Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

Sensitivity study for $B^{\pm} \to K^{\pm} a$ (displaced $a \to \gamma\gamma$) at Belle II

ETP Weekly Meeting, May 16, 2022
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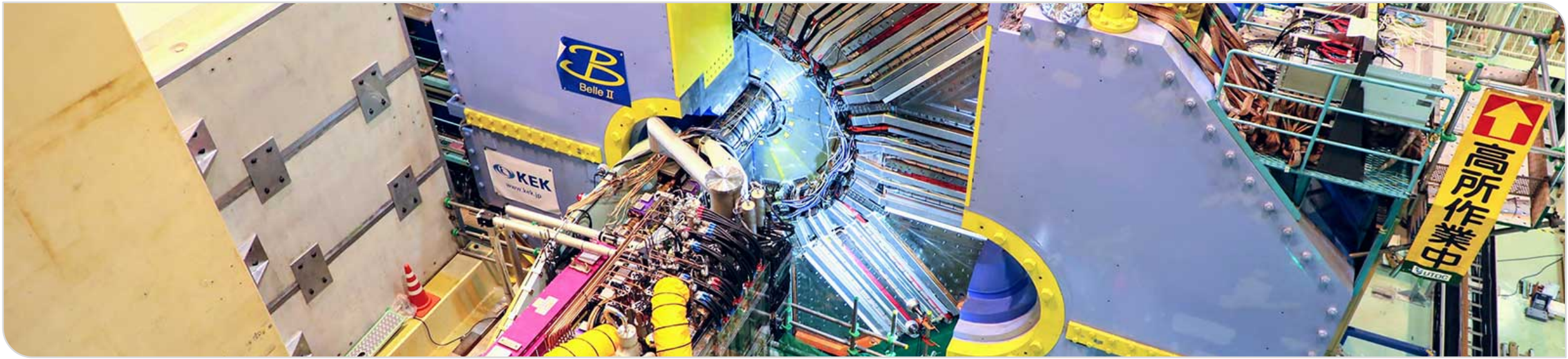
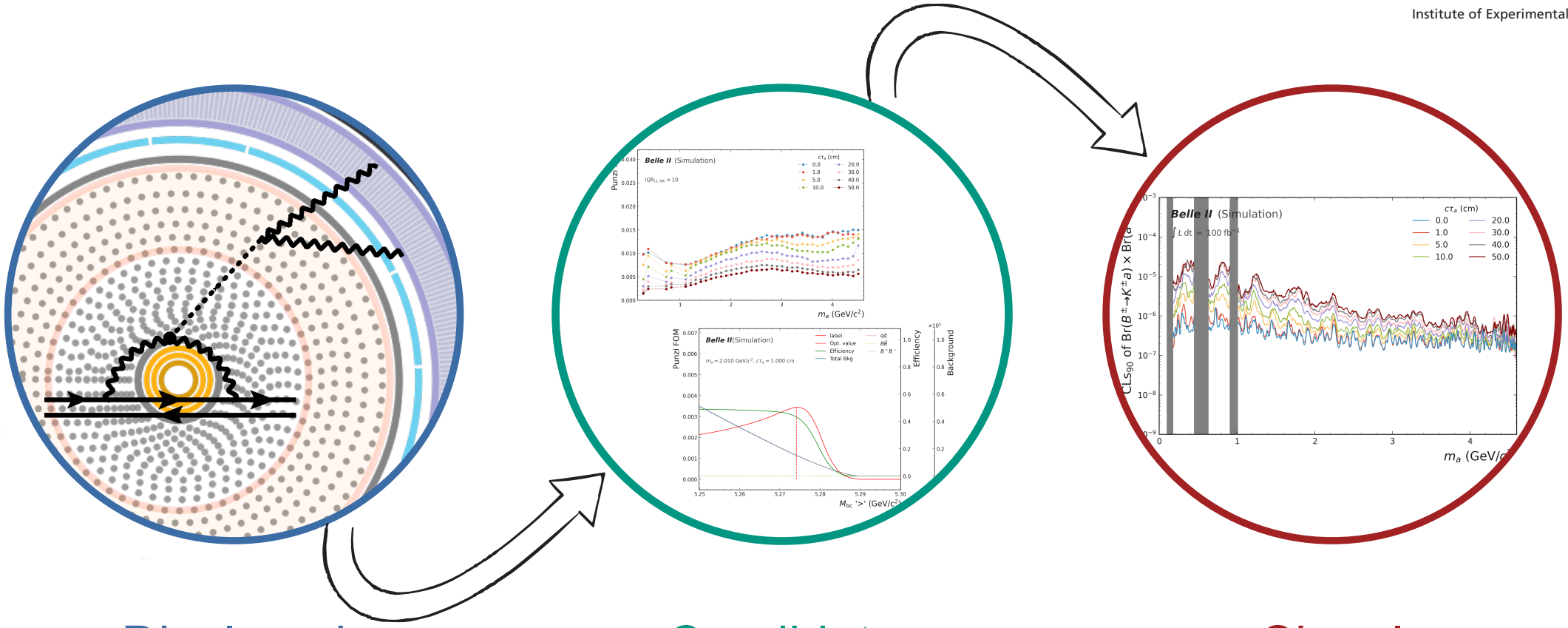


Outline


Belle II (Simulation)
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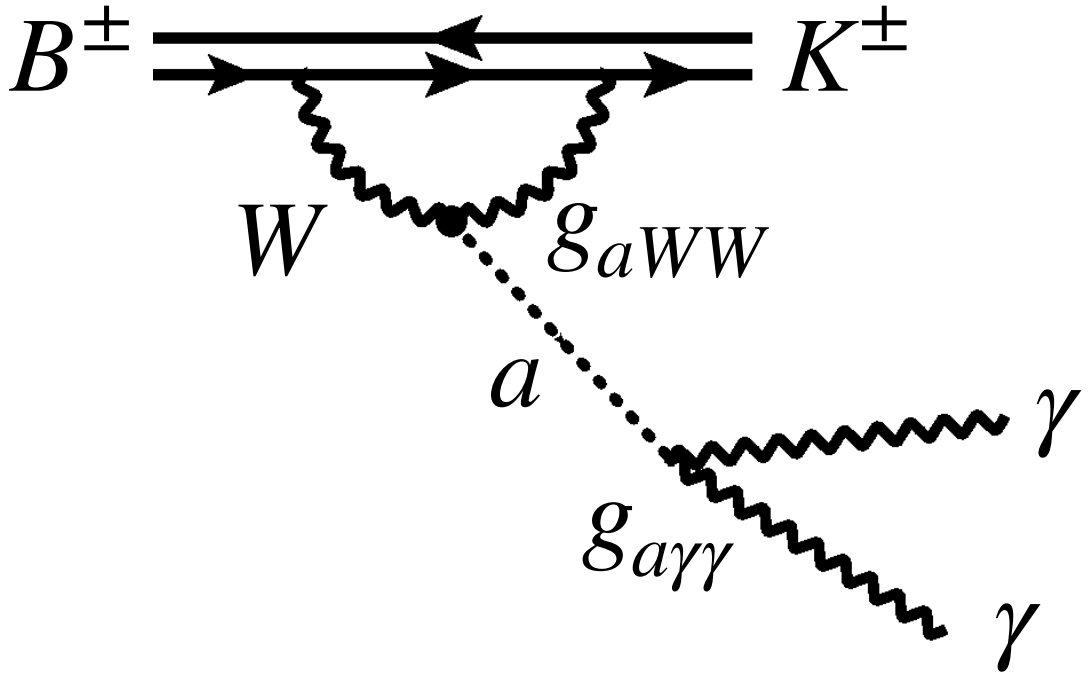
Belle II (Simulation)
Displaced ALPs
Candidate Selection
Signal Extraction

Introduction

- **A**xion **L**ike **P**articles (**ALP**s)
  - Pseudo Goldstone boson of *spontaneously broken* and under SM *anomalous* Peccei-Quinn symmetry
  - Weak coupling to SM W & γ bosons
- **Promising Signature**:
  $B^{\pm} \to K^{\pm}(a \to \gamma\gamma)$
  - Suppressed SM background
  - Scan of m_a up to $\sim 4.6\,\mathrm{GeV}/c^2$
  - Sensitivity to long-lived ALPs



Theoretical Foundation

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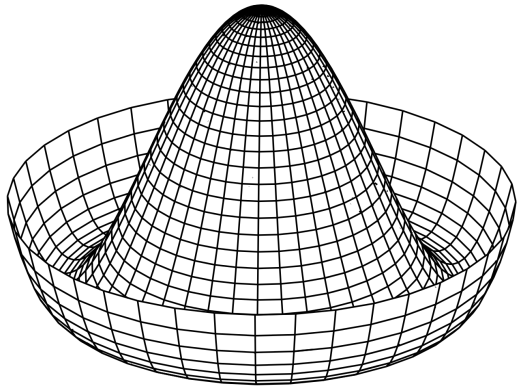
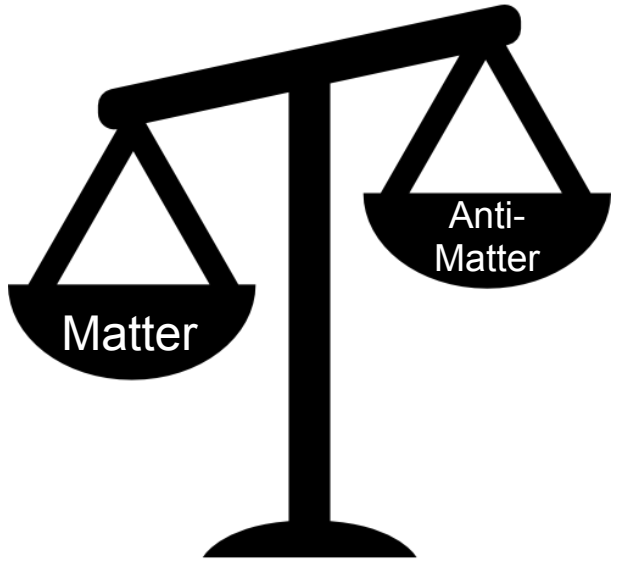
Spontaneous Breaking of Global Symmetries

- Symmetry of the theory ≠ Symmetry of the ground state
  ⇒ Massless Goldstone bosons



Global Anomalies in the Standard Model

- Symmetry of the classical theory ≠ Symmetry of the quantum theory
  ⇒ Noether current is not conserved
- E.g. baryon number violation



Theoretical Foundation

- Axions and Axion Like Particles
  - Strong CP problem:
    - Not-forbidden, CP- and P-odd Lagrangian:

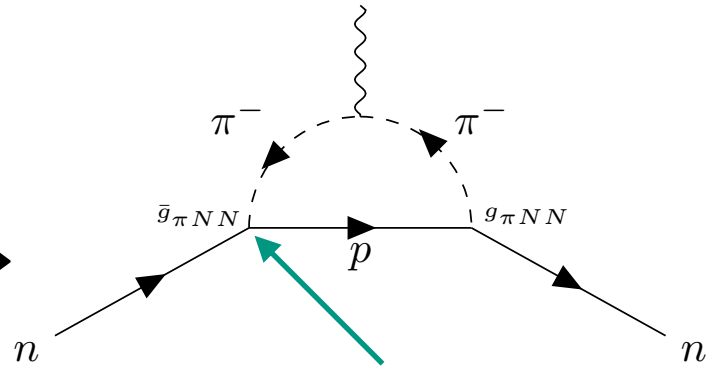
$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu}, \theta = \theta_{\mathrm{QCD}} + \mathrm{argdet}(M_u M_d)$$

  - Solution: Axion
    - New $U(1)_{\mathrm{PQ}}$ that is spontaneously broken and anomalous such that Goldstone boson a couples to gluons (mirrors $\mathscr{L}_\theta$)
    - Scalar potential V_a for a: $\langle a \rangle$ cancels θ and $m_a \approx m_\pi F_\pi / 2 f_a$

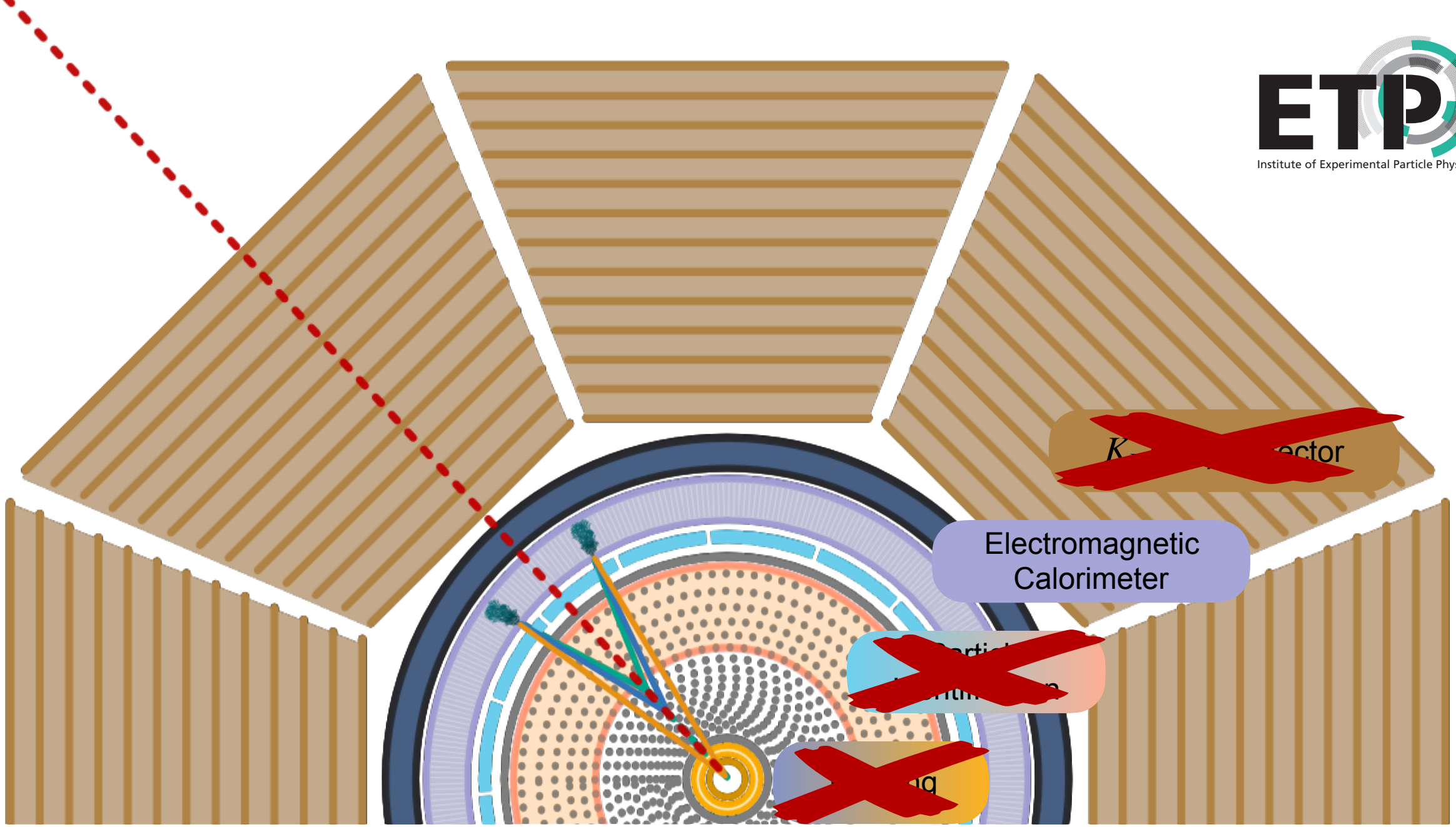
$$V_a = F_\pi^2 m_\pi^2 \cos\left(\theta - \frac{a(x)}{f_a}\right)$$

  - ALPs: Do not solve strong CP problem and couple to other Standard Model particles

Neutron Electric Dipole Moment

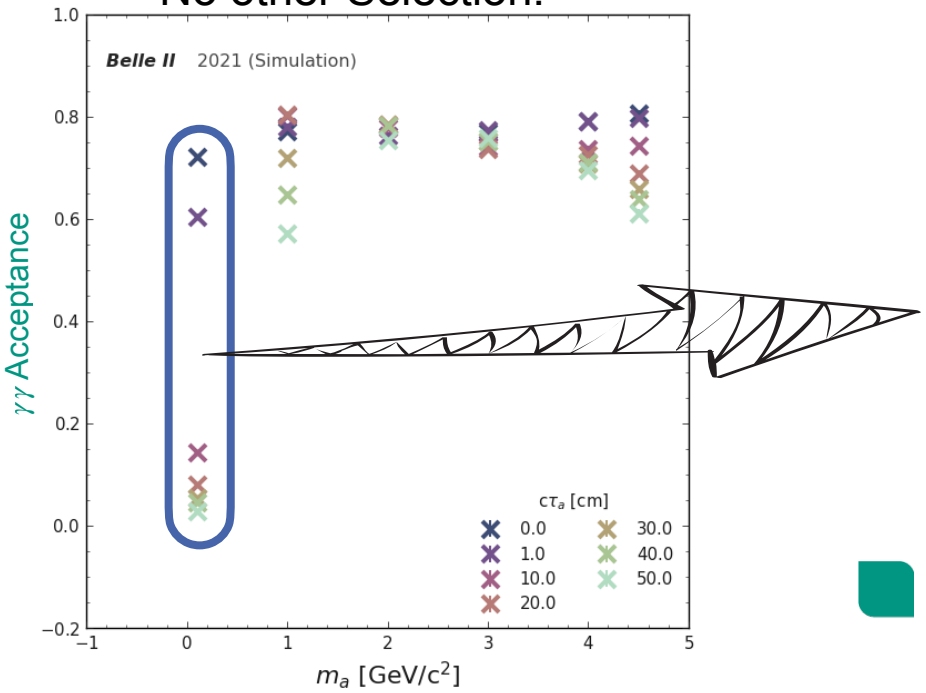


Experiment: $|\theta| < 10^{-10}$

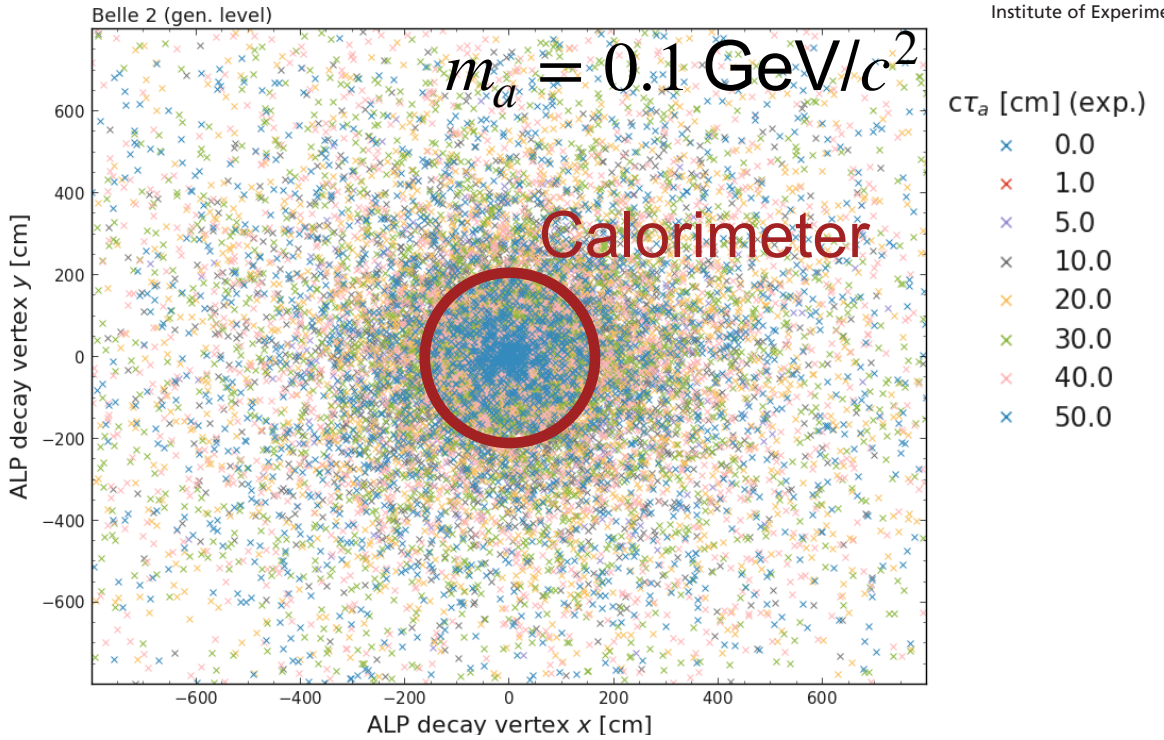

Electromagnetic
Calorimeter

Photon Acceptance

Both photons are ALP MC daughters.
No other Selection.



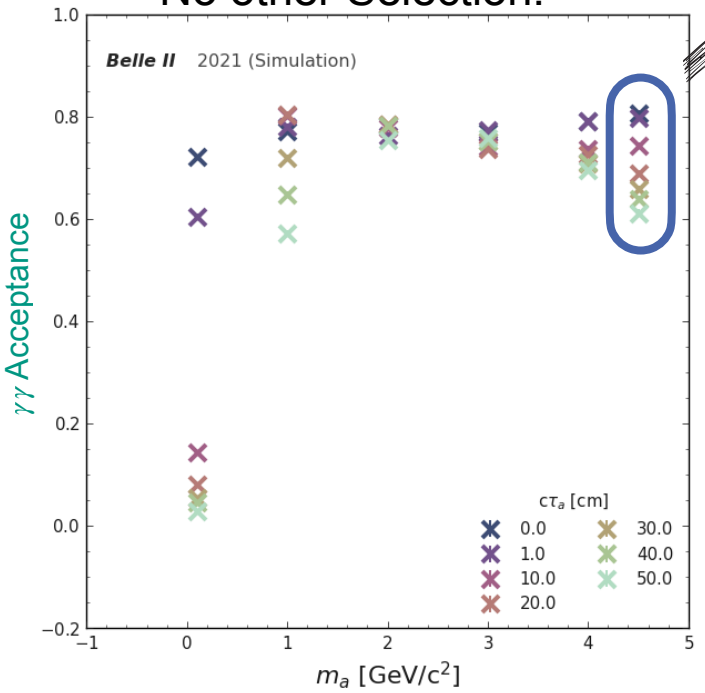
$$\frac{N\,(\text{Correctly reconstructed})}{N(\text{Generated})}$$



- Most of the light and displaced ALPs escape the detector before they decay
- The $B \to K(a \to \text{invisible})$ signature will be studied by Slavomira Stefkova

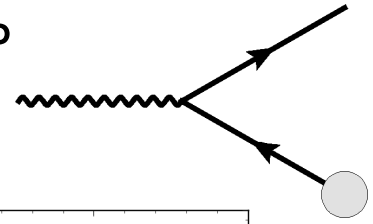
Photon Acceptance

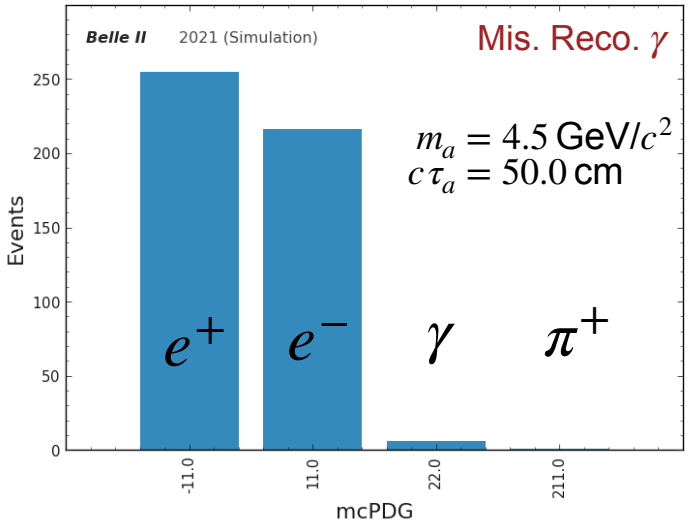
Both photons are ALP MC daughters.
No other Selection.

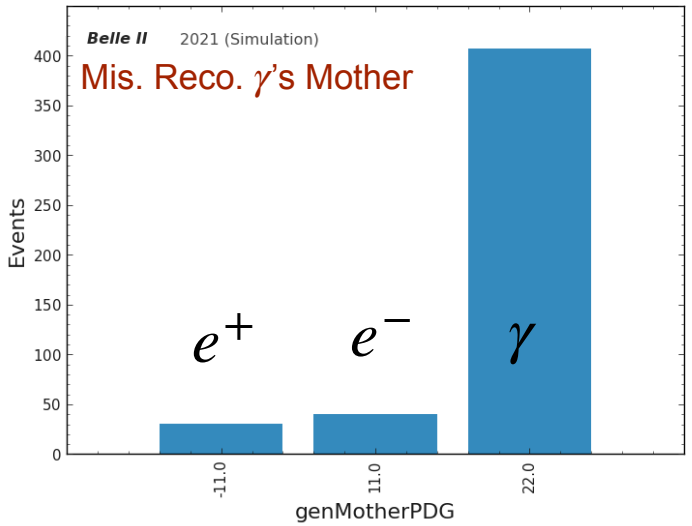


$$\frac{N\,(\text{Correctly reconstructed})}{N(\text{Generated})}$$

- Photon pair is not accepted due to one of the photons being misreconstructed
- Most common observation for the lower energetic photon:
  - We detected an electron whose mother is a photon
  - This photon originated from the generated ALP
  - Possible explanation: photon pair conversion







$M_{\gamma\gamma}$ Resolution for Displaced ALPs

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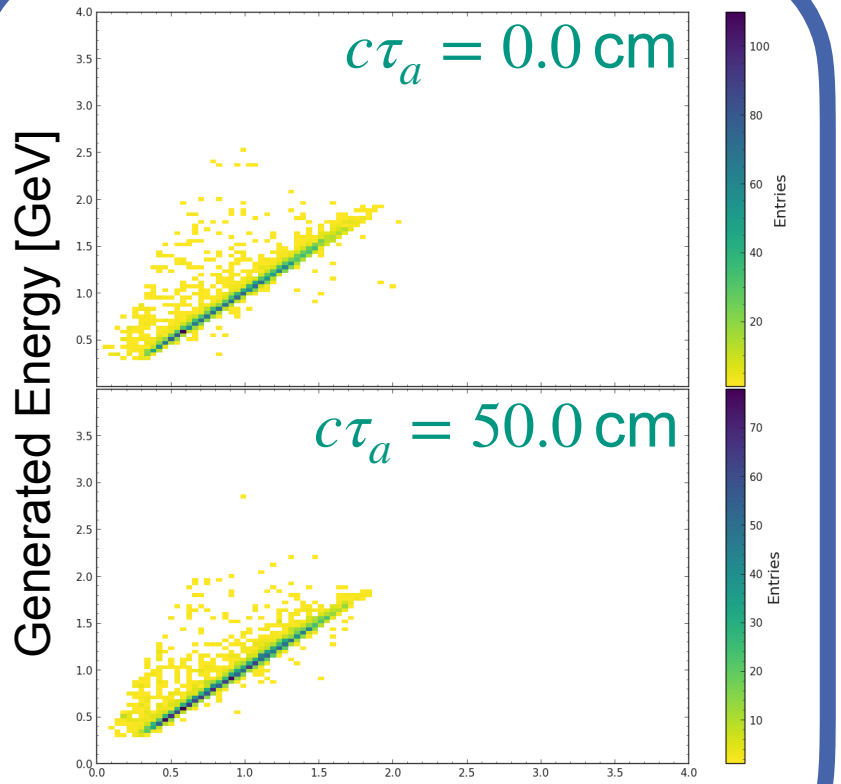
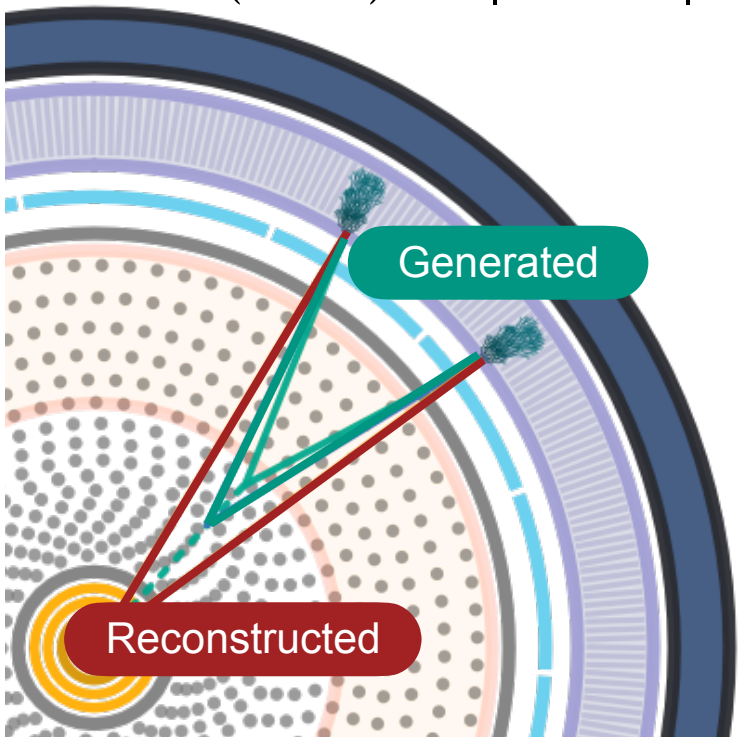
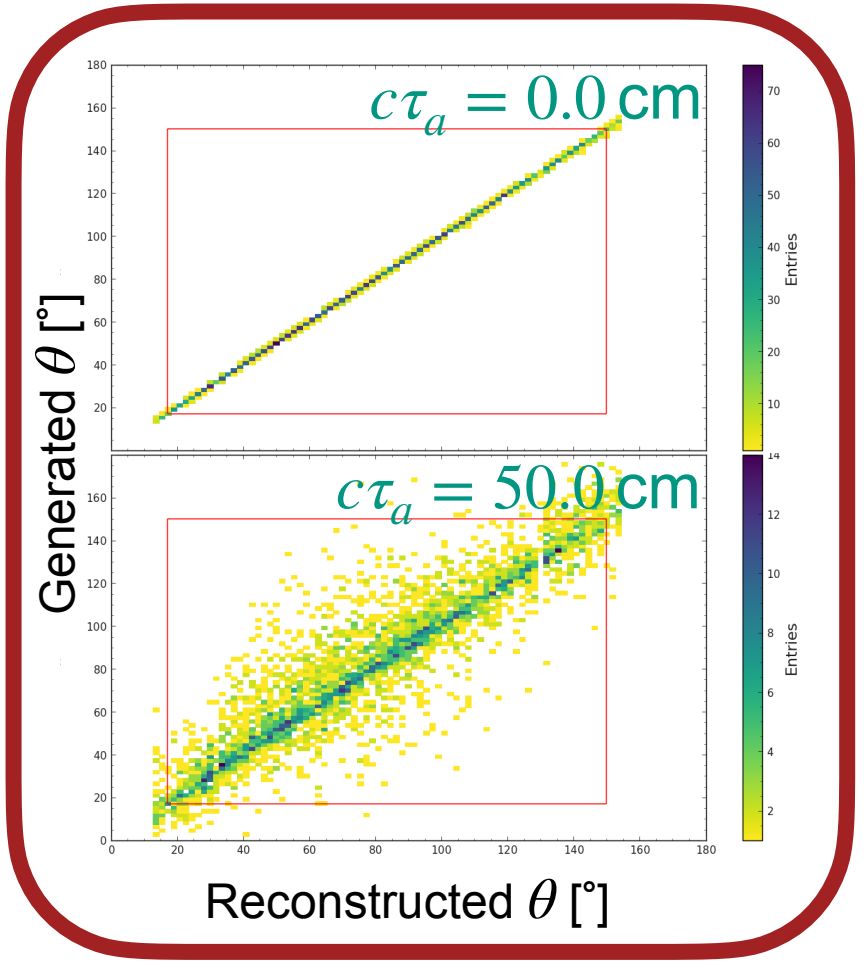
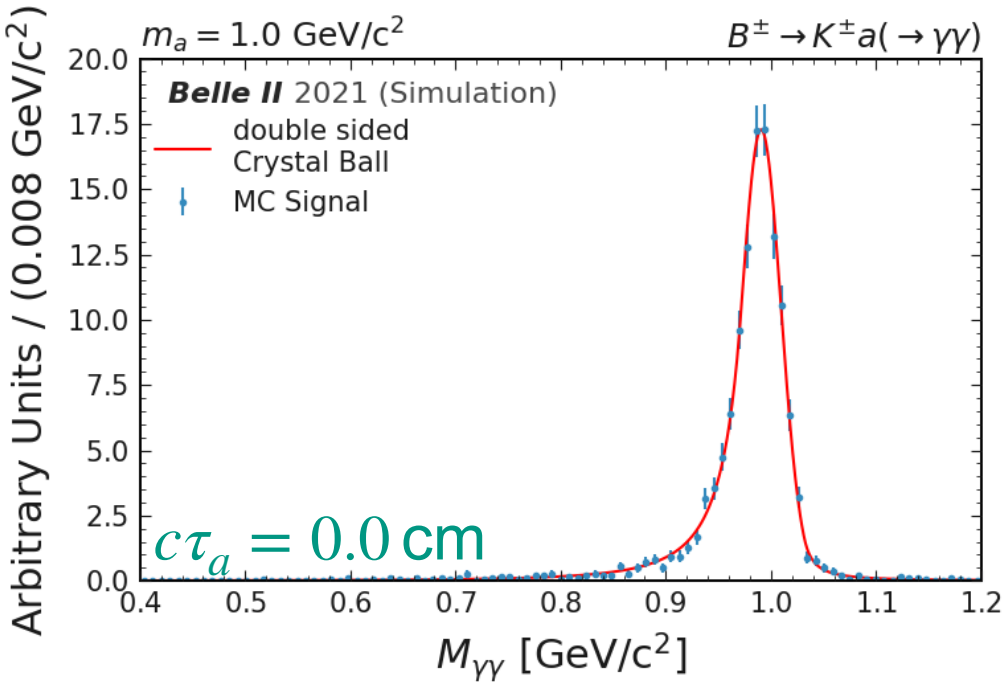


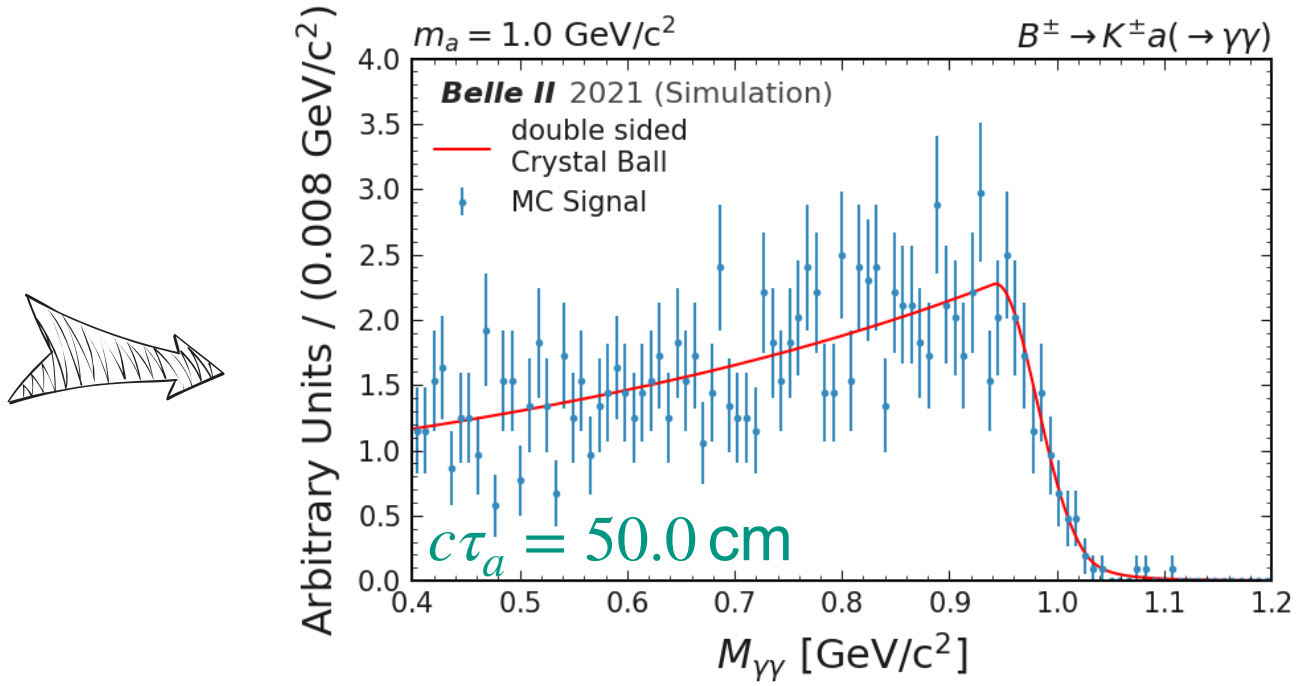
$$M_{\gamma\gamma}^2 c^4 = \left(\sum_\gamma E \right)^2 - \left| \sum_\gamma \vec{p} c \right|^2$$





$M_{\gamma\gamma}$ Resolution for Displaced ALPs





⇒ Perform the following analysis for each lifetime independently

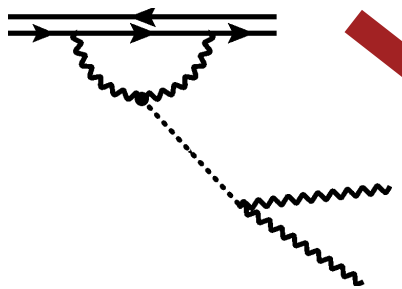
Analysis Setup

- **Privately Generated Signal Samples**
  - $m_a \in [0.175, 4.600]$ GeV/c^2 in steps 0.1 GeV/c^2 excluding $m_\eta \in [0.45, 0.63]$ GeV/c^2 and $m_{\eta'} \in [0.91, 1.01]$ GeV/c^2
  - $c\tau_a \in \{0.0, 1.0, 5.0, 10.0, 20.0, 30.0, 40.0, 50.0\}$ GeV/c^2 (exponential distribution)
  - $N_{\mathrm{MC}} = 50\,000$
  - Detector setup and beam background corresponding to *early-phase 3*
- **Belle II MC samples corresponding to** $100\,\mathrm{fb}^{-1}$
  - Charged: $e^+e^- \to \Upsilon(4S) \to B^+B^-$
  - Mixed: $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$
  - Continuum: $e^+e^- \to q\bar{q}$

Candidate Selection

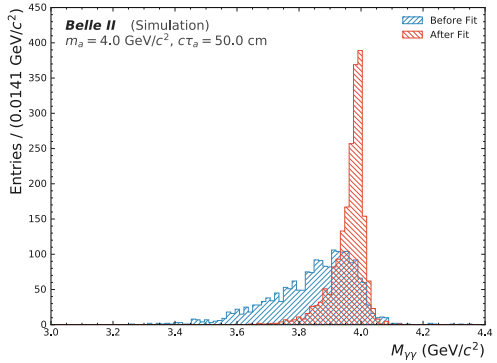
Each mass- and lifetime separately

Simulation & Reconstruction



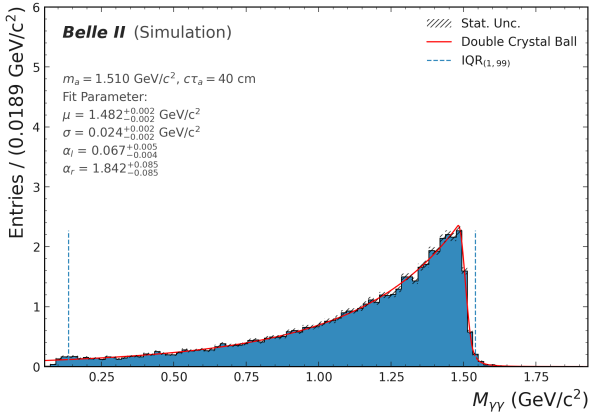
+ Preselection

Mass Constrained Fit



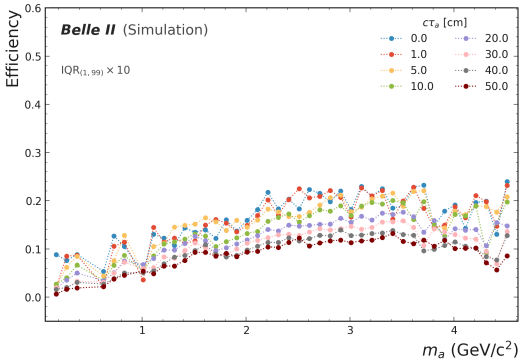
Selection Variables:

$M_{\mathrm{bc}}, \Delta E, R_2, \cos T_B T_O, E_{\gamma^l}$



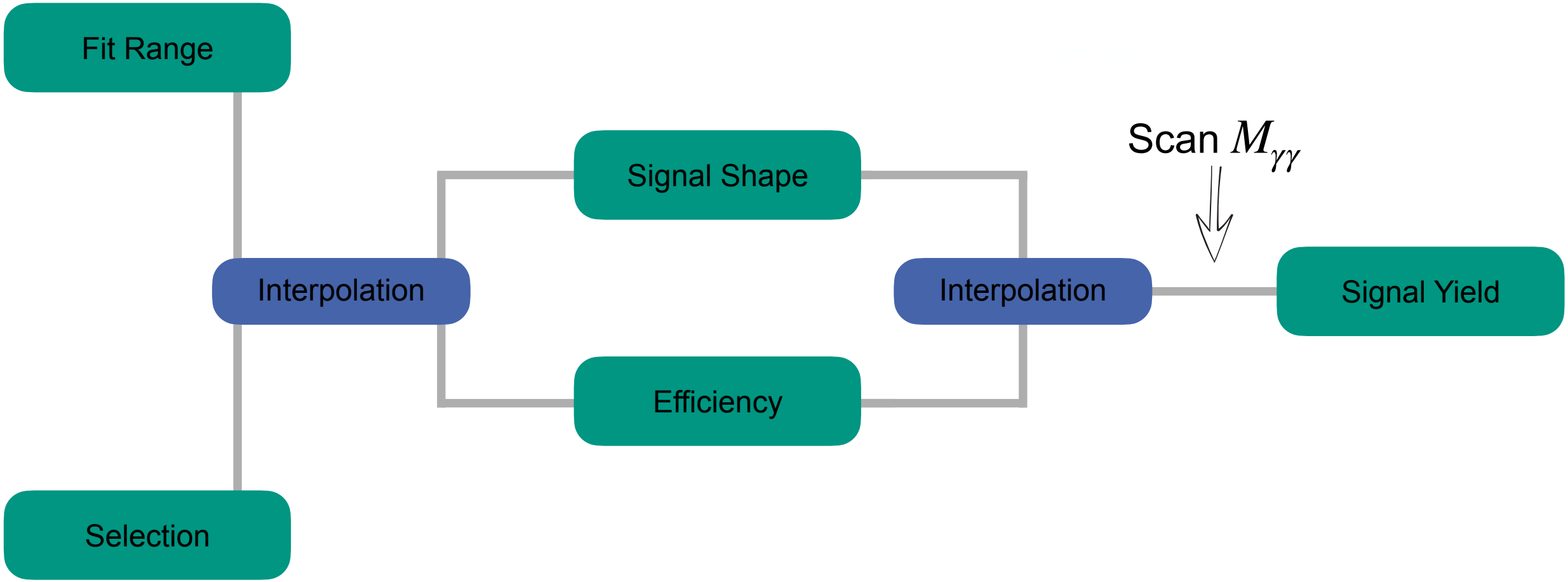
Optimisation Range

$$\frac{\epsilon}{\frac{5}{2} + \sqrt{N_{\mathrm{BKG}}}}$$

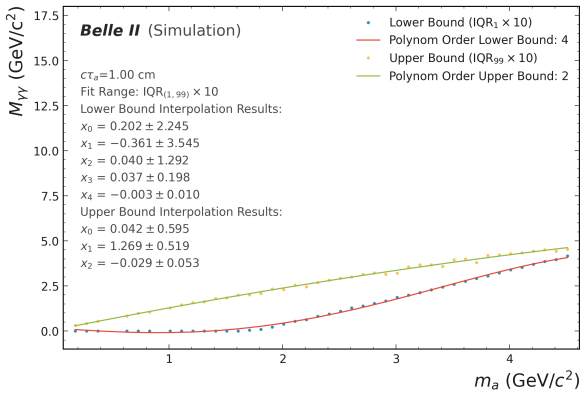


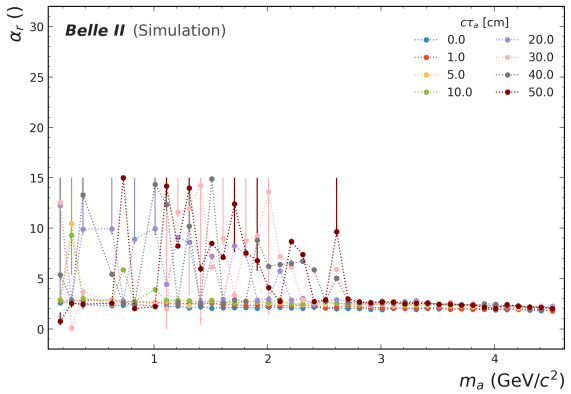
Punzi FOM Optimisation

Signal Extraction Strategy

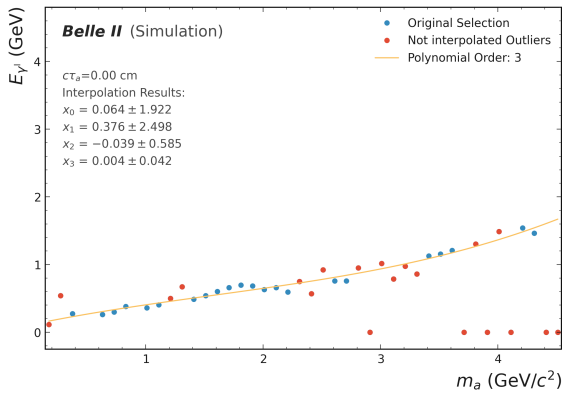


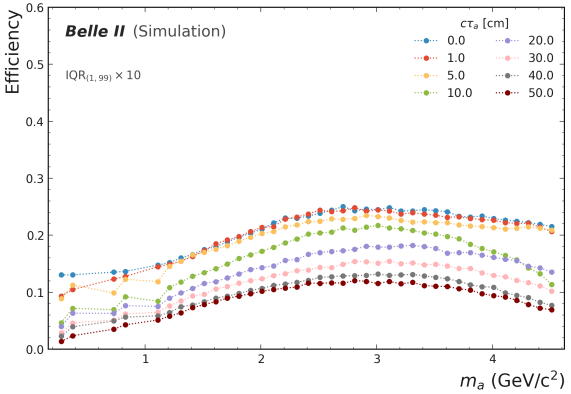
Signal Extraction Strategy





Interpolation





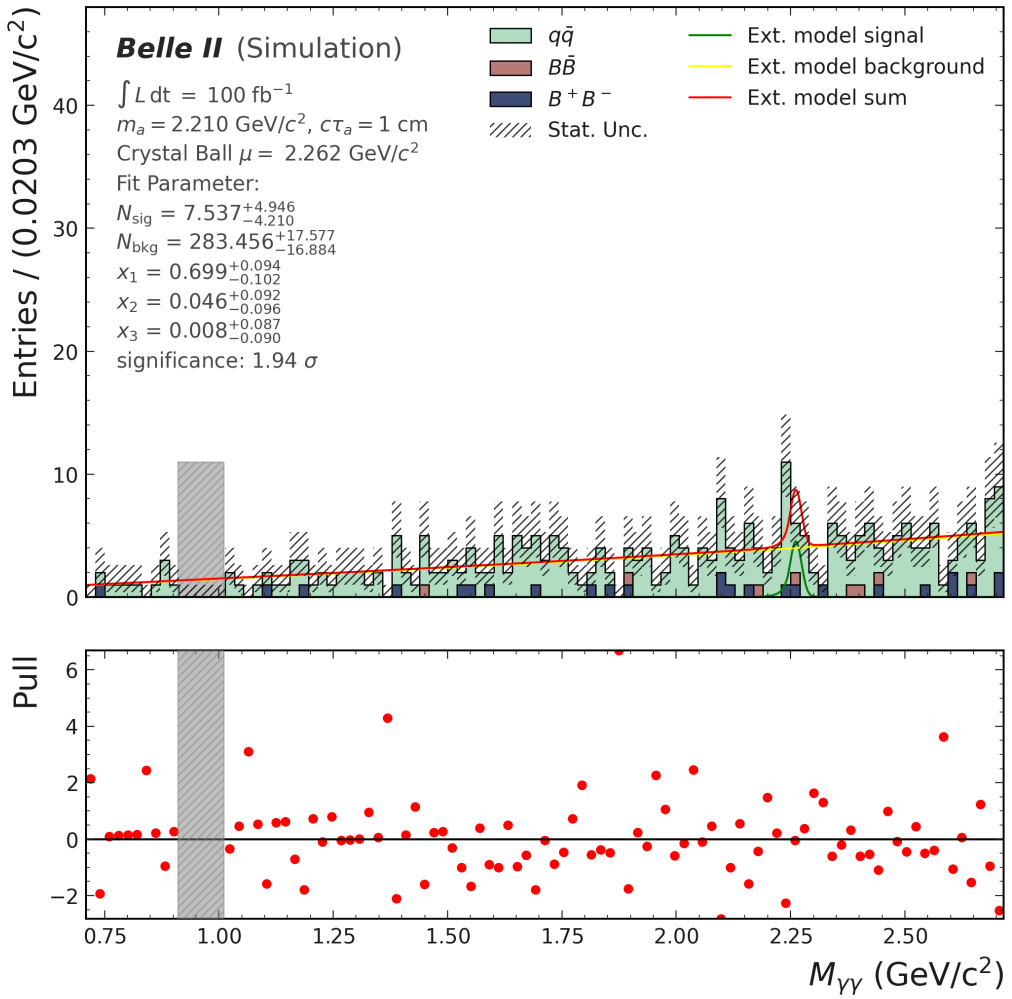
Interpolation

Scan $M_{\gamma\gamma}$

Signal Yield

Signal Extraction

- **Signal PDF**: Double-Sided Crystal Ball
  - n_r, n_l: fixed (empirical)
  - $\mu, \sigma, \alpha_r, \alpha_l$: fixed (interpolated)
- **Background PDF**: Chebyshev Polynomials
  - 3^{rd} order polynomials are stable
  - $x_{1,2,3}$: floating
- **Bump Hunt Scan**: $M_{\gamma\gamma} \in [0.175, 4.600]\ \mathrm{GeV}/c^2$
  - For each lifetime independently
  - Steps of $2.5\ \mathrm{MeV}/c^2$
  - Excluding η, η' resonances



Belle II Group,
ETP, Karlsruhe Institute of Technology

Sensitivity

- Branching Ratio:

$$\mathrm{Br}(B \to Ka) \times \mathrm{Br}(a \to \gamma\gamma) = \frac{N_{\mathrm{Sig}}}{2N_{B\bar{B}}\mathrm{Br}(\Upsilon(4S) \to B^+B^-)\epsilon_{\mathrm{Sig}}}$$

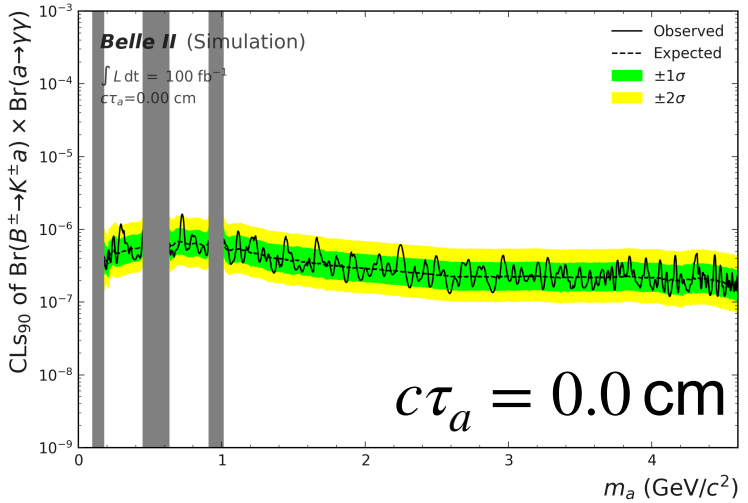
- Upper Limit Calculation:

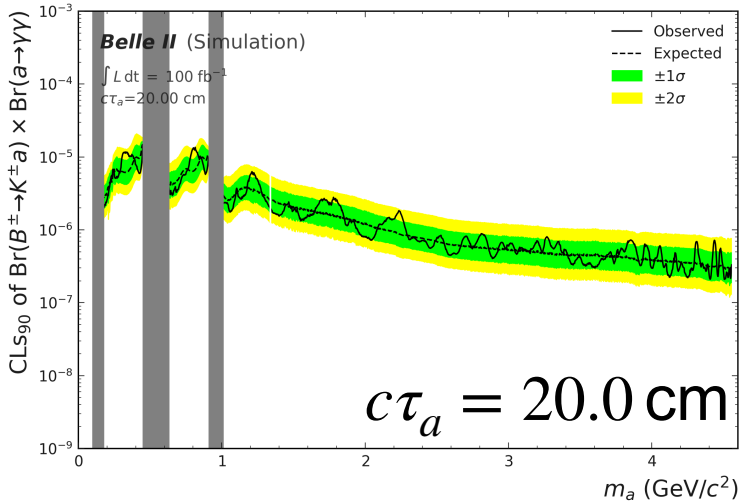
$$q_{N_{\mathrm{Sig}}} = \begin{cases} -2\ln\dfrac{\mathscr{L}(N_{\mathrm{Sig}}, \hat{\theta}')}{\mathscr{L}(N_{\mathrm{Sig}} = \hat{N}_{\mathrm{Sig}}, \hat{\theta})}, & \hat{N}_{\mathrm{Sig}} \leq N_{\mathrm{Sig}} \\ 0, & \hat{N}_{\mathrm{Sig}} > N_{\mathrm{Sig}} \end{cases}$$

  - Asymptotic Approximation (Cowan et al.):

$$1 - \mathrm{CL} = p_{N_{\mathrm{Sig}}} = 1 - \Phi\left(\sqrt{q_{N_{\mathrm{Sig}},A}}\right)$$

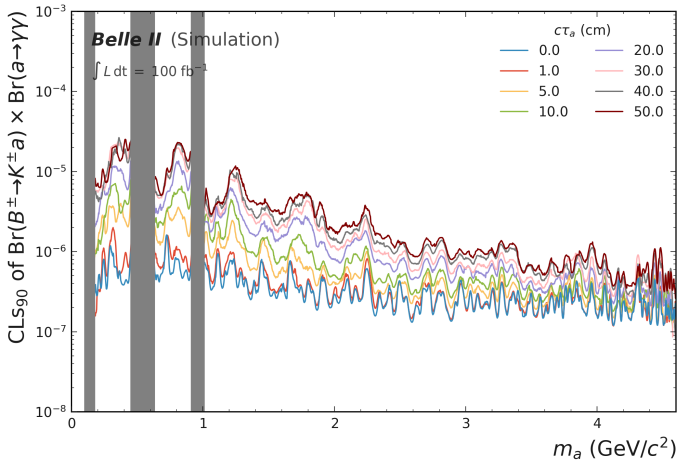
  - To-Do: Toy MC study to compare calculated limit

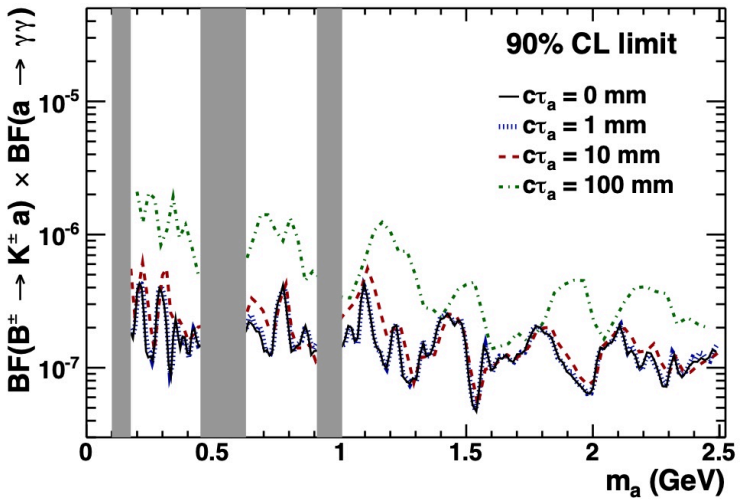


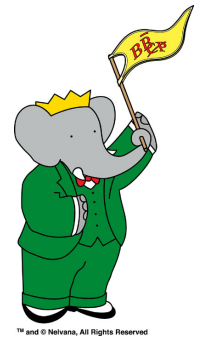


Sensitivity

- We can achieve a comparable (~2 less) sensitivity on $100\,\text{fb}^{-1}$ Belle II MC as compared to the published BaBar results for $424\,\text{fb}^{-1}$ data
- We extended the sensitivity to displaced ALP decays with a mass $m_a > 2.5\,\text{GeV}/c^2$
- We extended the search for ALP lifetimes up to $c\tau_a \leq 50\,\text{cm}$







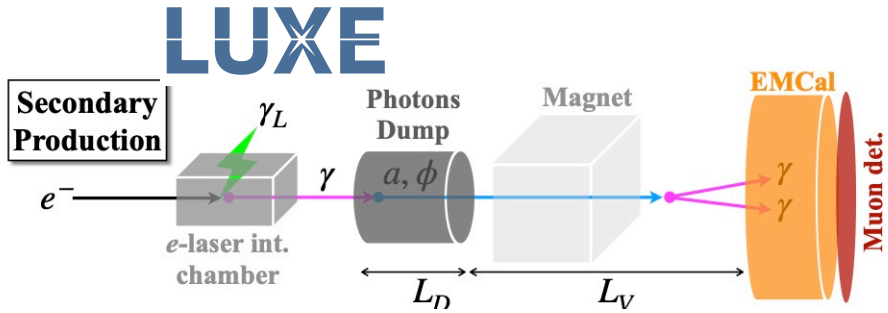
arxiv:2111.01800

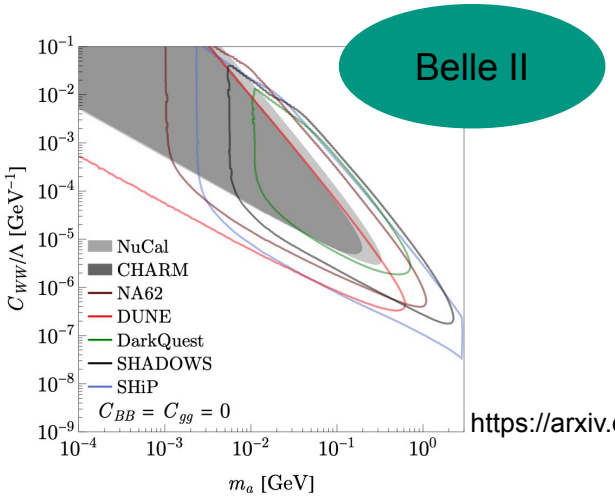
Outlook

- $B^{\pm} \to K^{\pm}(a \to \gamma\gamma)$ **at Belle II**
  - Produce more MC signal samples for small ALP masses
  - Perform a scan of $M_{\gamma\gamma}$ on Belle II MC samples corresponding to $500\,\text{fb}^{-1}$
  - Include leptonic background samples $e^+e^- \to l^+l^-$
  - Present search in Dark Sector Belle II meeting and ask permission to unblind on sideband data
  - Control channel study
  - Assess systematic uncertainties and consider the look-elsewhere effect
  - Possibly change cut-based candidate selection approach to ML based ansatz (pending BA thesis based on https://arxiv.org/abs/2110.00810)

Outlook

- **ALP searches at beam dump experiments**
  - General Goals:
    - Development of tracking calorimeter prototypes
    - ALP data analysis
  - LUXE-NPOD (https://arxiv.org/abs/2107.13554)
    - Optical dump at XFEL → large flux of hard photons
    - Sensitive to ALP to photon couplings
  - SHADOWS (https://arxiv.org/abs/2110.08025)
    - Proton beam dump experiment placed off-axis
    - Sensitive to $B^{\pm} \to K^{\pm}(a \to \gamma\gamma)$





https://arxiv.org/abs/2201.05170