A measurement of the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay

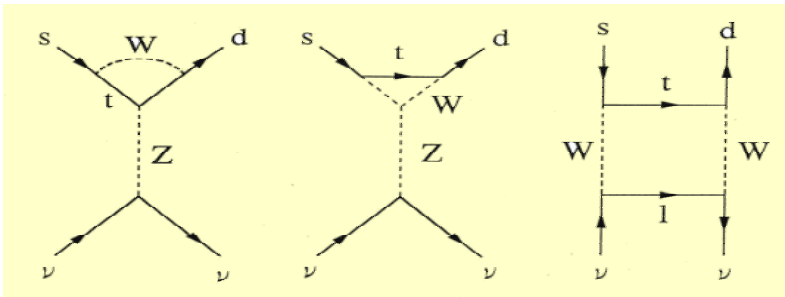
Doroshenko M. Yu.

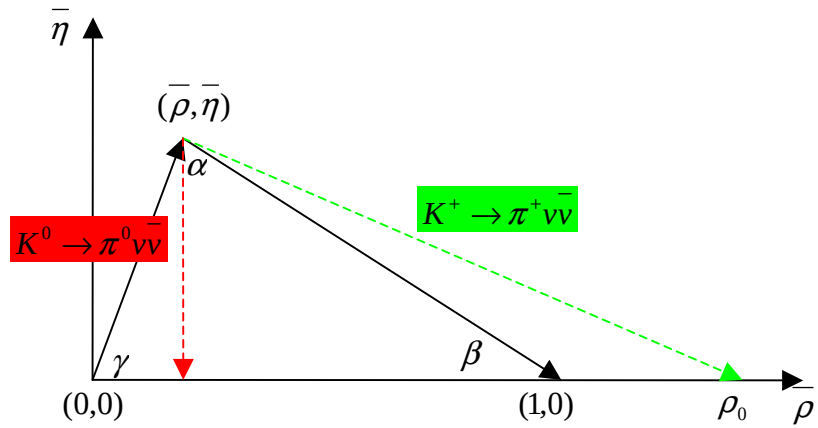
Outlines

- Motivation of experiment
- Experimental method
- Analysis of one day sample
- Conclusions

Motivation of experiment

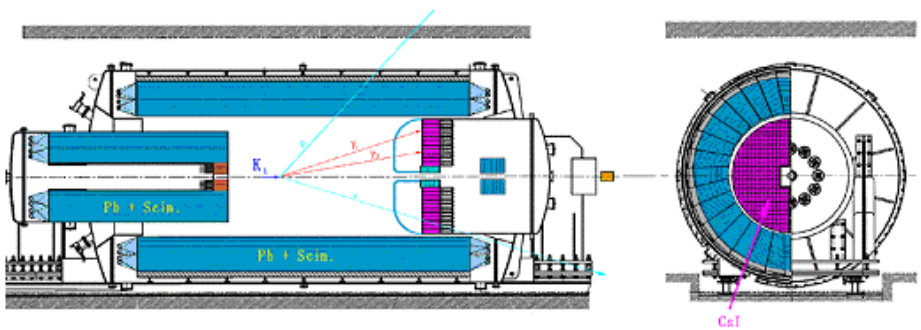
- Direct CP-violation
  - $\Delta S=1$
- Small theoretical errors
  - Mass of top quark is big
  - Charm contribution is suppressed
- BR ~ η^2 (η – 15%)



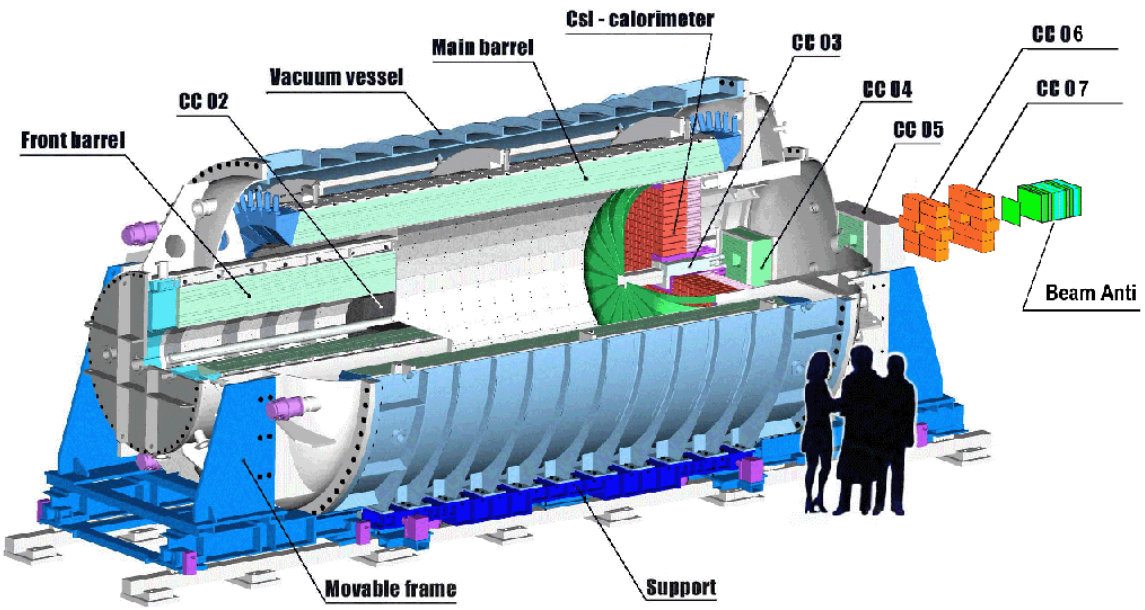


Experimental method

- Signal: $K_L^0 \rightarrow \pi^0(\rightarrow 2\gamma$ calorimeter) + $\nu\nu$ (nothing)
  - Pencil beam
  - High vacuum in decay volume
    - Detector region ~1Pa
    - Decay volume ~10^{-4}Pa
  - Double decay chamber
  - Highly sensitive veto system



Exp. method: setup



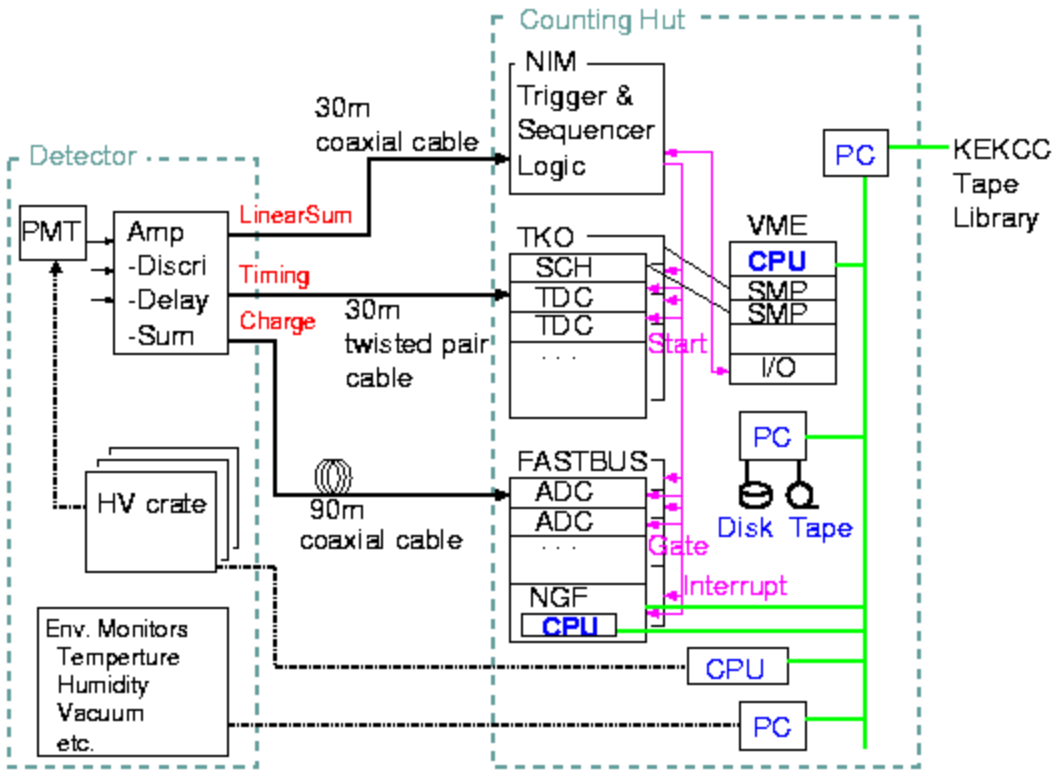
- Undoped CsI calorimeter
- Barrels: MBR, FBR
- Collar counters:
  - CC02-CC07
  - BA
- Charged veto
  - CHV (before calorimeter)
  - CC04,CC05 charge layers
  - BCHV (along MBR)
  - BHCHV (before BA)

4π veto: veto detectors + CsI as veto

Requirement of inefficiency ~ 10^{-4} per single γ

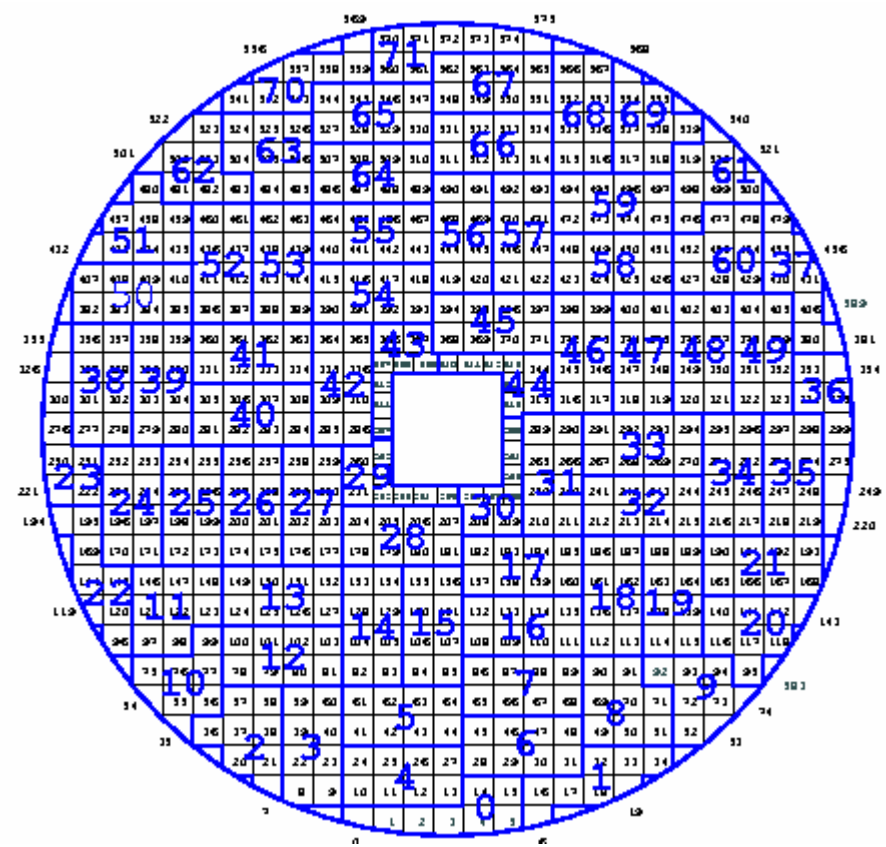
DAQ and electronics

- ~1000 channels in total
  - ADC:
    - 0.05 pC/ch(low gain)
    - 0.4pC/ch(high gain)
  - TDC: 0.05 ns/ch
  - MTDC: 0.5 ns/ch up to 16 hit/event
- Environmental monitors
  - Temperature
  - Vacuum
  - Beam conditions
- Amp/Disc module
  - Analog signal -> ADC
  - Logical signal -> TDC stop
  - Sum 8 channels -> trigger



Trigger: Nclus>=2

- 576 channels were divided on 72 clusters (Amp/Disc modules)
- Energy threshold for one cluster – 60 MeV
- Count number of cluster



Data taking

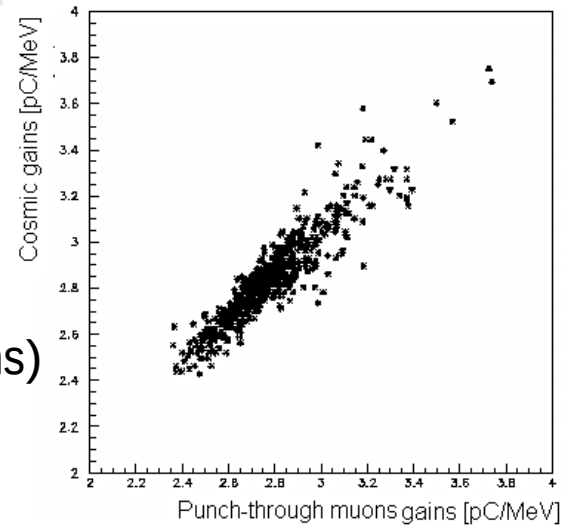
- Beam time
  - 16 Feb – 30 June,2004
  - 300 shifts
    - 187 shifts physics data
    - 24 shifts π^0 calibration
    - 89 shifts beam tuning, accidental, calibration
  - 6 TB data – ~57 days
  - One day run – ~110 GB
- Triggers
  - Physics
    - N>=2
  - Monitors
    - Pedestal
    - Cosmic
    - Xe/LED
    - CC04 & CC05
  - Accidental triggers
    - by TMON
    - by BA
    - by C6

Stability of data

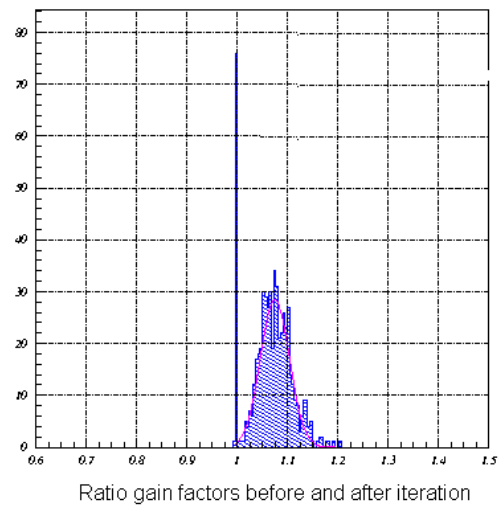
- Various monitors during data taking
  - Pedestals
    - Sigma of pedestal peaks ~1-2ch, stable
    - Peak position stable during long data taking
  - Xenon/LED
    - Xenon monitor PMT's
    - On/off spill <1% for CsI, <10% for veto
    - BA has a shift of 15%

CsI calibration

- Energy calibration
  - By tracking of cosmic muons
  - By punch through muons
  - π^0 production on a target
- Timing calibration by cosmic muons
  - T0 for each channel (Sigma of timing 3.1ns->1.0ns)
  - Delays between crystals in one cluster reduced $\pm 6ns \rightarrow \pm 2ns$ after trimming of cables

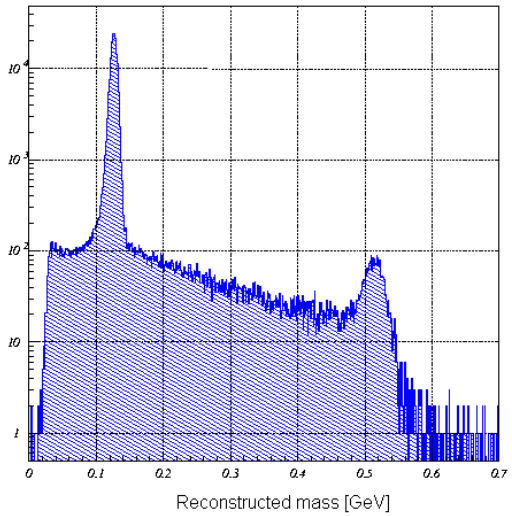


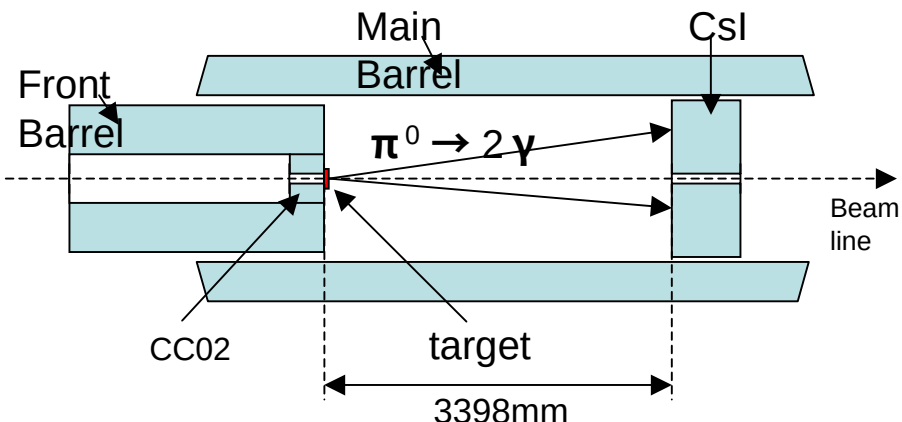
- Good consistency between cosmic muons and punch through muons calibration
- π^0 calibration results in ~7% shift of gain constant
  - Non calibrated crystals were simple shifted constantly on a 7%



Calibration by π^0

- Decrease noise to signal ratio 2.2%->0.9% cuts
- Iteration procedure for correction
  - Collect events where one γ hit n^{th} crystal
  - Calculate mass $M^{n}_{\gamma\gamma} = \sqrt{2 \cdot E_n E(1-\cos\theta)}$
  - Correction factor = $M_{\pi} / M^{n}_{\gamma\gamma}$





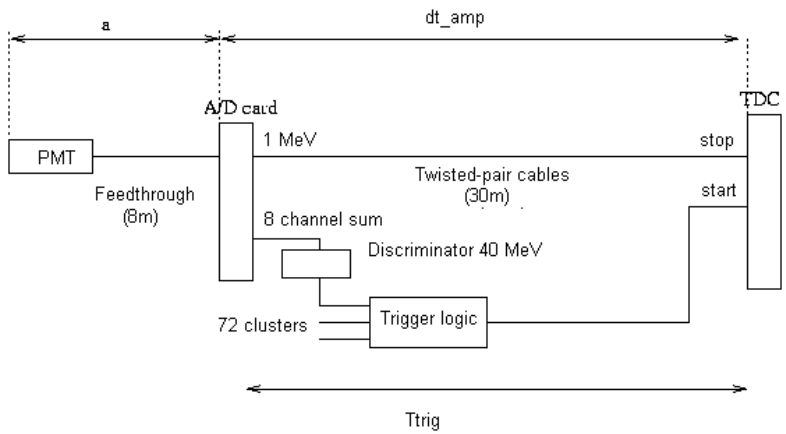
	Before iteration	After iteration	PDG
π^0 mass [MeV/c^2]	126 (4.81)	135 (4.27)	135
η mass [MeV/c^2]	508 (19.1)	548 (13.5)	547.3

Timing calibration of CsI

- For i-th crystal and j-th event

$$TDC^{j}{}_{i} = Ttrig^{j} + a_i + dt_amp_i + TOF^{j}{}_{i} + TOLP^{j}{}_{i}$$

Ttrig: trigger timing
a: PMT-Amp/Disc module
dt_amp: Amp/Disc module – TDC (pulser)
TOF: time of flight (v=30cm/ns)
TOLP: time of light propagation in CsI

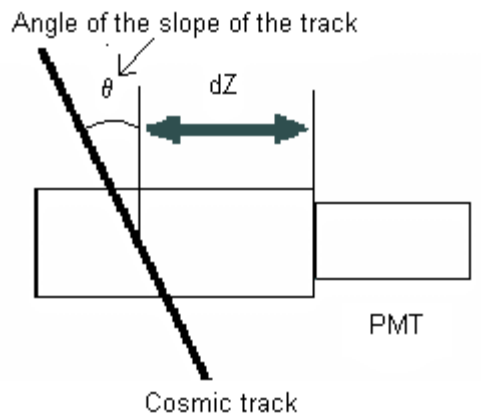


- Estimate Ttrig as

$$Ttrig^{j^*} = \frac{1}{N}\sum_{1}^{N} Ttrig_i^j = \frac{1}{N}\sum_{1}^{N}(TDC_i - a_i - dt_amp_i - TOF_i - TOLP_i)$$

- Correction factor as

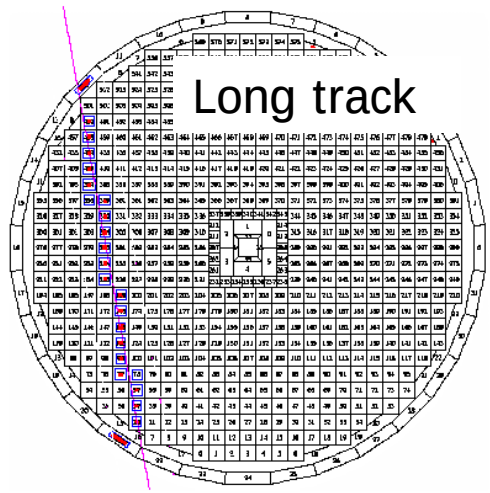
$$\Delta a_i = Ttrig_i^j - Ttrig^{j^*}$$



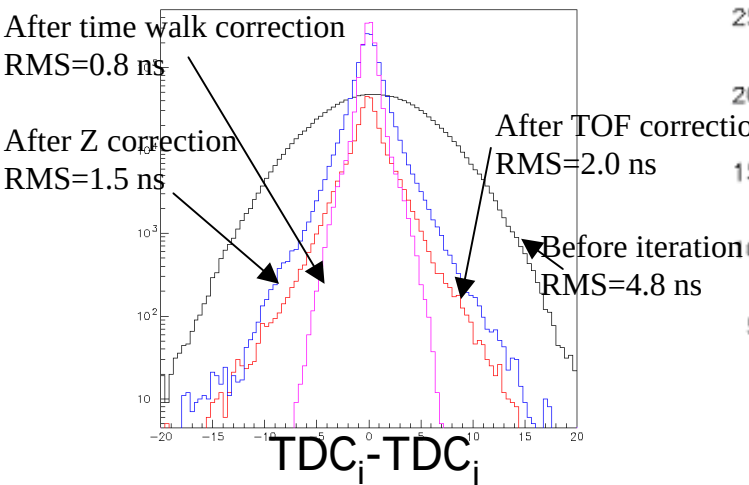
TOLP correction

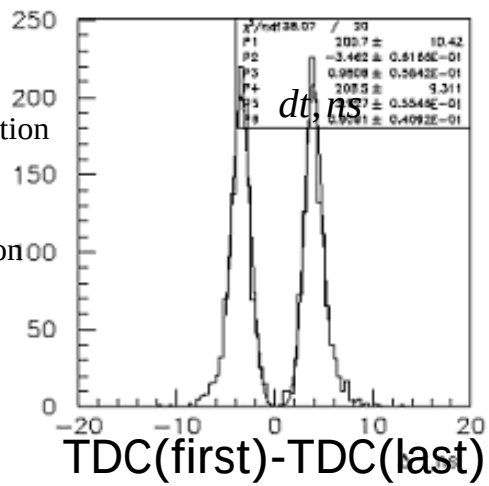
Timing calibration of CsI(2)

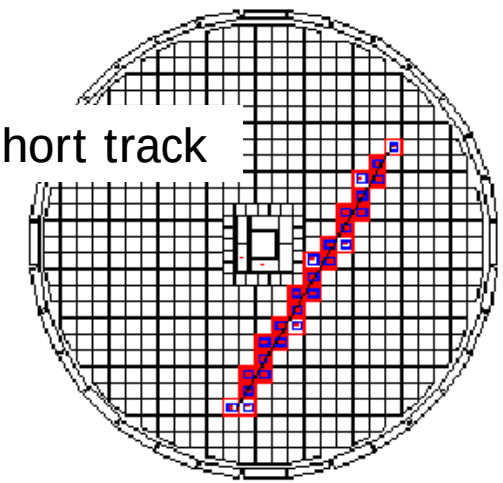
- Iteration process
  1. a=0, TOLP=0, long tracks
  2. Add TOLP, short tracks for inner crystals (c=8.2cm/ns)
  3. Extend TOLP to long tracks, Slope in Z direction is estimated from timing of inner crystals



$$Ttrig^{j^*} = \frac{1}{N}\sum_{1}^{N} Ttrig_i^j = \frac{1}{N}\sum_{1}^{N}(TDC_i - a_i - dt_amp_i - TOF_i - TOLP_i)$$







Timing calibration of CsI(3)

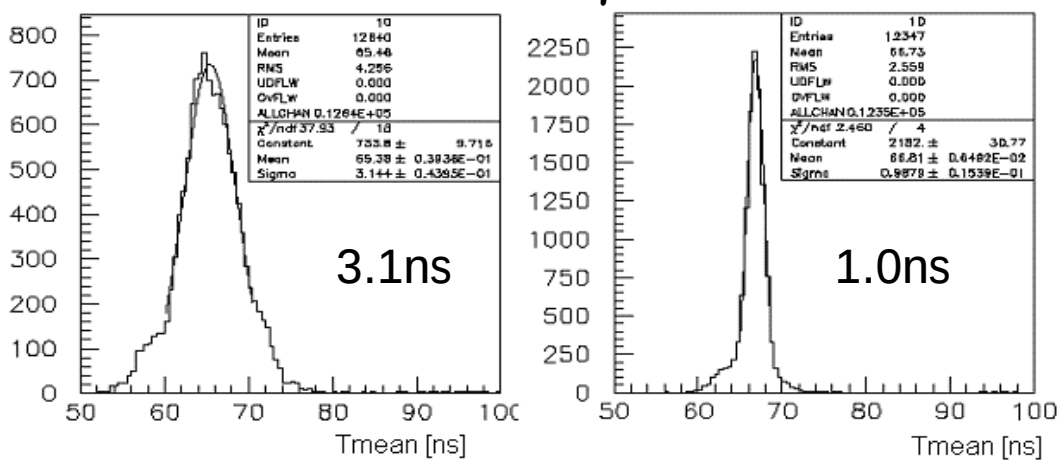
- Results
  - T0 for individual channel
    - Timing resolution of γ's for K3π^0

      3.1ns->1.0ns
  - Delays between crystals in a cluster

    $\pm 6ns \rightarrow \pm 2ns$

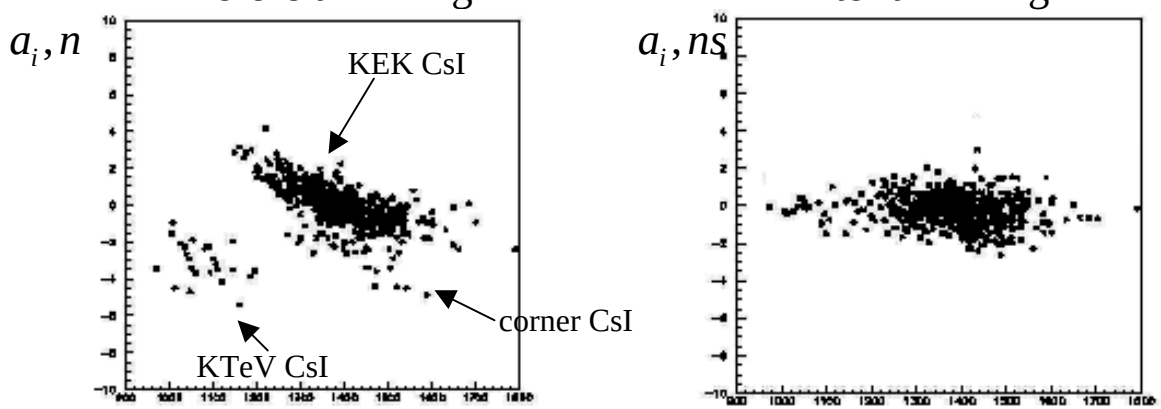
    after trimming

Mean TDC of 6γ's for K3π^0



Before trimming

After trimming



Reconstruction procedure

- Hit position:
  COG 3x3 matrix + angular correction
- Gamma energy:
  sum 3x3 matrix + 5%
- Decay vertex:
  - Calculate w/o angle and energy corrections
  - Estimate angles of gamma
  - Apply corrections
  - Recalculate decay vertex
  - XY=0
- Tree decays $K_L^0 \to 3\pi^0 \to 6\gamma$
  - Calculate Z for each π^0
  - Z(K^0)=mean Z(π^0)
  - Combination with minimum

$$\chi^2 = \sum_1^n \frac{(Z_i - Z)^2}{\sigma(Z_i)^2}$$

  - XY $\neq$0 (no missing particles)

$$\cos\phi = 1 - \frac{m^2}{2E_1E_2}$$

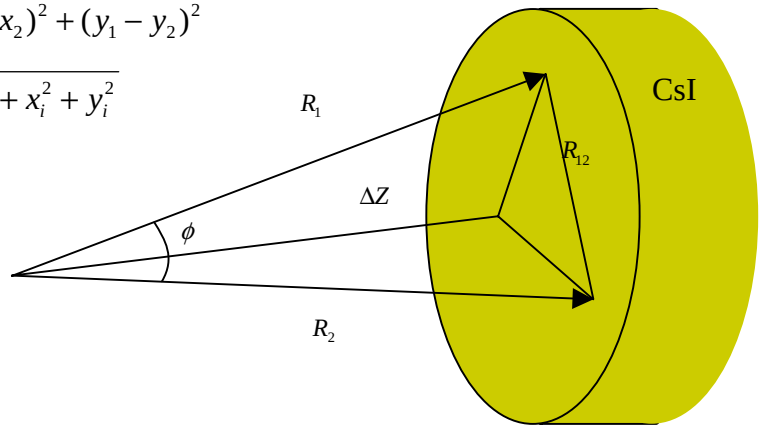
$$R_{12}^2 = R_1^2 + R_2^2 - 2R_1R_2\cos\phi$$

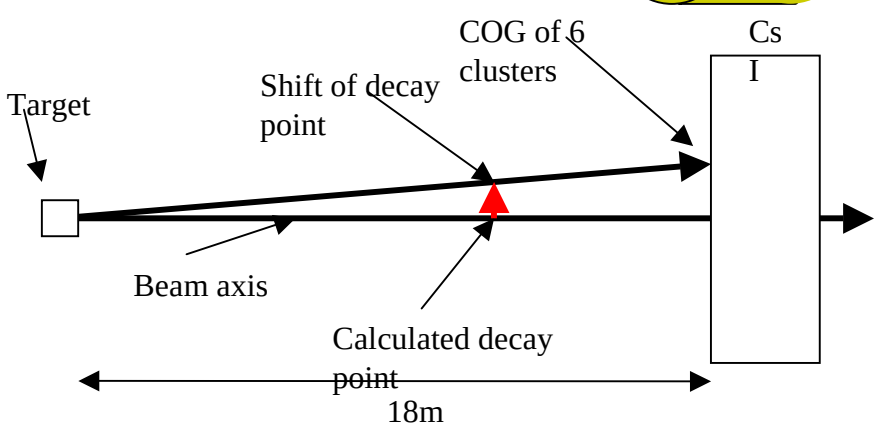
$$R_{12} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

$$R_i = \sqrt{(\Delta Z)^2 + x_i^2 + y_i^2}$$

$$\sigma(x) = 1.5cm$$

$$\sigma(E) = E\sqrt{2\%/\sqrt{E} \oplus 2\%}$$



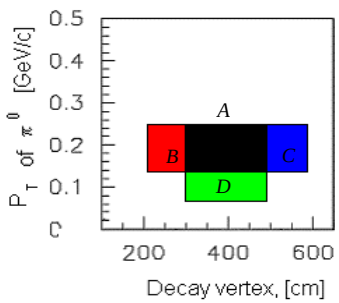


Analysis: strategy

- Separation of the data
  - One-day (this thesis)
    - Identifying of the main sources of background
    - Test our MC
    - Seeing final view and critical check of experiment
    - Comparable sensitivity with KTeV
    - Easy to handle
  - One week, 1/3 and full data sets

Analysis process (I)

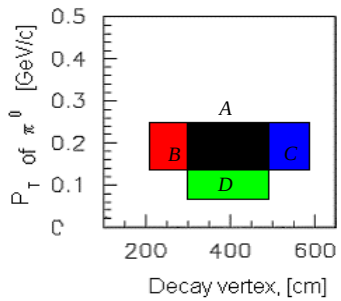
- Normalization channel
  - K3π,K2π,Kγγ
  - Matching MC and data (online type veto for MC)
  - Consistency between them
  - Pure K3π, K2π, Kγγ samples (online type veto for MC)
    - Purity estimation – from MC or data
  - Background samples of 4γ and 2γ



- Kπνν study at online type veto
  - Identify source of backgrounds
    - Match MC and data raw spectrums
  - Kinematical cuts
    - Select samples of 2γ events of main background sources.
      - Around signal box (B,C,D samples)
    - $K\pi^0\nu\nu$ MC in signal box – acceptance loss
    - Optimize the rejection power and acceptance loss

Analysis process (II)

- $K\pi^0\nu\nu$ study (continue)
  - Veto cuts by using real data
    - Background structure
      - Comparison pure signal and background samples
    - Optimize the veto cuts
      - $K3\pi$, $K2\pi$, $K\gamma\gamma$ pure samples – acceptance loss
      - "D" sample of 2γ events – background rejection
      - Take the ratio of events loss
    - Extrapolate to the $K\pi^0\nu\nu$ decay



- Estimation of the SES for $K\pi^0\nu\nu$
  - Acceptance =

    Acc ($K\pi^0\nu\nu$ MC+kinematical cuts)*Veto acc. (pure samples)
  - Normalization on $K3\pi/K2\pi/K\gamma\gamma$ decays

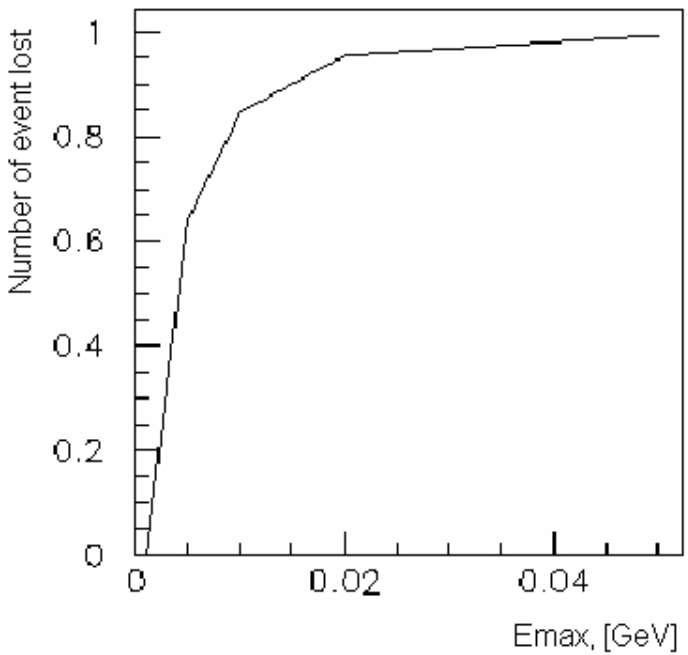
- Background estimation

Skimming of data

- Skimming of data
  - Reduce data size
    - ~10% for 2-gamma stream
  - Preliminary sorting by number of gamma
    - Gamma candidate: Emax>50 MeV
    - No add. clusters with Emax>20MeV (CsI veto)
  - No serious acceptance loss <1%

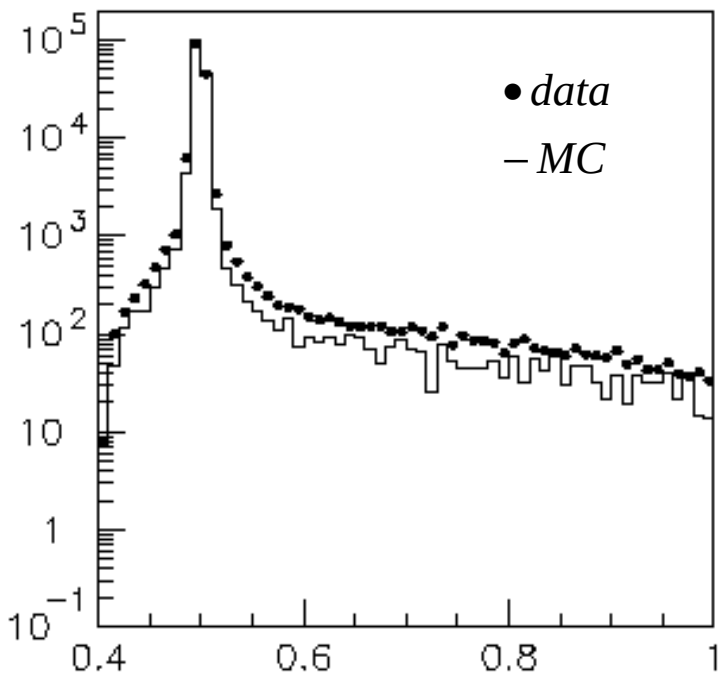
All data	Non-physical triggers	Local max in KTeV
100%	19.5%	37.9%

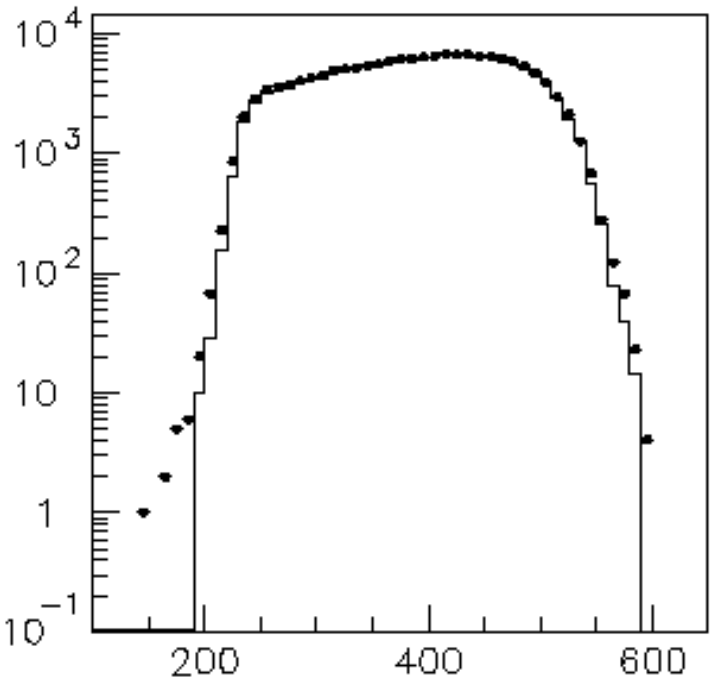
gam1	gam2	gam3	gam4	gam5	gam6	gam7+	gam+bad
15.2%	9.3%	1.9%	1.9%	4.0%	3.9%	0.02%	5.0%



Pure sample K3π^0

- MC well reproduce the data spectrums
  - except best χ^2
  - High and low mass tails come from miss-pairing
    - Cut for second χ^2 is useful



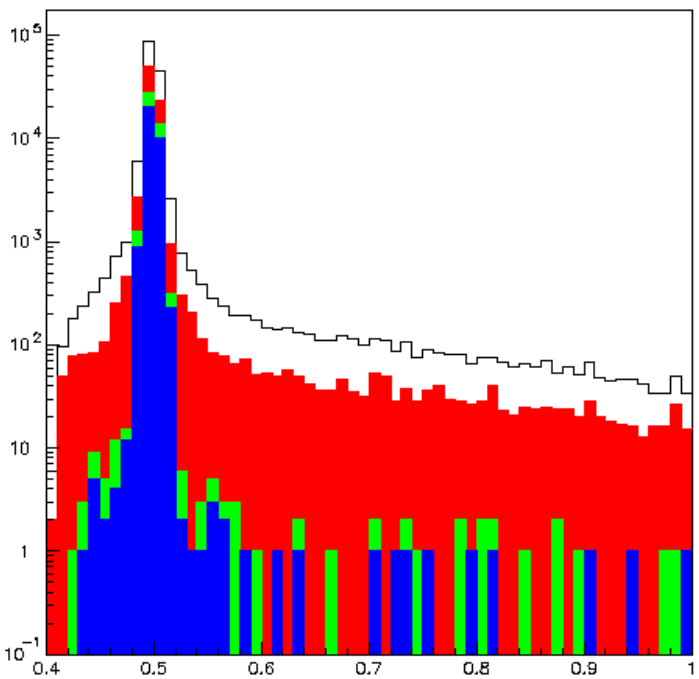


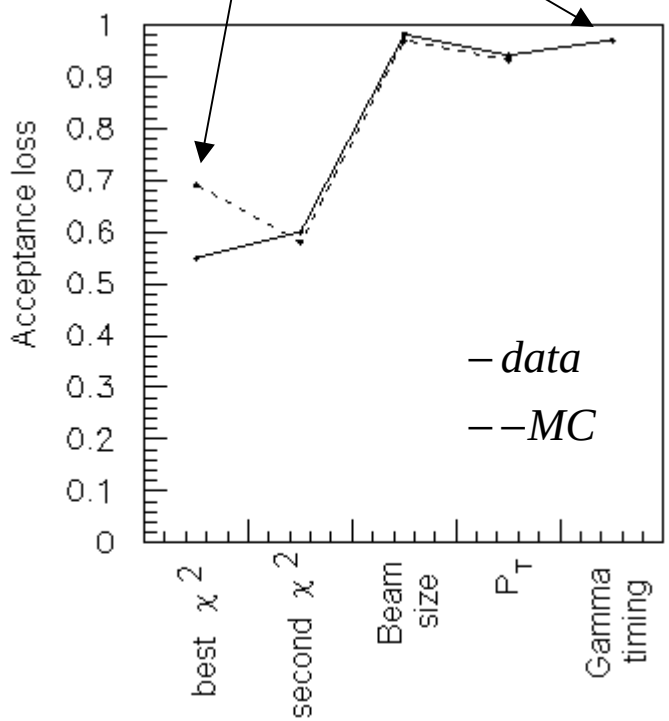
Pure sample K3π^0

- Pure signal sample: 3sigma around mass peak after all cuts.
- No background sample

- 29669 events
- Acc=1.9x10^{-5} (K0@C6)

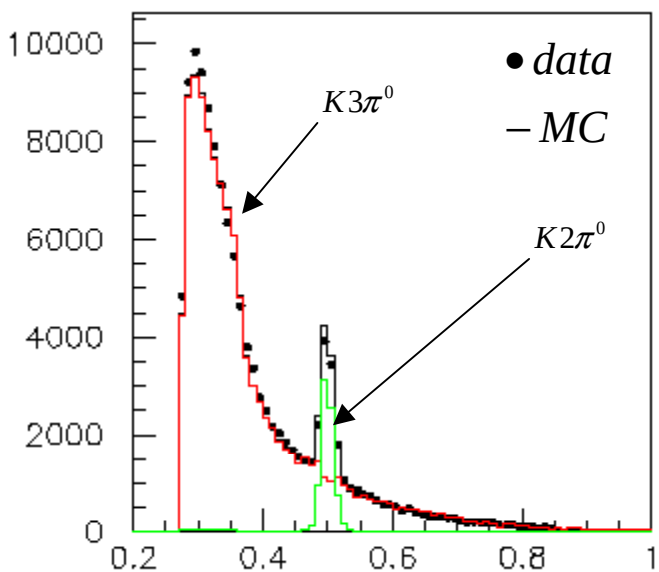
-> x0.77x0.97=1.4x10^{-5}

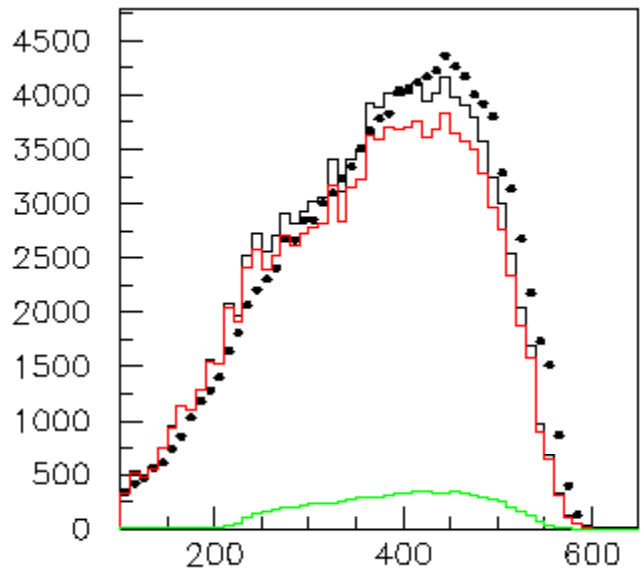




Pure sample $K2\pi^0$

- MC well reproduces the data
  - Main background is $K3\pi^0$ decays
  - Pure background sample: no cuts, outside of 3sigma of mass peak





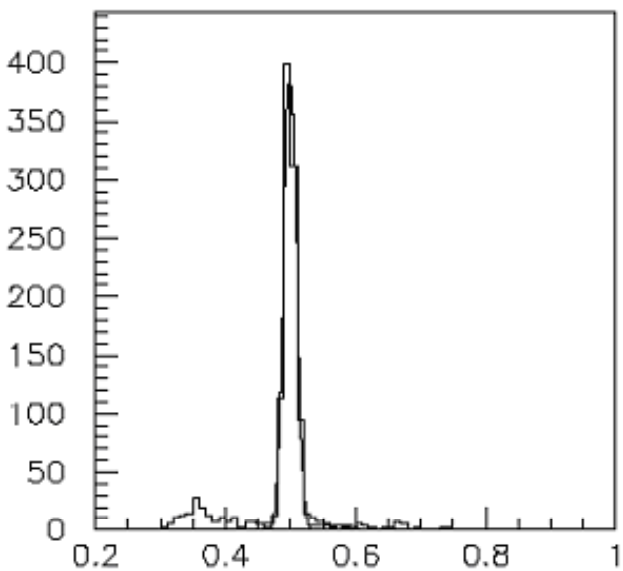
Pure sample K2π^0

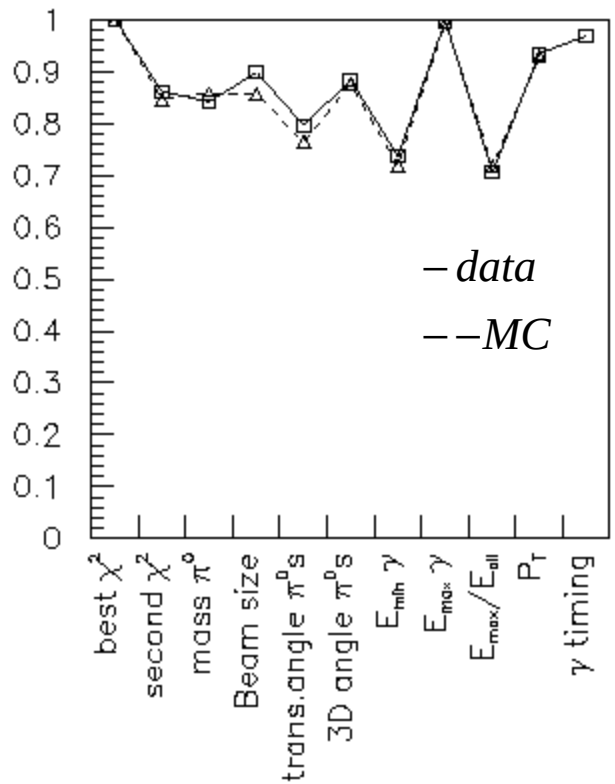
- Pure signal sample: 3sigma of mass peak after all cuts
- Mass peak fit by Gauss+line

991.4 K2p event

2.7% bgr

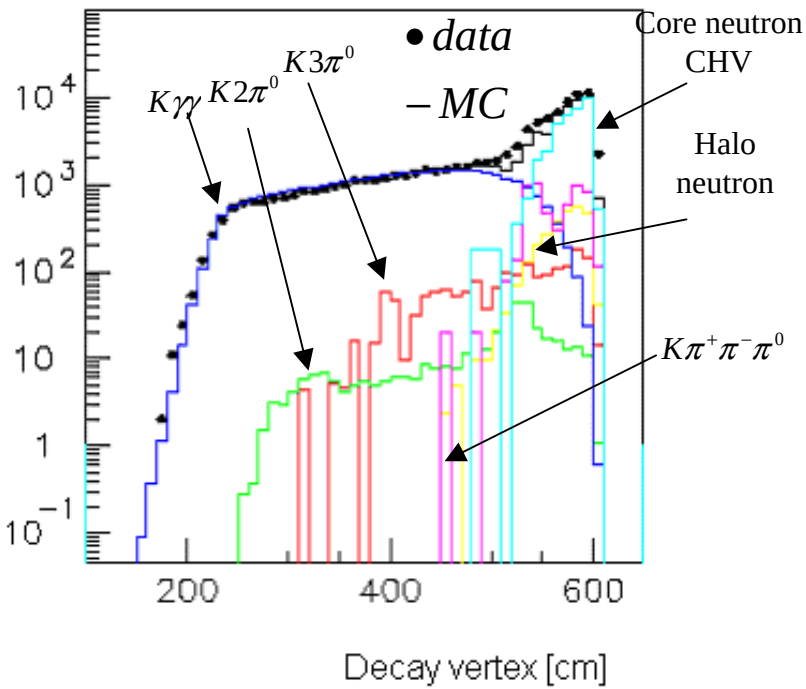
Acc=1.12x10^{-4}(K0@C6)

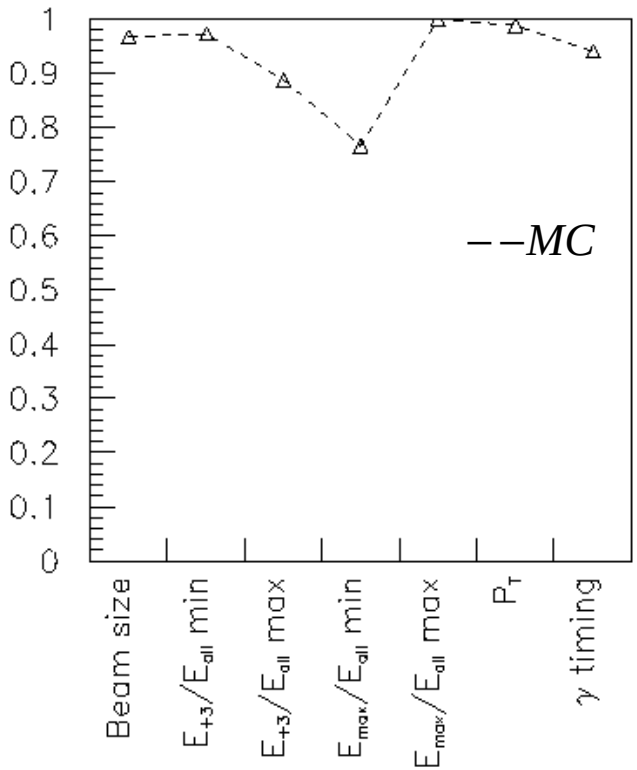




Pure sample Kγγ

- Overlap k3π, K2π, Kγγ, halo neutrons, core neutrons, chg K3π MC
- Z<500cm mostly contains Kγγ
- Background sample: Z>500cm





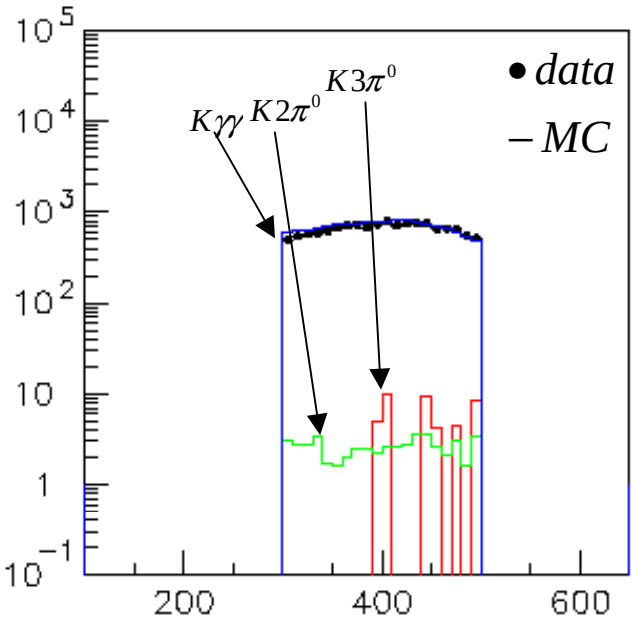
Pure sample Kγγ

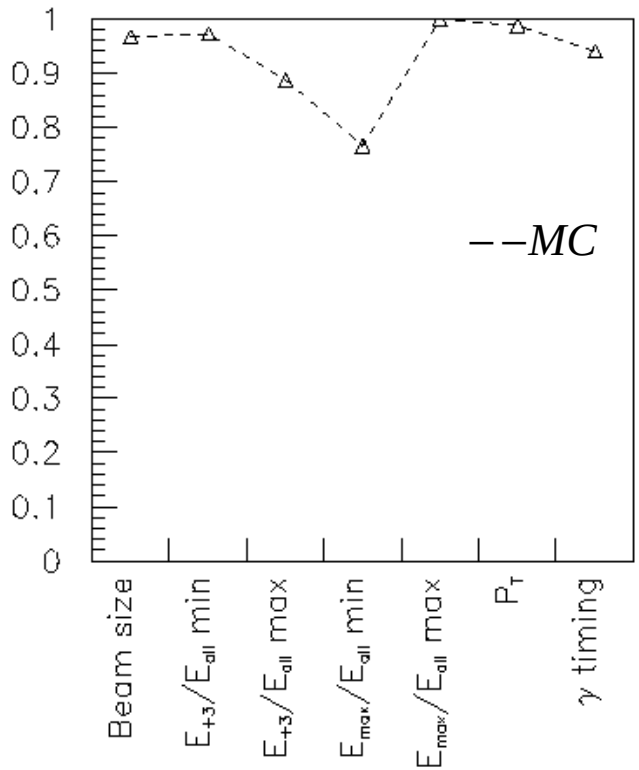
- Pure signal sample: apply all cuts

12951 Kγγ events

0.7% bgr

Acc=2.16x10^{-3}(K0@C6)





Comparison channels

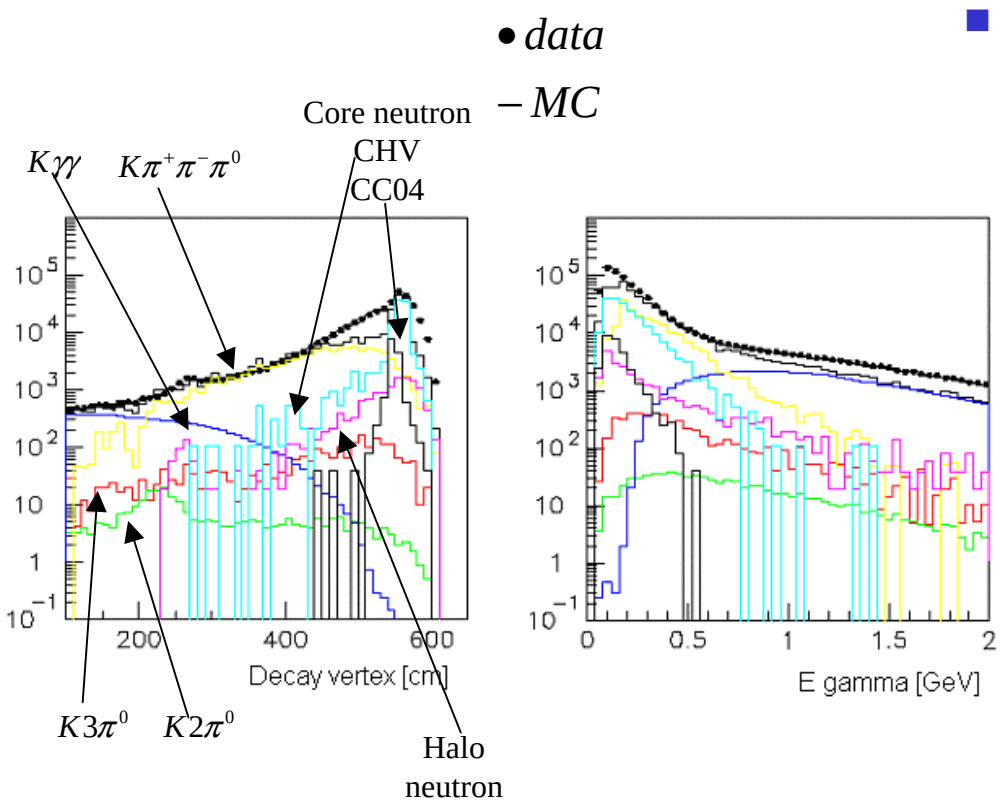
	$K_L^0 \to 3\pi^0$	$K_L^0 \to 2\pi^0$	$K_L^0 \to \gamma\gamma$
BR(PDG)	21.13%	9.27×10^{-4}	5.86×10^{-4}
N event	29669	991.4	12951
Acceptance	1.41×10^{-5}	1.09×10^{-4}	2.16×10^{-3}
Backgrounds contribution	$<10^{-4}$	2.7%	0.7%
Number of K^0_L@C6	0.99×10^{10}	0.98×10^{10}	1.02×10^{10}

$$\frac{N^*(K3p)}{N^*(K2p)} = 1.02 \pm 0.04$$

$$\frac{N^*(K2p)}{N^*(K\gamma\gamma)} = 0.96 \pm 0.04$$

$$\frac{N^*(K3p)}{N^*(K\gamma\gamma)} = 0.97 \pm 0.02$$

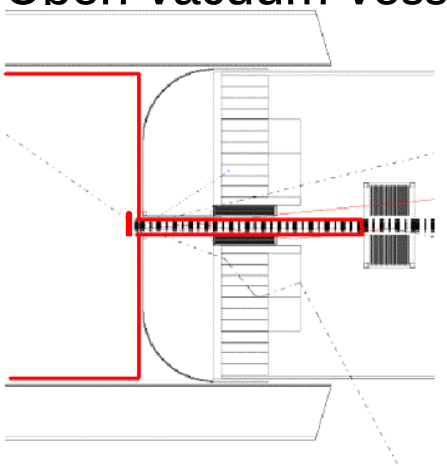
$K^0_L \to \pi^0\nu\nu$ ($\pi^0 \to \gamma\gamma$) decay

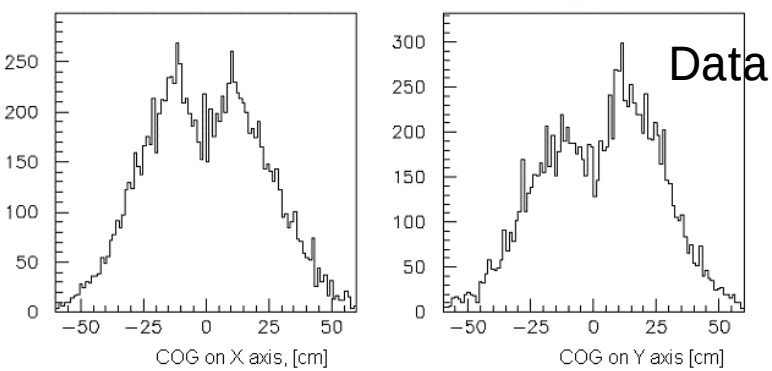


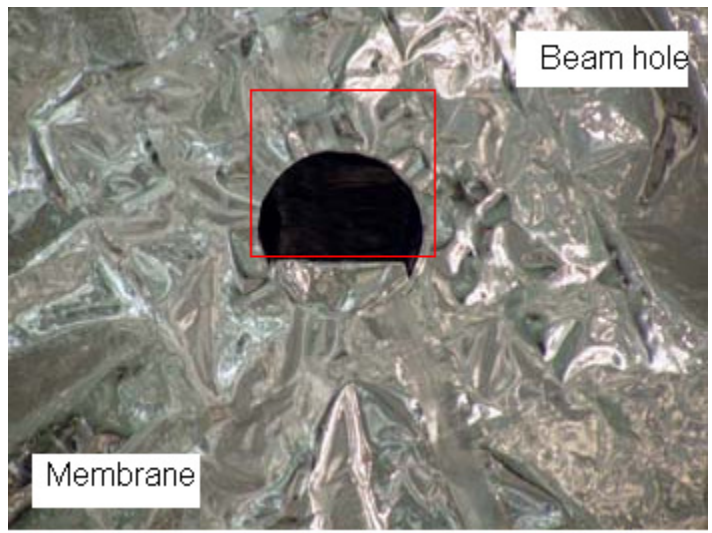
- Backgrounds
  - $K3\pi^0$,$K2\pi^0$,$K\gamma\gamma$
  - $K\pi^0\pi^+\pi^-$ where chrg π escape to beam hole
  - Halo neutrons make production point @ CC02
  - Core neutrons hit membrane produce a peak before CsI calorimeter
    - Need factor ~3 to match the spectrum
    - Contribution from π^0 produced @ CC04 end cap of membrane

Core neutron simulation

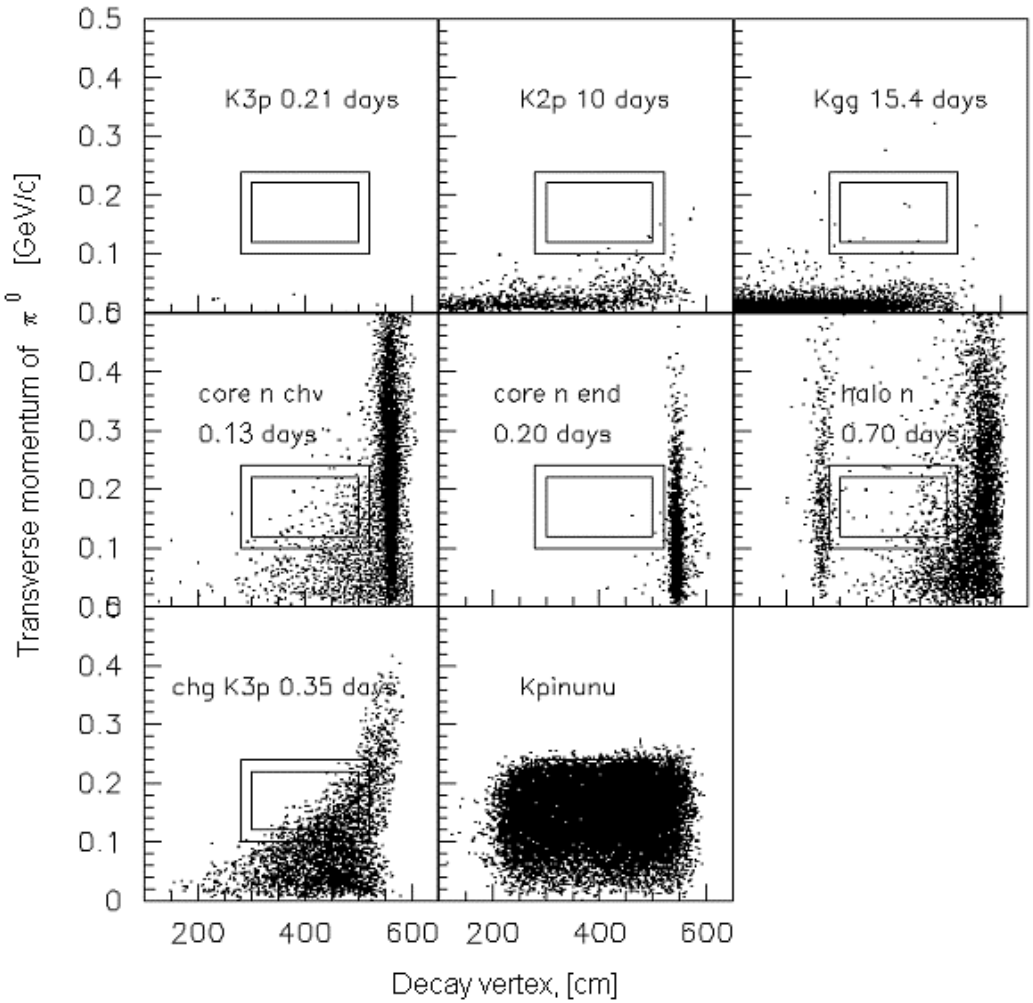
- For MC simulation installed membrane material @ CHV + CC04
  - ρ: 1->10g/cm^3, thickness 0.2->2mm
- Open vacuum vessel to confirm the membrane drop







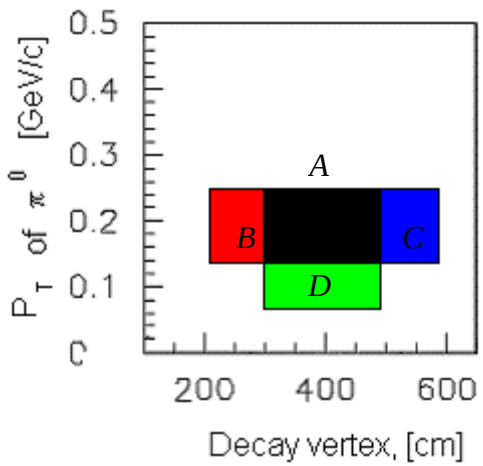
Backgrounds



- Neutral decays are concentrated under signal box
- Core neutrons produce the structure before CsI calorimeter (on the right of signal box)
- Halo neutron born π^0 @ CC02 (on the left of signal box)

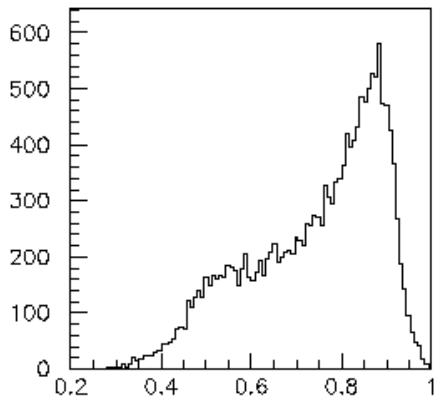
"A" sample – $K\pi^0\nu\nu$ MC

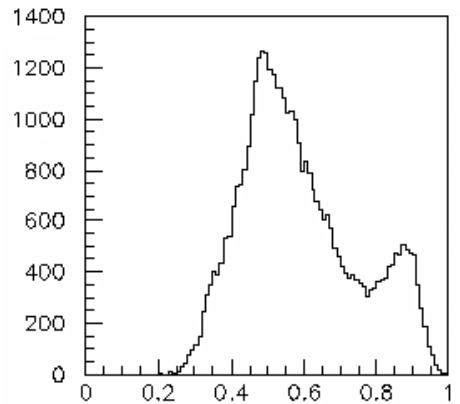
"B,C,D" samples - data



Cluster shape analysis

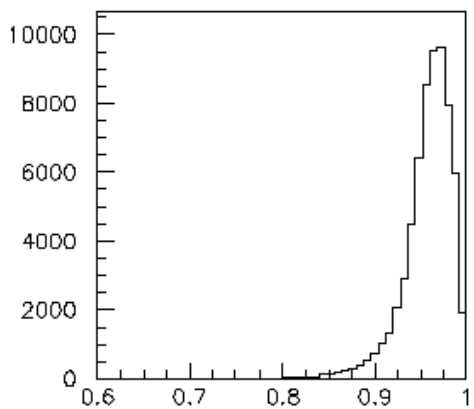
$$E_{\max} / E_{cluster}$$

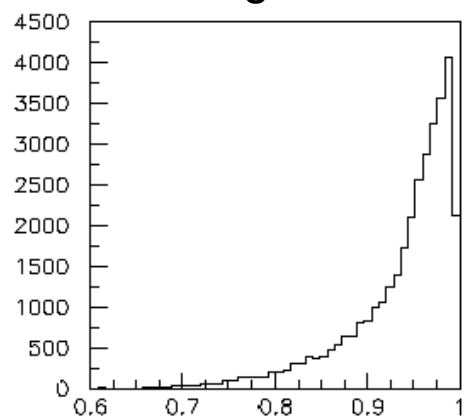




Single gamma cluster Fused gamma cluster

$$\frac{E_1 + E_2 + E_3}{E_{cluster}}$$

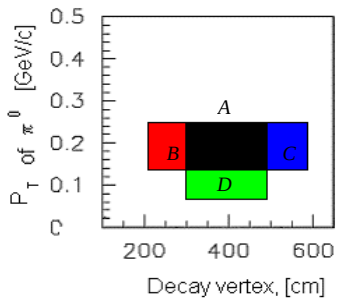


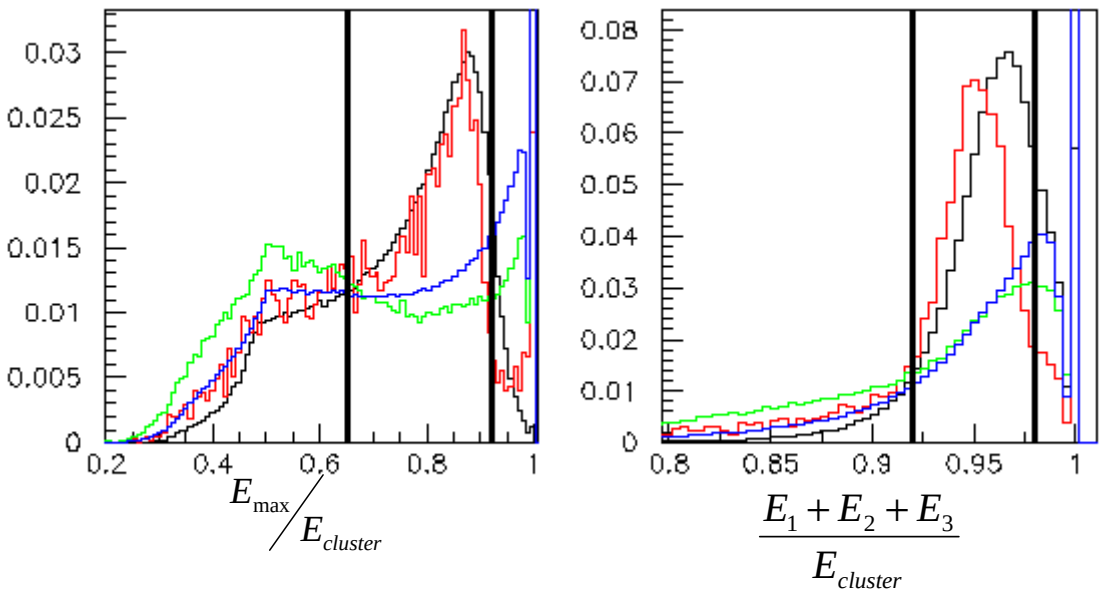


Gamma cluster Neutron cluster

Cluster shape analysis

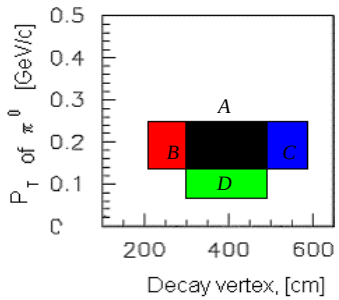
- "D" sample
  - Fusion dominate
  - Neutron events exist
- "C" sample
  - Mixing gamma and neutron clusters
- "B" sample
  - Contains only gamma clusters

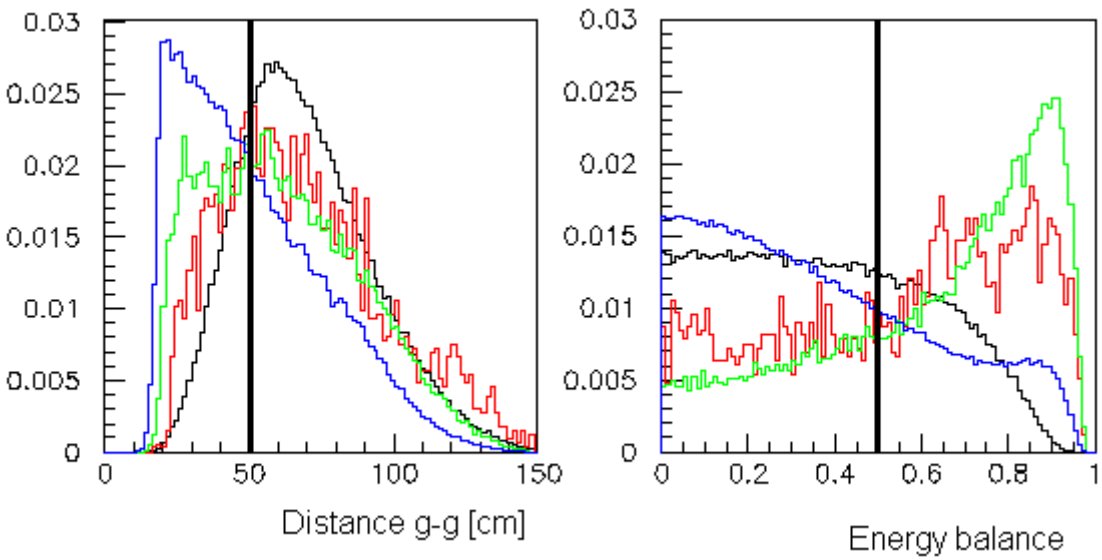




Kinematics of decay

- Clusters produced by neutrons have a small distance between gammas
- Fusion results in unbalanced energy of gamma

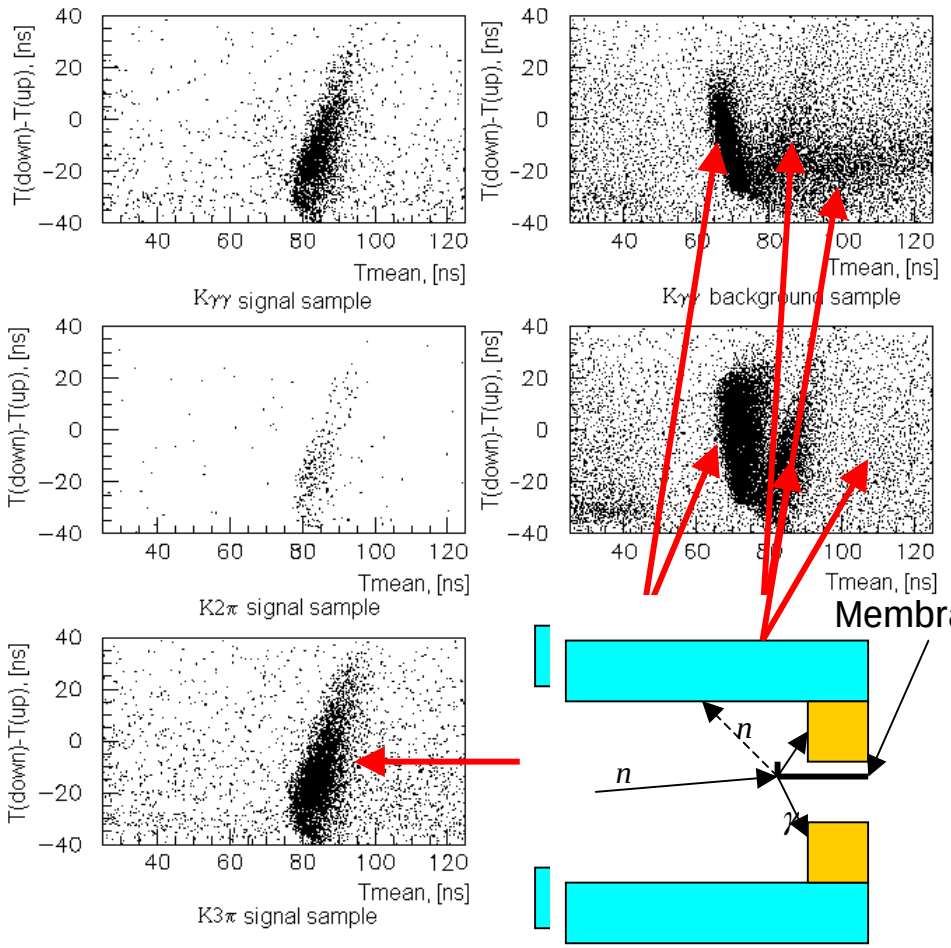




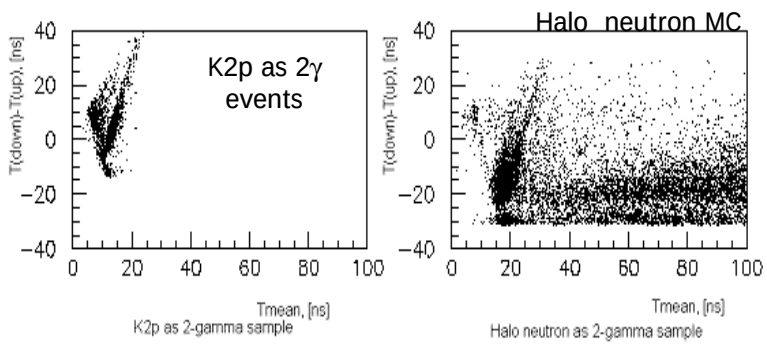
Veto study

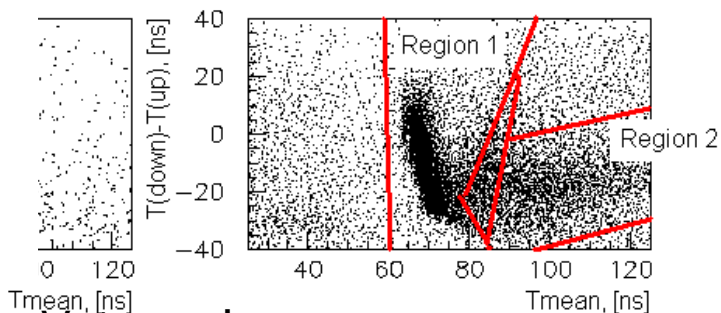
- Use a real data samples
  - MC response of veto counters is not well tuned yet
  - Contains all effects
  - Correct timing information
  - Pure background and pure signal samples
    - Study the structure of the background
    - Define time window for vetoing
  - Study acceptance loss due to veto cuts of each sample.
    - Extrapolate it to $K\pi^0\nu\nu$ decay

Veto study: MBR inner

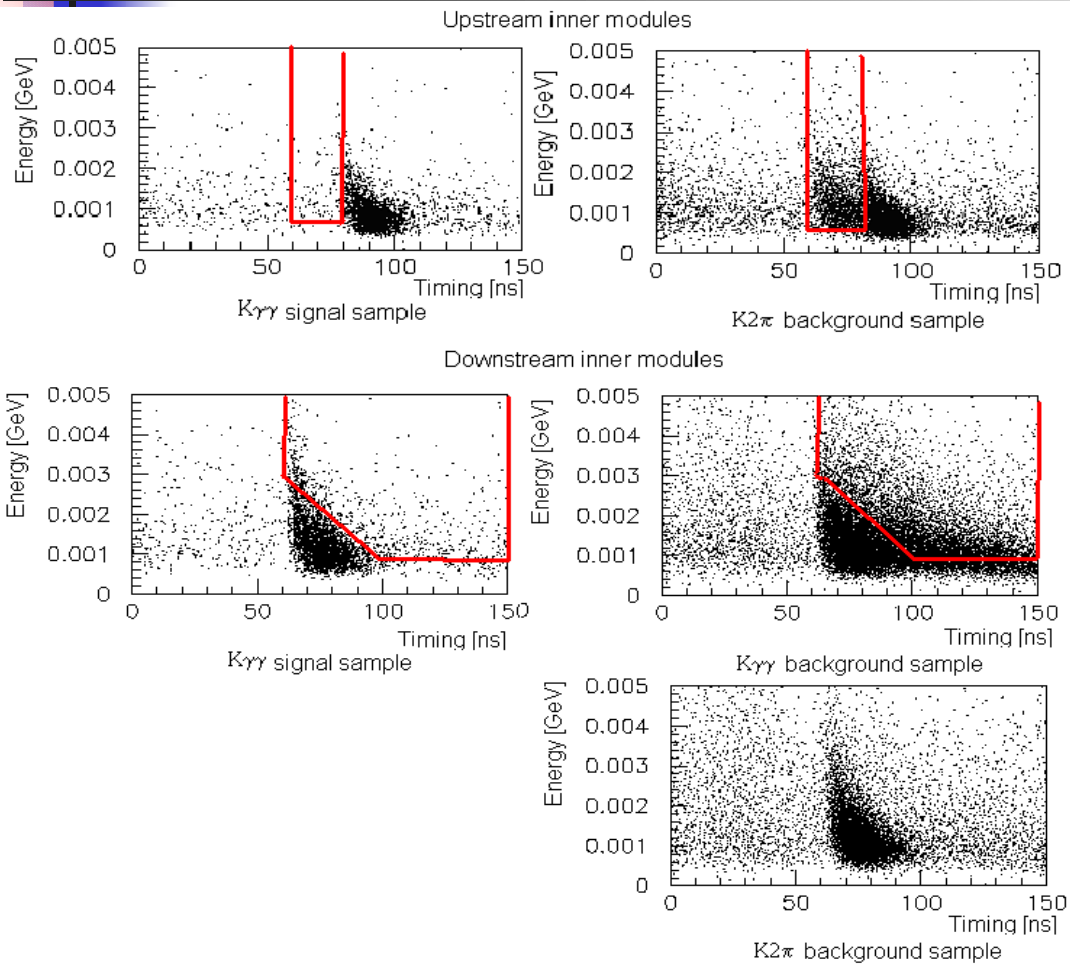


- T(down)-T(up) vs. Tmean
  - Shower leakage from CsI calorimeter
  - Direct gamma hit events
  - Neutron events



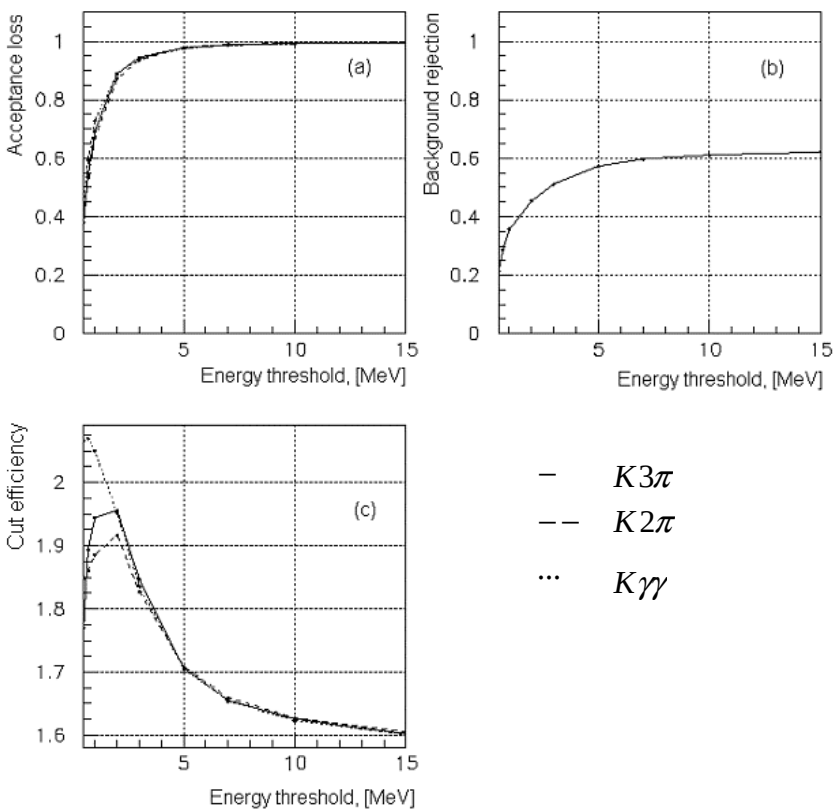


Veto study: MBR inner(2)



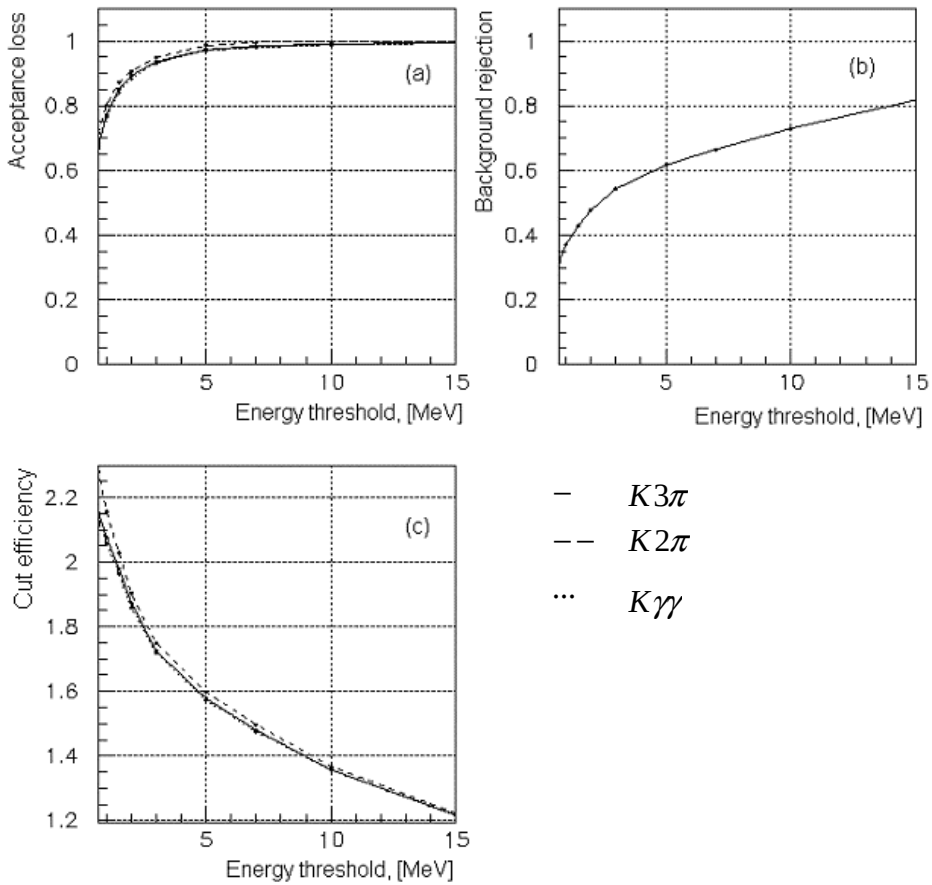
- If there is only one TDC
  - Energy vs. TDC correlation plot
    - Direct hit and shower leakage can be separated for upstream PMT's
    - Not possible for downstream PMT's
    - Neutron events can be seen for downstream PMT's

Veto study: MBR inner(3)



- Acceptance loss is well consistent between 3 samples
  - Doesn't depend on kinematics of decays and number of gammas
- Very efficient for background rejection
- Cut efficiency has a maximum @3MeV

Veto study: MBR outer



- Outer modules are less suffered by shower leakage
- Less sensitive to acceptance loss
- No maximum for cut efficiency -> 1MeV

Acceptance loss due to veto

- After applying all veto cuts :
  - K3π veto Acc. (37.4$\pm$0.8)%
  - K2π veto Acc. (38.5$\pm$3.8)%
  - K$\gamma\gamma$ veto Acc. (37.9$\pm$0.7)%
- Well consistent with each other
  - Timing windows for veto don't touch shower leakage region
  - Acceptance loss mostly coming from accidental
- Total weighted veto acceptance is

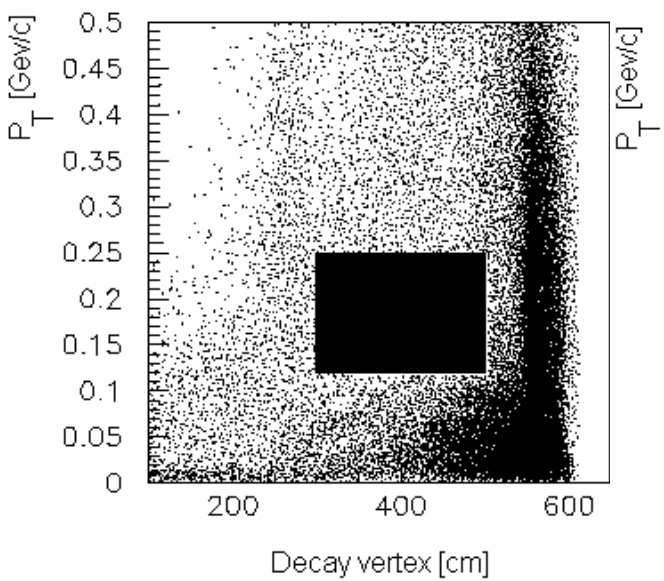
  (37.7$\pm$0.5)%
- Kp0nn veto acceptance is (extrapolated)

  (37.7$\pm$0.5)%

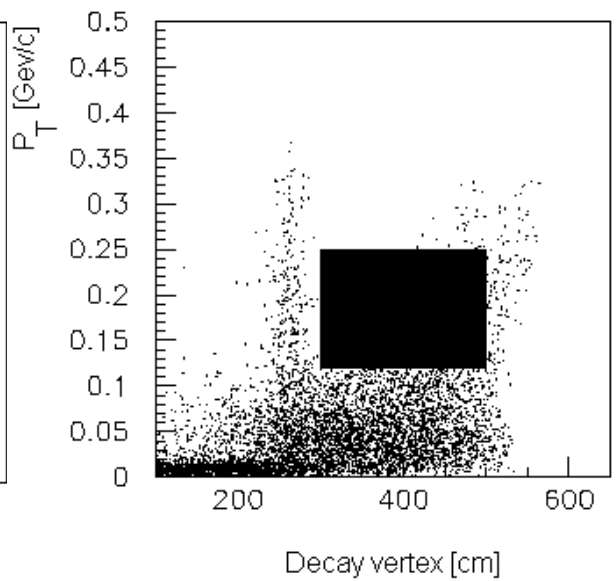
Signal box

- P_T vs. Z (decay vertex)
  - 120MeV/c <P_T< 250MeV/c
  - 300cm <Z< 500 cm

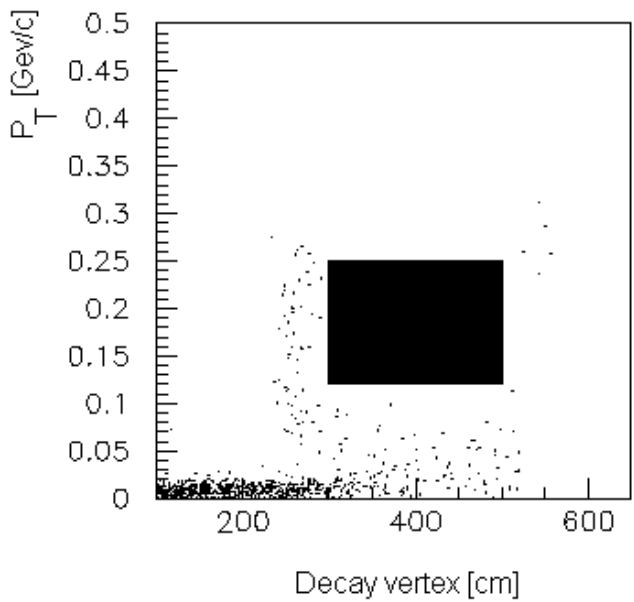
Raw data



After kinematical cuts

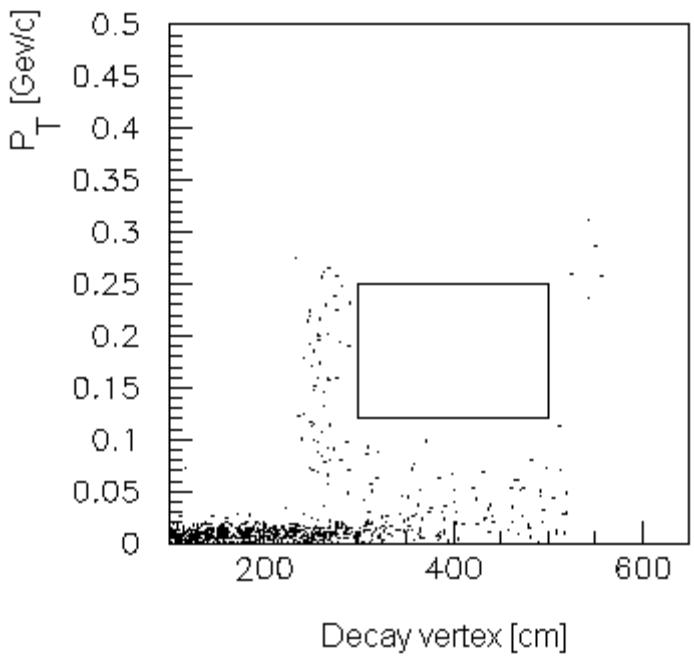


Add veto cuts



Signal box

- No events inside
- Events around signal box:
  - π^0 production @ CC02
  - K$\gamma\gamma$ decays
  - Core neutron events are suppressed by kinematical cuts



Acceptance for $K\pi^0\nu\nu$

- Use $K\pi^0\nu\nu$ MC for kinematical cuts
- Use pure signal samples for lose due to veto
- Decay probability is included

Cuts	Acceptance
Decay + geometry + skimming	5.49×10^{-3}
E gamma >200MeV	3.55×10^{-3}
Distance γ–γ >50 cm	2.77×10^{-3}
$0.92< \frac{E_1+E_2+E_3}{E_{cluster}} <0.98$	1.71×10^{-3}
$0.6< E_{max}/E_{cluster} <0.92$	9.46×10^{-4}
Energy balance < 0.5	7.56×10^{-4}
signal box: 300 < Z < 500 cm + $0.12< P_T < 0.25$ GeV/c	3.20×10^{-4}
Veto	1.21×10^{-4}

$K\pi^0\nu\nu$ branching ratio

- Acc $= (1.21 \pm 0.03) x 10^{-4}$ (decay probability included)
- Normalized on a K3π:

$$BR(Kpnn) < BR(K3p)\frac{N(Kpnn)}{N(K3p)}\frac{Acc(K3p)}{Acc(Kpnn)} =$$

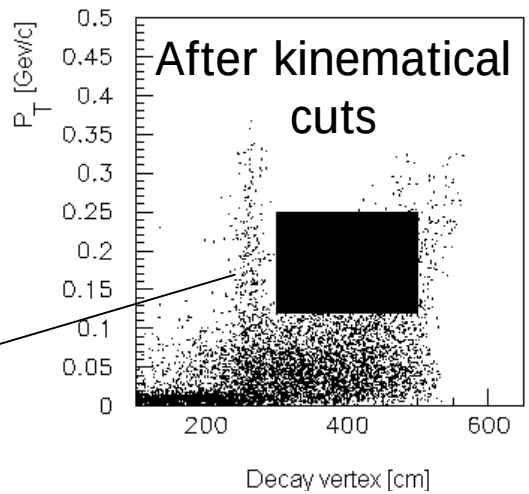
$$= 0.2113\frac{1}{29669}\frac{1.41x10^{-5}}{1.21x10^{-4}} = (8.3 \pm 0.2)x10^{-7}$$

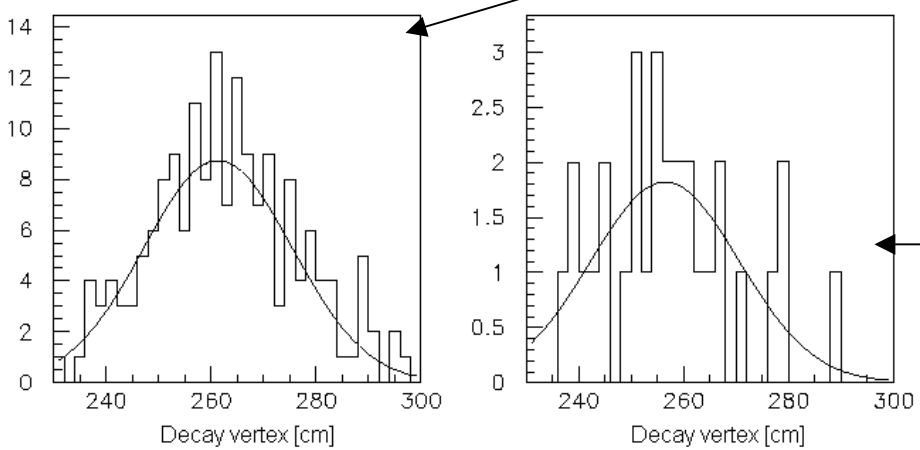
$$= (1.91 \pm 0.05)x10^{-6}(90\%CL)$$

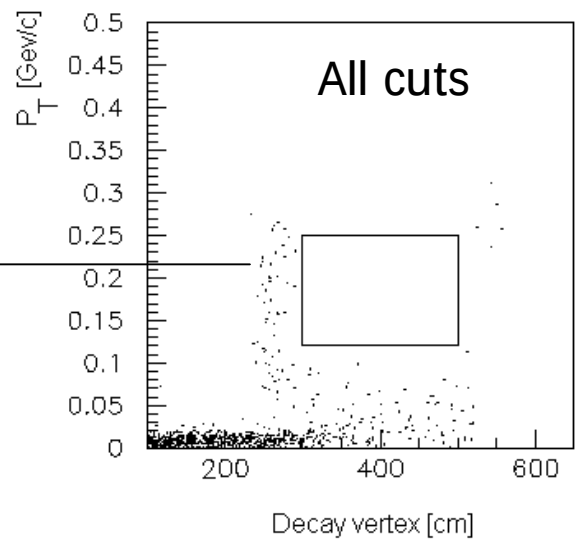
- KTeV results BR < 5.9×10^{-7} (90%CL)

Background estimation in signal box

- π^0 production @ CC02
  - ~0.03 events
- KL decays
  - <0.1 from K2p decay
- Core neutron events are suppressed by kinematical cuts
  - Negligible small







Conclusions (1)

- E391 experiment successfully run (15.Feb-1July) for data taken
  - Test method
  - Study backgrounds
- Collect 6 TB physics data (~57 days)
  - Stable data taken during long period
  - Various physics data
- Calibration of CsI calorimeter
  - Cosmic and punch through muons calibrations are well consistent
  - π^0 production on a target shows 7% shift
    - Shower leakage
    - Muon momentum spectrum
  - Timing calibration by cosmic
    - Improve gamma timing resolution
    - Trim cables to trigger logic

Conclusions (2)

- Pure signal and background samples of K3π,K2π,Kγγ
  - Background structure
    - Time window for veto
    - Found the events induced by neutron in MBR
      - Exist in Kgg bgr. sample and not exist in K2p bgr. sample
  - Acceptance loss is well consistent among pure signal samples
  - Normalization
    - Pure signal samples are well consistent

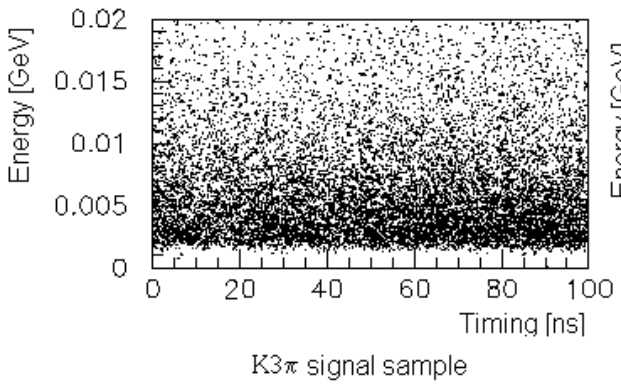
- Background sources for 2γ events
  - Beam core neutrons hit some part of membrane, which was found to be dropped
  - Halo neutrons produce the π^0 on CC02
  - Fusion for neutral decay backgrounds is dominated

- No events in signal box
  - Acceptance = $(1.21 \pm 0.03) x 10^{-4}$ (decay probability included)
  - BR(K$\pi^0\nu\nu$)< $(1.91 \pm 0.05) x 10^{-6} (90\% CL)$
  - Full statistics ~ 57 days

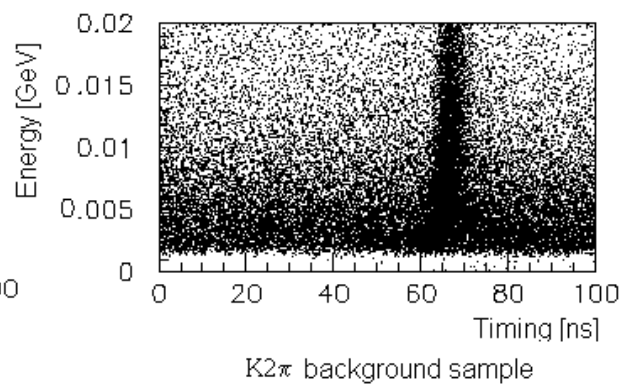
Conclusions (3)

- Small acceptance
  - 1.21×10^{-4} = 0.5% x 2.4%(decay prob.) vs. 8% as proposed
  - Improvement
    - More effective γ/n cluster separation cuts
    - How to distinguish fusion clusters?
    - Clusters near border of CsI calorimeter
    - More careful treatment of veto
- Background limit
  - 0.03 events from π^0 produced @CC02
    - Factor ~33 vs. our full data sample factor ~60
    - Improvement of the decay vertex resolution
    - Reduce the veto threshold for CC02
- This work is a first step of the analysis of E391a data
  - One day run
  - More statistics for background study is needed
  - MC is needed to be more tuned
  - Quick analysis was important for RUN II preparation (Jun.2005)

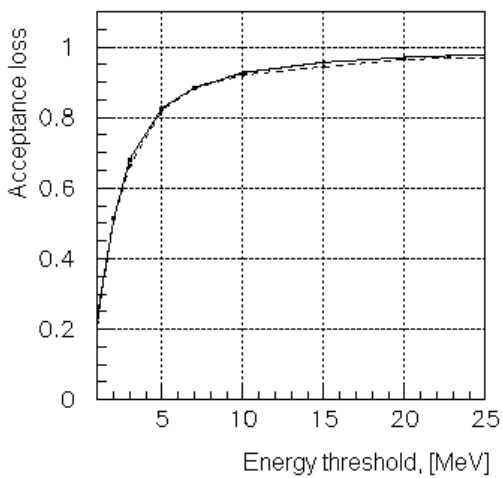
Veto study: CC07

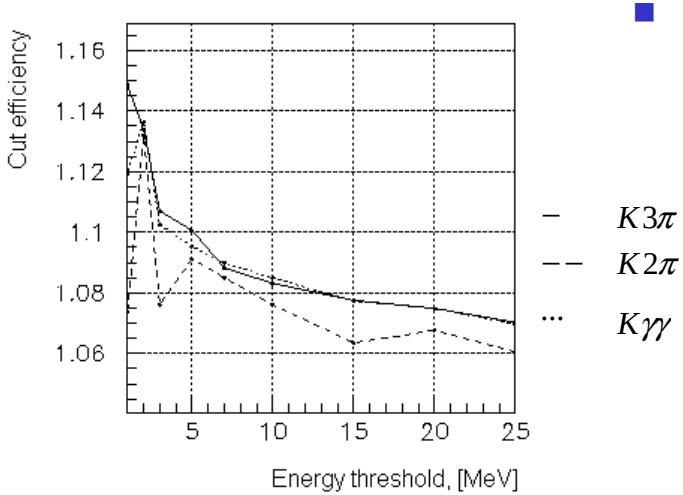


K3π signal sample



K2π background sample





- Installed just before BA
- Greatly suffered by accidental and backsplash from BA
- Set time window of 3 sigma for veto
- Set energy threshold @ 10MeV
  - Acceptance lose ~ 10%