Progress at E391a

Working Towards a New Result for $K_L \rightarrow \pi^0 \nu\nu$

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May 25th
In (Lovely) Frascati, Italy

Overview

- E391a will not announce new a physics result for $K_L \to \pi^0 \upsilon\upsilon$ today. We hoped to do so here, but we are not quite ready.
- Instead of withdrawing from the conference, we decided instead to try to provide convincing evidence that we understand our detector, we know what we don't understand, and that we are now very close to a new result.
- We broke these tasks up into two presentations. This is the first, and in this talk I will cover the following:
  - First, a (very) short comment on the motivation for studying $K_L \to \pi^0 \upsilon\upsilon$, and an introduction the experiment and our collaboration.
  - Second, a discussion of the detector layout and method.
  - Third, an examination of the E391a Monte Carlo (MC).
  - Fourth, the flux for our major normalization and calibration modes.
  - Finally, a brief discussion of Kaon-related backgrounds.
- We will discuss other background sources in another presentation (provided by T. Sumida).

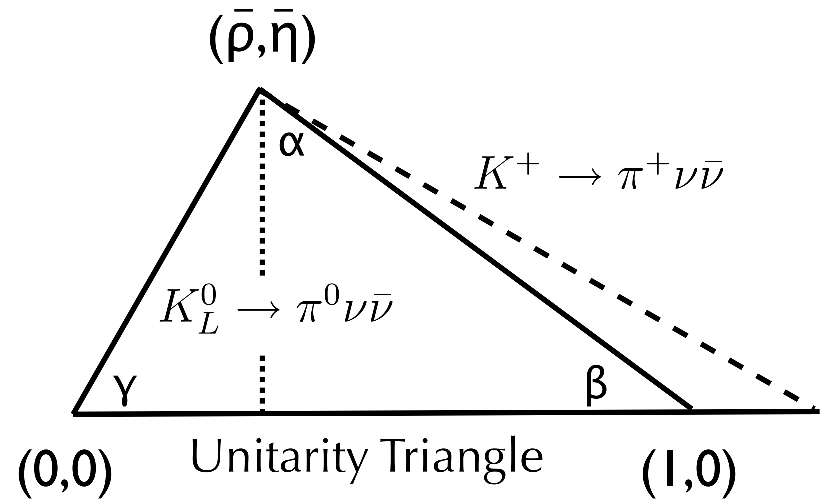
E391a

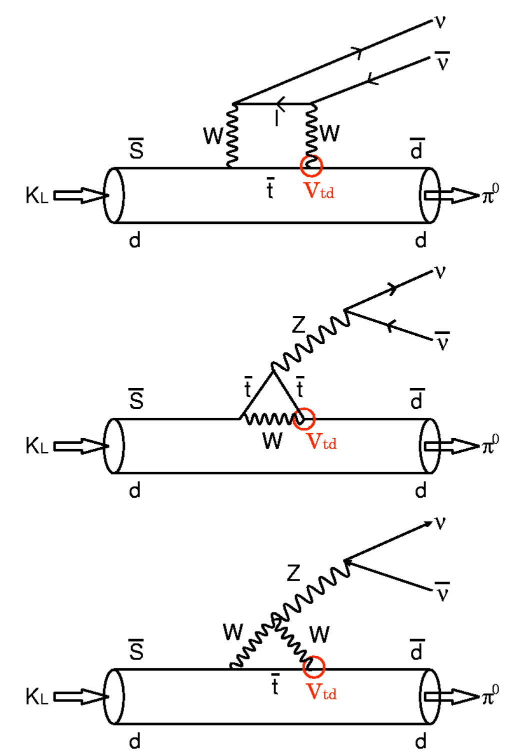
- E391a is a dedicated search for the rare decay $K_L \rightarrow \pi^0 \upsilon\upsilon$.
- The E391a collaboration is small for a particle physics experiment. It is a multinational group of ~50 members from almost a dozen institutions. Our experiment ran at the KEK 12 GeV proton-synchrotron in Tsukuba, Japan.
  - In addition to Japan, The United States, Taiwan, South Korea, and Russia are participants.
  - Member institutions include: KEK, Osaka University, Kyoto University, Saga University, Yamagata University, NDA, The University of Chicago, National Taiwan University, Pusan National University, and JINR.
- E391a took three main data taking runs:
  - Run I: February - July of 2004.
  - Run II: February - April of 2005 - *the topic of this talk*.
  - Run III: October - December of 2005.

Theoretical Motivation - A Brief Overview

- Direct CPV Process.
- Measures the CKM parameter η.
- Theoretically clean (Δ ~ 1.5%)
  - Dominated by Short-range processes.
  - Very little hadronic uncertainty.

$$\mathrm{Br}(K_L^0 \to \pi^0 \nu \bar{\nu}) \propto \eta^2$$





- The expected branching ratio is very small.

$$\mathrm{Br}(K_L^0 \to \pi^0 \nu \bar{\nu})_{\mathrm{SM}} = (2.54 \pm 0.4) \times 10^{-11}$$

- The experimental signature is not kinematically well constrained.

- E391a published the best limit from a direct search*:

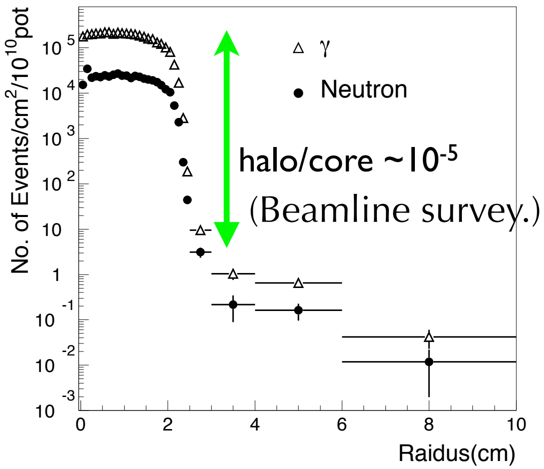
$$\mathrm{Br}(K_L^0 \to \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-7} \ (90\% \mathrm{C.L.})$$

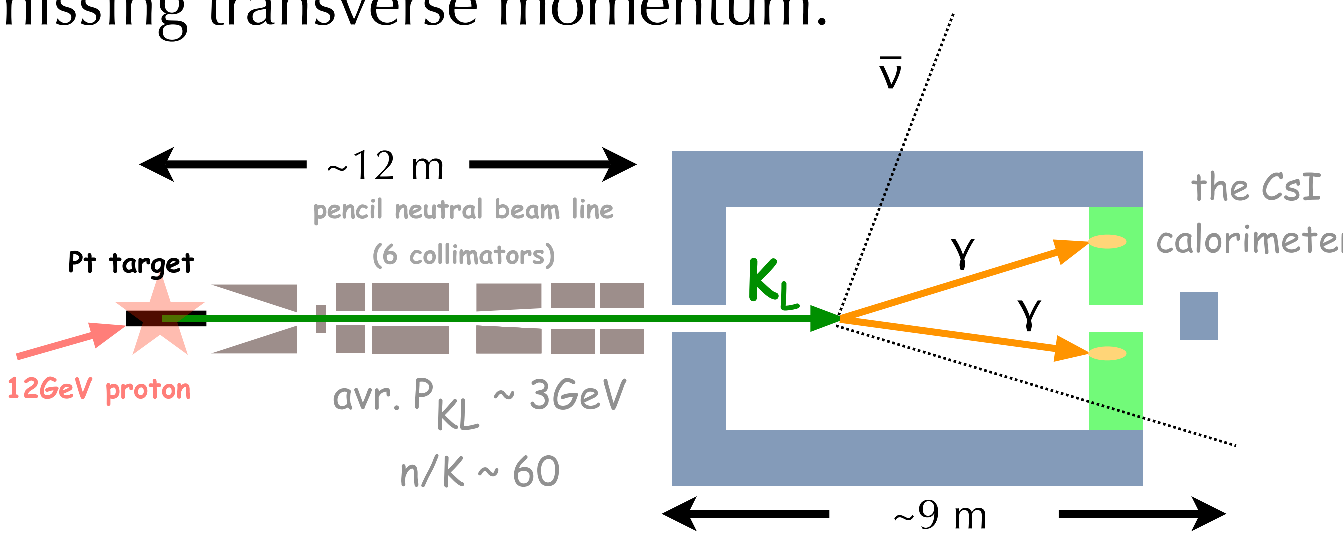
- Using the BNL charged Kaon results and isospin symmetry, Grossman and Nir have set a tighter limit:

$$\mathrm{Br}(K_L^0 \to \pi^0 \nu \bar{\nu})_{\mathrm{GN}} < 1.4 \times 10^{-9}$$

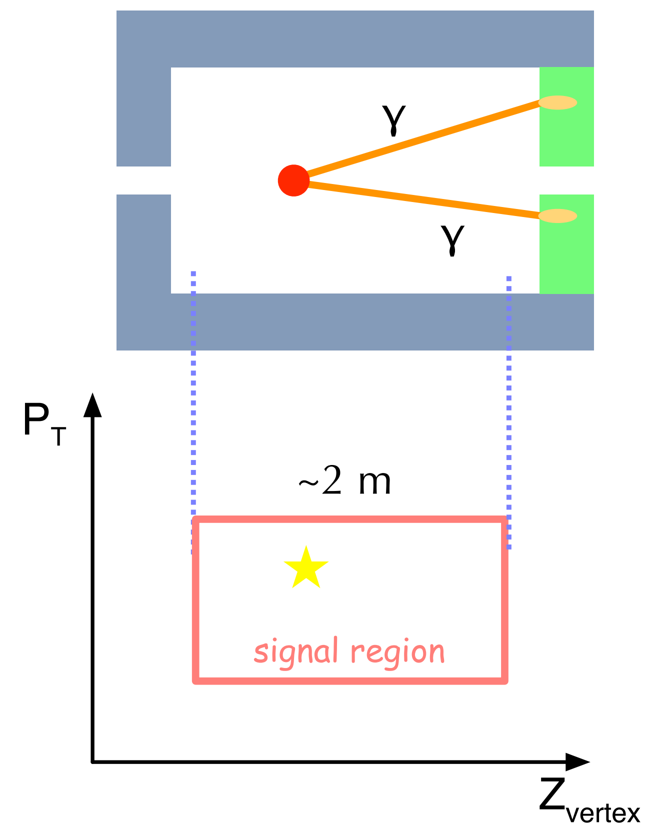
*Ahn et al, Phys Rev D 74, 051105(R) (2006)

The experimental signature is two photons from a single neutral pion and missing transverse momentum.



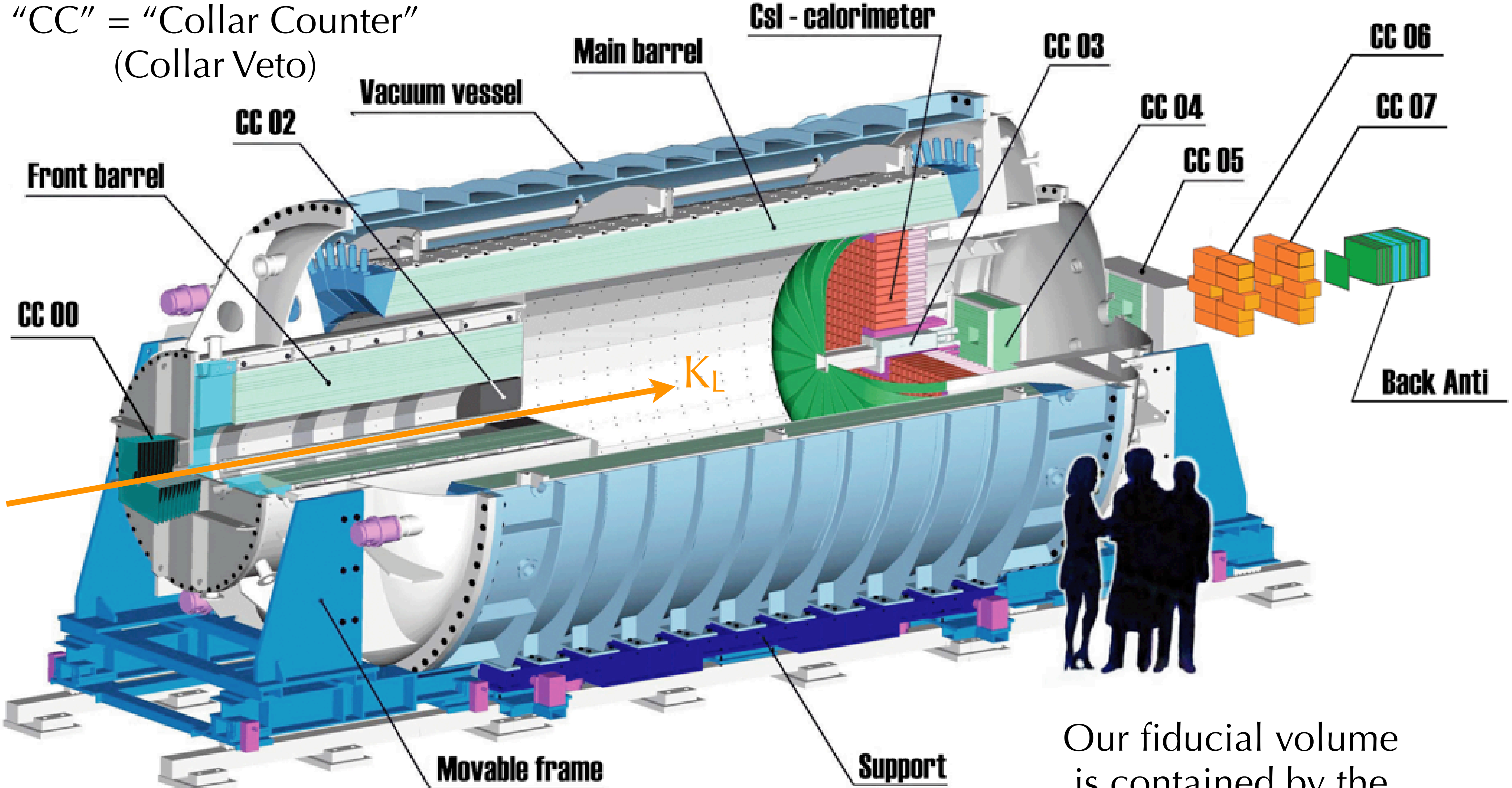


- A tightly collimated *pencil beam* restricts the Kaon vertex.
- A full 4π-coverage hermetic veto system identifies events with final state particles that miss the calorimeter.
- Our signal box is defined by the reconstructed π^0 vertex and transverse momentum (P_T).



The E391a Detector:

"CC" = "Collar Counter"
(Collar Veto)



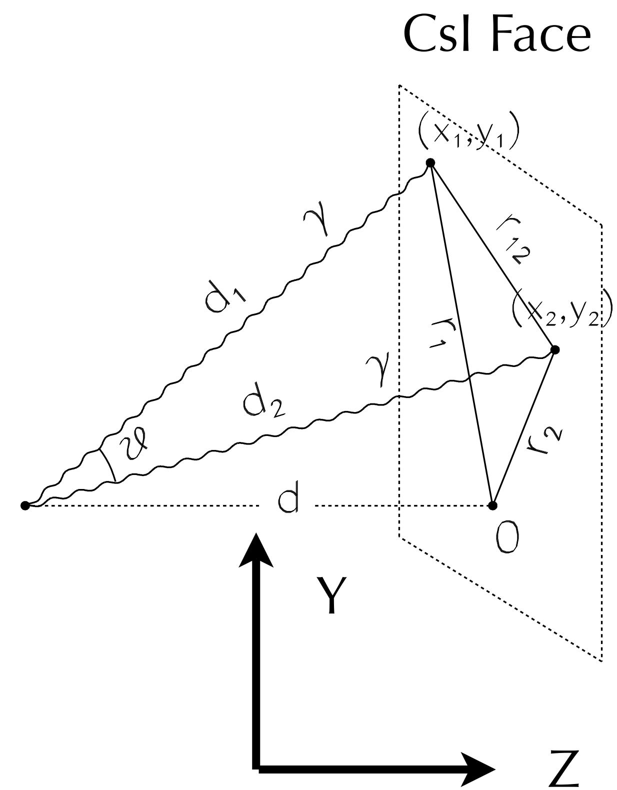
Our fiducial volume is contained by the Main Barrel (MB).

(~12 m back to the target.)

Our veto counters are primarily lead-scintillator sandwiches.

Kaon Reconstruction & Cuts

- First we pair photons and reconstruct the (π^0/K) vertex by assuming the correct mass and that the decay took place on the beam axis.
- In decays with multiple π^0's we group and sort them in order of agreement in the vertices. When appropriate, we then shift the (x,y) vertex to a center of energy projection from the target.
- We reject events with in-time energy deposition in our veto counters above tightly set thresholds (typically ~1 MeV).
- Finally, we also impose kinematic and photon reconstruction quality cuts.



$$m_\pi^2 = (p_{\gamma_1} + p_{\gamma_2})^2 = 2\,E_1\,E_2 \times (1 - \cos\,\theta)$$

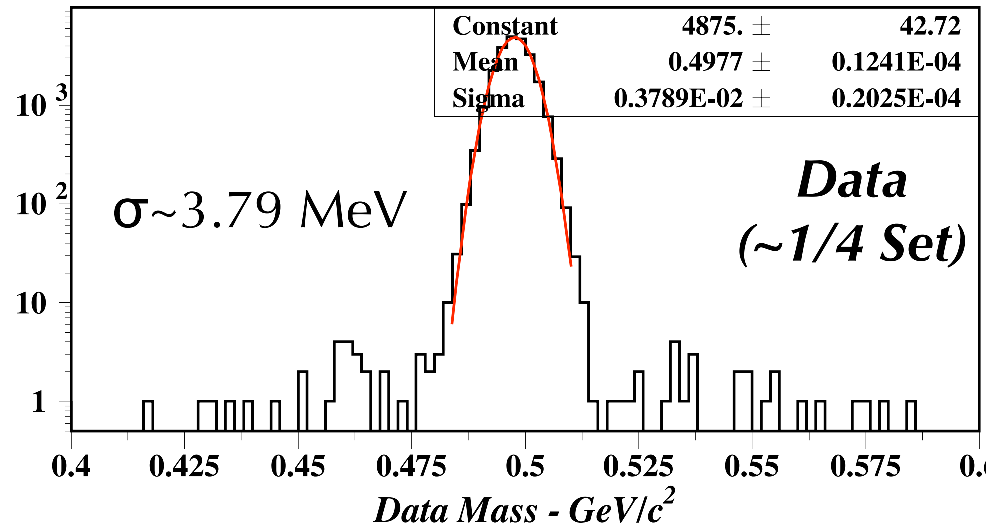
$$r_{12}^2 = d_1^2 + d_2^2 - 2\,d_1\,d_2 \cos\,\theta$$

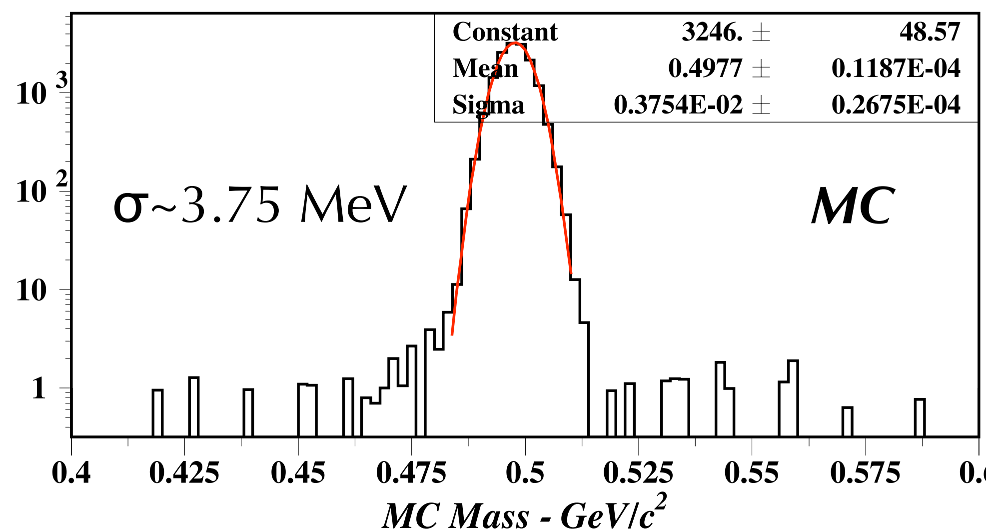
(Low E ⇒ Large ϑ)

- Our MC reproduces our normalization and calibration Kaon modes quite well.
    - We define our systematic error for our flux according to integrals over the disagreements between our MC and Data in the major cut variables.
- Our full detector geometry is implemented in a GEANT3 framework.
- It incorporates accidental activity (underlying events) from the data directly.
- We can match the Kaon mass resolution to the sub-percentage level (3.79 MeV in Data, 3.75 MeV in our MC).

$K \rightarrow \pi^0\pi^0\pi^0$

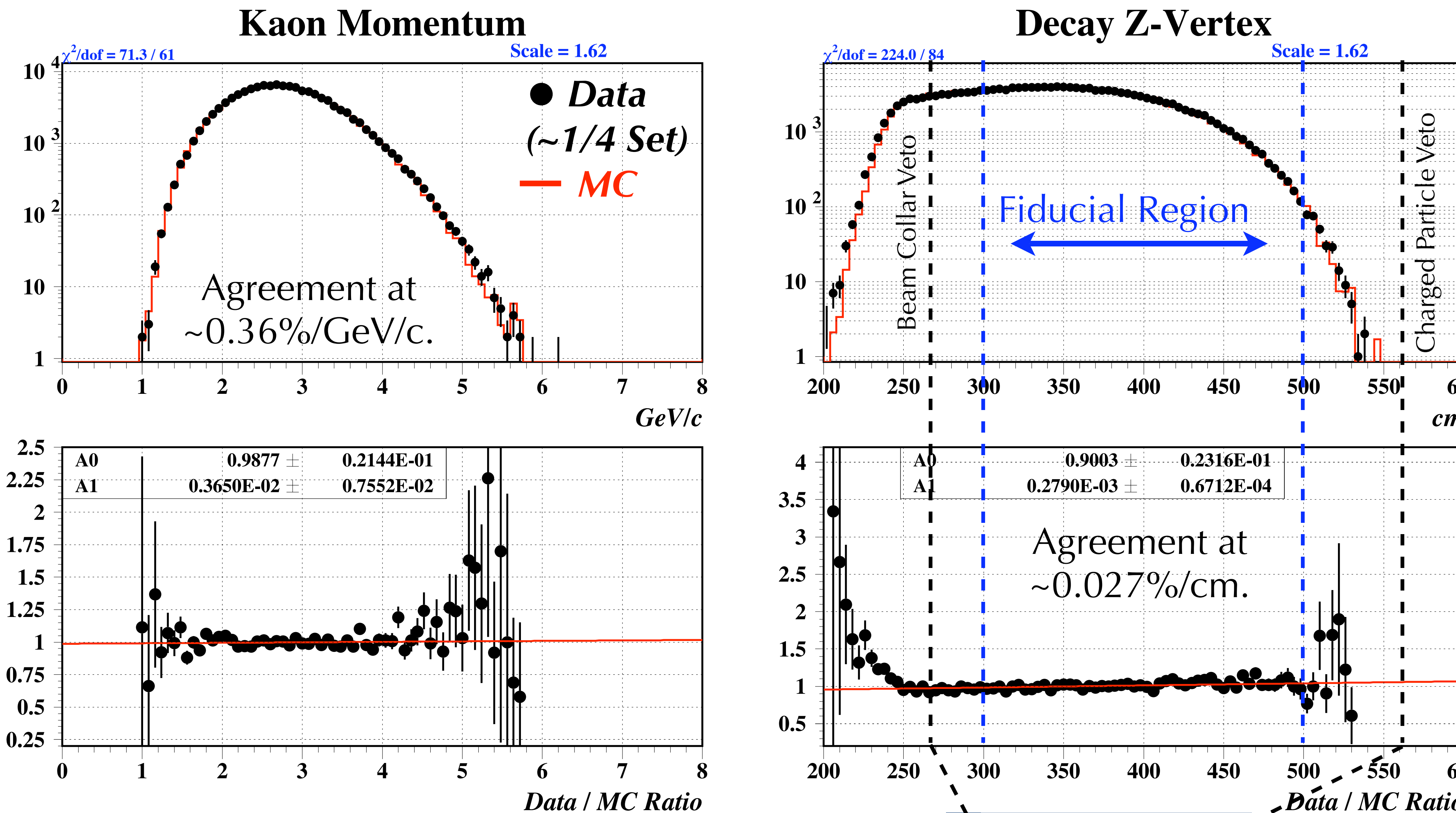
Kaon Mass with All Cuts



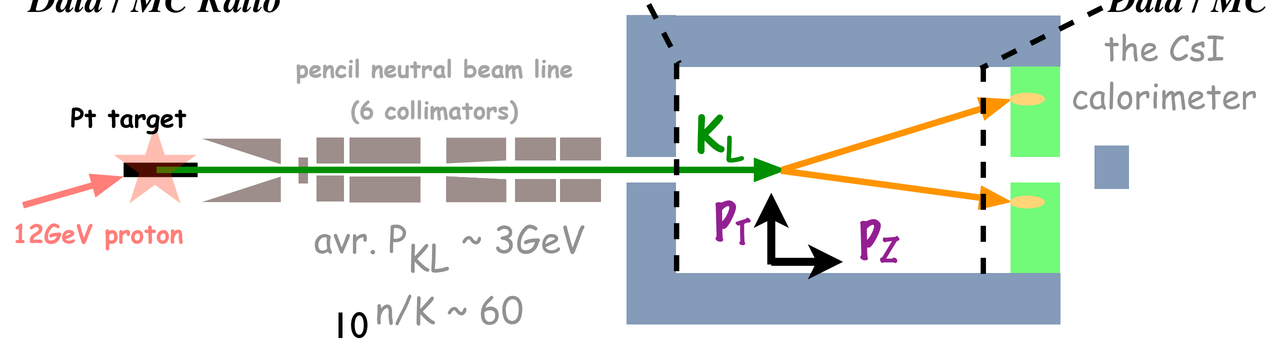


(The ***Data "Set"*** on this and the following pages is ***Run II***.)

$K \rightarrow \pi^0\pi^0\pi^0$

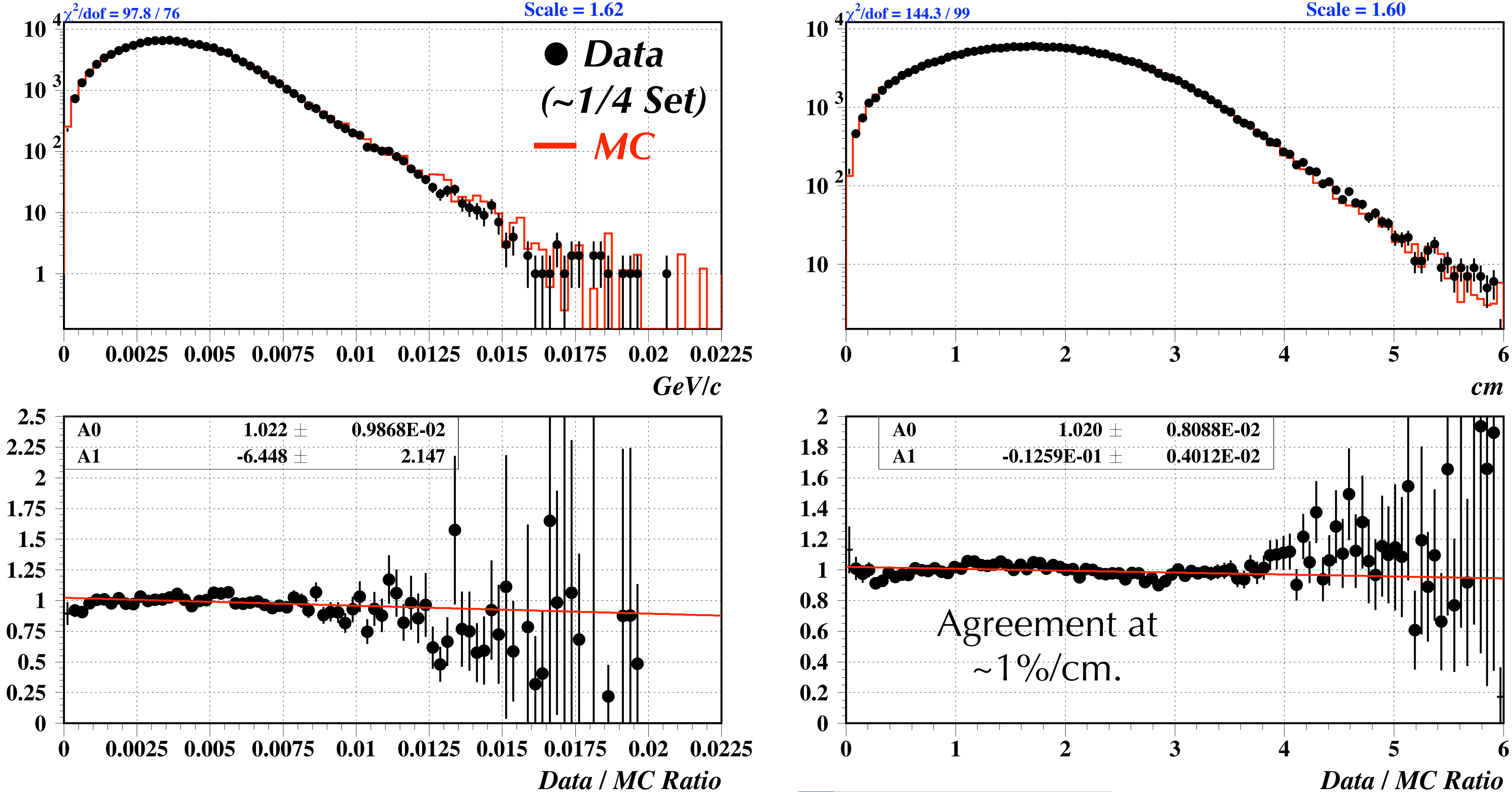


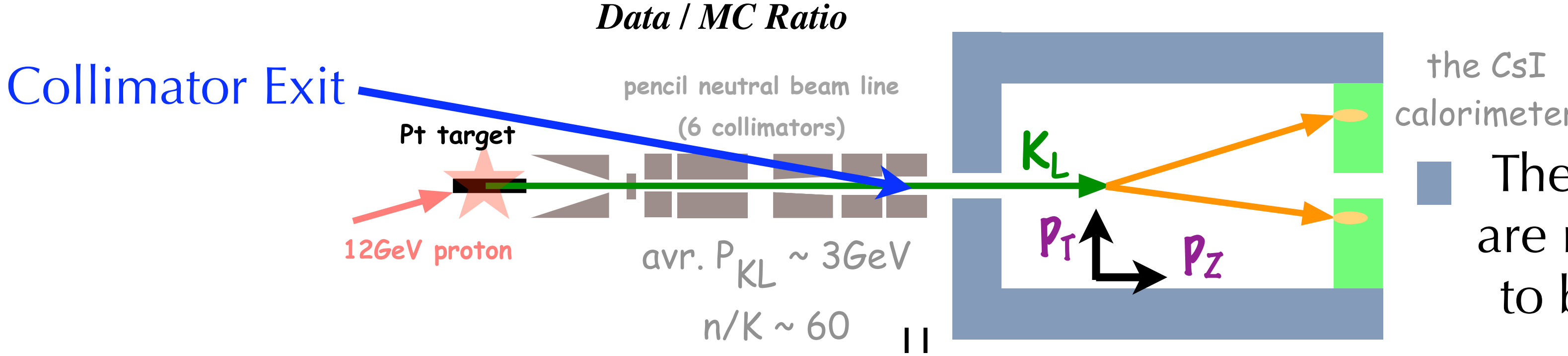
The photon vetoes are relaxed in order to boost statistics.



$K \rightarrow \pi^0\pi^0\pi^0$

Transverse Momentum | **Kaon Radius at Collimator Exit**





The photon vetoes are relaxed in order to boost statistics.

- Here we combine $K \rightarrow \pi^0\pi^0$ and $K \rightarrow \pi^0\pi^0\pi^0$ MC, weighted by sample size and branching ratio, and compare the result to our data.

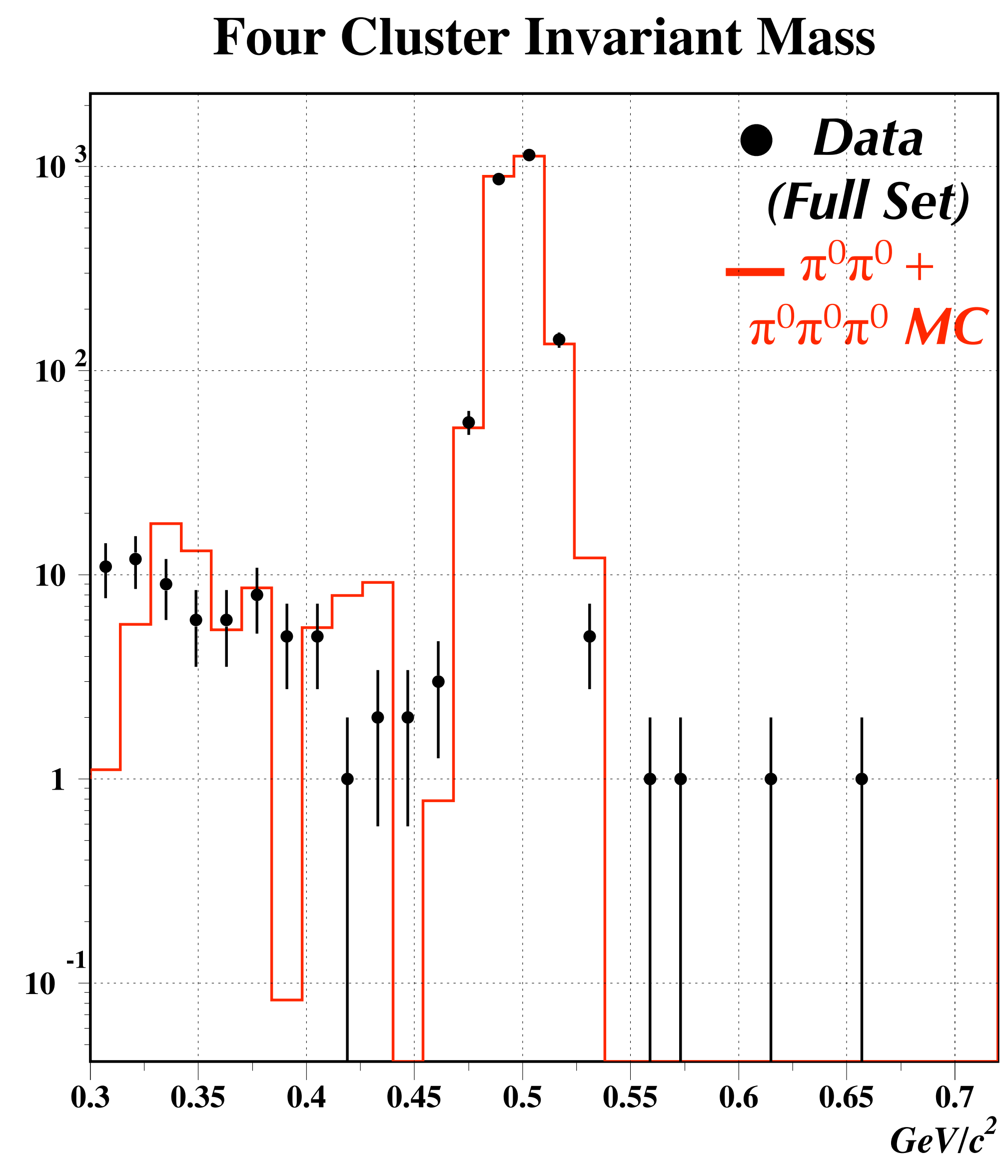
- The plot shown here is normalized to the signal peak.

- The integral sums of the sidebands:

  - Data = 208 events.

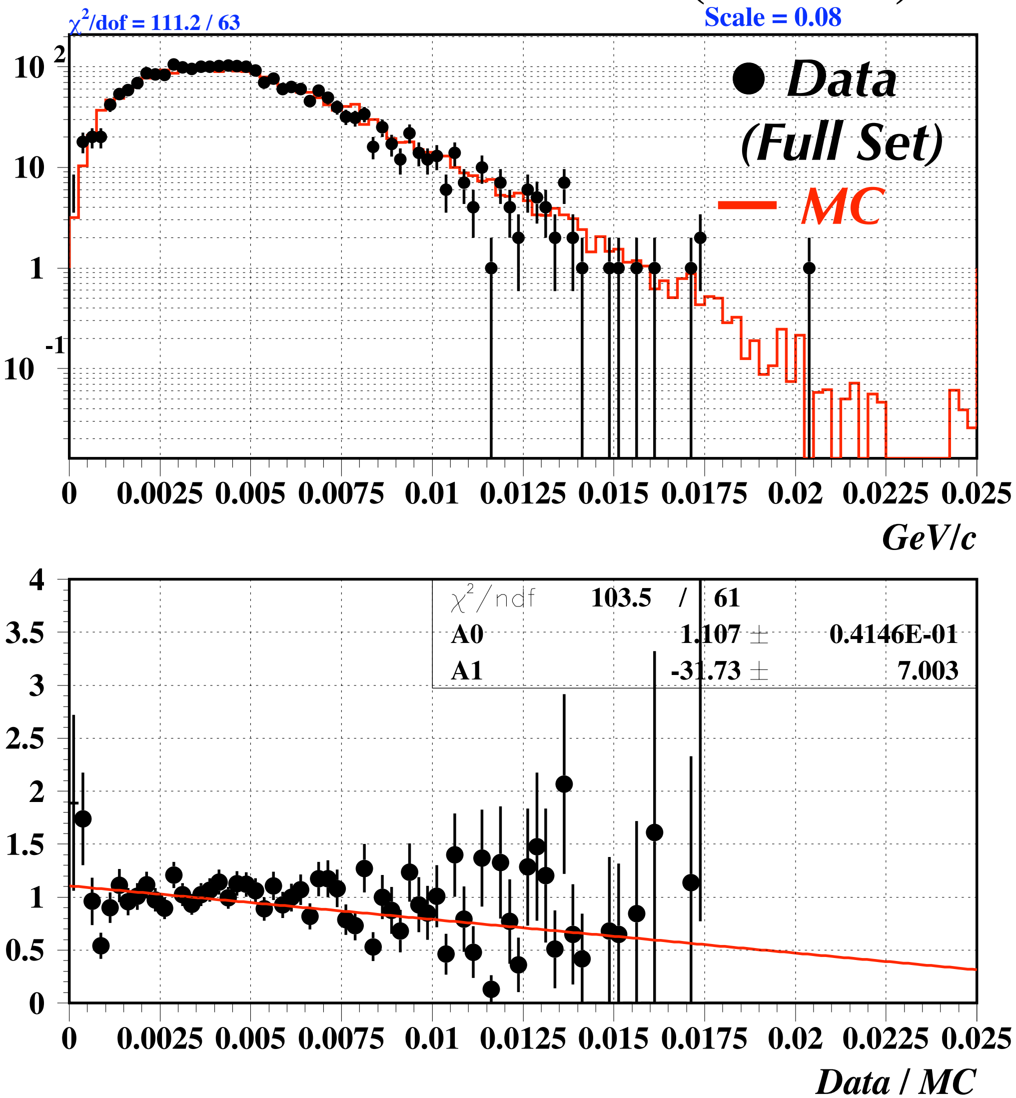
  - MC = 209 ± 23.32 events.

  - Our large error bar is dominated by the re-scaling of our $\pi^0\pi^0\pi^0$ MC - our $\pi^0\pi^0$ MC is ~10x the size of our Data sample, while our $\pi^0\pi^0\pi^0$ MC is only ~10% of our the size of our Data sample.

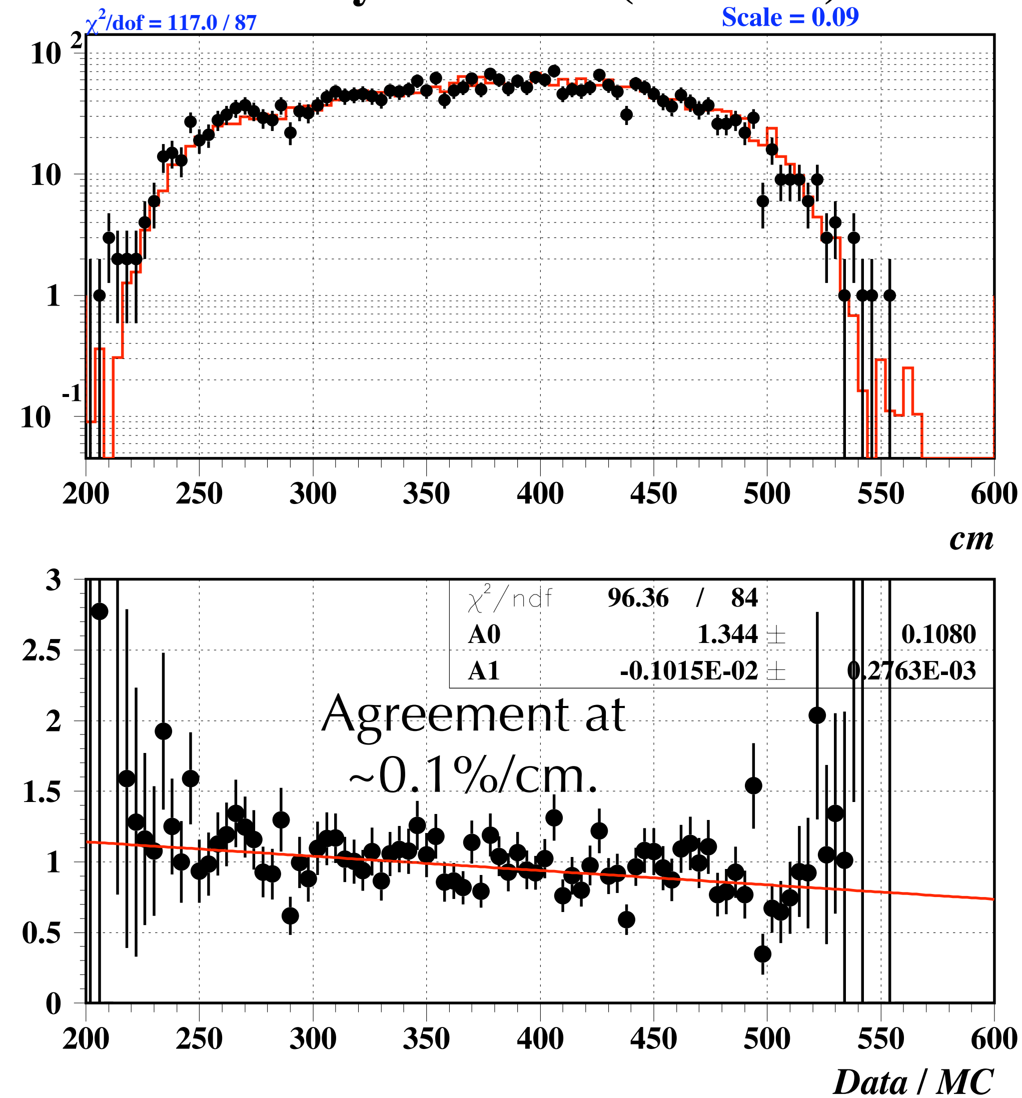


$K \to \pi^0\pi^0 + K \to \pi^0\pi^0\pi^0$

Transverse Momentum (All Cuts)



Decay Z-Vertex (All Cuts)



These are the same four photon events from the previous page (***Data*** & $\pi^0\pi^0 + \pi^0\pi^0\pi^0$ *MC*).

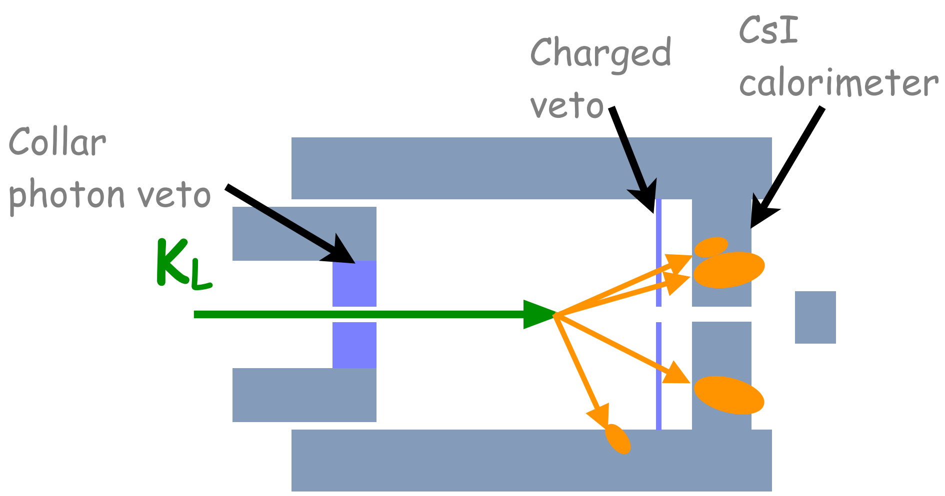
Our flux calculations for our three main normalization & calibration modes agree to ~4%.

Mode	*Acceptance*	*Signal Events in Data (Full Run II Set)*	*Flux (w/o systematic errors)*
$K \rightarrow \gamma\gamma$	$(1.0 \pm 0.0039_{Stat} \pm 0.097_{Syst})\%$	28,523 (Signal: 300-500 Z) ($\pi^0\pi^0$ contamination is at the 10^{-4} level → Neglected.)	***Agreement at ~3.4%*** $(5.1 \pm 0.50) \times 10^9$
$K \rightarrow \pi^0\pi^0$	$(4.5 \pm 0.032_{Stat} \pm 0.61_{Syst}) \times 10^{-4}$	2,081 (Signal: 497-3x5.2 MeV to 497 + 3x5.2 MeV) ($\pi^0\pi^0\pi^0$ contribution ~4 events.)	***$(5.4 \pm 0.74) \times 10^9$***
$K \rightarrow \pi^0\pi^0\pi^0$	$(9.6 \pm 0.092_{Stat} \pm 0.11_{Syst}) \times 10^{-5}$	95,549 (Signal: 497-3x5.2 MeV to 497 + 3x5.2 MeV) (Background contamination is at the 10^{-4} level → Neglected.)	***Agreement at ~4.3%*** $(5.1 \pm 0.57) \times 10^9$

Our error is dominated by a systematic uncertainty in the acceptance loss for the Main Barrel veto and the CsI veto (the CsI fills both calorimeter and veto roles).

Kaon Backgrounds

- E391a integrates down into nothing more than an extremely demanding exercise in background rejection.
- The two major potential background sources for our experiment are other K_L decays and by-products from the interactions of beam-halo neutrons (see T. Sumida's presentation).
- Because our signal final state contains missing particles, other Kaon modes become backgrounds to $K_L \to \pi^0\nu\nu$ by forming two clusters in our calorimeter with some transverse momentum and with other daughter particles ending up outside the calorimeter.



For example, $K \to \pi^0\pi^0$ becomes a background whenever two photons escape identification if we cannot veto the event. In that case, the remaining signature is a single π^0 with missing P_T.

For *E391a Run II* flux and sensitivity...

$K \rightarrow \pi^0\pi^0$	0.17 ± 0.13 Events
$K \rightarrow \pi^{\pm}e\upsilon$	Negligible*
$K \rightarrow \pi^+\pi^-\pi^0$	Negligible*
$K \rightarrow \gamma\gamma$	Negligible

*For a charged veto inefficiency of $\sim 10^{-2}$. Beam-line muon studies suggest an upper limit on the charged veto inefficiency well below this.

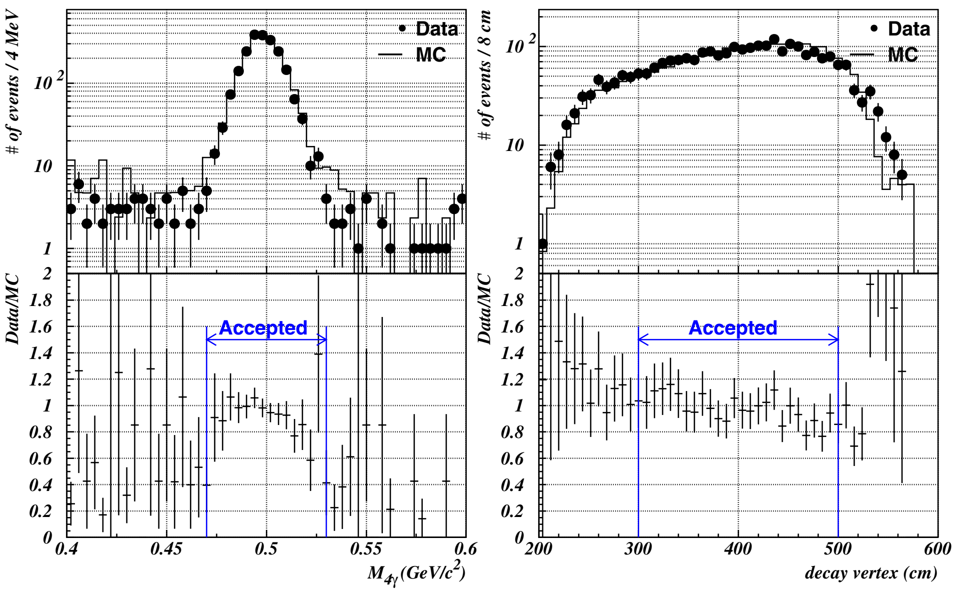
$K \rightarrow \pi^0\pi^0$ is our only truly threatening Kaon background. The largest problem at our current sensitivity is not inefficiency in our veto counters. Instead, because our CsI array is simultaneously a bit more granular and thin than we would like (7 cm^2 by ~15 Radiation Lengths in the bulk) we are being hurt by photon fusion and by EM shower leakage and photon punch-through. Future $K_L \rightarrow \pi^0\upsilon\upsilon$ should be able to avoid these issues.

Conclusions

- We understand the behavior of our detector to high order and believe our MC simulation is providing a capable description of known Kaon interactions.
- Given our encouraging progress, we hope to announce a result sometime this year.
- Thank you for your attention!

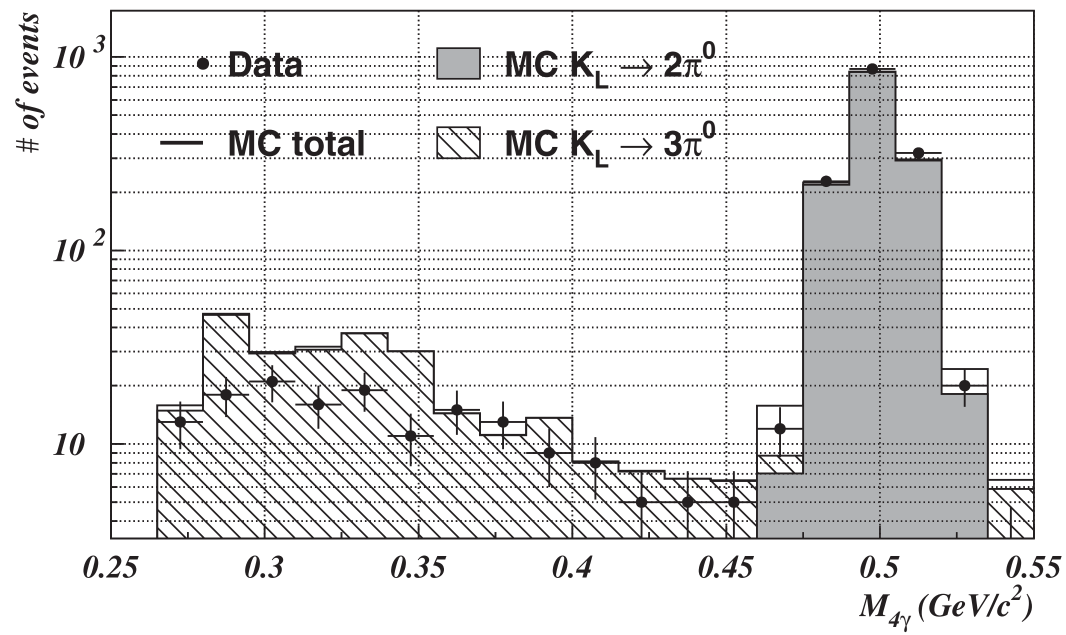
Back-Up Slides

PHYSICAL REVIEW D **74,** 051105(R) (2006)

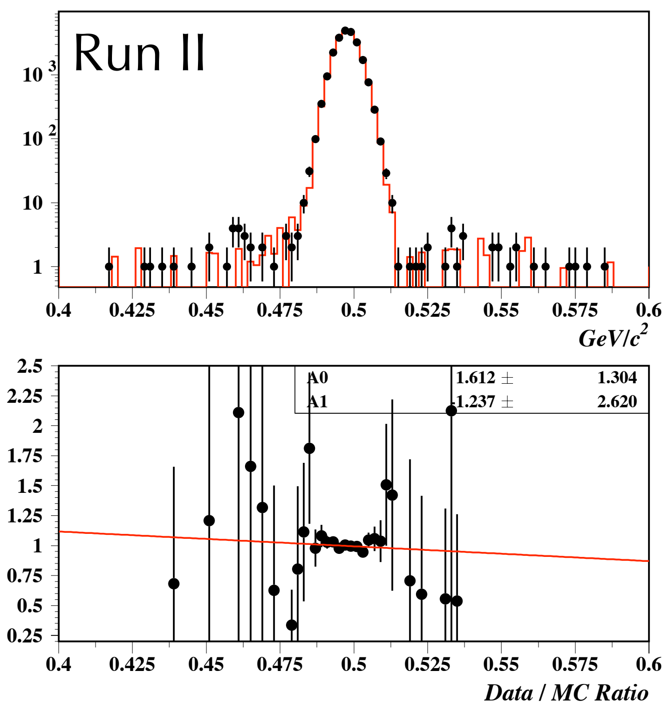


Run I

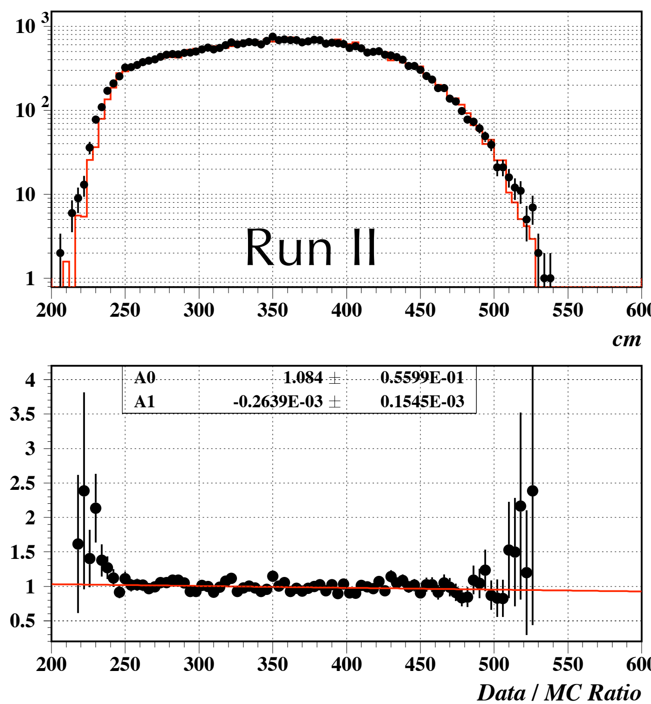
PHYSICAL REVIEW D **74,** 051105(R) (2006)



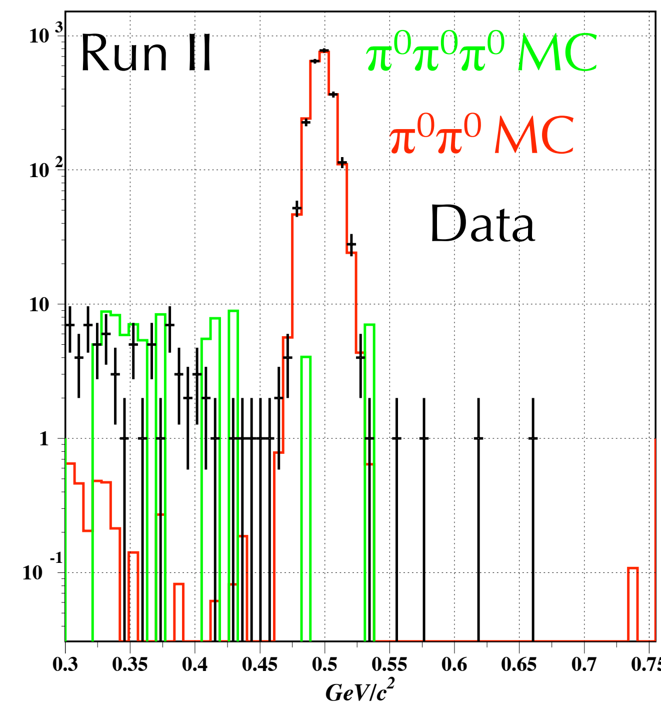
Kaon Mass with All Cuts



Decay Z-Vertex (All Cuts)

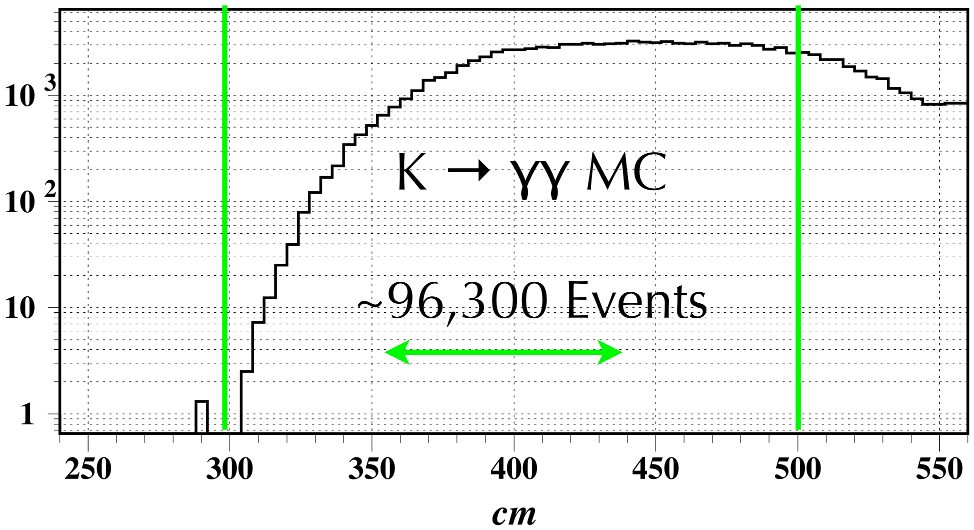


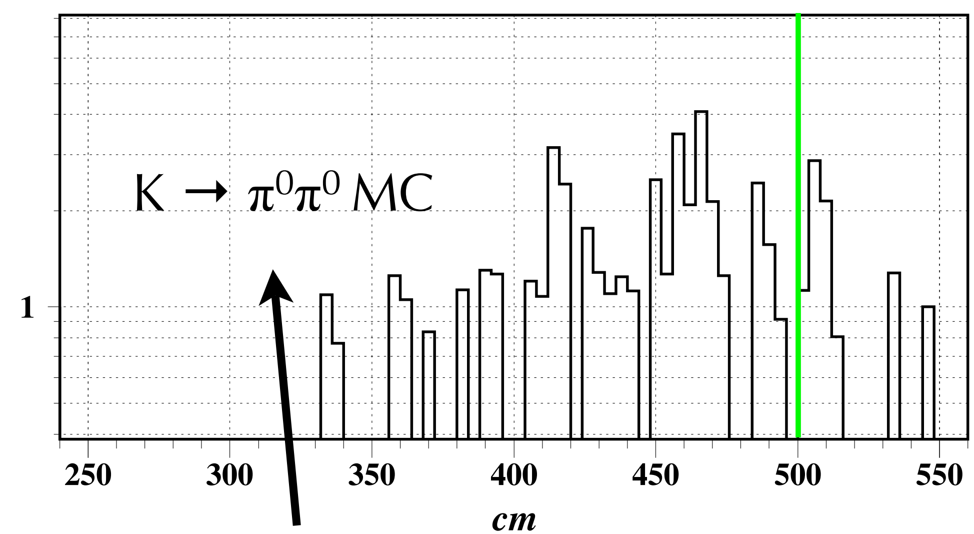
Four Cluster Invariant Mass



Reconstruction is performed by assuming the Kaon mass.

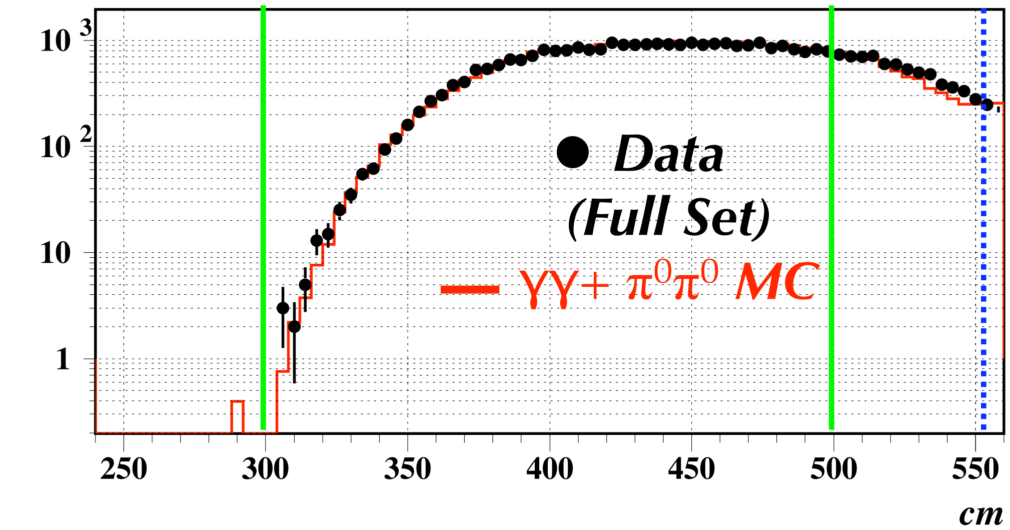
Two Cluster Z-Vertex Spectrum (All Cuts)

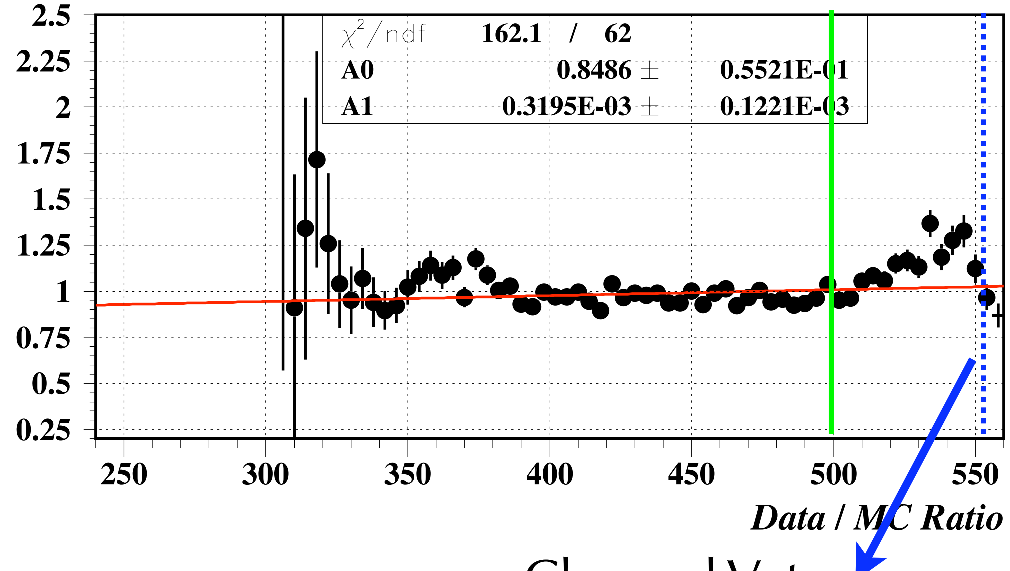




44.8 $\pi^0\pi^0$ Events
(10.6 Scaled by MC sample & Branching Fraction)

Two Cluster Z-Vertex Spectrum (All Cuts)





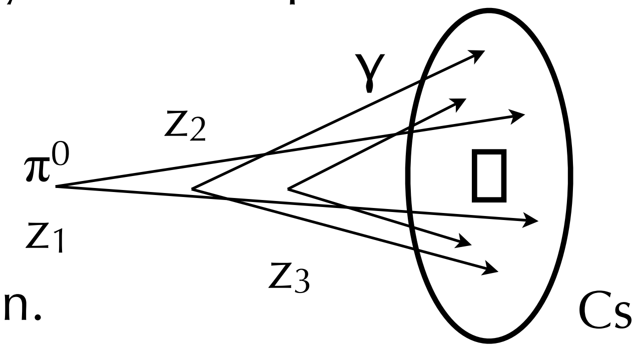
Charged Veto
(Online veto at ~1 MeV not included in the MC.)

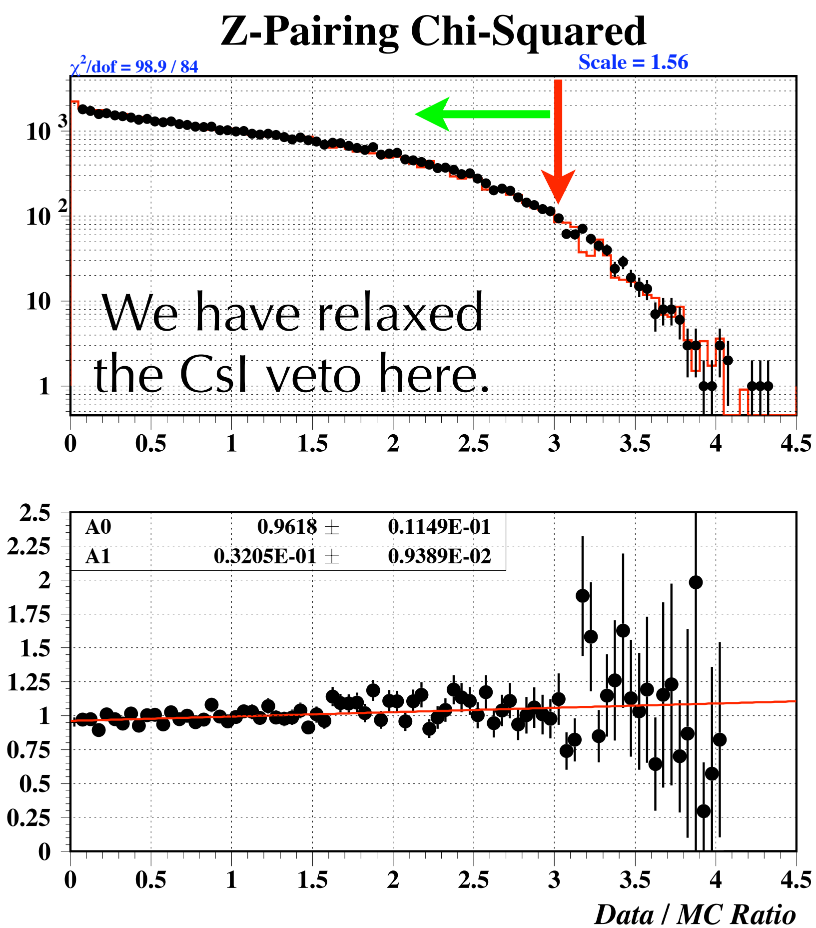
The pairing χ^2 is sensitive to the position and energy resolution.
This cut ends up imposing a relatively small acceptance loss.

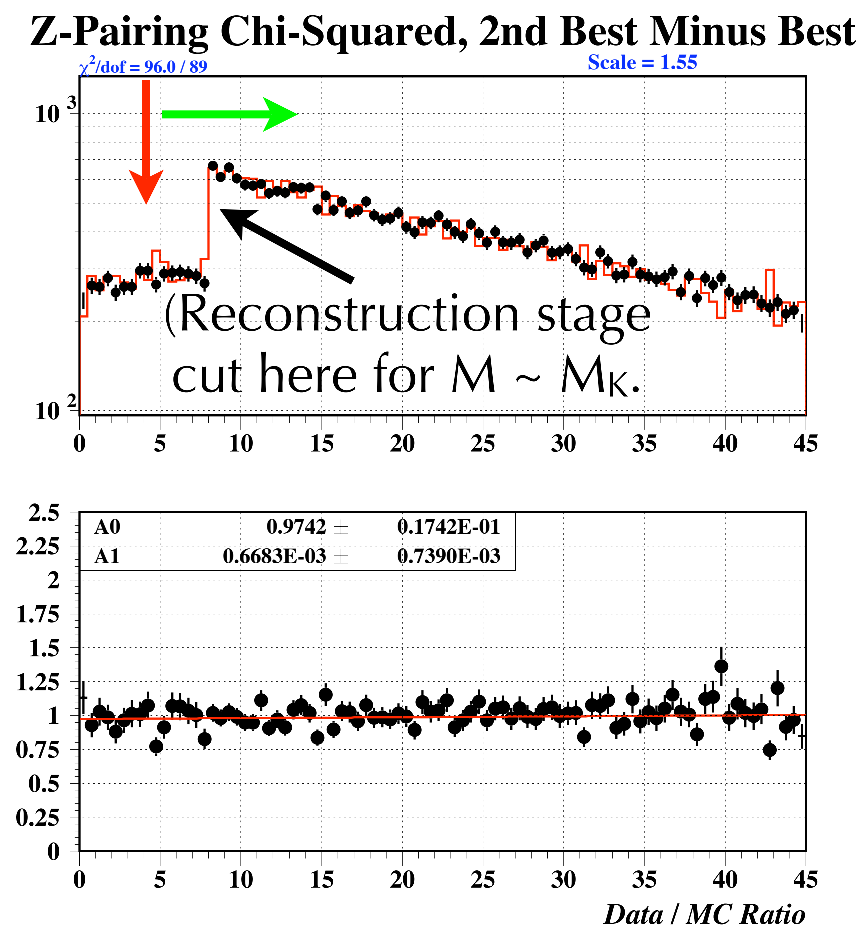
$$\chi^2 = \sum_{i=1}^{3} \frac{(z_i - \bar{z})^2}{\sigma_i^2}$$

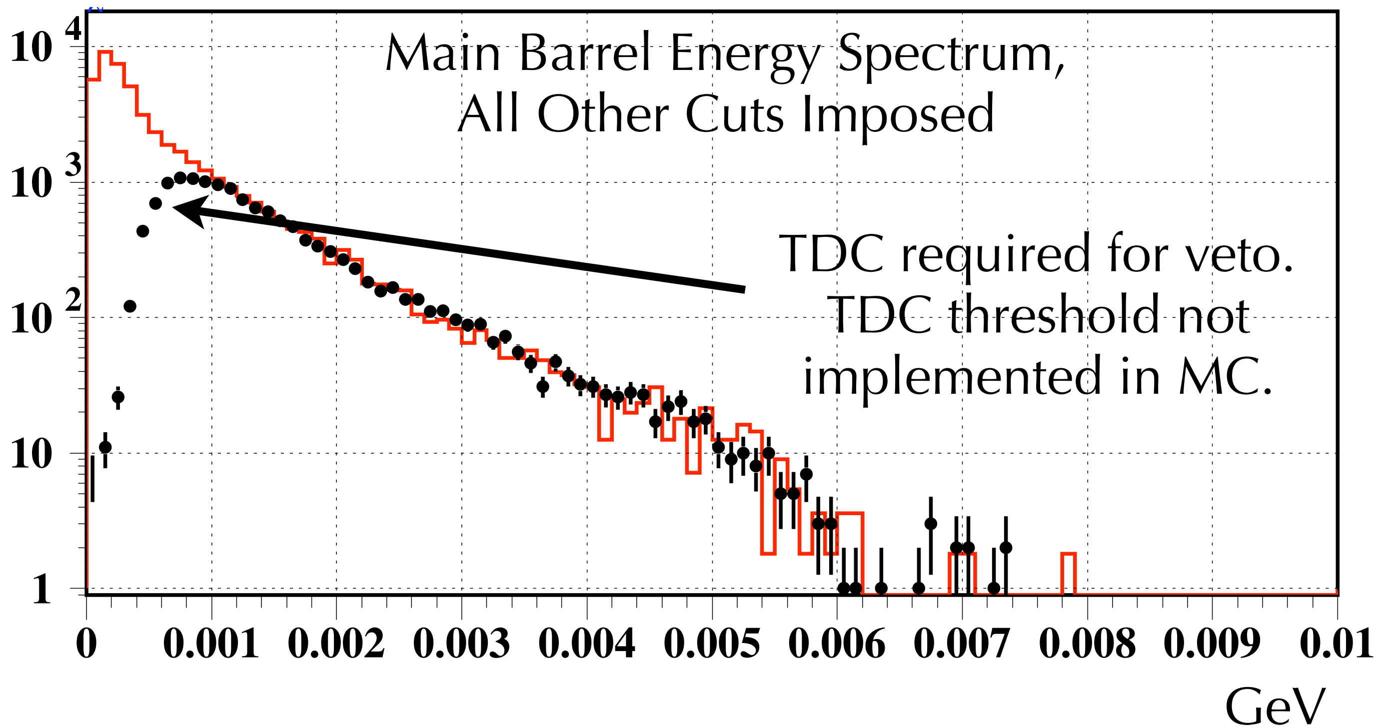
$$\bar{z} = \frac{\sum_i z_i/\sigma_i}{\sum_i 1/\sigma_i}$$

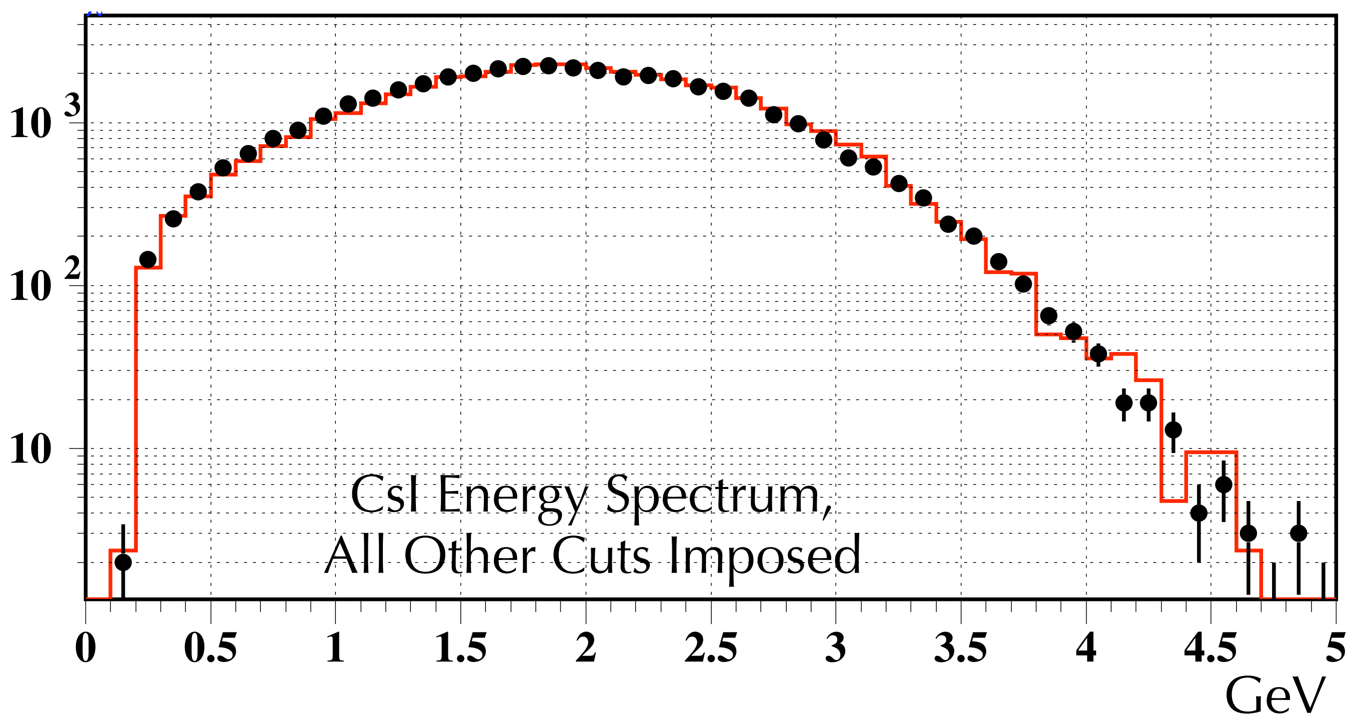
σ is a function of the energy and position resolution.







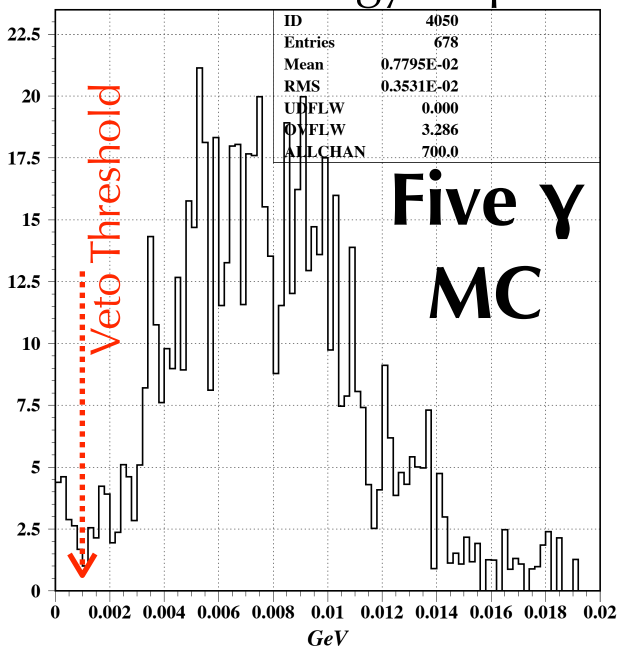

Main Barrel Energy Spectrum,
All Other Cuts Imposed
TDC required for veto.
TDC threshold not
implemented in MC.
GeV


CsI Energy Spectrum,
All Other Cuts Imposed
GeV

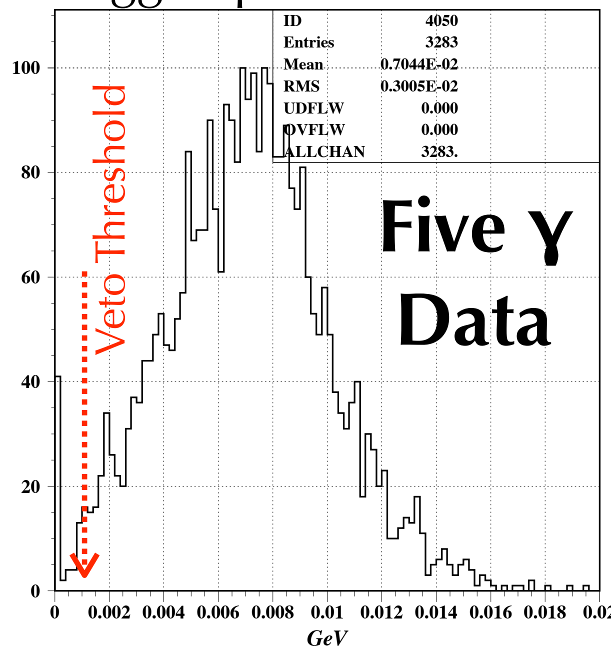
In-situ photon veto inefficiency estimation for the MB with five cluster $K \rightarrow \pi^0\pi^0\pi^0$ events:

The sub-MeV shape is dominated by the TDC threshold: ~0.9 MeV in Data and ~0 in the MC.

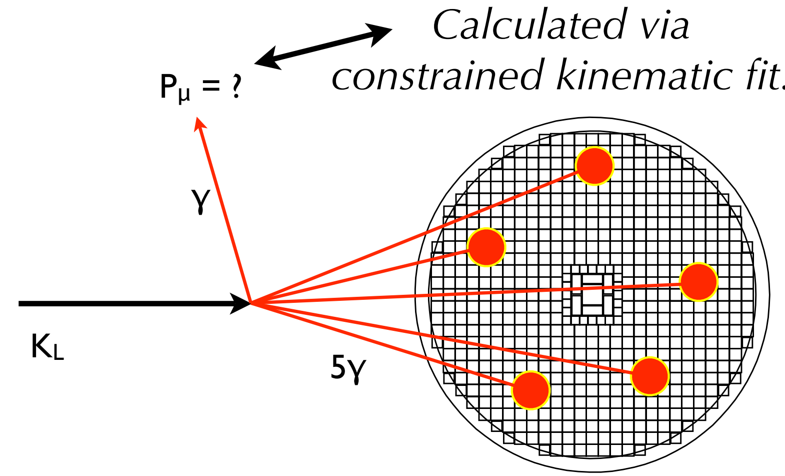
MB energy response for tagged photons.



Integration below 1 MeV = 16.2 Events.



Integration below 1 MeV = 64 Events.



Within the MC, the events that fail our veto threshold are those for which *we have not tagged their directions correctly*.

Therefore "inefficiency" in the MC is purely due to mis-reconstructions. We will look for an excess of sub-threshold events in data.

We expect from the MC to see 78.4 ± 19.7 sub-threshold events, and see only 64. (We see no excess over our predicted tagging failure rate.)

If we subtract this "background" we might choose to set some limit on our inefficiency for the Main Barrel at:

~8 x 10^{-4} at the 90% CL.

Very preliminary!