Searches for dark Higgsstrahlung and invisible Z’ at the Belle II experiment

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33rd Rencontres de Blois - Dark Universe(s)

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Introduction

- B-factories have a unique reach in searches for the light dark sector with low mass mediator particles on the MeV-GeV scale.

- **Belle II** has great advantages in **dark sector searches**
  - Hermetic detector
  - Clean collision environment
  - Excellent PID
  - Dedicated low-multiplicity triggers

This talk focuses on two searches:
- **Dark Photon** that obtains mass through spontaneous symmetry breaking, introducing a **Dark Higgs Boson**.
- **Z' boson** that couples to 2\textsuperscript{nd} and 3\textsuperscript{rd} lepton generations and decays invisibly
Belle II & SuperKEKB

- **B-factory** located in Tsukuba, Japan.
- Asymmetric $e^+e^-$ collider operating at $m_{\Upsilon(4S)} = 10.58$ GeV/c$^2$ (7 GeV/c$^2$ $e^- + 4$ GeV/c$^2$ $e^+$)
- Pilot run in 2018, physics runs began March 2019
- Target $x50$ Belle data ($\approx 50 ab^{-1}$)
- Wide-ranging and varied physics program: B and D physics, quarkonium, $\tau$-physics, dark sector, …

*Increased beam backgrounds*

- Reduced boost requiring improved vertex reconstruction
- Solid angle coverage > 90%

*Beam backgrounds*

- $B_y = 0.28$ (vs 0.42 @ Belle)

*Vertex reconstruction*

- High hermeticity for $E_{miss}$ measurements.
**Belle II & SuperKEKB**

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- Asymmetric $e^+e^-$ collider, operating at $m_{\Upsilon}(4S) = 10.58$ GeV/$c^2$ ($7$ GeV/$c^2 e^- + 4$ GeV/$c^2 e^+$).
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**384fb^{-1} recorded integrated luminosity**

- Increased beam backgrounds:
  - upgraded trigger system with dedicated low multiplicity lines
- Reduced boost requiring improved vertex reconstruction
- Solid angle coverage > 90%
  - High hermeticity for $E_{miss}$ measurements.

- Electromagnetic calorimeter (ECL): CsI(Tl) crystals, waveform sampling to measure time and energy (possible upgrade: pulse-shape)
  - Non-projective gaps between crystals
- Vertex detectors (VXD): 10layer DEPFET pixel detectors (PXD)
  - 4 layer double-sided silicon strip detectors (SVX)
- Central drift chamber (CDC): 
  - He/50%/C2H4, (50%) small cells, fast electronics

**Belle II Online luminosity**

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**Dark Higgsstrahlung and Invisible Z' @ Belle II**

Huw Haigh

25/05/2022
Trigger System

- Two-tier trigger system:
  - Hardware based low level trigger (L1)
  - Software based high level trigger (HLT)
- Reduce effects from beam backgrounds (Touschek effect, beam-gas scattering, radiative Bhabha, …)
- L1 trigger
  - Max trigger rate 30KHz
  - Combines 4 sub-detector triggers; Drift Chamber, Cherenkov detectors, Muon System, Electromagnetic Calorimeter
- Dedicated trigger lines for dark sector and low-multiplicity physics (not available in Belle):
  - Single photon / track
  - Multi-track triggers
    - 2 full tracks with opening angle requirement used in dark higgsstrahlung/Z’ searches
  - 3D neural trigger
Dark Higgsstrahlung - Theory

Next to minimal dark photon model

- Single dark photon, $A'$, and a single dark Higgs, $h'$
- Dark photon coupled to SM photon via kinetic **mixing parameter** $\epsilon$

Mass hierarchy scenarios

- $M_{h'} > M_{A'}$: $h' \rightarrow A' \rightarrow 4l, 4\text{had}, 2l + 2\text{had} \Rightarrow 6$ charged tracks
  - Searches conducted by **BaBar (2012)** and **Belle (2015)**
- $M_{h'} < M_{A'}$: $h'$ is long-lived and so invisible $\Rightarrow 2$ charged tracks
  - Partially constrained by **KLOE (2015)**
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Exploring unconstrained region at Belle II
**Data sample:** 2019 dataset $\Rightarrow 8.34 \text{fb}^{-1}$

**Detector signature:**
- Looking for invisible $h'$ with $A' \rightarrow \mu^+\mu^- \Rightarrow \mu^+\mu^- + \text{missing energy}$.
- 2D peak in $M_{\mu\mu}$ vs $M_{\text{rec}}$ ($M_{\text{rec}}$ - invariant mass of system recoiling from $\mu^+\mu^-$).

**Search strategy:**
- $M_{\mu\mu}$ & $M_{\text{rec}}$ correlated $\Rightarrow$ search in tilted elliptical mass windows.
- Spacing $\propto M^2$ 2D resolution.
- $\approx9000$ overlapping windows (large look-elsewhere effect).
- Counting experiment in each window (on average, 1 event in $\approx3$ windows).
Surviving Backgrounds:

- Main contributions
  - $\mu^+\mu^-(\gamma)$ (79%)
  - $\tau^+\tau^-\rightarrow\mu^+\mu^-$, 4$\nu$ (18%)
  - $e^+e^-\mu^+\mu^-$ (3%)
- Mostly localised near the kinematic limit, especially for $M_{\mu\mu} > 9$GeV/c$^2$

Helicity angle ($C_n$):

- Cut on angle between flight direction of $A'$ in CMS and $\mu^-$ in the $A'$ rest frame (Punzi FOM optimised in each search window)
- Signal eff. 10-25% for $M_{\mu\mu} > 4$GeV/c$^2$ (rapidly drops below due to trigger)
Data validation in control samples:

- $\mu^+\mu^-\gamma$: require energetic photon (usually vetoed)
- $\tau^+\tau^-\rightarrow e\mu, 4\nu$: require electron instead of muon

- Split 2D mass plane into orthogonal macro-regions
  - Each enriched by a single source of background
  - Data vs MC: normalisation, background shape modelling, recoil mass resolution.
  - Overall good agreement observed.
  - Discrepancies assigned as systematic uncertainties.

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty</th>
<th>target</th>
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</thead>
<tbody>
<tr>
<td>Pre-selections</td>
<td>2 - 9.1%</td>
<td>BKG &amp; signal</td>
</tr>
<tr>
<td>BKG shape</td>
<td>9.3% (region specific)</td>
<td>BKG</td>
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<tr>
<td>$C_\eta$ cut</td>
<td>1%</td>
<td>BKG</td>
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<tr>
<td>Mass resolution</td>
<td>2.4% (on average)</td>
<td>signal</td>
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<tr>
<td>Eff. Inside windows</td>
<td>2 - 5%</td>
<td>signal</td>
</tr>
<tr>
<td>Theory (BR $A'$)</td>
<td>4%</td>
<td>signal</td>
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<table>
<thead>
<tr>
<th>Total uncertainties</th>
<th>BKG</th>
<th>signal</th>
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<tr>
<td>2.2 - 12.7%</td>
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<tr>
<td>5.4 - 11.3%</td>
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Uncertainties in majority of search plane are dominated by sample size (impact of systematics on ULs < 1%, see next slide)

Exception is $M_{A'} > 9$GeV/c$^2$ ($\approx 25\%$ impact on ULs)
Search for excesses above expected background independently in the ≈9000 search windows.

- Event counts in a single window interpreted as:
  \[ N = \epsilon_{\text{sig}} \times L \times \sigma_{\text{DH}} + B \]
  with systematic uncertainties taken into account.

- Find no significant excess above background.
  90% upper limits computed in a Bayesian approach on the cross section from 1.65 to 10.51 GeV/c² in \( M_{A'} (M_{h'} < M_{A'}) \)
Search for excesses above expected background independently in the ≈9000 search windows.

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with systematic uncertainties taken into account.

Find no significant excess above background.

90% upper limits computed in a Bayesian approach on the cross section from 1.65 - 10.51 GeV in \( M_{A'} (M_{h'} < M_{A'}) \)

World leading ULs for \( 1.65 < M_{A'} < 10.51 \text{ GeV/c}^2 \)
Invisible Z’ - Theory

- U(1)’ extension of standard model -> new massive gauge boson
- Couples to μ and τ leptons (L_μ - L_τ) via g’
- Decay to DM or neutrinos -> neither of which detectable.
- possibilities;
  - (g-2)_μ
  - B → sμμ
  - Mediator between SM and DS

\[
\mathcal{L} = \sum_{\ell} \theta g' \bar{\ell} \gamma^\mu Z'_{\mu} \ell
\]

\[
\begin{align*}
M_{Z'} < 2M_\mu & \implies BF[Z' \to invisible] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau & \implies BF[Z' \to invisible] \approx 1/2, \\
M_{Z'} > 2M_\tau & \implies BF[Z' \to invisible] \approx 1/3.
\end{align*}
\]

if \( M_{Z'} > 2M_x \)
\( BF(Z' \to \chi \bar{\chi}) = 1 \)
Invisible Z’ - Analysis

Data sample: 2018 dataset ⇒ 276pb⁻¹

Detector signature:
- Looking for e⁺e⁻ → μ⁺μ⁻Z’ ⇒ signature μ⁺μ⁻ + recoil.
- Peak in the squared recoil mass distribution (M_{rec} - invariant mass of system recoiling from μ⁺μ⁻)

Search strategy:
- Search for peak in M_{recoil} distribution.
- Background suppression by 2D cuts to kinematic variables.

Background Rejection:
- τ suppression - reduces e⁺e⁻ → τ⁺τ⁻(γ), τ→μ, ττ
- Cut applied to 2D p_{rec}^{t, lmin} vs p_{rec}^{t, lmax} distribution + p_{μμ}^{t} > p_{cut}^{t}
- Selected to maximise FOM in recoil mass search windows
Invisible Z' - Result

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- Peak in the squared recoil mass distribution (M_{rec} - invariant mass of system recoiling from μ⁺μ⁻ )

Search strategy:
- Search for peak in M_{rec} distribution.
- Background suppression by 2D cuts to kinematic variables.

First published Belle II result - 2018 using 276pb⁻¹ (pilot run data)

Invisible Z’ - Update

Trigger & pre-selections:
- Events fire two-track, ffo (later ff30) trigger
- 2 good quality tracks
- MuonID, P_Tμμ > 0.1GeV/c²
- Recoil pointing in ECL barrel, no nearby photon
- Event extra energy < 0.5 GeV/c²
- 3D opening angle < 179.5°
- M_recoil < 9 GeV

Surviving Backgrounds:
- Main contributions
  - τ+τ→μ+μ−, 4ν
  - e+e−μ+μ−
  - μ+μ−(γ)
- Mostly localised in higher recoil mass (M^2_{rec} > 45 GeV²/c⁴)

Punzi-net:
- NN trained with novel ‘Punzi-loss’ - designed to optimise for Punzi FOM
  
\[ \sigma_{\text{min}}(t) = \frac{b^2}{2} + a \sqrt{B(t)} \right \frac{b^2 + 4a \sqrt{B(t)} + 4B(t)}{\varepsilon(t) \cdot L} \]
- Single cut to output of Punzi-net provides optimum FOM across search space.

Update expected soon!
Invisible Z’ - Update

Trigger & pre-selections:
- Events fire two-track, fff (ff30) trigger
- 2 good quality tracks
- MuonID, $P_T^{\mu\mu} > 0.1$ GeV
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- 3D opening angle < 179.5°
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Surviving Backgrounds:
- Main contributions
  - $\tau^+\tau^- \rightarrow \mu^+\mu^-$, $4\nu$
  - $e^+e^-\mu^+\mu^-$
  - $\mu^+\mu^-(\gamma)$
- Mostly localised in high recoil mass ($M_{\text{recoil}}^2 > 45$ GeV)

Punzi-net:
- NN trained with novel 'Punzi-loss' - designed to optimise for Punzi FOM
- Single cut to output of Punzi-net provides optimum FOM across search space.

*preliminary (conservative) systematics

Update expected soon!
Belle II has collected 384 fb$^{-1}$ thus far -> will collect $\approx$ 50 ab$^{-1}$ in the next decade.

Advantages in dark sector searches;
- Hermetic detector
- Clean collision environment
- Excellent PID
- Dedicated low-multiplicity triggers

Dark Higgsstrahlung search
- Search for invisible h' with $A' \rightarrow \mu^+\mu^- \rightarrow \mu^+\mu^- + \text{missing energy.}$ $\Rightarrow$ 2D peak in $M_{\mu\mu}$ vs $M_{\text{rec}}$
- No significant excess above bkg, 90% upper limits computed for 1.65 - 10.51 GeV in $M_{A'} (M_{h'} < M_{A'})$
- World leading ULs for $1.65 < M_{A'} < 10.51$ GeV/c$^2$

Z' to invisible search
- First Belle II physics paper with 276 pb$^{-1}$ - world leading result.
- Update with much more data, inclusive trigger, optimised selection on the way very soon $\Rightarrow$ will probe $g'$ coupling associated with muon g-2