Searches for dark particles at Belle/Belle II

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for the Belle/Belle II Collaborations

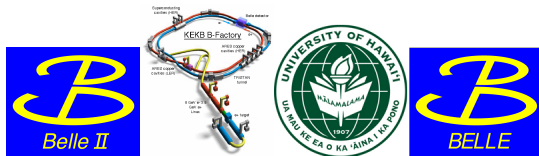Dark Interactions, Wednesday 11th June 2014

Table of contents

Dark gauge bosons / Introduction

Dark gauge bosons, or dark photons, $\gamma' = A = A' = U$, have been searched since the late 80s and are postulated to have:

- Very small couplings to Standard Model particles
- Low mass: of order MeV to GeV

Recent interest in dark sector models (Unified DM) that:

- Explain observed anomalies
- Often Introduce, in addition, a dark Higgs, h', by a Higgs mechanism
  - ▶ Plot below shows astrophysical and cosmological constraints and experimental limits:
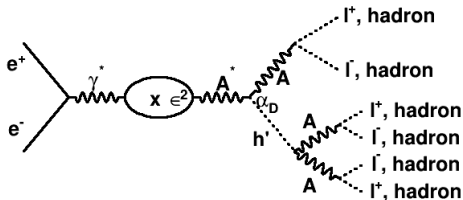   kinetic mixing ($\chi = \epsilon$) vs. A boson mass J. Jaeckel and A. Ringwald - arXiv:1002.0329v1
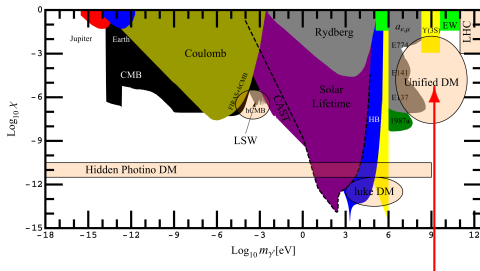
=> BaBar, Belle and Belle II can cover region between a few MeV/c^2 and 10 GeV/c^2

Searches for dark photons and dark Higgs at Belle

Presented today for the first time, a new limit in the search for a dark photon and a dark Higgs with:

- A and h' prompt
- $m_{h'} > 2m_A$
- $0.1 < m_A < 3.5$ GeV/c^2 and $0.2 < m_{h'} < 10.5$ GeV/c^2

α_D: dark sector constant
ϵ^2: kinetic mixing

- 10 exclusive channels: $3e^+3e^-$, $3\mu^+3\mu^-$, $2e^+2e^-\mu^+\mu^-$, $2\mu^+2\mu^-e^+e^-$, $3\pi^+3\pi^-$, $2\pi^+2\pi^-e^+e^-$, $2\pi^+2\pi^-\mu^+\mu^-$ $2e^+2e^-\pi^+\pi^-$, $2\mu^+2\mu^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-\pi^+\pi^-$
- 3 inclusive channels for $m_A > 1.1$ GeV/c^2: $2e^+2e^-X$, $2\mu^+2\mu^-X$, $e^+e^-\mu^+\mu^-X$

If $\alpha_D = 1$, Higgs-strahlung channel most sensitive to A

Event selection / Belle results

Reconstruction of exclusive(inclusive) lepton/hadron final states from $e^+e^- \to Ah' \to AAA$

- 3(at least 2) lepton/hadron pairs of opposite charge
- Impact parameters and χ^2 vertex fit cuts
- Require energy conservation
- Calculate invariant mass for each combination of leptons/hadrons consistent with three(two) distinct $A \to l^+l^-$/hadrons
- Keep combinations with three masses "equal"
- Plots below show signal Monte Carlo simulation events surviving selection with $m_{h'} = 5$ GeV/c^2 and $m_A = 2.19$ GeV/c^2
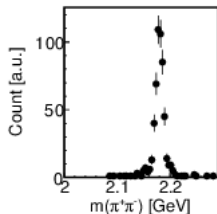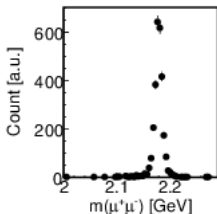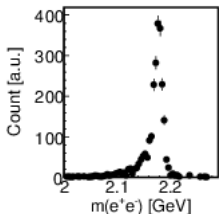

=> 20 % detection efficiency on average for all channels

Background estimation method / Belle results

- Estimate background using "same sign" events $e^+e^- \to (l^+l^+)(l^+l^-)(l^-l^-)$
- Order masses of lepton(hadron) pairs $m_{ll}^1 > m_{ll}^2 > m_{ll}^3$ and plot $m_{ll}^1 - m_{ll}^3$ vs. m_{ll}^1
- Select region in m_{ll} and predict background there using same sign
- Sideband used to normalize same sign to opposite sign
- Background estimated from the number of counts in the signal regions of the same sign distributions

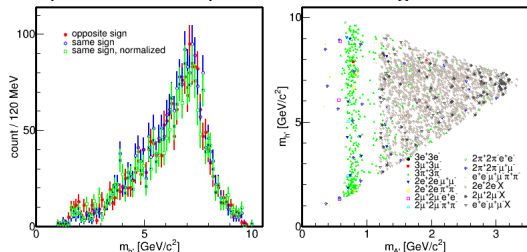▶ $m_{\pi\pi}^1 - m_{\pi\pi}^3$ vs. $m_{\pi\pi}^1$ for 6π
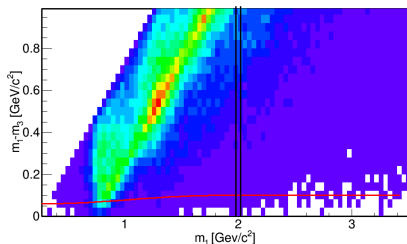
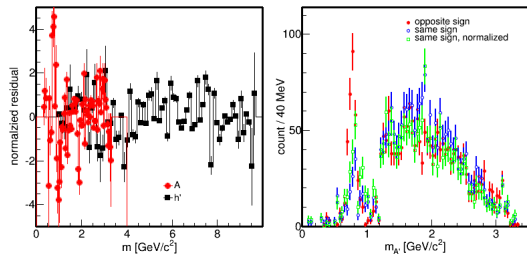▶ Projection on $m_{\pi\pi}^1 - m_{\pi\pi}^3$ for $m_\pi^1 = 2$ GeV/c²
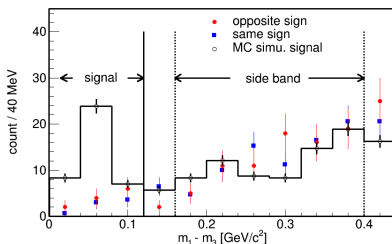
Background estimation results / Belle results

Comparison between predicted Belle background and Belle number of events observed

- Marker size larger than cell size
- Signal region divided in 61306 boxes
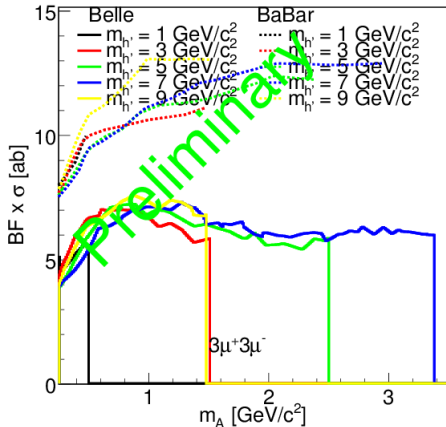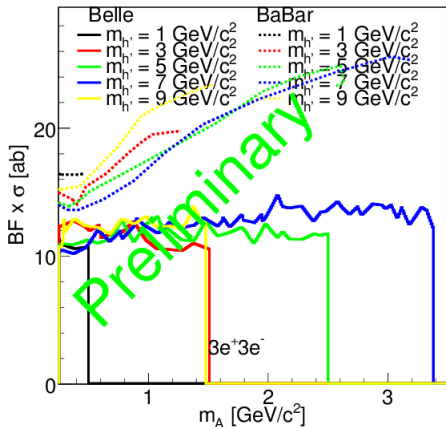- Only 5% of boxes with at least 1 count

Events measured consistent with background estimation

- Background: Standard Model 2γ processes with ρ's or ω's in the final state
- Discontinuity at 1.1 GeV due to selection criteria

Belle limits / new results

- Belle preliminary limits for $L = 980$ fb^{-1}
- BaBar limits for $L = 520$ fb^{-1} BaBar Collaboration - PRL 108 (2012) 211801
- $e^+e^- \to 3e^+3e^-$
- $e^+e^- \to 3\mu^+3\mu^-$

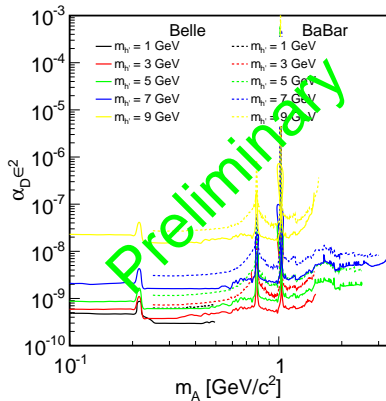

- Upper limit (90 % CL) determined by Bayesian inference method with the use of Markov Chain Monte Carlo A. Caldwell et al., CPC 180 (2009) 2197-2209
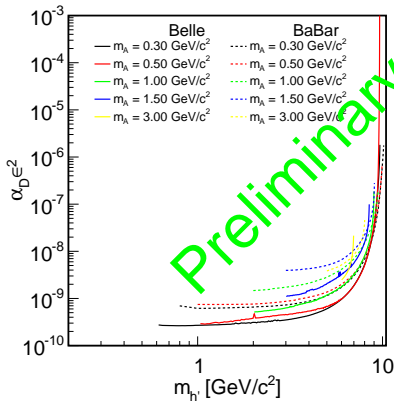- Improvement in limit scales linearly with integrated luminosity

Limit on the product of $\alpha_D \epsilon^2$ / new results

Belle combined limit compared to BaBar combined limit

- Dark photon 90 % CL sensitivity
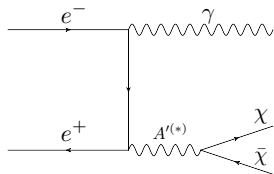- Dark Higgs 90 % CL sensitivity

Assuming branching fractions, couplings versus cross section, and dark photon and dark Higgs masses from B. Batell et al. PRD 79 (2009) 115008

Search for dark matter at Belle II

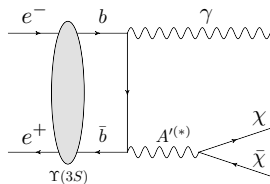Belle II may also produce dark matter, χ, in radiative decay:

- $e^+ e^- \to \gamma X$
- $e^+ e^- \to \Upsilon(nS) \to \gamma X$

  - $X = \chi \bar{\chi}$
  - $X = A$
  - $A \to \chi \bar{\chi}$

★ Two-body decays ★ Upsilon decays
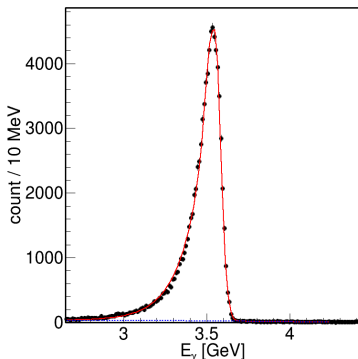
MC simulation of signal signature

- Off-shell i.e. $e^+e^- \to \gamma\chi\bar{\chi}$
- On-shell i.e.:
  - $e^+e^- \to \gamma A, A \to \chi\bar{\chi}$
  - $A \to l^+l^-$ or hadrons, where the A decays outside the detectors

- Simulated photon spectra
- Off-shell case
- On-shell case, $m_A = 1$ GeV/c^2
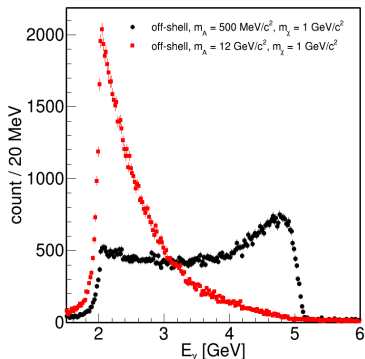
- Off-shell signature => broad energy distribution
- On-shell signature => mono-photon, => dark photon with displaced vertex decaying into leptons not detected by Belle II will have the same signature

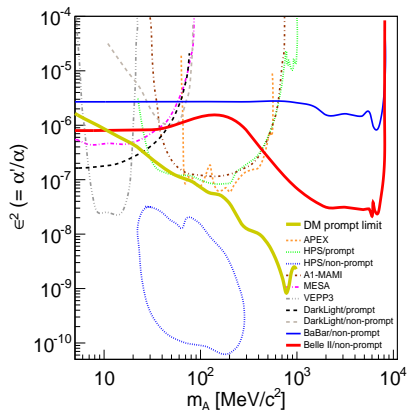# Searches for dark photons at Belle II in $e^+e^- \rightarrow \gamma A$

6 experiments have been approved/commissioned and will cover region between 1 MeV/c² and 1 GeV/c²

- All experiments will look for a prompt decay and $A \rightarrow l^+l^-$ by detecting the leptons
- HPS and DarkLight will also look for a displaced vertex.
- Belle II could set a limit between a few MeV/c² and 7 GeV/c²

▶ Predicted sensitivity

▶ VEPP3/Russia (new setup), $e^+ + p \rightarrow \gamma A$
▶ APEX/USA-JLAB (new setup), $e^- + \text{nucleus} \rightarrow \gamma A$
▶ HPS/USA-JLAB, $e^- + \text{nucleus} \rightarrow \gamma A$
▶ DarkLight/USA-JLAB (new setup), $e^- + H \rightarrow \gamma A$
▶ A1-MAMI/Germany, $e^- + \text{nucleus} \rightarrow \gamma A$
▶ MESA/Germany (new accelerator and setup),

 $e^- + \text{nucleus} \rightarrow \gamma A$

A not necessarily prompt

▶ Belle II expected sensitivity determined by R. Essig et al. JHEP 1311 (2013) 167 for $A \rightarrow$ invisible

  and $m_\chi = 1$ MeV/c²

▶ Belle/Belle II can also search for prompt decay

Radiative channels, γA

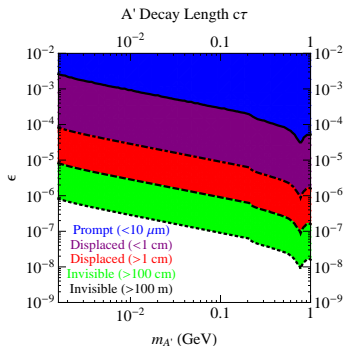Belle II expected sensitivity determined by R. Essig et al. JHEP 1311 (2013) 167

- Full luminosity, 50 ab^{-1}, and 1 % trigger fraction
- $A \rightarrow$ invisible and $m_\chi = 1$ MeV/c^2
- Belle II could set a limit between a few MeV/c^2 and 7 GeV/c^2

▶ Predicted sensitivity
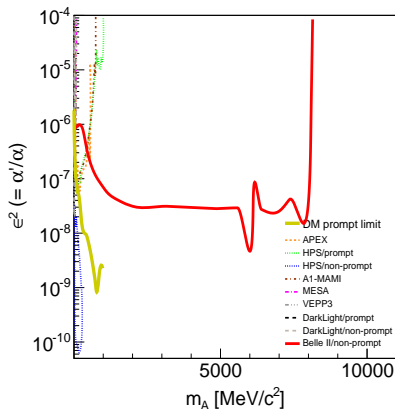
▶ Plot shows lifetime of A as a function of its mass, m_A, and ϵ
R. Essig et al, PRD 80 (2009) 015003

Conclusion

Belle and Belle II can contribute to the dark sector particles searches for the prompt and displaced vertex cases

- New preliminary Belle limits for prompt decays of the dark photon and dark Higgs in the mass ranges:
    - Prompt decays
    - $0.1 < m_A < 3.5$ GeV/c^2
    - $0.2 < m_{h'} < 10.5$ GeV/c^2
    - We found that:
        - ★ No significant excess over the background estimation
        - ★ That the preliminary Belle limit improvement scales nearly linearly with integrated luminosity

- Belle II will search for dark matter in radiative decays
- With 50 ab^{-1}, Belle II might potentially also cross-check any signals discovered by fixed target experiments

Thanks for your attention

Many thanks to Yiming Zhong, Rouven Essig and also to Bertrand Echenard (from BaBar) for their help.

KEKB and SuperKEKB

KEKB/SuperKEKB collider, located in Japan, Tsukuba, is the world's highest-luminosity electron-position collider

- 1999-2010: Belle collected $L = 1050$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 4S, 5S)$ and continuum
- 2016-2026: Belle II (upgrade version of Belle) expects to collect $L = 50$ ab^{-1}
- Figure shows a schematic view of KEKB.
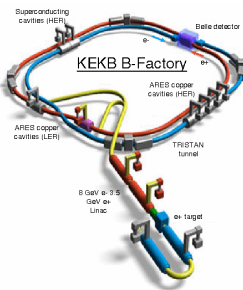
S. Kurokawa and E. Kikutani, NIM A 499, 1 (2003)

Belle/Belle II setup

Belle CP violation meas. in the B-meson sys. together w/ BaBar Exp. at SLAC, established the Kobayashi Maskawa mechanism as a valid description of CP violation in the Standard Model.

- Main motivations for Belle and Belle II experiments
  - ▶ Study of CP violation (i.e. matter-antimatter asymmetry)
  - ▶ Study of heavy flavor
  - ▶ Search for physics beyond the Standard Model
- Complementary to efforts at energy frontier
- Figure bellow: Belle setup
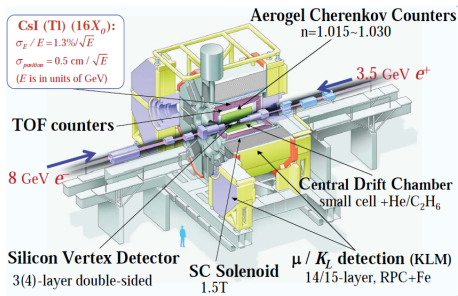
Belle II detectors is an upgrade version of Belle