Latest dark sector searches at the Belle Experiment

Seokhee Park

seokhee.park@kek.jp

KEK

on behalf of the Belle collaboration

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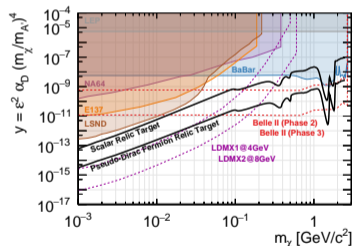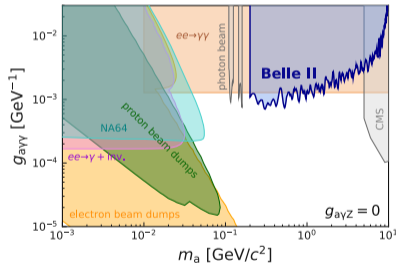
EPS-HEP 2021

Introduction

- **B-factories are also strong observatory of various dark sector candidates**
  - Precise $\sqrt{s}$, high luminosity, clean event signature
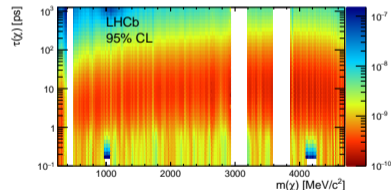- → **Various scenarios can be tested: visible, invisible, vertex displacement, colored**

Invisible dark photon search through ISR at BaBar with Belle II projection

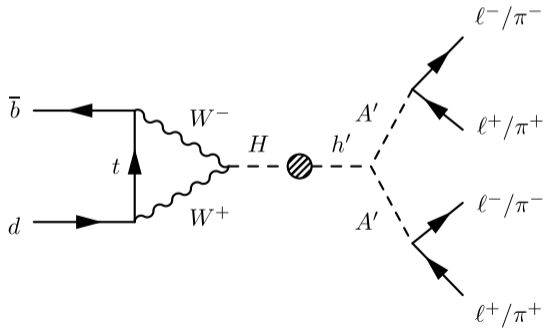Axion-like particle search with tri-photon at Belle II

$B \rightarrow K h'$ upper limits of branching fraction with displaced vertex at LHCb
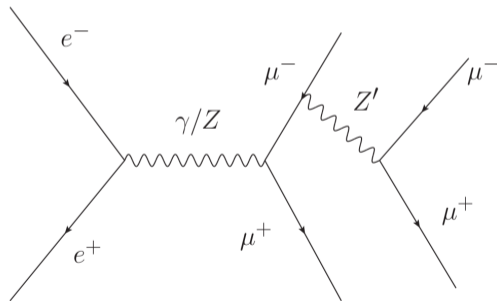
Introduction

- $B^0 \rightarrow A' A'$

  ▶ A': visible, prompt-decaying dark photon

  ▶ h': virtual dark Higgs coming from kinetic mixing with H, decaying into A' pair
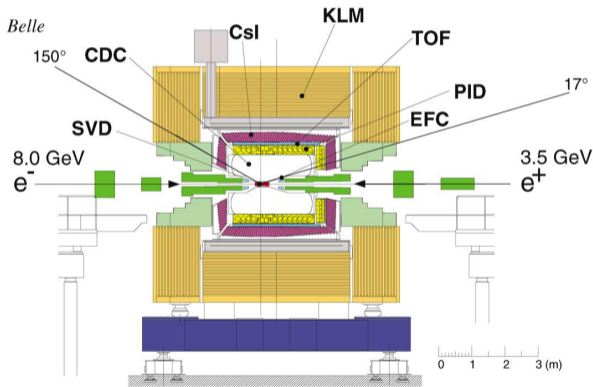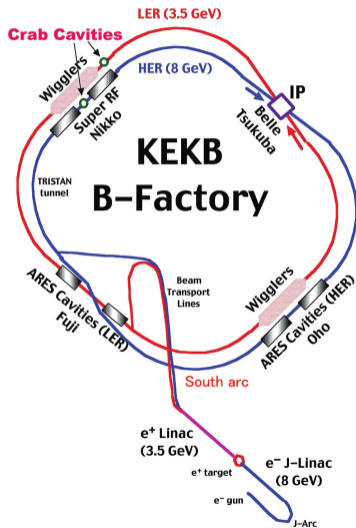
- $e^+ e^- \rightarrow \mu^+ \mu^- Z'_{L_\mu - L_\tau} \rightarrow 4\mu$

  ▶ Assume prompt decay

  ▶ Reconstruct $Z' \rightarrow \mu^+ \mu^-$ only

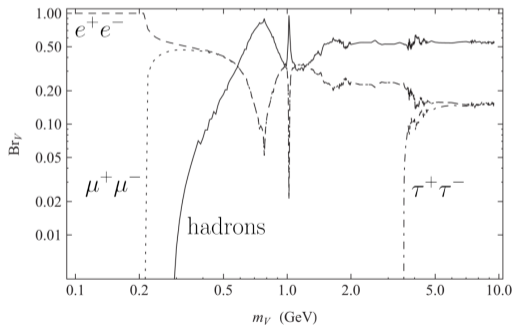- **1040 fb^{-1} of data was collected by Belle**
  - ▶ 711 fb^{-1} of $\Upsilon(4S) = 772 \times 10^6 B\bar{B}$

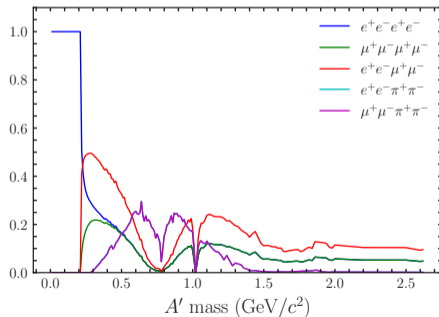- **In this analysis, short-lived and 100% visible dark photon is assumed.**
- **Target final states**
  - ▶ 5 decay modes ($4e$, $2e2\mu$, 4μ, $2e2\pi$, and $2\mu2\pi$) to combine $B^0 \rightarrow A'A'$
  - ▶ Kinematically allowed A' mass ($10 - 2620$ MeV) with $10 - 20$ MeV interval

Relative A' branching fraction [PRD **79**, 115008]

Relative B^0 branching fraction for each final state

$B^0 \to A'A'$: Background suppression

- **Possible SM resonances to be identified by A' are rejected**
  - ▶ $J/\psi, \psi(2S) \to \ell^+\ell^-$
  - ▶ $D^0 \to \pi^+\pi^-$, including $K^-\pi^+$ with misidentified $K^\pm$
  - ▶ Light mesons (K_s, ρ^0, ϕ, etc.)
- **$e^+e^- \to q\overline{q}$ suppression using 16 event shape variables**
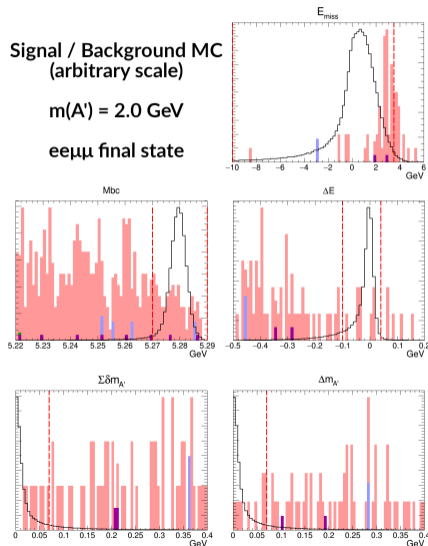 - ▶ Including B^0 cand. momentum direction, angle between trhust axis of B^0 cand. and other particles, and (modified) Fox-Wolfram moments
  - ▶ Only applied for $\ell^+\ell^-\pi^+\pi^-$ final states
  - ▶ Fisher discriminant training is performed by TMVA
- **Small amount of combinatorial backgrounds**
  - ▶ Leptons are mostly from semi-leptonic decay of quarks
 - → missing energy from neutrinos

$B^0 \to A'A'$: Event reconstruction

- **Require at least 4 charged tracks, including at least one e^+e^- or $\mu^+\mu^-$ pair**
  - Each track should appear near the intraction point with good track fitting

- **After combining A' and B^0, five variables are used to judge the quality of B^0**
  - M_{bc}: beam-constrained mass
  - ΔE: energy difference b/w beam and B cand.
  - Missing energy of an event
  - $\Delta M_{A'}$: $|M_{A'_1} - M_{A'_2}|$
  - $\Sigma\delta M_{A'}$: $|M_{A'_1} - m_{A'}| + |M_{A'_2} - m_{A'}|$
    - $M_{A'_{1,2}}$: reconstructed $A'_{1,2}$ mass
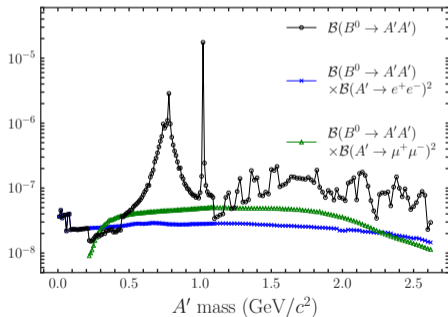   - $m_{A'}$: target A' mass

Signal / Background MC (arbitrary scale)

m(A') = 2.0 GeV

eeμμ final state

E_{miss}

Mbc

ΔE

Σδm$_{A'}$

Δm$_{A'}$

$B^0 \to A'A'$: Results

- **No significant access to the signal → upper limits are obtained**
- **Calculate upper limits using Feldman-Cousins unified approach (clean background)**
  - Mostly $\mathcal{O}(10^{-8} - 10^{-7})$ of U.L.
  - Near the light meson rejection region, up to $\mathcal{O}(10^{-5})$
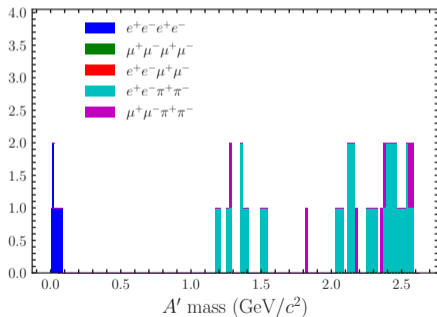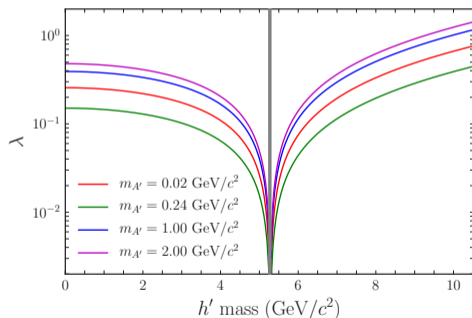

Observed events in Belle data
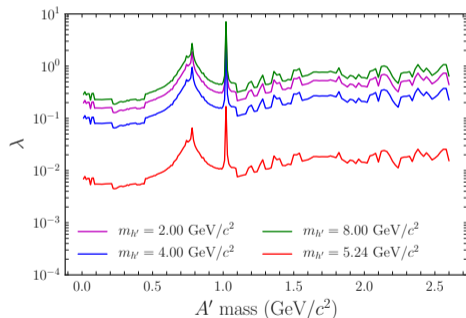

90% C.L. upper limits of branching fraction

$B^0 \rightarrow A'A'$: Results

- **Higgs portal coupling λ is derived by the following equation:** [PRD 83 054005]

$$\mathcal{B}(B^0 \rightarrow A'A') \simeq 7 \times 10^{-7} \times \lambda^2 \times V_{A'A'}^{1/2} \times \frac{V_{A'A'} + 12 m_{A'}^4 / m_{B^0}^4}{(1 - m_{h'}^2 / m_{B^0}^2)^2}, \quad V_{A'A'} = 1 - 4 m_{A'}^2 / m_{B^0}^2 \qquad (1)$$

90% C.L. limits of λ versus h' mass for various A' mass

90% C.L. limits of λ versus A' mass for various h' mass

- $Z'_{L_\mu - L_\tau}$ **can be** [PRD 89 113004]
  - a source of muon $g - 2$ anomaly
  - an accessing channel for sterile neutrinos (dark matter candidate)

- **The target final state is** $Z' \to \mu^+\mu^-$ **within kinematically allowed mass range**
  - The branching ratio of $Z' \sim 0.5$ and $Z' \sim 0.33$ for each below and above $\tau^+\tau^-$ threshold
  - Full Belle dataset ($\sim 1\ \mathrm{ab}^{-1}$) is used

- Z' **coupling was obtained by BaBar** [PRD 94 011102]
  - Belle also try to give a same g' result
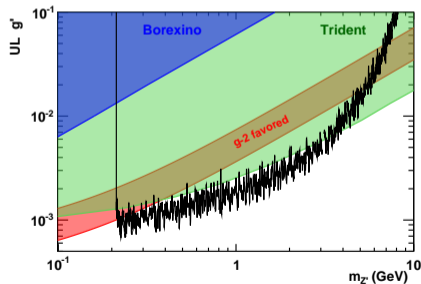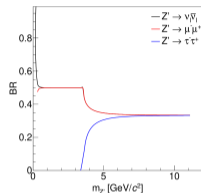
90% C.L. limit of coupling g' from BaBar

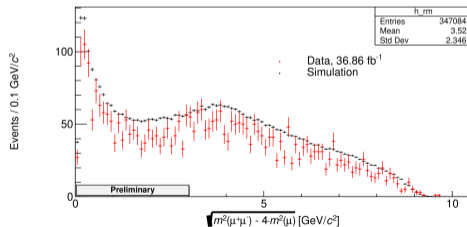- **Require 4 charged tracks and sum of charge should be 0**
  - At least, 2 same-signed tracks are identified as muon
- **Selection creteria**
  - Energy remaining in ECL without track association < 200 MeV
  - $m_{J/\psi} \pm 30$ MeV, $m_{\Upsilon(1S)} \pm 100$ MeV rejection from di-muon invariant mass
  - 4-muon invariant mass within initial beam energy ± 500 MeV
- **Backgrounds in Belle data**
  - $e^+ e^- \to 4\mu$
  - $e^+ e^- \to 4\pi$
  - $e^+ e^- \to 2e2\mu$
  - $e^+ e^- \to 2\mu 2\tau$
  - $e^+ e^- \to 2\mu J/\psi$ or $2\pi J/\psi$
  - $e^+ e^- \to 2\mu$
  - $e^+ e^- \to 2\tau$
  - $e^+ e^- \to q\overline{q}$
  - $e^+ e^- \to p\overline{p}$ or $n\overline{n}$
  - etc.

Validation check with 36.9 fb^{-1}

- **Signal extraction**
  - The coupling constant g' is obtained by Born cross section
  - Born cross section is calculated by signal yield (N_{obs}) by following the equation

$$g'^2 / g_0'^2 = \sigma_{\mathrm{Born}} / \sigma_{\mathrm{theory}}, \ \sigma_{\mathrm{Born}} = N_{\mathrm{obs}} / (\mathcal{L} \times \mathcal{B} \times \epsilon_{\mathrm{rec}}) \qquad (2)$$

  where σ_{theory} is theoritical cross section by g_0', $\mathcal{L}$ is int. luminosity, $\mathcal{B}$ is branching ratio of $Z' \rightarrow \mu^+\mu^-$, and ϵ_{rec} is reconstruction efficiency. N_{obs} is extraced by $M_{Z'}$ fitting
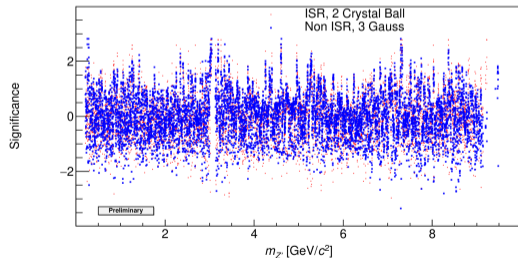
Significance of N_{obs}
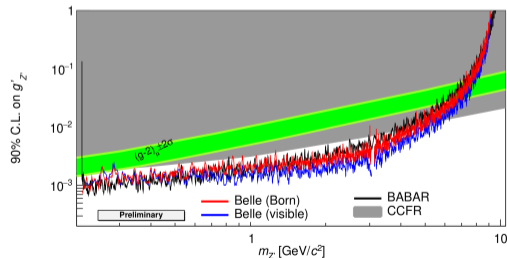
90% C.L. upper limits of g'

Summary

- **No significant observation for dark sector**
- $B^0 \to A'A'$ **result was published on JHEP**
  - ▶ 90% C.L. upper limits of branching fraction are mostly $\mathcal{O}(10^{-8})$
  - ▶ Higgs portal coupling constraint versus $m(h')$ and $m(A')$ are obtained
- $e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$ **gives the limit of $Z'\ell\ell$ coupling constant**
  - ▶ The result is competetive with BaBar

Thank you for listening!