Physics Motivation
- Features of this decay mode
  - "direct" CP violating process
  - measures $\eta$ in CKM matrix
  - small theoretical uncertainty
    - a few %: called as "gold-plated" mode
  - rare decay: $2.5 \times 10^{-11} \ @ \ SM$
- Comparison to the measurement in B-system
  - precise check of $\Sigma$-model
  - probe to NP

E391a Experiment
- Measures $K_L \rightarrow \pi^0 \nu \bar{\nu} \ @ \ KEK \ 12\text{GeV} \ PS \ (Japan)$
  - first dedicated experiment to this decay mode
  - pilot experiment for $K^0\rightarrow\pi^0\eta$ (U-PARC E14)
  - physics runs are taken in 2004-2005

Detection Principle
- To identify $K_L \rightarrow \pi^0 \nu \bar{\nu}$ state
  - $2\gamma \rightarrow \gamma^* \gamma \ cannot \ detect$
- To say "2$\gamma$ + nothing"
  - $2\gamma \rightarrow \text{Csl calorimeter \ (energy, \ position)}$
  - nothing $\rightarrow$ hermetic veto detector
  - Reconstruect decay vertex with $M(\pi^0)$:
    $M(\pi^0)^2 = 2E_1E_2(1 - \cos \theta)$
    $\rightarrow$ "pencil" beam to improve pt resol.
  - select signal using decay vertex and transverse momentum

What makes background?
- Halo neutron BG: the dominant BG
  - neutron flux surrounding beam core hits detector around beam
    $\rightarrow$ creates $\pi^0$ or $\eta$ ($\rightarrow 2\gamma$)

Background Estimation
- Halo neutron BG was estimated by FLUKA simulation
  - $\pi^0$ & $\eta$ production rate was confirmed by a dedicated run
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Results & Summary
- Opening the signal box for the final data sample
  - Statistics
    - $(8.70 \pm 0.61) \times 10^6 \ K_L \ decays$
    - estimated by $K_L \rightarrow 2\pi^0$
  - event sample

Optimized Event Selection
- Event selection was optimized from our previous analysis
  - introduced new selections on the Csl crystal hit pattern

Acceptance: $0.67\% \rightarrow 1.04\% \ (+50\%)$ with keeping the S/N as same level

E391a Final Upper Limit
$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \ @ \ 90\% \ C.L.$

- Improvements
  - $\times 20$ from previous experiment (kTeV)
  - $\times 2.6$ from our previous result