Analysis of Neutral Long-Lived Kaons Reconstruction Efficiency via a Missing 4-Momentum Method at the Belle II Experiment

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Purpose of the Missing 4-Momentum Method

In this methodology K_L^0 is not reconstructed directly. Its kinematics are calculated as the recoil 4-momentum to the system of all other detected charged hadrons.

$$P_{K_L^0} = P_{e^+e^-} - \sum P_{hadrons,\, charged}$$

- Analyze reconstruction efficiency for neutral long-lived particles in the Belle II experiment.
- Optimize background suppression.
- Use $e^- + e^+ \rightarrow K_L^0 + charged\ hadrons$ events to get K_L^0 reconstruction efficiency to ensure that Monte Carlo simulations accurately reproduce experimental data.
- While established methods exist for probing high-energy K_L^0 ($P > 1.4$ GeV/c), there is a critical need for a method targeting the low-energy regime ($P < 1.4$ GeV/c).

Challenge

Determine suitable combinations of charged hadrons to get pure K_L^0 sample.

Steps

- Optimize reconstruction of charged kaons, pions, and protons.
- Isolate missing component of 4-momentum and obtain reconstructed mass and momentum of K_L^0.
- Perform Monte Carlo (MC) reconstruction using Belle II detector model.
- Conduct analysis of decay modes embedded in s-quark event generator.
- Isolate processes where background is suppressed.

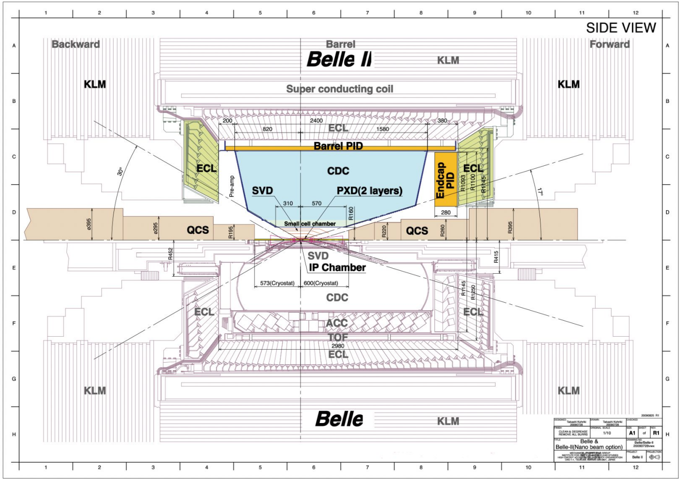
The Analysis

Utilizing Python, C++, NumPy/SciPy frameworks and basf2 (the main software of the Belle II experiment).

The Belle II Experiment at SuperKEKB (Tsukuba, Japan)

- **Main Advantages:**
  - Asymmetric e^+e^- collider.
  - Electron ring (HER) is near 7 GeV energy. Positron ring (LER) - 4 GeV.
  - Primarily operates at energy corresponding to the $\Upsilon(4S)$ resonance and 60 MeV below.
  - Hermetic (closed) detector providing nearly 4π coverage.
  - Precisely known initial state kinematics (beam energy-constrained).
  - Relatively clean environment compared to hadron colliders.
- **World Records**:
  - Achieved a new luminosity world record of $5.1 \times 10^{34}\, cm^{-2}s^{-1}$, for a total data sample of $599.49\, fb^{-1}$.
  - The ambitious goal is to accumulate an integrated luminosity of $50\, ab^{-1}$.
- **Physics Reach:** Ability to reconstruct channels with multiple neutral particles (π^0, K_L^0, and neutrinos via missing energy).

The Belle II Detector



Source: Belle II Technical Design Report, arXiv:1011.0352

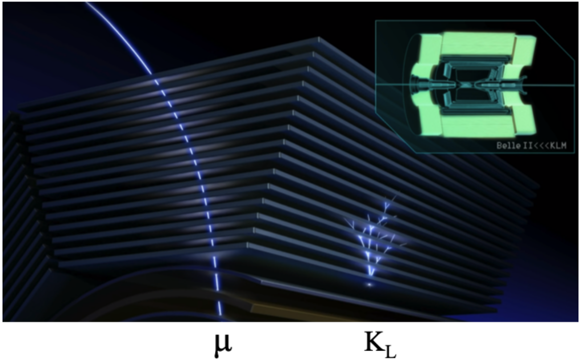
Belle II spectrometer (top half) as compared to the previous Belle detector (bottom half).

Sub-detectors:

- **PXD:** Pixel Detector
- **SVD:** Silicon Vertex Detector
- **CDC:** Central Drift Chamber
- **ARICH:** Aerogel Ring Imaging Cherenkov Counter
- **TOP:** Time-Of-Propagation Counter
- **ECL:** Electromagnetic Calorimeter
- **KLM:** K_L^0 and Muon Detector

K_L^0 and Muon Detector

The KLong and Muon (KLM) Detector System



Source: @belle2collab on X, posted on July 2, 2021

- Consists of iron plates and detector layers.
- The iron plates act as the magnetic flux return path to stabilize and contain the solenoid's field.
- The iron plates is filter for particles, only muons and K_L^0 mesons typically penetrate deep enough to reach the KLM layers.
- K_L^0 mesons can shower hadronically here (about 2 hadronic interaction lengths).
- K_L^0 can also shower in ELC (about 1 hadronic interaction length).

Neutral Kaons in Belle II

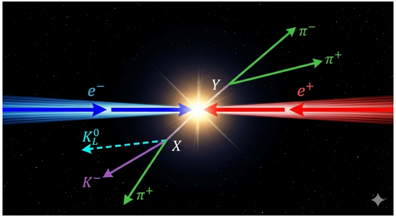
- Neutral kaons exist as K_S^0 (short-lived) or K_L^0 (long-lived).
- K_S^0 typically decays within the tracking volume ($K_S^0 \to \pi^+\pi^-$).
- K_L^0 survives to reach the Electromagnetic Calorimeter (ECL) and K_L^0-Muon detector (KLM).
- Accurate MC-data agreement is critical for reliable physics results.

Note

K_L^0 reconstruction is challenging.

K_L^0 Reconstruction Efficiency Estimation

- Efficiency knowledge is vital for measuring branching fractions.
- Established methods exist for K_L^0 with $P > 1.4$ GeV/c (e.g., in $e^+e^- \to \phi\gamma$).
- **New Method:**
  - We use "missing mass" peaks in $e^- + e^+ \to K_L^0 + \textit{charged hadrons}$ events to identify the K_L^0.
  - Do not explicitly reconstruct K_L^0. Predict its direction and momentum from beam information and charged hadrons.
  - Search for K_L^0 signal where recoil is (in ECL/KLM).
  - Efficiency = (Reconstructed K_L^0) / (Total Expected Recoils).



A scientific illustration of particle collision that was drawn by Gemini Nano Banana Pro

Charged Hadron Selections

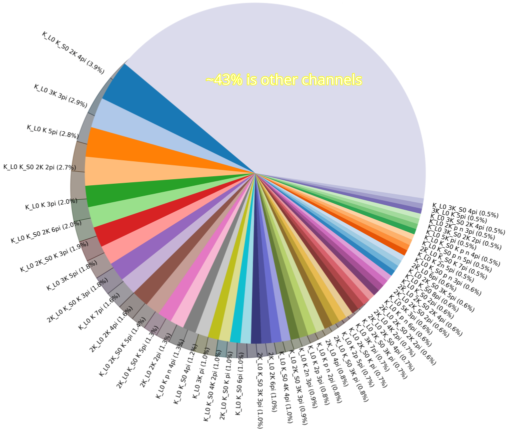
Selection criteria applied to improve signal purity:

- **Track Quality:** $dr < 1$ cm, $|dz| < 1$ cm (proximity to Interaction Point).
- **CDC-hits**: we require at least 1 interaction in this part of detector.
- **Particle Identification (PID):** Utilizing Central Drift Chamber (CDC), Aerogel Ring Imaging Cherenkov Counter (ARICH) and Time-of-Propagation (TOP) counters to built Specific Likelihood ratios used to distinguish $K^{\pm}$, $\pi^{\pm}$, and $p/\bar{p}$.

Also, we require the squared missing mass to be positive and within a reasonable kinematic range, specifically $0 < M^2_{recoil} < 25\ \mathrm{GeV}^2/\mathrm{c}^4$.

The Analysis

Base selections to build the charged-hadrons system.



Events without π^0 and photons at the generator level.

- Below the $\Upsilon(4S)$ data does not contain $B\bar{B}$ pairs and MC consist of $u\bar{u}, d\bar{d}, c\bar{c}, s\bar{s}, \tau^+\tau^-$-files.
- Initial studies using $s\bar{s}$ sample: 3.86×10^5 events.
- After vetoing events with π^0 or γ at generator level: ~ 5300 events remain.
- Top decay channels by relative abundance:
  - 3.9% $K_L^0\, K_S^0\, 2K\, 4\pi$;
  - 2.9% $K_L^0\, 3K\, 3\pi$;
  - 2.8% $K_L^0\, K\, 5\pi$;
  - 2.7% $K_L^0\, K_S^0\, 2K\, 2\pi$;
  - 2% $K_L^0\, K\, 3\pi$;
  - ...

Table of Explored Channels

Event products	Signal events	Background events	$\frac{\text{Signal events}}{\text{Background events}} \cdot 10^4$
K_L^0 K π	22	9625	23
K_L^0 KS 2K 4π	207	6688	310
K_L^0 3K 3π	155	5635	280
K_L^0 K 5π	150	17880	84
K_L^0 KS 2K 2π	146	4948	300
K_L^0 K 3π	106	16891	63
K_L^0 KS 2K 6π	105	3524	320
K_L^0 2KS K 3π	103	3515	290
K_L^0 3K 5π	98	4435	220
K_L^0 K 7π	88	9650	90
K_L^0 3K π	56	2615	210
K_L^0 2p K 3π	44	1626	270
K_L^0 5K π	27	335	**810**

Event Selection and Background Suppression

ECL Cluster Variables (Masking)

- `clusterTiming`: Time difference relative to event t_0. For IP photons ≈ 0 [ns].
- `minC2TDist` d_{track}: Distance to the nearest extrapolated track [cm]. Separates photons from hadrons.
- `clusterE`: Energy of cluster in ECL [GeV].

Final Event Cuts (retain $> 95\%$ of signal)

- `roeEextra` < 2.0 GeV
- `roeNeextra` < 2.0 GeV
- `nROE_Photons` < 4
- `pRecoil` > 0.1 GeV/c

Rest Of Event (ROE) Selection

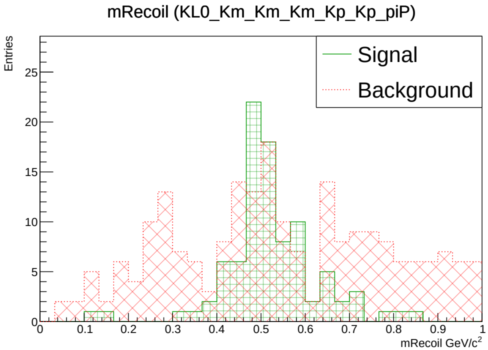
- `roeEextra`: Sum of extra cluster energies not associated with the signal.
- `roeNeextra`: Energy sum of only neutral clusters in ROE.
- `pRecoil`: Missing momentum of the recoil system.
- `nROE_Photons`: Multiplicity of extra photons in the mask.

Background Mask Definition

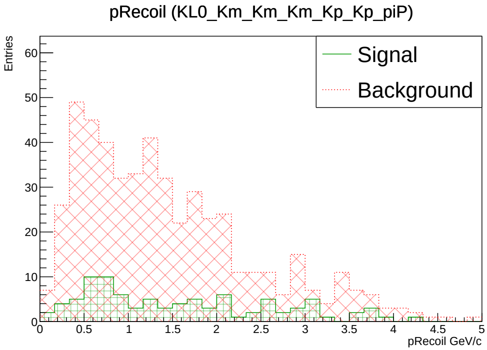
$|t_{cluster} - t_0| < 200\,\text{ns}$ & $d_{track} > 20\,\text{cm}$ & $E > 30\,\text{MeV}$

Distribution: $e^- + e^+ \to X \to K_L^0 + 3K^\pm + 2K^\mp + \pi^\mp$

Look at recoil invariant mass and identify K_L^0 peak. Approximately 50% of events are concentrated in the low-momentum region ($P < 1.4$ GeV/c). Signal and background are separated by checking generated information: for the signal only one neutral generated particle K_L^0 must be present.



Recoil mass spectrum (Off-resonance MC)

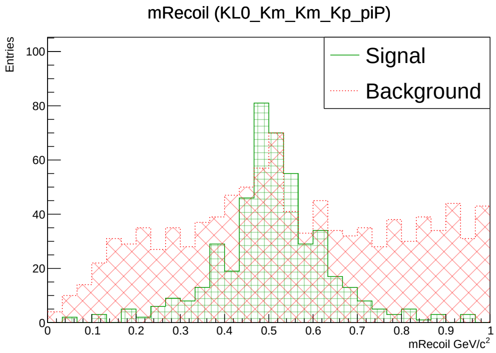


Recoil momentum (Off-resonance MC)

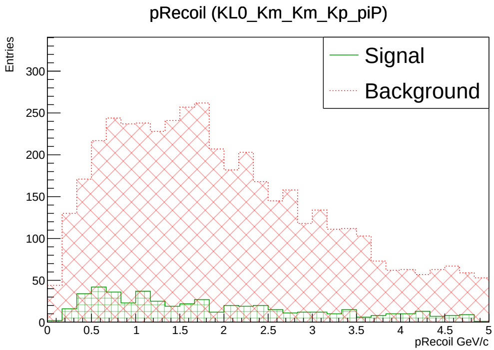
The K_L^0 peak is prominent in both signal and background distributions.

Distribution: $e^- + e^+ \to X \to K_L^0 + 2K^\pm + K^\mp + \pi^\mp$

Look at recoil invariant mass and identify K_L^0 peak. Approximately 45% of events are concentrated in the low-momentum region ($P < 1.4$ GeV/c). Signal and background are separated by checking generated information: for the signal only one neutral generated particle K_L^0 must be present.



Recoil mass spectrum (Off-resonance MC)

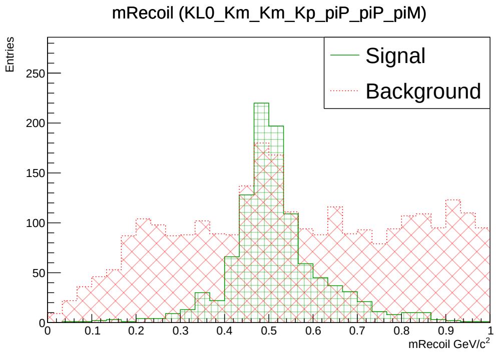


Recoil momentum (Off-resonance MC)

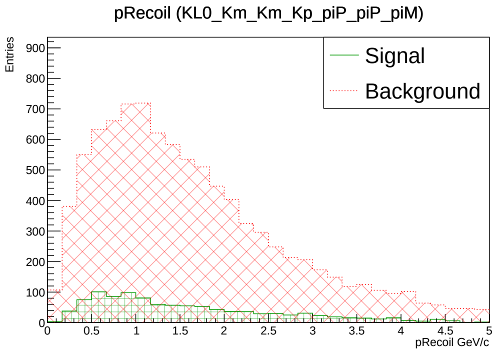
The K_L^0 peak is prominent in both signal and background distributions.

Distribution: $e^- + e^+ \to X \to K_L^0 + 2K^\pm + K^\mp + 2\pi^\mp + \pi^\pm$

Look at recoil invariant mass and identify K_L^0 peak. Approximately 55% of events are concentrated in the low-momentum region ($P < 1.4$ GeV/c). Signal and background are separated by checking generated information: for the signal only one neutral generated particle K_L^0 must be present.



Recoil mass spectrum (Off-resonance MC)

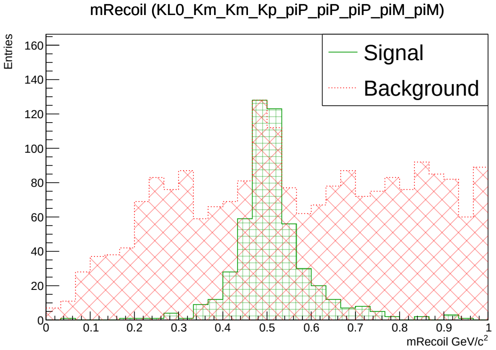


Recoil momentum (Off-resonance MC)

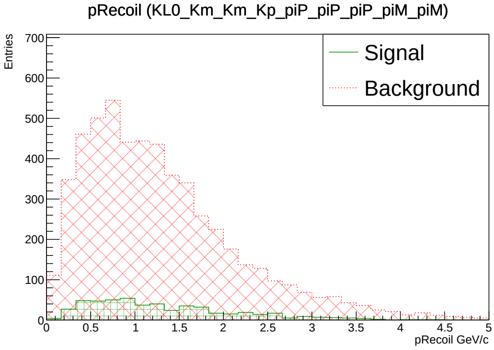
The K_L^0 peak is prominent in both signal and background distributions.

Distribution: $e^- + e^+ \to X \to K_L^0 + 2K^\pm + K^\mp + 2\pi^\pm + 3\pi^\mp$

Look at recoil invariant mass and identify K_L^0 peak. Approximately 60% of events are concentrated in the low-momentum region ($P < 1.4$ GeV/c). Signal and background are separated by checking generated information: for the signal only one neutral generated particle K_L^0 must be present.



Recoil mass spectrum (Off-resonance MC)

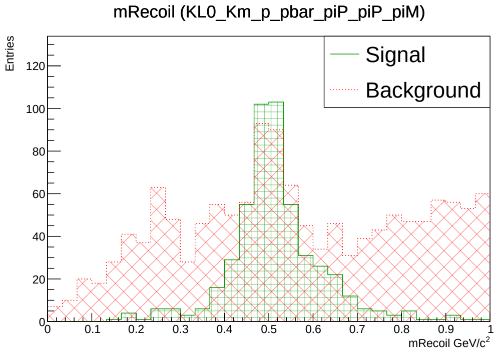


Recoil momentum (Off-resonance MC)

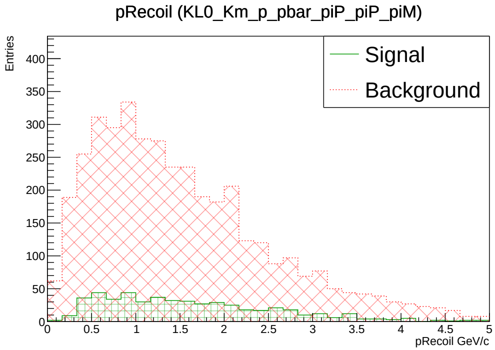
The K_L^0 peak is prominent in both signal and background distributions.

Distribution: $e^- + e^+ \to X \to K_L^0 + K^\pm + p^+ + \bar{p}^- + 2\pi^\pm + \pi^\mp$

Look at recoil invariant mass and identify K_L^0 peak. Approximately 50% of events are concentrated in the low-momentum region ($P < 1.4$ GeV/c). Signal and background are separated by checking generated information: for the signal only one neutral generated particle K_L^0 must be present.



Recoil mass spectrum (Off-resonance MC)



Recoil momentum (Off-resonance MC)

The K_L^0 peak is prominent in both signal and background distributions.

Current Results and Analysis

Top 5 Candidate Channels Selected:

1. $e^- e^+ \to X \to K_L^0\, 3K^\pm\, 2K^\mp\, \pi^\mp$
2. $e^- e^+ \to X \to K_L^0\, 2K^\pm\, K^\mp\, \pi^\mp$
3. $e^- e^+ \to X \to K_L^0\, 2K^\pm\, K^\mp\, 3\pi^\mp$
4. $e^- e^+ \to X \to K_L^0\, 2K^\pm\, K^\mp\, 2\pi^\pm\, 3\pi^\mp$
5. $e^- e^+ \to X \to K_L^0\, K^\pm\, p^+\, \bar{p}^-\, 2\pi^\pm\, \pi^\mp$

Observations:

- Signal peaks for K_L^0 are clearly visible and well-separated in most channels.
- Efficiency vary from 15% (in $e^- e^+ \to X \to K_L^0\, 2K^\pm\, K^\mp\, 2\pi^\pm\, 3\pi^\mp$ channel) up to 35% (in $e^- e^+ \to X \to K_L^0\, 2K^\pm\, K^\mp\, \pi^\mp$ channel).
- **Background Issue:** A peaking background is observed at the K_L^0 mass.
- **Hypothesis:** This peak is caused by "mirror" decays involving $K_S^0 \to \pi^0\pi^0$ and "leaked" K_S^0 that mimic the signal topology.

Summary

- Analysed K_L^0 reconstruction efficiency using the recoil technique in off-resonance MC.
- Established robust selection criteria (ECL masks and ROE variables) to suppress beam background.
- **Identified 5 optimal decay channels** for K_L^0 tagging.
- Discovered and localized the peaking background from "leaked" K_S^0 and $K_S^0 \to \pi^0\pi^0$ "mirror" decays.
- Ongoing work focuses on K_S^0 veto development and scaling the analysis to the full Belle II dataset to reach target precision.
- The developed technique provides a robust tool for mapping K_L^0 reconstruction efficiency in the low-energy regime ($P < 1.4$ GeV/c).