Report for the final review
on the KEK 12-GeV PS activities

E391a: Study of the rare decay
\[ \text{K}_L \rightarrow \pi^0 \nu \bar{\nu} \]

January 23, 2008
Takao Inagaki (KEK)
$K_L \rightarrow \pi^0 \nu \nu$ decay

- $K_L \rightarrow \pi^0 \nu \nu$ decay is a pure and clean process, which can directly measure a CKM element, $\text{Im}V_{td}(\eta)$, with a small theoretical ambiguity.

- The experimental motivation becomes more clear after the extensive studies in B-decay. The branching ratio of $K_L \rightarrow \pi^0 \nu \nu$ is predicted to be $(2.49 \pm 0.39) \times 10^{-11}$, which is evaluated from various B-decays based on the CKM unitarity. The error is $\pm 15\%$. Although a room for improvement of $\eta$ measurement still exists, now, the goal of $K_L \rightarrow \pi^0 \nu \nu$ experiment is mostly focused on a search for new physics.
Beyond the Standard Model

KL → π⁰ννν is one of most promising process in a search for new physics

Lepton flavor + isospin conservations

\[ \frac{\Gamma (K_L \rightarrow \pi^0 \nu \nu)}{\Gamma (K^+ \rightarrow \pi^+ \nu \nu)} = \sin^2 \theta \leq 1 \]

K_L → π⁰ννν is one of most promising process in a search for new physics

Review on the KEK 12-GeV PS Activities

January 23, 2008  Takao Inagaki
E391a collaboration

- Start from 8 members in 1995

- 12 institutes, ~50 members
  - Dept. of Physics, Pusan National Univ.
  - Dept. of Physics, Saga Univ.
  - Joint Institute for Nuclear Research
  - Dept. of Physics, National Taiwan Univ.
  - Dept. of Physics and Astronomy, Arizona State Univ.
  - KEK & SOKENDAI
  - Dept. of Physics, Osaka Univ.
  - Dept. of Physics, Yamagata Univ.
  - Enrico Fermi Institute, Univ. of Chicago
  - National Defense Academy
  - Dept. of Physics, Kyoto Univ.
  - Research Center for Nuclear Physics, Osaka Univ.

- Countries: Japan, the US, Taiwan, South Korea, and Russia
Detection method

Only 2 $\gamma$ are measurable and we have to reach $10^{-11}$.

From the energies and hit positions of 2 $\gamma$, the opening angle can be measured by assuming the parent of 2 $\gamma$ as $\pi^0$ and it provides the information of the vertex of $\pi^0$ ($K_L$) decay in $z$ direction.
Detection method

Pencil (very thin) beam provides the information in the x-y directions.

$P_T$ of $\pi^0$ with respect to the beam axis can be measured, and high $P_T$ selection greatly reduces the backgrounds from other decays and beam.

The hermetic veto assures the exclusive process of $K_L \rightarrow \pi^0$ nothing.
Detection method

This cost-saving set-up is worse.

Production points of $\pi^0$ by beam halo are not localized.
Detection method

Production points by beam halo are localized at certain $z$ outside the fiducial decay region.
Detection method

Double decay chamber reject BG from multi-$\pi^0$ decay with odd combination in the upstream region
Detection method

Inner part of the calorimeter is used for veto and various collar counters (CC) and BA are installed in order to cover the downstream decays.
Interaction rate of beam (mostly neutrons) with air is % level of the $K_L$ decay rate. To reach $10^{-11}$ sensitivity high vacuum of $10^{-5}$ Pa and no thick material in front of detector are required. Differential pumping using thin foil (membrane) was adopted.
E391a Detector
Run Summary

• Running conditions
  K0 beamline in the East Counter Hall of KEK 12 GeV PS
  • Intensity:
    2 \times 10^{12} \text{ protons on target (POT) per 2sec spill, 4sec cycle}
  • production angle: 4°, K_L peak momentum 2\text{GeV/c}, n/K_L ratio: 60\text{~}40

• Physics and calibration runs
  – Run I: February to July of 2004 w/o Be
    • \sim 3 \times 10^{18} \text{ POT}
  – Run II: February to April of 2005 w/ Be
    • \sim 2 \times 10^{18} \text{ POT}
  – Run III: October - December of 2005 mostly w/ Be
    • \sim 1.4 \times 10^{18} \text{ POT}
Result from Run-I

• Using 10% of Run-I data (Run-I one week)

• set new limit
  – $\text{Br} < 2.1 \times 10^{-7}$ (@90\%C.L.)
    (PRD 74:051105, 2006)
A serious problem in Run-I

- Beam core hits the membrane, which are accidentally drooped into the beam-line - core neutron background -
Result of Run-I full sample

It was very hard to apply the same selection to the full sample, because 1.9 events of BG were already expected in the small sample.

Removed the tail and Improved S/N by a factor of 1.6

SES : $9.1 \times 10^{-8} \rightarrow 5.1 \times 10^{-8}$, Nexp: 1.9 $\rightarrow$ 2.1

Masking of TDC data of BA was reduced by changing the time window 40 $\rightarrow$ 140 ns.

Time difference between subsequent hits of BA
Result of Run-II full sample

- Fixed the membrane problem,
- Changed the pulse widths of all veto counters,
- Lowered the TDC thresholds, *etc.*

The analysis, whose result was not described in the document report, was recently finished.
Channels used for normalization (KL flux estimation) and tuning of MC simulation

\[ \text{KL} \rightarrow 3 \pi^0 \]
Invariant mass of $2\pi^0$

PV + kinematics

PV only
## Systematic Errors on the flux

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI Veto</td>
<td>6.1%</td>
</tr>
<tr>
<td>Decay Vertex (Z) Spectrum</td>
<td>2.3%</td>
</tr>
<tr>
<td>Decay Vertex (Radial) Spectrum</td>
<td>1.8%</td>
</tr>
<tr>
<td>Charged Veto</td>
<td>1.3%</td>
</tr>
<tr>
<td>Fusion Neural-Network</td>
<td>1.3%</td>
</tr>
<tr>
<td>Photon Hit Position (CsI Position)</td>
<td>1.2%</td>
</tr>
<tr>
<td>23 Others (Total)</td>
<td>2.9%</td>
</tr>
<tr>
<td><strong>TOTAL (In Quadrature)</strong></td>
<td><strong>7.7%</strong></td>
</tr>
</tbody>
</table>
# Summary of $K_L$ flux

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal Events (Full Data Set)</th>
<th>Acceptance (with Accidental Loss)</th>
<th>Flux (w/ systematic errors)</th>
<th>Discrepancy $(X - \pi^0 \pi^0) / \pi^0 \pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \to \gamma \gamma$</td>
<td>20,685</td>
<td>$(0.697 \pm 0.004_{\text{Stat}})%$</td>
<td>$(5.41 \pm 0.37) \times 10^9$</td>
<td>5.0%</td>
</tr>
<tr>
<td>$K \to \pi^0 \pi^0$</td>
<td>$1494.9 (1500 - 5.1)$ ($\pi^0 \pi^0 \pi^0$ contribution)</td>
<td>$(3.35 \pm 0.03_{\text{Stat}}) \times 10^{-4}$</td>
<td>$(5.13 \pm 0.40) \times 10^9$</td>
<td>0%</td>
</tr>
<tr>
<td>$K \to \pi^0 \pi^0 \pi^0$</td>
<td>70,054</td>
<td>$(7.13 \pm 0.06_{\text{Stat}}) \times 10^{-5}$</td>
<td>$(5.02 \pm 0.35) \times 10^9$</td>
<td>-1.9%</td>
</tr>
</tbody>
</table>
K_L \rightarrow \pi^0 \nu \nu \text{ search: background study}

Blind analysis

- Hided signal (+ Control region) regions
- Estimated the backgrounds from outside with itemizing the expected sources
- After then, opened the hided region

The process is important not only to avoid human error but to understand the background sources for future.
Backgrounds from $K_L \rightarrow \pi^0 \pi^0$ decays

Estimated by MC simulations, relying on the good reproduction of the $\pi^0 \pi^0$ distribution at low mass by $K_L \rightarrow \pi^0 \pi^0 \pi^0$ MC. The missing 2-photon feature is similar.

With all cuts applied, only these two events survive.

Statistics are $\sim 11x$ Data.
Backgrounds from the other $K_L$-decays

$K_L \rightarrow 2\gamma$

Energy mis-measurement or response tail can make higher $P_T$ events, but the a-coplanar angle cut is quite effective to reduce them.

$K_L \rightarrow$ charged

(Ke3, $K\mu 3$ and charged-$K\pi 3$)

Backgrounds from all these decays are negligibly small
Halo neutron backgrounds

• Tails of 2 $\gamma$ produced by halo neutrons at the detectors
  - "CC02"
    • Tail of $\gamma$ energy measurement due to leakage or mis-measurement
  - "CV"
    • Multi-$\pi^0$ + odd combination
    • $\eta$: shift of vertex due to the assumption of $M_{2\gamma} = M_{\pi^0}$
CC02 background

Estimated from the special run data, which were normalized to the CC02 events.

Upstream edge of the signal region was determined by S/N.
CV- $\pi^0$ background

Estimated from the data using a bifurcation method. We also checked the reproduction of CV events by a halo neutron MC.

Cut sets

- **set-up cuts**
  - upstream veto detectors, CsI, and $\pi^0$ kinematics
- **set A**
  - downstream veto detectors
- **set B**
  - gamma selection
CV- $\eta$ background

Estimated from MC with 200 times statistics, after carefully checked the cross section, momentum and PT distributions using the target run data.
Background summary

- (1) 300-340cm : $1.9 \pm 0.2$
  - CC02: $1.9 \pm 0.2$
  - observed: 3 events

- (2) 340-400cm: $0.15 \pm 0.05$
  - CC02: $0.11 \pm 0.04$
  - CV- $\eta$: $0.04 \pm 0.02$

- (3) 400-500cm: $0.26 \pm 0.11$
  - CC02: $0.05 \pm 0.03$
  - CV- $\eta$: $0.02 \pm 0.01$
  - CV- $\pi^0$: $0.08 \pm 0.04$
  - $K_L \rightarrow \pi^0 \pi^0$: $0.11 \pm 0.09$
  - $0.41 \pm 0.11$ for signal region

- (4) 300-500cm, $P_t < 0.12$ GeV/c
  - CC02: $0.26 \pm 0.07$
  - CV- $\eta$: $0.04 \pm 0.01$
  - CV- $\pi^0$: $0.09 \pm 0.04$
  - total: $0.39 \pm 0.08$
  - observed: 2 event
Open the signal region

No event observed!!
Result of Run-II

• Acceptance: $A = 0.666\%$
• Flux: $N_{KL} = (5.13 \pm 0.40) \times 10^9$
• S.E.S = $1 / (A \cdot N_{KL})$
  \[= (2.93 \pm 0.25) \times 10^{-8}\]

• Upper Limit
  - 0 event observation
    • interval: 2.3 w/ Poisson stat.
  - $\text{Br}(K_L \rightarrow \pi^0 \nu \nu) < 6.7 \times 10^{-8}$
    (@90% C.L.)

arXiv:0712.4164
Status of Run-III

Finished calibration and MC mass production is ready.

Analysis strategy:

• 70% of the Run-II sample
• Almost similar run condition. We only changed BA and installed a prototype of BA (BHPV) of the J-Parc experiment.

⇒
Cut optimization to improve acceptance for both runs, in addition to the cross-check using the present Run-II cut.
Temporal evaluation of the E391a experiment by ourselves for summary

Two goals at the proposal

(1) Pilot experiment for future measurement
(2) Reach a sensitivity of $3 \times 10^{-10}$ and exceed the Grossman-Nir limit

For (1), confirmation of the detection principle, development of various technologies in hard- and soft-wares. We also obtain many experiences. “high”

For (2), it will be difficult to exceed the G-N limit; however, we accessed to the level of another one order to the G-N limit and got clues to solve the problems. ”moderate ”

*E391a was a fruitful step for the measurement of $K_L \rightarrow \pi^0 \nu \nu$.  

Example: Calibration

No good sample of Ke3 as other K experiments

Redundant step for calibration

1. Electron beam to confirm linearity
2. Cosmic rays and punch trough muons
3. Target run
4. Iteration of $K\pi 3$ data

Energy resolution of EM calorimeter
\[
\frac{\sigma_E}{E} = a + \frac{b}{\sqrt{E}} + \frac{c}{E}
\]

$a$: calibration, $b$: photon statistics, $c$: noise
$c \sim 0$, $b \sim 0.008$ and “$a$” was estimated from the width of $K\pi 3$ to be 0.004.

$a=0.0045$, $b=0.02$ and $c=0$ (KTeV-CsI),
$a=0.0042$, $b=0.03$ and $c=0.09$ (NA48-lqKr)

However, in our case $E$ is $E_{\text{deposit}}$. $E=E_{\text{deposit}} + E_{\text{leak}}$

If we have a thick calorimeter, it can be operated as the best calorimeter.
Major parts of loosing factor

- KL yield (estimated by S-W formula): ~1/3
- Loss of the major period Run-I: ~1/2 due to mistakes
  - Drooping membrane
  - Wide width of discriminator pulse of veto counters
- Acceptance loss due to neutron-BG : ~1/10
  - Position of CV (unnecessary to cover the CC03)
  - Type of CC02 (should be all-active)
  - Short and large block size of CsI
Back slides
Electronics and DAQ

- **Number of channels**
  - CsI calorimeter: ~600ch
  - Veto counters: ~400ch
- **“AmpDiscri” Module**
  - Discrimination for TDC
  - Set near the detector
    - low noise; min. threshold: ~0.5 mV (ex. ~0.7MeV for CsI)
    - 8ch sum for the trigger
- **Trigger**
  - Logic
    - CsI hardware clustering (thres. 80MeV) + Veto (20-100MeV)
    - ~300 events / 2 sec spill = 150Hz
- **DAQ live time**
  - ~90%
Problems in Run-I

- Minimum pulse width for TDC: 80ns
  - Large acceptance loss in BeamAnti counter due to high accidental hit rate
    - To avoid the inefficiency with the masking effect
Improvements in Run-II

- **Be absorber** in the beam-line
  - *merit, demerit*
    - KL flux: $x0.56$
    - DAQ live time ratio: 0.90 (w/o 0.72)
    - Accidental loss: 0.83 (w/o 0.61)
    - Neutron flux: core: $x0.34$, halo: $x0.40$
  - Sensitivity
    - $0.56 \times (0.90/0.72) \times (0.83/0.61) = 0.95$
  - S/N assuming the halo neutrons is all the source of BG
    - $0.95 / 0.40 = 2.4$

- **Other upgrades**
  - Beam Hole Charged Veto
    - 1mm thick $\rightarrow$ 3mm
    - 4ch $\rightarrow$ 8ch
  - Extra Collar Counter (CC00) installed
  - Data transfer speed from ADC
    - 100 Mbps $\rightarrow$ GbE
$K_L \rightarrow \pi^0 \pi^0 \pi^0$

Data (~1/4 Set)

MC

Agreement at ~1%/cm.

Transverse Momentum

Kaon Radius at Collimator Exit

\begin{align*}
A0 & \quad 1.022 \pm 0.9868 \times 10^{-2} \\
A1 & \quad -6.448 \pm 2.147 \\
\end{align*}

\begin{align*}
A0 & \quad 1.026 \pm 0.8985 \times 10^{-2} \\
A1 & \quad -0.1259 \pm 0.4012 \\
\end{align*}
Slight MC geometry mis-matches - we have to simply eat the associated systematics.

$\sigma_{\text{Data}} / \sigma_{\text{MC}} = 1.01$
$K_L \rightarrow \gamma \gamma$

Two Cluster Z-Vertex Spectrum (All Cuts)

Data (Full Set)

$\gamma \gamma + \pi^0 \pi^0$

MC

Data / MC Ratio

KL → γ γ
The Aluminum plate run

- Setting 5 mm thick Al target at 6.5 cm from the CC02’s surface
- statistics
  - $5.57 \times 10^{16}$ POT (data: $1.40 \times 10^{18}$)
- BG estimation using the Al run
  - CC02 events
    - contamination to downstream by
      - shower leakage
      - photo nuclear effect
  - $\eta$ production
    - evaluate the cross section

\[ \pi^0, \quad \eta \rightarrow \gamma \gamma \]

\[ \text{5mm Al target} \]

\[ \text{invariant mass (GeV/c}^2) : \quad \text{assuming } Z = Z_{\text{target}} \]
The Aluminum plate run

- Setting **5 mm thick Al target** at 6.5 cm from the CC02’s surface
- statistics
  - $5.57 \times 10^{16}$ POT (data: $1.40 \times 10^{18}$)

- BG estimation using the Al run
  - CC02 events
    - contamination to downstream by
      - shower leakage
      - photo nuclear effect

\[ \pi^0, \eta \rightarrow \gamma \gamma \]
\[ 5 \text{mm} \text{t Al target} \]
CC02 events distribution

- using target run sample
  - $0.12 < P_T < 0.24$ GeV/c

- taking S/N w/ target run sample and signal MC
  - set boundary at $z=340$ cm

GeV PS Activities
CC02 background

- CC02 events in 200-300cm
  - data: 120 target run: 6824
    - use these numbers for normalization

- Open Control Region
  - 300-340: 106 events → 1.9±0.2 events
    - observed: 3 events

- Result of BG at 340-500cm
  - signal in target run: 9
    - 9*(120/6824) = 0.16±0.05 events
η production by the halo neutrons

- η's produced at CV by halo neutrons
  - could be reconstructed into signal box assuming π^0 mass
  - ex.) η generated at z = 570cm
    → reconstructed at z = 370cm

- statistics
  - 2.79x10^{20} POT
    - ~ x200 of data(1.41x10^{18}POT)
The E391a Beam-line
Hardware clustering

• In the CsI calorimeter
  – 8ch analog sum
  – threshold: ~80MeV

• trigger
  – $N_{HWC} \geq 2$
<table>
<thead>
<tr>
<th>counter</th>
<th>threshold (MeV)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB</td>
<td>1.0</td>
<td>take sum of inner and outer channels</td>
</tr>
<tr>
<td>CC02</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td></td>
<td>E = sqrt( $E_{up}$ * $E_{dn}$), x0.95 for data</td>
</tr>
<tr>
<td>CV</td>
<td>outer: 0.3</td>
<td>convert gamma position to crystal number,</td>
</tr>
<tr>
<td></td>
<td>inner: 0.7</td>
<td>then check corresponding CV plane</td>
</tr>
<tr>
<td>CsI</td>
<td></td>
<td>require the local flag</td>
</tr>
<tr>
<td></td>
<td>d &lt; 17 cm :</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17 &lt; d &lt; 25 cm :</td>
<td>5.0 $\rightarrow$ 2.0</td>
</tr>
<tr>
<td></td>
<td>d &gt; 25 cm :</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Sandwich</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>CC03</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>CC04</td>
<td>calorimeter : 2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>scintillator : 0.7</td>
<td></td>
</tr>
<tr>
<td>CC05</td>
<td>calorimeter : 3.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>scintillator : 0.7</td>
<td></td>
</tr>
<tr>
<td>BA</td>
<td>scintillator sum : 20.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>quarts : 0.5 MIPs</td>
<td>take AND of both conditions</td>
</tr>
<tr>
<td>BCV</td>
<td>0.75</td>
<td>E = sqrt( $E_{up}$ * $E_{dn}$)</td>
</tr>
<tr>
<td>CC06</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>CC07</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>BHCV</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>CC00</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
### gamma, $\pi^0$ cuts

<table>
<thead>
<tr>
<th></th>
<th>minimum</th>
<th>maximum</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal box $z$-vertex</td>
<td>340 cm</td>
<td>500 cm</td>
<td></td>
</tr>
<tr>
<td>signal box $Pt$</td>
<td>0.12 GeV/c</td>
<td>0.24 GeV/c</td>
<td></td>
</tr>
<tr>
<td>gamma time difference</td>
<td>-3.4000</td>
<td>2.8922</td>
<td></td>
</tr>
<tr>
<td>gamma energy low</td>
<td>0.25 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma energy high</td>
<td>0.15 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma size 5MeV</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma size 1MeV</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma energy ratio</td>
<td>0.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma TDI</td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>gamma RMS</td>
<td></td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>gamma energy balance</td>
<td></td>
<td>0.75</td>
<td>$(E_{\text{high}} - E_{\text{low}}) / (E_{\text{high}} + E_{\text{low}})$</td>
</tr>
<tr>
<td>gamma distance</td>
<td></td>
<td>15 cm</td>
<td></td>
</tr>
<tr>
<td>gamma hit position</td>
<td></td>
<td>18 cm</td>
<td>square region</td>
</tr>
<tr>
<td>gamma hit radii</td>
<td></td>
<td>88 cm</td>
<td>circle</td>
</tr>
<tr>
<td>acoplanarity angle</td>
<td></td>
<td>45 degrees</td>
<td></td>
</tr>
<tr>
<td>$\pi^0$ energy</td>
<td></td>
<td>2.0 GeV</td>
<td></td>
</tr>
<tr>
<td>$\chi^2\theta$</td>
<td></td>
<td>1.0</td>
<td>$\chi^2 = \Sigma \left( \frac{(\theta_{r1} - \theta_{\text{rec}})^2}{\sigma\theta_{r1}^2} \right)$</td>
</tr>
<tr>
<td>projection R</td>
<td></td>
<td></td>
<td>in the ($z$, $Pt/Pz$) plane, take the inside of $(300, 0.1), (400, 0.1), (500, 0.15), (500, 0.34), (300, 0.2)$</td>
</tr>
<tr>
<td>($\pi^0$ kinematics cut)</td>
<td></td>
<td></td>
<td>assuming the invariant mass of mu-mu bar system is 0:</td>
</tr>
<tr>
<td>reconstructed KL momentum</td>
<td></td>
<td>2.0 GeV</td>
<td>two body decay</td>
</tr>
</tbody>
</table>
Acceptance & Rejection
## Accidental Losses

<table>
<thead>
<tr>
<th></th>
<th>$K_L \rightarrow \pi^0\pi^0$</th>
<th>$K_L \rightarrow \pi^0\pi^0\pi^0\pi^0$</th>
<th>$K_L \rightarrow \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive acceptance, all cuts except CsI</td>
<td></td>
<td>84.76 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>Loss due to extra clusters</td>
<td></td>
<td>99.33 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>Mode specific CsI Loss</td>
<td>97.99 ± 1.35</td>
<td>98.45 ± 1.43</td>
<td>97.95 ± 0.57</td>
</tr>
<tr>
<td>Total</td>
<td>82.50 ± 1.35</td>
<td>82.89 ± 1.43</td>
<td>82.47 ± 0.57</td>
</tr>
<tr>
<td>Weighted average</td>
<td></td>
<td></td>
<td>82.57</td>
</tr>
</tbody>
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What happens in “the” event?
Angle difference cut

- definition
  - injection angle of gamma
    - reconstructed: \( \theta_{\text{rec}} \)
    - measurement w/ energy shape: \( \theta_{r1} \)
  - \( \chi^2_\theta = \sum (\theta_{r1} - \theta_{\text{rec}})^2 / \sigma^2_{r1} \)

\[
r_i = \sqrt{\frac{\sum E_i \times [d_i P_i(\cos \alpha)]^2}{E_{\text{total}}}}
\]

\( P_i \): Legendre Poly.
$\pi^0$-R cut

- hit position in CsI extrapolating pi0s’ direction
  - $R = \left(\frac{P_t}{P_z}\right) \times (Z_{\text{CsI}} - Z_{\text{decay}})$
Step by Step approach

- **To event observation**
  - **E391a**
    - The first experiment dedicated to $K_L \rightarrow \pi^0 \nu \bar{\nu}$
      - To establish the experimental method
  - **J-Parc E14**
    - **Step1**
      - Prompt start
        - The E391a Detector
        - Common beamline
      - The first event observation
        - goal: ~3 events
    - **Step2**
      - Precise measurement
        - New detector
        - Dedicated beamline
      - goal: ~100 events
Detector Upgrade in E14

- E391a

- E14

Review on the GeV PS Activities
Detector Upgrade in E14

- CsI
  - 7x7x30cm³ → 2.5x2.5x50cm³, 5x5x50cm³ (from KTeV)
    - Reduce leakage
    - Better positioning

- Read Out Electronics
  - Wave-form digitization

- New Detectors
  - Beam Hole Photon Veto
  - Full active CC02
  - MB liner
  - New CV