# First Search for $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$

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# Introduction

- We will present our attempt to the first experimental search for rare decay $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$ with blind analysis.
- Results after opening box will be presented.

# Background

- In Standard Model, variant of $K_L^0 \to \pi^0\gamma\gamma$ ($\mathcal{BR} \approx 1.2 \cdot 10^{-6}$).

$$K_L^0 \to \pi^0\gamma^*\gamma^*, \quad \gamma^* \to e^+e^- \Rightarrow \mathrm{K}_L^0 \to \pi^0 e^+e^-e^+e^-$$

  Assuming virtual photon decay is not affected by the adjacent mesons, SM predicts $\mathcal{BR} \sim 10^{-10}$.

- In dark sector model, this decay can be achieved through

$$K_L^0 \to \pi^0 XX, \quad X \to e^+e^-$$

  Theory suggests measurement with sensitivity at least $\mathcal{O}(10^{-6})$ can improve the constraints on their novel model of an MeV-scale QCD-axion.

  [Hostert and Pospelov, PHYSICAL REVIEW D 105, 2022]

## Motivation

Our data taken in 2021 with special triggers ($\sim 1.47 \cdot 10^{12}\ K_L^0$) allow us to achieve a sensitivity close to $\mathcal{O}(10^{-8})$ allowing for exploration of BSM signatures.

# KOTO Experiment

- KOTO is an international collaboration with dedicated experiment to search the Golden Decay $K_L^0 \to \pi^0 \nu \bar{\nu}$
- Produce $K_L^0$ through the below setup using accelerated proton beam at J-PARC (Japan Proton Accelerator Research Complex)

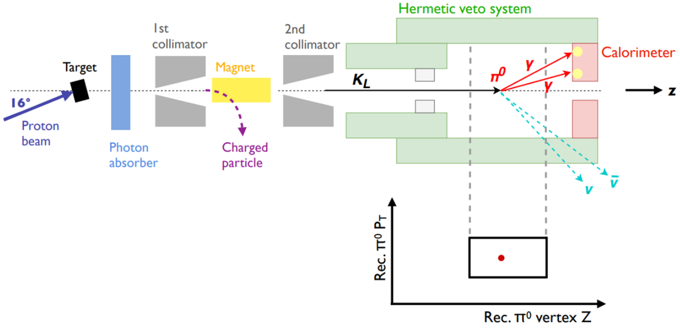



Figure: Schematic Diagram of Experiment Setup

- Data taken by Experiment in 2021 – special runs with CV in Trigger ($\sim$ 1 month of physics data)
- CV (Charged Veto) – two layers of scintillation counter plane
- CSI (Cesium Iodide) - Calorimeter

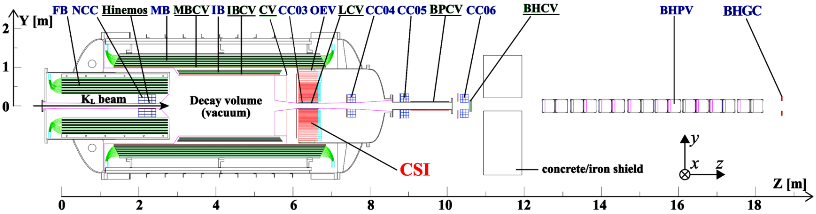



Figure: Schematic Diagram of Detectors in KOTO Experiment

Figure: CV Detector

1. Keep events with 6 hits on CSI (6 clusters)
2. Find Vertex Z assuming $K_L^0$ x, y = COE x, y (center of energy) with $K_L^0$ mass constraint
3. Use vertex to find CV Hit positions
4. Map with CV plane and identify charged particles
5. Use the two uncharged particles to reconstruct $\pi^0$ vertex

$$M_{K_L}^2 = \sum_{i<j}^{6} 2E_iE_j(1 - cos\theta_{ij})$$

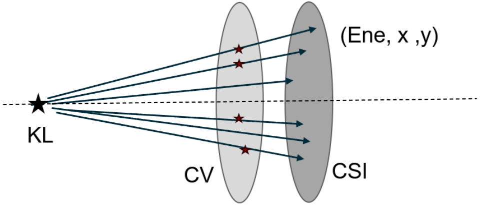



Figure: Step 3

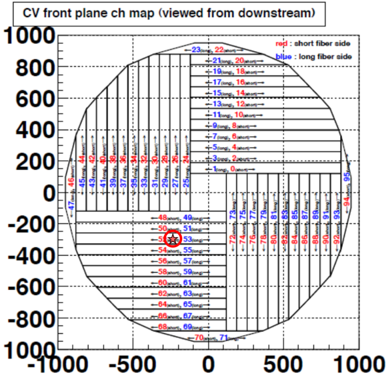



Figure: Step 4 - CV Plane Geometry

# Background Decays

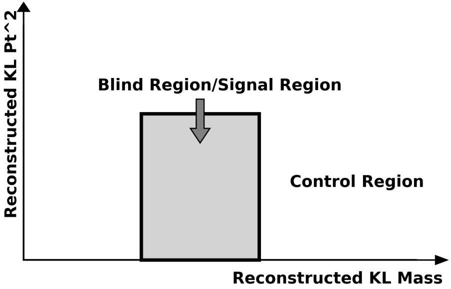
- 5 major backgrounds considered with large amount of Monte Carlo simulation data generated with Geant4 on KEKCC (KEK central computer system) and OSG (Open Science Grid).

| Decay Name | Decay Mode | $(\mathcal{BR})$ | $N_{exp}$ | $N_{MC}$ |
|---|---|---|---|---|
| $\pi+$ - 0 | $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ | 0.1254 | $1.84 \cdot 10^{11}$ | $6.03 \cdot 10^{11}$ |
| 3 $\pi^0$ | $K_L^0 \rightarrow \pi^0\pi^0\pi^0$ | 0.1952 | $2.87 \cdot 10^{11}$ | $3 \cdot 10^{12}$ |
| 3 $\pi^0$ 1 Dalitz | 1 $\pi^0 \rightarrow \gamma e^+ e^-$ | $2.2 \cdot 10^{-3}$ | $3.2 \cdot 10^9$ | $1.1 \cdot 10^{10}$ |
| 3 $\pi^0$ 2 Dalitz | 2 $\pi^0 \rightarrow \gamma e^+ e^-$ | $2.6 \cdot 10^{-5}$ | $3.8 \cdot 10^7$ | $8.4 \cdot 10^9$ |
| 3 $\pi^0$ double Dalitz | 1 $\pi^0 \rightarrow e^+ e^- e^+ e^-$ | $6.3 \cdot 10^{-6}$ | $9.3 \cdot 10^6$ | $2.4 \cdot 10^9$ |

- Accidental Events from real data are overlayed.
- Other backgrounds proved to be negligible from preliminary study, including $K^+$ decays and $K_L^0 \rightarrow \pi^0\pi^0$.

# Blind Analysis

- Signal events should have reconstructed $K_L^0$ mass close to true value and low $K_L^0$ transverse momentum since no particle is missing.
- Blind analysis: Events inside the blind region were inaccessible until selection criteria were determined




- Besides the reconstruction, signal identification is based on a set of physical cuts that highly depress all relevant background sources.
- Three major kinds of cuts: Veto detector cuts, kinematic cuts, and cluster shape cuts.

# Background Reduction - Example of Cuts

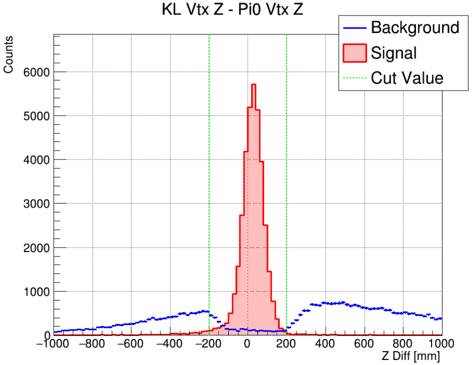



Figure: Vertex Z Difference Distribution

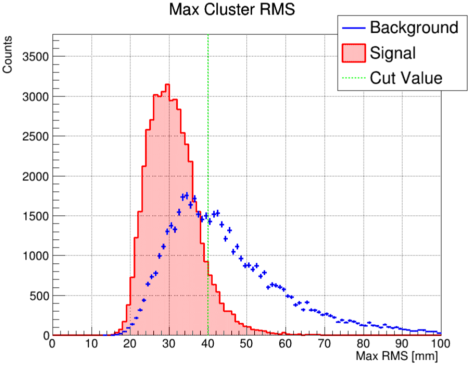
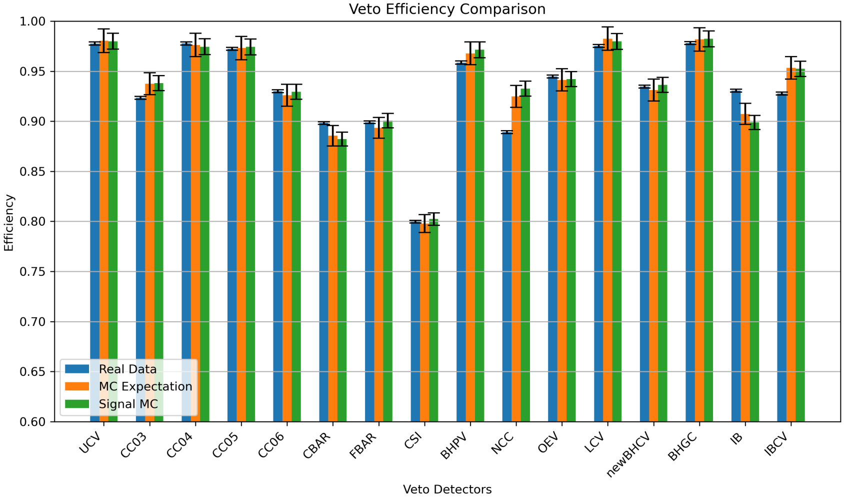



Figure: Cluster Shape RMS Distribution

- MC of backgrounds (normalized based on branching ratio and acceptance) compared to MC of signal
- Complete cut set with thresholds used is attached in backup slides

# Data and MC Agreement - Veto Efficiency




**Definition**

Efficiency of Cut X $=$

$$\frac{\#\ \textit{after all Veto Cuts}}{\#\ \textit{after all Veto Cuts except X}}$$

- Precuts: Geometry cuts on CSI Hits (Max R, Min(x,y)) and Max cluster shape $\chi^2$

# Data and MC Agreement - Cut Variable Distributions

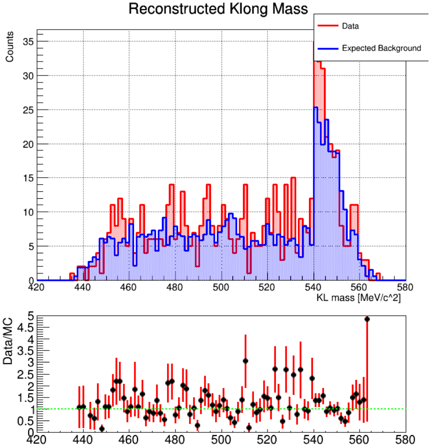



Figure: Reconstructed $K_L^0$ Mass

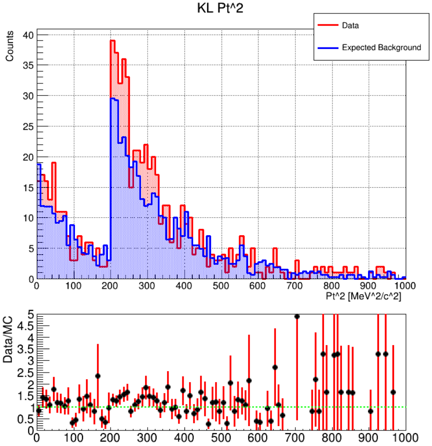



Figure: Reconstructed $K_L^0$ transverse momentum square

- PreCuts: VetoCuts, CSI geometry cuts, 4 CV Hits, Pi0 Vertex Cut, Vertex Difference Cut, COE XY cut.
- The distributions of data and backgrounds expectation from MC shows agreement.
- This agreement suggests no major missing backgrounds at this stage.

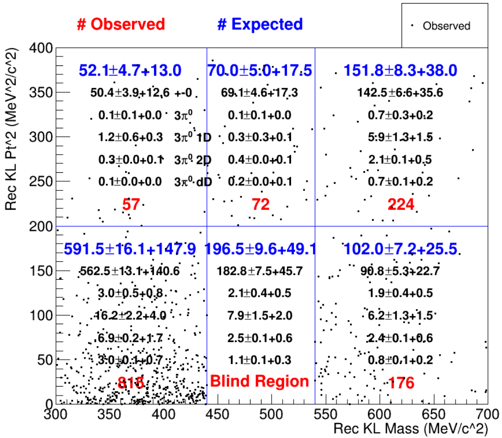



Figure: $\chi^2$ Cut

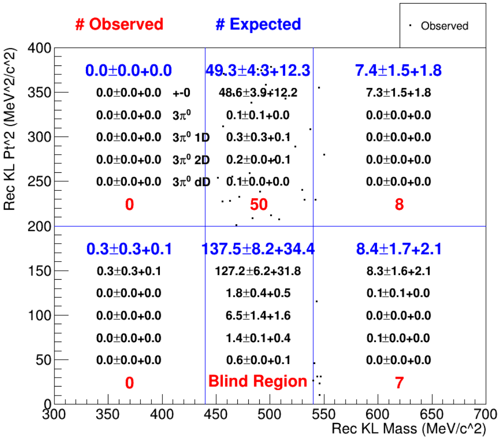



Figure: Cuts: $\chi^2$, RMS, $\pi^0$ Vertex Z, Vertex Z Diff

- Black numbers = expected number of each background source.

# Data and MC Agreement - Control Regions

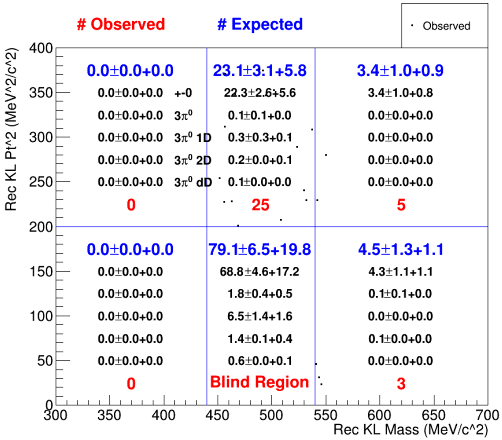



Figure: Cuts: $\chi^2$, RMS, $\pi^0$ Vertex Z, Vertex Z Diff, COE X, COE Y

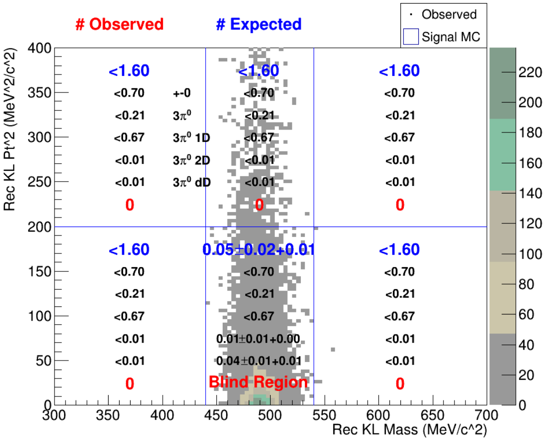
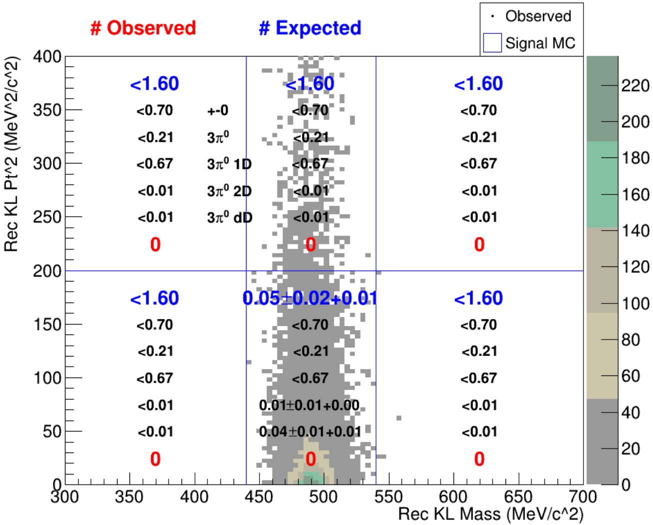



Figure: With All Cuts (complete cut set in backup). 90% C.L. limits provided

- Shaded area represents signal events distribution from MC.

# Open Box




- With the final cut set, we expect $< 1$ background event in signal region.
- After Opening Box, we see **0** events in signal region.

# Preliminary Results

- Total yield of $K_L^0$ is calculated through normailzation to $3\pi^0$ with a different trigger: $Y \approx 1.47 \times 10^{12}$.
- Signal Acceptance calculated from MC:

$$A_{sig} = \frac{N_{sig\ MC\ accepted}}{N_{sig\ MC\ generated}} = \frac{11839}{3.9 \cdot 10^9} \approx 3.04 \times 10^{-6}$$

- Single Event Sensitivity:

$$SES = \frac{1}{Y \cdot A_{sig}} \approx 1.79 \times 10^{-7}$$

- Finally, at 90% C.L., we can set a upper limit

$$\mathcal{BR}(K_L^0 \to \pi^0 e^+ e^- e^+ e^-) < \mathbf{4.11 \times 10^{-7}}$$

# Summary

- Algorithm developed to reconstruct signal decay.
- Set of cuts used to reduce background sources.
- With blind analysis, agreement between MC and data is presented.
- No signal events observed within signal region after opening the box.
- We set the first upper limit on this decay mode (Preliminary),

$$\mathcal{BR}(K_L^0 \to \pi^0 e^+ e^- e^+ e^-) < 4.11 \times 10^{-7} \text{ (at 90\% C.L.)}$$

# BACKUP

# Backup

| Cut Variable Name | Threshold |
|---|---|
| Max Cluster Chi2 | < 6 |
| Max Cluster RMS | < 40 mm |
| Reconstructed KL vertex Z | [3000, 5000] mm |
| Reconstructed Pi0 vertex Z | [3000, 5000] mm |
| KL Z - Pi0 Z | [-200,200] mm |
| Max CSI Fiducial R | < 850 mm |
| Min CSI (\|x\|, \|y\|) | > 150 mm |
| Min Cluser Energy | > 50 MeV |
| Min Cluster Distance | > 150 mm |
| Delta Vertex Time | < 3 ns |
| Delta Cluster Time | < 4 ns |

Figure: Full Cut Set

| Cut Variable Name | Threshold |
|---|---|
| CV Hit Min Energy | > 0.1 MeV |
| CV Hit Time - Estimated time | [48.8, 57.9] ns |
| Min Front CV Hits Distance | > 250 mm |
| Min Rear CV Hits Distance | > 300 mm |
| COE X and COE Y | [-100, 100] mm |
| Min CSD | > 0.9 |
| Reconstructed KL Pt^2 | < 200 MeV^2 |
| Reconstructed KL Mass | [440, 540] MeV |

Figure: Full Cut Set continued.

# Veto Cuts Thresholds

| Veto Detector Name | Cut Threshold (MeV) |
|---|---|
| UCV | 0.05 |
| CC03 | 3 |
| CC04 | 3 |
| CC05 | 3 |
| CC06 | 3 |
| CBAR | 2 |
| FBAR | 2 |
| BHPV | 2.5 |
| NCC | 2 |
| OEV | 2 |
| LCV | 0.6 |
| BHGC | 2.5 |
| IB | 2 |
| IBCV | 1 |

# Backup - Cuts

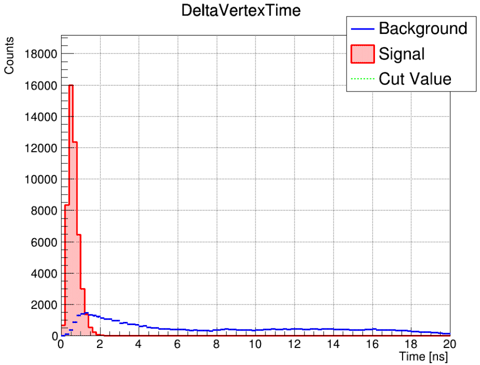



Figure: Delta Vertex Time

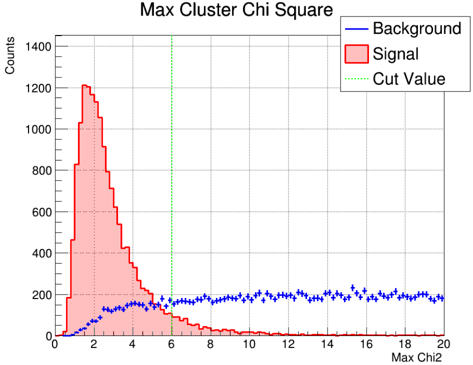



Figure: Cluster Chi2

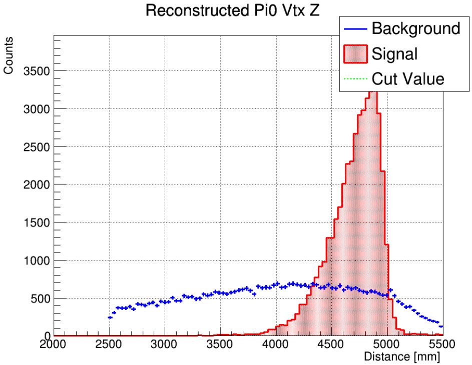



Figure: Pi0 Vertex Z

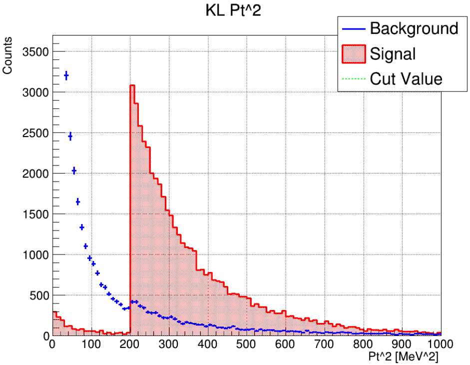



Figure: Rec KL Pt2

# Backup - Cuts

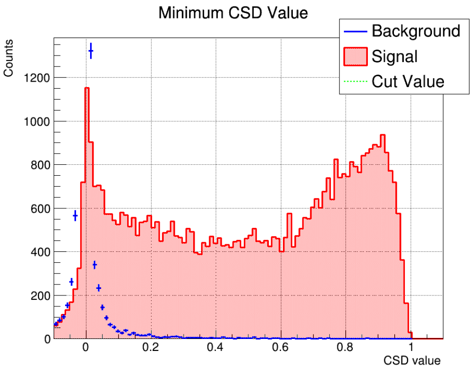



Figure: Min CSD value

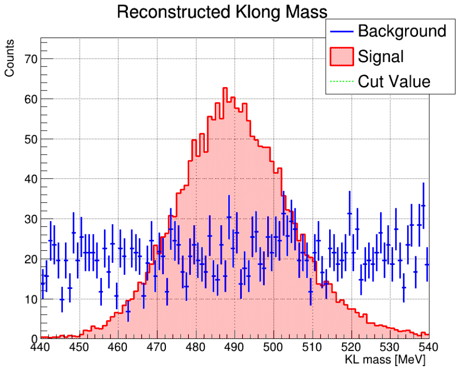
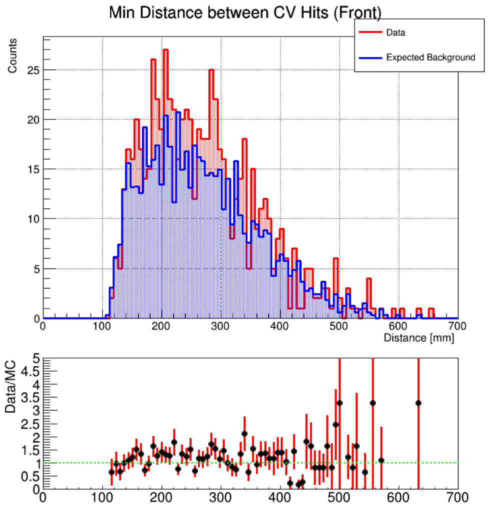
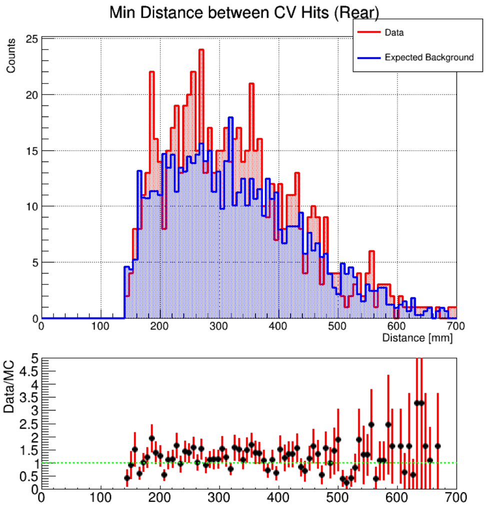



Figure: Rec KL Mass

# Backup - Data MC Comparison



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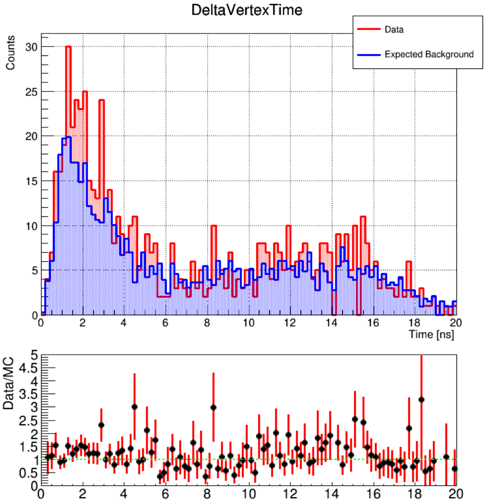


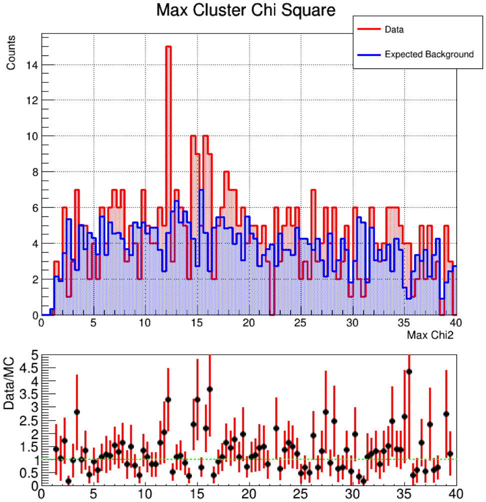

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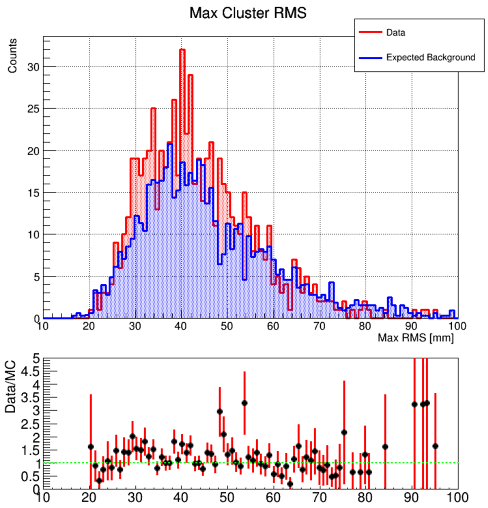


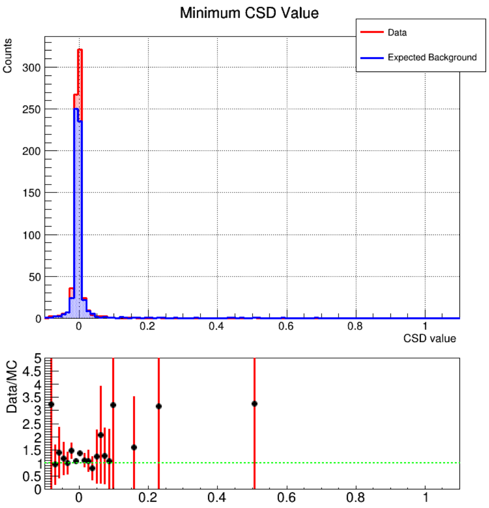

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