Search for Dark Matter and Dark Sector at Belle II

Heavy Quarks and Leptons 2018, Yamagata, Japan

Thomas Hauth for the Belle II Collaboration | 1. June 2018

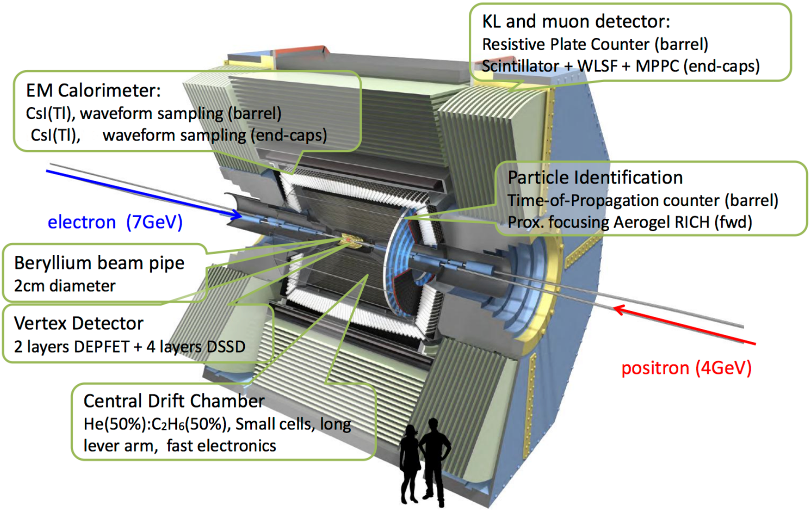
KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) - GERMANY

The Belle II Experiment and its Goals

- KEKB was an electron-positron collider at KEK in Tsukuba/Japan which studied the decay of B mesons at the Υ(4S) resonance
- Nobel Prize in Physics 2008 to Kobayashi and Maskawa
- The SuperKEKB collider and the Belle II detector will build on the previous success:
  - Study the B meson system in far greater precision
  - Probe for new physics in a wide range of interesting topologies
  - Spectroscopy of Quarkonium systems
- The Belle II Collaboration: 756 members from 104 institutes in 25 countries

	KEKB	Super KEKB	Factor
Instantaneous Luminosity	$2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	40
Integrated Luminosity	$1\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$	50
Runtime	1998 to 2010	start in 2017	
Detector	Belle	Belle II	
Raw Data	1 PB	100 PB (projected)	100

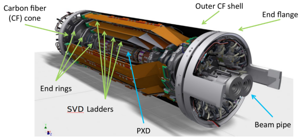
Belle II Detector

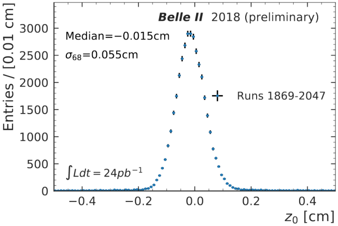


Highlights of the Belle II Design

Completely new VerteX Detector (VXD):

- Two inner DEPFET Pixel Layer (PiXel Detector) : PXD
- Four outer Silicon Strip Layers (Silicon Vertex Detector) : SVD
- Very light mechanical structure: $X/X_0 \approx 0.5\%$ per SVD layer, $X/X_0 \approx 0.19\%$ per PXD layer
- Factor 1.5 improvement of the impact parameter over a wide range with the new inner tracking system (compared to Belle)



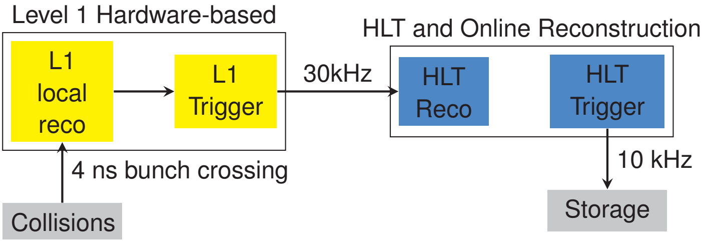


- Improved Central Drift Chamber which builds on Belle's established design: Denser inner layer and larger radius for better momentum reconstruction
- New Time-of-Flight (TOP), Aerogel-RICH detectors and drift chamber dE/dX for particle identification
- Upgrade to the hardware Level-1 trigger to support triggers for low-multiplicity events

Belle II Commissioning and Early Physics Opportunities

- **BEAST Phase I** completed Feb-June 2016: SuperKEKB commissioning with the BEAST detector to characterize the beam environment
- **Phase II** End of 2017 / early 2018:
  - Roll-in of Belle II detector: 11. April 2017
  - Belle II without the inner silicon-based VXD tracking system
  - Characterize background radiation innermost tracking system is exposed to
  - Estimated duration ~ 5 month and recording of $20 - 40\,\text{fb}^{-1}$ at various energies
  - First months of Phase II already with many exciting results: **26. April 2018: First e+e- collisions in SuperKEKB and first observation of hadronic event with Belle II!**
- **Phase III** Beginning 2019:
  - Start of data taking with the complete Belle II detector
  - Primary running at $\Upsilon(4S)$ for B-pair production

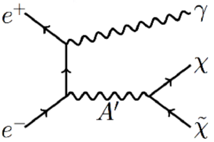
Belle II Trigger Processing Chain



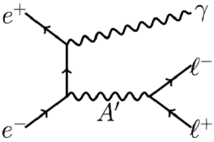
- Belle II's new trigger system enables many of the dark matter and dark sector searches presented here
  Level 1 Trigger features: CDC trigger with 3d tracking, ECL Trigger with clustering and bhabha-veto logic, Track-Cluster Matching
  HLT Trigger features: Complete reconstruction (incl. PID), sophisticated background rejection methods using multi-variate methods
- Additionally to the hadron and low-multiplicity topologies triggered with Belle I, the new system will also have triggers for single photon events
- Reliable detection and pre-scaling of QED and machine background processes important already already on trigger level

Dark Photon Search

Monophoton Mode



Dilepton Mode



- Hypothetical dark photon (A') production in e^+e^- annihilation

$$e^+e^- \rightarrow \gamma A'(\rightarrow \chi\overline{\chi})$$

  where the dark photon decays to two invisible DM particles

- Mixing parameter ϵ between the SM current J^μ_{SM} and the vector particle V^μ:

$$\mathcal{L} \subset \epsilon V_\mu J^\mu_{SM}$$

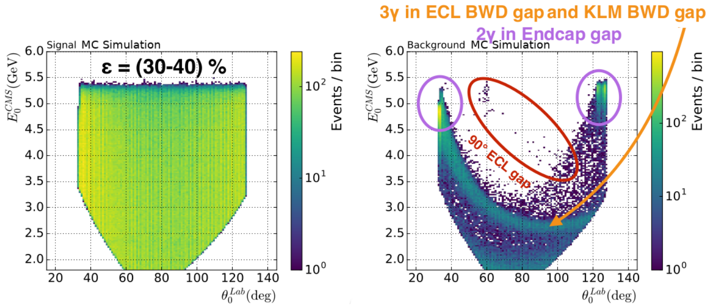
- Measurable detector signal: one ISR photon with the energy

$$E_\gamma = (E^2_{CM} - E^2_{A'})/(2E_{CM})$$

- With 20 fb^{-1} of recorded events, a preliminary projection shows a big exclusion potential for Belle II's early data taking
- BaBar recently published a dark photon search with 53 fb^{-1} `https://arxiv.org/abs/1702.03327`
- Using a single-photon trigger with an effective threshold of 1.8 GeV, BaBar was able to study dark photon masses up to 8 GeV/c^2.

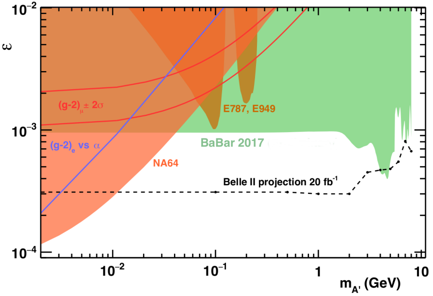
Dark Photon to invisible Search Method

- Very challenging experimental signature: A'(invisible) and only one γ
- Special single photon trigger required:
  - Cascaded: different pre-scales for different thresholds
  - Different pre-scales for Barrel and Endcap regions
- Irreducible dominant background $ee \to ee\gamma$ where both electrons are outside of the detector acceptance
- Good tracking efficiency required to reject events with tracks
- Using KLM cluster information to reject events falling into ECL gaps

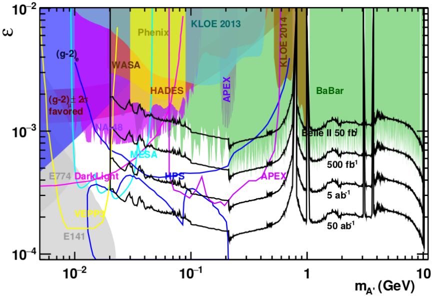


[Fer17]

Belle II's Dark Photon Search



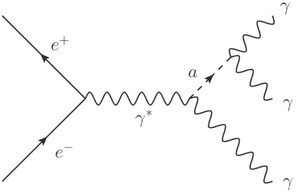
Projected upper limits on the kinematic mixing parameter ϵ between the dark photon A' and the SM for the process $e^+e^- \rightarrow \gamma A'(\rightarrow \text{invisible})$ for a 20 fb^{-1} Belle II dataset [b2t].

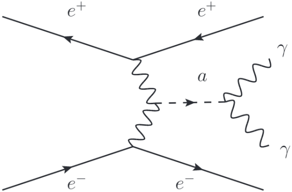


Projected upper limits on the kinematic mixing parameter ϵ between the dark photon A' and the SM for the process $e^+e^- \rightarrow \gamma A'(\rightarrow$ *lepton lepton*$)$ [b2t].

Axion Search

- Axion-like Particles (ALP) are a generic feature of many extensions of the SM
- Furthermore, they are a candidate for cold dark matter
- In the following we consider ALP masses in the MeV to GeV range and couplings primarily to SM gauge bosons
- Production in Belle II either via ALP-Strahlung or photon fusion





Feynman diagrams for ALP production in e^+e collisions via ALP-strahlung (left) and photon fusion (right) and the subsequent decay of the ALP into two photons [DFH+17].

ALP to 2 photons detection with Belle II

- The focus is to detect the 3γ final state, where both photons from the ALP can be resolved in the electormagnetic calorimeter
- Strategy: Search directly for a peak in the 2γ invariant mass spectrum

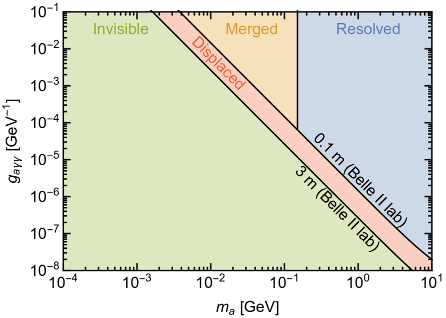
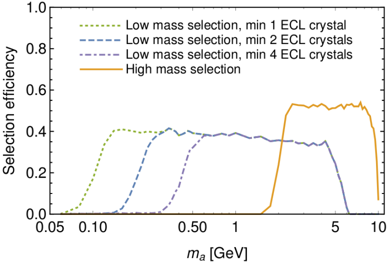


Illustration of the different kinematic regimes relevant for ALP decays into two photons with Belle II [DFH+17].

Main backgrounds:

- $e^+e^- \to \gamma\gamma\gamma$
- $e^+e^- \to \gamma\gamma$ + beam background photon
- $e^+e^- \to \gamma\gamma(\to e^+e^-)$ from photon conversion outside the tracking volume

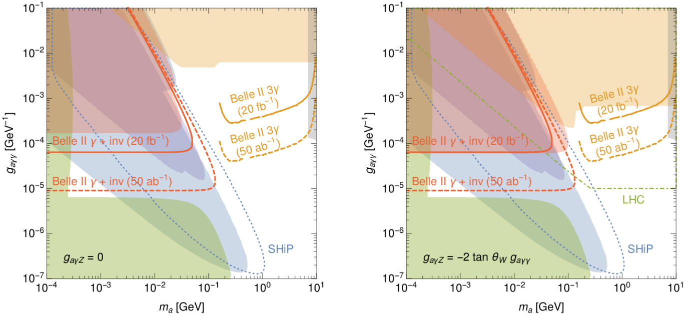
ALP to 2 photons detection with Belle II



Belle II 3γ efficiency as a function of ALP mass [DFH$^+$17]

- The low mass selection performs only photon pair combination with the lowest invariant mass
- For a lower minimum distance between ECL crystals, a lower ALP mass m_a can be accessed
- The high mass selection combines all possible photon pairs
- While the *high mass selection* has a better signal efficiency for larger m_a, the *low mass selection* has a lower combinatorial backgrounds

ALP to 2 photons Sensitivity



Projected Belle II sensitivity (90 %CL) compared to existing constraints on ALPs with photon coupling (left) and hypercharge coupling (right), [DFH+17]

ALP to DM Detection in Belle II

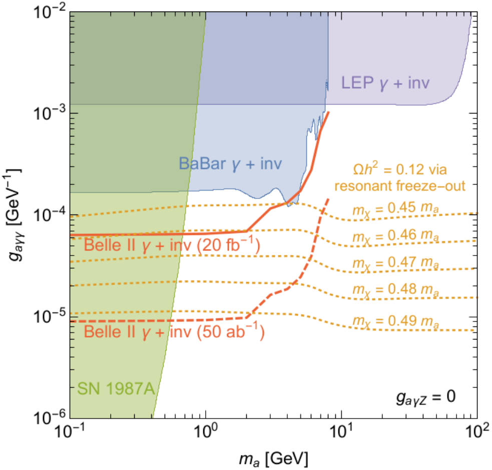
- ALP decays into DM-particle, so final signature is one photon with an energy

$$E_\gamma = \frac{s - m_a^2}{2\sqrt{s}}$$

  with $\sqrt{s} = 10.58\ GeV$ as the collision energy of Belle II.
- Background for this process: high cross section QED processes $e^+e^- \to e^+e^-\gamma(\gamma)$ and $e^+e^- \to \gamma\gamma(\gamma)$ where only one photon is detected
- The sensitivity to high mass ALPs is limited by the trigger threshold for a single photon

Trigger Energy Treshold (GeV)	ALP mass upper limit (GeV)	
1.8	8.6	planned
1.2	9.3	feasible

ALP to DM Detection Sensitivity



Present and future constraints on ALPs decaying into DM compared to the parameter region where one can reproduce the observed DM relic abundance via resonant annihilation of DM into photons. [DFH$^+$17]

Low Mass Dark Matter Searches

- In the SM, invisible decays like $Y(1S) \to \nu\bar{\nu}$ (BR $\approx 10^{-5}$) exist and could be enhanced by an additional light DM particle
- As the $Y(1S)$ decay has no detectable final state products, transitions like $Y(3S) \to \pi^+\pi^- Y(1S)$ need to be exploited
- The signal of $Y(1S) \to \mathrm{invisible}$ is an excess of events in the recoil mass for the two-pion system M_r distribution at a mass equivalent to that of the $(1S) = 9.460 GeV/c^2$.
- Belle used a special trigger for $Y(3S) \to \pi^+\pi^- Y(1S)$ during the $Y(3S)$ datataking, no special trigger was used during the $Y(2S)$ data taking
- ARGUS, CLEO, Belle and BABAR experiments have set the limit for the BR[$(1S) \to \mathrm{invisible}$] to $< 3 \cdot 10^{-4}$

Belle II expected event yield, assuming standard model ($1 \cdot 10^{-5}$) and new physics ($3 \cdot 10^{-4}$) rates for $(1S) \to \mathrm{invisible}$. ϵ is the total efficiency.

Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$	$0.2, \Upsilon(2S)$	0.1-0.2	2.3×10^8	232-464	6960-13920
$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$	$0.2, \Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	$50.0, \Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S)$	$5.0, \Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma\Upsilon(2S) \to (\gamma)\pi^+\pi^-\Upsilon(1S)$	$50.0, \Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma\Upsilon(3S) \to (\gamma)\pi^+\pi^-\Upsilon(1S)$	$50.0, \Upsilon(4S)$	0.1-0.2	6.5×10^7	65-130	1950-3900

Summary

- Many improvements in Belle II's detector design enable the search for Dark Matter and Dark Sector topologies not possible with Belle
- Existing limits can already be improved in the first years of data taking
- The next months will be vital to establish the performance of all Belle II subsystems and collect sufficient events for first physics analyses
- The comprehensive B2Tip Report [b2t] in preparation for publication and describes the Belle II detector, simulation and reconstruction and physics program (incl. dark matter and dark sector searches) in great detail

References I

- *B2TiP ReportStatus*, `https://confluence.desy.de/display/BI/B2TiP+ReportStatus` (21/05/2018) Click on 'PTEP draft version' on the top of the page.
- M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, *Revised constraints and Belle II sensitivity for visible and invisible axion-like particles*, Journal of High Energy Physics **12** (2017), 94.
- Torben Ferber, *Status of Belle II/SuperKEKB and plans for dark sector physics*, Lake Louise 2017 `https://docs.belle2.org/record/492`.