Search for the Rare Decay of the Neutral Kaon, $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$

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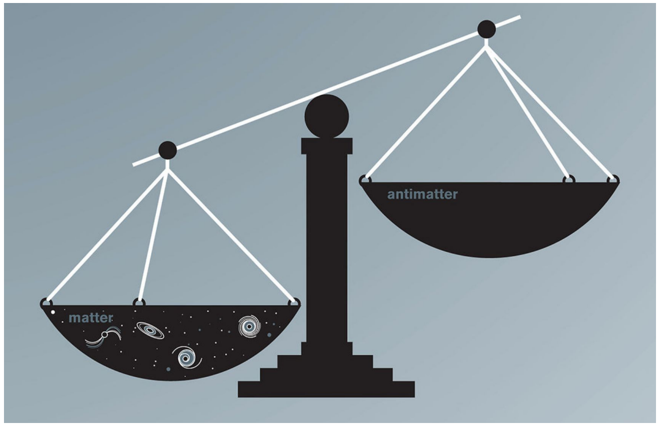
SLAC FPD Seminar

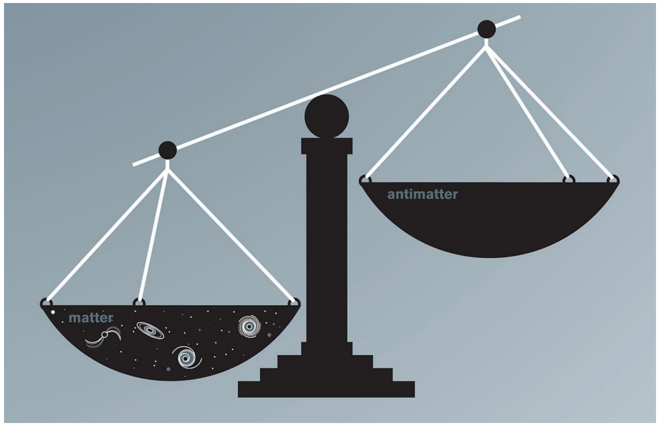
Unanswered Questions

- Dark matter?
- Accelerating expansion of the universe?
- Gravity in the SM?
- Neutrino mass hierarchy & neutrino oscillations?
- ***Why is there more matter than antimatter in the universe?***



Courtesy of Symmetry magazine

Unanswered Questions



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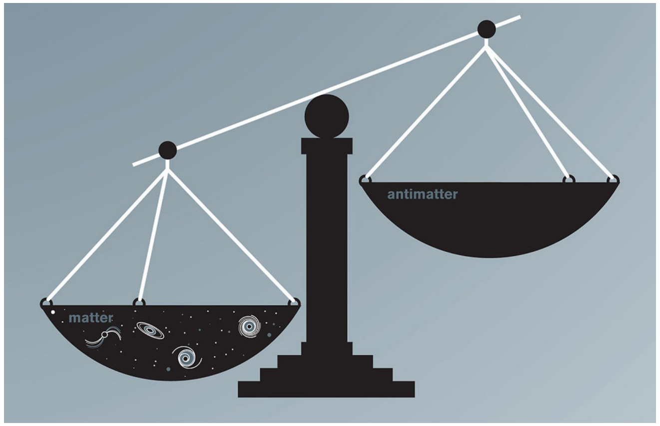

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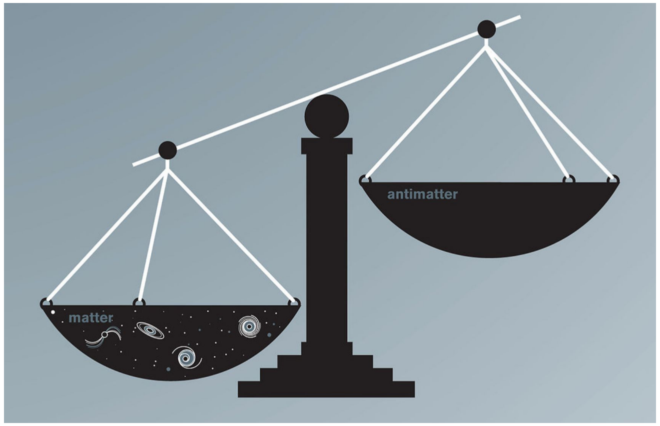
- Charge-Parity (CP) violation (does not fully explain) → new physics?

- CKM (Cabibbo-Kobayashi-Maskawa) Matrix
  - Describes the strength of flavor-changing weak decays

$$\begin{array}{ccccc} \text{Weak eigenstates} & & \text{CKM} & & \text{Mass eigenstates} \\ \begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} & = & \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} & & \begin{bmatrix} d \\ s \\ b \end{bmatrix} \end{array}$$

Unanswered Questions



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- CKM (Cabibbo-Kobayashi-Maskawa) Matrix
  - Describes the strength of flavor-changing weak decays
  - In Wolfenstein parametrization: 3 real parameters (λ, ρ, A) and 1 imaginary (η)

CP contribution

CKM elements determined from experimental measurements

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

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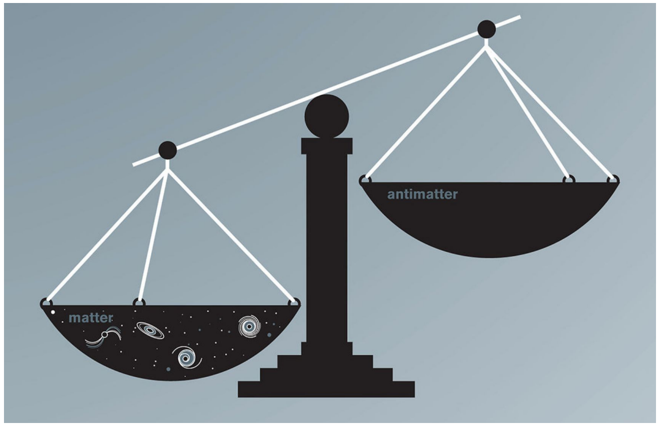

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- Charge-Parity (CP) violation (does not fully explain) → new physics?

- CKM (Cabibbo-Kobayashi-Maskawa) Matrix
  - Describes the strength of flavor-changing weak decays
  - **Unitary**

Weak eigenstates CKM Mass eigenstates

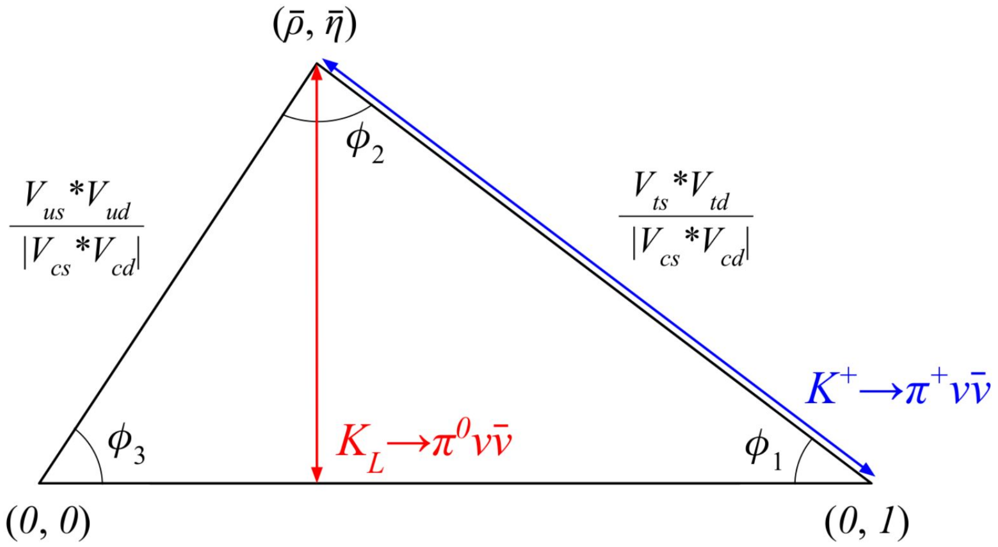
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

CKM Matrix

- Because the CKM matrix is unitary,
  $V_{us}{}^{*}V_{ud} + V_{cs}{}^{*}V_{cd} + V_{ts}{}^{*}V_{td} = 0$

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} V_{ud}^{*} & V_{cd}^{*} & V_{td}^{*} \\ V_{us}^{*} & V_{cs}^{*} & V_{ts}^{*} \\ V_{ub}^{*} & V_{cb}^{*} & V_{tb}^{*} \end{bmatrix} = \mathrm{I}$$

- Draw a triangle in complex plane (normalize)
- CP violation contributions are seen if height is non-zero
- Test SM by measuring the 3 sides and 3 angles and see if the triangle closes



Investigating CP violation

- Look for SM processes that exhibit CP violation and are
    - ***Well known***
    - ***Rare***

→ Search for large deviations from the prediction

- Many ways to study CP violation (quark/lepton)

  Golden processes
    - $K_L \to \pi^0 \nu \bar{\nu}$
    - $K^+ \to \pi^+ \nu \bar{\nu}$
    - Asymmetries in $B^0 \to J/\psi K_s$
    - Ratio of B_s to B_d mixing

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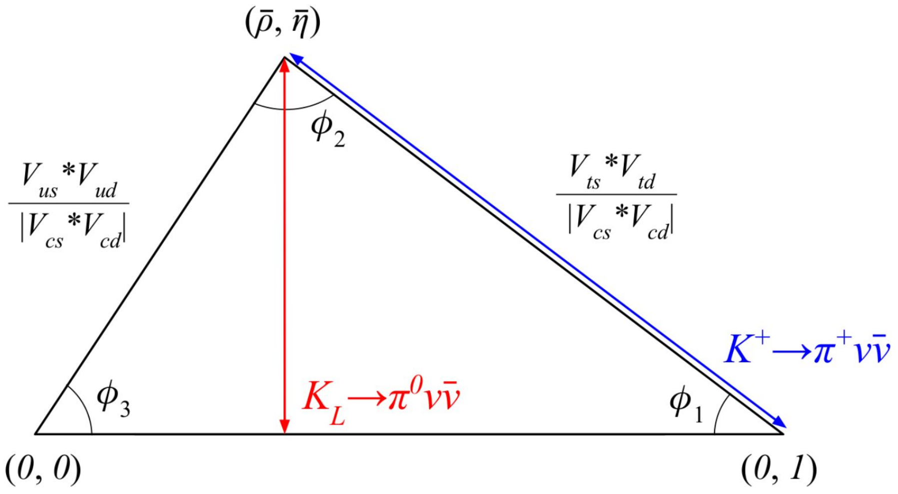

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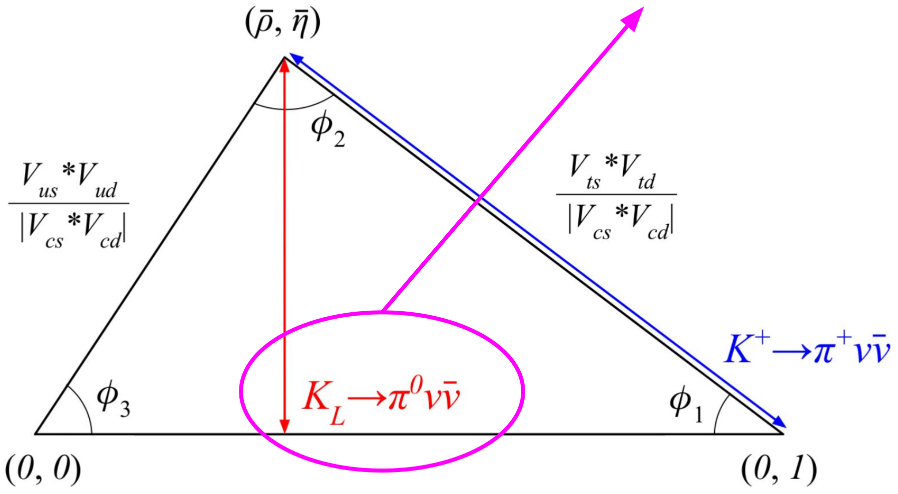
KOTO Experiment

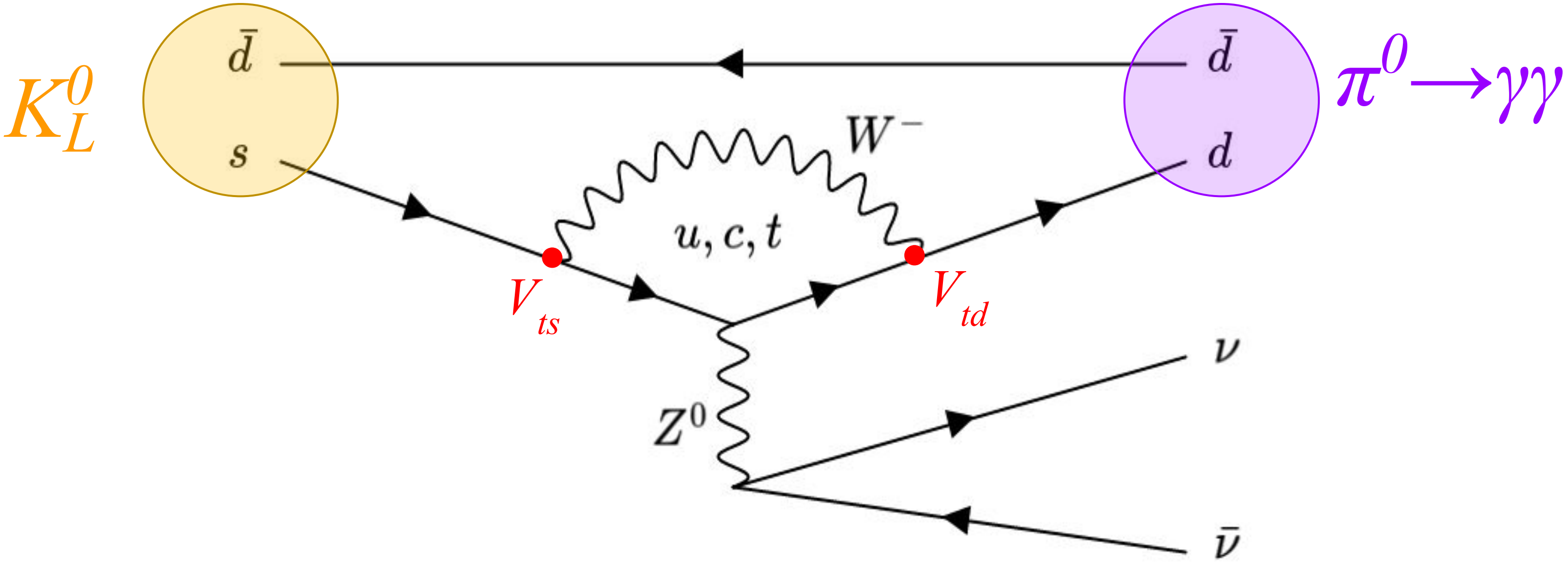
Constrain height of Unitarity Triangle



$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$

- 2nd order Flavor Changing Neutral Current (FCNC) that directly violates CP
- SM predicted BR of **(3.00 ± 0.30) x 10^{-11}** *rare* ✓
- Clean channel, small theoretical uncertainties (~1-2%) *well known* ✓

→ Good probe to search for new physics



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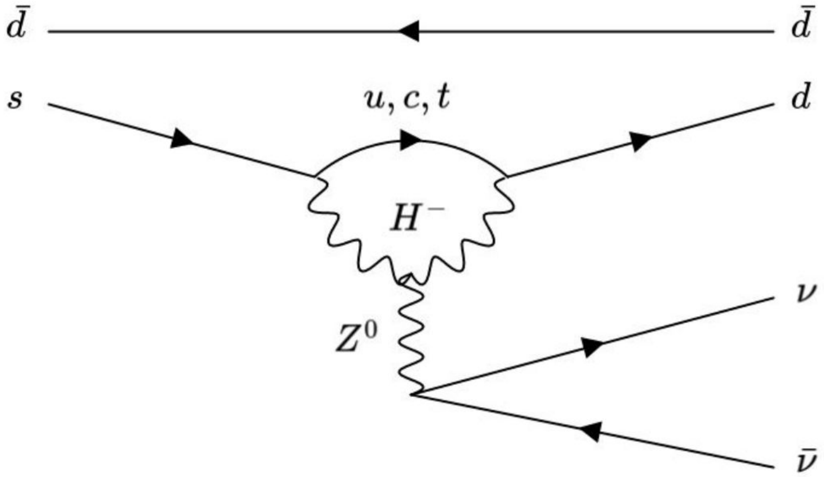
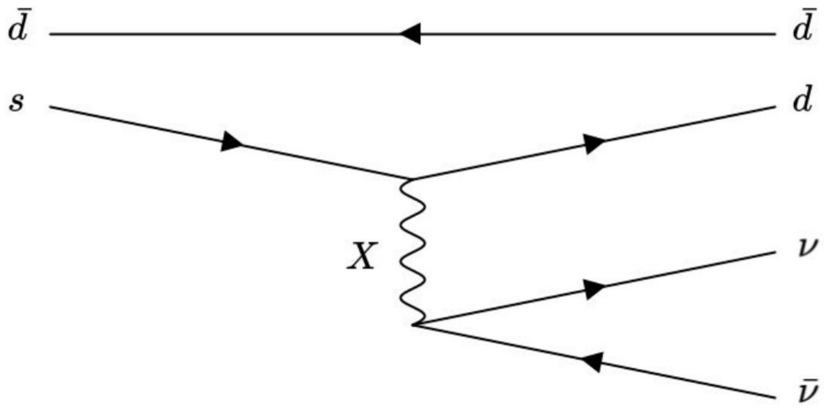
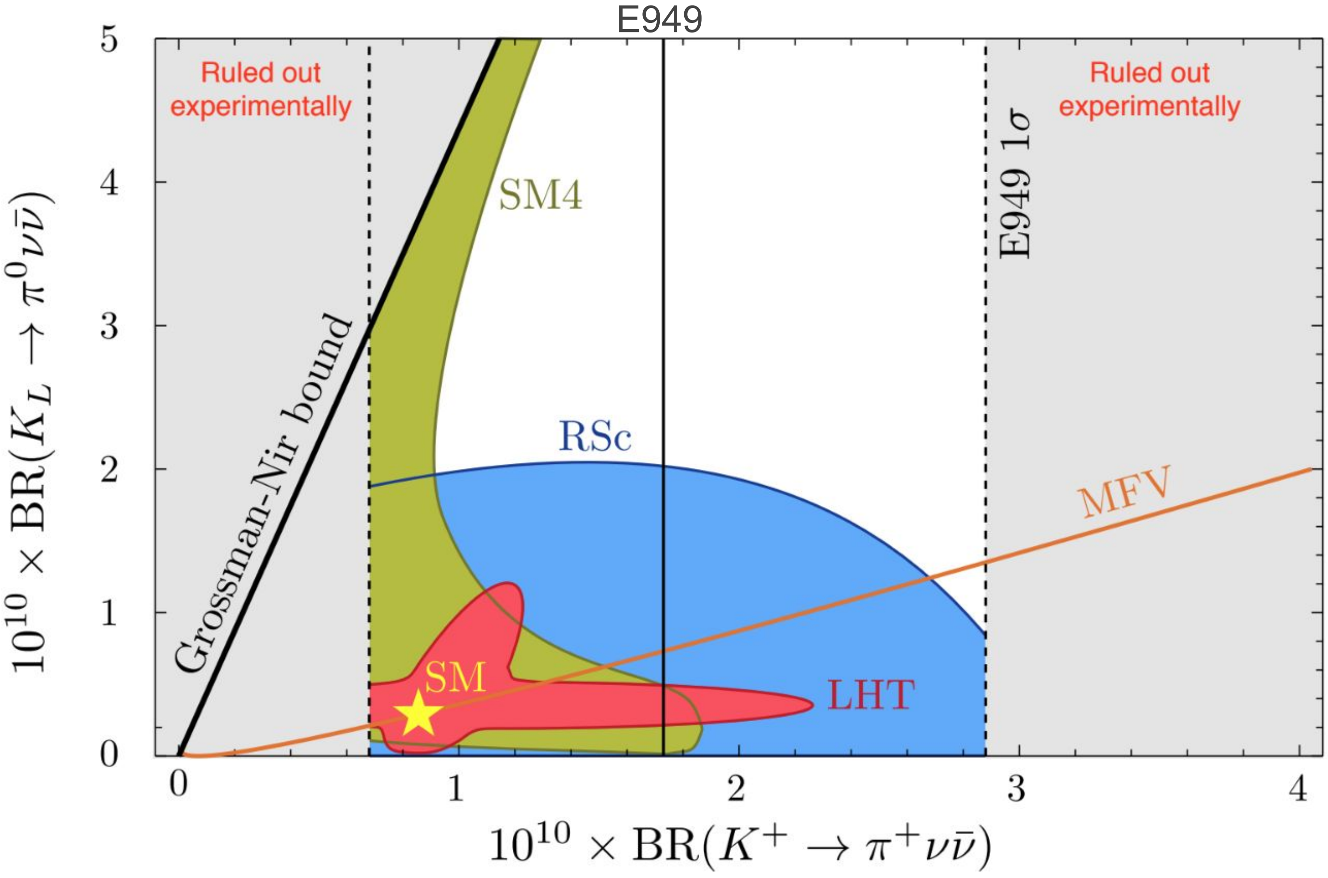
- Possible beyond the SM diagrams





$K^+ \to \pi^+ \nu\bar{\nu}$ & Grossman-Nir Bound

- Charged decay equally as important (NA62)
- Set model independent, indirect limit on $K_L^0 \to \pi^0 \nu\bar{\nu}$ based on isospin symmetry
  → Grossman-Nir bound
- BR($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 4.4 x BR($K^+ \to \pi^+ \nu\bar{\nu}$) → BR($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 1.5×10^{-9}



LHT: Littlest Higgs (T-parity)
MFV:Minimum Flavor Violation
RSc: Randall-Sundrum
SM4: SM w/ 4th gen

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

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ & Grossman-Nir Bound

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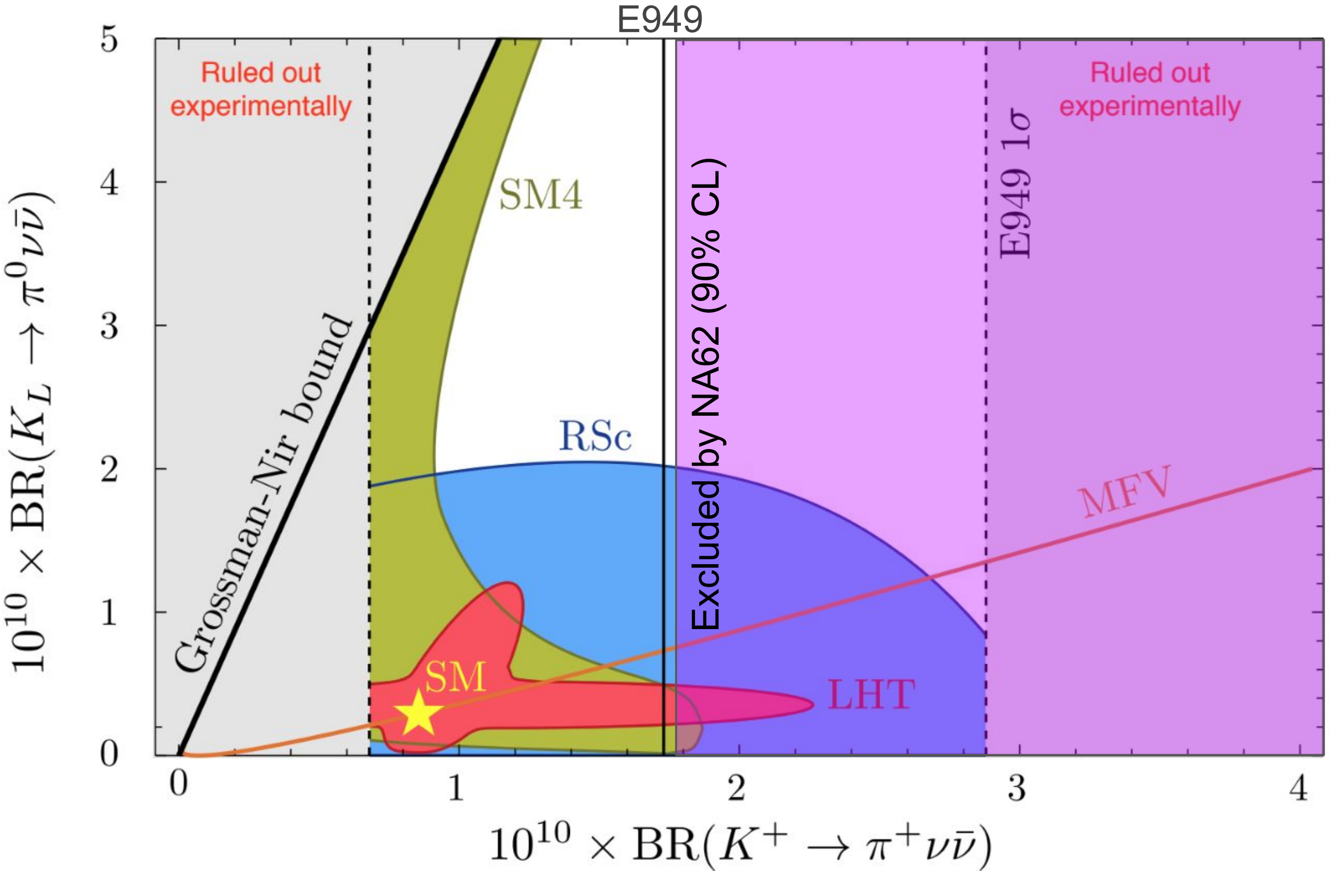
- Set model independent, indirect limit on $K^0_L \rightarrow \pi^0 \nu\bar{\nu}$ based on isospin symmetry
  - → Grossman-Nir bound
- $\mathrm{BR}(K^0_L \rightarrow \pi^0 \nu\bar{\nu}) < 4.4 \times \mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) \rightarrow \boxed{\mathrm{BR}(K^0_L \rightarrow \pi^0 \nu\bar{\nu}) < 1.5 \times 10^{-9}}$



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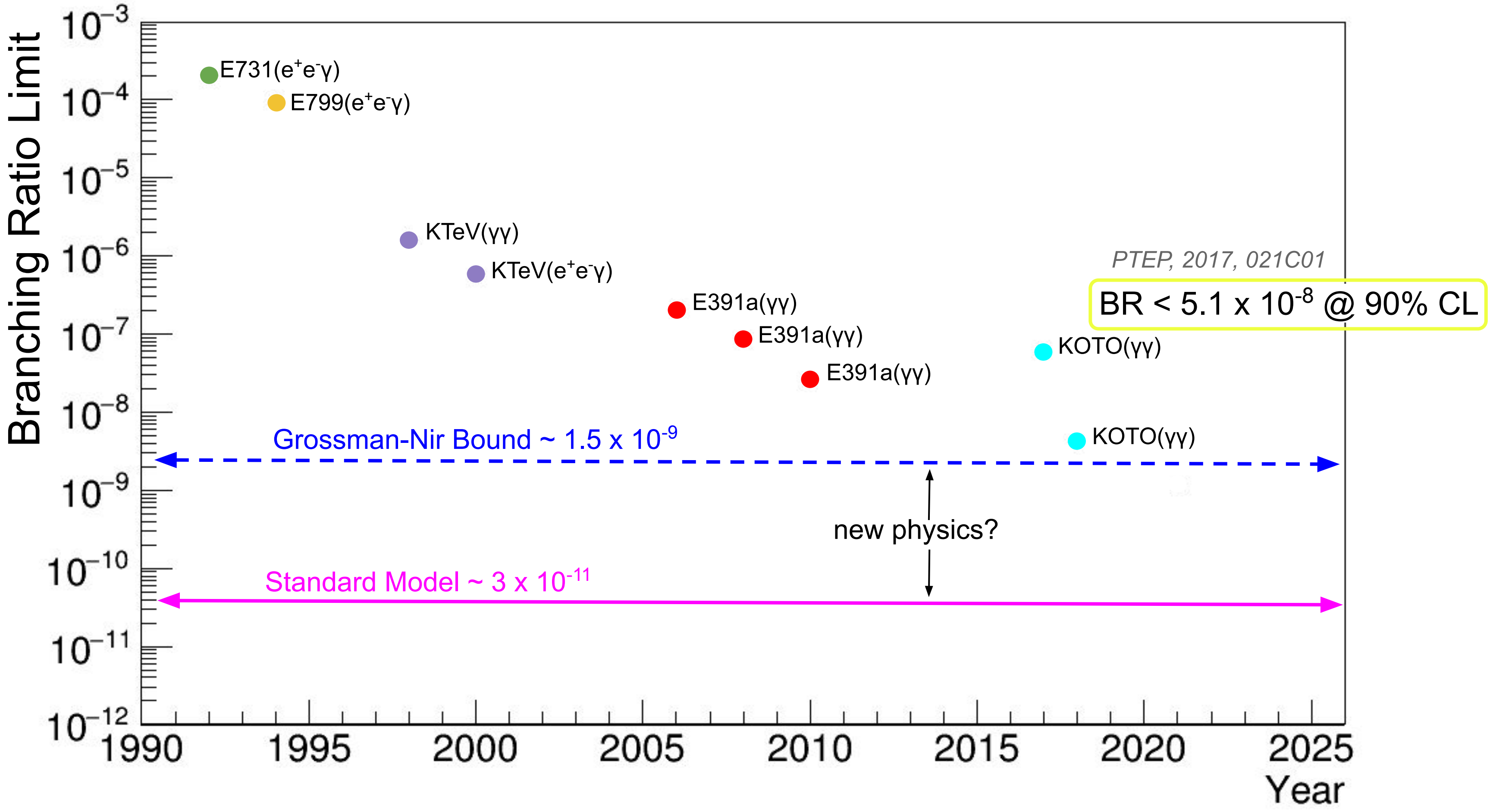
E949 (2008):
BR = $(1.7 \pm 1.1) \times 10^{-10}$

NA62 (2020):
BR < 1.78×10^{-10} @ 90% CL

Search History

- Best experimental limit set by KOTO in 2019 is BR < **3.0×10^{-9}** at the 90% CL *(Phys. Rev. Lett. 122, 021802)*
- Improved previous limit (E391a) by an order of magnitude
- KOTO aims to measure the Branching Ratio (BR) to SM sensitivity



PTEP, 2017, 021C01

BR < 5.1×10^{-8} @ 90% CL

Experimental Setup

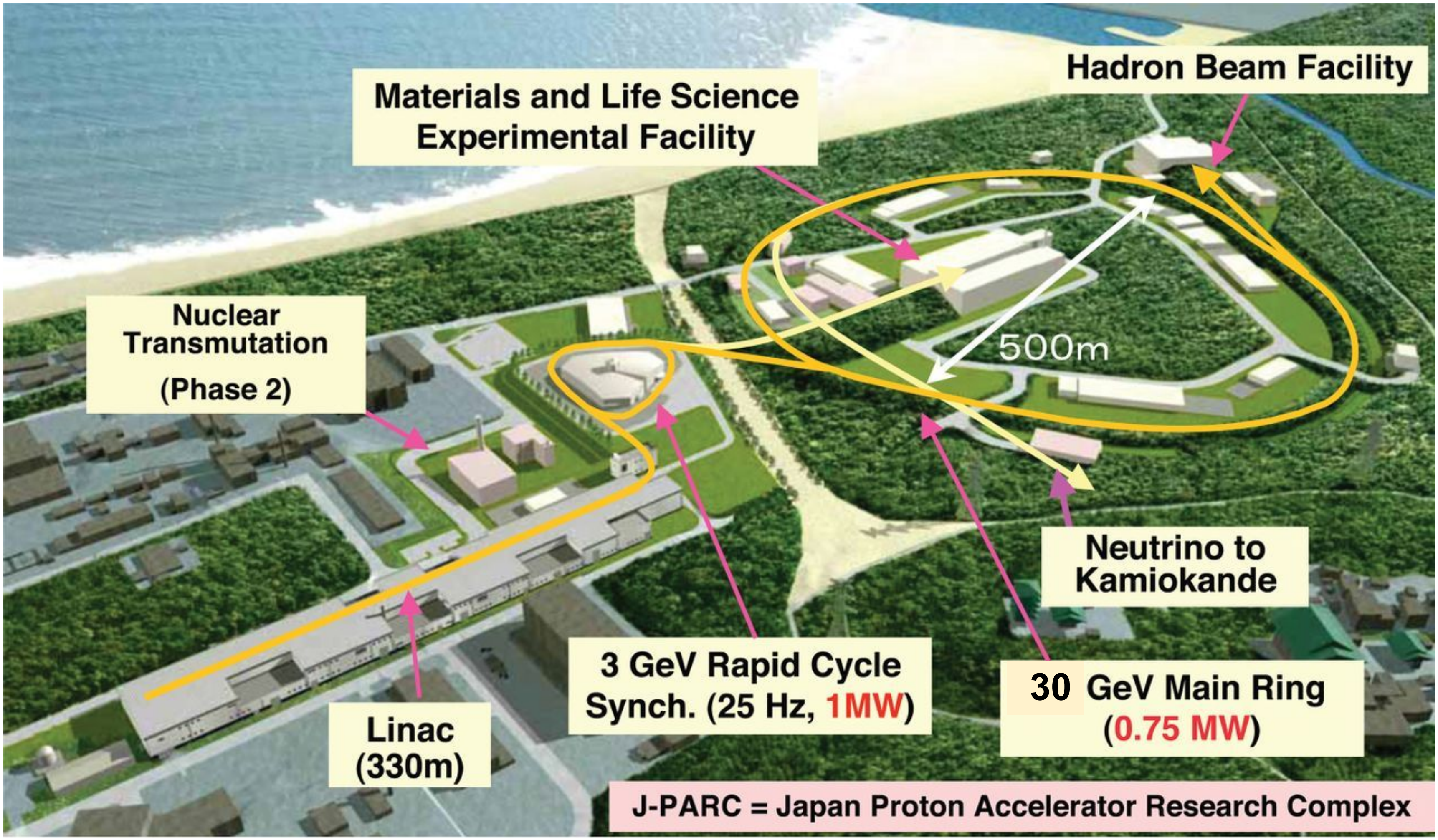
- Located in Tokai, Ibaraki Prefecture, Japan

“K^0 at TOkai”

Japan Proton Accelerator Research Complex

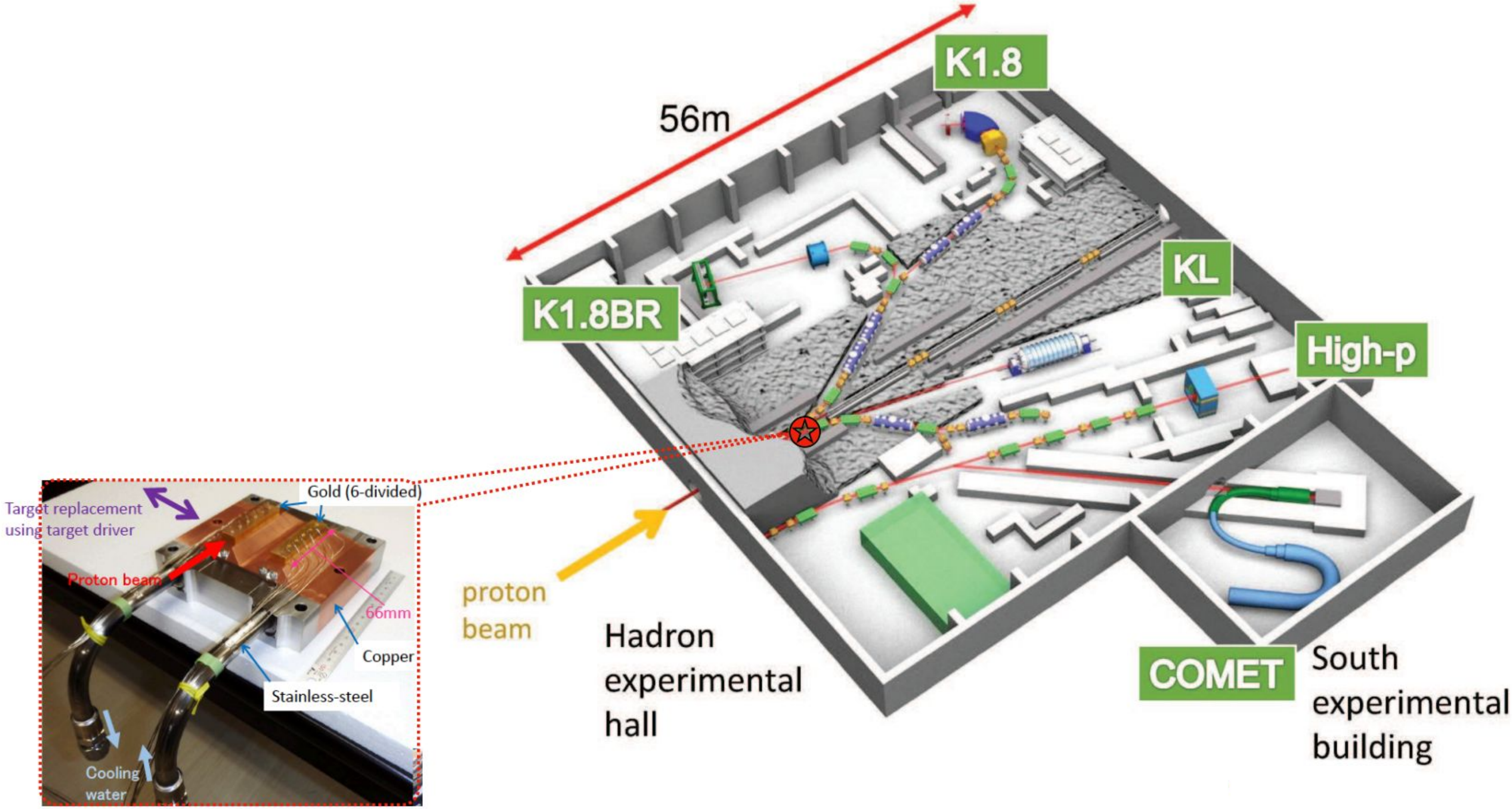
J-PARC Research Facility

- Located in Tokai, Ibaraki, Japan
- 30 GeV protons → stationary gold target



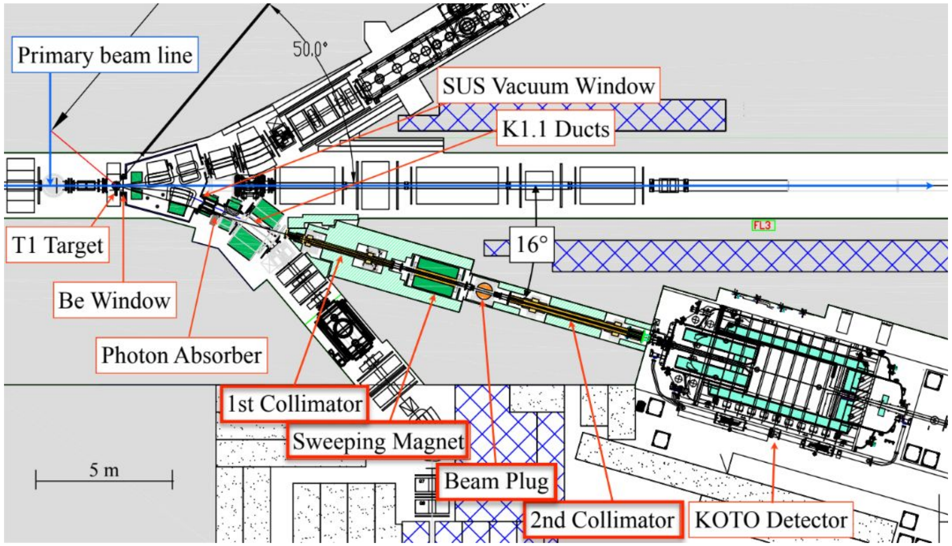
K_L Production

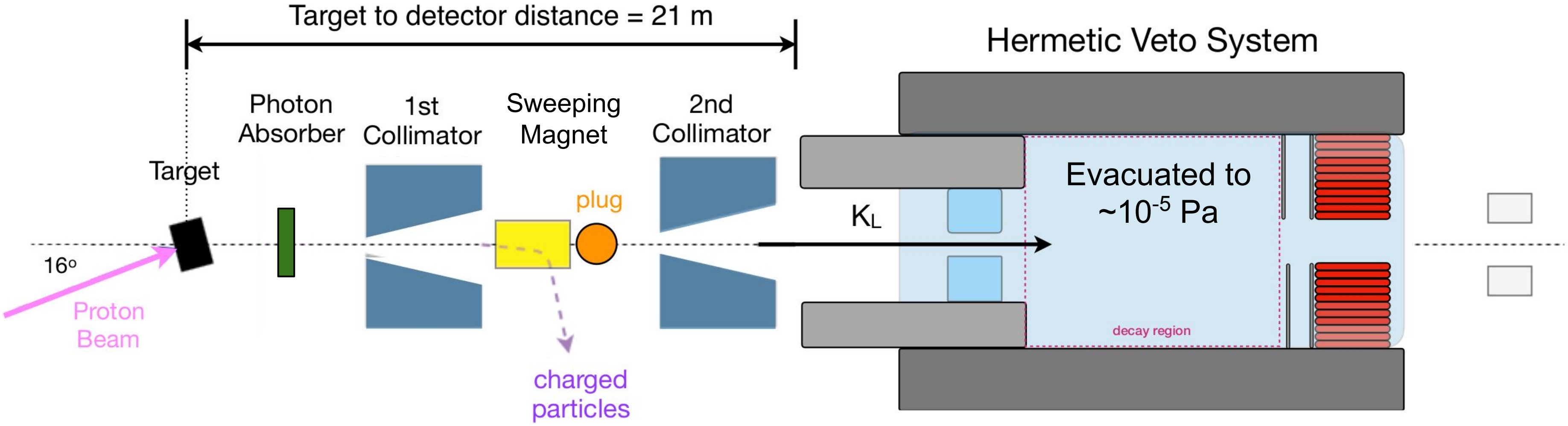
- 5×10^{13} protons per 2s spill at 50 kW beam power
- ~ 10^{8} K_L per spill w/ momentum peak at 1.4 GeV/c



K_L Beamline

- Secondary K_L beamline collimated to pencil beam ~ 8x8 cm^2
- K_L ~100x longer lifetime than most particles
- Neutral beam of kaons, neutrons, & photons





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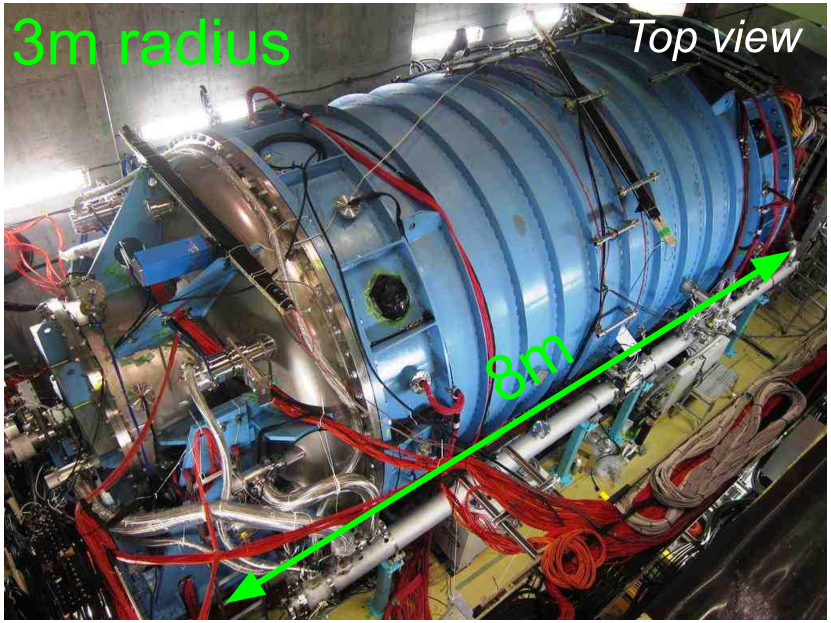
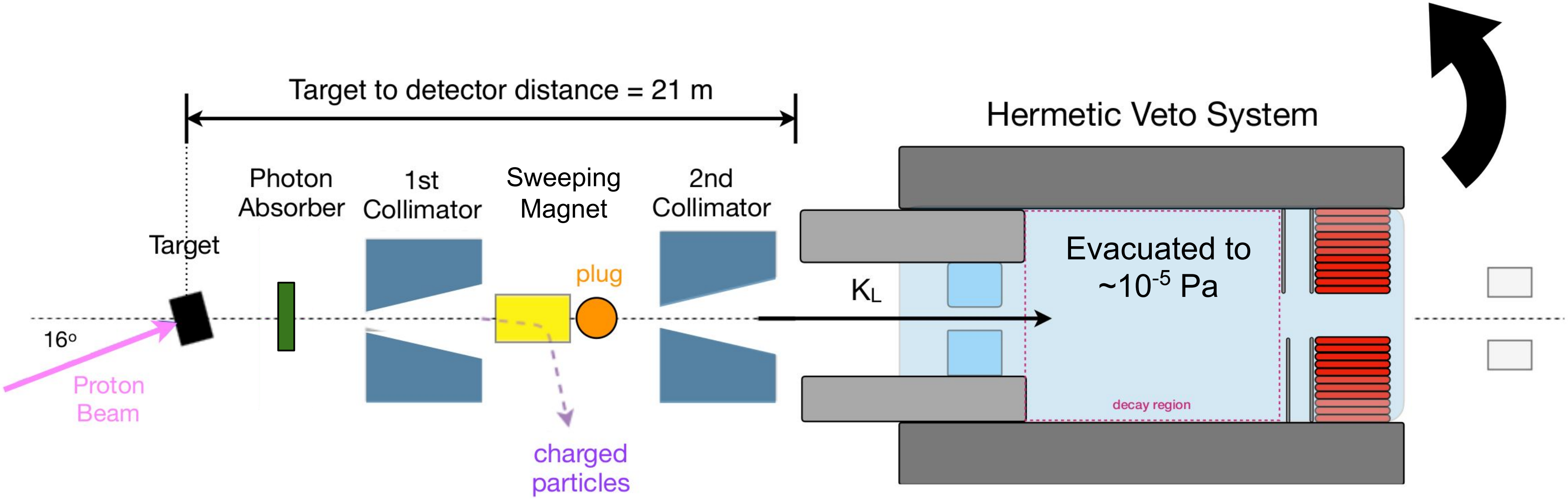
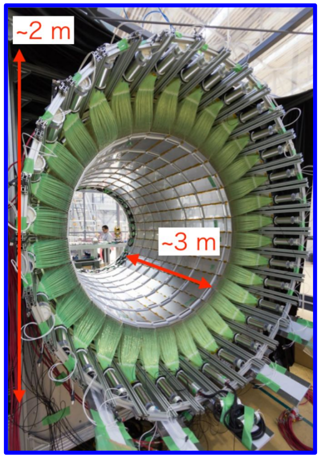




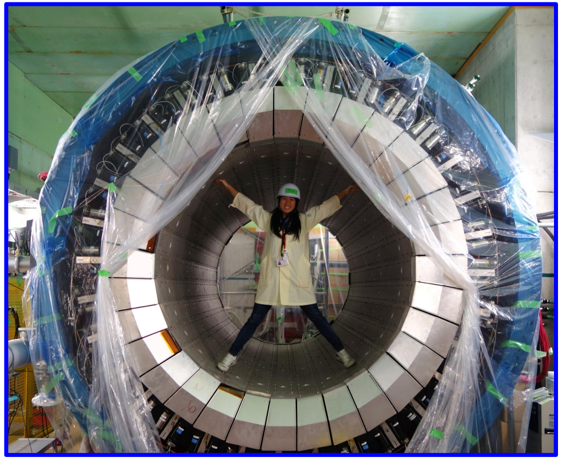
KOTO Detectors

- Cesium Iodide (CsI) calorimeter detects photons from signal decay
- Hermetic veto detector system (charged/photon) in place to reject other events

Inner Barrel (IB)

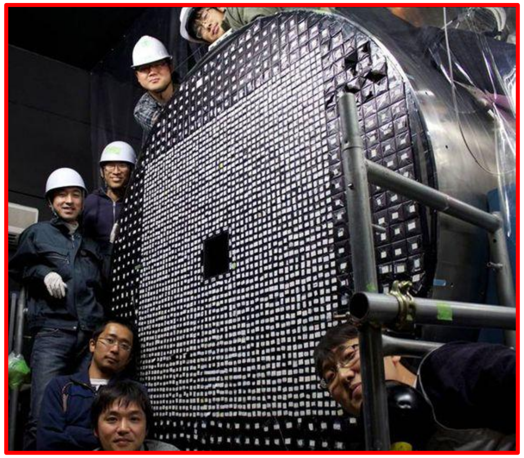


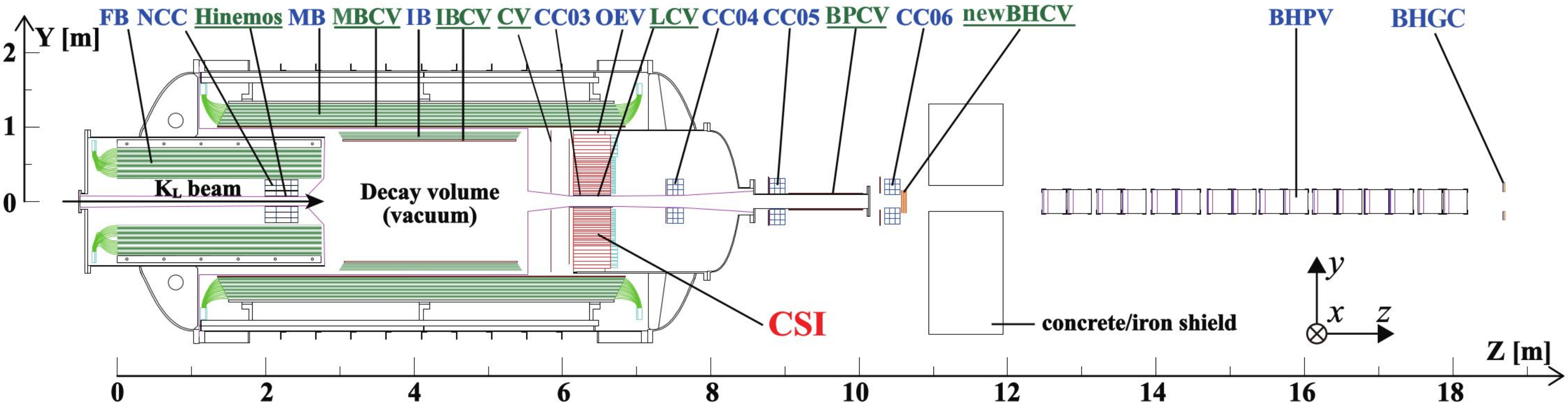
Main Barrel (MB)



Charged Veto (CV)

CsI Calorimeter (CsI)



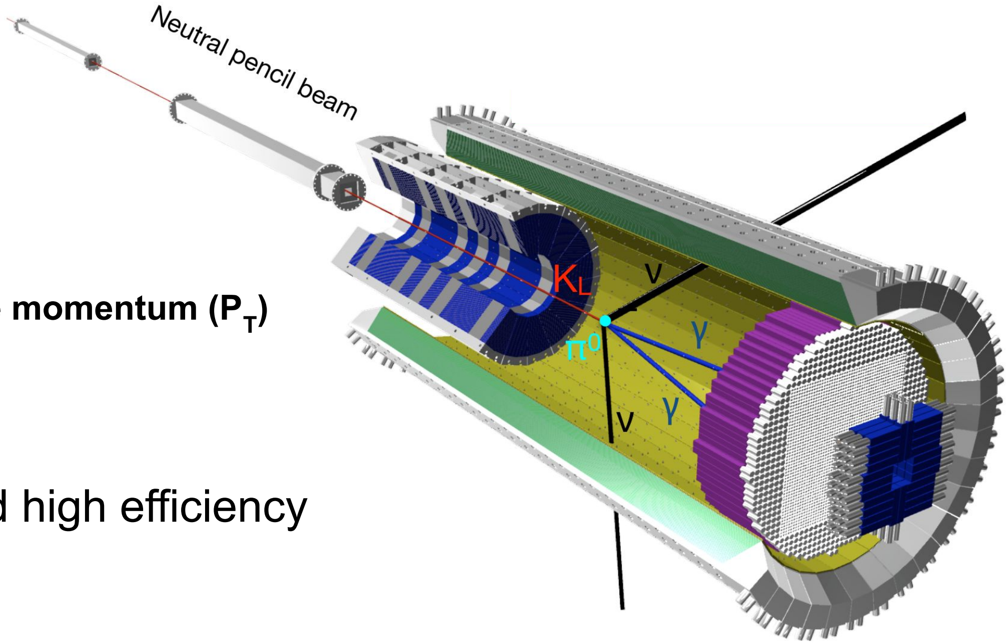


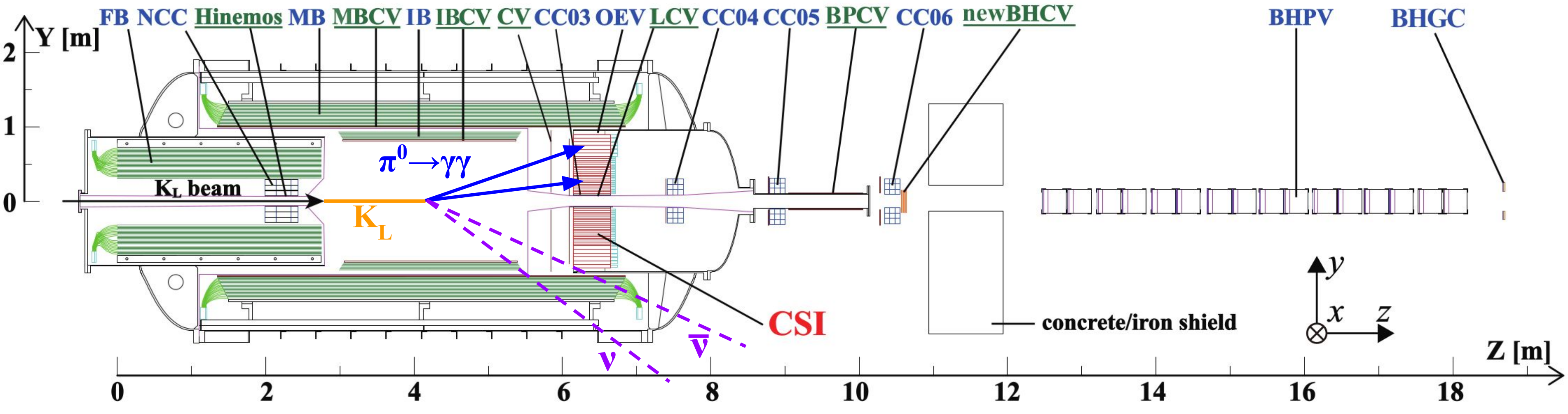
Experimental Strategy

- Cesium Iodide (CsI) calorimeter detects 2 photons from signal decay

- **Requirements:**
    - **Observe 2 photons with large transverse momentum (P_T)**
    - **no other particles seen**

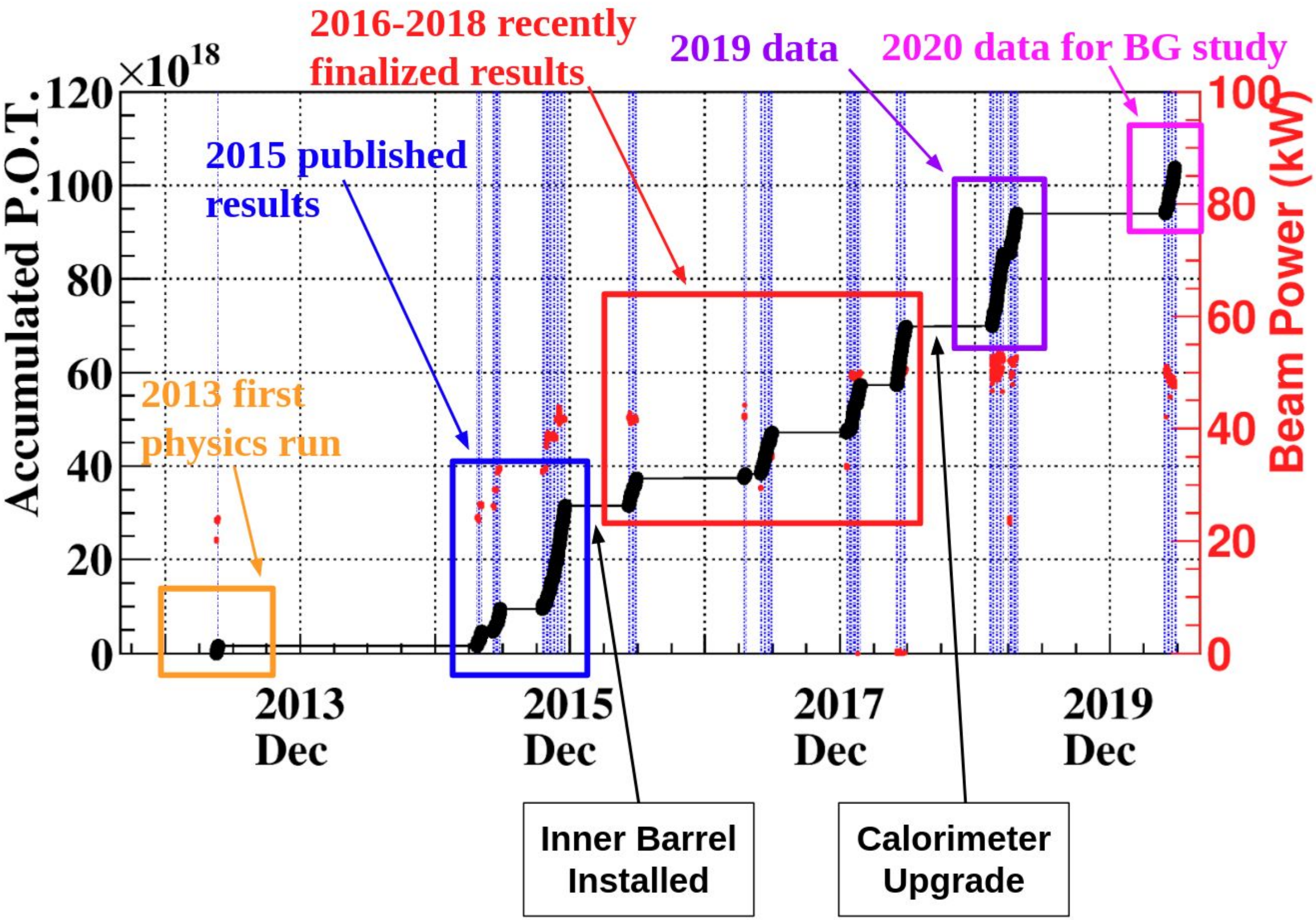
- Difficulty → no charged particles and high efficiency required to detect all other particles





Data Collection History

- POT = Protons on Target



Analysis

- Challenge → background reduction
- Blind analysis method + Monte Carlo simulations
  1. Signal reconstruction
  2. Normalization
  3. Background estimation and reduction

- Three variables needed to calculate BR
  - Number of signal events
  - Number of K_L^0s generated at beam exit
  - Signal acceptance

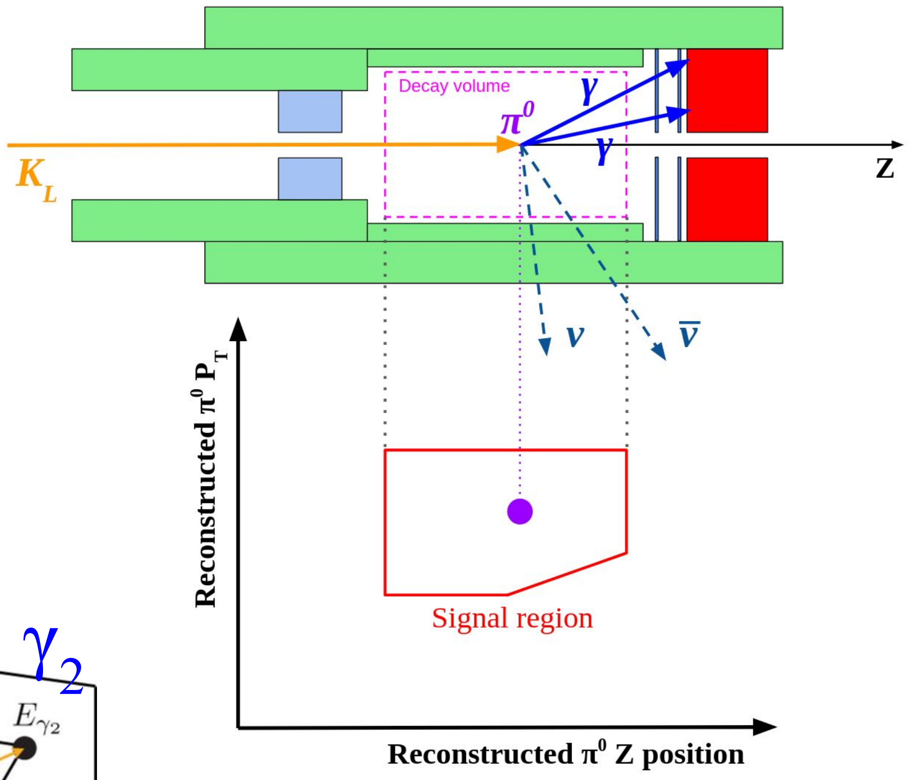
$$BR(K_L^0 \to \pi^0 \nu \bar{\nu}) = \frac{N_{\text{signal}}}{N_{K_L^0} \times A_{\text{signal}}}$$

- Single Event Sensitivity

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

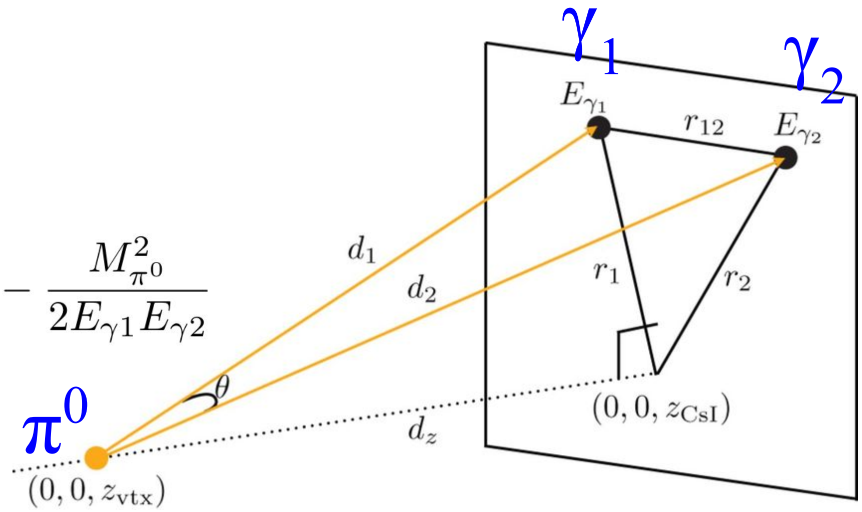
Signal Reconstruction

- Identify $K_L^0 \to \pi^0\nu\bar{\nu}$ events to calculate N_{signal}
  - → Use information about the pion
- 2 clusters hit on CsI
  - Position
  - Energy
- Constraints
  - π^0 mass
  - Decay position on beamline



Reconstruct π^0 decay vertex (Z position) and transverse momentum (P_T)

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



$$P_T^{\pi^0} = \left| \sum_{i=1,2} E^i_{cluster} \frac{\vec{r_i}}{\sqrt{r_i^2 + \Delta Z^2}} \right|$$

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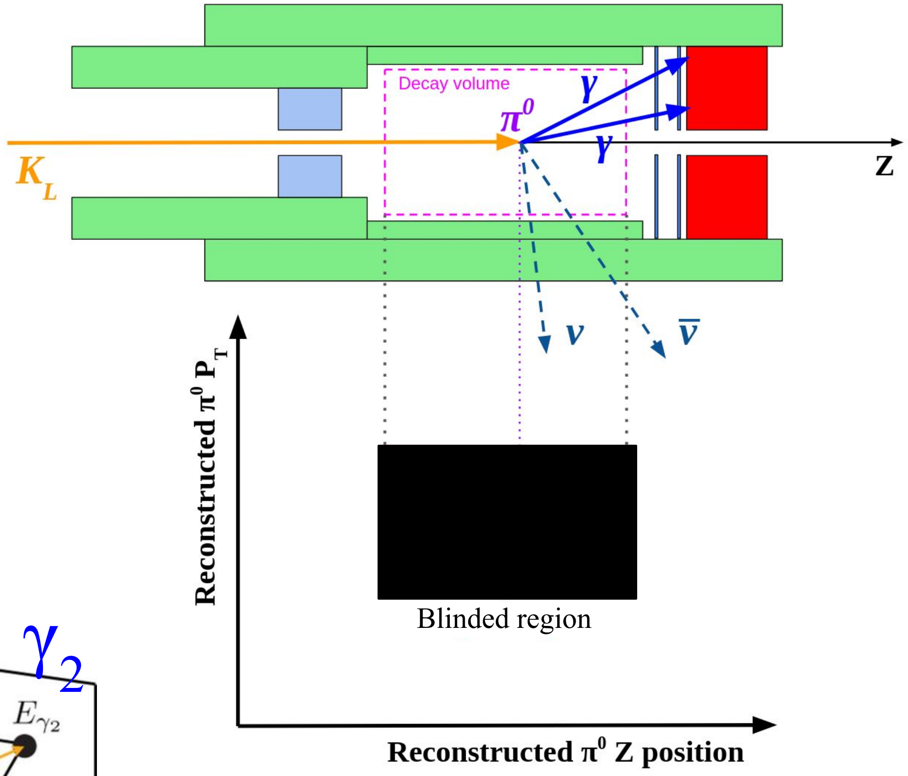

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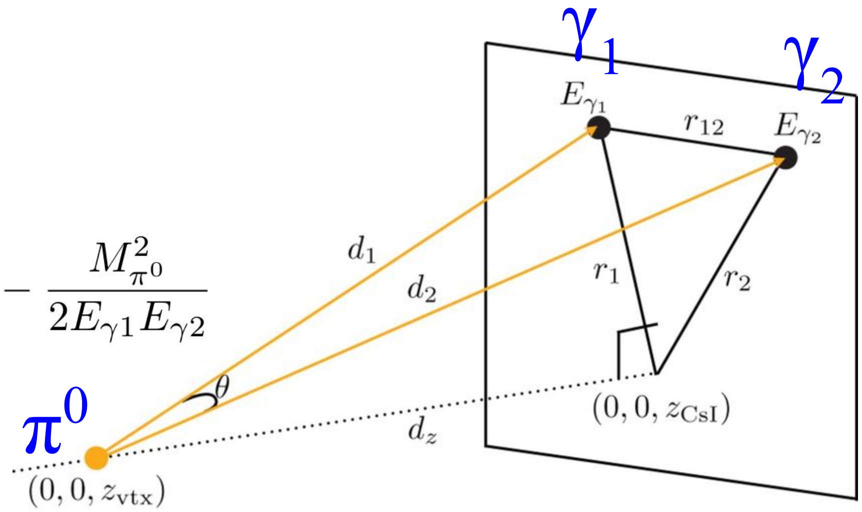

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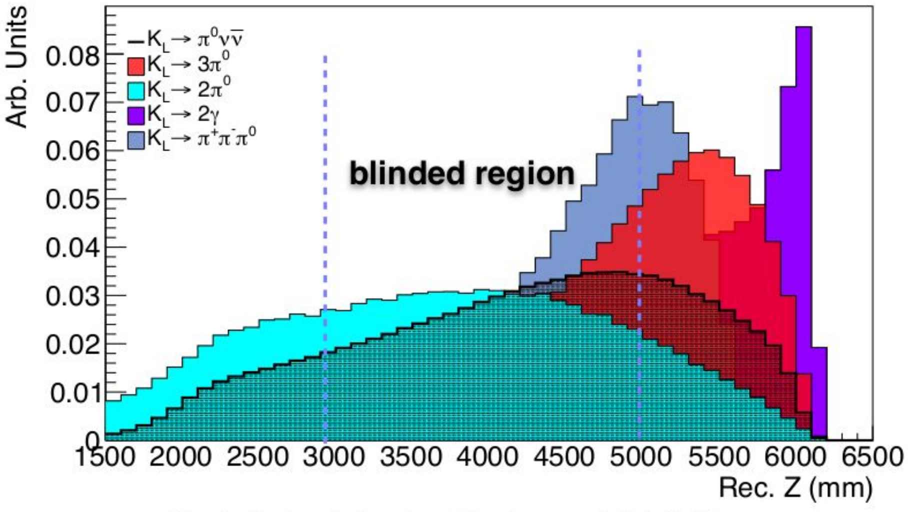
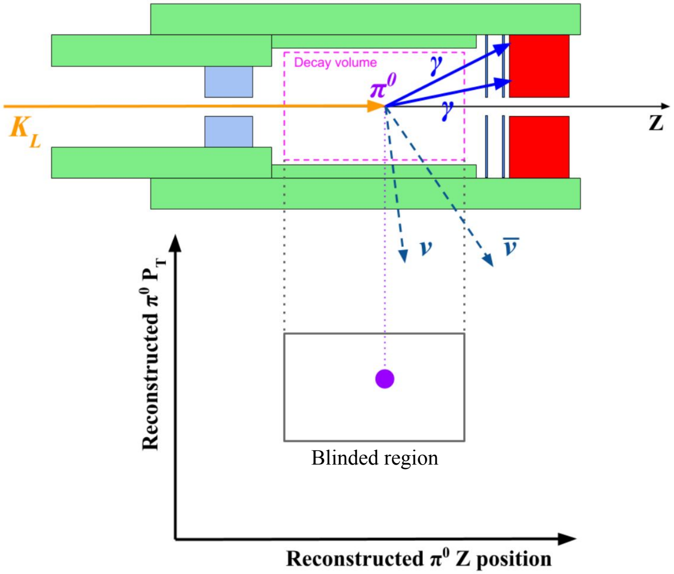
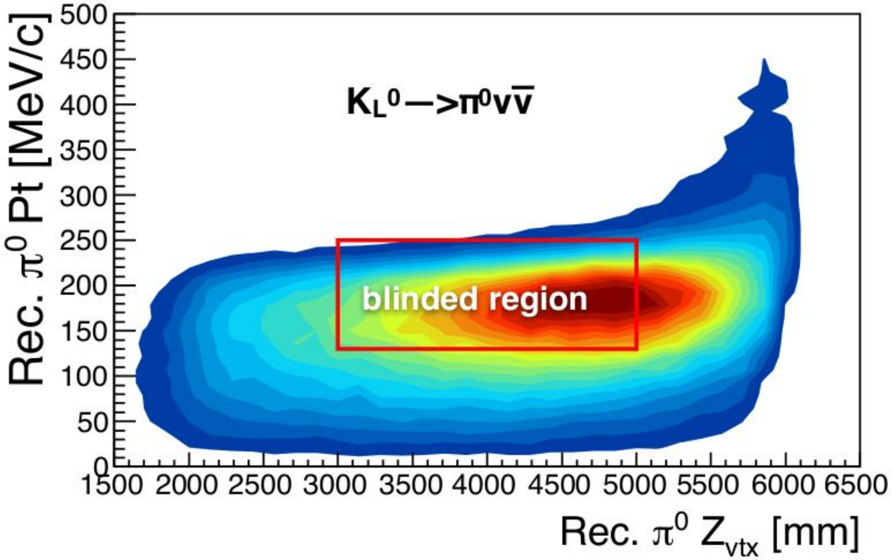
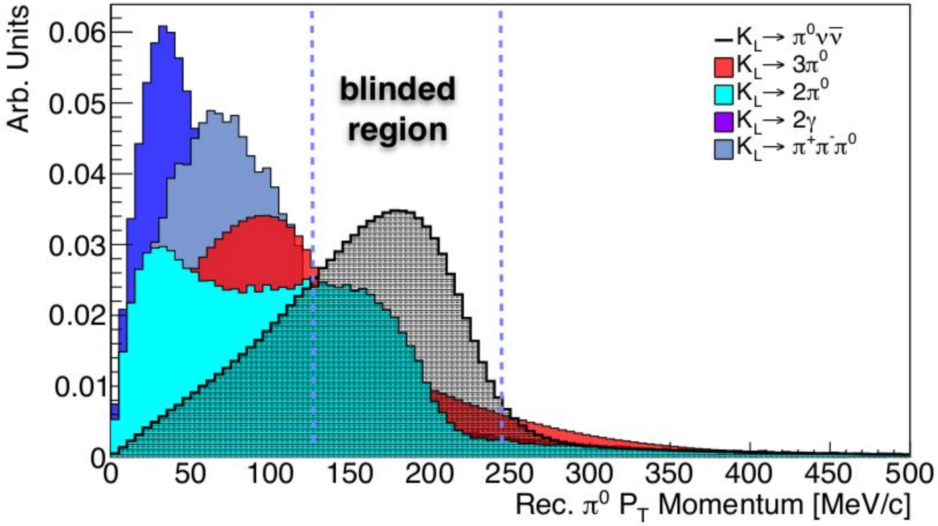
Signal Distribution



Monte Carlo of signal and background distributions







Monte Carlo of signal and background distributions

Normalization

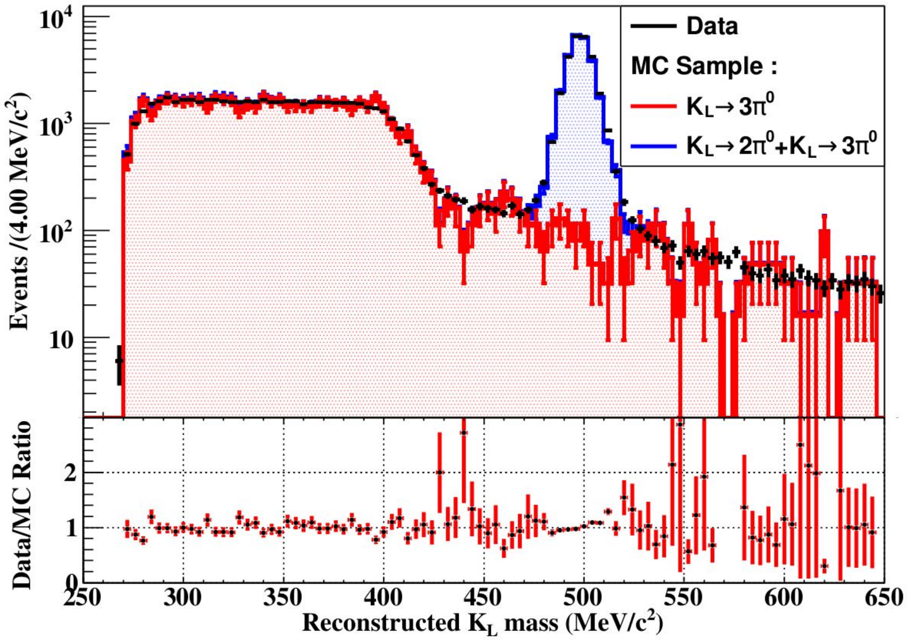
- Calculate the number of K_Ls at the beam exit, $N_{K_L^0}$
- 3 normalization modes
- Use $K_L \rightarrow 2\pi^0$ mode for final result

  (similar energy profile & momentum dist.)

K_L Decay Mode	BR
$K_L \rightarrow 3\pi^0$	19.52%
$K_L \rightarrow 2\pi^0$	8.65 x 10^{-4}
$K_L \rightarrow 2\gamma$	5.47 x 10^{-4}

- Normalization modes also used for
  - Measure kaon mass ($3\pi^0$)
  - Measure z vertex of kaon
  - Data checking and evaluating kinematic and veto cut efficiencies
  - Evaluate MC reproducibility of data
  - Calculate K_L flux into detectors
- Signal acceptance, A_{signal}
  - Geometric acceptance of detectors
  - Kinematic and veto cut efficiencies

Reconstructed K_L mass 2016-2018 data



Backgrounds

- Three types of background sources
  - Other K_L decays
  - Masking background
  - Neutron induced events

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- Three types of background sources
  - ★ Other K_L decays *→ estimated primarily with MC*
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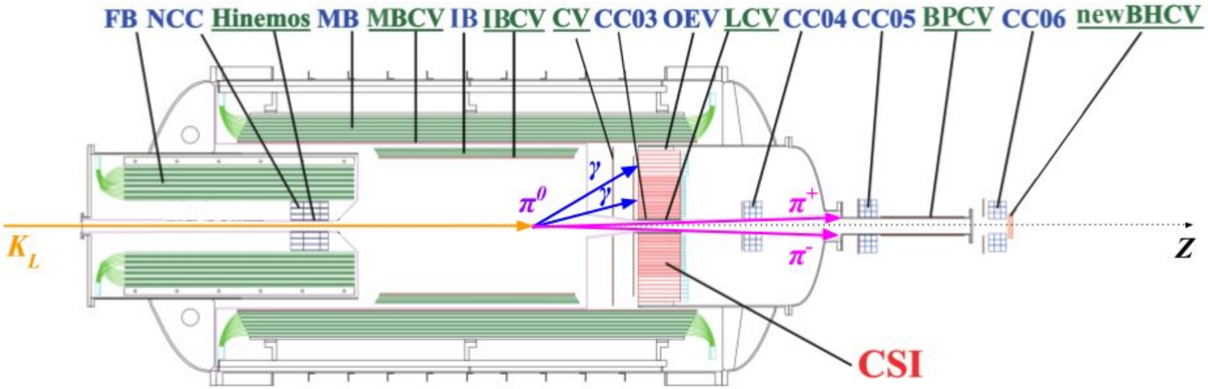
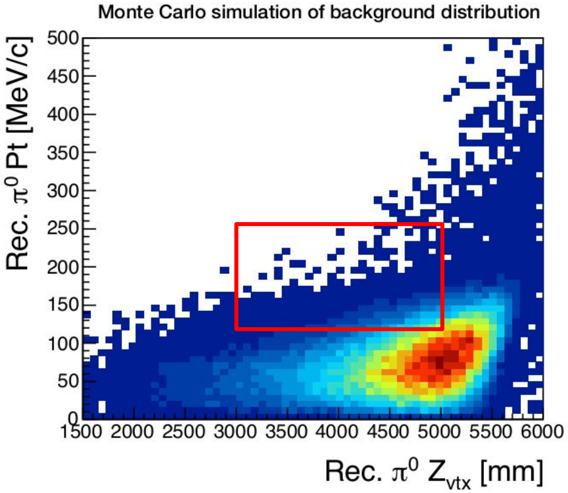
Decay process	**Branching Ratio**
$K^0_L \to \pi^\pm e^\mp \nu_e$	40.55 ± 0.11 %
$K^0_L \to \pi^\pm \mu^\mp \nu_\mu$	27.04 ± 0.07 %
$K^0_L \to \pi^0 \pi^0 \pi^0$	19.52 ± 0.12 %
$K^0_L \to \pi^+ \pi^- \pi^0$	12.54 ± 0.05 %
$K^0_L \to \pi^0 \pi^0$	$(8.64 \pm 0.06) \times 10^{-4}$
$K^0_L \to \gamma\gamma$	$(5.47 \pm 0.04) \times 10^{-4}$

Ex. $K_L \to \pi^+ \pi^- \pi^0$





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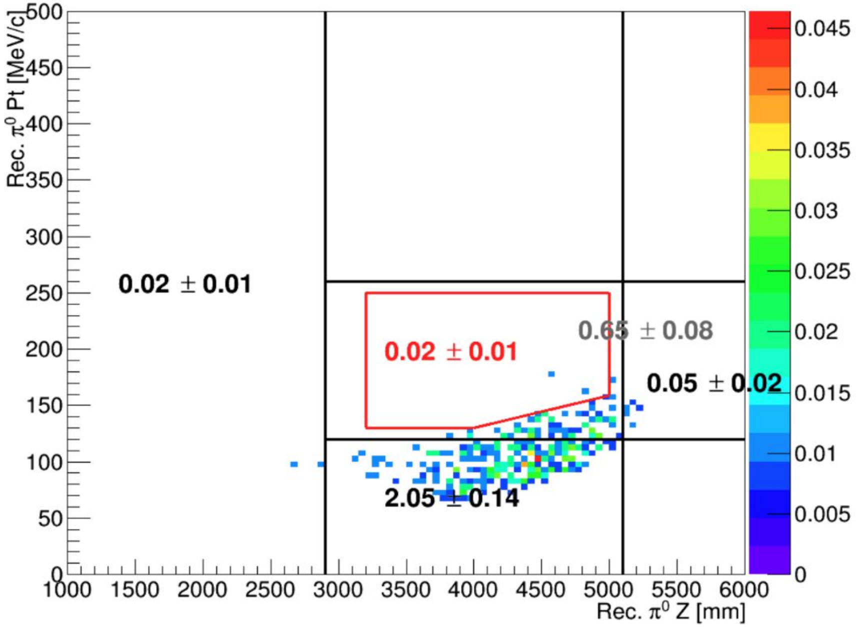
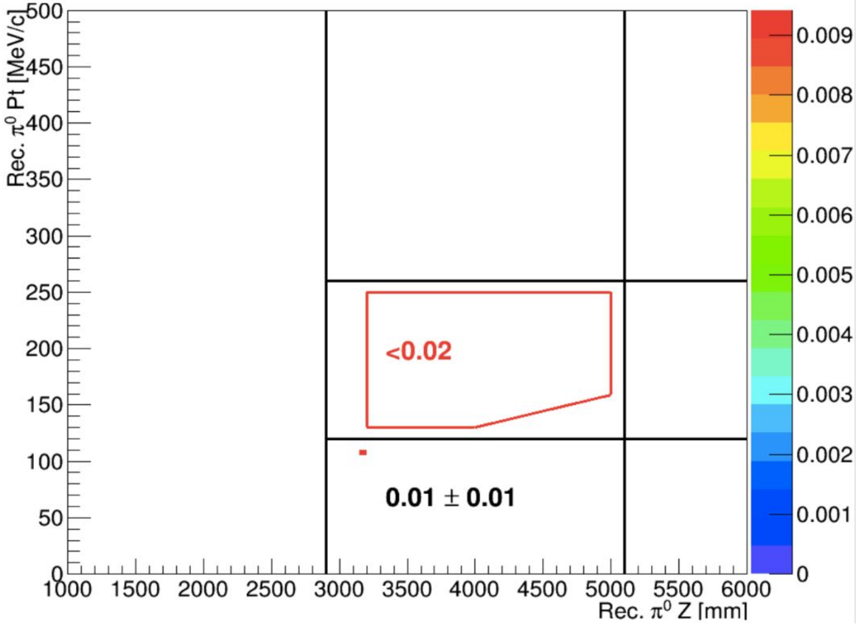
  - ★ Other K_L decays → *estimated primarily with MC*
  - ○ Masking background
  - ○ Neutron induced events

Ex. $K_L \to \pi^+ \pi^- \pi^0$

With loose cut selection



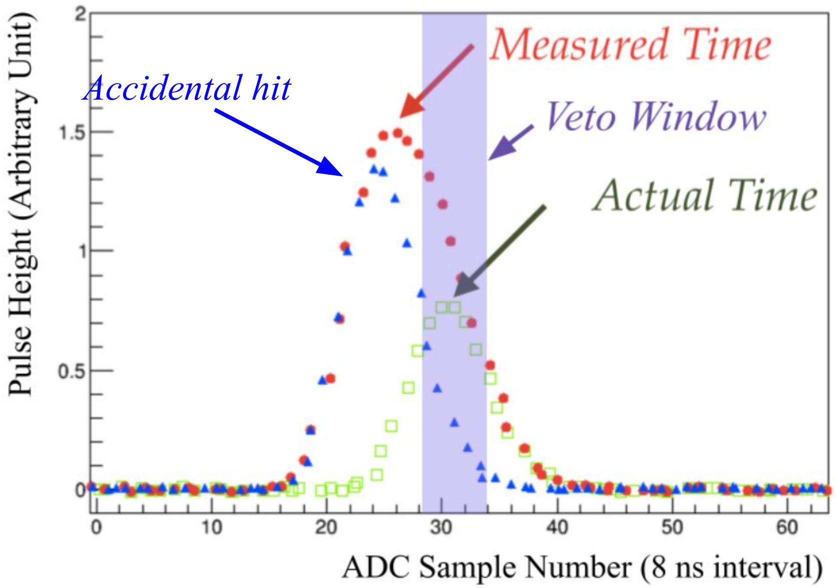
with all cuts



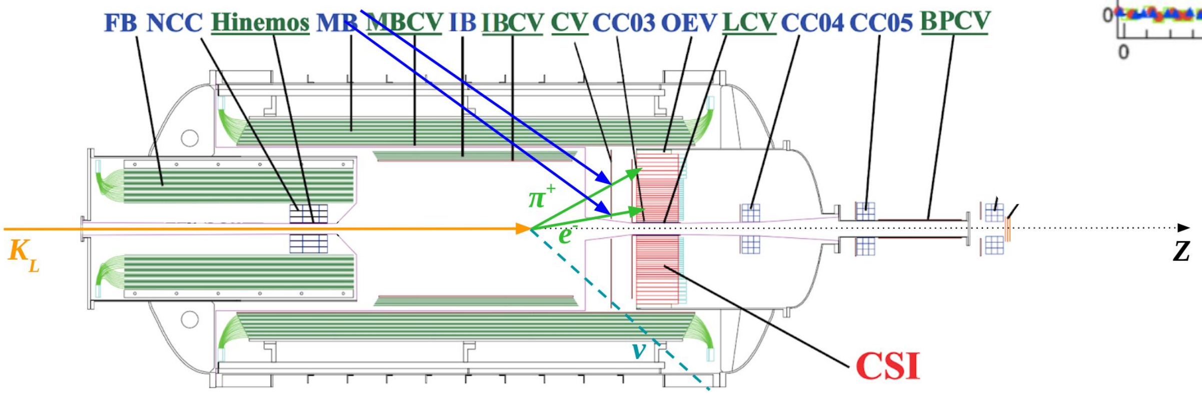
Backgrounds

- Three types of background sources
    - Other K_L decays *→ estimated primarily with MC*
    - ★ Masking background *→ estimated with MC and accidental overlay*
    - Neutron induced events

Masking background
→ accidental activity causes overlapped pulses and veto timing is incorrectly calculated



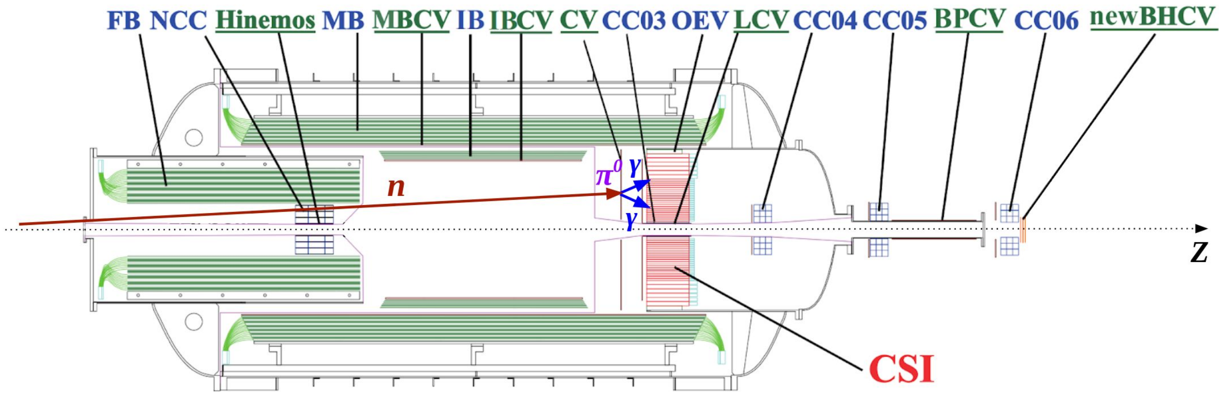
Ex. $K_L \to \pi^+ e^- \nu$

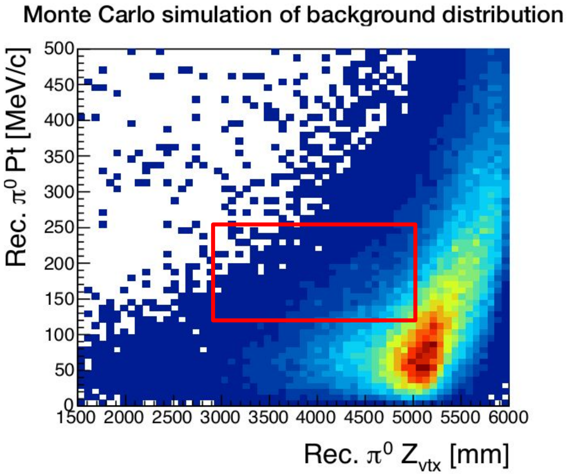


Backgrounds

- Three types of background sources
    - Other K_L decays *→ estimated primarily with MC*
    - Masking background *→ estimated with MC and accidental overlay*
    - ★ Neutron induced events *→ estimated with MC and data-driven methods*

Ex. neutron hits CV detector, produces π^0 *(MC)*



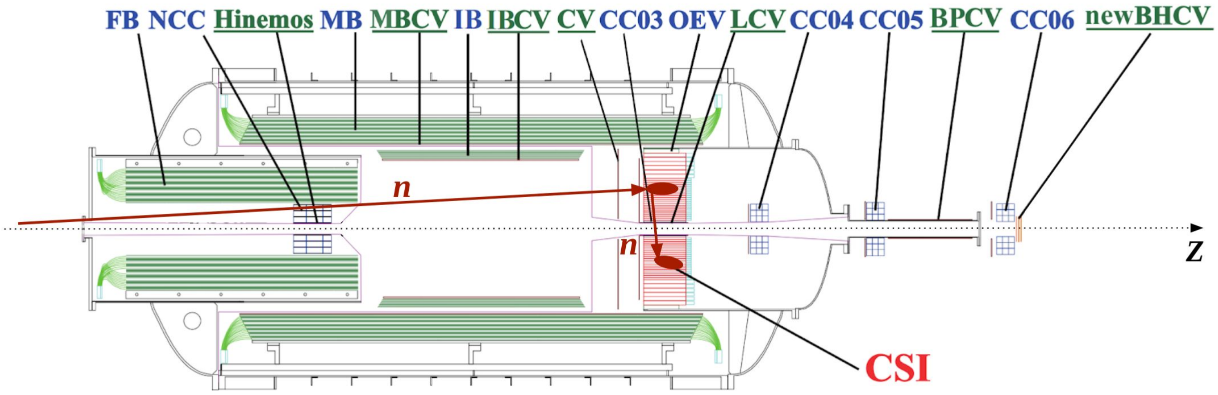


Reconstructed π^0 Pt vs. decay vertex position

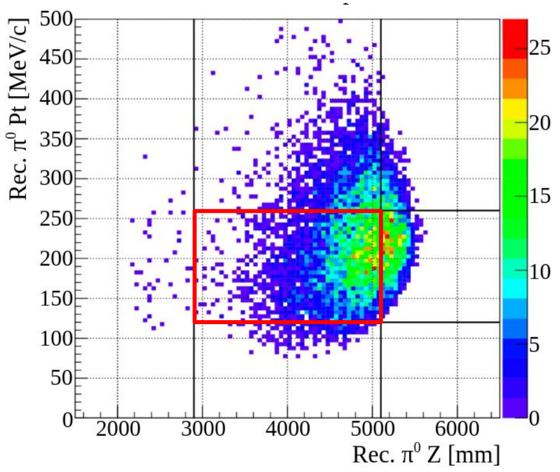
Backgrounds

- Three types of background sources
    - Other K_L decays → *estimated primarily with MC*
    - Masking background → *estimated with MC and accidental overlay*
    - ★ Neutron induced events → *estimated with MC and data-driven methods*

Ex. Neutron hits CsI creates 2 hadronic showers *(data-driven)*

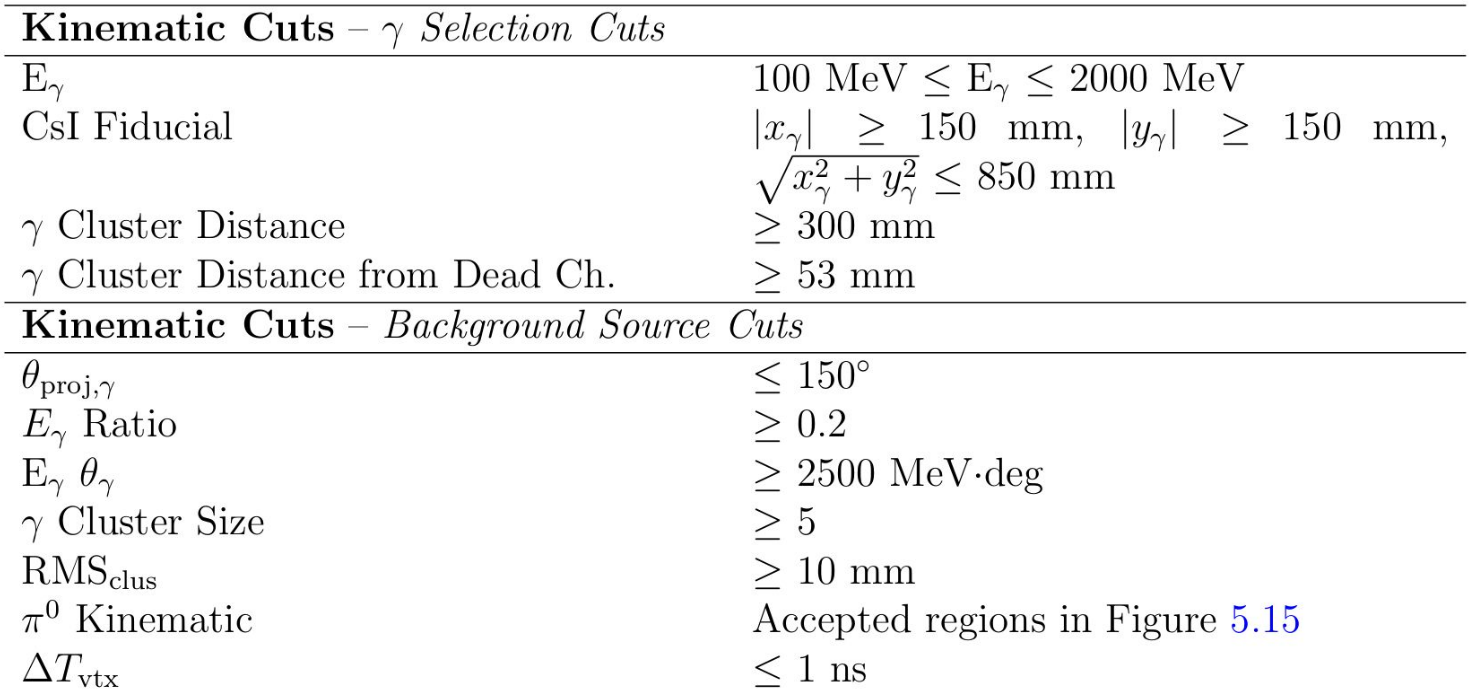


Data control sample of background distribution



Background Reduction Methods

- **Goal** → apply cuts to *reduce background, retain signal*
- 2 types of background reduction methods
  - ★ Traditional → energy, time, kinematics, veto information
  - ○ Novel → machine learning/Fourier analysis

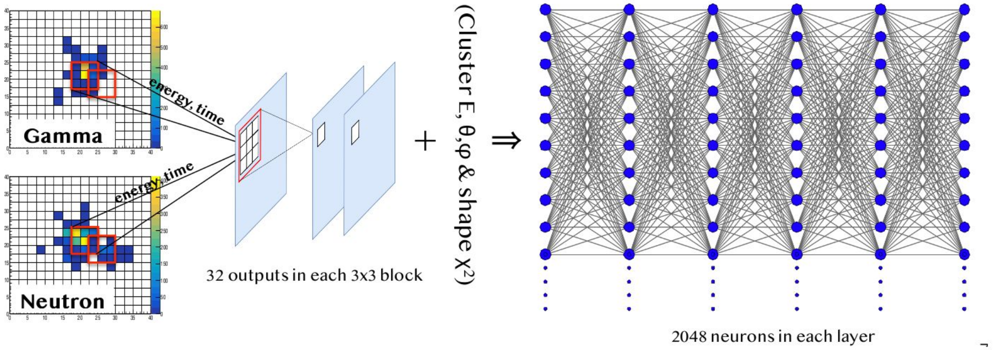


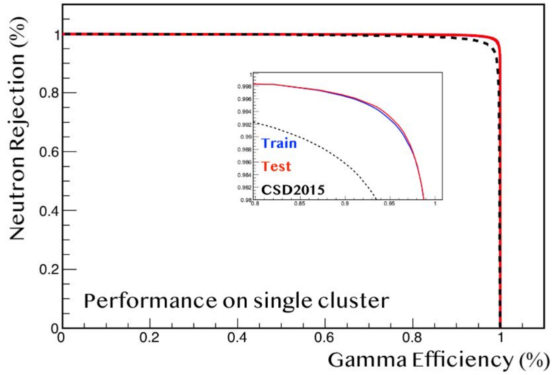
Kinematic Cuts – *γ Selection Cuts*	
E_γ	100 MeV $\leq E_\gamma \leq$ 2000 MeV
CsI Fiducial	$\lvert x_\gamma \rvert \geq$ 150 mm, $\lvert y_\gamma \rvert \geq$ 150 mm, $\sqrt{x_\gamma^2 + y_\gamma^2} \leq$ 850 mm
γ Cluster Distance	$\geq$ 300 mm
γ Cluster Distance from Dead Ch.	$\geq$ 53 mm
Kinematic Cuts – *Background Source Cuts*	
$\theta_{\text{proj},\gamma}$	$\leq 150^\circ$
E_γ Ratio	$\geq$ 0.2
$E_\gamma\ \theta_\gamma$	$\geq$ 2500 MeV·deg
γ Cluster Size	$\geq$ 5
RMS_{clus}	$\geq$ 10 mm
π^0 Kinematic	Accepted regions in Figure 5.15
ΔT_{vtx}	$\leq$ 1 ns

Background Reduction Methods

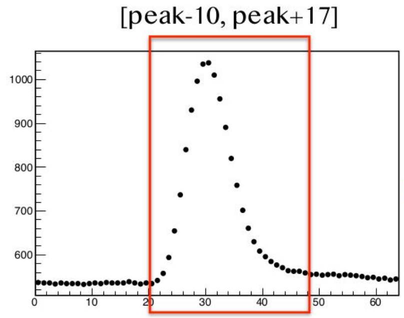
- **Goal** → apply cuts to *reduce background, retain signal*
- 2 types of background reduction methods
  - Traditional → energy, time, kinematics, veto information
  - ★ Novel → machine learning/Fourier analysis

Cluster shape discrimination with neural networks *(1/1500 neutrons remaining)*

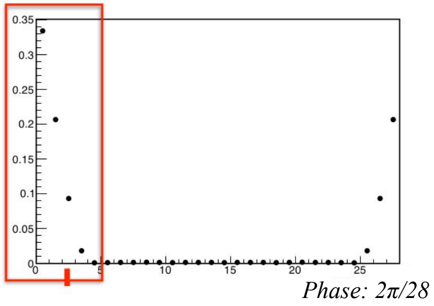


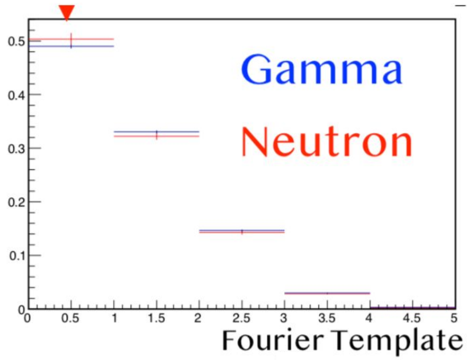


Pulse shape discrimination with Fourier analysis *(4/125 neutrons remaining)*



$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i}{N}kn}$$





Results

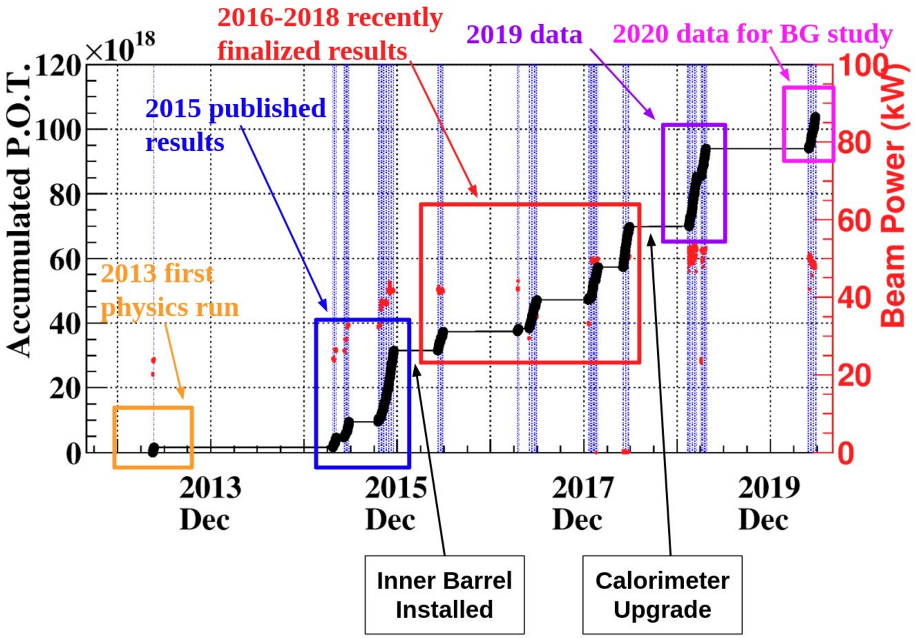
- Once normalization analysis is complete →

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

- Finalize all background estimations
- Apply final cut set to reduce background and retain signal
- Unblind the data

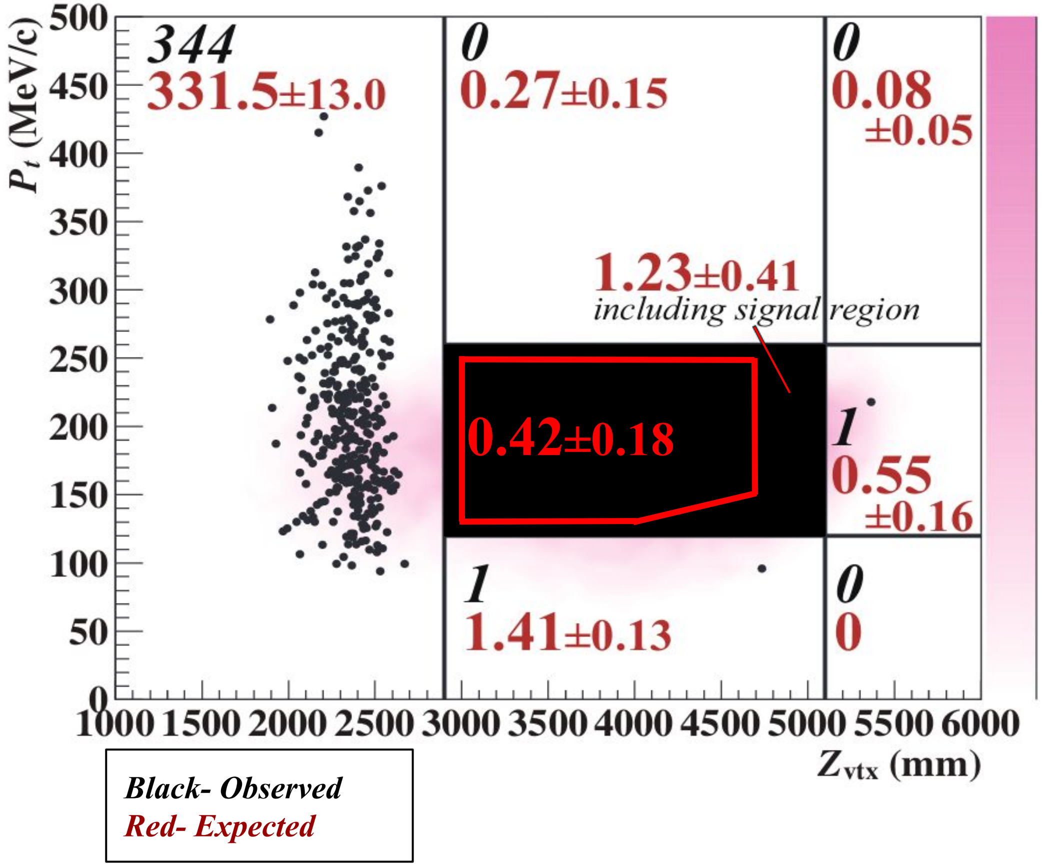
→ 2015 results (briefly)

→ **2016-2018 results**



2015 Results

- Before unblinding, estimated 0.42 ± 0.18 BG
- **SES = $(1.3 \pm 0.01_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-9}$**



Background source	**Expected no. events**
K_L Decays	
$K_L \rightarrow \pi^+\pi^-\pi^0$	0.05 ± 0.02
$K_L \rightarrow 2\pi^0$	0.02 ± 0.02
Other K_L decays	0.03 ± 0.01
Neutron induced	
Hadron cluster on CsI	0.24 ± 0.17
Upstream π^0 from NCC	0.04 ± 0.03
CV η	0.04 ± 0.02
Total background	**0.42 ± 0.18**

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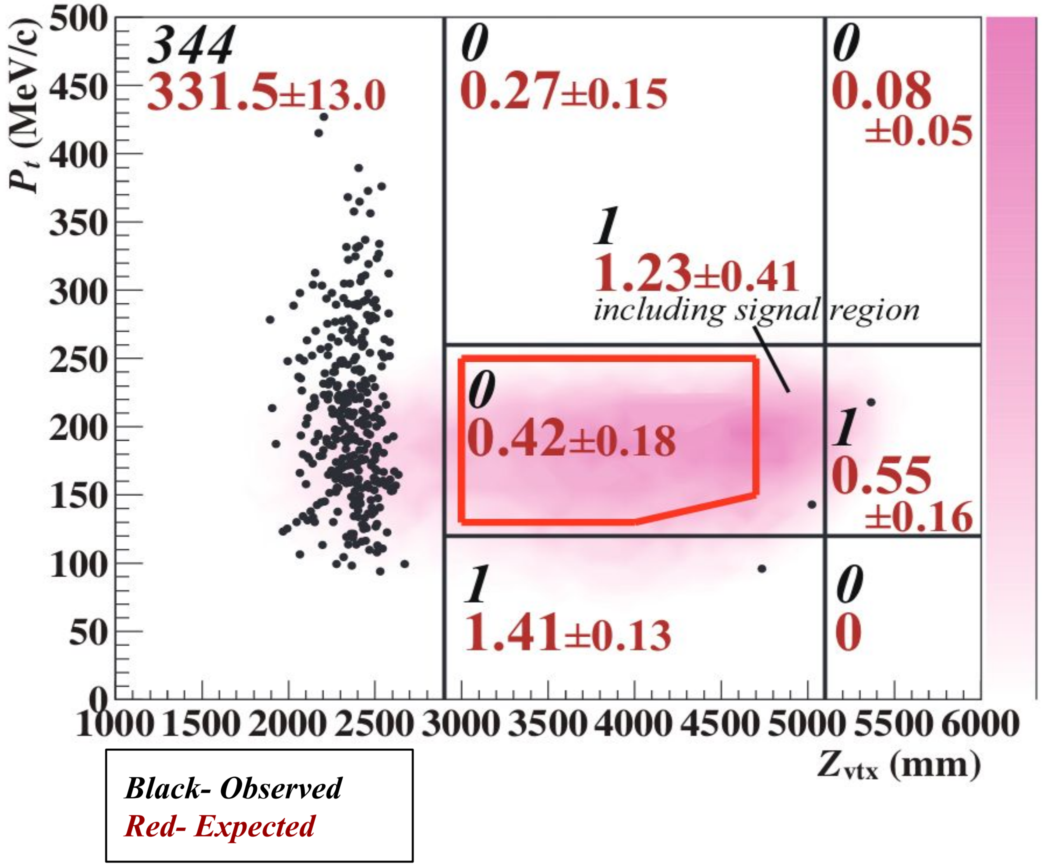

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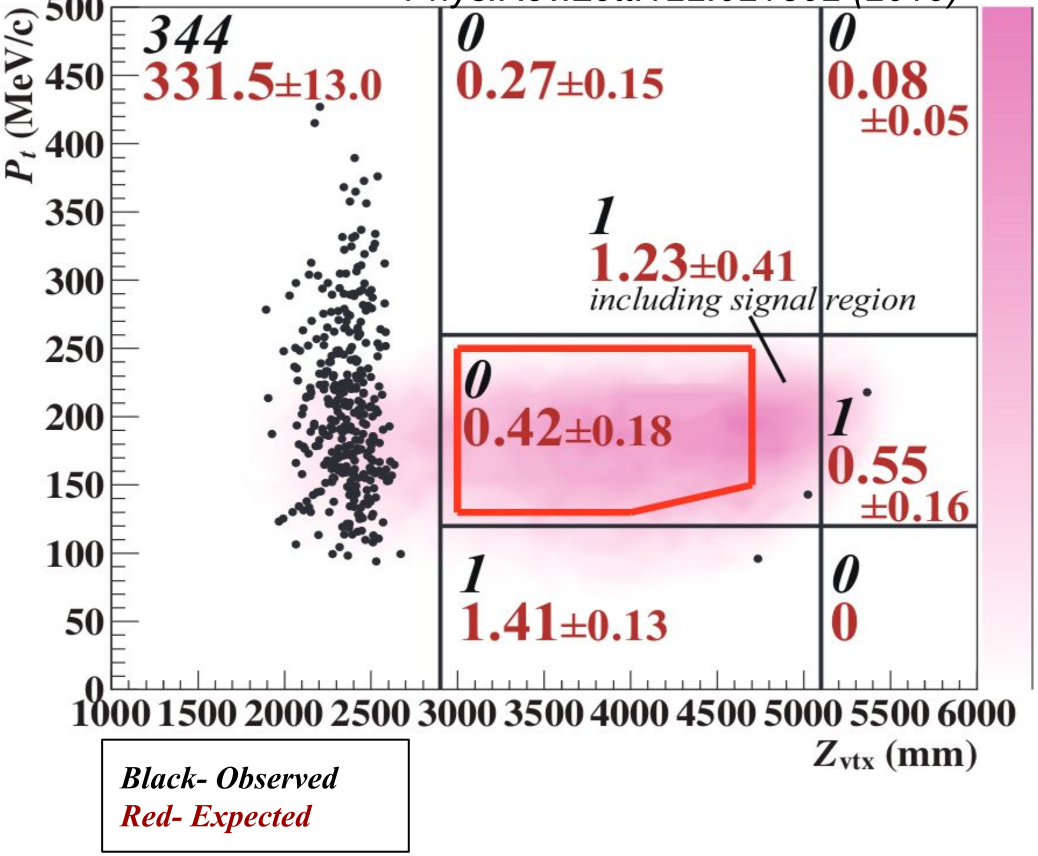
BR($K^0_L \to \pi^0 \nu\bar{\nu}$) < 3.0×10^{-9} (@ 90% CL)

Phys.Rev.Lett.122.021802 (2019)



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Upstream π^0 from NCC	0.04 ± 0.03
CV η	0.04 ± 0.02
Total background	**0.42 ± 0.18**

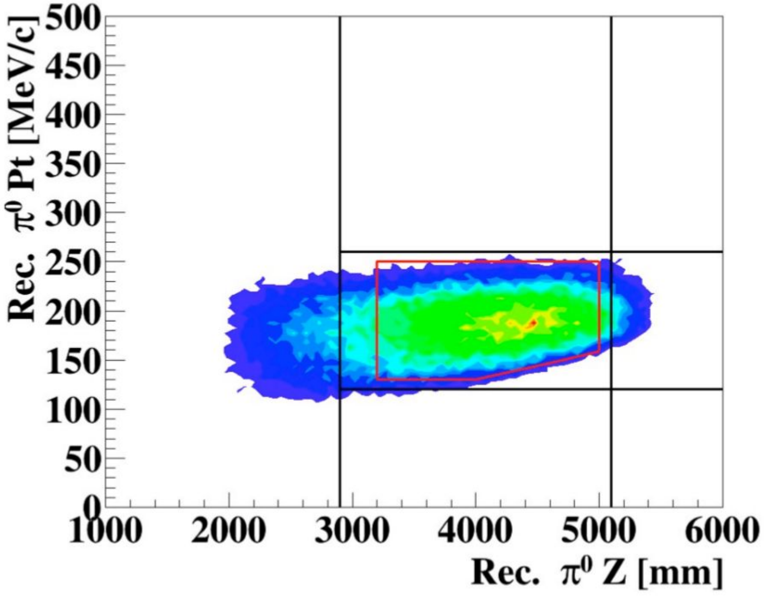
Improved previous limit (E391a) ~1 order of magnitude

2016-2018 Results

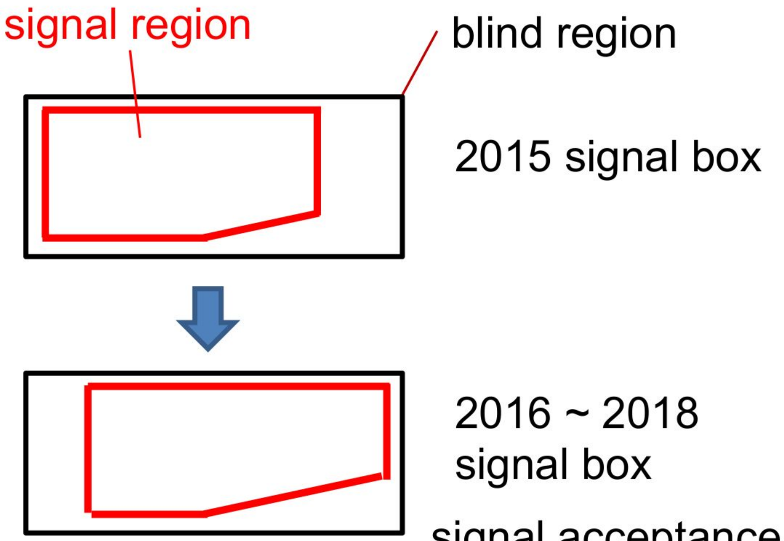
- Collected ~1.5x more data than 2015
  → 6.83 x 10^{12} K_L at beam exit (3.1 x 10^{19} POT)

- Improved SES by 1.8x from 2015 results
  → **SES = $(7.2 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$**

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



signal acceptance : 2.0×10^{-4}



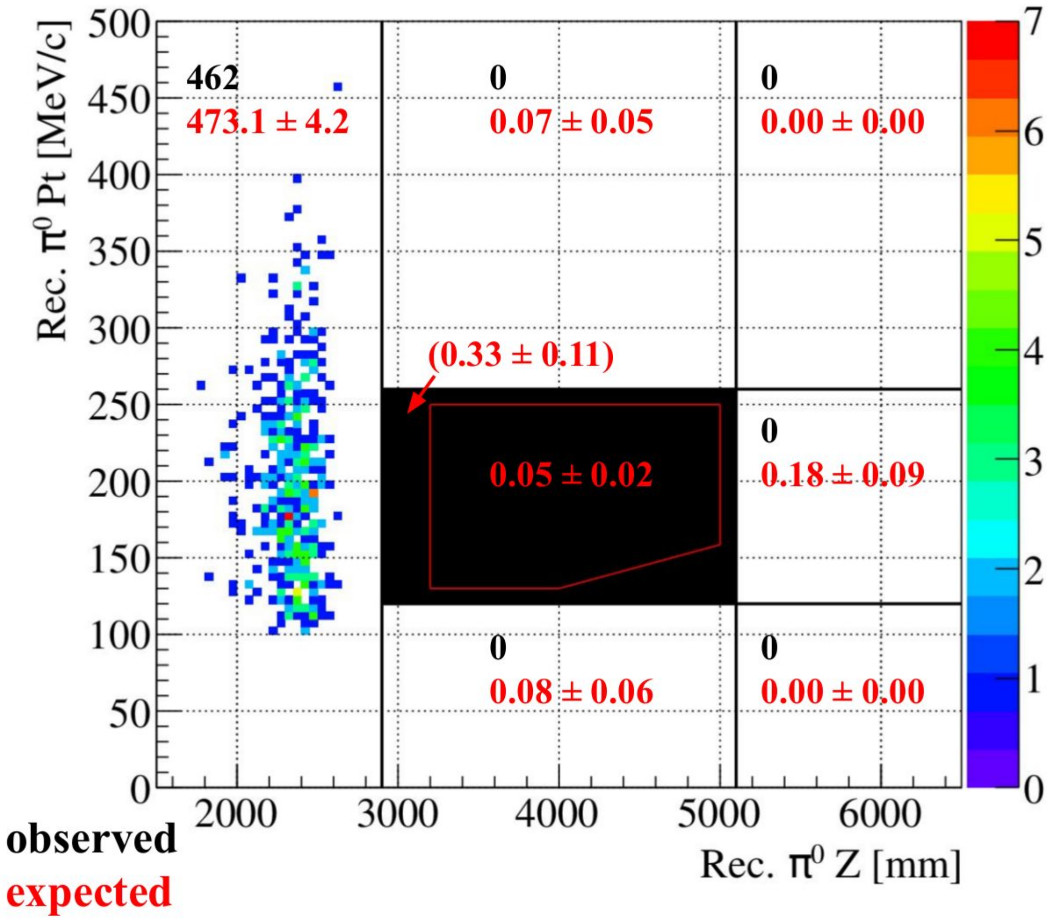
2015 signal box

2016 ~ 2018
signal box

signal acceptance :
+ 6% (from 2015 signal box)

2016-2018 Results

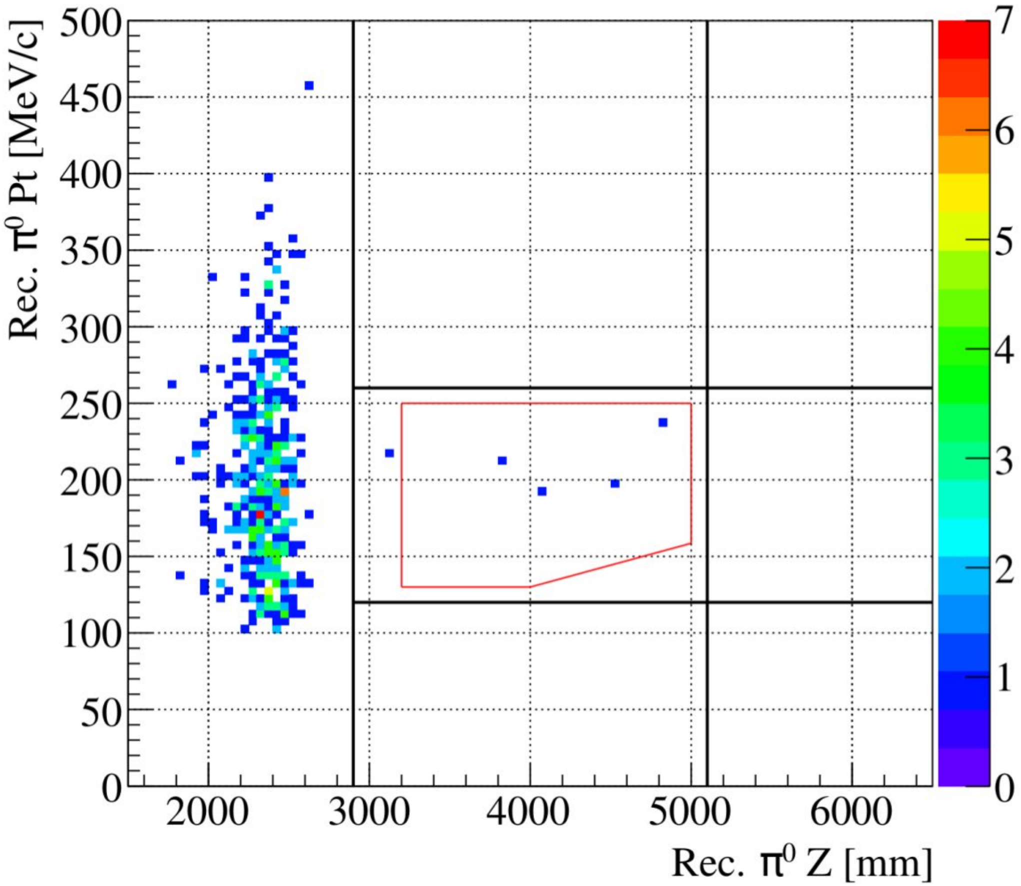
- Before unblinding, estimated 0.05 ± 0.02 BG
- **SES = $(7.2 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$**



Background source	**Expected no. events**
K_L Decays	
$K_L \to \pi^+\pi^-\pi^0$	< 0.02
$K_L \to 2\pi^0$	< 0.18
$K_L \to 2\gamma$	0.005 ± 0.005
$K_L \to 3\pi^0$ (masking)	< 0.04
$K_L \to \pi^\pm e^\mp \nu$ (masking)	< 0.09
Neutron induced	
Hadron cluster on CsI	0.017 ± 0.002
Upstream π^0 from NCC	0.001 ± 0.001
CV η	0.03 ± 0.01
CV π^0	< 0.10
Total background	**0.05 ± 0.02**

2016-2018 Results

- Unblinded data end of August 2019
- After unblinding 4 candidate events in signal region



Background source	**Expected no. events**
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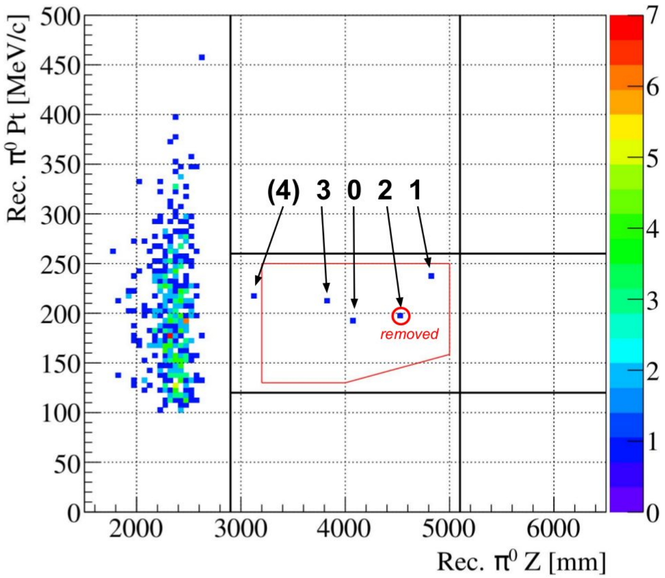
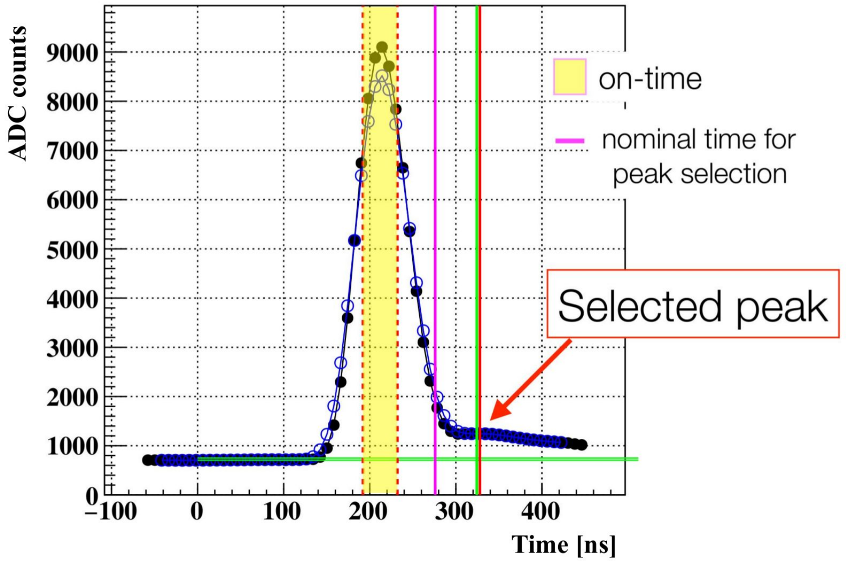
Neutron induced	
Hadron cluster on CsI	0.017 ± 0.002
Upstream π^0 from NCC	0.001 ± 0.001
CV η	0.03 ± 0.01
CV π^0	< 0.10
Total background	**0.05 ± 0.02**

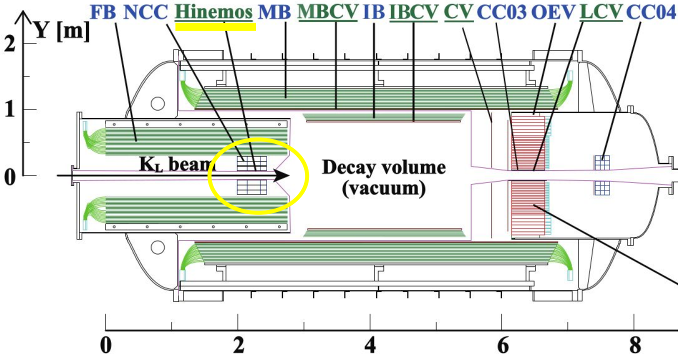
Properties of candidate events

Event 2 (Run 75)

- After rechecking analysis parameters→ **incorrect timing parameter set for vetoing**







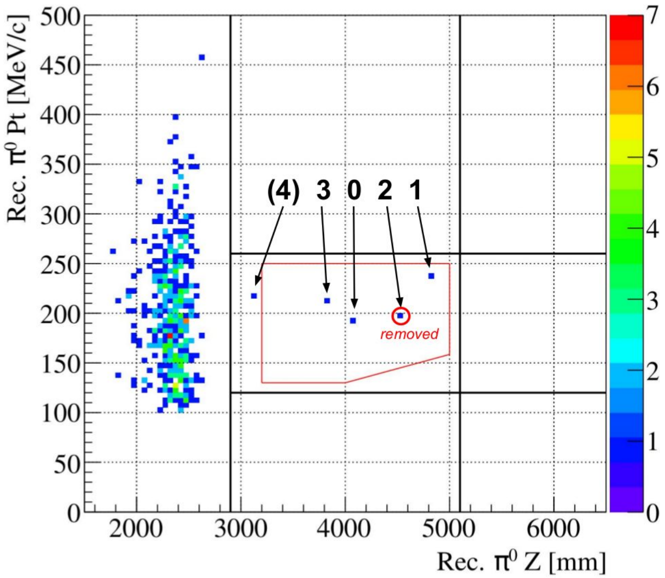
On-time hit was not selected due to incorrect nominal time setting (peak selection)

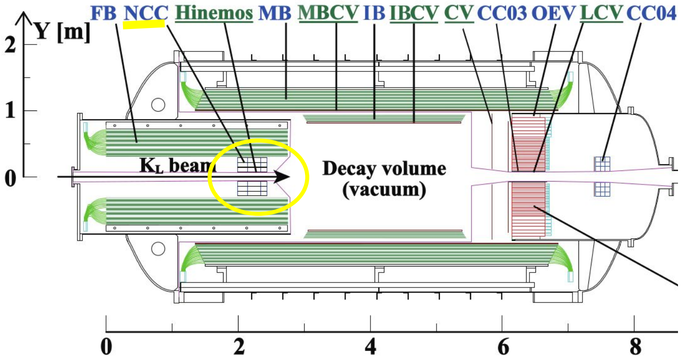
→ **Reprocess→ event removed**

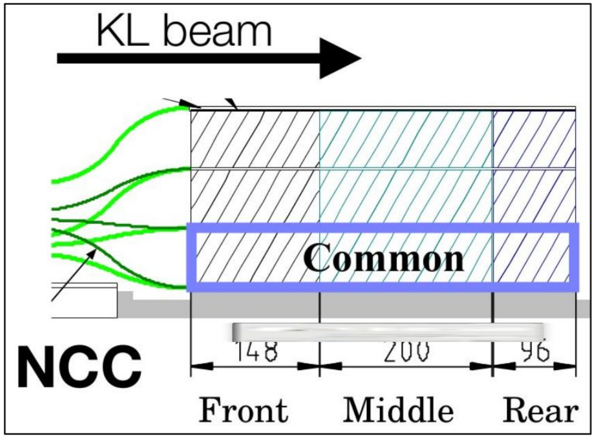
Properties of candidate events

Event 0 (Run 69)

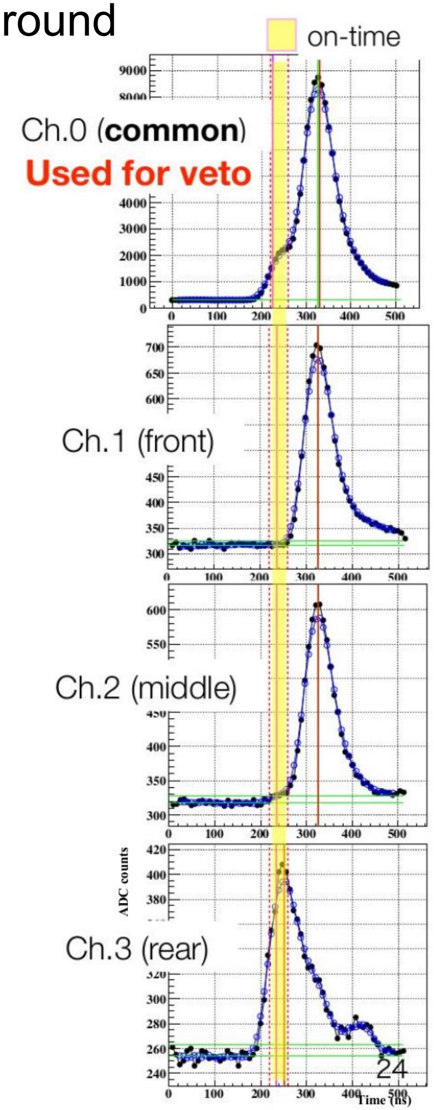
- **Overlapped pulse in NCC detector** → likely masking background







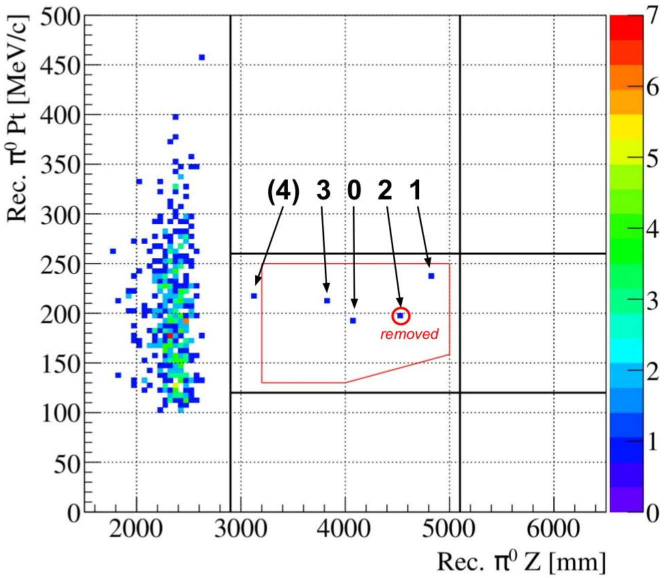
"Common" of 3 modules used for vetoing

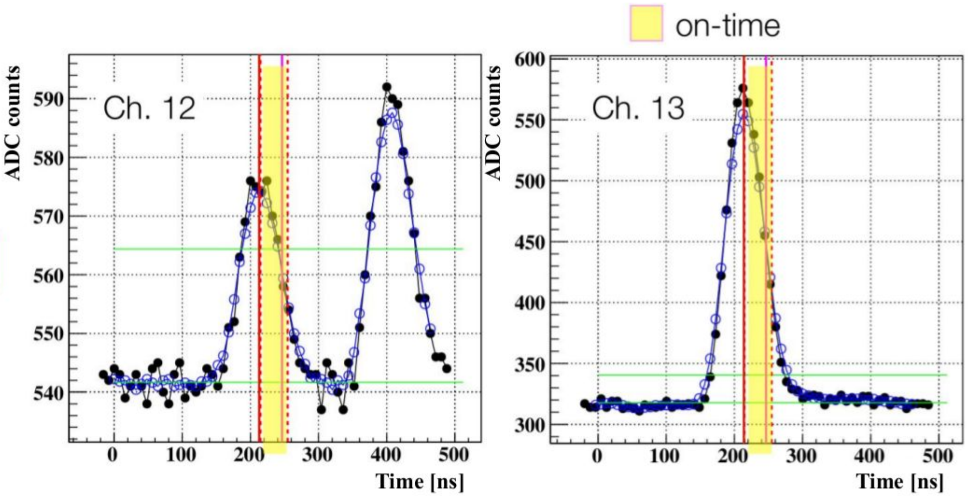


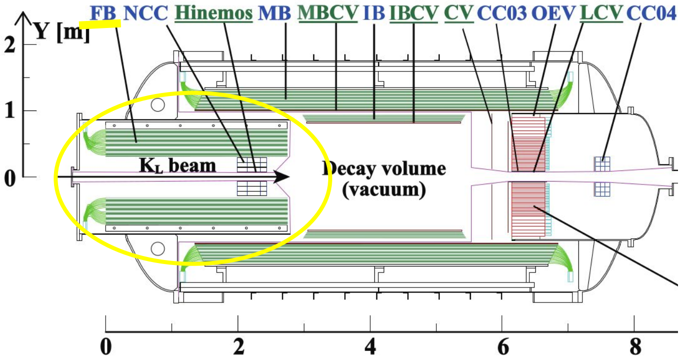
Properties of candidate events

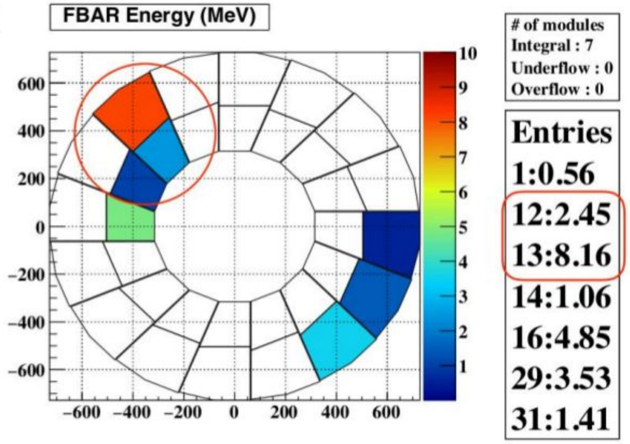
Event 3 (Run 79)

- **Hit in FB just outside veto window**



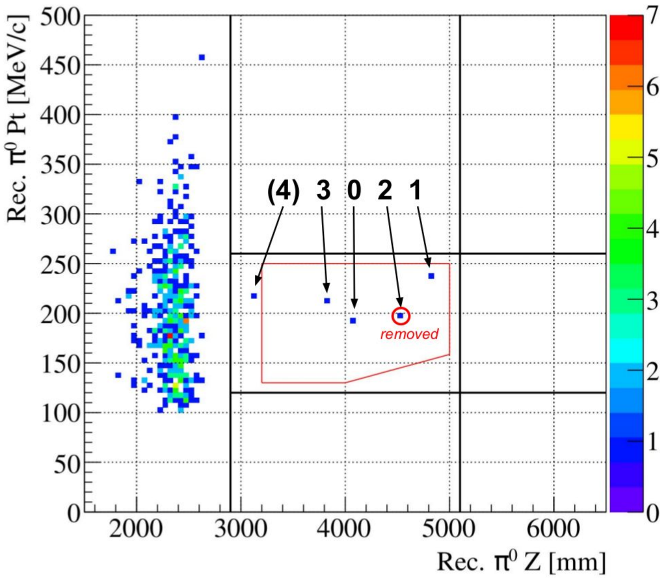




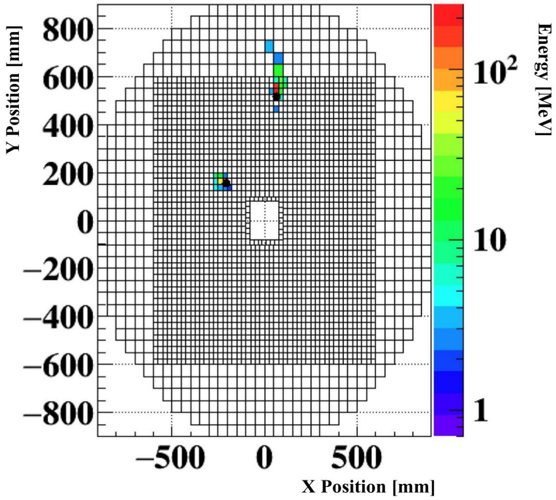


Properties of candidate events

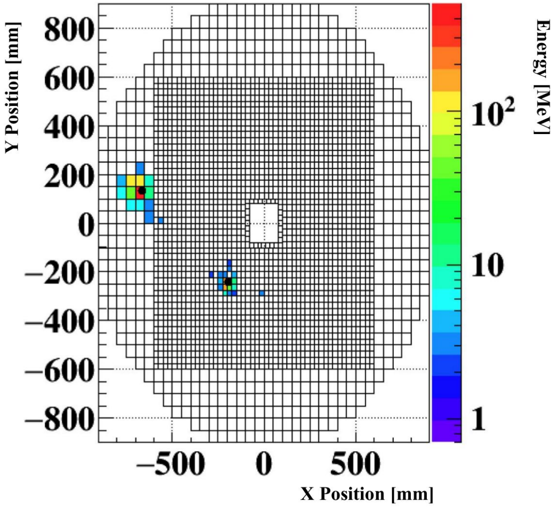
Event 1 and event (4) have no distinguishing features



Event 1



Event (4)



Outside signal region→
not a candidate event

Additional Background Studies

- Reevaluated previous K_L backgrounds with higher statistics
- Estimated BG from other K_L decays expected to have small contributions

Upper limits on BG @ 90% CL

BG Source	Estimated # of BG
Other K_L Decay Backgrounds	
$K_L^0 \to \pi^\pm e^\mp \nu_e$ ($\pi^\pm \to \pi^0$ conversion)	< 0.04
$K_L^0 \to \pi^\pm e^\mp \nu_e$ ($\pi^\pm$ beta decay)	< 0.01
$K_L^0 \to \pi^\pm e^\mp \nu_e \gamma$	< 0.05
$K_L^0 \to \pi^0 \pi^\pm e^\mp \nu_e$	< 0.04
$K_L^0 \to \pi^+ \pi^-$	< 0.03
$K_L^0 \to ee\gamma$	< 0.09
$K_L^0 \to K^\pm e^\mp \nu_e$	< 0.04
$K_L^0 \to 2\gamma$ (core-like)	< 0.11

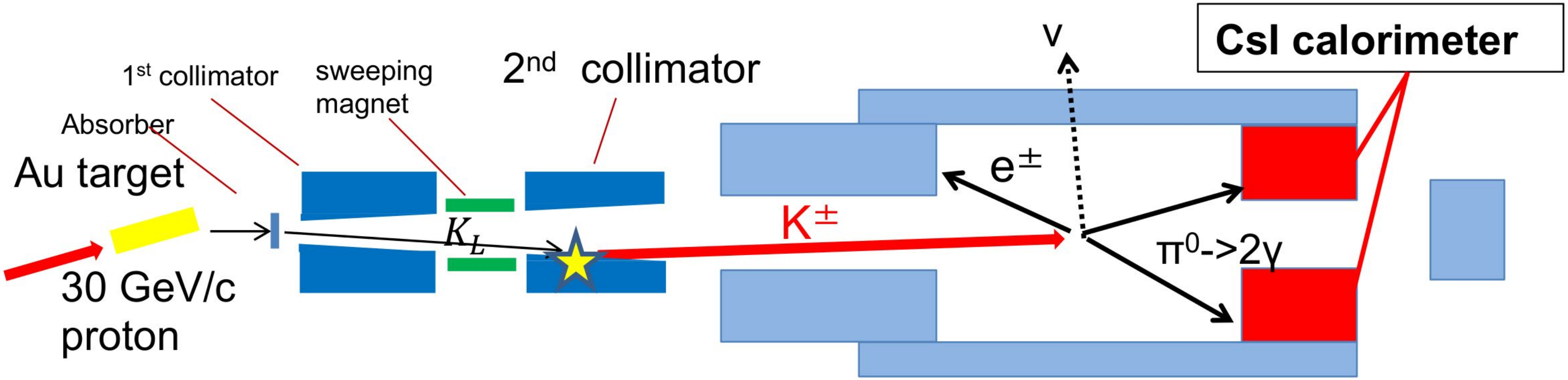
- Considered two main, new sources of background

  → **$K^\pm$ background**

  → **$K_L \to 2\gamma$ background from halo-K_L**

Charged Kaon Background

- $K^\pm$ generated in beamline at 2nd collimator
- **Dangerous BG: $K^\pm \rightarrow \pi^0 e^\pm \nu$ decay** (BR~5%)
  - π^0 kinematics similar to π^0 in signal decay
  - Only $e^\pm$ for vetoing (backwards $e^\pm$ → small energy → large inefficiency)

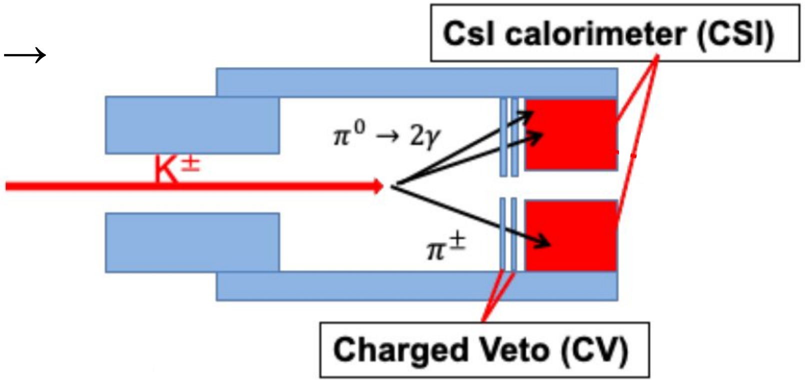


- Background depends on $K^\pm$ flux → estimated w/ simulation→ $K^+/K_L \sim 1.3\times10^{-6}$
  - Measure $K^\pm$ flux in dedicated run (June 2020)
  - Normalize MC BG estimation with $K^\pm$ flux measurement

K± Flux Measurement

- Dedicated trigger to collect K± → π±π^0 events →
- Collected **847** K± → π±π^0 candidate events
- Measured K± flux ratio = (2.6 ± 0.1) x 10^{-5}

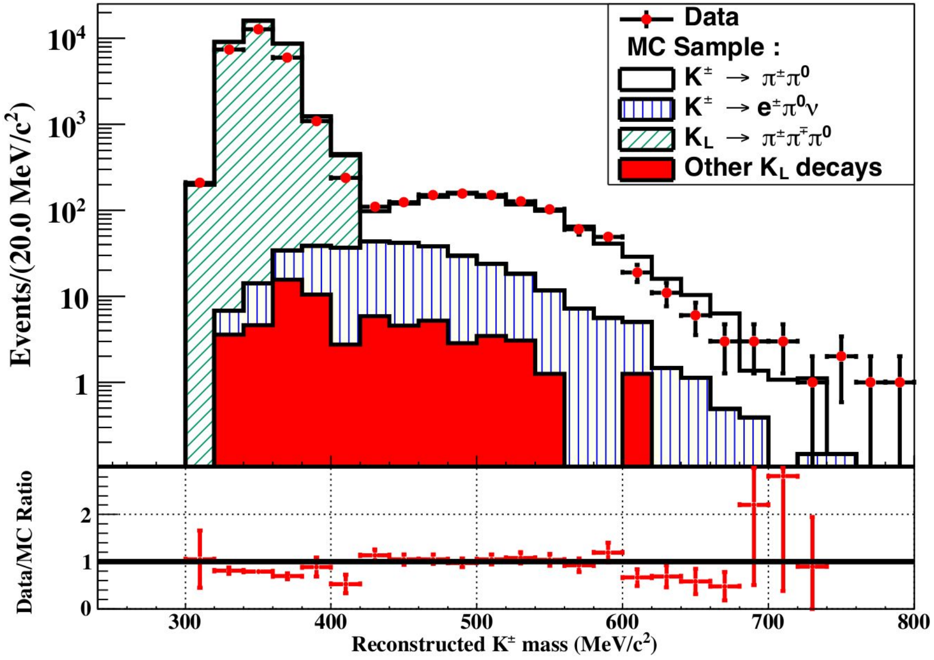
$$R_{K^\pm} = F_{K^\pm}/F_{K_L}$$



Measured K± flux is 3x larger than MC

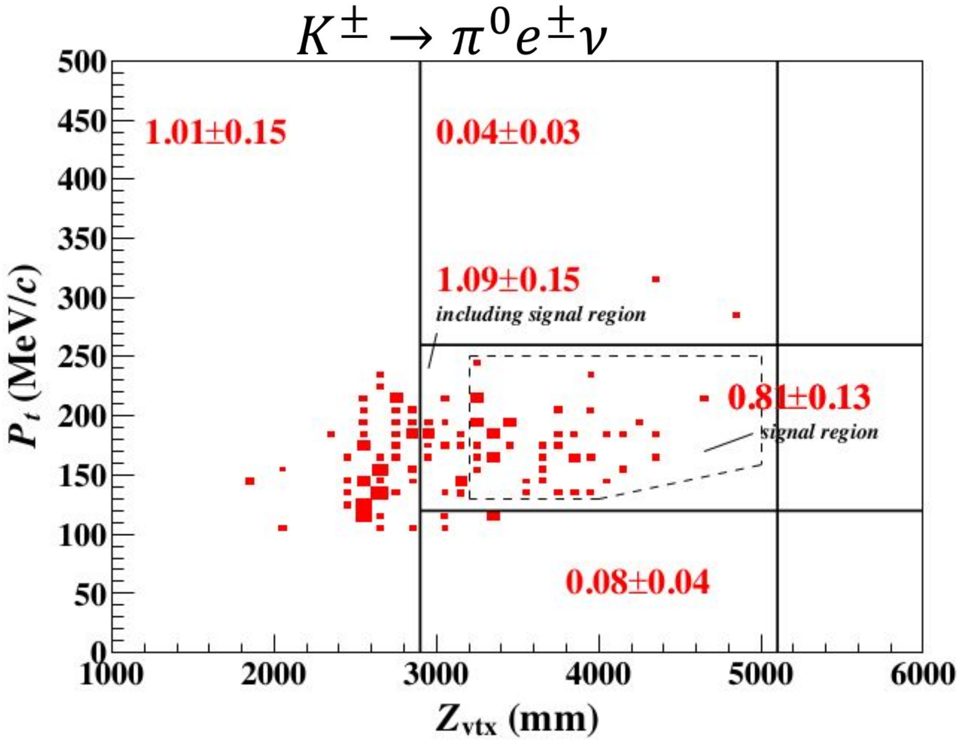
Distribution of K± events is well reproduced by MC

Reconstructed K± mass



K± Background Estimation

- Simulated 6 major K± decays
- Normalized BG estimation to measured K± flux



$K^{\pm}$ Decay Mode	Estimated # of BG
$K^{\pm} \to \pi^0 e^{\pm} \nu_e$	0.81 ± 0.13
$K^{\pm} \to \pi^0 \mu^{\pm} \nu_{\mu}$	0.02 ± 0
$K^{\pm} \to \pi^0 \pi^{\pm}$	0.004 ± 0
$K^{\pm} \to \mu^{\pm} \nu_{\mu}$	0
$K^{\pm} \to \pi^{\pm} \pi^{\pm} \pi^{\mp}$	0
$K^{\pm} \to \pi^0 \pi^0 \pi^{\pm}$	0
Total $K^{\pm}$ BG	0.84 ± 0.13

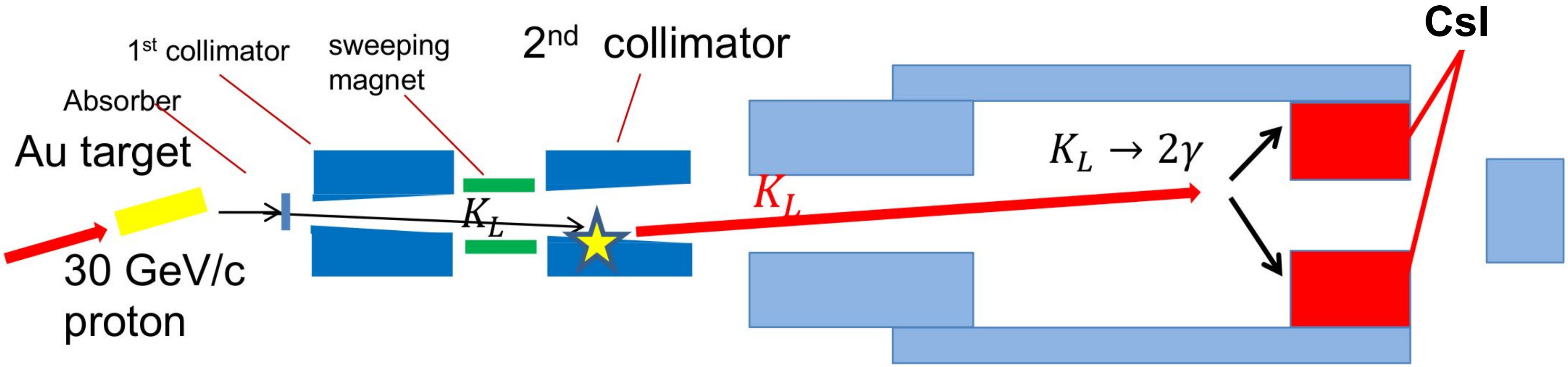
No events remaining in MC

Correct K± background estimation with acceptance ratio of K± events with $K_L \to \pi^0 \nu\nu$ selection cuts (data-driven method)

→ Total K± background = **0.87 ± 0.25**

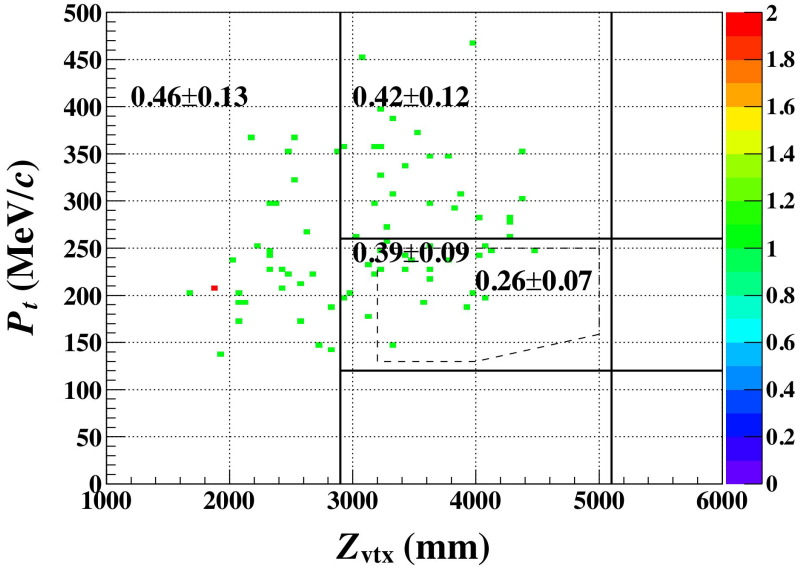
Halo K_L Background

- K_L scatters @ second collimator → finite transverse momentum
- Dangerous: no extra particles to veto



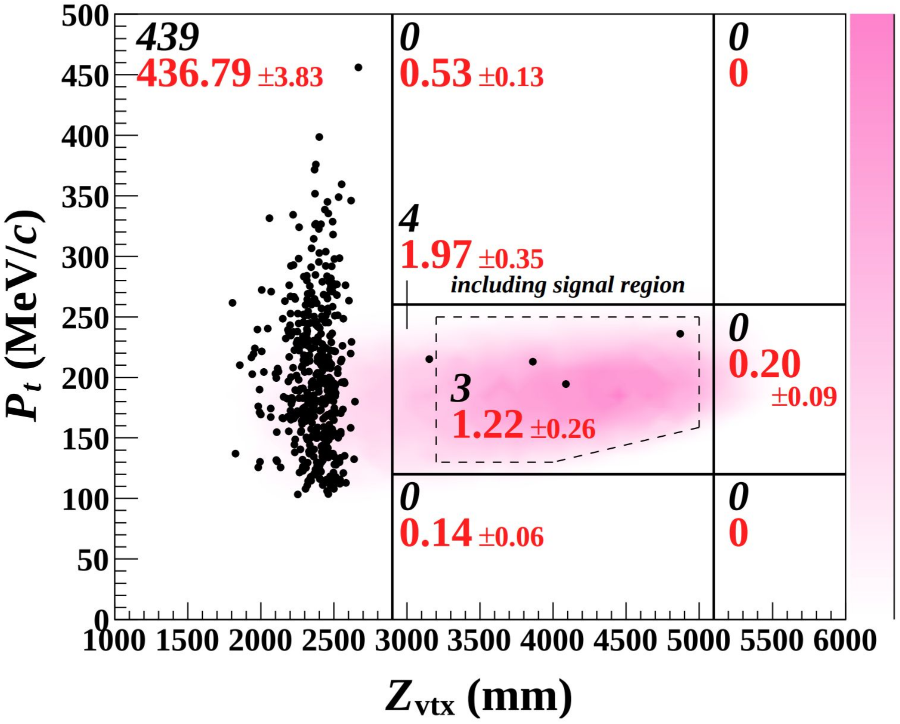
- Estimate Halo K_L flux using sample of $K_L \to 3\pi^0$ events
  - Select events with large COE radius
  - Halo K_L flux measurement ~7x MC estimation
- MC BG estimation scaled to halo K_L flux

→ **Halo K_L BG = 0.26 ± 0.07**



Final BG Estimation

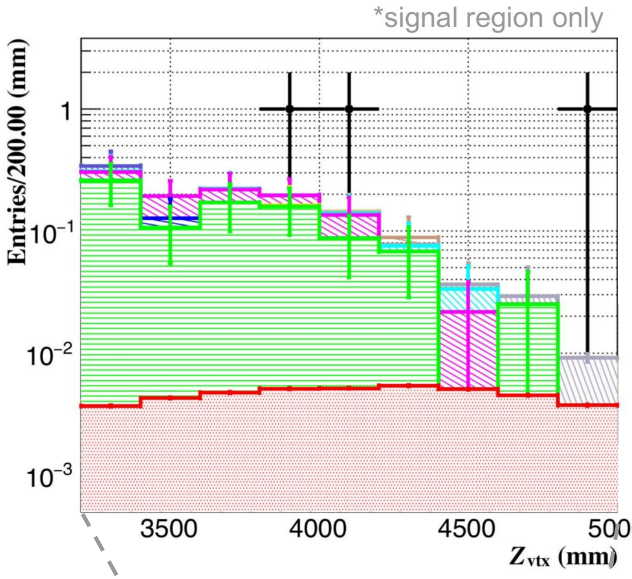
- Central values of all BGs
  → **Total BG = 1.22 ± 0.26**



Black: observed
Red: expected

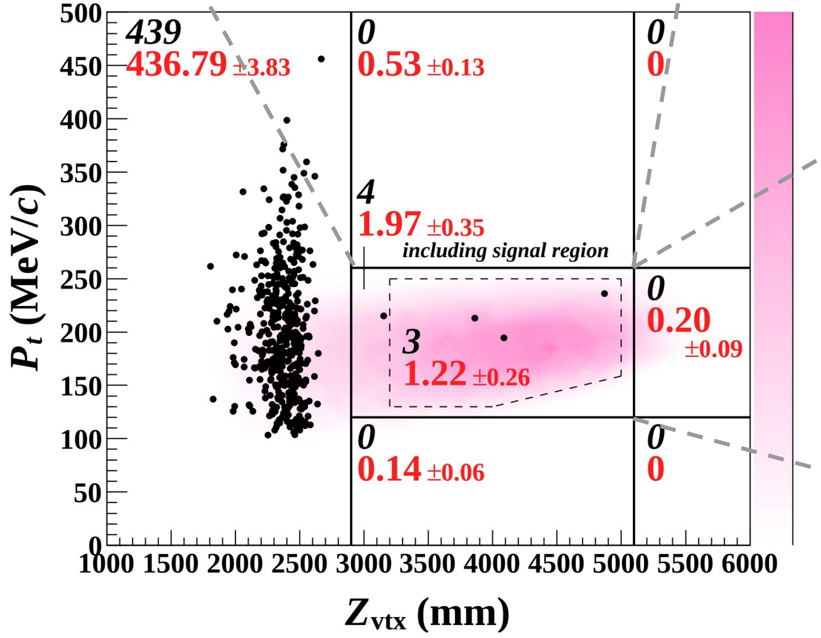
Background source	Expected no. events	Note
K_L Decays		
$K_L \rightarrow \pi^+\pi^-\pi^0$	< 0.02	
$K_L \rightarrow 2\pi^0$	< 0.08	Updated, incr. MC stat.
$K_L \rightarrow 2\gamma$ (vacuum window)	0.005 ± 0.005	
$K_L \rightarrow 3\pi^0$ (masking)	0.01 ± 0.01	Updated, incr. MC stat.
$K_L \rightarrow \pi^\pm e^\mp \nu$ (masking)	< 0.08	Updated, 5% timing diff
$K_L \rightarrow 2\gamma$ (halo K_L)	0.26 ± 0.07	Newly estimated
$K^\pm$ Background		
$K^\pm \rightarrow \pi^0 e^\pm \nu$	0.84 ± 0.25	Newly estimated
$K^\pm \rightarrow \pi^0 \mu^\pm \nu$	0.02 ± 0.02	Newly estimated
$K^\pm \rightarrow \pi^0 \pi^\pm$	0.004 ± 0.004	Newly estimated
Neutron induced		
Hadron cluster on CsI	0.017 ± 0.002	
Upstream π^0 from NCC	0.03 ± 0.03	Updated, wrong veto thresh.
CV η	0.03 ± 0.01	
CV π^0	< 0.10	
Total background	1.22 ± 0.26	

Final 2016-2018 Results

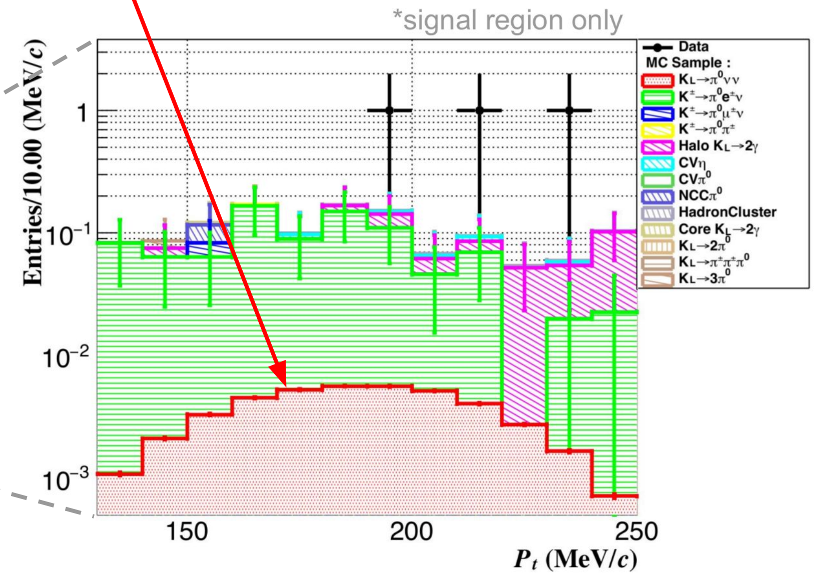


- SES = $(7.2 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$
- 3 candidate events in signal region
- Total background estimation = 1.22 ± 0.26

BR($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 4.9 x 10^{-9} (@ 90% CL)

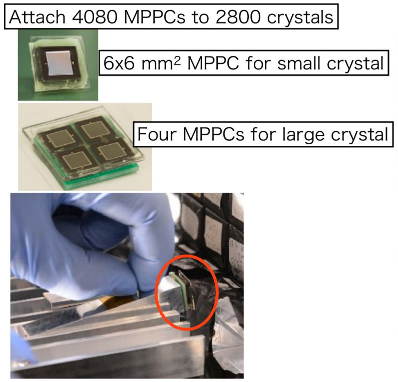


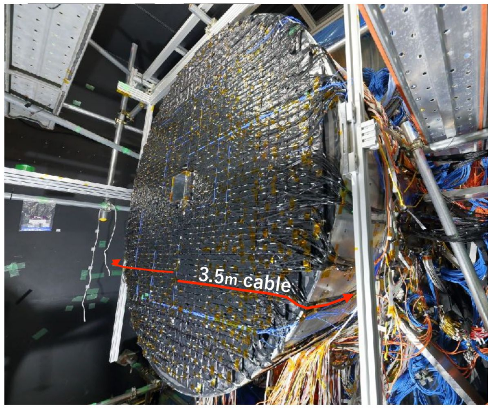
$K_L \to \pi^0 \nu\nu$ expectation @ this SES

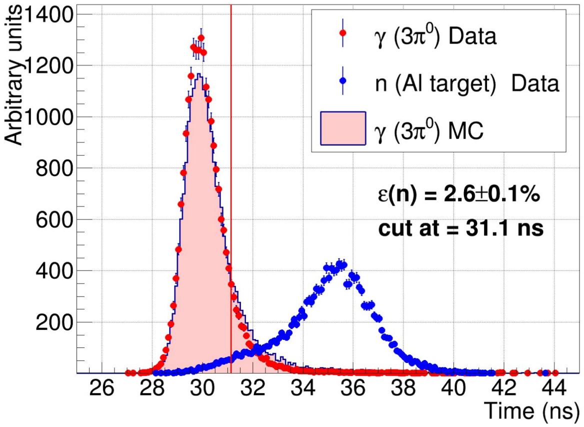


Improvements after 2018

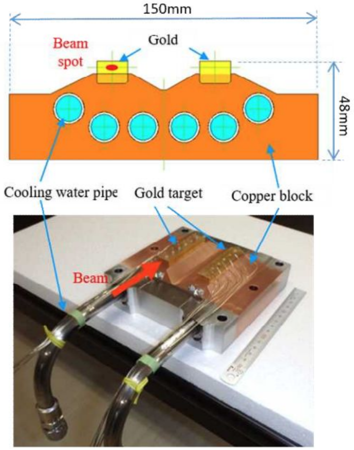
- Installed MPPCs for dual-ended readout (n/γ discrimination) on CsI after 2018 runs



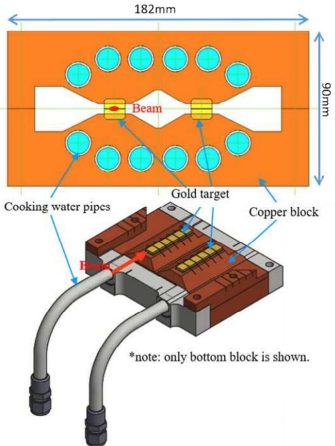




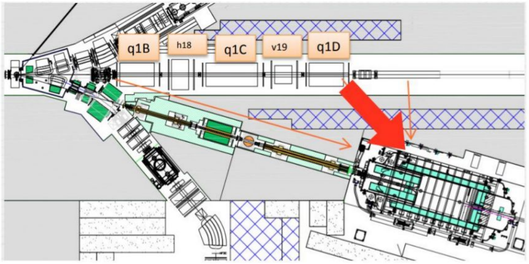
- New T1 target installed in Hadron Hall in Fall 2019 → higher beam power
- Iron walls installed in 2019 and 2020 to reduce accidental activity



Old target

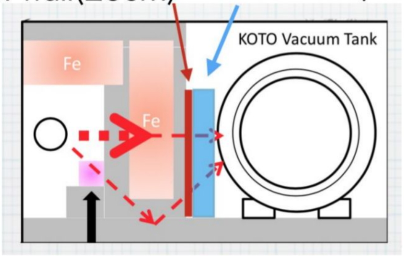


New target



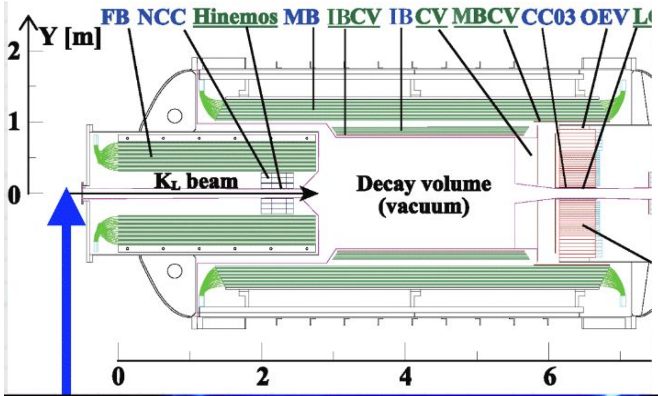
Newly installed iron wall(20cm)

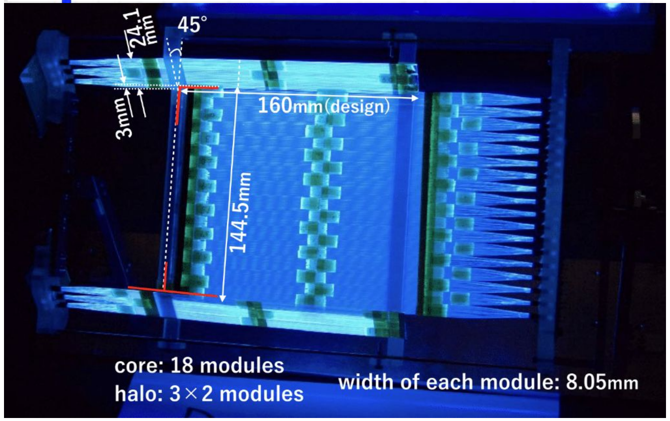
water wall(30cm)



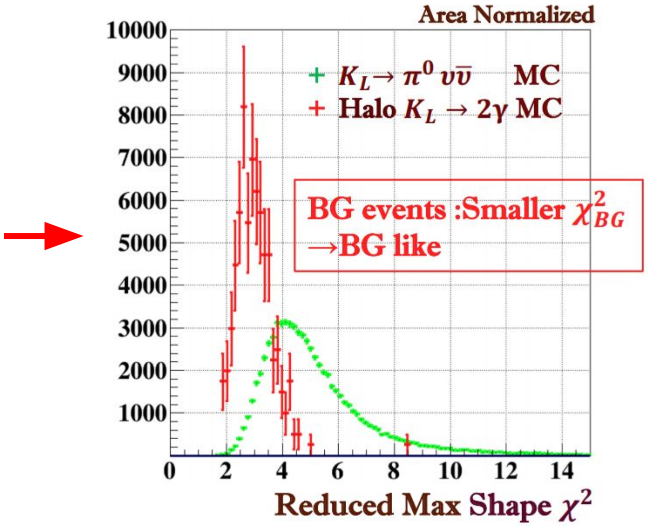
Improvements after 2020

- Developed new veto detector to reduce $K^{\pm}$ background
    - **Upstream Charged Veto (UCV)**
      0.5mm-thick scintillator fibers, read out with MPPC
    - Prototype tested in 2020 June run
    - New UCV installed for 2021 data collection
    - Reduce $K^{\pm}$ BG by 95%





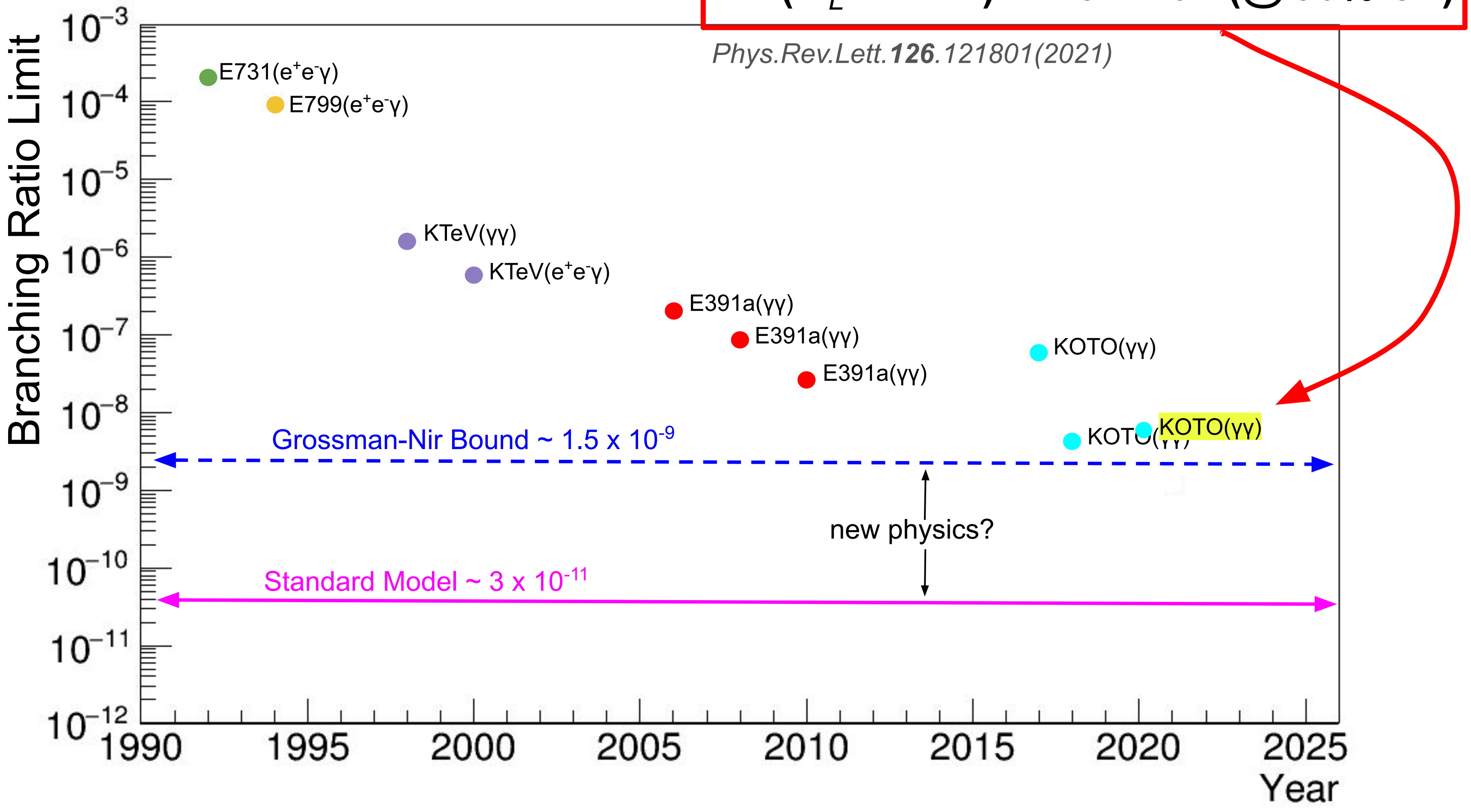
- Developing new cuts for halo K_L background
    - cluster shape discrimination
    - Reduce halo K_L BG by 96%



Impact and Conclusions

- Highest sensitivity for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ search
- Considered 2 new backgrounds→ developing ways to reduce
- Continued data collection is necessary → 2021 experimental runs

BR($K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$) < 4.9 x 10^{-9} (@ 90% CL)



Summary

- Finalized analysis of the 2016-2018 data set for the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ search
- Achieved a SES = $(7.2 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$
- 3 candidate events observed in the signal region with background expectation of 1.22 ± 0.26 *(probability = 13%)*
- Identified 2 new background sources → important for reaching SM sensitivity
- $BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ (@ 90% CL) *Phys. Rev. Lett.* ***126****, 121801 (2021)*
- KOTO will continue collecting data and continues to push down to SM sensitivity with new background reduction methods

Thank You

Dec ’17 collaboration meeting