Search for Sub-GeV Axion-Like Particles at EBES Pilot Run

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Pheno2026

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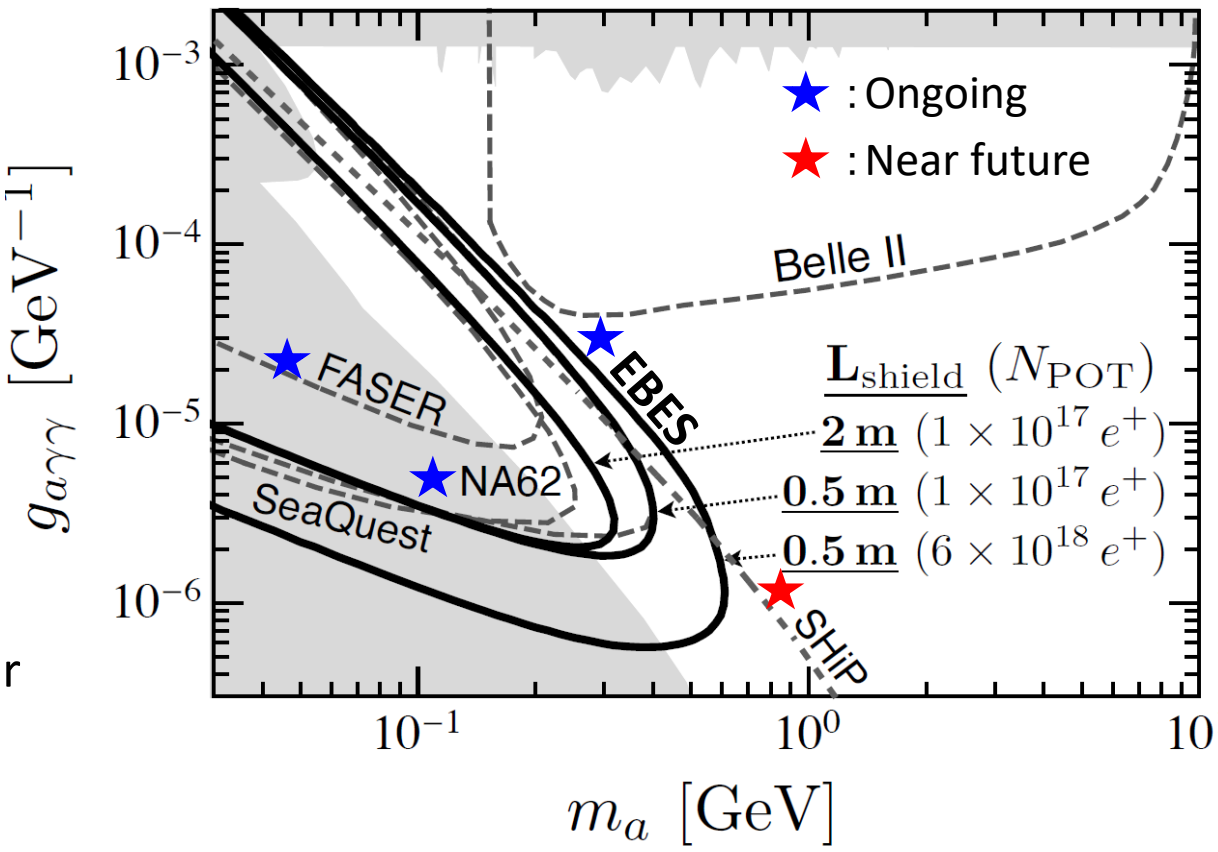
Introduction

- ✓ **EBES (Electron Beam dump Experiment at KEK LINAC Switch yard 3)** is a beam-dump experiment to search for new particles in the MeV-GeV mass range.

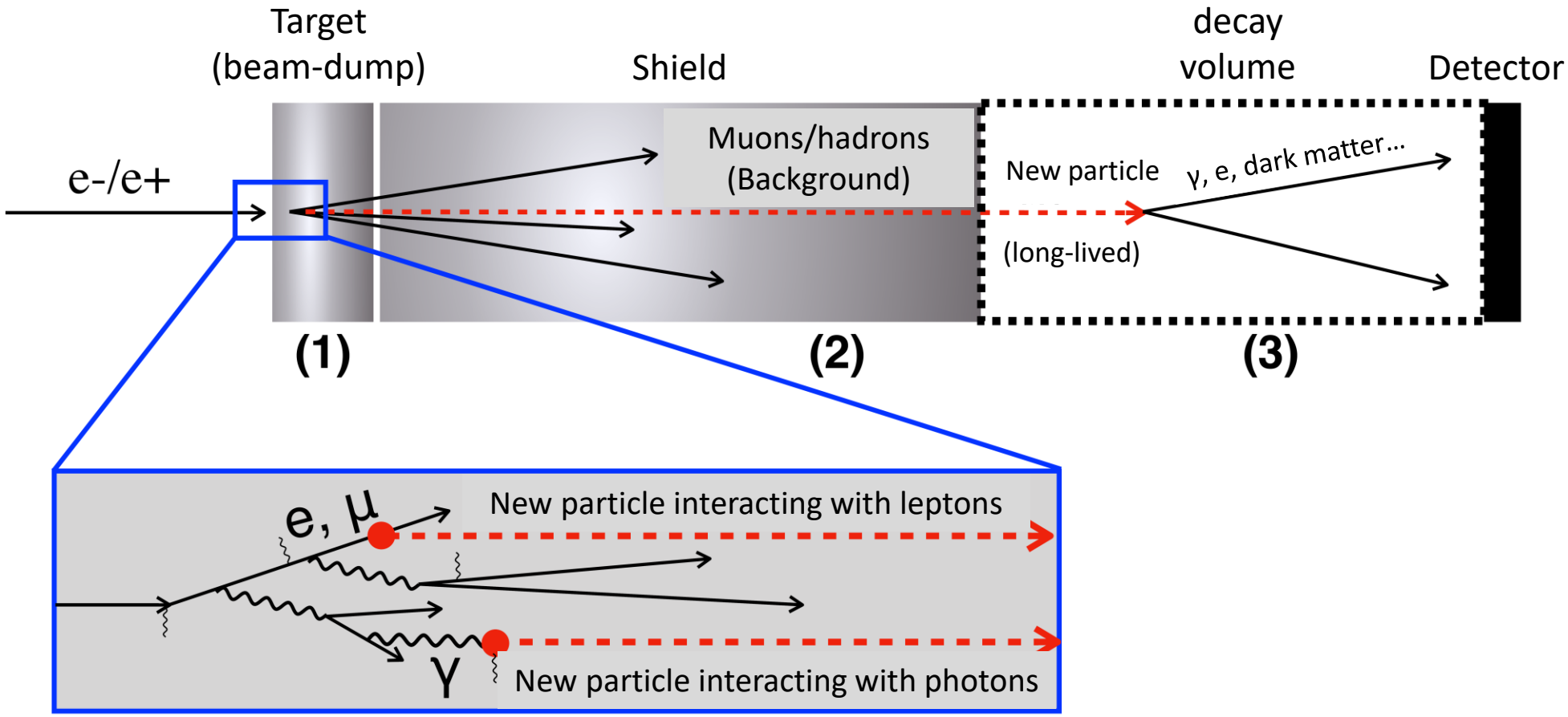
- ✓ The current primary target is **Axion-Like Particles (ALPs)**
  - **A pseudoscalar particle** that appears in various theories beyond the Standard Model.
  - They can span **a wide range of masses and interaction strengths**, and are considered **candidates for dark matter in the MeV-GeV range**.
    - A variety of experiments are currently running or planned in order to explore a wide range of masses and coupling strengths.
  - They can decay into a variety of particles.
    - We consider an ALP that couples **only to photons**.



Projected ALP sensitivities in the mass-coupling plane

In this talk, I present the results of sensitivity estimates to ALPs as a function of their mass and coupling, based on beam test data collected in December 2023.

What is Beam-Dump Experiment?



- ✓ New particles are produced via electromagnetic showers and **interactions with nuclei or electrons** in the target.
  - In this study, ALPs that couple only to photons are produced **via bremsstrahlung photons**.
- ✓ Backgrounds (pair-produced muons and photo-nuclear hadrons) are **attenuated by the shield**.
- ✓ The **new particles decay into SM particles** in the decay volume downstream of the shield.

MeV-GeV ALPs Search

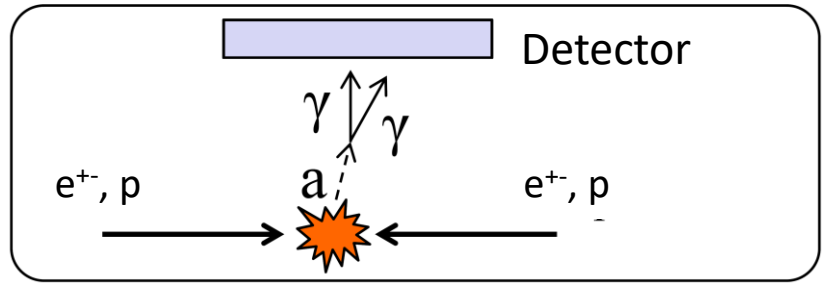
✓ In this study, we consider ALPs that couple only to photons.

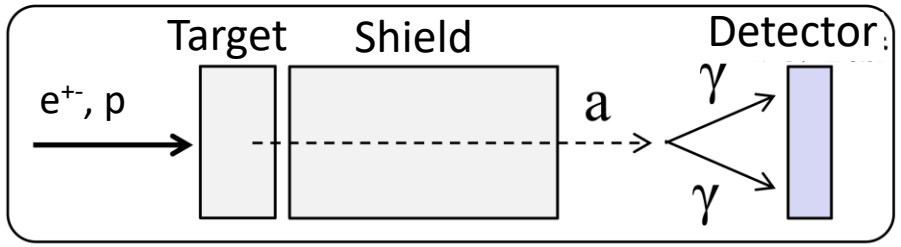
$$\delta\mathcal{L} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2$$

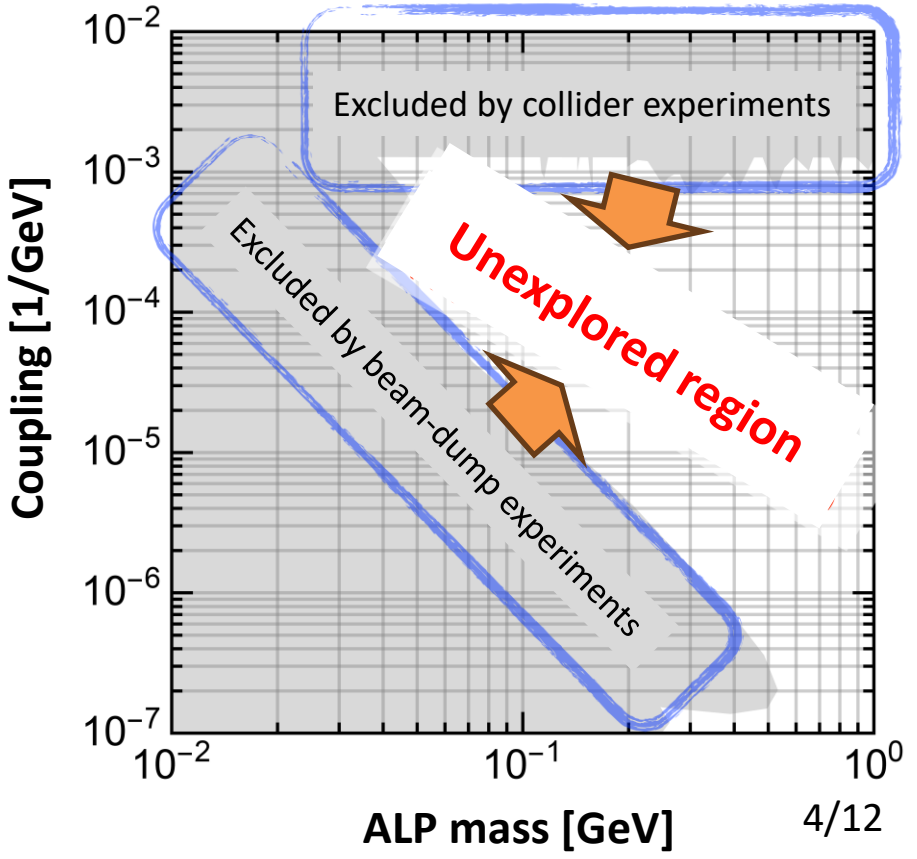
✓ The ALP lifetime is determined by its mass and coupling.

$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}.$$

← The smaller the mass and coupling, the longer the lifetime.





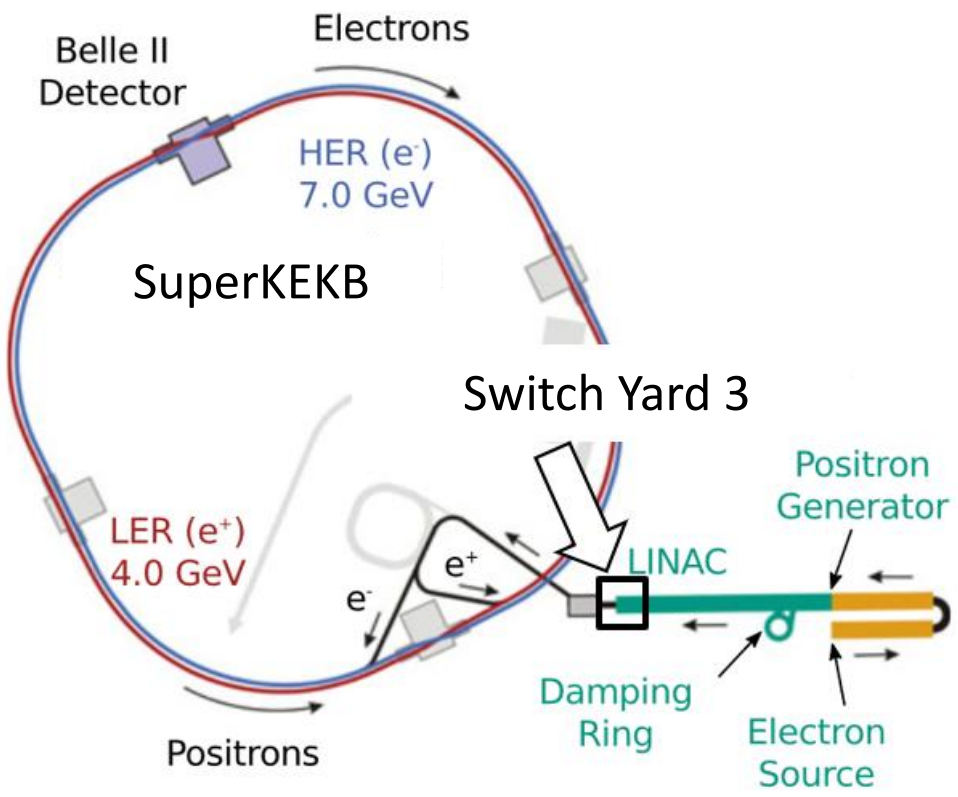


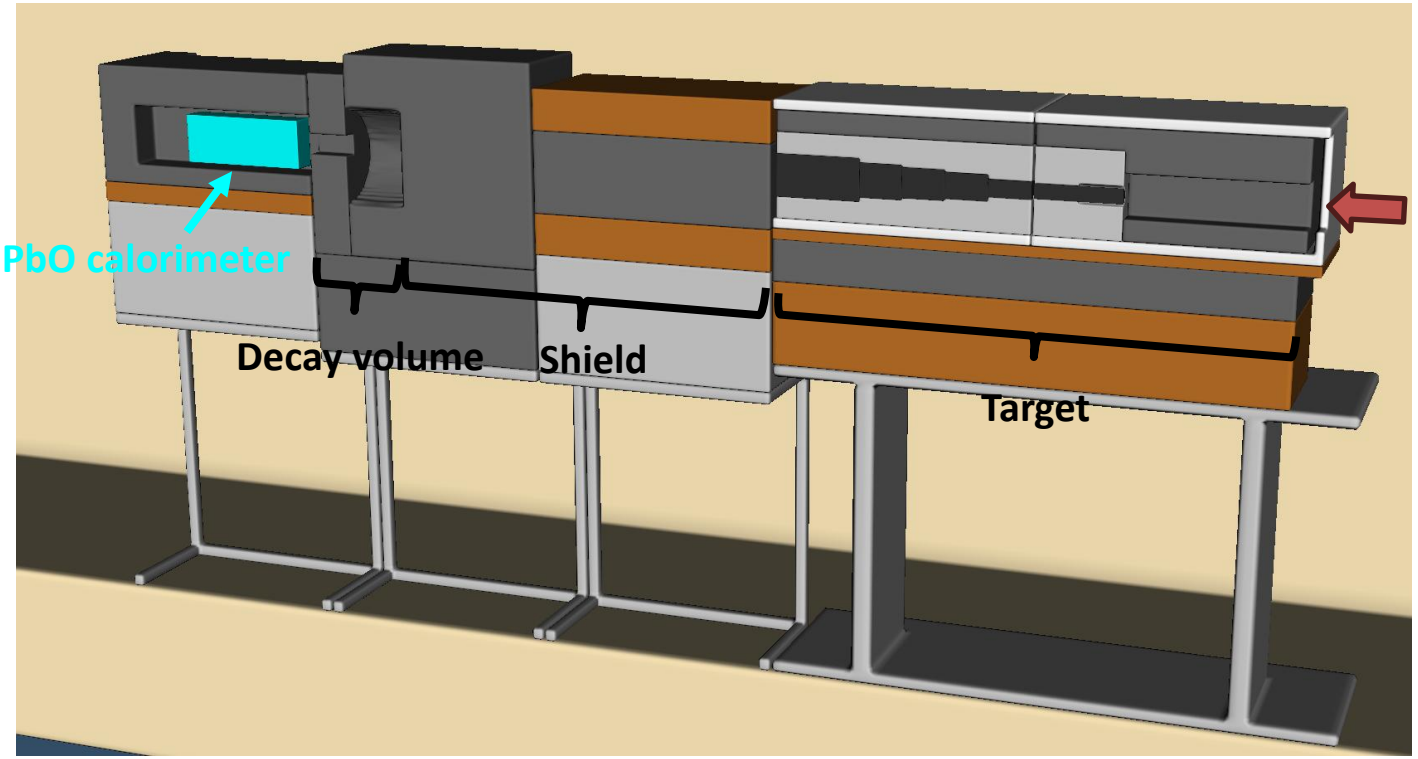
Complementary searches by collider and beam-dump experiments

✓ **Collier experiments**
- Well suited to probing **the high-mass, large-coupling region**, taking advantage of their high center-of-mass energy.

✓ **Beam-dump experiments**
- High luminosity enables sensitivity to **the small-coupling region by accumulating large event statistics**.
- Probe the target parameter space by **optimizing the beam energy, the thickness of the target and shield, and the distance to the detector.**

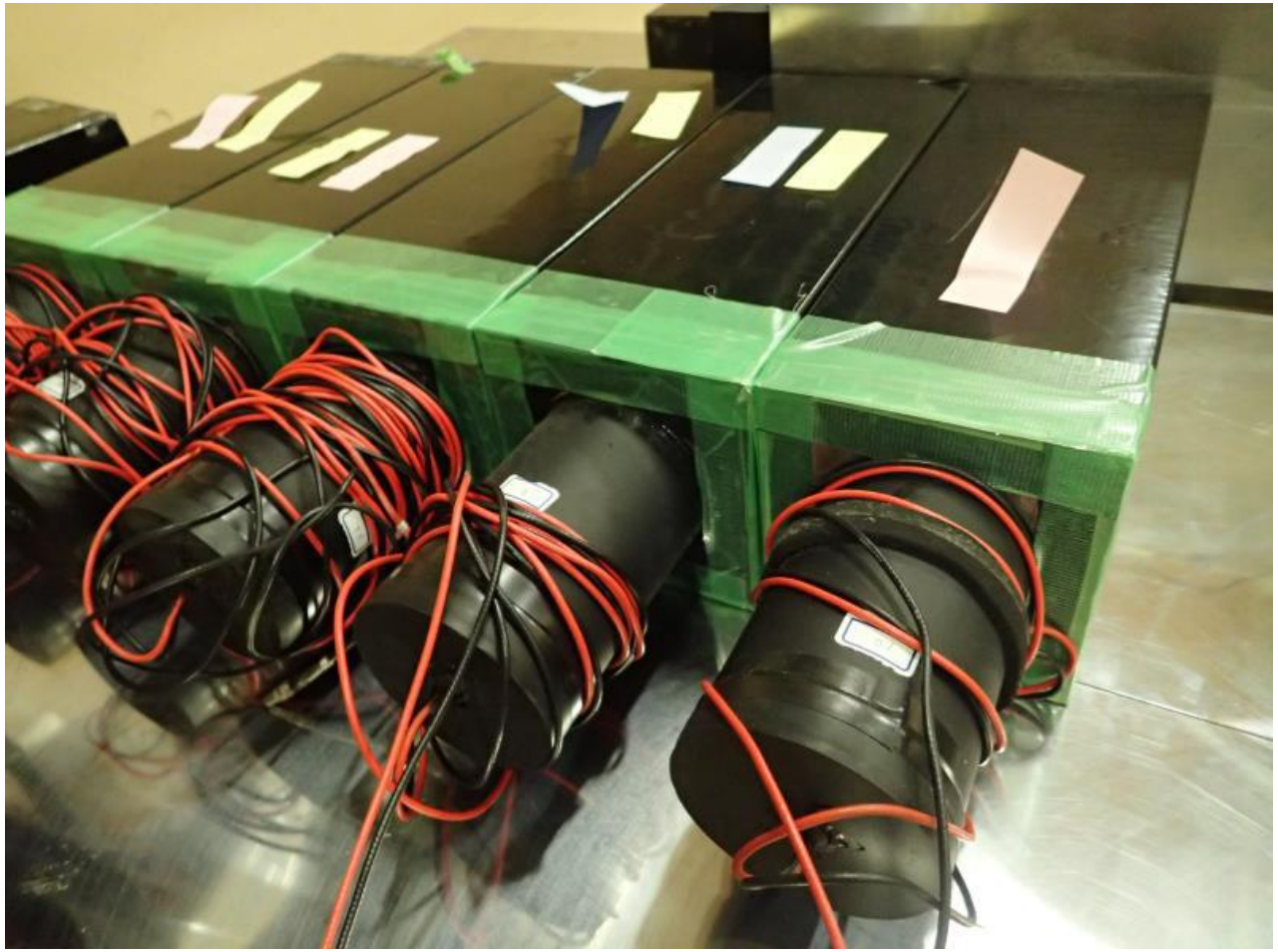
EBES Beam Test Setup in December 2023





- ✓ In December 2023, a beam test collected **~1.3 × 10^{14} events** in 3 hours with ~0.1 nC beam charge.
- ✓ A 4 GeV positron beam is directed onto a tungsten target, and photons (γ) from ALP decays are detected.
- ✓ To suppress background events, a shield consisting of **120 cm of lead and 80 cm of tungsten** is installed.
- ✓ **A 28 cm decay volume** is followed by **a lead-glass detector** downstream of the shield.
- ✓ The target region, background shielding, DAQ system, and beam parameters have been optimized.

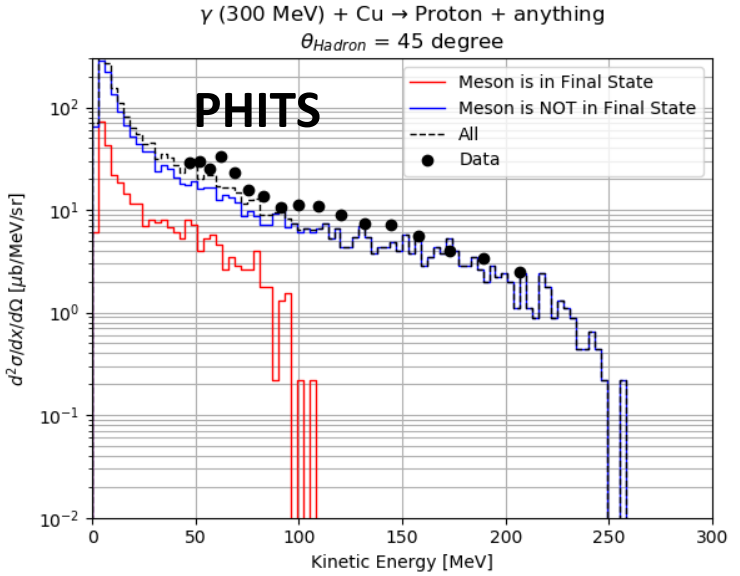
Detector: Lead-Glass Calorimeter



- ✓ PbO Calorimeter
- ✓ Reused from the barrel electromagnetic calorimeter of the TOPAZ experiment.
- ✓ 12.5 cm × 12.5 cm × 30 cm ($20X_0$)
- ✓ Composition: 55% PbO, 45% SiO_2
- ✓ Measures the energy of particles penetrating the shield and photons from ALP decays.

MC Generation and Simulation of Signals

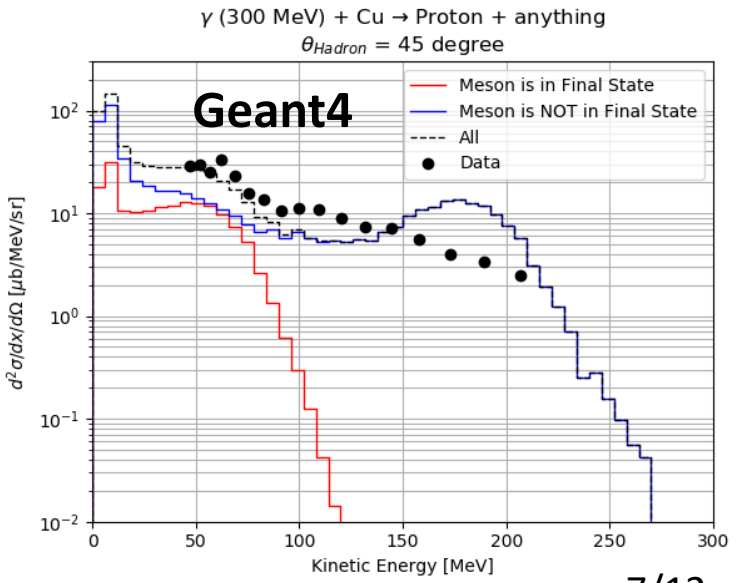
- ✓ **PHITS** is used for signal generation and for interactions.
  - The accuracy of the physics model is **comparable to that of Geant4**.
  - **Dedicated models are implemented** for electromagnetic showers, photo-nuclear interactions, nuclear reactions, and neutron transport.
  - Very easy to use, with many features suited for beam-dump studies.
    - Variance reduction techniques such as **biasing** (enhancing specific processes), **importance sampling** (improving particle transport efficiency), and **forced collision/decay** are available.



- ✓ Signal generation uses functions for the differential cross section and lifetime.

$$d\sigma = \frac{1}{2^5\pi}\frac{1}{E_\gamma^2 M_N}\overline{|\mathcal{M}|^2}\,dE_a$$

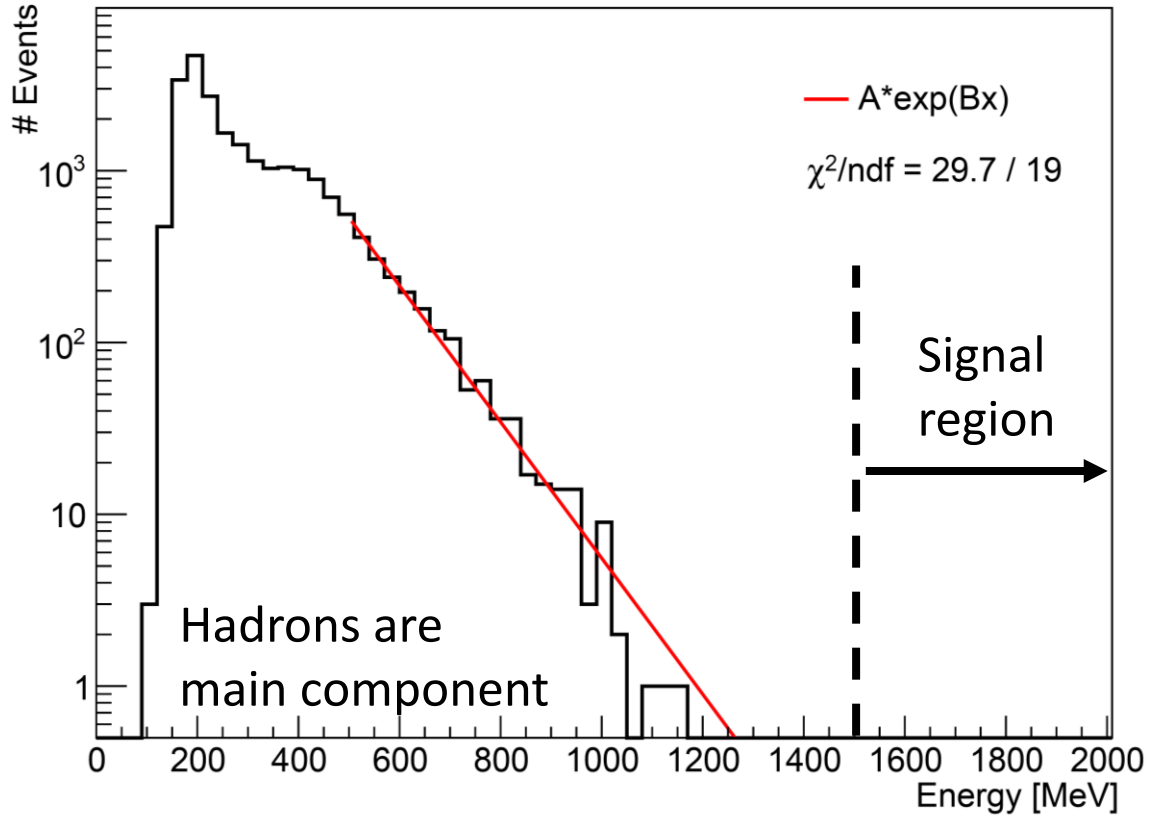
$$\tau = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3}$$



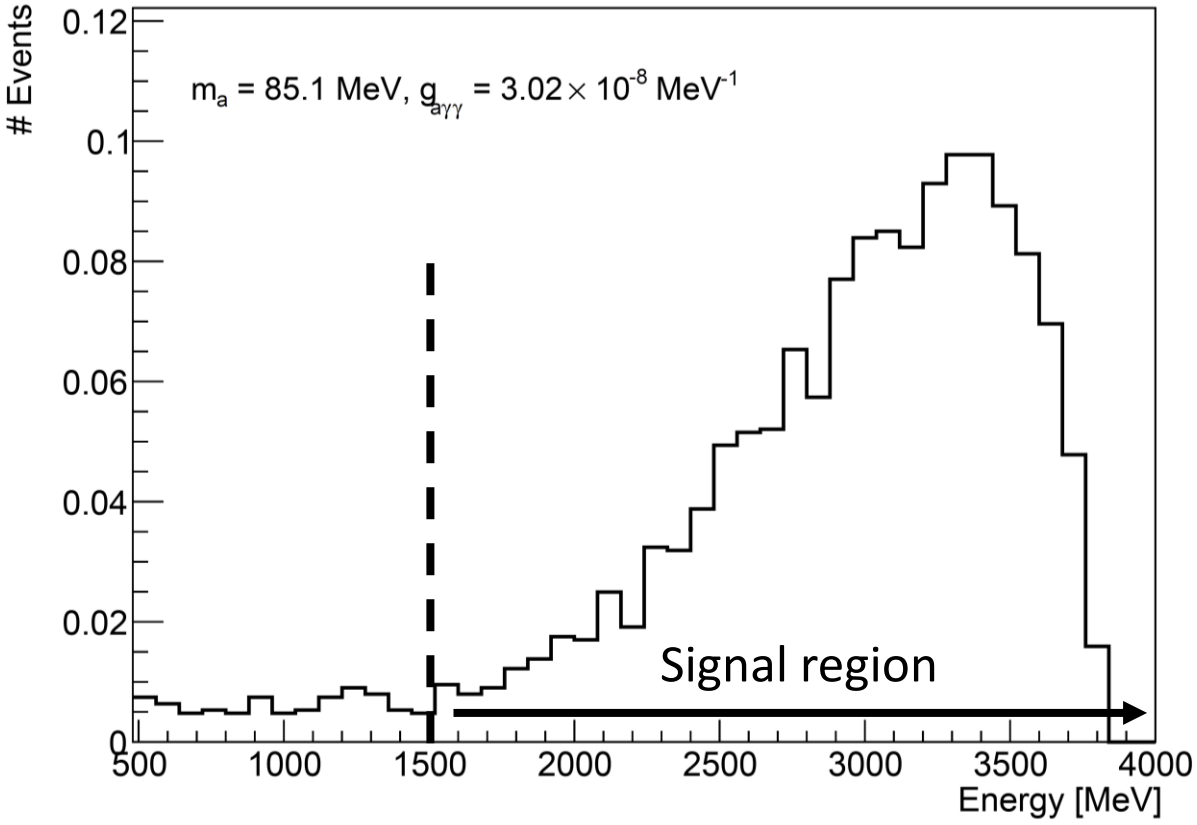
- ✓ PHITS is used because the forward neutron distributions from photo-nuclear interactions are more realistic than in Geant4.

Energy Distribution for Signals and Bkgs

Data taken with a PMT voltage of 1700 V (background)

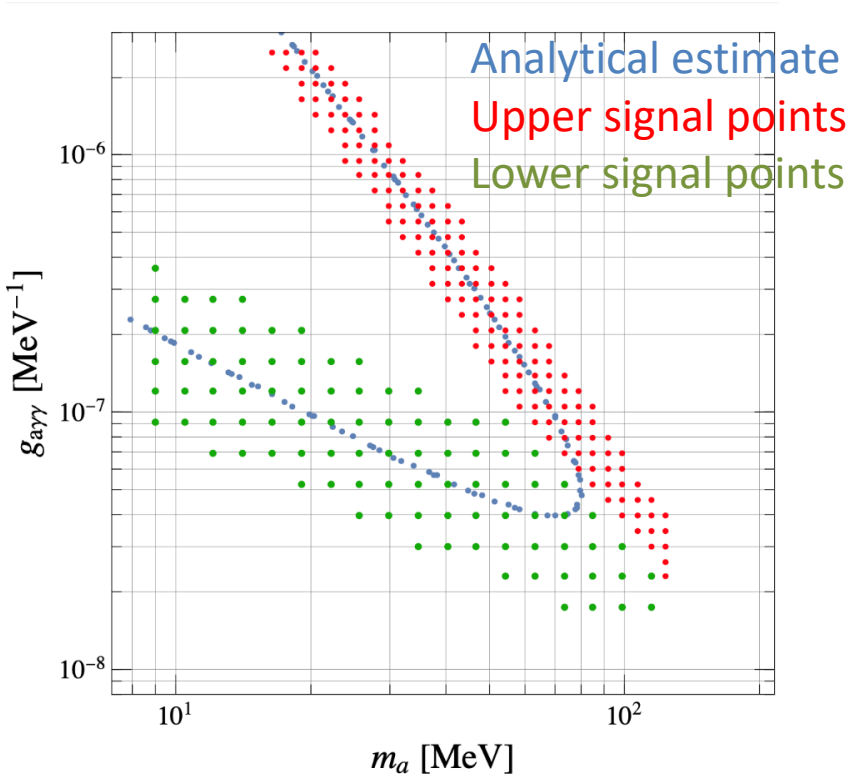


Signal MC events

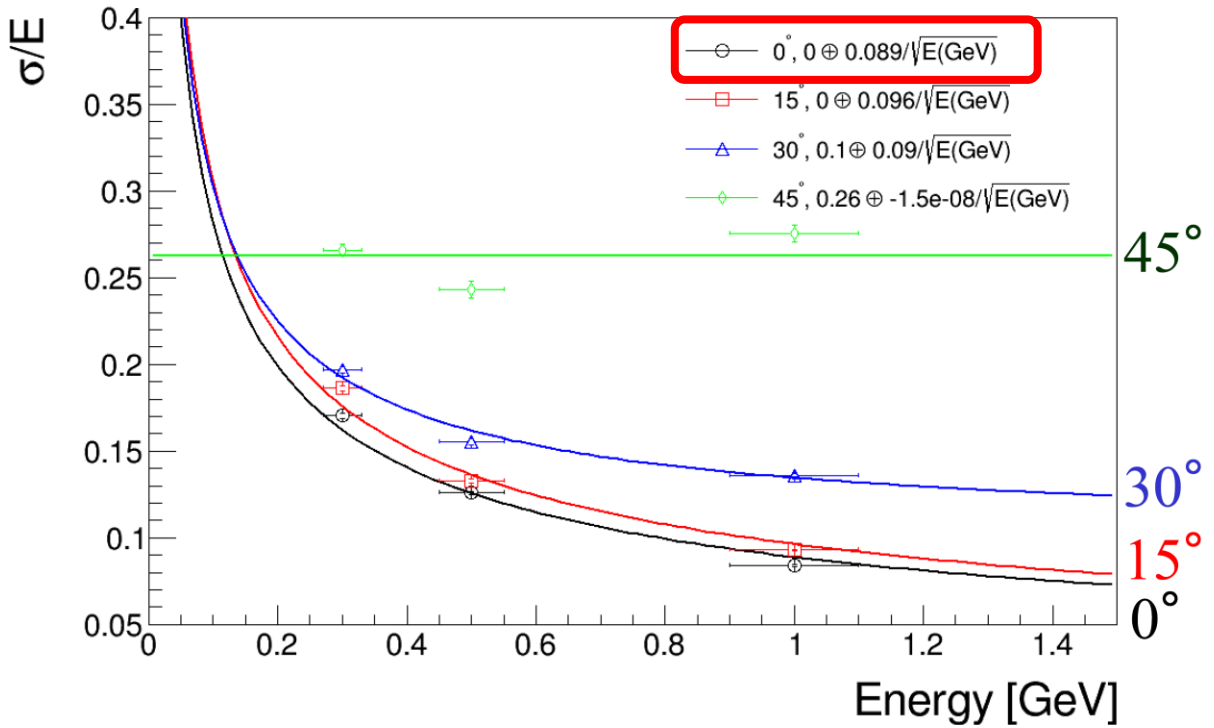


- ✓ The left plot shows data taken with a PMT voltage of 1700 V scaled to 1800 V using the energy resolution.
  - Use as background distribution
- ✓ **Signal extends up to ~4500 MeV, while background is limited to ~1000 MeV**.
- ✓ Background is fitted with A·exp(B·x), and **the region above 1500 MeV where expected background events are < 0.1 events is defined as the signal region**.

Statistical Analysis Setup

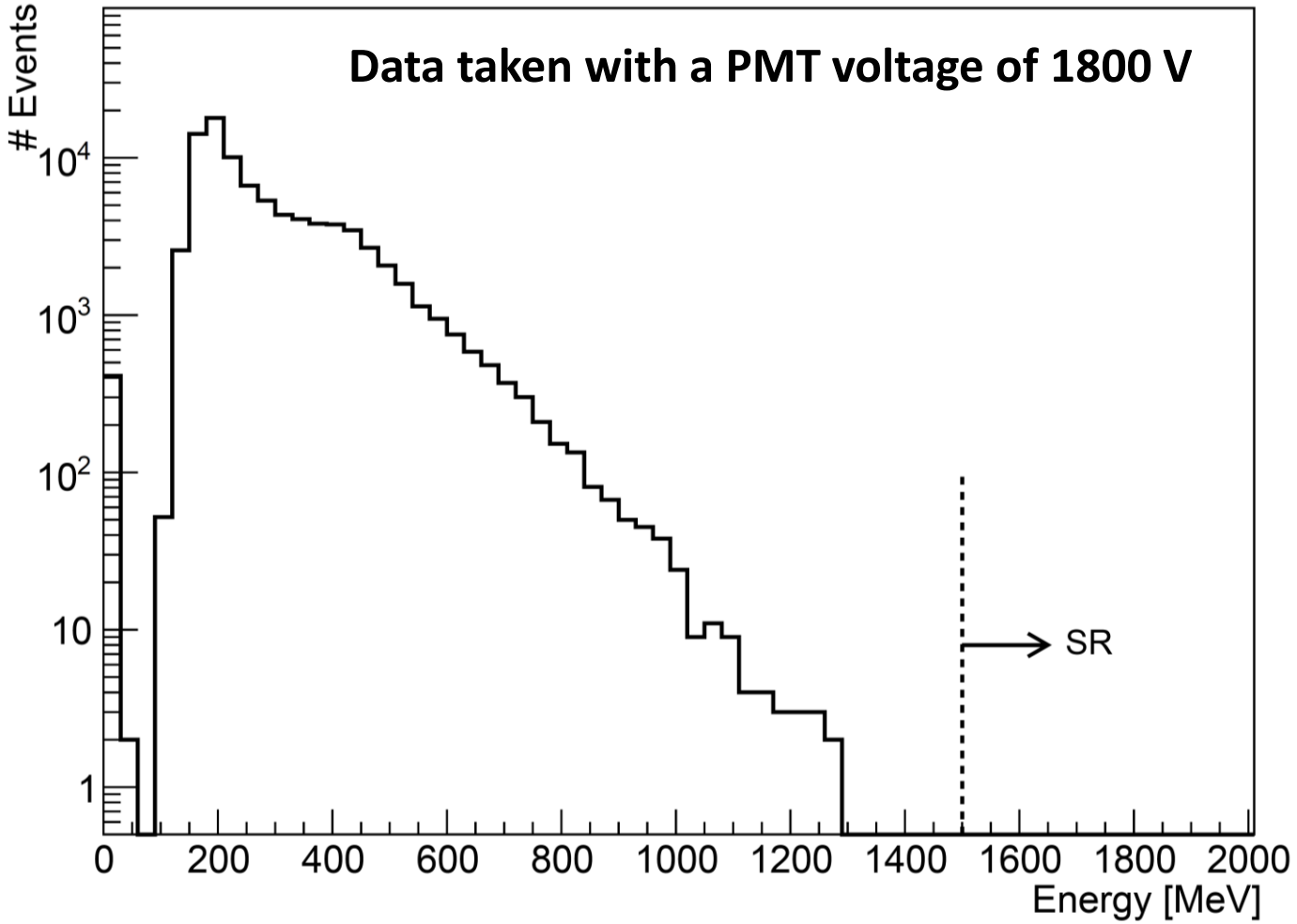


Correlation between energy and resolution



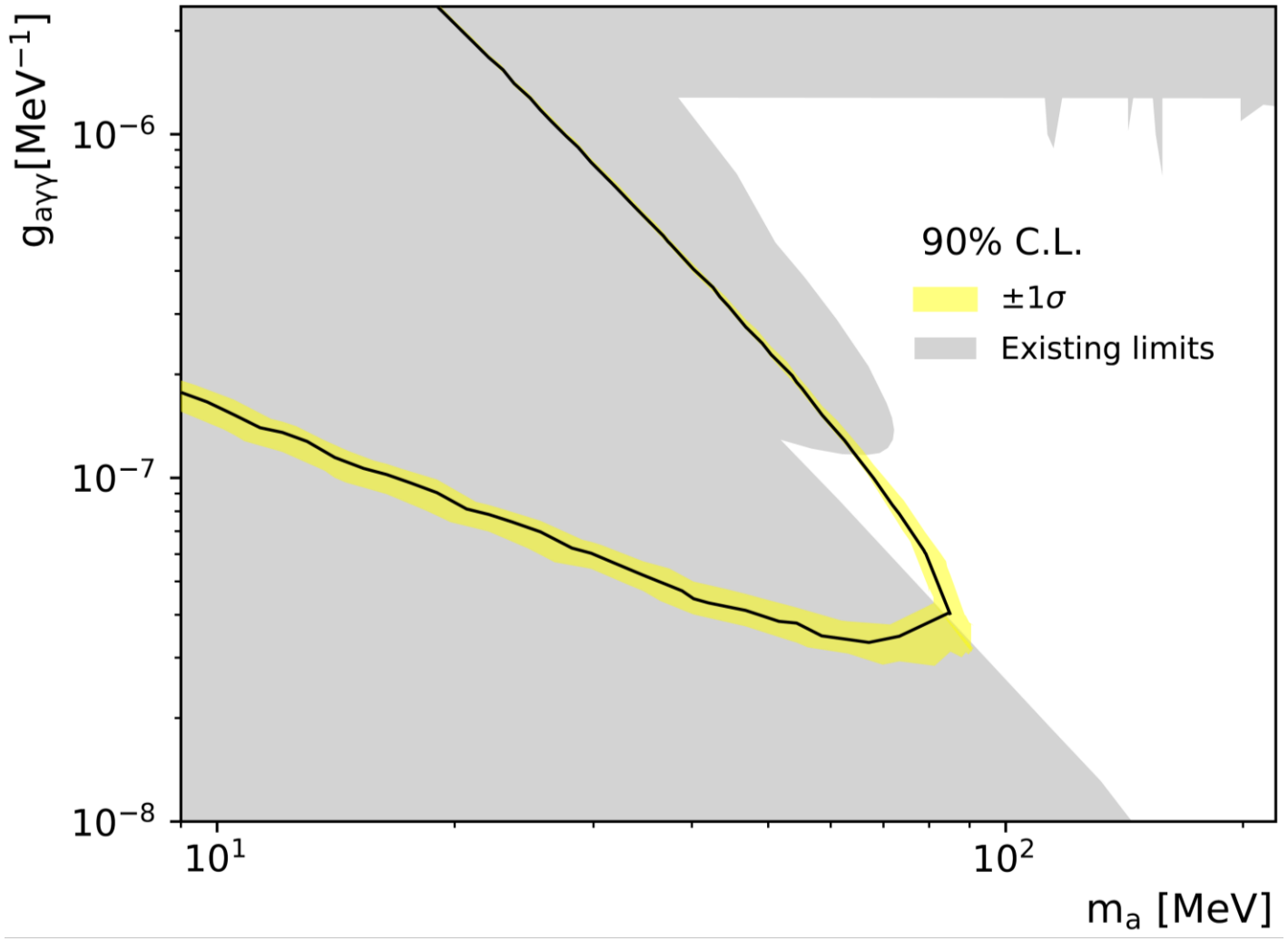
- ✓ **250 signal MC points are generated** around the expected limits based on the analytical calculation.
- ✓ **A single-bin fit** is used (shape information is not relevant), with no expected background in the signal region.
- ✓ **Toy MC** is used at each mass-coupling point to derive **90% CL limits** on the signal strength.
- ✓ Systematic uncertainties considered:
  - **Absolute value of the beam bunch charge**: evaluated using cosmic-muon data and 7 GeV beam data.
  - **Energy resolution**: evaluated by varying the energy up/down using the calibrated resolution.
  - **Cut variation**: signal yield changes evaluated by shifting the threshold to 1200 and 1800 MeV.

Unblinding of the Signal Region



- ✓ No events observed above 1500 MeV in the data of PMT voltage 1800 V.
  - Unfortunately, no signal was observed.

Sensitivity to Photon-Coupled ALPs



- ✓ Since no events are observed in the signal region, **90% CL upper limits in the mass-coupling plane** for photon-coupled ALPs
- ✓ Good agreement with analytical estimates.
- ✓ **Already probe previously unexplored regions**.
  - Achieved with **just 3 hours of data taking!**
  - More data with upgraded detector were already collected. **Stay tuned!**

First physics sensitivity evaluation for the EBES experiment!

Summary and Plan

Summary

✓ **EBES is a new beam-dump experiment at the KEK LINAC, searching for ALPs decaying into photon pairs.**
- Collider and beam-dump experiments are complementary in ALP searches.
- EBES can probe new ALP parameter space with <1 month of data taking.

✓ **1.3 × 10^{14} events collected in the December 2023 beam test were used for the ALP search.**
- The signal region is defined by fitting the background energy distribution.
- First EBES data yield a sensitivity curve **probing regions complementary to existing experiments**.

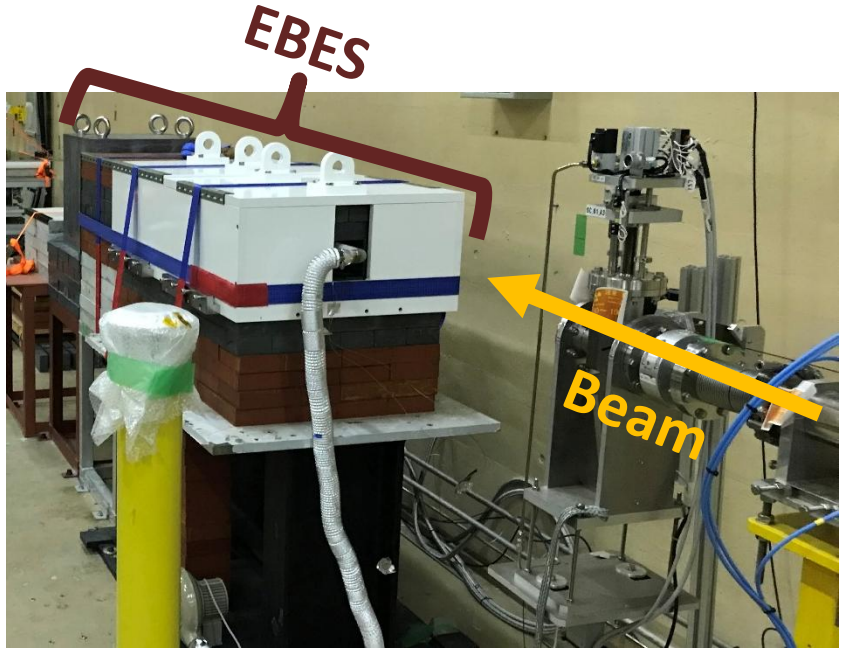
→ **Established the analysis framework for the full experiment**.

Plan

✓ These results will be published in the near future.
- Arxiv was ready yesterday!: 2605.07108

✓ Data were collected during physics runs in late 2025!
- **About 16 times more data with upgraded detector** using 4 GeV positron beam.
- Data **with 7 GeV electron beam** were also collected.

✓ Phase-II planned within a few years with upgraded target/shield/detector.



Will significantly expand searches for ALPs and other new particles in the MeV-GeV range!