Observation of the decay mode $K_L \to \pi^+\pi^-e^+e^-$

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January 17, 2000

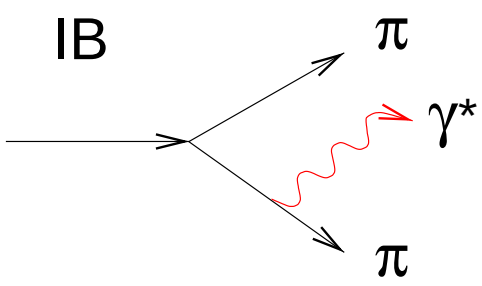
Contents

- Physics Motivation
- Experimental apparatus (KEK-E162)
- Analysis
  - Normalization Mode : $K_L \to \pi^+\pi^-\pi^0_D$ ($\pi^0_D \to e^+e^-\gamma$)
  - Signal Mode : $K_L \to \pi^+\pi^-e^+e^-$
  - Calculation of Branching ratio
- Conclusion

Physics Interest of $K_L \to \pi^+\pi^-e^+e^-$

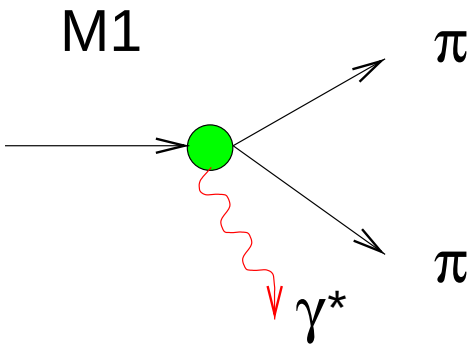
- Occur via $\pi^+\pi^-\gamma^*$ intermediate state
- Two dominant contributions to $\pi^+\pi^-\gamma^*$
  - Bremsstrahlung related to $K_L \to \pi^+\pi^-$
    - ⇨ CP-violating
  - Magnetic-type direct emission
    - ⇨ CP-conserving
  - Interference between Two
    - ⇨ CP-violating γ^* polarization

Two dominant contributions to $\pi^+\pi^-\gamma^*$



Internal Bremsstrahlung

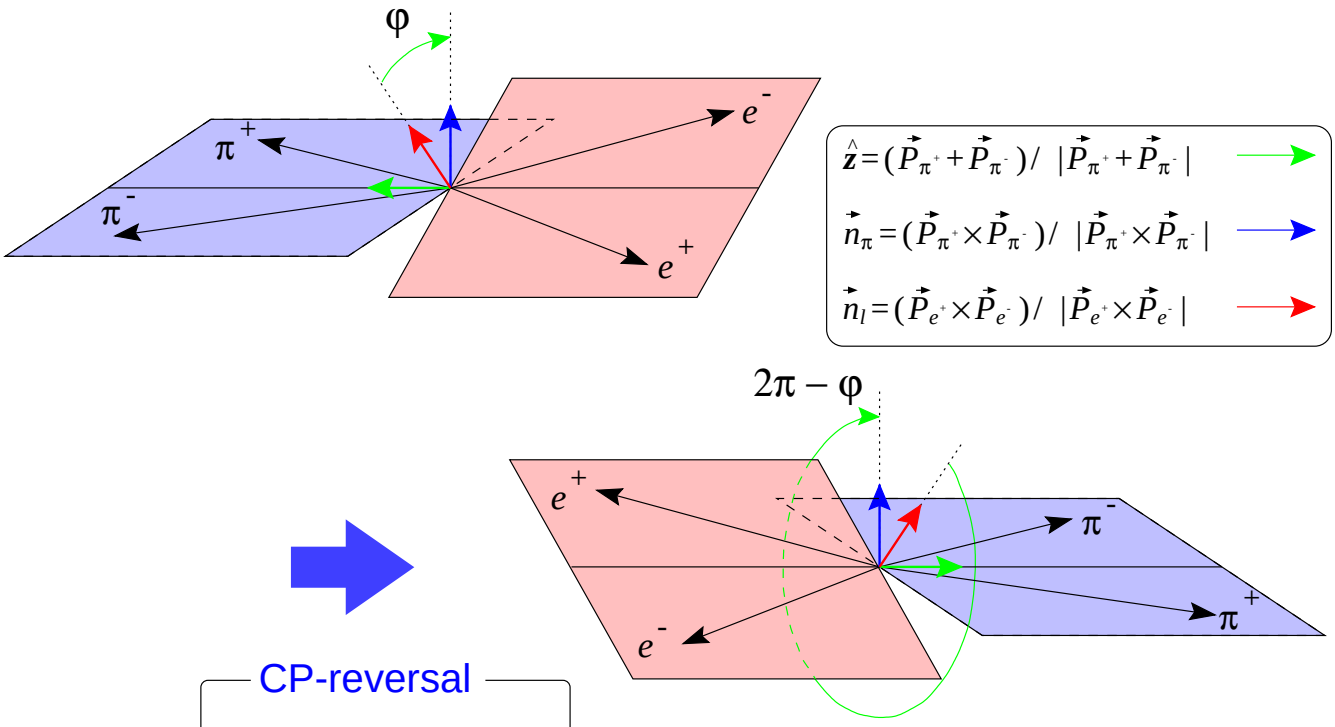
CP even



Magnetic dipole component

CP odd

Physics Interest of $K_L \to \pi^+\pi^-e^+e^-$



$$\hat{z} = (\vec{P}_{\pi^+} + \vec{P}_{\pi^-}) / |\vec{P}_{\pi^+} + \vec{P}_{\pi^-}|$$

$$\vec{n}_\pi = (\vec{P}_{\pi^+} \times \vec{P}_{\pi^-}) / |\vec{P}_{\pi^+} \times \vec{P}_{\pi^-}|$$

$$\vec{n}_l = (\vec{P}_{e^+} \times \vec{P}_{e^-}) / |\vec{P}_{e^+} \times \vec{P}_{e^-}|$$

CP-reversal

$\varphi \to 2\pi - \varphi$

$\sin\varphi \to -\sin\varphi$

$\cos\varphi \to \cos\varphi$

$$\frac{d\Gamma}{d\varphi} = \Gamma_1 \cos^2\varphi + \Gamma_2 \sin^2\varphi + \Gamma_3 \sin\varphi\cos\varphi$$

$$A \equiv \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\varphi} d\varphi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\varphi} d\varphi}{\int_0^{\pi/2} \frac{d\Gamma}{d\varphi} d\varphi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\varphi} d\varphi} \sim 14\%$$

⇨ A good testing ground to study CP-violating phenomena

Theoretical Prediction

❑ $Br(K_L \to \pi^+\pi^-e^+e^-) \sim 3\times10^{-7}$

Experimental Status

❑ $Br(K_L \to \pi^+\pi^-e^+e^-) < 2.5\times10^{-6}$

M. Y. Balats *et al.* Sov. J. Nucl. Phys. 38, 556 (1983)

❑ $Br(K_L \to \pi^+\pi^-e^+e^-) < 4.6\times10^{-7}$ ($M_{ee} \geq 4\mathrm{MeV/c^2}$, 90%C.L.)

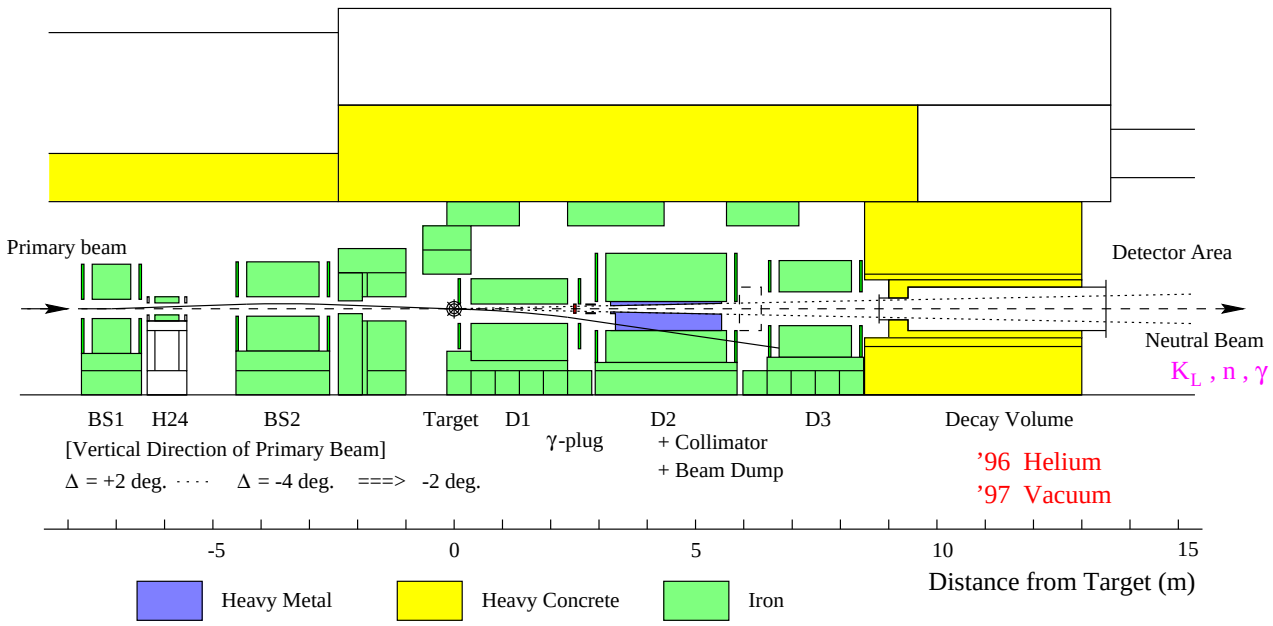
T. Nomura *et al.*, Phys. Lett. B408, 445 (1997)
KEK-E162

❑ Observation of the decay mode $K_L \to \pi^+\pi^-e^+e^-$

Y. Takeuchi *et al.*, Phys. Lett. B443, 409 (1998)
KEK-E162

Experimental Apparatus (KEK-E162)

K0 Beamline



KEK 12 GeV/c Proton Synchrotron — K0 Beamline

- ❑ Primary beam: 12 GeV/c proton 1×10^{12} ppp
- ❑ Collimator aperture: ± 4 mrad (Horz) $\times \pm 20$ mrad (Vert)
- ❑ Target: Cu 60 mm$l$ $\times$ 10 mmϕ 2° Production

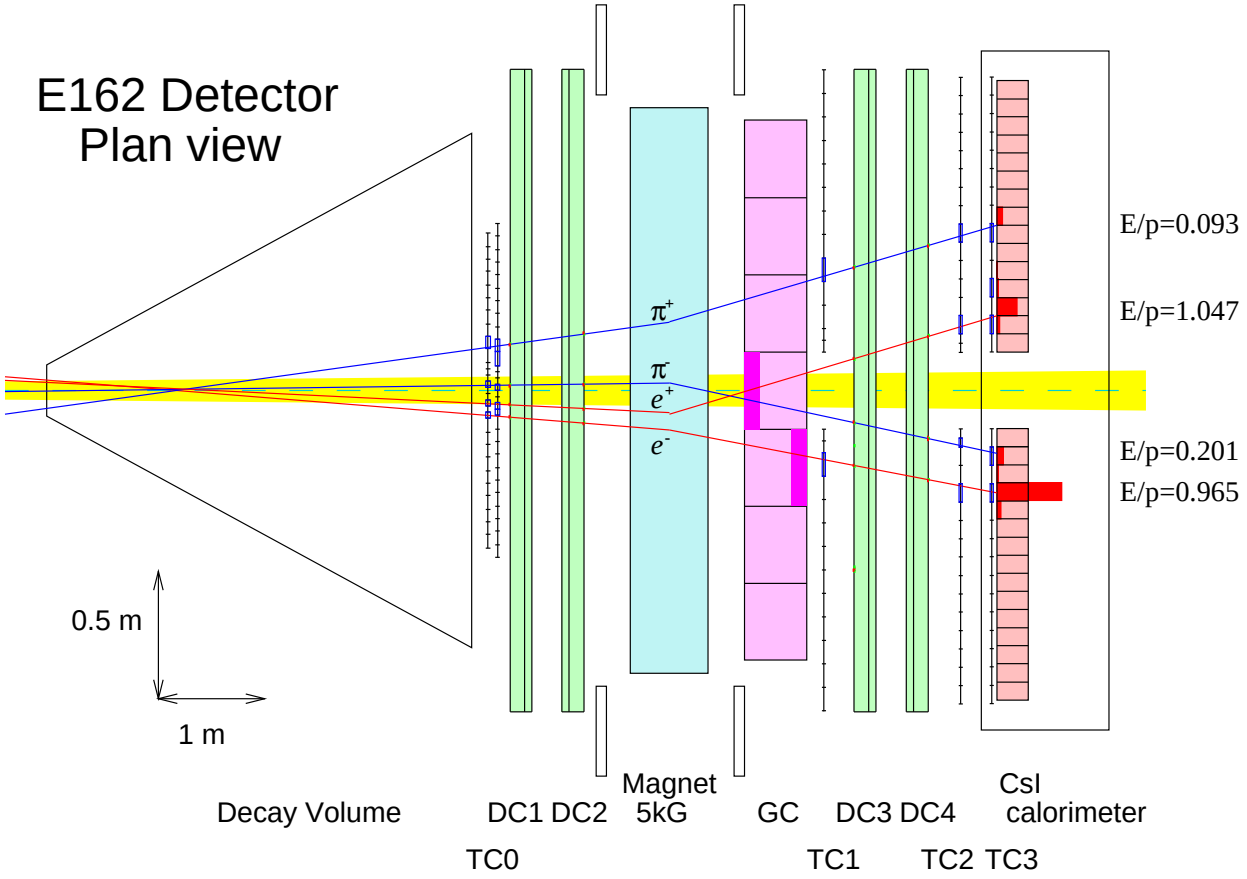
Decay Volume — filled with

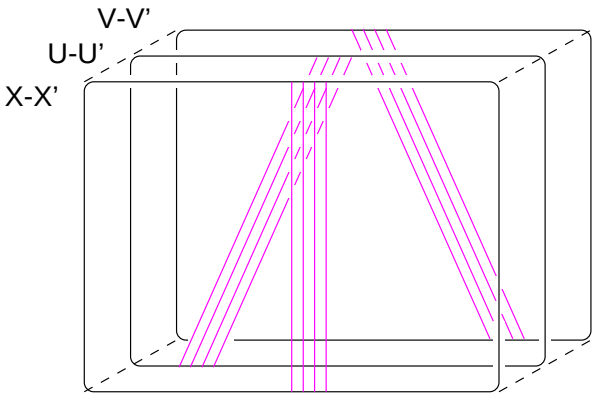
- ❑ Helium 1 atm (3 beam cycles in 1996)

  ⇨ Helium Run

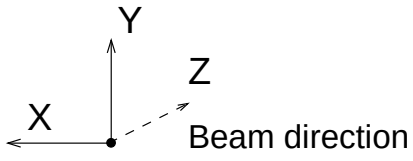
- ❑ Vacuum 8×10^{-3} Torr (5 beam cycles in 1997)

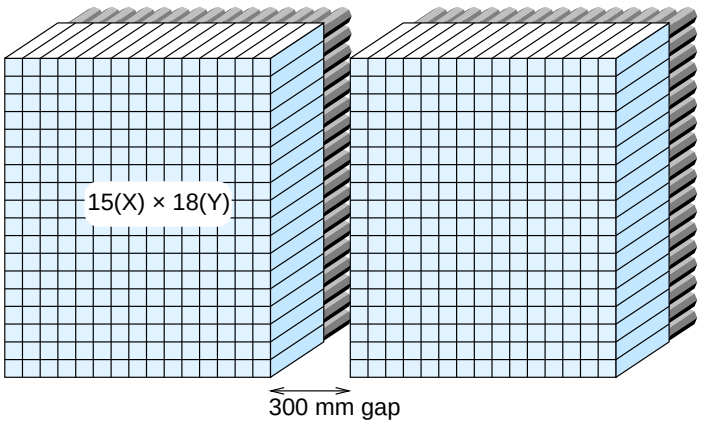
  ⇨ Vacuum Run





- **Spectrometer**
  - Analyzing magnet ($\Delta P_x \approx 136$ MeV/c)
  - Drift chambers : 4 set × 6 Layer (X-X', U-U', V-V')
- **Calorimeter**
  - Pure CsI (70mm × 70mm × 300mm)
    15 (X) × 18 (Y) × 2 arms
- **Gas CherenkovCounter**
  - N_2 at 1 atm, electron ID
- **Trigger hodoscopes**
  - TC0X, TC1X, TC2X/Y and TC3X





Trigger for $K_L \rightarrow \pi^+\pi^-e^+e^-$

Policy

- Charged Track ≥ 3
- Electron like ≥ 2

Level 1 (NIM logic)

- N(TC23) ≥ 3
- N(TC0X) ≥ 3
- N(TC1X) ≥ 2
- N(TC2Y) ≥ 2
- N(GC) ≥ 2
- N(CSIX) ≥ 2
- N(CSIY) ≥ 2

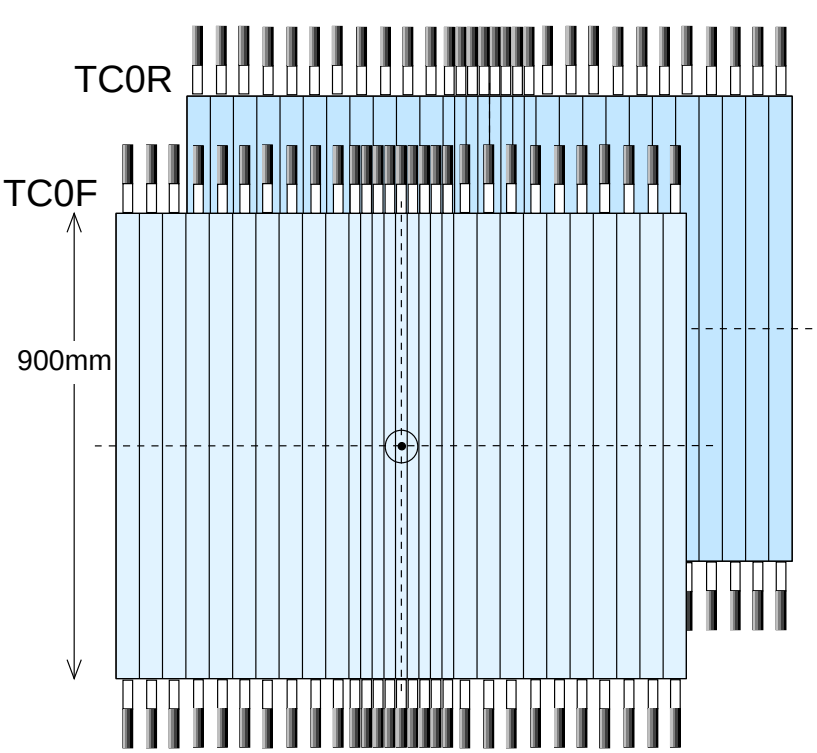
Trigger rate : 490/spill

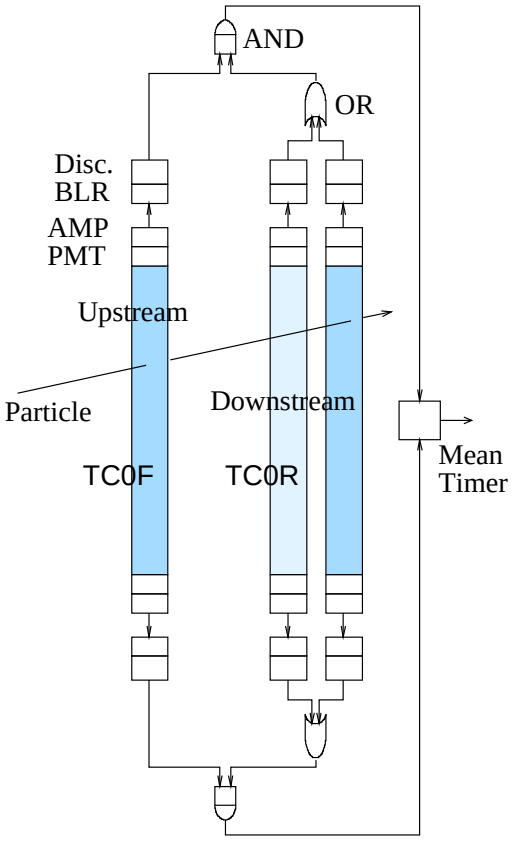
Level 2 (Hardware Processor)

- Coarse Tracking Processor : CTP
  - N(electron-cand.) ≥ 2 (≥ 1 in each arm)
  - N(tracks) ≥ 3
- Cluster Finding Processor : CFP
  - N(electron-cand.) ≥ 2 (≥ 1 in each arm)

Trigger rate : 170/spill

Upstream Trigger Hodoscope TC0X





- Two layers of plastic scintillators
  - 1.5 mm thickness with 900 mm length
  - 2 MHz/PMT (Inside beam region)
- Efficiency for $K_L \rightarrow \pi^+\pi^-e^+e^-$ (Trig.3 : TC0X $\geq$ 3)
  84%
- Trigger Rate Reduction (Trig.3 : TC0X $\geq$ 3)
  ~11.8

Analysis Overview

Normalization Mode

$K_L \to \pi^+\pi^-\pi^0_D$

➥ $e^+e^-\gamma$

Signal Mode

$K_L \to \pi^+\pi^-e^+e^-$

- ❍ Large branching ratio
- ❍ Similar topology to Signal

General Event Selection

- ❍ Event Topology

  π^+ , π^- , e^+ and e^- with Good Vertex
- ❍ Background Rejection

Candidate Sample

Normalization Mode

- ❍ $\pi^0 \to e^+e^-\gamma$ ID
- ❍ K_L mass , θ^2

Reconstructed $\pi^+\pi^-\pi^0_D$

K_L-flux

Signal Mode

- ❍ π^0 Inclusive Cut
- ❍ χ^2_D Cut
- ❍ K_L mass , θ^2
- ❍ B.G. Subtraction

Reconstructed $\pi^+\pi^-e^+e^-$

Final Results

Systematic Error Estimation

General Event Selection

❑ Event Topology

⇨ π^+, π^-, e^+ and e^- with Good Vertex

❑ Background Rejection

❍ Photon Conversion

$K_L \to \pi^+\pi^-\pi^0\,(\pi^0 \to 2\gamma)$ with γ-conv. ⇨ $\pi^+\pi^-\pi^0_D$

$K_L \to \pi^+\pi^-\gamma$ with γ-conv. ⇨ $\pi^+\pi^-e^+e^-$

$M_{ee} \geq 4\,\mathrm{MeV/c^2}$ and $N_{share} < 8$

❍ Pion Momentum Blance

$$A_{+-} \equiv \frac{P_{\pi^+} - P_{\pi^-}}{P_{\pi^+} + P_{\pi^-}}$$

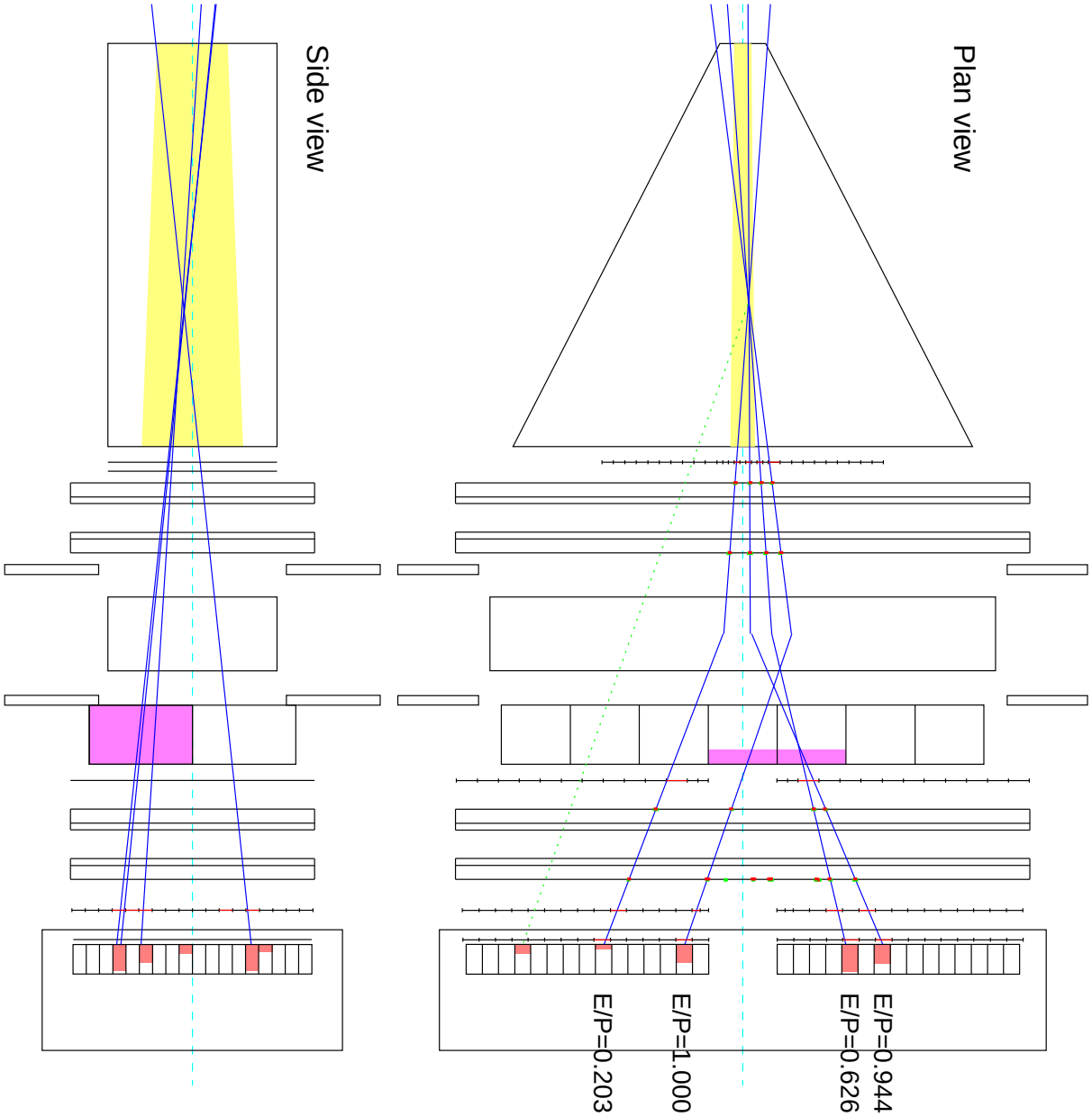
¶ Nuclear interaction event

¶ $\pi \to \mu\nu$ decay event

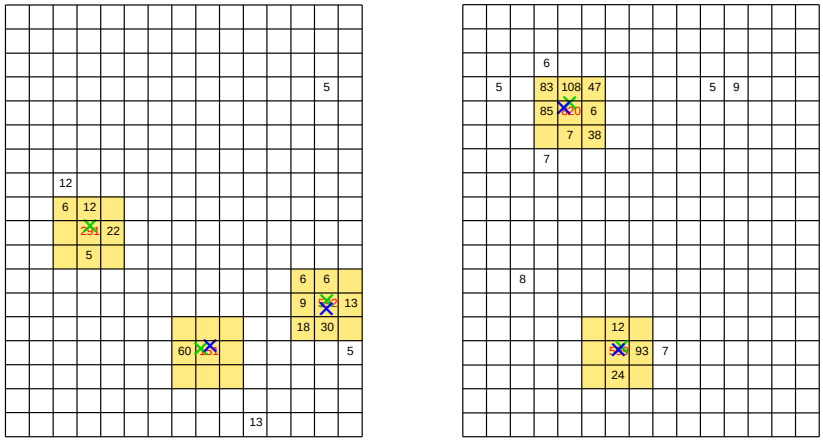
⇨ Large asymmetry in pion momentum

$|A_{+-}| < 0.5$

Event Reconstruction



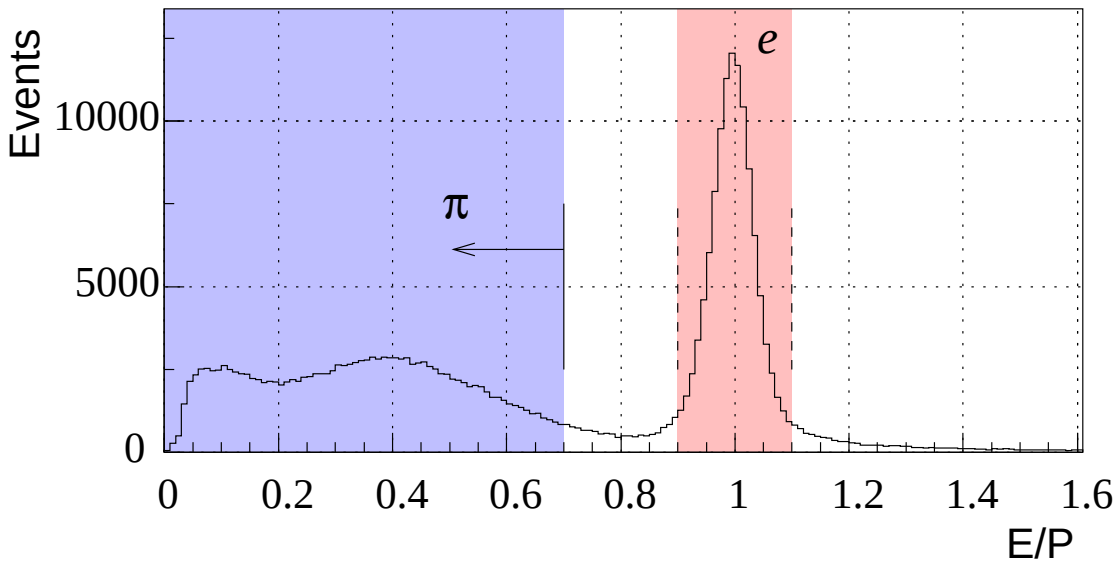
CsI rear view



Extrapolated track position

Cluster center

Particle Identification

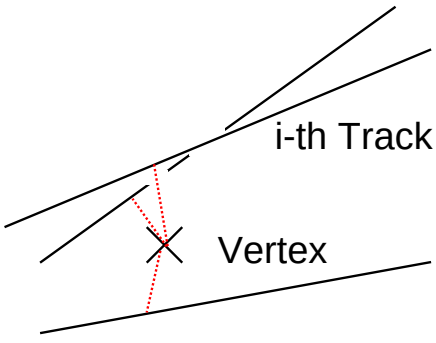


- Electron : $|E/P - 1.0| < 0.1$ with GC cell hit
- Pion : $E/P < 0.7$
- Photon : Neutral cluster with $E \geq 200$ MeV

Vertex Finding

- Vertex χ^2 definition

$$\chi_v^2 \equiv \sum_i \left(\frac{d_i}{\sigma_i(z_i, p_i)} \right)^2$$



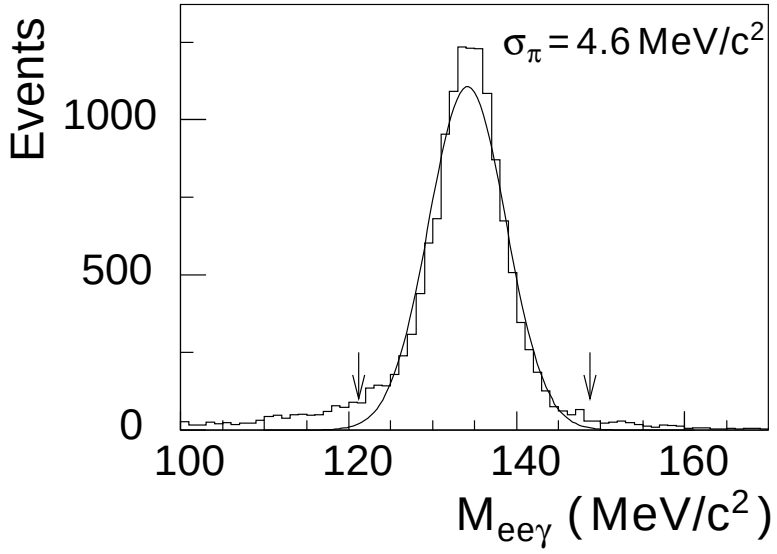
Track-Vertex distance d_i

- Vertex χ^2 Cut
  - ⇨ $\chi_v^2 < 20$
- Vertex Position
  - ⇨ Beam region in the decay volume

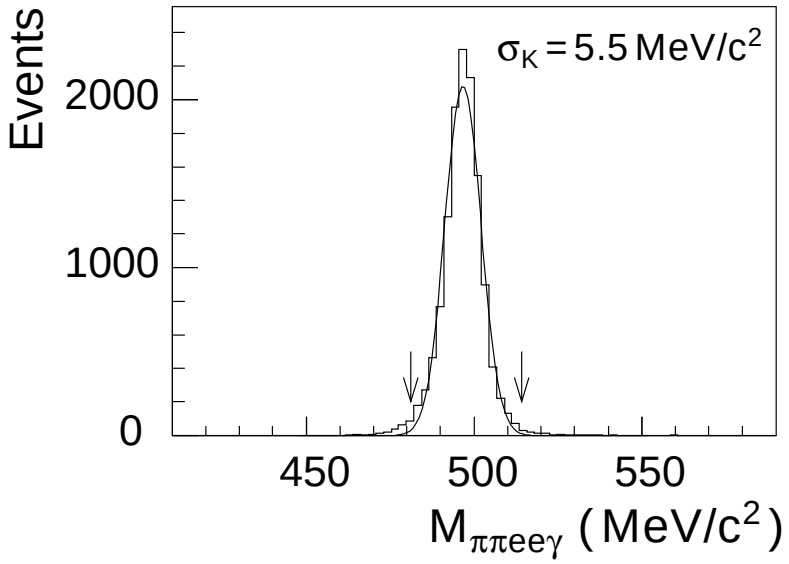
Normalization Mode

$$K_L \to \pi^+\pi^-\pi^0_D \ (\ \pi^0_D \to e^+e^-\gamma\ )$$

- Existence of Photon candidate(s)
- $\pi^0 \to e^+e^-\gamma$ Identification (π^0 mass cut)

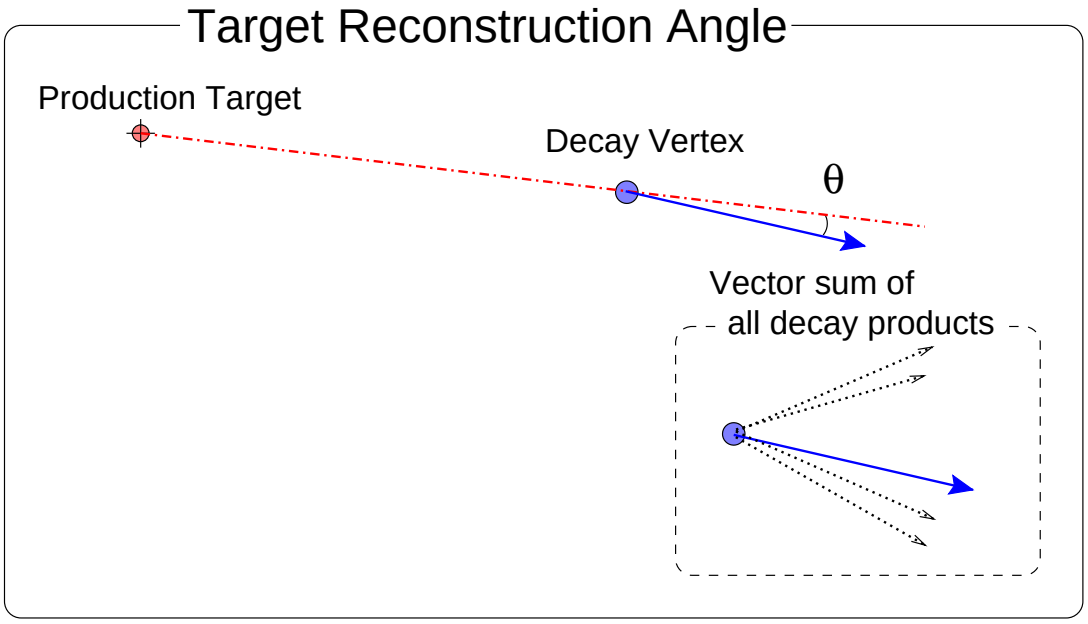


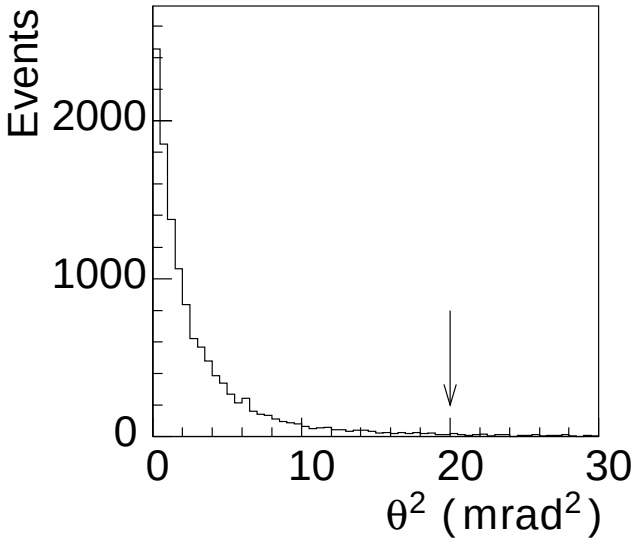
- Invariant Mass of $\pi^+\pi^-e^+e^-\gamma$ ⇨ K_L mass (K_L mass cut)

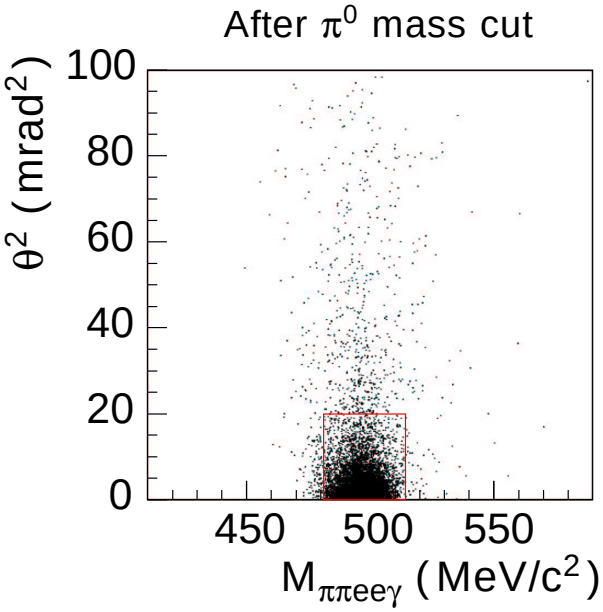


Normalization Mode

- Another kinematical constraint (θ^2 cut)





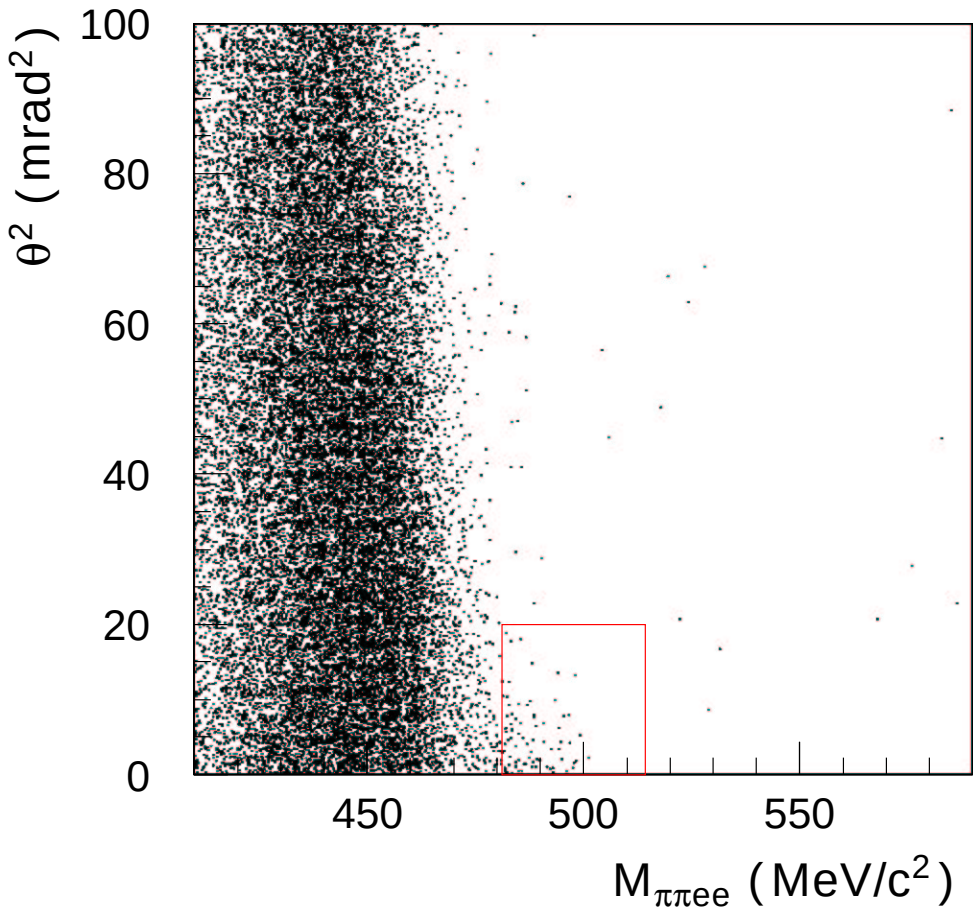


12212 events reconstructed
with less than 1% backgrounds.

Signal Mode

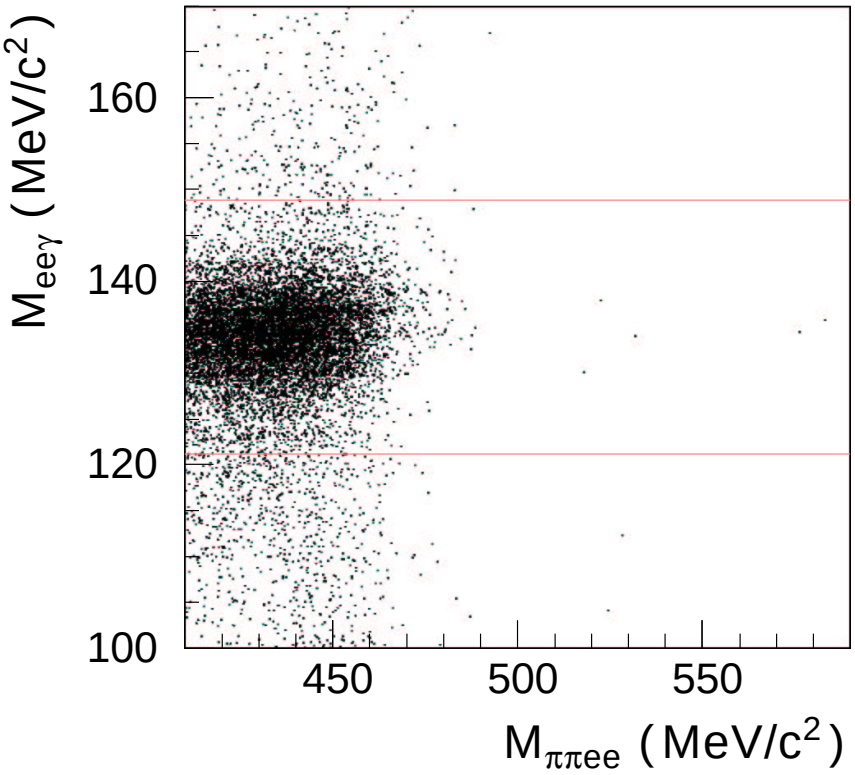
- Overwhelming backgrounds from $\pi^+\pi^-\pi^0_D$

$$\frac{Br(K_L \to \pi^+\pi^-\pi^0_D)}{Br(K_L \to \pi^+\pi^-e^+e^-)} \sim 5\times10^4$$



π^0 Inclusive Cut

- If γ exists and $M_{ee\gamma} \Rightarrow M_{\pi^0}$
  - ⇨ Reject
  - Reconstructed $\pi^+\pi^-\pi^0_D$ ⇨ Reject
  - π^0 inclusive nuclear interaction ⇨ Reject



- Over-veto probability
  - ⇨ ~1%

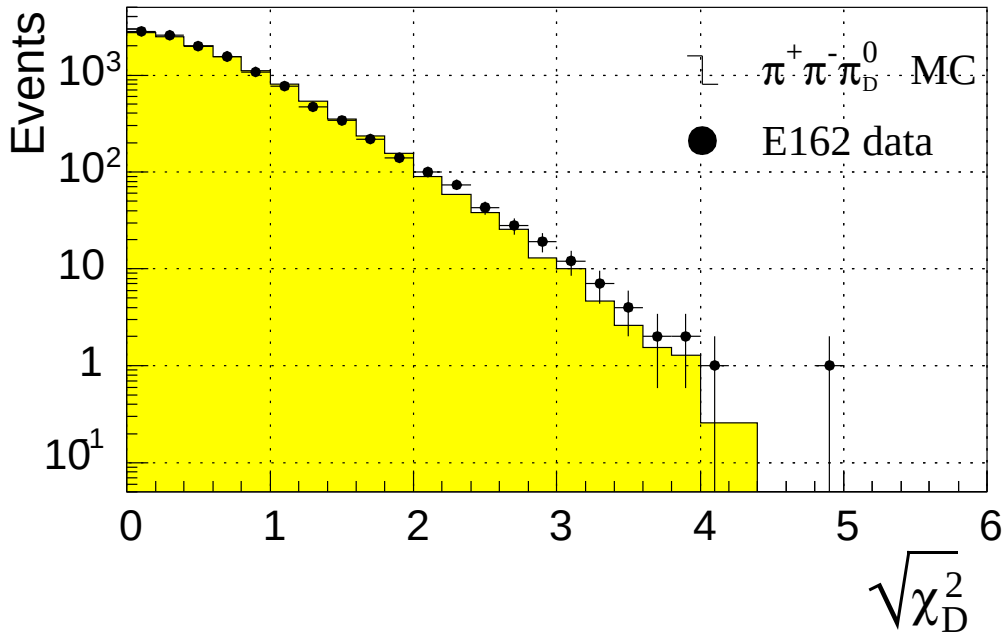
Backgrounds from $K_L \to \pi^+\pi^-\pi^0_D$ with missing γ

- Assumming existence of a photon with an arbitarary momentum $\vec{P}_\gamma$
- Define χ^2_D as

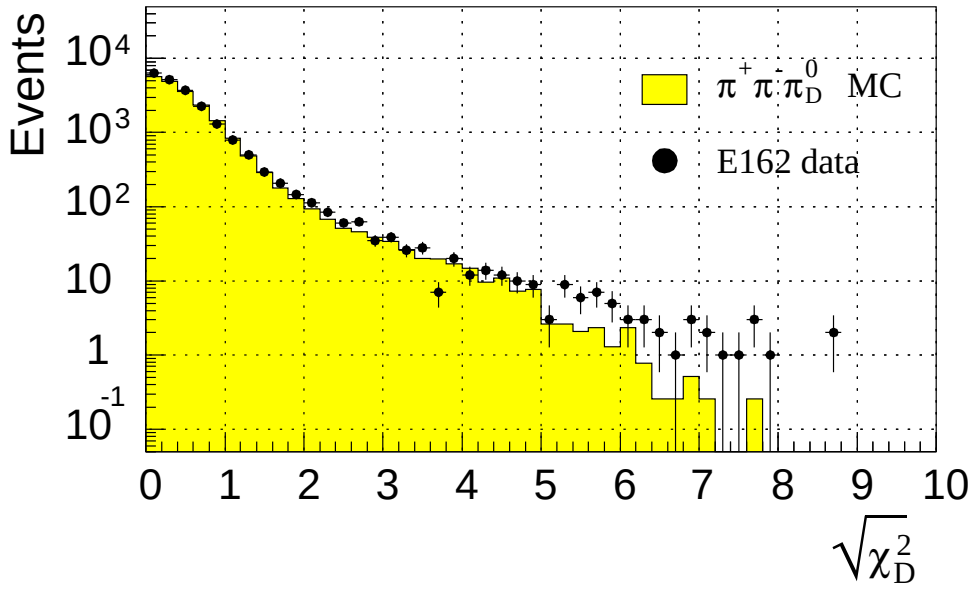
$$\chi^2_D(\vec{P}_\gamma) \equiv \left(\frac{M_{ee\gamma} - M_{\pi^0}}{\sigma_\pi}\right)^2 + \left(\frac{M_{\pi\pi ee\gamma} - M_{K_L}}{\sigma_K}\right)^2 + \left(\frac{\theta}{\sigma_\theta}\right)^2$$

  - Choose $\vec{P}_\gamma$ minimizing χ^2_D
  - $K_L \to \pi^+\pi^-\pi^0_D$ origin
    - ⇨ χ^2_D is expected to be small with an appropriate $\vec{P}_\gamma$

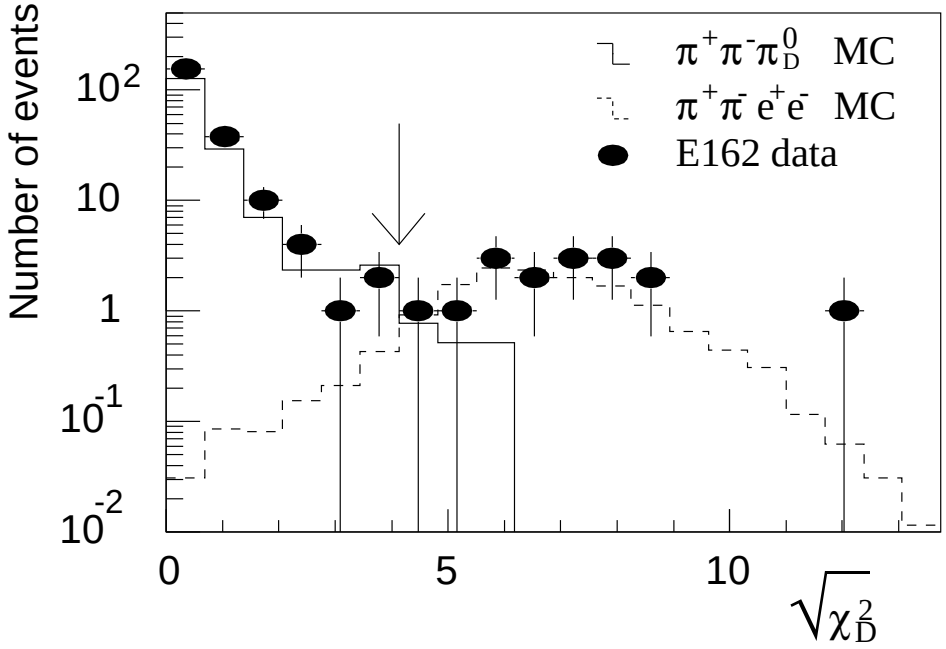
Reconstructed $\pi^+\pi^-\pi^0_D$ events



After π^0 inclusive cut



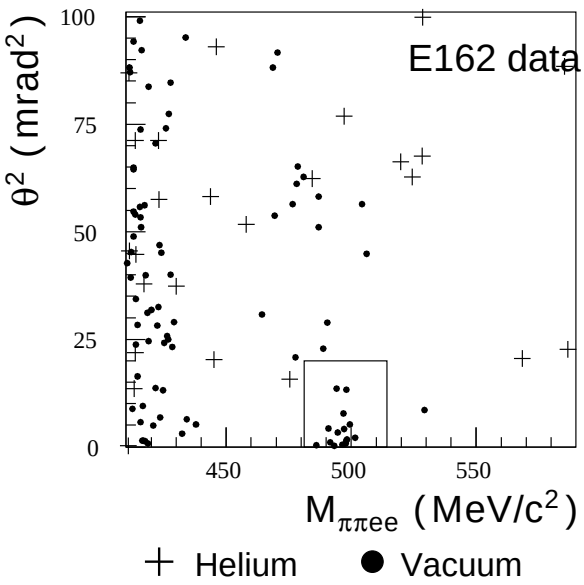
⇨ Most of events are consistent with $\pi^+\pi^-\pi^0_D$ origin

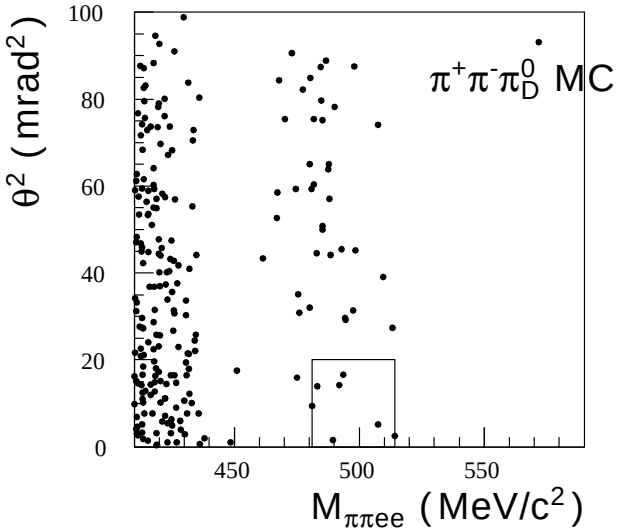


Events with $|M_{\pi\pi ee} - M_{K_L}| < 5\sigma_K$ & $\theta^2 < 20\,\mathrm{mrad}^2$

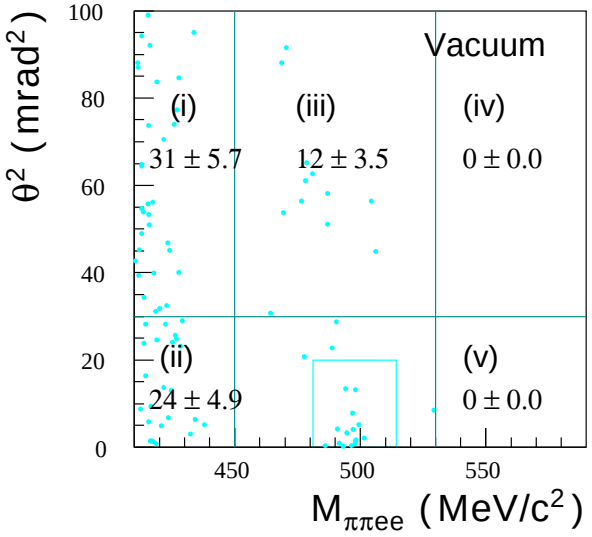
- $\chi^2_D \geq 17$
  - Efficiency for $\pi^+\pi^-e^+e^-$: 92%
  - Rejection for $\pi^+\pi^-\pi^0_D$: 99.7%

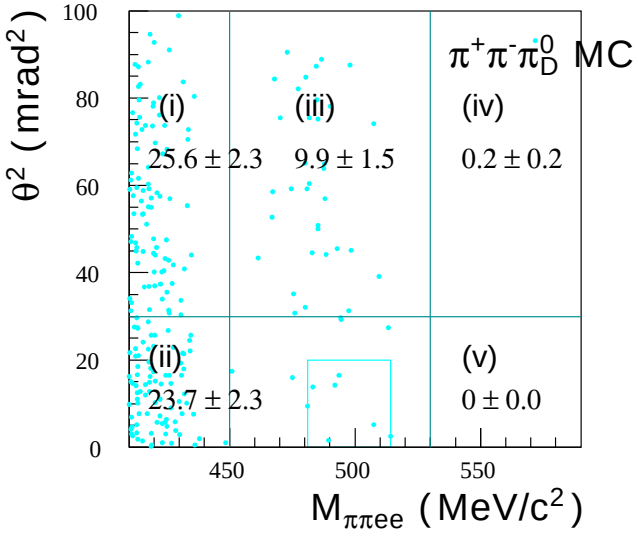
After χ^2_D Cut





15 events observed
in the signal region

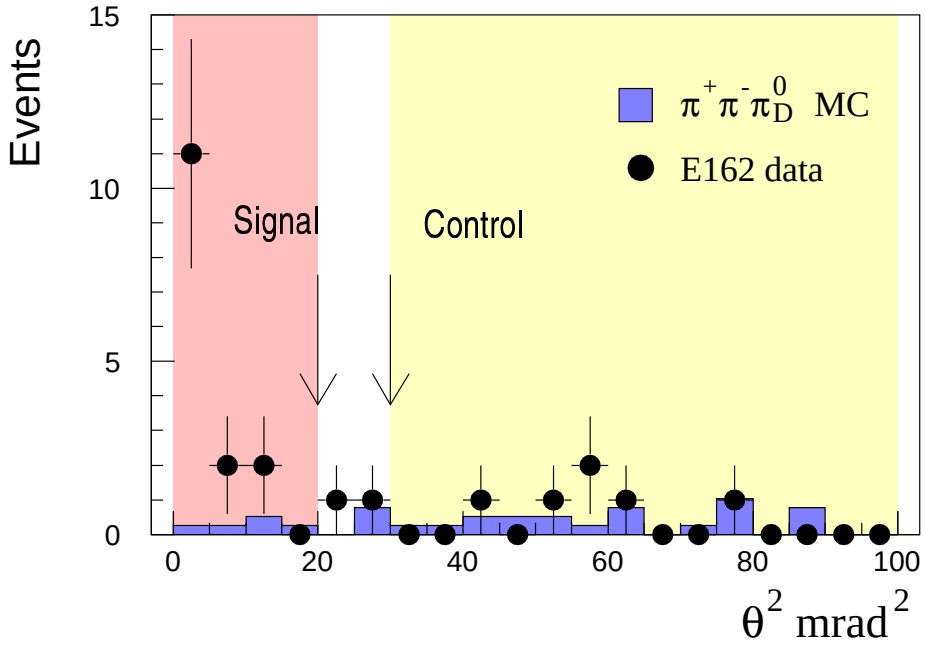




- Backgrounds are consistent with $\pi^+\pi^-\pi^0_D$ MC (Vacuum)
- Uniform backgrounds in $M_{\pi\pi ee}$-θ^2 plane(Helium)
  - ➥ Nuclear interaction events

Background subtraction

- Backgrounds have no structure along θ^2-axis
  - Project events with $|M_{\pi\pi ee} - M_{K_L}| < 3\sigma_K$ onto θ^2-axis



  - Clear peak at $\theta^2 = 0$ only in the data
  - Uniform backgrounds along θ^2-axis

- Control region

  $30\,\text{mrad}^2 \le \theta^2 \le 100\,\text{mrad}^2$

- Renormalize $\pi^+\pi^-\pi^0_D$ MC with

  the number of events in the control region

  ⇨ 1.5 ± 1.0 events expected in the signal region

- Final signal events

  $15 - 1.5 = 13.5 \pm 4.0$

Calculation of Branching Ratio

$$Br(K_L \to \pi^+\pi^-e^+e^-) = \frac{N(\pi^+\pi^-e^+e^-)}{A(\pi^+\pi^-e^+e^-)\cdot\eta(\pi^+\pi^-e^+e^-)} \times \frac{1}{F(K_L)}$$

A : Acceptance

η : Efficiency

N : Number of observed events

F : K_L flux

$$Br(K_L \to \pi^+\pi^-e^+e^-) = Br(K_L \to \pi^+\pi^-\pi^0_D) \times \frac{A(\pi^+\pi^-\pi^0_D)}{A(\pi^+\pi^-e^+e^-)} \times \frac{\eta(\pi^+\pi^-\pi^0_D)}{\eta(\pi^+\pi^-e^+e^-)} \times \frac{N(\pi^+\pi^-e^+e^-)}{N(\pi^+\pi^-\pi^0_D)}$$

	$\pi^+\pi^-\pi^0_D$	$\pi^+\pi^-e^+e^-$
N	12212 ± 110	13.5 ± 4.0
A	9.77×10^{-4}	2.64×10^{-3}
η	0.0529	0.0723

$\Rightarrow Br(K_L \to \pi^+\pi^-e^+e^-) = [4.4 \pm 1.3] \times 10^{-7}$

Summary of Systematic errors

	Source	Uncertainty
Acceptance Efficiency	K_L momentum spectrum	4.8%
	Matrix element	3.9%
	Others	3.1%
Number of Events	Background subtraction	7.4%
	Nuclear interaction	3.6%
	Other contamination	1.4%
	$Br(K_L \to \pi^+\pi^-\pi^0_D)$	3.1%
	Total	11.3%
	Statistical error	30%

$$Br(K_L \to \pi^+\pi^-e^+e^-) = [4.4 \pm 1.3(stat) \pm 0.5(syst)] \times 10^{-7}$$

Summary & Conclusion

- The decay mode $K_L \to \pi^+\pi^-e^+e^-$
  - Theoretical interest : CP-violation phenomena
  - $Br \sim 3\times10^{-7}$ (Prediction)
- Experiment conducted with KEK-E162
- 15 candidates observed with 1.5 background level
  - Clear evidence of $K_L \to \pi^+\pi^-e^+e^-$
- Normalization mode : $K_L \to \pi^+\pi^-\pi^0_D$ ($\pi^0_D \to e^+e^-\gamma$)
  - 12212 events with less than 1% B.G.
- $Br(K_L \to \pi^+\pi^-e^+e^-) = [4.4 \pm 1.3(stat) \pm 0.5(syst)]\times10^{-7}$
  - ⇨ consistent with
    theoretical prediction and
    recent measurement at FNAL (KTeV)

    $Br = [3.2 \pm 0.6 \pm 0.4]\times10^{-7}$

    J. Adams *et al.*, Phys. Rev. Lett. 80, 4123 (1998)

    based on 36.6 events

We have established
the decay mode $K_L \to \pi^+\pi^-e^+e^-$.