# Study of the normalization modes in the search for the rare $K_L^0 \longrightarrow \pi^0 \nu \bar{\nu}$ with the KOTO detector

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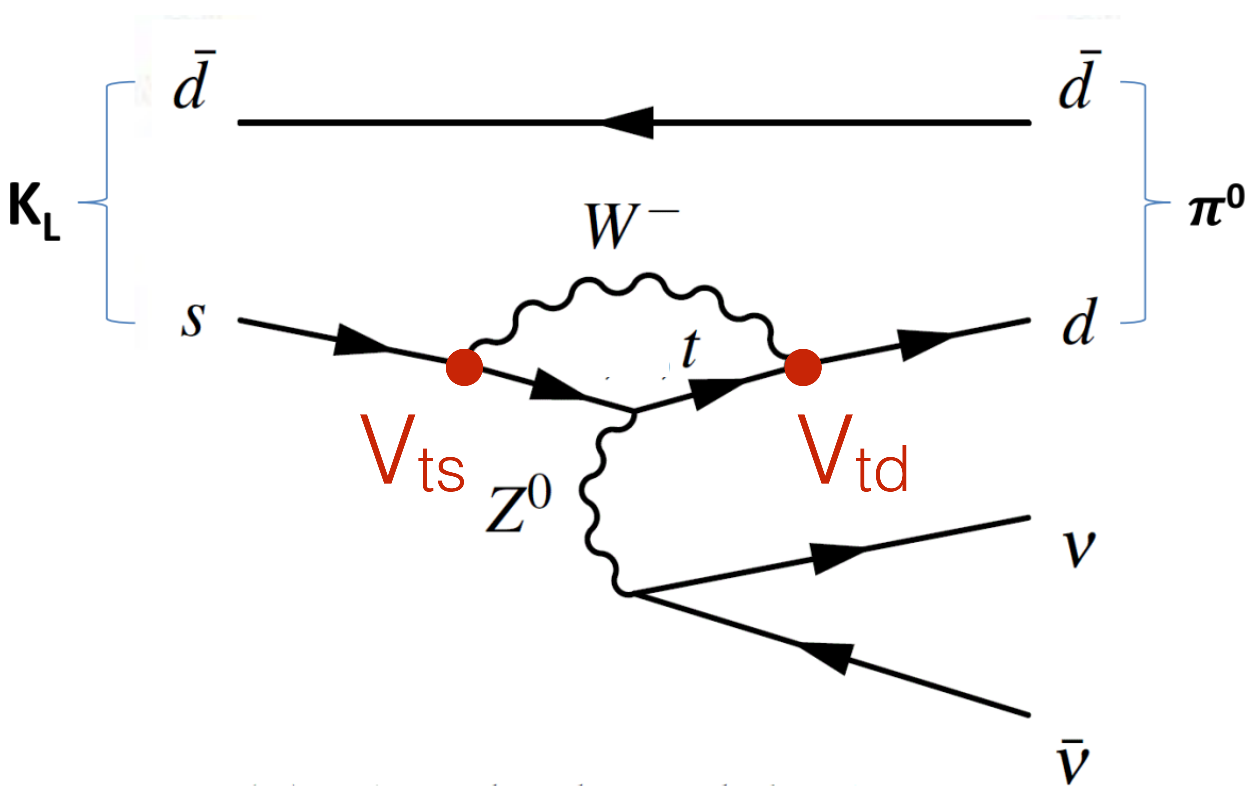
# $K_L^0 \longrightarrow \pi^0 \nu \bar{\nu}$

- SM predicted Branching Ratio of ($K_L^0 \longrightarrow \pi \nu \bar{\nu}$) predicted to be $(3.00 \pm 0.30) \times 10^{-11}$
- Clean channel with small theoretical uncertainties (1-2%)
- 2nd order FCNC process directly violates CP




BR ($K^+ \longrightarrow \pi^+ \nu\nu$) = $(9.11 \pm 0.72) \times 10^{-11}$ (Buras …et. al 2015)

BR ($K_L \longrightarrow \pi^0 \nu\nu$) = $(3.00 \pm 0.30) \times 10^{-11}$ (Buras …et. al 2015)

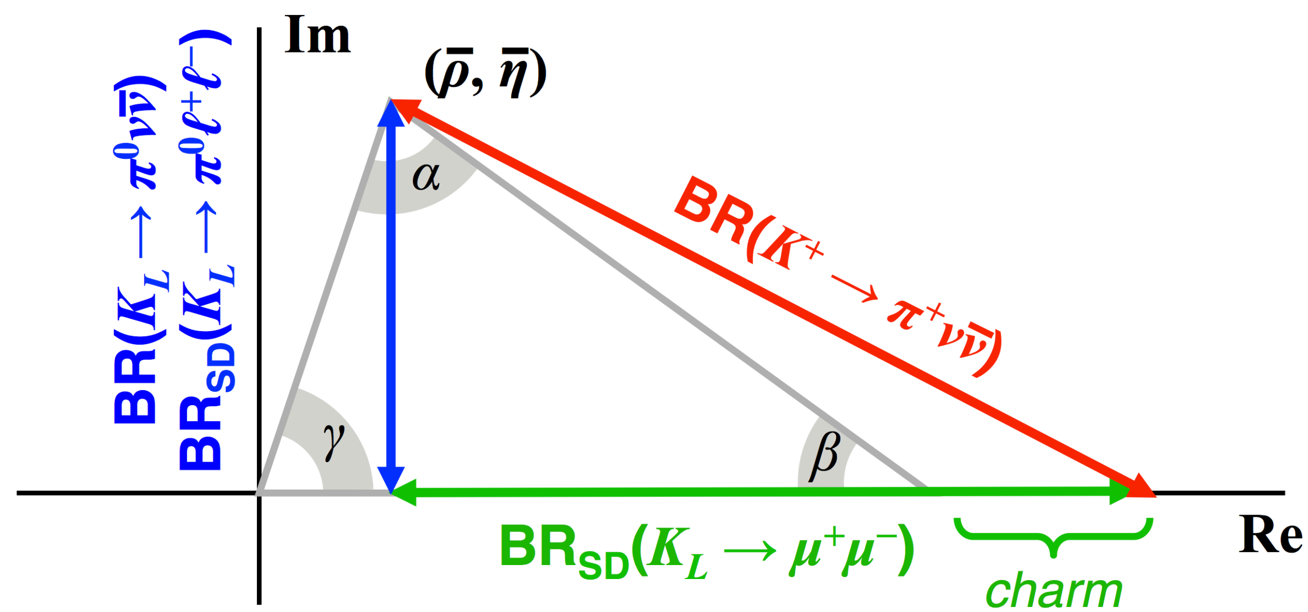
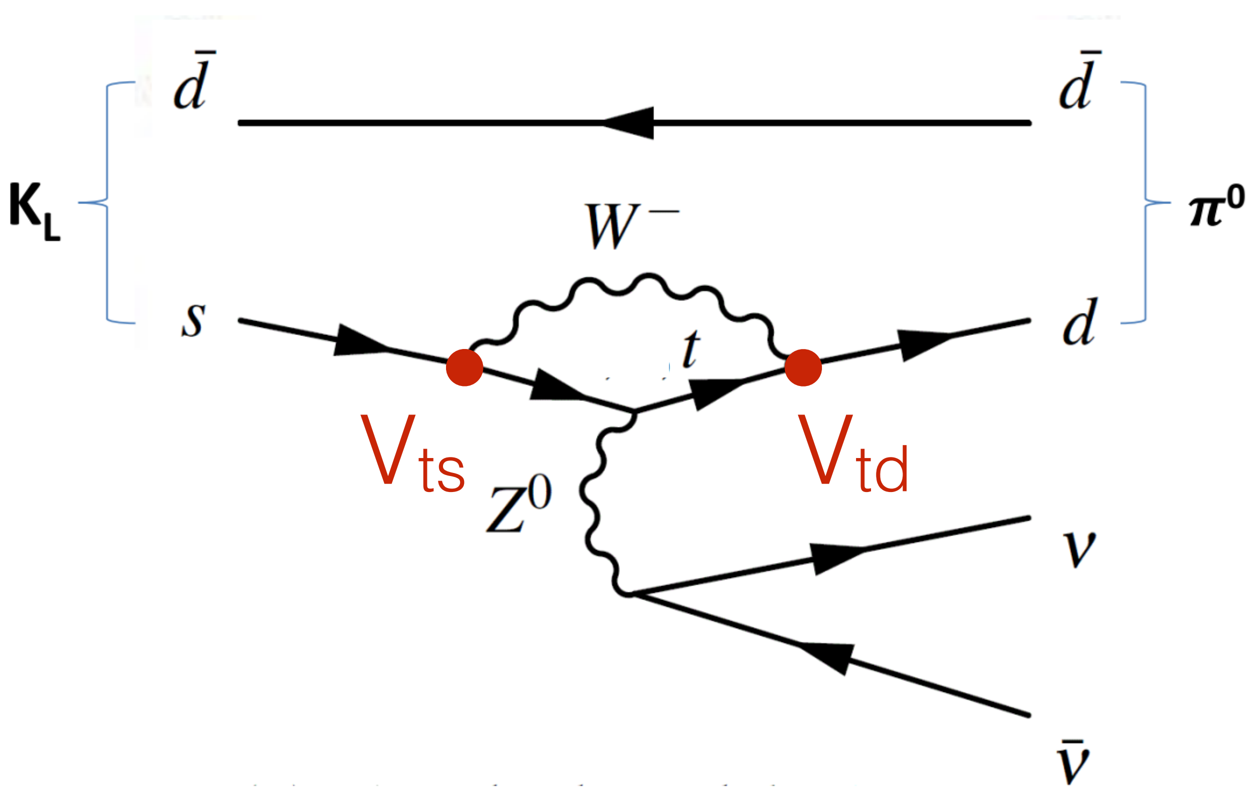
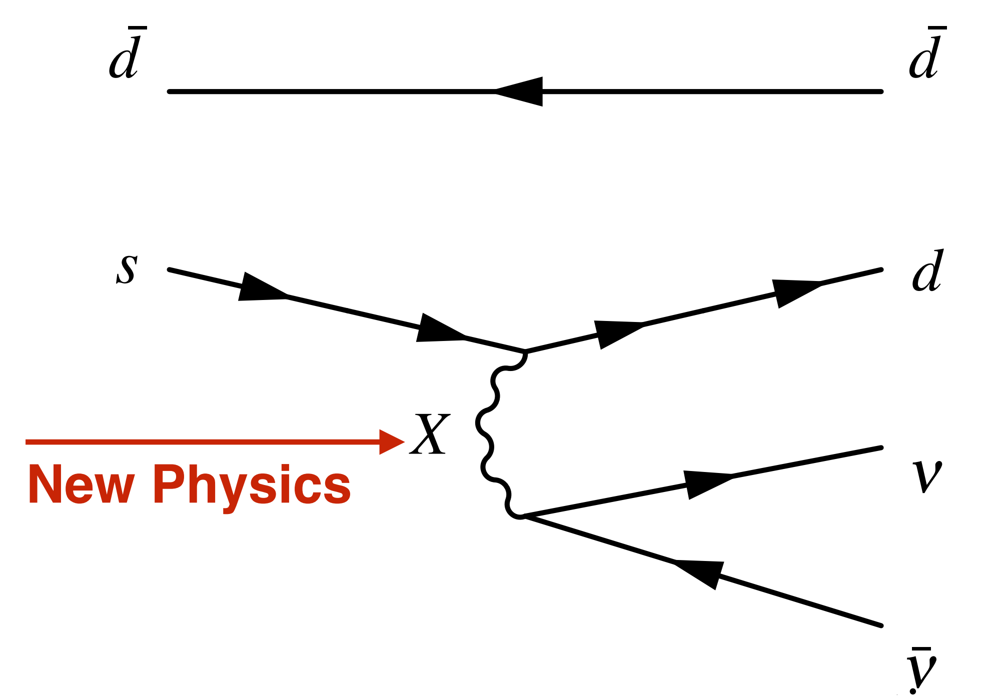



**Fig. Unitarity triangle**

# $K_L^0 \text{—>} \pi^0 \nu \bar{\nu}$

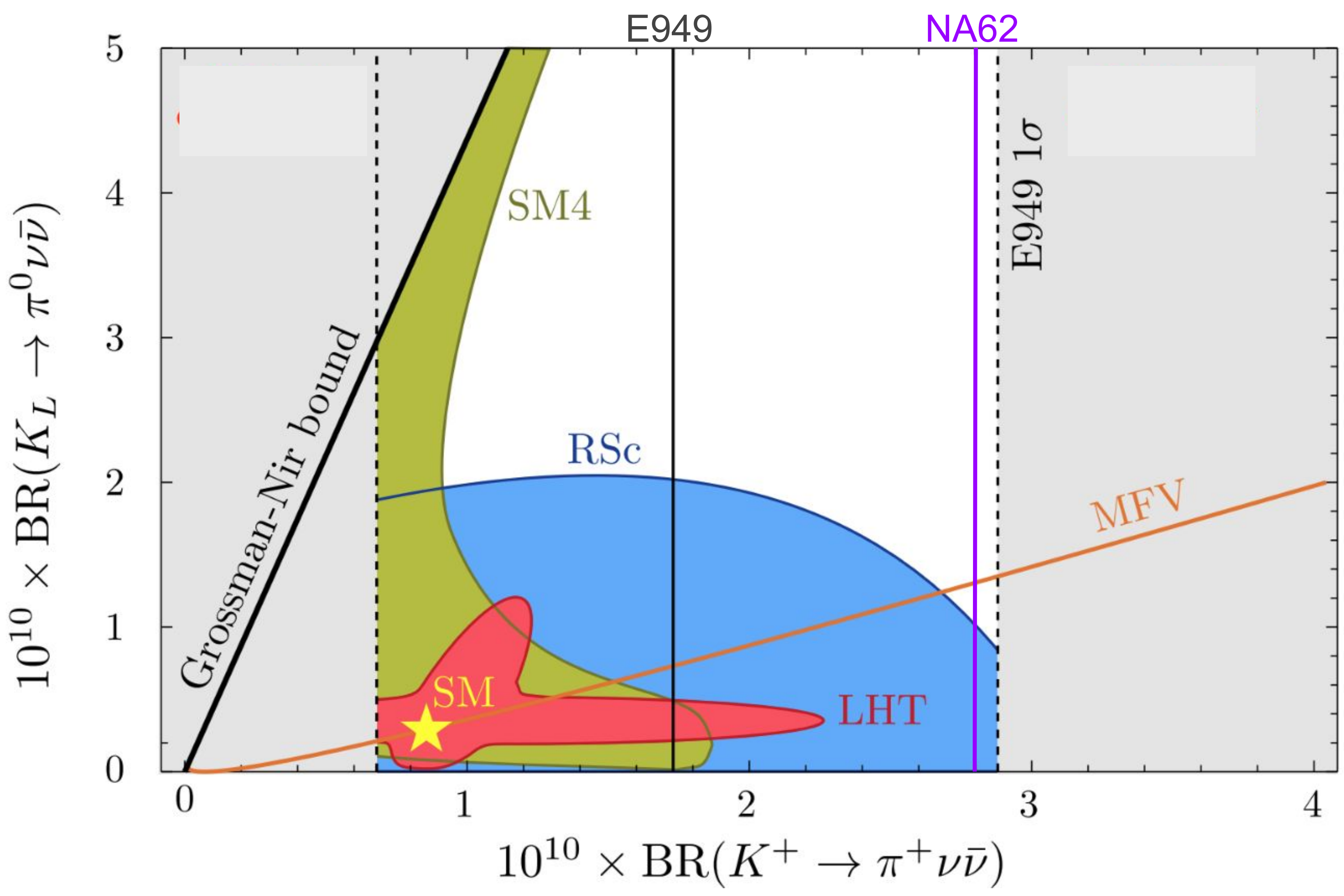
- SM predicted Branching Ratio of ($K_L^0 \text{—>} \pi \nu \bar{\nu}$) predicted to be $(3.00 \pm 0.30) \times 10^{-11}$
- Clean channel with small theoretical uncertainties (1-2%)
- 2nd order FCNC process directly violates CP
- Sensitive to New Physics (NP) beyond the Standard Model



# K—>πνν searches

- Charged decay measurement (NA62) provides important information
  - SM BR ($K^+$—>πνν) predicated to be (9.11+-0.72) x $10^{-11}$
- Grossman-Nir: indirect limit based on isospin relations between ($K^+$—>πνν) and ($K_L^0$—>πνν)
- BR ($K_L^0$—>πνν) < 4.4 x BR($K^+$—>πνν) ⟶ BR ($K_L^0$—>πνν) < 1.5 x $10^{-9}$




LHT: Littlest Higgs (T-parity)
MFV:Minimum Flavor Violation
RSc: Randall-Sundrum

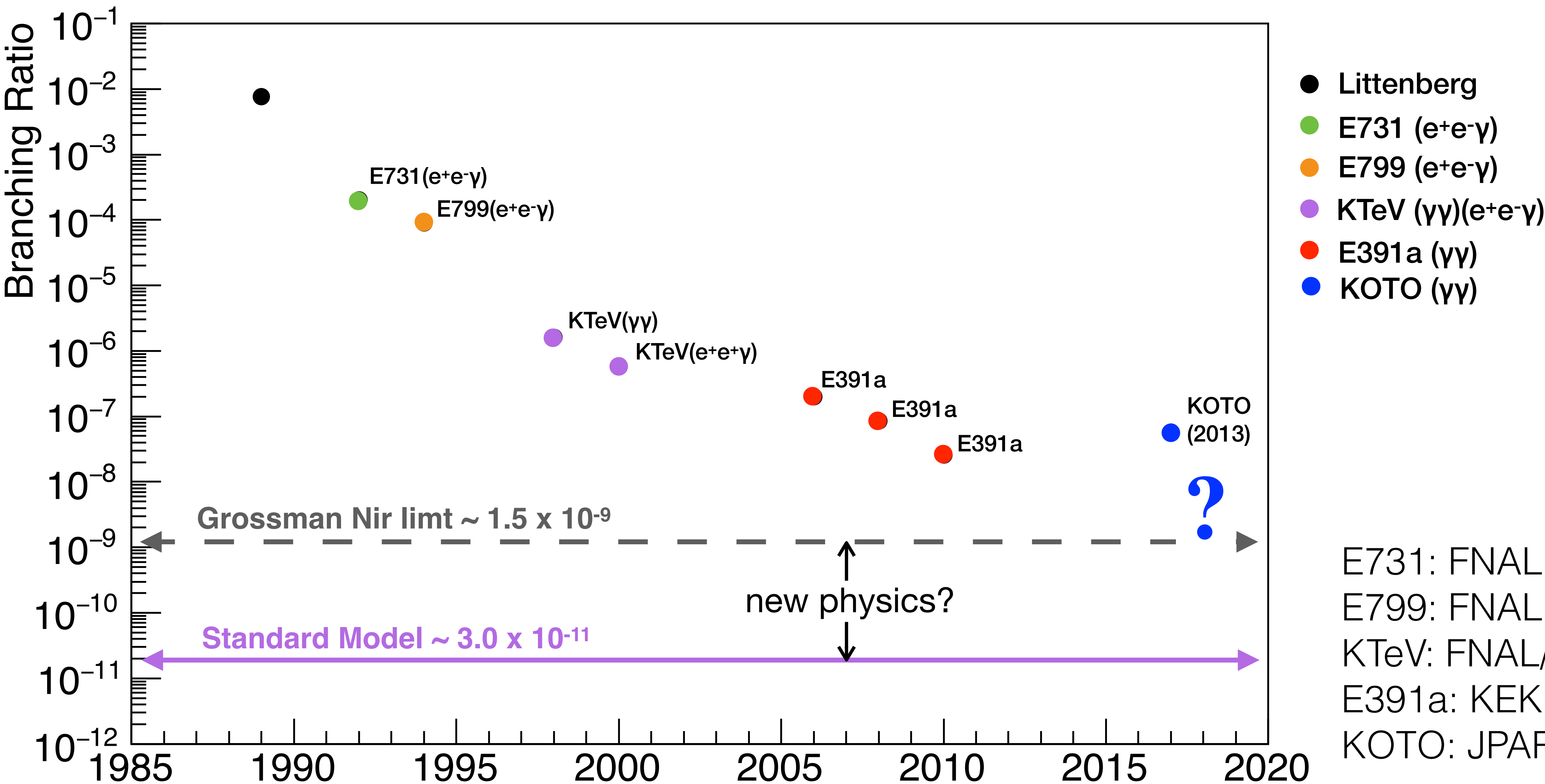
E949 (2008):
BR = (1.7 ± 1.1) x $10^{-10}$

NA62 (2018):
BR <11 x $^{-10}$ @ 90%CL

CERN-SPSC-2018-010 / SPSC-SR-229

# $K_L^0 \longrightarrow \pi^0 \nu \bar{\nu}$

- KOTO will contribute a new arc to the narrative



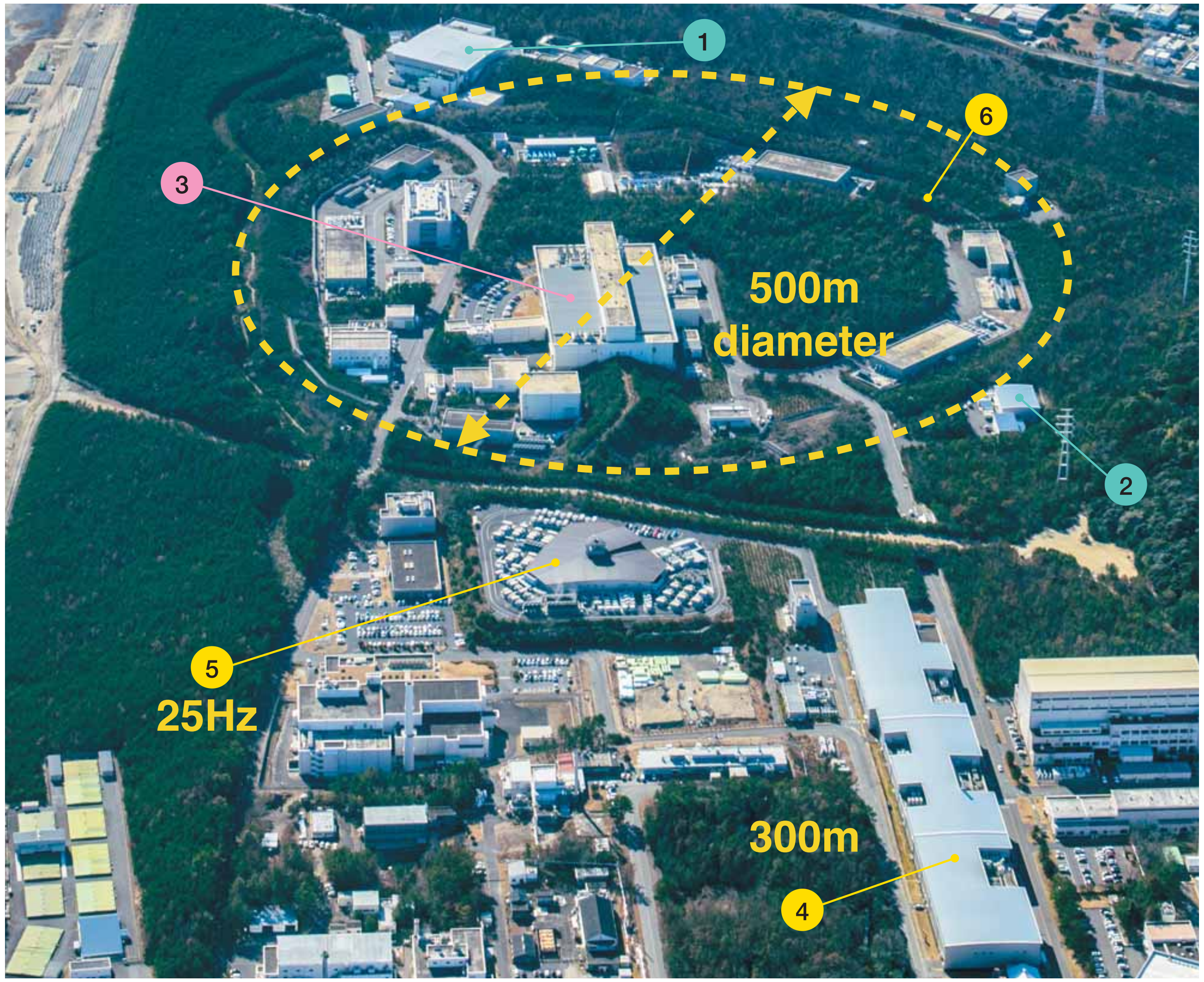

E731: FNAL
E799: FNAL
KTeV: FNAL/KEK
E391a: KEK
KOTO: JPARC

# Experimental setup

- Experiment performed in the Hadron Experimental Facility (HEF) at J-PARC
- 30 GeV proton beam on stationary gold target
- Secondary neutral beam extracted for KOTO experiment

"$K^0$ at TOkai"

1. **Hadron Experimental Facility** IPNS: nuclear and particle physics
2. **Neutrino Experimental Facility** IPNS: neutrino physics
3. **MLF** Materials and Life Science Experimental Facility IMSS: material science & life science
4. **Injector Linac** 400 MeV proton linac
5. **RCS, Rapid Cycle Synchrotron** 3 GeV proton synchrotron
6. **MR, Main Ring** 50 GeV proton synchrotron




Sciences at J-PARC, Japan Proton Accelerator Research Complex, in the Tokai campus.
(Note) J-PARC is operated jointly by KEK and JAEA, Japan Atomic Energy Agency.

**Fig. View of the J-PARC facility**

# KOTO beam line

## Highly collimated neutral “pencil” beam

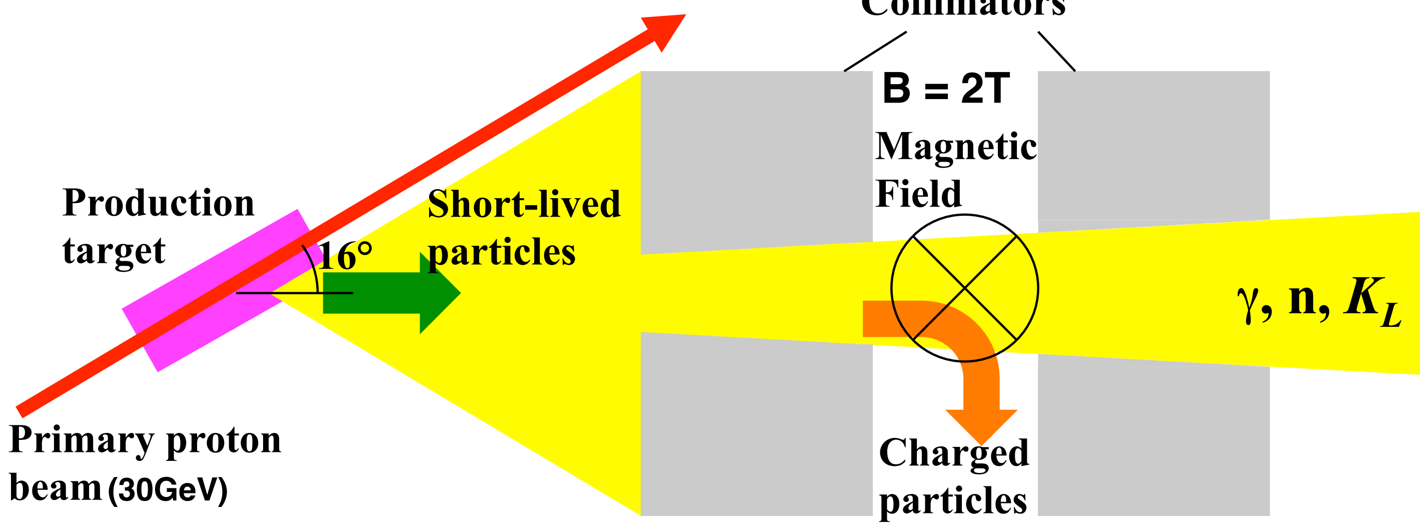



**Fig. Depiction of neutral beam line production**

Target to detector distance = 21.5 m

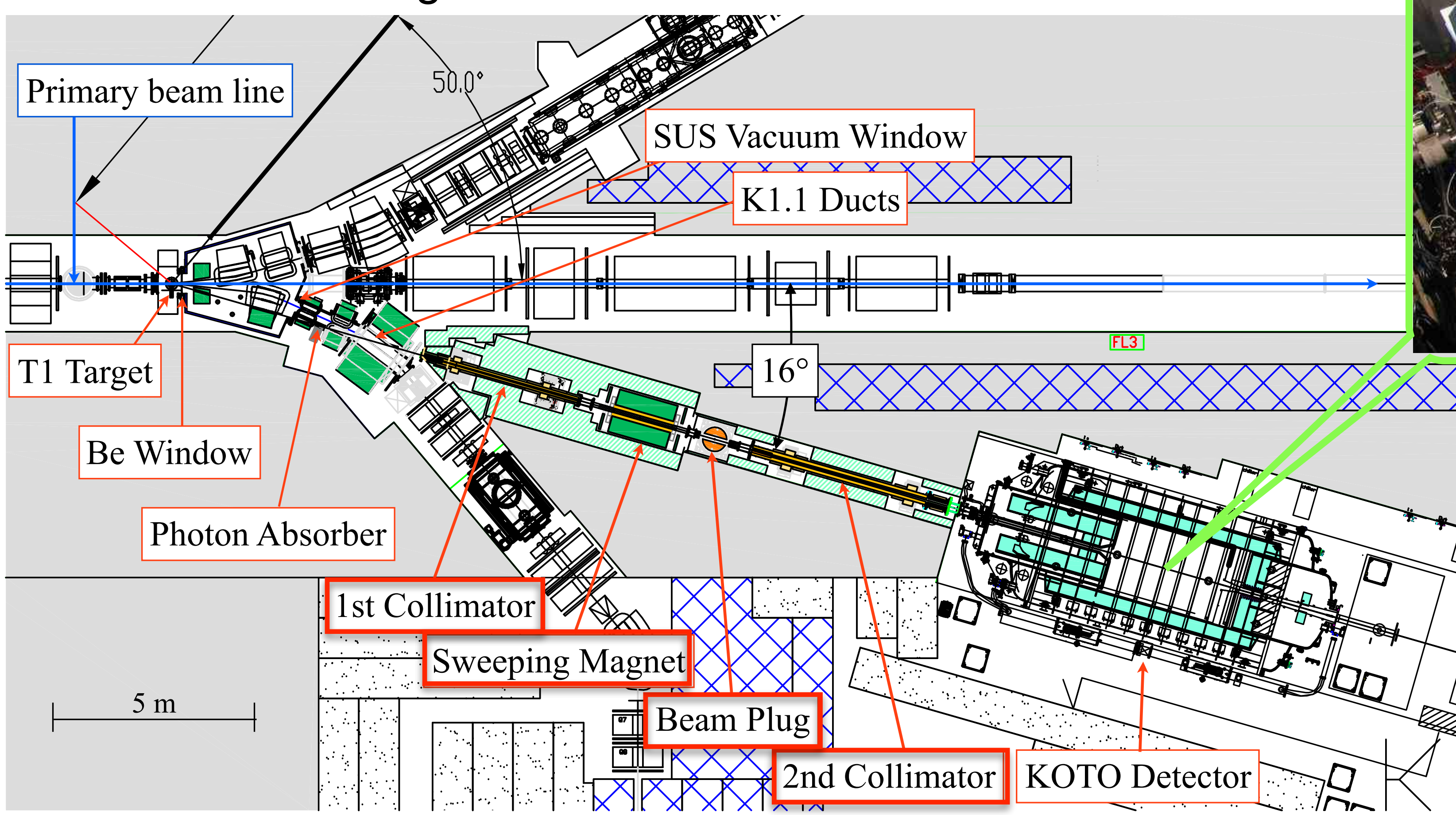



**Fig. Layout inside Hadron Hall**

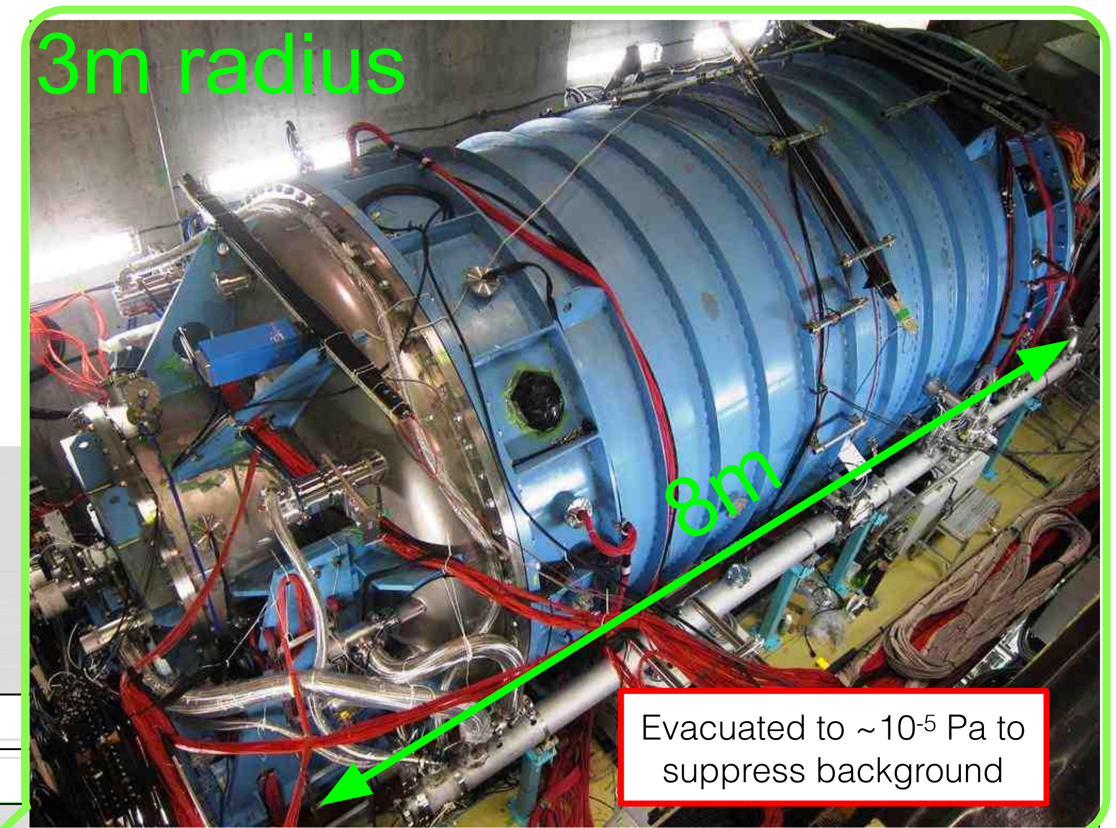



**Fig. Outer vacuum container houses all main KOTO detectors**

# KOTO detectors

- **Two sub-system design and operation:**
  - Cesium Iodide Calorimeter (CsI)
  - Hermetic veto detectors
    - Charged vetoes removes events with charged particle
    - Photon vetoes to detect other $K_L^0$ decays

**Background is not our friend**

| Decay Mode | Branching Ratio |
|---|---|
| $K_L^0 \to \pi^\pm e^\mp \nu_e$ | $0.4055 \pm 0.0011$ |
| $K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$ | $0.2704 \pm 0.0007$ |
| $K_L^0 \to 3\pi^0$ | $0.1952 \pm 0.0012$ |
| $K_L^0 \to \pi^+\pi^-\pi^0$ | $0.1254 \pm 0.0005$ |
| $K_L^0 \to 2\pi^0$ | $(0.864 \pm 0.006) \times 10^{-3}$ |
| $K_L^0 \to 2\gamma$ | $(0.547 \pm 0.004) \times 10^{-3}$ |

**Table. Branching ratios of various Kaon decays (PDG)**

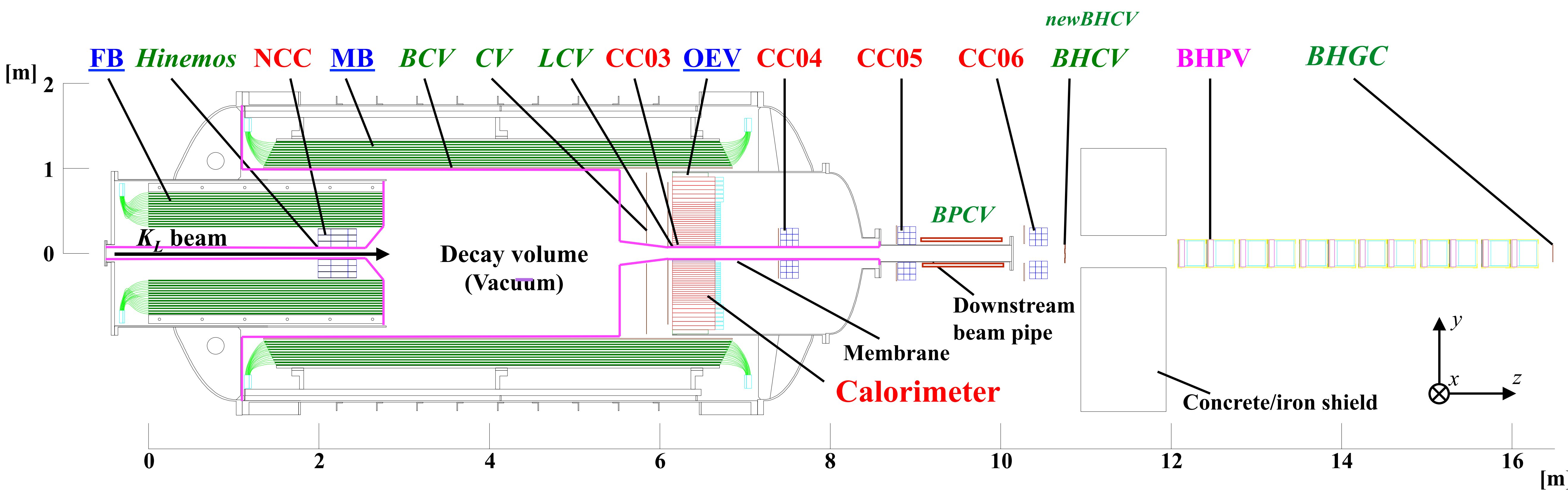
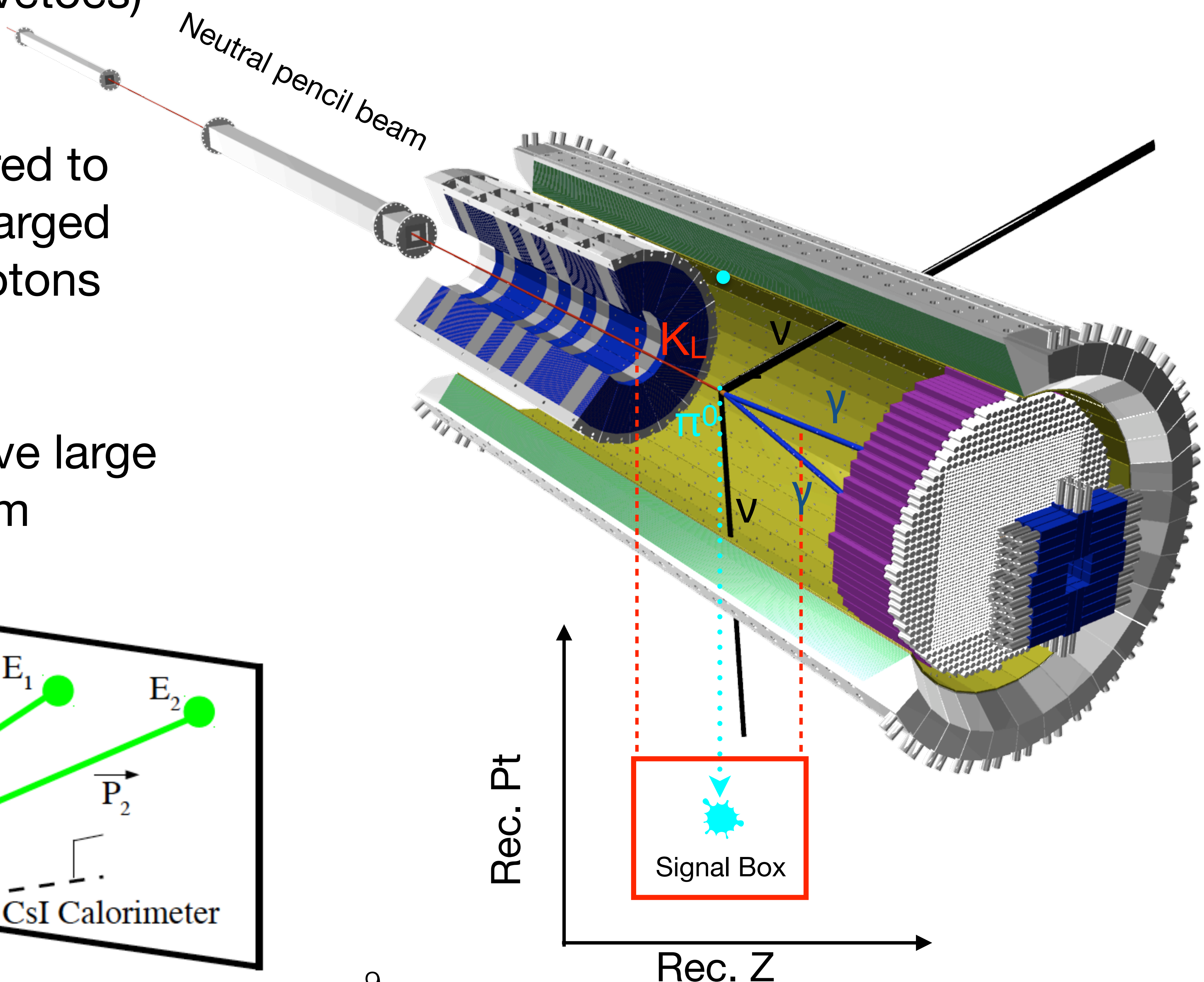


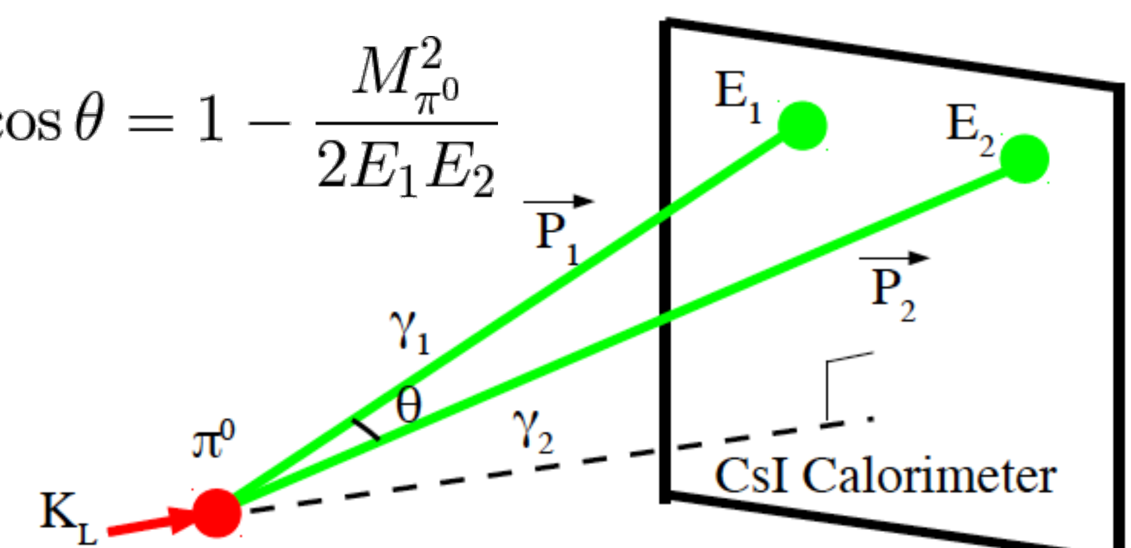

**Fig. KOTO detector components**

# Experimental approach

- Detect 2 photon hits from $\pi^0$ (CsI) + nothing else (Vetoes)
- High efficiency required to reject events with charged particles or other photons
- Require events to have large transverse momentum




$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$



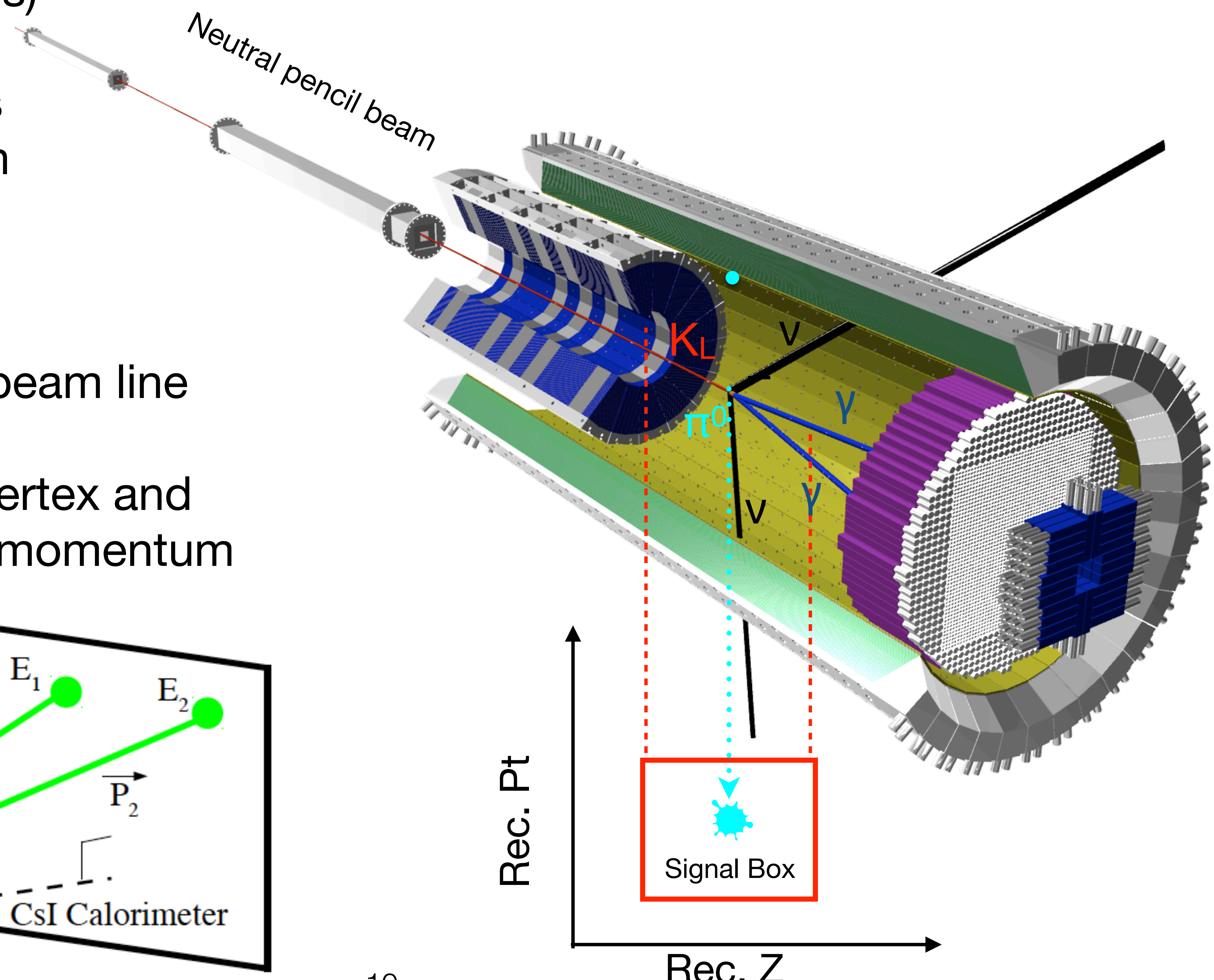
# Signal reconstruction

- Detect 2 photon hits from $\pi^0$ (CsI) + nothing else (Vetoes)

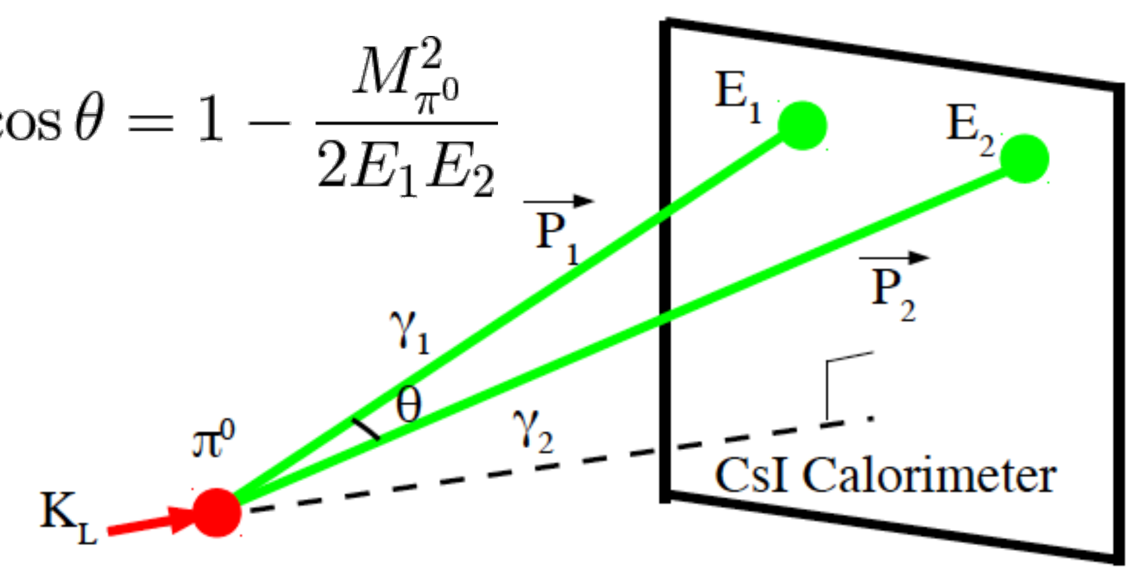
- CSI—> 2 photon hits
  - Energy and position

- Constraints
  - $\pi^0$ mass
  - Decay position on beam line

- Reconstruct decay vertex and calculate transverse momentum




$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$



# Signal distribution

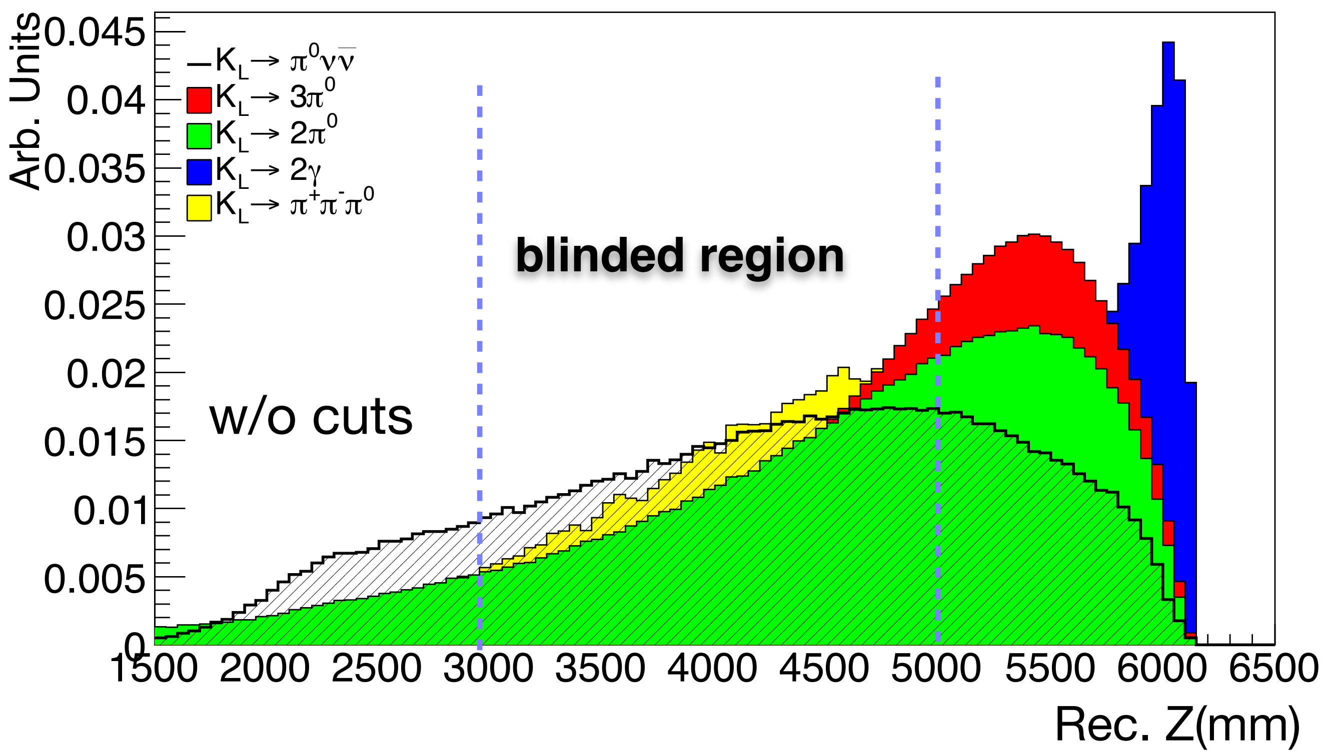
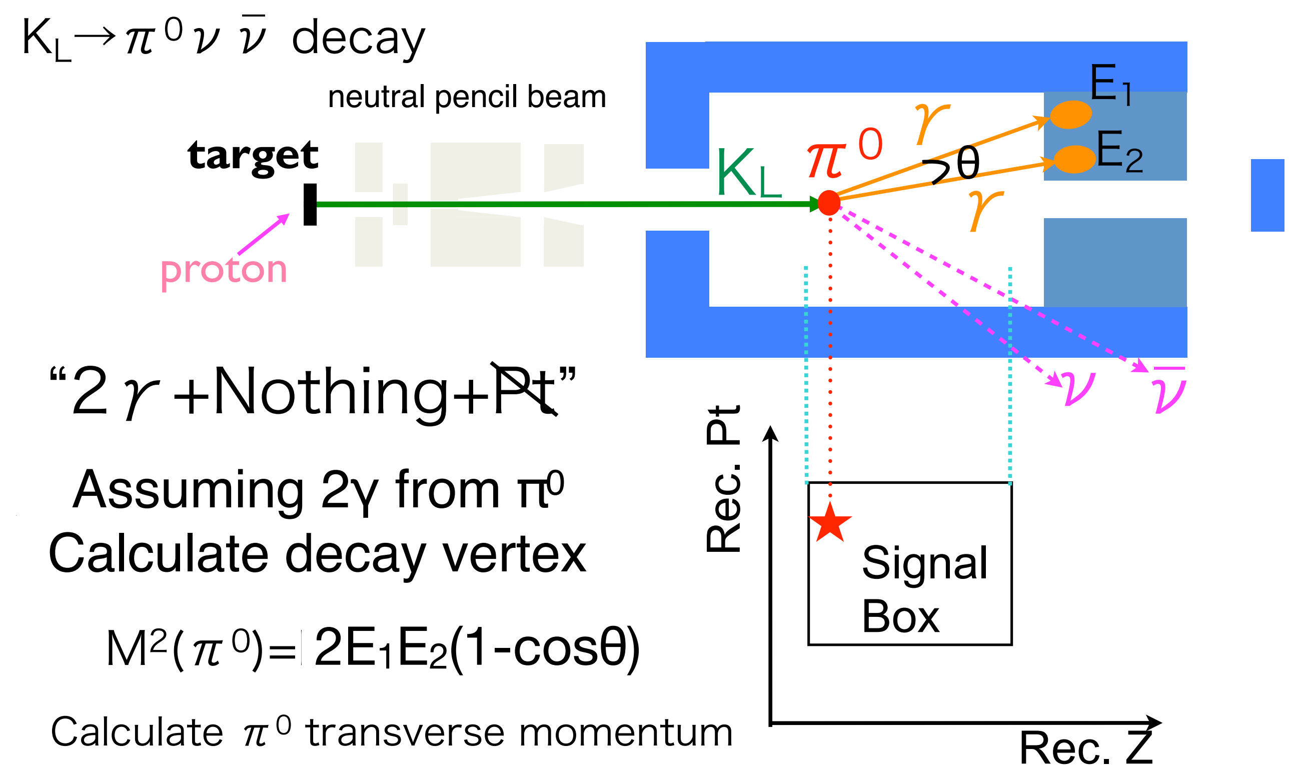



**Fig. Monte Carlo of signal and background distributions**



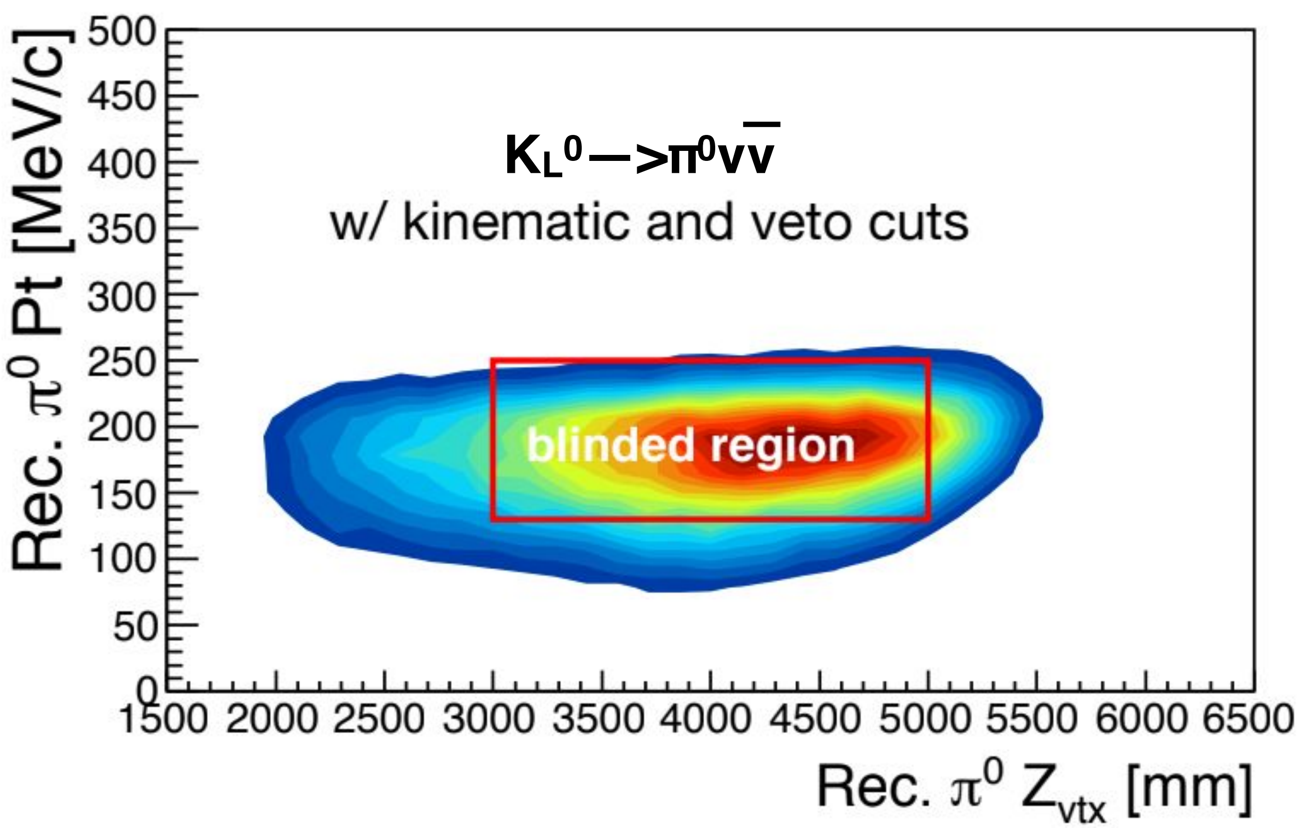




**Fig. Monte Carlo sample of signal ($K_L^0 \to \pi\nu\bar{\nu}$) distribution**

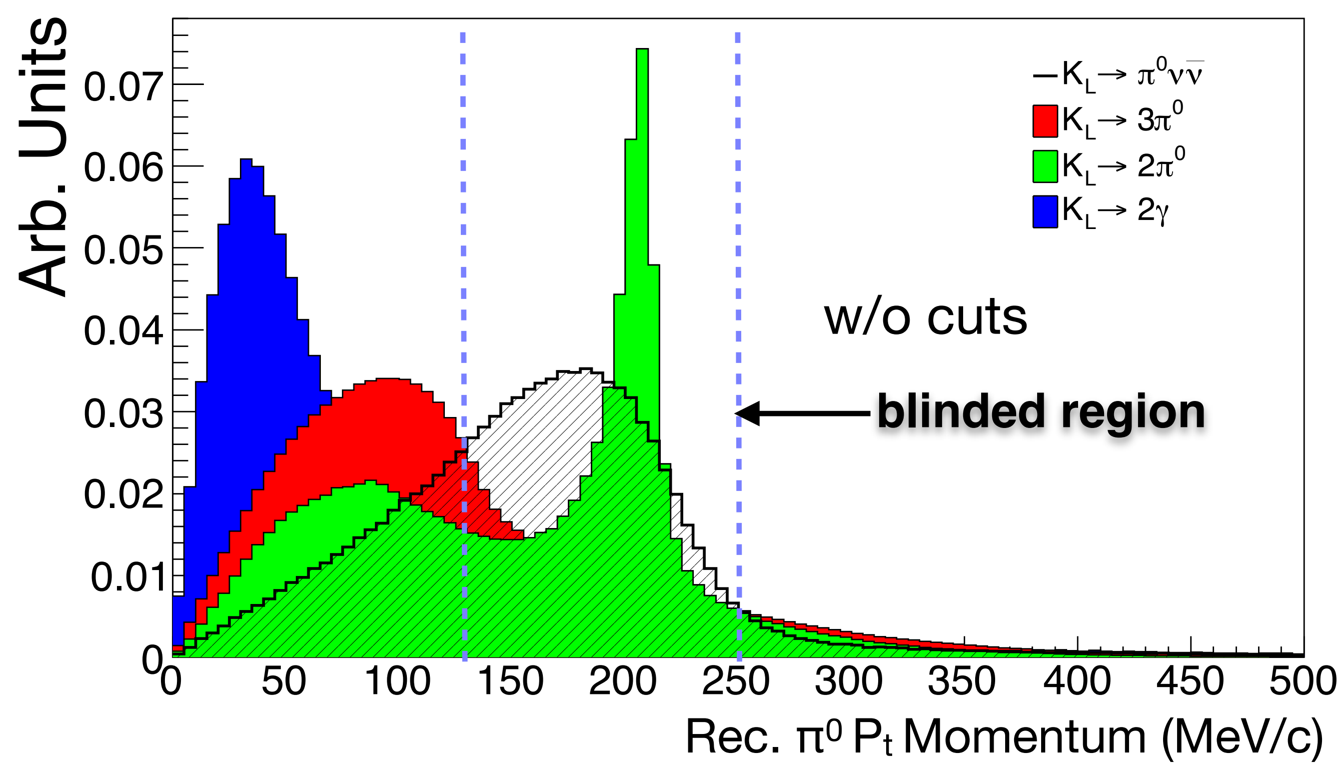
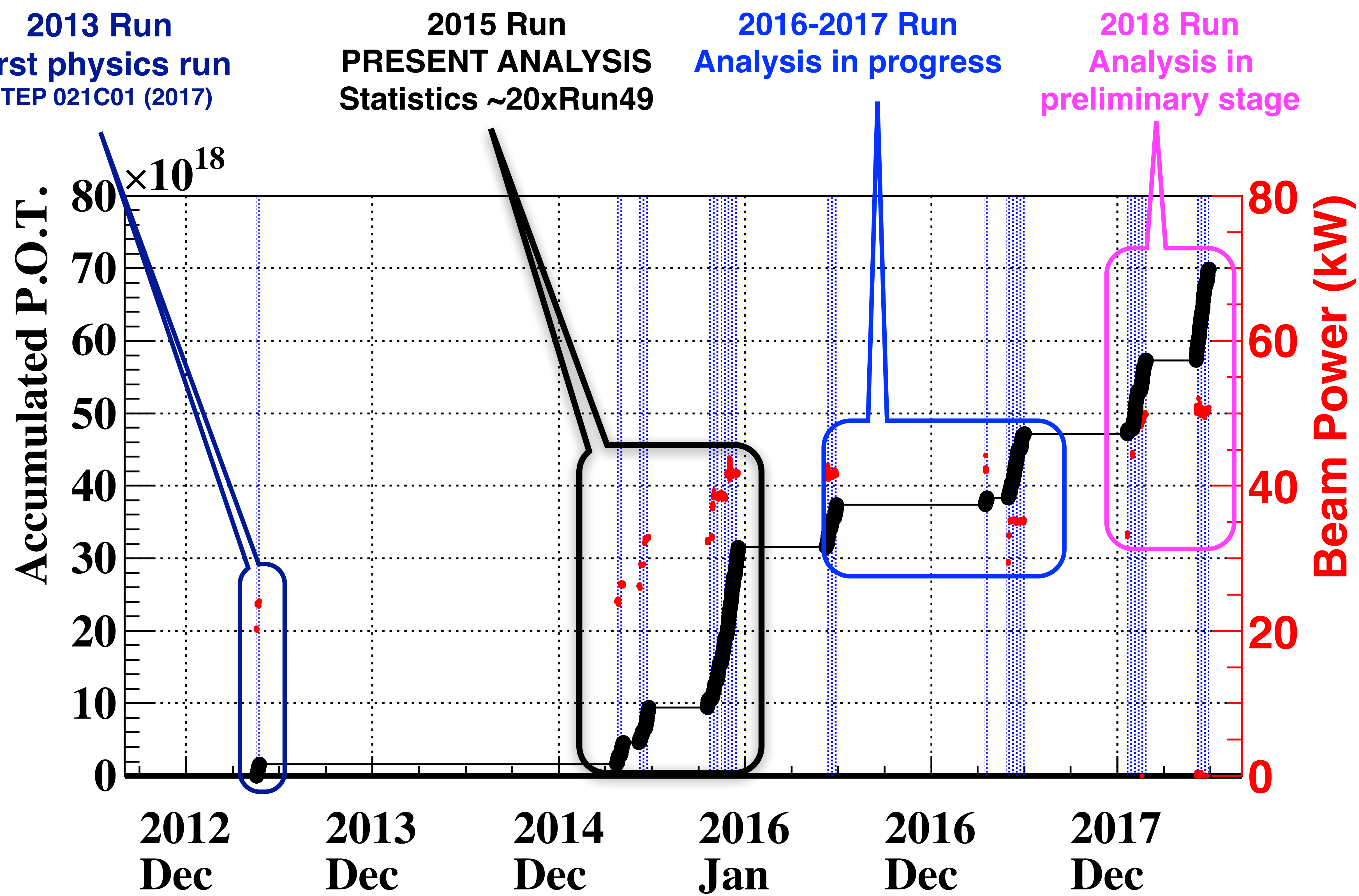



**Fig. Monte Carlo of signal and background distributions**

# KOTO timeline



# First run results

2013 results showed the largest background contribution for neutron generated events

- *Expected / observed = 0.34/1*
- *BR ($K_L^0 \rightarrow \pi\nu\bar{\nu}$) < 5.1 x $10^{-8}$ at 90% C.L.*

**Improvements since 2013 run**

- Suppression of neutron background
  - *Improved collimator alignment*
  - *Replaced vacuum window*
  - *Special runs to study neutron events*
- Photons and charged pions
  - *Additional downstream vetoes*

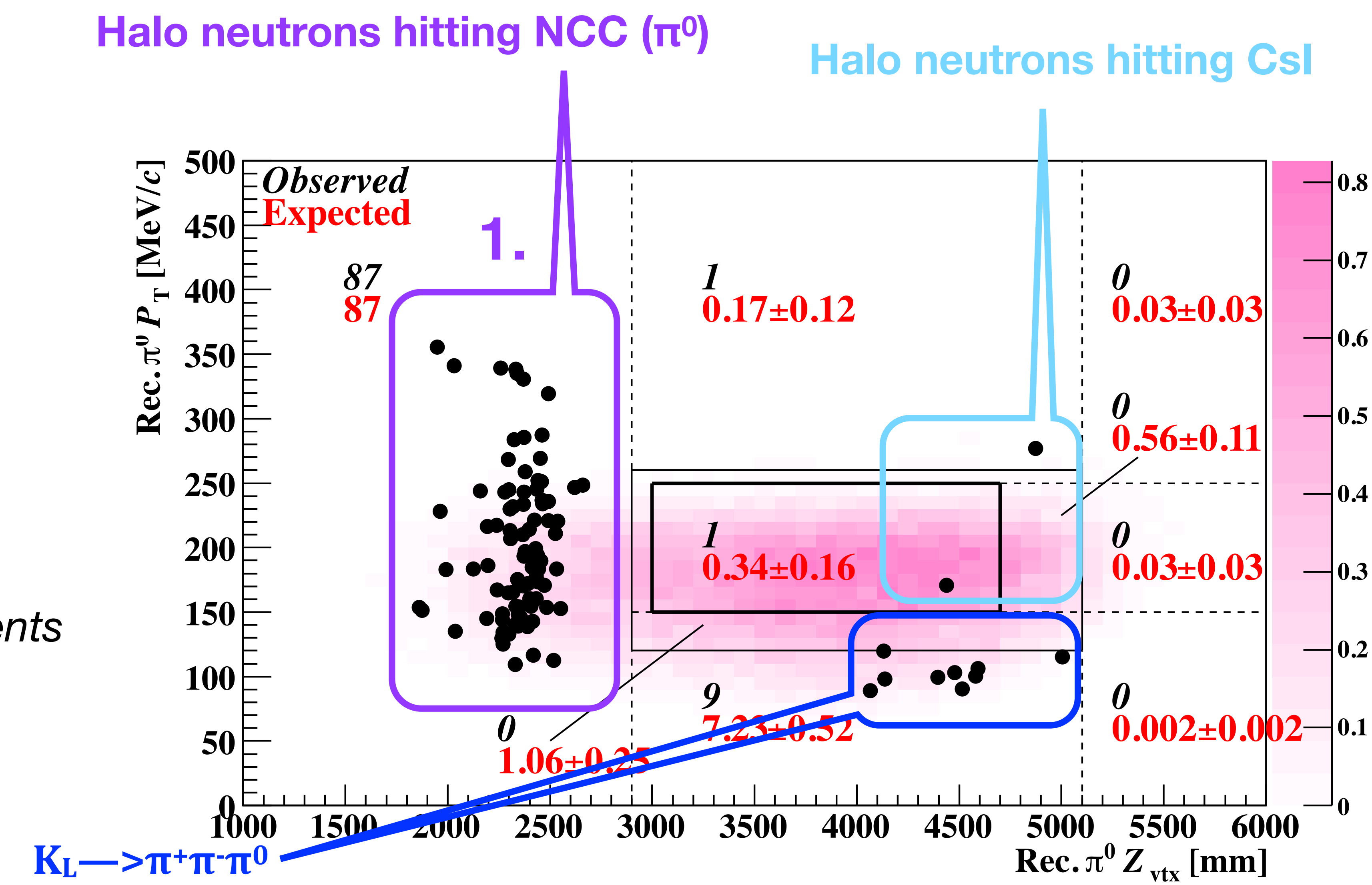
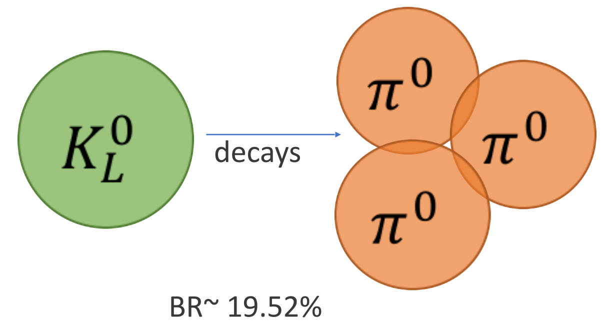
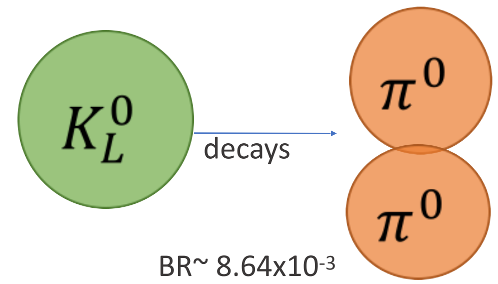


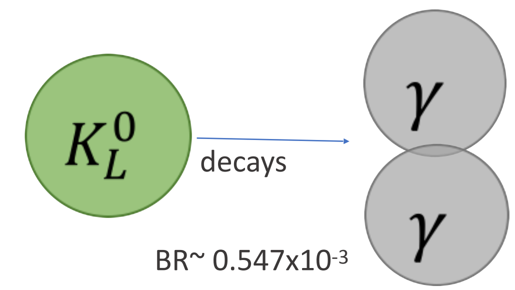

Fig. Reconstructed π⁰ Pt vs. decay vertex position

# Analysis

- Blind analysis
  - Signal reconstruction
  - Study of neutral normalization modes because they were fully reconstructed and clearly identified.
  - Background estimation




- Single Event Sensitivity
  - $K_L^0$ yield
  - Signal acceptance

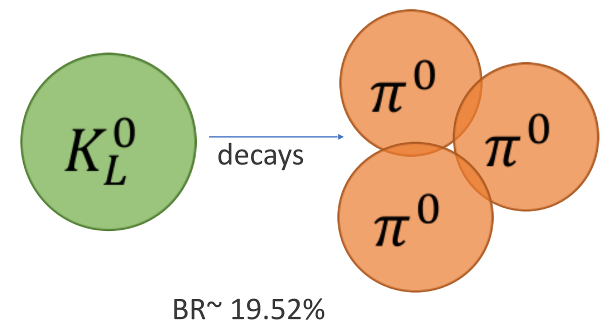
$$SES = \frac{1}{N_{K_L^0} \times A_{\text{signal}}}$$

- Branching Ratio
  - Number of observed events

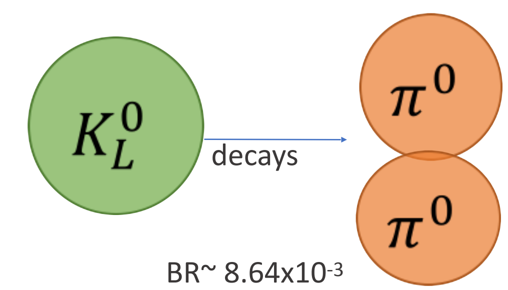
$$BR(K_L^0 \to \pi^0 \nu \bar{\nu}) = \frac{N_{\text{signal}}}{N_{K_L^0} \times A_{\text{signal}}}$$

# Normalization modes

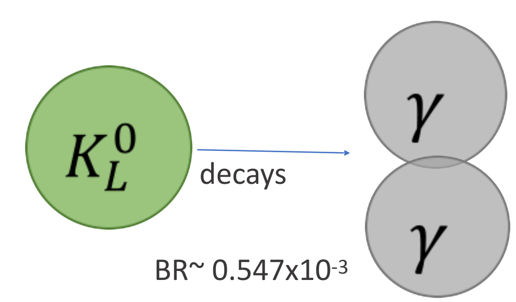
- Determine the number of $K_L^0$
    - $K_L^0$ flux ~ number passing through the beam exit




    - $K_L^0$ yield ~ number of remaining reconstructed events after veto and kinematics cuts




- Normalization modes are also used to:
    - Evaluate of kinematic and veto cut efficiencies

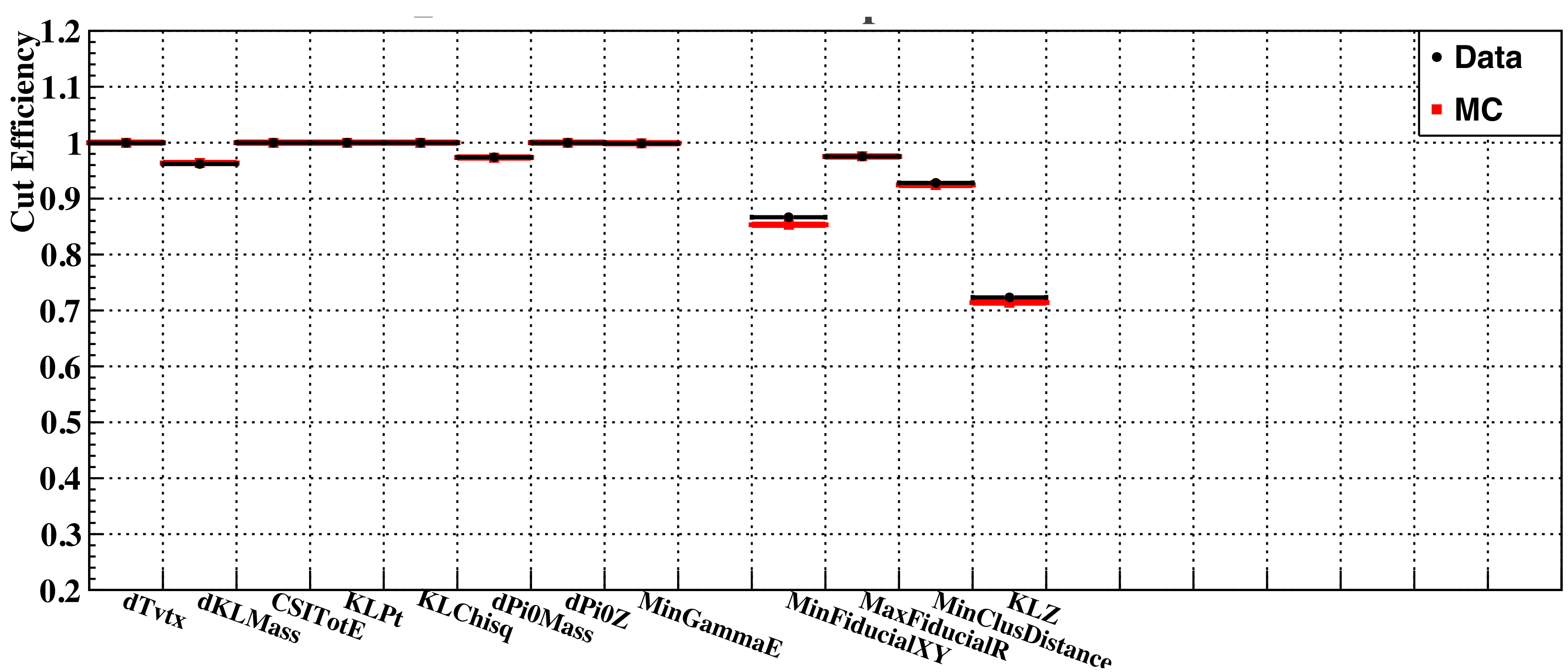



    - Evaluate MC reproducibility of data

# $K_L^0$—>$3\pi^0$ Event distributions

**$K_L^0$—>$3\pi^0$**

- Efficiency of kinematic requirements
- $\varepsilon^i$= (Number of reconstructed $K_L^0$ events with all cuts) / (Number of reconstructed $K_L^0$ events w/o $i^{th}$ cut )
- Data well reproduced by MonteCarlo




KL mass

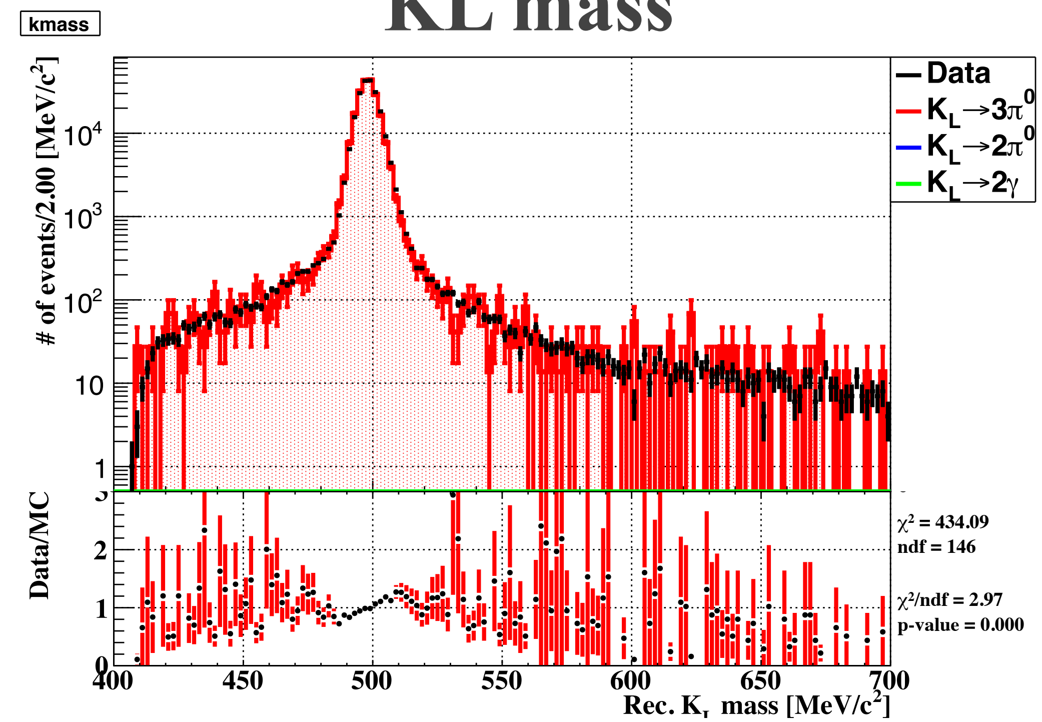



Fig. Reconstructed mass

Rec. Z

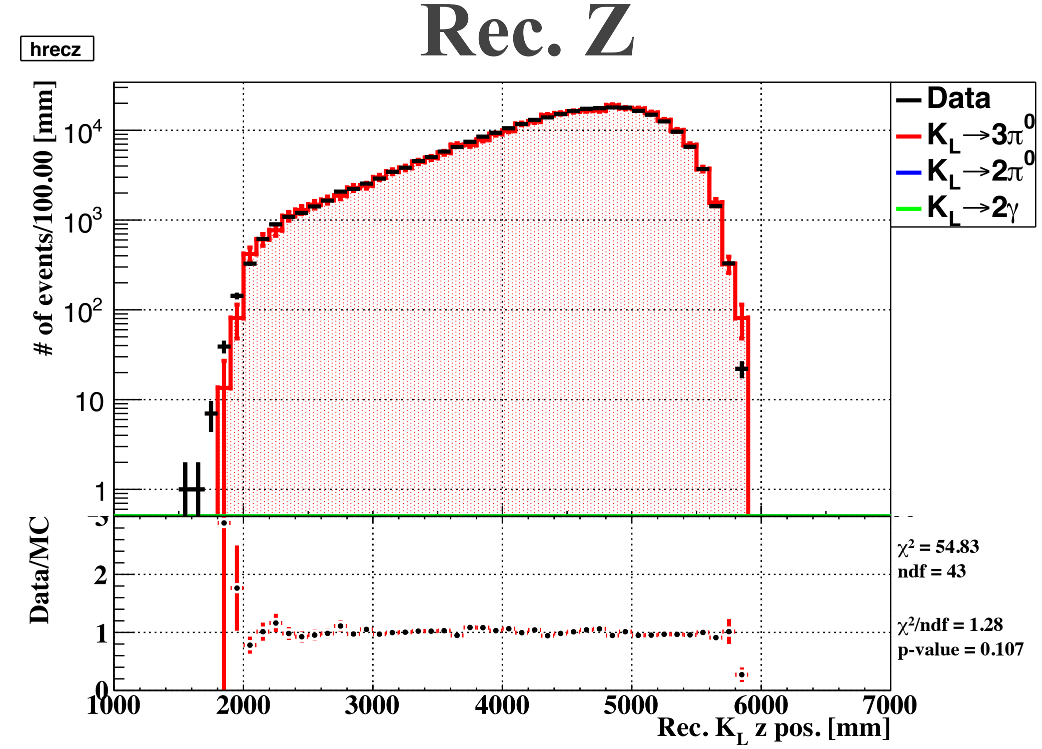
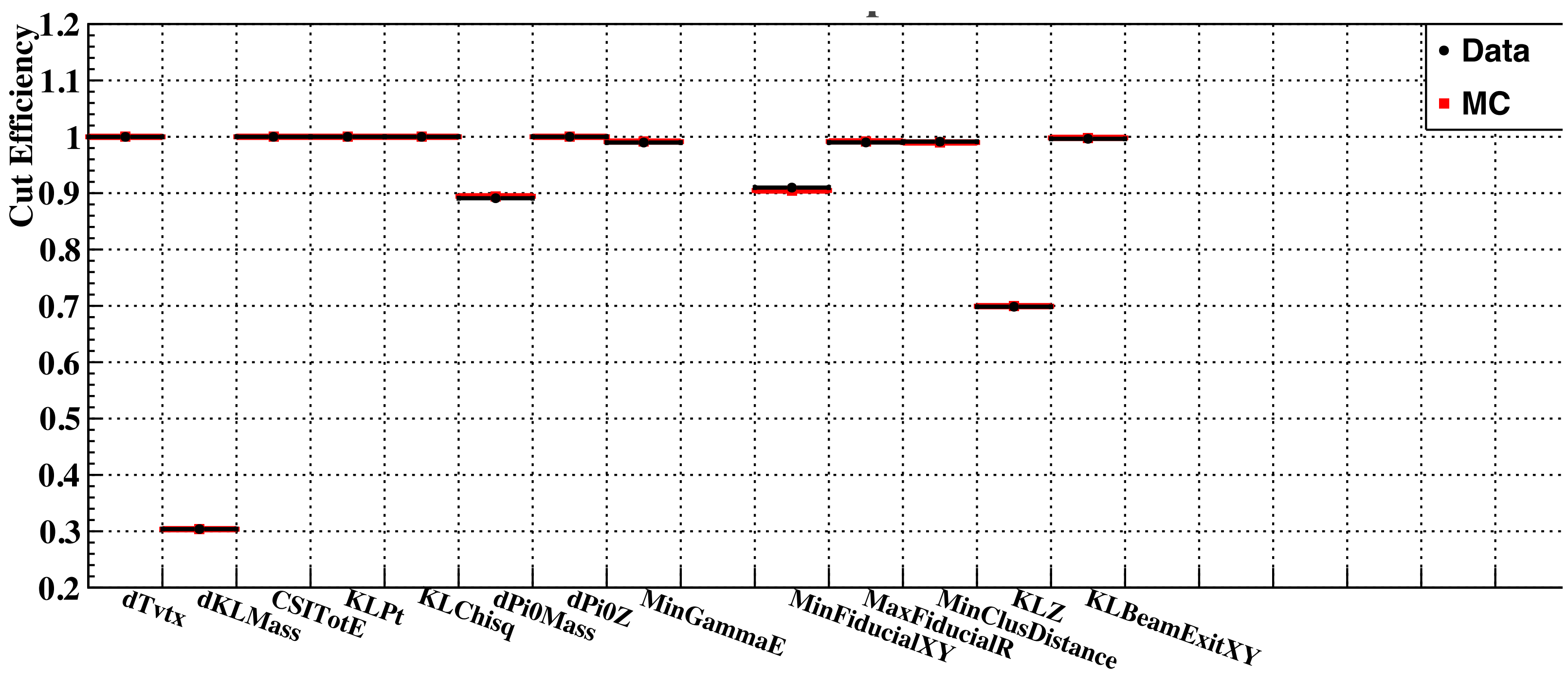



Fig. Reconstructed decay vertex position

# $K_L^0$—>$2\pi^0$ Event distributions

**$K_L^0$—>$2\pi^0$**

- Efficiency of kinematic requirements
- $\varepsilon^i$= (Number of reconstructed $K_L^0$ events with all cuts) / (Number of reconstructed $K_L^0$ events w/o $i^{th}$ cut )
- Data well reproduced by MonteCarlo




KL mass

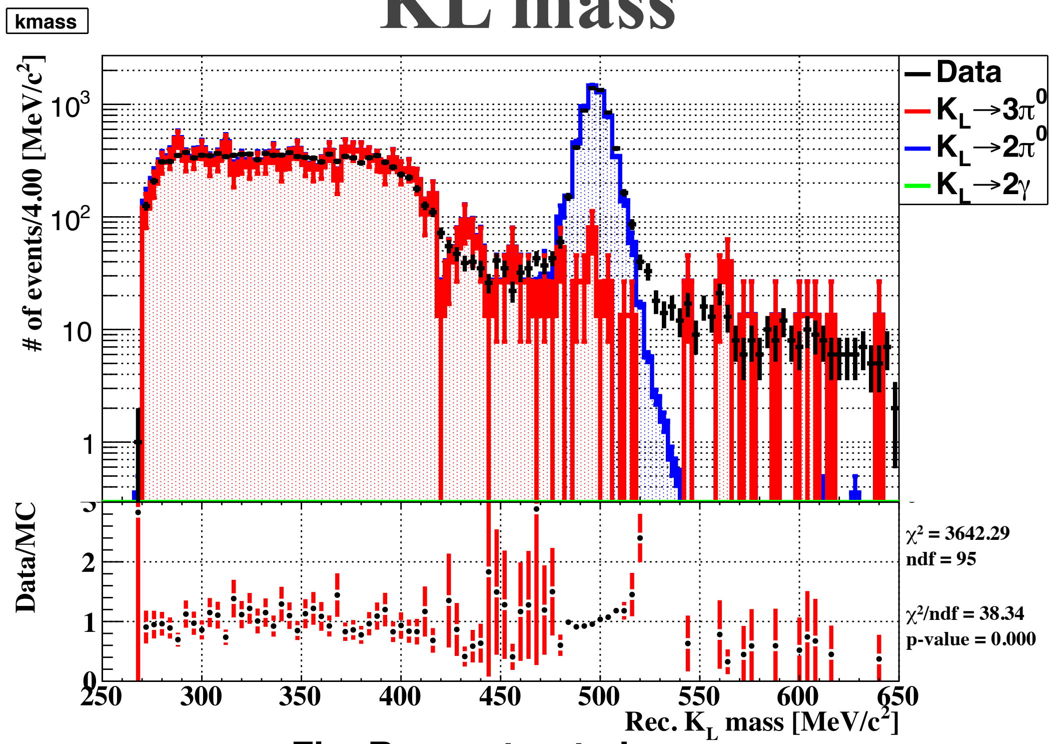



Fig. Reconstructed mass

Rec. Z

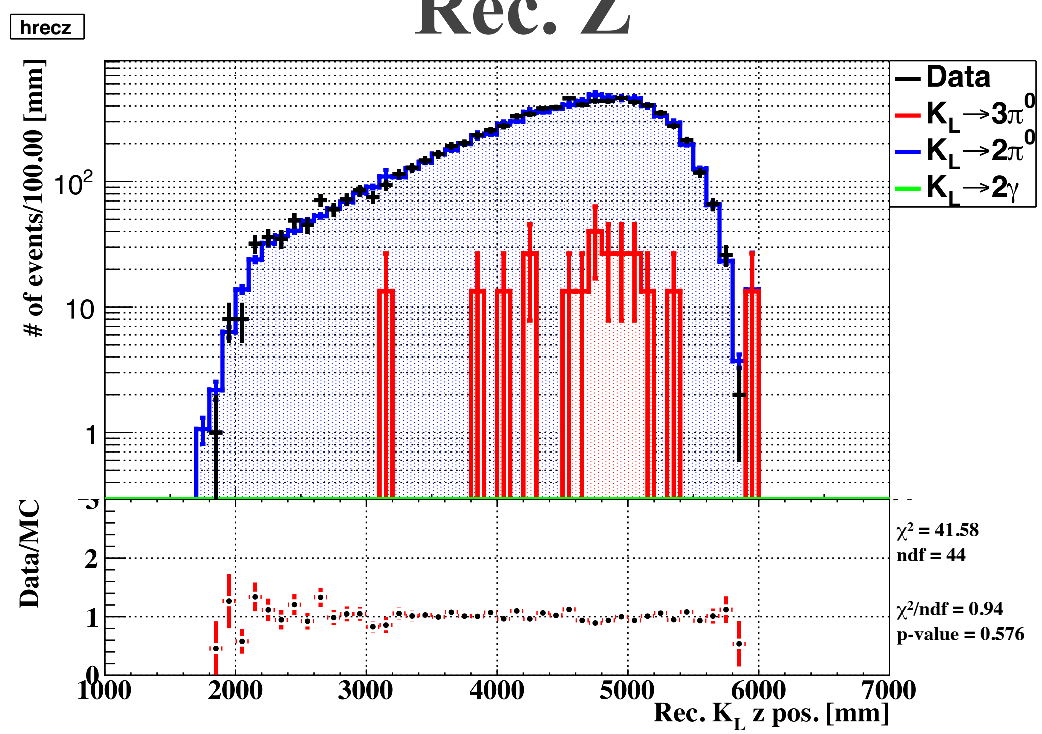



Fig. Reconstructed decay vertex position

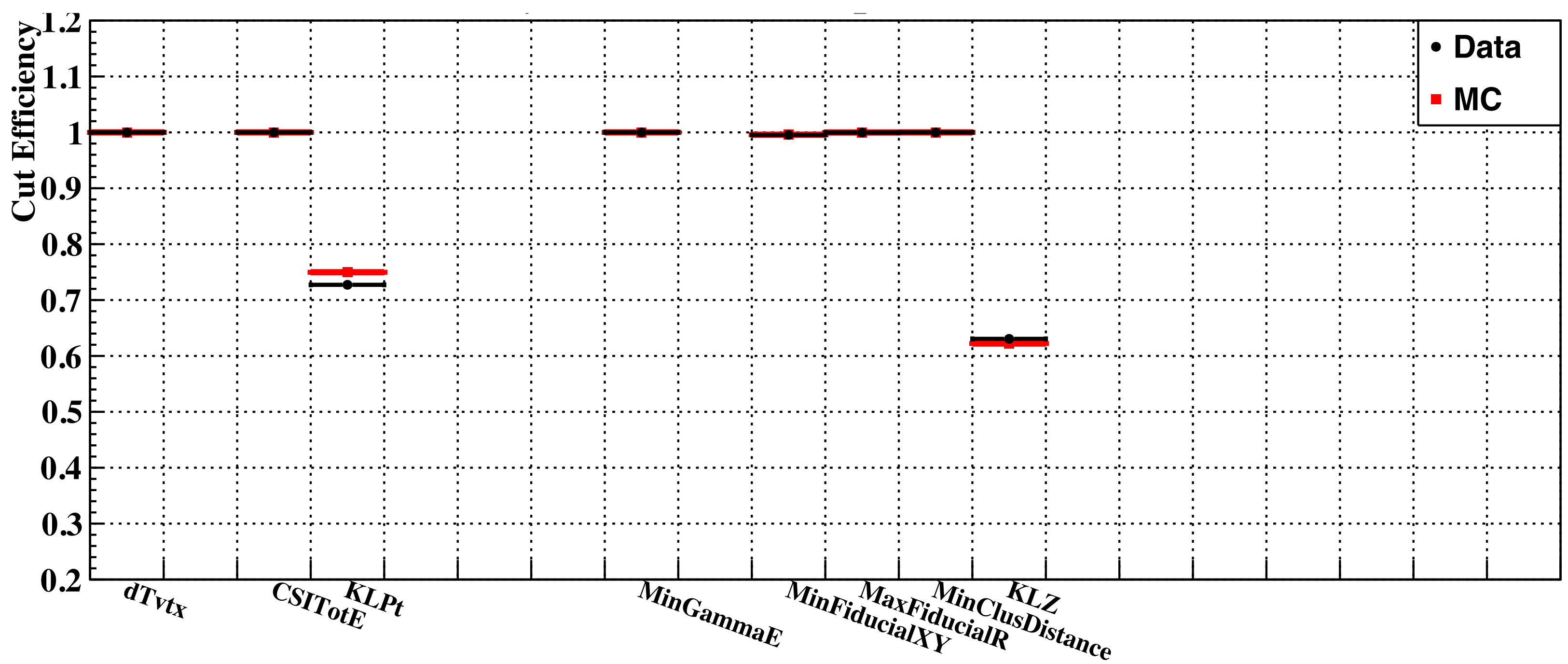
# $K_L^0 \longrightarrow 2\gamma$ Event distributions

## $K_L^0 \longrightarrow 2\gamma$

- Efficiency of kinematic requirements

- $\varepsilon^i$= (Number of reconstructed $K_L^0$ events with all cuts) / (Number of reconstructed $K_L^0$ events w/o $i^{th}$ cut )

- Data well reproduced by MonteCarlo




KL Pt

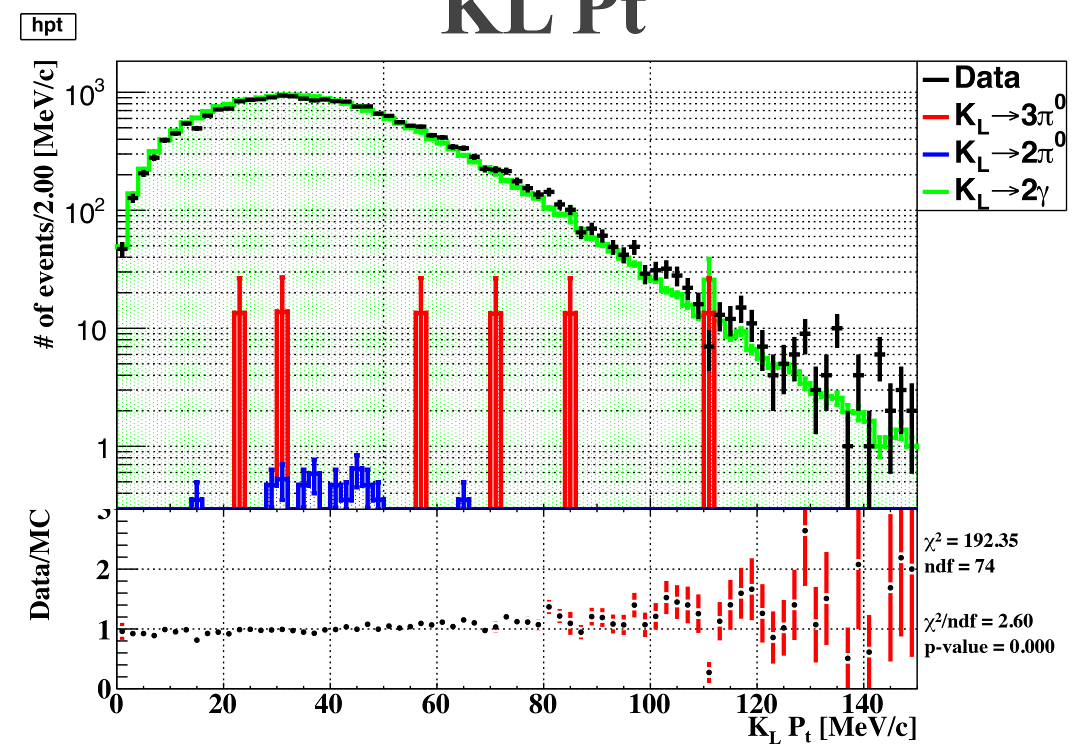



Fig. Reconstructed traverse momentum

Rec. Z

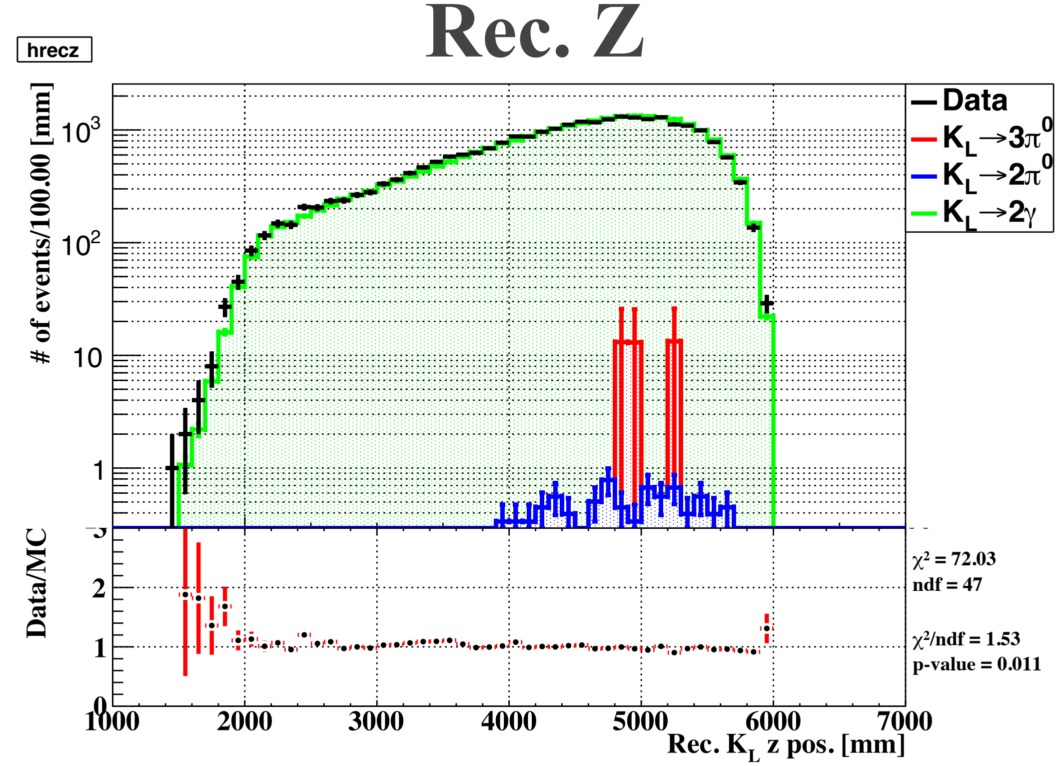



Fig. Reconstructed decay vertex position

# $K_L^0$ yield

- Yield obtained from three normalization modes are within systematics
- $K_L^0$ yield ($K_L^0 \rightarrow 2\pi^0$) = $4.58 \times 10^{12}$ from $2.2 \times 10^{19}$ POT

| ***Mode*** | **Yield at Beam Exit** |
|---|---|
| *$KL \rightarrow 2\pi^0$* | $(4.58 \pm 0.04) \times 10^{12}$ |
| *$KL \rightarrow 2\gamma$* | $(4.38 \pm 0.02) \times 10^{12}$ |
| *$KL \rightarrow 3\pi^0$* | $(4.62 \pm 0.02) \times 10^{12}$ |

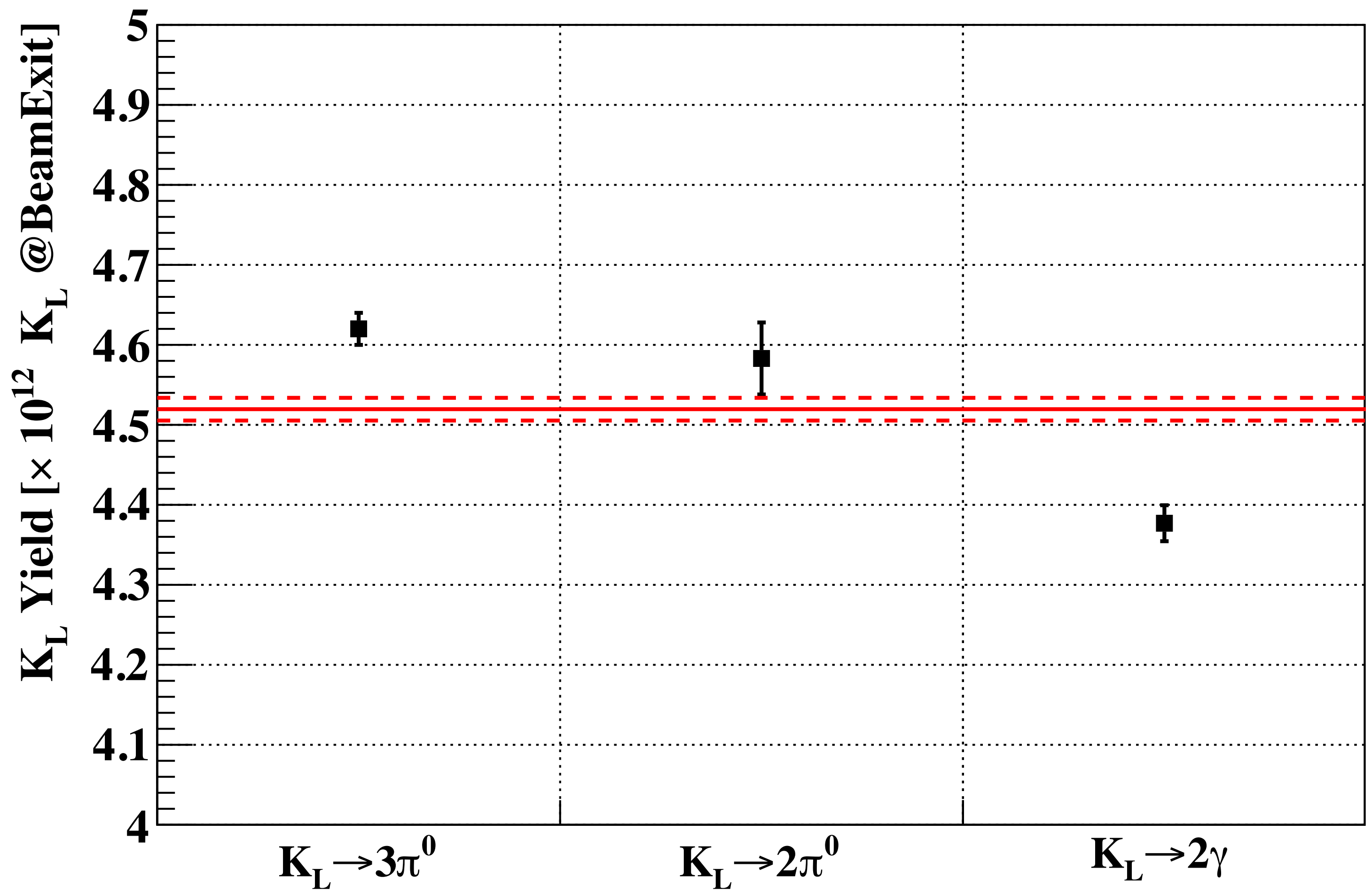
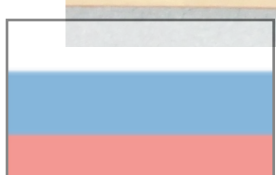



**Fig. Calculated $K_L^0$ yield at beam exit**

# Summary

- Summary of KOTO first results
  - *2013 first run set a BR($K_L \rightarrow \pi^0 \nu\nu$) upper limit of < $5.8 \times 10^{-8}$ (90% C.L.) (PTEP 021C01)*
- Present status
  - *In 2015, collected 20 times larger data set than the 2013 run*
  - *$K_L^0$ yield ($K_L^0 \rightarrow 2\pi^0$) = $4.58 \times 10^{12}$ (at beam exit)*
  - *Sensitivity of 2015 run will be determined based on this result*
  - *Data collected in 2016-2018 is being analyzed*
- 2015 run results will be presented in the next talk
- DON'T MISS IT!

# Thank You



Dec ’17 collaboration meeting