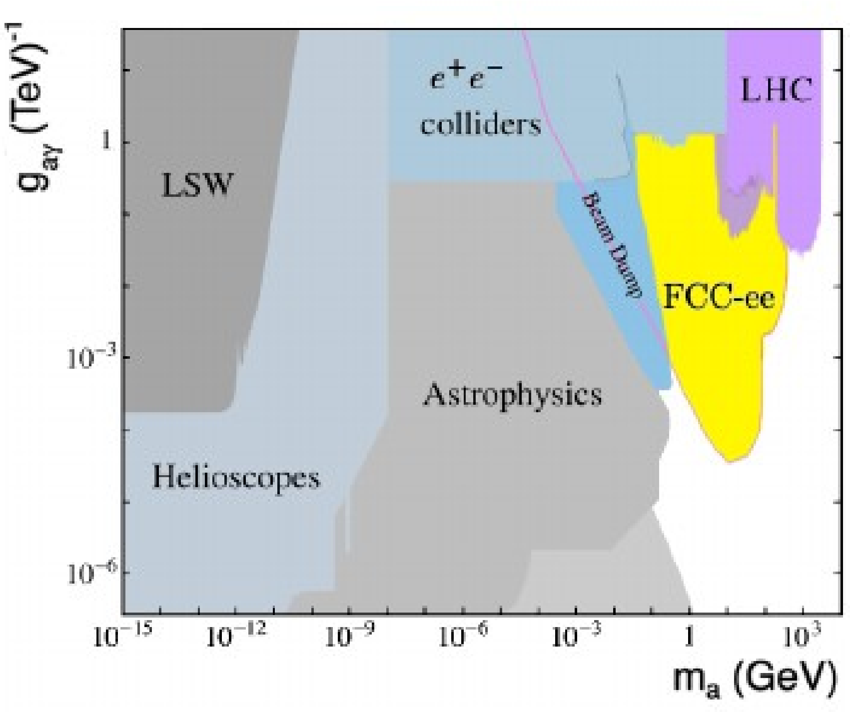
Reach sensitive to EM calorimeter energy and position resolution

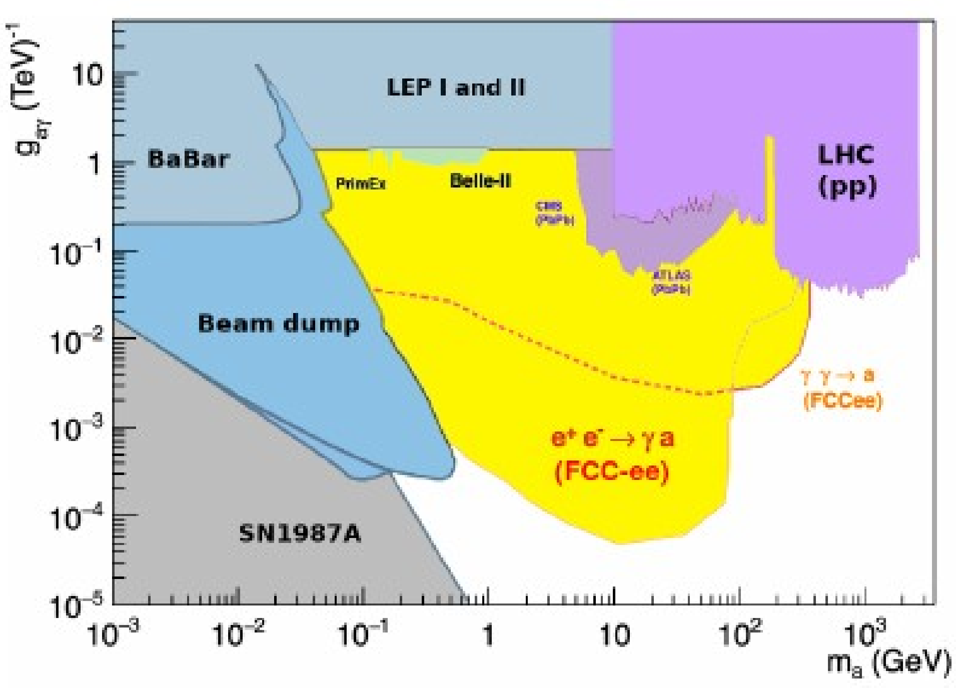
Work in progress to refine the analysis:

- Consider reducible backgrounds for prompt analysis
- More realistic treatment of long flight paths for prompt analysis
- Study resolution on impact angle on photons and apply to LLP decays
- Develop mass-reconstruction algorithm based on CNNs for fiber calorimeter to study coalescing photons
- Use 4π simulation of both calorimeter setups (longer term)

Backup

Parameter space coverage



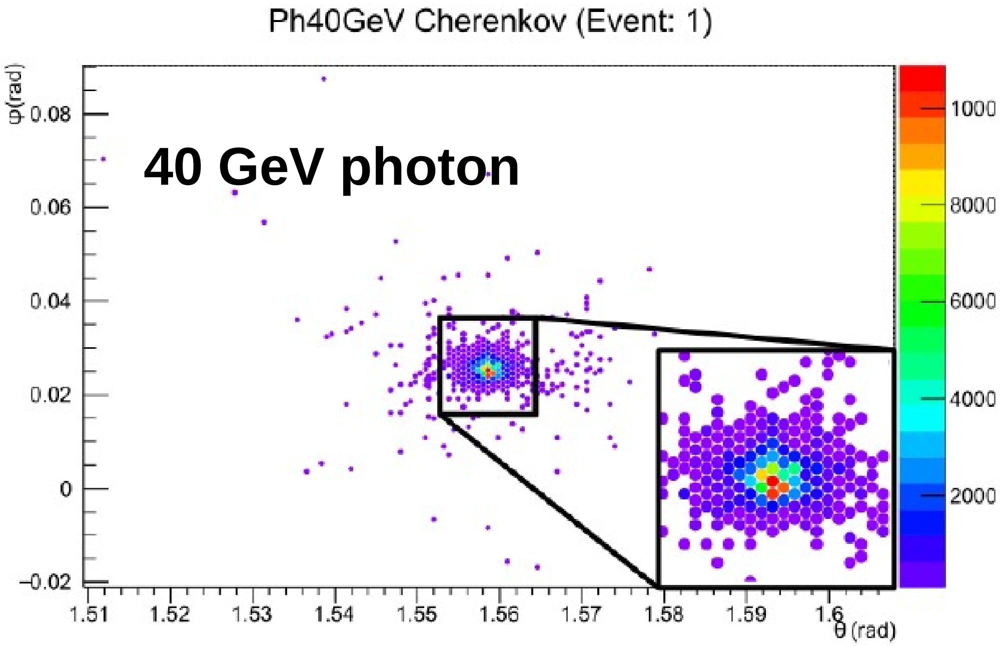


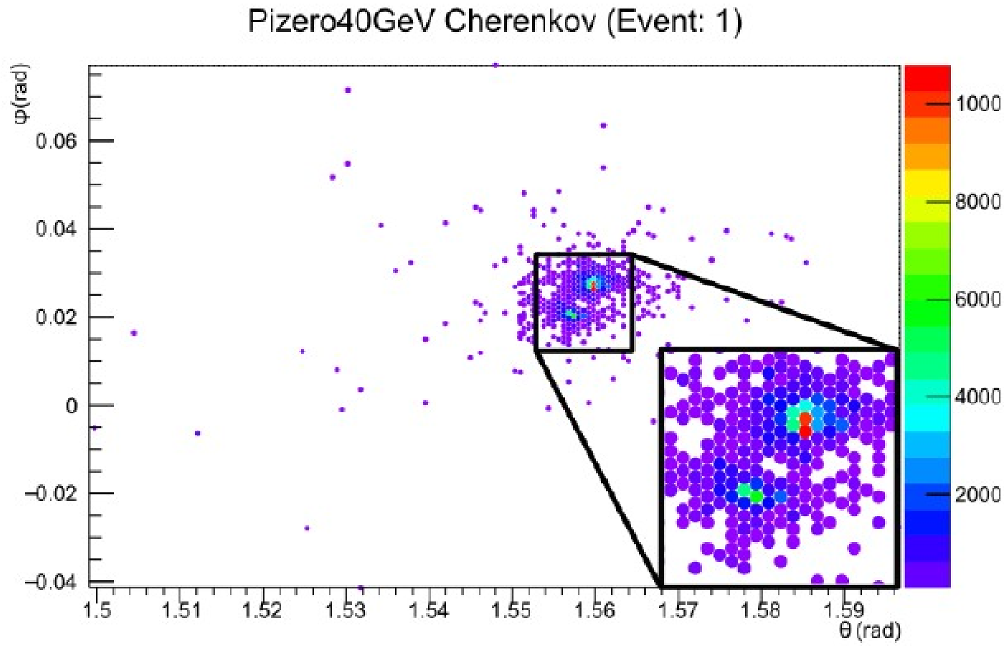
Plot in the MT report: $e^+e^- \to \gamma a$ line is theory calculation requiring 4 ALP decays inside detector. 4 events might work for long-lived but prompt analysis has a huge irreducible background $e+e+ \to \gamma\gamma\gamma$, requiring detailed background analysis

Plots originally from Rebello Teles et al.

Example: exploiting the full granularity of IDEA DR Calo

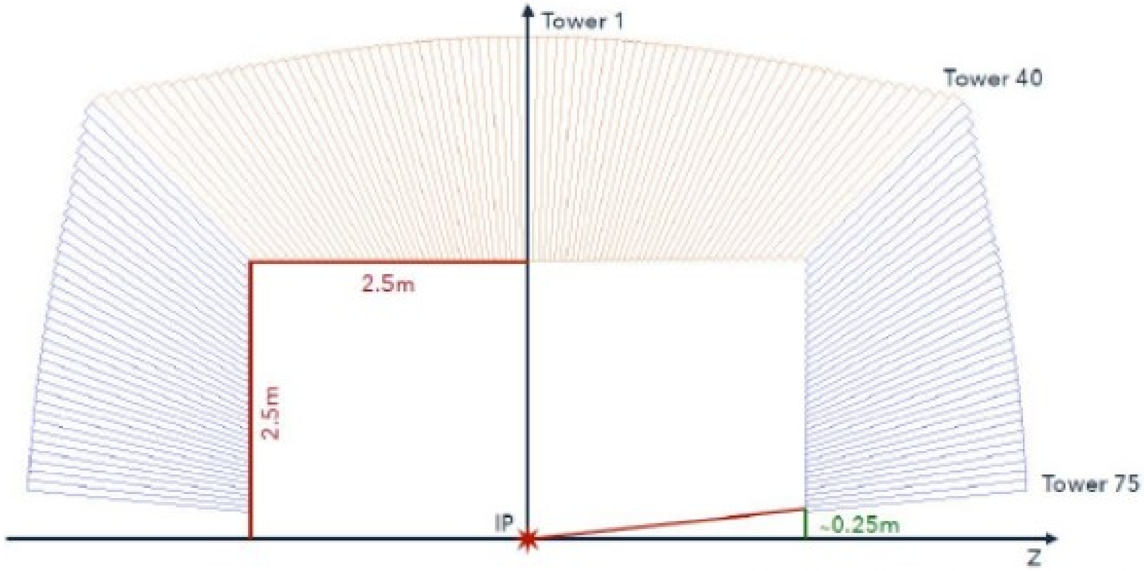
With Silicon PMs it is possible to read one by one all of the fibers in the calorimeter → possibility to separate very close photons and to precisely measure invariant mass

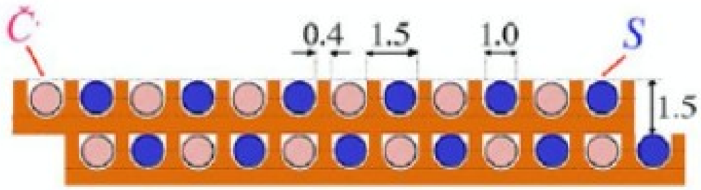


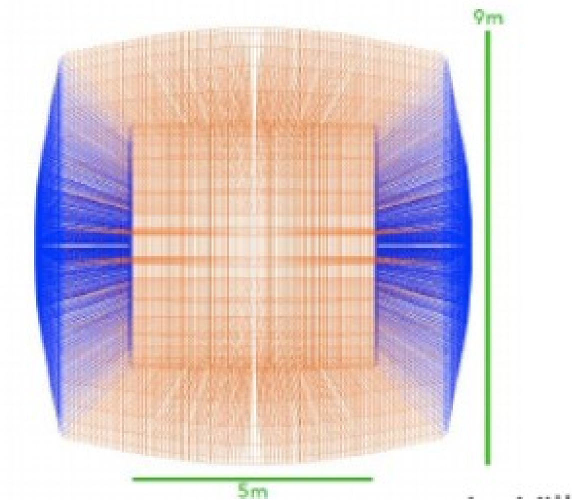


Ideal field of application for ML image recognition, work ongoing in Pavia (master thesis A. Villa)

IDEA DR Calorimeter, old version

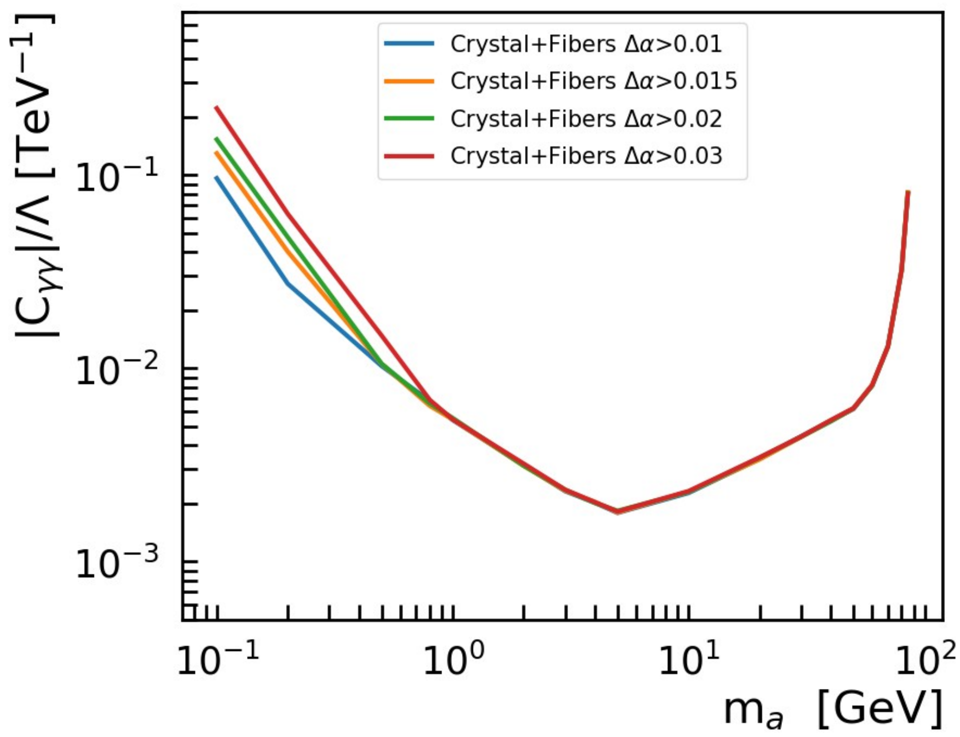




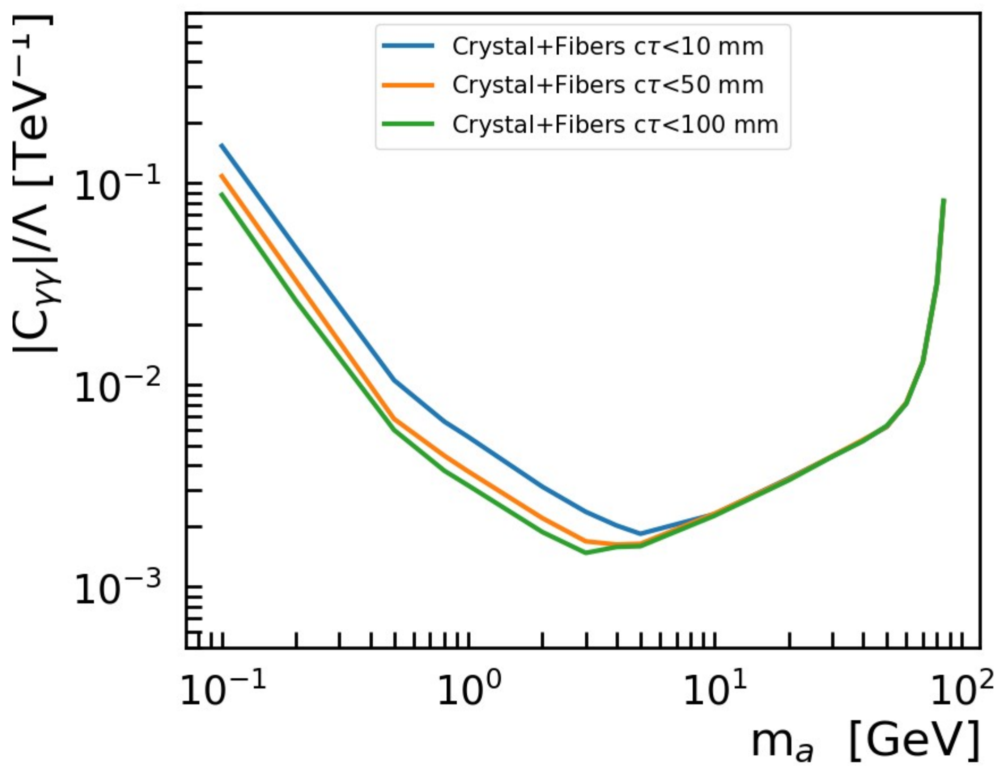


Reach as a function of Δα and of cut on cτ

Cτ<10 mm



Δα>0.02

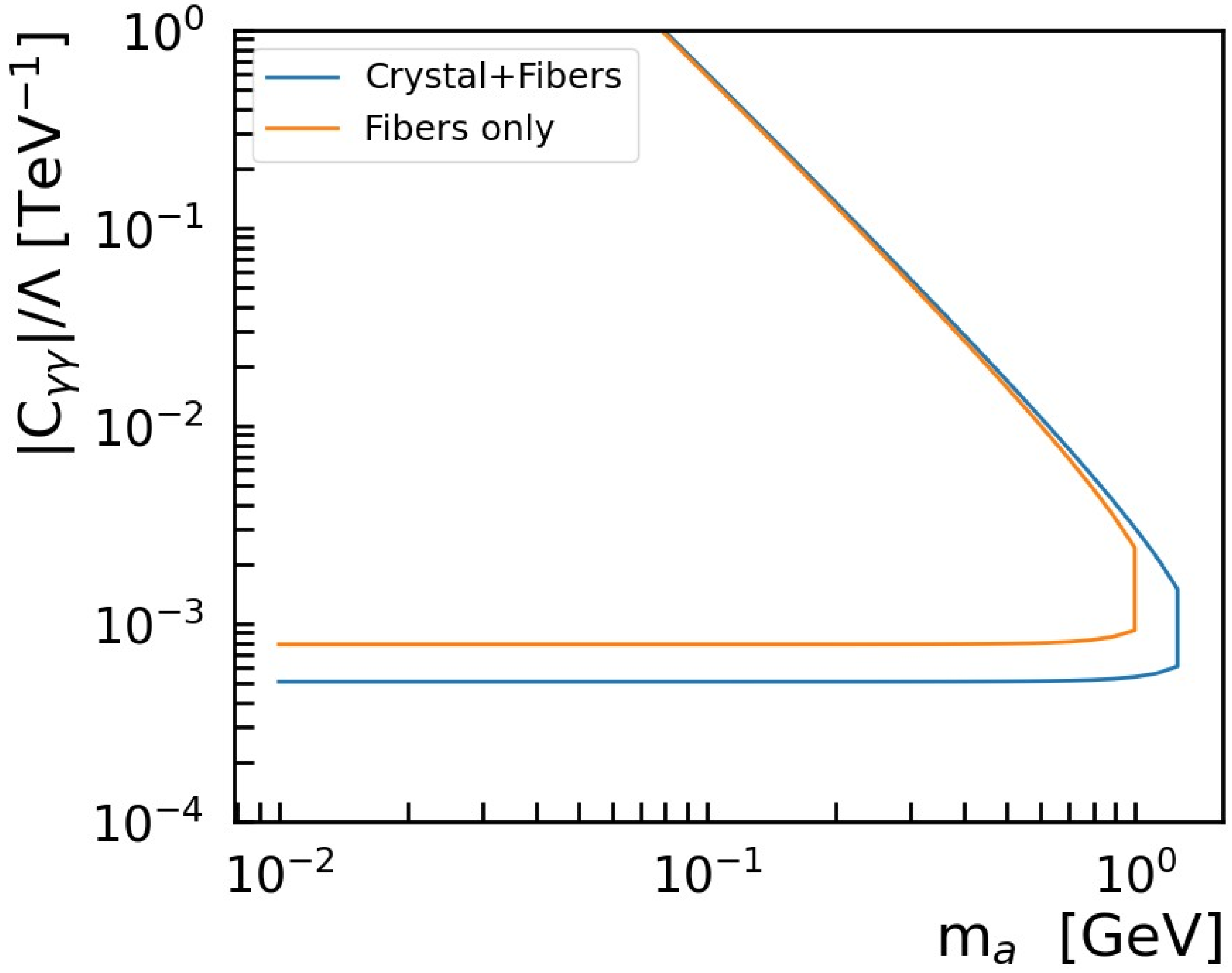


Plot 2σ reach as function of mass and coupling, assuming 0.1% systematics
Define significance as:

s=number of signal events after cuts
b=background events after cuts
n=s+b, σ = systematic uncertainty on b

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

Results



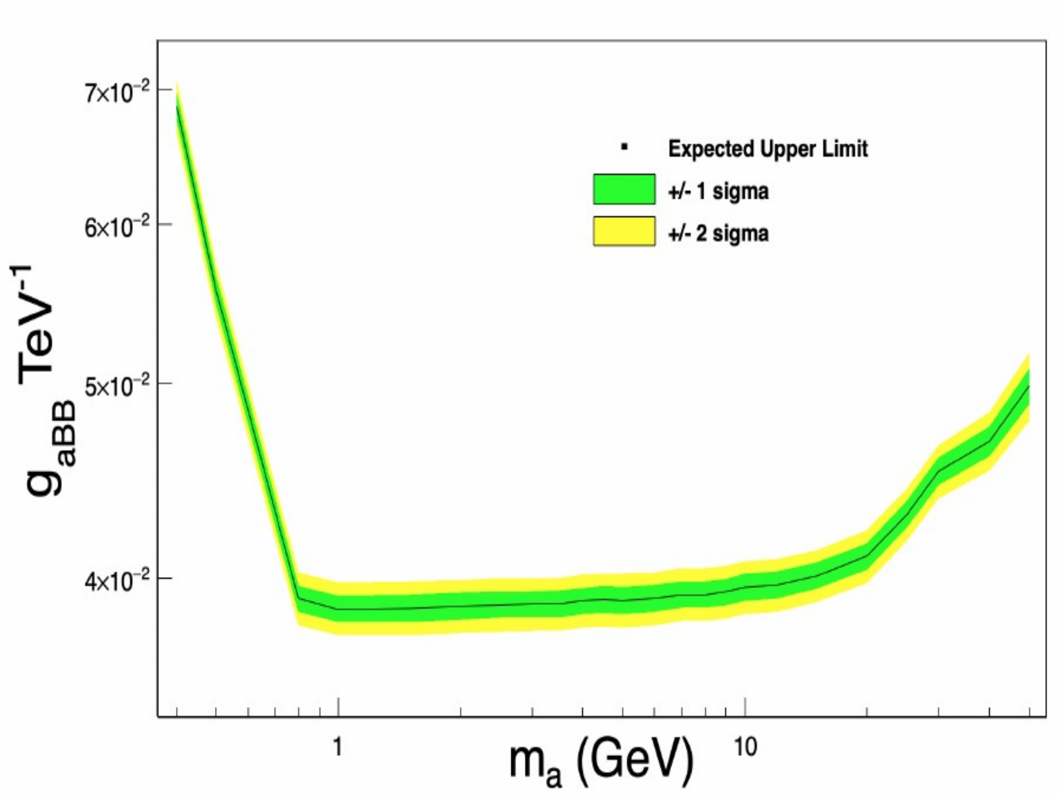
Irreducible background small at 45.6 GeV, but it increases very fast as energy goes down.

Smaller energy window determined by better resolution significantly increases reach

A similar exercise

Recent paper: Steinberg, Wells, arXiv:2101.00520

Addressing the same model in the framework of ILC GigaZ
ILC detector: R(ECal)~1.85 m. GARLIC photon reco: require photons with ΔR>0.035 and with less than 10% of energy in reconstructed cone from nearby photon



Simple analysis, require:

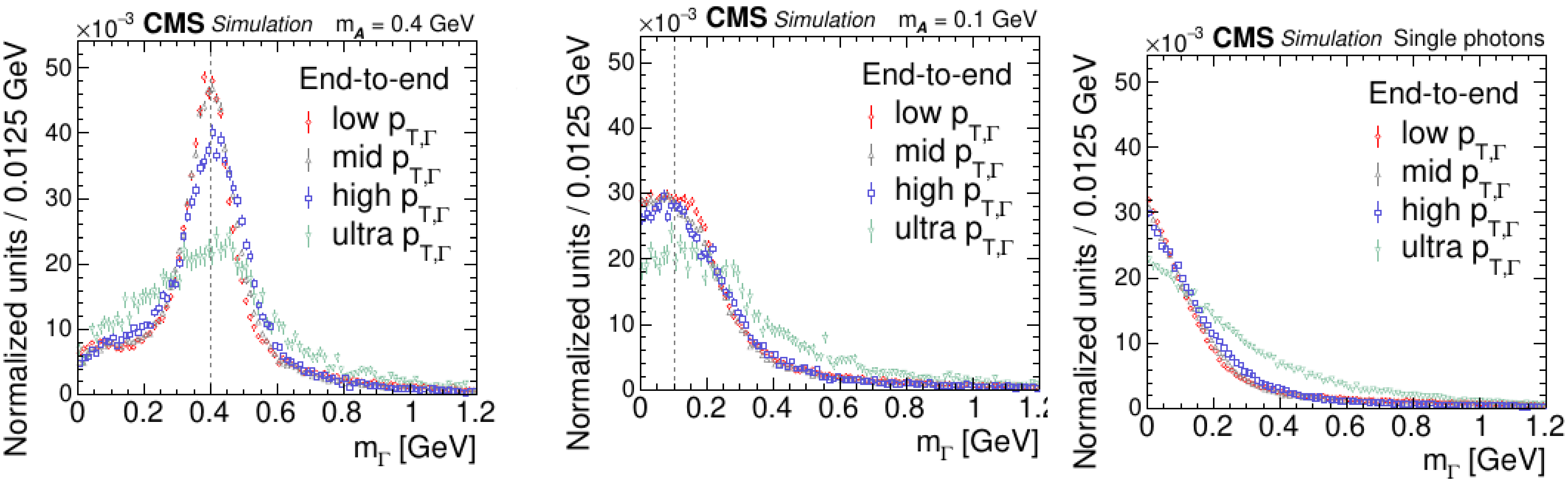
- 3 non-overlapping photons E>2 GeV
- $E\gamma - E\gamma^{recoil} < 5$ GeV

$$E^{\gamma}_{\rm recoil}(m_a) = (M_Z^2 - m_a^2)/2M_Z$$

Significant loss in sensitivity, but in this setup search extended down to ALP masses if few hundred MeV

An encouraging example from CMS

PRD 108 (2023) 052002



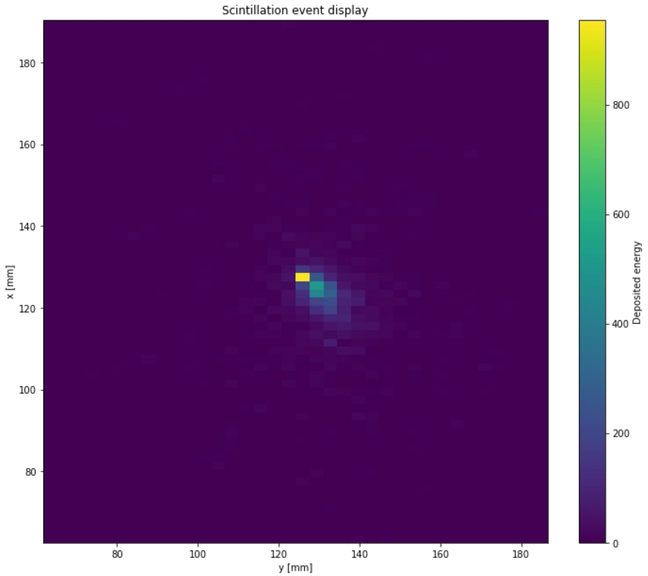
Using a CNN-based algorithm, reconstruct peak of 100 MeV particle.

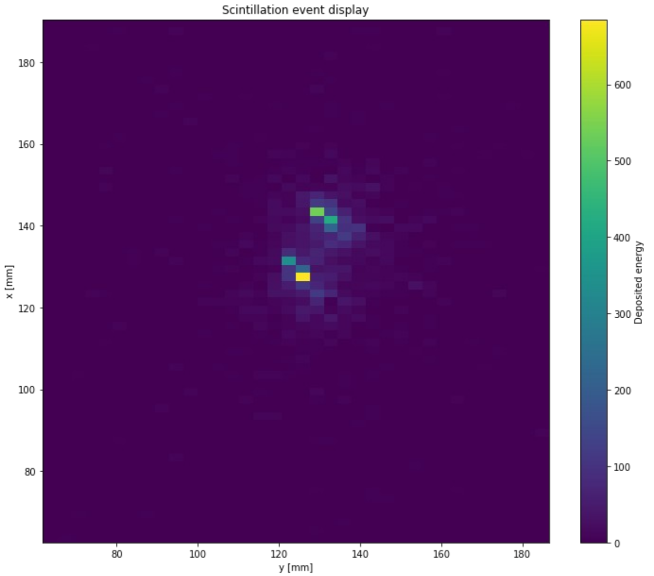
CMS granularity: 2.3 cm, IDEA Crystal: 1 cm IDEA Fiber: 2 mm

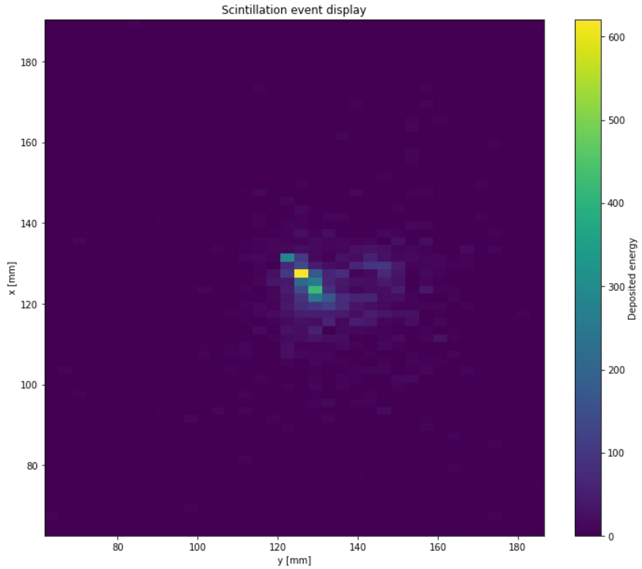
Can probably improve on CMS result

Two photons in fiber calorimeter

One fiber every 2 mm read with SiPMs







G4 simulation of energy deposition of a 40 GeV photon (left),

and of two examples 40 π^0 produced at 2m from a fiber calorimeter prototype

(Master thesis G.Salsi)

Very high granularity can be exploited to measure the two clusters using image reconstruction techniques → start work soon on that

Waiting for results becoming available, reject events where Δα between two photons smaller than 0.01, 0.015, 0.02, 0.03 and study reach as a function of cut