Searches for LLP's at Belle II

Doris Yangsoo Kim
Soongsil University

October 23, 2018
Searching for long lived particles at LHC:
4th Workshop of the LHC LLP Community
Amsterdam Science Park
(remote connection)
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• Phase III: Preparation

• Summary
SUPERKEKB
BELLE II
## Upgrade from KEK/Belle to SuperKEKB/Belle II

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity:</strong></td>
<td>$2.1 \times 10^{34}$</td>
<td>$8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$</td>
<td>(x 40)</td>
</tr>
<tr>
<td><strong>Integrated Luminosity:</strong></td>
<td>1 ab$^{-1}$</td>
<td>50 ab$^{-1}$</td>
<td>(x 50)</td>
</tr>
<tr>
<td><strong>Runtime:</strong></td>
<td>1998 to 2010</td>
<td>2017 started</td>
<td></td>
</tr>
<tr>
<td><strong>Detector:</strong></td>
<td>Belle</td>
<td>Belle II</td>
<td></td>
</tr>
<tr>
<td><strong>Raw Data:</strong></td>
<td>1 PB</td>
<td>100 PB</td>
<td>(x 100)</td>
</tr>
</tbody>
</table>

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As of 2018.10.18
• 26 countries/regions
• 113 institutions
• ~ 850 colleagues
• America 17%, Asia 24%, Europe 37%, Japan 17%, Russia 5%
SuperKEKB: Nano Beam Collision

- Extremely small $\beta_y^*$ at IP
- Increase beam currents $I_{e\pm}$
- Increase $\xi_y$

$$L = \frac{\gamma_{e\pm}}{2e r_e} \left( 1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \left( \frac{I_{e\pm} \cdot \xi_{y,e\pm}}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right)$$

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The Belle II Detector

KL and muon detector:
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (fwd)

EM Calorimeter:
- CsI(Tl), waveform sampling

Electrons (7GeV)

Beryllium beam pipe
- 2cm diameter

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
- He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

Positrons (4GeV)

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Belle II Experiment in Nutshell

• $e^+e^-$ collisions at Y(4S), and other energies.
  • Y(4S) decays into B B meson pairs

• High tagging efficiency of B particles.

• Direct detection of neutrals such as $\gamma$, $\pi^0$, $K_L$.

• A hermitic detector:
  • Detection of neutrinos or invisibles as missing energy/momentum.
Beam Commissioning Phases

• BEAST Phase I in 2016.
  – Simple background measuring detector (diodes, diamonds TPCs, crystals)
  – Only single beam circulated for LER/HER.
• BEAST Phase II April 26 – July 17 2018.
  – 1/8 of vertex detector
  – Full Belle II outer detector,
  – Physics data collected ~ 0.5/fb
  – Flexible hardware trigger & pass-through software trigger
• Belle II Phase III at the end of JFY 2018.
  – The most precise silicon inner detector included. (layers 1, 3-6)
  – Physics mode with the full Belle II detector.
PHASE II STATUS
The BEAST Vertex Detector
The two beams were squeezed with the superconducting final focus down to \( \beta_y^* = 3 \text{mm} \).

However, instantaneous luminosity suffered as \( \beta_y^* \) got squeezed due to beam blowup at high current.

Expected to reach the design luminosity in 2022.

The physics data was taken mostly during the night when beam R&D was not done.

Collected \( \sim 0.5 / \text{fb} \).
Progress on Beam Size

- For Phase 3, we will start with $\beta_y^* = 3\text{mm}$.
- The record is 400 nm at beam currents of only $\sim 15\text{mA}$.
- The vertical height of the nano beams was measured using vertical luminosity scanning of the diamond detectors.
Candidate: $e^+e^- \rightarrow q \bar{q}$
Candidate: $e^+ e^- \to B \bar{B}$
Phase II Particles as Charged Tracks

$$K_s \rightarrow \pi^+\pi^-$$

No displaced vertex cut

$$J/\psi \rightarrow \mu^+\mu^-$$

$$J/\psi \rightarrow e^+e^-$$

Belle II 2018 Preliminary

Entries / 0.01 GeV/c^2

Entries / 0.01 GeV/c^2

muonID > 0.001

E/p > 0.9
Phase II Events with Photons

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

Note: Dark sector search
- \( e^+ e^- \rightarrow \gamma A' \)
- \( e^+ e^- \rightarrow \gamma ALPS \rightarrow \gamma(\gamma\gamma) \)
- \( e^+ e^- \rightarrow ... \)

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BELLE2-NOTE-PH-2018-010.pdf
~571 (= 389 charged + 182 neutral) fully reconstructed B mesons from the full Phase II data set
Some Ideas on LLP Signature

• In the LLP field, the current Belle II search signatures include
  – particles decaying outside the detector, i.e., invisible modes.
  – displaced vertices in tracker or outer detectors
  – magnetic monopoles
  – …

• These signatures have topologies different from the SM particles. Hence, dedicated reconstruction strategies are needed.
(LLP) or (LLP+Prompt)

DARK PHOTON
Dark Photon to Leptons

Visible mode

Case: Dark Photon A' mixes with the SM.

Depending on its mass, it decays into a pair of fermions (visible mode)

\[ e^+ e^- \rightarrow \gamma l^+ l^- \]

Signature:
An energetic single photon with a pair of leptons.

PRD79: 1115008 (2009)
Projected Sensitivity

Note: These numbers are for the prompt case for the visible mode.
AXION LIKE PARTICLES
Axion-like Particles (ALP)

• ALP: pseudo-scalar particles from the extensions of SM

\[ L \sim -\frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} aF_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} aZ_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} aW_{\mu\nu} \tilde{W}^{\mu\nu} \]

• Look for ALP's decaying into
  – Nothing (invisible mode)
  – a couple of photons. i.e., ALP strahlung, in the detector (visible mode).
Simulated Example of ALP

ALP → 2 photons

Recoil photon
Selection Regime and Efficiency

Selection Regime of ALP → 2 photons

Selection efficiency of (recoil photon + ALP → 2 resolved photons)

JHEP 1712, 094 (2017)
Expected Sensitivity

3γ: 3 resolved photons
γ + inv: 1 resolved recoil photon + ALP decaying to 2 photons outside Belle II

Photon coupling \(g_{a\gamma\gamma} \ll g_{aZZ}\)

Hypercharge coupling \(g_{a\gamma\gamma} \approx -g_{aZZ}\)

JHEP 1712, 094 (2017)
MAGNETIC MONOPOLE
(small charge) Magnetic Monopole

- MoEDAL 2017 searched $g > 68.5e$.
- ATLAS 2016 searched $34e < g < 137e$.
- Low magnetic charges $g < 10e$ have not been excluded yet.

- Signature: a pair of tracks straight in XY, curved in RZ planes.
Monopole Tracks

- Number of hits in CDC for different magnetic charges (unit e).
- We need a dedicated tracking algorithm!
dE/dx vs Particle Type

- Monopole tracks show weaker dE/dx curves, since the $1/\beta^2$ term is missing from Bethe-Bloch equation for ionization.
Monopoles: Sensitivity

Projected sensitivity

\[ R = \frac{\sigma(e^+e^- \rightarrow MM)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

\[ \text{TASSO } g = 10e \]
\[ \text{TASSO } g = 20e \]

\[ \text{CLEO } g = 8e \]
\[ \text{CLEO } g = 5e \]
\[ \text{CLEO } g = 5e \]
\[ \text{20fb}^{-1} \text{ Belle II } g = 1e \]
\[ \text{20fb}^{-1} \text{ Belle II } g = 3e \]

Mass (GeV/c^2)

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Dmitrii Neverov @AEPSHEP2018, ICHEP2018
PHASE III: PREPARATION
The Full Vertex Detector

Half-shell assembled

One layer of PXD in 2019. Two PXD layers after.
SuperKEKB/Belle II Luminosity Plan

Yukiyoshi Ohnishi @ KEK
Summary

• Phase II mode of the Belle II Experiment has been executed successfully.
  – This is an excellent opportunity to search for new physics such as dark matter or ALP.
  – Preparing for dark sector papers.

• Phase III of Belle II will start early 2019.
  – Competing and complementary to LHCb.
  – SuperKEKB will become the highest luminosity machine in the World.
  – Stay tuned for the exciting physics!
SuperKEKB Collider

Tokyo

Belle II

positrons (4GeV)

electrons (7GeV)
Separation power is expected to be improved with further alignment and calibration efforts.
Expected Sensitivity for ALP decays to Dark Matter

\[ \gamma + \text{inv} : \text{1 resolved recoil photon + ALP decaying to dark matter} \]

\[ e^+ e^- \to \gamma a, \quad a \to \chi \chi \]

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