Dark matter search at

3rd DMNet 2023 - Padova

Thomas Czank
on behalf of the Belle(II) collaborations
2023, September 28th
Origins of the dark sector

KEKB and Belle

Dark sector searches in Belle

Extra Leptophilic $U(1)$ gauge boson, $Z'$

The invisible $Z'$ search

Punzi Loss Neural Net

The leptophilic scalar search @ Belle

Summary
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Summary
What is dark matter (DM)?

- Coma galaxy cluster gravitational mass luminosity discrepancy (Fritz Zwicky - 1937)
- CMB (Cosmic Microwave Background) radiation fluctuations
- Gravitational Lensing
- Galaxy rotation velocity problem
Figure 1: Black dots are the observed rotation velocities. The blue solid line represents all the visible components of the galaxy velocities added together.

There is extra invisible matter!
Weakly Interacting Massive Particle (WIMP) Searches

\[ \chi \bar{\chi} \leftrightarrow e^+ e^-, \mu^+ \mu^-, q\bar{q}, W^+ W^-, ZZ, HH, \ldots \]

- Naturally produced with the correct thermal relic density (the WIMP miracle)
- WIMPS are Beyond the Standard Model candidates
- Prediction of signals that may be seen in the current and near-future experiments, collider experiments and direct detection
APPEC 2021 status

- Sensitive for 10 GeV $\sim$ 1 TeV
- No Signal Found! Yet
- Under 10 GeV there is a **region without any constraints**, it could be studied by collider experiments
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Summary
The KEKB Accelerator

KEKB is an $e^+e^-$ collider made up of two rings, a High Energy Ring, HER and a Low Energy Ring, LER.

Located in Tsukuba and has achieved a record Luminosity of $1\text{ ab}^{-1}$

Operated from 1999 to 2010

KEKB together with the Belle detector were responsible for confirming the CPV formalism in the quark sector, the 2008 Nobel Prize of Physics.
The **Belle** Detector

- SVD (Silicon Vertex Detector)
- EFC (Extreme Forward Calorimeter)
- ACC (Aerogel Cherenkov Counter)
- TOF (Time Of Flight)
- CDC (Central Drift Chamber)
- ECL (Electromagnetic Calorimeter)
- KLM ($K^0_L - \mu$)
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**Dark sector searches in Belle**

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Summary
Belle dark sector searches summary

1. Dark photon and dark higgs
   - \( e^+e^- \rightarrow A'h'(\rightarrow A'A') \)
2. Quark coupled gauge boson
   - \( \eta \rightarrow U'(\rightarrow \pi\pi)\gamma \)
3. CP-odd Higgs Boson and low mass DM
   - \( \Upsilon(1S) \rightarrow \gamma A^0(\rightarrow \chi\chi) \)
4. Dark photon from \( B^0 \)
   - \( B^0 \rightarrow A'A'(\rightarrow ee, \mu\mu, \pi\pi) \)
5. Visible \( Z' \)
   - \( e^+e^- \rightarrow Z'(\rightarrow \mu^+\mu^-)\mu^+\mu^- \)
   - Check out Martina’s talk on Belle II results
6. Leptophilic Scalar
   - \( e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow ee, \mu\mu) \)
7. Invisible \( Z' \)
   - Check out Enrico’s talk for Belle II results
   - Check out Laura’s talk for Belle II results
   - \( Z' \rightarrow \nu_l\nu_l(\chi, \bar{\chi}) \)
8. Dark photon
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Summary
### $(g - 2)_\mu$ 2021 measurement

PRL 126, 141801 - 2021

$$\Delta a_\mu \equiv a_\mu^\text{exp} - a_\mu^\text{SM} = (251 \pm 59) \times 10^{-11}$$

corresponding to $4.2\sigma$

### $(g - 2)_\mu$ 2023 measurement

2308.06230

$$\Delta a_\mu \equiv a_\mu^\text{exp} - a_\mu^\text{SM} = (249 \pm 48) \times 10^{-11}$$

corresponding to $5.1\sigma$
Some options

1. The gap between SM and the Experimental result can be bridged with an improved calculation of $a^\text{SM}_\mu$

2. Experimental corrections

3. **New Physics is the reason for the gap**
   - Apparently not, check Giovanni’s talk from yesterday

4. ?
$L_{e,\mu,\tau}$ are the lepton numbers

$L_1 = L_e - L_\mu$, $L_2 = L_e - L_\tau$ and $L_3 = L_\mu - L_\tau$

Three different new gauge groups

so that $G_{\text{SM}} \otimes U(1)_{L_{1,2,3}}$

allows for an additional neutral gauge boson ($Z'_1$, $Z'_2$, and $Z'_3$)

$Z'_1$ and $Z'_2$ mediate $L_1 = L_e - L_\mu$ and $L_2 = L_e - L_\tau$
\[ \mathcal{L}_{Z'} = -\frac{1}{4} (Z')_{\alpha\beta} (Z')^{\alpha\beta} + \frac{1}{2} m^2_{Z'} Z'_{\alpha} Z'^{\alpha} + g' Z'_{\alpha} (\bar{\ell}_2 \gamma^\alpha \ell_2 - \bar{\ell}_3 \gamma^\alpha \ell_3 + \bar{\mu}_R \gamma^\alpha \mu_R - \bar{\tau}_R \gamma^\alpha \tau_R) \]

where the \( g' \) is the \( U(1) \) gauge coupling, \((Z')_{\alpha\beta} = \partial_{\alpha} Z'_\beta - \partial_{\beta} Z'_\alpha \) is the field strength, \( \ell_2 = (\nu_\mu, \mu_L) \) and \( \ell_3 = (\nu_\tau, \tau_L) \) are the electroweak doublets. The \( g' \) coupling the new gauge boson \( Z' \) to the electroweak doublets and the that enhances the rate of neutrino trident production in the \( \nu_\mu N \rightarrow N \nu_\mu^+ \mu^- \) process.

**Neutrino trident production has not been observed so far!**
Assuming that a sterile neutrino $\nu_s$, that mixes weakly with the active $\nu_a(\mu, \tau)$ states, is added to the SM.

\[
\begin{pmatrix}
\nu_a \\
\nu_s
\end{pmatrix} \equiv \begin{pmatrix}
\cos \theta_0 & \sin \theta_0 \\
-\sin \theta_0 & \cos \theta_0
\end{pmatrix} \begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

\[
\Gamma_{Z' \rightarrow \nu_S} = \frac{g'^2 M_{Z'}}{12\pi} \frac{\sin^2 2\theta_m}{4} (1 + \tan^2 \theta_m)
\]

A massive $Z'$ with MeV < $m_{Z'}$ < GeV with coupling $10^{-2} < g' < 10^{-6}$ results in the correct relic abundance of sterile neutrinos DM.
Sterile neutrino candidates

- $M_{Z'} - g'$ plane
- Magnetic moment of the muon anomaly favored region
- $N_{\text{eff}} \rightarrow M_{Z'} \gtrsim 2.0$ MeV from Planck measurement constraint 1303.5076
- Sterile neutrino candidates

- $m_s = 7.1$ keV sin $2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV sin $2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV sin $2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV sin $2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\text{DM}} = 4.7 \times 10^{-4}$ keV$/m_s)$
\[ \Gamma(Z' \to \ell^+ \ell^-) = \frac{(g')^2 m_{Z'}}{12 \pi} \left( 1 + \frac{2 m_{\ell}^2}{m_{Z'}^2} \right) \sqrt{1 - \frac{4 m_{\ell}^2}{m_{Z'}^2}} \theta(m_{Z'} - 2 m_{\ell}) \]

\[ \Gamma(Z' \to \nu_{\ell} \bar{\nu}_{\ell}) = \frac{(g')^2 m_{Z'}}{24 \pi} \]

Diagram showing the branching ratio (BR) as a function of the mass of the \(Z'\) boson. The graph plots BR on the y-axis against \(m_{Z'}\) on the x-axis. The graph includes lines for different decay modes:
- \(Z' \to \nu_{\ell} \bar{\nu}_{\ell}\)
- \(Z' \to \mu^- \mu^+\)
- \(Z' \to \tau^- \tau^+\)
• reduced mass, $m_R$, scan
  \[ m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2} \]
• 1 background
  • $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
• non ISR MC
• Detection efficiency for ISR and non ISR
• No $Z'$ signal was found

• Limit set for $0.212$ (dimuon mass) $\sim 10 \text{ GeV}/c^2$
The invisible $Z'$ search

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Summary
$Z' \to \text{invisible or not fully visible}$

- $Z' \to \tau^+ \tau^-$
  - Recent Belle II publication renders Belle analysis not competitive
- $Z' \to \chi \bar{\chi}$
- $Z' \to \nu_\ell \bar{\nu}_\ell$
What does it look like?
How were the cuts elaborated?

- 2D histogram $x : M_{Z'}^2$
- Signal resolution $\sigma$ is obtained under the studied cut
- $\varepsilon$ detection efficiency at fixed $Z'$ mass under cuts
- $B$ is the integration of backgrounds around $(\pm 3\sigma)$ $Z'$ mass
- $\frac{\varepsilon}{\sqrt{B}}$ maximized
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<td>$e^+ e^- \rightarrow d^- d^+$</td>
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<tr>
<td></td>
<td>$e^+ e^- \rightarrow s^- s^+$</td>
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</tr>
<tr>
<td></td>
<td>$e^+ e^- \rightarrow \tau^+ \tau^-$</td>
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<tr>
<td></td>
<td>$e^+ e^- \rightarrow \mu^+ \mu^-$</td>
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<tr>
<td>BBBREM</td>
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<tr>
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<td>$e^+ e^- \rightarrow e^+ e^-$</td>
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</table>
$Z'$ invisible selection criteria list

1. 2 tracks of opposite charge only, 2 $\mu$ ID
2. Vertex fit of the the 2 tracks, CL cut
3. Energy conservation dependent on $M_{Z'}^2 = s + m_{\mu\mu}^2 - 2E_{\mu\mu}^*\sqrt{s}$
4. Energy sum of neutral cluster, ECL
5. $p_t$ of the two tracks sum dependent on $M_{Z'}$
6. 6.1 Mass conservation on $M_{Z'}$
   6.2 Opening angle between tracks
7. Recoil muon pair polar angle
8. Azimuthal angle difference between final state 4-vector and neutral clusters
9. $Z'$ missing angle cut
10. $p_{tZ'}^*$ projection on $p_{\text{max}}^\mu$ and $p_{\text{min}}^\mu$
Cut effects on $m_{Z'} = 50 \text{ MeV}/c^2 \sigma = 185.5 \text{ MeV}/c^2$

$m_{Z'} = 0.050 \text{ GeV}/c^2, \sigma = 185.49 \text{ MeV}/c^2$

- $e^+e^-\rightarrow\mu^+\mu^-Z'$, $Z'\rightarrow\nu\bar{\nu}$ or $\rightarrow\chi\bar{\chi}$
- $e^+e^-\rightarrow\mu^+\mu^-$
- $e^+e^-\rightarrow\tau^+\tau^-$
- $e^+e^-\rightarrow\mu^+\mu^+\mu^-$
- $e^+e^-\rightarrow e^+e^-\mu^+\mu^-$

#0, no cuts
#1, 2 tracks & $\sum Q=0$
#2, CL_vtx
#3, Energy conservation
#4, $E_{\text{sum}}$
#5, $p_t$
#6, Mass conservation
#6a, Open angle between tracks
#7, Recoiling muon pair polar angle
#8, $\cos(\phi_{FS} - \phi_{\gamma})$
#9, $\theta_{\text{missing } Z'}$
Diagonal cut

\[ e^+ e^- \rightarrow \tau^+ \tau^- \]

- Missing transverse momentum in cms: \( p_t^{*Z'} \)
- Maximum momentum muon in cms: \( p_{\mu}^{*\mu} \)
- Minimum momentum muon in cms: \( p_{\mu}^{*\mu} \)

- \( \angle p_t^{*Z'} p_{\mu}^{*\mu} \equiv \alpha_M \)
- \( \angle p_t^{*Z'} p_{\mu}^{*\mu} \equiv \alpha_m \)

- Projection:
  \[ p_t^{*Z'} \sin \alpha_M \equiv p_{\max} \]
- Projection:
  \[ p_t^{*Z'} \sin \alpha_m \equiv p_{\min} \]
The Neural Net outperforms the handmade cuts!
The Punzi Loss Neural Net selection

- **Layers:**
  1. input (32 nodes)
  2. hidden (64 nodes)
  3. hidden (64 nodes)
  4. hidden (32 nodes)
  5. hidden (16 nodes)
  6. hidden (8 nodes)
  7. output (1 node)

- $E^{*}_{\mu\mu}$
- $\cos \theta^*_{\text{rec}}$
- $E_{\text{sum}}$
- $p — value$
- $\Delta M$
- $\Delta M_{g}$
- $p_{\text{thrust}}$
- $p_{l\min}^{\mu}$
- $p_{l\max}^{\mu}$
- $p_{t}^{*}Z' \sin \alpha_{M}$
- $p_{t}^{*}Z' \sin \alpha_{m}$
- $p_{t}^{\mu\mu}$
- $\angle p_{t}^{\mu-} p_{\text{thrust}}$
- $\angle p_{t}^{\mu+} p_{\text{thrust}}$
Background sources and detection efficiency

- Hand Crafted Cuts (HCC)
- PINN trained with 60 ab$^{-1}$ MC samples
Preliminary Limit in Comparison with Belle II $79.1 \text{ fb}^{-1}$

- Belle II has a much better data for the $Z' \rightarrow \text{invisible}$
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Summary
What if instead of the vector boson mediator \((Z', A')\) a leptophilic dark Higgs \((\phi_L)\) is responsible for \((g - 2)_\mu\) ?

\[
\mathcal{L} = -\xi \sum \frac{m_\ell}{v} \bar{\ell} \phi_L \ell
\]

- \(\ell\) are all leptons, and \(m_\ell\) their masses
- \(\xi\) is the coupling strength
- \(v = 246\) GeV is the vacuum expectation value of the Higgs Field
**Signal decay modes (MadGraph 5)**

- $e^+e^- \rightarrow \tau^+\tau^- \phi_L$
  1. $\phi_L \rightarrow e^+e^-$ for $m_{\phi_L} \leq 2m_\mu$
  2. $\phi_L \rightarrow \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu(\tau)$

**Data sample and backgrounds**

- $626 \text{ fb}^{-1} = 562(\Upsilon(4S)) + 64(\Upsilon(4S) - 60 \text{ MeV})$
  1. $e^+e^- \rightarrow q\bar{q}, q = u, d, s, c$
  2. $e^+e^- \rightarrow \ell^+\ell^-, \ell = e, \mu, \tau$
  3. unsimulated $e^+e^- \rightarrow \tau^+\tau^-e(\mu)^+e(\mu)^-$
Selection Criteria 2207.07476

1. events with 4 track
2. Transverse distance from IP < 1 cm
3. Longitudinal distance from IP < 5 cm
4. Net charge of the event is zero
5. At least one track ID is \( \mu \) or \( e \)

Reconstruction

1. \( \phi_L \) from \( ee \) or \( \mu \mu \) common vertex
2. remaining 2 tracks are daughters from \( \tau \)
3. Efficiencies corresponding to 98\% and 83\%

Major background

- \( e^+ e^- \rightarrow \tau \tau \)
- to remove radiative Bhabha (\( \mu \mu \)) a rectangular cut
  1. \( M_{\text{miss}} \in [2, 6] \text{ GeV/c}^2 \)
  2. \( \theta_{\text{miss}}^{\text{CM}} \in [30^\circ, 150^\circ] \)
To suppress the surviving background a boosted decision tree (BDT), `GradientBoostingClassifier` from `scikit-learn` assigns 5 BDT scores

<table>
<thead>
<tr>
<th>Signal</th>
<th>1. $\phi_L \rightarrow e^+e^-(\mu^+\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>2. $\tau^+\tau^-$&lt;br&gt;3. $e^+e^-(\mu^+\mu^-)$&lt;br&gt;4. $q\bar{q}$&lt;br&gt;5. $BB$</td>
</tr>
</tbody>
</table>
Results: GCR and SR 2207.07476

Background

Signal
Results: $\xi$ coupling limit 2207.07476

- Finally touching very low mass parameter spaces in Belle
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Summary

- Belle full data (~1 ab\(^{-1}\)) analysis of the \(Z'\) invisible hopefully before winter
  - Currently using Belle II machinery tuned to the Belle background and efficiency
- Belle searches are still viable (For a while)
- Belle II machinery can work greatly provided some tuning considering Belle data conditions
Back up
Z’ visible search @ Belle
What did we learn in the $Z'$ visible search?

**HadronB skim**

![Graph](image1.png)

**tauskimA**

![Graph](image2.png)
\[ 2 \leq q \leq 8 \]
\[ |\text{charge sum}| \leq 2 \]
\[ \sum P^{CM} < 10 \text{ GeV/c} \]
\[ \sum E(ECL) < 10 \text{ GeV/c} \]
\[ P_{t\text{max}} > 0.5 \text{ GeV/c} \]
\[ \text{Evt vtx } |r| < 0.5 \text{ cm, } |z| < 3 \text{ cm} \]

for 2 tracks events
- Sum of \( P^{CM} < 9 \text{ GeV/c} \)
- Sum of \( E(ECL) < 9 \text{ GeV} \)
- \( 5 < \theta_{\text{missingmomentum}} < 175^\circ \)

\[ E_{\text{rec}} > 3 \text{ GeV or } P_{t\text{max}} > 1.0 \text{ GeV/c} \]

for 2 \sim 4 \text{ charged tracks}
- \( E_{\text{tot}} < 9 \text{ GeV or max opening angle} < 175^\circ \)
- \( N_{\text{barrel}} \geq 2 \text{ or } E(ECL)_{\text{trk}} < 5.3 \text{ GeV} \)

Too tight for the visible \( Z' \)
\( P_{t_{\text{max}}} > 0.5 \text{ GeV/c} \)

\( 2 \leq q \leq 8 \)

\( \left| \text{charge sum} \right| \leq 2 \)

\( \sum P_{\text{CM}} < 10 \text{ GeV/c} \)

\( \sum E(\text{ECL}) < 10 \text{ GeV/c} \)

Evt vtx \( |r| < 1.0 \text{ cm, } |z| < 3 \text{ cm} \)

for 2 tracks events

- Sum of \( E(\text{ECL}) < 11 \text{ GeV} \)
- Sum of \( P_{\text{CM}} < 9 \text{ GeV/c} \)
- \( 5 < \theta_{\text{missing momentum}} < 175^\circ \)

\( E_{\text{rec}} > 3 \text{ GeV} \) or \( P_{t_{\text{max}}} > 1.0 \text{ GeV/c} \)

for 2 ∼ 4 charged tracks

- \( E_{\text{tot}} < 9 \text{ GeV} \) or max opening angle \( < 175^\circ \) or \( 2 < \sum E(\text{ECL}) < 9 \text{ GeV} \)
- \( N_{\text{barrel}} \geq 2 \) or \( E(\text{ECL})_{\text{trk}} < 5.3 \text{ GeV} \)

Too loose for the invisible \( Z' \)
Z’ invisible search @ Belle
Cut example: p-value

Track quality, p-value, based on Vertex Fitter

Selection curve for all $Z'$ mass hypotheses signal MC.

Selection curve for exp65 data.
Cut example: $\Delta E$

How many $\sigma$ should be taken to maximize FOM?
Trigger Efficiency (Signal)

Belle Trigger

Belle II Trigger

![Graph showing trigger efficiency vs. m_\(Z'\) for Belle Trigger and Belle II Trigger.]