



Dark Matter Search with e⁺ e⁻ collider (B05)

Shohei Nishida KEK Dark Matter Symposium Apr. 24, 2025

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B05 Members



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B05 "Dark Matter Search with Electron-Positron Collider"

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Thomas Czank \rightarrow Company

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(due to trigger setting etc.) and may be searched with initial Belle II data.



SuperKEKB and Belle II





SuperKEKB and Belle II

- Located at KEK, Tsukuba, Japan
- SuperKEKB: asymmetric e⁺e⁻ collider (4 GeV e⁺ + 7 GeV e⁻)
 - ✓ Nano-beam scheme to achieve high luminosity
- Belle II: flavor physics experiment at SuperKEKB
- Successor of KEKB, Belle in operated in 1999-2010
 - Verified Kobayashi-Maskawa theory in the study of CP violation in B mesons





Kibayashi, Maskawa (2008 Nobel Prize)

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Belle II



Superconducting **K**_L, μ Solenoid(1.5T) Detector KLM Electromagnetic Calorimeter ECL Particle Indentification Electron(7GeV) TOP(barrel), ARICH(endcap) **Central Drift** Chamber _{CDC} Positron(4GeV) Silicon Vertex Detector • General purpose 4π detector PXD, SVD with good vertexing (for time © Rey.Hori/KEK CP violation) and particle Belle II Detector (8m×8m×8m, 1400t) identification.

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Luminosity



• Luminosity is a key for the experiment.

- ✓ Luminosity $[cm^{-2} s^{-1}] = (event rate [s^{-1}]) / (cross-section [cm^{-2}])$
- ✓ Integrated luminosity [fb⁻¹] = Luminosity × time : collected data size



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SuperKEKB has an issue of Sudden Beam Loss (SBL)

• All the beam is lost within a few turns.



- SBL can cause QCS (final focusing magnet) quench or damage the detector.
- One of the causes of SBL seemed to be identified.

Many more challenges: injection, high background ...

For B05 project (dark matter study with e⁺e⁻ collider)....

- High beam background is problematic to some of the dark sector analysis.
- The dataset collected in 2020-2024 was much smaller than expected.
 - ✓ SuperKEKB issue + high electricity cost.

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研費 Dark Matter Searches at Belle (II)





- $e^+e^- \rightarrow \gamma A'(\rightarrow invisible)$ [on-going at Belle II]
- $Z' \rightarrow invisible [PRL 130, 231801 (Belle II)]$
- + $Z' \rightarrow \mu^+\mu^-$ [PRD 106, 012003 (Belle), PRD 109, 112015 (Belle II)]
- $Z' \rightarrow \tau^+ \tau^-$ [Phys.Rev.Lett 131, 121802 (Belle II)]
- ALP (Axion Like Particle) $e^+e^- \rightarrow a(\rightarrow\gamma\gamma) \gamma$ [PRL125 (2020), 161806]
- Dark Higgsstrauhlung $e^+e^- \rightarrow A'(\rightarrow \mu^+\mu^-) h'(\rightarrow invisible)$ [PRL 130, 071804 (2023)]
- Heavy neutral lepton [PRD 109, L111102 (2024)] reported by S.Dey last year
- Inelastic Dark Matter [presented at Moriond2025]
- Dark Matter etc. from B ($\Upsilon,\,\tau,\,\ldots$) decays.
 - ✓ $B \rightarrow K S$ (→ leptons) : dark scalar
 - ✓ $B \rightarrow K S$ (long-lived) : long-lived dark scalar [Phys.Rev.D 108, 111104 (Belle II)]
 - ✓ $B \rightarrow Ka (\rightarrow \gamma \gamma)$: ALP search [presented at Moriond2025]
 - ✓ $B \rightarrow K a$ (→ hadrons) : heavy QCD axion (S.Ito → S.Dey, E.Waheed)
 - ✓ $\Upsilon(1S) \rightarrow \gamma$ + invisible : light Higgs [PRL 128, 081804 (2022) (Belle)]
 - ✓ $\tau \rightarrow I \alpha$ [Phys.Rev.Lett. 130 (2023) 181803] → new Belle result (K.Uno)

On-going analysis. S. Dey's presentation

T.Czank worked an analysis with

Belle data, but he left...

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Invisible Mode



$e^+e^- \rightarrow \gamma$ + invisible



- Final state: a single photon only.
- Bump in a recoil mass or photon energy.
- Need special "single photon trigger" to collect such events.
 - ✓ Belle didn't have this trigger.
 - ✓ BaBar had it (for some period).
 - ✓ Belle II has (some) single photon trigger.

On-going analysis at Belle II

Dark Photon A', SIMP (Strongly Interacting Massive Particle)...



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Invisible Mode



$e^+e^- \rightarrow \gamma + A'$ (invisible)

• Measure the photon energy and calculate the recoil mass.

$$m_{A'}^2 = 4E_b(E_b - E_{\gamma}^*), \ E_b = \sqrt{s/2}$$

- Struggling with large beam background of SuperKEKB.
- Main background $e^+e^- \rightarrow \gamma\gamma(\gamma)$
 - $\checkmark\,$ Photon inefficiency study is going on.
 - Photon missed by the calorimeter (ECL) is detected by outer KLM.
 - Data reprocess.
- Study of signal extraction, trigger efficiencies, systematic errors going on.

Top priority analysis in dark sector. Taking time...





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Inelastic Dark Matter



Inelastic Dark Matter

- Expanded dark sector with two dark matter states with a small mass splitting and a dark photon.
 - ✓ Stable χ_1 (relic candidate) and long-lived χ_2
- Explains why no observation in direct detection.
- Focus on a specific model large A' mass (A' $\rightarrow \chi_1 \chi_2$) and with a dark Higgs (h') that provides A' mass.
 - $\checkmark\,$ h' mixes with SM Higgs with θ
 - $\checkmark\,$ h' becomes long-lived for small θ

• We have 4 dark sector particles: A', h', χ_1 and χ_2

• We have 7 parameters: $m_{A'}$, $m_{h'}$, $m_{\chi 1}$, Δm_{χ} , θ , ε , α_D

Duerr, M., et al., J. High Energ. Phys. 2021, 146 (2021)





 $e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1e^+e^-),$

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Signature

- 4 tracks with two displaced vertex (pointing one and non-pointing one).
- Missing energy.





- Challenging for tracking and trigger
- Almost zero background analysis

Searches for displaced vertex etc. (+ trigger study)

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$\tau \rightarrow I \alpha$ (Belle)



$\tau \rightarrow I \alpha \ (I = e, \mu)$

[arXv:2503.22195]



- τ decays with invisible scalar α : predicted in models with ALP etc.
- Belle II obtained best limit with 63 fb⁻¹ [Phys.Rev.Lett. 130 (2023) 181803] \rightarrow New result with 800 fb⁻¹ taken at Belle.
- Peak in the lepton momentum in τ rest frame is the signature, but it cannot be calculated due to missing neutrinos in the tag side \rightarrow approximation.



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- SuperKEKB achieved world highest luminosity in the end of 2024.
 - ✓ However, it suffers many problems including Sudden Beam Loss.
 - \checkmark Electricity cost is a serious problem (no run till autumn this year).
- The accumulated data (integrated luminosity) of Belle II is still similar to the previous Belle experiment.
- Many results on dark matter search from Belle II (and Belle).
 - \checkmark New triggers for low multiplicity events (and single photon trigger).
 - ✓ Improved analysis technique.
 - No signature of the dark matter; but excluding some of the models, parameter space.
- Many analyses are going on; continue the searches with available + coming data.





Backup

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Belle II Plan





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