Missing Energy and Displaced Vertices at Belle II

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Anomalies and Precision in the Belle II Era
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The main ingredients
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**Electromagnetic calorimeter (ECL):**
- CsI(Tl) crystals
- Waveform sampling (energy, time, pulse-shape)

**Vertex detectors (VXD):**
- 2 layer DEPFET pixel detectors (PXD)
- 4 layer double-sided silicon strip detectors (SVD)

**Central drift chamber (CDC):**
- He(50%):C2H6 (50%), small cells, fast electronics

**Magnet:**
- 1.5 T superconducting

**Trigger:**
- Hardware: < 30 kHz
- Software: < 10 kHz

**K_{L} and muon detector (KLM):**
- Resistive Plate Counters (RPC) (outer barrel)
- Scintillator + WLSF + MPPC (endcaps, inner barrel)

**Particle Identification (PID):**
- Time-Of-Propagation counter (TOP) (barrel)
- Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

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**Diagram:**
- Mediator mass $m_M$
- Dark matter mass $m_{DM}$
- Off-shell
- Invisible
- Visible
- Long-lived

**Graph:**
- $L_{peak}$ Before IR upgrade
- $L_{peak}$ After IR upgrade
- Peak luminosity [10^{35} cm^{-2} s^{-1}]

**Table:**
- Belle II (Preliminary)
- $\int L dt = 8.8$ fb
- $e^+e^-\rightarrow \tau^+\tau^-$ → 1x3 prong

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**Figure 1:**
- The overall L1 trigger efficiencies for SM ee → ττ → 1x3 prong events in the (a) combined and (b) individual channels. The data comes from the 2019a, 2019b and 2019c periods.
- The following trigger combinations are considered:
  - 2 full tracks
  - 3 full tracks
  - Short tracks
  - ECL total energy
  - 4 clusters
  - 3 clusters
  - Low multiplicity back-to-back clusters
  - Low multiplicity high energy cluster
  - ECL $\mu\mu$

- Statistical uncertainties are shown, although they are too small to be visible.
analysis covered today:
1. Invisible Z’
2. Dark Higgsstrahlung
3. Inelastic Dark Matter
Invisible Z’
**Invisible Z’**

- extend SM by adding a U(1)’ group
- new massive gauge boson Z’ couples only to leptons of 2\(^{\text{nd}}\) and 3\(^{\text{rd}}\) generation
- Z’ coupled to L\(_L\)-L\(_\tau\) via g’
- focus on invisible Z’ decay produced with a pair of muons
- invisible decay channel explored for the first time

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**PRD 89, 113004 (2014)**

\[
M_{Z'} < 2M_\mu \implies BF[Z' \rightarrow \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau \implies BF[Z' \rightarrow \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau \implies BF[Z' \rightarrow \text{invisible}] \simeq 1/3.
\]

if \(M_{Z'} > 2M_\chi\)

\[
BF(Z' \rightarrow \chi\bar{\chi}) = 1
\]

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

- may serve as mediator between SM and DS  
- may explain \((g-2)_\mu\)  
- may address anomalies in \(b\rightarrow s\mu^+\mu^-\)
Invisible $Z'$

- reconstruct recoiling mass against $\mu\mu$-pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkgd arise from QED processes:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$, $\tau\rightarrow\mu\nu\nu$
  - $\mu^+\mu^-e^+e^-$

\[
M_r = s + M_{\mu\mu}^2 - 2\sqrt{s}E_{\mu\mu}^{\text{CMS}}
\]
Invisible Z’

- reconstruct recoiling mass against μμ-pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkgs arise from QED processes:
  - μ+μ−(γ)
  - τ+τ−(γ), τ−μνν
  - μ+μ−e+e−
- main challenge: tau-pair events give the biggest contribution
  - apply dedicated tau-suppression procedure
  - based on the different origin of missing momentum in sig and bkg

\[
\text{Punzi FOM} = \frac{\epsilon_{\text{sig}}}{a/2 + \sqrt{N_{\text{bkg}}}}
\]

(a=1.6 for CL=90%)

\[
P_{\text{rec}}^{T_{\text{r}} \text{max}} \quad (P_{\text{rec}}^{T_{\text{r}} \text{min}}) : \text{the transverse recoil momentum with respect to the lepton with the higher (lower) momentum}
\]

\[
p_{\text{rec}}^{T_{\text{r}} \text{min}} : \text{the transverse momentum of the dimuon pair}
\]
Invisible $Z'$

- reconstruct recoiling mass against $\mu\mu$-pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkgs arise from QED processes:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$, $\tau\rightarrow\mu\nu\nu$
  - $\mu^+\mu^-\nu^+\nu^-$
- main challenge: tau-pair events give the biggest contribution
  - apply dedicated tau-suppression procedure
  - based on the different origin of missing momentum in sig and bkg
- compute UL on production cross section and coupling constant $g'$

\[ \int Ldt = 276 \text{ pb}^{-1} \]

\[ \text{Counts vs. Recoil mass [GeV/c}^2\text{]} \]

\[ \text{Belle II 2018} \]

\[ \text{M}_{Z'} [\text{GeV/c}^2] \quad \text{PRL 124, 141801 (2020)} \]

\[ \alpha (\text{obs.}) 90\% \text{ CL UL} \]

\[ \alpha (\text{sensitivity}) \text{ UL} \]
To the future and beyond

- the Z' searches allowed to demonstrate the capabilities of Belle II
- much more data has been recorded in the mean time (x1000)
- further progress:
  - deeper knowledge of the detector
  - improved particle identification
  - advanced MVA tools (Punzi-net)
Dark Higgsstrahlung
What about a Dark Higgs?

- extend SM by adding a U(1)’ group
- new minimal model includes dark photon (A’ boson), coupled to SM γ via kinetic mixing parameter ε
- introduce in analogy to SM a spontaneous symmetry breaking mechanism of U(1)’ with new particle, dark Higgs h’
- $e^+e^-\rightarrow A'h'$ (Higgsstrahlung), distinguish different signatures according to mass hypothesis
  - $m_{h'} > 2m_{A'}$, h’ decays to A’ pair, six charged particle final state, investigated by BaBar and Belle
  - $m_{h'} < m_{A'}$, h’ has large lifetime to escape detection, 2 charged particle final state plus missing energy, only investigated by KLOE

\[ \sigma \propto \varepsilon^2 \times \alpha_D \]

\[ m_{h'} - m_{A'} \]

\[ m_{h'} - m_{U} \]

Dark Higgsstrahlung

- look for two oppositely charged muons plus missing energy
- find a peak in two dimensional distribution of recoiling mass vs dimuon mass
- main SM background contributions arise from
  - $\mu^+\mu^-$
  - $\tau^+\tau^-$
  - $e^+e^-\mu^+\mu^-$
- **main challenge**: measurement strategy
  - scan+count in elliptical mass windows
  - continuous grid of 9k (overlapping) ellipses

\[
\begin{align*}
M_{\text{rec}} &= M_{\mu\mu} \\
M_{\text{rec}} + M_{\mu\mu} &= \sqrt{s}
\end{align*}
\]
- look for two oppositely charged muons plus missing energy
- find a peak in two dimensional distribution of recoiling mass vs dimuon mass
- main SM background contributions arise from
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$
  - $e^+e^-\mu^+\mu^-$
- **main challenge:** measurement strategy
  - scan+count in elliptical mass windows
  - continuous grid of 9k (overlapping) ellipses
- background suppression based on helicity angle, energy asymmetry between muons

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**Belle II Simulation**

Considered backgrounds:
- $\mu\mu(\gamma)$, $\tau\tau(\gamma)$, $ee\mu\mu$

**Low trigger efficiency**

**Candidates**

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• look for two oppositely charged muons plus missing energy
• find a peak in two dimensional distribution of recoiling mass vs dimuon mass
• main SM background contributions arise from
  ° $\mu^+\mu^-(\gamma)$
  ° $\tau^+\tau^-(\gamma)$
  ° $e^+e^-\mu^+\mu^-$
• **main challenge:** measurement strategy
  ° scan+count in elliptical mass windows
  ° continuous grid of 9k (overlapping) ellipses
• background suppression based on helicity angle, energy asymmetry between muons
• set UL on the kinematic mixing parameter times dark coupling constant $\varepsilon^2\alpha_D$
• very promising result with „small“ dataset
  ° probing unconstrained regions in 2D mass plane
  ° probing non trivial regions of $\varepsilon^2\alpha_D$
• expect huge LEE
• ongoing analysis, recently unblinded

**KLOE result**
**Dark Higgsstrahlung**

- Look for two oppositely charged muons plus missing energy.
- Find a peak in two-dimensional distribution of recoiling mass vs dimuon mass.
- Main SM background contributions arise from:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma)$
  - $e^+e^-\mu^+\mu^-$.
- Main challenge: measurement strategy
  - Scan+count in elliptical mass windows
  - Continuous grid of 9k (overlapping) ellipses

UL on $\epsilon$ (visible searches):

- $90\%$ C.L. UL on $\epsilon$ in Dark Photon searches (BaBar) stay in $\sim 10^{-7}$ regime.

Expected UL on $\epsilon^2$:

- $\approx 7 \times 10^{-4}$

BaBar limit on $\epsilon$:

- $\epsilon < 7 \times 10^{-4}$
Inelastic Dark Matter
Inelastic Dark Matter (iDM)

- model introduces a dark photon $A'$ and two dark matter states $\chi_1$ and $\chi_2$ with a small mass splitting
  - $\chi_1$ is stable (relic)
  - $\chi_2$ is long-lived at small values of kinetic-mixing coupling
- unconstrained by direct detection experiments, as both inelastic and elastic scattering suppressed
- focus on $m_{A'} > m_{\chi_1} + m_{\chi_2}$, such that $A' \rightarrow \chi_1 \chi_2$ is dominant decay channel
- production at Belle II via ISR

5 parameter model:

- $m_{A'}$ (fixed relative to $m_{\chi_1}$)
- $m_{\chi_1}$ (scan)
- mass difference $\Delta = m_{\chi_2} - m_{\chi_1}$ (categorical)
- dark coupling $\alpha_D$ (fixed to benchmarks)
- kinetic mixing parameter $\epsilon$ (limit)

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**iDM signature**

- **main challenge:** detector signature includes
  - an ISR photon
  - a displaced vertex which is non-pointing
  - missing energy
- search for a peak in the photon CMS energy distribution
- bkg contribution arise from
  - photon conversion: $e^+e^- \rightarrow \gamma \gamma (\gamma) \rightarrow e^+e^-$
  - meson decays: $e^+e^- \rightarrow K^0_S K^0_L (\gamma), K^0_S$ decays
iDM background suppression

- most of prompt $l^+l^-(\gamma)$ background is rejected by requirement of displaced vertex
- cut on $V^0$ momentum can be very effective
  - undetected $\chi_1$ lowers signal $V^0$ momentum w.r.t background
- the pointing angle $\alpha_{PA}$ offers further discriminating power
  - the 3-body iDM decay leads to a non-pointing $V^0$
  - most of the considered backgrounds are 2-body processes

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**FIG. 5.** Magnitude of the centre-of-mass frame momentum of $V^0$ selected from background with several signal samples overlaid. Results are shown after the iDM selection is applied, excluding the $|\vec{p}_{CMS}| < 2$ GeV/c cut [2]. As the $V^0$ decay emits an undetected $\chi_1$ in addition to the detected leptons which form the $V^0$, the $V^0$ in iDM signal events will tend to have lower momentum relative to the $V^0$ reconstructed in backgrounds from $e^+e^\rightarrow(K^0_S)^0L(\gamma)$ and $e^+e^\rightarrow(K^0_S)^0L(\gamma)$. The cut of $|\vec{p}_{CMS}| < 2$ GeV/c rejects a large fraction of the $e^+e^-\rightarrow(K^0_S)^0L(\gamma)$ and $e^+e^-\rightarrow(K^0_S)^0L(\gamma)$ background while maintaining a high signal efficiency.

**FIG. 6.** The quantity $\ln(1-\cos(\alpha_{PA}))$ is shown for the $V^0$ selected from background with several signal samples overlaid. Results are shown after the iDM selection is applied, excluding the $\alpha_{PA}$ cut [2]. The pointing angle, $\alpha_{PA}$, is defined as the angle between the $V^0$ vertex vector and the $V^0$ momentum vector. To allow the structure of the distribution to be visualized the transformation $\ln(1-\cos(\alpha_{PA}))$ is used. As the iDM $V^0$ originates from a 3-body decay it tends to result in a non-pointing $V^0$ relative to the $V^0$ selected from $e^+e^-\rightarrow(K^0_S)^0L(\gamma)$ and $e^+e^-\rightarrow(K^0_S)^0L(\gamma)$ backgrounds.
Inelastic Dark Matter (iDM)

- estimate signal yield by counting events in ISR photon window (final analysis will use template fit)
- maximum reach of $\chi_1$ is determined by 2GeV trigger threshold
- new displaced vertex trigger under consideration
- Belle II can explore a large region of new iDM parameter space

$\alpha_D = 0.1$, $m_{A'} = 2.5 m_{\chi_1}$, $\Delta = 0.4 m_{\chi_1}$

![Belle II Simulation](image)

$\chi_1$ Mass (GeV/c²) vs. Signal Events per 100 fb⁻¹

Log scale is used for the $x$-axis to accommodate the wide range of masses.
Conclusion

- broad and active program of DS physics at Belle II
- available phase-space is probed with many different models
- further analysis with displaced vertices include $B \rightarrow K a$, $B \rightarrow K h'$...
- advanced MVA tools developed
- first results published and more to come
Conclusion

- broad and active program of DS physics at Belle II
- available phase-space is probed with many different models
- further analysis with displaced vertices include $B \rightarrow K\alpha$, $B \rightarrow K\ell\nu$ …
- advanced MVA tools developed
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Backup
Additional searches: $B \rightarrow K h'$

- Search for long-lived scalar in rare $B$ meson decays
  - $B \rightarrow K h', h' \rightarrow \mu \mu, \pi \pi, KK$
  - generic scalar that mixes with the Higgs sector
  - LHCb and Belle II complementary due to different $B$ momenta
  - reach towards even smaller mixing angle by searching for $B \rightarrow K+$invisible

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Invisible Z’ - LFV

- look for LFV Z’ that couples to eμ
- model-independent search with same selection criteria
- included in same publication

Belle II 2018
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Counts vs. Recoil mass [GeV/c^2]

Belle II 2018
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\[ \varepsilon \sigma (\text{obs.}) \text{ 90\% CL UL} \]
\[ \varepsilon \sigma \text{ expected UL} \]

PRL 124, 141801 (2020)