Search for a light pseudoscalar particle in the decay $K_L^0 \rightarrow \pi^0 \pi^0 X$ at the KEK-PS E391a experiment

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Yu-Chen Tung (National Taiwan Univ.)

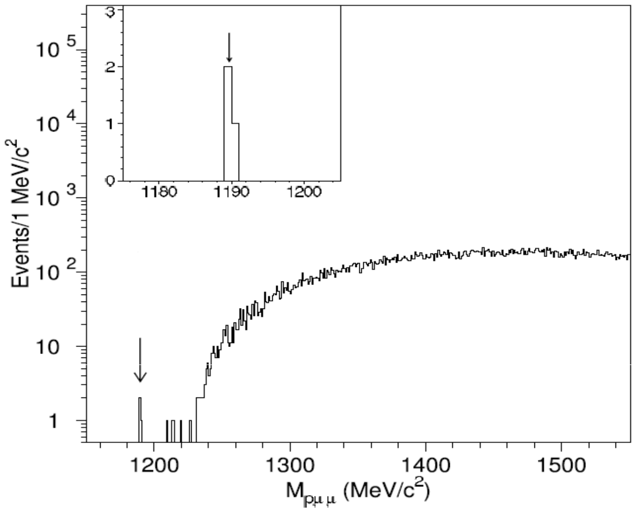
Outline

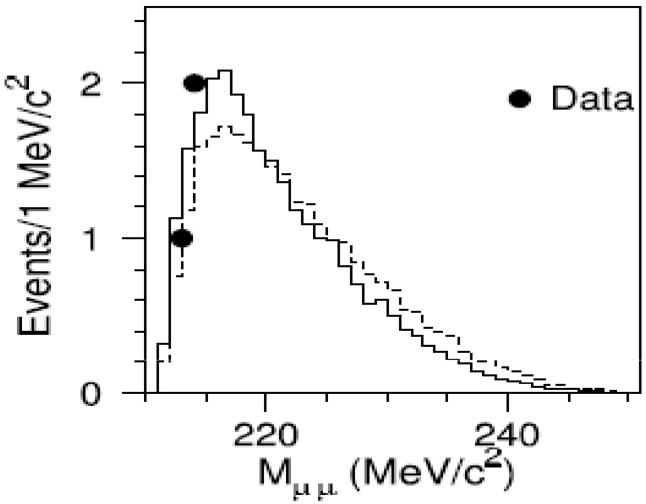
Introduction
- Motivation
- Theoretical model
- E391a experiment

Analysis
- Reconstruction
- Background study
- Results

Motivation: HyperCP observation

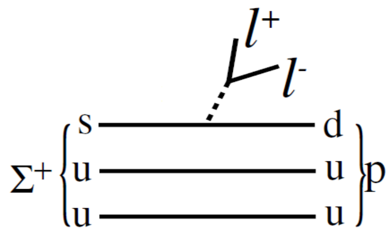
H. K. Park et al. PRL 94, 021801





- HyperCP experiment observed 3 events for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays with a narrow $M_{\mu\mu}$ distribution around 214.3 MeV
  - Probability to have the $M_{\mu\mu}$ distribution within 1 MeV less than 1%

- Signal interpretation: $\Sigma^+ \rightarrow p\ X,\ X \rightarrow \mu^+\mu^-$



GMSB model for X

D. S. Gorbunov and V. A. Rubakov, PRD 73, 035002

The GMSB (Gauge Mediated SUSY Breaking) model said

- Spontaneous SUSY breaking generates Goldstone fermion, called Goldstino, which gives the longitudinal component of gravitino.
- There should exist superpartners of Goldstino: sgoldstinos
- Mass of sgoldstino is arbitrary and can be only a few MeV

And shows HyperCP observation is consistent in model with

- Parity conservation in sgoldstino interaction
- m_X is in reasonable pseudoscalar sglodstino mass region
- Low SUSY breaking scale $\sqrt{F}$=2.5-60 TeV

GMSB model for X

D. S. Gorbunov and V. A. Rubakov, PRD 73, 035002

For X with mass = 214.3 MeV in GMSB model:

- Possible decay channels: $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$ & gravitinos.
- X's BR is almost saturated by $\gamma\gamma$, $\mu^+\mu^-$ channels.
- $BR(X \to \gamma\gamma) / BR(X \to \mu^+\mu^-) \sim 10^4$.
- The lifetime of X is generally small: $c\tau$ = 0.02 - 0.0002 cm.

$$\Gamma(P \to \gamma\gamma) = \frac{m_P^3 M_{\gamma\gamma}^2}{32\pi F^2}$$

$$\Gamma(P \to \mu\bar{\mu}) = \frac{m_P m_\mu^2 A_\mu^2}{16\pi F^2}\left(1 - \frac{4m_\mu^2}{m_P^2}\right)^{1/2}$$

GMSB model for X

Possible neutral Kaon decays for probing X

D. S. Gorbunov and V. A. Rubakov, PRD 73, 035002

The GMSB model shows:

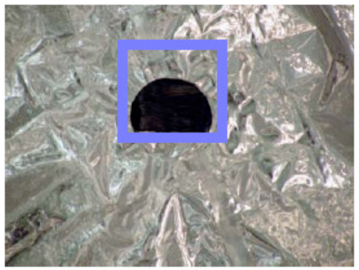
- $BR(K_L^0 \rightarrow \pi^0 \pi^0 X)$ is proportional to $Re[h^{(D)}_{12}]$
- $h^{(D)}_{12}$ is complex coupling constant only its absolute value known
- if $Re[h^{(D)}_{12}] = h^{(D)}_{12}$,
  $BR(K_L^0 \rightarrow \pi^0 \pi^0 X, X \rightarrow \gamma\gamma) = 1.2\text{x}10^{-4}$
  $BR(K_L^0 \rightarrow \pi^0 \pi^0 X, X \rightarrow \mu^+\mu^-) = 1.2\text{x}10^{-8}$
- No other mode made the prediction for this decay

The E391a experiment

The experiment was located at the KEK 12 GeV proton-synchrotron in Tsukuba, Japan.

- ✓ ~50 members from 14 institutions
- ✓ Japan, the US, Taiwan, South Korea, and Russia are participants.

a photo of the membrane

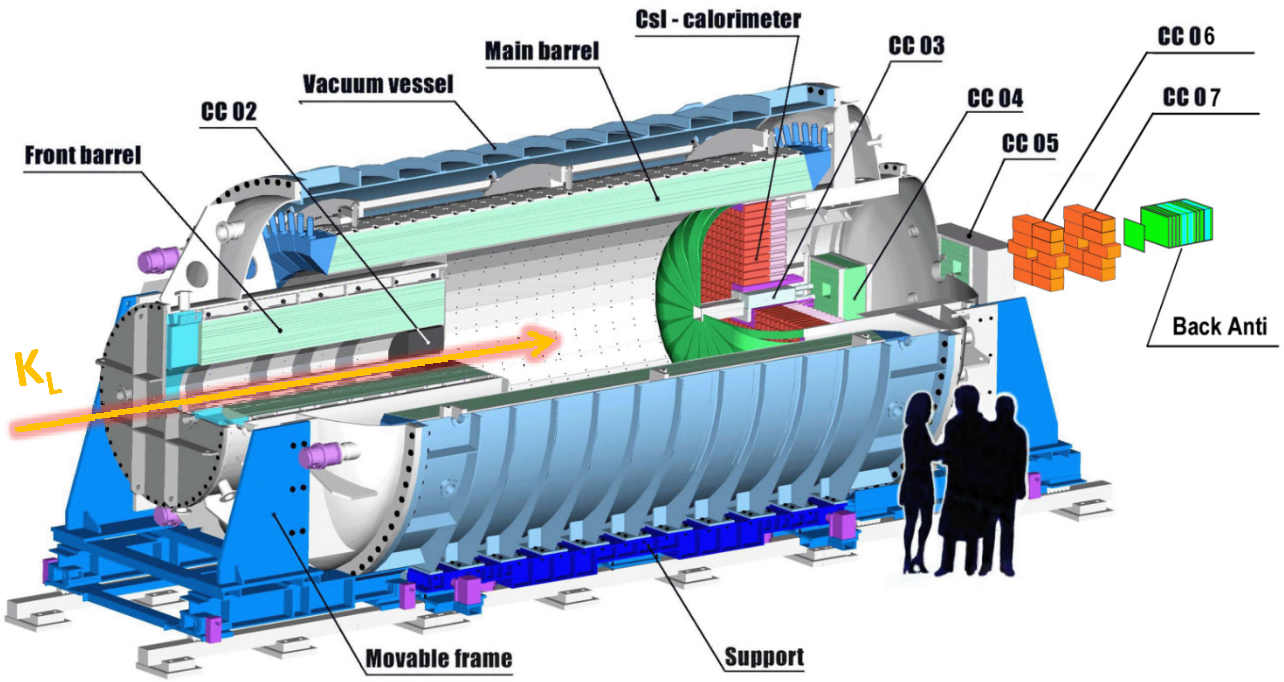


Three main Data Runs:

- Run I: February – July of 2004
  - ✓ discarded due to a membrane problem
- Run II: February – April of 2005
  - ✓ published results of $K_L^0 \rightarrow \pi^0 \pi^0 X, X \rightarrow \gamma\gamma$ analysis
- Run III: October – December of 2005

The E391a Detector

- Use CsI calorimeter for photon detection (7x7x30 cm^3)
- Veto detectors cylindrically cover the CsI calorimeter
- No momentum-measurement + we use charged veto before CsI
  - ✓ Hard to measure $K_L^0 \rightarrow \pi^0 \pi^0 X$, $X \rightarrow \mu^+ \mu^-$



$K_L^0 \to \pi^0 \pi^0$ X, X $\to \mu^+\mu^-$ analysis

Challenge to measure the decay using the upgraded BA in run-III.

(Lead plate + plastic scinti. + quartz

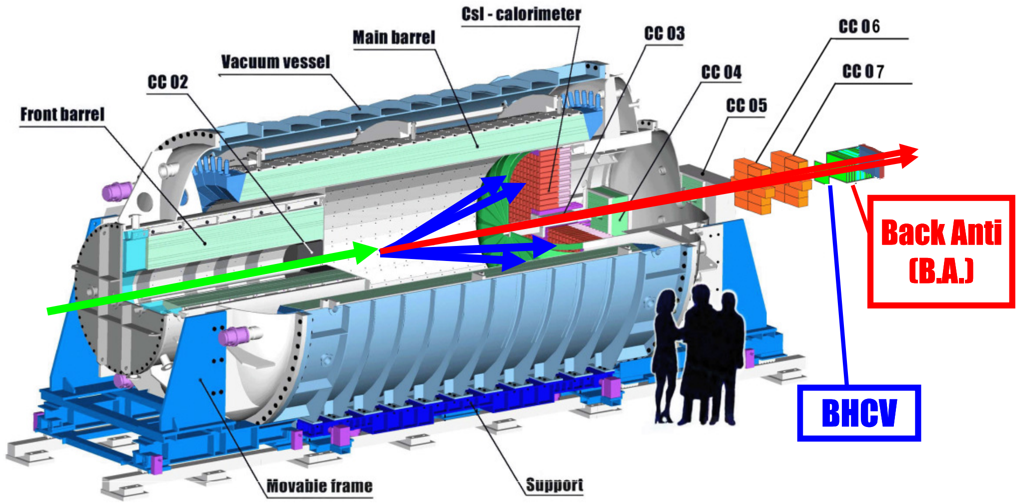
$\to$ PWO crystal + quartz)

- Small q-values of
  - ✓ $K_L^0 \to \pi^0 \pi^0$ X
  - ✓ X $\to \mu^+\mu^-$
  - $\to$ Small open angle of $\mu^+\mu^-$

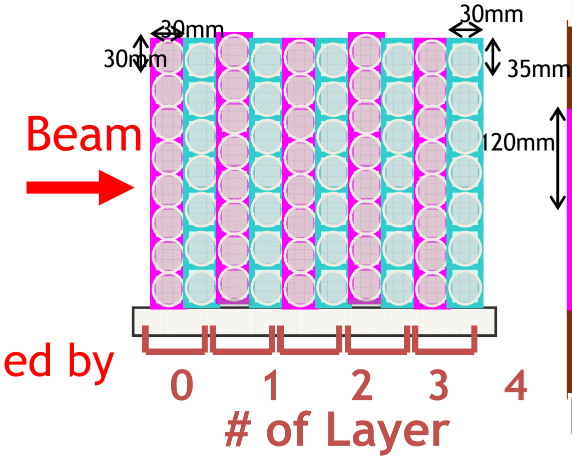
- Signal is signatured by
  - ✓ 4 photons on CsI
  - ✓ 2 muons in BA & BHCV

- UP (90% C.L.) <1.7 x 10^{-6}

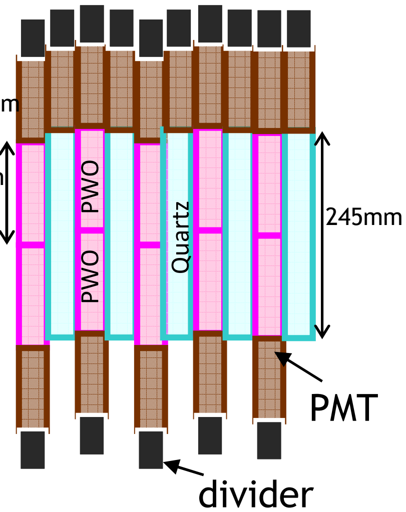
$K_L^0 \to \pi^0 \pi^0$ X, X $\to \mu^+\mu^-$ analysis is performed by Risa Ogata from Saga University.



Side view of B.A



Upper view of B.A



$K_L^0 \rightarrow \pi^0 \pi^0 X, X \rightarrow \gamma\gamma$ analysis:

Monte Carlo & Signal signature

Both K3pi0 & K2pi0X MC were simulated using GEANT3 and were overlaid with accidental events taken from the target-monitor accidental trigger.

$K_L^0 \rightarrow \pi^0 \pi^0 X, X \rightarrow \gamma\gamma$ events are first selected by

- Six photons on CsI calorimeter – the same as K3pi0 decays
- No in-time hits on other detectors

Reconstruction

Event is reconstructed using Constrained Fit to require

- ✓ Six photons to have KL mass x1
- ✓ Two photon pairs to have Pion mass x2
- ✓ The KL momentum from target to COE of photons on the CsI plane x2

$$\chi^2(x_i, y_i, E_i) = \sum \frac{(x_i - x_i^m)^2}{\sigma_x^2} + \sum \frac{(y_i - y_i^m)^2}{\sigma_y^2} + \sum \frac{(E_i - E_i^m)^2}{\sigma_E^2}$$

- 5 constraints
- 3 unknowns: KL decay vertex (Vx, Vy, Vz)
- Two-degree-of-freedom fit
- 45 possible combinations → The combination with Minimum χ^2 is chosen

In successful reconstructions, M_{56} (mass of 3rd gamma pair)

= [Pion mass for K3pi0 decays
X mass for K2pi0X decays

Selection Condition

Photon Veto			
CC02	**CC03**	**CC04**	**CC05**
3 MeV	0.35 MeV	1 MeV	5 MeV
Inner MB	**Outer MB**	**Inner CV**	**Outer CV**
5 MeV	7 MeV	5 MeV	0.3 MeV
FB	**BHCV**	**BA scint.**	**BA quartz**
5 MeV	0.1 MeV	0.06 GeV	1 MIPs

Kinematical Cut	
KL Z region	250 – 550 cm
KL pt	< 25 MeV
Center E of clusters	< 6 cm
Gamma hit pos.	12.5 cm square from beam – 88 cm circle
Gamma fusion	Gamma NN > 0.2
Constrained fit χ^2	< 6

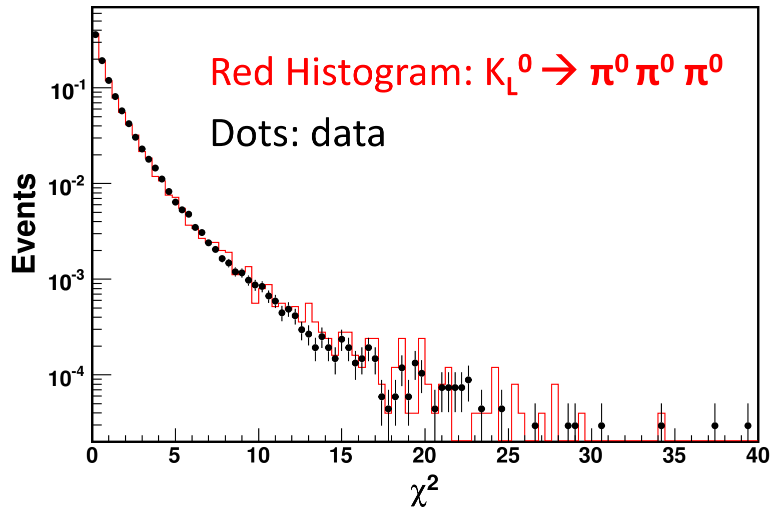
Reconstruction Results

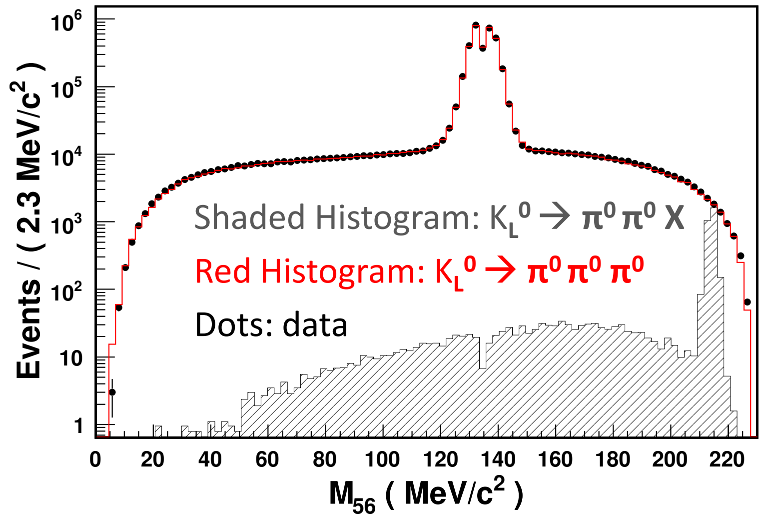
Solution to the dip in the Pion peak:

→ 3 correct combinations for K3pi0 decays.

→ Only the mass of 1st & 2nd gamma pairs is constrained.

→ The combination with minimum χ^2 leaves the worst rec. Pion mass in 3rd gamma pair.





Background Study

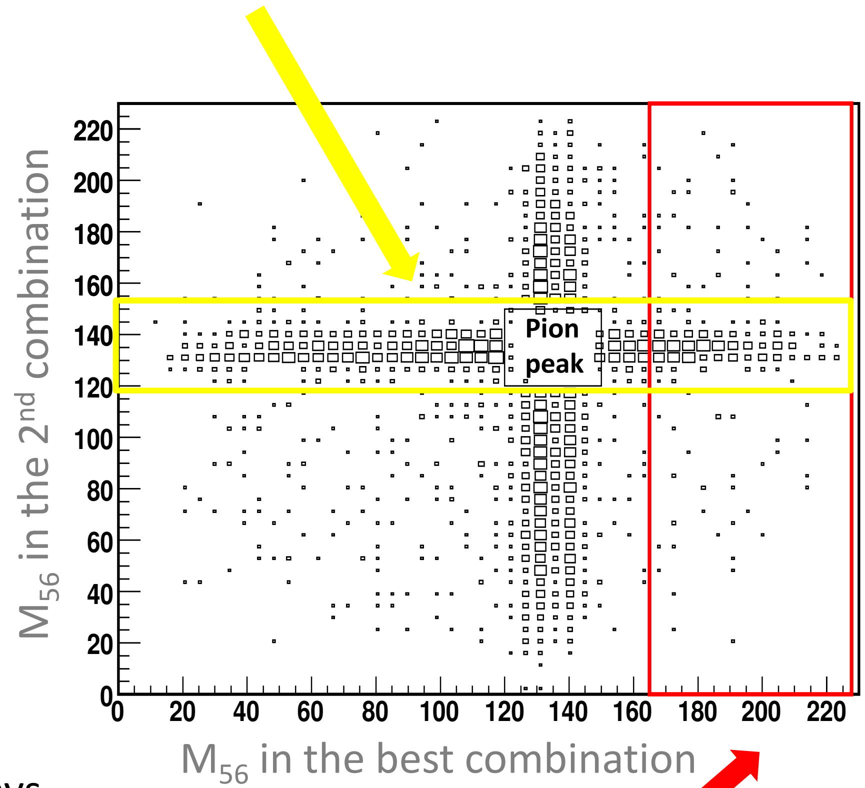
K3pi0 decay:

- Large BR, BR = 19.56 %
- Six photons in final state same as the K2pi0X decays

→ Main background source

→ K3pi0 background are mainly due to wrong photon pairing.

Mis-reconstructed events in 1st combination were Successfully reconstructed in 2nd combination



Sideband + signal region

Other backgrounds:

K2pi0 decays, background from other decays….

- MC study shows those backgrounds are negligible

K3pi0 background suppression

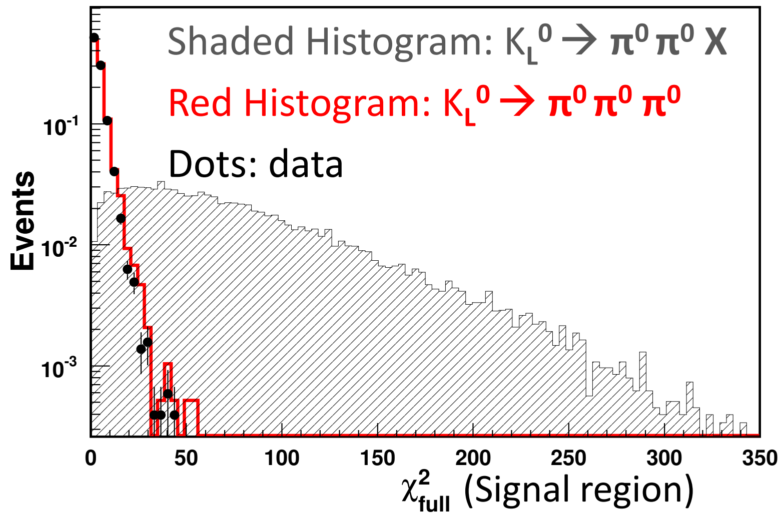
Use “full constrained fit” to reject all K3pi0 events

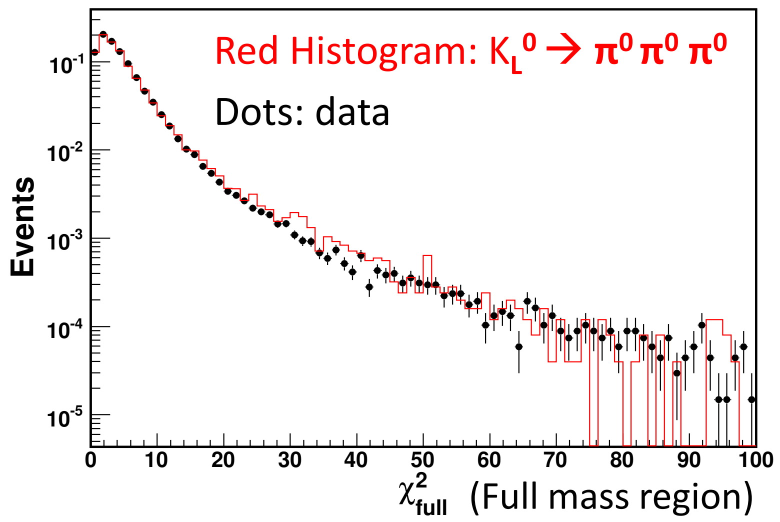
- ✓ Six photons to have KL mass x1
- ✓ Three photon pairs to have Pion mass x3
- ✓ The KL momentum from target to COE of photons on the CsI plane x2

- Event, which is consistent with K3pi0 decay, has small χ^2.

Acceptance (cut: $\chi^2 < 50$)

- K3pi0: 0.15 %
- K2pi0X: 61.0 %





Signal extraction

After all cuts on data

- 2 events in signal region (211.3 – 217.3 MeV)
- 250 events in sideband
  (165 – 211.3 MeV & > 217.3 MeV)

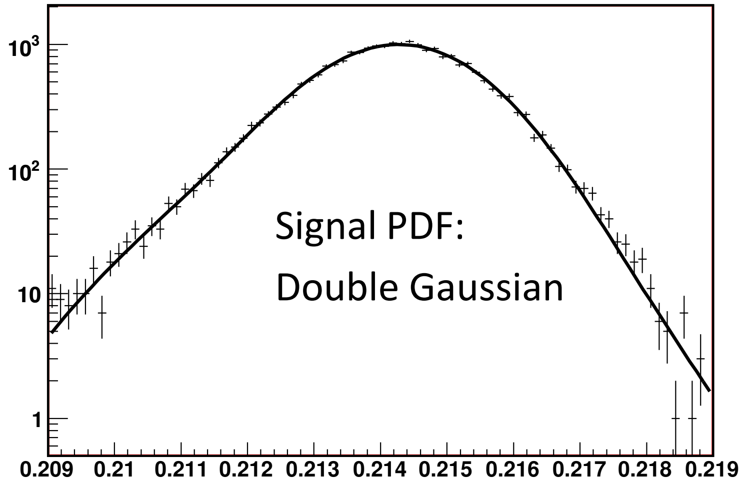
Use unbinned likelihood method to extract signal

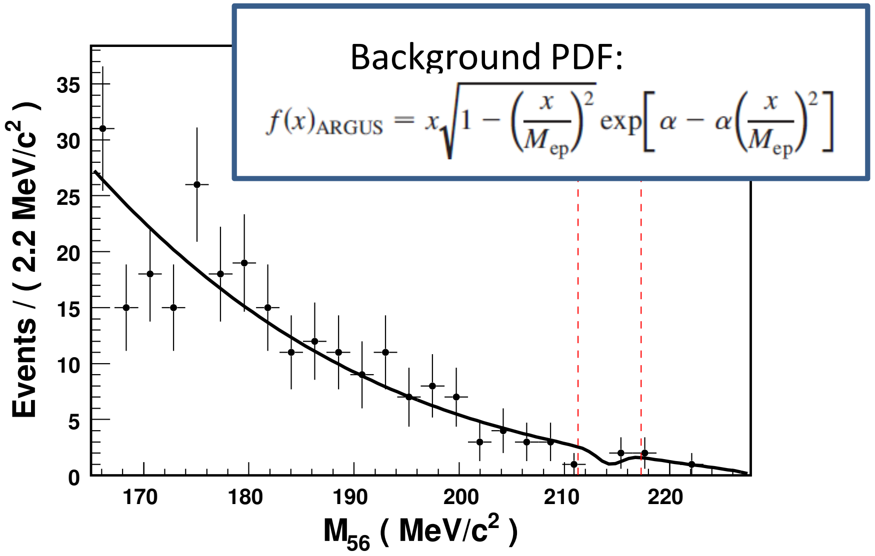
- Signal PDF: double Gaussian function
  for asymmetric peak
- BKGD PDF: ARGUS function for tail shape

The number of signal events yielded:

- $N_S = -1.4^{+1.7}_{-0.9}$

Modeling result of signal shape





Error estimation

- **The signal shape modeling** (4.07 %)
  - Consider the 1 sigma error in signal shape modeling
- **The signal shape difference between data & MC** (1.79 %)
- **The signal efficiency** (0.93 %)
- **KL flux** (2.88 %)
  - Calculated from K3pi0: (1.32 $\pm$ 0.04)x10^{11}
    - Use this value for further calculation
  - Calculated from K2pi0: (1.36 $\pm$ 0.04)x10^{11}
- **Background shape modeling** ($\triangle$Ns = 0.80)
  - Error from the background shape assumption

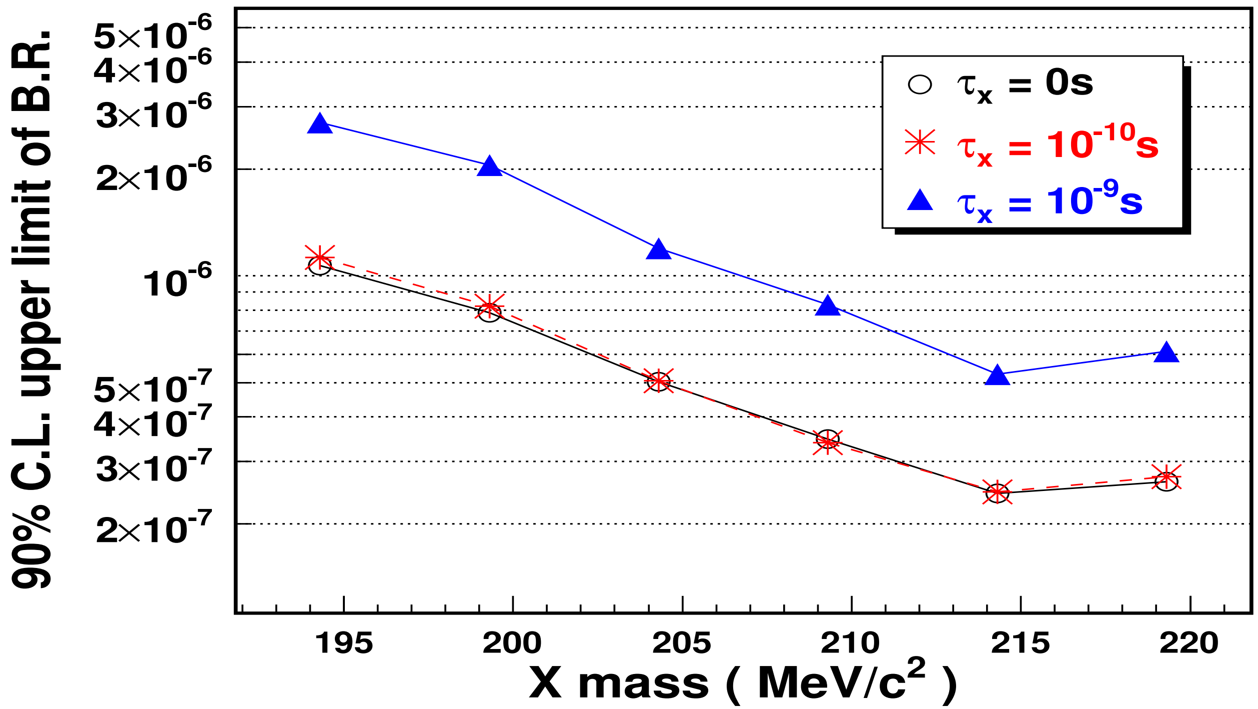
Upper Limit

- 2 events observed in signal region
- Signal acceptance: $(1.08 \pm 0.01)10^{-4}$
- KL flux: $(1.32 \pm 0.04) \times 10^{11}$
  - Calculated from K3pi0 decays
- SES: $(7.0 \pm 4.0)10^{-8}$
- U.L. at 90% confidence level: 2.4×10^{-7}
  - Calculated by integrating the likelihood function up to 90% area.

Results of $K_L^0 \rightarrow \pi^0 \pi^0$ X, X $\rightarrow \gamma\gamma$

The results of the X mass region from 194.3 to 219.3 MeV and the X lifetime region from 0 to 10^{-9}s are all performed.

- ✓ U.L. doesn't change if X lifetime < 10^{-10}s
- ✓ U.L. weaken by a factor of 2-3 if X lifetime 10^{-9}s



Summary

- We performed the $K_L^0 \rightarrow \pi^0\pi^0 X$, $X \rightarrow \gamma\gamma$ analysis at E391a. No evidence of X is found and the upper limit for m_X = 214.3 MeV is placed at 2.4×10^{-7} [PRL 102, 051802].

- The results for different m_X & τ_X are also performed. There is no evidence of X found in other mass region, either.

- The $K_L^0 \rightarrow \pi^0\pi^0 X$, $X \rightarrow \mu^+\mu^-$ analysis is also performed at E391a by a student from Saga university. There is also no evidence of X and the upper limit is placed at 1.7×10^{-6}.