New Result from E391a on the search for the decay $K_L \to \pi^0 \nu \bar{\nu}$

Toshi SUMIDA
(Kyoto University)

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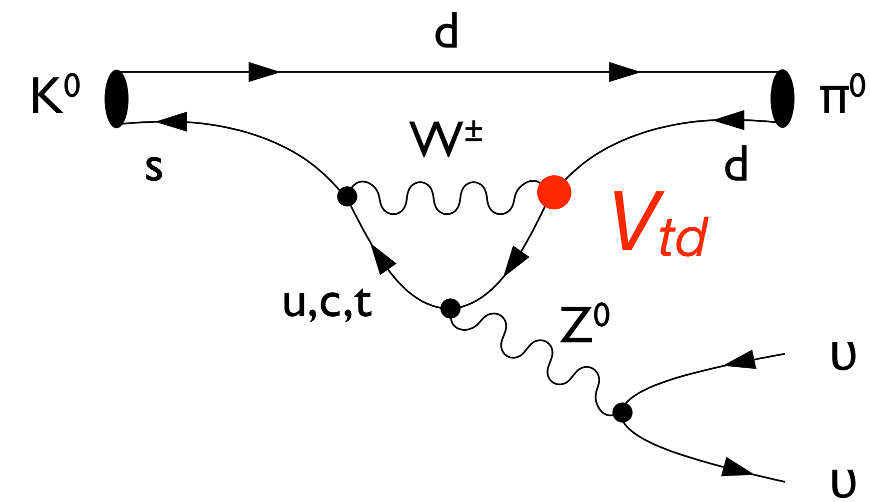
Outline

- Introduction
  - Theoretical motivation
  - $K_L \to \pi^0 \nu \bar{\nu}$ experiments
- The E391a experiment
  - Method
  - Detector
  - Data analysis
    - K_L flux
    - Backgrounds
    - Results

The $K_L \to \pi^0 \nu \bar{\nu}$ decay

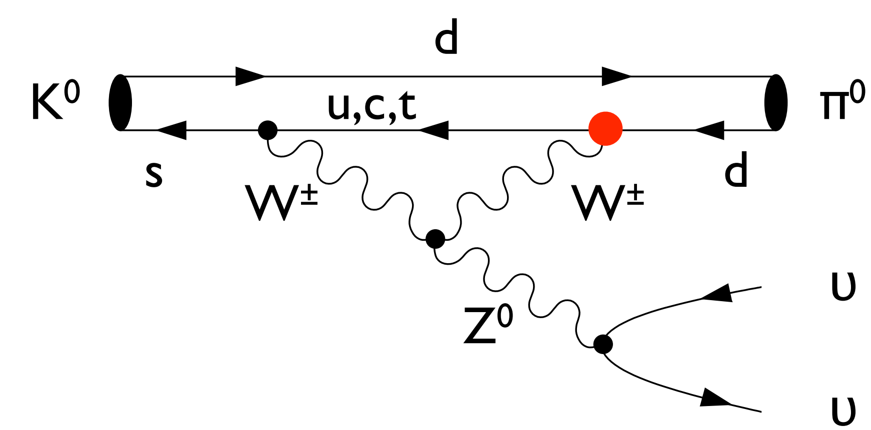
- "Direct" CP violation process



- Measurement of the parameter η in CKM

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

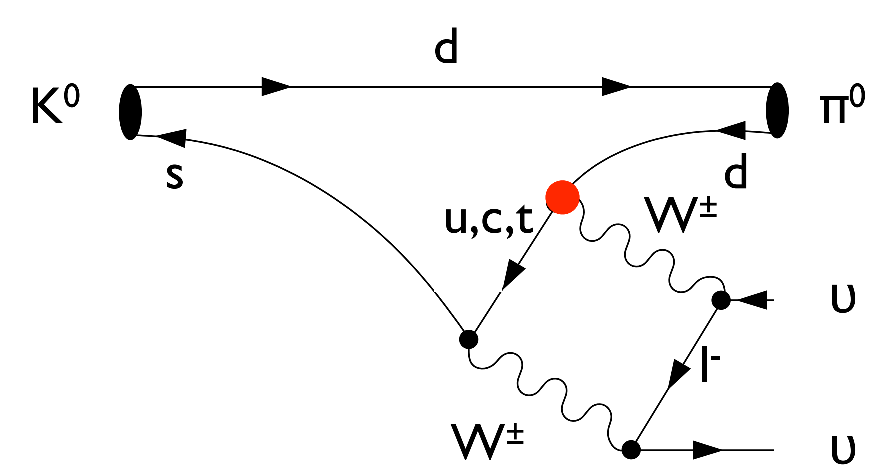
$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



- Amplitude
  - $A(K_L \to \pi^0 \nu \bar{\nu}) \propto A(K^0 \to \pi^0 \nu \bar{\nu}) - A(\bar{K}^0 \to \pi^0 \nu \bar{\nu})$

    $\propto V_{td}{}^* V_{ts} - V_{ts}{}^* V_{td}$

    $= 2 \times V_{ts} \times \mathrm{Im}(V_{td}) \propto \eta$



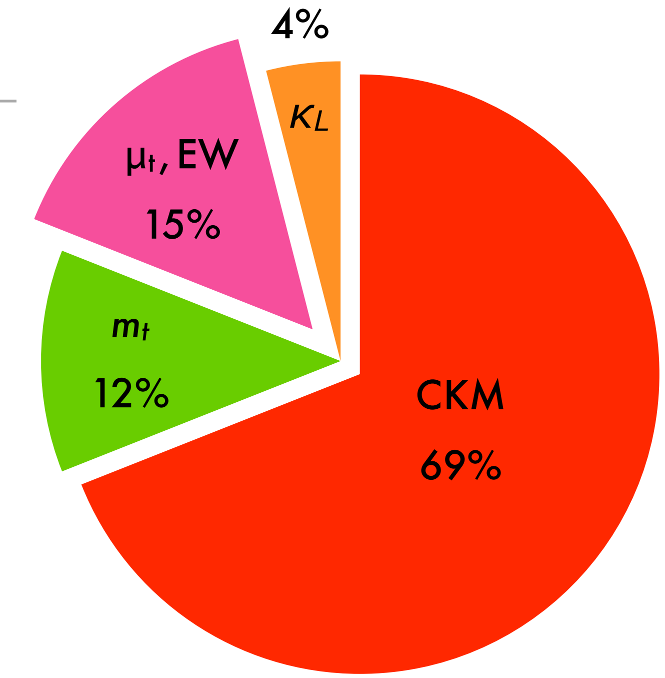
SM prediction of $K_L \to \pi^0 \nu \bar{\nu}$

- $Br(K_L \to \pi^0 \nu\bar{\nu})_{SM} = \kappa_L \left[\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X \right]^2$

  $= (2.49 \pm 0.39) \times 10^{-11}$

  (F. Mescia and C. Smith, PRD76, 074017(2007))

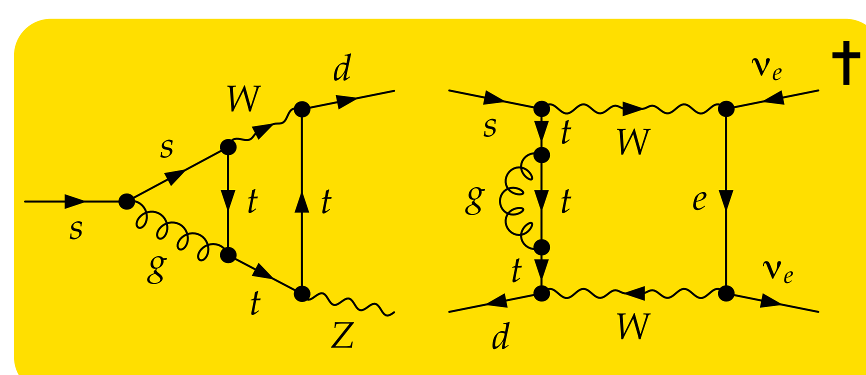
U. Haisch, KAON'07
(arXiv:0707.3098)

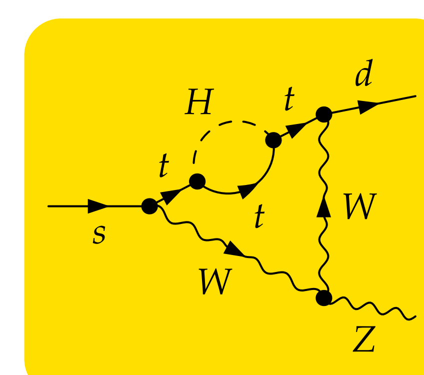


- Theoretical uncertainty: 1-2%
  - ✓ dominated by NNLO QCD & EW
  - "Golden mode"
  - An exceptional tool to
    - check SM
    - discover New Physics

$$\kappa_L = (2.229 \pm 0.017) \times 10^{-10} \left(\frac{\lambda}{0.225} \right)^8 \quad *$$

$$X = 1.456 \pm 0.017_{m_t} \pm 0.013_{\mu_t} \overset{?}{\pm} 0.015_{\mathrm{EW}} \quad ‡$$



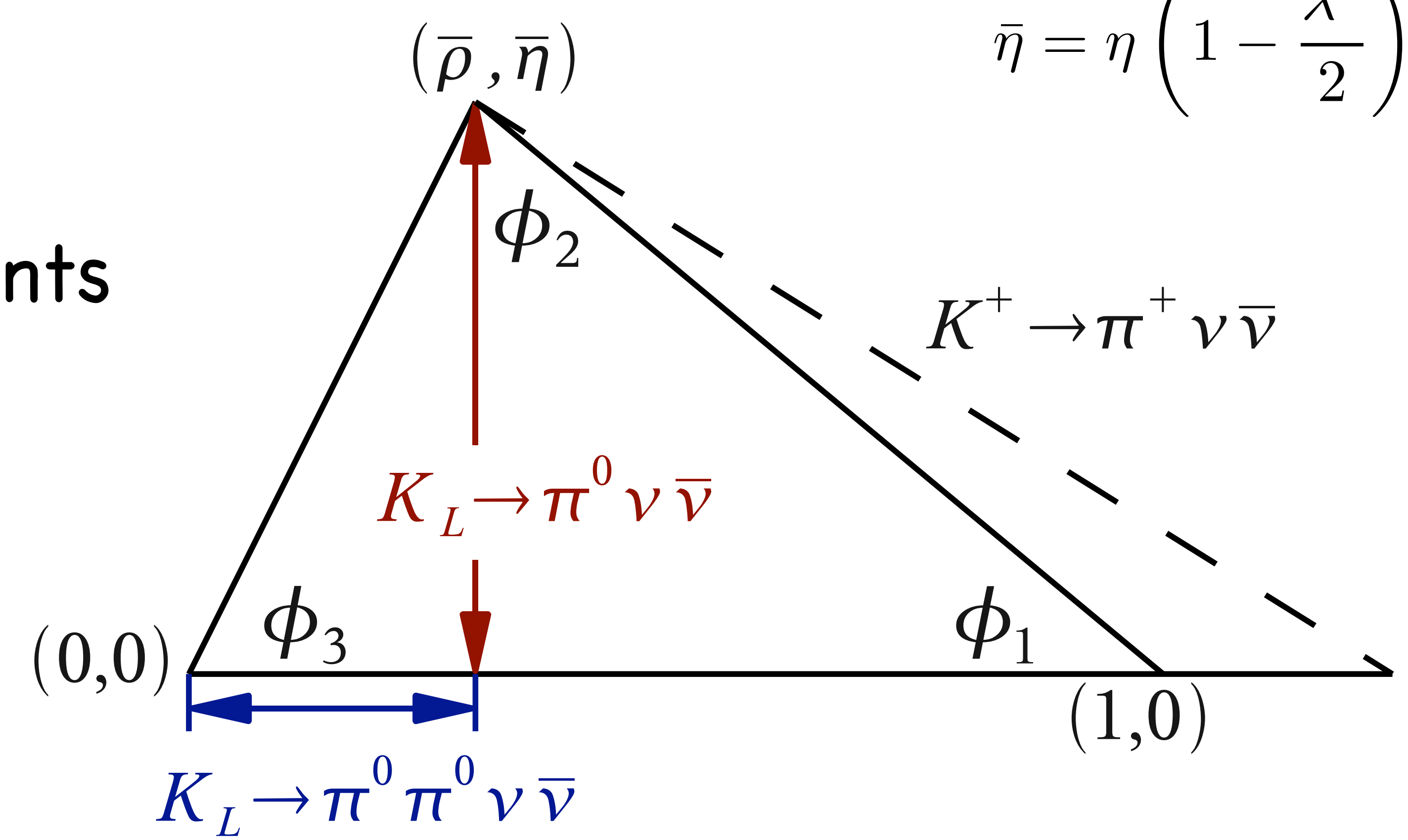


$K \to \pi\nu\bar{\nu}$ decays on the ρ-η plane

- Kaon Decays on the Unitary Triangle
  - $Br(K_L \to \pi^0 \nu\bar{\nu}) \propto \eta^2$
  - $Br(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{td}|^2$

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right)$$

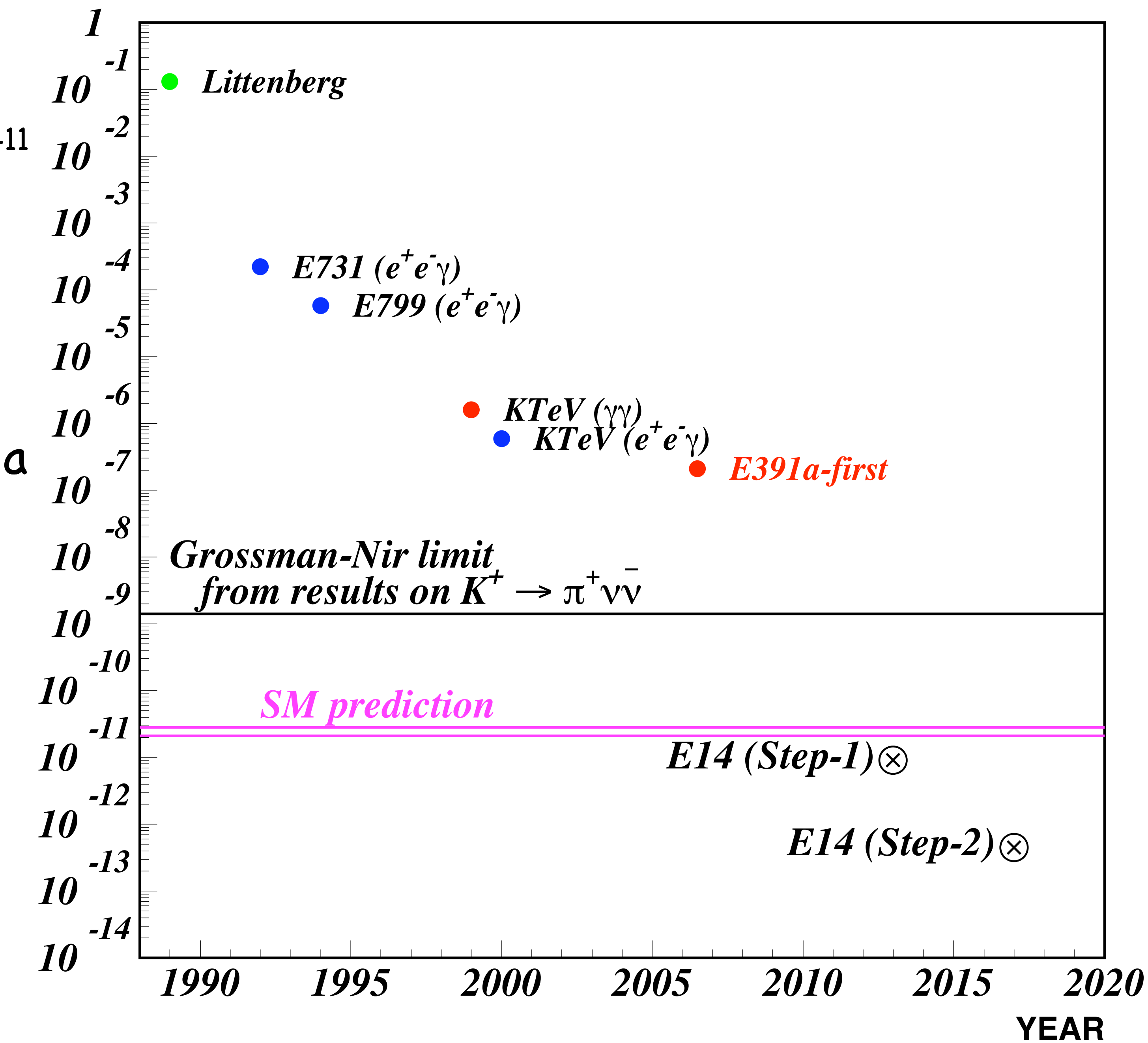
$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right)$$



- Comparison to the measurements in the B-meson experiments
  - to check
    - consistency within SM
    - flavor coupling of NP

$K_L \to \pi^0 \nu \bar{\nu}$ experiments

- Challenging Task
  - $Br(K_L \to \pi^0 \nu \bar{\nu})_{SM} = (2.49 \pm 0.39) \times 10^{-11}$
- History of upper limit
  - L.S. Littenberg
  - FNAL: $2.2 \times 10^{-4} \to 5.9 \times 10^{-7}$
  - KEK: 2.1×10^{-7} (@90%C.L.) by E391a
    - $\pi^0 \to e^+ e^- \gamma$
      - $Br(\pi^0 \to e^+ e^- \gamma) \sim 1\%$
      - decay vertex by tracking
    - $\pi^0 \to \gamma\gamma$
      - no kinematical constraint
      - $Br(\pi^0 \to \gamma\gamma) \sim 99\%$



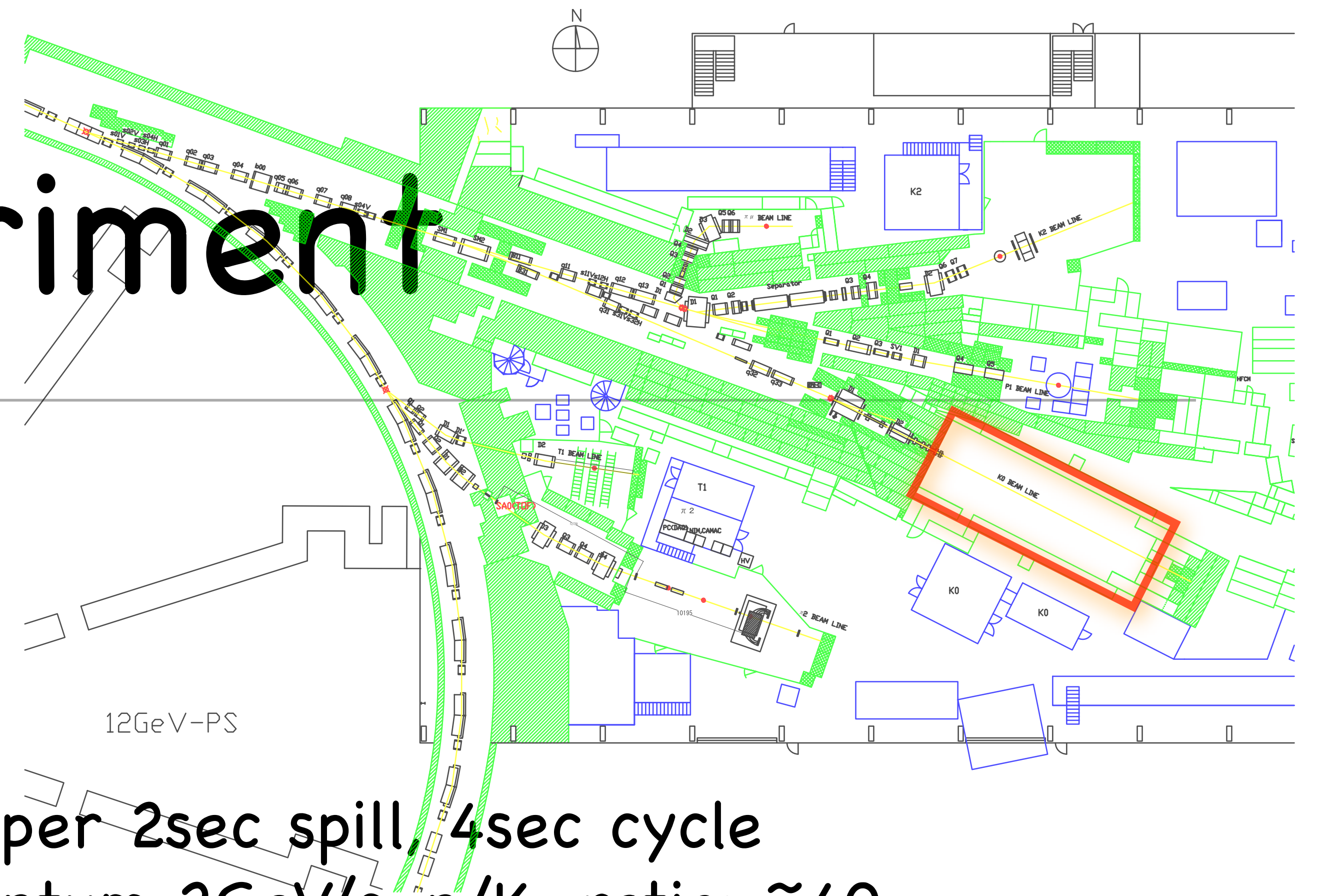
The E391a experiment

The E391a collaboration

- 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

The E391a experiment

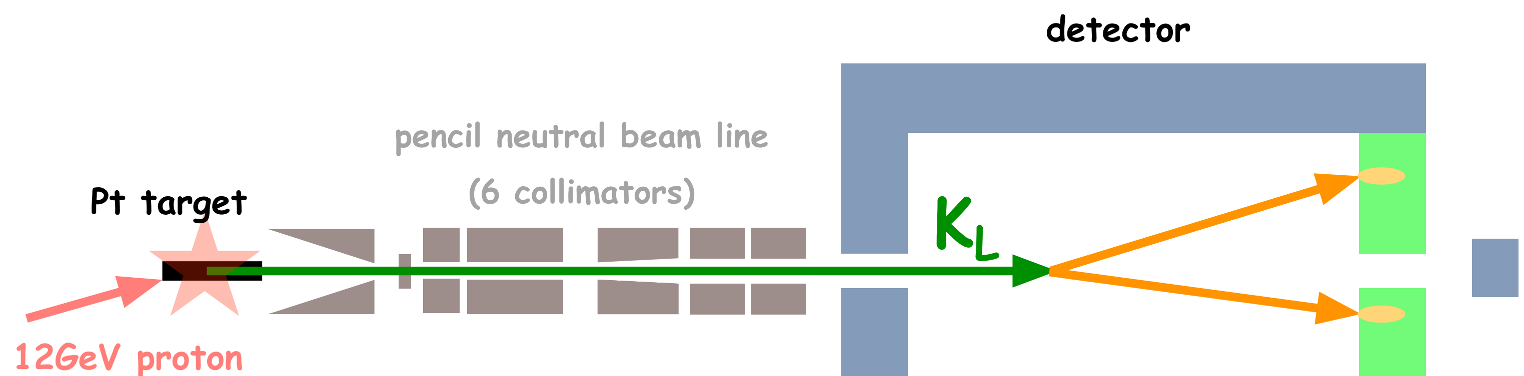


- K_L production with KEK 12GeV PS
  - Slow extraction
  - K0 beamline in the East Counter Hall
    - Intensity
      - 2×10^{12} protons on target (POT) per 2sec spill, 4sec cycle
    - production angle: 4°, K_L peak momentum 2GeV/c, n/K_L ratio: ~40

- Physics runs
  - Run I: February to July of 2004
    - "Express" analysis with 10% data published in PRD (2006)
  - Run II: February to April of 2005
    - Full data analysis
      - Integrated protons: 1.4×10^{18} POT
        - ✓ ~ 32 days without break
  - Run III: October - December of 2005
    - Calibration ready, MC development in progress

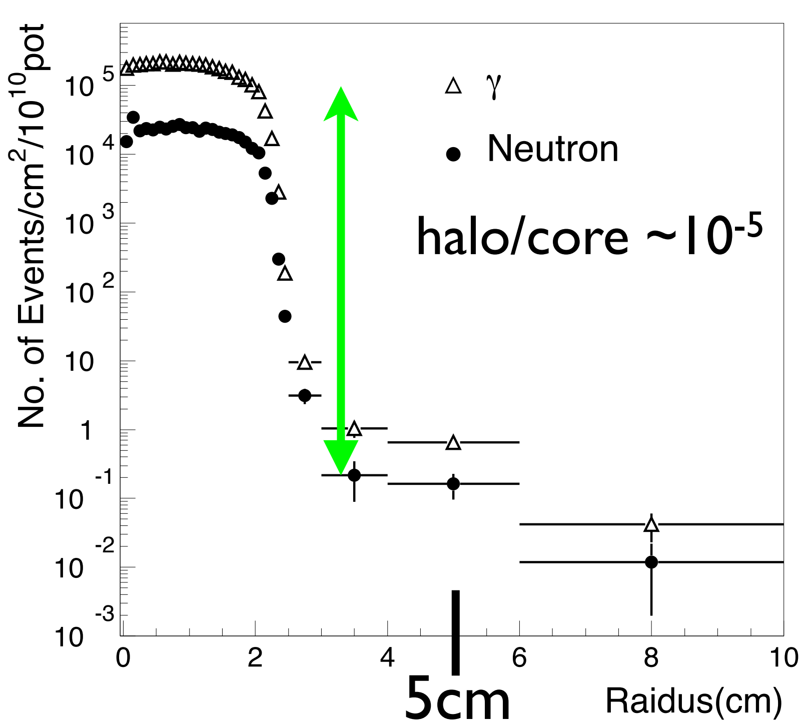
Principle of the experiment

1. require 2 photons
   - Hermetic veto system

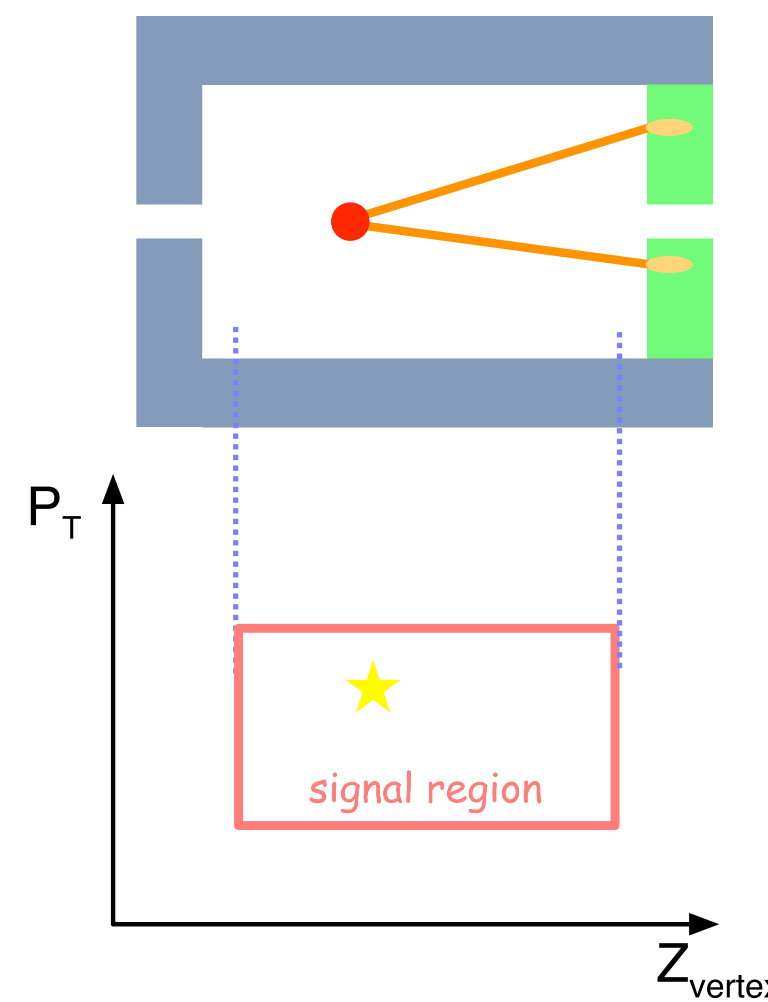


2. measure the photon energies and positions

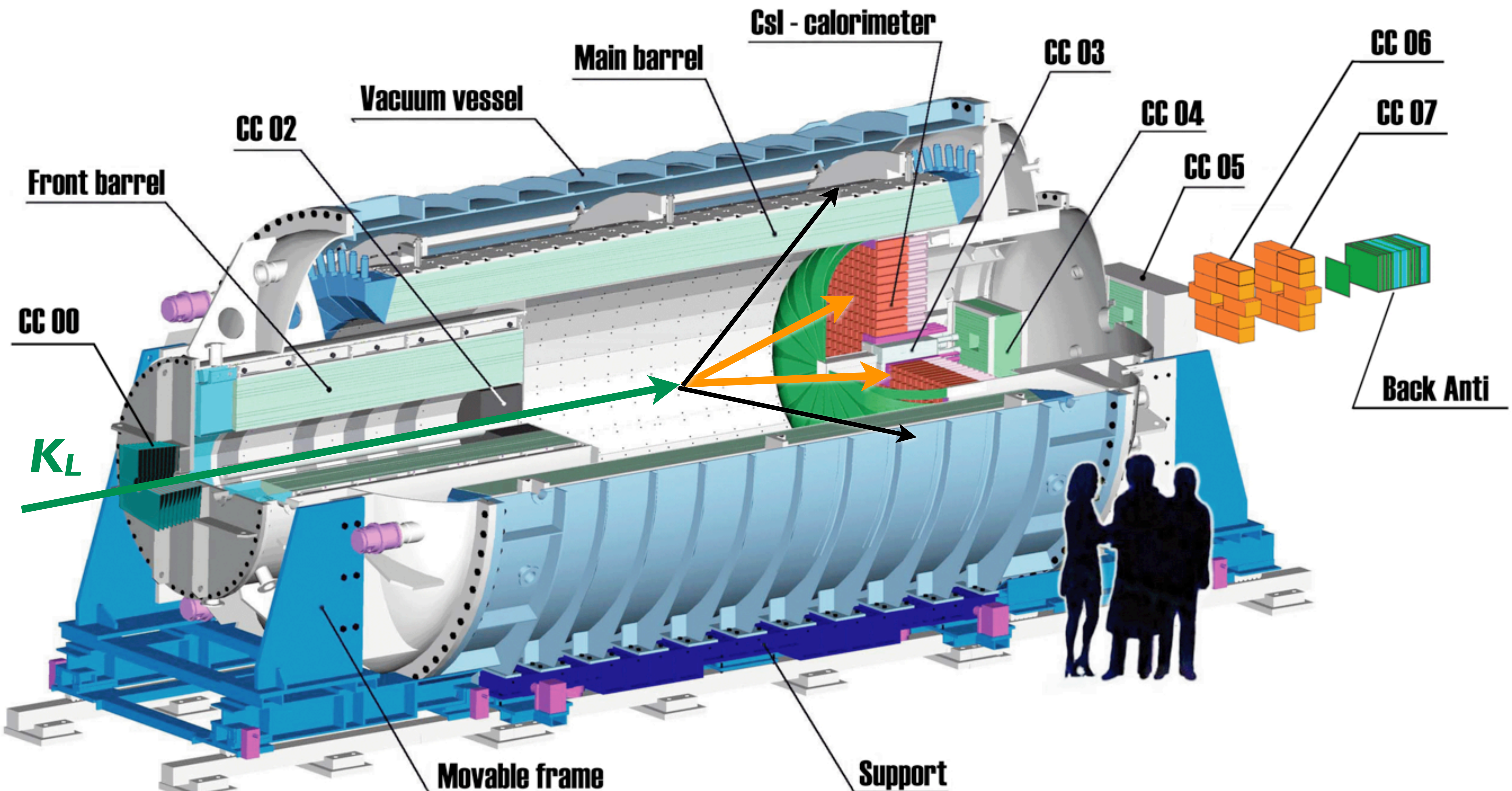
3. reconstruct the decay vertex
   on the beamline assuming $M_{2\gamma} = M_{\pi 0}$



4. require missing P_T and the vertex in the fiducial region
   - "Pencil" beam line
     to improve P_T resolution
     – 8cm diameter @ 16m
     from the target

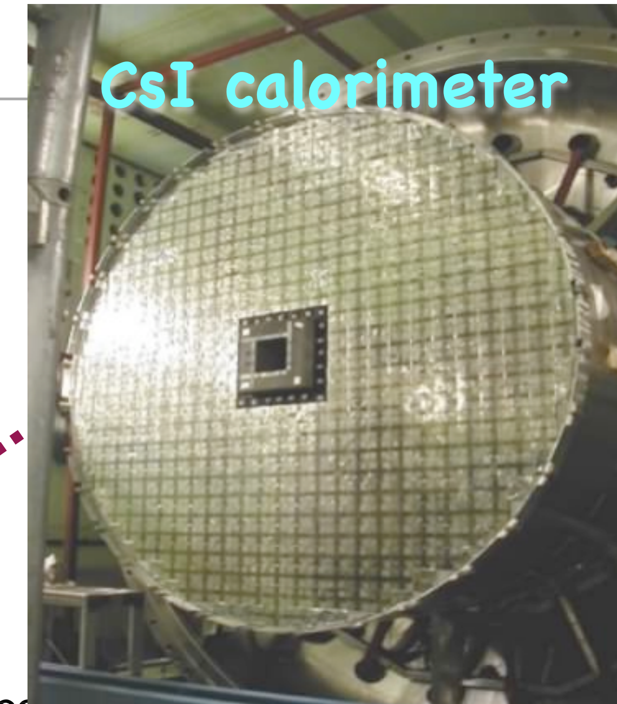


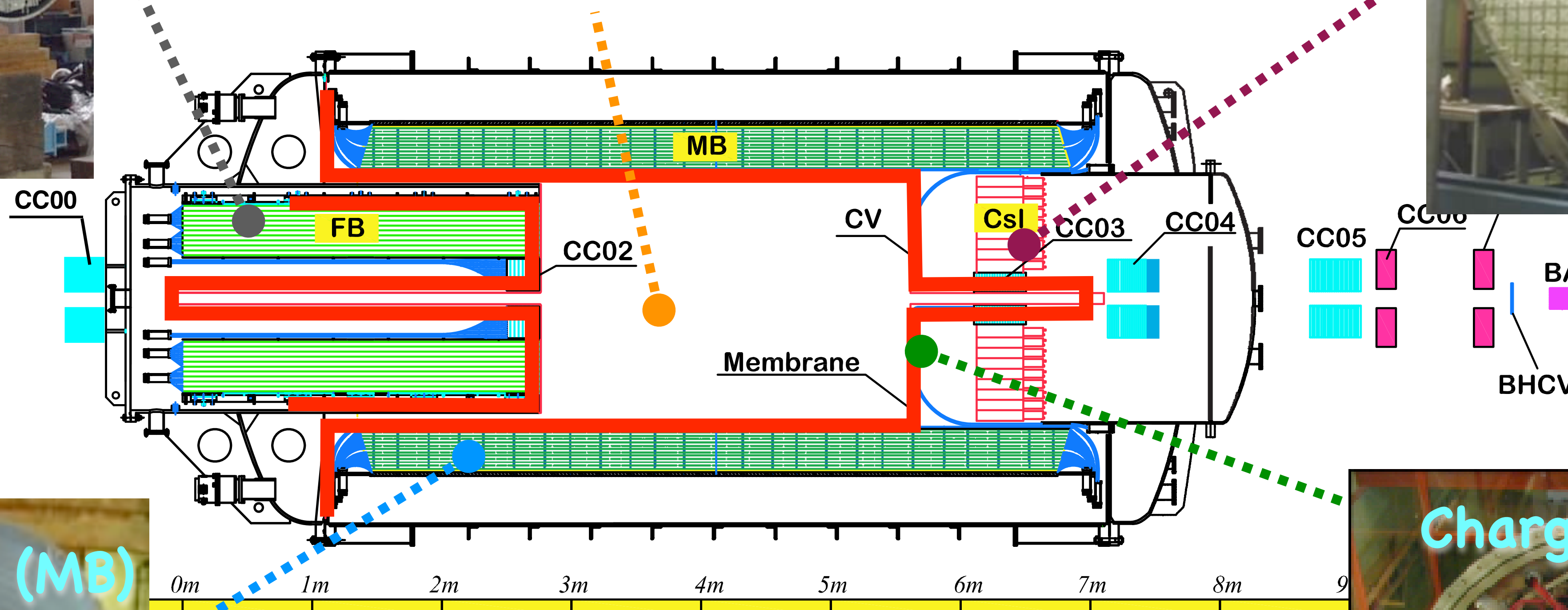
The E391a Detector

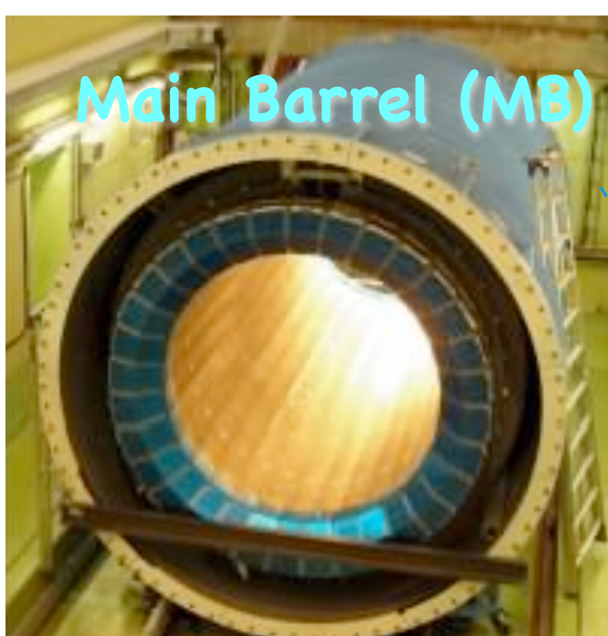


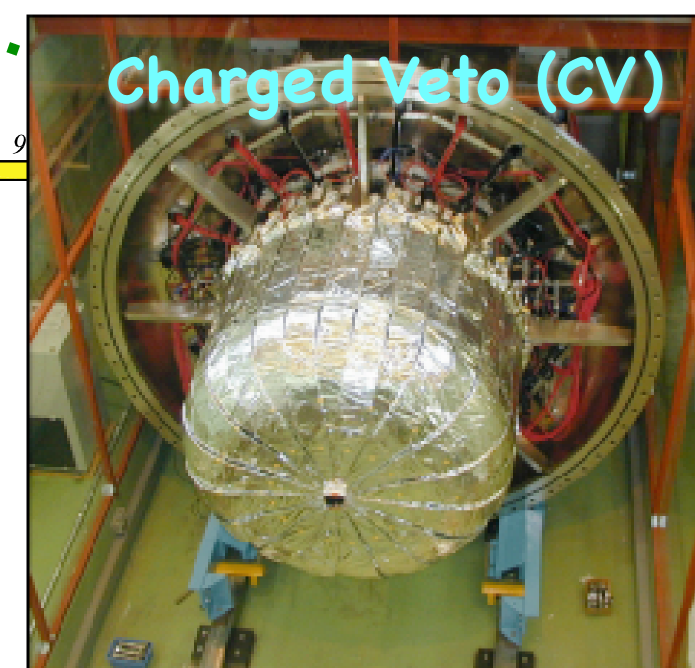
Features of E391a apparatus

- Decay region
  - High vacuum: 10^{-5} Pa
    - to suppress the background from interactions w/ residual gas









- Detector components
  - Set in the vacuum: 0.1 Pa
    - separating the decay region from the detector region with "membrane": 0.2mmt film

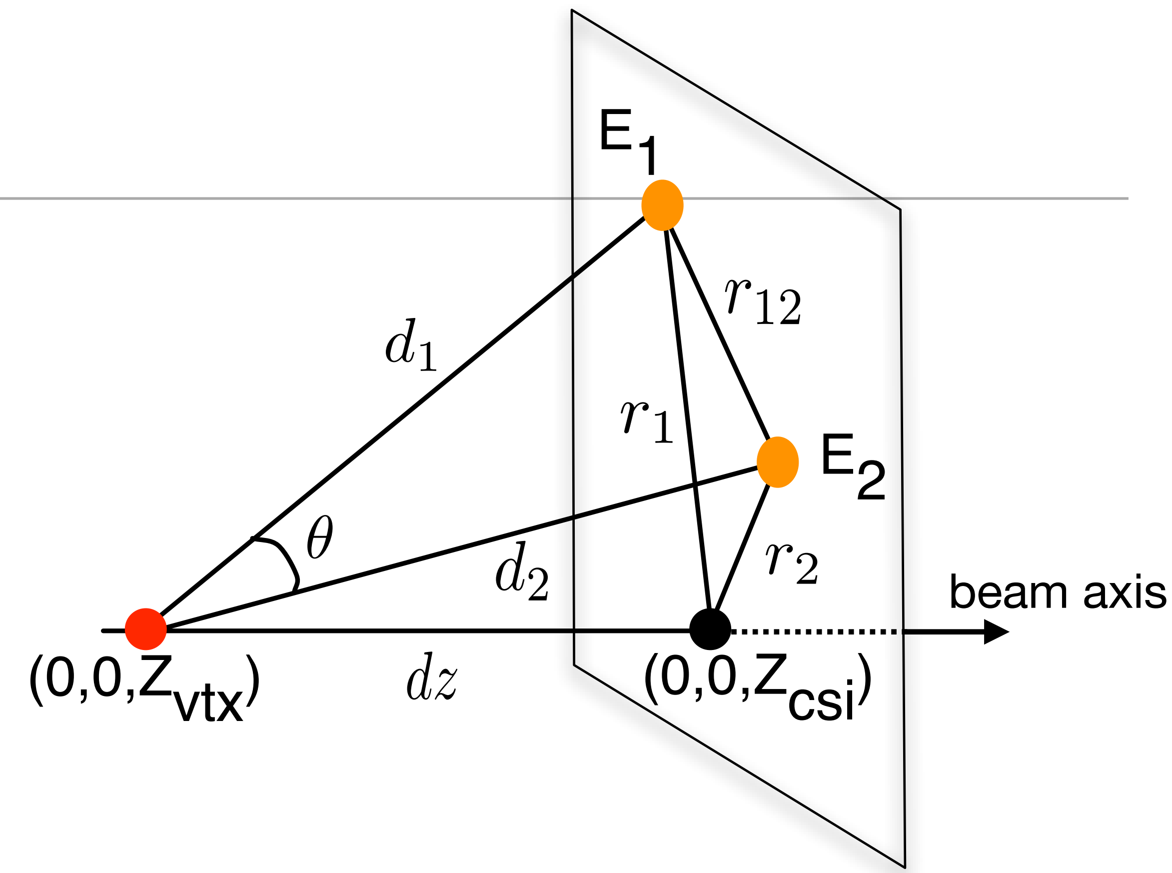
Analysis overview

- K_L flux calculation
  - Result of K_L reconstruction
    - 6γ: $K_L \to \pi^0\pi^0\pi^0$
    - 4γ: $K_L \to \pi^0\pi^0$
    - 2γ: $K_L \to \gamma\gamma$
  - Normalization by MC
  - Systematics

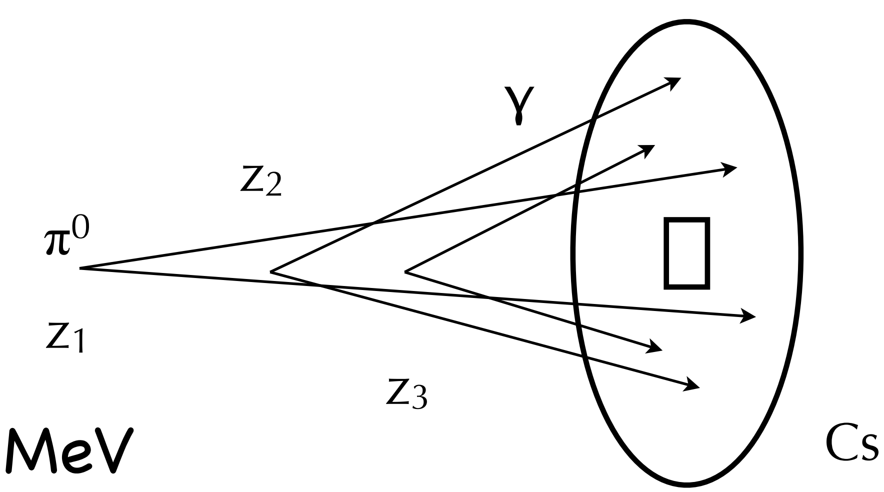
- $K_L \to \pi^0 \nu\bar{\nu}$ search
  - Backgrounds
  - Result

K_L reconstruction

- $\pi^0(K_L)$ reconstruction w/ 2 photons
  - $$\begin{aligned} cos\theta &= 1 - \frac{M_{\pi^0}^2}{2E_1E_2} \\ r_{12}^2 &= d_1^2 + d_2^2 - 2d_1d_2cos\theta \\ d_1 &= \sqrt{r_1^2 + (dz)^2} \\ d_2 &= \sqrt{r_2^2 + (dz)^2} \\ dz &\equiv Z_{csi} - Z_{vtx} \end{aligned}$$

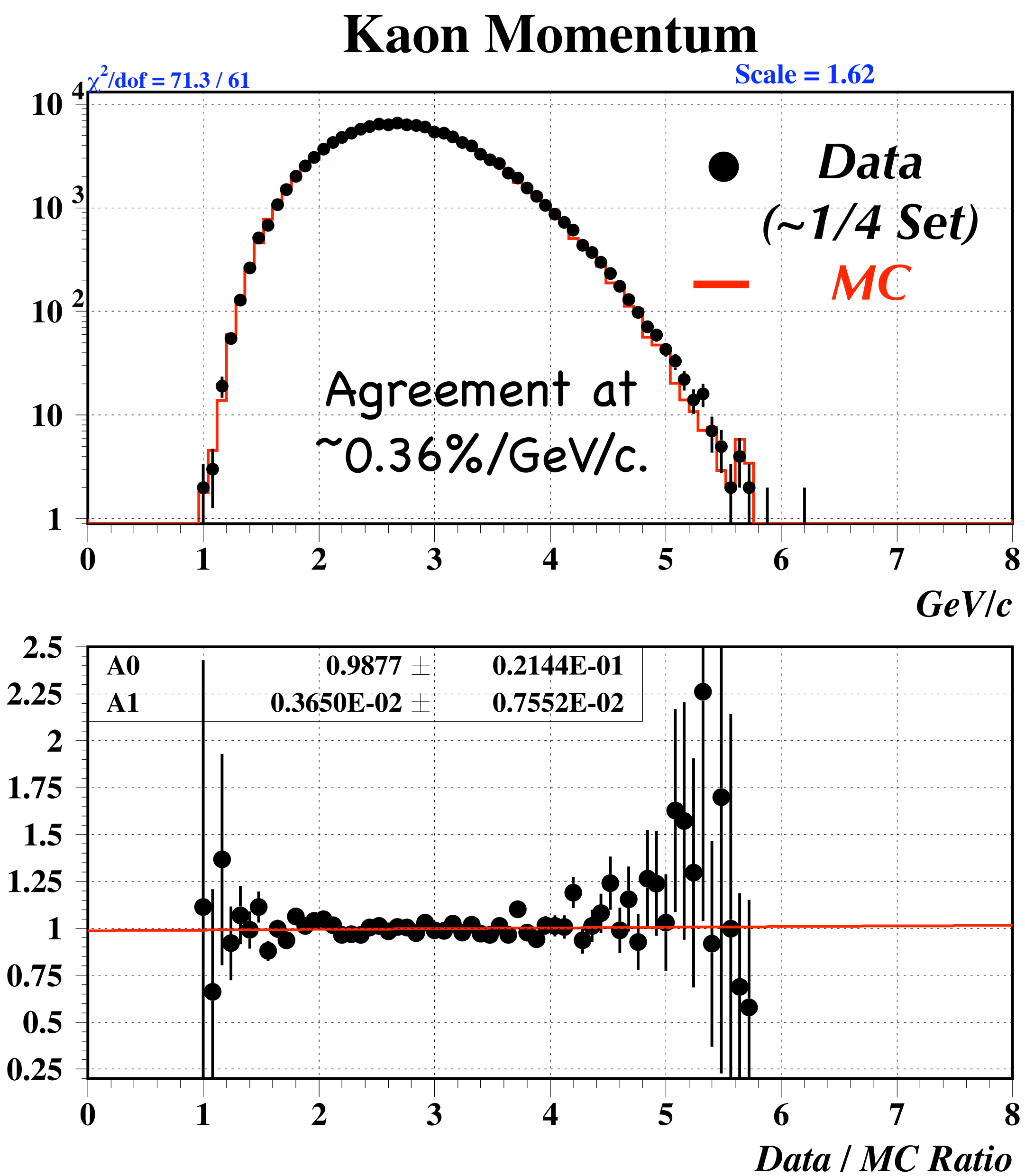


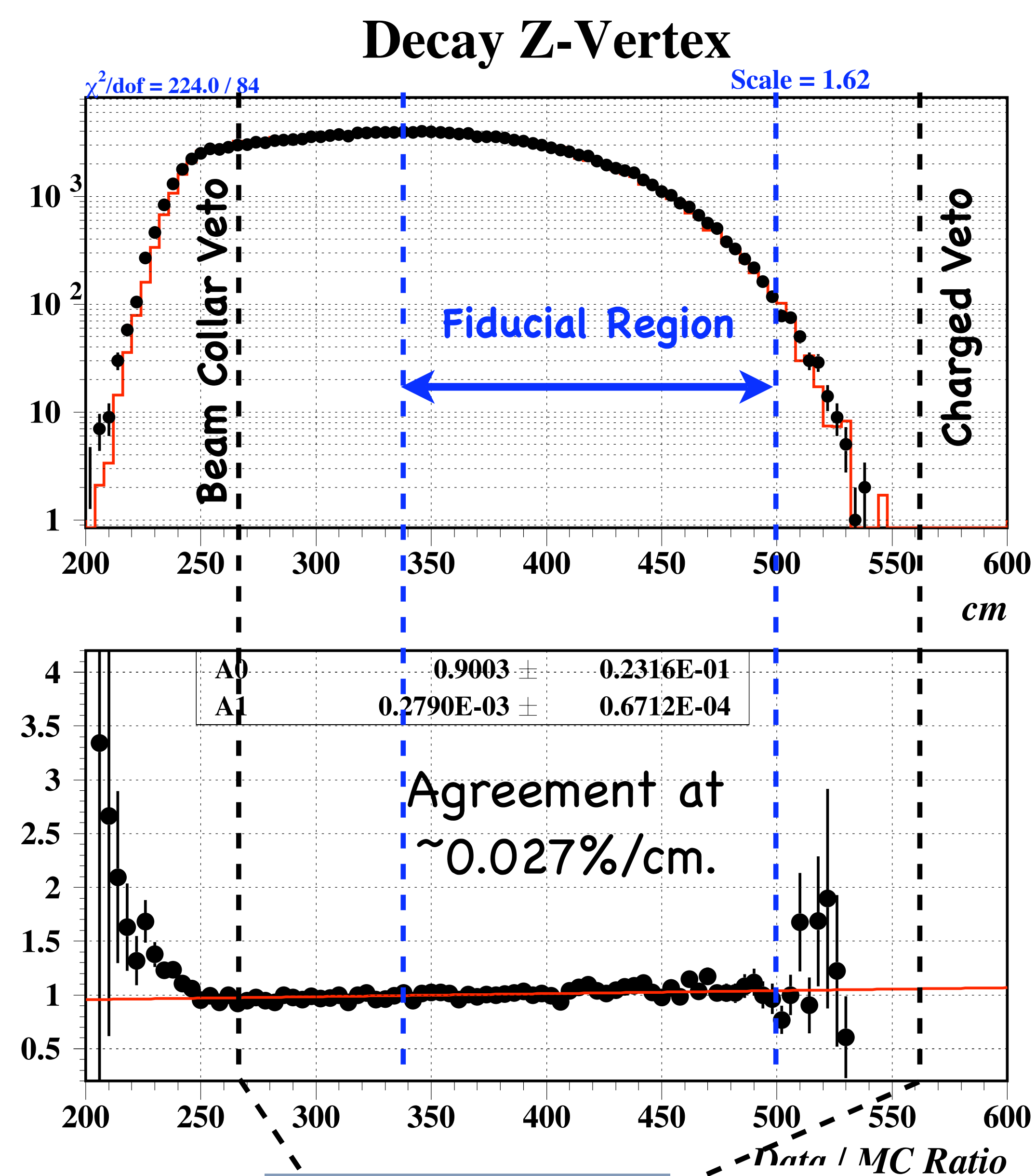
- K_L reconstruction w/ $KL \to 2\pi^0$, $3\pi^0$
  - Take the best χ2 for the vertex distribution in paring
    - $$\chi^2 = \sum_{i=1}^{3} \frac{(z_i - \bar{z})^2}{\sigma_i^2}$$
      $$\bar{z} = \frac{\sum_i z_i/\sigma_i}{\sum_i 1/\sigma_i}$$



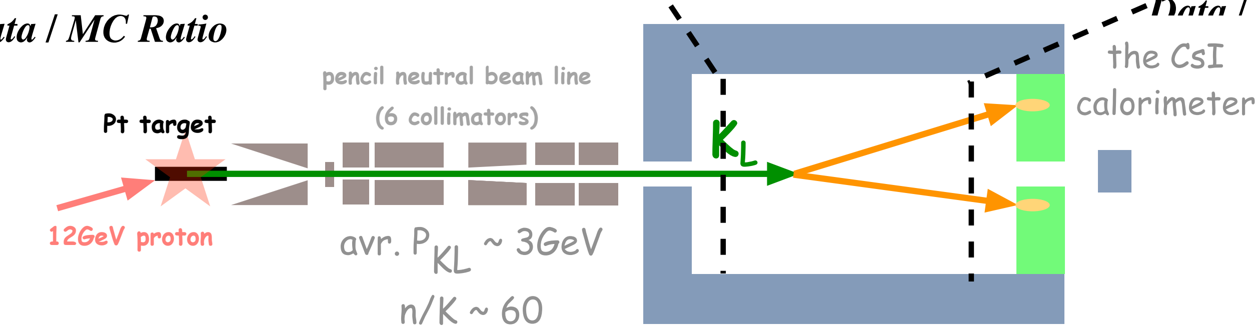
- Cuts
  - Photon Vetoes: typically O(1) MeV
  - Kinematic cuts
  - Photon quality cuts

$K_L \to \pi^0\pi^0\pi^0$

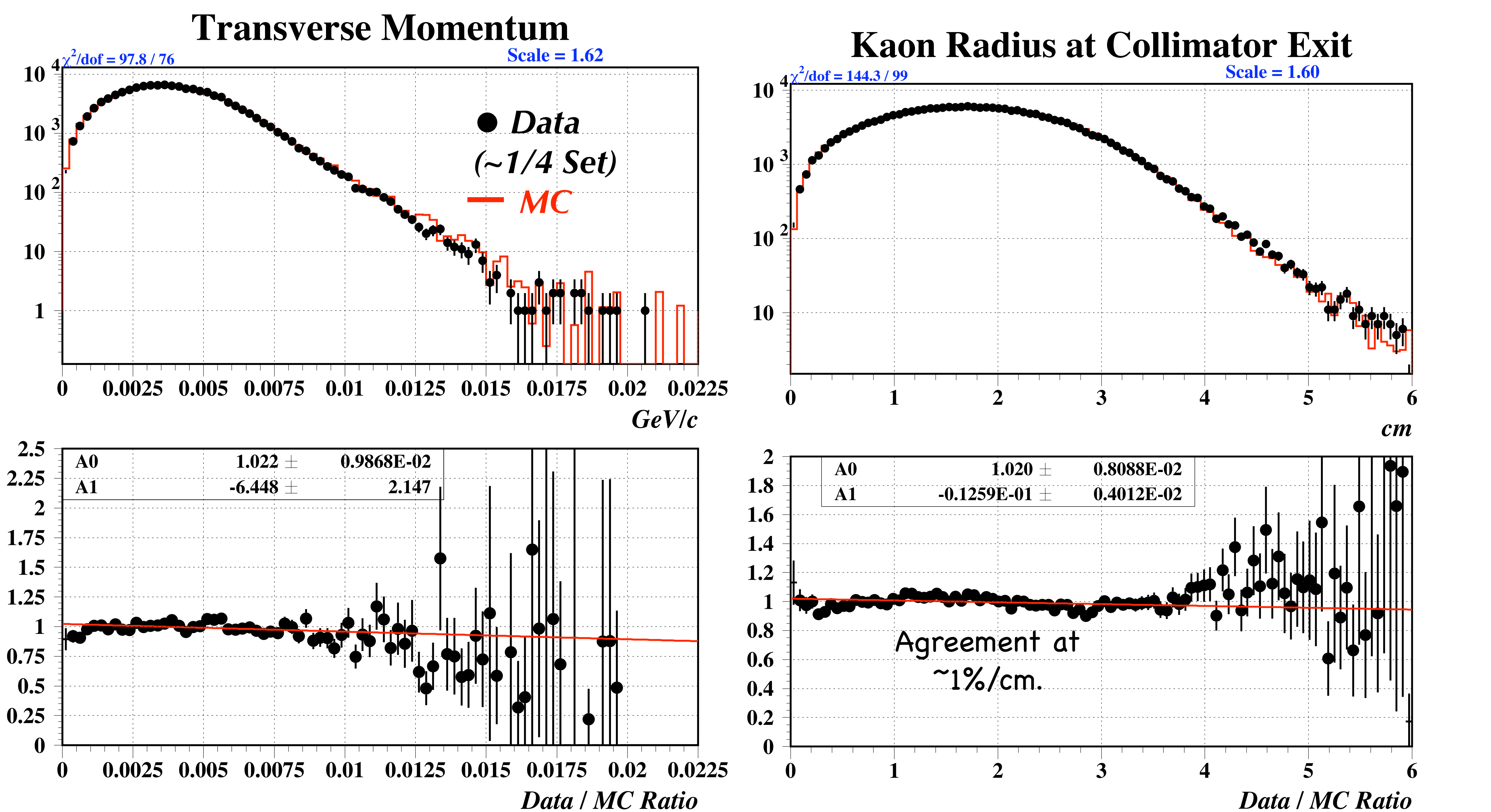




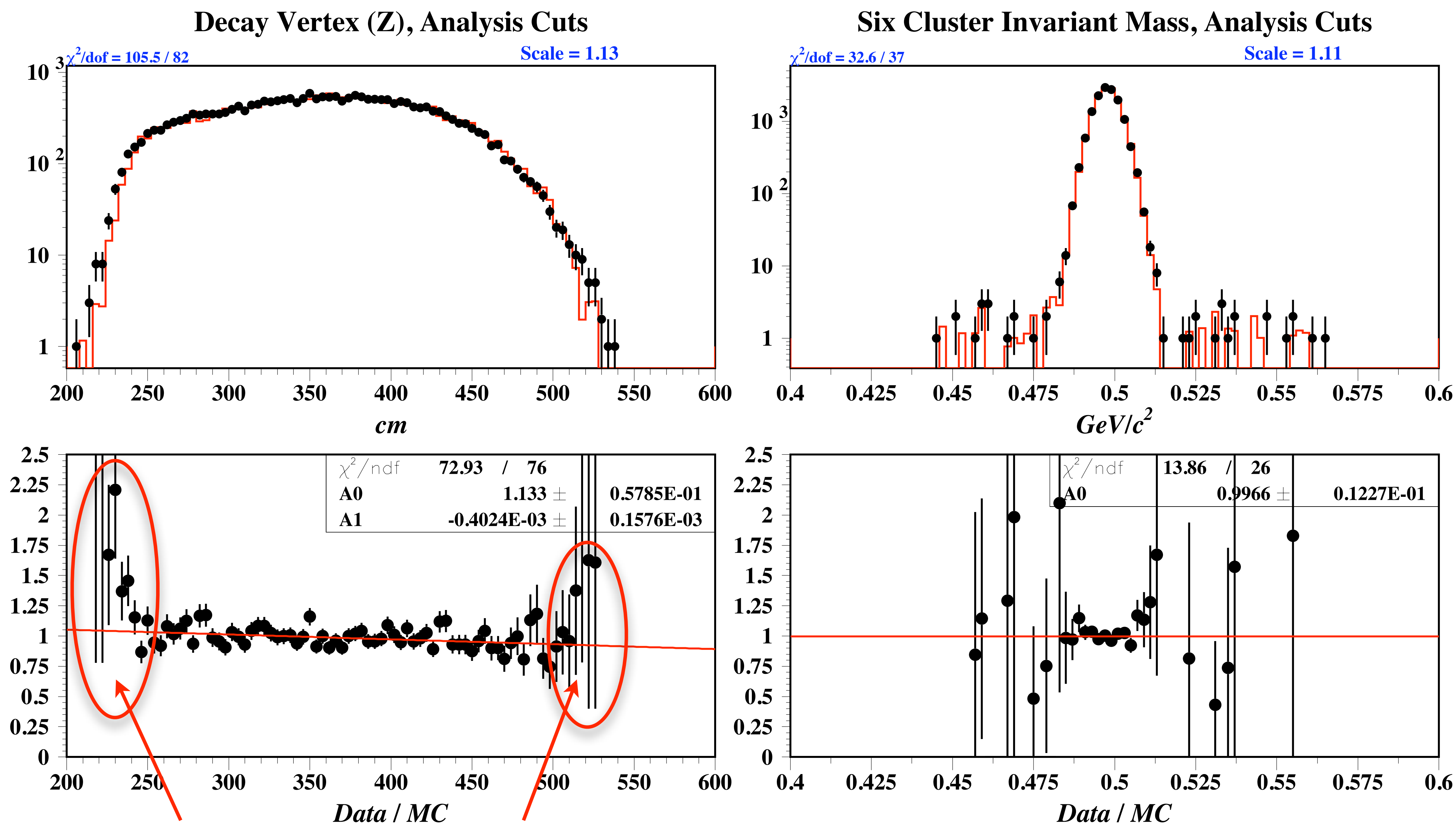
The photon vetoes are relaxed in order to boost statistics.



$K_L \to \pi^0\pi^0\pi^0$



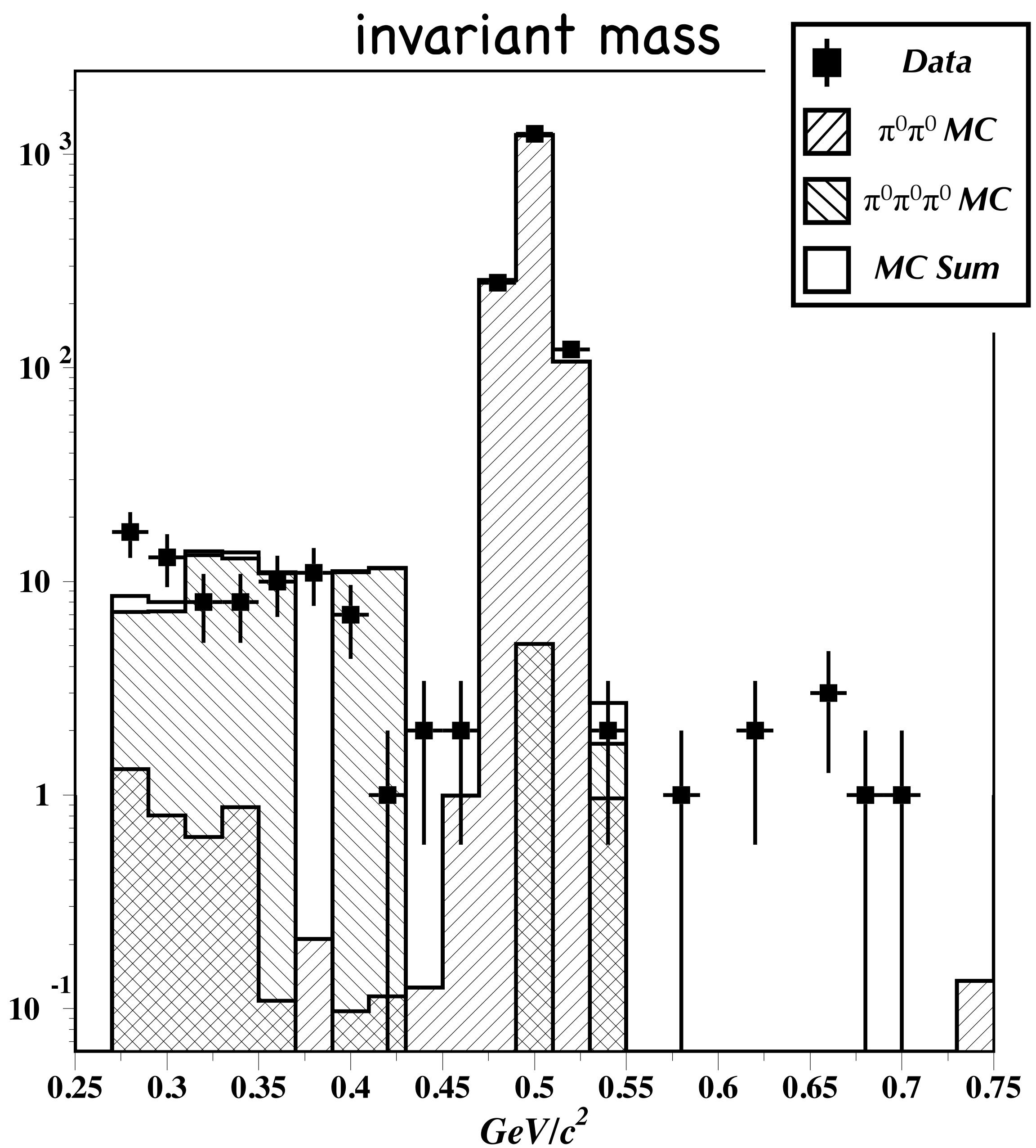
$K_L \to \pi^0\pi^0\pi^0$

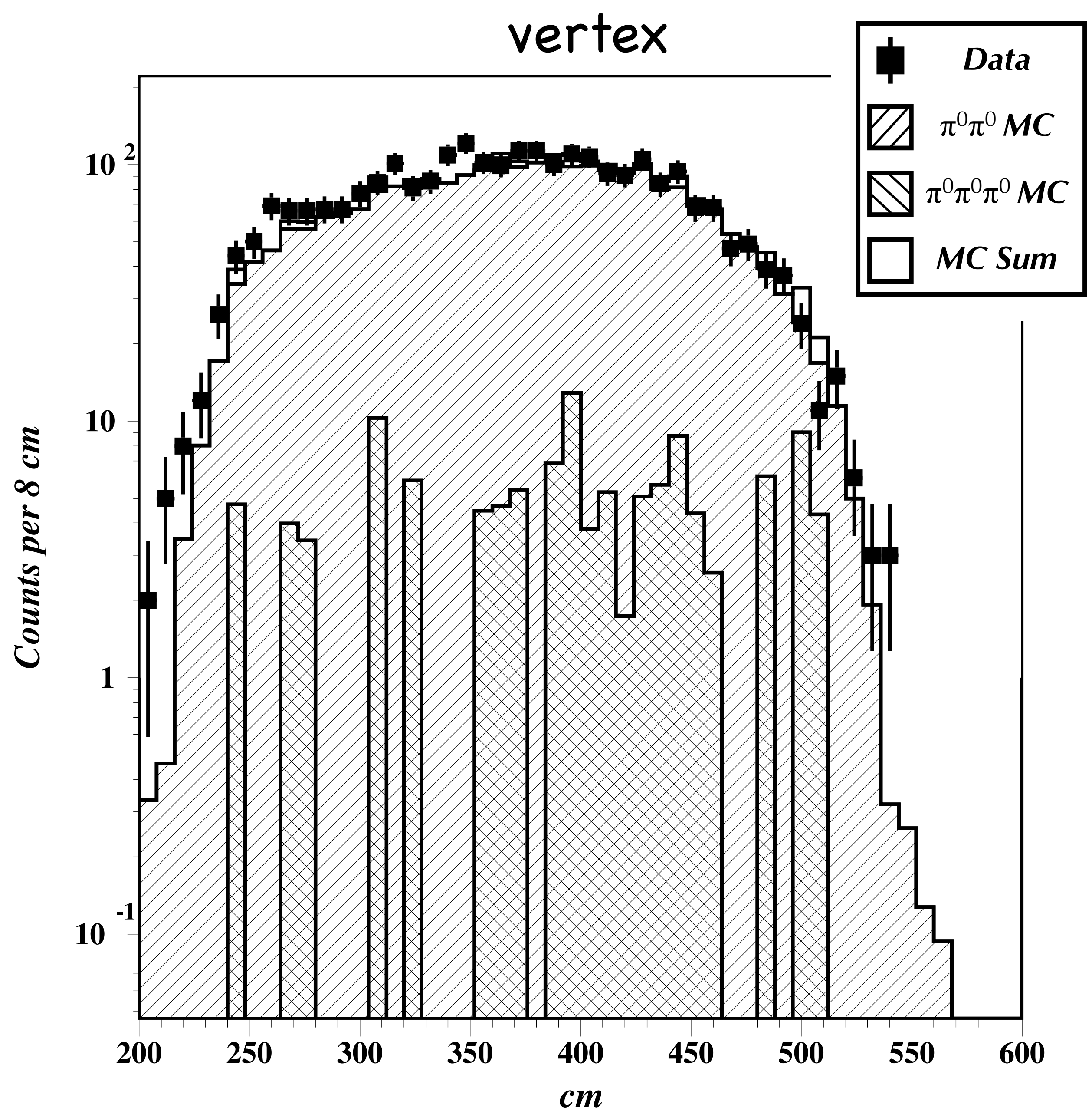


Slight MC geometry mis-matches - we have to simply eat the associated systematics.

$\sigma_{Data}/\sigma_{MC} \approx 1.01$

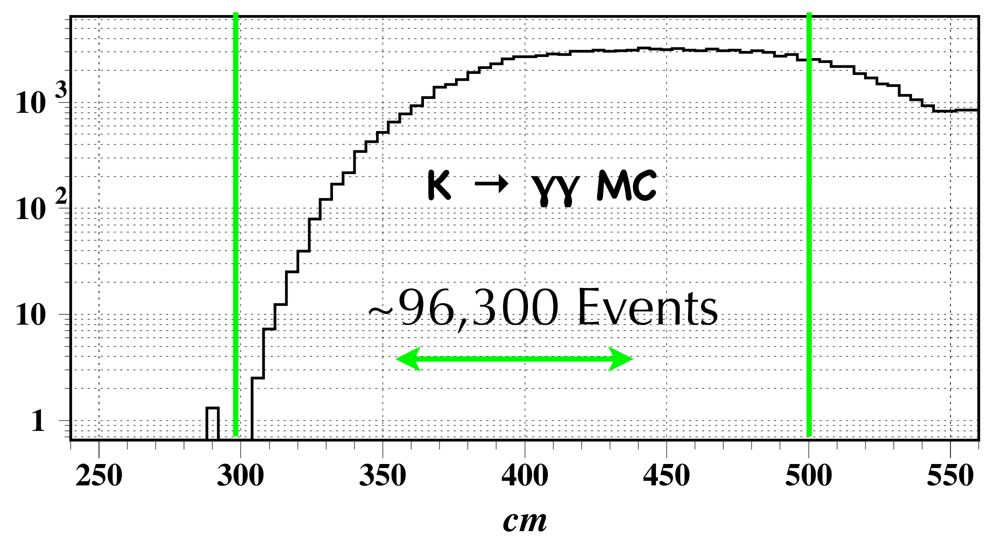
$K_L \to \pi^0\pi^0$

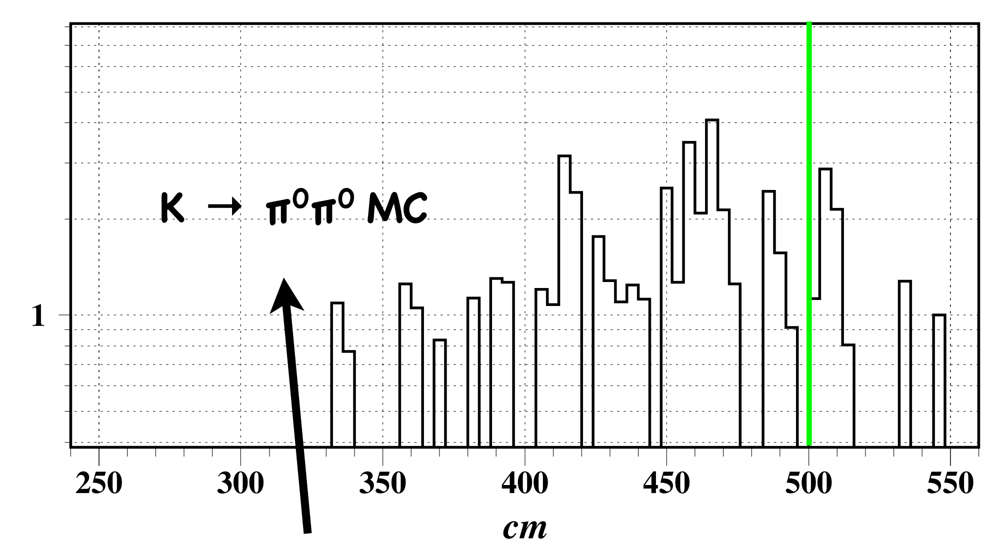

invariant mass
Data
π0π0 MC
π0π0π0 MC
MC Sum
10 3
10 2
10
1
10 -1
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75
GeV/c2


vertex
Data
π0π0 MC
π0π0π0 MC
MC Sum
Counts per 8 cm
10 2
10
1
10 -1
200 250 300 350 400 450 500 550 600
cm

$K_L \to \gamma\gamma$

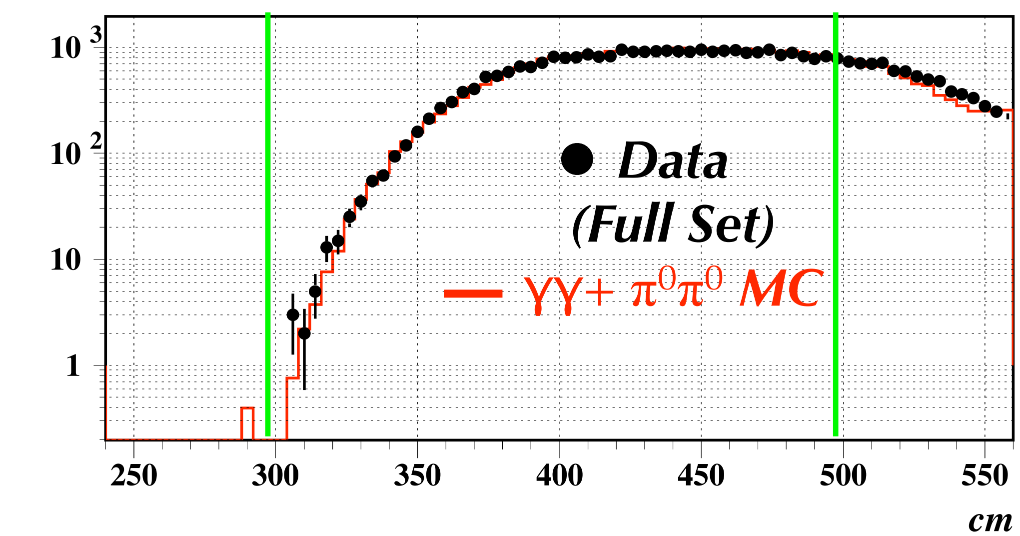
Two Cluster Z-Vertex Spectrum (All Cuts)

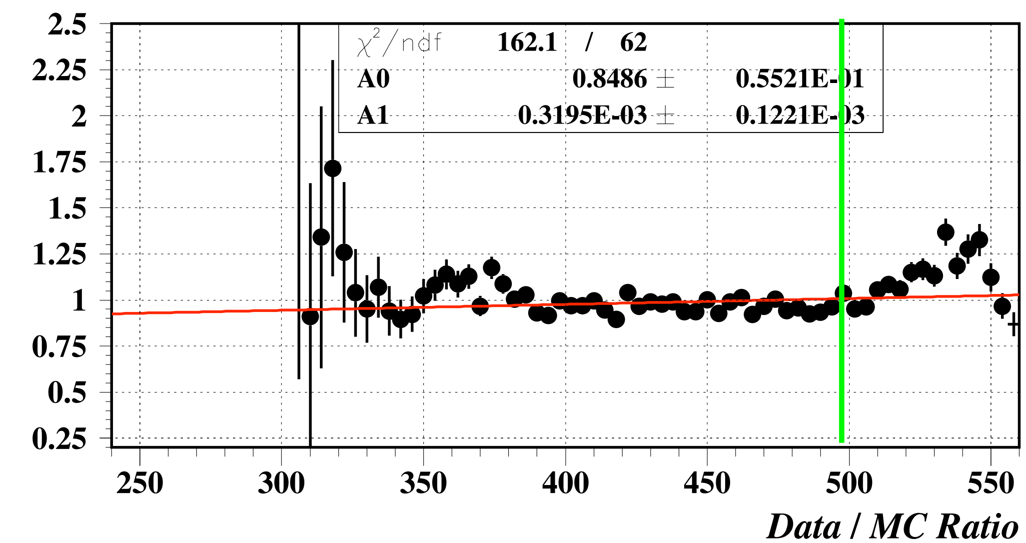




44.8 $\pi^0\pi^0$ Events
(10.6 Scaled by MC sample & Branching Fraction)

Two Cluster Z-Vertex Spectrum (All Cuts)





Summary of K_L flux

Mode	Signal Events (Full Data Set)	Acceptance (with Accidental Loss)	Flux (w/ systematic errors)	Discrepancy $(X - \pi^0\pi^0)/\pi^0\pi^0$
$K \rightarrow \gamma\gamma$	20,685	$(0.697 \pm 0.004_{Stat})$%	$(5.41 \pm 0.37) \times 10^9$	5.0%
$K \rightarrow \pi^0\pi^0$	1494.9 (1500 - 5.1) ($\pi^0\pi^0\pi^0$ contribution)	$(3.35 \pm 0.03_{Stat}) \times 10^{-4}$	$(5.13 \pm 0.40) \times 10^9$	0%
$K \rightarrow \pi^0\pi^0\pi^0$	70,054	$(7.13 \pm 0.06_{Stat}) \times 10^{-5}$	$(5.02 \pm 0.35) \times 10^9$	-1.9%

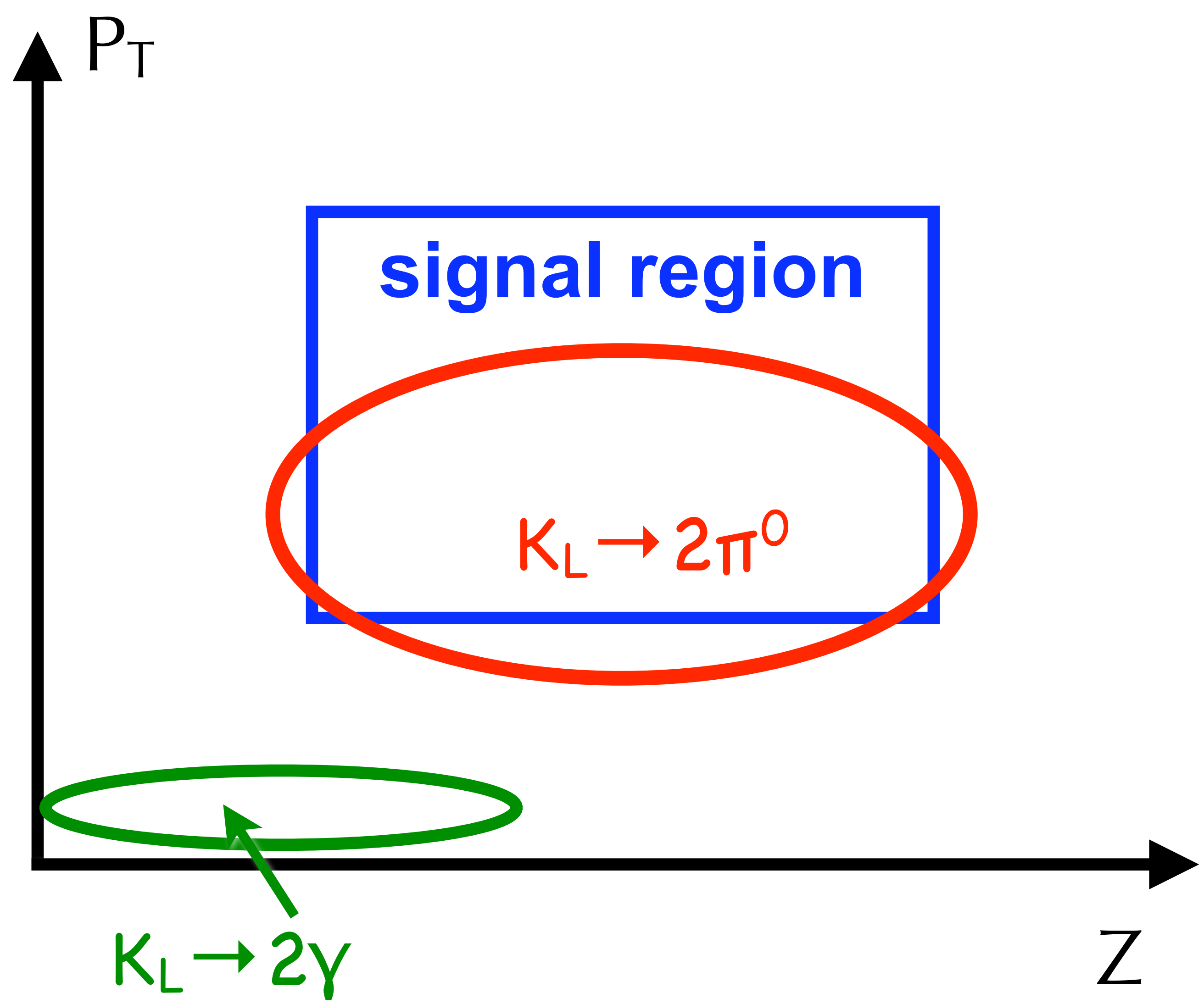
- Signal: 340-500, $497-3\times5.2 < M < 497+3\times5.2$ MeV for $\pi^0\pi^0$, $\pi^0\pi^0\pi^0$

$K_L \to \pi^0 \nu\bar{\nu}$ search

- Blind analysis
  - Hide signal region (+ Control region)
    - The blind "Box": on P_T - Z plot
  - All backgrounds are estimated w/o looking into the Box
  - After completion of BG estimation, the Box will be opened

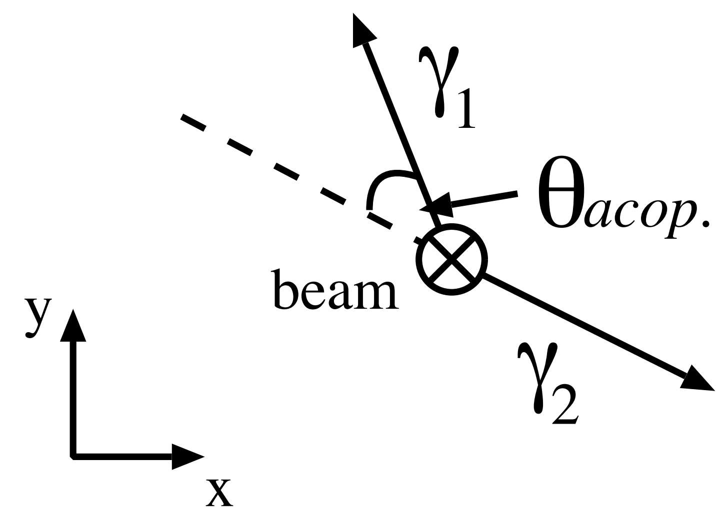
Kaon backgrounds

- BG w/ Kaon decays
  - $K_L \to \gamma\gamma$
    - by P_T mis-measurement
  - $K_L \to \pi^0\pi^0 \to \gamma\gamma$~~$\gamma\gamma$~~
    - missing 2 photons
    - Main background in Kaon decays

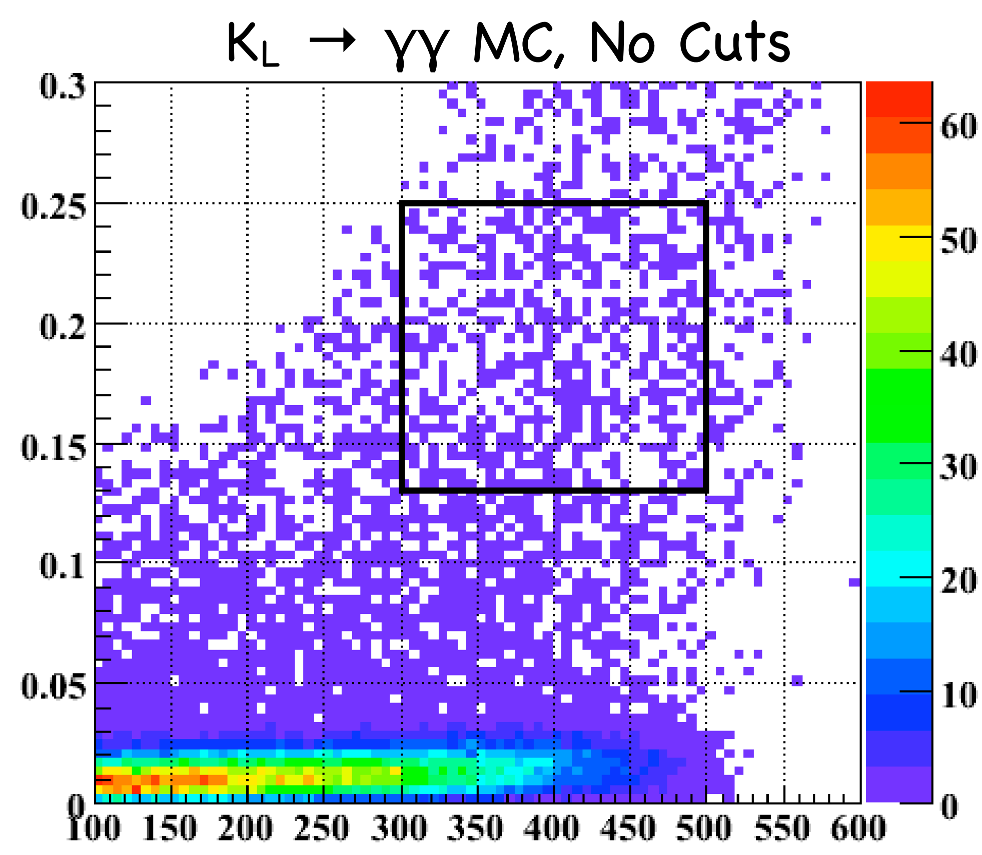


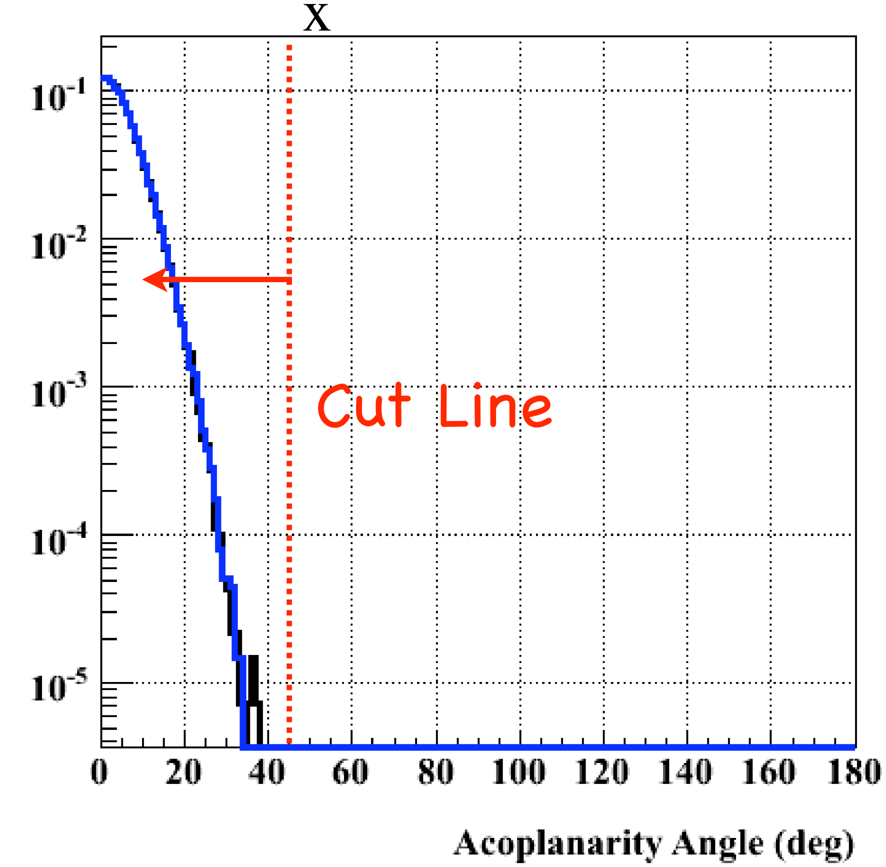
$K_L \to \gamma\gamma$ BG

- "Acoplanarity" angle cut for P_T mismeasurement



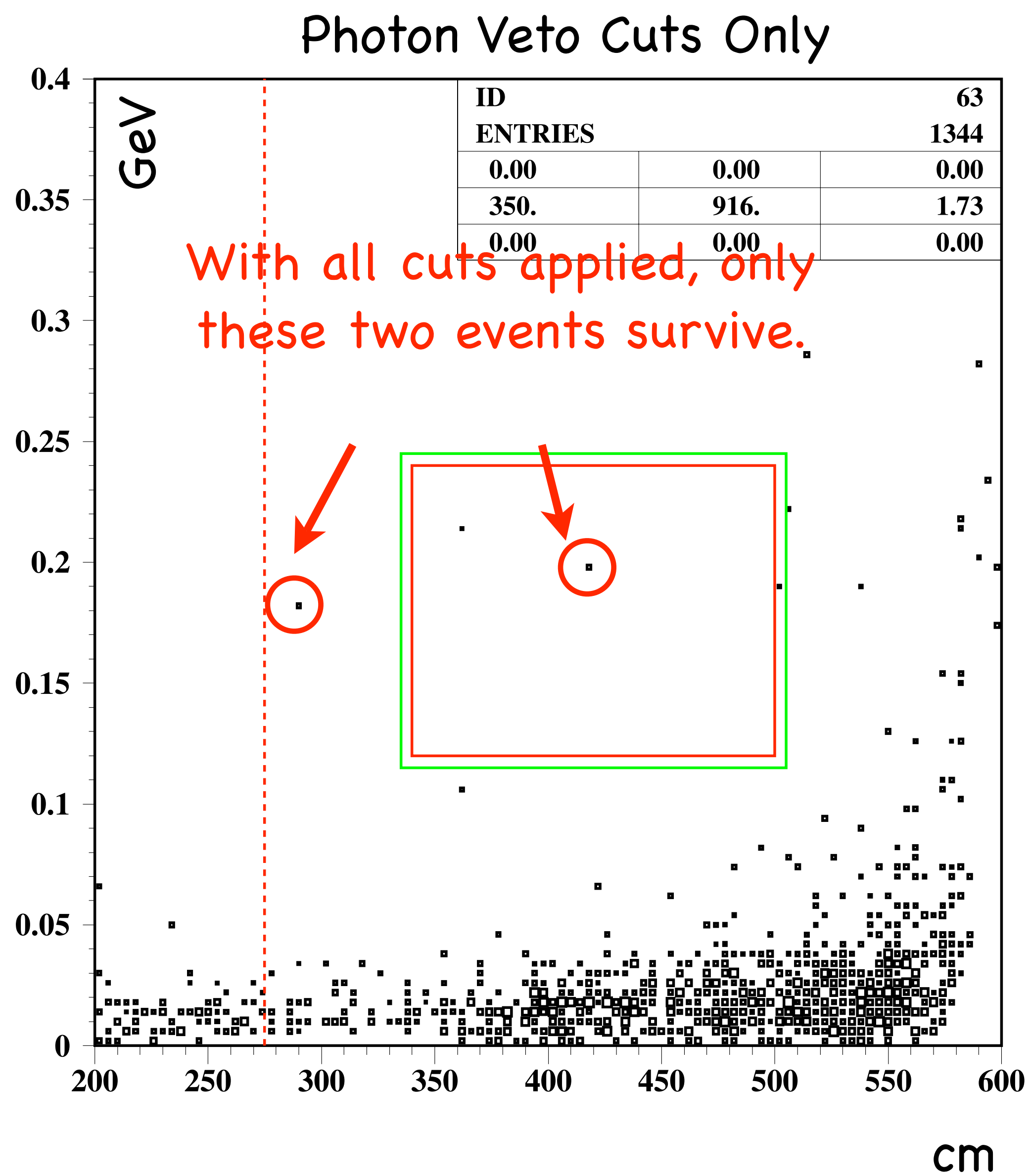
- Result
  - negligible

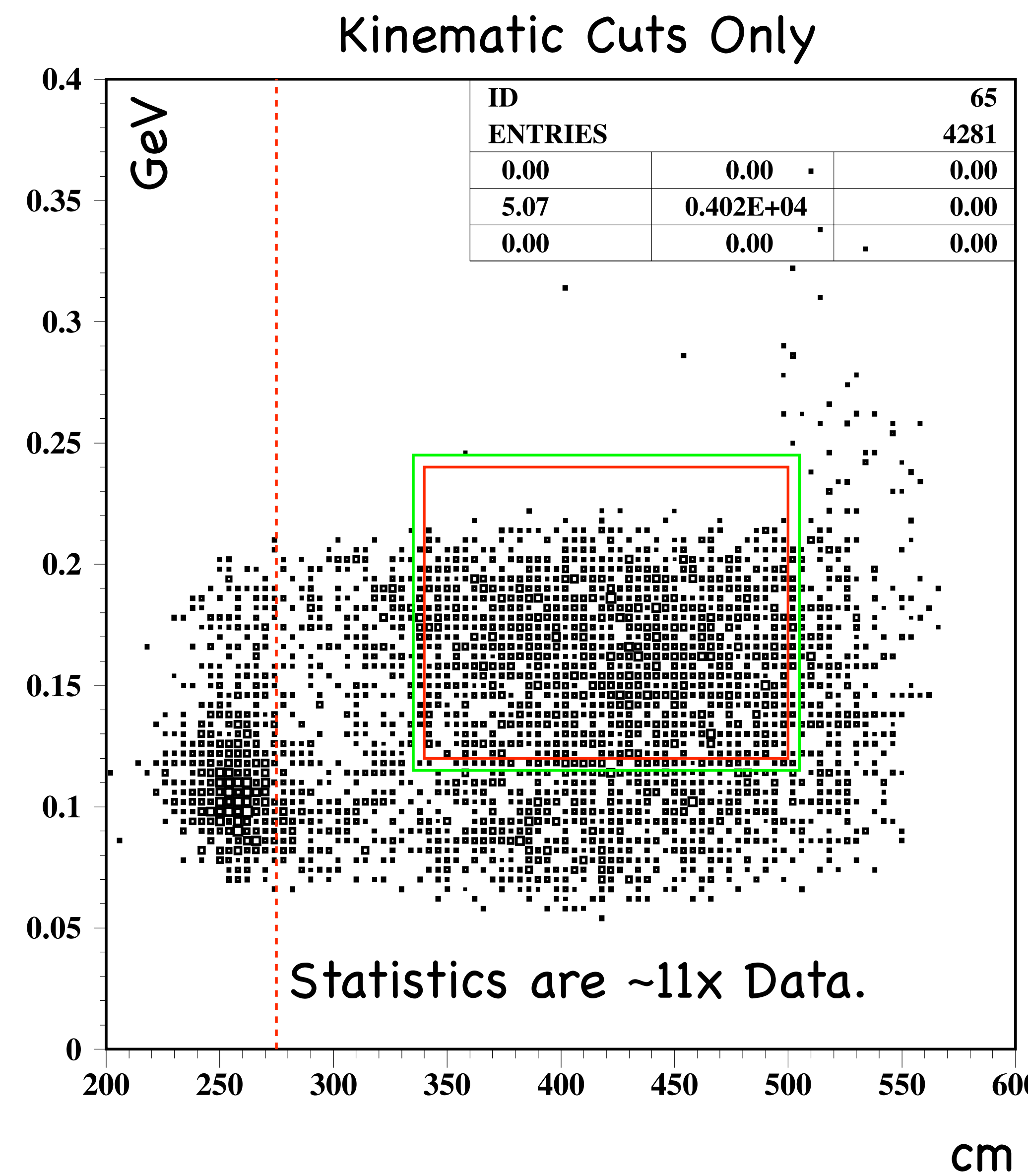




$K_L \to \pi^0\pi^0$ BG

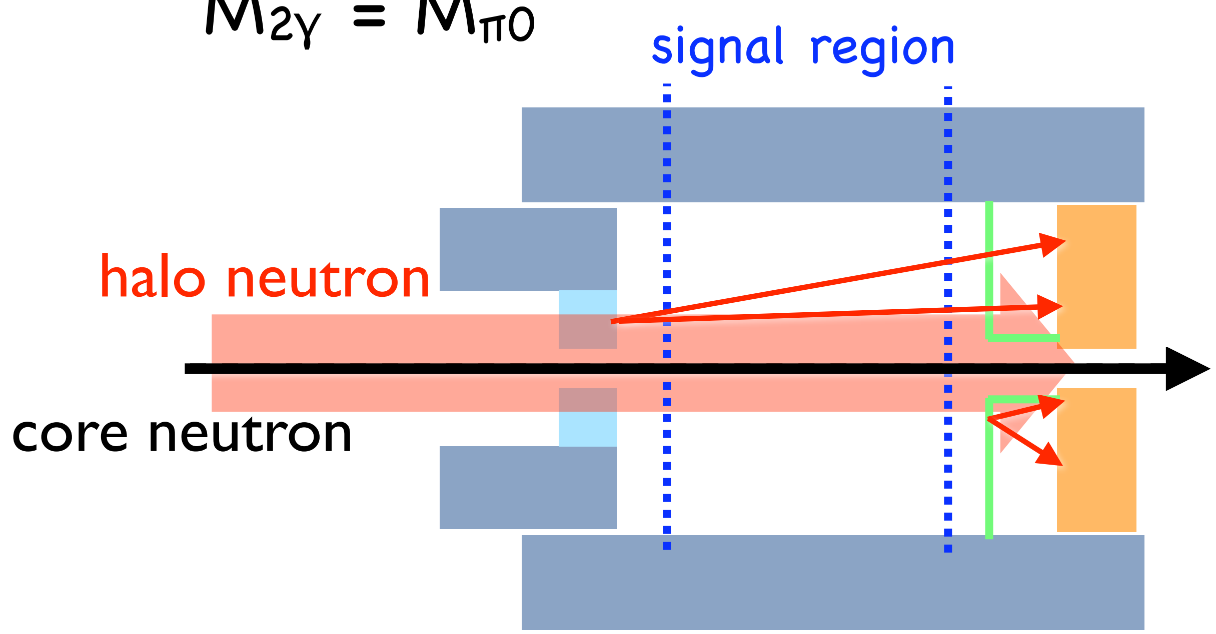
- ~x10 statistics

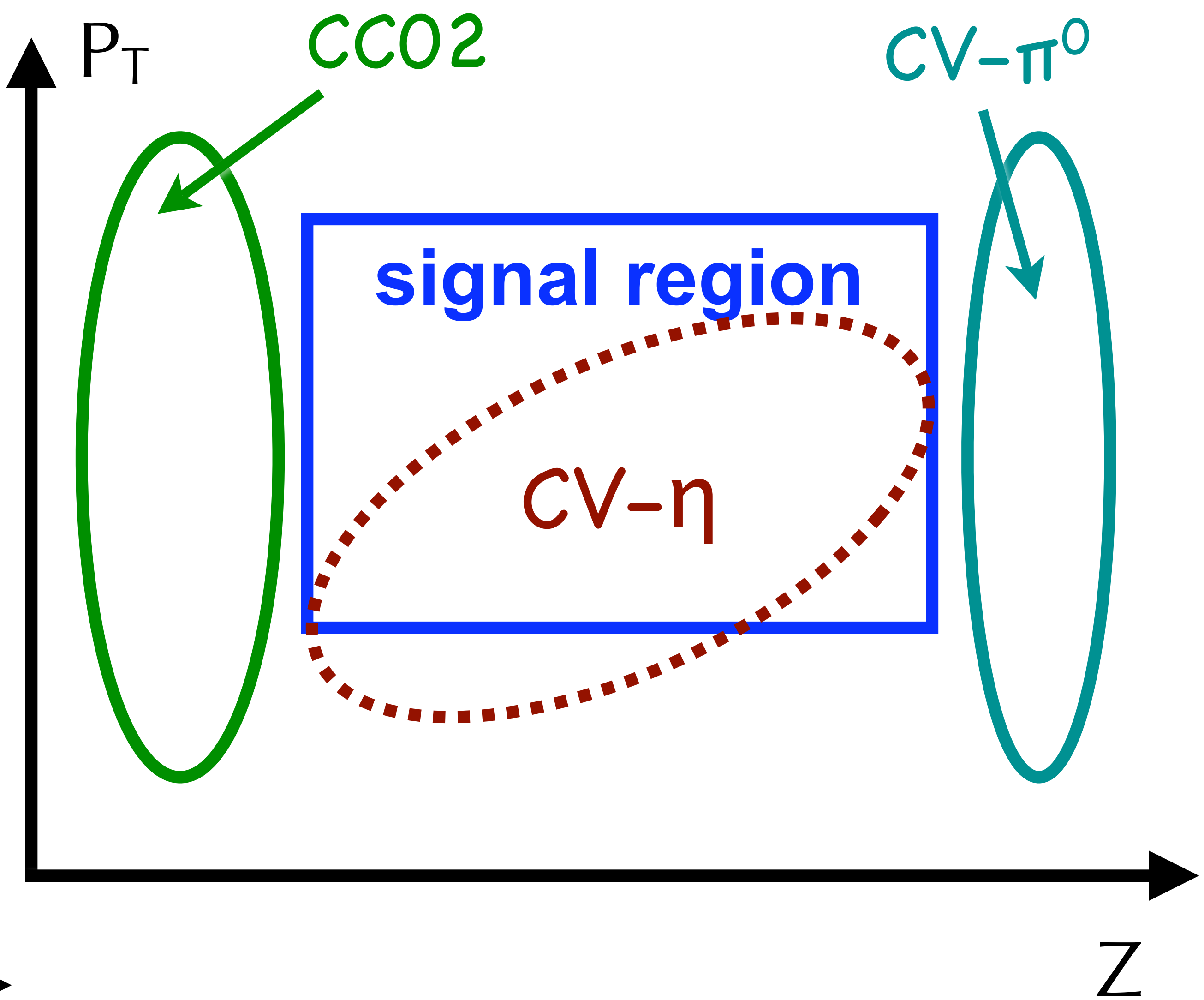




Halo neutron backgrounds

- Interactions of the halo neutrons with detectors
  - "CC02"
    - upstream of the decay region
      - π^0 with energy leakage
  - "CV"
    - π^0 + X
      - w/ extra energy
    - η
      - reconstruction assuming $M_{2\gamma} = M_{\pi 0}$





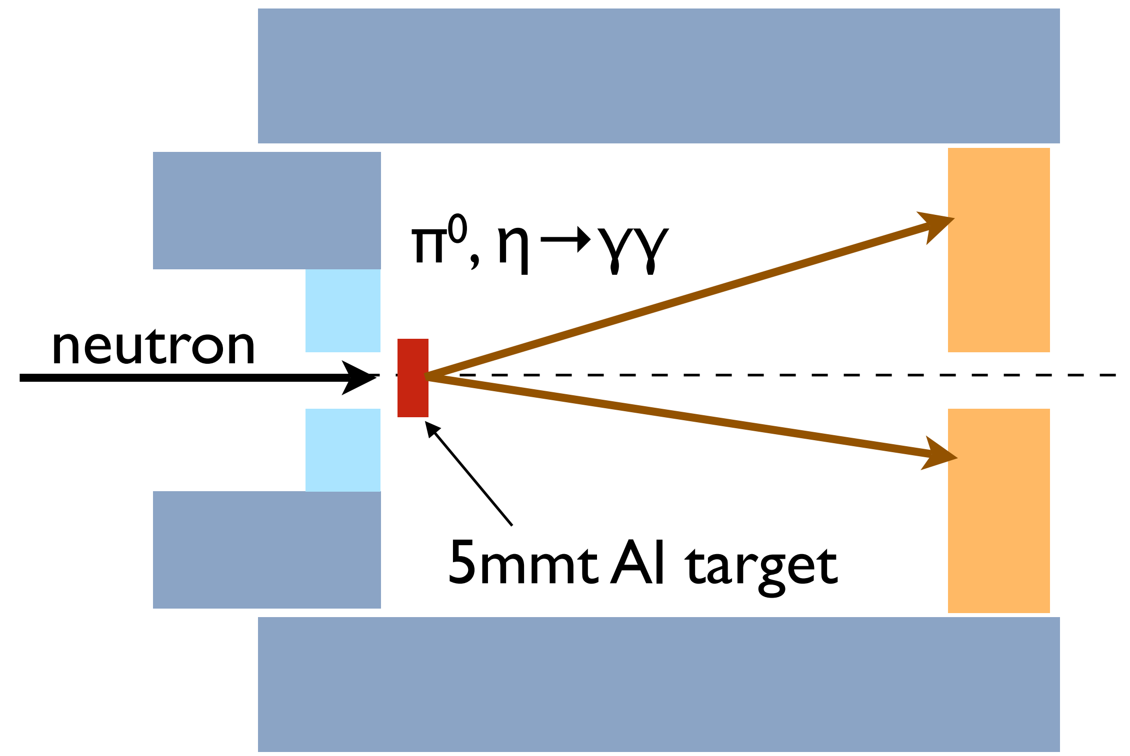
Methods to estimate Halon BG

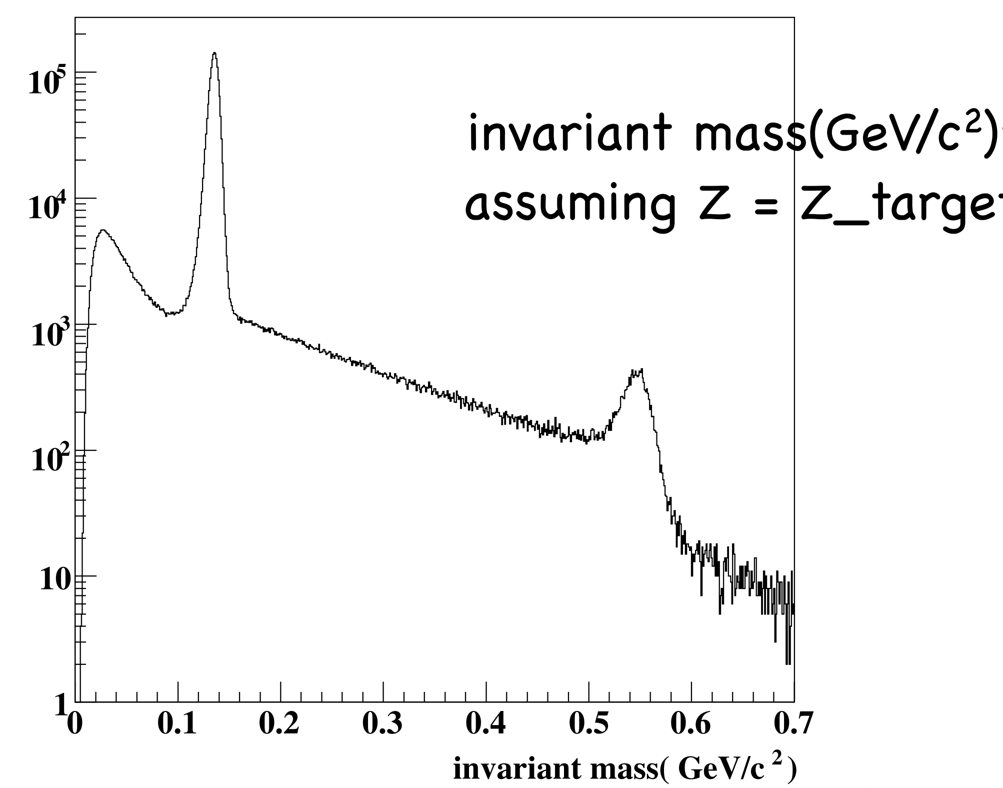
- CC02
  - special run w/ production target
- CV
  - π^0: Geant3 MC
  - η
    - Cross section normalized by the special run
    - Geant4 (QBBC, Binary Cascade) + Geant3

The Aluminum plate run

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

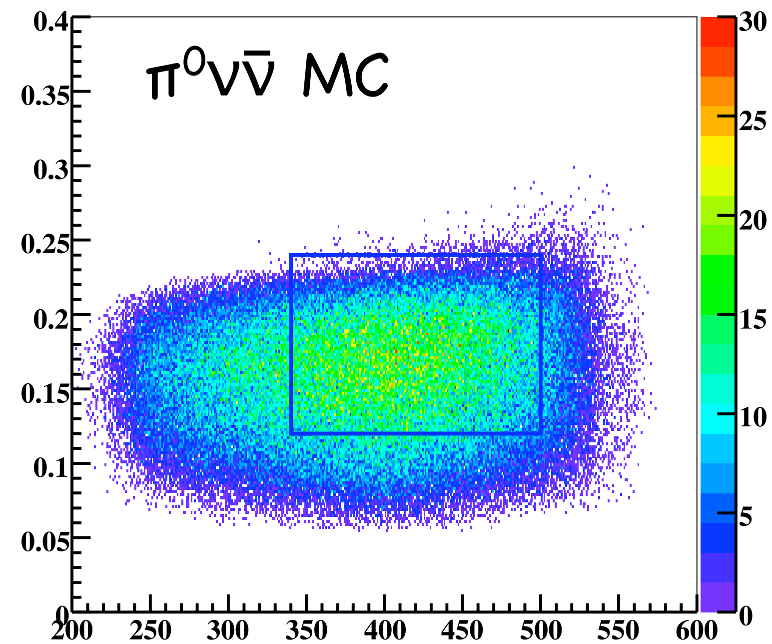
- BG estimation using the Al run
  - CC02 events
    - contamination to downstream by
      - shower leakage
      - photo nuclear effect
  - η production
    - evaluate the cross section

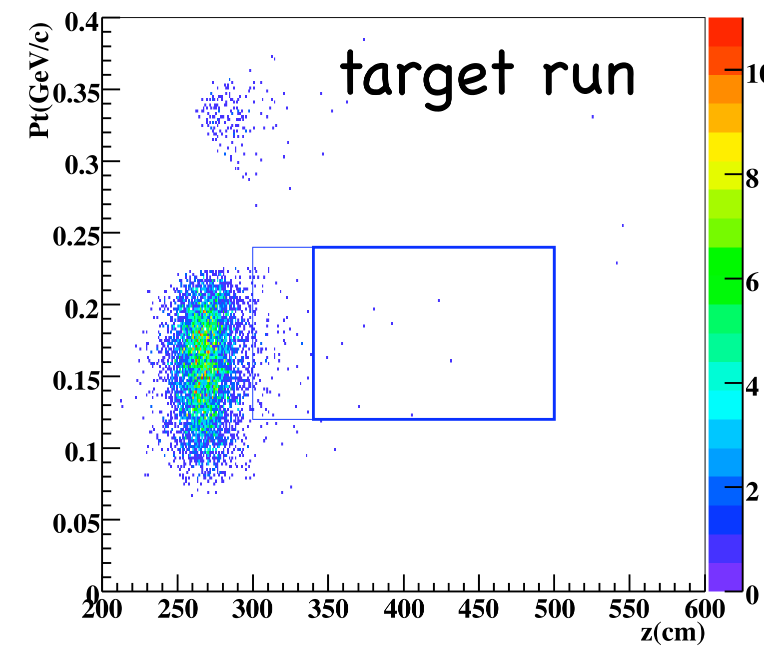


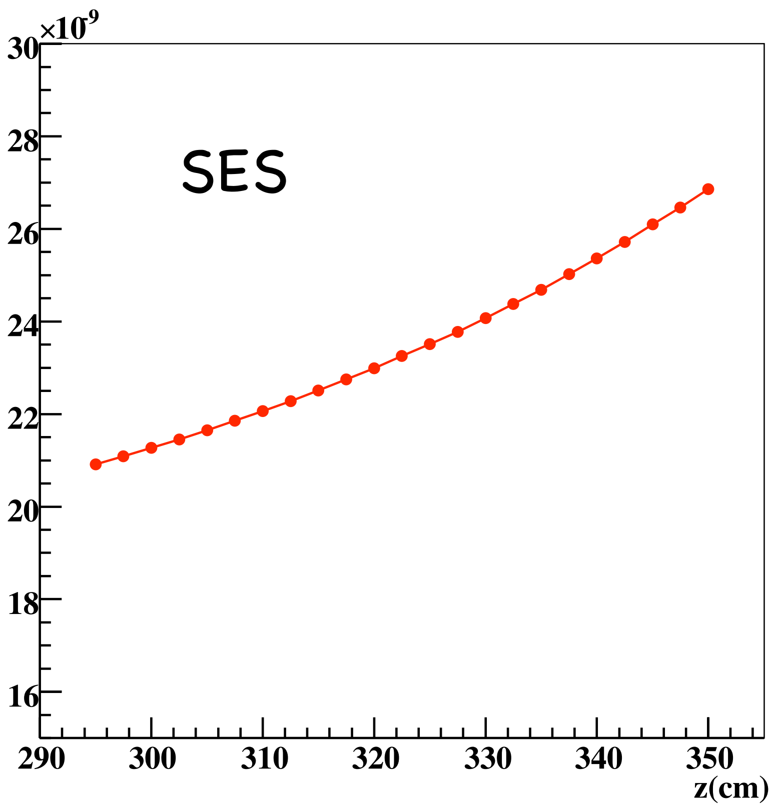


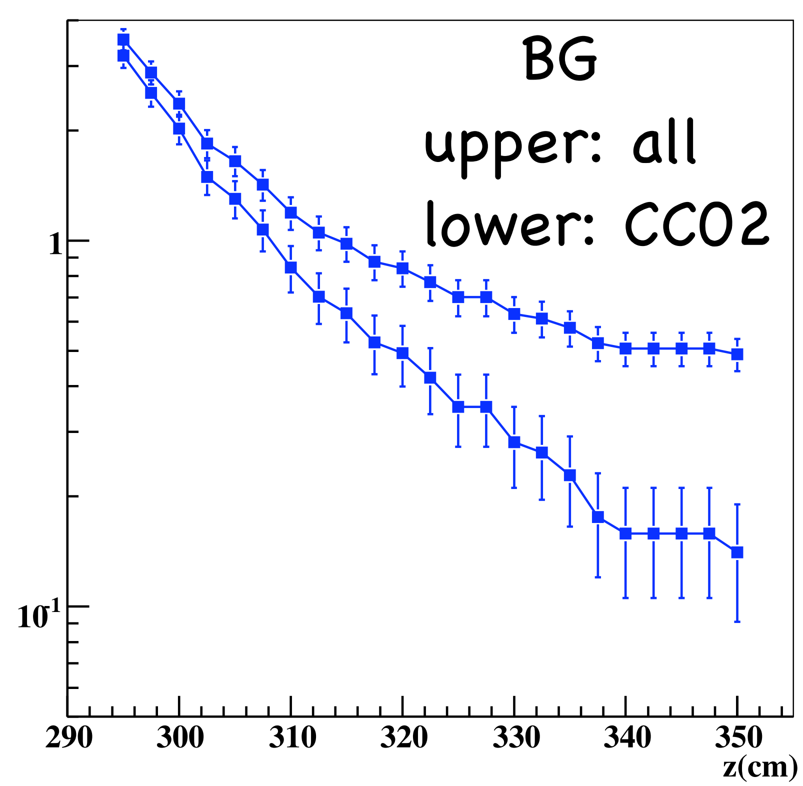
CC02 events distribution

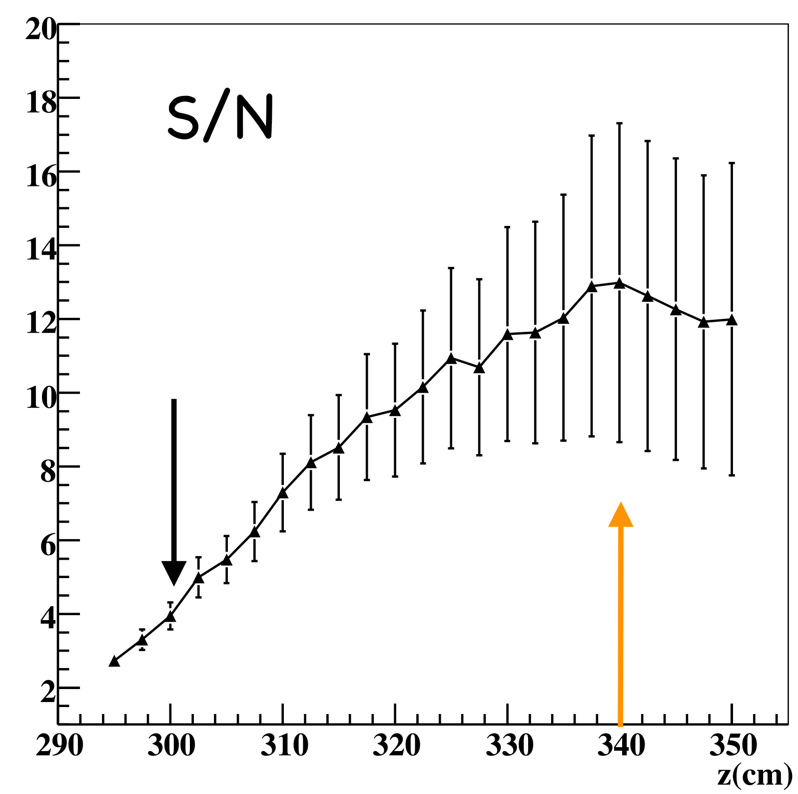
- using target run sample
  - $0.12 < P_T < 0.24$ GeV/c
- taking S/N w/ target run sample and signal MC
  - set boundary at z=340cm
    - 300-340: Control region





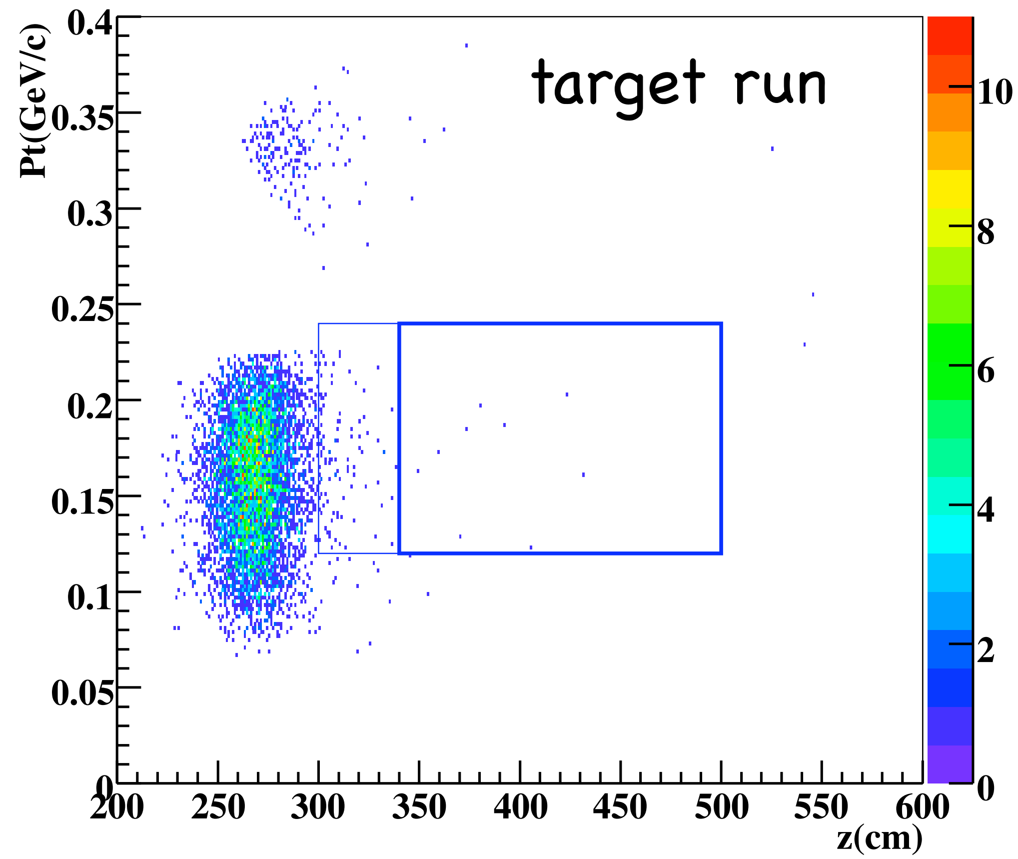


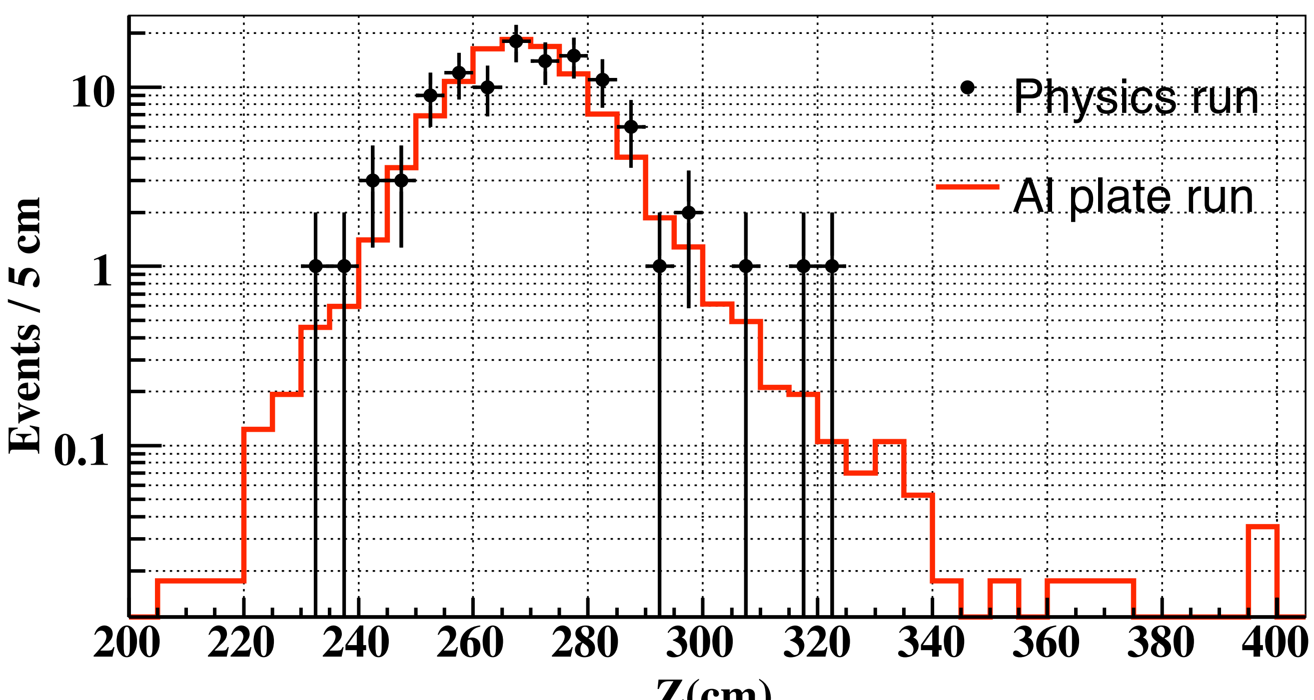


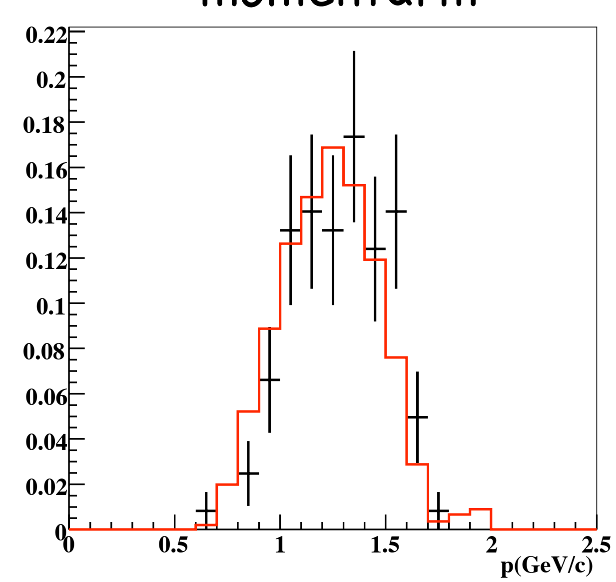


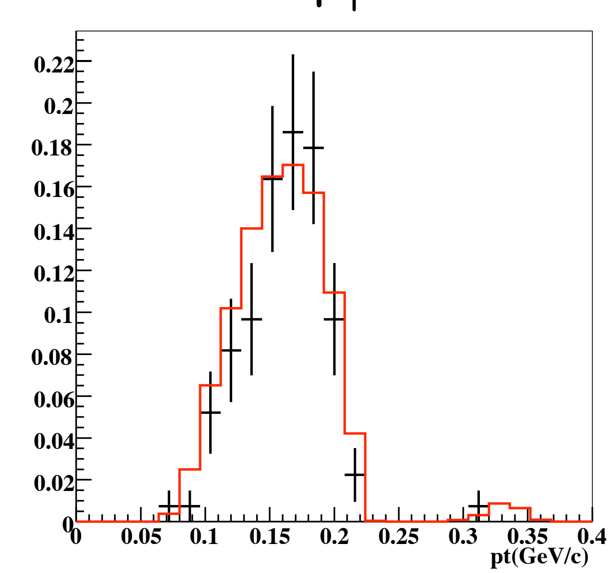
CC02 background

- CC02/Al events in 200-300cm
  - normalization by the number of events
  - smearing using the distribution by MC
- Opening the 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



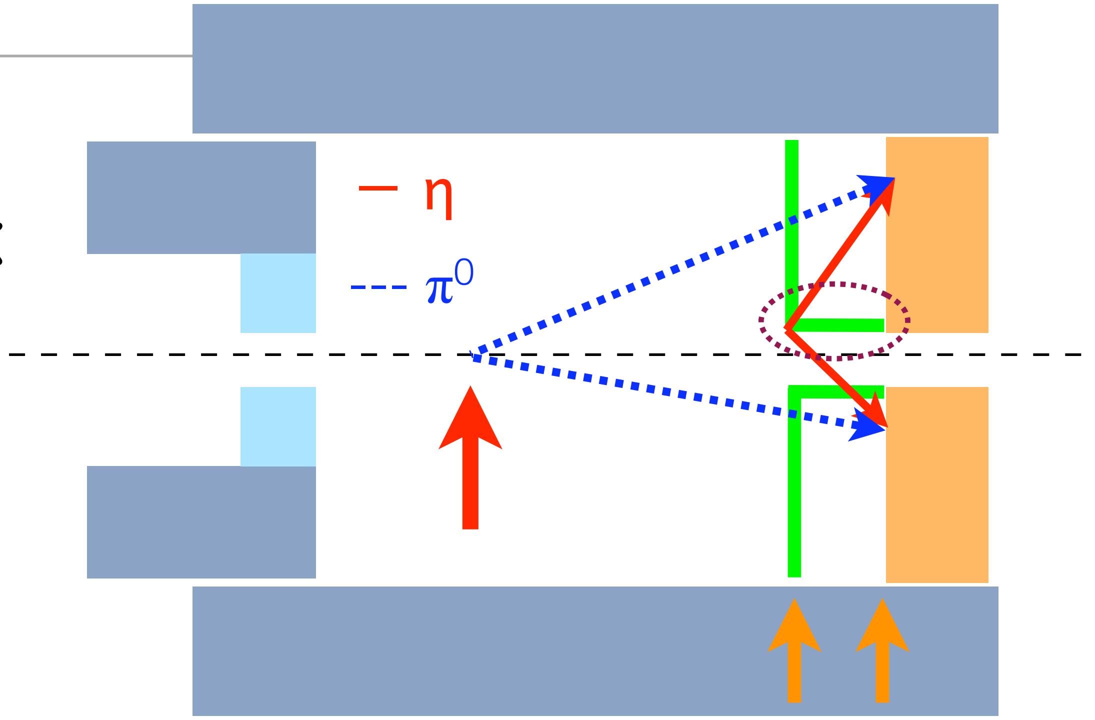




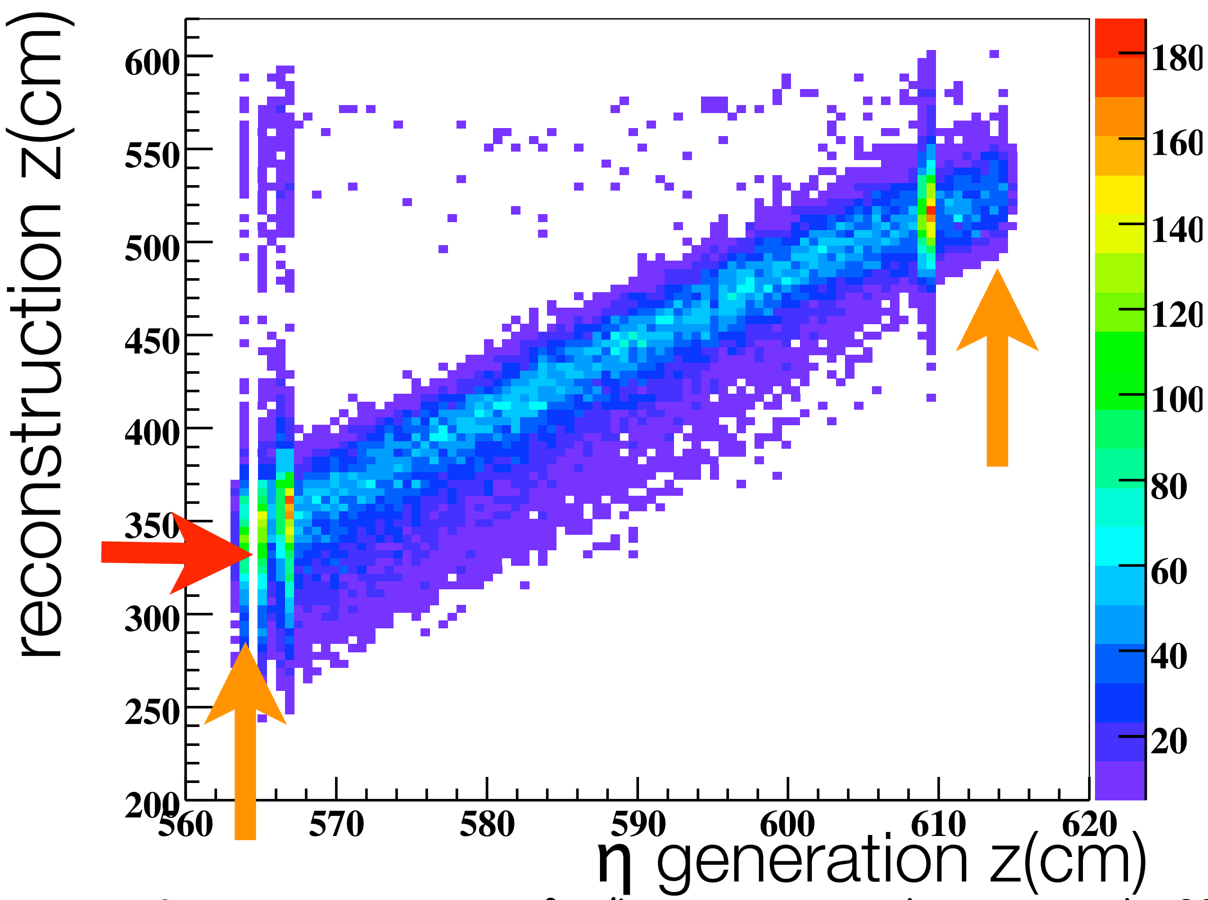


η production by the halo neutrons

- 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



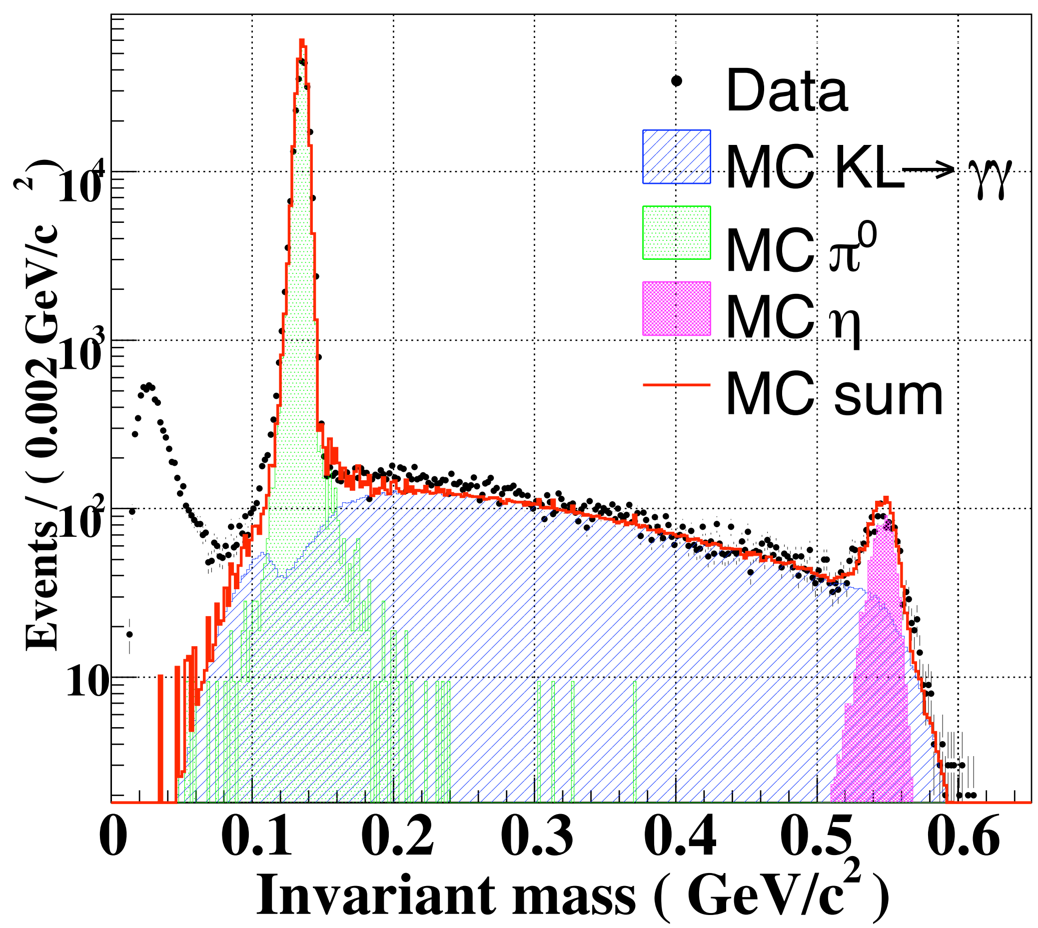
  - Evaluation of the cross section
    : by Al plate run



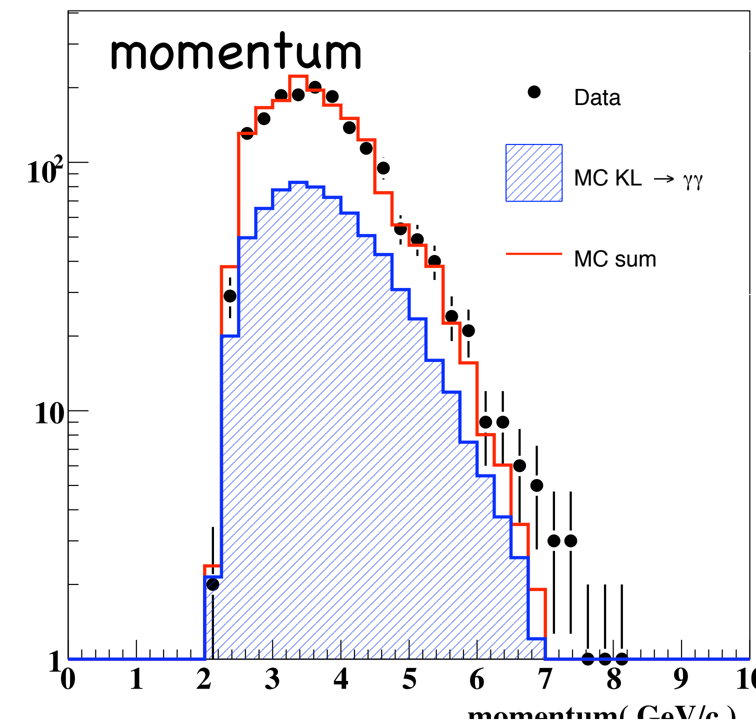
η production in the target run

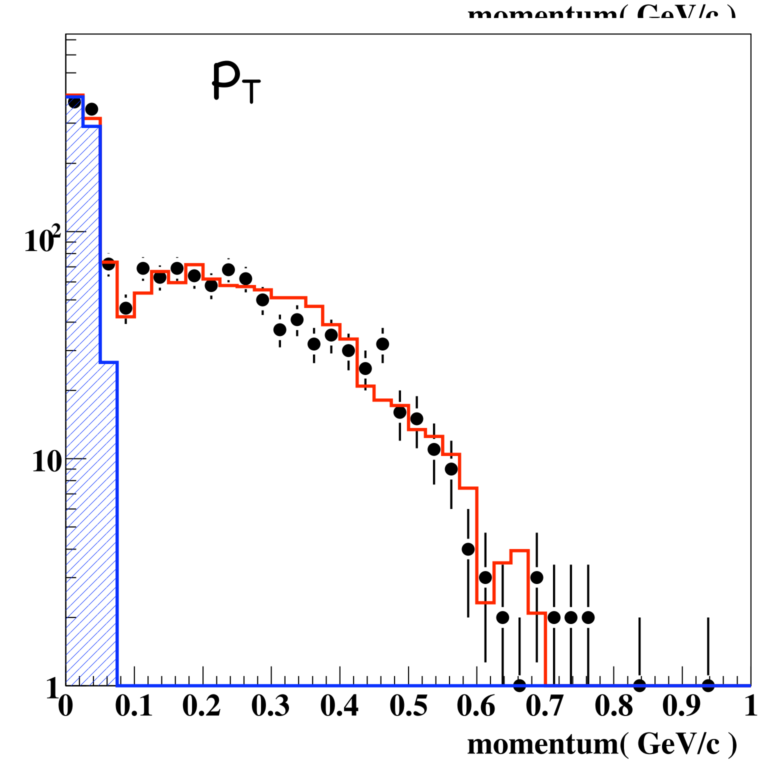
- Assuming the vertices at the Al plate
- number of η event
  - accidental loss factor: 0.8020
  - data = MC x 1.0
    w/ invariant mass > 0.52 GeV/c^2

  - well-reproduced by the Binary Cascade Model



m>0.52 GeV/c^2



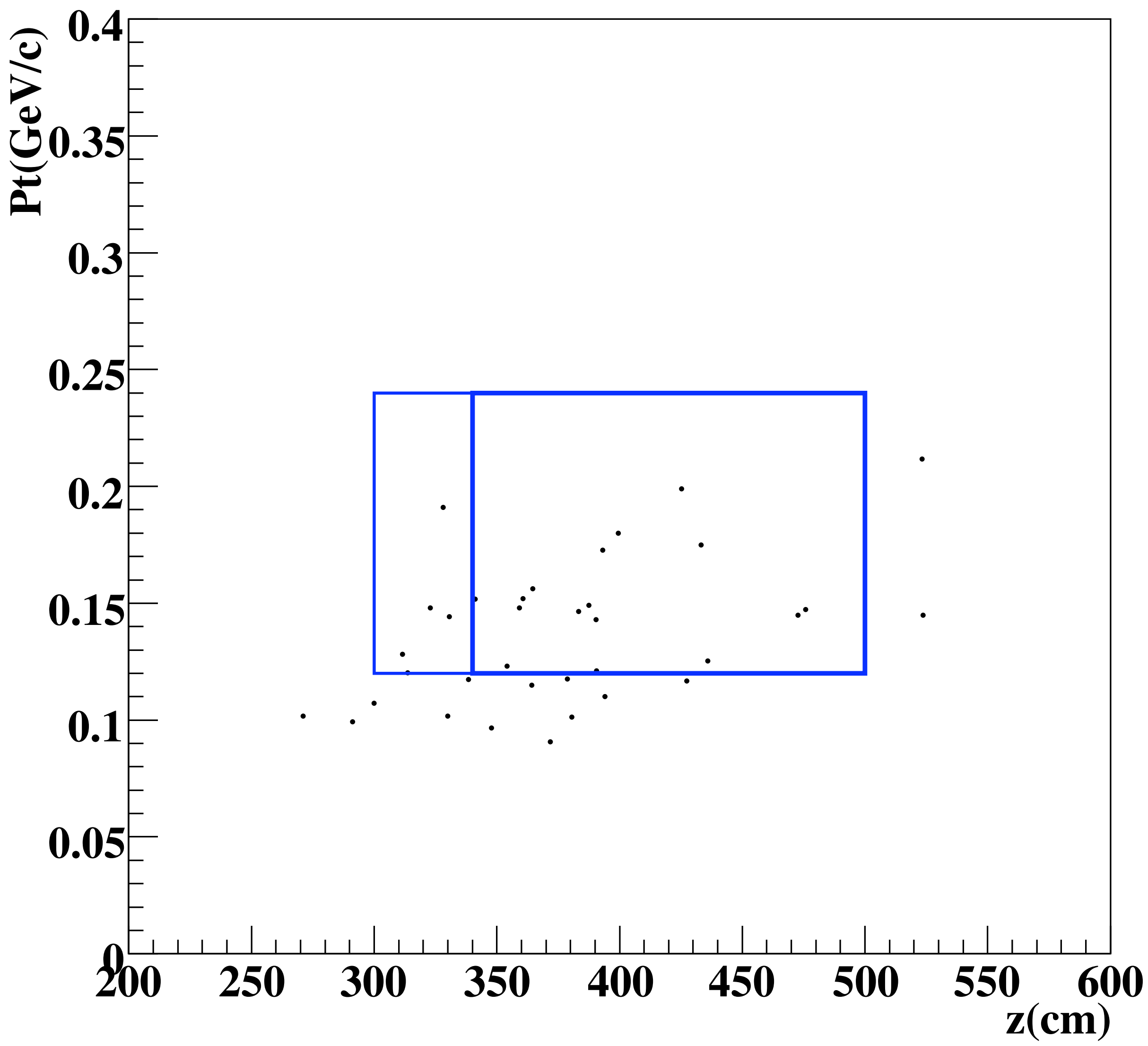


Result of η background

- estimation
  - POT normalization: 1.41×10^{18} / 2.79×10^{20}
  - BG events: 16
  - additional factor
    - target run η production: 1.0
    - accidental loss: 0.8257
    - TDI selection: 0.967^2
    - Time difference: 0.974

- BG Result
  - $16*(1.41\times10^{18}$ / $2.79\times10^{20})$ * 0.8257 * 0.967^2 * 0.974
    = 0.06 ± 0.02

η MC w/ all cuts

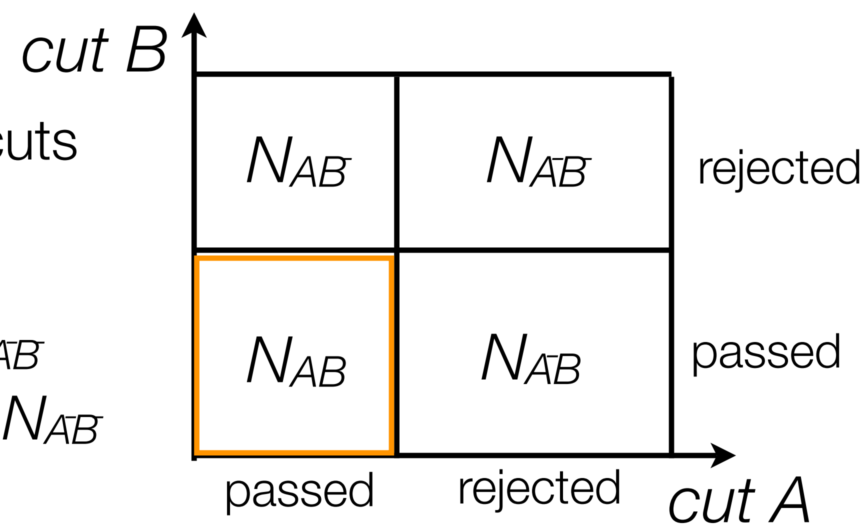


CV background

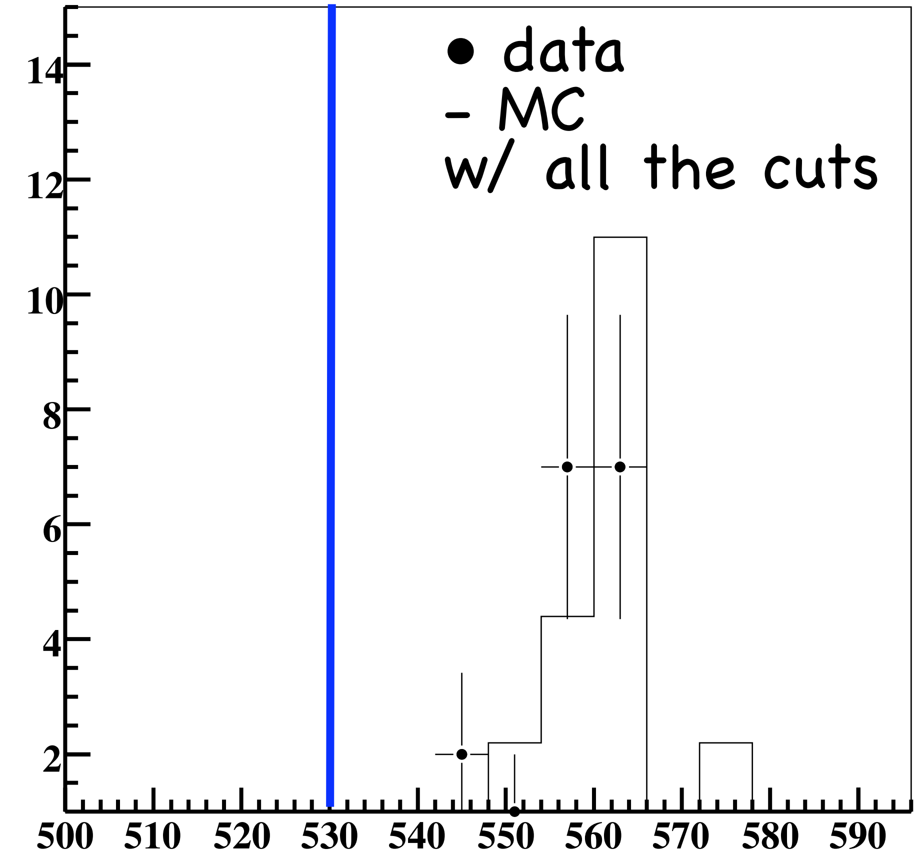
- π^0 productions at CV
  - data: 17 events, MC: 18.2±6.1 events
- BG sources: multi π^0 production,
  π^0 + neutron hit
  - bifurcation method
    - experience in Run-I
      - work at the downstream
      - BG estimation w/ MC

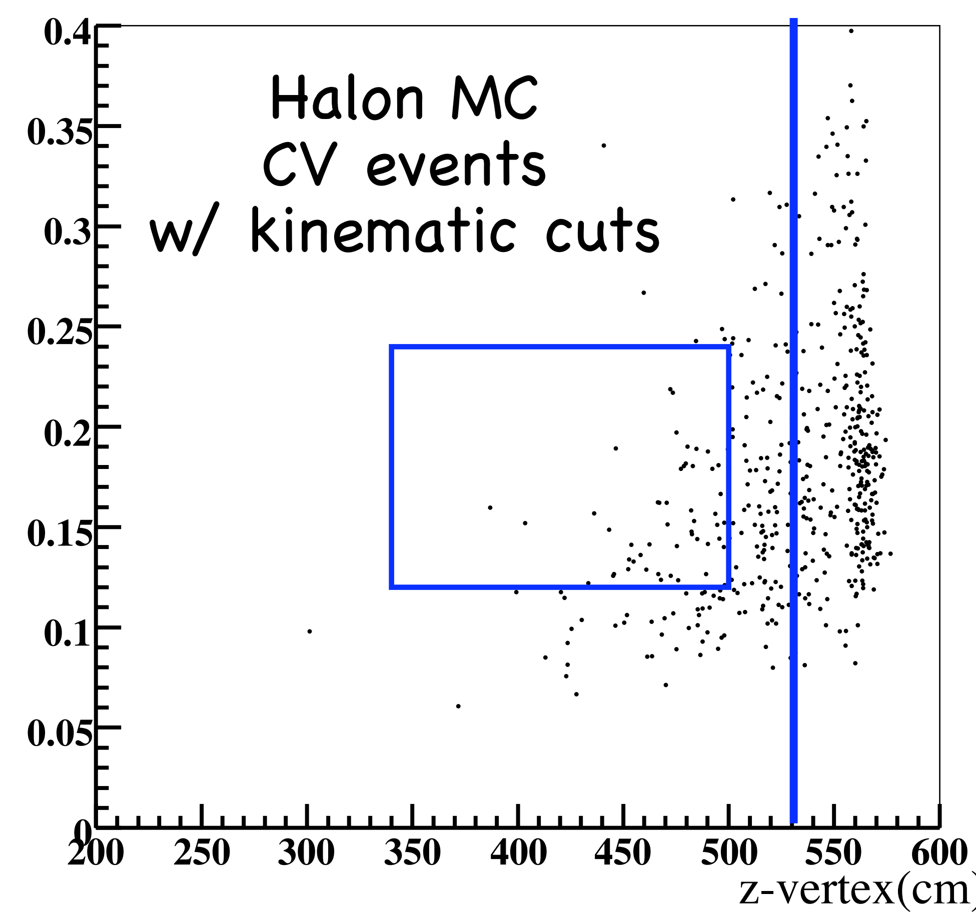
N_{XY} : number of events w/ cuts
" ‾ " : rejected

$$N_{AB} / N_{A\bar{B}} = N_{\bar{A}B} / N_{\bar{A}\bar{B}}$$
$$\Rightarrow N_{AB} = (N_{\bar{A}B} \times N_{A\bar{B}}) / N_{\bar{A}\bar{B}}$$



- Cut sets
  - set-up cuts
    - upstream veto detectors, CsI, π^0 kinematics
  - set A
    - downstream veto detectors
  - set B
    - gamma selection
- Result
  - 0.08±0.04 events

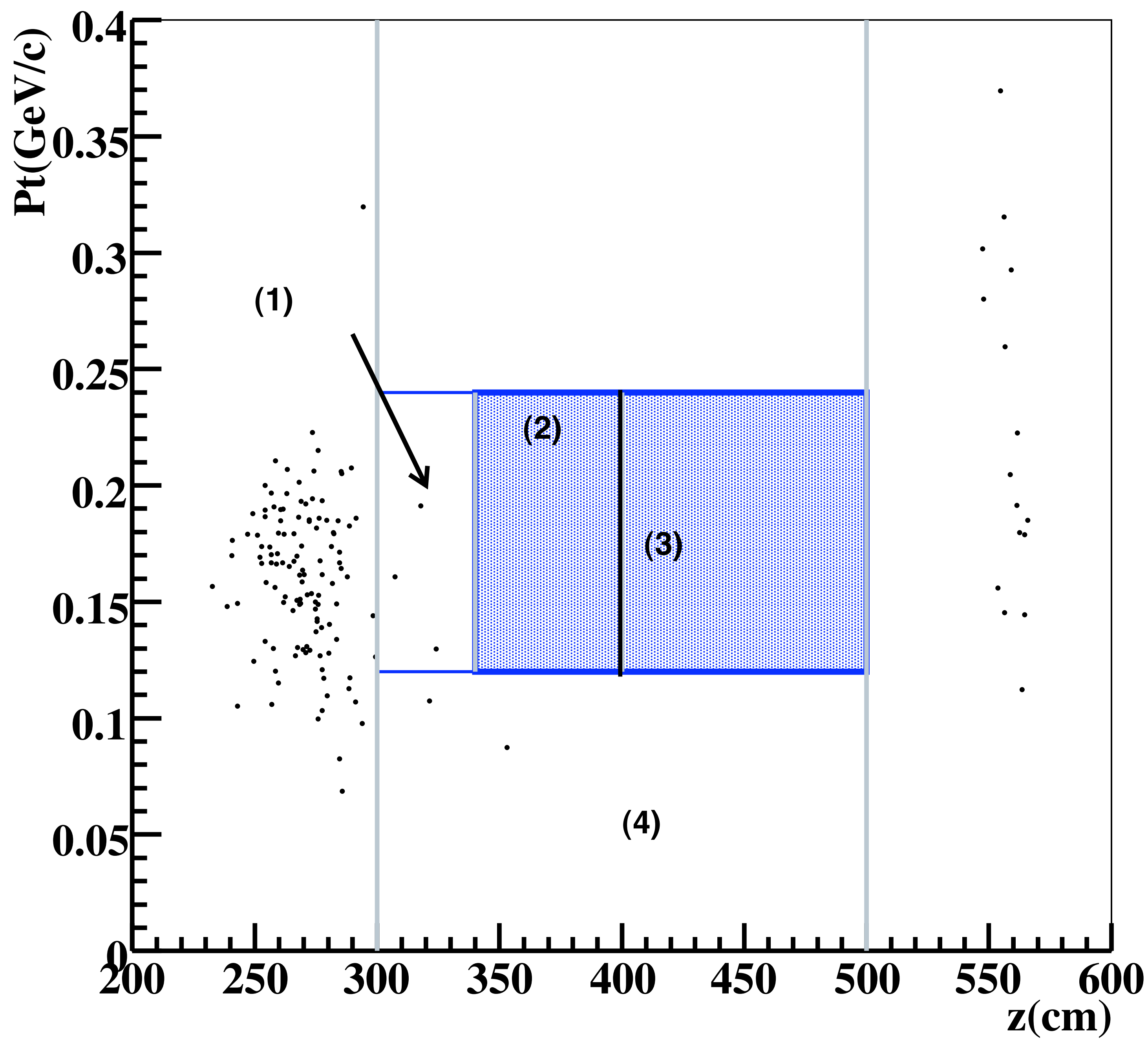




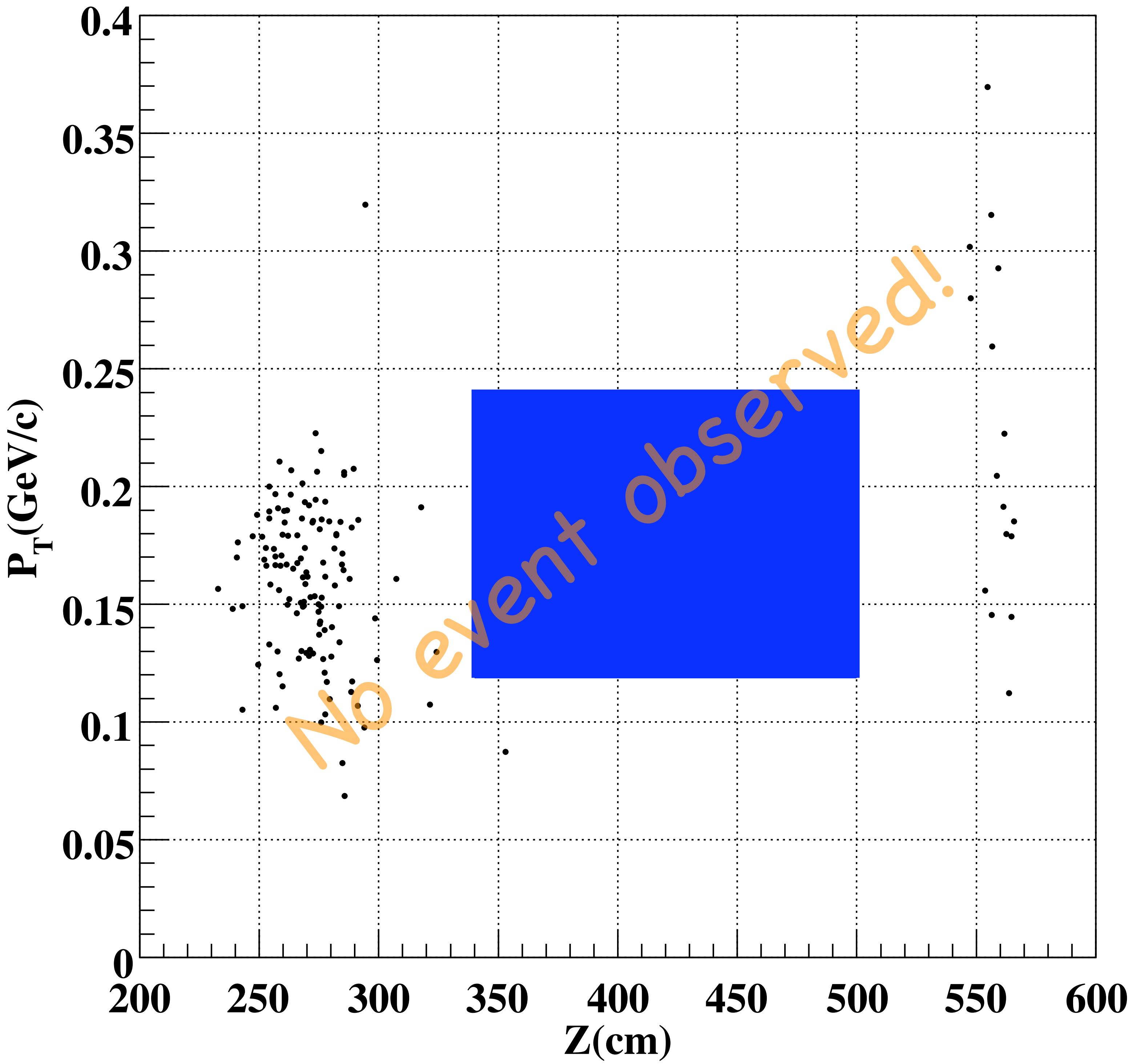
Background summary

- Control region
  - (1) 300-340cm : 1.9±0.2
    - CC02: 1.9±0.2
      - observed: 3 events
  - (4) 300-500cm, Pt<0.12 GeV/c
    - CC02: 0.26±0.07
    - CV-η: 0.04±0.01
    - CV-π^0: 0.09±0.04
      - total: 0.39±0.08
      - observed: 2 event
- Signal region:
  - (2) 340-400cm: 0.15±0.05
    - CC02: 0.11±0.04
    - CV-η: 0.04±0.02
  - (3) 400-500cm: 0.26±0.11
    - CC02: 0.05±0.03
    - CV-η: 0.02±0.01
    - CV-π^0: 0.08±0.04
    - $K_L \to \pi^0\pi^0$: 0.11±0.09
  - total: 0.41+0.11

Data w/ all the cuts



Opening the box



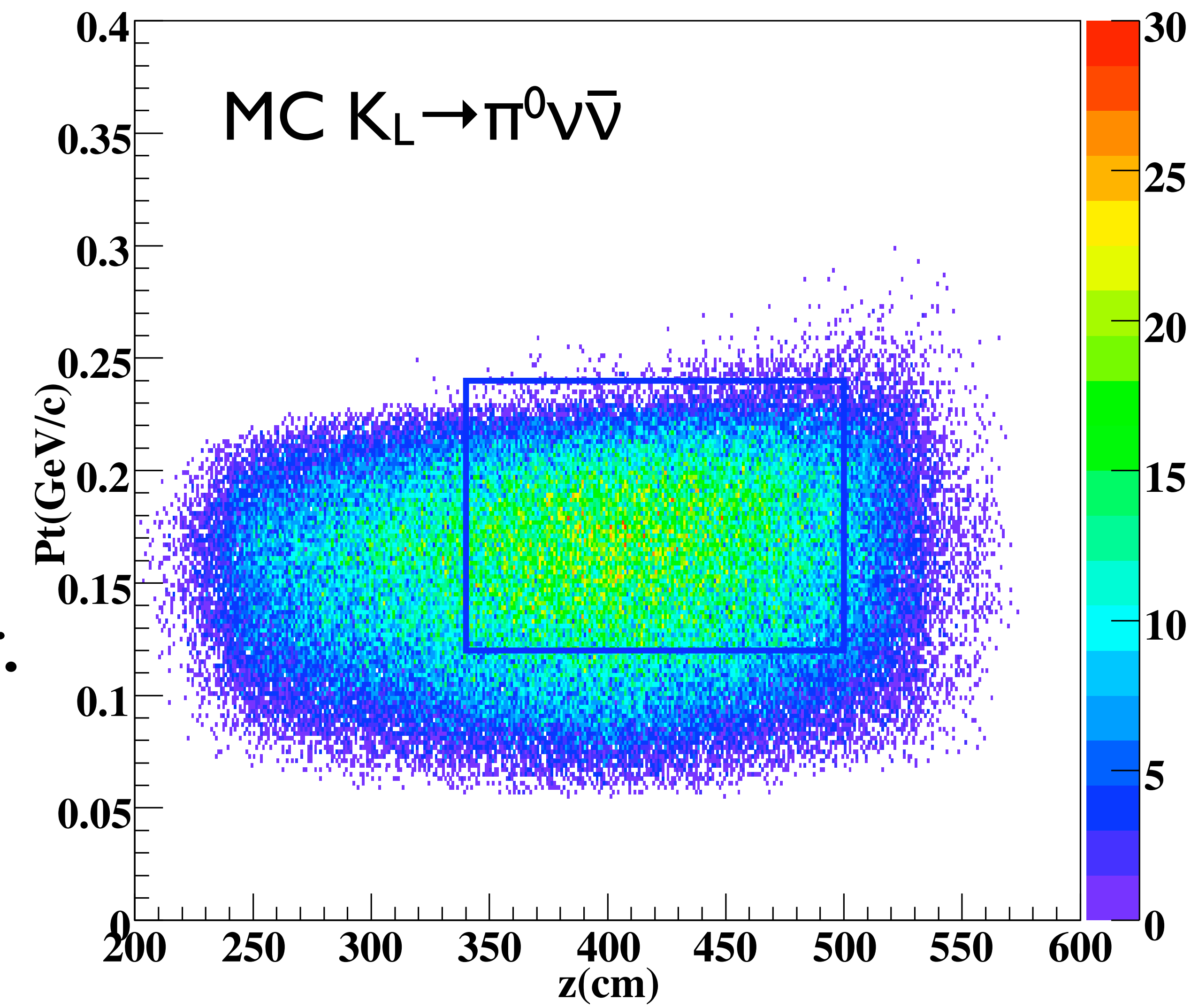
Result

- Acceptance: A = 0.666%
- Flux: N_{KL} = (5.13 ± 0.40) x 10^9

- S.E.S = 1 / (A · N_{KL})
  = (2.93 ± 0.25) x 10^{-8}

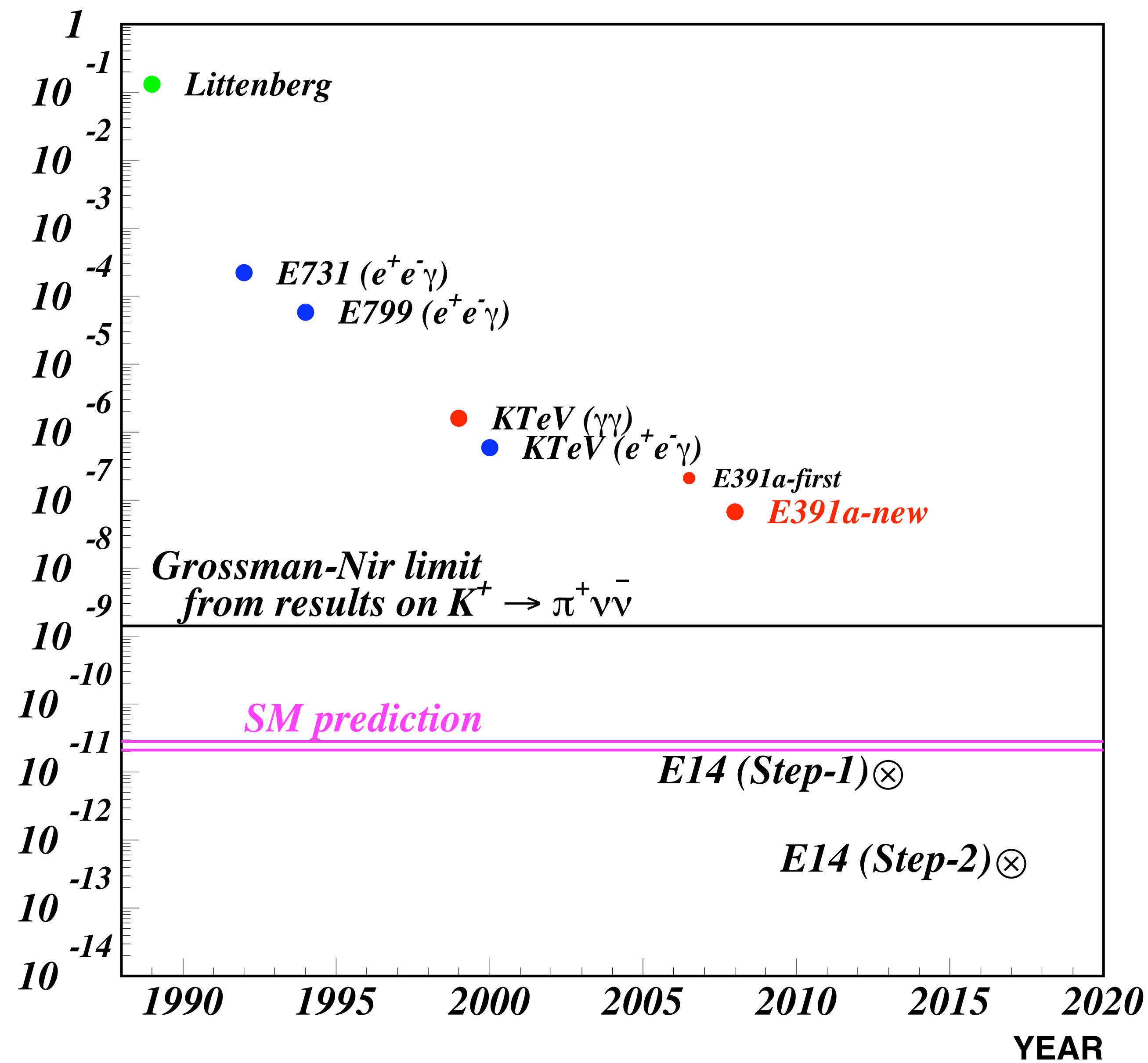
- Upper Limit
  - 0 event observation
    - interval: 2.3 w/ Poisson stat.
  - Br($K_L \to \pi^0 \nu\bar{\nu}$) < 6.7 x 10^{-8}
    (@90% C.L.)

✓ arXiv:0712.4164



Improvement in the Upper Limit

- Upper limit
  - New result by E391a Run-II
    - $Br(K_L \to \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8}$
  - KTeV
    - $\pi^0 \to \gamma\gamma$
      - $Br < 1.6 \times 10^{-6}$: x 24
    - $\pi^0 \to e^+e^-\gamma$
      - $Br < 5.9 \times 10^{-7}$: x 8.8
  - Run-I 1week
    - $Br < 2.1 \times 10^{-7}$: x 3.1



- Future Plans
  - E391a Data Analysis
    - Run I : remaining data sample (x9 of 1week)
    - Run III: ~70% K_L of Run II
      - Further optimization
        - ✓ Final result combining all runs
  - J-Parc E14 R&D
    - E391a detector + many upgrades
      - CsI : 7x7x30cm → 2.5x2.5x50cm
      - CC02 : full active, fine segment
      - CV : set far from the beamline, close to CsI

Summary

- $K_L \to \pi^0 \nu\bar{\nu}$ decay
  - Direct measurement of CP violation parameter η
  - Sensitive to New Physics
- The E391a experiment
  - First dedicated experiment to $K_L \to \pi^0 \nu\bar{\nu}$
  - 3 physics runs
    - Analysis of Run-II full data completed

- Result
  - Single Event Sensitivity
    - S.E.S. = $1/(A \cdot N) = (2.9 \pm 0.3) \times 10^{-8}$
  - Background
    - $N_{BG} = 0.41 \pm 0.11$
  - Upper Limit
    - 0 event observed
    - $Br(K_L \to \pi^0 \nu\bar{\nu}) < 6.7 \times 10^{-8}$ (@90% C.L.)