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Axion-Like Particles at the ILC Giga-Z

ILC Physics meeting– August 12th 2021

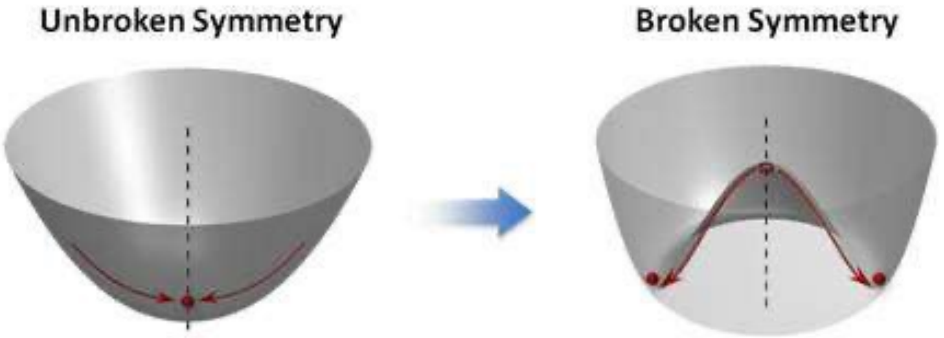
arXiv:2101.00520v1 [hep-ph]

Landscape of BSM Physics

- BSM Landscape is extremely vast
- Important step of moving through this landscape is to construct generic models that have states present in a wide array of BSM theories
- Evaluating the discovery capabilities of future experiments to these generic models serves as benchmarks for more specific searches

Figure from Jürgen Reuter
BSM Physics Vol. 1: Models and Motivations

Axion Like Particles (ALPs)



- Generic pseudo-scalar
  - Shows up as pseudo-nambu goldstone boson from SSB
    - Axion, majaron, familion, composite Higgs theories etc..

- Couple to two gauge bosons and possibly to SM fermions

$$\mathcal{L}_a \supset g_{aBB} a \tilde{B}_{\mu\nu} B^{\mu\nu} + g_{aWW} a \tilde{W}^i_{\mu\nu} W^{i\mu\nu} + g_{aGG} a \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$$

- Couplings and mass not directly related like QCD axion (enlarged parameter space)

- Complementary search direction for weakly coupled new physics with masses near or below EW scale

Coupling to Hypercharge

- For the sake of simplicity, assume that ALP couples only to hypercharge

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{g_{aBB}}{4} a B_{\mu\nu}\tilde{B}^{\mu\nu}$$

- Below EW scale this leads to three operators

$$a(g_{aBB} c_w^2 \tilde{F}_{\mu\nu} F^{\mu\nu} + g_{aBB} c_w s_w \tilde{F}_{\mu\nu} Z^{\mu\nu} + g_{aBB} s_w^2 \tilde{Z}_{\mu\nu} Z^{\mu\nu})$$

  - ALP couples to $\gamma\gamma,\ \gamma Z,\ ZZ$

- Many probes of this model, depending on ALP mass, m_a and g_{aBB}
  - Note that most of these constraints arise from the photon-ALP coupling
  - $\Gamma_{Z\gamma} / \Gamma_{\gamma\gamma} \propto (s_w/c_w)^2$
  - $\Gamma_{ZZ} / \Gamma_{\gamma\gamma} \propto (s_w/c_w)^4$

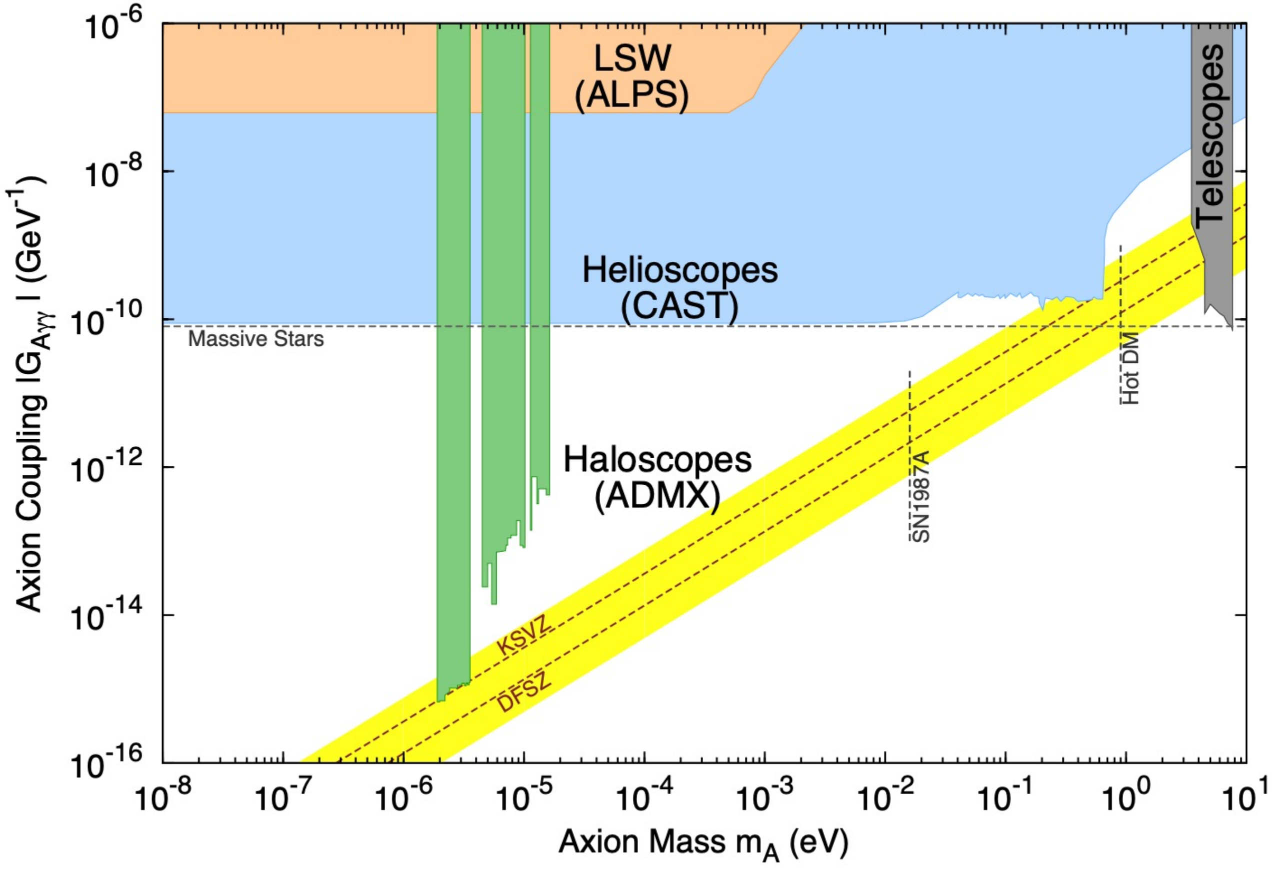
Coupling to Hypercharge: $m_a << m_{weak}$

- Variety of terrestrial, astrophysical, and cosmological constraints on Axion-Like Particles

- Light Shining Through Wall Experiments (LSW)
  - Photons convert into ALPs via transverse magnetic field, then re-converted to photons after passing through optical shield

- Stellar Cooling and Direct searches for solar ALP flux
  - Production of ALPs (produced by Primakov process) carries additional energy from sun, i.e. enhanced nuclear energy production -> constraints from neutrino production

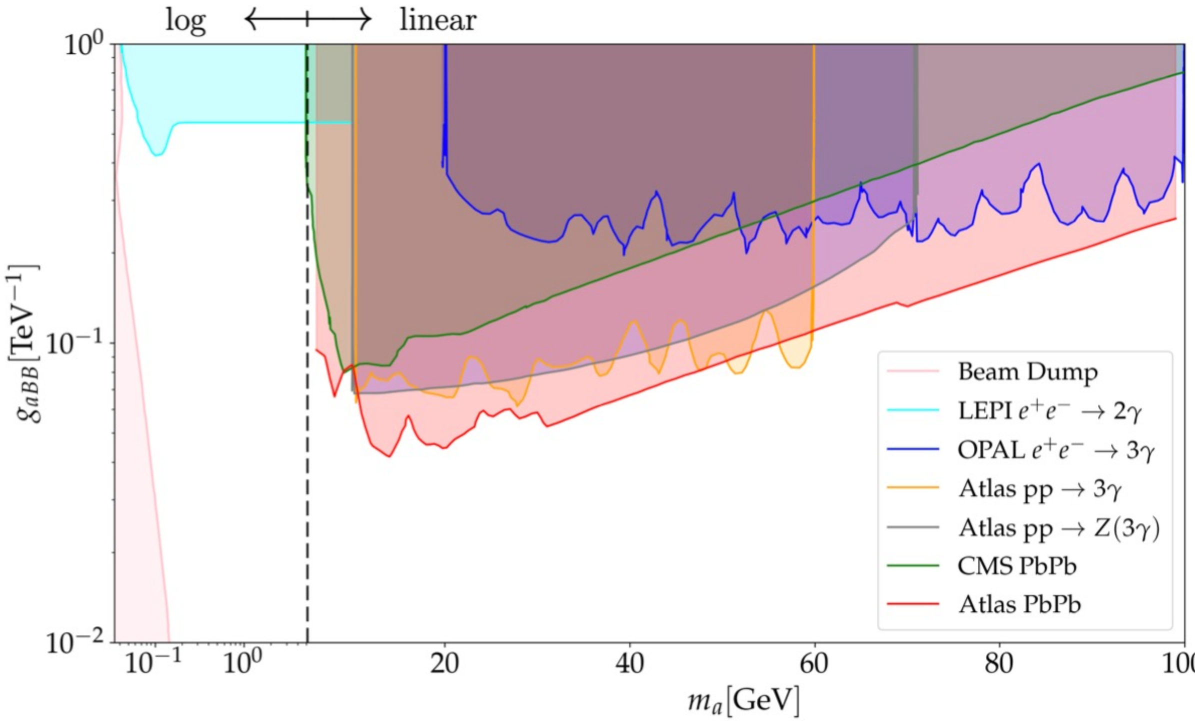
- Additional cosmological constraints based on ALPs being some significant fraction of the Dark Matter



- ALP couples to $\gamma\gamma,\ \gamma Z,\ ZZ$

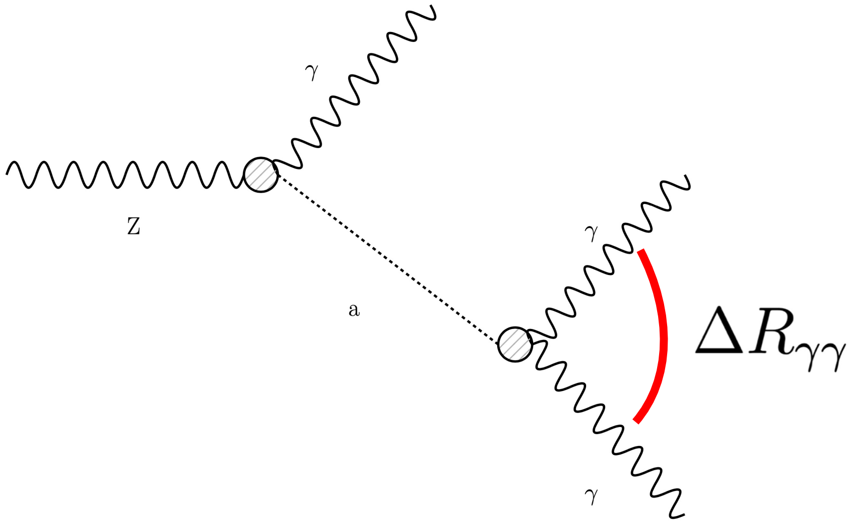
Coupling to Hypercharge: $m_a \leq m_{weak}$

- Beam Dump Experiments
  - Rely on macroscopic ALP travel distance
  - Requires smaller couplings for larger masses
- LEP
  - $e^+ e^- > \gamma a$ with a undetected (mono-photon)
  - $e^+ e^- > 2\gamma$ or 3 γ depending on mass of ALP
- ATLAS pp -> 3 photon + pp -> Z -> 3 photon
  - 3 Photon search for generic resonances as well as search for intermediate Z decaying to 3 photons
    - B(Z->3 γ) < 2.2*10^-6
- CMS and ATLAS UPC search
  - Utilize Z^4 enhancement in EM fields in Lead Ion UPC collisions
  - Large photon flux leads to enhanced ALP production cross section



arXiv:2101.00520

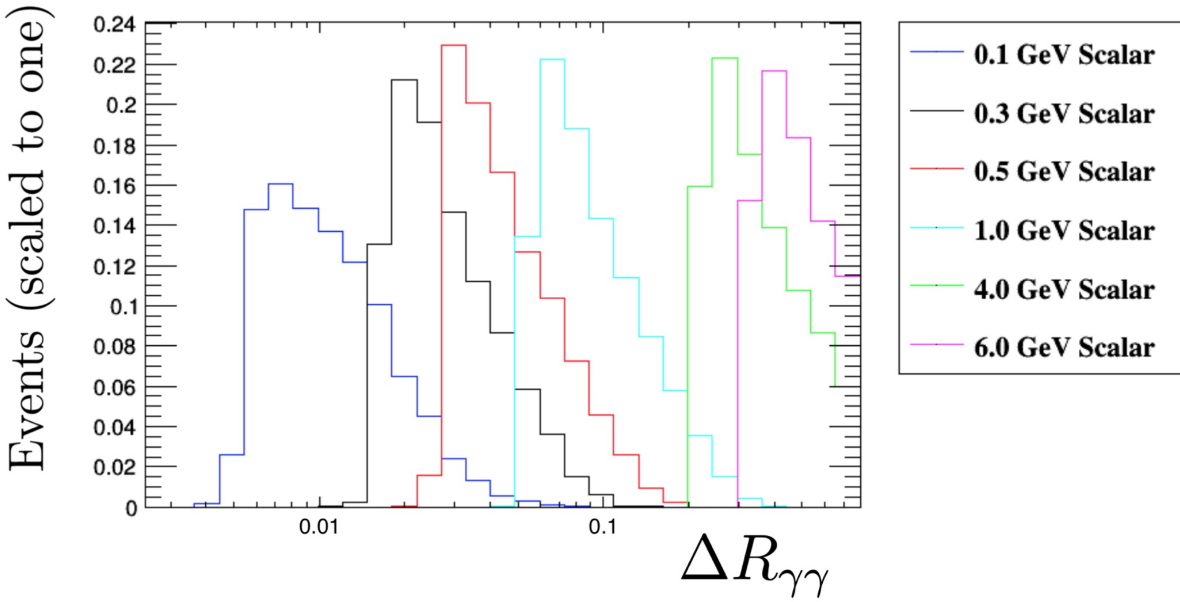
Filling in the Gaps – Low Masses



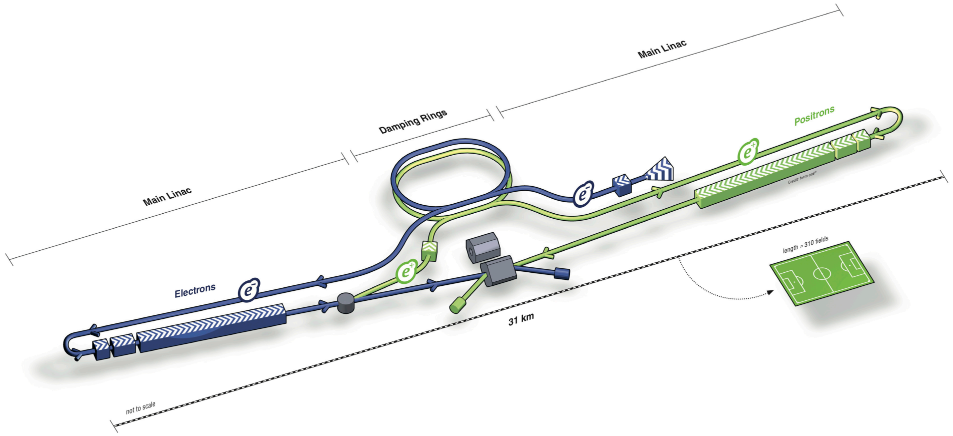
- Rare Z decays become an interesting probe of ALPs
  - Loop induced in SM with tiny (10^{-10}) BR
  - Constraints come from LEP and LHC searches
    - Constraints highly depend on ALP mass

- ALP decay to photons plays key role in the Z decay process
  - $\gamma_a = E_a/m_a$
  - $\Delta R_{\gamma\gamma} = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx 4m_a/m_z$

- Can lead to signal looking like 2 photons, 3 photons, or 1 photon + a "photon jet"



ILC-Giga Z



- Need to be able to separate photons with small angular separation
  - highly granular detector

- Also need many Z bosons!

- International Linear Collider (ILC) provides both!

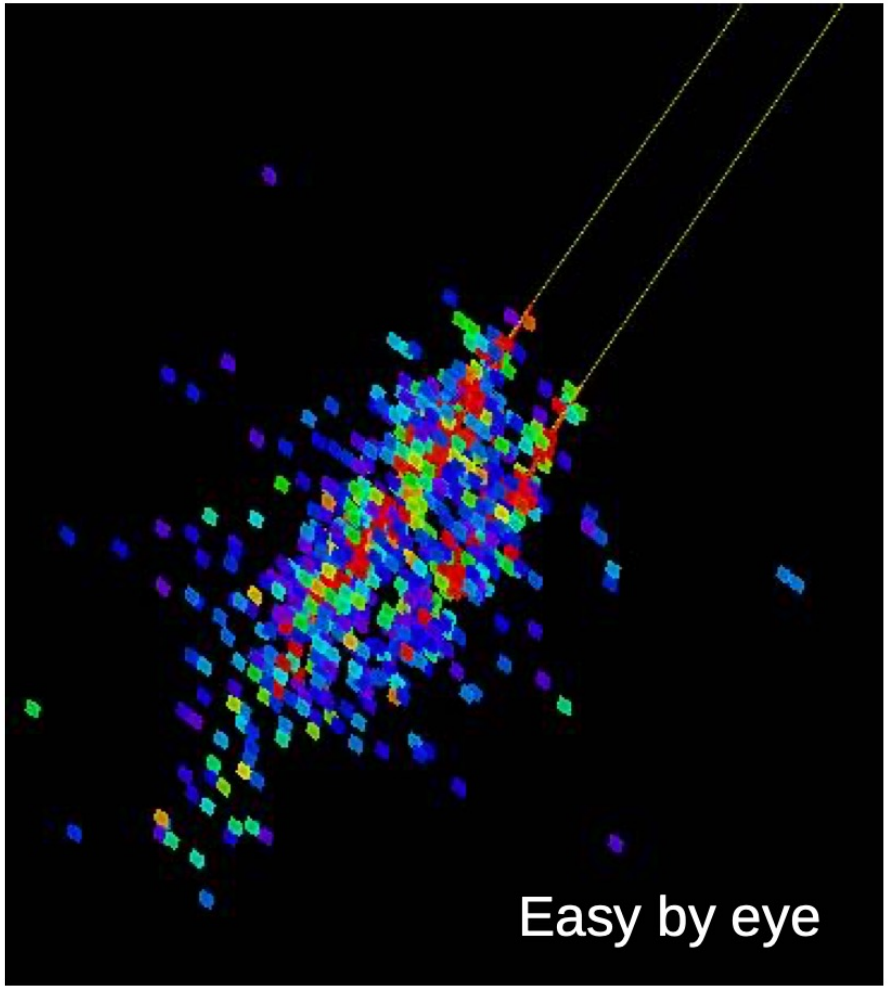
  - Proposal to run at the Z pole to do precision EW physics with 100 fb^{-1} integrated luminosity
    - Produce $2 * 10^9$ Z's

arXiv:1903.01629
arXiv:0005024

- Can ID collimated photons with GARLIC (**arXiv:1203.0774**) down to $\Delta R \approx .035$
  - Validated by reconstructing pairs of photons from neutral pions (similar boosted topology as our signal)

Photon Reconstruction

- Need to be able to separate photons with small angular separation
  - highly granular detector
- GARLIC (GAmma Reconstruction at a LInear Collider experiment)
  - Photon identification often first step in Particle Flow Reconstruction
    - Distinguishing deposits of charged and neutral particles
  - Designed to achieve highly efficient identification of photons with hadronic showers at the ILD (International Large Detector)
    - Mostly come from high energy neutral pion decays
- Photons from neutral pions tend to be highly collimated as $E_\pi >> m_\pi$
  - Take what we learn here and apply to photons from ALP decay

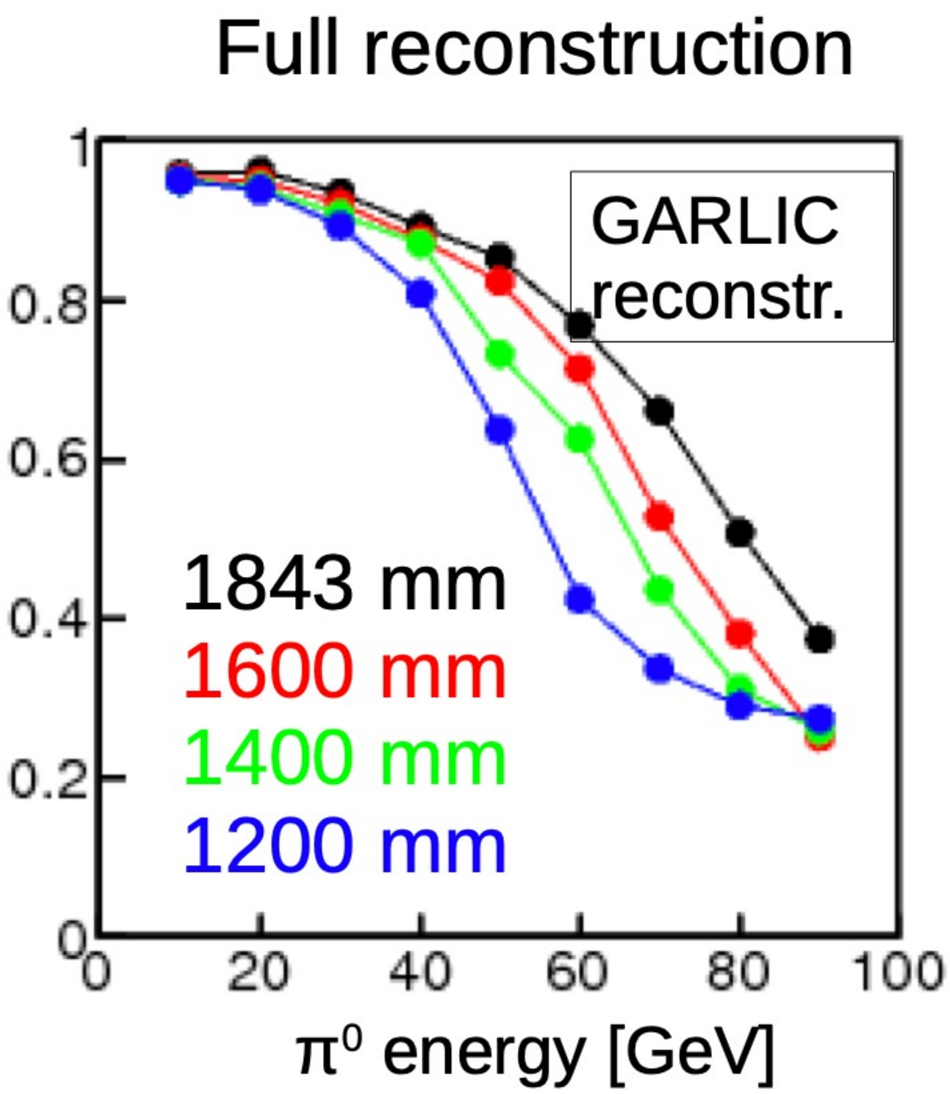


Two photons from
30 GeV Pi0

https://indico.in2p3.fr/event/11192/contributions/4601/attachments/3966/5002/llr_meeting_2015.pdf

Photon Reconstruction

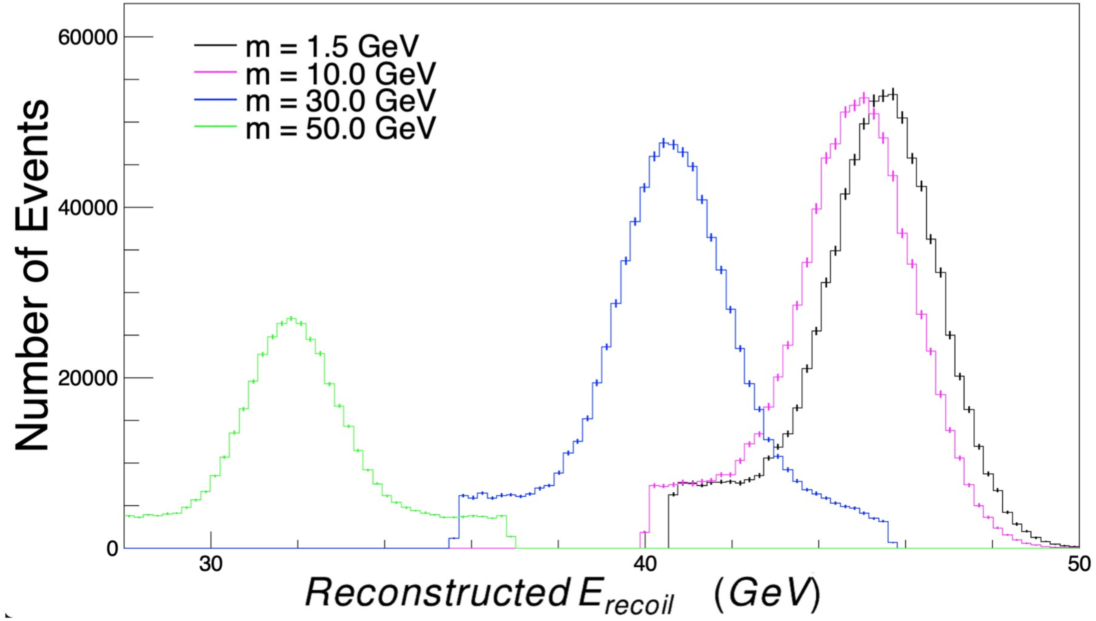
- Implementing GARLIC reconstruction algorithm (arXiv:1203.0774v2 [physics.ins-det]) allows for photon identification when distance between photons is only 0.5 moliere radii apart
- 20 GeV Pi0 has two photons reconstructed 85% of the time
- Adopt performance
  - What is the minimum ΔR between photons that we can reconstruct?
- Take 20 GeV Pion results
  - $\Delta R = 4\, m_{\pi} / E_{\pi} = .027$
  - We chose ΔR = .035 conservatively with an 85% efficiency



Efficiency for Pi0 reconstruction

Signal selection and Backgrounds

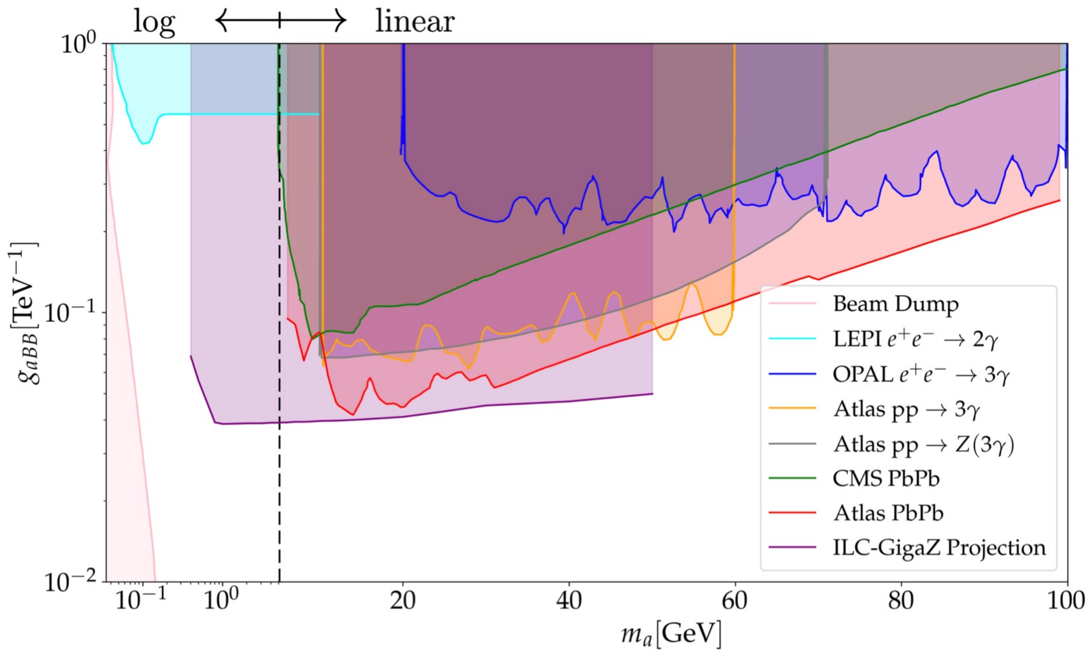
- Simple signal topology, event with 3 photons which are separated by $\Delta R > .035$
- Main SM background is $e^+e^- \rightarrow 3\gamma$
  - 4.1 pb xsec at Z pole
- Signal can be isolated by looking at energy of the recoiling photon
  - 2 body kinematics -> $E^{\gamma}_{\text{recoil}}(m_a) = (M_Z^2 - m_a^2)/2M_Z$
- Search for ALP with mass m_a, require that at least 1 photon out of the three have a recoil energy within 5 GeV of m_a
- With $g_{aBB} = (10\ TeV)^{-1}$ can expect almost 10,000 signal events at ALP masses of 10 GeV



Constraints on m_a, g_{aBB}

- At 95% confidence level, ILC will be able to place constraints on this ALP model down to (50 TeV)^-1 from 0.4 to 50 GeV
- Order of magnitude better than LEP in the the 1 – 10 GeV region
- Slightly better or similar reach as UPC at LHC
- Can refine search further for low mass ALPs (< 20 GeV) by requiring two photons with a small separation
  - Backgrounds fall quickly in this region
- Also for very small masses can look for highly collimated photons that appear as a single photon and use shower shape variables

  Ellis – arXiv:1210.3657



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Thank you! Questions?