Trigger and Data Acquisition (DAQ) Systems at Belle II Experiment

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IHEP, Beijing
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An asymmetric electron-positron collider
\(e^+ \sim 4\text{GeV} \quad e^- \sim 7\text{GeV}\)
\(~3\text{km circumference}\)

SuperKEKB

Belle II detector

@KEK, Tsukuba
One hour away from Tokyo
SuperKEKB Luminosity Project

Goal of Belle II/SuperKEKB

- $L_{\text{int}} > 50 \text{ ab}^{-1}$ by 2024 (50 x Belle)
- $L_{\text{peak}} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (40 x KEKB)

Commissioning starts in early 2016.

Shutdown for upgrade

Integrated luminosity ($\text{ab}^{-1}$)

Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)

Calendar Year


10^{-36} 10^{-34} 10^{-33} 10^{-32} 10^{-31} 10^{-30} 10^{-29} 10^{-28}

SuperKEKB

Nano-Beam Scheme
Belle II Detector

Belle II Detector features various components for particle detection and identification:

- **ECL**: Energy, timing (EM Calorimeter: CsI(Tl), waveform sampling (barrel), pure CsI + waveform sampling (end-caps))
- **PXD,SVD**: Decay vertex position
- **CDC**: Track, momenta, dE/dx
- **KLM**: Muon, K^0_L
- **TOP**: K/pi ID

The diagram illustrates the placement of these components within the Belle II Detector, with specific parts highlighted:

- **EM Calorimeter**
  - CsI(Tl), waveform sampling (barrel)
  - Pure CsI + waveform sampling (end-caps)
- **Beryllium beam pipe**
  - 2 cm diameter
- **Vertex Detector**
  - 2 layers DEPFET + 4 layers DSSD
- **Central Drift Chamber**
  - He(50%):C_2H_(50%), small cells, long lever arm, fast electronics
- **Particle Identification**
  - Time-of-Propagation counter (barrel)
  - Prox. focusing Aerogel RICH (fwd)
- **KL and muon detector**
  - Resistive Plate Counter (barrel)
  - Scintillator + WLSF + MPPC (end-caps)

The diagram also shows particles of interest, such as an electron (7 GeV) and a positron (4 GeV).
Belle II Collaboration

722 Colleagues
104 Institutions
24 Countries/regions
Awaiting for the First Collision

Live broadcast of SuperKEKB/Belle II first collision started on 12:00, April 20, 2018 on Niconico

http://live.nicovideo.jp/gate/lv312372695

First collision will happen in the next few days!
Trigger and DAQ Challenges

- High Luminosity, High background
  - Peaking luminosity at SuperKEKB: $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (40 x KEKB)
  - Total physics trigger rate $\sim 15\text{kHz}@8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
  - Large beam-related, QED backgrounds
  - Huge data flow from pixel detector ($\sim 1\text{MB/event}$)

- Physics processes triggers
  - Y(4S)+continuum: almost 100% efficiency
  - Low multiplicity processes challenge trigger

Dark photon

Leptonic tau decay

LFV tau decay

Precision electroweak tests
Belle II Beam Background

- Due to the low final state particle multiplicity of dark matter processes, background from beams become a major challenge.
- Total background is significantly higher than Belle

- **Touschek effect**
  - Intra bunch scattering
  - Rate $\propto$ the inverse beam size, number of bunches et al
  - Suppressed with movable collimators

- **Beam gas**
  - Coulomb and bremsstrahlung scattering by the residual gas atoms
  - Rate $\propto$ the vacuum level and the beam current

- **Synchrotron radiation**
  - Rate $\propto$ the beam energy squared and magnetic field squared

- **Physical backgrounds**
  - Bhabha $e^+e^-\rightarrow(\gamma)e^+e^-$
  - Two photon: $ee\rightarrow eeee$
  - Rate $\propto$ luminosity

Due to the low final state particle multiplicity of dark matter processes, background from beams become a major challenge. Total background is significantly higher than Belle.

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  - Intra bunch scattering
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Trigger

Scheme: Hardware trigger + Software trigger
• Level 1 (L1): hardware based
• High Level Trigger (HLT): software based, a component of DAQ
L1 Trigger Scheme

Sub-Detector Triggers + Global Decision Logic (GDL)

Trigger Rate < 30 kHz
CDC Trigger

- Track segment finder (TSF)
  - Realized using one universal trigger board (UT3)
  - 9 UT3 boards in total

- 2D Track Finder
  - Aiming at charged track with Pt>0.3 GeV
  - Using conformal transformation to detect circle

- 3D Track
  - Measurement of the axial coordinate of a track
  - Neuro network
  - 3D finder

Event Display
Tracking Efficiency

Study based on TSIM
$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow \text{Invisible}$
\( \Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S), \Upsilon(1S) \rightarrow \text{Invisible} \)

\( \Upsilon(4S) \rightarrow \gamma_{\text{ISR}} \Upsilon(3S), \Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S), \Upsilon(1S) \rightarrow \text{Invisible} \)
Study based on TSIM

$N_{trk} \geq 3$

**BB_general**
- $R(N \geq 3) = 93.5\%$

**B$\rightarrow\pi\pi\pi\pi$**
- $R(N \geq 3) = 52.7\%$

**B$\rightarrow\nu\nu$**
- $R(N \geq 3) = 48.7\%$

**$\tau\tau$**
- $R(N \geq 3) = 18.2\%$

Ntrk (2D_trackfinder)
ECL Trigger

- Upgrade Bhabha logic at Belle II
  - 3D Bhabha Veto Logic
  - Use $r$-$\theta$-$\phi$ (3-D) information
  - Keep efficiencies of $\tau\tau$ and low multiplicity

Procedure of 3-D Bhabha veto

1. Find clusters in whole ECL based on ICN logic.
2. Divide ECL 2 parts.
3. Find the most energetic Clusters in each part.
   - Now we have two clusters.
4. Check two clusters (cluster1, cluster2) satisfy the back to back topology (saved as table).

- Tagging Bhabha or not using the topology satisfaction and two clusters information
  - Energy of clusters
  - Position of clusters
• CDC track and ECL cluster matching (*new at Belle II*)

- Match in $r$-$\phi$ and $Z$ directions
- $\Delta r$, $\Delta z$: the deviations between cluster position and expected hit position in $r$-$\phi$ and $Z$ directions, respectively.

- $\Delta r < 20$ cm and $|\Delta z| < 40$ cm

- $\Delta r$, $\Delta z$ selections
- Match track $t_0$ to the cluster $c_1$ with the smallest $\Delta r$ in its ($\Delta r$, $\Delta z$) region
- The rest are neutral clusters
- Electron ID with E/P
Study based on TSIM

Proposed L1 Trigger Menu (Phase II)

\[ L = 4 \times 10^{34} \text{ cm}^{-2}/\text{s} = 40 \text{ nb}^{-1}/\text{s} = 5\% \text{ of nominal} \]

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<tr>
<th>Bit</th>
<th>Description</th>
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<th>e+e- 122760 nb</th>
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<td>Rate, phase2 backgrounds, luminosity (nb(^{-1})/s) =</td>
<td></td>
<td>40</td>
<td>7358</td>
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</tbody>
</table>
Study based on TSIM

Proposed L1 Trigger Menu (Phase II)

\[ L = 4 \times 10^{34} \text{ cm}^{-2}/\text{s} \]

5% of nominal

<table>
<thead>
<tr>
<th>Bit</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>3 or more 3D tracks</td>
</tr>
<tr>
<td>1</td>
<td>2 3D tracks, ≥1 within 25 cm, not a trkBhabha</td>
</tr>
<tr>
<td>2</td>
<td>2 3D tracks, not a trkBhabha</td>
</tr>
<tr>
<td>3</td>
<td>2 3D tracks, trkBhabha</td>
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<td>1 track, &lt;25 cm, clust same hemi, no 2 GeV clust</td>
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<td>≥3 clusters inc. ≥1 300 MeV, not an eclBhabha</td>
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<td>2 GeV E* in [4,14], not a trkBhabha</td>
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<td>8</td>
<td>2 GeV E* in [4,14], trkBhabha</td>
</tr>
<tr>
<td>9</td>
<td>2 GeV E* in 2,3,15 or 16, not a trkBhabha or eclBhabha</td>
</tr>
<tr>
<td>10</td>
<td>2 GeV E* in 2,3,15 or 16, trkBhabha or eclBhabha</td>
</tr>
<tr>
<td>11</td>
<td>2 GeV E* in 1 or 17, not a trkBhabha or eclBhabha</td>
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<tr>
<td>12</td>
<td>2 GeV E* in 1 or 17, trkBhabha or eclBhabha</td>
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<td>13</td>
<td>exactly 1 E*&gt;1 GeV and 1 E&gt;300 MeV, in [4,15]</td>
</tr>
<tr>
<td>14</td>
<td>exactly 1 E*&gt;1 GeV and 1 E&gt;300 MeV, in 2,3 or 16</td>
</tr>
<tr>
<td>15</td>
<td>clusters back-to-back in phi, both &gt;250 MeV, no 2 GeV</td>
</tr>
<tr>
<td>16</td>
<td>clusters back-to-back in phi, 1 &lt;250 MeV, no 2 GeV</td>
</tr>
<tr>
<td>17</td>
<td>clusters back-to-back in 3D, no 2 GeV</td>
</tr>
</tbody>
</table>

Percentage selected by at least 1 trigger

Cross section (nb)

Rate, phase2 backgrounds, luminosity (nb-1/s) = 40 7358

Hadronic events

Two-track events, \( \tau \tau \), \( \gamma \pi \pi \), \( Y(1S) \) inv. decay et.al

w/ a large cluster events \( \tau \tau \), \( \gamma \pi \pi \), dark photon, et.al

Back-to-back clusters \( \tau \tau \), \( \gamma \pi \pi \), dark photon
**Study based on TSIM**

**Proposed L1 Trigger Menu (Phase II)**

Hadronic events

Two-track events, ττ, γππ, Y(1S) inv. decay et.al

w/ a large cluster events ττ, γππ, dark photon, et.al

Back-to-back clusters ττ, γππ, dark photon

Some trigger lines are designed for

- Detector performance study
- Trigger efficiency
- Calibration
- Luminosity measurement

Tighten some trigger lines once the trigger and DAQ system can not undertake the rate.
**Proposed L1 Trigger Menu (2020)**

\[ L = 2 \times 10^{35} \text{ cm}^{-2}/\text{s} = 200 \text{ nb}^{-1}/\text{s} = 25\% \text{ nominal} \]

<table>
<thead>
<tr>
<th>Bit</th>
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<th>% Selected</th>
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<td>0</td>
<td>3 or more 3D tracks</td>
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<td>0.0047</td>
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<tr>
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<tr>
<td>13</td>
<td>exactly 1 ( E^* \geq 1 \text{ GeV} ) and 1 ( E \geq 300 \text{ MeV} ), in [4,15]</td>
<td>1</td>
<td>0.0042</td>
<td>0.0030</td>
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<tr>
<td>14</td>
<td>exactly 1 ( E^* \geq 1 \text{ GeV} ) and 1 ( E \geq 300 \text{ MeV} ), in 2,3 or 16</td>
<td>5</td>
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Percentage selected by at least 1 trigger: 0.0842
Cross section (nb): 103
Rate, phase2 backgrounds, luminosity (nb-1/s) = 20061
**Efficiency**

$L = 2 \times 10^{35} \text{ cm}^{-2}/\text{s} = 200 \text{ nb}^{-1}/\text{s} = 25\% \text{ nominal}$

<table>
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<th>Sample</th>
<th>Note</th>
<th>Generated sigma nb</th>
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<th>Accepted sigma nb</th>
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<th>Fiducial efficiency %</th>
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DAQ

Components:
- Unified data link (Belle2Link)
- Common pipeline platform for electronics readout (COPPER)
- Merge data pieces from all detectors (Event builder I)
- High level trigger (HLT): software based
HLT in Belle II DAQ

- Parallel processing: Multi-core, Multi-node
- ~10 HLT units, 20 nodes x 16 cores per unit
- Input: 100kB/event, 3kHz/unit, Output: 200kB/event, 1kHz/unit

Developed by Prof. Z.A. Liu's group
Important contribution by IHEP, China!!!
**HLT**

- **Physics Trigger**: suppress event rates from 30 kHz to 10 kHz

- **PXD RoI**: provide HLT trigger result and tracking information of SVD and CDC to calculate Region of Interest of PXD.

- **Calibration**: Flag samples for the calibration of detectors

- **DQM**: Information from Reconstruction for data quality monitoring
 HL T S oftware

Standard Offline Reconstruction

CDC Track Finding → VXD Track Finding → Track Fitting → ECL Rec → Other Rec

HLT Standard Reconstruction and Trigger

CDC Track Finding → ECL Rec → Fast Reco Trigger → VXD Track Finding → Track Fitting → Other Rec → Physics Trigger
HLT Commissioning

Realistic strategy of HLT commissioning in Phase 2

1. At the beginning of Phase 2, HLT is operated without any processing. All the events are pass-through to Storage
   * An intensive debugging of “FastReco(=CDC+ECL recon)” and “Level3” is supposed to be done offline.
   * Also RoI generation is supposed to be debugged.

2. After FastReco(Level3) is proven to be stable, we will implement FastReco(Level3) in HLT.
   * The software trigger by FastReco only may be turned on in case the trigger rate is too high.
   * Debugging of full HLT script is done offline.

3. Then the full HLT script is implemented.
   * FastReco trigger is turned on.
   * But final software trigger is not turned on during Phase 2.
Software performance on HLT

Test
• 20 cores (node 1, hlt03)
• ~2000 BB events

Processing time per event as a function of Number of cores

~550 ms/event/core

The times of processing time of single core to that of N cores

Number of cores

Number of cores
Average readin event rate per run on HLT03 test bench
# HistoManager for real HLT
histoman = basf2.register_module('DqmHistoManager')
histoman.param("Port", int(argvs[3]))
histoman.param("Port", 9991)
histoman.param("DumpInterval", 180)
histoman.param("WriteInterval", 180)
main_path.add_module(histoman)

# Raw data unpackers
add_unpackers(crashsafe_path, components=components)

# cosmic reconstruction
add_cosmics_reconstruction(crashsafe_path, components=components)
add_fast_reco_software_trigger(crashsafe_path)
add_hlt_software_trigger(crashsafe_path)
add_calibration_software_trigger(crashsafe_path)
if enable_graceful_crash_handling:
crashhandler = main_path.add_module('CrashHandler', path=crashsafe_path)
in case of crashes, save the event and continue normally with the following modules
save_crashing_events_path = basf2.create_path()
save_crashing_events_path.add_module('SeqRootOutput', outputFileName='crashing_events.sroot')
crashhandler.if_false(save_crashing_events_path, basf2.AfterConditionPath.CONTINUE)
crashhandler.set_log_level(basf2.LogLevel.WARNING)
else:
main_path.add_path(crashsafe_path)
add_cosmic_dqm(main_path, components=components)
cosmic_hltdqm(main_path)

# Output to RingBuffer
output = basf2.register_module("Ds2Rbuf")
output.param("RingBufferName", argvs[2])
# Specification of output objects
output.param("saveObjs", saveobjs)
main_path.add_module(output)

##########
# Other utilities
##########
progress = basf2.register_module('Progress')
main_path.add_module(progress)
Physics Prospects

- There is still space for new physics contributions
- Open questions, e.g.
  - New CPV phases?
  - Sources of LFV beyond the SM?
  - Multiple Higgs bosons, dark sectors?
  - Discrepancies between experimental results and SM predictions (e.g. enhancements in semi-tauonic decays)?

[Diagram of Physics Prospects]

- Dark Photon
- LFV tau decay: $\tau^\pm \rightarrow \nu_\tau W^\pm$ and $e^-, \mu^-$
- Leptonic tau decay
- Precision Electroweak tests
Penguin $b \to s$ decays

- Precision measurements of $\sin(2\beta)$ is important for the search of new sources of CPV
- $b \to s$ transition via penguin diagram
- Sensitive to possible new heavy particle contributions

$$\sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}})$$

**Belle II**

<table>
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<tr>
<th>$\sin(2\beta)$</th>
<th>$\sigma(\text{stat}@Belle II \ 50 \ ab^{-1})$</th>
<th>$\sigma(\text{stat}@Belle II)$</th>
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<tr>
<td>$B \to \Phi K^0$</td>
<td>0.09</td>
<td>0.018</td>
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<td>$B \to \eta' K^0$</td>
<td>0.07</td>
<td>0.011</td>
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<tr>
<td>$B \to KsKsKs$</td>
<td>0.32</td>
<td>0.033</td>
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</table>
**EWP: B → K(∗) νν**

- **SM: penguin + box diagram**
  
  \[ B_{SM}(B^+ \to K^+ \nu \nu) = (4.0 \pm 0.5) \times 10^{-6} \]
  
  \[ B_{SM}(B^0 \to K^{*0} \nu \nu) = (9.2 \pm 1.0) \times 10^{-6} \]

  arXiv: 1409.4557

- **Belle:**
  
  \[ B(B^+ \to K^+ \nu \nu) < 5.5 \times 10^{-5}, \]
  
  Nsig=13.3+7.4-6.6, 2.0σ
  
  \[ B(B^0 \to K^{*0} \nu \nu) < 5.5 \times 10^{-5} \]

Belle, PRD 87, 111103(R) (2013)

Belle II:

Nsig~91.5±32.2@50 ab⁻¹
Semi-leptonic B decays

Semi-tauonic decay modes are highly sensitive to new physics

\[ B \to D^{(*)} \tau \nu : \text{WA is } \sim 4\sigma \text{ from the SM!} \]

\[
R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \bar{\nu}_\tau)}{B(B \to D^{(*)} \ell \bar{\nu}_\ell)}
\]

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\[
R(D)
\]

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LFV $\tau$ decays

- Lepton Flavour Violation is highly suppressed in the SM (e.g. $\text{Br}(\tau \to \mu \gamma) \sim 10^{-40}$), LFV $\tau$ decays are clean probes for New Physics effects
- Belle II: Sensitivity for LFV decay rates is at least one order higher than Belle

Extrapolations for Belle II (50 ab$^{-1}$)
Dark Sector

- Dark photon $A'$, motivated be in MeV-GeV mass
- Probe leptonically decaying dark photons through mixing
- Probe sub-GeV dark matter in invisible decays

$$A'\rightarrow ee/\mu\mu$$

$$A'\rightarrow\text{invisible}$$
Search for dark matter in Y(1S) invisible decays

- Y(1S) invisible decay
  - In SM, $B(Y(1S) \rightarrow \nu\nu) \approx 10^{-5}$ (PLB 441(1998) 419-424)
  - If low mass dark matter less than b quark mass exist, $Y(1S) \rightarrow \text{invisible}$ is enhanced

- Production at Belle II
  - $e^+e^- \rightarrow Y(2,3S) \rightarrow \pi^+\pi^-Y(1S), Y(1S) \rightarrow \text{invisible}$
  - Two slow charged $\pi$ in the final state

- Dedicated trigger
  - Trigger with low threshold of transverse momentum is needed
  - Study is in progress

- Main backgrounds
  - Two photon process $e^+e^- \rightarrow e^+e^- X$, where $e^+e^-$ are out of detector, and $X=\pi^+\pi^-/\mu^+\mu^-$,
Charmonium(-like) states

- B decay, two photons collision, double charmonium production, initial state radiation
Summary

• The trigger system have been improved significantly compared to Belle
  • 3D tracking.
  • 3D ecl Bhabha logics.
  • GRL, match between CDC-Track and ECL-Cluster.
  • Abundant trigger menu.

• DAQ
  • Large readout bandwidth, 3GB/s.
  • New scheme of software trigger at Belle II, powerful trigger capability.
  • HLT operation is smooth during cosmic ray test.

• First collision of Belle II is coming, many puzzles are expected to be solved at Belle II.
LNNU experimental particle physics group

- Location
  - LNNU is located in DALIAN, Liaoning province

- Job opportunity
  - There is a strong theoretical particle physics group in LNNU with 6 faculties.
  - We are building the experimental group. 2 faculty positions for BESIII/Belle II projects are opening, please contact to me if you are interested in.