Long-lived Particle reconstruction at Belle II
Belle II: event properties and tracking challenges

- Typical $Y(4S)$ event:
  - On average 11 charged tracks with soft momentum spectrum
  - High machine background: number of background hits about 2 orders of magnitude larger than signal hits

- Operated at asymmetric collider SuperKEKB, CM boosted
- Precise measurement of primary and secondary vertices
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- Standard Model V^0s
  - K_s: cτ ~ 2.7 cm
  - Λ: cτ ~ 7.9 cm

- In some sense they are long-lived particles / can be used in benchmark studies for LLP

- …not without downsides
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Two charged tracks appearing from nowhere

We will refer in particular to 2 specific decays
\[ K_s \rightarrow \pi^+ \pi^- \quad [BR = 69.2\%] \]
\[ \Lambda \rightarrow p \pi^- \quad [BR = 63.9\%] \]

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Bubbles became hits

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Belle II detector - tracking systems

EM Calorimeter
CsI(Tl), waveform sampling electronics

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

Belle II TDR, arXiv:1011.0352

EM Calorimeter
CsI(Tl), waveform sampling electronics

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(End Caps, inner 2 barrel layers)

pXD: PiXel Detector
SVD: Silicon Vertex Detector
CDC: Central Drift Chamber

Bianca Scavino
University of Mainz
Belle II detector - tracking systems

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**SVD**: Silicon Vertex Detector  
**CDC**: Central Drift Chamber

*VXD* = *PXD* + *SVD*
After the reconstruction, the individual hit patterns are not available to the standard user.

The final object delivered to analysts is a track.

Collection of 5 parameters at the POCA (*):

- $p_{1}$
- $p_{0}$
- $d_{0}$
- $z_{0}$
- $\phi$
- $\lambda$
- $\omega$

Track parameters = $[dO, zO, \tan\lambda, \phi, \omega]$
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The final object delivered to analysts is a track.

Collection of 5 parameters at the POCA (*)

V0s: two tracks with a common vertex and opposite charge.

Track description is not ideal for displaced vertices (and displaced tracks in general).

Material effects

Extrapolated to the IP, less precise.

(*) POCA: Point Of Closest Approach
During reconstruction we have a dedicated treatment for V0s.

Before throwing away the precious information from the hit patterns, we exploit it performing the vertex fit of possible V0 candidates.

When the fit succeeds, we store the object and deliver it to analysts.

Final “analysis” V0s:
Combination of these objects and offline V0s

Offline V0s:
2 tracks combined w/ successful vertex fit
What does everything I just said mean *practically*?
Belle II VOs, practice

\[ \mathcal{K}_s \rightarrow \pi^+ \pi^- \]

\[ \Lambda \rightarrow p \pi^- \]

Belle II simulation
\[ \int L \, dt = 200 \text{ fb}^{-1} \]
The full samples are the most inclusive that one can get
- Contain huge combinatorial background
- Adding kinematics cuts and exploiting PID information
  - We can get a cleaner peak

As a side note:
From now on I will focus on $\Lambda$, I am sorry for $K_0$ fans
The full samples are the most inclusive that one can get.

- Contain huge combinatorial background

- Adding kinematics cuts and exploiting PID information
- We can get a cleaner peak

- ...also with data

As a side note:
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Effect of the inner detectors on the resolution
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Real life VS simulation: beam background

- Real life is not so easy

- We have to deal with high machine background
  - Random hits firing your detector that make the pattern recognition of real particles harder

- Not easy to simulate in a realistic way

- We use two different types of BG, a simulated one and random triggered events

- We also simulate higher background levels with respect to the “nominal” expected background (BGx1)
  - (BGx0, BGx1, BGx2, BGx5)
Consider a very simple situation

1 $\Lambda \rightarrow p \pi$ per event (generated with a particle gun)

Event display of Monte Carlo truth
Consider a very simple situation

1 Λ → p π per event (generated with a particle gun)

Event display of Monte Carlo truth

We take this same event and

Simulate the detector response including different levels of background (BGx0, BGx1, BGx2, BGx5)

Reconstruct the event

Also, making use of the Monte Carlo truth, we compute the reconstruction efficiency (♦) in such cases, as a function of the xy-distance of the vertex

♦ # generated events = 20K
Reconstruction efficiency for different background levels

Simulate the detector response and reconstruct the event in a background-free environment (BGx0)
Simulate the detector response and reconstruct the event with nominal background (BGx1)

**Reconstruction efficiency for different background levels**
Reconstruction efficiency for different background levels

Simulate the detector response and reconstruct the event with 2x nominal background (BGx2)
Reconstruction efficiency for different background levels

Simulate the detector response and reconstruct the event with 5x nominal background (BGx5)
Drop in efficiency (vs xy-distance) as a function of BG level is more severe for Λ decaying far from the interaction point
We need a way to monitor the background effects on data

In simulation everything is easy to monitor, we know the Monte Carlo truth.

For this we rely on two observations:

- Drop in efficiency (vs xy-distance) as a function of BG level is more severe for \( \Lambda \) decaying far from the interaction point.
- Some event-based measured quantities depend on the background level.

Example: \textit{nExtraCDCSegments}

- Number of segments reconstructed using CDC informations and not used in any of the tracks in the event.
- Very intuitively:
  - In a clean environment all segments would belong to a track.
  - Increasing the number of backgrounds hits will increase the number of fake segments.
We need a way to monitor the background effects on data

Divide the Lambda sample in two categories, “short” and “long”
- “short” Lambda: xy-distance < 15 cm
- “long” Lambda: xy-distance ≥ 15 cm (decaying outside the SVD volume)

Divide the considered background-dependent variable in bins

For each bin count the number of long and short Λ and plot the ratio between long and short
Short and long $\Lambda$s

**Belle II simulation**

$\int L \, dt = 200 \text{ fb}^{-1}$

xy-distance $< 15 \text{ cm}$

“short”

Cand / 0.01 MeV/c$^2$

M($\rho\pi$) [GeV/c$^2$]

xy-distance $\geq 15 \text{ cm}$

“long”

Cand / 0.01 MeV/c$^2$

M($\rho\pi$) [GeV/c$^2$]
Long/short ratio VS nExtraCDCSegments

We see a clear dependence of the long/short ratio on the nExtraCDCSegments.

The study is ongoing, we are double checking the results with different samples:

- $K_s$ from B decays
- Exclusive $\Lambda$ sample (from $\Lambda_c^+$ decay)
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$K_S$ from $B$ decays

Exclusive $\Lambda$ sample (from $\Lambda_c^+$ decay)

Data and simulation are in fair agreement.

$\int L \, dt = 72.05 \, fb^{-1}$
Summary

- The Belle II experiment is optimized for B physics
- (SM) long-lived particles not originally considered priority
  - Nevertheless the interest is alive and we do have dedicated tools

- For LLP, high background level is a problem
  - Clear degradation of the performance as a function of the xy-distance of the vertex from the interaction point

- We are developing a way to monitor the background impact directly on LLP using data
  - (without relying on the Monte Carlo truth)
  - The study is ongoing, data and Monte Carlo show fair agreement

- Last thing worth mentioning (not part of this talk):
  - There are ideas and possibilities to improve the tracking algorithms specifically for LLP
Backup slides
**Belle II Detector**

**455 collaborators, 101 institutes, 23 nations**

- **Electrons (7 GeV)**
- **Positrons (4 GeV)**

**Vertex Detector**
- 2 layers Si Pixels (DEPFET) + 4 layers Si double sided strip DSSD

**Central Drift Chamber**
- Smaller cell size, long lever arm

**EM Calorimeter**
- CsI(Tl), waveform sampling electronics

**Particle Identification**
- Time-of-Propagation counter (barrel)
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**KL and muon detector**
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Bianca Scavino

University of Mainz