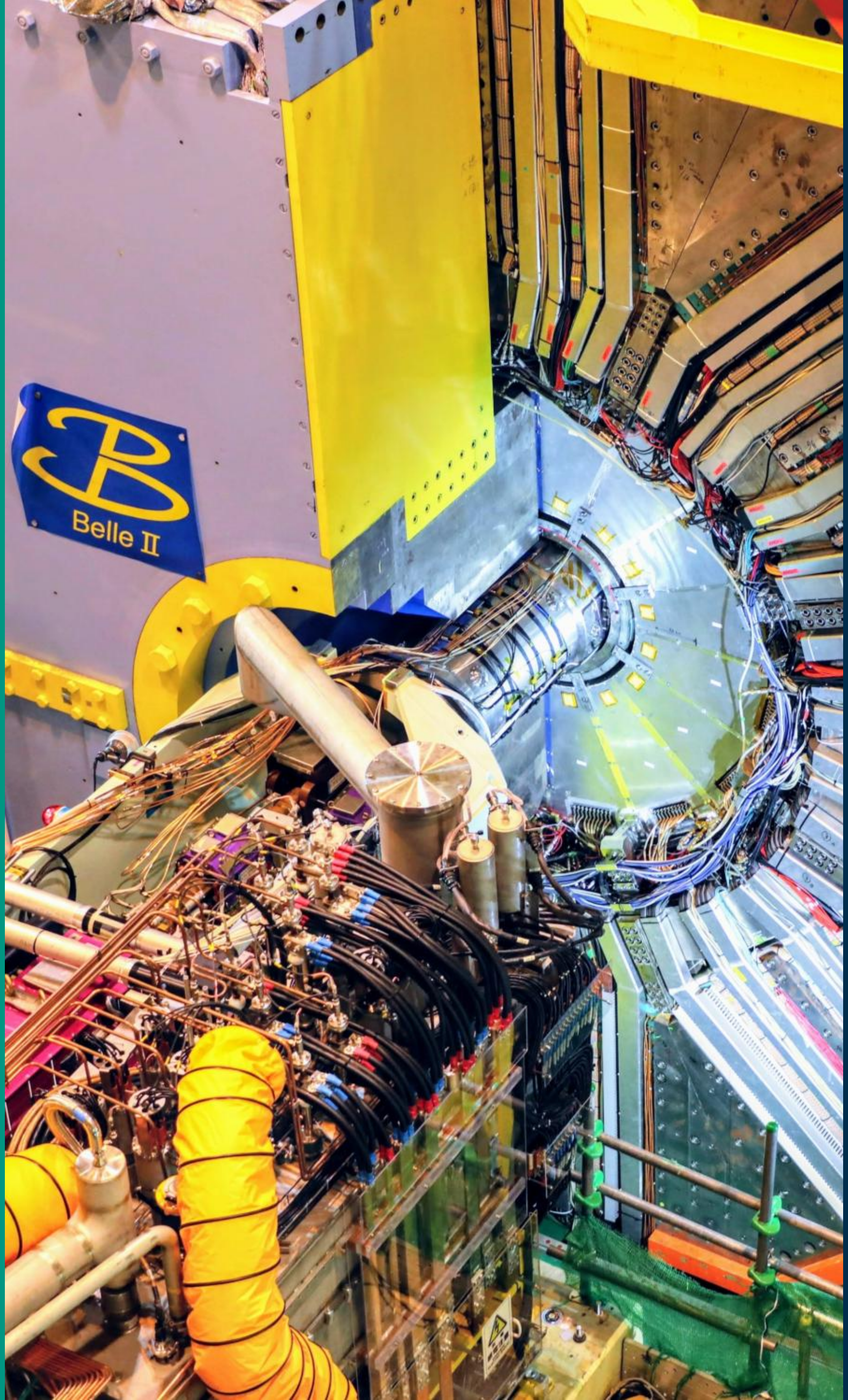
# Search for ALPs with gluon couplings in $B \to Ka(\to \pi^+\pi^-\pi^0)$




57th Herbstschule HEP

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Belle II

ETP Institute of Experimental Particle Physics

# Axion-Like Particles

**Strong CP Problem**: why is CP violation so small in strong interaction? ($\bar{\theta}$ ~$10^{-10}$)

$$\mathcal{L}_{\mathrm{QCD}} \supset -\frac{\alpha_s}{8\,\pi}\,\bar{\theta}\,\mathrm{G}\widetilde{\mathrm{G}}$$

Solution: **QCD Axion**

- Pseudo Nambu-Goldstone boson of spontaneously broken $\mathrm{U(1)_{PQ}}$ symmetry
- Potential has minimum at $a = \bar{\theta} f_a$
- Fixed relation between mass and decay constant: $m_a \sim m_\pi f_\pi / f_a$
  → parameter space highly constrained

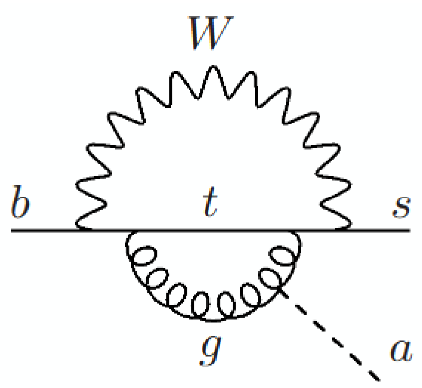
$$\mathcal{L} \supset \mathcal{L}_{\mathrm{QCD}} + \frac{\alpha_s}{8\,\pi}\,\frac{1}{\mathrm{f_a}}\,\mathrm{a}\,\mathrm{G}\widetilde{\mathrm{G}} - \frac{\mathrm{m_a^2}}{2}\,\mathrm{a}^2$$

**Axion-Like Particles (ALPs)**

- Pseudo NG boson of any spontaneously broken U(1) symmetry
- Mass and decay constant decoupled

possible **dark matter** candidate or **mediator to dark sector**

# Heavy QCD Axion



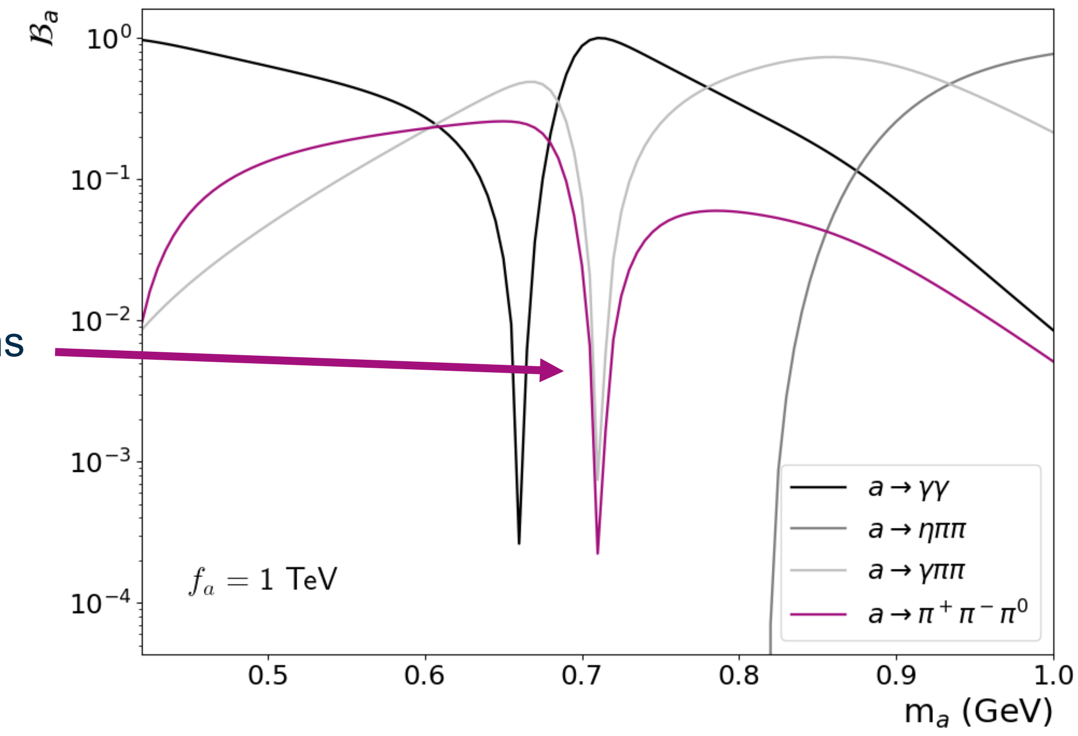

**QCD Axion:**

- Dominant axion-gluon coupling
  $\rightarrow$ accessible via hadronic production mode: $\boldsymbol{B^{\pm} \rightarrow K^{\pm}\, a}$

**„Heavy"**:

- Mass in GeV range
- $m_a$ and $f_a$ treated as independent parameters

$\rightarrow$ **0.42 ≤ $m_a$ ≤ 1.0 GeV/c²** : $a \rightarrow \pi^+\pi^-\pi^0$ one of leading contributions to total decay width



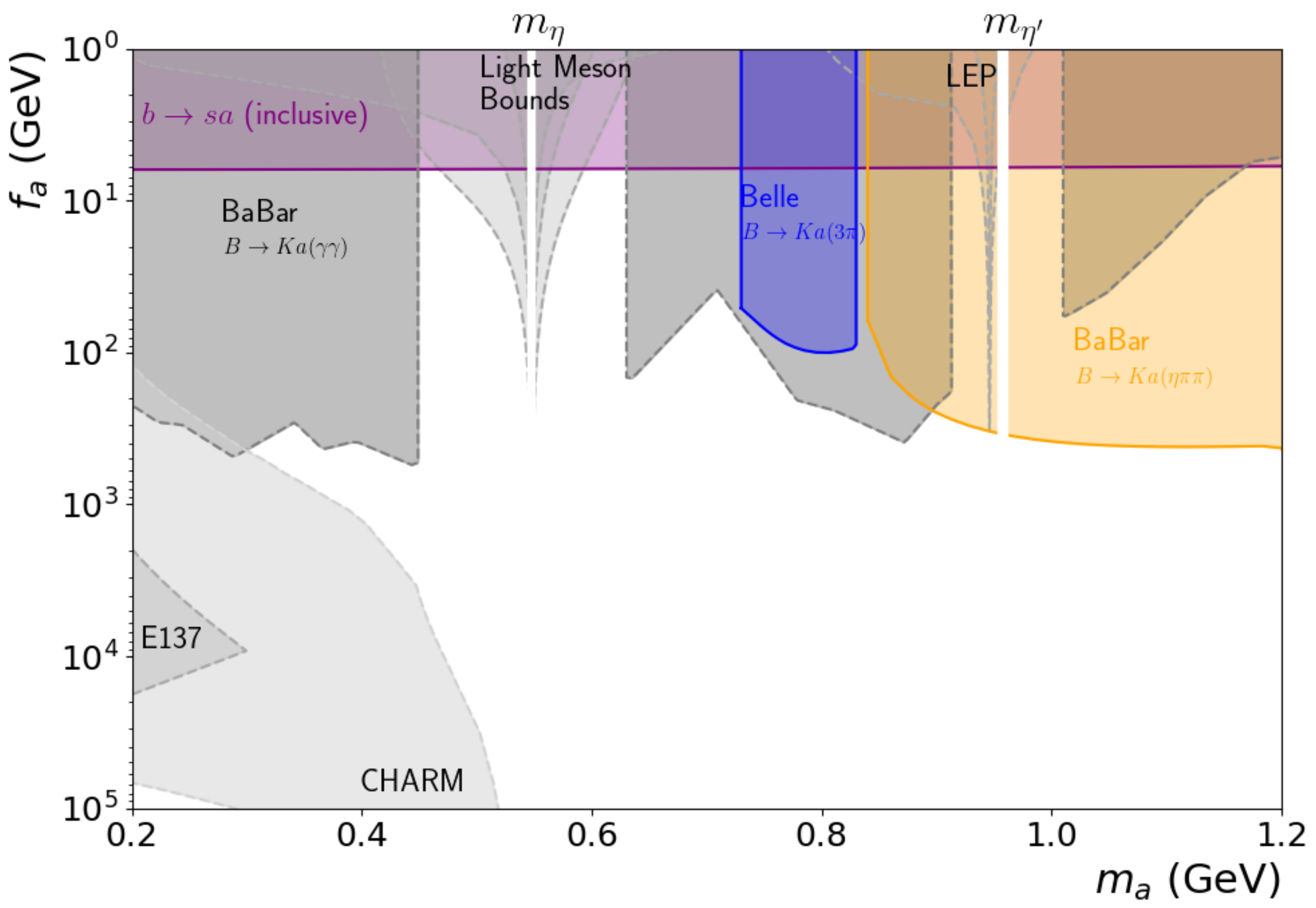
# Motivation

**Why $a \to \pi^+\pi^-\pi^0$ ?**

- Provides opportunity to extend ALP-gluon limits
- For $f_a \sim$ 1-10 TeV: ALP lifetimes up to 1000 cm
  $\rightarrow$ exploiting the displaced signature can increase limits even further

**Why Belle II?**

- Gluon coupling: hadronic production predominant
  $\rightarrow$ in our mass range:
  $B \to Ka$ **strongest probe to-date**



# Motivation

**Why $a \to \pi^+\pi^-\pi^0$ ?**

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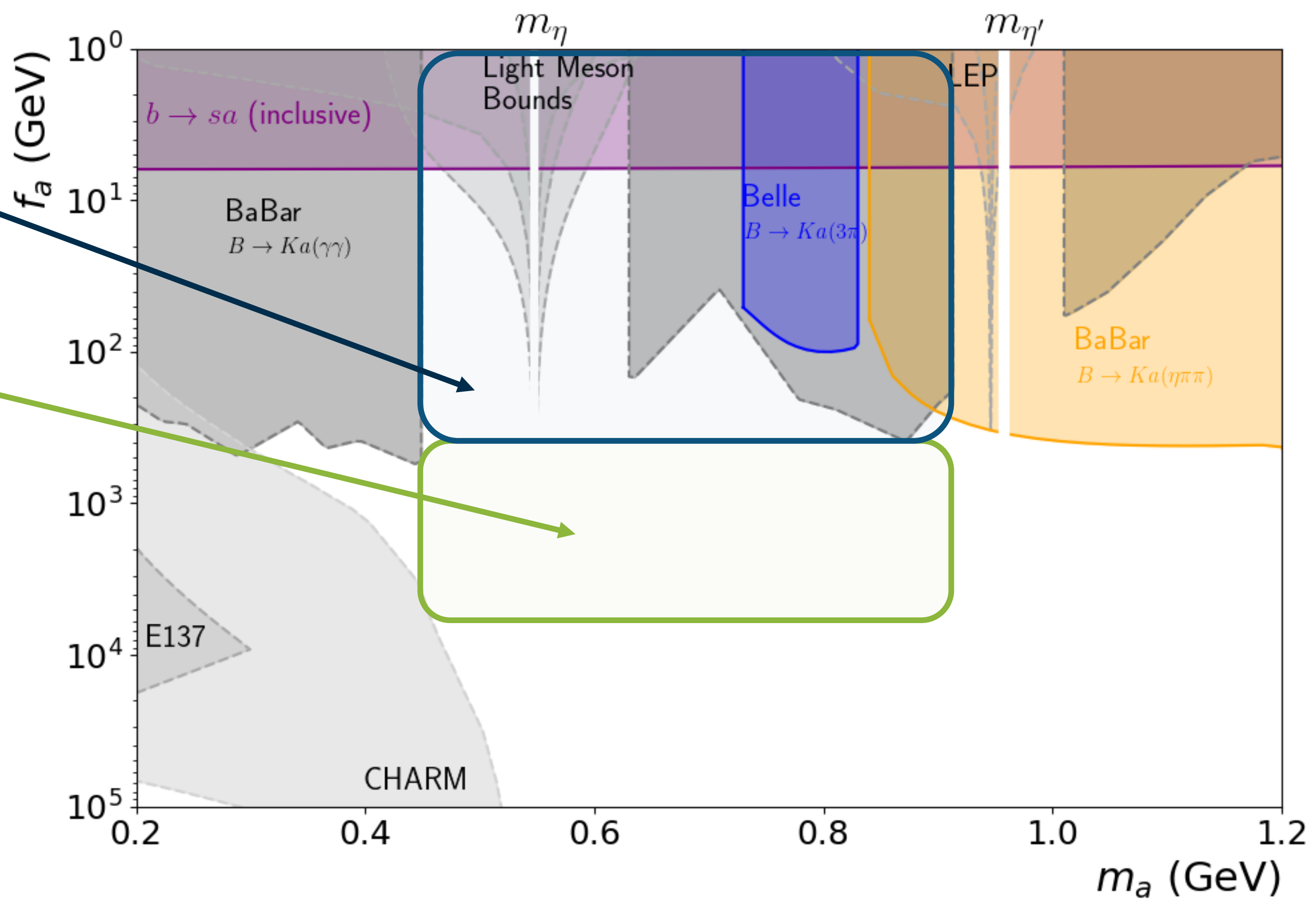
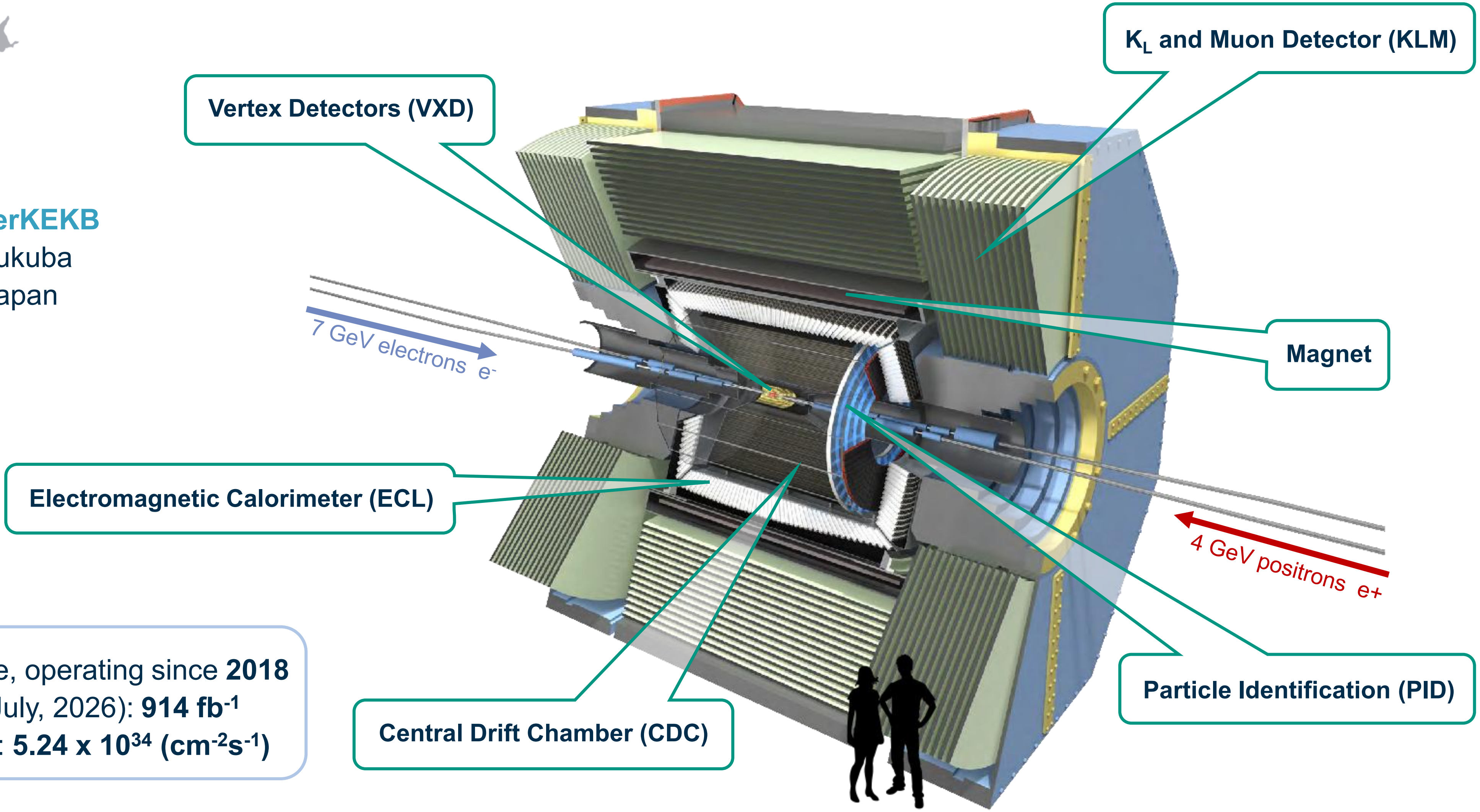


# Belle II


Upgrade of Belle, operating since **2018**
Int. luminosity (July, 2026): **914 $fb^{-1}$**
Peak luminosity: **5.24 x $10^{34}$ ($cm^{-2}s^{-1}$)**

# Analysis Strategy

**Event Generation** → **Reconstruction** → **Selection** → **Sensitivity Estimation** → **Upper Limit Extraction**

### Event Generation

- Generator: **EvtGen**
- **Minimally model-dependent:** generic phase space model
- **Signal:**
  ALP masses
  in [0.42, 1.0] GeV/c$^2$,
  lifetimes in [1e-5, 100] cm
- **Background:**
  $e^+e^- \to B\bar{B}, q\bar{q}, \tau^+\tau^-$

### Reconstruction

basf2

- Reconstruction of signal B meson:
  $\boldsymbol{B^\pm \to K^\pm\, a\, (\to \pi^+\pi^-\pi^0(\to \gamma\gamma))}$
- Decay **vertex fit** using the charged tracks

### Selection

- **MVA-based** selections

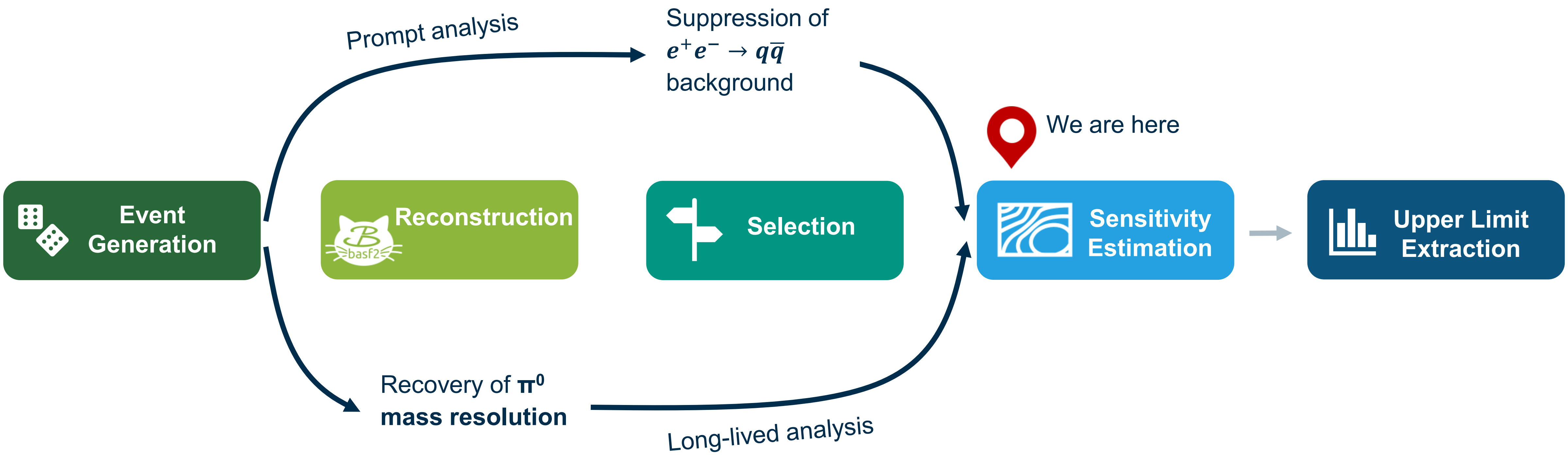
### Sensitivity Estimation

- Extraction of **signal efficiency** and background count
- Comparison with prediction from **theory model**

### Upper Limit Extraction

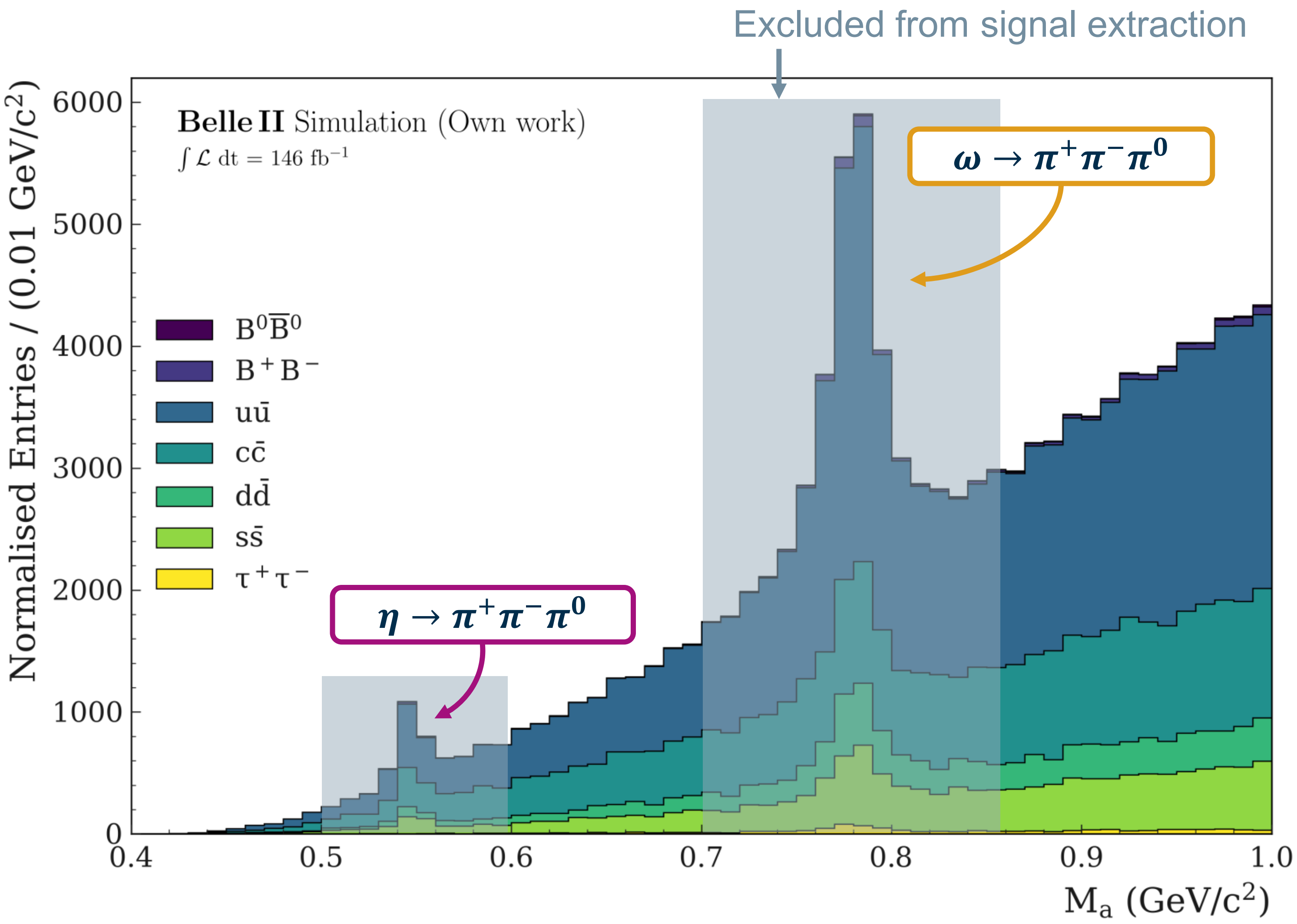
- Calculation of **upper limit** in case of no significant excess

# Analysis Challenges



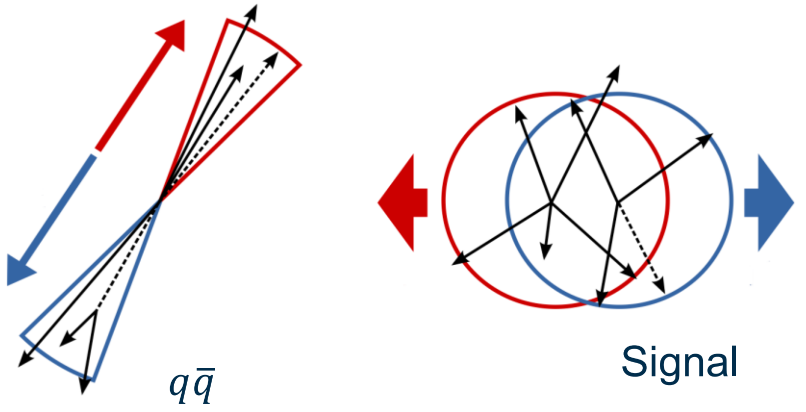
Prompt Analysis

# Background after Pre-Selection



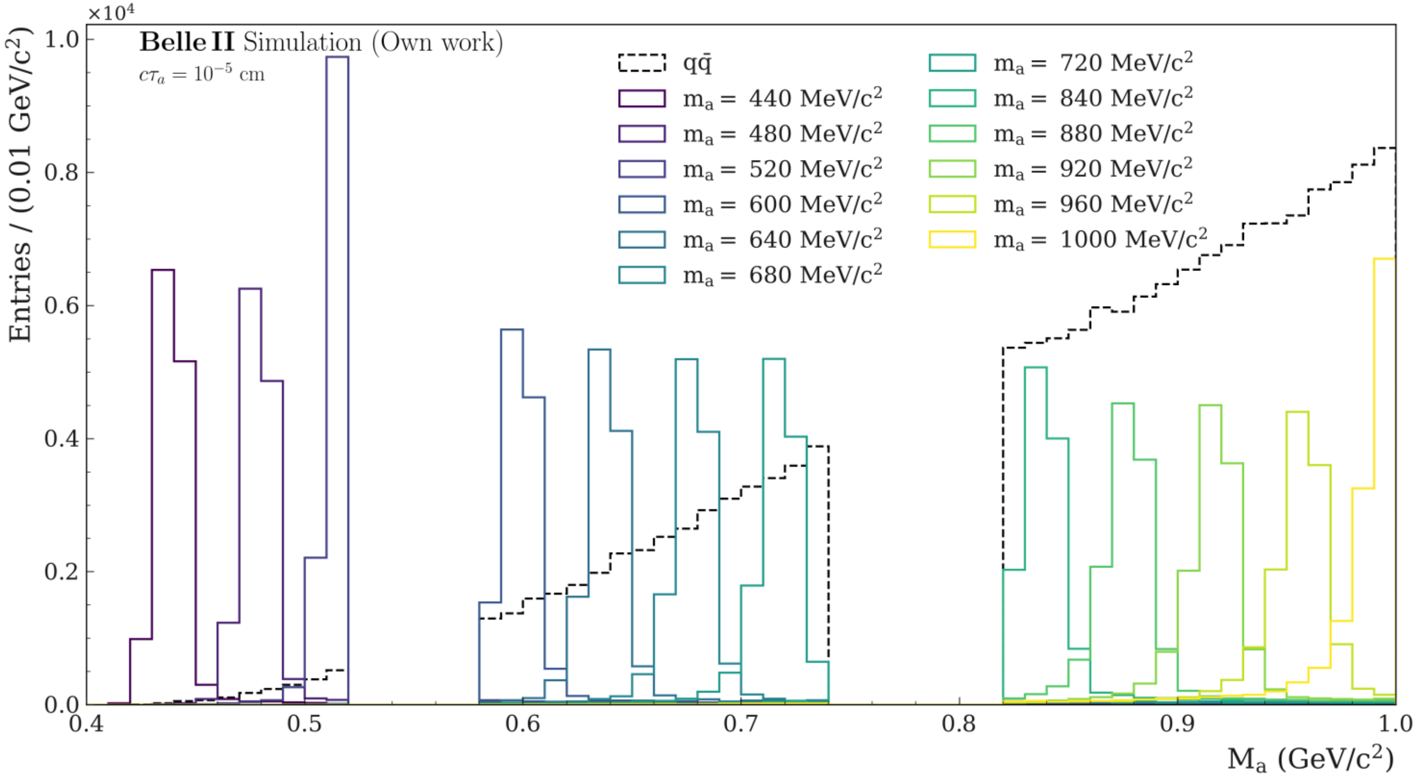
# Prompt Analysis
# BDT for Continuum Suppression

- Input features: variables decribing the different event topologies



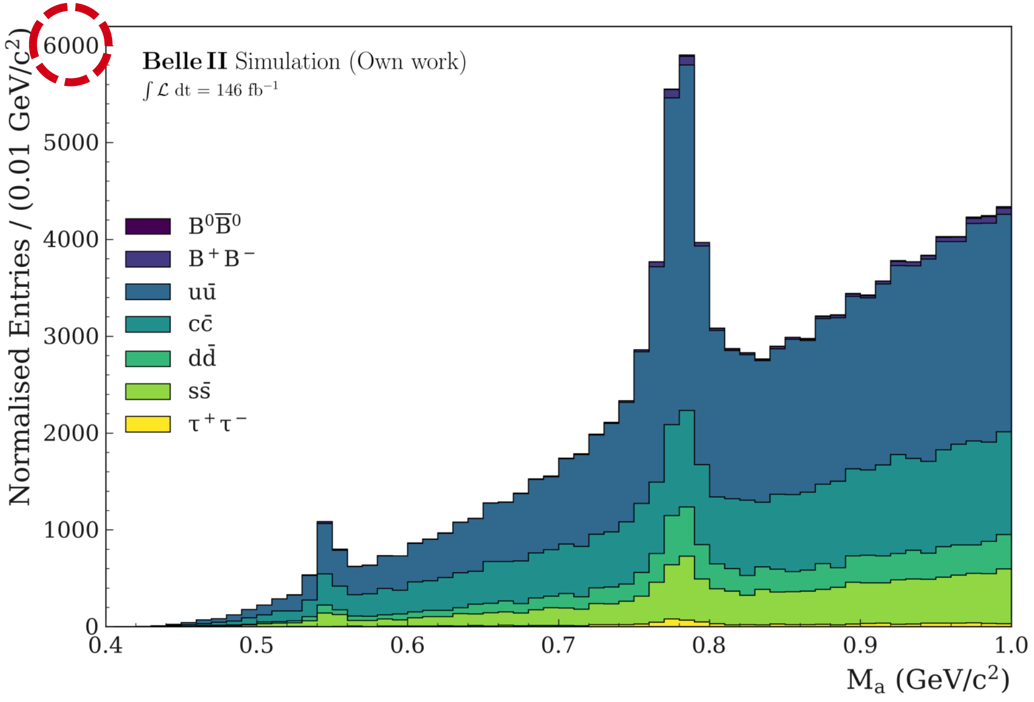

- Signal sample:
  - **one combined sample with 12 different ALP** masses and lifetime of $10^{-5}$ cm
  - same number of events per mass **after pre-selection**
- $q\bar{q}$ sample:
  - consists of simulated samples (332 / fb) **after pre-selection**

- **Mass range** restricted to $M_a$ < 1 GeV/c$^2$, excluding peaking regions

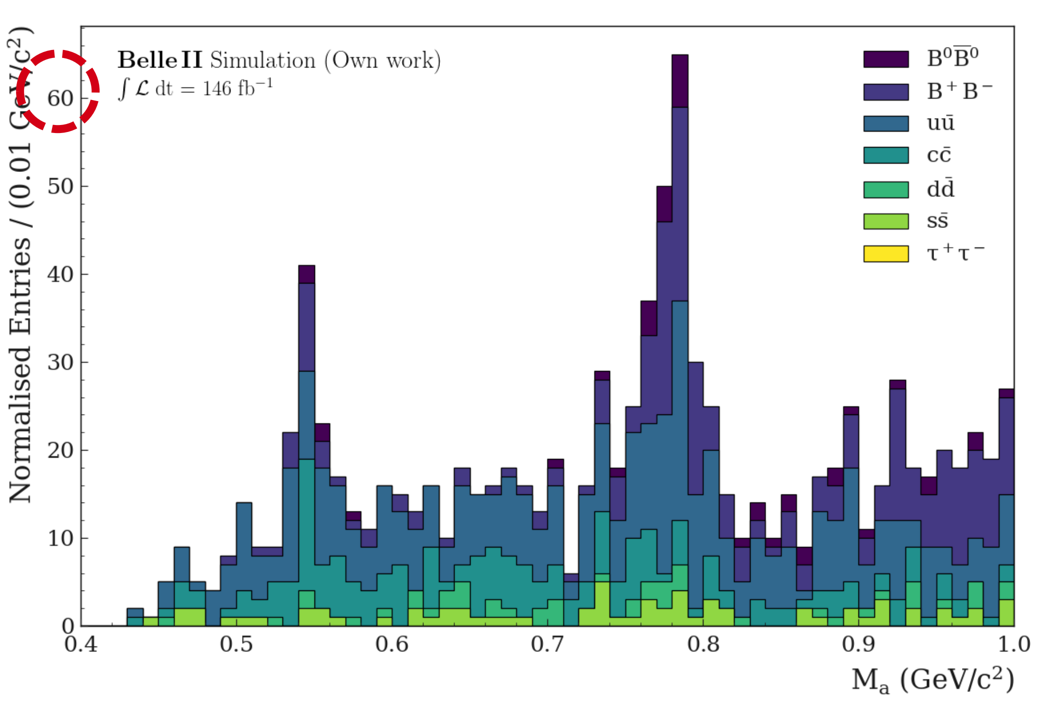


## Prompt Analysis
# BDT Output

- BDT output: ContinuumProbability
- Selection optimized for **each signal mass individually**
- **Below:** one example for signal with $m_a$ = 420 MeV/c$^2$




ContinuumProb.
< 0.04



## Prompt Analysis
# Minimally Model-dependent Sensitivity

= **Expected upper limit on** $\mathcal{B}(B^+ \to K^+ a) \cdot \mathcal{B}(a \to \pi^+\pi^-\pi^0)$

- Signal generation: generic phase-space model from EvtGen
- No assumptions about specific signal model

- **Signal extraction:** counting events in 95 % window of signal

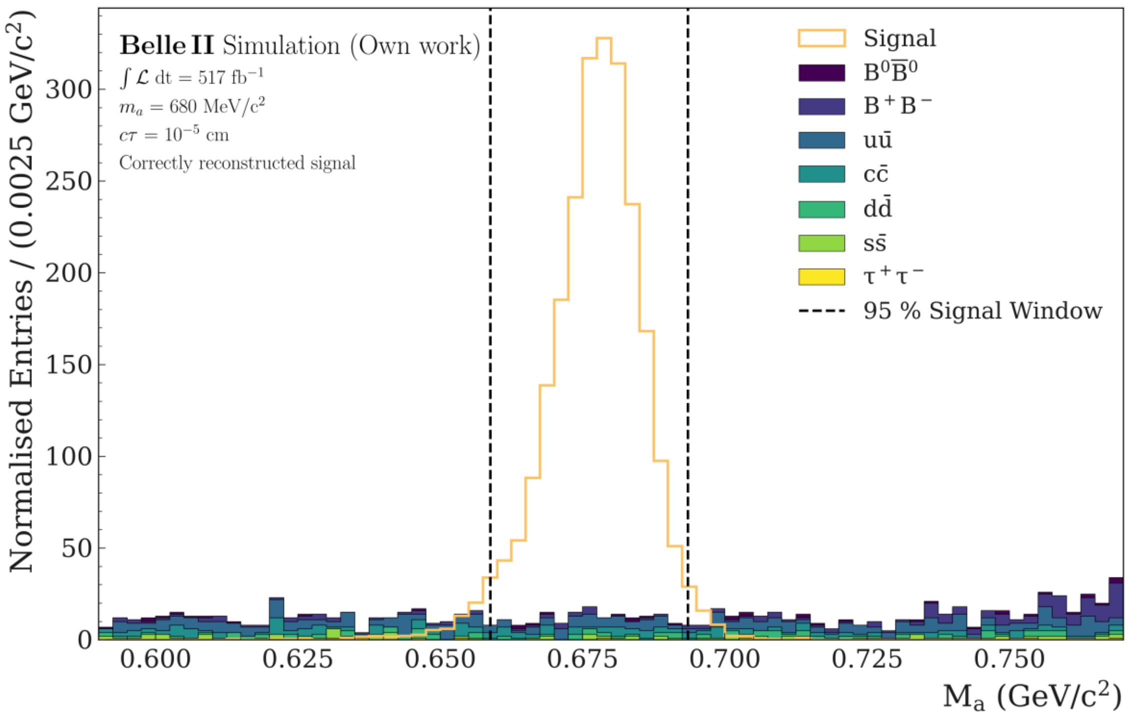
➡ **Signal efficiency:**

$$\varepsilon_S = \frac{\#\ events\ reconstructed}{\#\ events\ generated}$$

- **Tool**: Bayesian Analysis Toolkit (BAT)
  - Poisson model counting: $P_{Poisson}(N_{Obs}|N_S + N_{Bkg})$
    → consider case of **observing no signal events** $(N_{Obs} = N_{Bkg})$

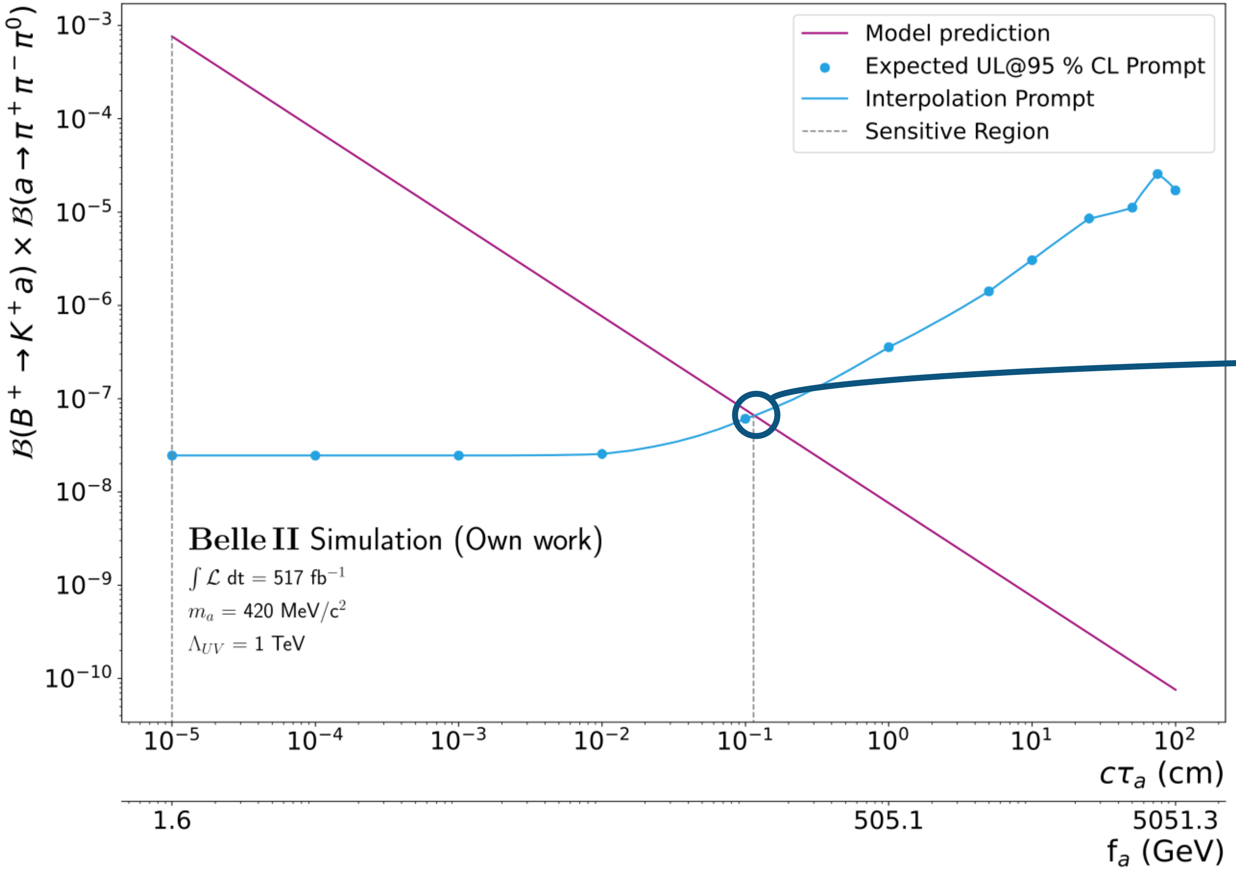
→ get UL on branching fraction with $\boldsymbol{N_S} = 2 \cdot \sigma_{B^+B^-} \cdot \mathcal{L} \cdot \varepsilon_S \cdot \mathcal{B}(B^+ \to K^+ a) \cdot \mathcal{B}(a \to \pi^+\pi^-\pi^0)$

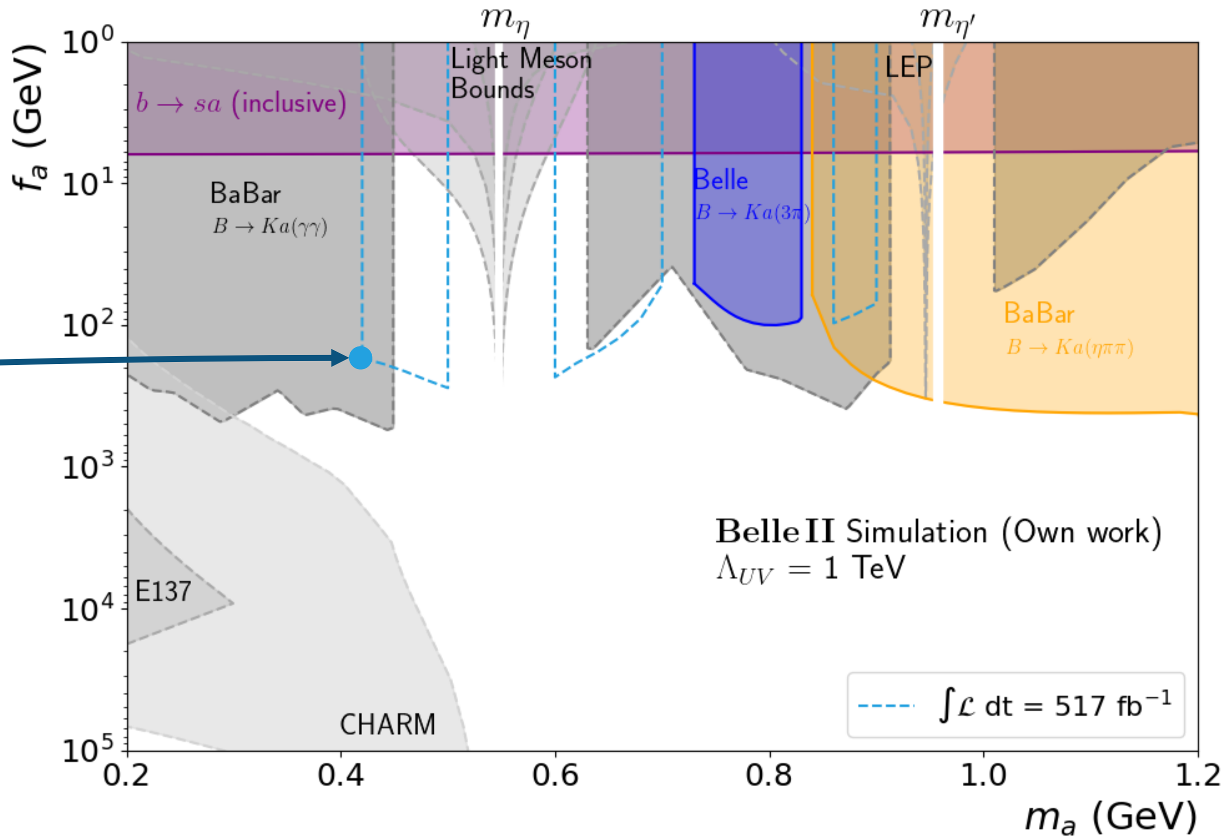
$\mathcal{L}$ = 517 / fb



## Prompt Analysis
# Model-dependent Sensitivity

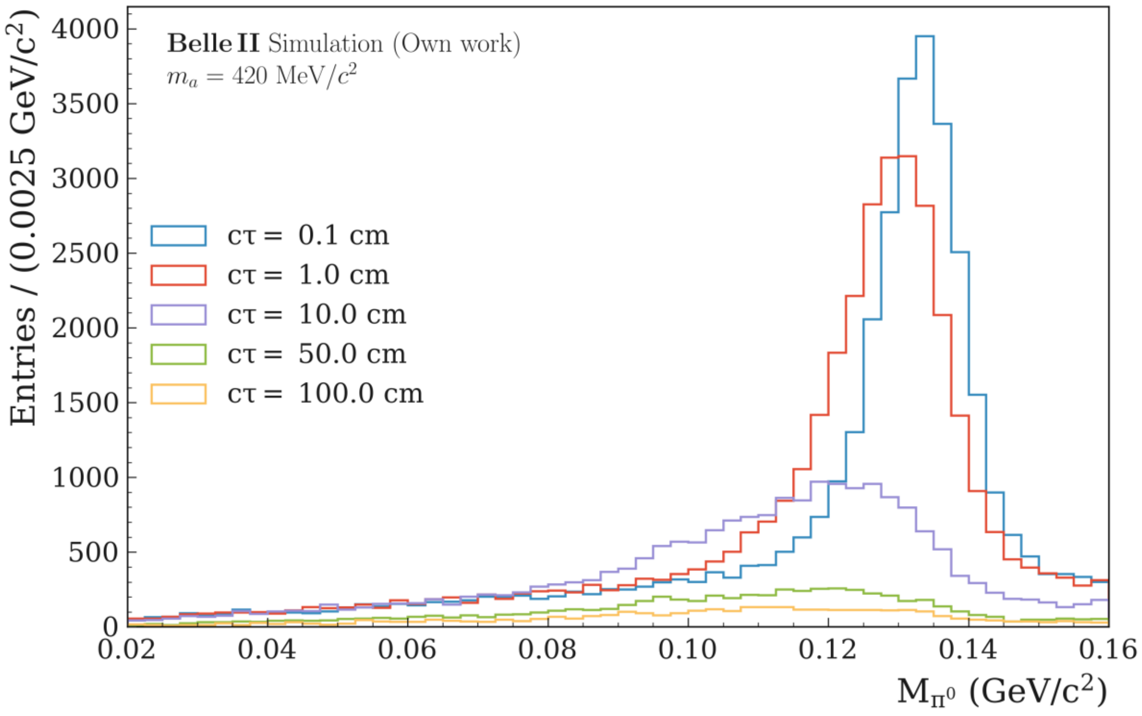
- Comparison with prediction from **theory model** for $\mathcal{B}(B^+ \to K^+a) \cdot \mathcal{B}(a \to \pi^+\pi^-\pi^0)$

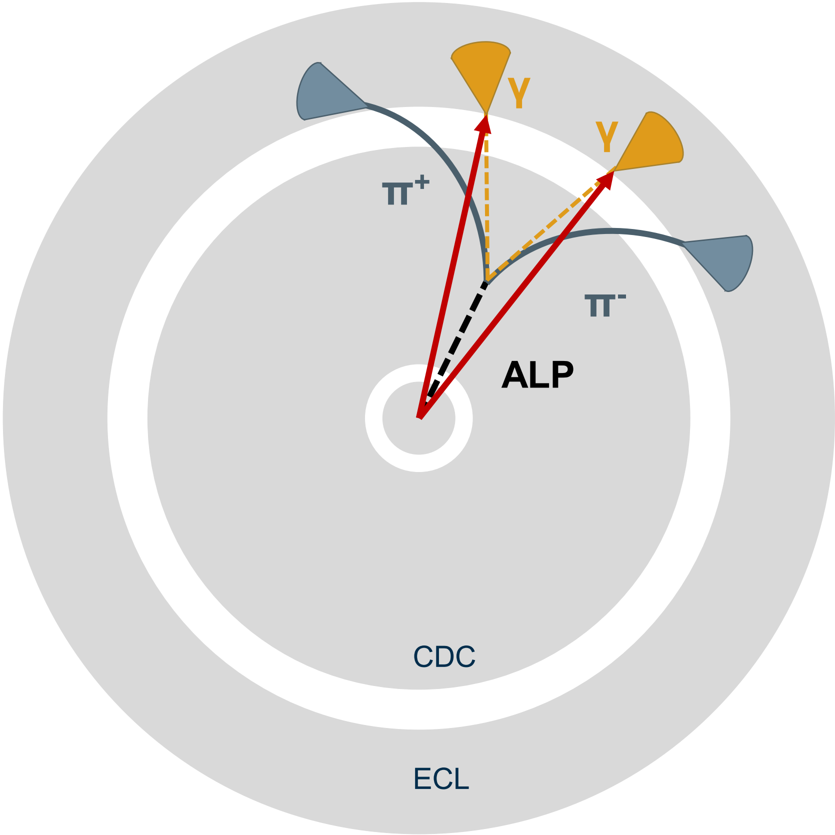


# Long-lived Analysis
# Degrading $\pi^0$ Resolution

**Challenge:** $\pi^0$ invariant mass resolution worsens with increasing ALP lifetime

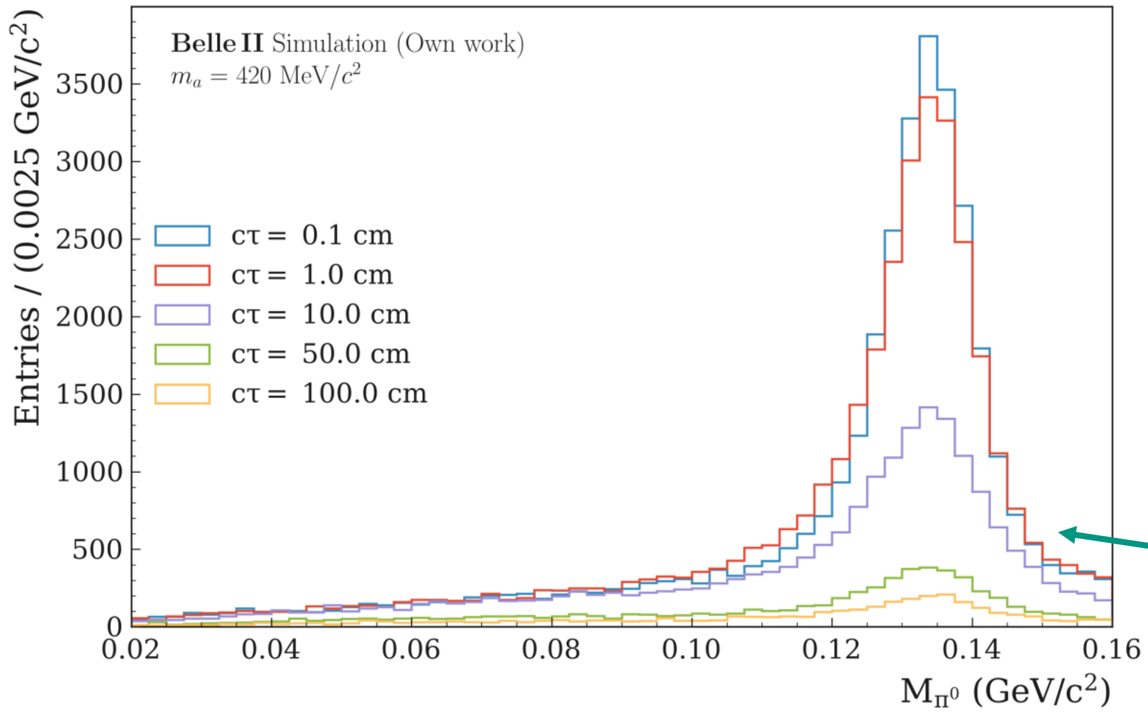


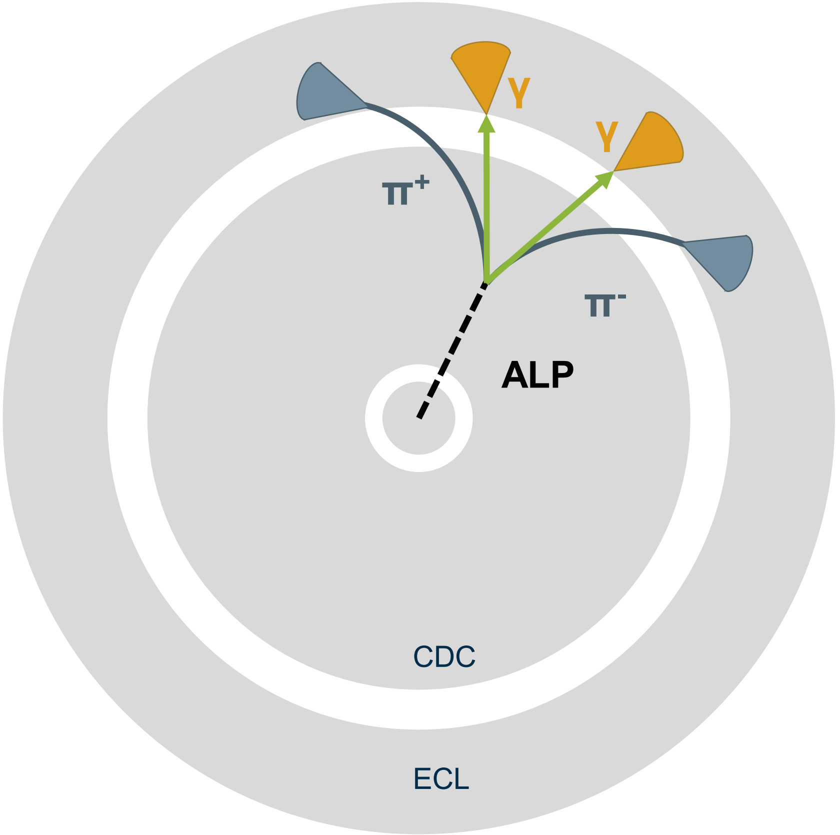



## Long-lived Analysis
# Degrading $\pi^0$ Resolution

**Challenge:** $\pi^0$ invariant mass resolution worsens with increasing ALP lifetime

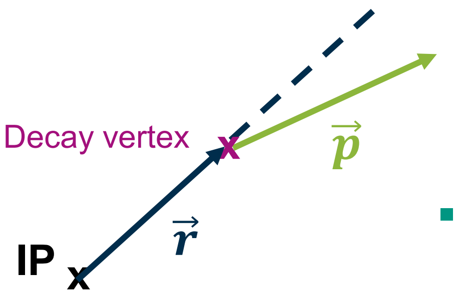
**Solution:** first calculate the ALP vertex, then update the $\pi^0$ kinematics



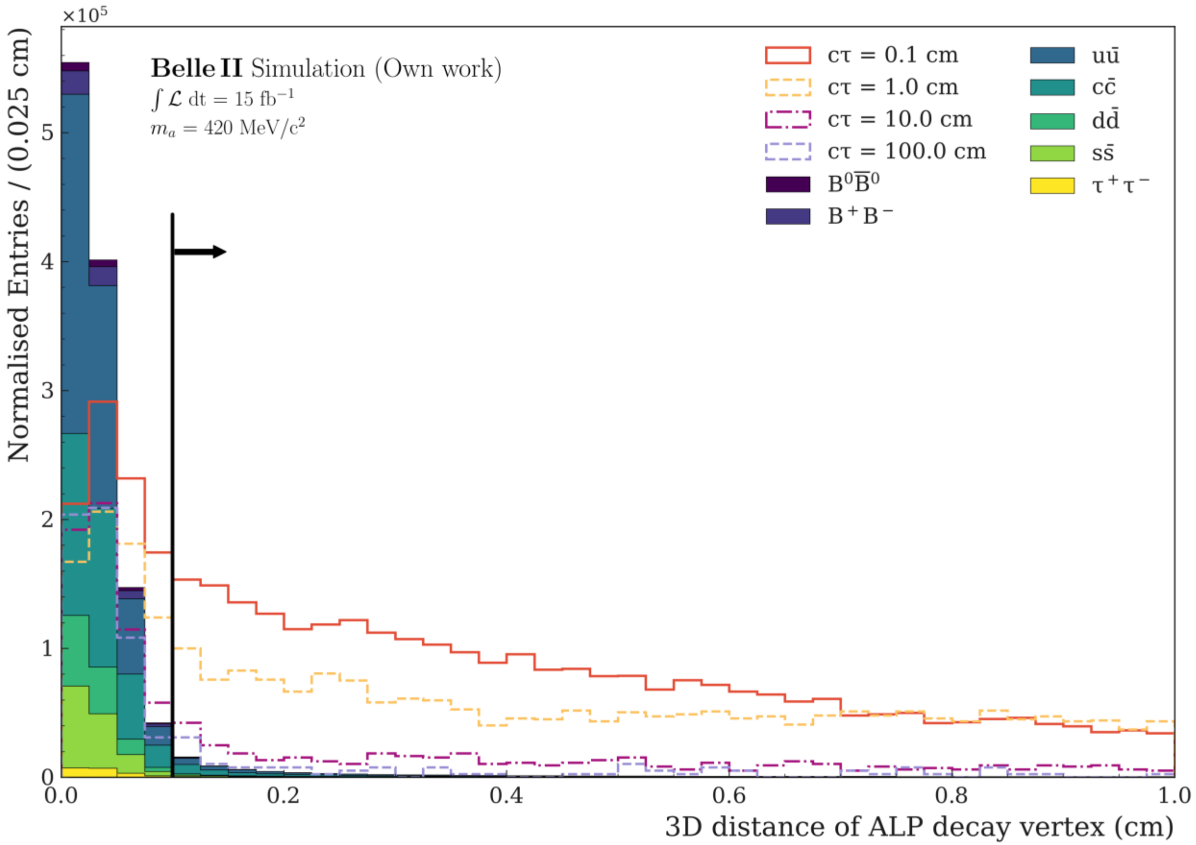



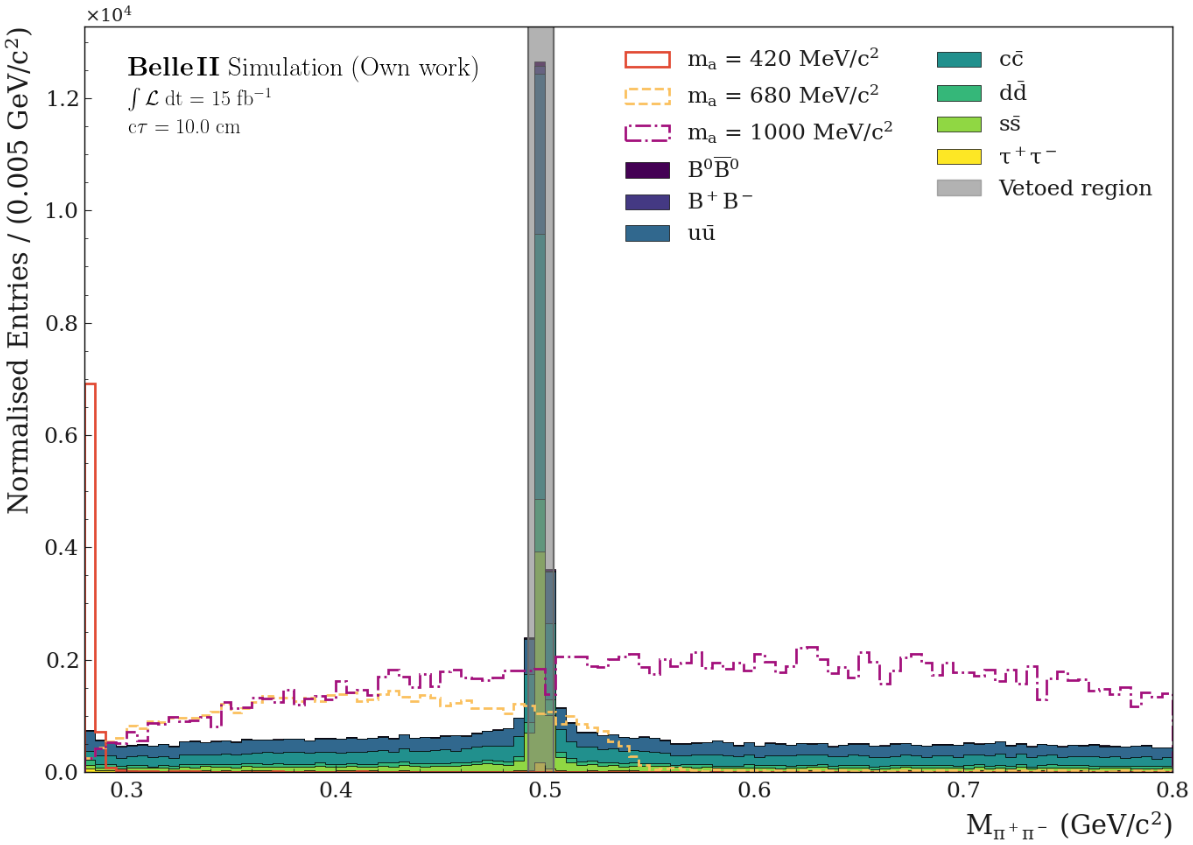

For longer ALP lifetimes:
More events decay outside detector acceptance
→ **signal efficiency decreases**

# Long-lived Analysis
# Selection Strategy



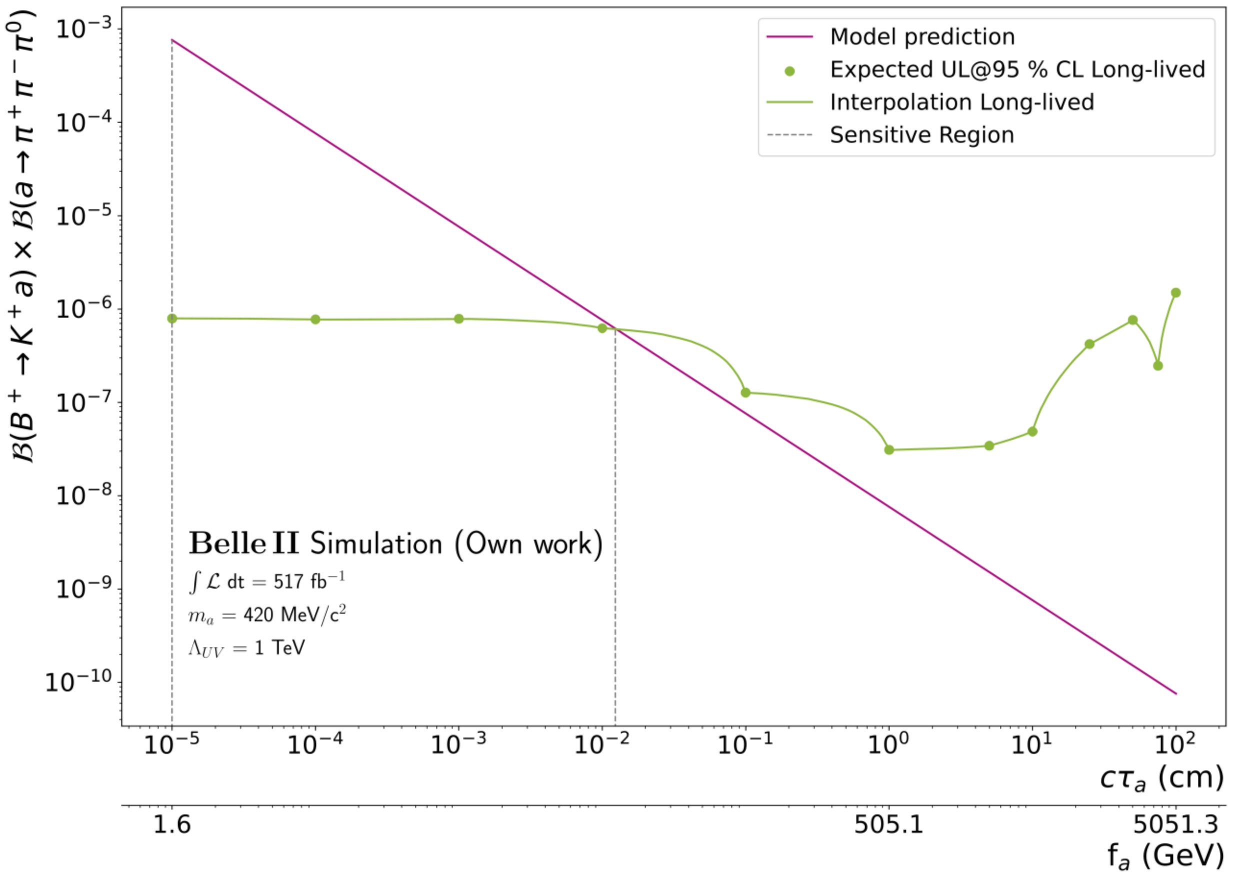

- Prompt SM background
  → Pointing Angle Selection
  → Displacement of ALP: 3D distance of decay vertex
- $K_S^0 \to \pi^+\pi^-$
  → veto 3$\sigma$ mass region of peak

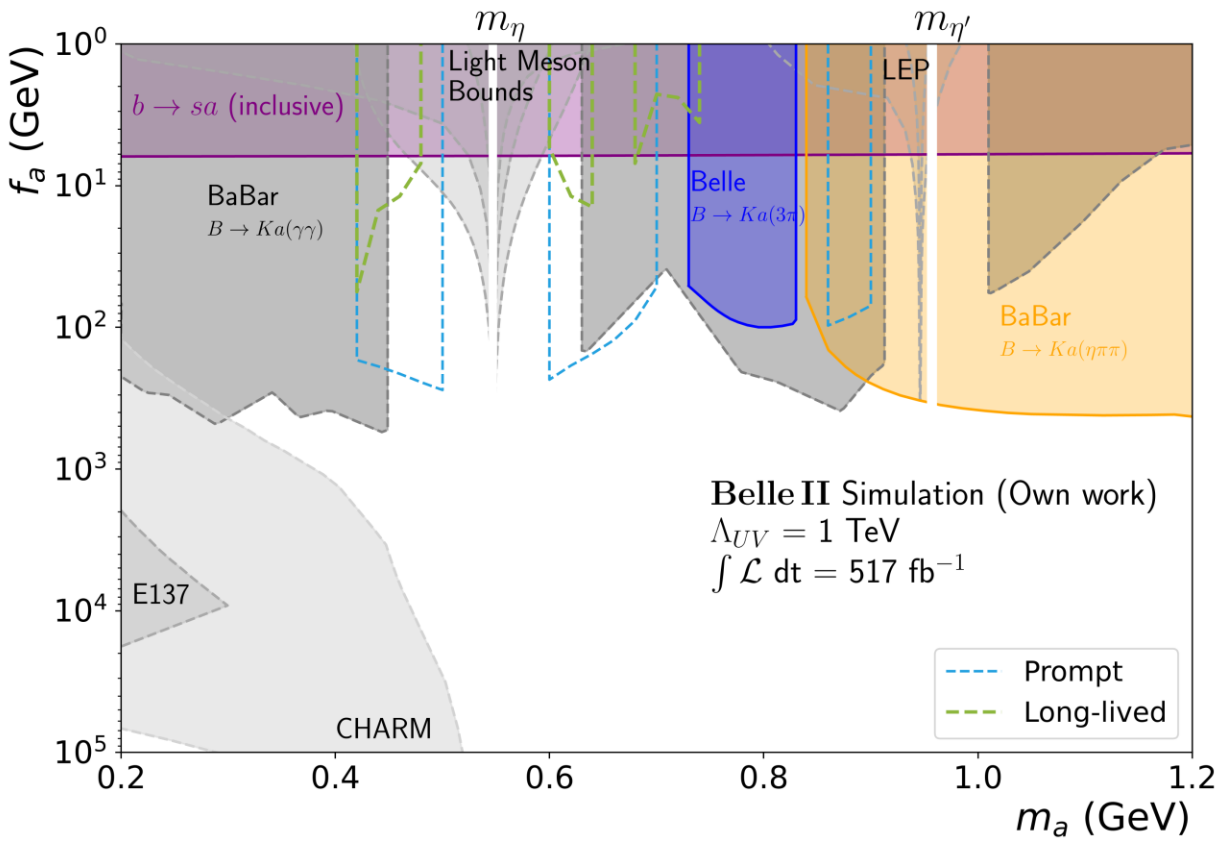


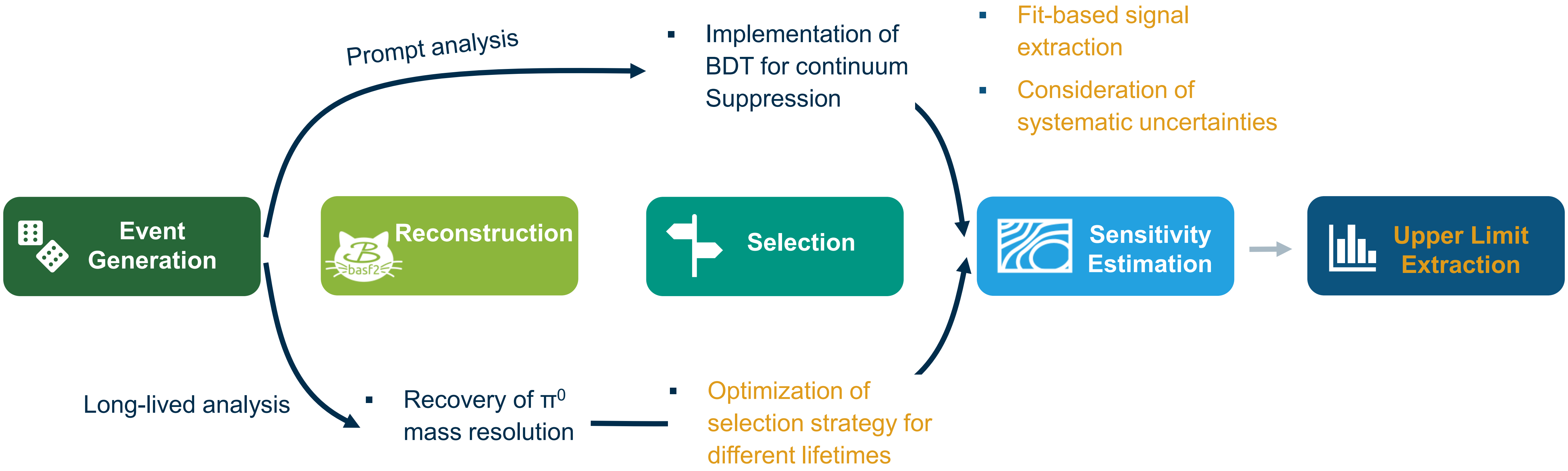
# Long-lived Analysis
# Model-dependent Sensitivity

- Extapolated to $\mathcal{L}$ = **517 / fb**



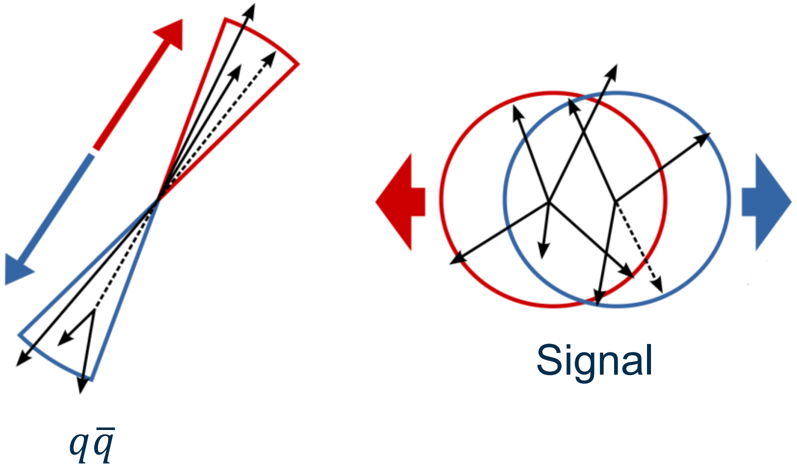
# Summary & Outlook for PhD



KIT

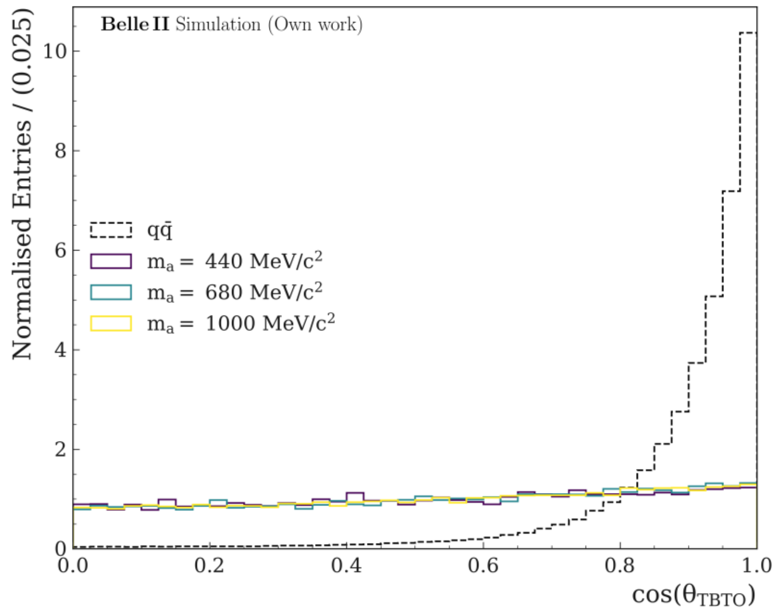
# Backup

# Prompt Analysis
# BDT for Continuum Suppression




- 32 **Input features** decribing the different event topologies:
  - $\cos\theta_{TBTO}$ **(1)**, $\cos\theta_{TBz}$
  - $R_2$
  - 18 KSFW moments
  - 9 Cleo cones
  - thrustBm **(2)**, thrustOm

**(1)**




**(2)**