New results of $K_L \to \pi^0 \nu \bar{\nu}$ from J-PARC KOTO

Kota Nakagiri (Kyoto Univ.)
on behalf of the KOTO collaboration

16th Conference on Flavor Physics & CP Violation

FPCP 2018

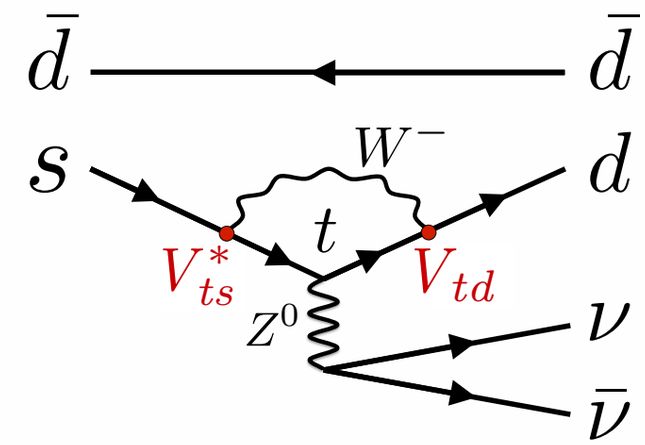
14 -18 July 2018, Hyderabad, India

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

- direct CPV
- highly suppressed in the SM : Br = **3×10^{-11}**
- theoretically clean : ~2%

➡ good probe for new physics that breaks CP symmetry

s→d FCNC



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

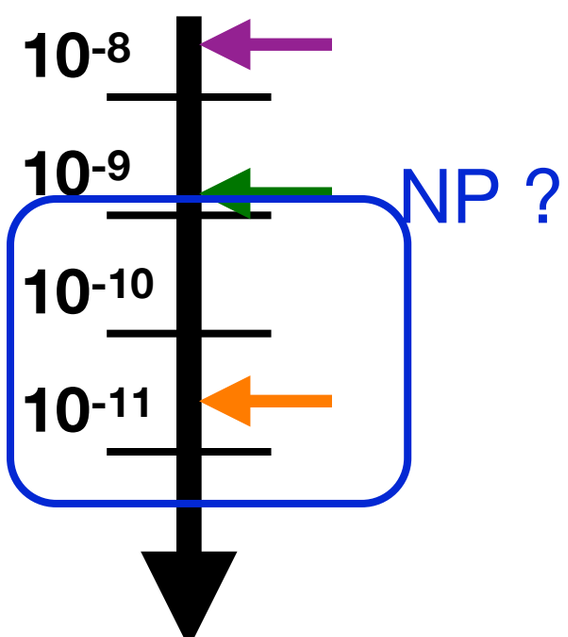
V_{td}: λ^3, V_{ts}: λ^2, V_{tb}: 1, $\lambda \sim 0.2$

K system ~λ^5 << B_d system ~λ^3

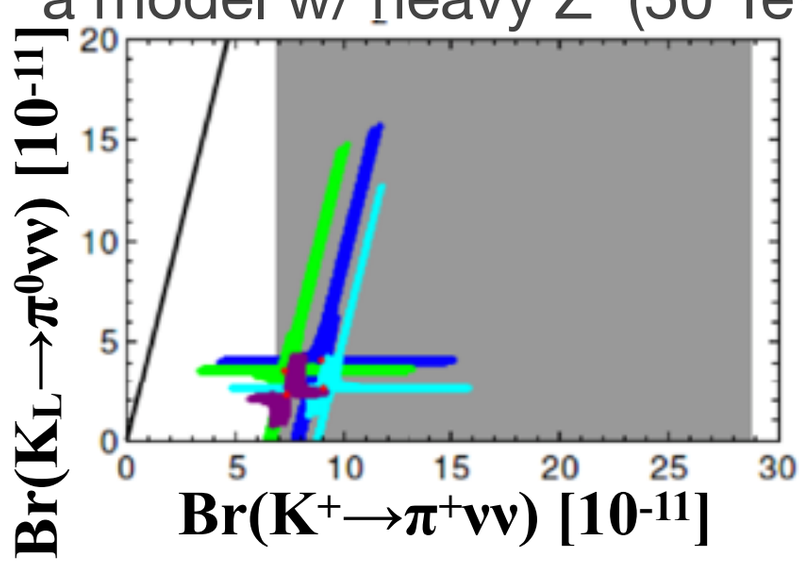
direct limit : **2.6×10^{-8}** (90% C.L.)

indirect limit (Grossman-Nir bound)

$Br(K_L) < 4.4 \times Br(K^+) =$ **1.5×10^{-9}**

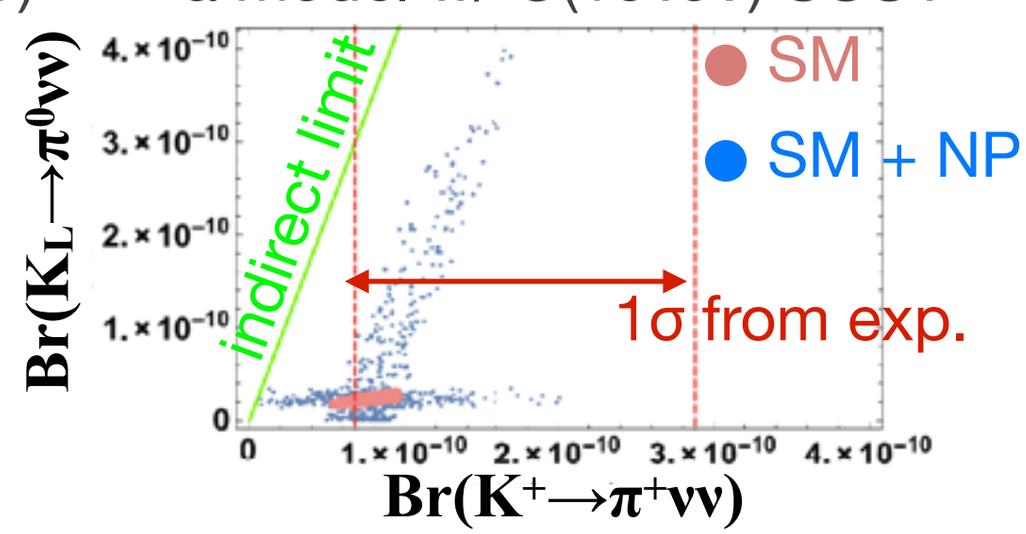


a model w/ heavy Z' (50 TeV)



A.J.Buras, et al. JHEP11(2014)121

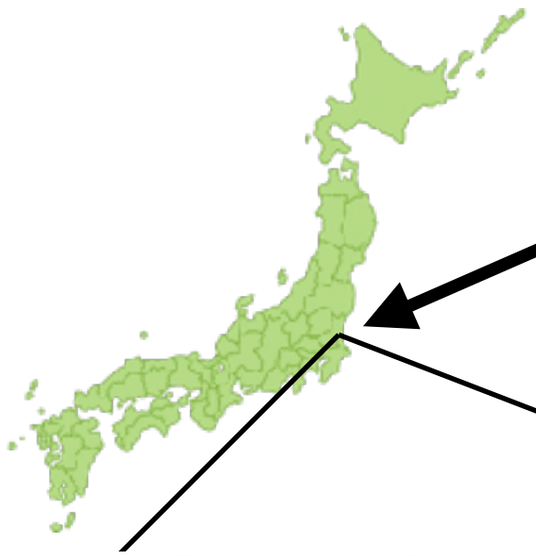
a model w/ O(10TeV) SUSY



M.Tanimoto, K.Yamamoto, PTEP2016,12,123B02

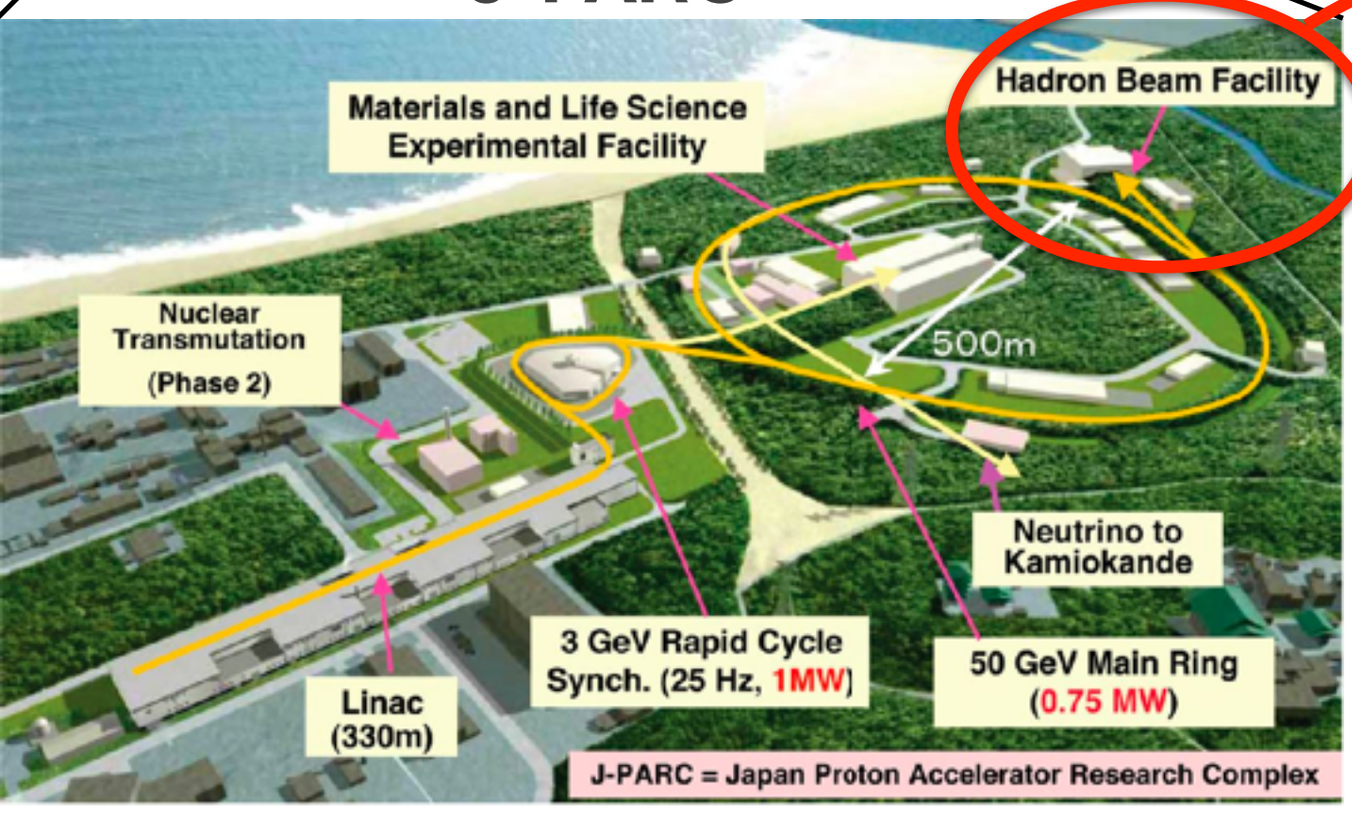
KOTO Experiment @ J-PARC

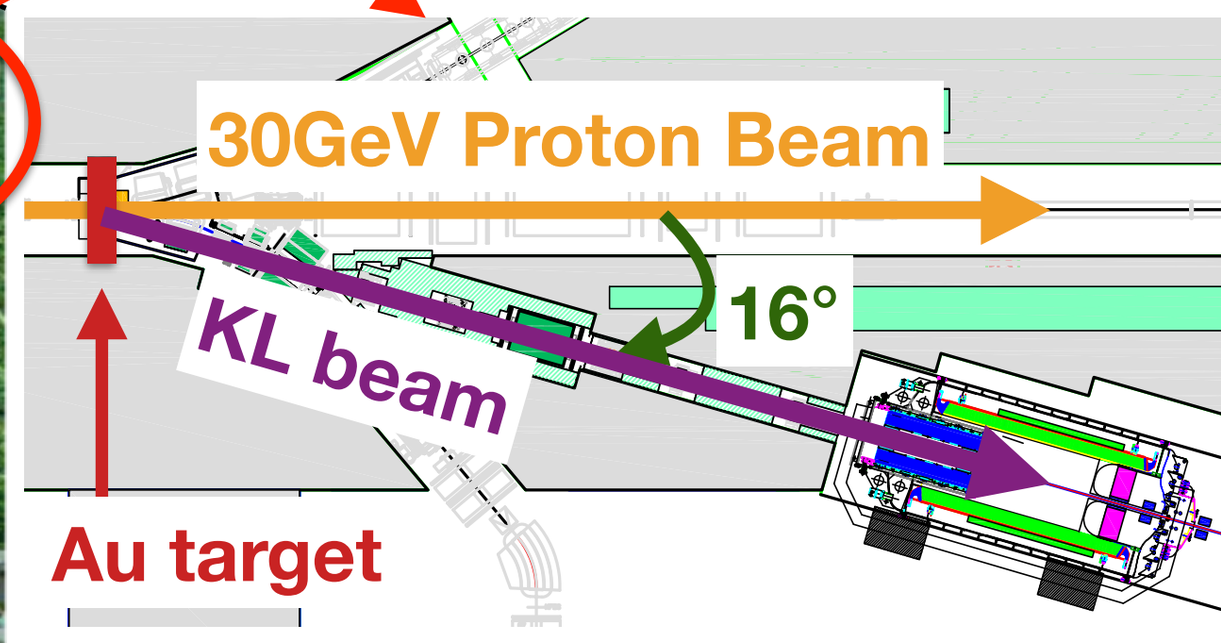
K^0 at TOkai



Tokai village

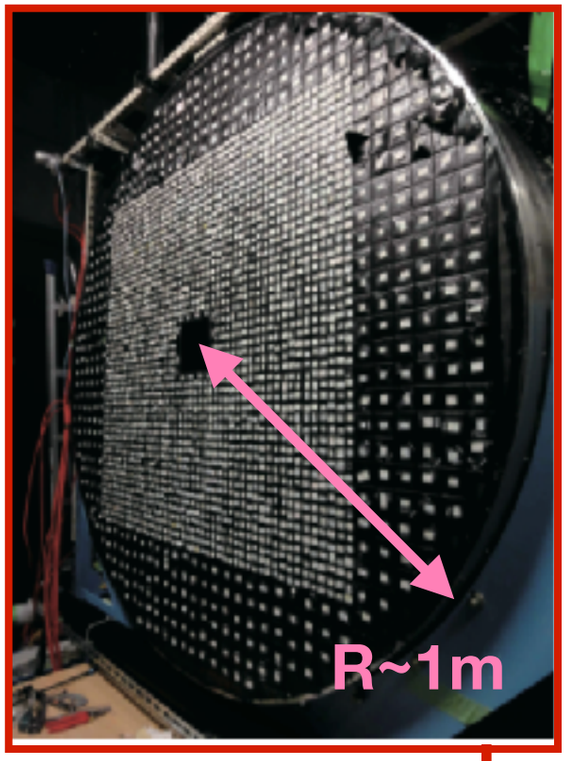
Japan Proton Accelerator Research Complex
= J-PARC





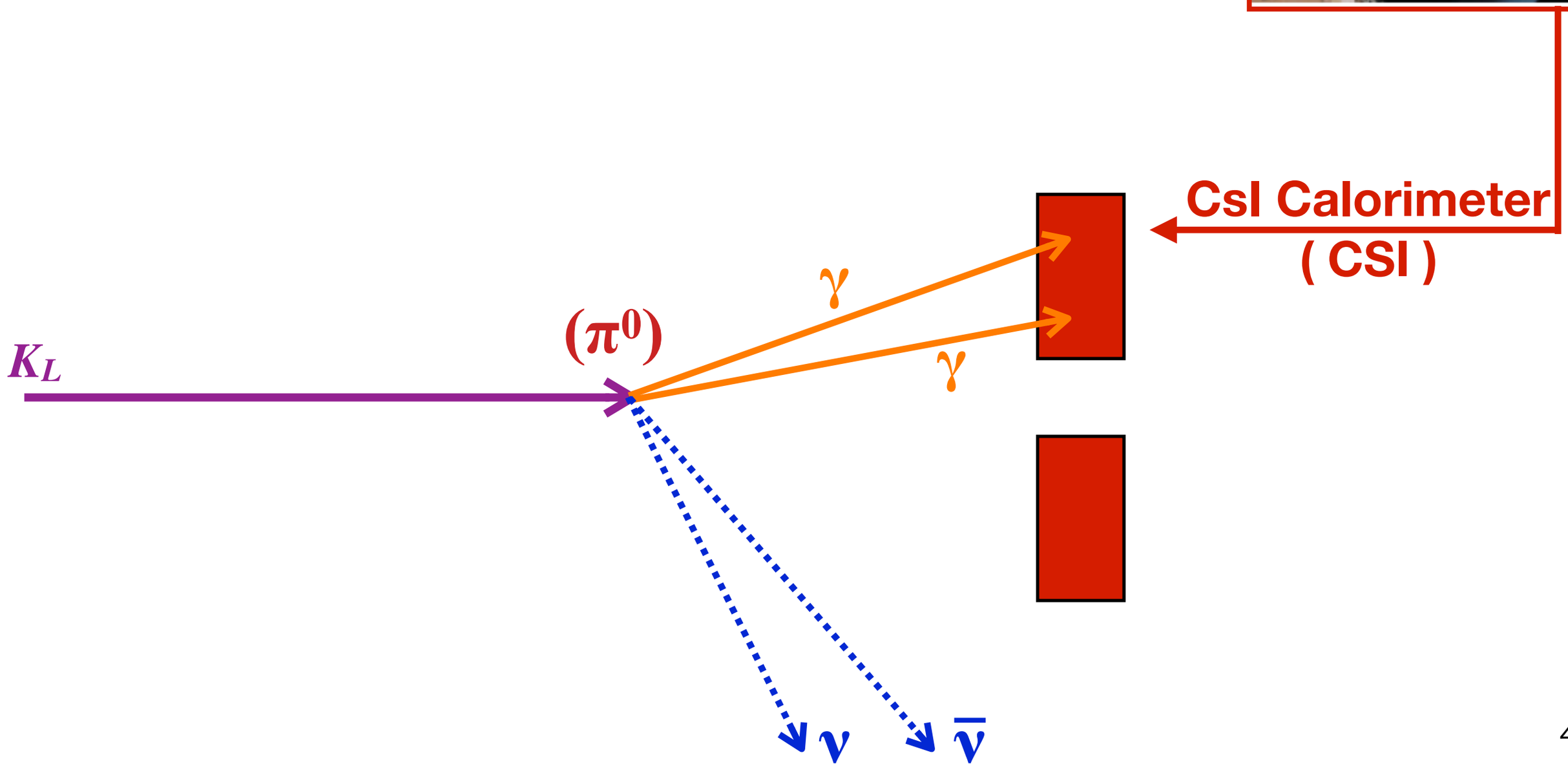
KOTO

Experimental Method
: Signal detection

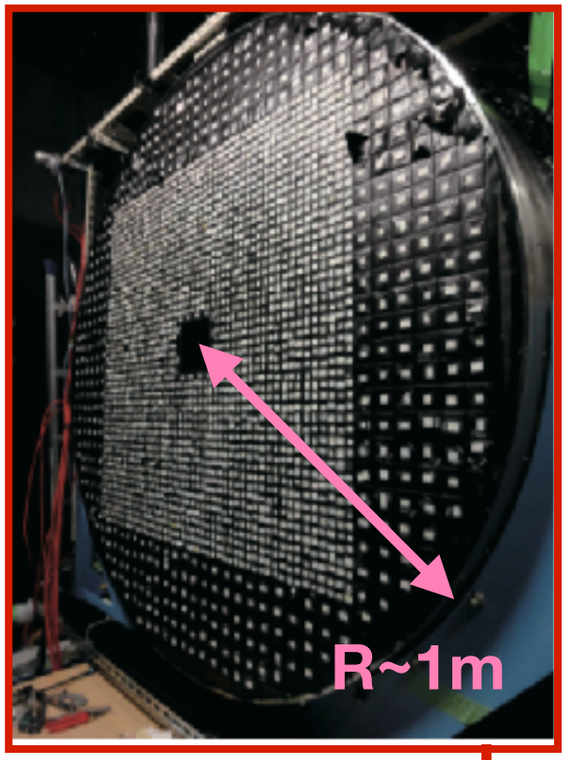


$\pi^0 \rightarrow 2\gamma$ on CSI calorimeter

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



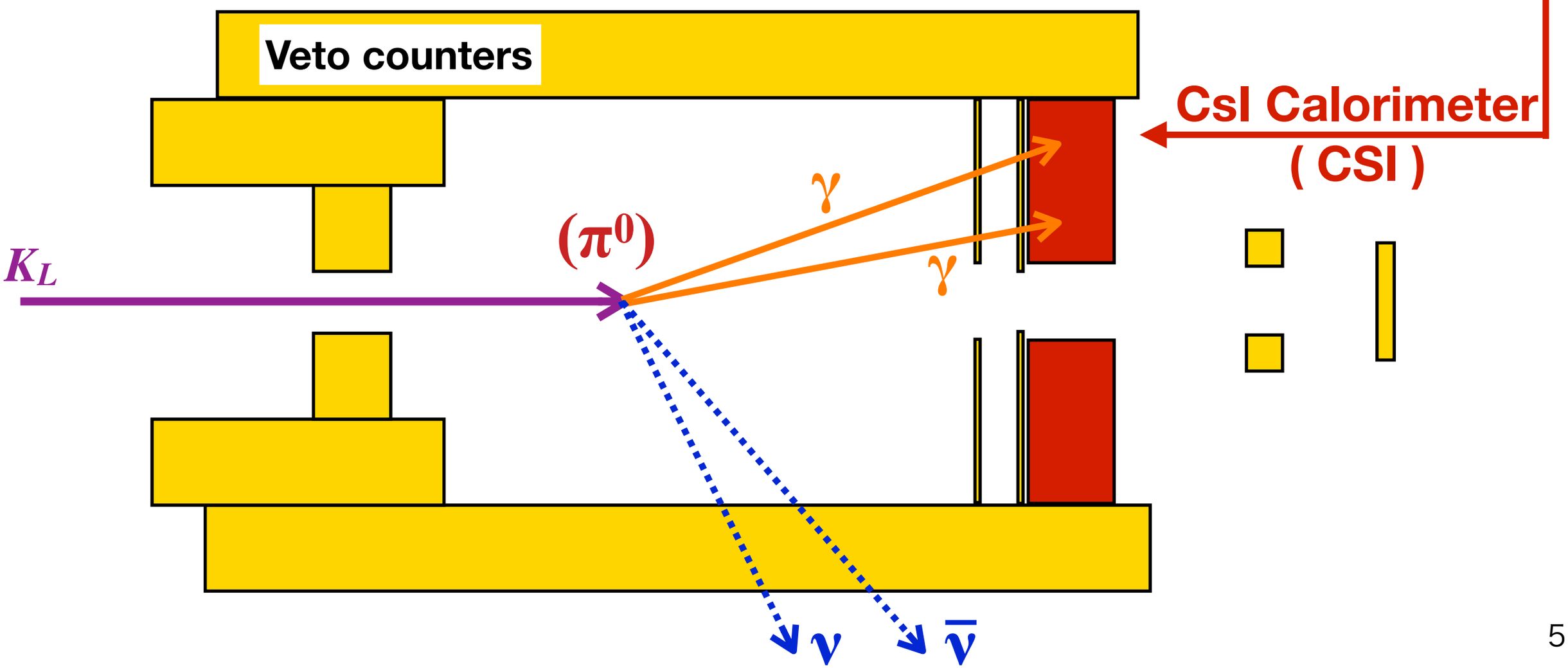
Experimental Method
: Signal detection



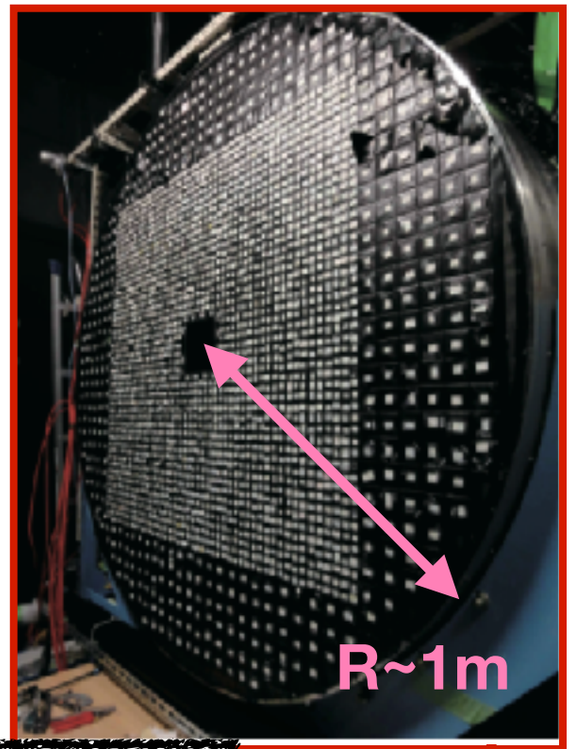
$\pi^0 \rightarrow 2\gamma$ on CSI calorimeter

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

missing : hermetic veto around the decay volume



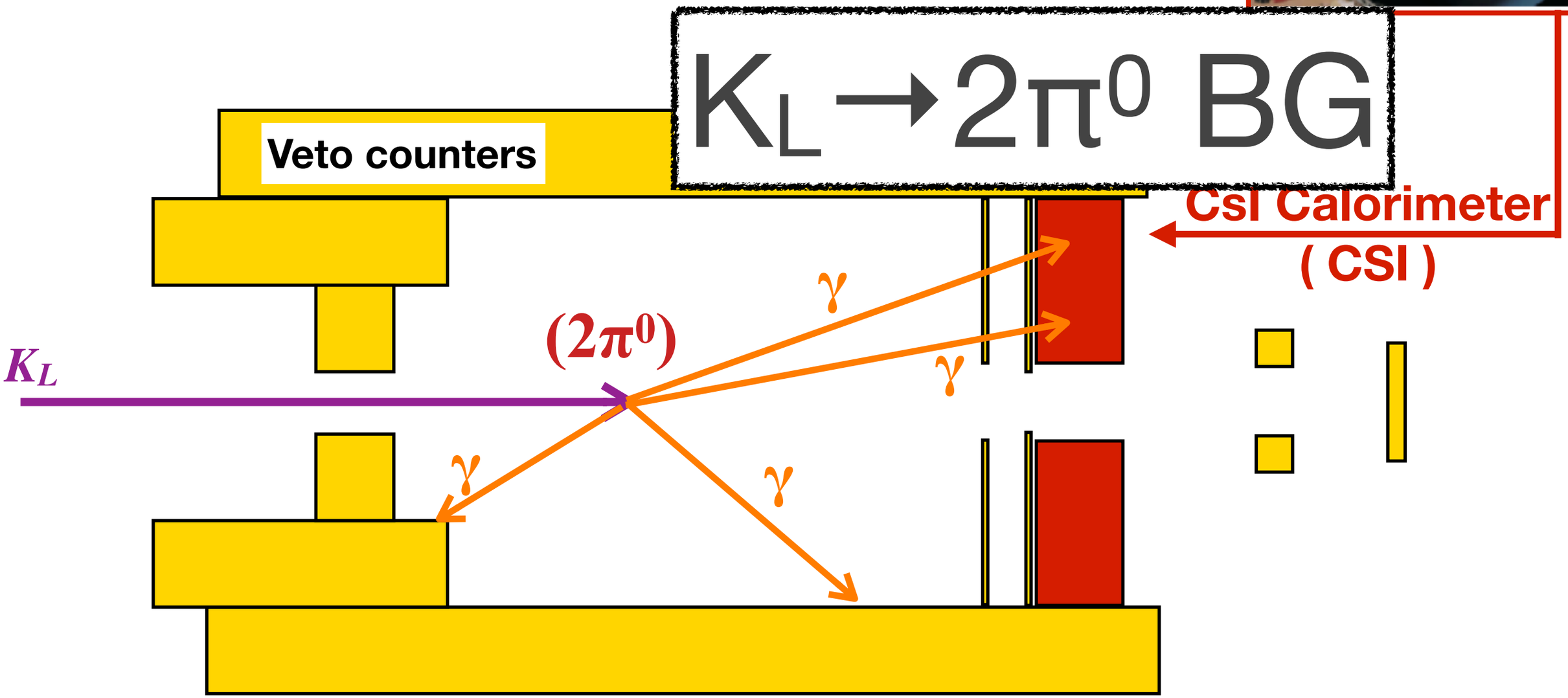
Experimental Method
: Background rejection



$$K_L \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$$

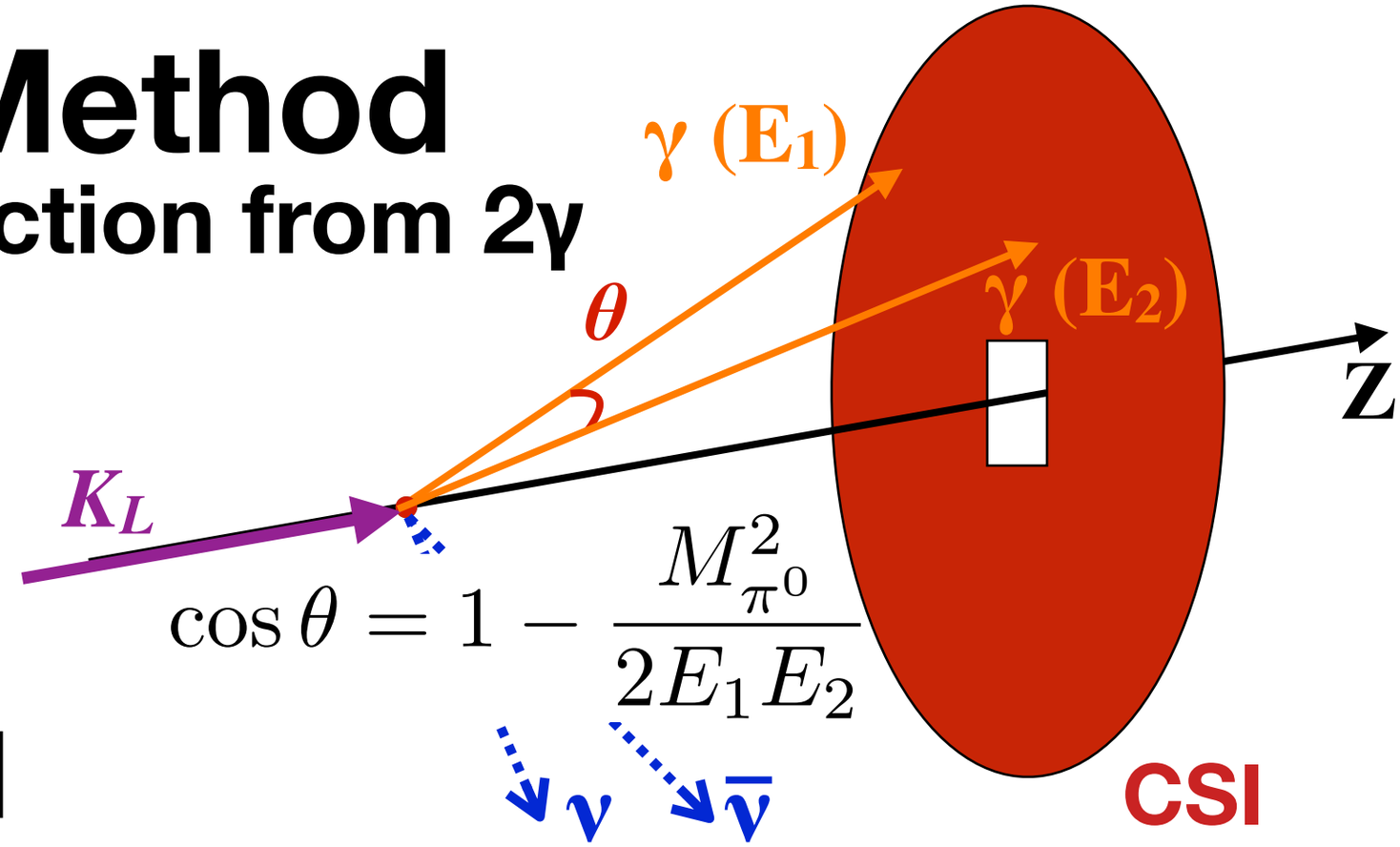
CSI

Veto

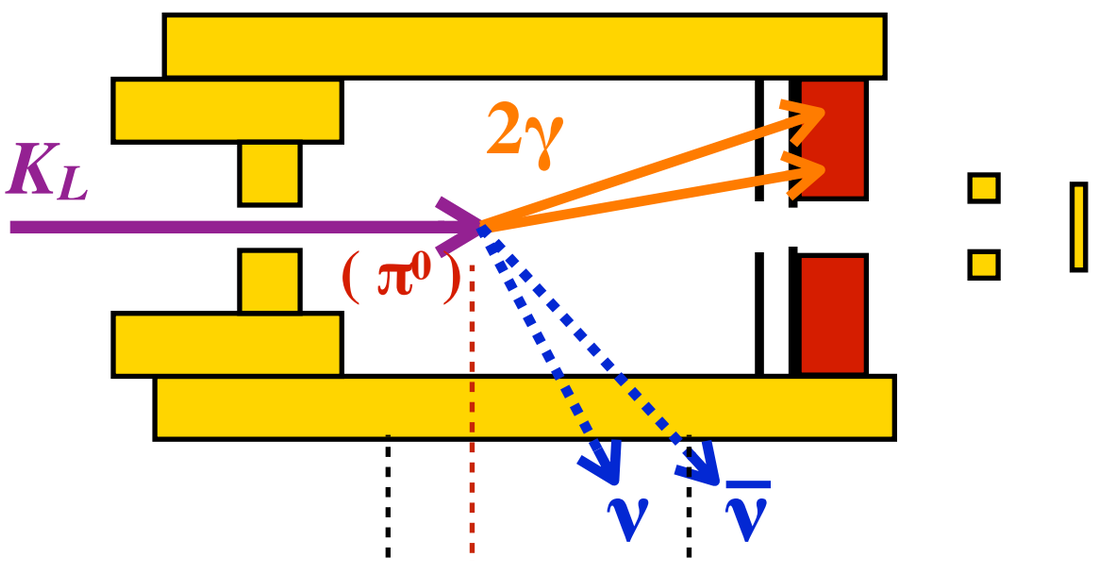


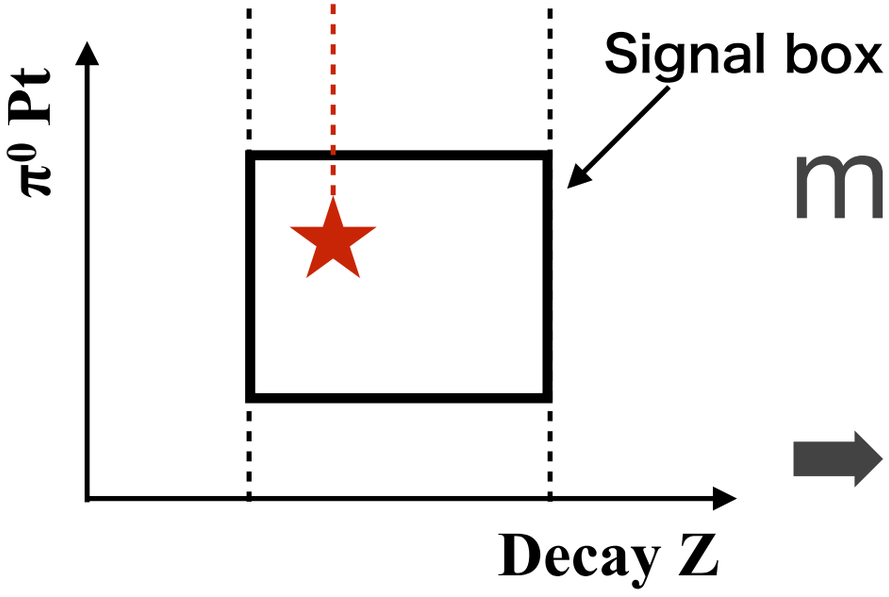
Experimental Method

: π^0 reconstruction from 2γ



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



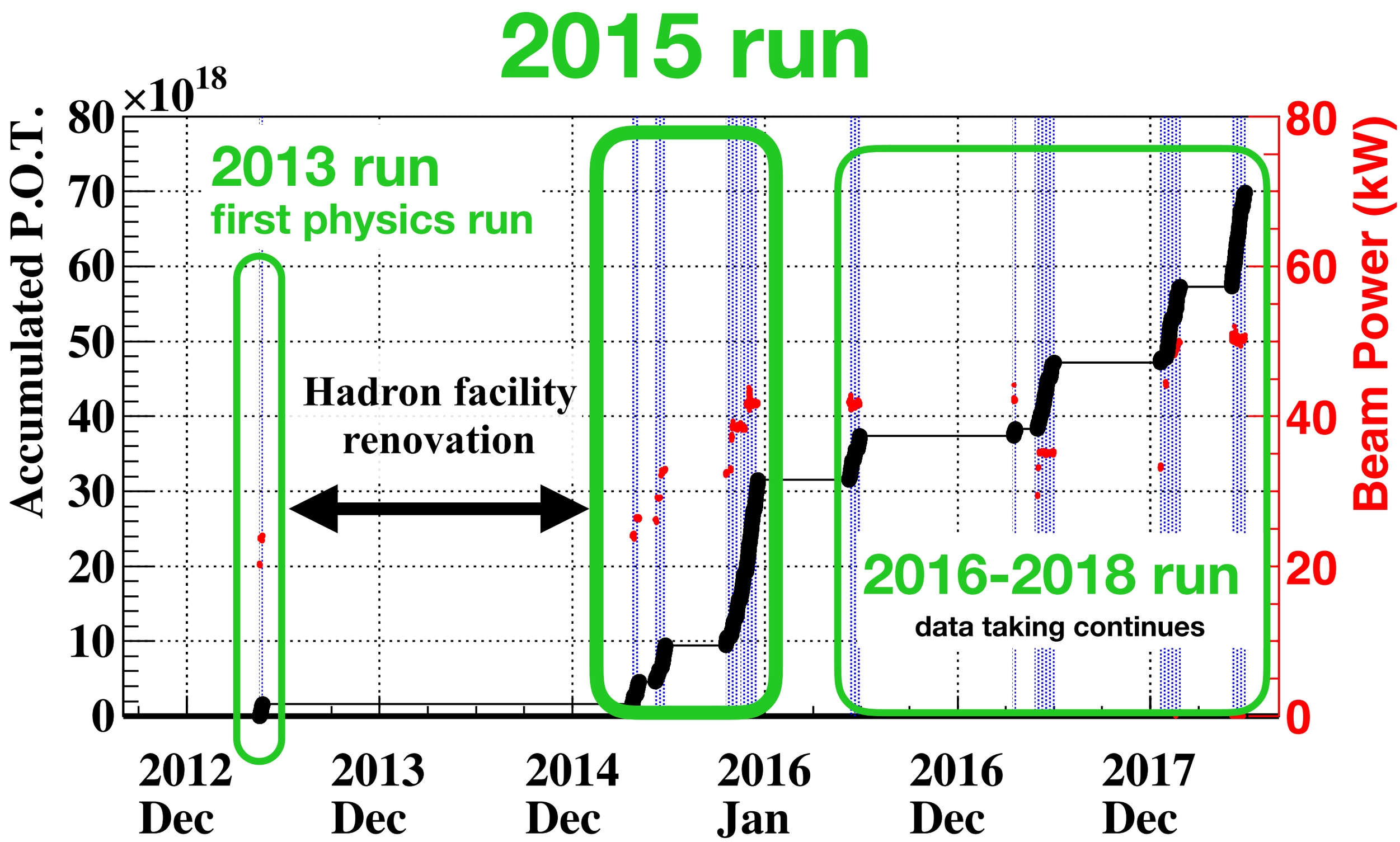


missing Pt by two neutrinos

= finite π^0 Pt

➡ signal region on Pt - Z plane

History of the KOTO data taking



First physics run in 2013

PTEP

Prog. Theor. Exp. Phys. **2017**, 021C01 (11 pages)
DOI: 10.1093/ptep/ptx001

Letter

A new search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ decays

J-PARC KOTO Collaboration
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H. Haraguchi[3], T. Hineno[9], Y. B. Hsiung[6], M. Hutcheson[4], T. Ir
T. Kamibayashi[11], I. Kamiji[9], N. Kawasaki[9], E. J. Kim[12], Y. J.
T. K. Komatsubara[10,14], A. S. Kurilin[15,†], G. H. Lee[12], H. S. Le
S. K. Lee[12], G. Y. Lim[10,14], C. Lin[6], J. Ma[5], Y. Maeda[9,24,*], T. M
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Y. Odani[8], R. Ogata[8], H. Okuno[10], T. Ota[8], Y. D. Ri[3], M. Sasak
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J. Stevens[7,32], S. Su[4], Y. Sugiyama[3,28], S. Suzuki[8], Y. Tajima[11], C
M. Tecchio[4], I. Teo[5,33], M. Togawa[3], T. Toyoda[3], Y. C. Tung[6,34]
H. Watanabe[10,14], N. Whallon[4,35], J. K. Woo[13], J. Xu[4], M. Yama
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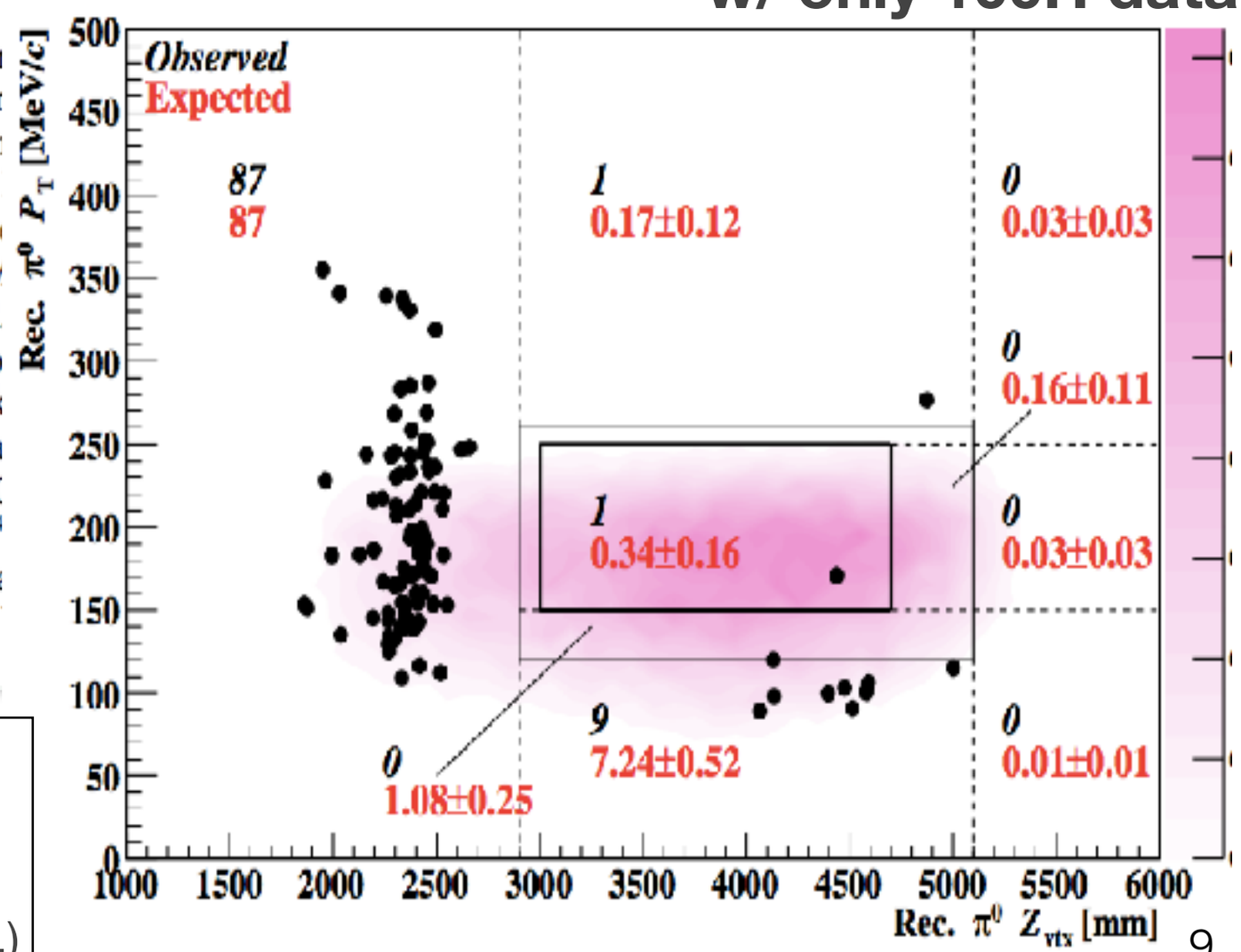
H. Yoshimoto[3]

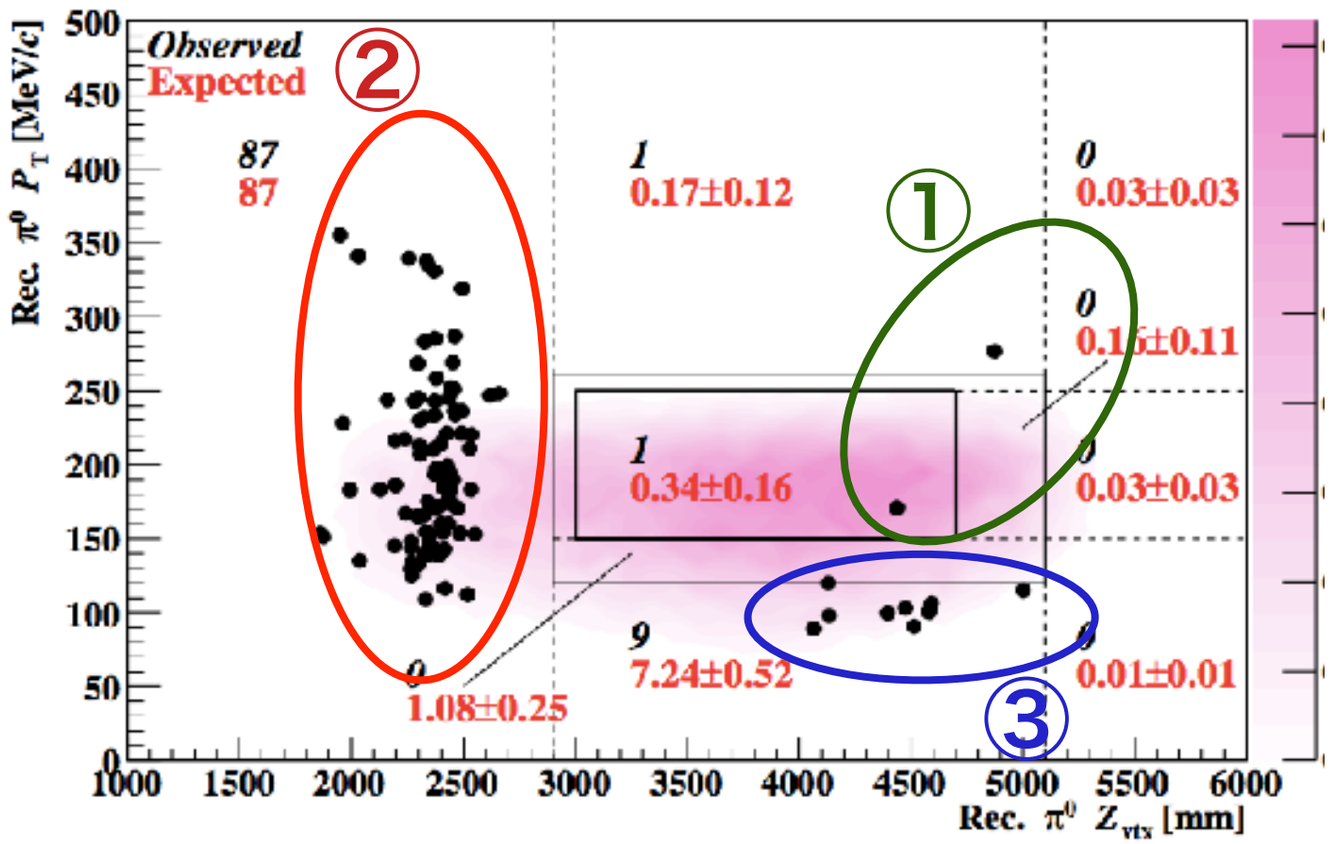
cf. KEK E391a final
best upper limit so far
: SES $=1.11 \times 10^{-8}$

Single Event Sensitivity = 1.28×10^{-8}
w/ only 100H data

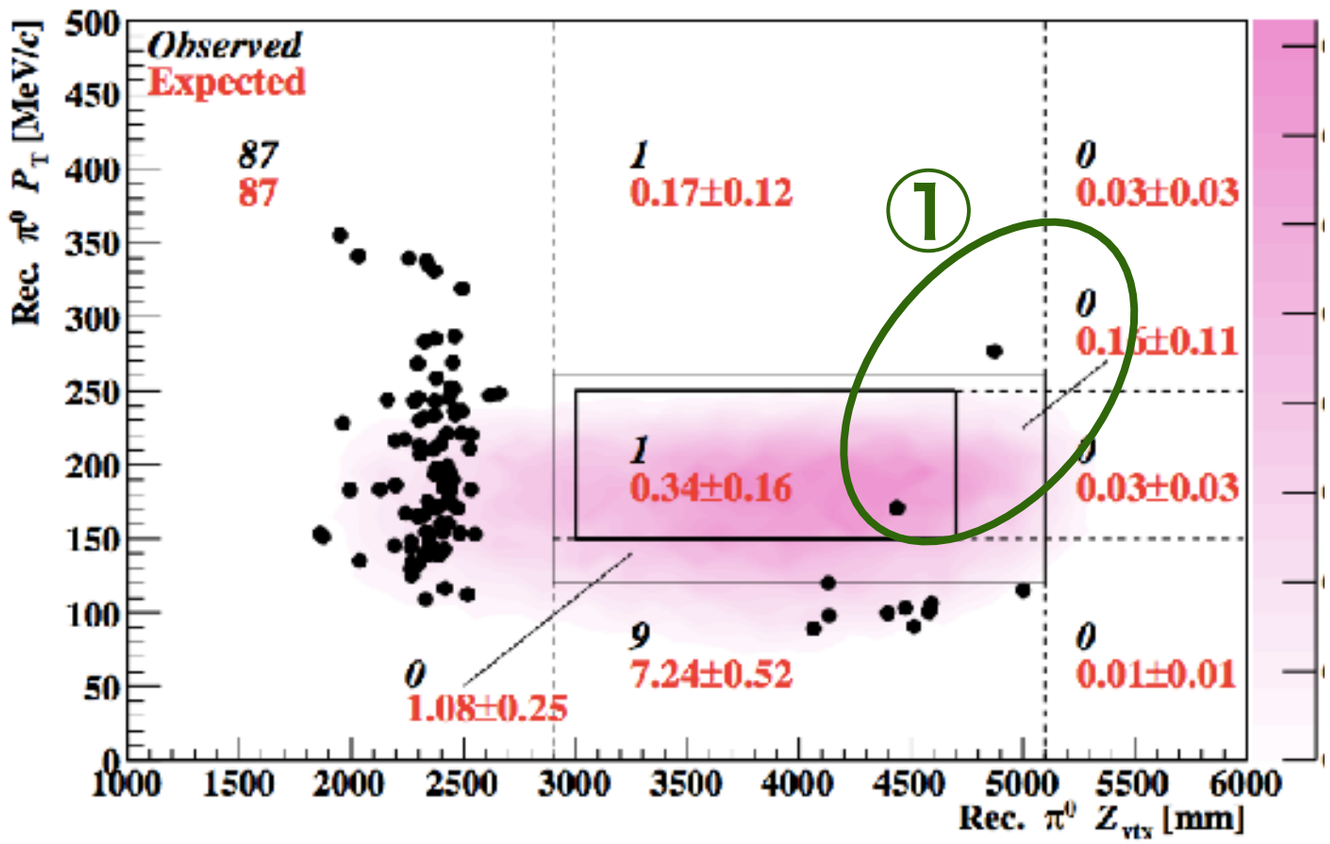


One candidate event observed
consistent with BG expectation
→ $Br(K_L \to \pi^0 \nu\nu) < 5.1 \times 10^{-8}$ (90%C.L.)

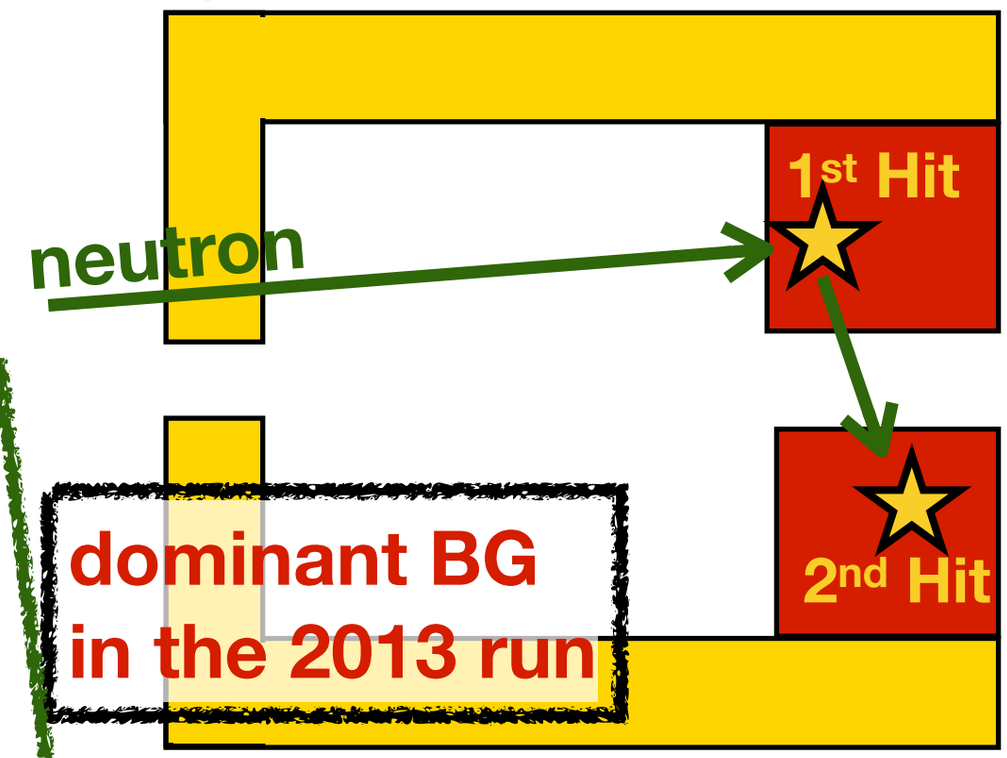
What we learned from the 2013 run



What we learned from the 2013 run



① hadron cluster BG

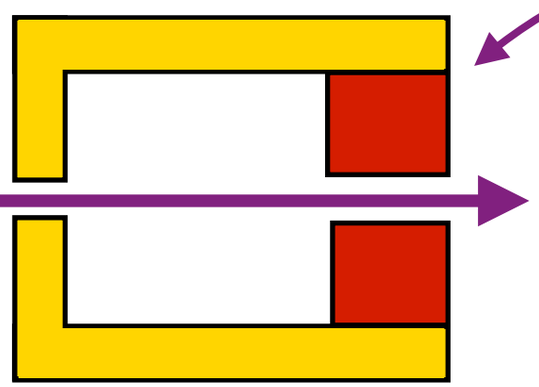


dominant BG in the 2013 run

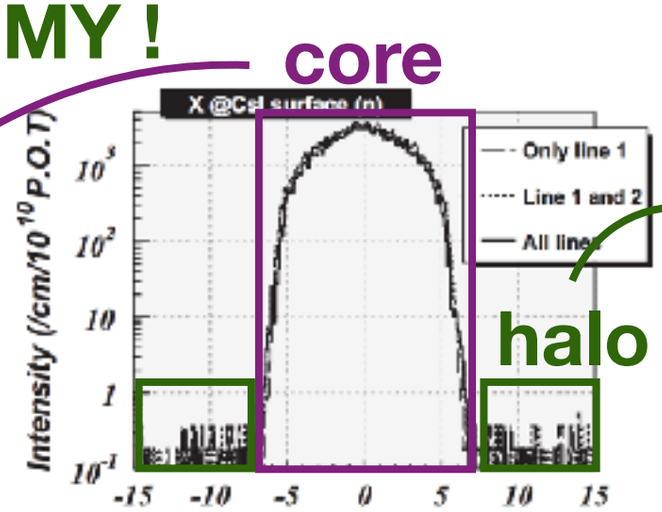
halo-neutron : our ENEMY !

"pencil" beam

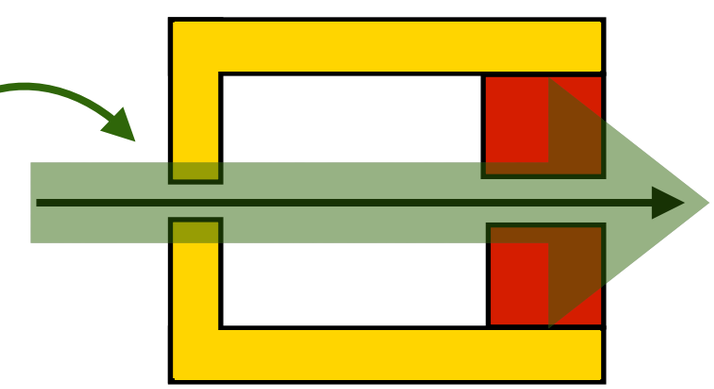
K_L, n, γ



go through beam hole

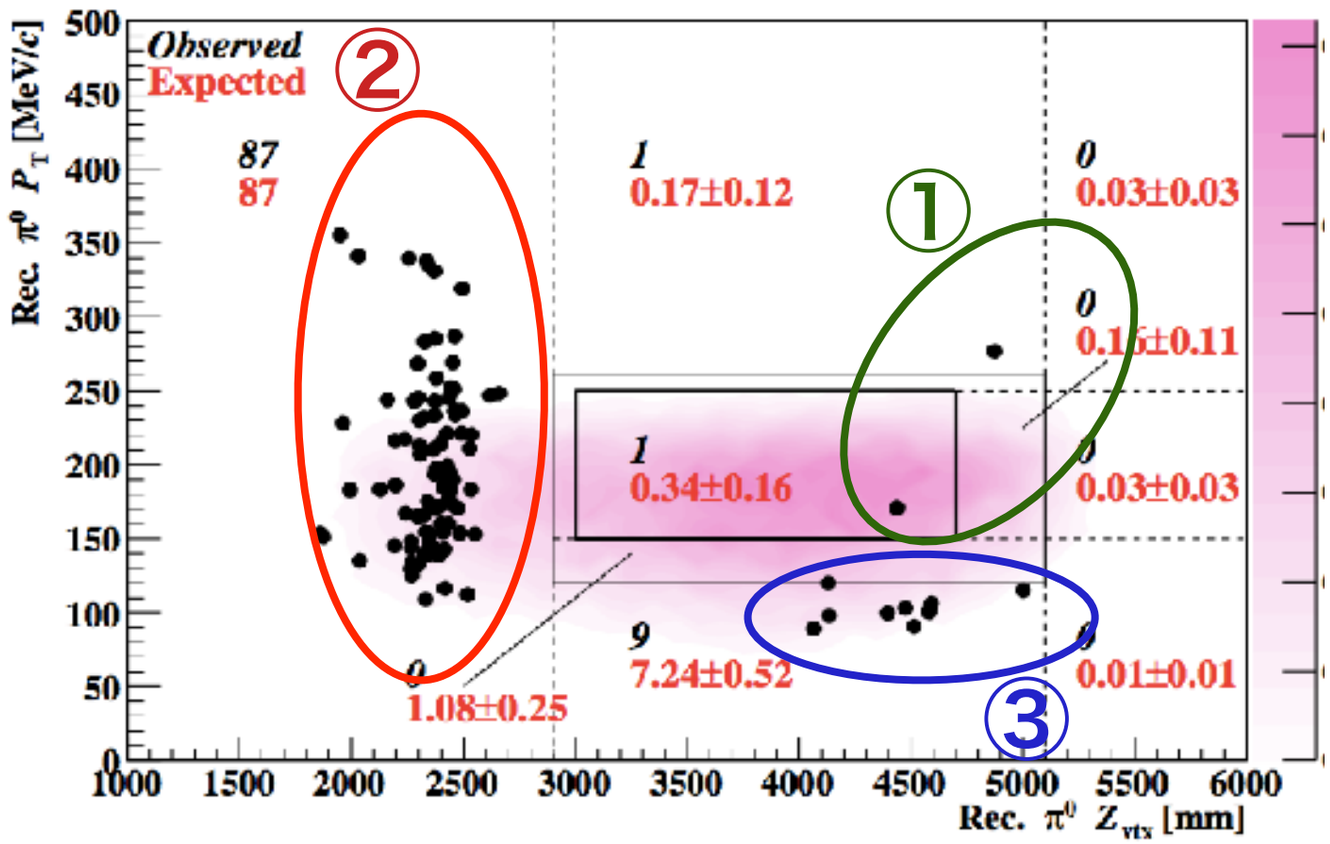


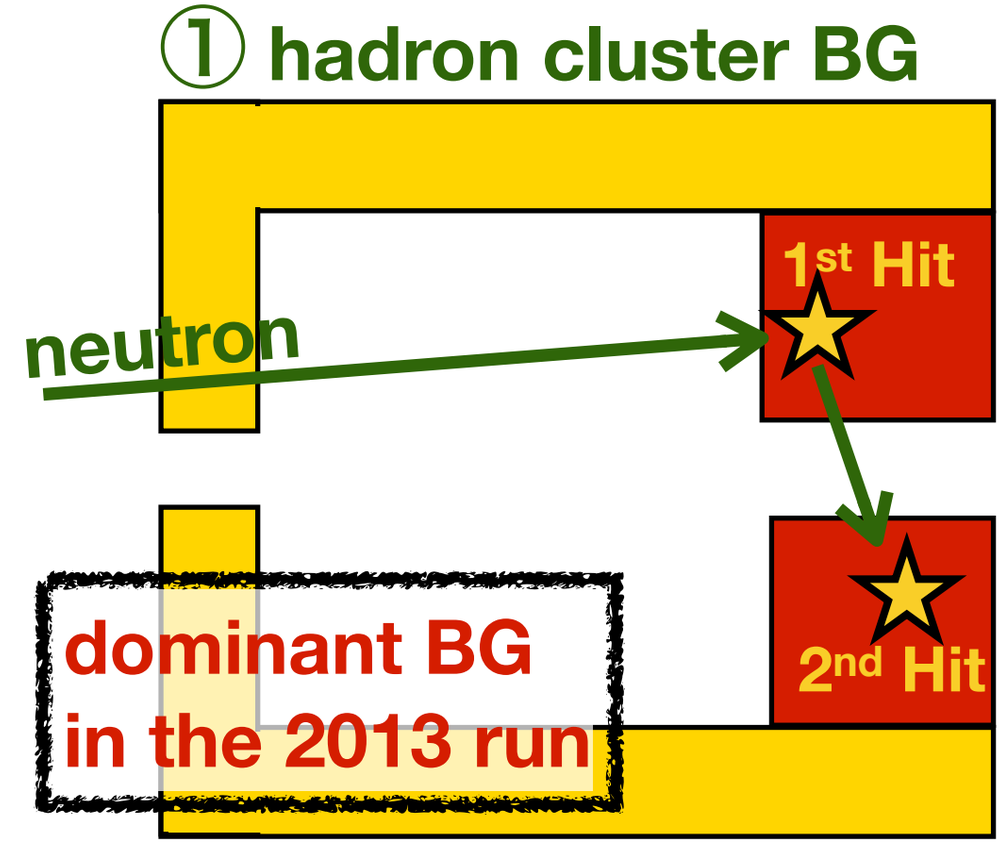
Beam profile(X[mm])
@ CSI surface

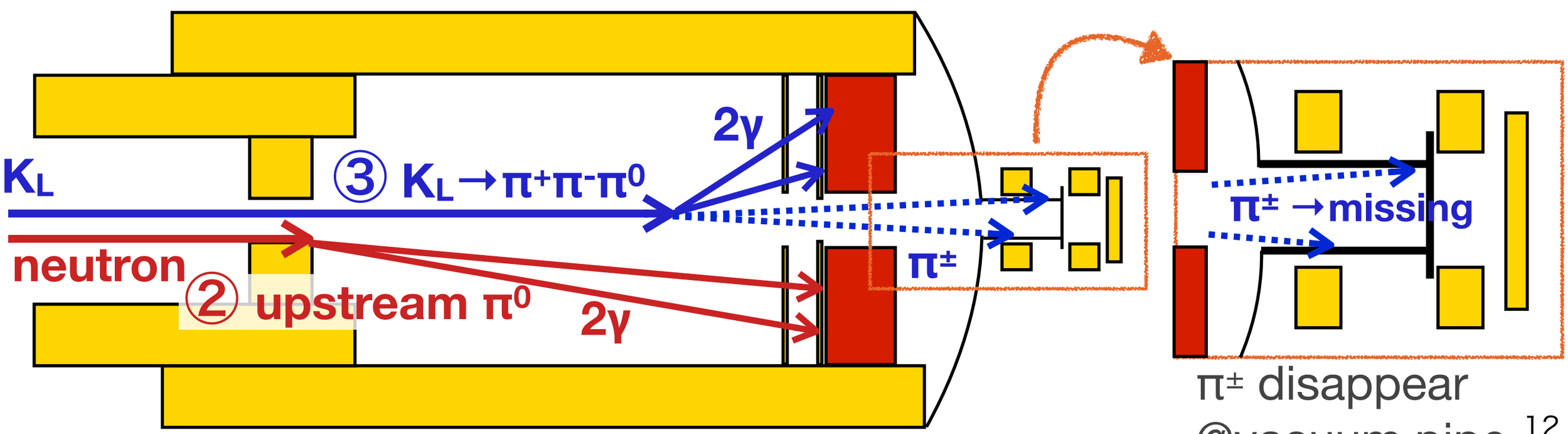


hit detector ➡ BG source

What we learned from the 2013 run







$\pi^\pm$ disappear
@vacuum pipe

Upgrades for the 2015 run

halo-neutron

source of Hadron cluster BG and Upstream π^0 BG

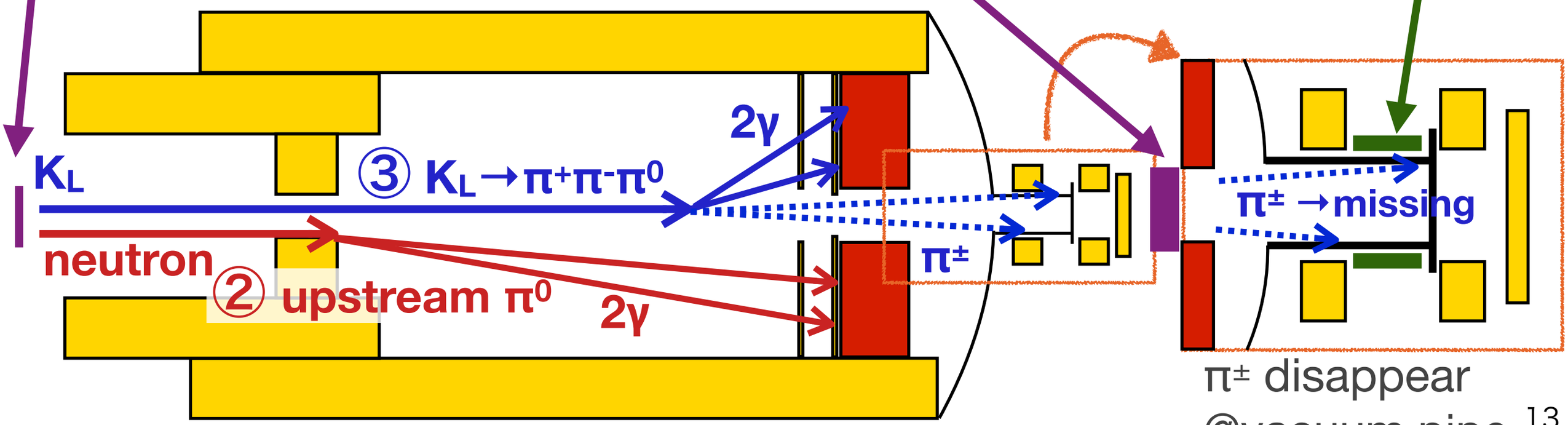
- thinner vacuum window
  125μm→12.5μm
- beam profile monitor for better beam alignment

➡ **N_{halo} ~1/2**

$K_L \to \pi^+\pi^-\pi^0$ BG

- low-mass beam pipe
  SUS → Al
- new scintillation counter

➡ **$N_{\pi^+\pi^-\pi^0\ BG}$ ~1/20**

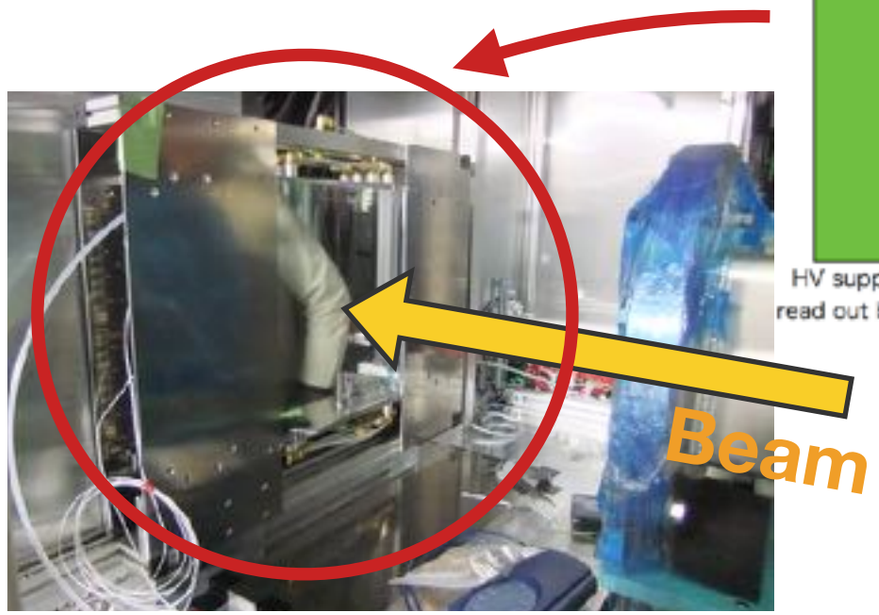


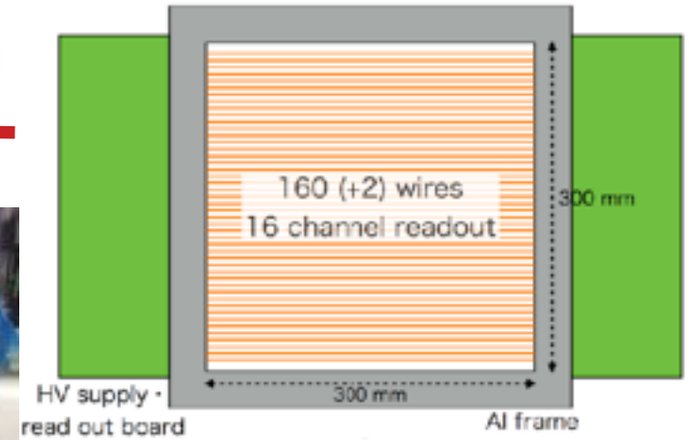
$\pi^\pm$ disappear @vacuum pipe

Other detector upgrades : downstream region

High rate capability

new in-beam charged veto

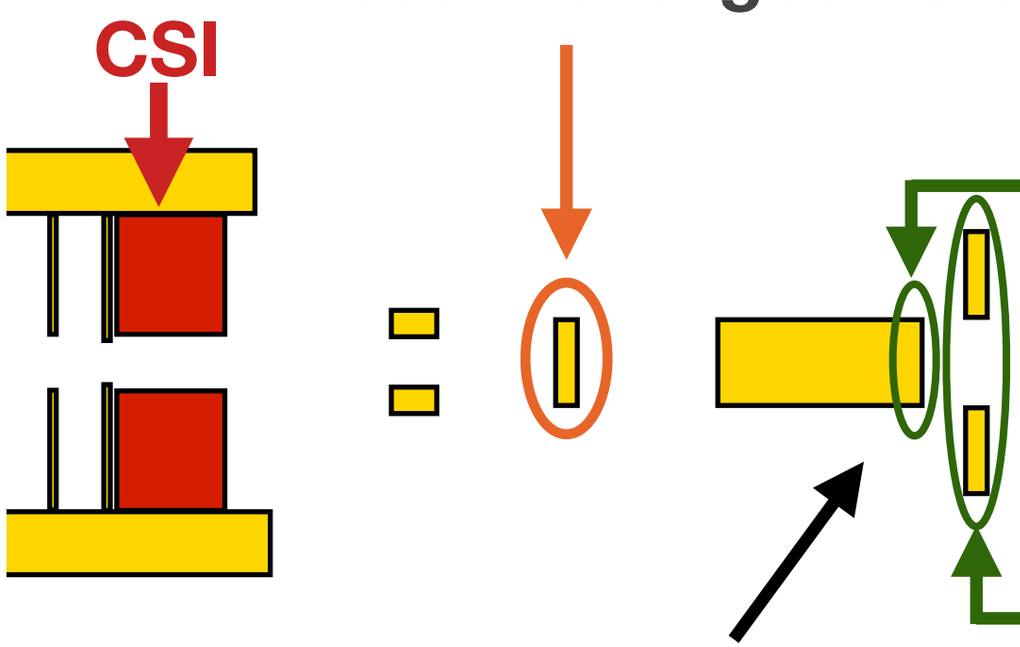




- wire chamber
  - insensitive to neutron

※ original one was
3-mm-thick plastic scintillator

in-beam charged veto



in-beam photon veto

More photon detection efficiency

additional photon counters

lead/aerogel Cherenkov counters
modules : 12 -> 16

new lead/acrylic
Cherenkov counter

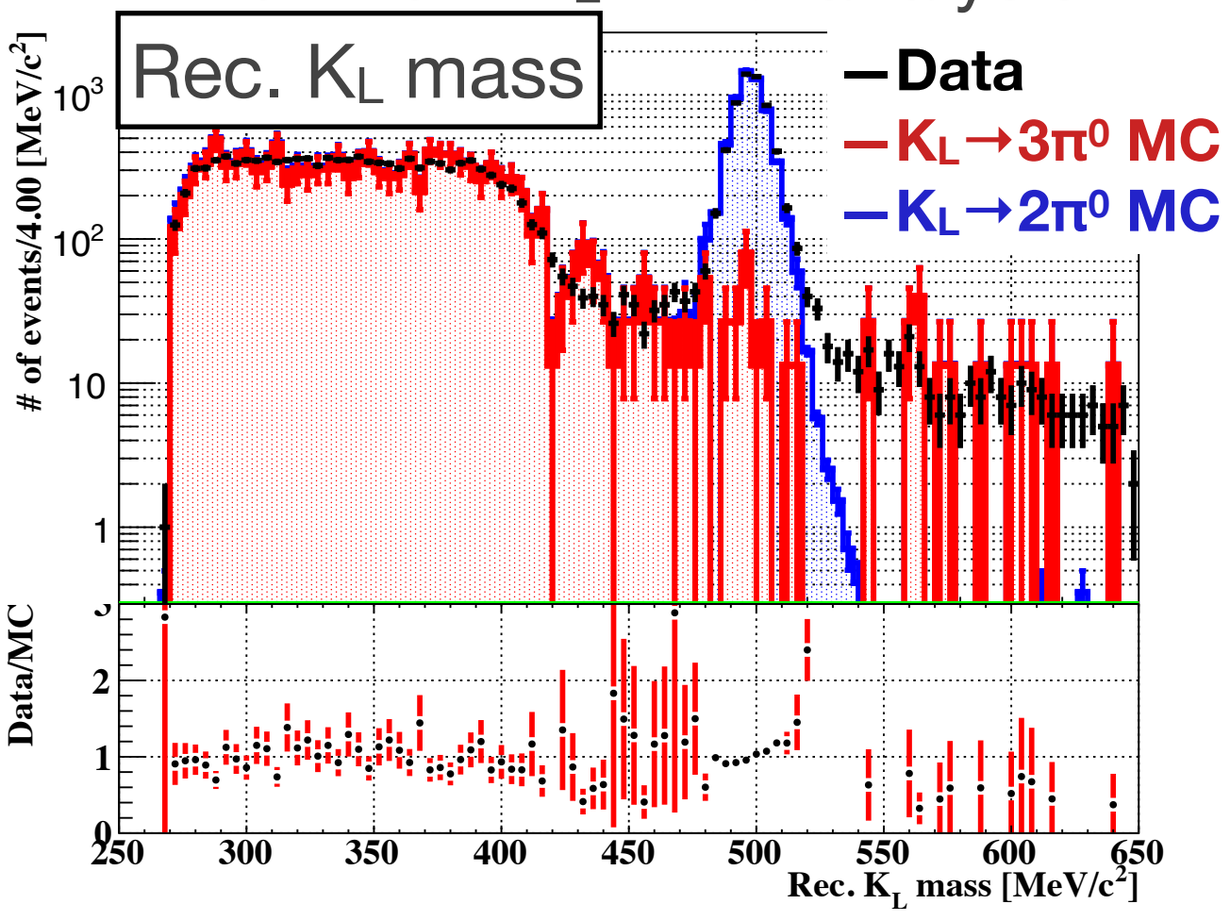
the 2015 run analysis

- Single Event Sensitivity
- K_L-decay background
- Neutron induced background

➡ unblind the signal region

Single Event Sensitivity (SES)

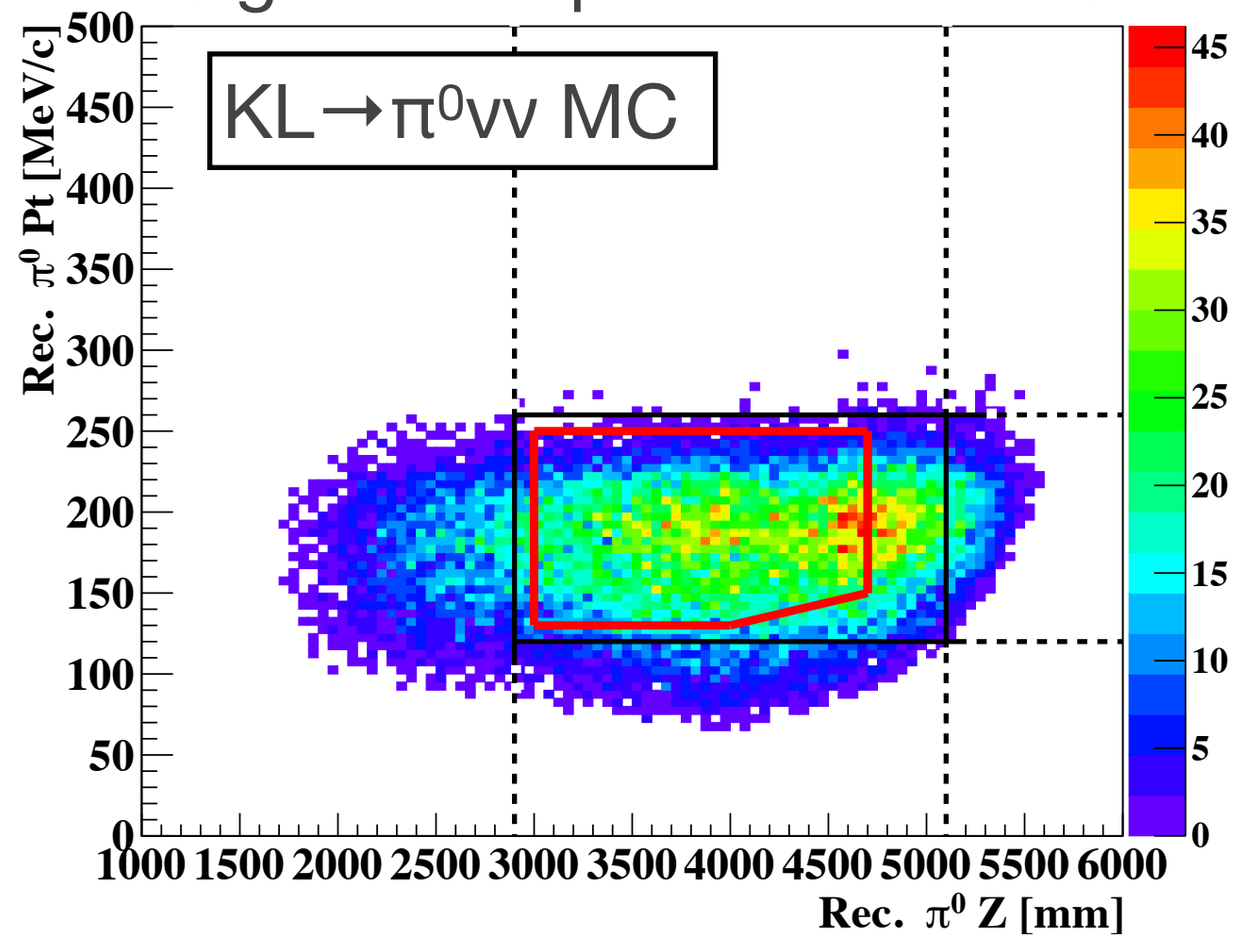
KL flux from $K_L \to 2\pi^0$ analysis



N Decay KL : 1.46×10^{11}

(3000 < Z[mm] < 4700)

Signal Acceptance from MC



Acceptance : 0.52%

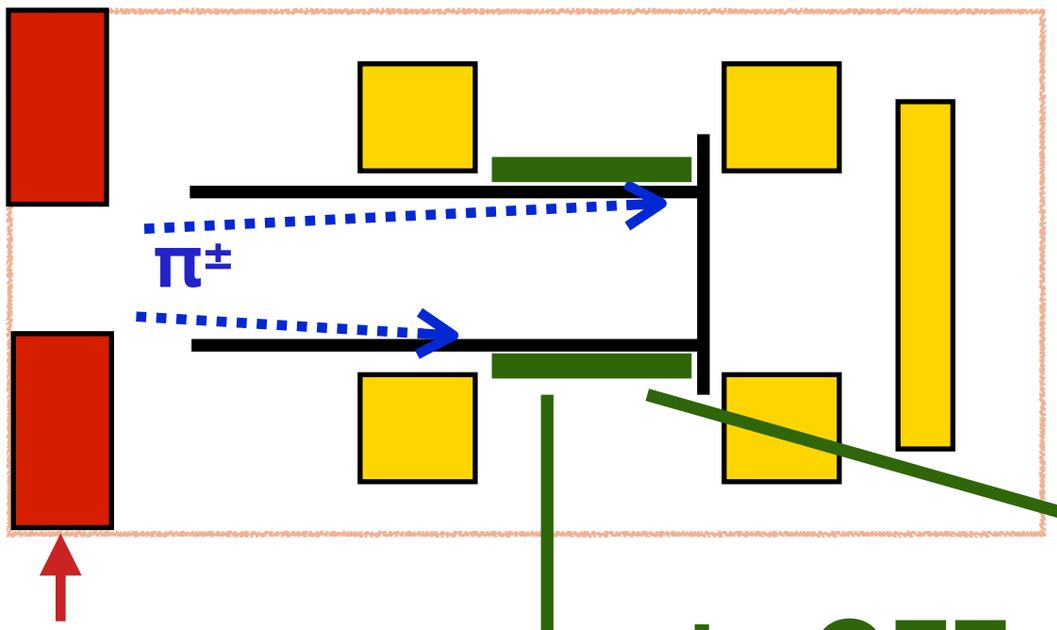
$$\text{Single Event Sensitivity} = \frac{1}{(\text{KL yield}) \times (\text{Signal acceptance})}$$

$$= \mathbf{1.3 \times 10^{-9}}$$

c.f. GN bound : $<1.5\times10^{-9}$

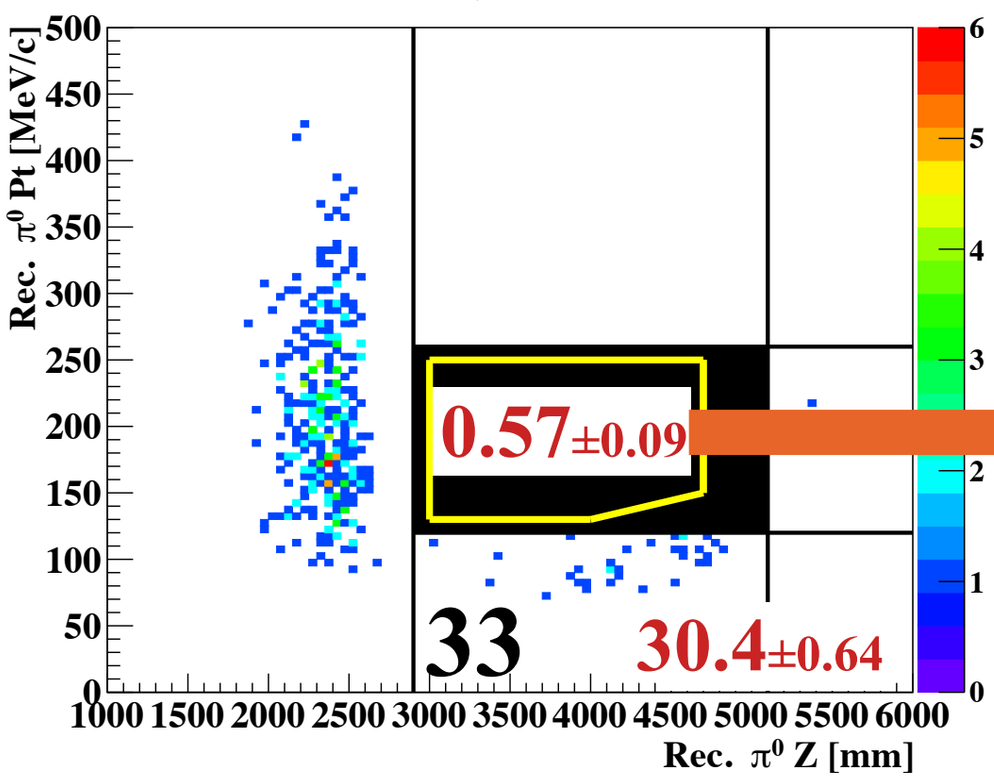
×10 better sensitivity than that of the 2013 run

$K_L \rightarrow \pi^+\pi^-\pi^0$ background



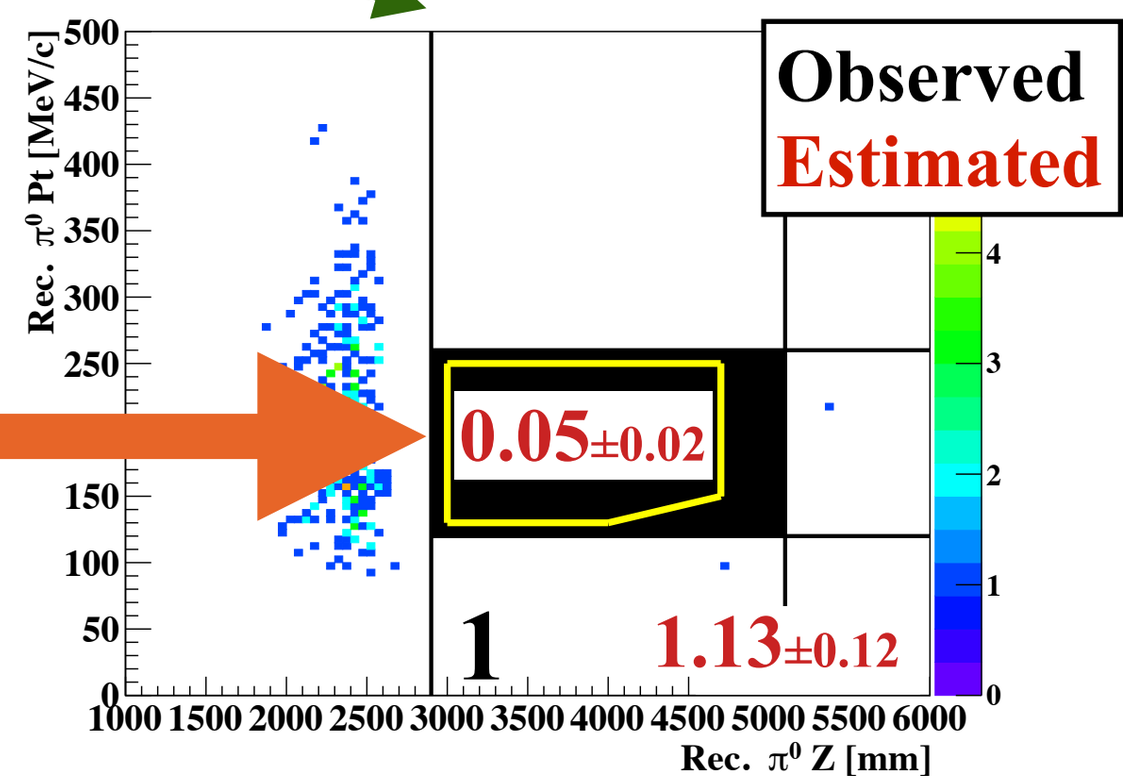
- low-mass beam pipe (**SUS→Al**)
  - ×2 reduction
- new scintillation counter
  - ×10 reduction

veto OFF



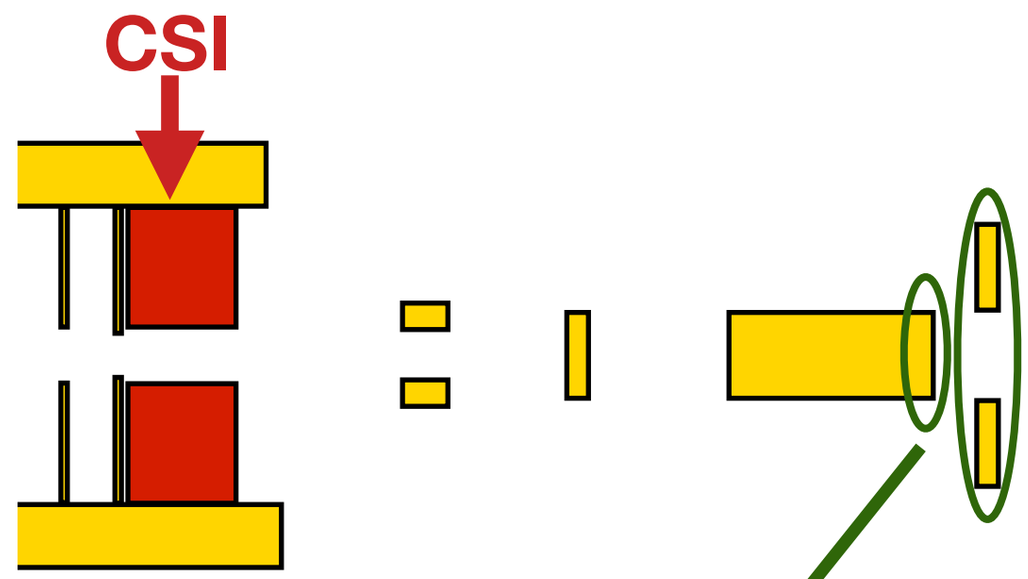
1/10

veto ON



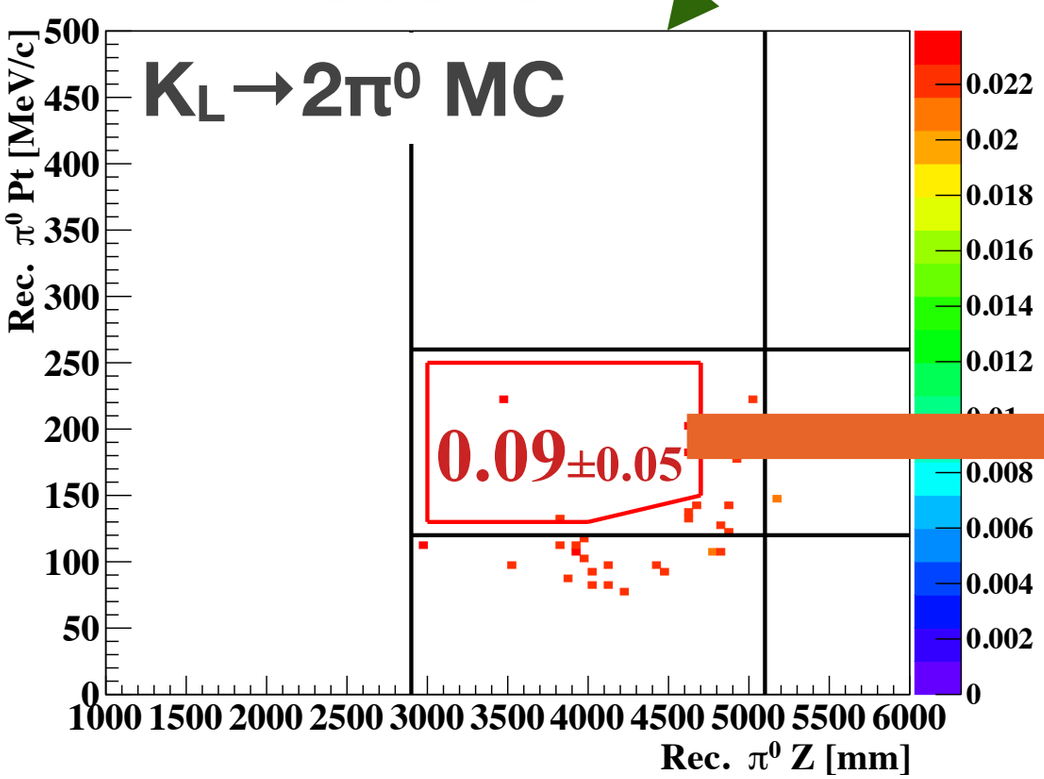
$$N_{K_L \rightarrow \pi^+\pi^-\pi^0\ BG} = 0.05 \pm 0.02$$

$K_L \rightarrow 2\pi^0$ background



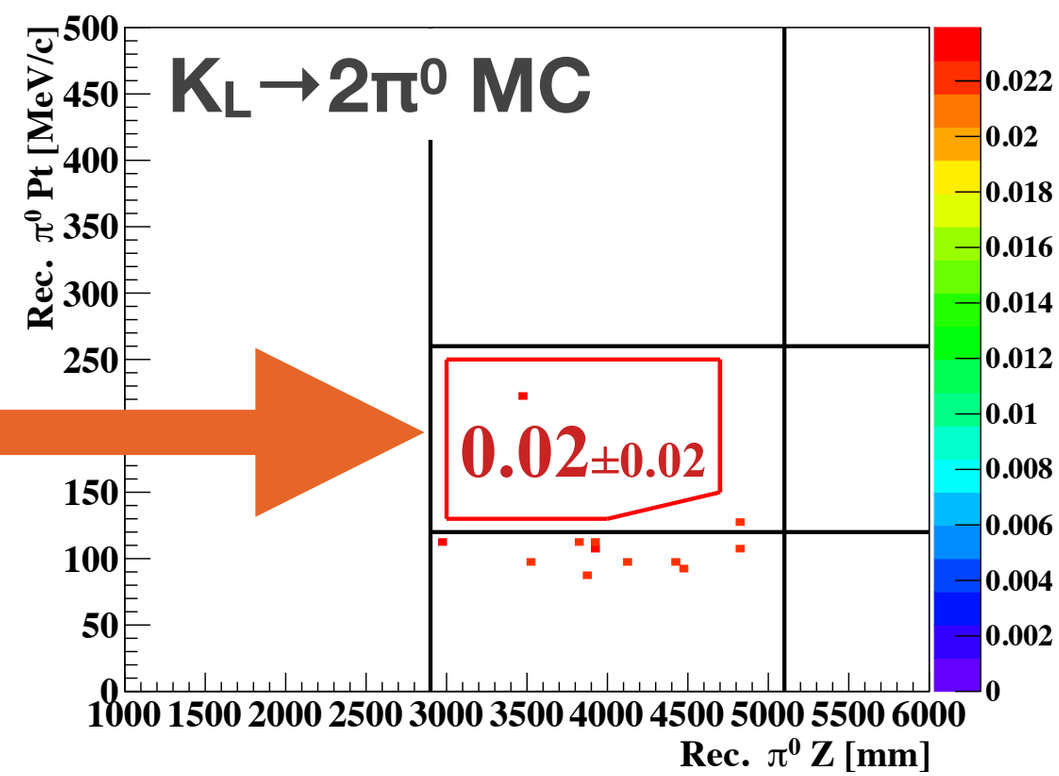
Additional photon counters
- lead/aerogel Cherenkov counters
- lead/acrylic Cherenkov counters

veto OFF



1/4

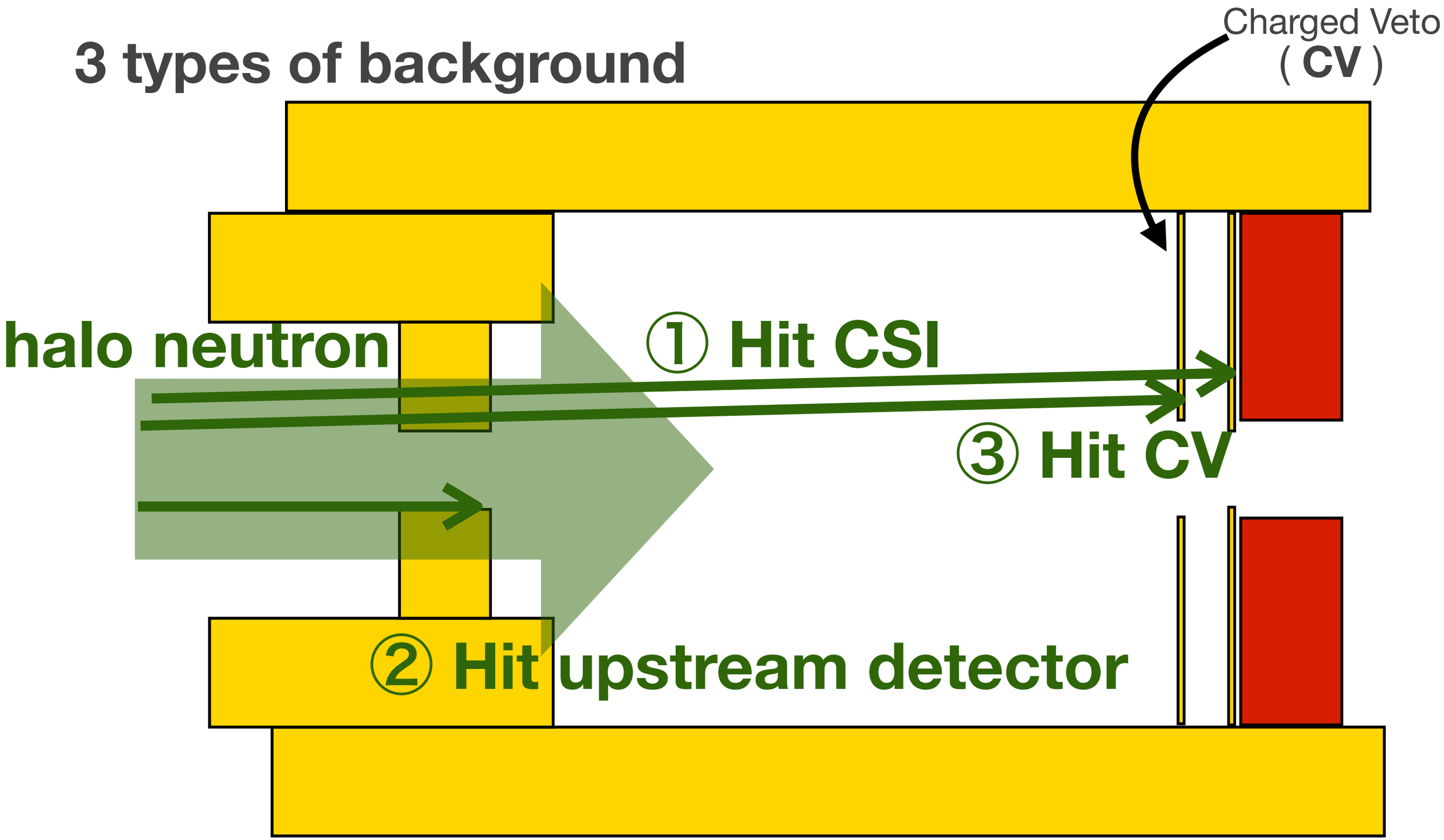
veto ON



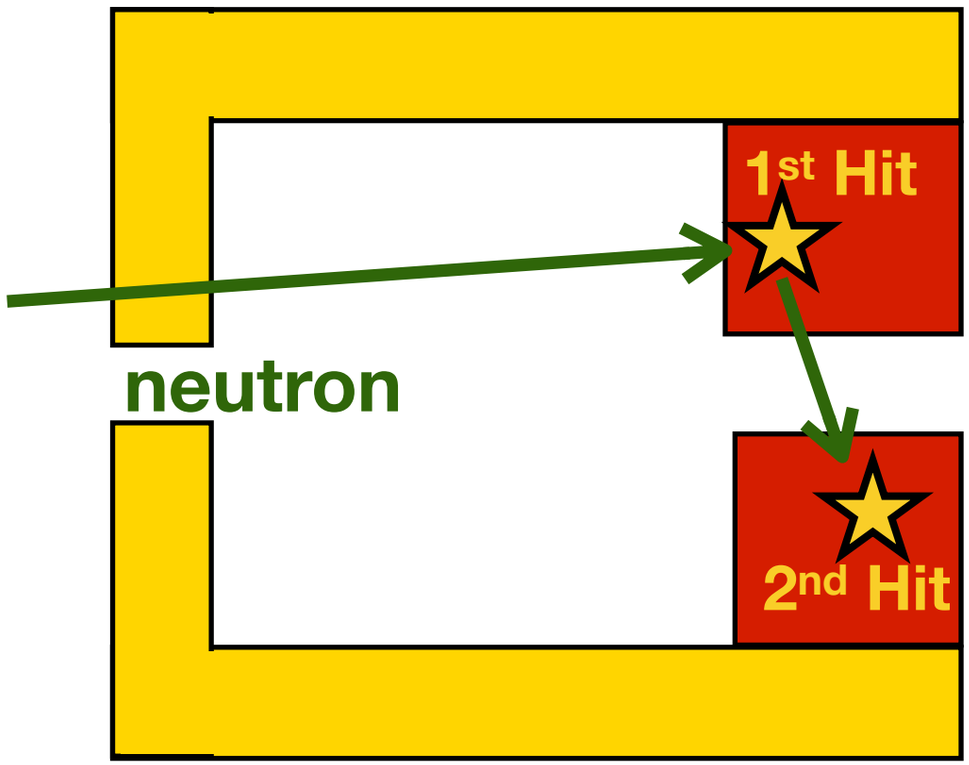
$$N_{K_L \rightarrow 2\pi^0\,BG} = 0.02 \pm 0.02$$

Neutron induced background

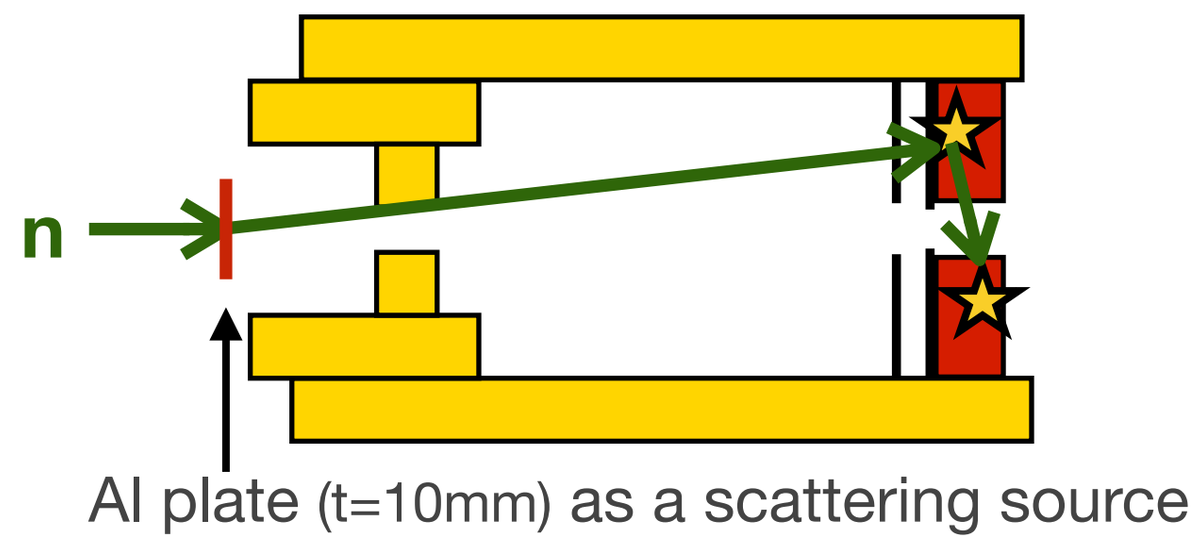
3 types of background



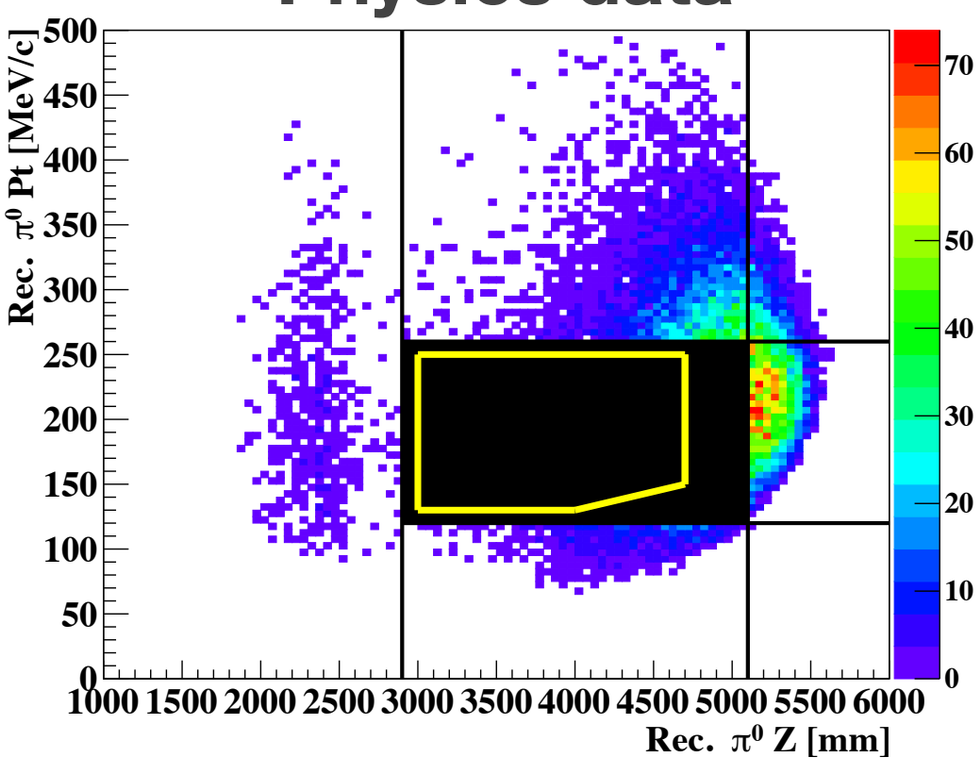
Hadron cluster background



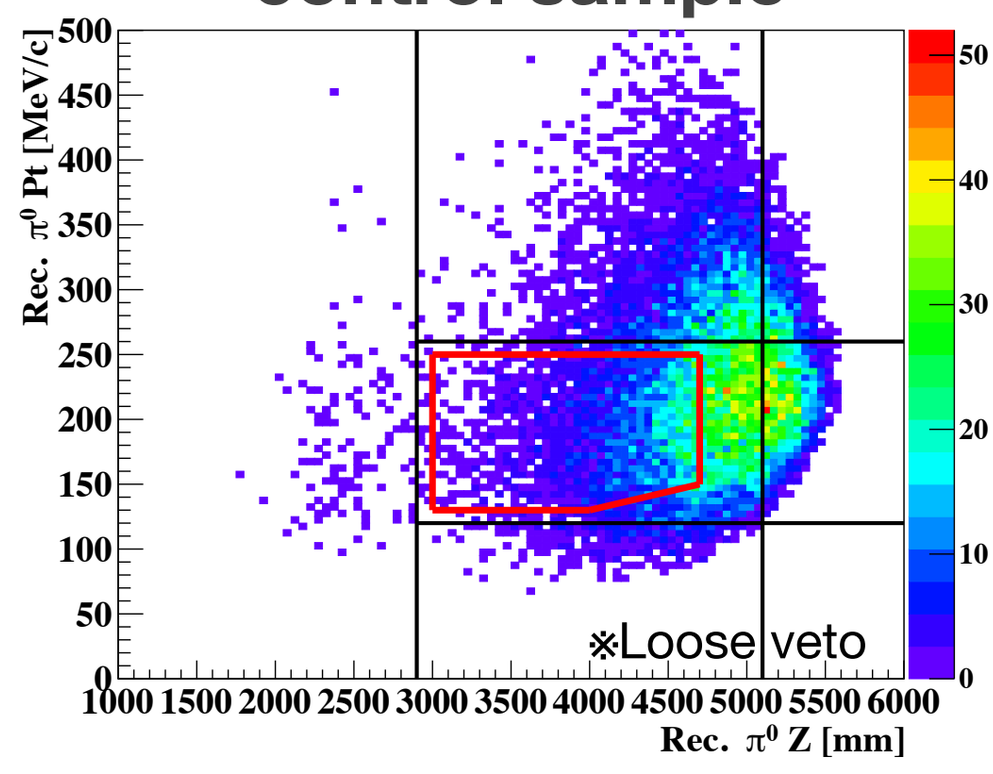
Special run to take control sample



Physics data



control sample



Reduction of the Hadron cluster BG

$K_L \to \pi^0 \nu\nu$ signal = 2 gammas on CSI + nothing

Hadron cluster BG = 2 clusters on CSI + nothing

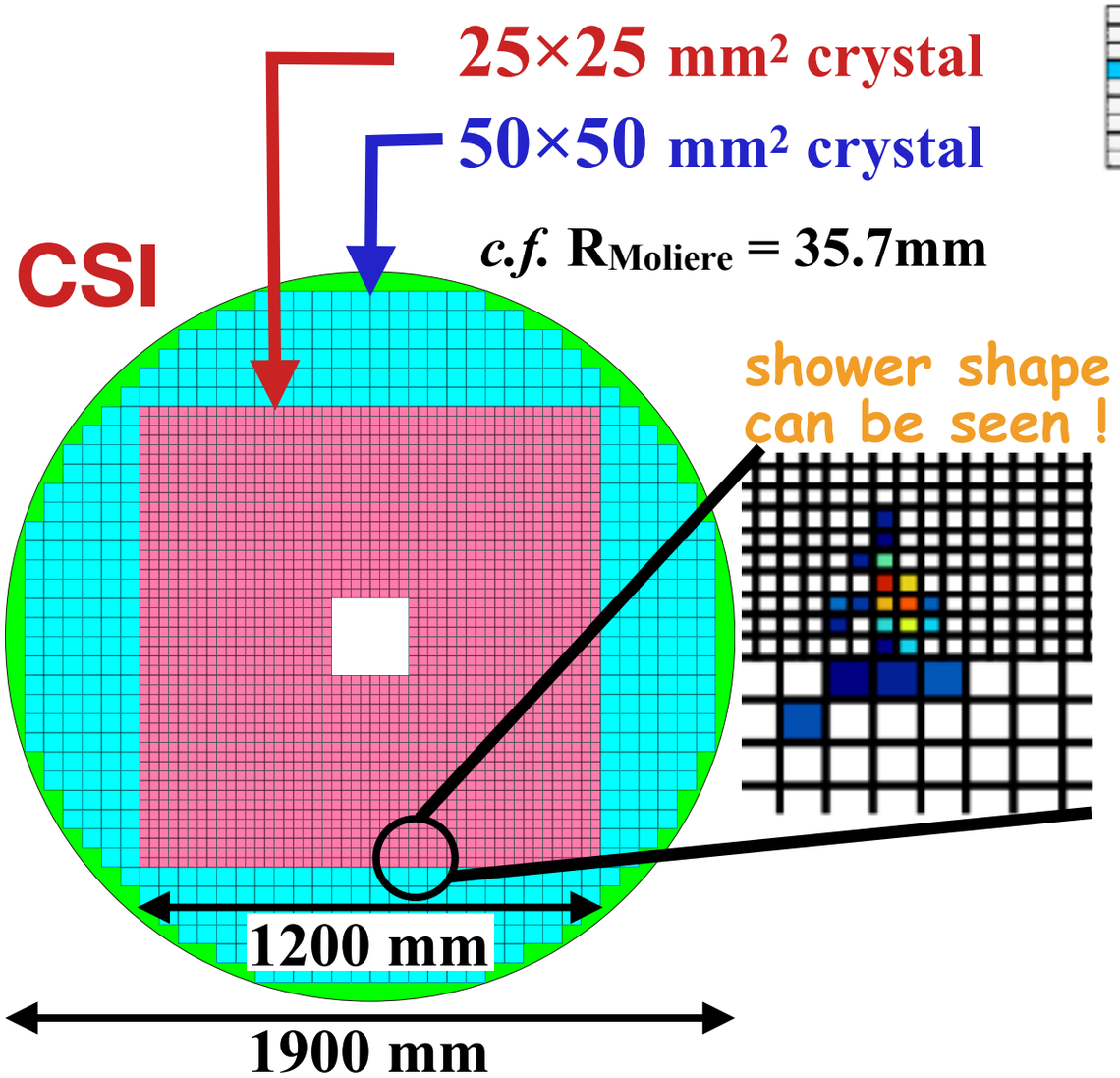
need n-γ discrimination w/ CSI information

- **EM-cluster (γ)**
- **Hadron-cluster (n)**

discrimination methods

- **Cluster Shape Discrimination**
- **Pulse Shape Discrimination**

n-γ discrimination with CSI
: Cluster Shape Discrimination



- **Shape χ2 method** (used in 2013 run)

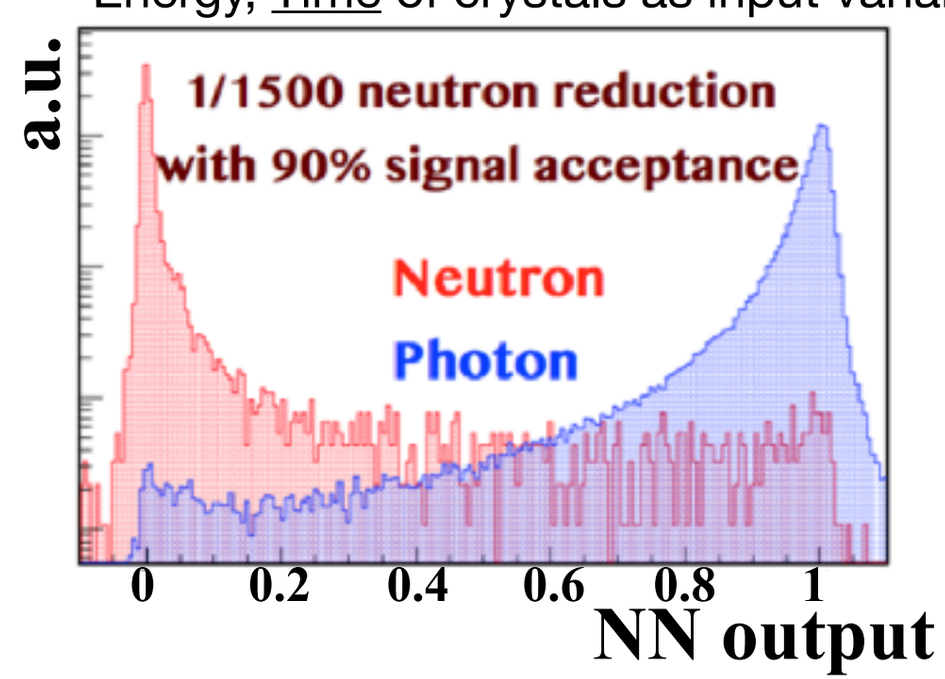
$$\chi^2 \equiv \frac{1}{N} \sum_{i}^{\text{in } 27\times 27 \text{ region}} \left(\frac{e_i/E_{inc} - \mu}{\sigma} \right)^2$$

if data is consistent with γ MC
➡ accept

➡1/300 BG reduction & 80% signal acceptance

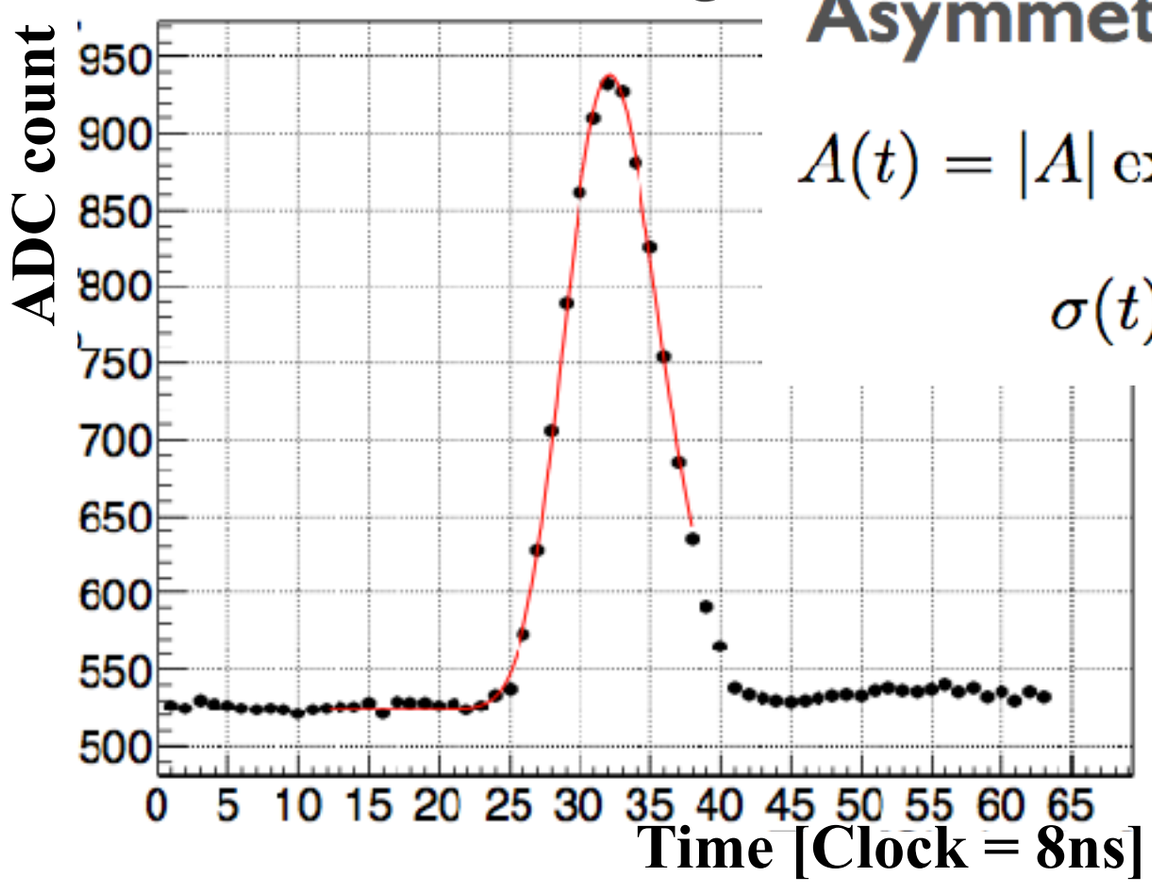
- **Shape neural net method**

Energy, Time of crystals as input variables



n-γ discrimination with CSI
: Pulse Shape Discrimination

waveform fitting



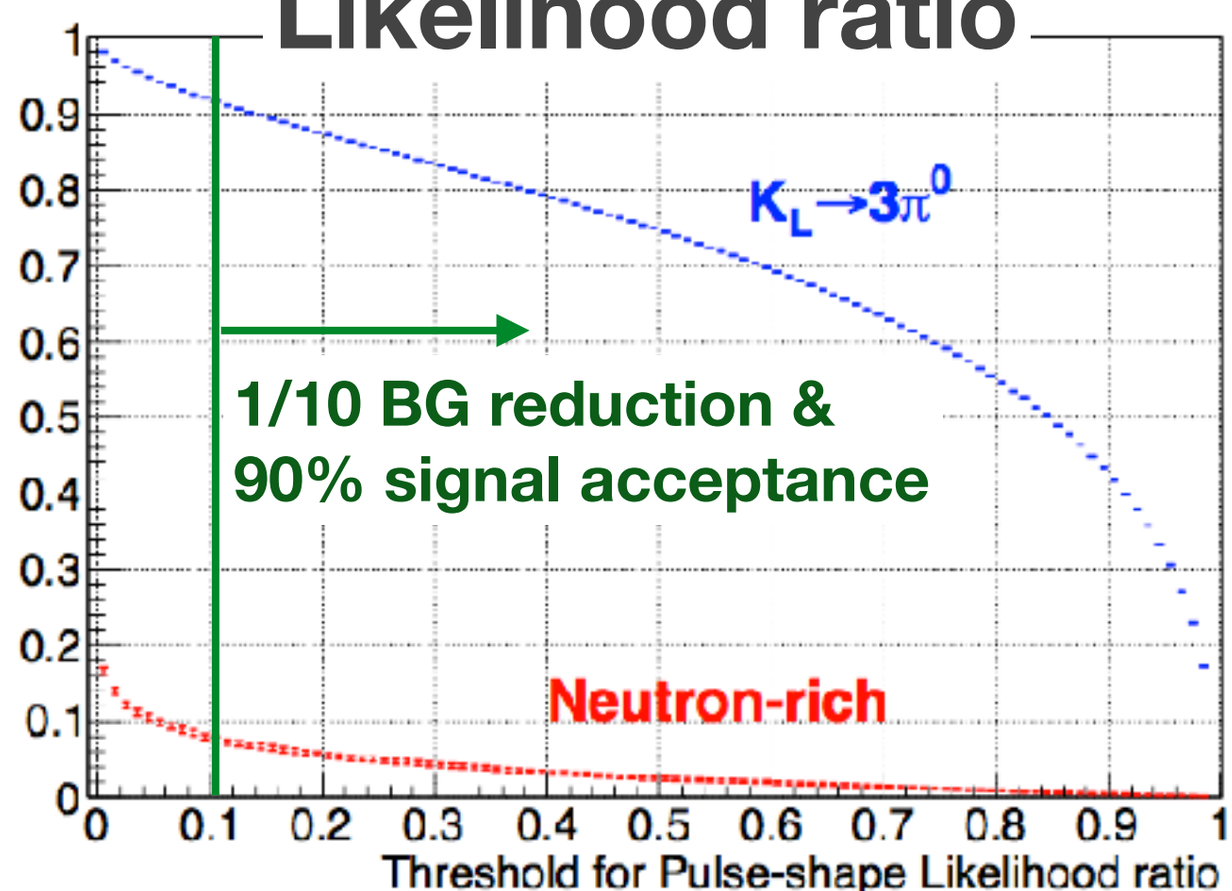
Asymmetric Gaussian:

$$A(t) = |A| \exp\left(-\frac{(t-t_0)^2}{2\sigma(t)^2}\right),$$

$$\sigma(t) = \sigma_0 + a(t-t_0)$$

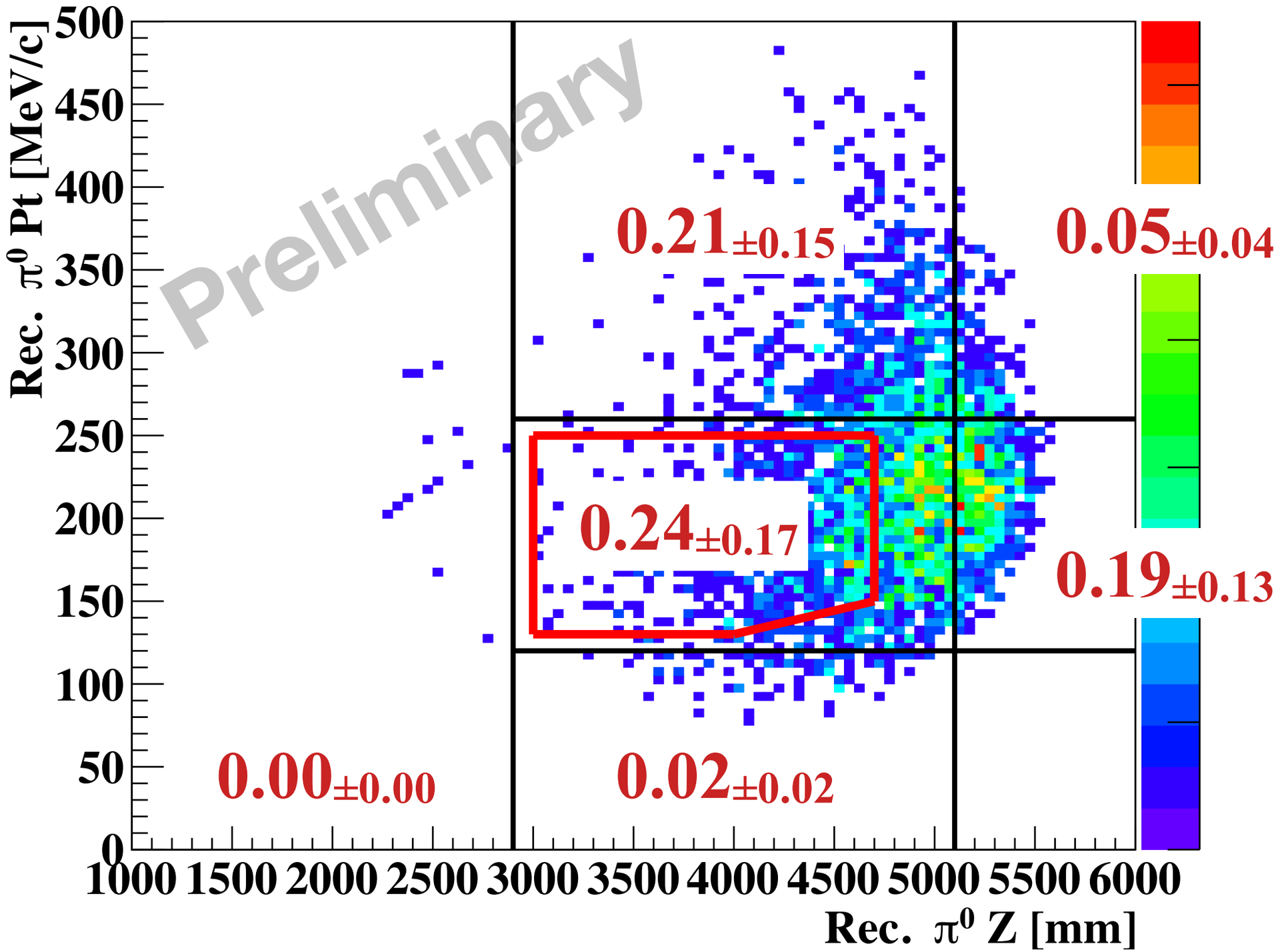
neutron pulse has a longer tail

Likelihood ratio



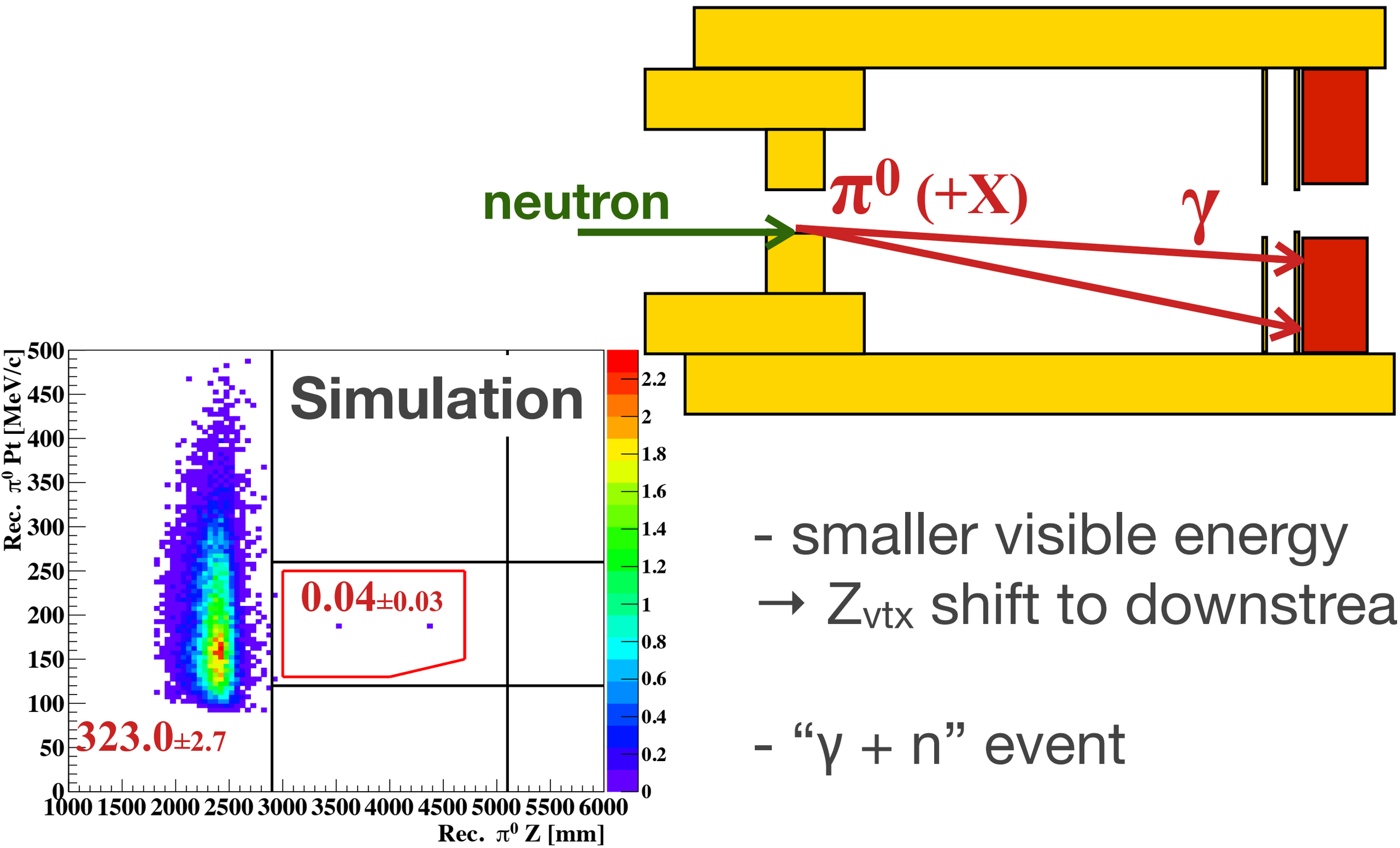
- waveform of individual crystals of CSI stored with 125MHz digitizer
- Template of neutron/gamma events to calculate likelihood

Hadron cluster background



$$N_{\text{Had. BG}} = 0.24 \pm 0.17$$

Upstream-π^0 background

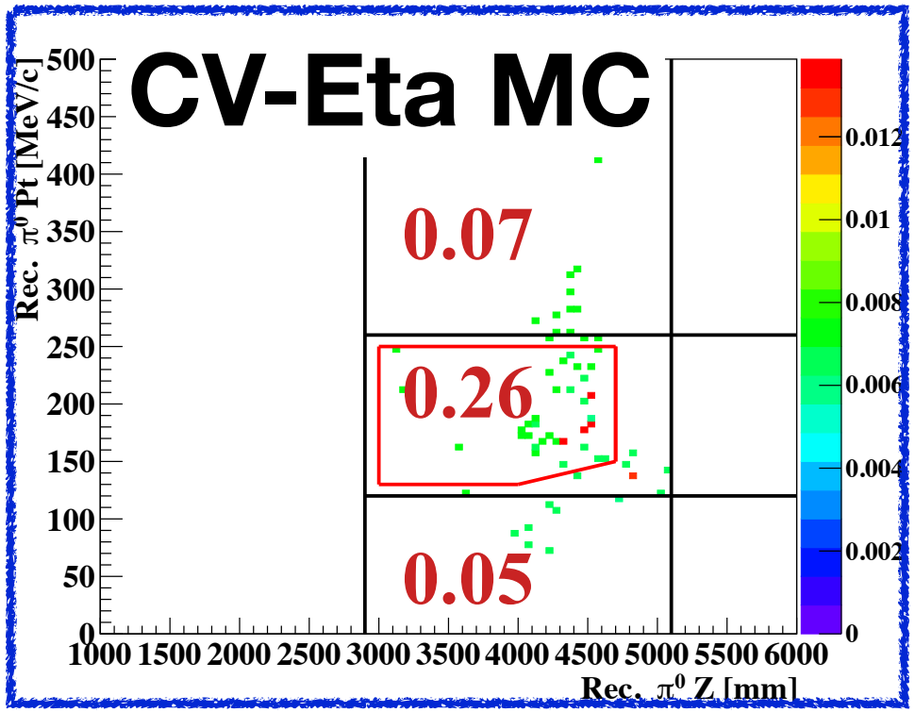


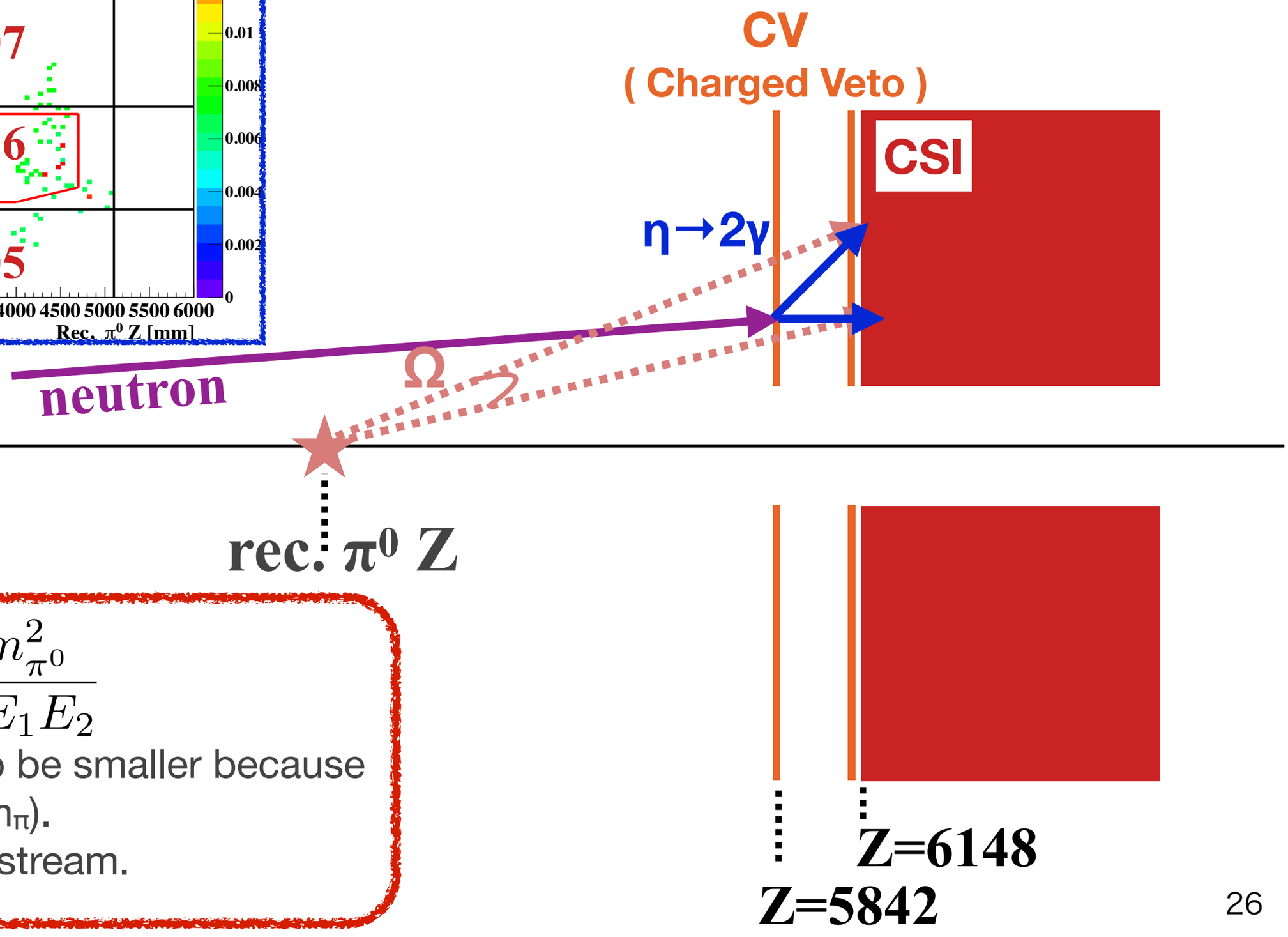
- smaller visible energy
→ Z_{vtx} shift to downstream

- "γ + n" event

$$N_{\text{Upstream-}\pi^0\text{ BG}} = 0.04 \pm 0.03$$

CV-Eta background : Mechanism





$$\cos\Omega = 1 - \frac{m_{\pi^0}^2}{2E_1E_2}$$

Ω is calculated to be smaller because $m_\eta > m_\pi$ ($m_\eta \sim 4m_\pi$).

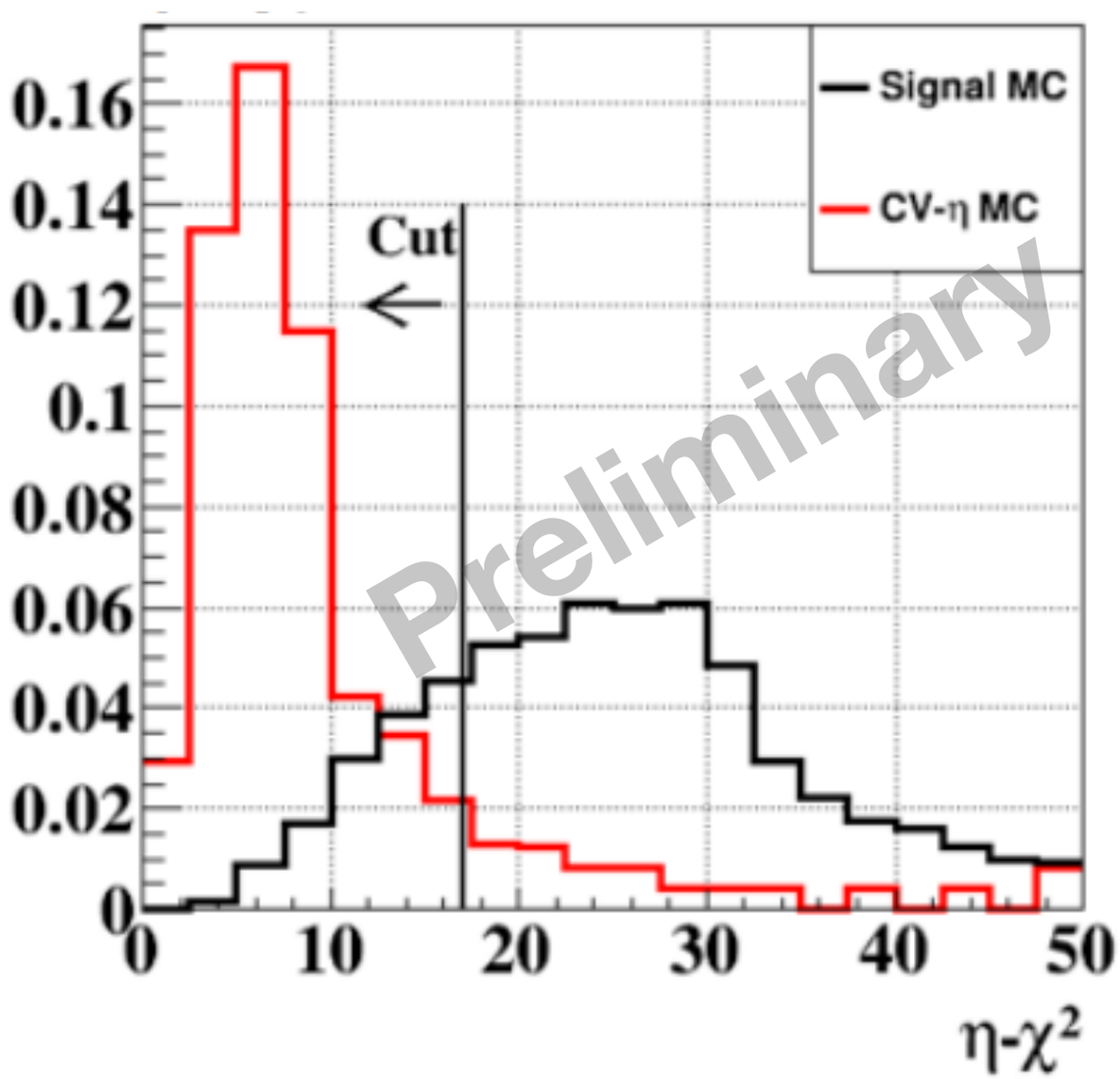
➡ rec. Z goes upstream.

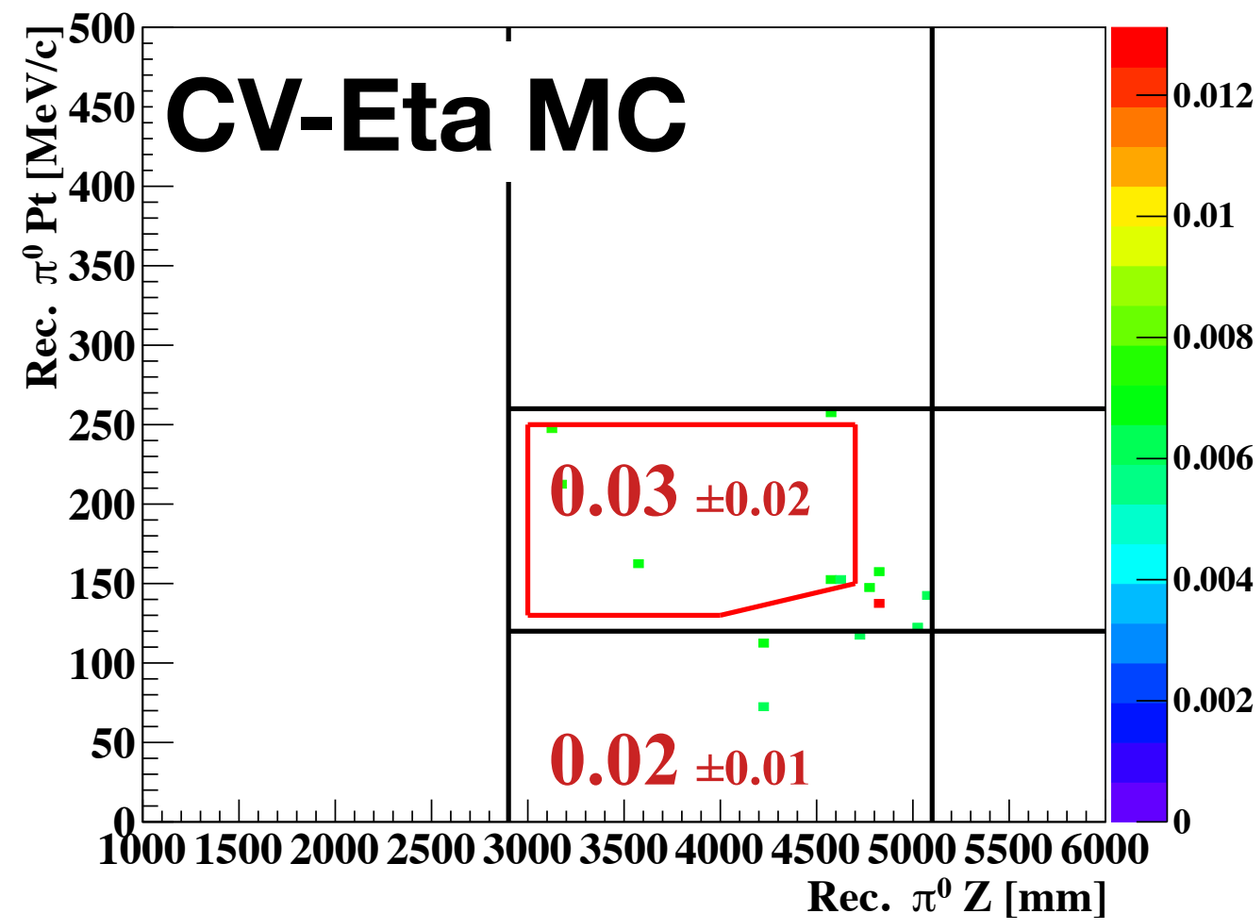
New Cut for the CV-Eta BG

η-χ2 cut :

- if the cluster shapes are consistent with the assumption that they are derived from η→2γ decay at CV, the event is rejected
  - good consistency = small χ2 value

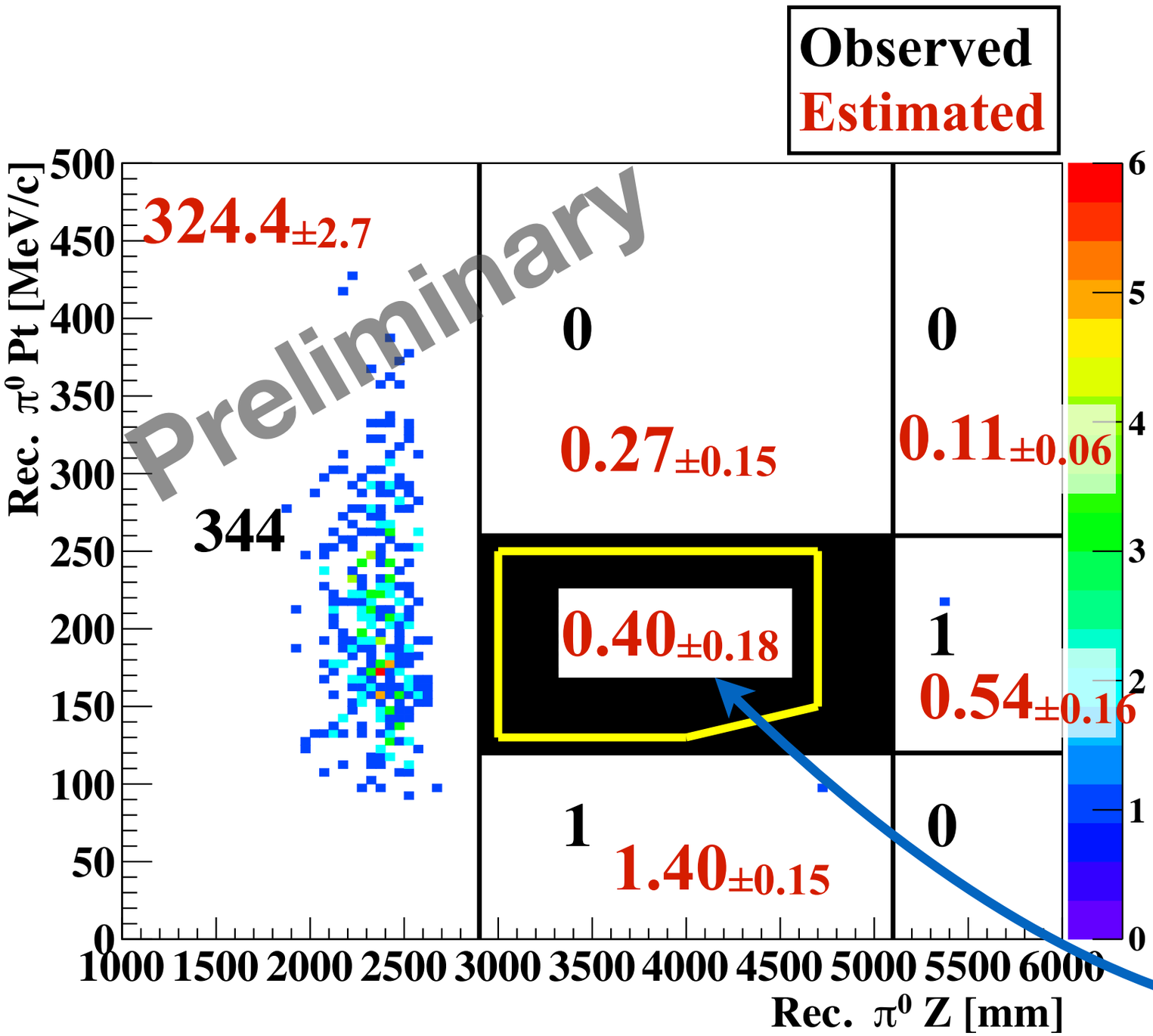
η-χ2 distribution





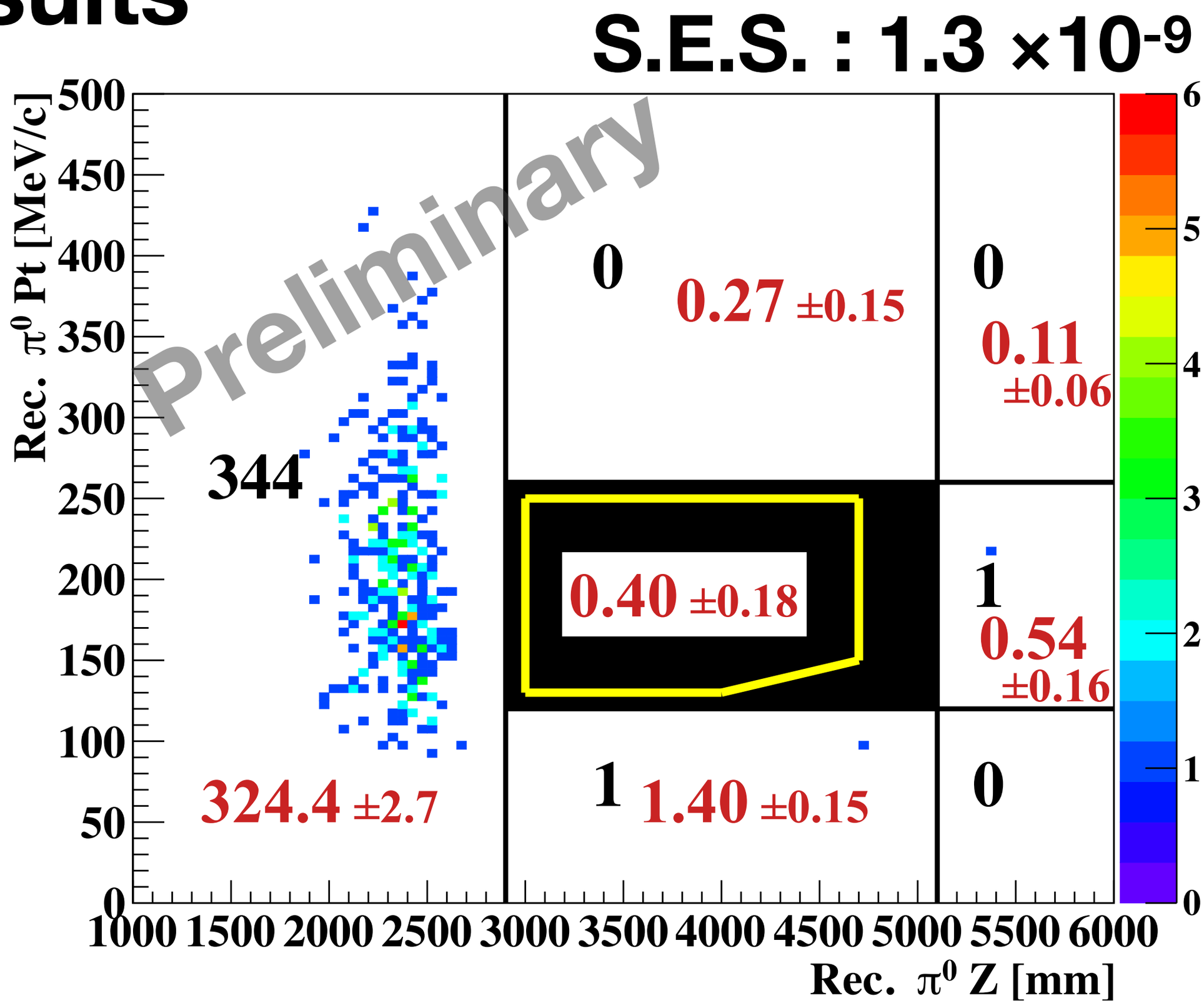
$$N_{CV\text{-}\eta\ BG} = 0.03 \pm 0.02$$

Background summary



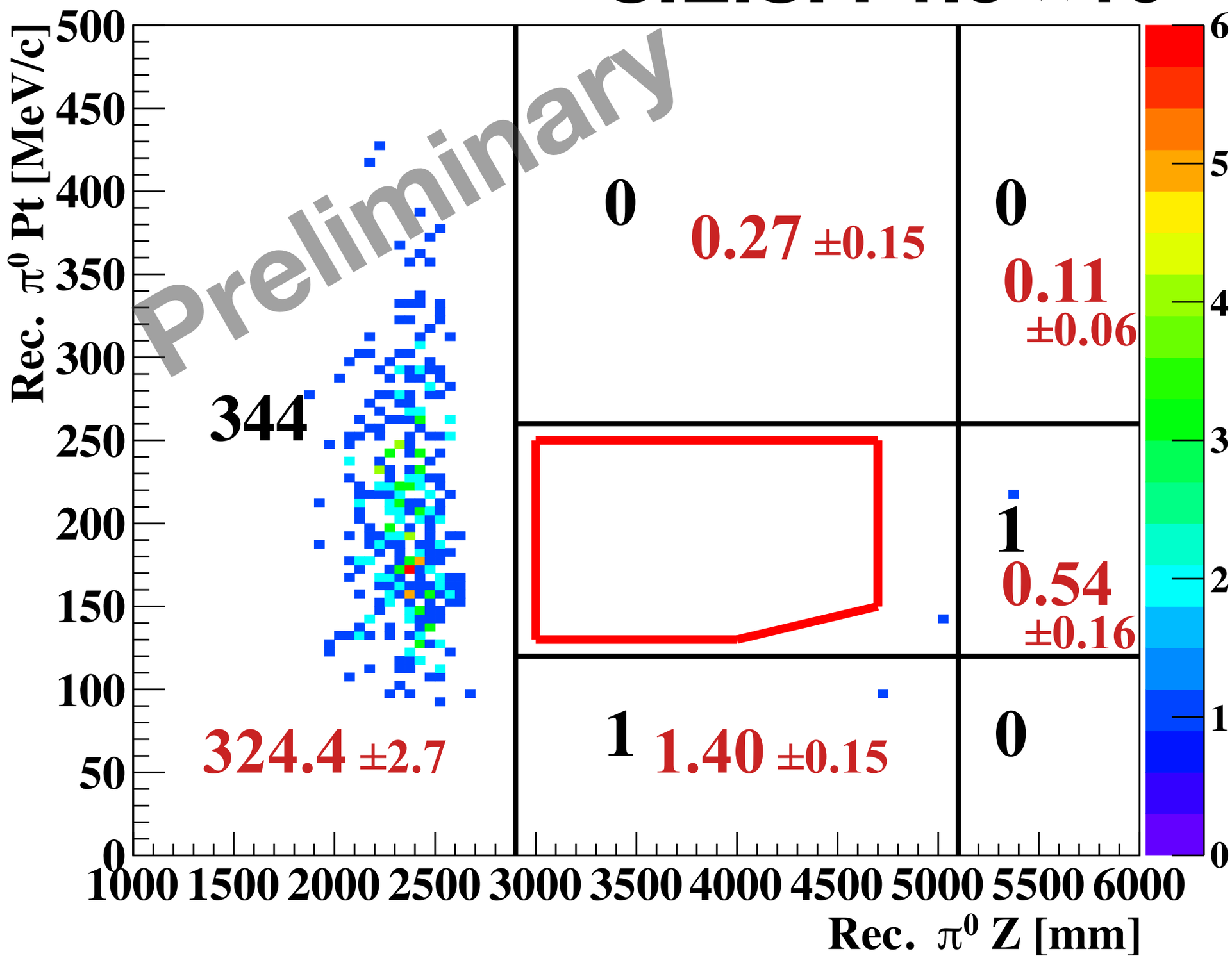
BG source	# of BG
$K_L \to 2\pi^0$	0.02 ± 0.02
$K_L \to \pi^+\pi^-\pi^0$	0.05 ± 0.02
Hadron Cluster	0.24 ± 0.17
Upstream-π^0	0.04 ± 0.03
CV-η	0.03 ± 0.02
others	0.02 ± 0.02
Total	0.40 ± 0.18

Results


S.E.S. : 1.3 ×10-9
Preliminary
Rec. π0 Pt [MeV/c]
Rec. π0 Z [mm]
344
324.4 ±2.7
0
0.27 ±0.15
0
0.11 ±0.06
0.40 ±0.18
1
0.54 ±0.16
1
1.40 ±0.15
0

Results

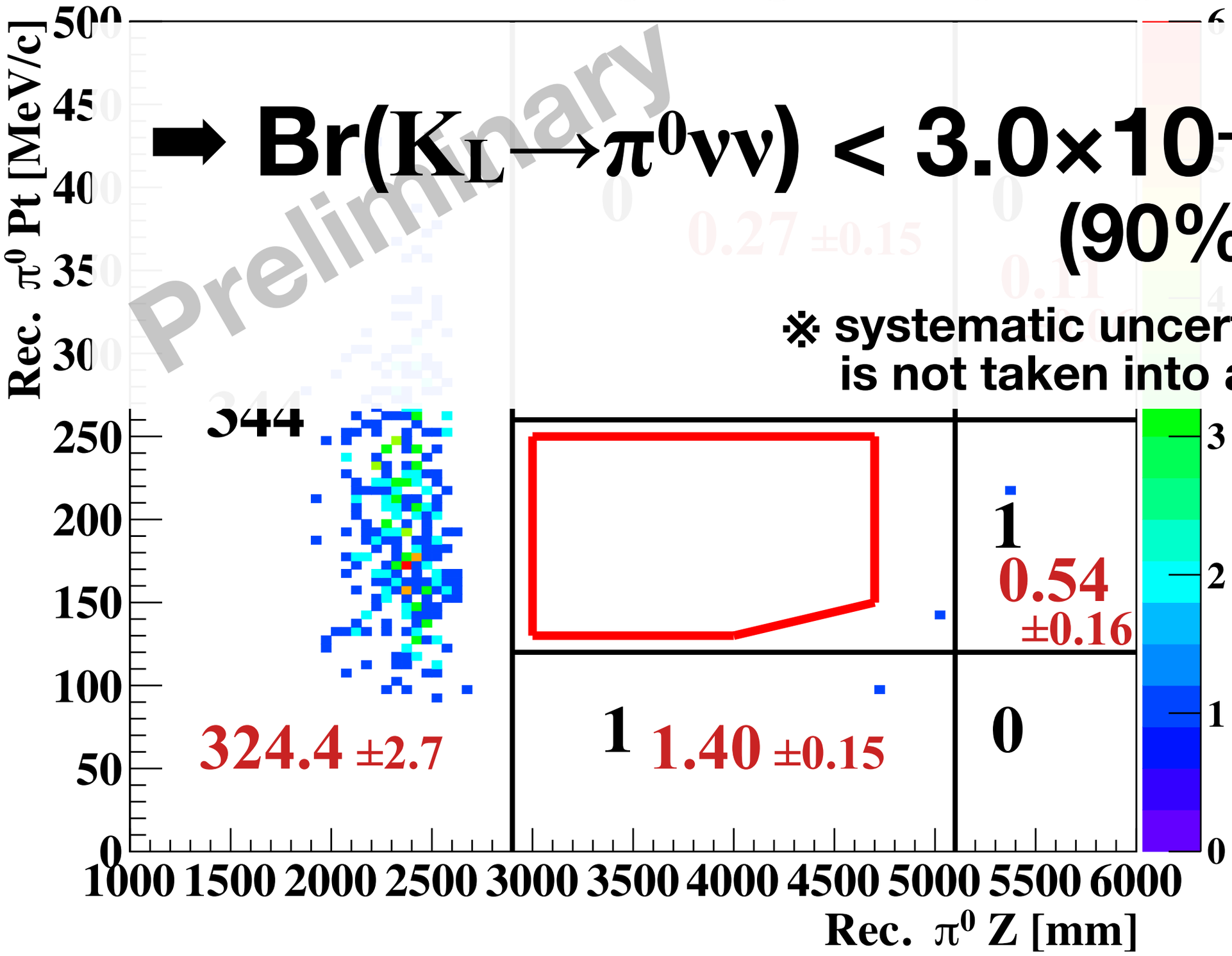
S.E.S. : 1.3 ×10^{-9}



No candidate event observed

Results

S.E.S. : 1.3 ×10^{-9}



➡ Br($K_L \to \pi^0 \nu\nu$) < 3.0×10^{-9}

(90% C.L.)

※ systematic uncertainty is not taken into account

No candidate event observed

Results

$$Br(K_L \rightarrow \pi^0 \nu\nu) < 3.0 \times 10^{-9}$$

(90% C.L.)

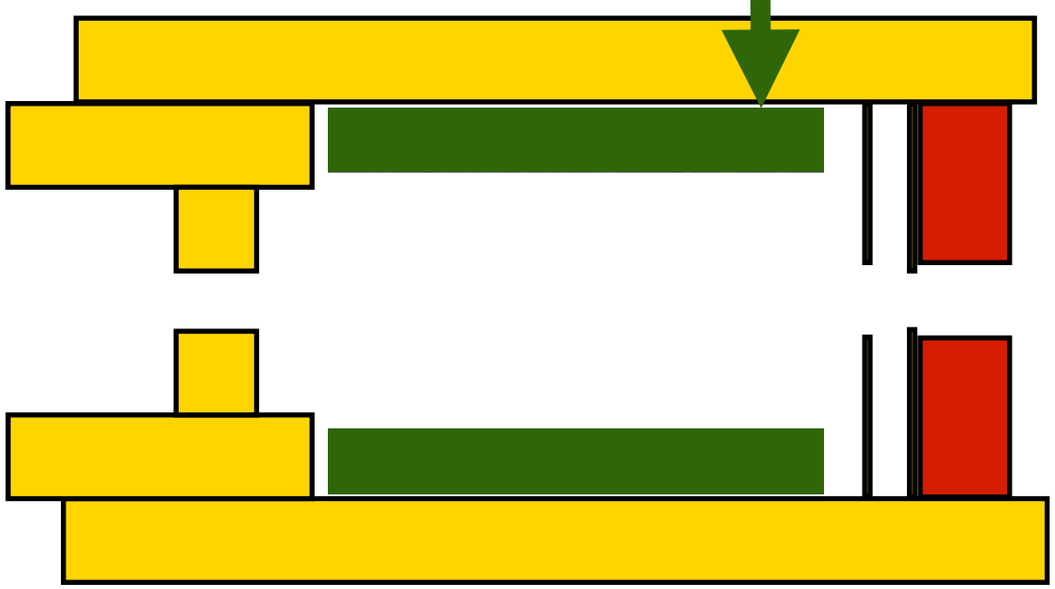
Preliminary

※ systematic uncertainty is not taken into account

upper limit by E391a : 2.6×10^{-8} (90% C.L.)

~ one order of magnitude improvement !

Prospects : 2016-2018 run



additional photon counter
($13.5X_0$+$5X_0$) ➡ $K_L \rightarrow 2\pi^0$ BG ↓1/3

- **additional ×1.5 physics data**
  ➡ SES ~ 5×10^{-10} (combined with 2015 run data)

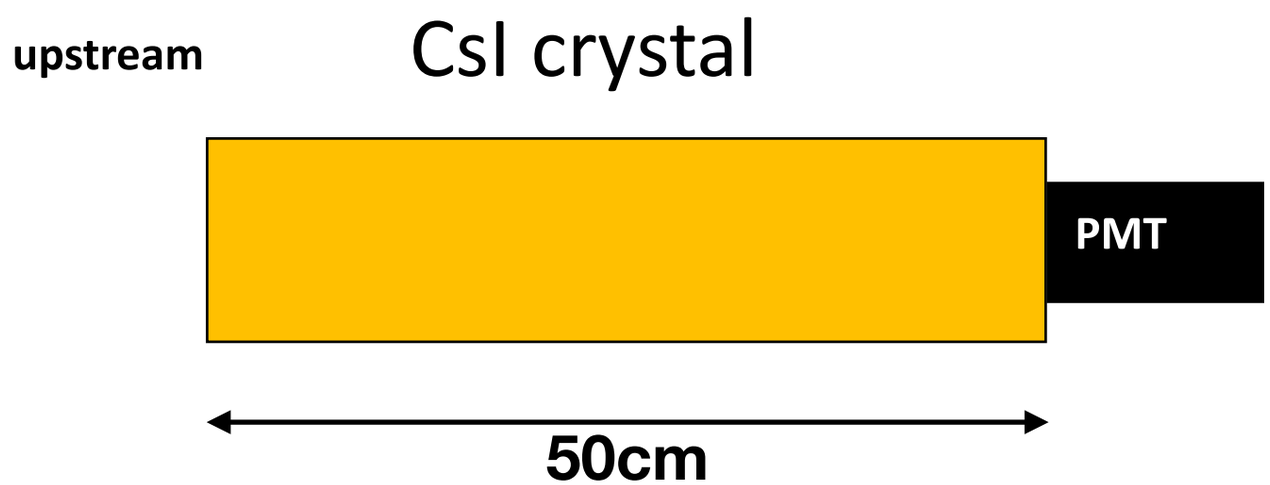
- **×10 control samples for the hadron cluster BG**
  ➡ improvement of the n-γ discrimination

Prospects : Detector upgrades

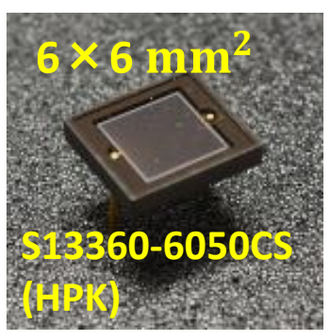
during THIS summer shutdown

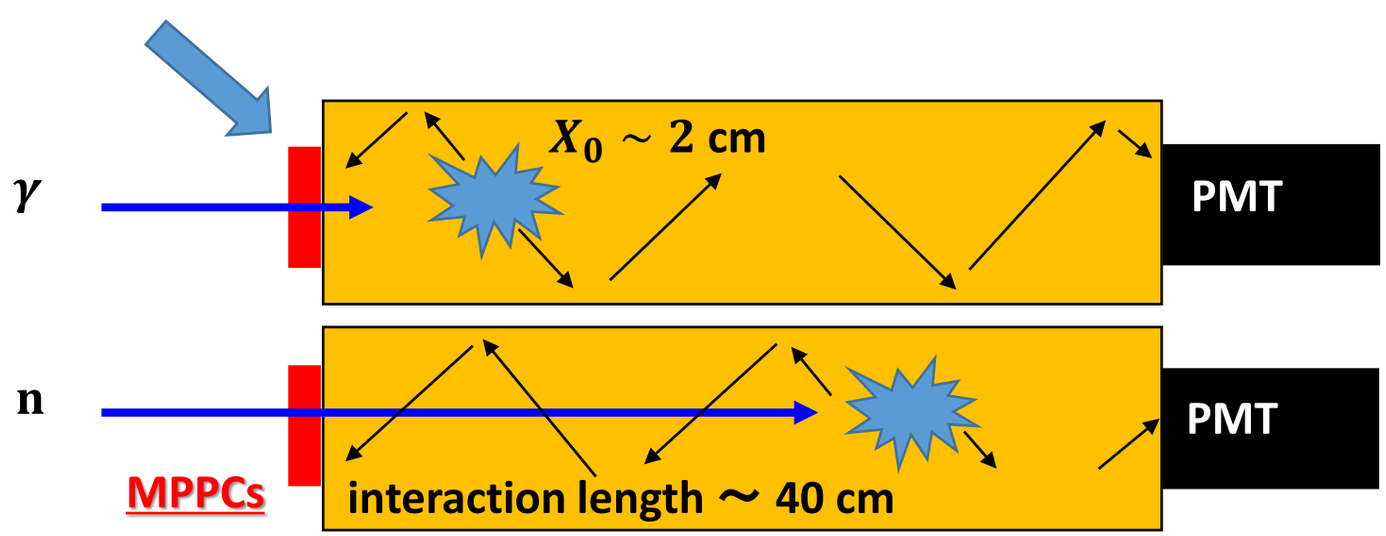
CSI upgrade to reduce the hadron cluster BG

Now



Attach MPPCs in this summer 2018





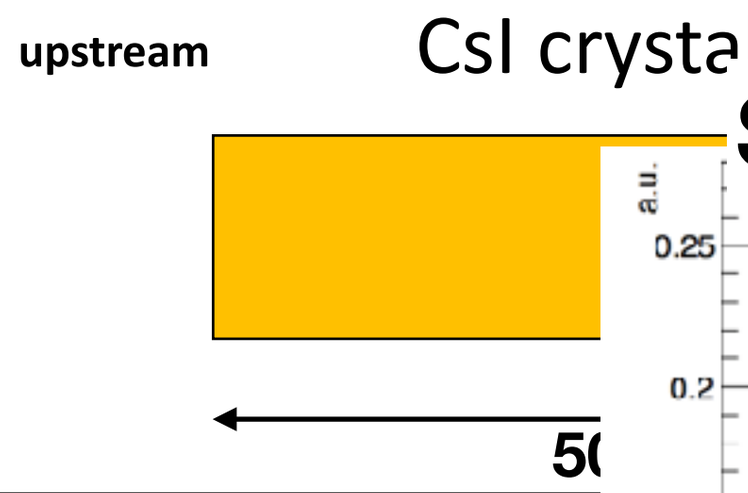
locate interaction Z position

Prospects : Detector upgrades

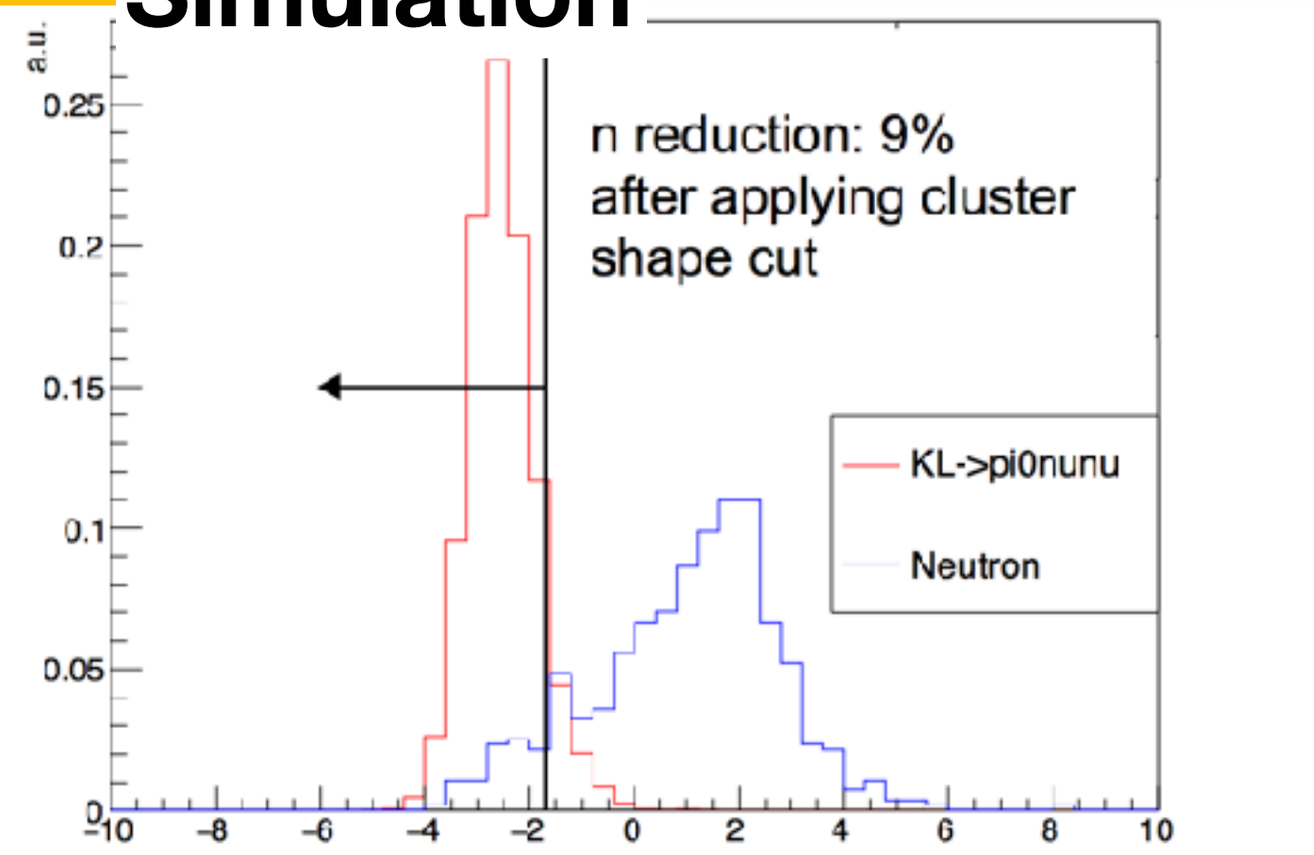
during THIS summer shutdown

CSI upgrade to reduce the hadron cluster BG

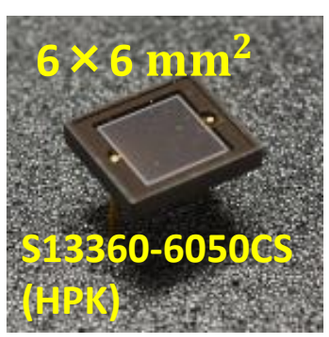
Now

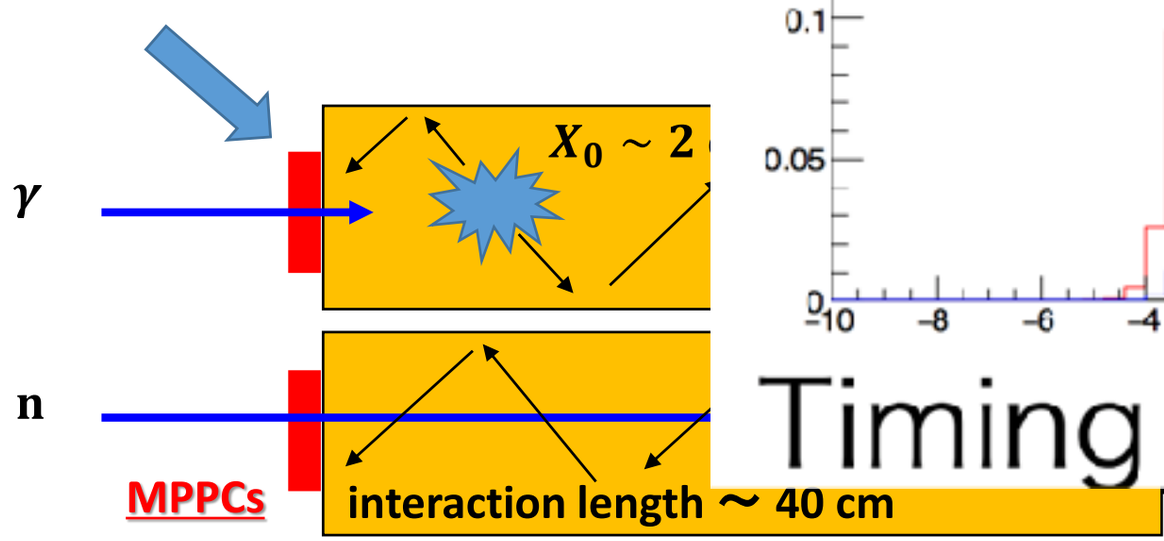


Simulation



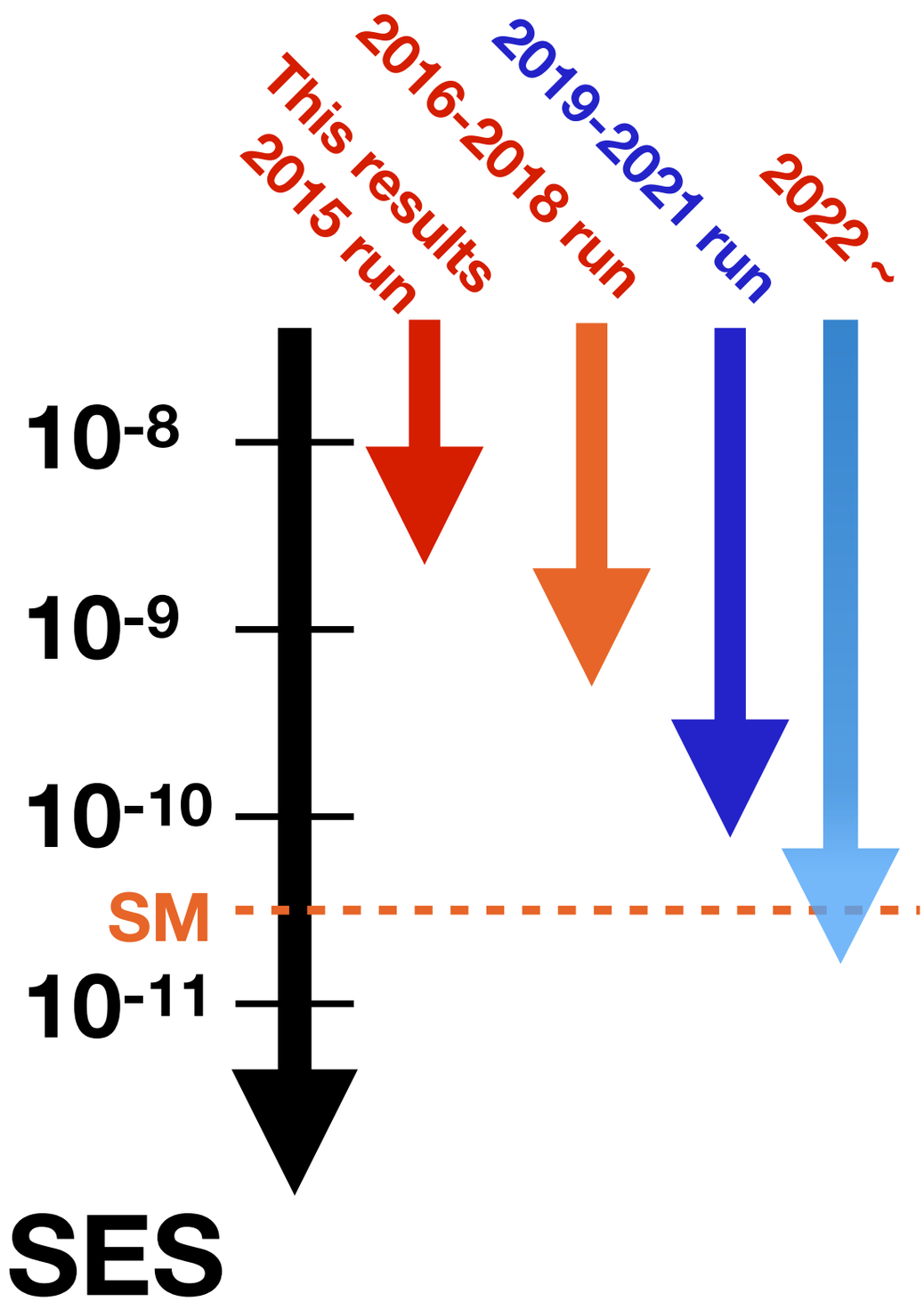
Attach MPPCs in this summer 2018





locate interaction Z position ➡ N_{BG} ~ 1/10

Prospects : Future run



- expect O(10^{-11}) SES with the next 3-year data
  - beam power 50→90kW and more
- aim to SM sensitivity
  - better beam condition by the power supply upgrade of the accelerator

Summary

- $K_L \to \pi^0 \nu\nu$ search at KOTO
- No candidate event in the 2015 run data
  - $Br(K_L \to \pi^0 \nu\nu) < 3.0 \times 10^{-9}$ @90% C.L. (preliminary)
    - one order of magnitude improvement