KTeV Collaboration Meeting
June 7, 2005

Status of $K_L \to \pi^+\pi^-\pi^0\gamma$ $K_L \to \pi^+\pi^-\pi^0 e^+e^-$ and $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

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overview

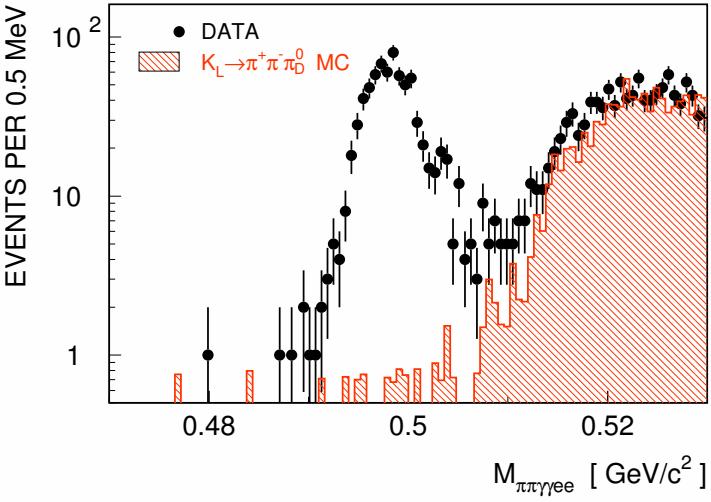
- Status of $K_L \to \pi^+\pi^-\pi^0\gamma$ and $K_L \to \pi^+\pi^-\pi^0 e^+e^-$. There is a document with more details than this talk.
  `/cdserv/taku/private/ktevdoc/e799/pppee_and_pppg_v1.pdf`

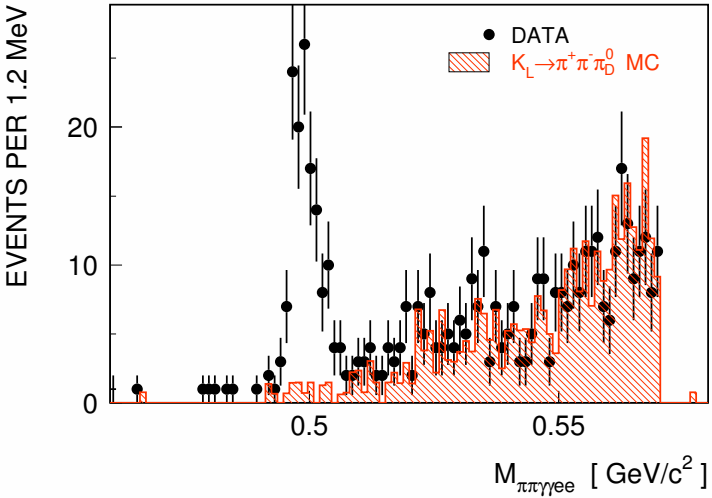
- Status of $K_L \to \pi^0\pi^0\pi^0 e^+e^-$.

last meeting

$K_L \to \pi^+\pi^-\pi^0_D\gamma$ candidates
$K_L \to \pi^+\pi^-\pi^0_D$ MC

$K_L \to \pi^+\pi^-\pi^0 e^+e^-$ candidates
$K_L \to \pi^+\pi^-\pi^0_D$ MC





single decay backgrounds

Several kaon decays were generated, normalized to kaon flux (deterimined by normalization mode) and added together.

Decay	BR	Size
$K_L \to \pi^+\pi^-\pi^0$(ext)	1.24×10^{-1}	3.10
$K_L \to \pi^+\pi^-\pi^0_D$	1.49×10^{-3}	1.34
$K_L \to \pi^0\pi^0_D\pi^0_D$	9.33×10^{-5}	1.26
$K_L \to \pi^0\pi^\pm e^\mp\nu$	5.18×10^{-5}	3.30
$K_L \to \pi^0\pi^0\pi^0_{DD}$	2.11×10^{-5}	8.17
$K_L \to \pi^+\pi^-\pi^0_{DD}$	4.05×10^{-6}	4.18
$K_L \to \pi^0_D\pi^\pm e^\mp\nu$	6.22×10^{-7}	4.47
$K_L \to \pi^+\pi^-e^+e^-$	3.60×10^{-7}	1.71

single decay backgrounds

$\Xi^0 \to \Lambda\pi^0_D$ was generated in Z region of (80-160) m with momentum in (50–600) GeV..

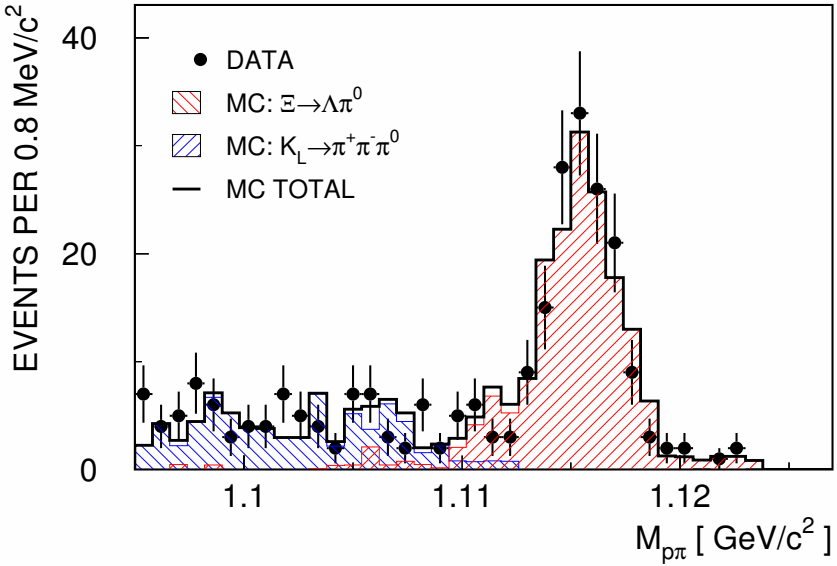
To calculate it's flux:

- photon cluster (HW) $0.125 \leq M_{ee\gamma} \leq 0.145$
- Proton is positive track with $E/p \leq 0.9$
- Momentum of a proton is greater than 100 GeV
- Ratio P_p/P_π is greater than 3.5
- $1.10 \leq M_{p\pi^-} \leq 1.13$ i
- $P_T^2 \leq 10^{-3}$
- $1.29 \leq M_{p\pi^- e^+ e^- \gamma} \leq 1.34$

$\Xi^0 \to \Lambda\pi^0_D$ background

Ξ^0 flux is 4.03×10^8

Dots: DATA after all cuts
Blue hist.: Background MC
Red hist.: $\Xi^0 \to \Lambda\pi^0_D$ MC



generating double decays

1: generate first decay using trigger 14 with accidentals. The only loss of events in TRIG14 is when particle hits the PHOTON VETO counters. Generate decays in Z=(80–186) m. Determine the acceptance for this step, A_1

2: generate second decay using trigger 4 with accidentals. Use the output of previous step as an accidental file. Generate decays in Z=(80–186) m. Determine the acceptance for this step, A_2

3: the rate of double decays accepted by 4TRK trigger is:

$$Rate = C_0 \cdot A_1 \cdot BR_1 \cdot A_2 \cdot BR_2$$

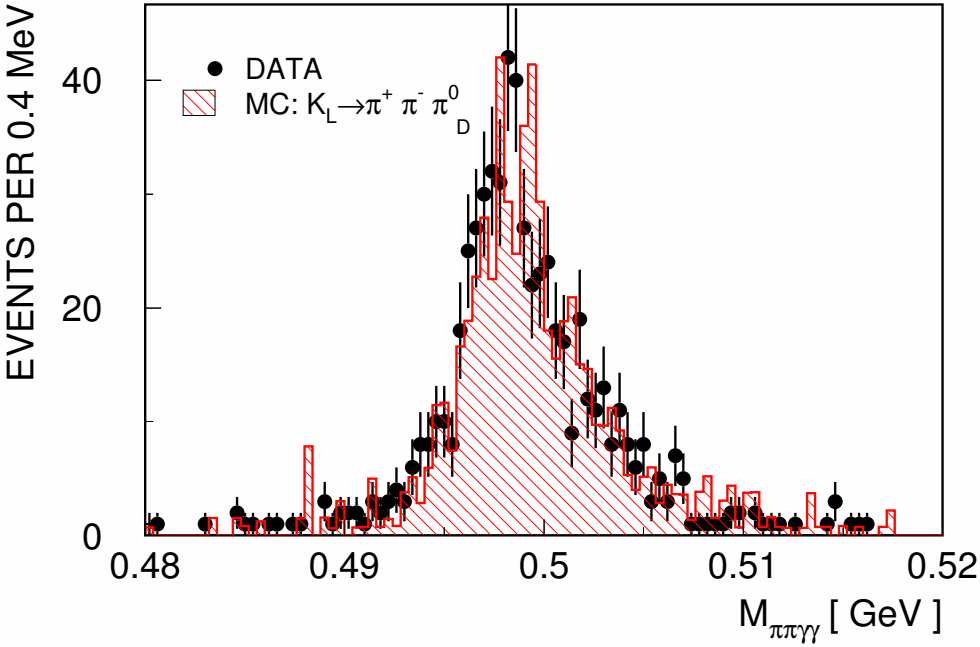
where C_0 is the same for any combination of the decays. It is measured in $K_L \to \pi^+\pi^-\pi^0_D$ and $K_L \to \pi^+\pi^-\pi^0$ double decays:

$$C_0 = 5.62 \times 10^9$$

double decays are in accid files

Each event has both $K_L \to \pi^+\pi^-\pi^0_D$ and $K_L \to \pi^+\pi^-\pi^0$ fully reconstructed

Invariant mass of $\pi^+\pi^-\gamma\gamma$ is shown
MC is $K_L \to \pi^+\pi^-\pi^0_D$ decay + accidentals, normalized to the flux



double decays: status

★- included in single decays, ★- generated

	$Ke3$ 4e-1	$K\mu3$ 3e-1	$\pi^0\pi^0\pi^0$ 2e-1	$\pi^+\pi^-\pi^0$ 1e-1	$\pi^0\pi^0\pi^0_D$ 8e-3	$\pi^+\pi^-$ 2e-3	$\pi^+\pi^-\pi^0_D$ 1e-3
$Ke3$	★	★	★	★	★	★	★
$K\mu3$	×	★	★	★	★	★	★
$\pi^0\pi^0\pi^0$	×	×	★	★	★	★	★
$\pi^+\pi^-\pi^0$	×	×	×	★	★	★	★
$\pi^0\pi^0\pi^0_D$	×	×	×	×	★	★	★
$\pi^+\pi^-$	×	×	×	×	×	★	★

	$\pi^0\pi^0$ 9e-4	$\gamma\gamma$ 6e-4	$\pi^0\pi^0_D\pi^0_D$ 9e-5	$Ke4$ 5e-5	$\pi^+\pi^-\gamma$ 5e-5	$\pi^0\pi^0_D$ 2e-5	$\pi^0\pi^0\pi^0_{DD}$ 2e-5
$Ke3$	★	★	★	★	★	★	★
$K\mu3$	★	★	★	★	★	★	★
$\pi^0\pi^0\pi^0$	★	★	★	★	★	★	★
$\pi^+\pi^-\pi^0$	★	★	★	★	★	★	★
$\pi^0\pi^0\pi^0_D$	★	★	★	★	★	★	★
$\pi^+\pi^-$	★	★	★	★	★	★	★

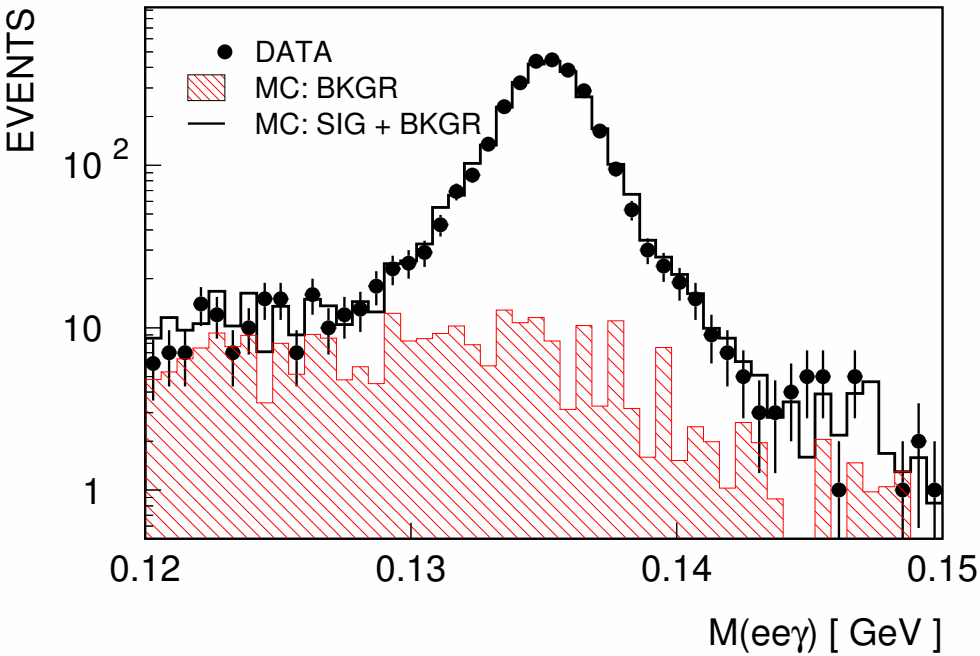
selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Common cuts with normalization mode to indentify $\pi^+\pi^-e^+e^-$ topology. In addition, the following cuts apply to select a pair of photon candidates (HW)

- one photon cluster gives $0.130 \leq M_{ee\gamma} \leq 0.140$
- $M_{ee\gamma\gamma} \geq 0.145$
- $M_{\pi^+\pi^-\pi^0_D} \leq 0.490$
- external brem cut: $\Delta R \geq 0.05$
- $P_T^2 \leq 10^{-4}$
- $0.490 \leq M_{\pi^+\pi^-e^+e^-\gamma\gamma} \leq 0.509$

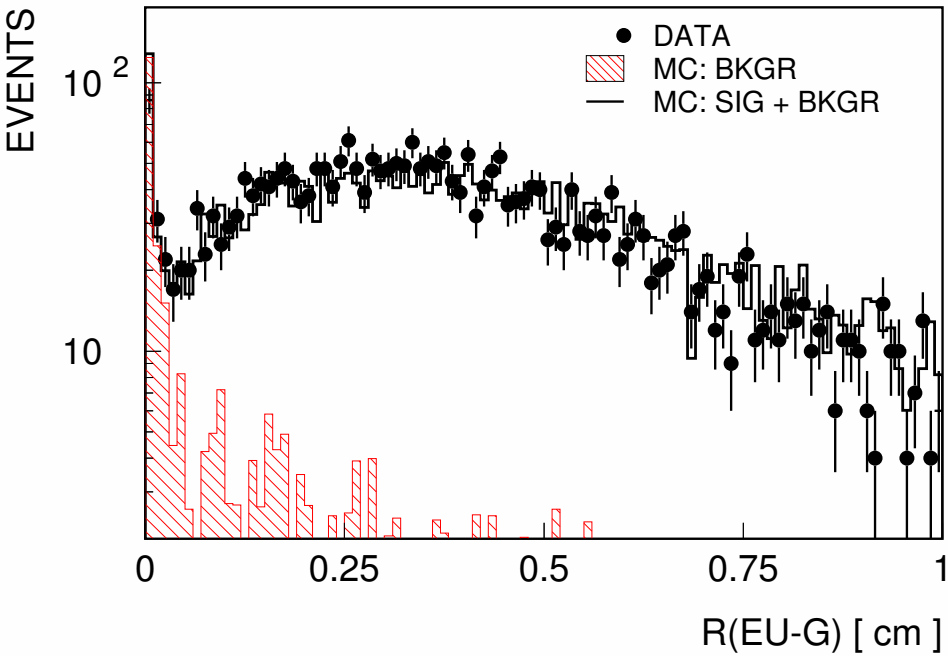
selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Invariant mass of $ee\gamma$ after all cuts except $0.130 \leq M_{ee\gamma} \leq 0.140$ cut for DATA, Signal MC and Background MC events



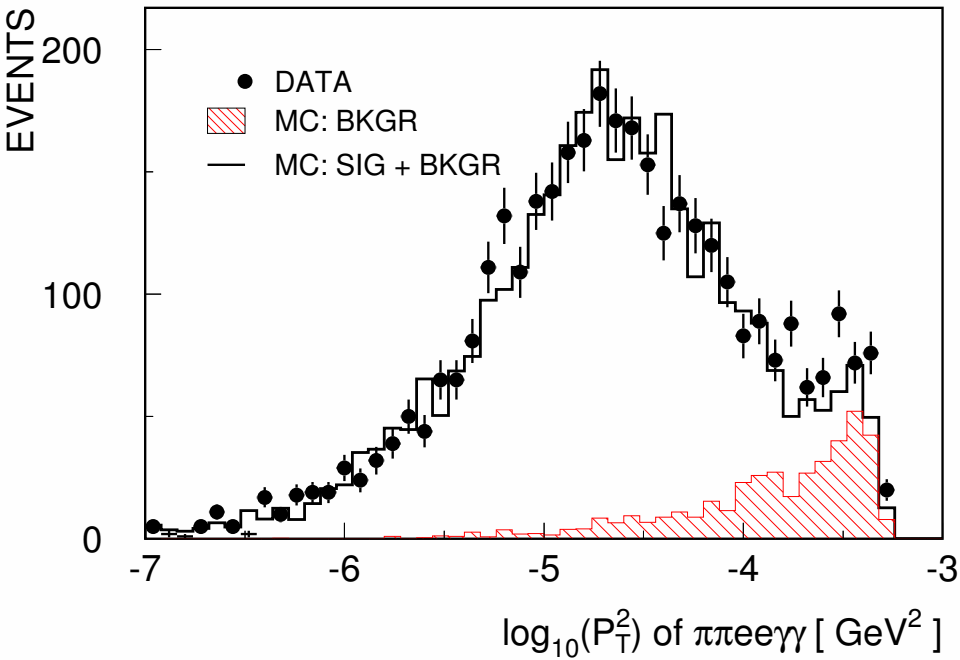
selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Minimum distance from projection of $e^{\pm}$ upstream track segments onto CsI and any photon cluster after all cuts except external brem $R \geq 0.05$ cut for DATA, Signal MC and Background MC events



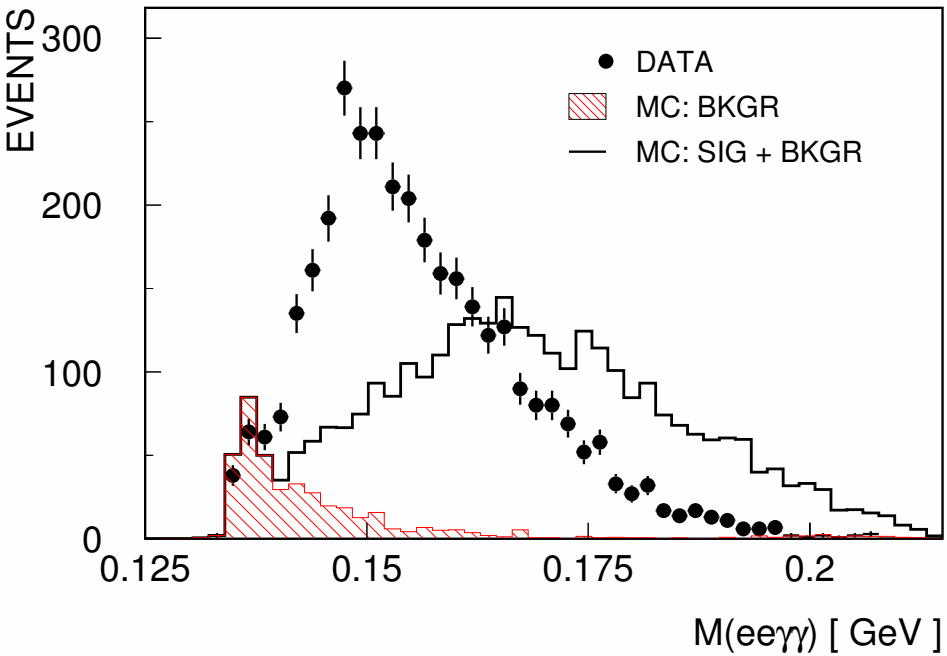
selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Distribution of $log_{10}(P_T^2)$ for a kaon after all cuts except $P_T^2 \leq 10^{-4}$ cut for DATA, Signal MC and Background MC events



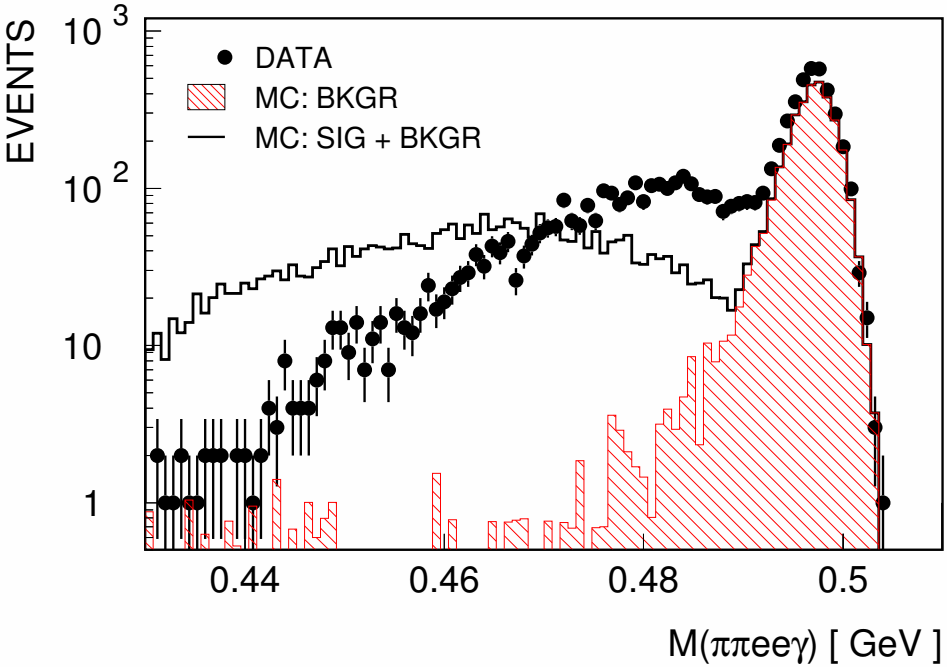
selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Invariant mass of $ee\gamma\gamma$ after all cuts except $M_{ee\gamma\gamma} \geq 0.145$ cut for DATA, Signal MC and Background MC events



selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Invariant mass of $\pi^+\pi^-\pi^0_D$ after all cuts except $M_{\pi\pi\pi} \leq 0.490$ cut for DATA, Signal MC and Background MC events

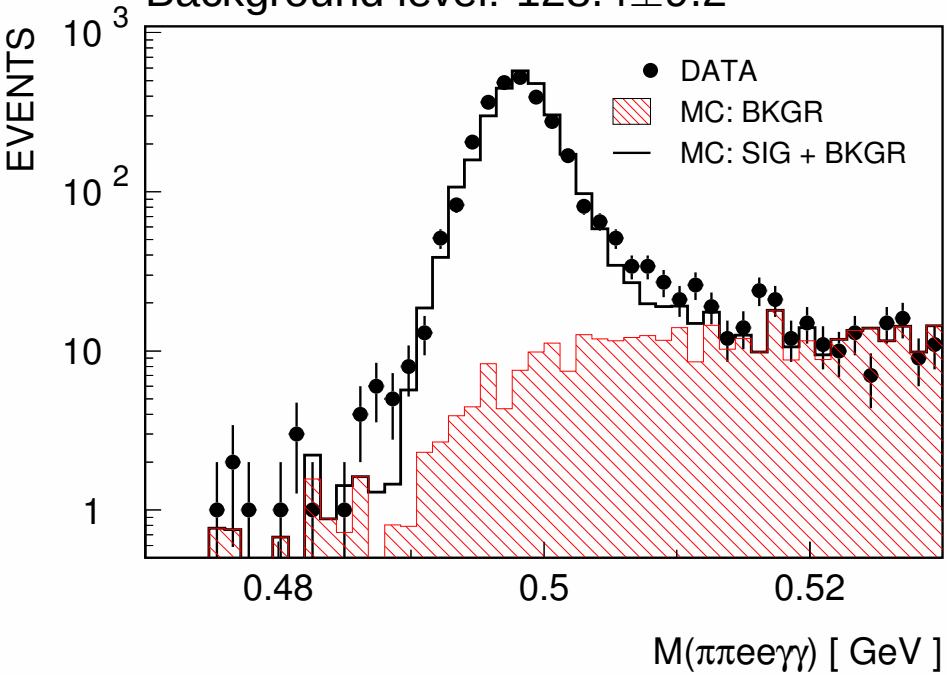


selection of $K_L \to \pi^+\pi^-\pi^0_D\gamma$

Invariant mass of $\pi^+\pi^-\pi^0_D\gamma$ after all cuts except $0.490 \leq M_{\pi\pi\pi\gamma} \leq 0.509$ cut for DATA, Signal MC and Background MC events.

Number of candidates: 2847

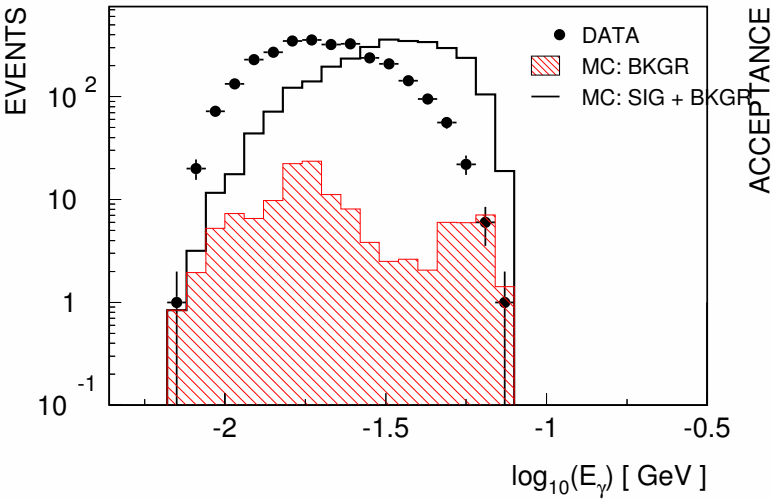
Background level: 128.4±9.2

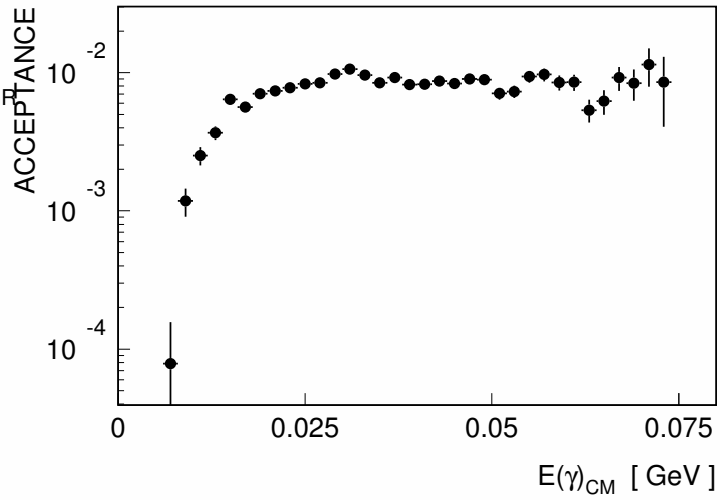


acceptance in E_γ^{CM} bins

Distribution of $log_{10}(E_\gamma^{CM})$ after all cuts for DATA, Signal MC and Background MC events

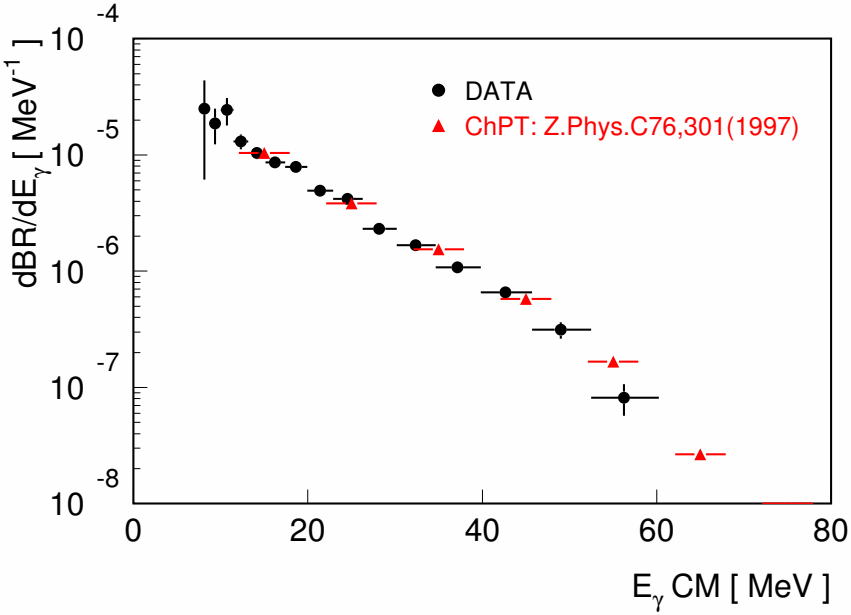
Total acceptance as a function E_γ^{CM} calculated using phase space MC





differential BR for $K_L \to \pi^+\pi^-\pi^0\gamma$

E_γ	ChPT	Measurement
$10-20$	$(1.04 \pm 0.02) \times 10^{-4}$	$(1.01 \pm 0.06) \times 10^{-4}$
$20-30$	$(3.84 \pm 0.06) \times 10^{-5}$	$(3.54 \pm 0.18) \times 10^{-5}$
$30-40$	$(1.55 \pm 0.03) \times 10^{-5}$	$(1.30 \pm 0.08) \times 10^{-5}$
$40-50$	$(5.76 \pm 0.10) \times 10^{-6}$	$(4.96 \pm 0.50) \times 10^{-6}$
$50-60$	$(1.67 \pm 0.03) \times 10^{-6}$	$(1.67 \pm 0.30) \times 10^{-6}$
$60-70$	$(2.67 \pm 0.05) \times 10^{-7}$	$(3.27 \pm 1.38) \times 10^{-7}$
$70-80$	$(6.32 \pm 0.13) \times 10^{-9}$	$\leq 10^{-8}$
$10-80$	$(1.65 \pm 0.03) \times 10^{-4}$	$(1.56 \pm 0.07) \times 10^{-4}$



selection of $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

Common cuts with normalization mode to indentify $\pi^+\pi^-e^+e^-$ topology. In addition, the following cuts apply to select a pair of photon candidates (HW)

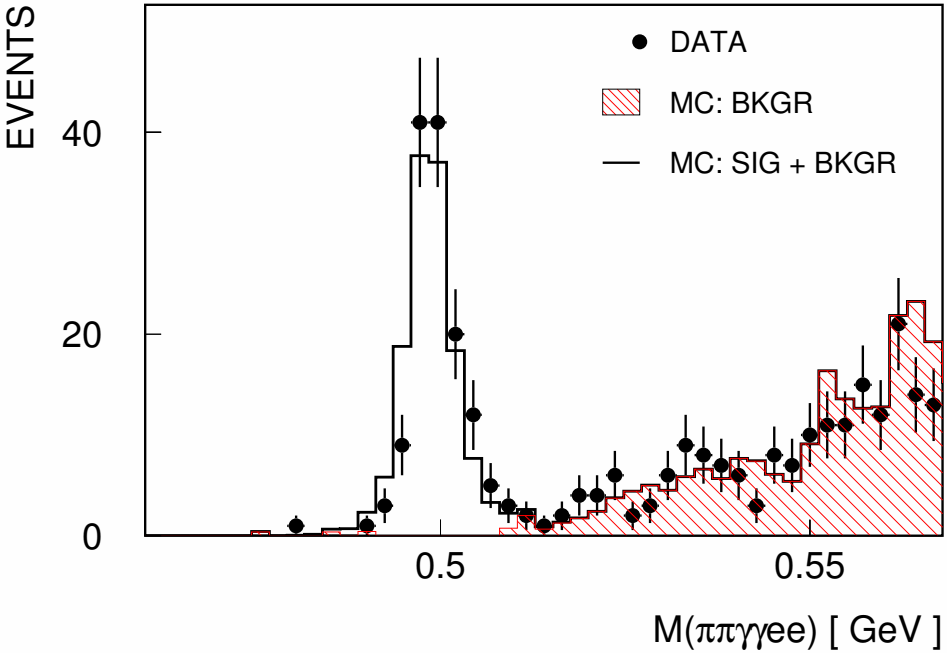
- $0.125 \leq M_{\gamma\gamma} \leq 0.147$
- $M_{ee\gamma\gamma} \geq 0.150$
- $M_{\pi^+\pi^-\pi^0 e^+e^-} \leq 0.490$
- external brem cut: $\Delta R \geq 0.04$
- $P_T^2 \leq 5 \times 10^{-4}$
- $0.490 \leq M_{\pi^+\pi^-e^+e^-\gamma\gamma} \leq 0.509$
- $M_{ee} \geq 0.002$
- $|M_{ee\gamma} - 0.135| \geq 0.010$

selection of $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

Invariant mass of $\pi^+\pi^-\gamma\gamma e^+e^-$ after all cuts except $0.490 \leq M_{\pi\pi\gamma\gamma ee} \leq 0.509$ cut for DATA, Signal MC and Background MC events

Number of candidates: 132

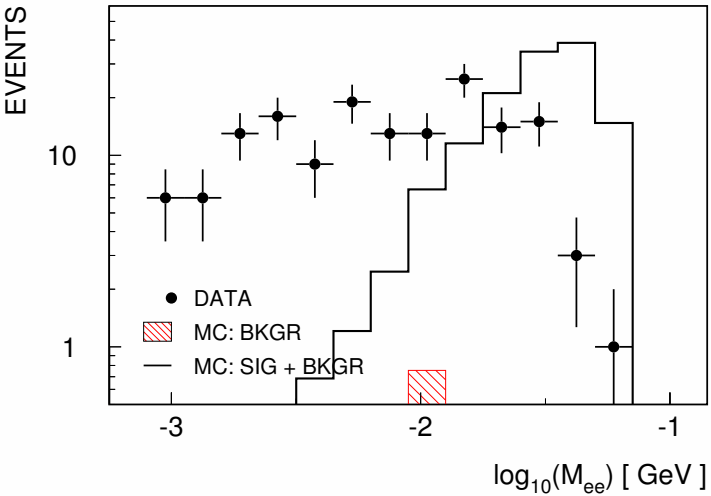
Background level: 1.2±0.9

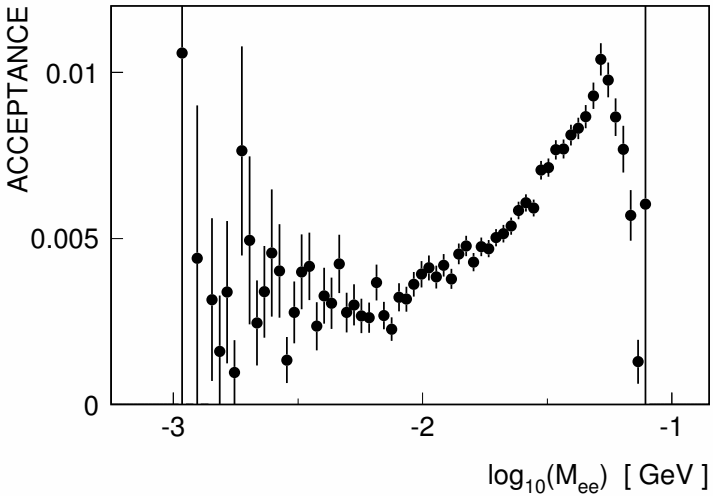


acceptance in M_{ee} bins

Logarithm of invariant mass of e^+e^- after all cuts except $M_{ee} \geq 0.002$ cut for DATA, Signal MC and Background MC events

Total acceptance for signal as a function of $log_{10}(M_{ee})$ as calculated with phase space MC

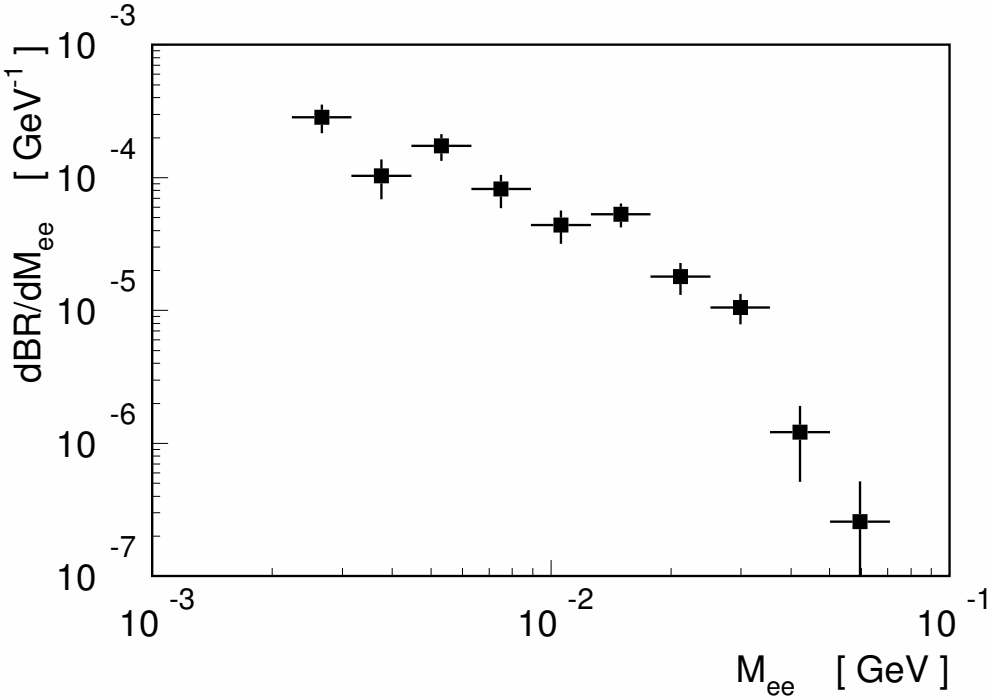




dBR/dM_{ee} for $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

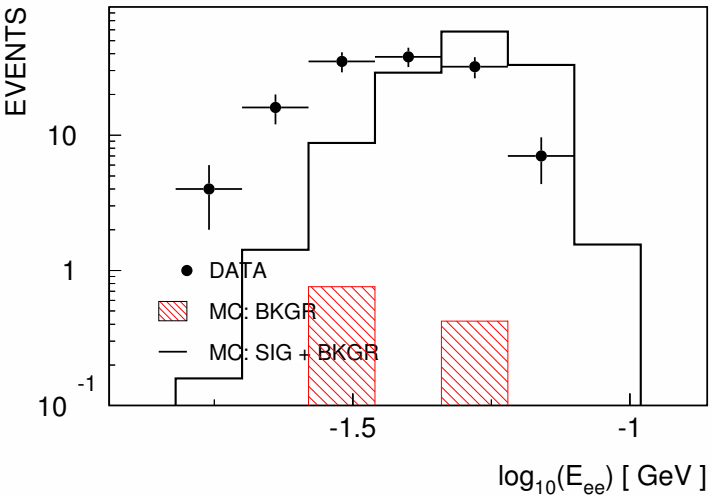
Measured dBR/dM_{ee} using phase space MC in each M_{ee} bin

$BR(M_{ee} \geq 0.002) = (1.41 \pm 0.13) \times 10^{-7}$ (stat only)

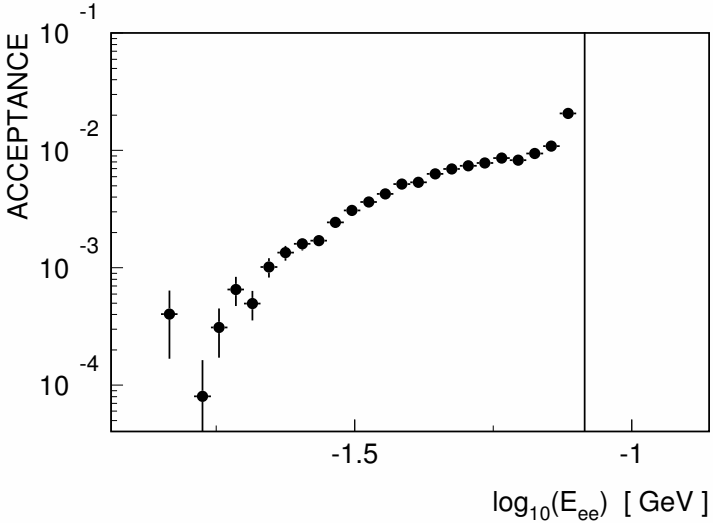


acceptance in E_{ee} bins

Logarithm of e^+e^- energy in kaon CMS after all cuts for DATA, Signal MC and Background MC events



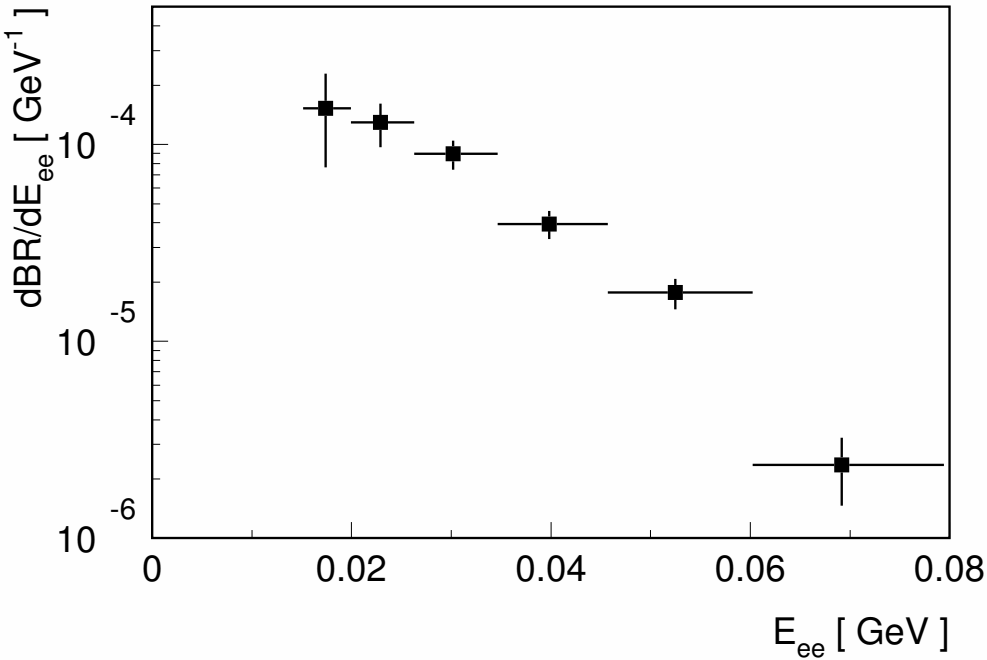
Logarithm of e^+e^- energy in kaon CMS after all cuts for DATA, Signal MC and Background MC events



dBR/dE_{ee} for $K_L \to \pi^+\pi^-\pi^0 e^+ e^-$

Measured dBR/dE_{ee} using phase space MC in each E_{ee} bin

$BR(E_{ee} \geq 0.020) = (1.60 \pm 0.18) \times 10^{-7}$ (stat only)



Status of $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

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

- Trigger 1: 2E-NCLUS
- 2E-NCLUS CRUNCH at Colorado
- Tag 2E8C:
  - 2-track vertex, but not 4-track vertex
  - Double pass on CsI clustering
  - 2 tracks exactly, both $E/p \geq 0.9$
  - L3 tags
  - 8 or more clusters
- Four DLT tapes: NQN601-NQN604 (both 97 and 99)

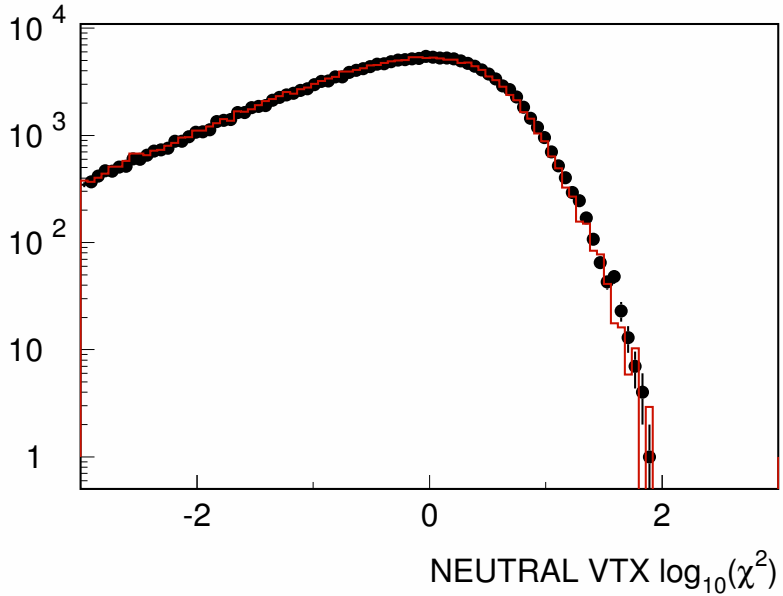
norm. mode $K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

- Major component of the CRUNCH output
- Clean reconstruction
  - 8 clusters only
  - bad spill mask is not set (disregard TRD)
  - reconstruct neutral vertex
  - check distance between tracks at Z neutral
  - $M_{ee} \geq 0.002$
  - find $\pi^0 \to e^+e^-\gamma\gamma$
  - check M_K and P_T^2
- Tune/Verify reconstruction cuts (many of them) by comparing DATA and MC

$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

Logarithm of neutral vertex χ^2 ($2\pi^0 \to 4\gamma$)

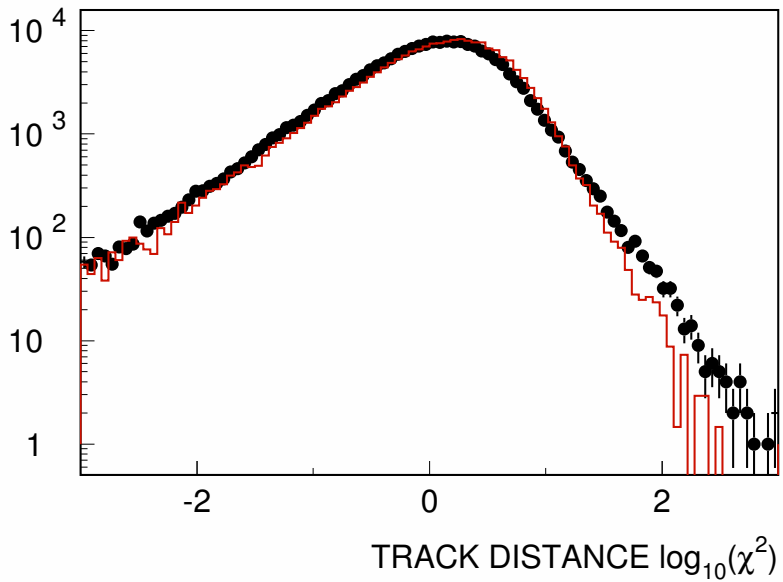
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC (includes radiative $\pi^0 \to e^+e^-\gamma\gamma$)



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

Logarithm of distance between tracks χ^2 at Z of neutral vertex (includes DC resolutions and momentum dependent scattering)

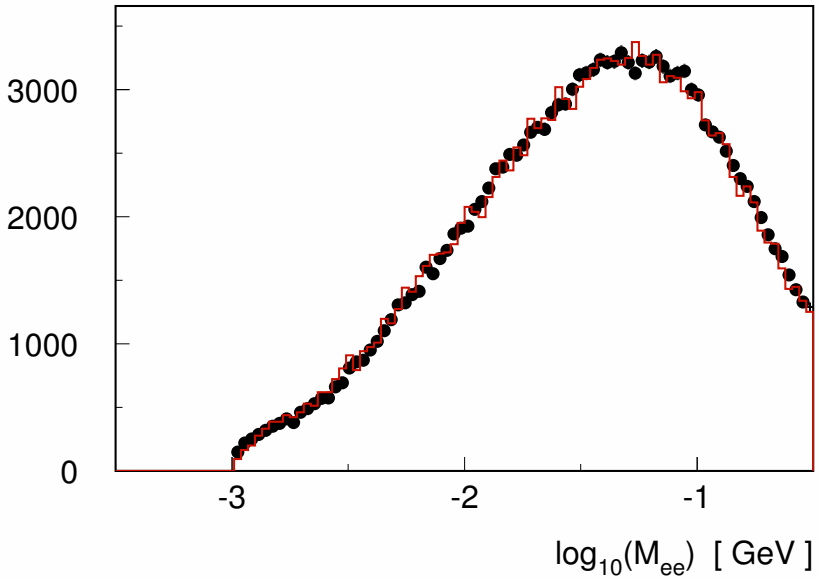
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

Logarithm of M_{ee}

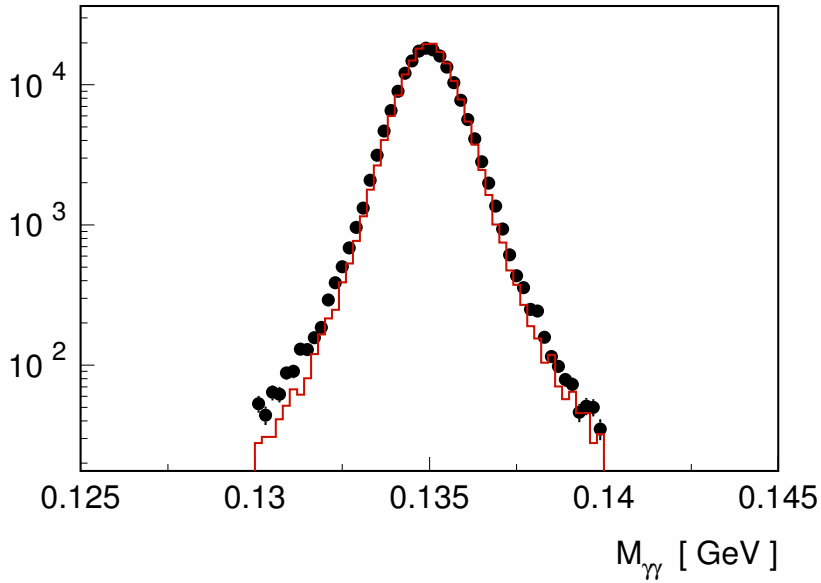
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

$M_{\gamma\gamma}$ distribution

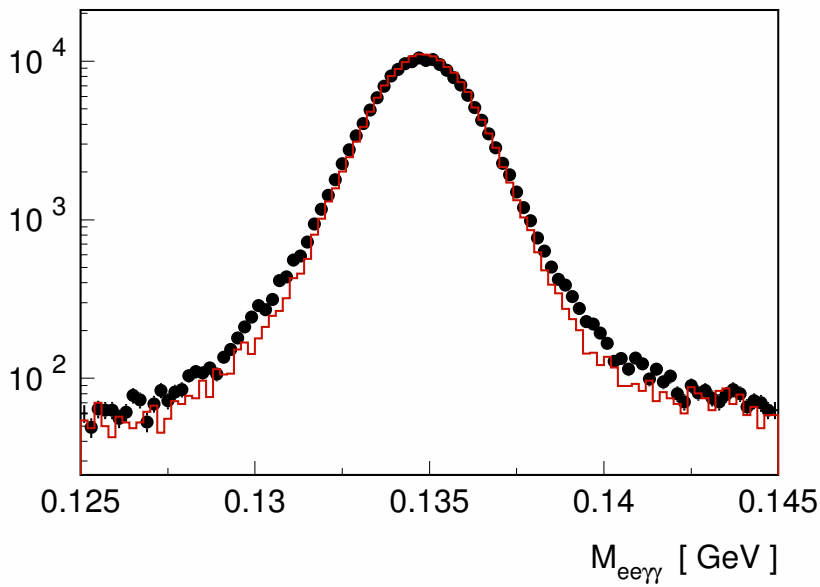
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

$M_{ee\gamma\gamma}$ distribution

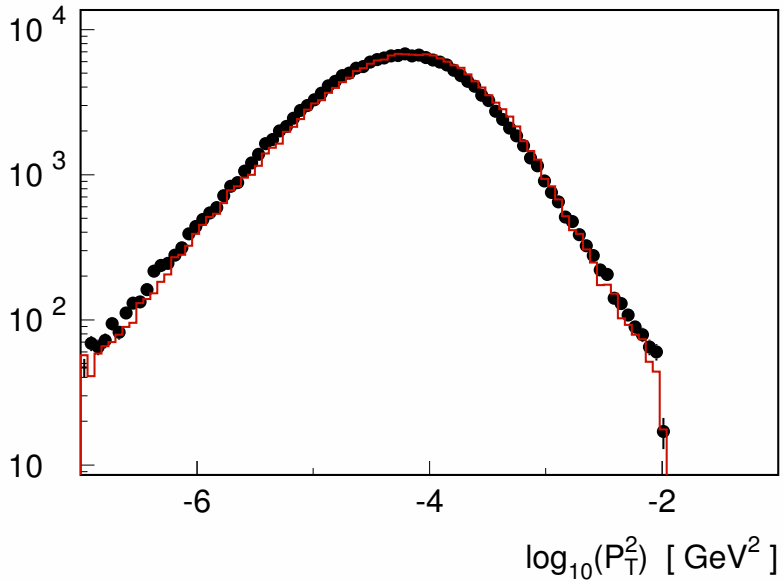
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

Logarithm of P_T^2 for $\pi^0\pi^0e^+e^-\gamma\gamma$ system

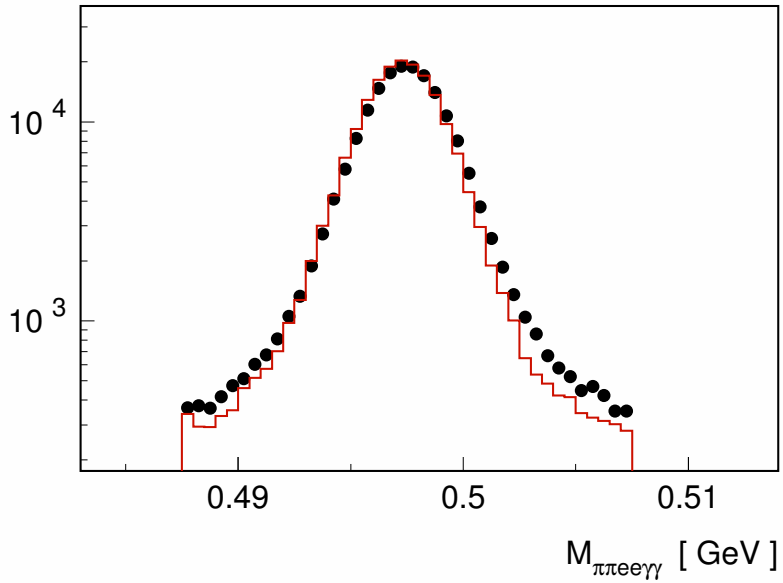
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$

$M_{\pi\pi ee\gamma\gamma}$ distribution

Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma$

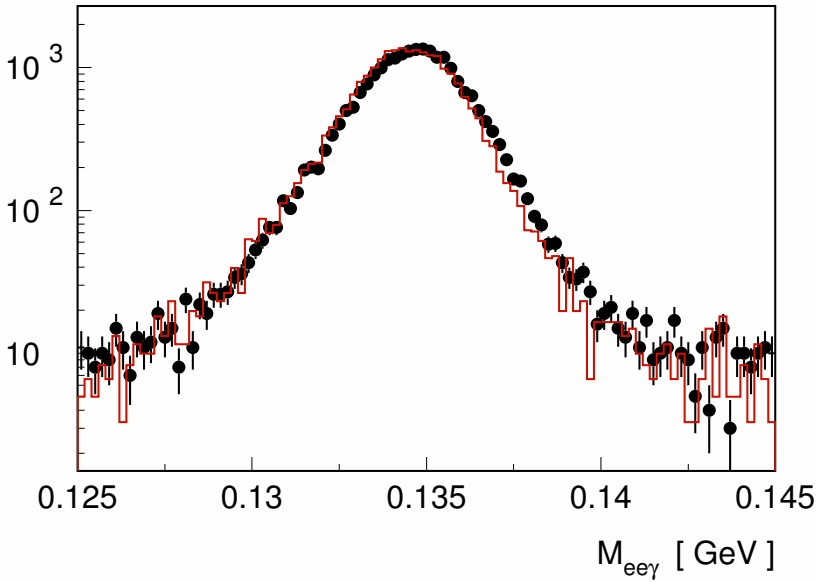
Another major component of the CRUNCH output

- If it is NOT $K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$
- Clean reconstruction
  - 8 clusters only
  - bad spill mask is not set (disregard TRD)
  - reconstruct neutral vertex
  - check distance between tracks at Z neutral
  - $M_{ee} \geq 0.002$
  - find $\pi^0 \to e^+e^-\gamma$
  - check M_K and P_T^2

$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma$

$M_{ee\gamma}$ distribution

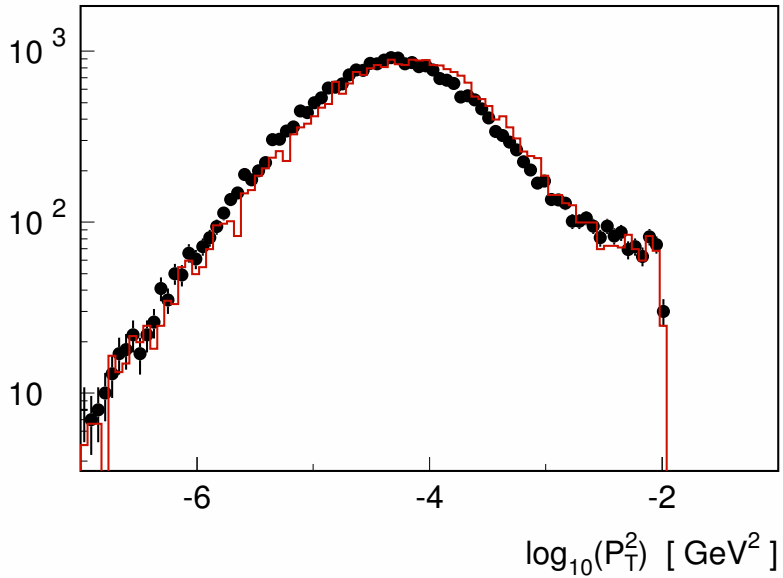
Black dots: DATA, $K_L \to \pi^0\pi^0\pi^0_D$ candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma$

Distribution of $log_{10}(P_T^2)$ for $\pi^0\pi^0e^+e^-\gamma$ system

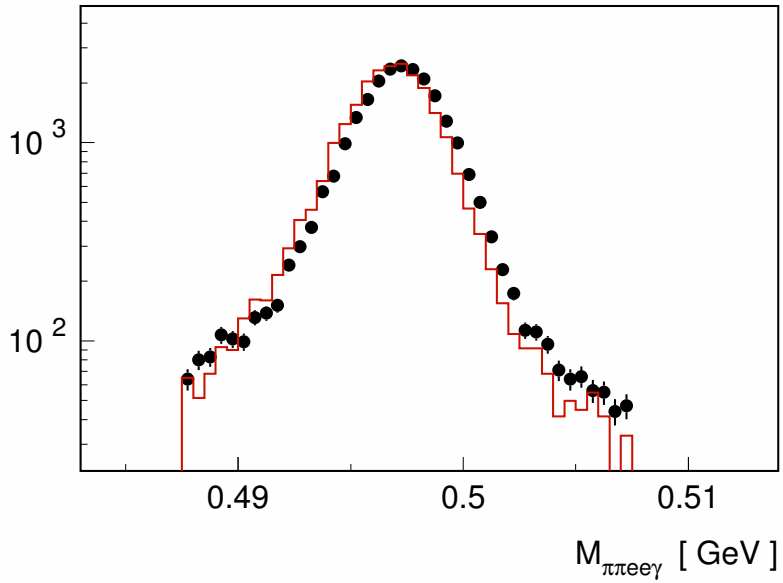
Black dots: DATA, $K_L \to \pi^0\pi^0\pi^0_D$ candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma$

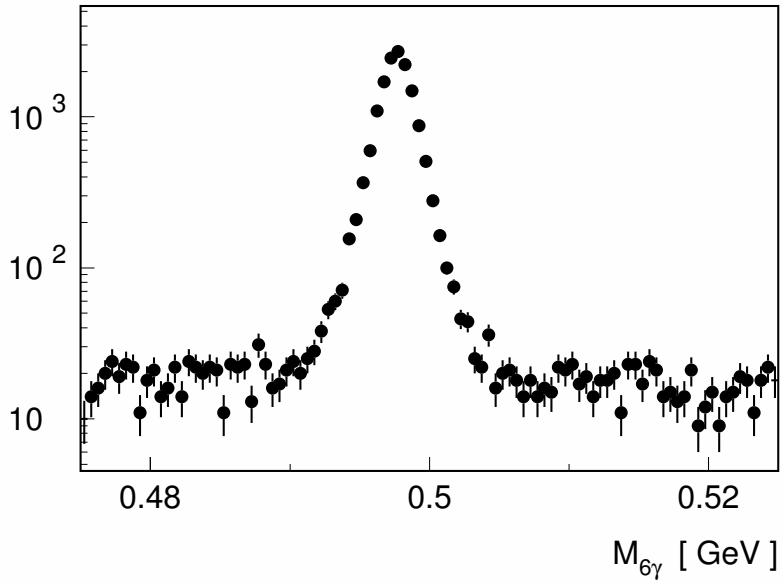
$M_{\pi\pi ee\gamma}$ distribution

Black dots: DATA, $K_L \to \pi^0\pi^0\pi^0_D$ candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



$K_L \to 3\pi^0$ with $\pi^0 \to \gamma\gamma$

$M_{6\gamma}$ distribution for events with $3\pi^0 \to 6\gamma$ neutral vertex. DATA shows double decays: $K_L \to \pi^0\pi^0\pi^0$ decay + mostly $Ke3$ decay

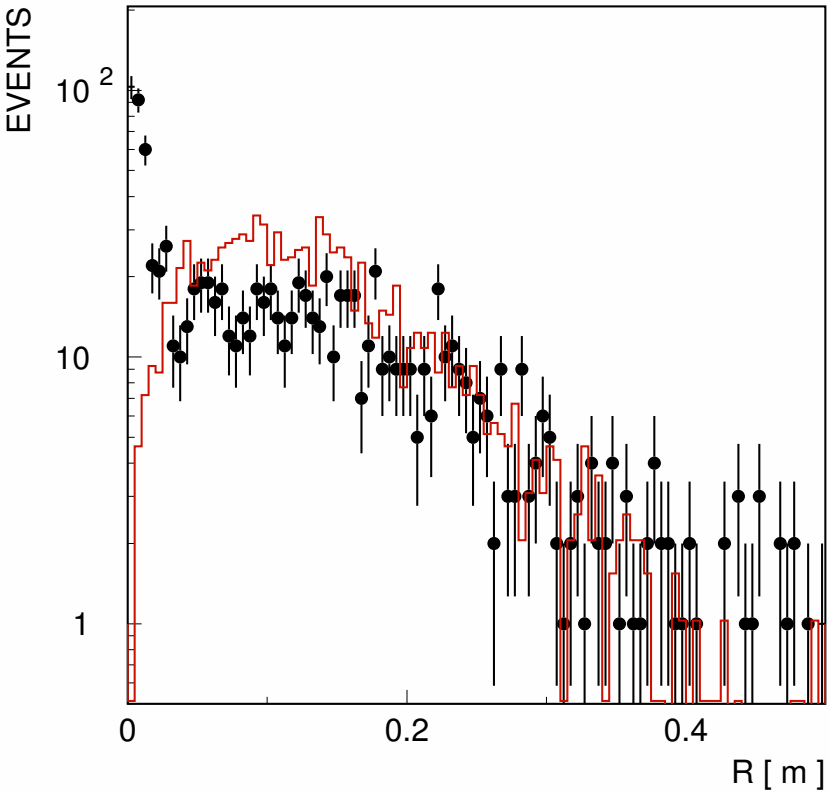


cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

- CRUNCH, NCLUS = 8, BAD SPILL/RUN cut
- not $K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma\gamma$
- not $K_L \to 3\pi^0$ with $\pi^0 \to e^+e^-\gamma$
- not $K_L \to 3\pi^0$ with all $\pi^0 \to \gamma\gamma$
- $3\pi^0$ neutral vertex, $\chi^2 \leq 10$
- track vertex at neutrtal Z_V, $\chi^2 \leq 10$
- $0.9 \leq E/p \leq 1.1$
- $0.130 \leq M_{\gamma\gamma} \leq 0.140$
- $P_T^2 \leq 10^{-3}$
- upstream γ conversion cut (see later)
- external brem cut (see later)

cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

External brem cut:
Minimum distance form photon cluster to upstream segment of a track in CsI

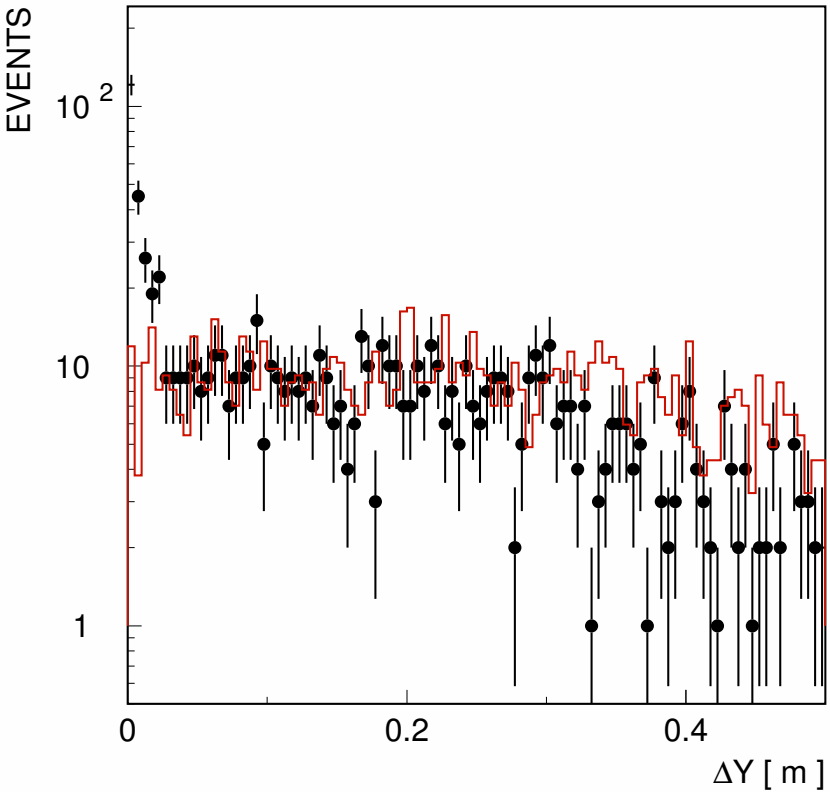


Black dots: DATA
Red histogram: Signal MC (phase space)

Accept events if R$\geq$5 cm

cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

upstream $\gamma \to e^+e^-$ conversion cut :
Min Y distance between γ's from $\pi^0 \to \gamma\gamma$



Black dots: DATA
Red histogram: Signal MC (phase space)

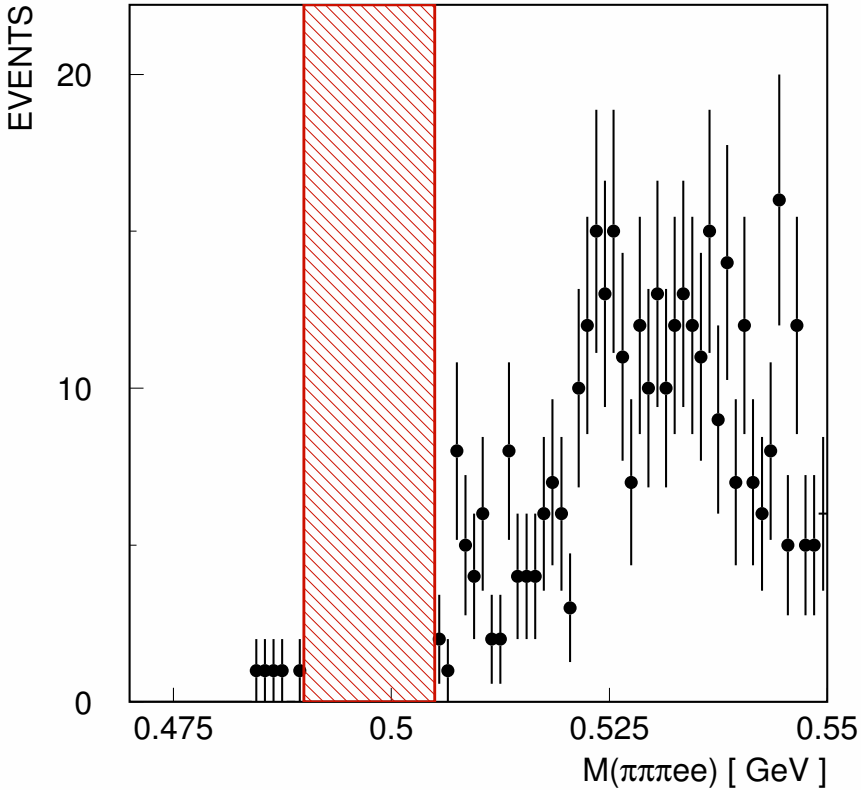
Accept events if
$\Delta Y \geq$5 cm

$K_L \to \pi^0\pi^0\pi^0 e^+e^-$ candidates

Signal region $0.490 \leq M_{3\pi ee} \leq 0.505$

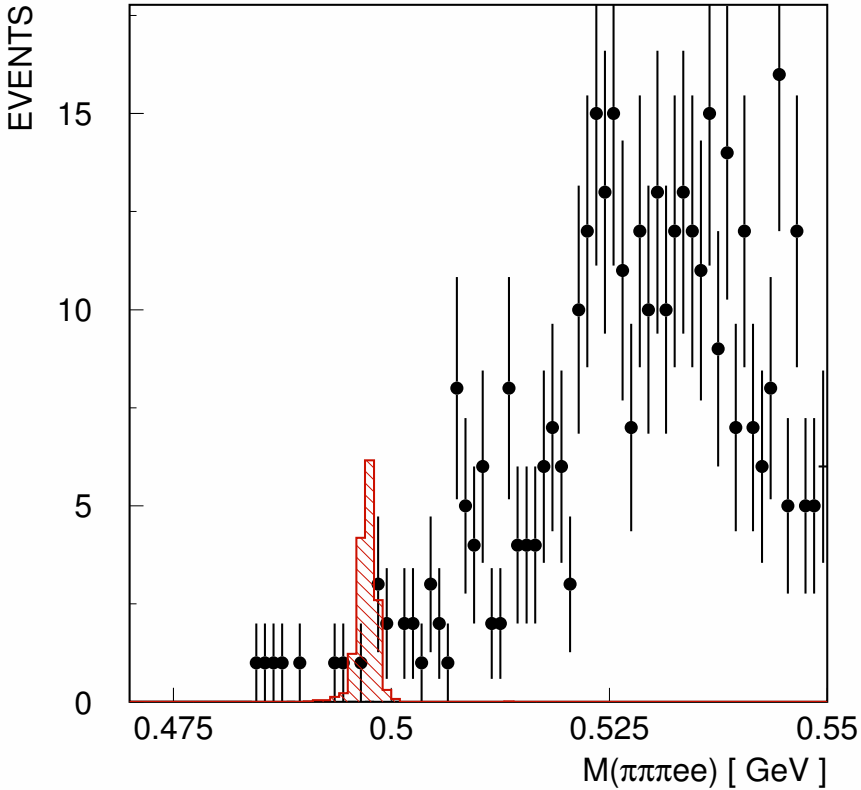
Next steps?

Desided to look into the box



$K_L \to \pi^0\pi^0\pi^0 e^+e^-$ candidates

No luck! Do it the hard way. Close the box.
Black dots: DATA
Red histogram: Signal MC (phase space)



more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

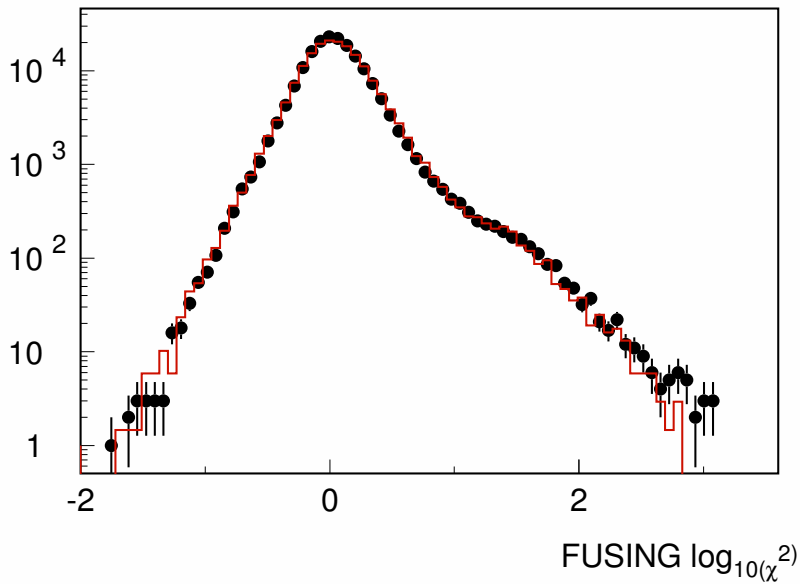
Summary of additional cuts (next few slides will give more details about each of these cuts)

- Fusing χ^2 for CsI clusters
- Timing χ^2 for CsI clusters
- Vertex Position in X and Y

more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

Logarithm of fusing χ^2 for CsI clusters
Accept events if $log_{10}(\chi^2) \leq 1.0$

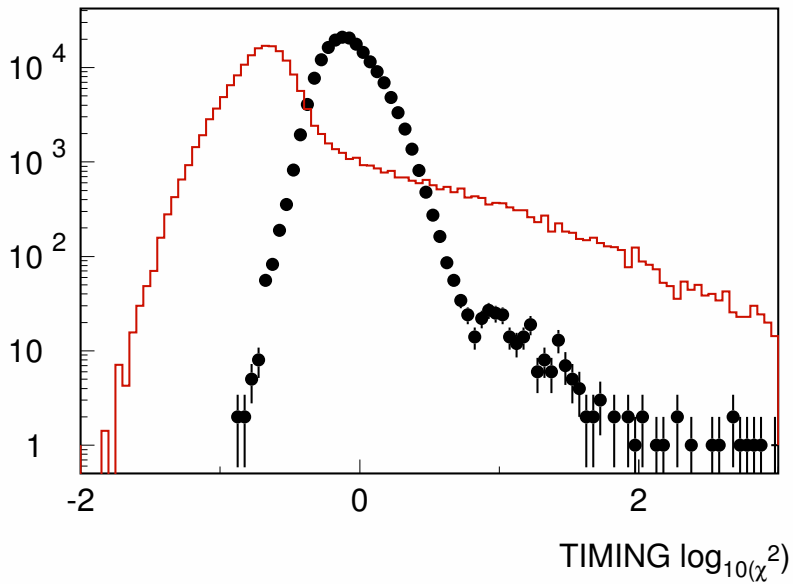
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

Logarithm of timing χ^2 for CsI clusters
Accept events if $log_{10}(\chi^2) \leq 1.0$

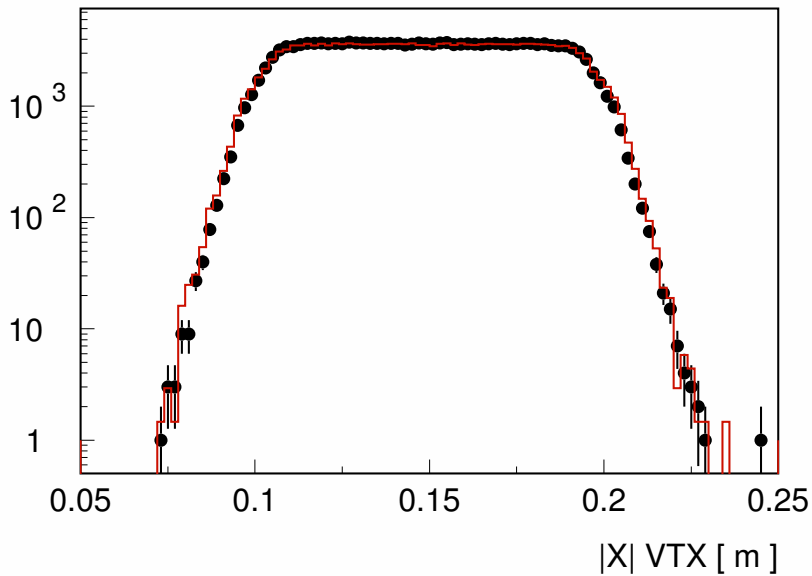
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

$|X|$ of vertex, projected onto CsI
Accept events if $0.09 \leq |X| \leq 0.21$

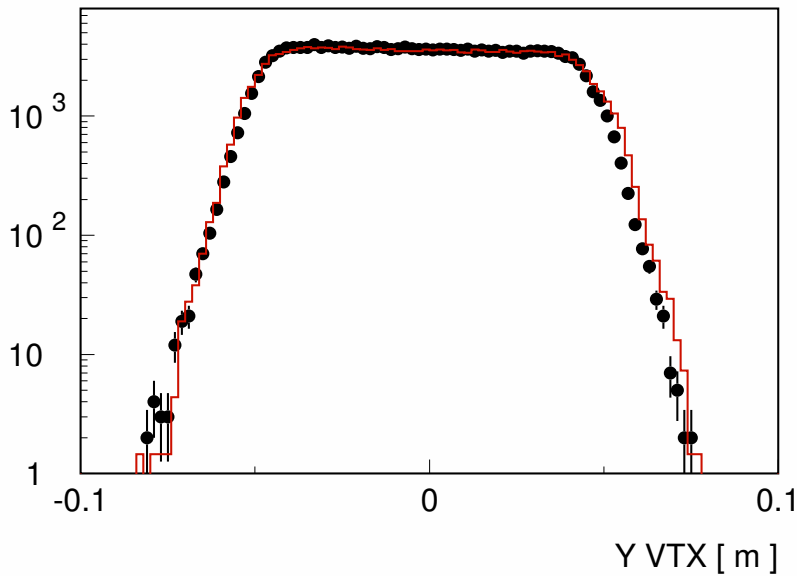
Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

Y of vertex, projected onto CsI
Accept events if $-0.06 \leq Y \leq 0.06$

Black dots: DATA, normalization mode candidates
Red histogram: $K_L \to \pi^0\pi^0\pi^0_D$ MC



even more cuts for $K_L \to \pi^0\pi^0\pi^0 e^+e^-$

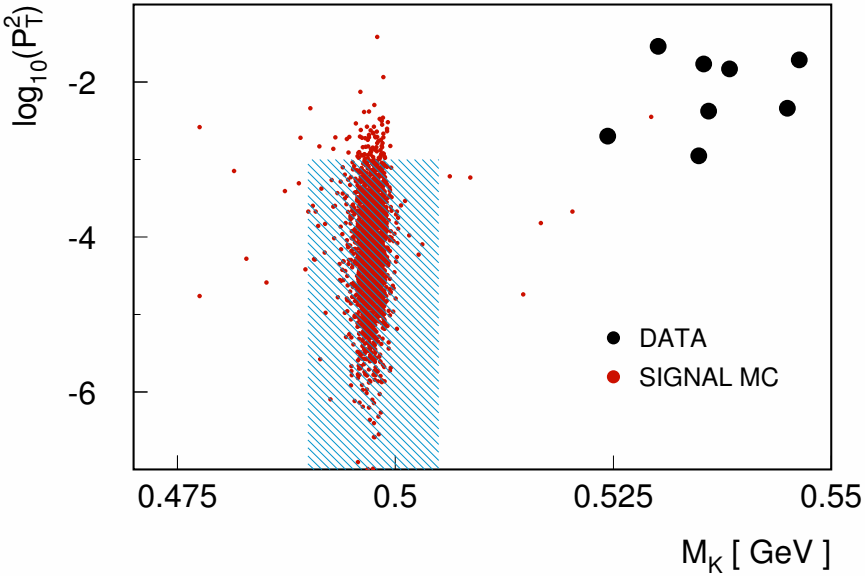
Summary of extra cuts (next few slides will give more details about each of these cuts)

- Cut against conversion before the magnet (again)
- Cut against conversion/radiation after the magnet
- Cut on total number of in-time DC hits
- Cut on extra Y tracks
- Cut on ambiguous events

$K_L \to \pi^0\pi^0\pi^0 e^+e^-$ candidates

Signal box is closed!

Black dots: DATA, signal candidates after all cuts
Red dots: Signal MC



conversion before magnet

A photon converts into e^+e^- pair before the magnet. e^+e^- split apart in the magent and leave 2 clusters in CsI

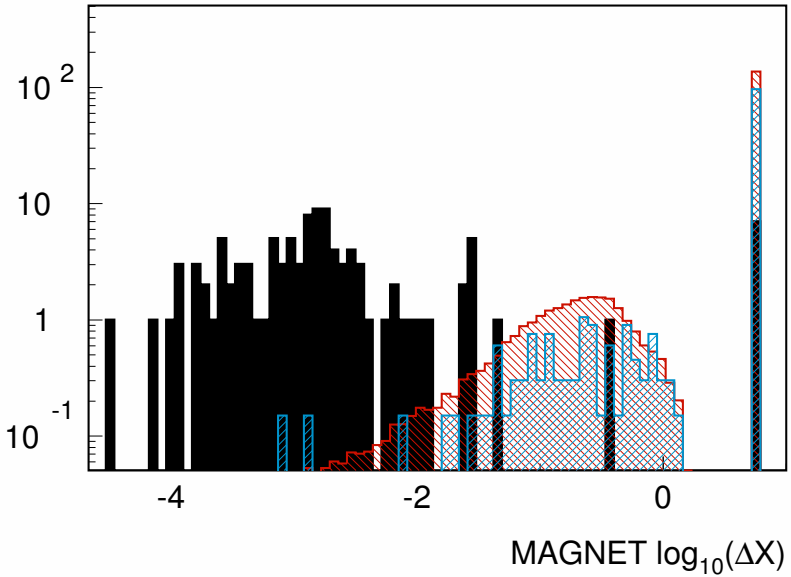
Signature for this process:

- Two clusters with $\Delta Y \leq 0.05$
- Downstream Y track segment points to these clusters within 0.03 m
- There is a pair of downstream X track segments that points to these clusters within 0.03 m and come close to each other at the magnet center.

conversion before magnet

Distance at the magnet center for downstream X track segments. Accept event if $\Delta X \geq 0.1$

Black hist: DATA, signal candidates
Red hist: DATA, clean norm. mode
Blue hist: Signal MC



conversion/radiation after magnet

A photon converts into e^+e^- pair after the magnet. e^+e^- split apart due to scattering and leave 2 clusters in CsI

Also, an electron radiates a photon after the magnet. $e\gamma$ split apart due to scattering and leave 2 clusters in CsI

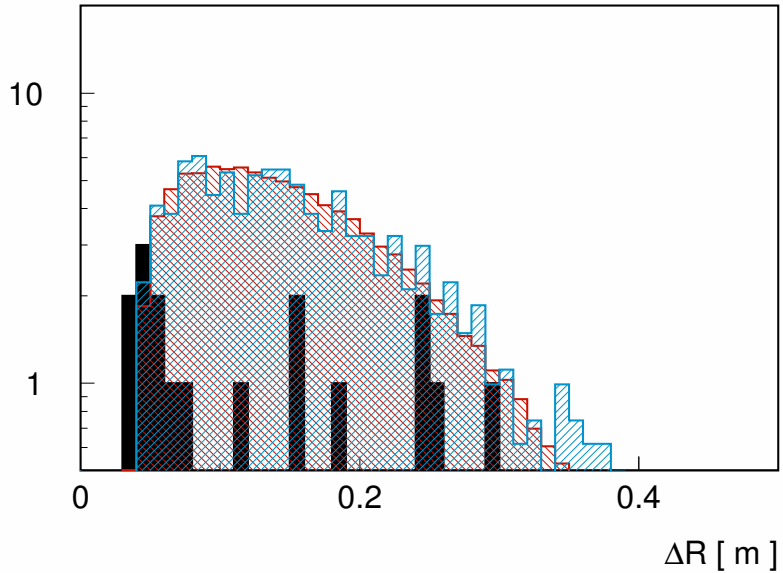
Signature for this process:

- Two clusters close to each other in CsI

conversion/radiation after magnet

Min distance between clusters. Accept event if $\Delta R \geq 0.08$

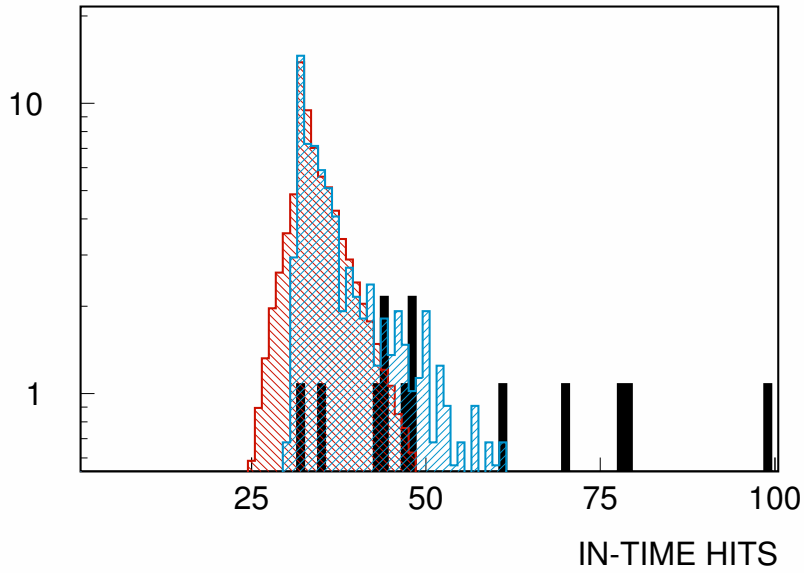
Black hist: DATA, signal candidates
Red hist: DATA, clean norm. mode
Blue hist: Signal MC



in-time DC hits

Number of in-time DC hits. Accept event if $N \geq 61$

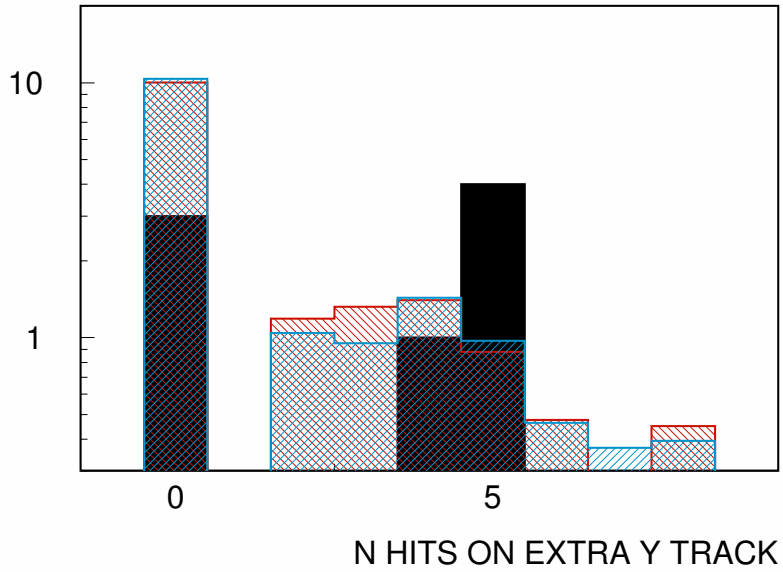
Black hist: DATA, signal candidates
Red hist: DATA, clean norm. mode
Blue hist: Signal MC



extra Y tracks

Hits in Y planes that do not belong to tracks may form a straight line (extra Y track)

Require hits in 3 different DC chambers at least. Accept event if $N \leq 4$



ambiguous events wrt $\pi^0 \to e^+e^-\gamma$

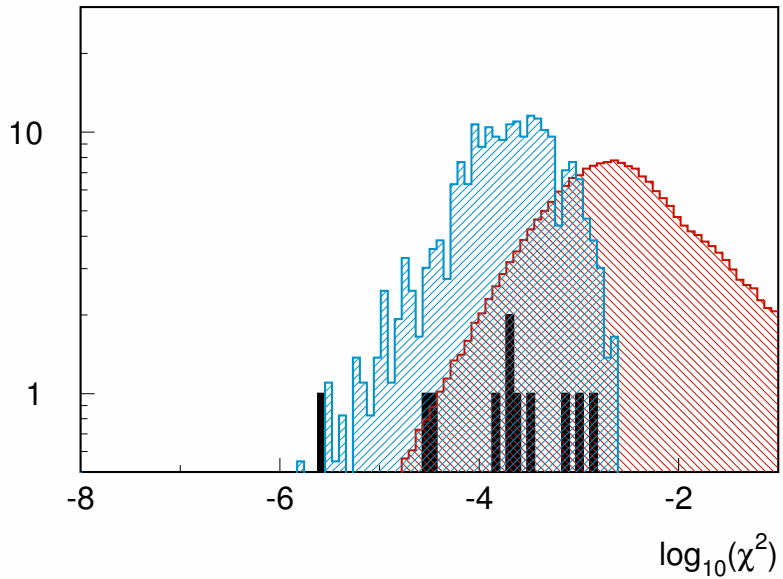
If event has a photon that makes a good $\pi^0 \to e^+e^-\gamma$ candidate, are we confident to call it a signal?

- Cannot aford to reject all events with $\pi^0 \to e^+e^-\gamma$ candidate. Will loose about half of the signal.
- Find best $\pi^0 \to e^+e^-\gamma$ candidate.
- Find best $\pi^0 \to \gamma\gamma$ pairing in addition to original $3\pi^0$
- Form $\chi^2 = (M_{ee\gamma} - M_{\pi^0})^2 + (M_{\gamma\gamma} - M_{\pi^0})^2$

ambiguous events wrt $\pi^0 \to e^+e^-\gamma$

$log_{10}(\chi^2)$ for ambiguous events w.r.t. $\pi^0 \to e^+e^-\gamma$
Accept event if $log_{10}(\chi^2) \geq -4.4$

Black hist: DATA, signal candidates
Red hist: DATA, clean norm. mode
Blue hist: Signal MC



ambiguous events wrt $\pi^0 \to e^+e^-\gamma\gamma$

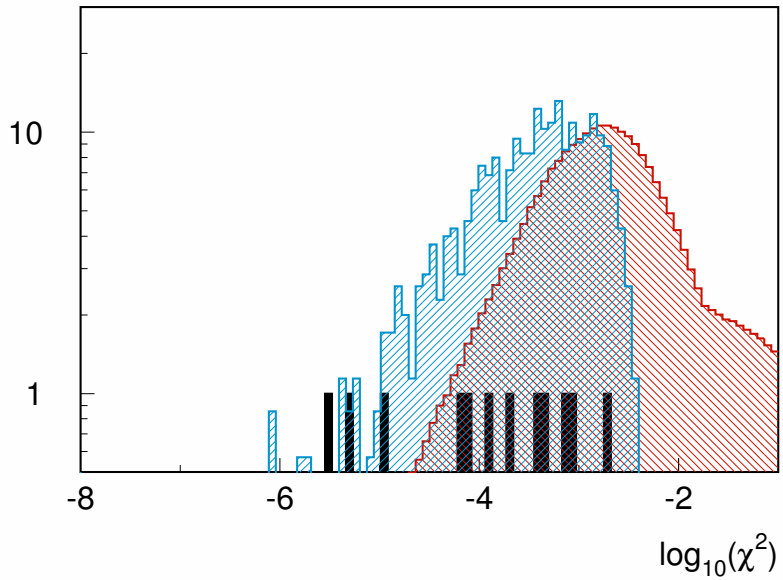
If event has a photon that makes a good $\pi^0 \to e^+e^-\gamma\gamma$ candidate, are we confident to call it a signal?

- Cannot aford to reject all events with $\pi^0 \to e^+e^-\gamma\gamma$ candidate. Will loose about half of the signal.
- Find best $\pi^0 \to e^+e^-\gamma\gamma$ candidate.
- Find best $\pi^0 \to \gamma\gamma$ pairing in addition to original $3\pi^0$
- Form $\chi^2 = (M_{ee\gamma\gamma} - M_{\pi^0})^2 + (M_{\gamma\gamma} - M_{\pi^0})^2$

ambiguous events wrt $\pi^0 \to e^+e^-\gamma\gamma$

$log_{10}(\chi^2)$ for ambiguous events w.r.t. $\pi^0 \to e^+e^-\gamma\gamma$
Accept event if $log_{10}(\chi^2) \geq -4.1$

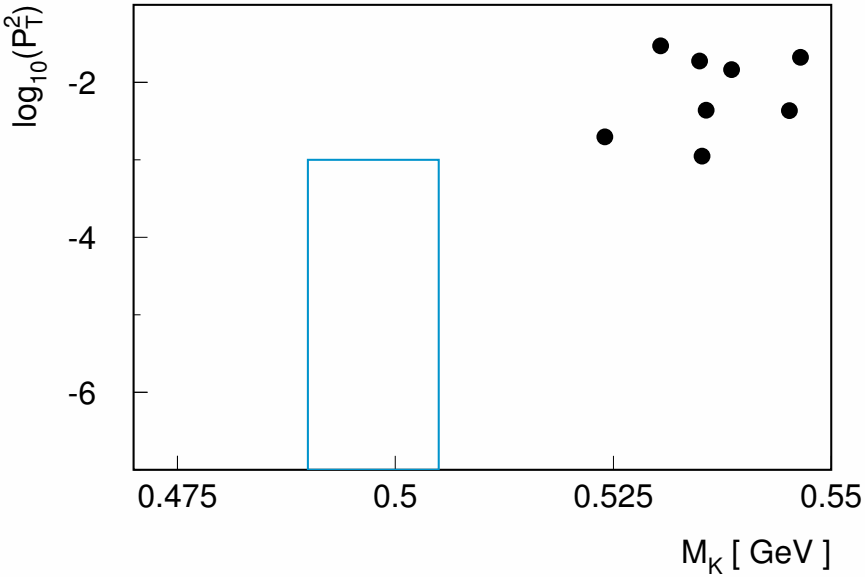
Black hist: DATA, signal candidates
Red hist: DATA, clean norm. mode
Blue hist: Signal MC



total acceptance and s.e.s

- Total acceptance was found 2.08×10^{-3} and 3.10×10^{-3} for '97 and '99 runs respectively.
- Kaon Flux estimation using normalization mode is still in progress (unfortunately)
- Use other people flux numbers: 2.5×10^{11} and 3.1×10^{11} for '97 and '99 runs respectively
- Total $S.E.S = 6.6 \times 10^{-10}$

open the signal box

Zero events in the box

$BR(K_L \to \pi^0\pi^0\pi^0 e^+e^-) \leq 1.5 \times 10^{-9}$