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

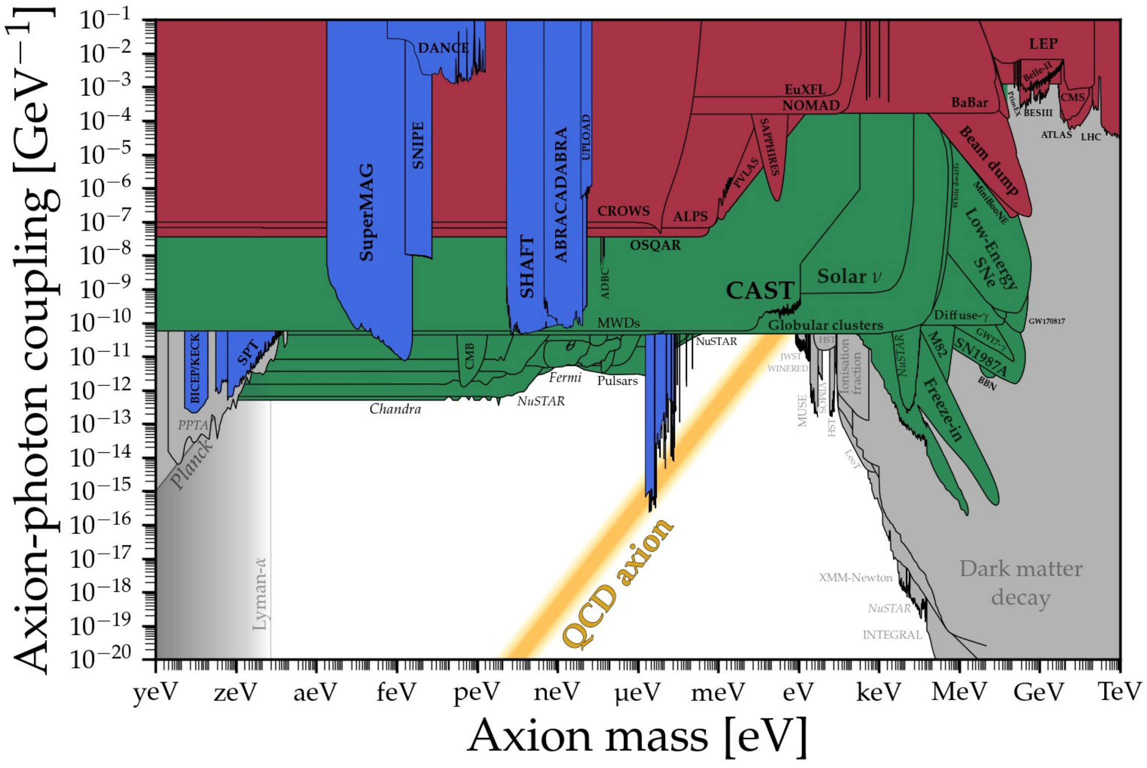
G. Polesello (INFN Pavia)

on behalf of the BSM PED group

Introduction

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

Couples to Z/photon, can be abundantly produced at FCC-ee



High statistics of FCC-ee Z-pole run allows exploration of much lower couplings to photons than tested to date in mass range 0.1-90 GeV

In BSM group ongoing studies for different ALP decay modes:

a→γγ, a→gluon gluon, a→μμ

Typical ALP Lagrangian

Bauer et al:arXv:1808.10323

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \underbrace{\sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f}_{\text{Fermions}}$$

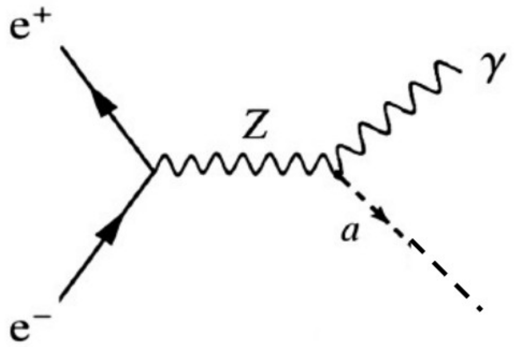
$$\underbrace{+ g_s^2\, C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}}_{\text{Gluons}} \underbrace{+ g^2\, C_{WW}\frac{a}{\Lambda}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2\, C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}}_{\text{Vector Bosons}}$$

After EWSB:

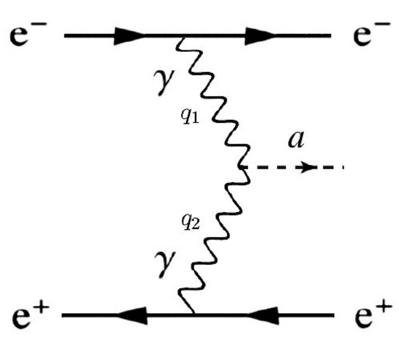
$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$C_{\gamma\gamma} = C_{WW} + C_{BB}, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB}, \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

Production in FCC-ee Z-pole run



Decay Z→ γa:
function of $C_{Z\gamma}$ coupling
Mode assumed in
all analyses shown today.
Interplay of $C_{Z\gamma}$ to other
couplings key to
phenomenology



Photon-photon fusion:
function of $C_{\gamma\gamma}$ coupling
Studied in:

Rebello Teles et al.

$a \to \gamma\gamma$

G. Polesello, S. Gascon-Shotkin,
G. Cacciapaglia, E. Jourd'huy,
J. Xiao

Canonical decay channel, several searches in literature. Regions of interest

- 0.1< ma < 10 GeV:
  loose limits from previous e+e- searches, out of reach of beam dump
- $10 < m_a < 90$ GeV:
  dominated LHC photon-photon fusion potential for FCC-ee Z pole run

Existing constraints from JHEP 12 (2017) 044

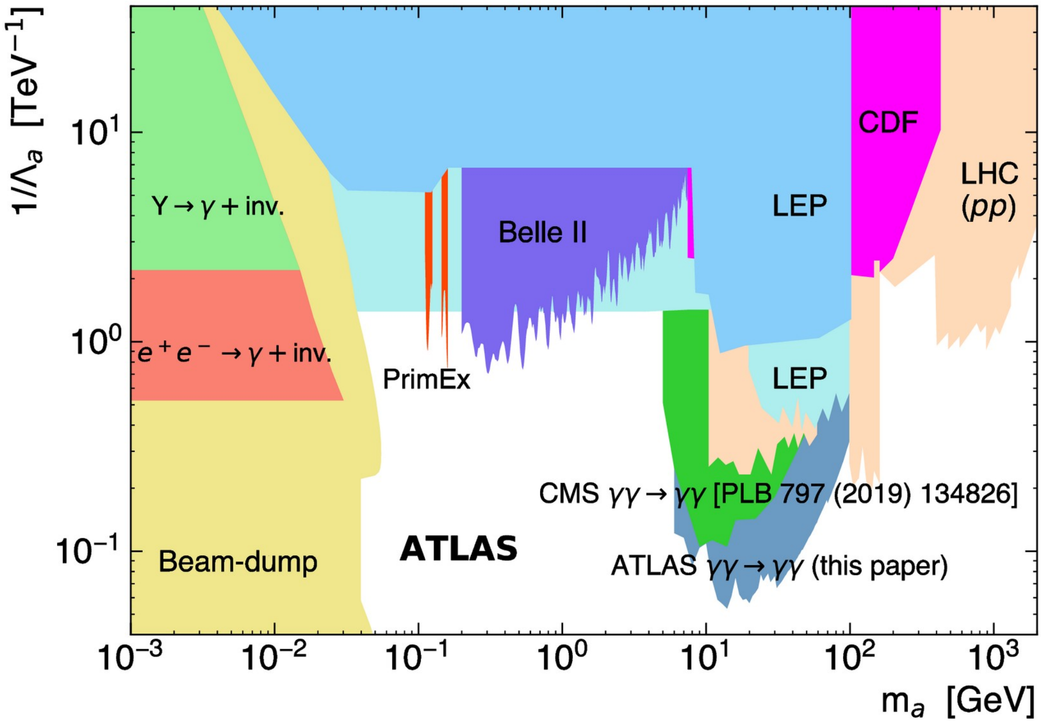


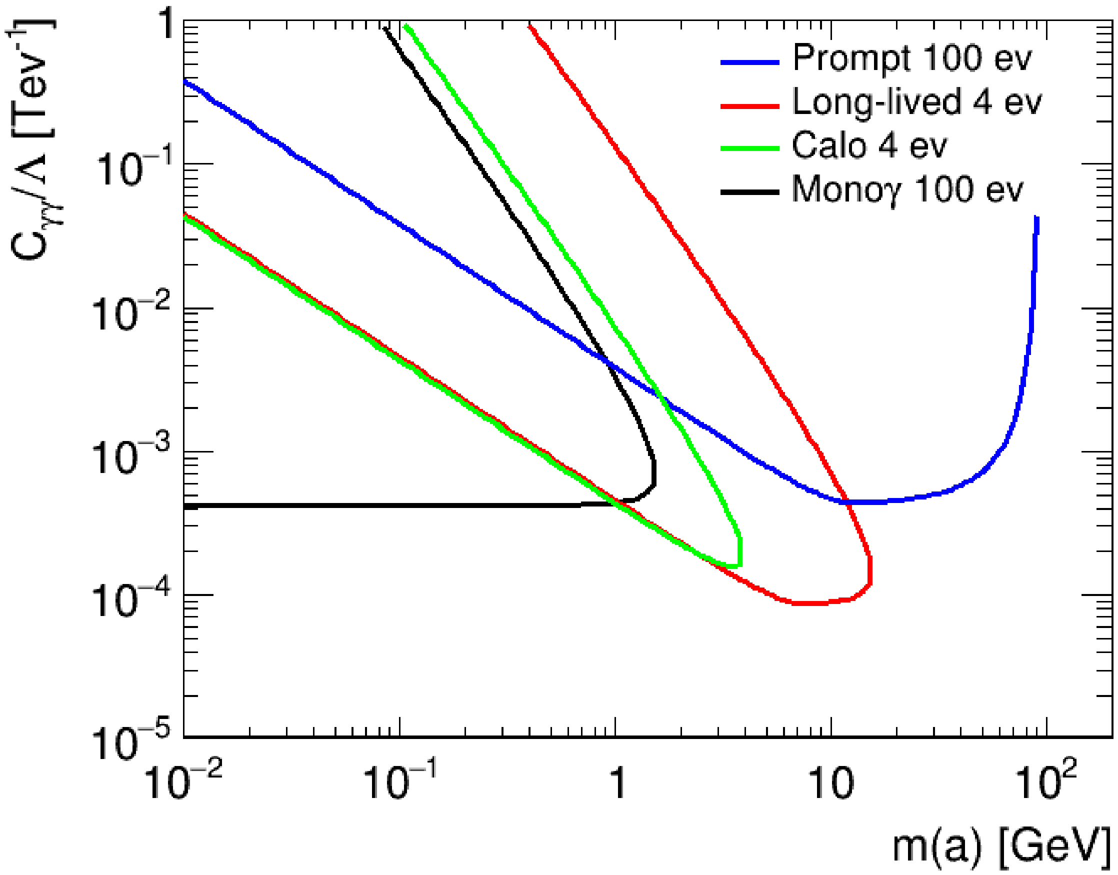
Figure from: ATLAS:arXiv 200805355

- Assume a couples to hypercharge and not to SU2 ($C_{WW}=0$)

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

- Assume BR($a\to \gamma\gamma$)=100% → three-photon signature

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



4 experimental regions depending on decay length L of ALP

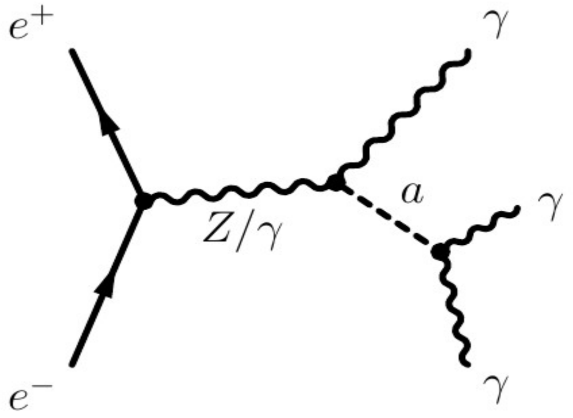
- 100 events for L<10 mm (prompt)
- 4 events for 10<L<2000 mm (Long lived)
  Decay in ID
- 4 events for 2000<L<4500 mm (Calo)
  Decay in calorimeter
- 100 events for L>4500 mm: ALP decays outside the detector, only accompanying photon detected (monophoton)

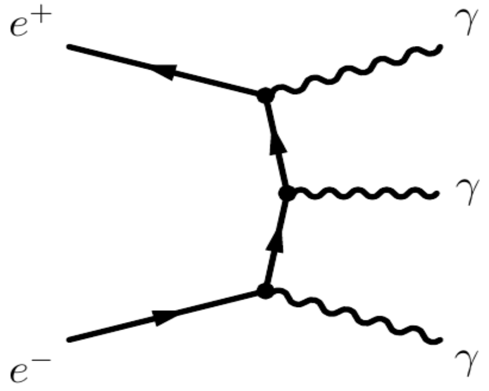
Experimental distinction of 3γ prompt analysis and LLP analyses depends on how well one can detect a ALP decay away from vertex → today show 3γ analysis making no assumptions on vertex detection.

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

3γ ALP signal and background simulation

Signal





Dominant background for 3γ analysis

Generation chain:

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

Crystal: $\frac{\sigma(E)}{E} = \frac{0.139}{\sqrt{E}} + 0.006$ Fibre $\frac{\sigma(E)}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005 \oplus \frac{0.002}{E}$

Better granularity for fibre option

Z-pole FCC-ee run, $6\text{x}10^{12}$ Z bosons, 205 ab^{-1} over three mass points

3γ analysis

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

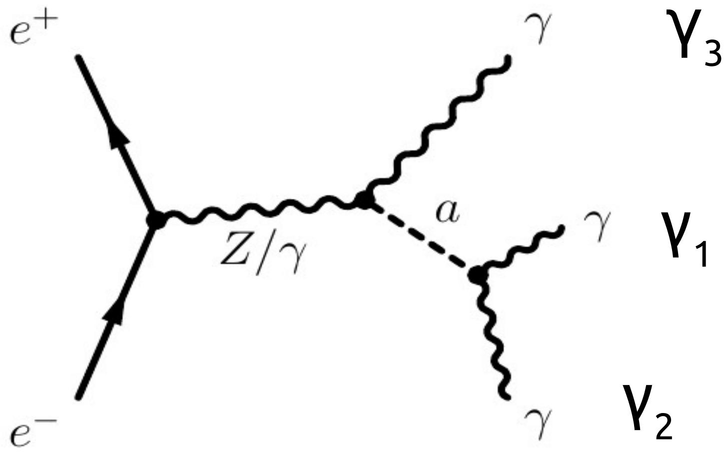
For each M and E_{CM} photon produced alongside ALP has energy $E_\gamma = \frac{E_{CM}^2 - M^2}{2E_{CM}}$

Assign three photons to ALP or to Z decay:

For given test mass and assignment:

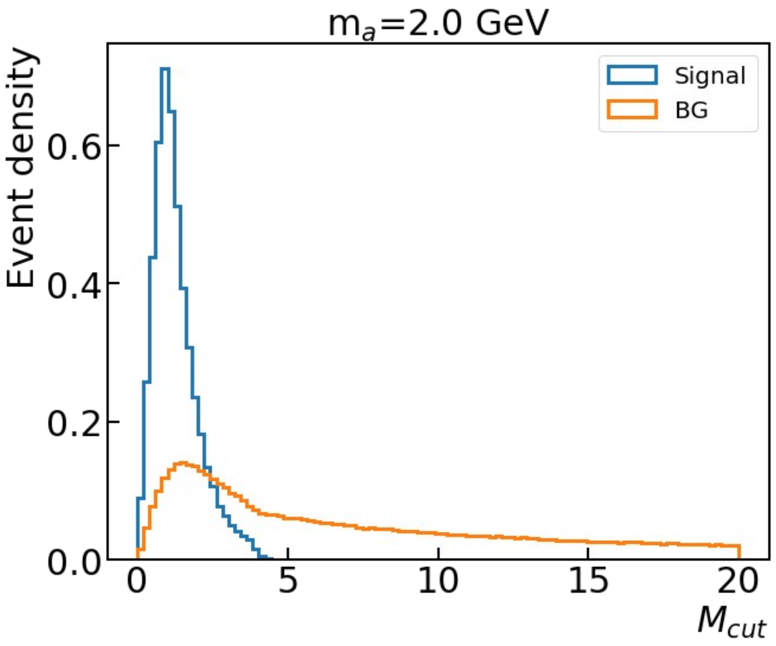
Measure compatibility with expected kinematics

$$M_{cut} = \sqrt{(M_a - M)^2/\sigma^2_{M_a} + (E_{\gamma_3} - E_\gamma)^2/\sigma^2_{E_{\gamma 3}})}$$

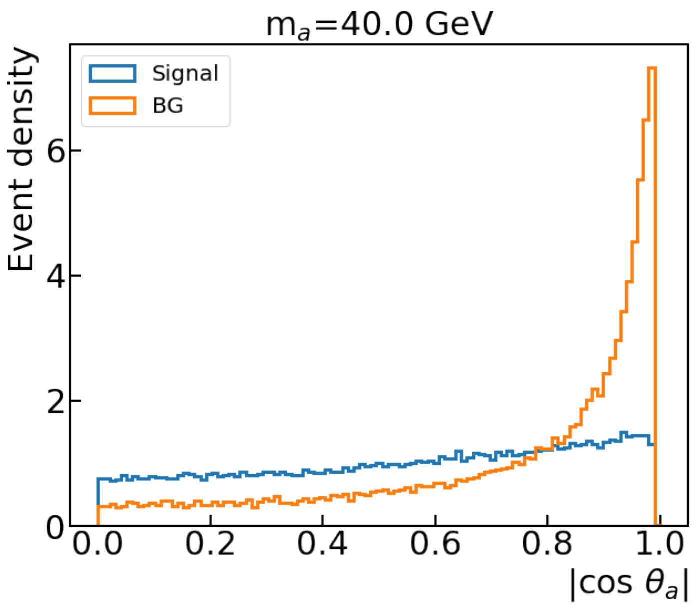


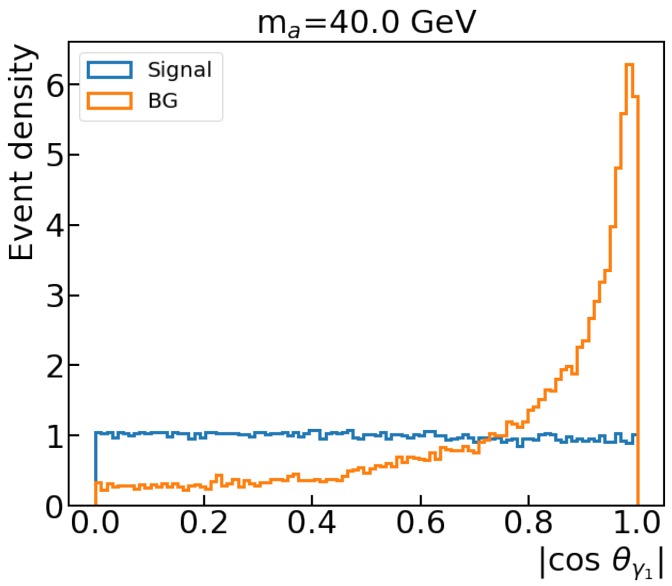
Choose assignment minimising M_{cut}

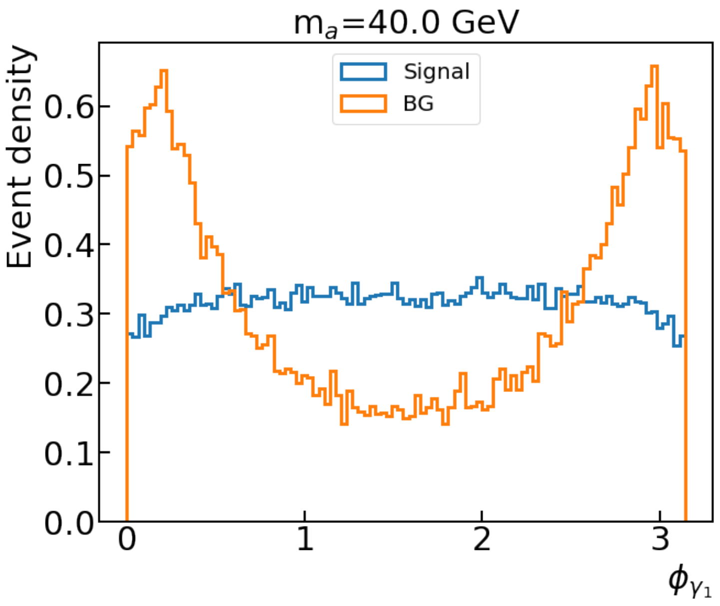
$m(\gamma 1, \gamma 2) \equiv M_a$



Discriminant variables





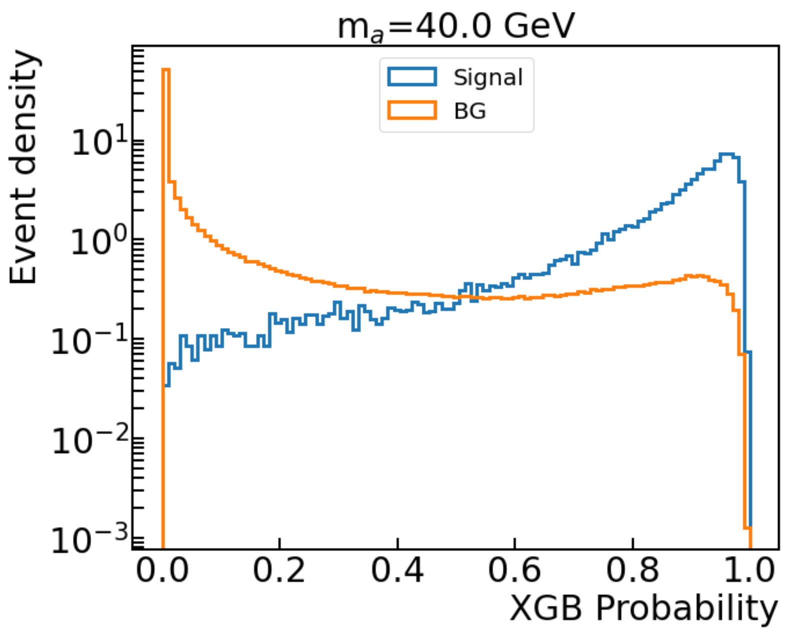


Require that event only contains three photons.

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+ $E_{\gamma 2}/E_{\gamma 1}$ and M_{cut}

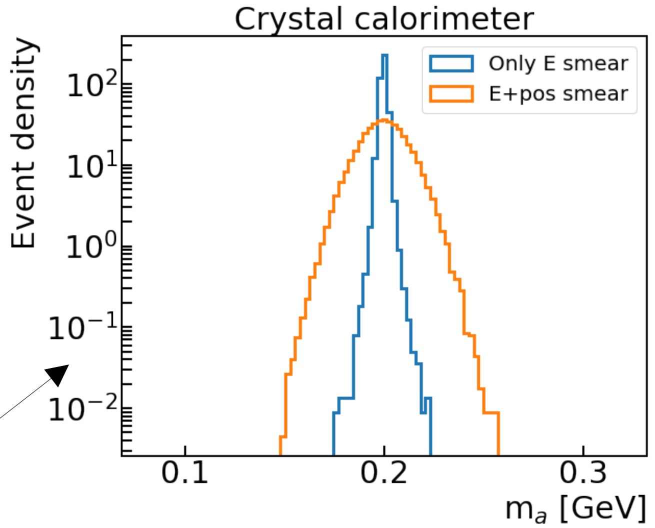


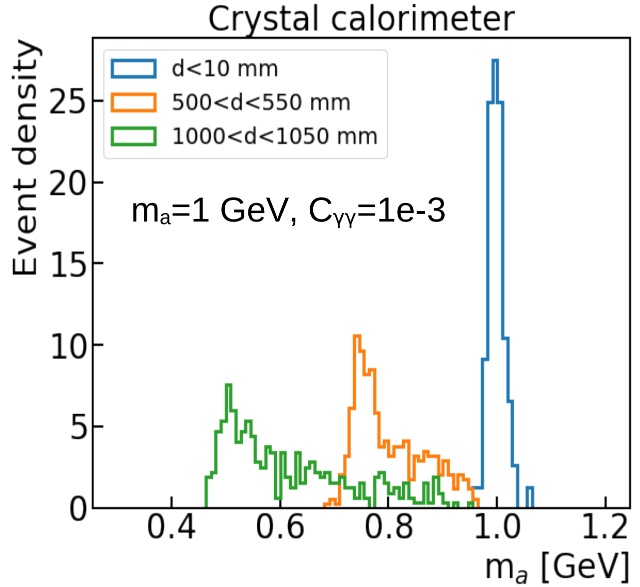
Experimental issues at low masses (~<5 GeV)

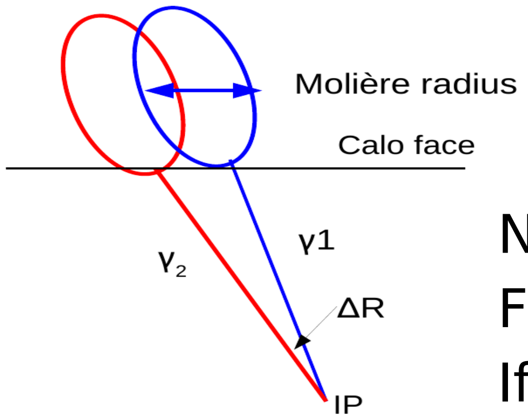
Signal acceptance strongly affected by width of measured ALP mass

At low masses three geometrical effects:

- γγ Mass resolution of dominated by uncertainty on measured photon impact point
- ALP decaying far from interaction point: mass reconstruction assumes photons produced in centre of detector. If long decay path, γγ angle Δα and mass underestimated
- γγ from ALP decay coalesce in calorimeter:







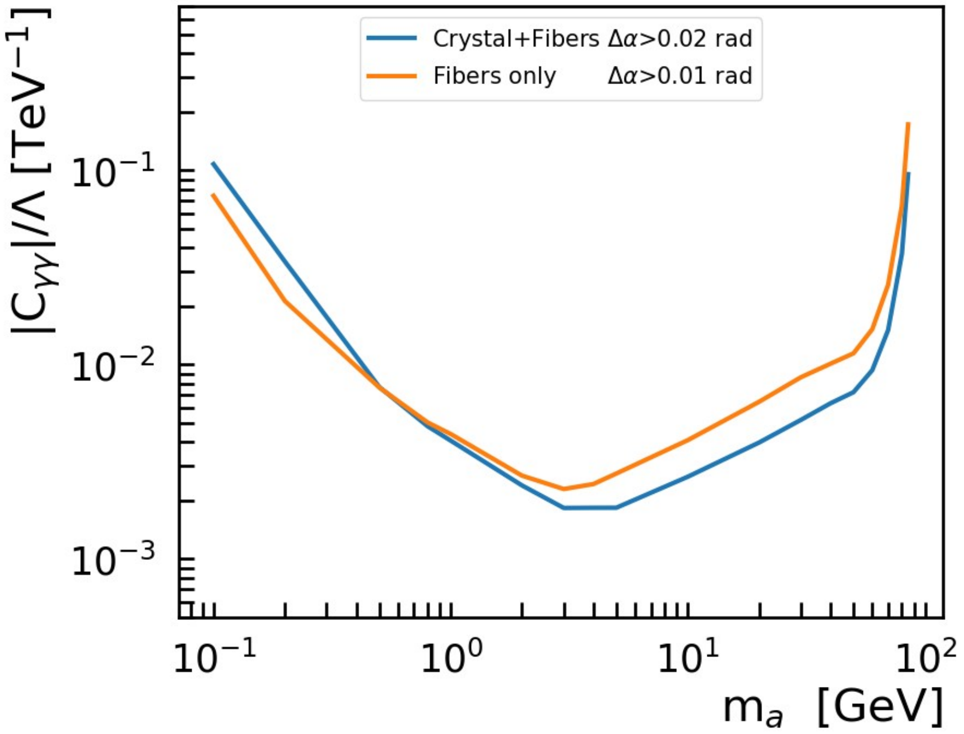
$$\Delta R_{\rm peak} = 4 m_a / m_Z$$

Need full simulation for separation of nearby photons

For this study assume two photons reconstructed as one

If Δα>02 (0.1) for crystal (fibre) EM calo

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

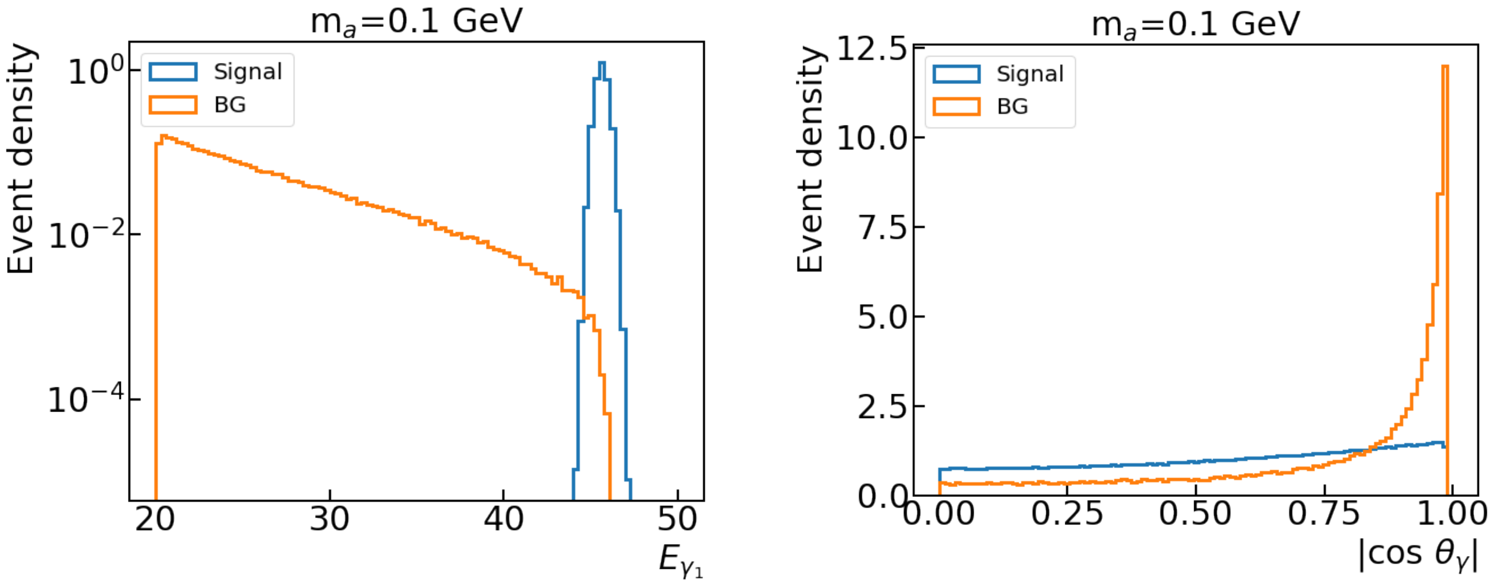
γ+MET analysis

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: $e+e-\to\gamma e+e-$ where the electron and positron are outside detector acceptance ($|\eta|>3$).

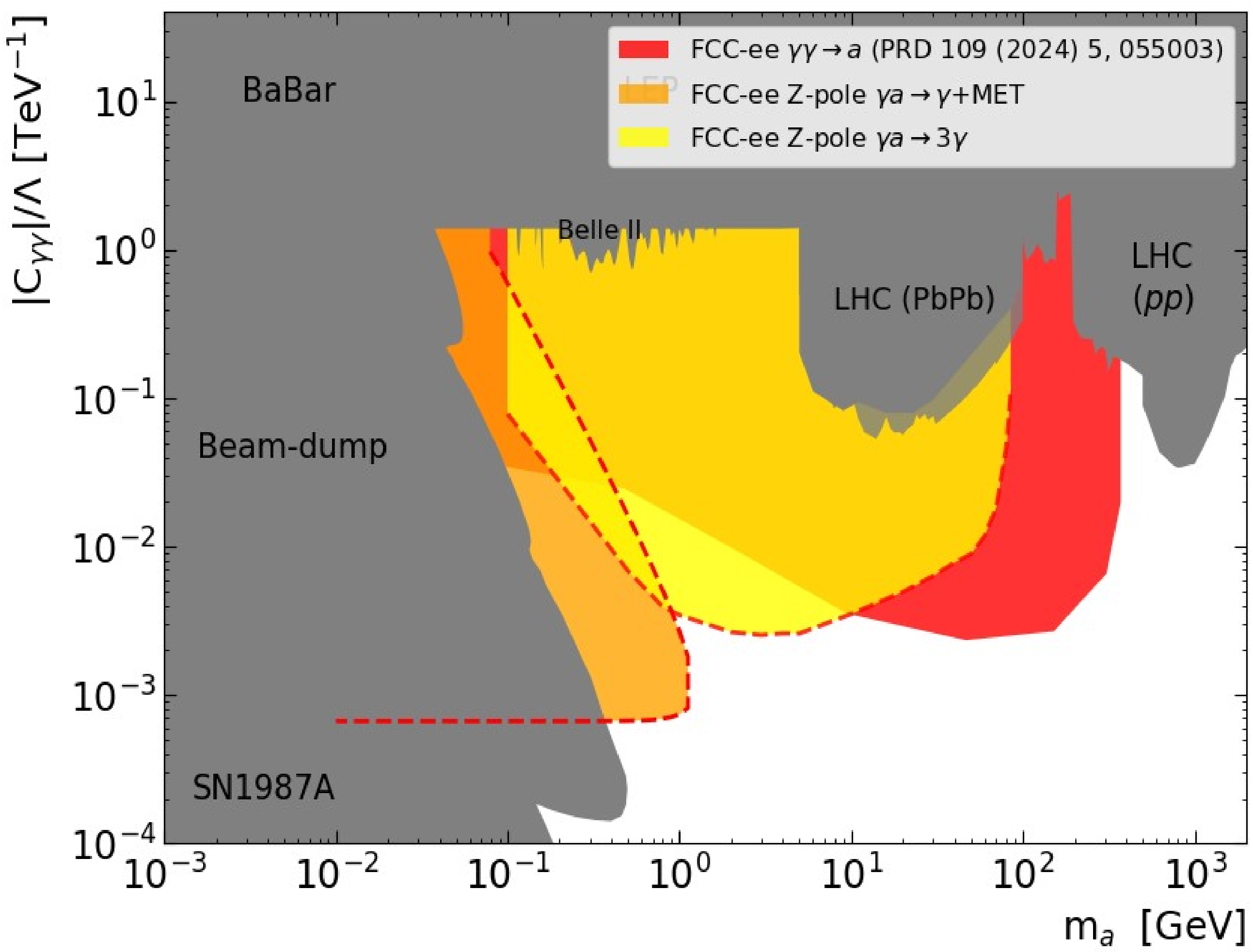
Signal and backgrounds produced with MG5MC@NLO and passed through the usual PYTHIA-DELPHES chain



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

13/01/2025.

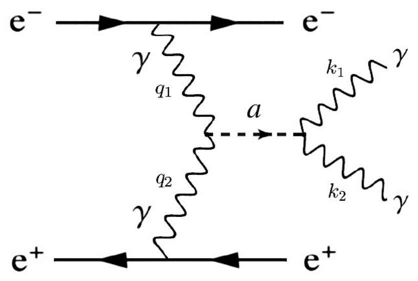
Combined plot FCC-ee



Grey areas :existing exclusions

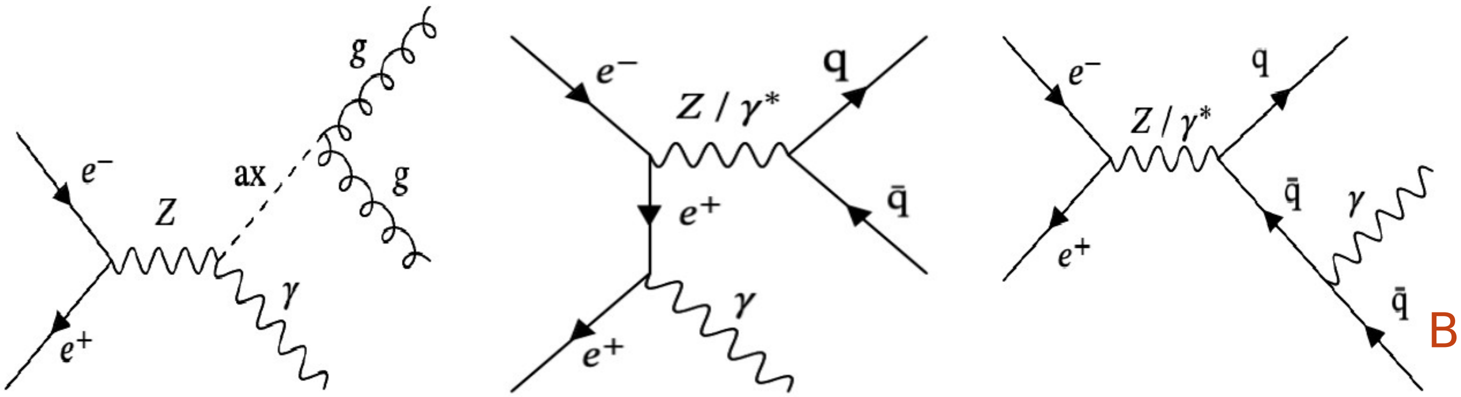
Yellow and orange areas are the two analyses of Previous slides

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



a → gg

M. Meena, J. Andrea



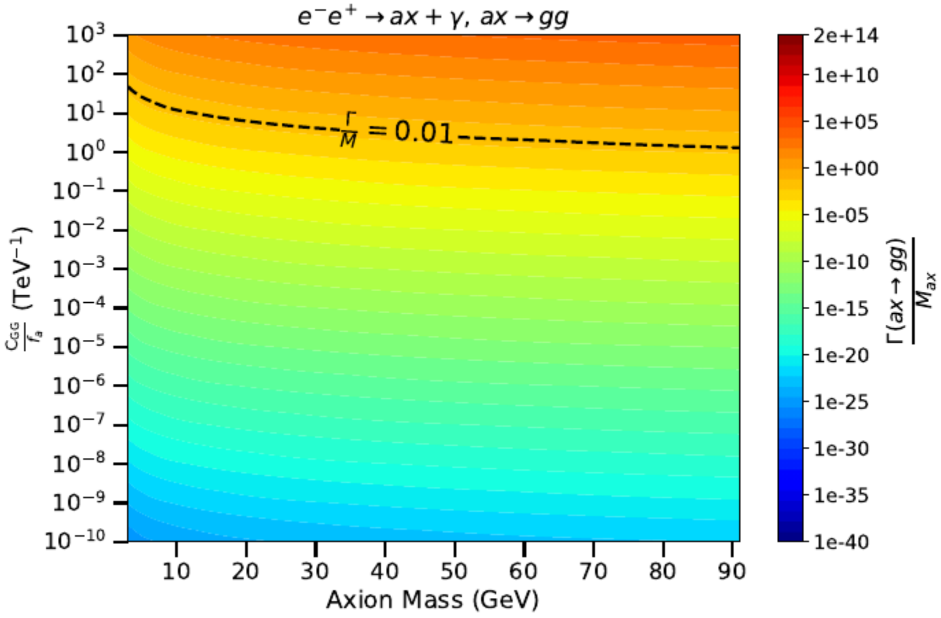
Signal (left) Backgrounds (middle & right)

Signal process:
$e^+e^- \to Z \to \gamma + a$ $(a \to gg)$

Use UFO from
Brivio et al.:arXiv: 1701.05379

Production inside tracker+signal XS at least 10% of BG XS
→ Bounds on Cww, CBB, CGG

- C_{GG}: Determines Γ_a,
  - Lower limit: lifetime bound,
  - Upper limit: require $\Gamma_a/M_a<0.01$
- C_{WW},C_{BB}
  - $C_{BB}=-0.3 \times C_{WW}$ to ensure BR($a\to\gamma\gamma$)=0
  - Upper limit: $\Gamma(Z\to\gamma a)<2.3\text{e-}3$, compatibilty with measured Z width
  - Lower limit from XS requirement



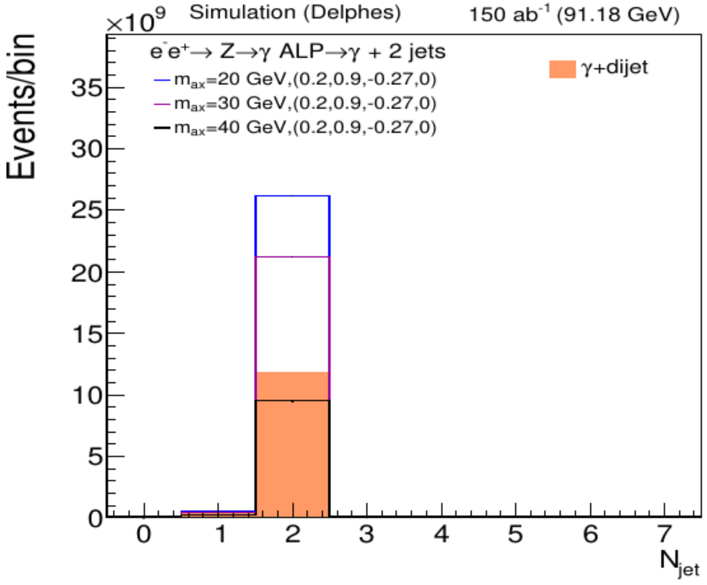
Preliminary analysis

BMP: C_{GG}=0.2, C_{WW}=0.9, C_{BB}=-0.27, C_{ϕ}=0, M_{ax}=20, 30, 40 GeV, fa=1 TeV, $N_T = 10^6$

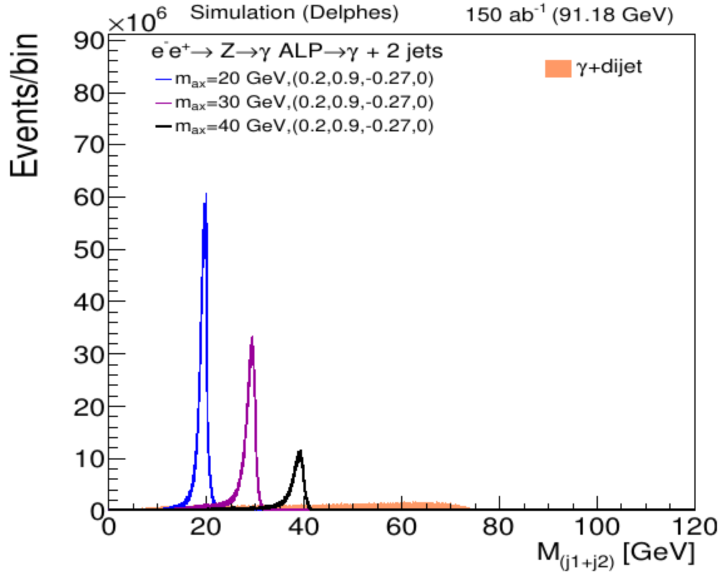
Event selection $\gamma \geq 1 + \geq 2$ jets:

- $p_T^{\gamma} >$15GeV, clean jets: ΔR (jets, γ)$>$ 0.5

Normalization: $\frac{L.\sigma}{N_T}$, Sensitivity(S): $\frac{n_{sig}}{\sqrt{n_{sig}+n_{bkg}}}$



No. jets after $\gamma \geq 1$



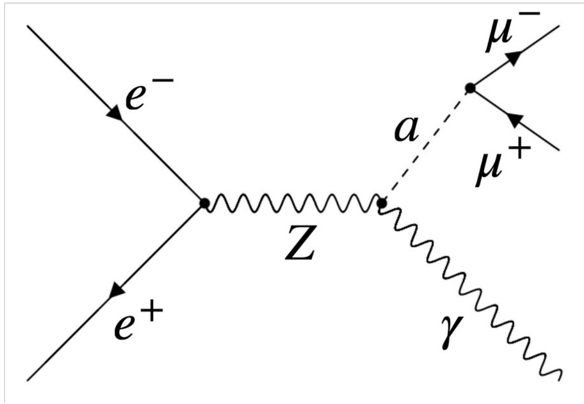
dijet mass after $\gamma \geq 1 + \geq 2$ jets

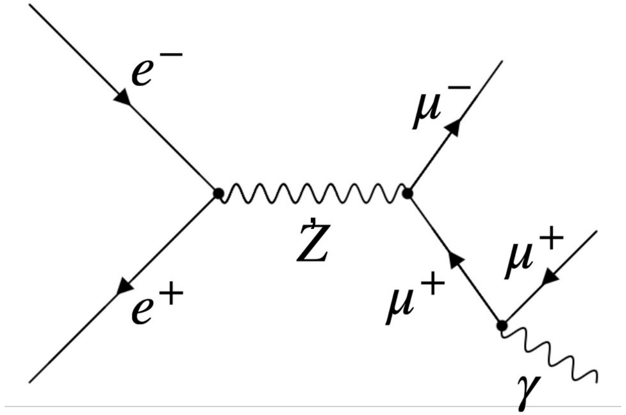
MC samples	Cross section (pb)	$\gamma \geq 1 + \geq 2$ jets, $p_T^{\gamma} >$ 15 GeV				$\gamma \geq 1 + \geq 2$ jets, $p_T^{\gamma} >$ 20 GeV			
		n_{raw}±stat.uncer(%)	n	Sel effi (n_{raw}/N_T)%	S	n_{raw}±stat.uncer(%)	n	Sel effi (n_{raw}/N_T) %	S
M_{ax}=20GeV	194.2±0.011	899023±948(0.1)	2.61885e+10	90	134021	829537±910(0.1)	2.41644e+10	83	135735
M_{ax}=30GeV	159.6±0.0084	886771±941(0.1)	2.12293e+10	89	116468	807566±898(0.1)	1.93331e+10	81	117959
M_{ax}=40GeV	118.6±0.0061	535105±731(0.1)	9.51952e+09	53	64900	475161±689(0.1)	8.45311e+09	47	66865
γ+dijet	225.1±0.084	355256±596(0.1)	1.19952e+10	35		222988±47(0.2)	7.52919e+09	22	

$a \to l^+l^-$

S.Naseem, G. Polesello,
R. Soualah, F. Arneodo

Signal





Background
example

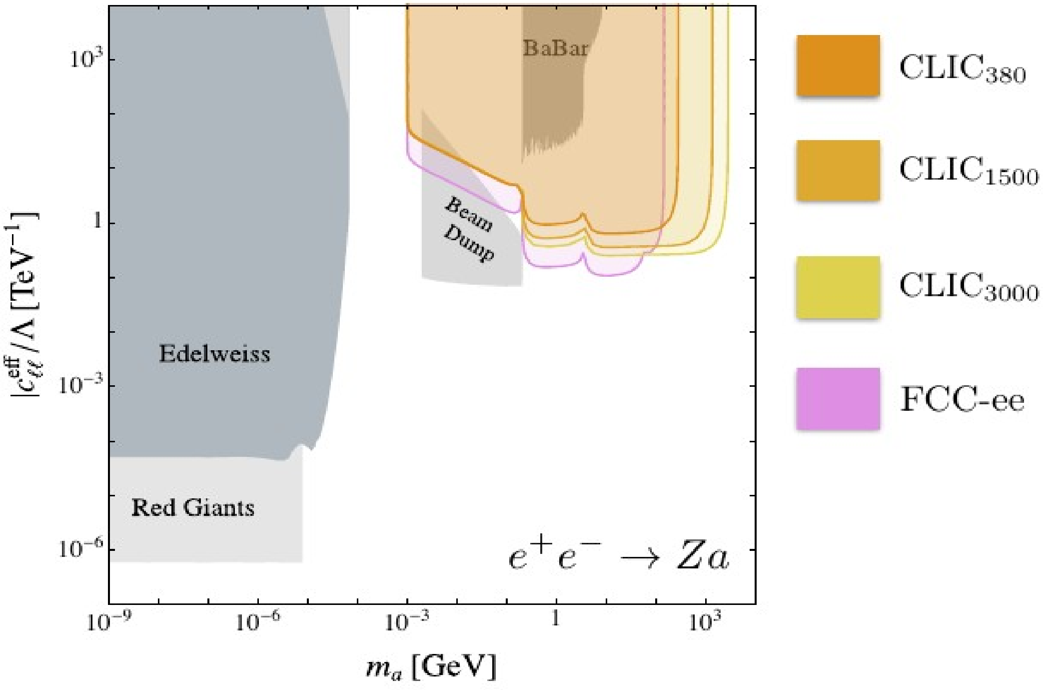
Parameter choice: high cross-section ($C_{Z\gamma}$) and dominant BR($a \to ll$)

Proposed benchmark (arXiv:1808.10323):

ALP only couples to leptons.

- C_{ll} universal over lepton flavours, BR($a \to ll$)~100% for heaviest lepton for which decay is open
- Loop induced non-zero values for $C_{\gamma\gamma}$ and $C_{Z\gamma}$

Benchmark with $C_{WW}=C_{BB}$ being also considered



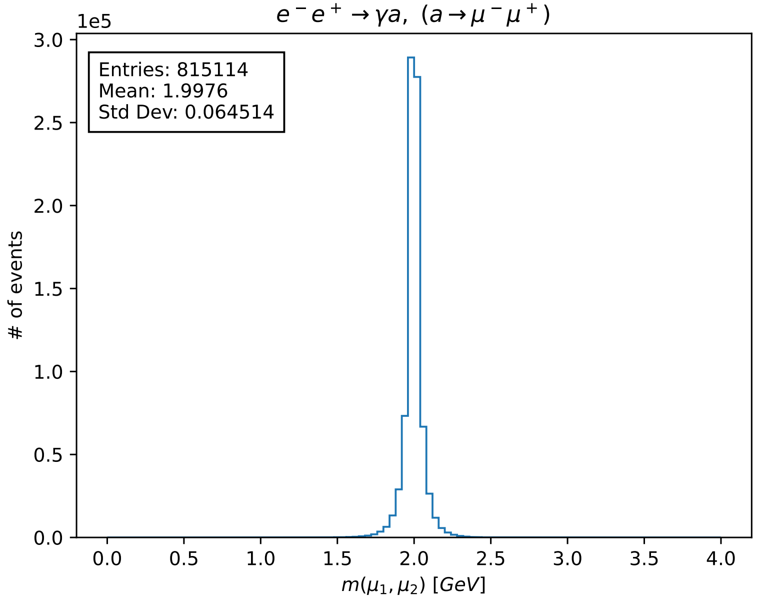
$a\to\mu^+\mu^-$ preliminary analysis

- Signal:Bauer et al. UFO, same simulation chain as for 3γ analysis
  Generate signal for ma=2 GeV ($2m_e < m_a < 2m_\tau$: BR($a\to\mu\mu$)=100%), C_{ll}=1
- Background: e+e-→a mu+mu- with MG5

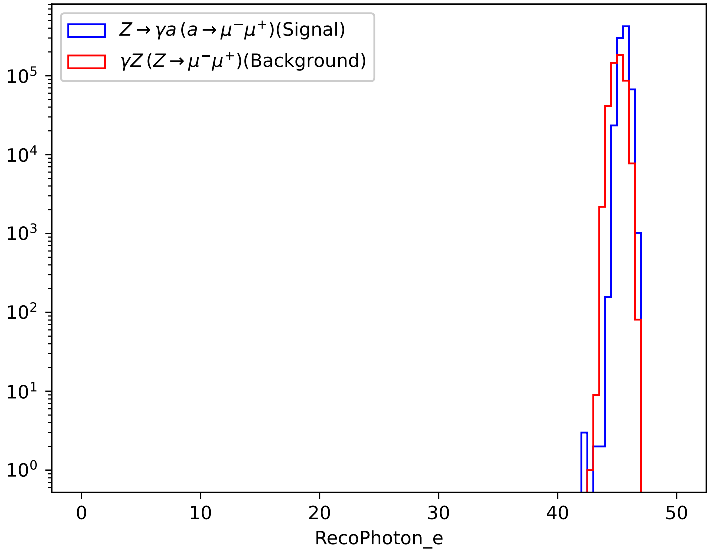
Photon for signal signal monochromatic with energy E_γ=45.58 GeV:

At generation level:

Require energy of photon between 44.5 and 46.5 GeV, photon η within 2.6



Reconstructed μμ mass



Reconstructed photon energy

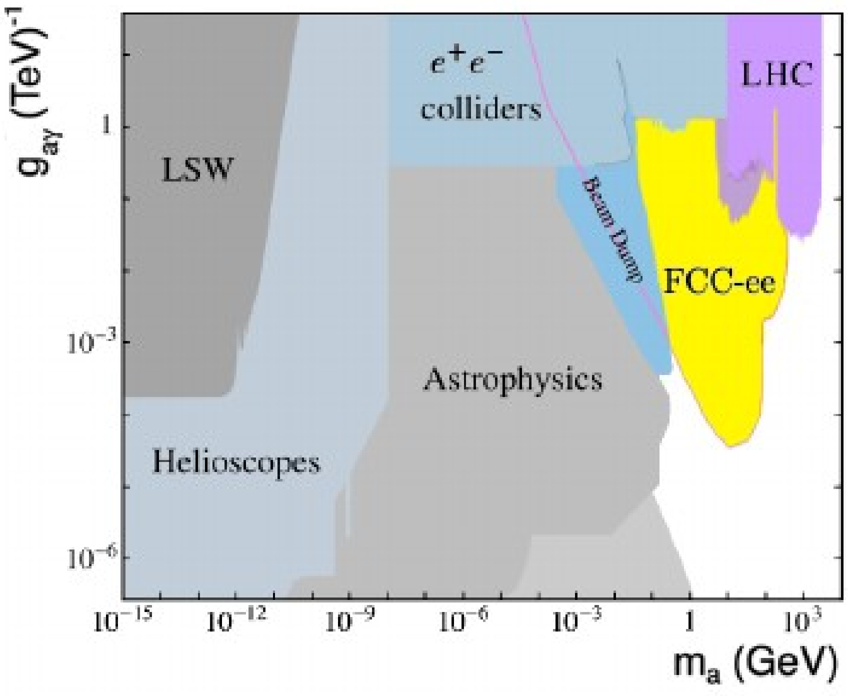
Conclusion and outlook

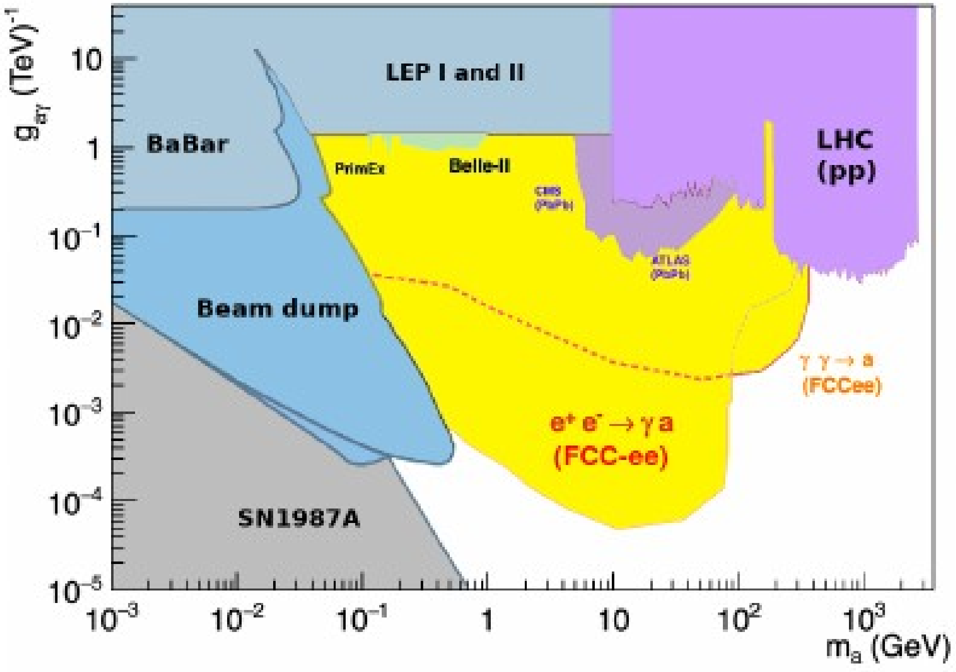
Study of FCC-ee potential for ALP discovery in Z-pole run being performed for different ALP decays:

- a →γγ
  - 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: add reducible backgrounds, study impact of photon angle measurement, study photon reconstruction in fullsim
- a→ gg, a→μμ:
  - Benchmarks in relevant parameter space defined
  - Analysis chain set up, and tested, with first signal and bg samples available
  - Full sensitivity analysis forthcoming

Backup

Parameter space coverage



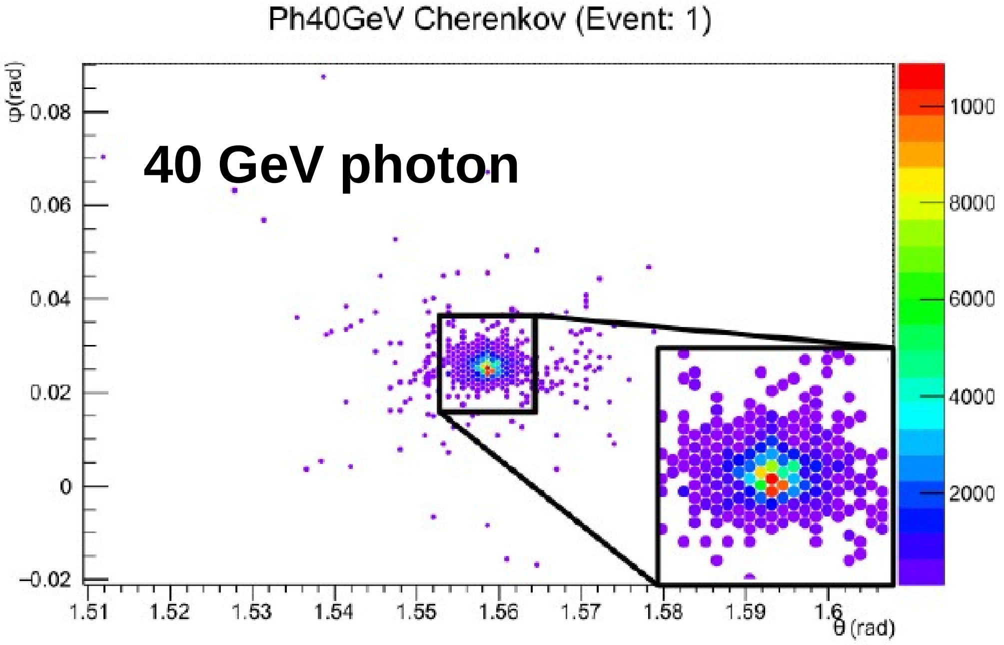


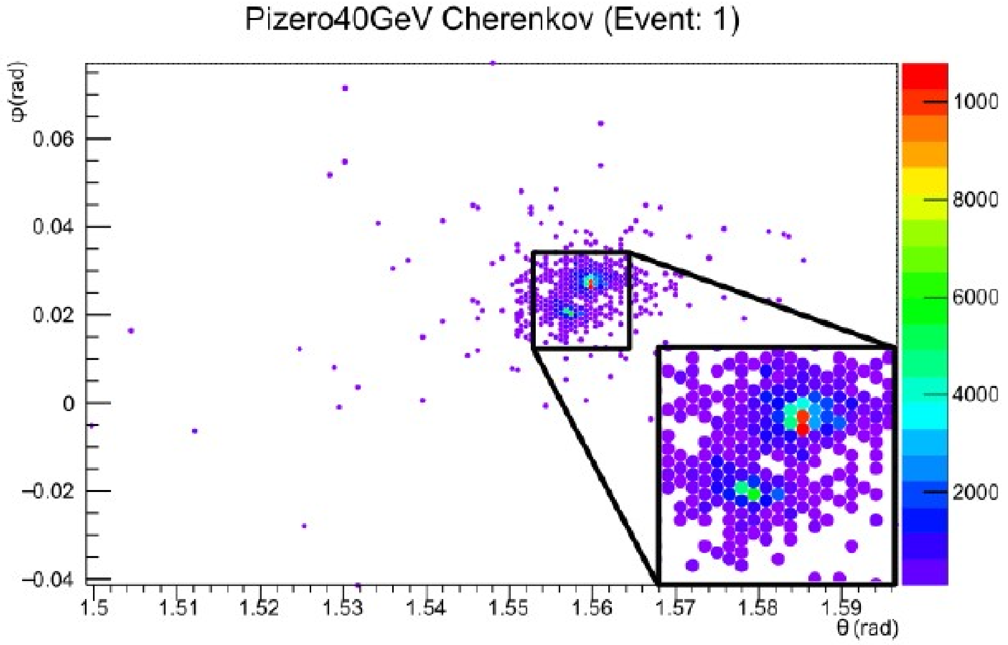
Plot in the MT report: $e^+e^- \to \gamma a$ line is theory calculation requiring 4 ALP decays inside detector. 4 events might work for long-lived but prompt analysis has a huge irreducible background e+e+ → γγγ, requiring detailed background analysis

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)

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

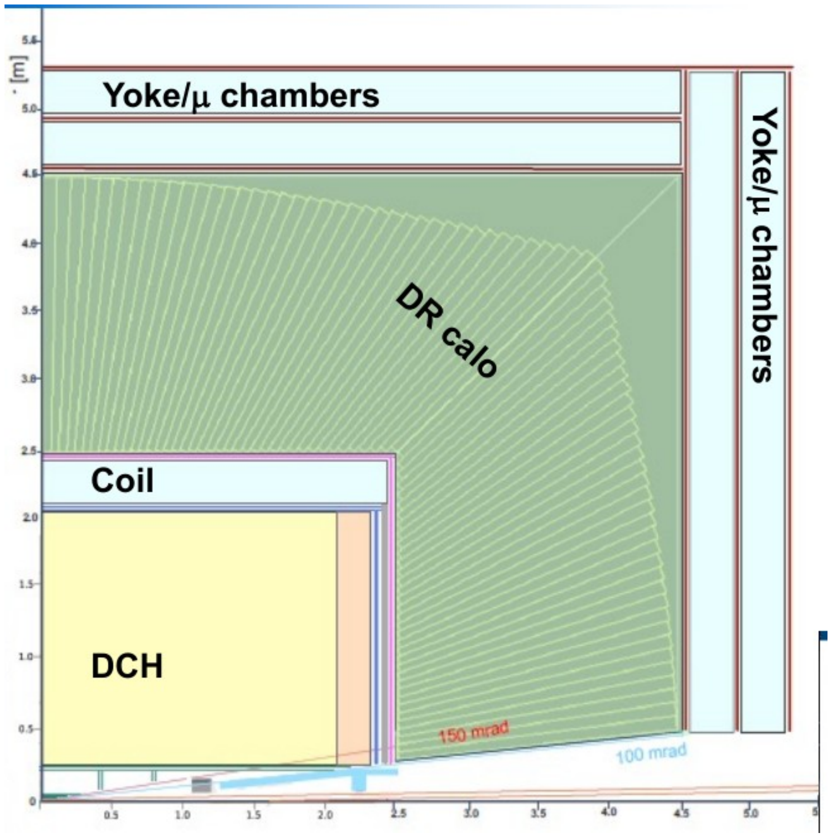
$$\frac{\sigma(E)}{E} = \frac{0.139}{\sqrt{E}} + 0.006$$

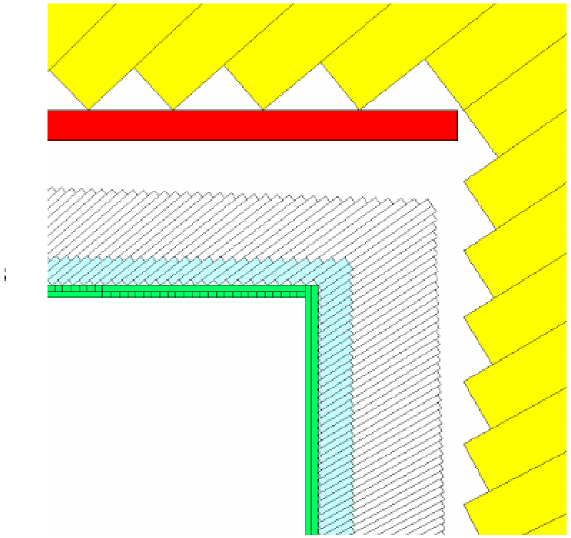
$$\sigma(x) = \frac{4.05}{\sqrt{E}} + 0.0 \qquad \sigma(y) = \frac{3.23}{\sqrt{E}} + 0.0055$$

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

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

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

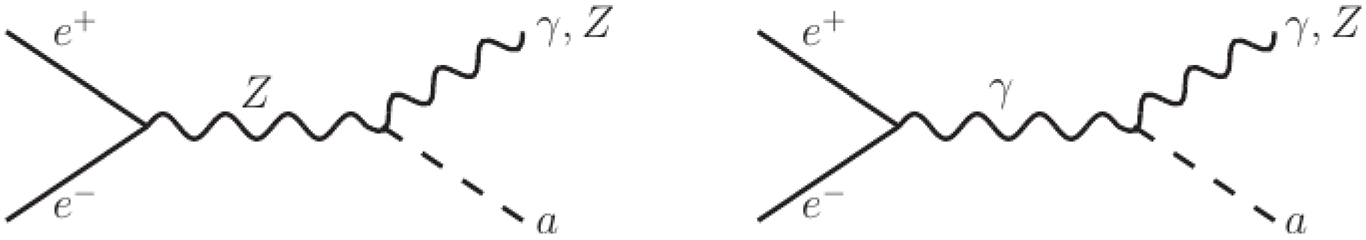




The model

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

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

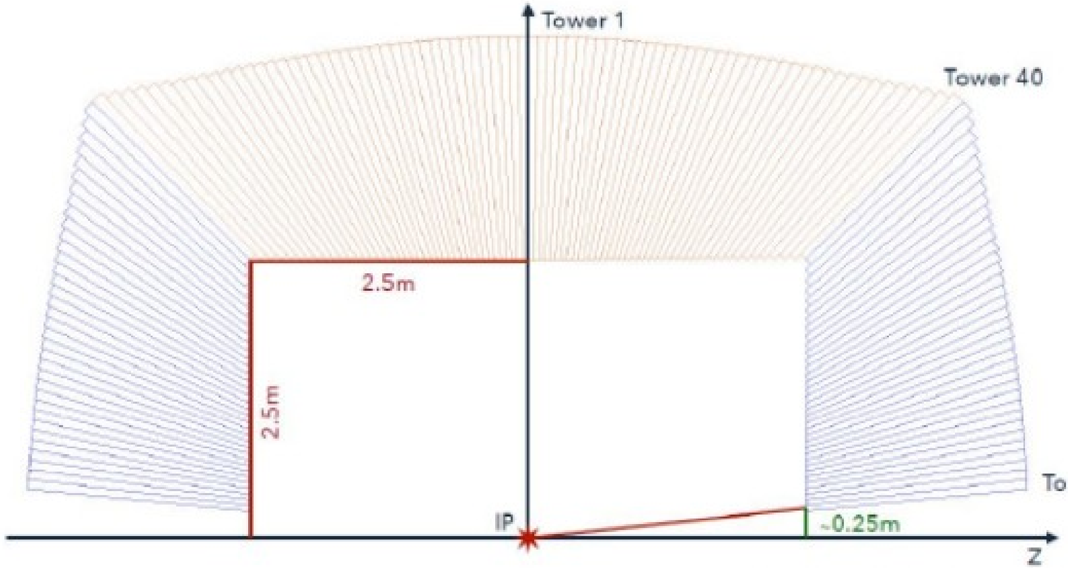
Experimental reach can be represented in 2-d M_a-$C_{\gamma\gamma}$ plane

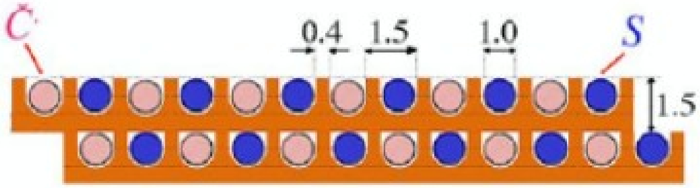
Implemented in two UFOs: Brivio et al.:arXiv: 1701.05379

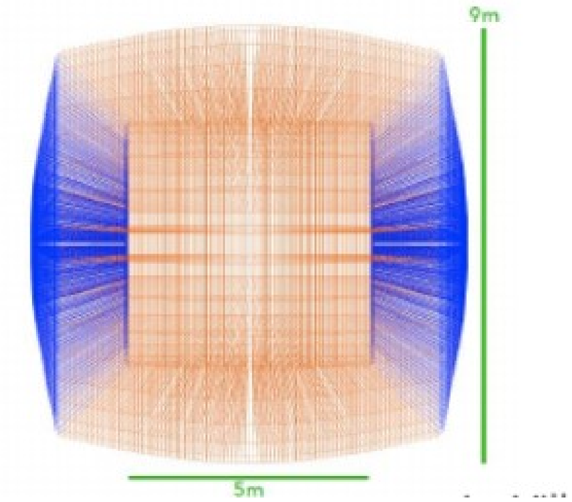
Bauer et al:arXv:1808.10323

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

IDEA DR Calorimeter, old version

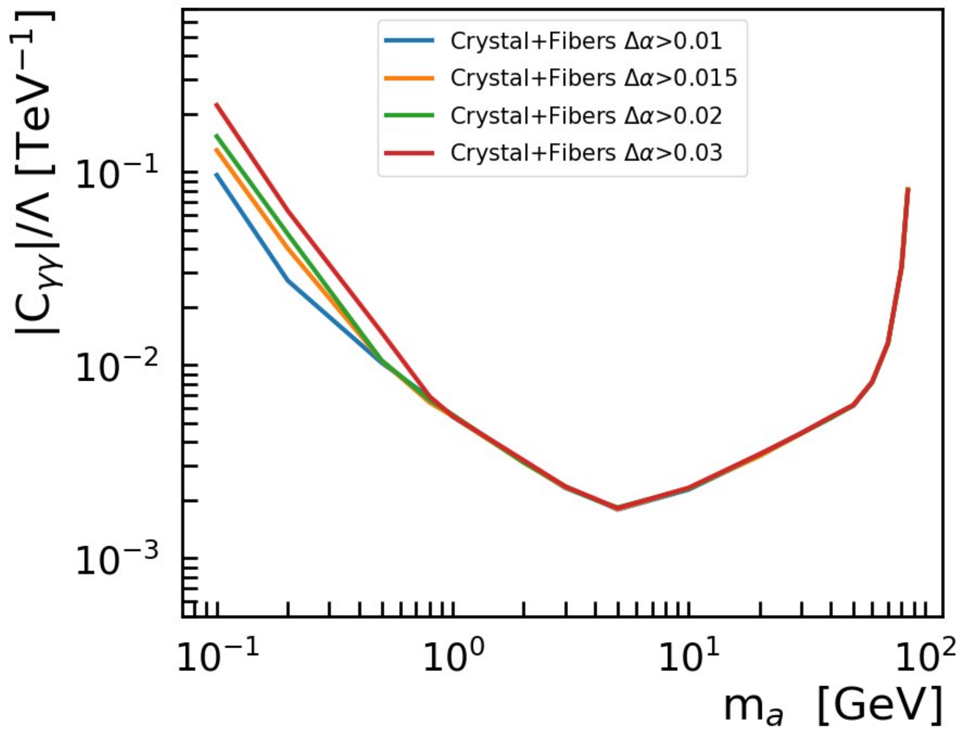




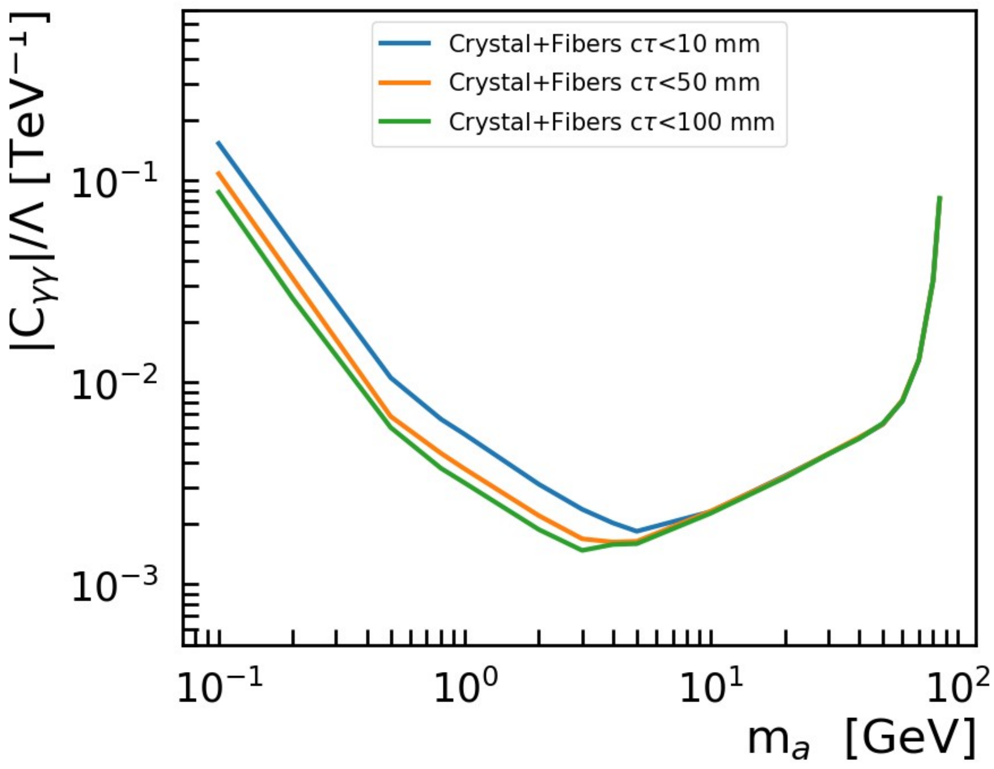


Reach as a function of Δα and of cut on cτ

Cτ<10 mm



Δα>0.02



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

Define significance as:

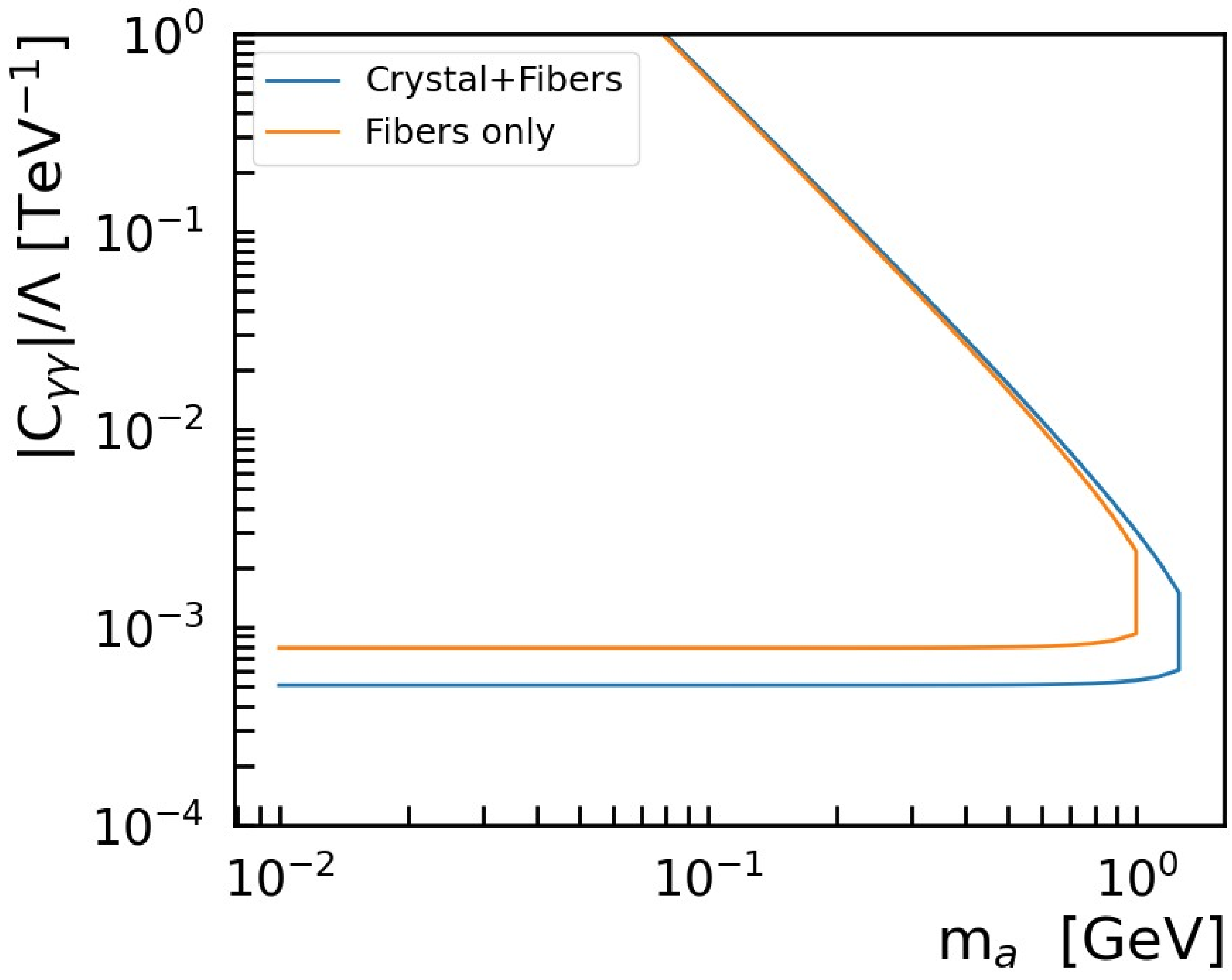
s=number of signal events after cuts

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



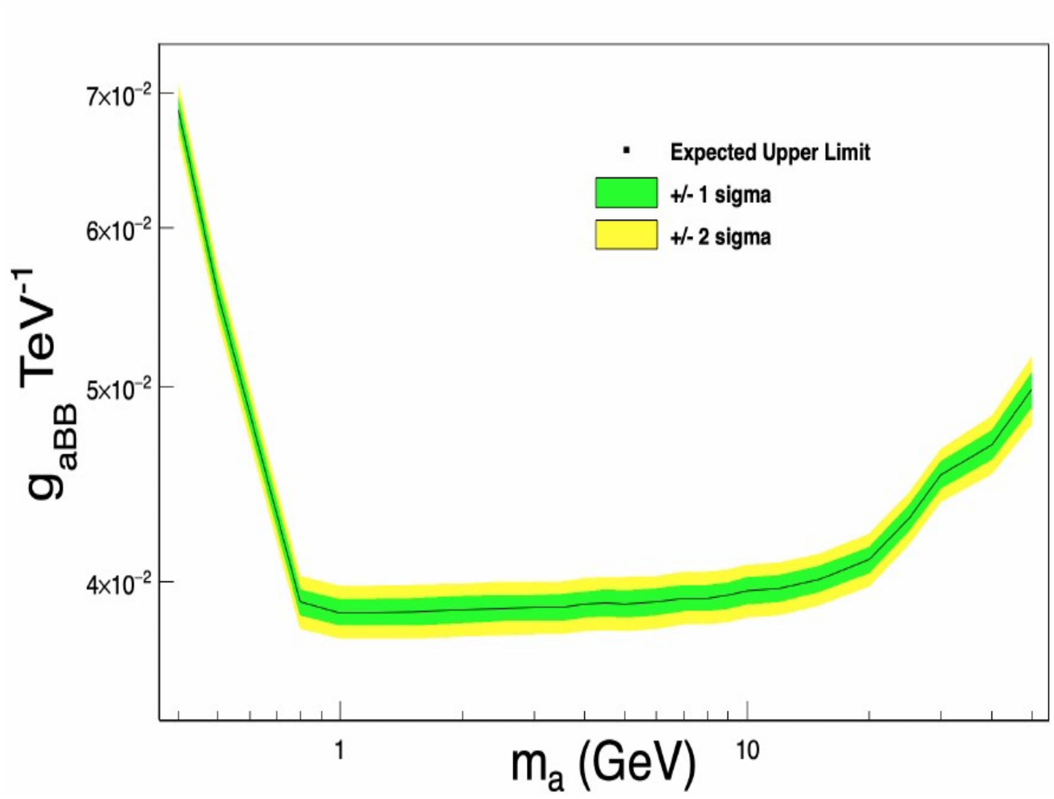
Irreducible background small at 45.6 GeV, but it increases very fast as energy goes down.

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



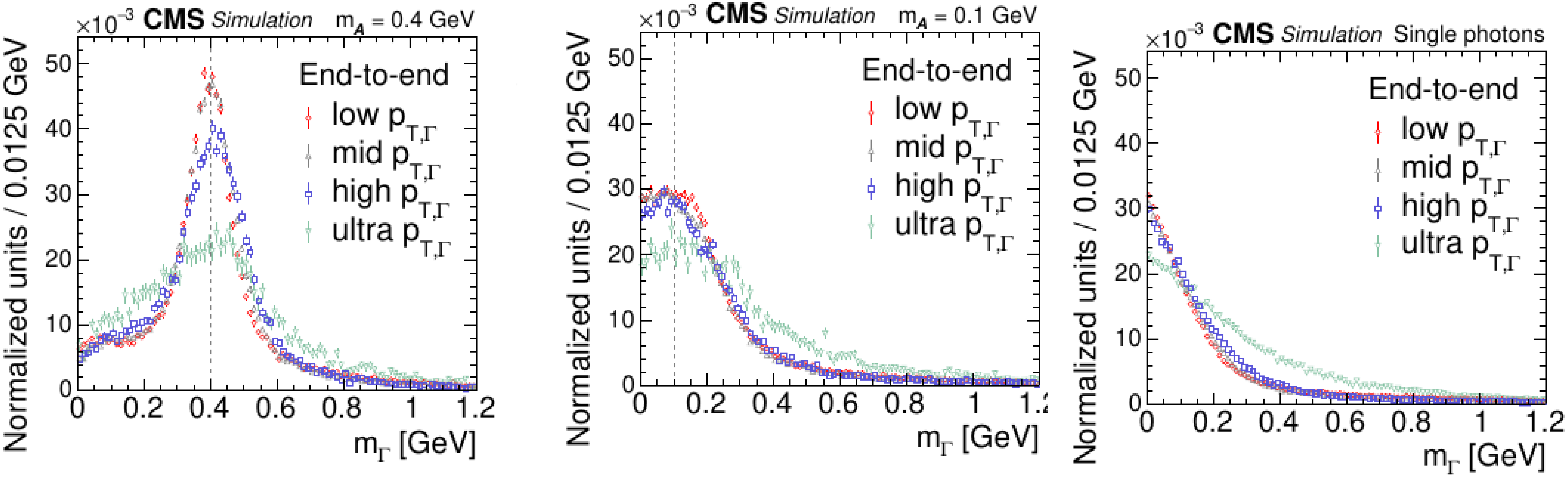
Simple analysis, require:
- 3 non-overlapping photons E>2 GeV
- $E\gamma - E\gamma^{recoil} < 5$ GeV

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

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



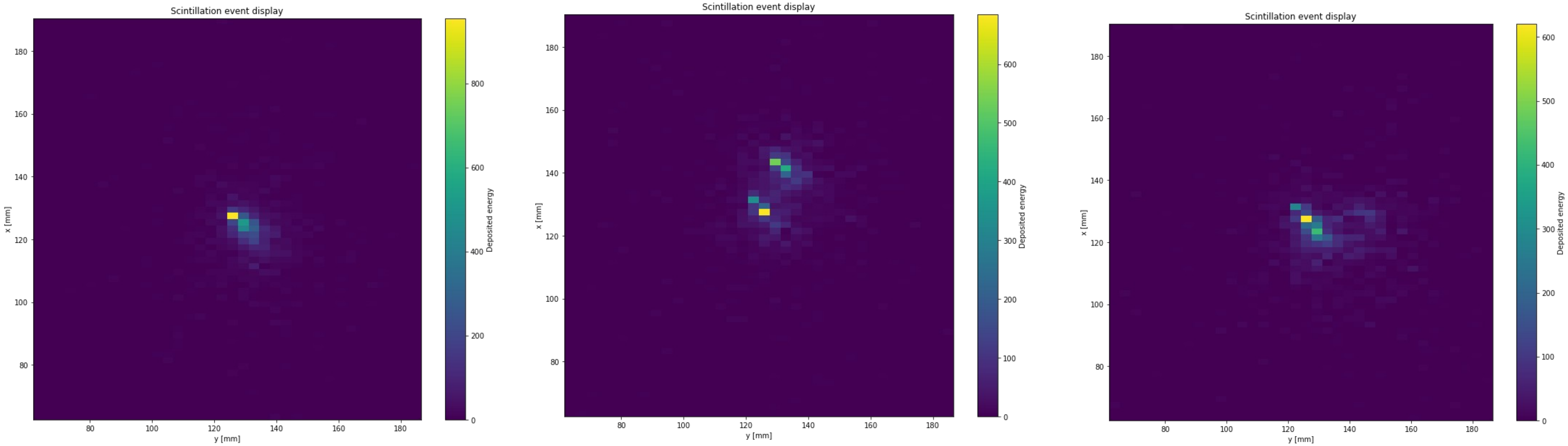
Using a CNN-based algorithm, reconstruct peak of 100 MeV particle.

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

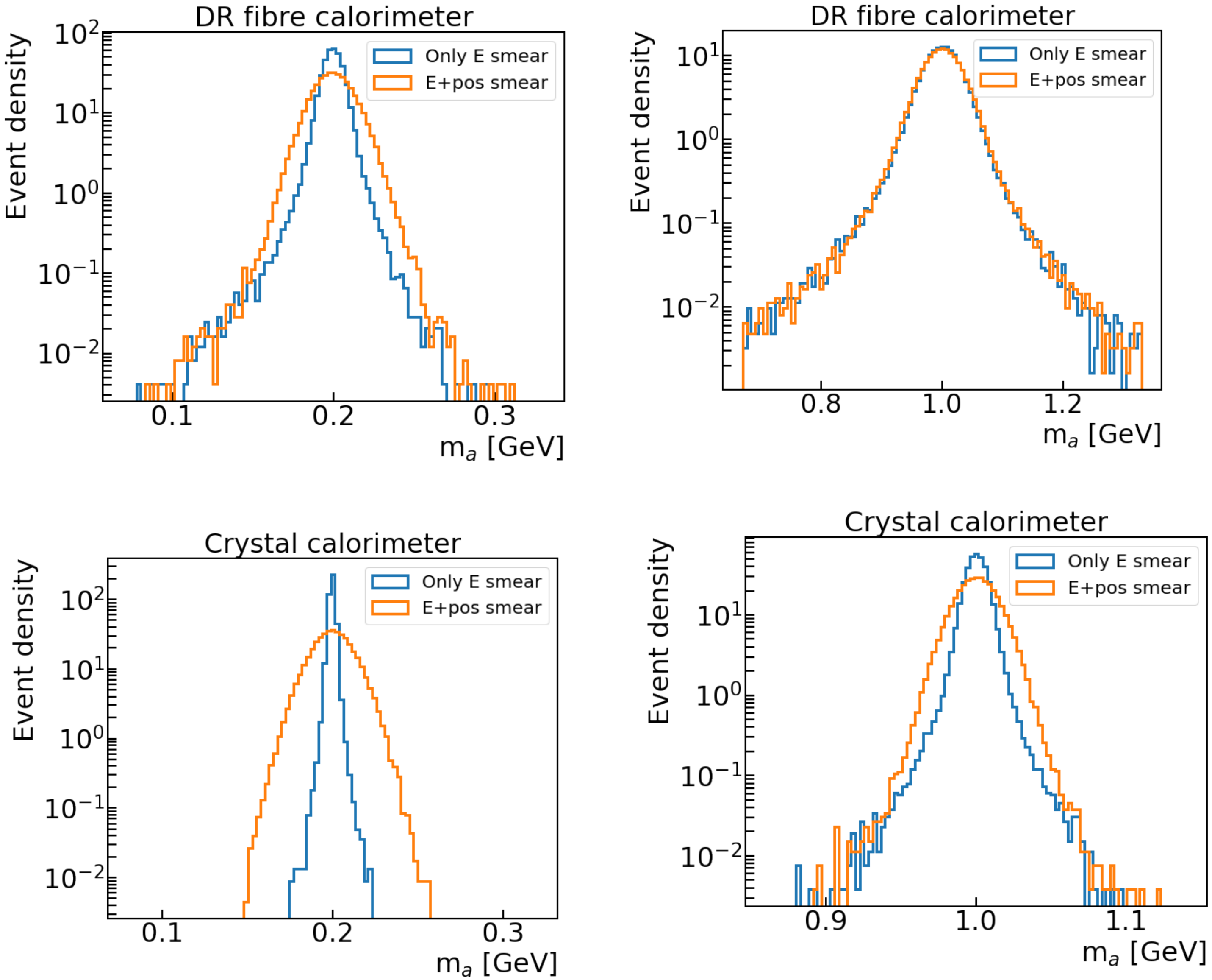


G4 simulation of energy deposition of a 40 GeV photon (left), and of two examples 40 π^0 produced at 2m from a fiber calorimeter prototype (Master thesis G.Salsi)

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 $\Delta\alpha$ between two photons smaller than 0.01, 0.015, 0.02, 0.03 and study reach as a function of cut

Mass resolution



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

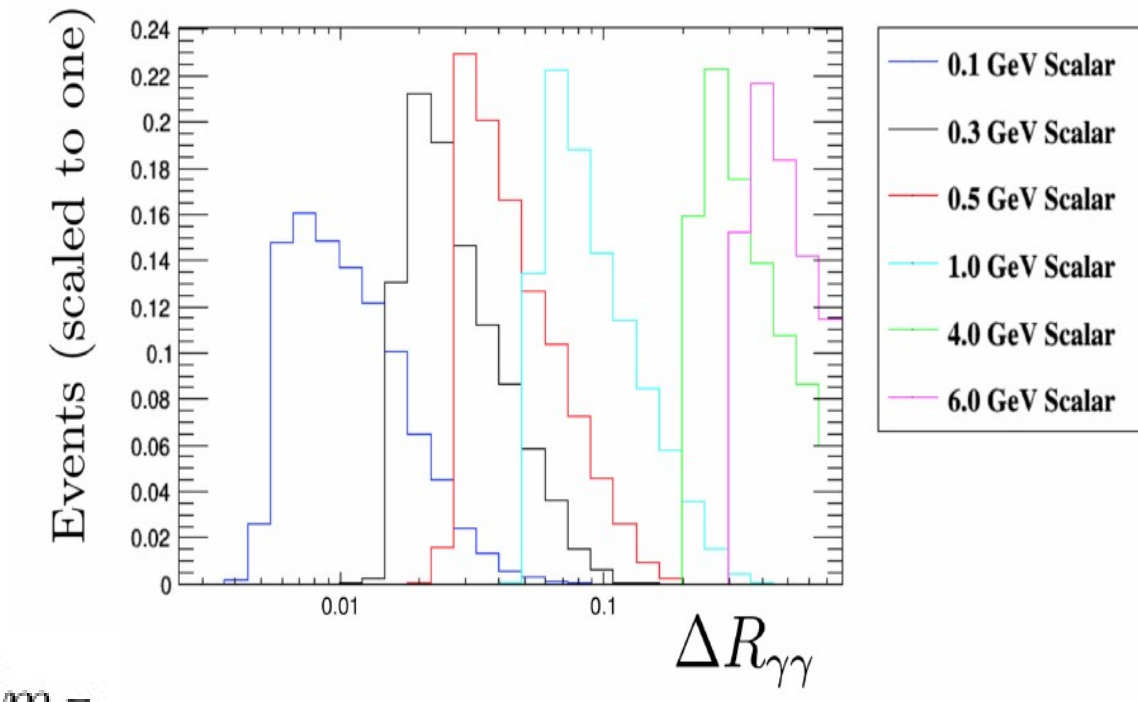
Position resolution dominant effect up to ~1 GeV

Coalescing Photons

Steinberg, Wells, arXiv:2101.00520

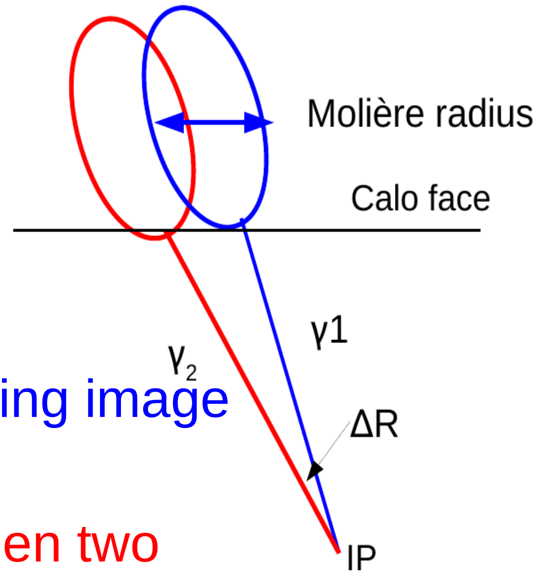
For M_a <~ 5 GeV two photons very collimated: e.g for M_a=0.5 GeV ΔR_{peak} ~ 0.03

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



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

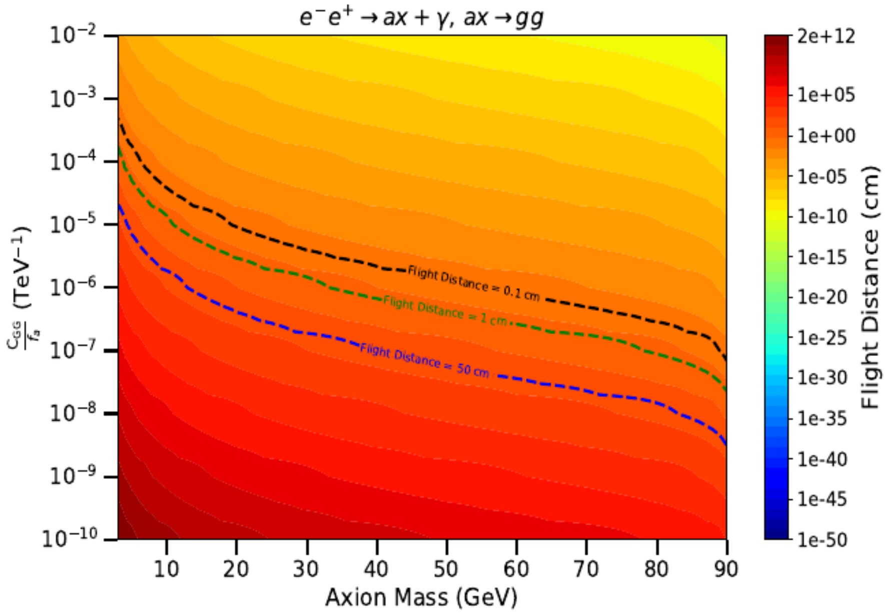
Size of photon shower in calorimeter: Molière radius, depends on material and geometry, around 2 cm for crystal calorimeter, ~2.4 cm for fibre calorimeter

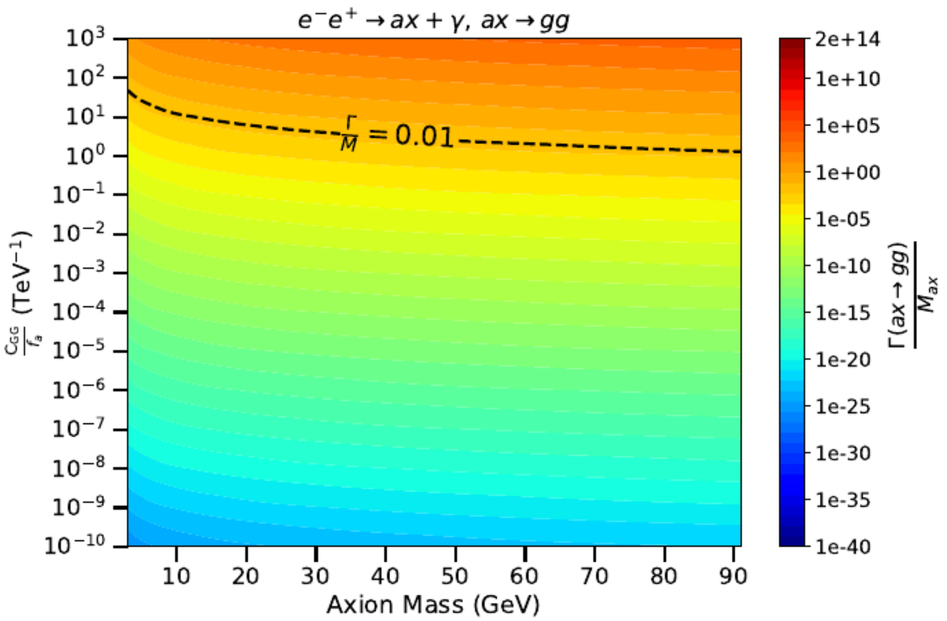


Very high granularity can be exploited to measure the two clusters using image reconstruction techniques → start work soon on that

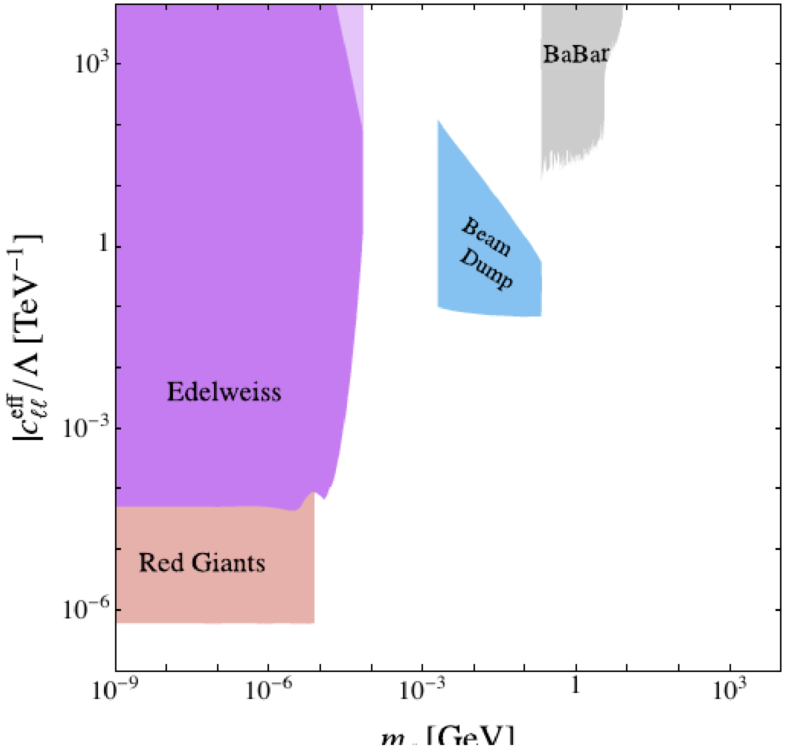
Waiting for results becoming available, reject events where Δα between two photons smaller than 0.01, 0.015, 0.02, 0.03 and study reach as a function of cut

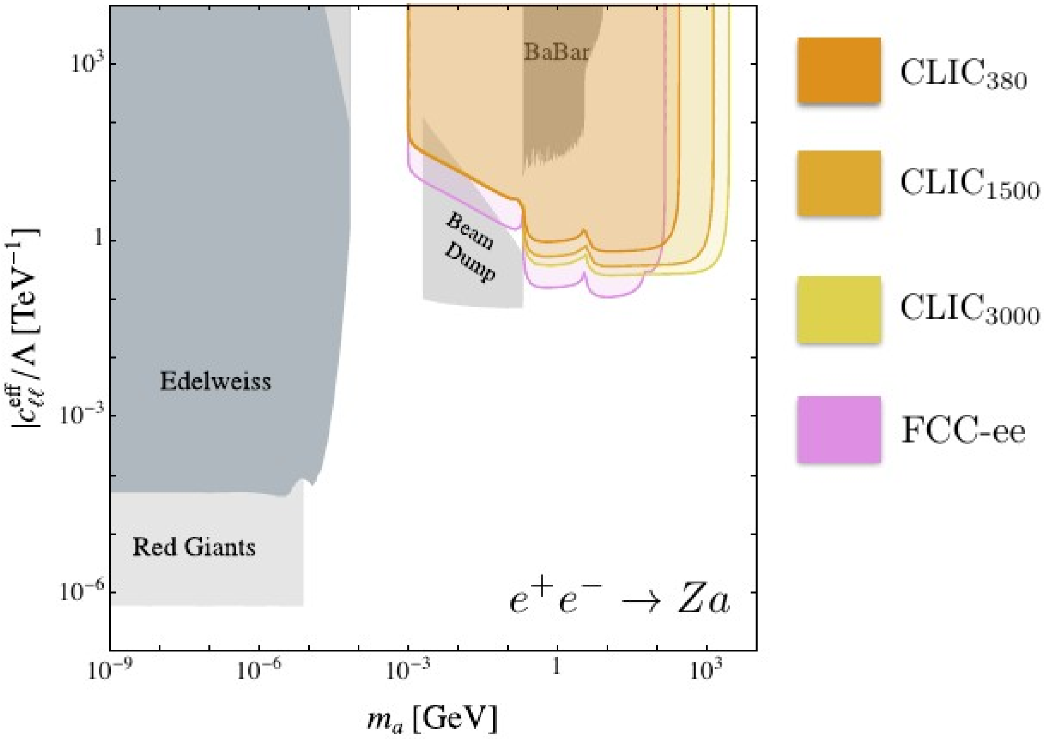
a→gg benchmark Choice





C_{ll} limits


BaBar
Beam Dump
Edelweiss
Red Giants
$|c_{\ell\ell}^{\rm eff}|/\Lambda$ [TeV^{-1}]
10^3
1
10^{-3}
10^{-6}
10^{-9}
10^{-6}
10^{-3}
1
10^3
m_a [GeV]


BaBar
Beam Dump
Edelweiss
Red Giants
$e^+e^- \to Za$
$|c_{\ell\ell}^{\rm eff}|/\Lambda$ [TeV^{-1}]
10^3
1
10^{-3}
10^{-6}
10^{-9}
10^{-6}
10^{-3}
1
10^3
m_a [GeV]
CLIC$_{380}$
CLIC$_{1500}$
CLIC$_{3000}$
FCC-ee