New Phenomena Session

Latest results on τ and dark sector physics at Belle II

31/03/2021
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KEKB to SuperKEKB

Expect x30 higher luminosity from $2.2 \times 10^{34} \rightarrow 6.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- New beam pipe & bellows
- New IR
- Colliding bunches
- New positron target / capture section
- New superconducting/permanent final focusing quads near the IP
- Add / modify RF systems for higher beam current
- Replace short dipoles with longer ones (LER)
- Redesign the lattices of HER & LER to squeeze the emittance
- Low emittance gun
- Low emittance positrons to inject
- Low emittance electrons to inject
- Belle II
- New IR
- BEll Laboratory Experiment

See also Saurabh Sandilya’s presentation
Belle II Detector Elements

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
(1 in 2019) layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C₂H₆(50%), small cells, long lever arm, fast electronics

See also Saurabh Sandilya's presentation
What happens in $e^+e^-$ collisions at SuperKEKB?

See *The Belle II Physics Book*

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Cross section [nb]</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(4S)$</td>
<td>1.05 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>$u\bar{u}(\gamma)$</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>$d\bar{d}(\gamma)$</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>$s\bar{s}(\gamma)$</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>$e^0(\gamma)$</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-(\gamma)$</td>
<td>300 ± 3 (MC stat.)</td>
<td>$10^\circ &lt; \theta^x_{e^\pm} &lt; 170^\circ$, $E^x_{e^\pm} &gt; 0.15$ GeV</td>
</tr>
<tr>
<td>$e^+e^-(\gamma)$</td>
<td>74.4</td>
<td>$e^\pm (p &gt; 0.5$ GeV) in ECL</td>
</tr>
<tr>
<td>$\gamma\gamma(\gamma)$</td>
<td>4.99 ± 0.05 (MC stat.)</td>
<td>$10^\circ &lt; \theta^x_{\gamma\gamma} &lt; 170^\circ$, $E^x_{\gamma\gamma} &gt; 0.15$ GeV</td>
</tr>
<tr>
<td>$\mu^+\mu^- (\gamma)$</td>
<td>3.30</td>
<td>$\gamma^\pm (p &gt; 0.5$ GeV) in ECL</td>
</tr>
<tr>
<td>$\mu^+\mu^- (\gamma)$</td>
<td>1.148</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^- (\gamma)$</td>
<td>0.831</td>
<td>$\mu^\pm (p &gt; 0.5$ GeV) in CDC</td>
</tr>
<tr>
<td>$\mu^+\mu^- (\gamma)$</td>
<td>0.242</td>
<td>$\mu^\pm (p &gt; 0.5$ GeV) in CDC, $\geq 1 \gamma (E_\gamma &gt; 0.5$ GeV) in ECL</td>
</tr>
<tr>
<td>$\tau^+\tau^- (\gamma)$</td>
<td>9.19</td>
<td></td>
</tr>
<tr>
<td>$\nu\bar{\nu}(\gamma)$</td>
<td>0.25 × 10^-3</td>
<td></td>
</tr>
<tr>
<td>$e^+e^-e^+e^-$</td>
<td>39.7 ± 0.1 (MC stat.)</td>
<td>$W_{e\ell} &gt; 0.5$ GeV</td>
</tr>
<tr>
<td>$e^+e^-\mu^+\mu^-$</td>
<td>18.9 ± 0.1 (MC stat.)</td>
<td>$W_{e\ell} &gt; 0.5$ GeV</td>
</tr>
</tbody>
</table>

**$\sigma$:** cross-section of the process to be studied in the specific experiment

**$N = L \times \sigma \times \varepsilon$:**

- **$N$:** number of events of a process
- **$L$:** luminosity of an experiment
- **$\varepsilon$:** total efficiency, including trigger.

@ Belle II many new triggers developed specifically for low multiplicity events

A **SuperB** factory is also a **Super-charm** factory, a **Super-\(\tau\)** factory, etc.

This is a great feature of this collision scheme that we can take advantage of.

As of today @ Belle II $\int L \, dt = O(100 \, fb^{-1})$
Physics with $\tau$ at Belle II

$\sigma[e^+e^\to \tau^+\tau^-]=0.92\,nb$ @ Belle II

Large production cross-section

Many final states

Different reconstruction techniques

$\tau$ as a probe of new physics and of detector performance

Some ongoing physics analyses

- $\tau$ mass/lifetime measurements
- LFV $\tau\to l\gamma$
- LFV $\tau\to lll$
- LFV $\tau\to l\pi^0$
- LFV & LNV $\tau\to lhh$
- LFUV $\tau^+\to l^+\nu\bar{\nu}_l$, $\tau\to h\nu$
- $|V_{us}|$ from $\tau\to h\nu$
- Absolute BF measurements for $\tau^+\to l^+\nu\bar{\nu}_l$
- Dalitz analysis of $\tau\to 3\pi\nu$
- Search for $\tau\to l\alpha$

Some technical studies

- Tracking efficiency
[BELLE2-NOTE-PL-2020-014]
- Trigger efficiency
[BELLE2-NOTE-PL-2020-015]
- Particle (mis-)identification
[BELLE2-CONF-PH-2021-002]
- Etc.
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τ mass measurement at Belle II

- τ mass poorly known compared to e or μ (a few orders of magnitude less precise)
- Important parameter in lepton universality tests

$$B_{\tau \to l}^{SM} \propto B_{\mu \to e} \frac{m_{\tau}^5}{m_{\mu}^5}$$

3x1 topology to extract the mass

“Pseudomass” calculated from the 4-momentum of the 3-pion system

Signal: $\tau \to \pi^+ \pi^- \pi^0 \nu_\tau$ (BF $\sim 9.3\%$)
Tag: $\tau \to l^- \nu_\tau, \pi^- \nu_\tau, \pi^0 \nu_\tau$ ($\sum BF \sim 71.52\%$)

$$M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$
\( \tau \) mass measurement at Belle II

Perform an unbinned maximum likelihood fit to the data using an empirical fit function

\[
F(M_{\text{min}}|\vec{P}) = (P_3 + P_4 M_{\text{min}}) \tan^{-1}\left(\frac{M_{\text{min}} - P_1}{P_2}\right) + P_5 M_{\text{min}} + 1
\]

\[
m_\tau = 1777.28 \pm 0.75_{\text{stat}} \pm 0.33_{\text{sys}} \text{ MeV}/c^2
\]

Main source of systematic uncertainties due to tracking corrections → expected to improve as we understand our detector better

As of today @ Belle II \( \int L \, dt = O(100 \text{ fb}^{-1}) \)
Search for $\tau \to l\alpha$ at Belle II

- Possible new light boson $\alpha$ in tau decays
- Previous search from ARGUS (1995, 476/pb) and MARK III (1985, 9.4/pb)

3x1 topology to search for $\alpha$

Signal and background share same final state but different kinematics.
- In the $\tau$ rest frame the lepton momentum has a peaking structure

We also test an alternative method in tau pseudo rest-frame using the thrust vector:

$$\vec{T} = \max \left( \sum \frac{\vec{p}_i \cdot \hat{T}}{|\vec{p}_i|} \right)$$
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3x1 topology to search for $\alpha$

UL is provided for the ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$

See BELLE2-NOTE-PL-2020-018

Dark matter?

Dark Sector Candidates, Anomalies, and Search Techniques

ArXiv: 1707.04591
Dark matter?

ArXiv: 1707.04591

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators, Microlensing
Searching for Dark Matter and Forces @ Belle/Belle II

Some ongoing searches

- Dark photon, visible and invisible decays
- Light Z’ boson, visible and invisible decays
- Dark higgs boson
- Magnetic monopoles
- Axion like particles
- Long lived particles

From Symmetry Magazine

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Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.
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- Long lived particles
Lepton non-universal coupling: the $L_\mu - L_\tau$ model and a dark $Z'$

The model is a new gauge boson, $Z'$, which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g' \bar{\nu}_\mu \gamma^\mu Z'_\mu \nu + g' \bar{\nu}_\tau \gamma^\mu Z'_\mu \nu + g' \bar{\nu}_{\mu,L} \gamma^\mu Z'_\mu \nu_{\mu,L} + g' \bar{\nu}_{\tau,L} \gamma^\mu Z'_\mu \nu_{\tau,L}. $$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+ \ell^-) = \frac{(g')^2 M_{Z'}}{12 \pi} \left(1 + \frac{2 M_\ell^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4 M_\ell^2}{M_{Z'}^2}} \theta(M_{Z'} - 2 M_\ell),$$

$$\Gamma(Z' \to \nu \bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24 \pi}.$$

$$BR(Z' \to \text{invisible}) = \frac{2 \Gamma(Z' \to \nu \bar{\nu}_\ell)}{2 \Gamma(Z' \to \nu \bar{\nu}_\ell) + \Gamma(Z' \to \mu \bar{\mu}) + \Gamma(Z' \to \tau \bar{\tau})}$$
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First physics paper @Belle II, PRL 124, 141801 (2020), arXiv:1912.11276
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New and improved PID system (KLM) and new machine learning analysis techniques based on artificial neural networks (ANNs), provide better selection and better sensitivities.
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In the near term
**Dark Higgs-strahlung @ Belle II**


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**Higgs-strahlung process**

$h' = \text{dark Higgs, } A' = \text{dark photon }$

Higgs-strahlung: $h'$ decays depending on $M_{h'}$ and $M_{A'}$. Measures the coupling constant of the dark photon to the dark Higgs, $\alpha_D$.

$M_{h'} > 2M_{A'} : h' \rightarrow A'A'$, Very low background.

- Exclusive: 3 charged tracks pairs with same invariant mass and total energy of the event.
- Inclusive: 2 charged tracks pairs, same invariant mass, third $A'$ from 4-mom. of $e^+e^-$ system

$M_{A'} < M_{h'} < 2M_{A'} : h' \rightarrow A'A^*$

$M_{h'} < M_{A'} : h' \text{ (very) long-lived}$

Thanks to (small) kinetic mixing with the standard model photon, the dark photon $A'$ can decay to standard model final states.
Dark Higgs-strahlung @ Belle II


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$e^+, \mu^+, \text{etc.}$

$e^-, \mu^-, \text{etc.}$

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Dark Higgs-strahlung @ Belle II with 10/fb


- Identical final state as for the invisible Z' search
- Low SM background
- Allows simultaneous search of a dark Higgs boson and of dark photon
- Existing limits only from KLOE

Higgs-strahlung process
h' = dark Higgs, A' = dark Photon

Current focus on μ+μ-+invisible final state, plans to extend to e+e-+invisible

Approaching data unblinding!
Axion Like Particles (ALPs) at Belle II

\[ \mathcal{L} = -\frac{g_{\alpha\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{\alpha Z\gamma}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{\alpha Z Z}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{\alpha W W}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu} \]

\[ s^{1/2} = 10.58 \text{ GeV}, \quad g_{\alpha\gamma\gamma} = 10^{-4} \text{ GeV}^{-1} \]

Photon fusion

ALP-strahlung
ALPstrahalung at Belle II

- Three photons that add up to the beam energy + bump on diphoton mass.
- SM background: $e^+e^- \rightarrow \gamma\gamma(y)$, $e^+e^- \rightarrow e^+e^-(\gamma)$, and $e^+e^- \rightarrow$ scalar+$\gamma(\gamma)$.
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Latest results on $\tau$ and dark sector physics at Belle II

Summary

• Presented a selection of recent results and ongoing analyses
• We are accumulating data at unprecedented luminosity
• Many new results to be expected in the near future

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Moriond QCD 2021: very unusual conference settings… Still an amazing event!

Thank you for your attention!

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