New result from the J-PARC KOTO experiment

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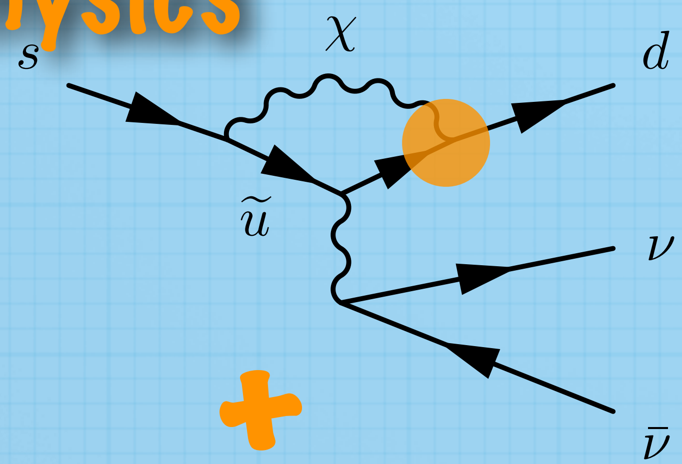
2021-02-11
DESY Seminar (online)

v1.1

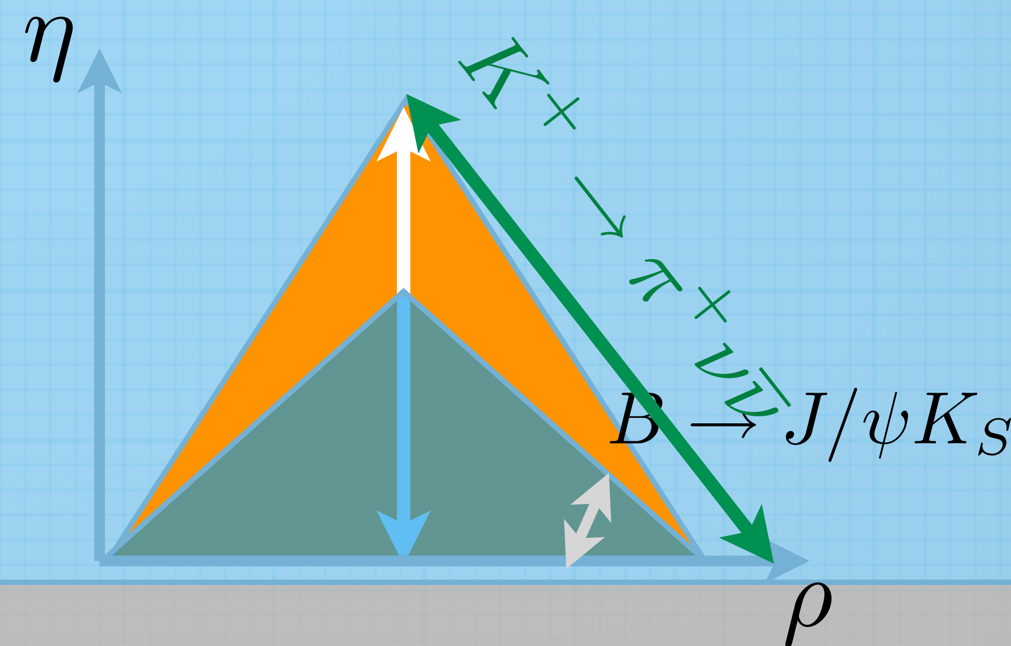
CP− CP+

Probe: $K_L \longrightarrow \pi^0 \nu \overline{\nu}$

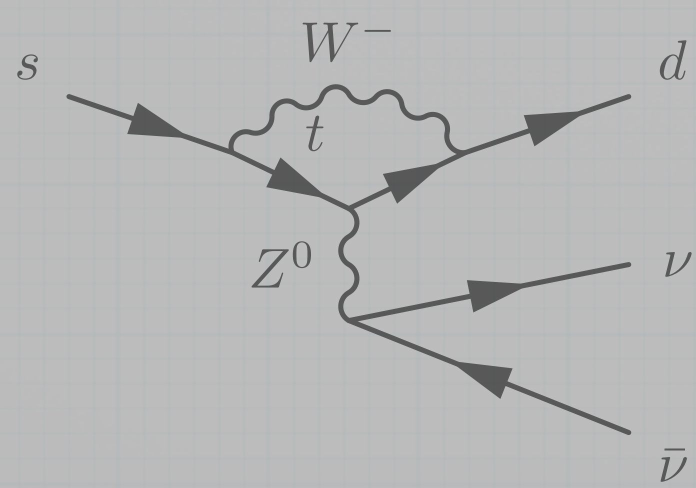
New Physics



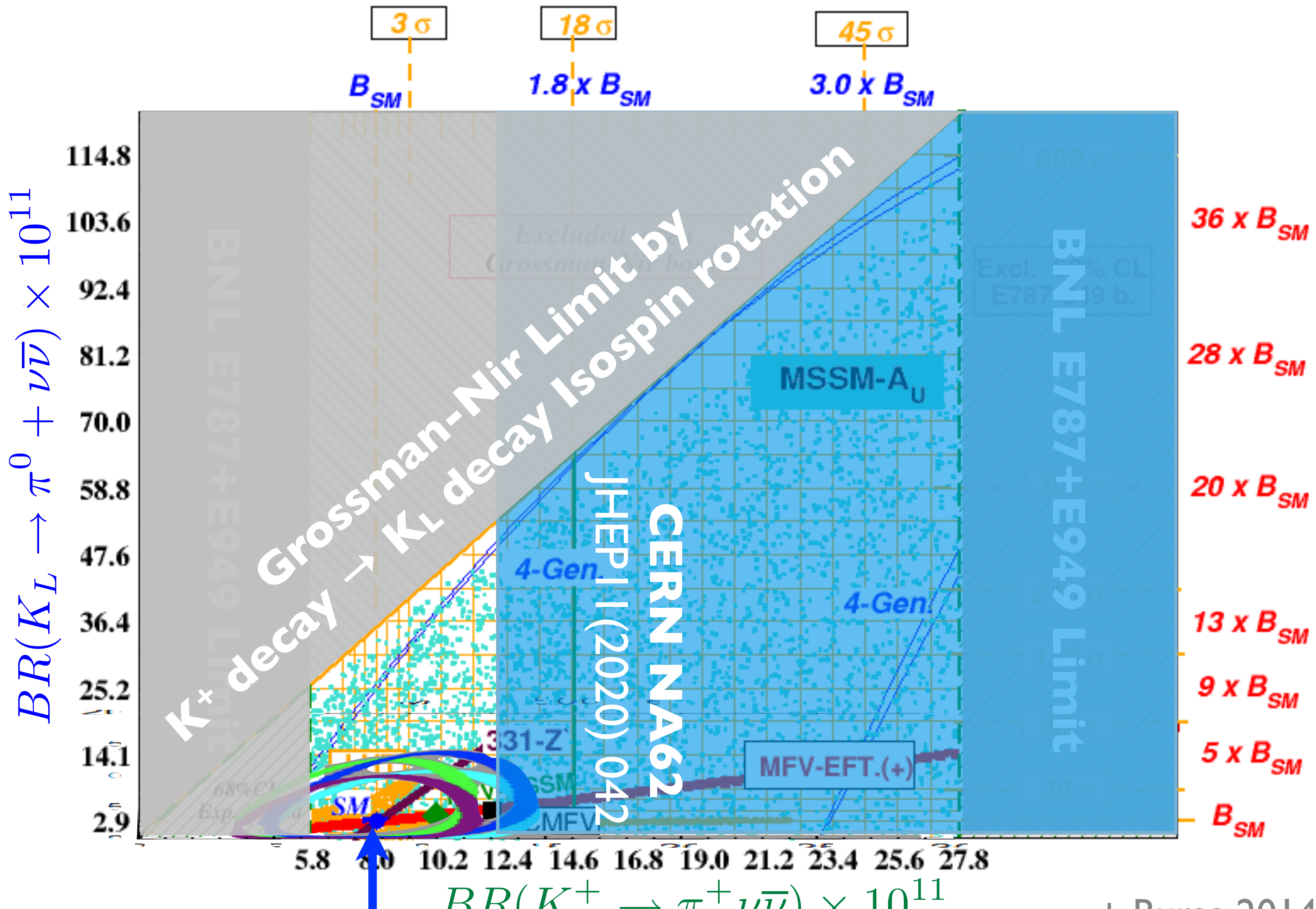
+



Standard Model



- SM background is
  - small (BR~3E-11)
  - well known (~2% theo. error)

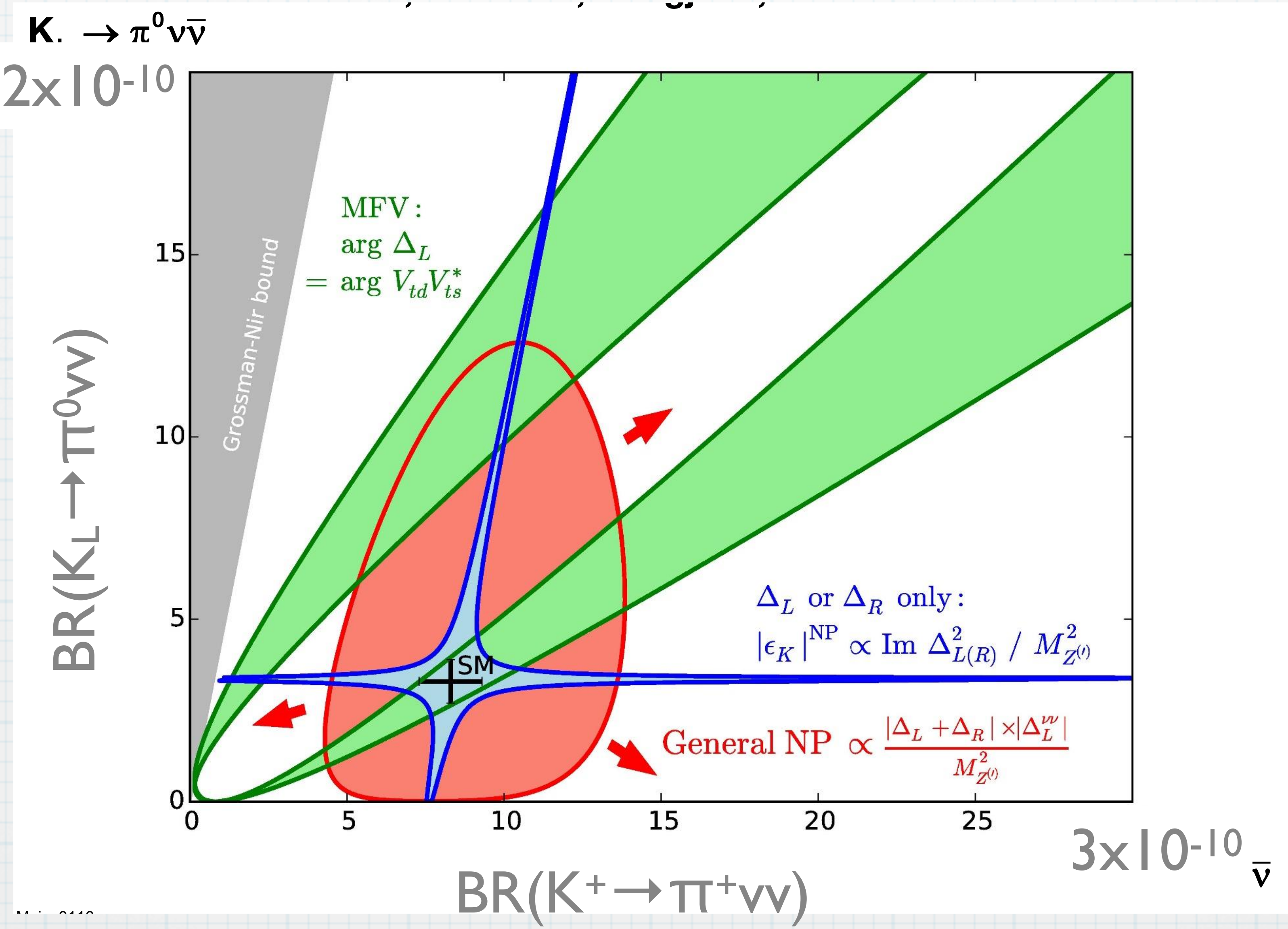


Standard Model

+ Buras 2014

http://www.lnf.infn.it/wg/vus/content/Krare.html

New Physics

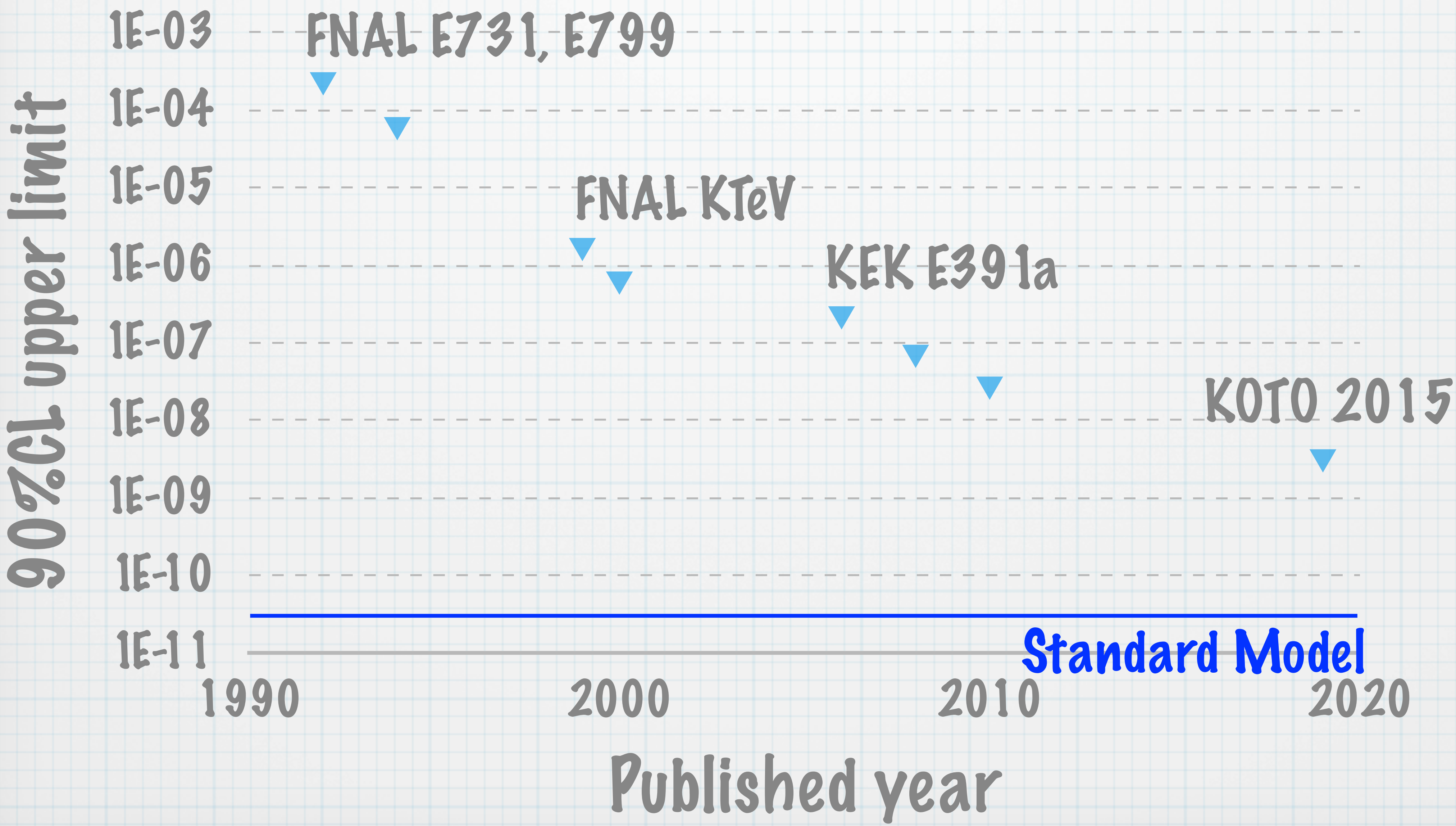


Buras et al, 1507.08672

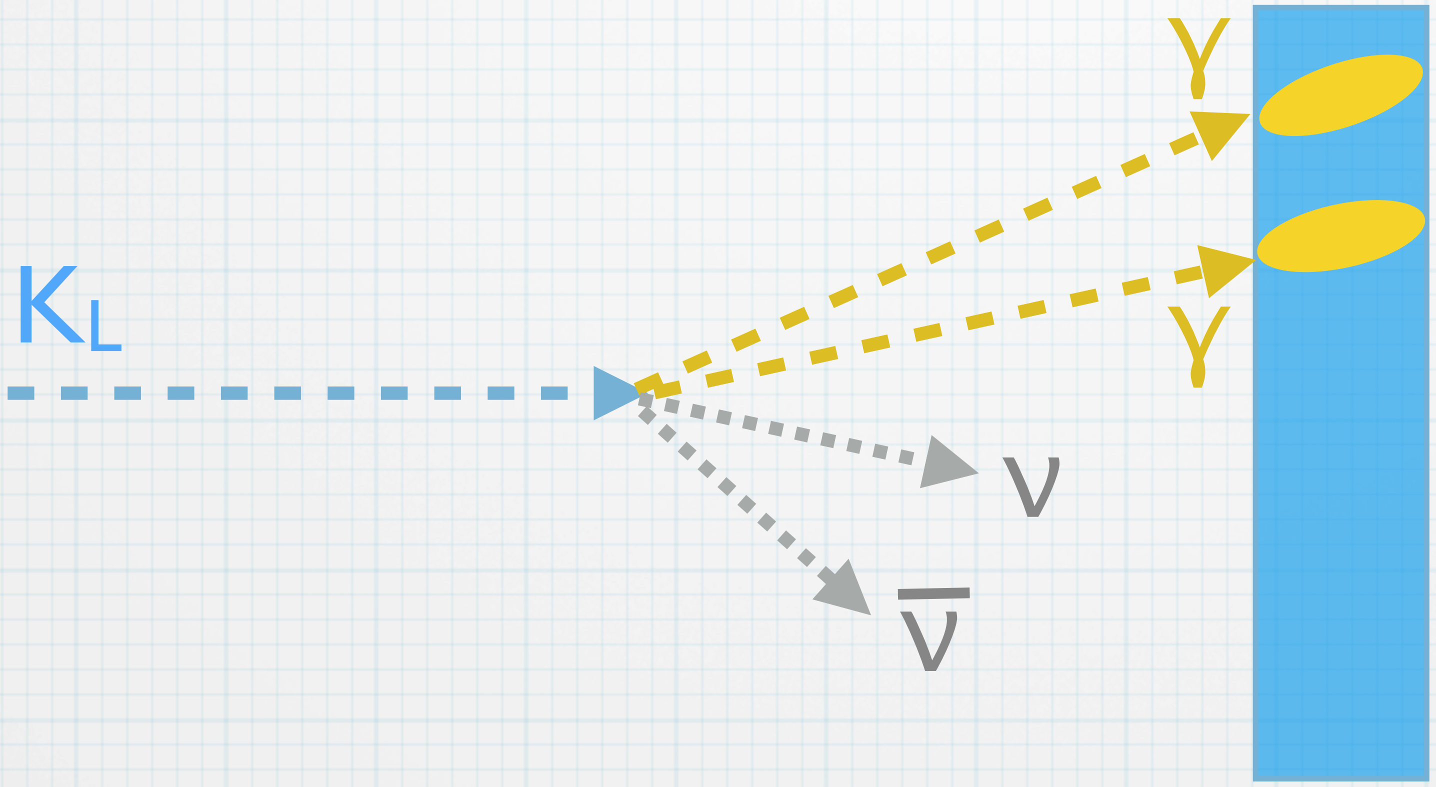
$K_L \longrightarrow \pi^0 \nu \overline{\nu}$

- Theoretically clean
- Nightmare for experimentalists
  - neutral K_L ➔ 2ϒ (from π^0)+ νν

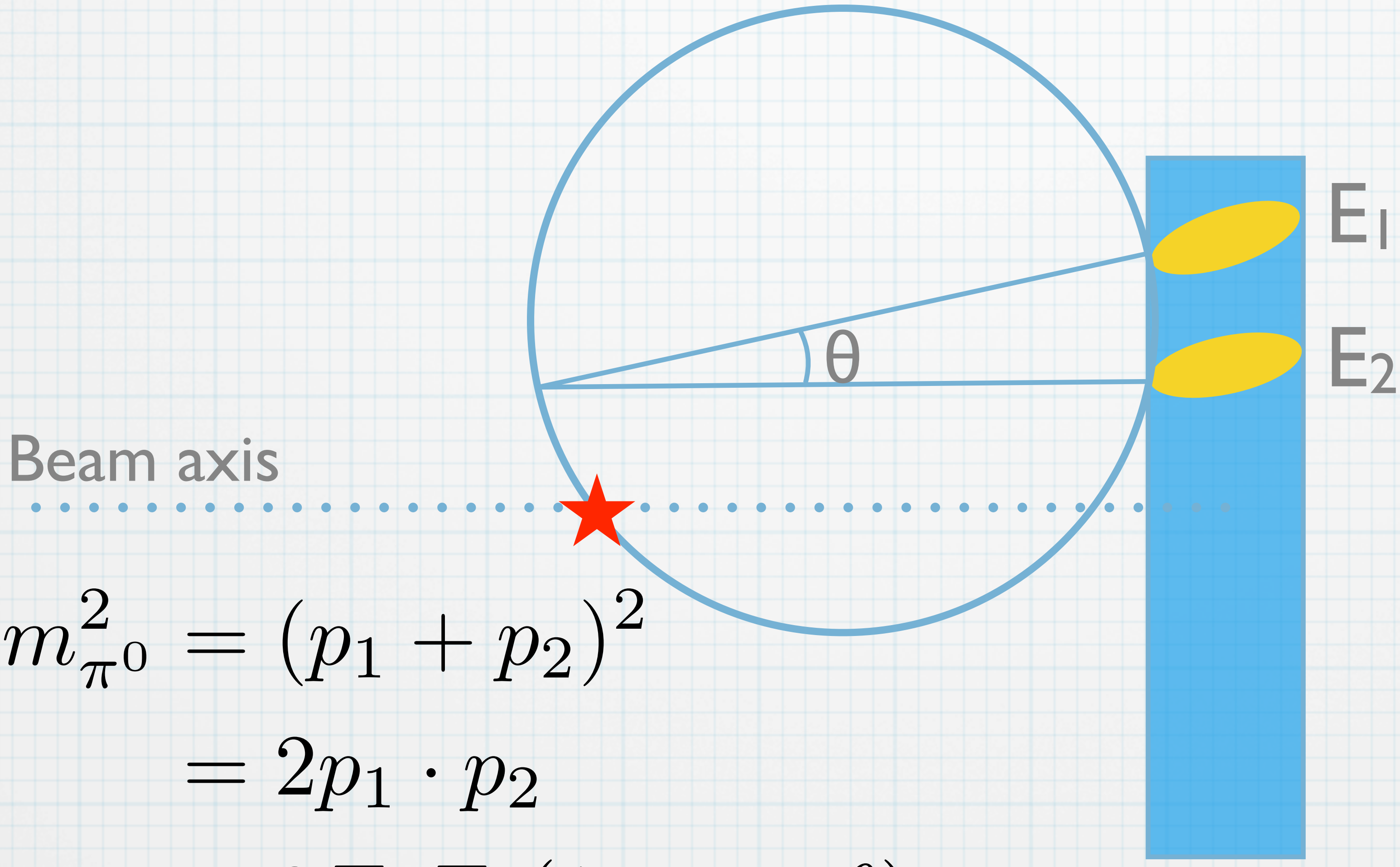
BR($K_L \rightarrow \pi^0 \nu \overline{\nu}$) limits



Signature of $K_L \rightarrow \pi^0 \nu \overline{\nu}$



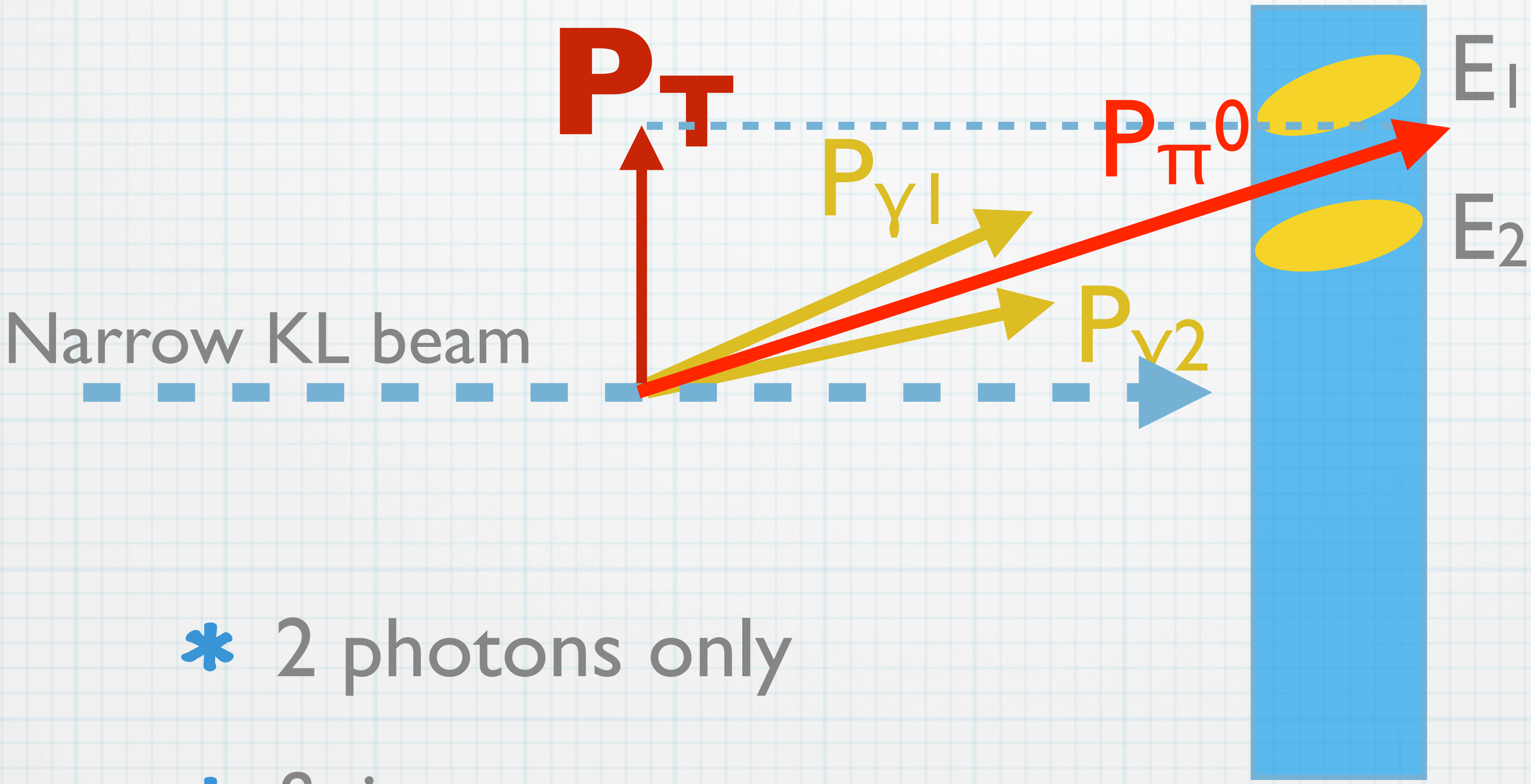
Reconstruction



$$m_{\pi^0}^2 = (p_1 + p_2)^2$$
$$= 2p_1 \cdot p_2$$
$$= 2E_1E_2(1 - \cos\theta)$$

* θ based on invariant mass

Properties of $K_L \to \pi^0 \nu \overline{\nu}$

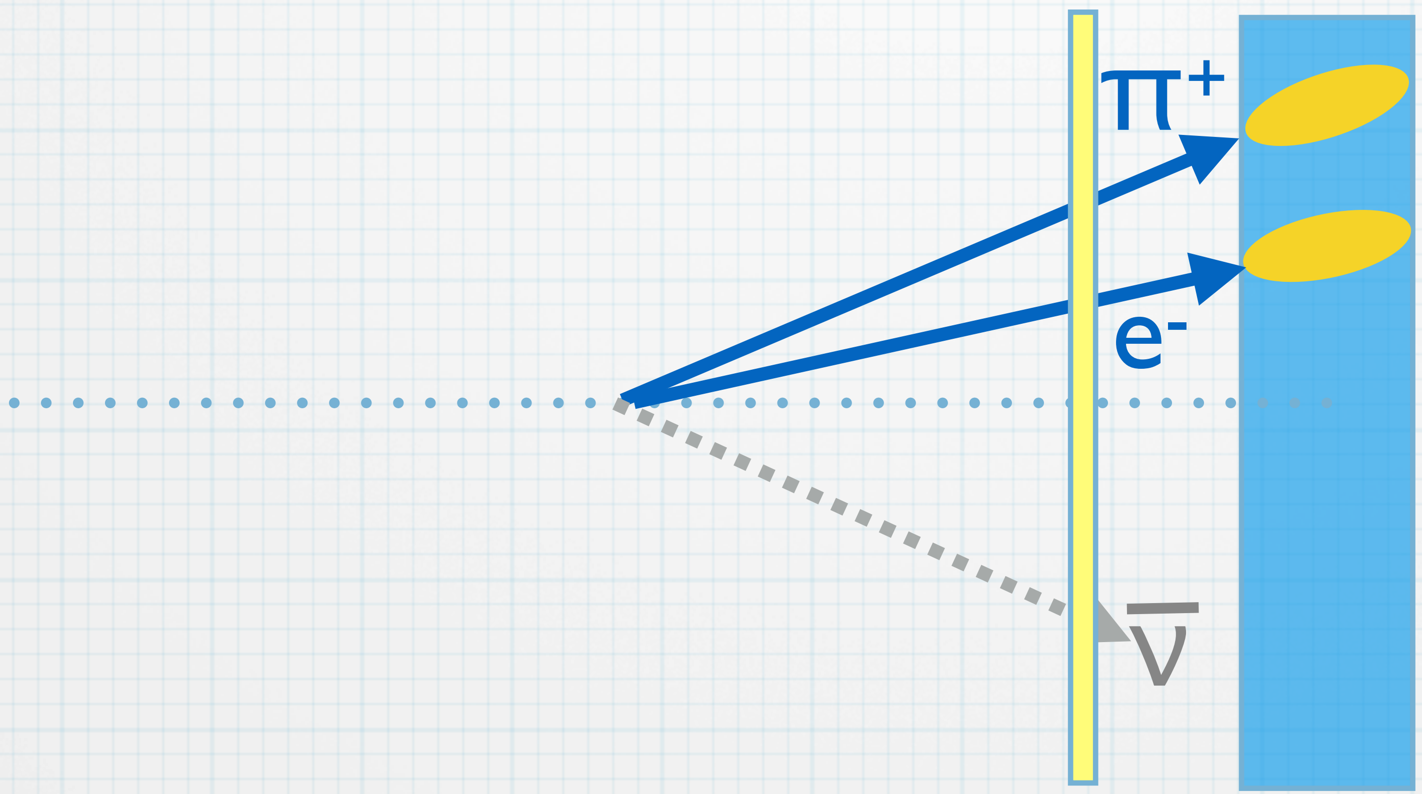


- 2 photons only
- finite transverse momentum

* … but there are backgrounds

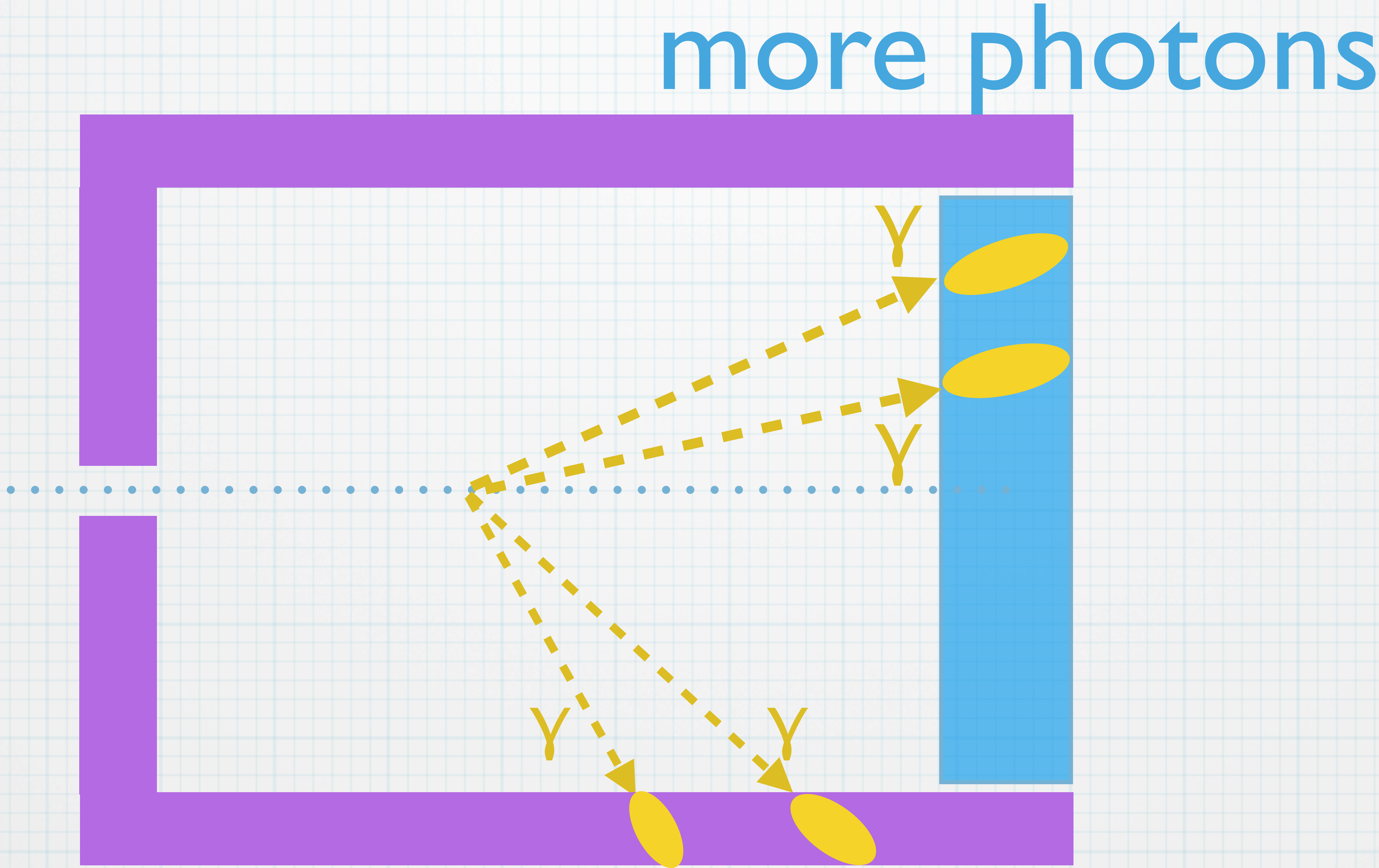
$K_L \to \pi^+ e^- \overline{\nu}$

charged particles



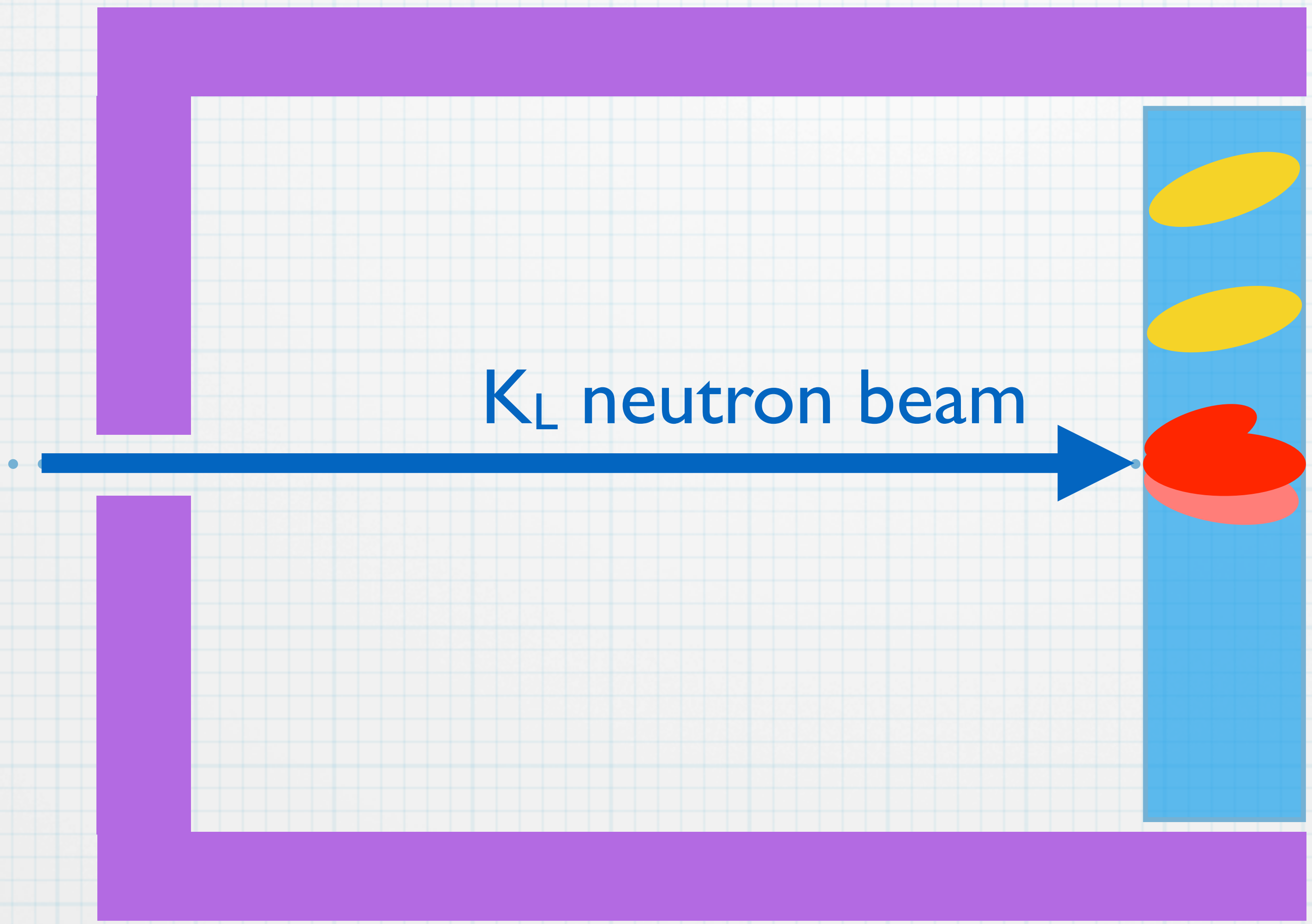
- Detect charged particles with plastic scintillators

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

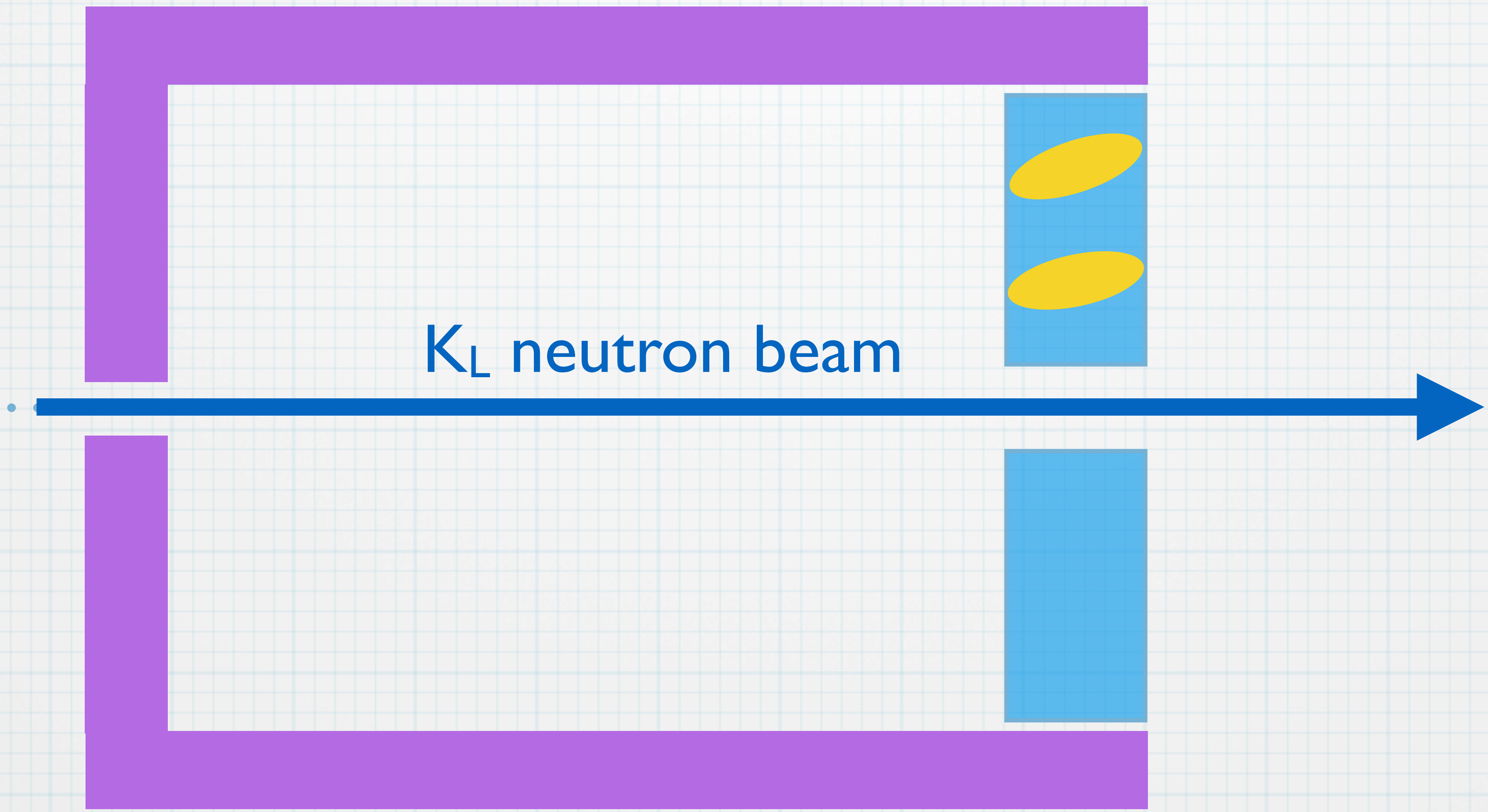


- Cover decay volume with Photon veto detectors

Beam hitting the detector



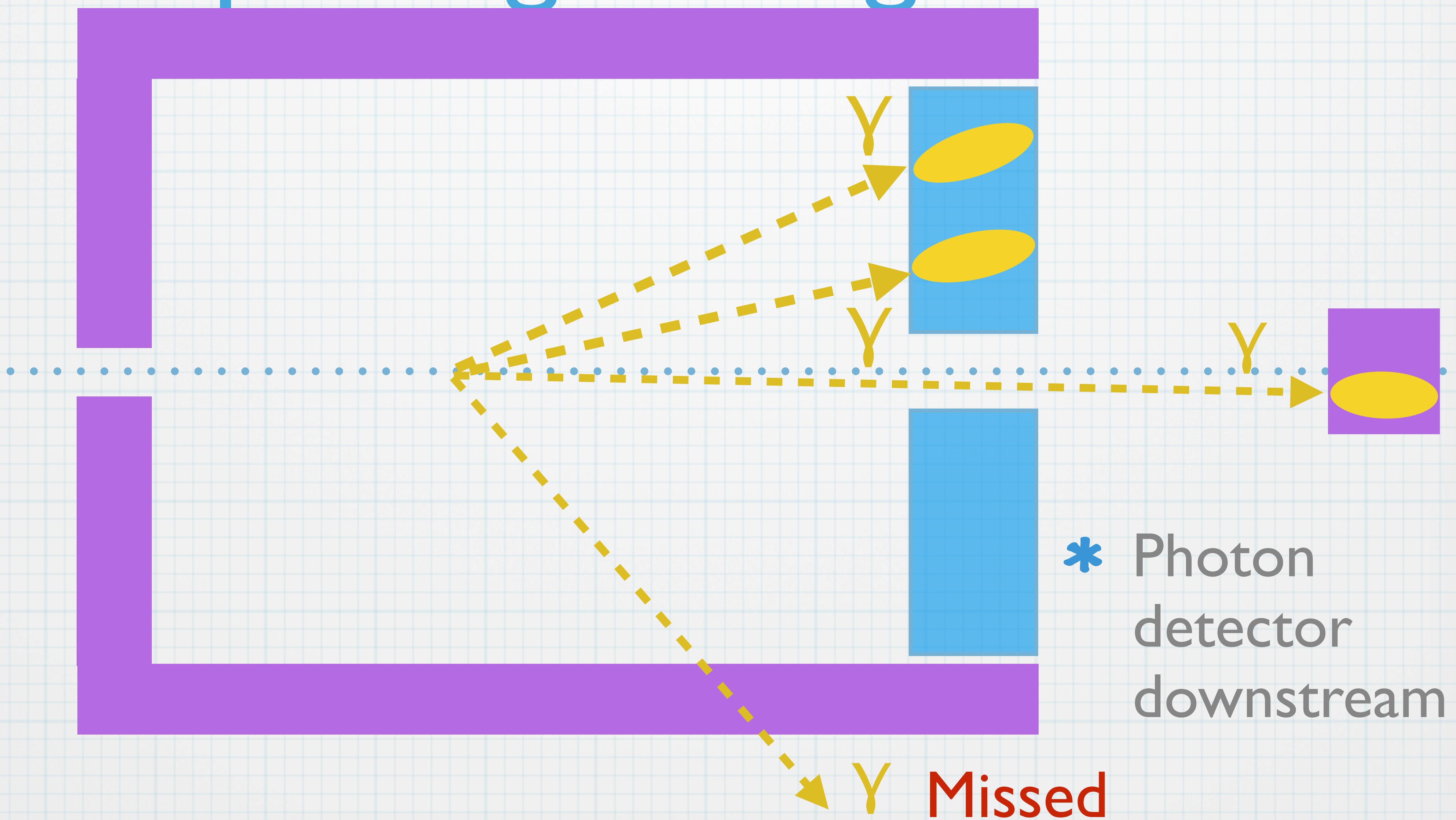
Beam hitting the detector



* Make a hole in the detector

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

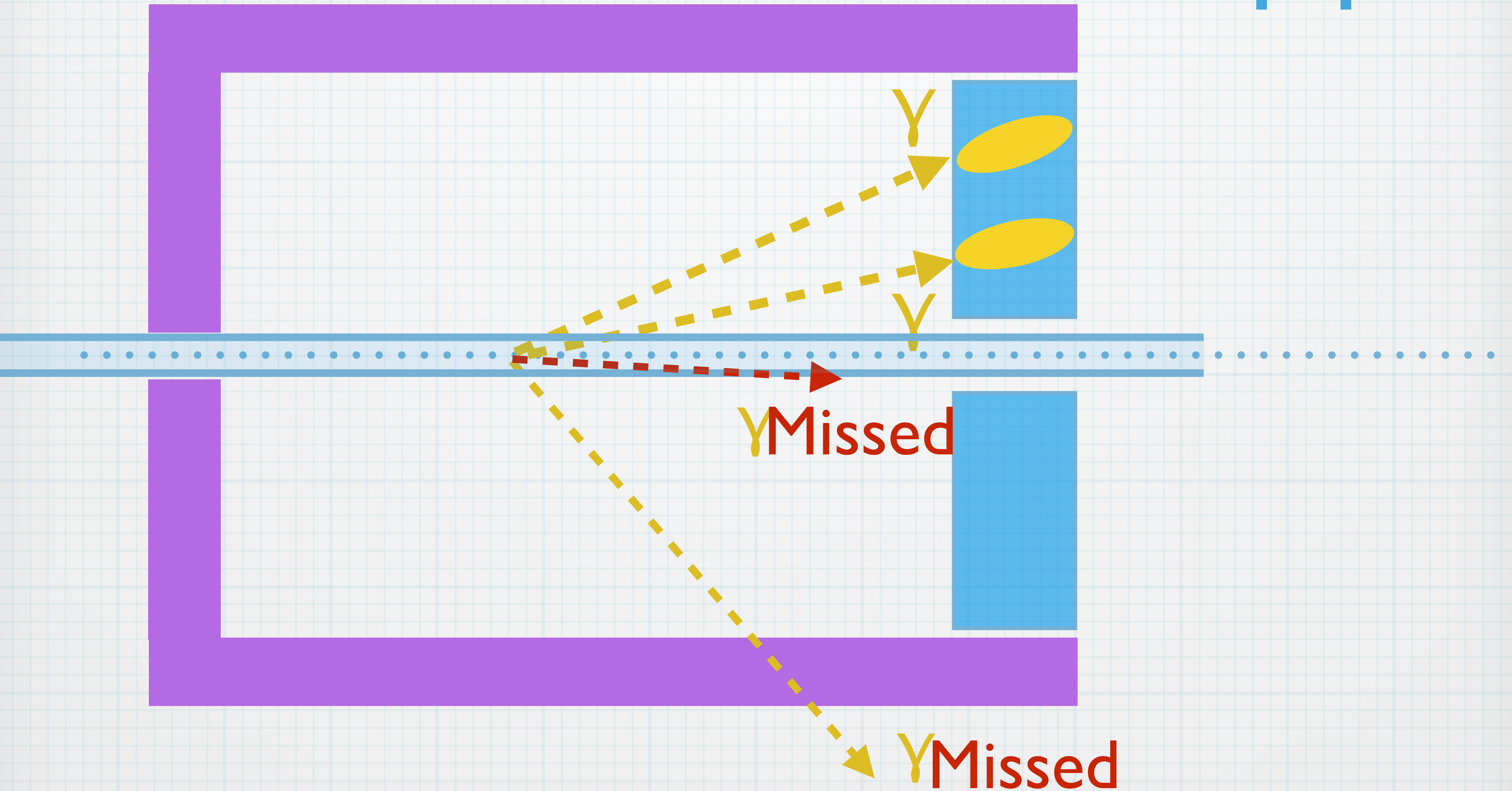
γ's passing through the hole



- Photon detector downstream

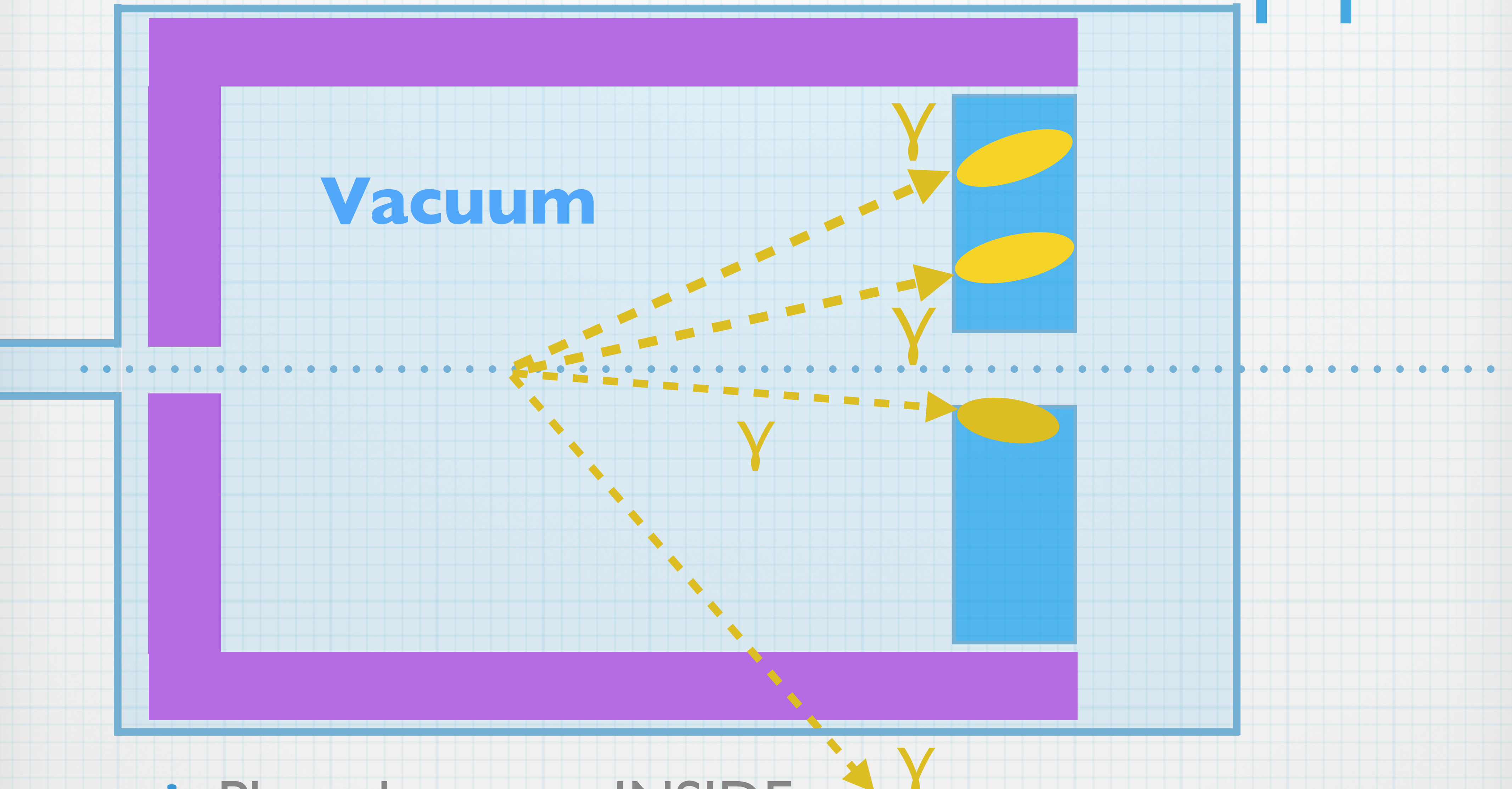
$K_L \to \pi^0 \pi^0$

γ's absorbed in beam pipe



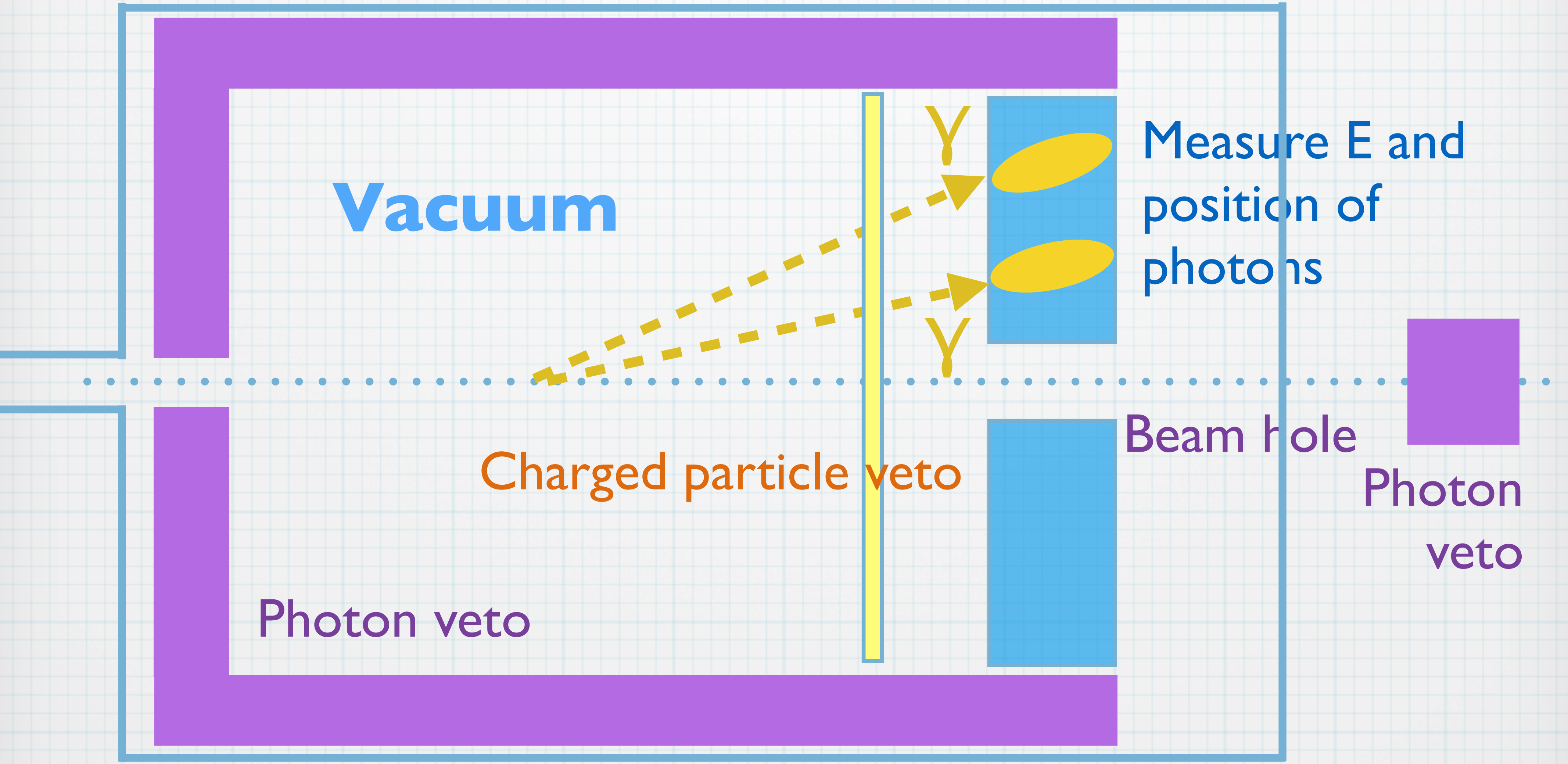
$K_L \to \pi^0 \pi^0$

ϒ's absorbed in beam pipe



* Place detectors INSIDE vacuum

Basic detector design



KOTO = K^0 at TOkai

Arizona State
Chicago
Michigan

KEK, Kyoto, NDA, Osaka,
Okayama, Saga, Yamagata

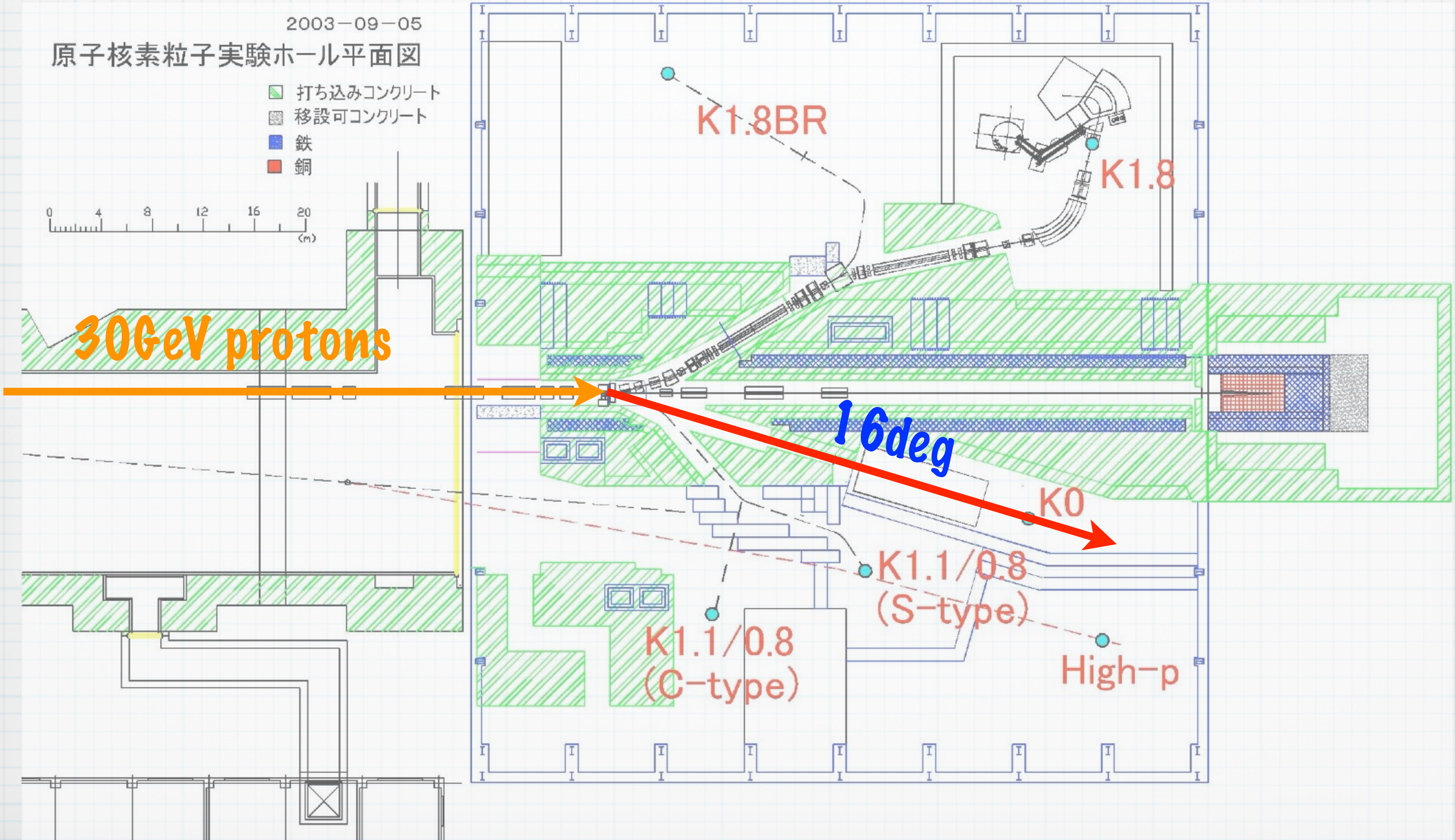
Chonbuk, Hanyang,
Jeju, Korea, JINR,
NTU

J-PARC

Japan Proton Accelerator Research Complex

J-PARC in Japan

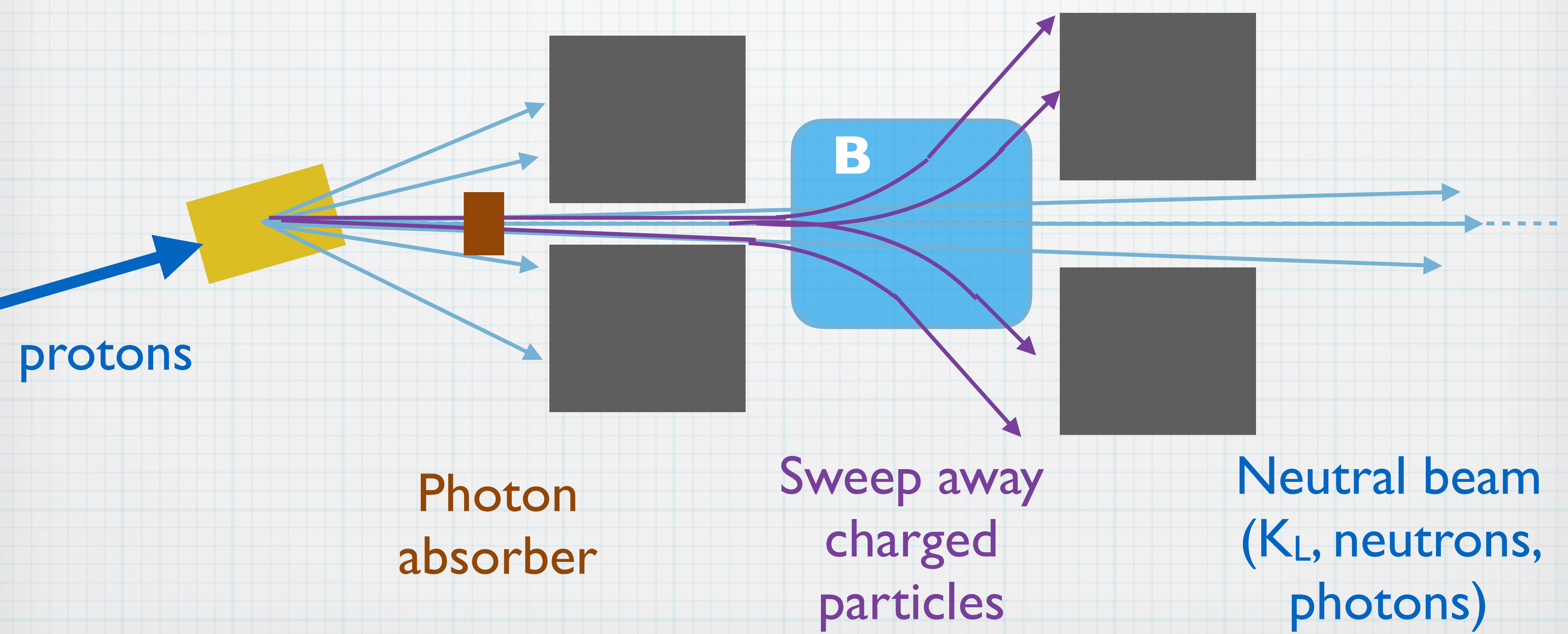
Experimental Hall



Hadron Hall

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

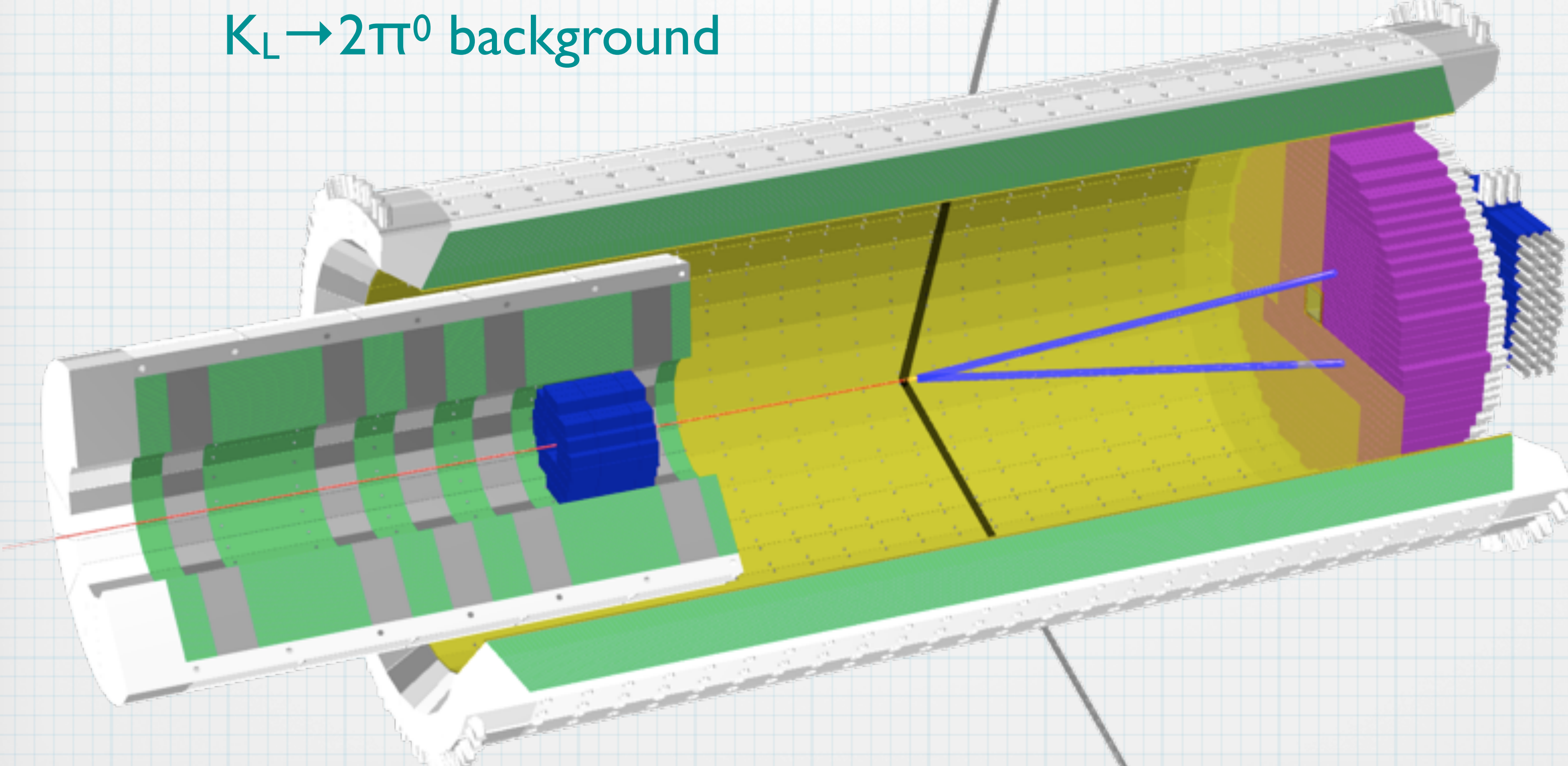
- How to make K_L beam

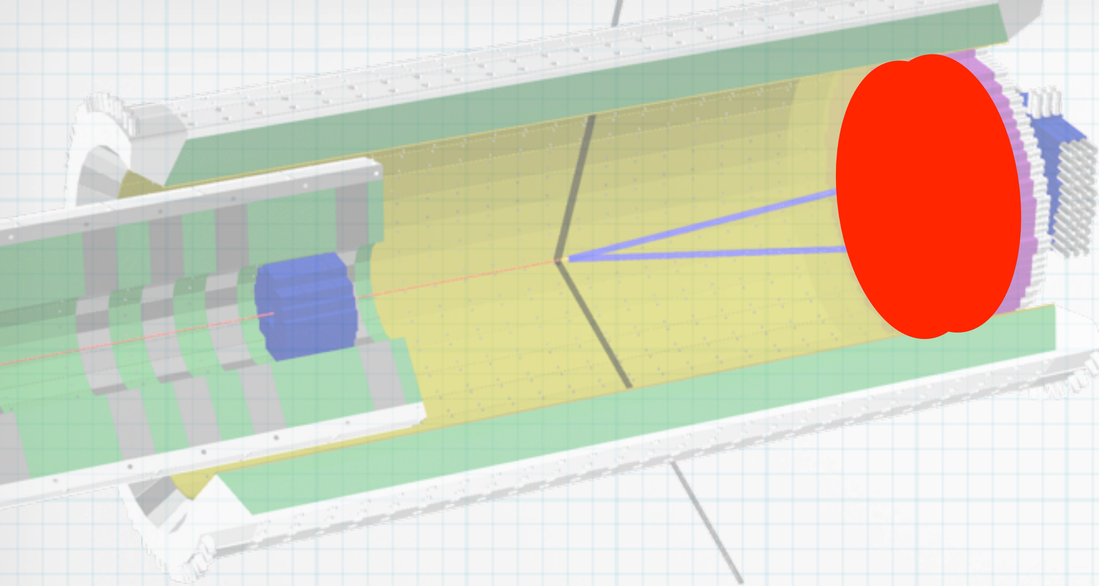


detector

Hermetic veto to suppress $K_L \rightarrow 2\pi^0$ background

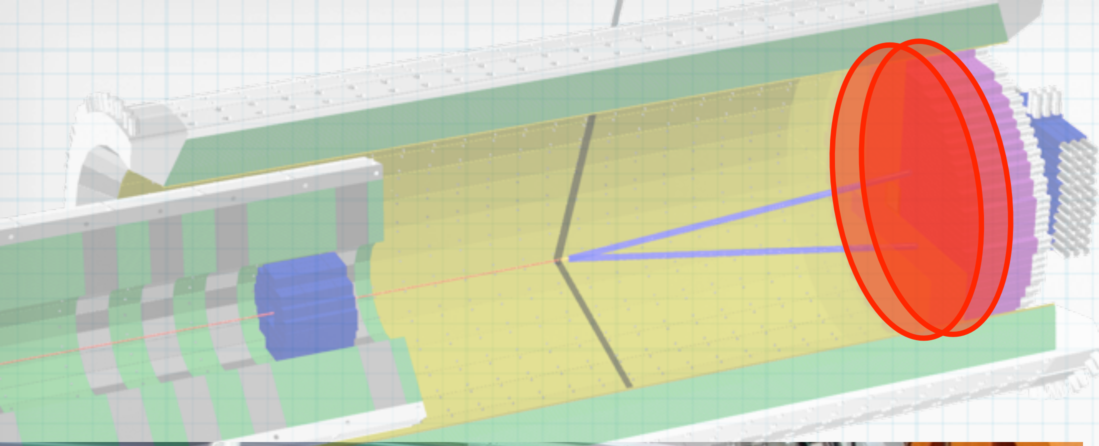
CsI Calorimeter for 2γ



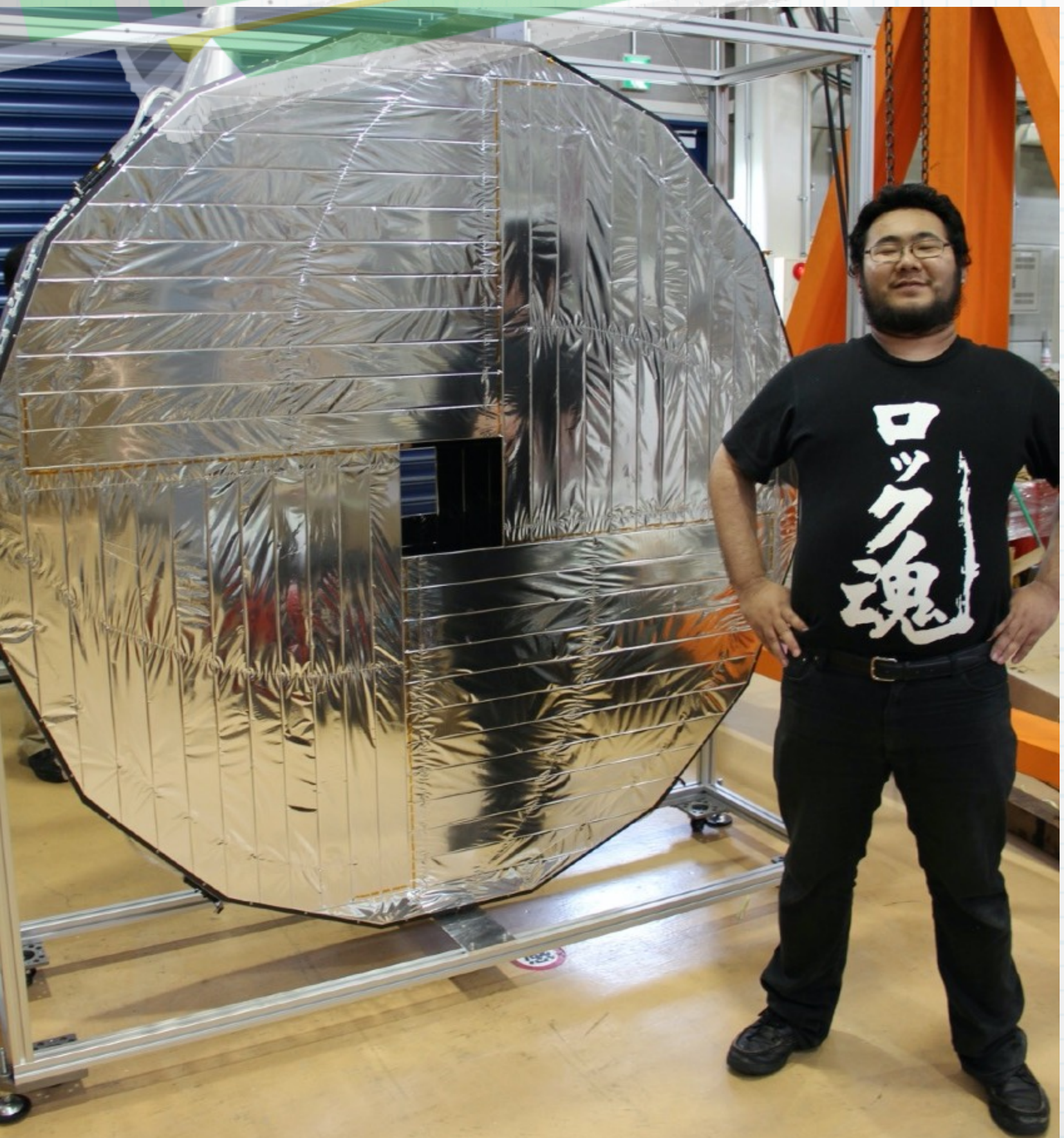


CsI Calorimeter

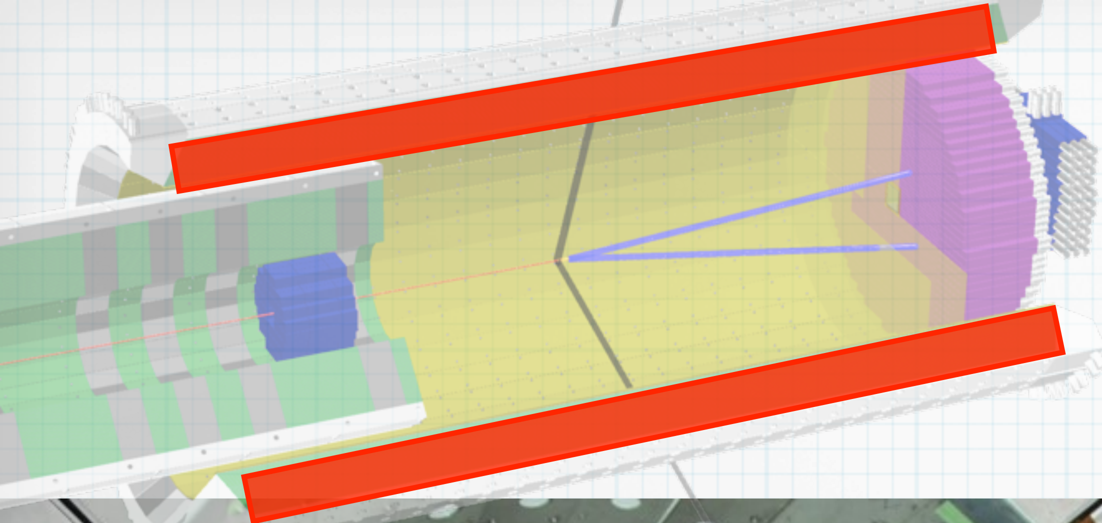
- 2716 CsI crystals from the Fermilab KTeV experiment
- 50 cm (27 X_0) long
- 2.5 cm and 5 cm square crystals



Charge Veto

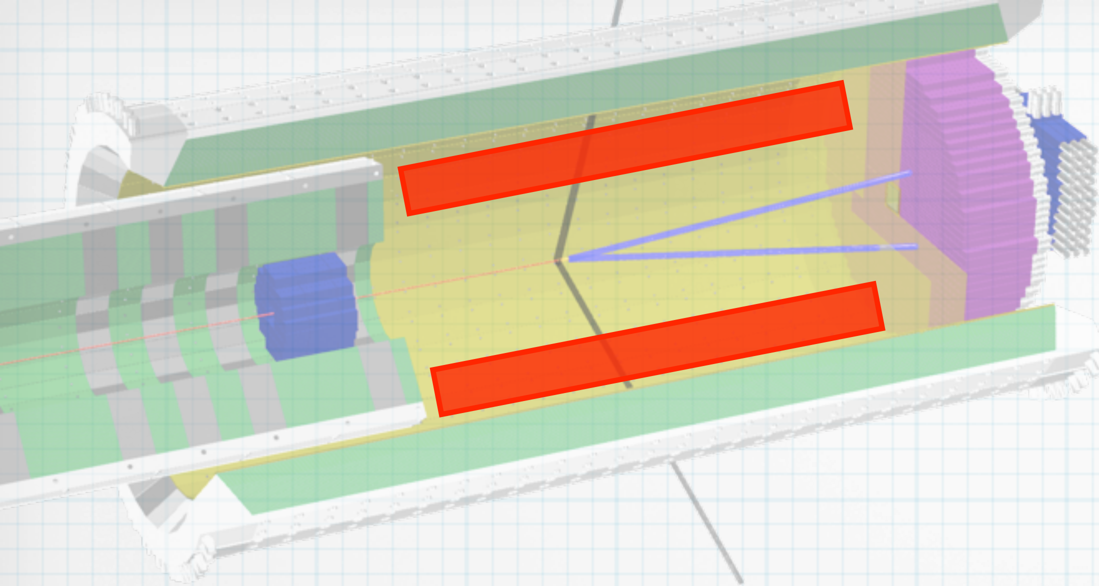


- Veto charged particles w/ $<10^{-3}$ inefficiency
- Only 3mm thick
- Made be Kyoto Univ.

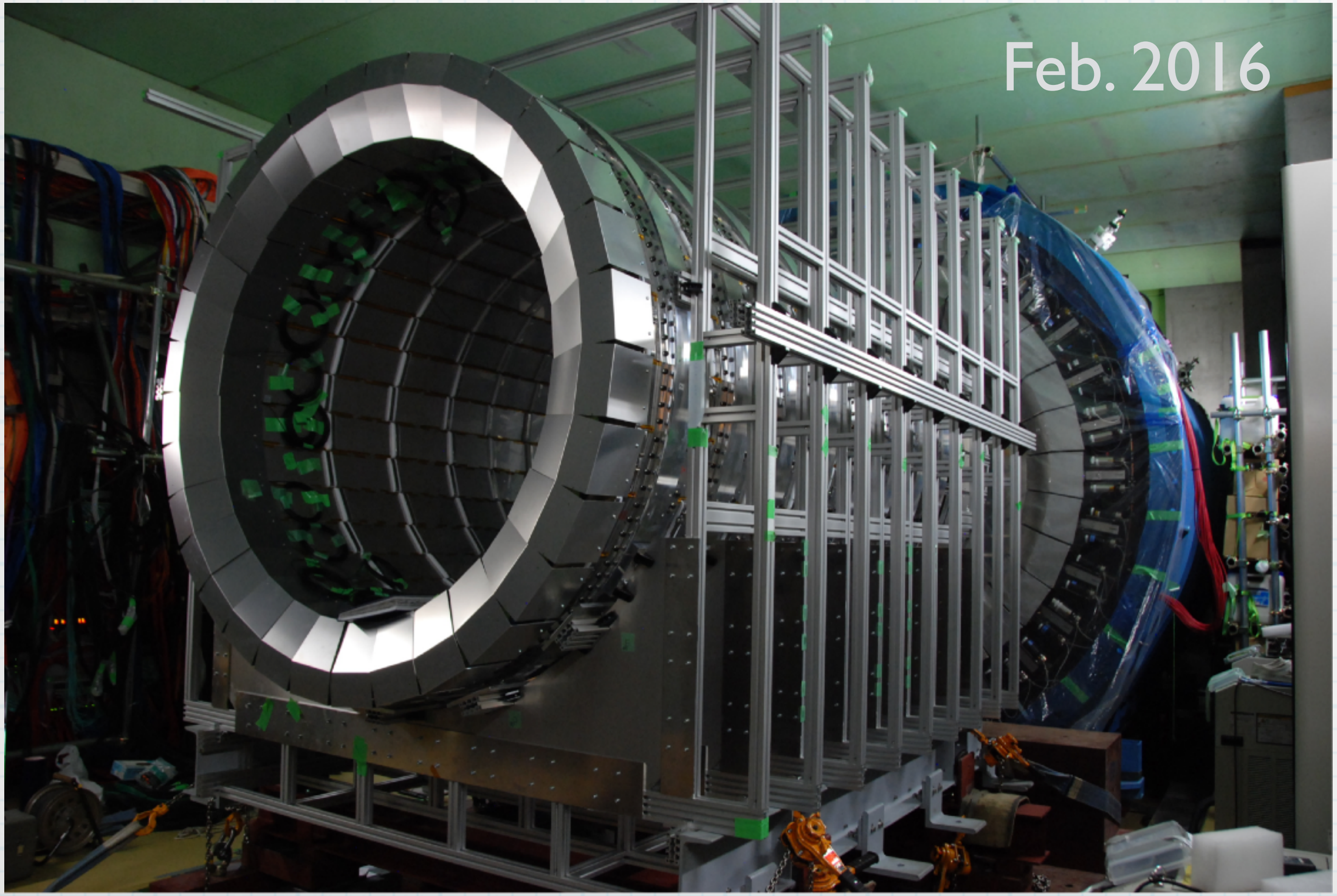


Photon Veto

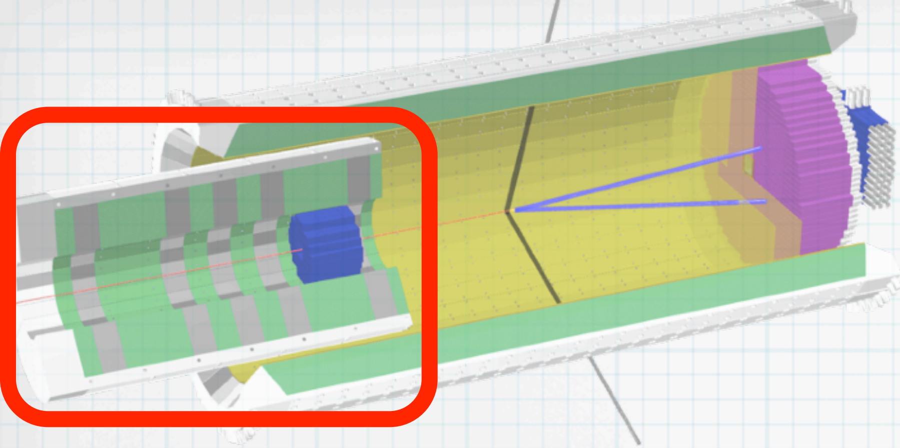
* To detect escaping photons
* 13.5 X_0



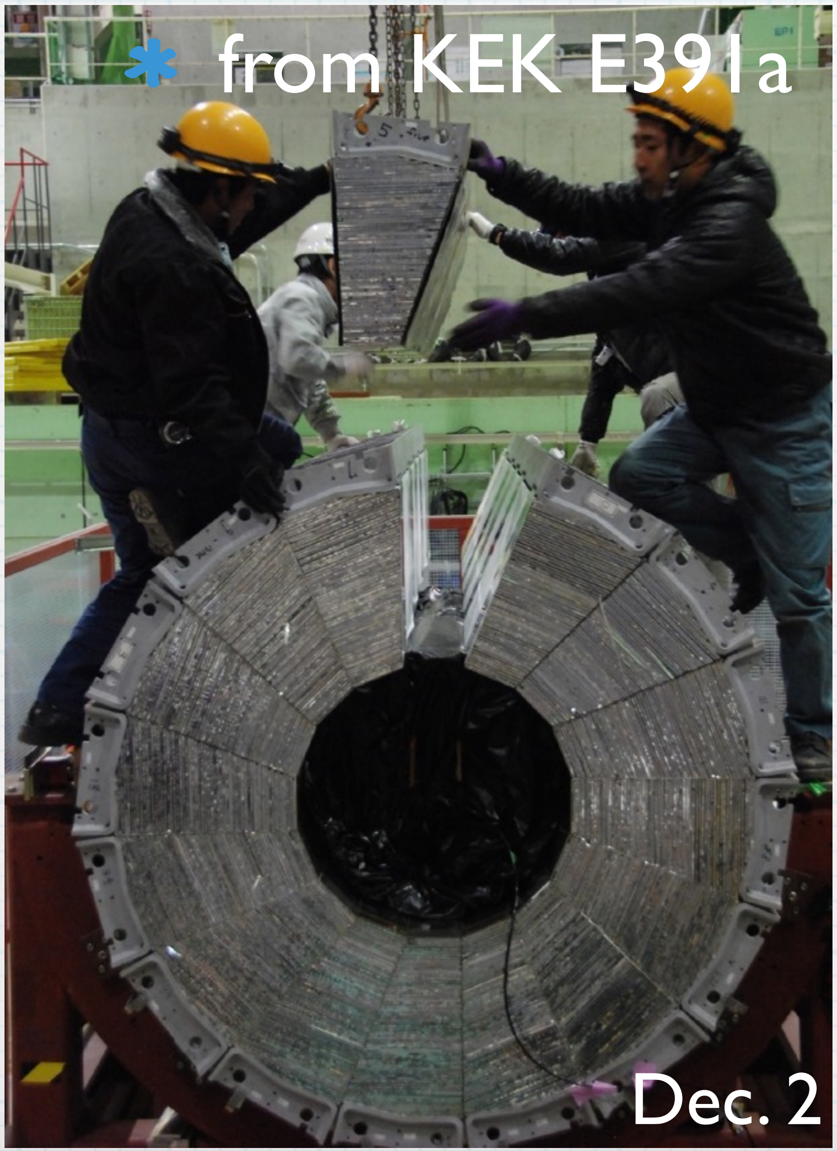
Additional Photon Veto

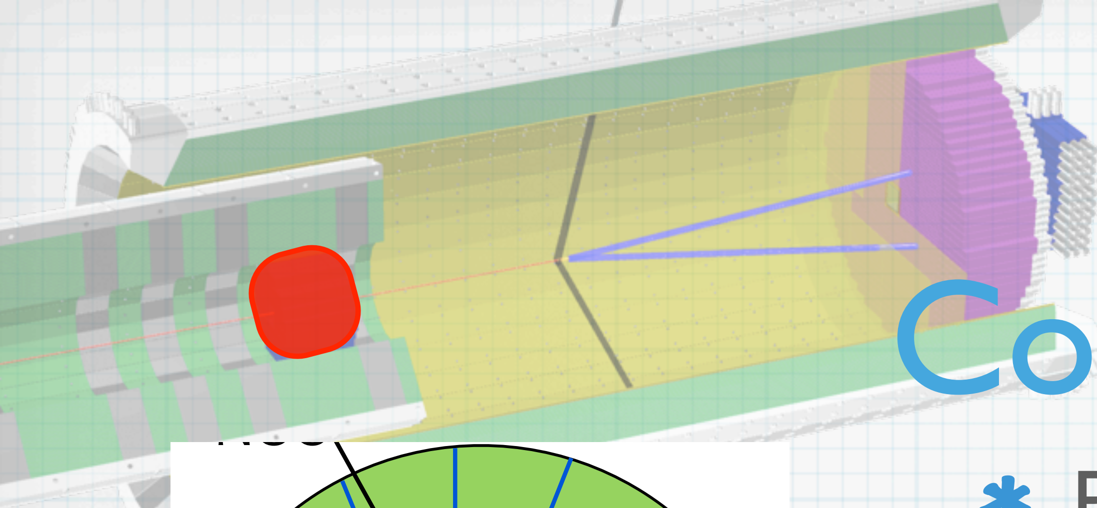


- Inserted another cylindrical photon veto
- + $5X_0$



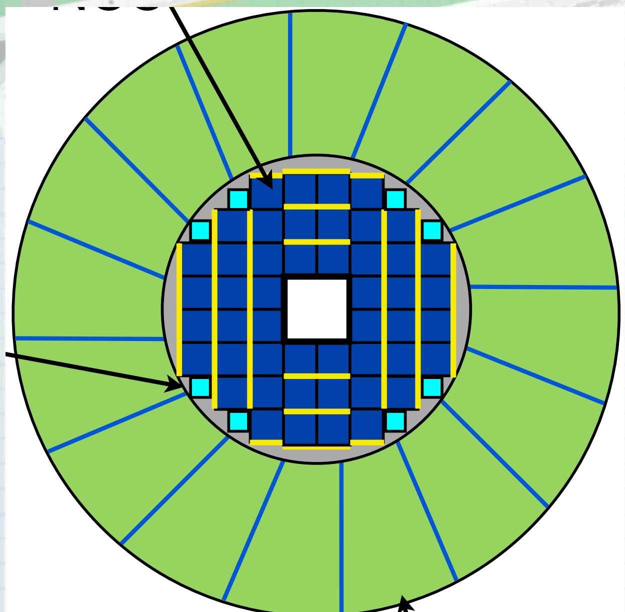
Front Barrel Photon Veto

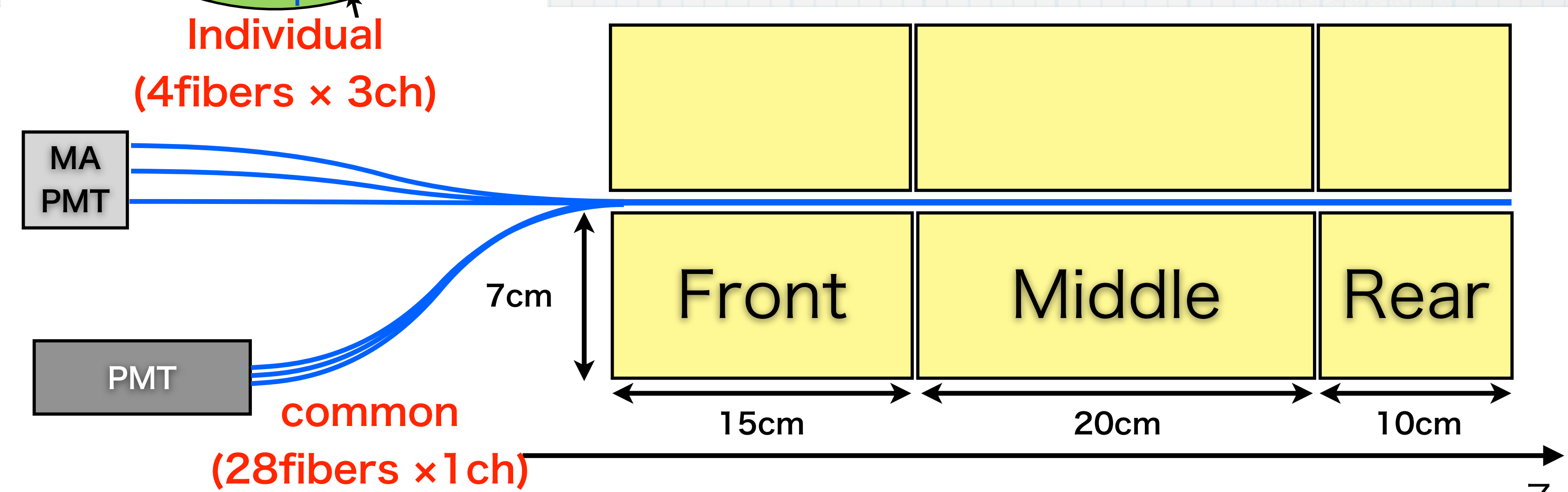




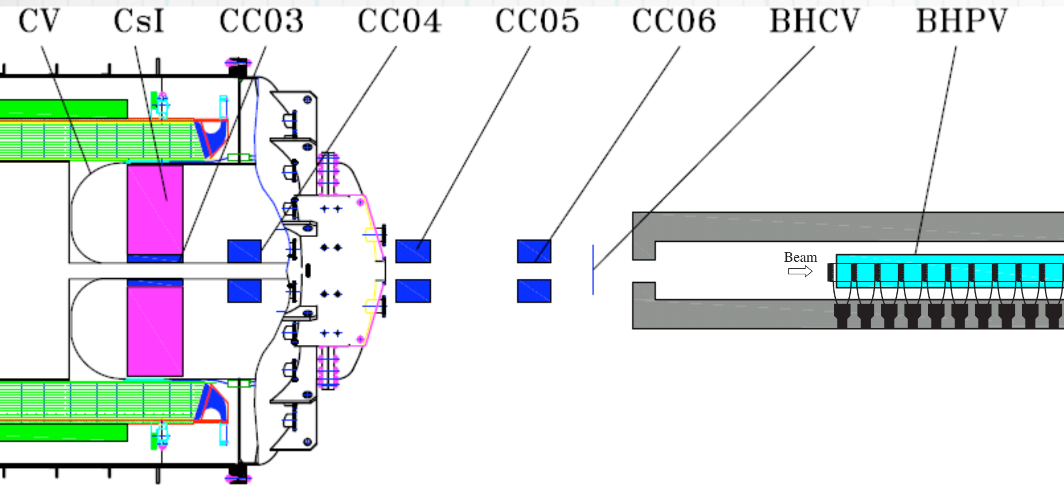
Neutron Collar Counter

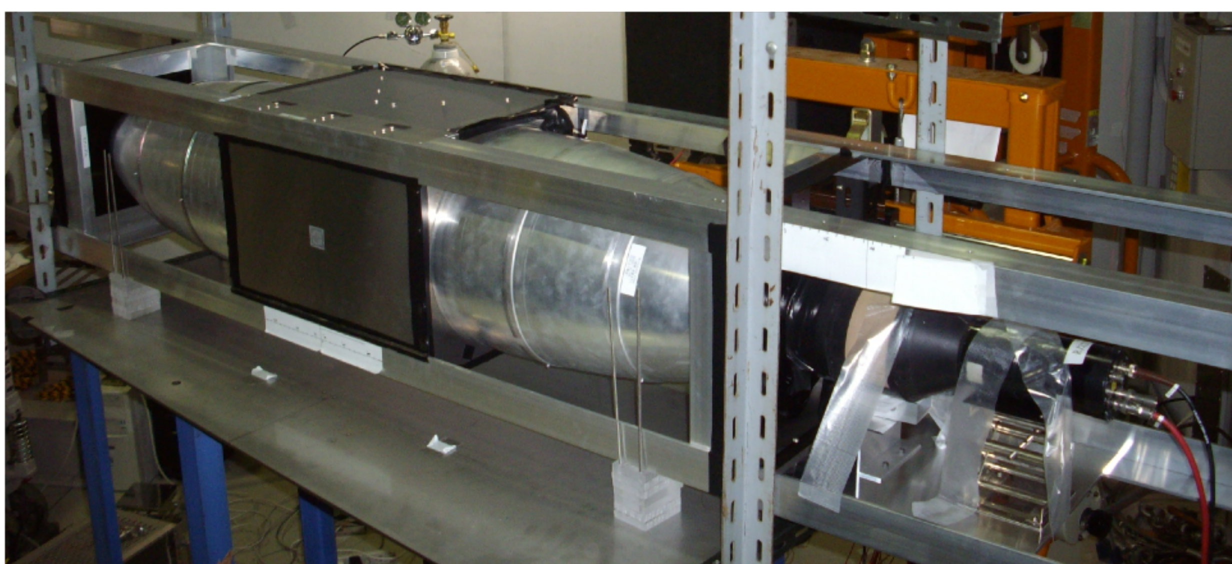
- Purpose
  - Veto photons
  - count halo neutrons
- 48 3-CsI-block modules

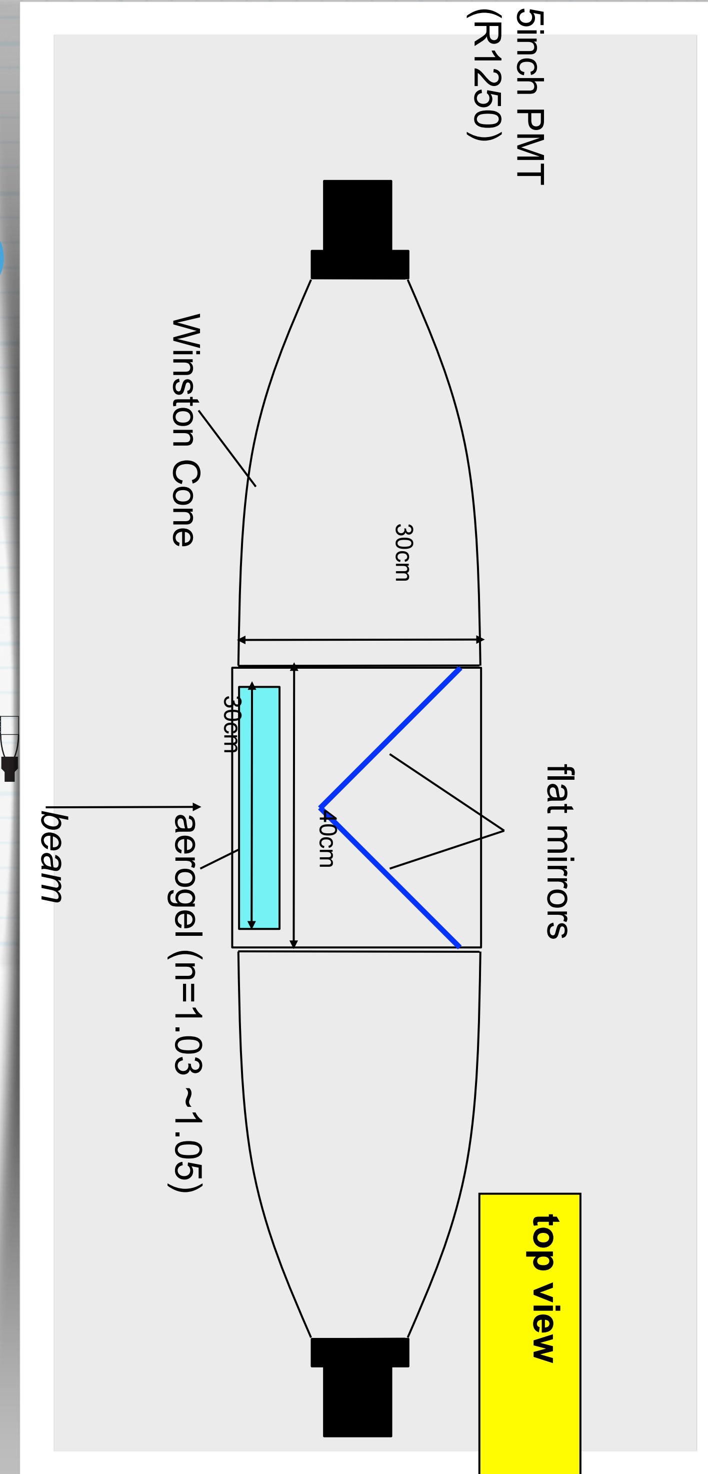


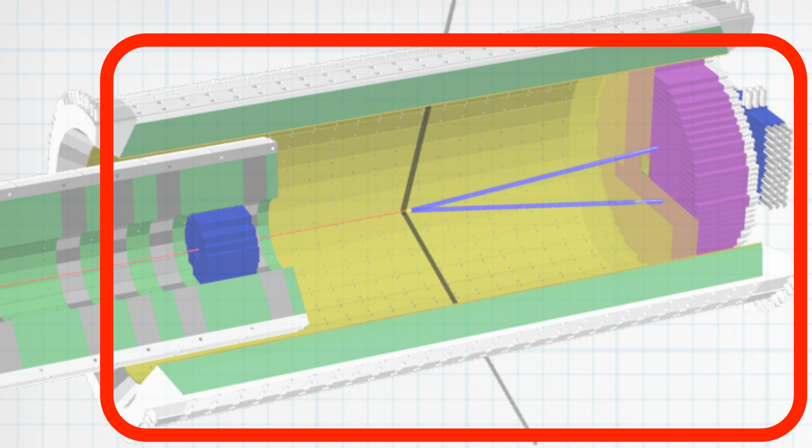


In-beam Photon Veto





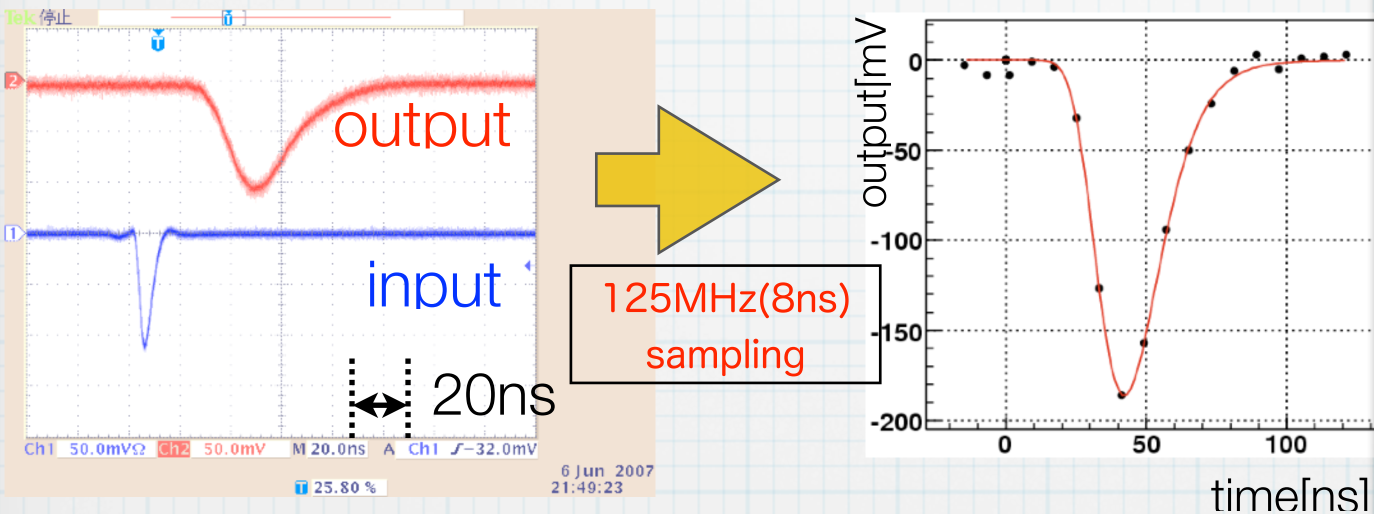


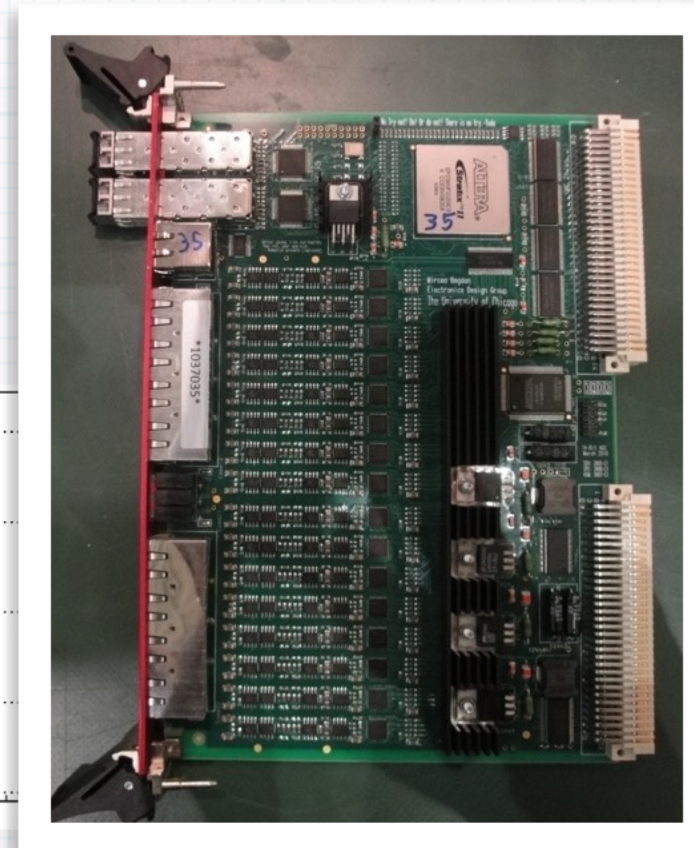


Main Barrel +CsI Calorimeter

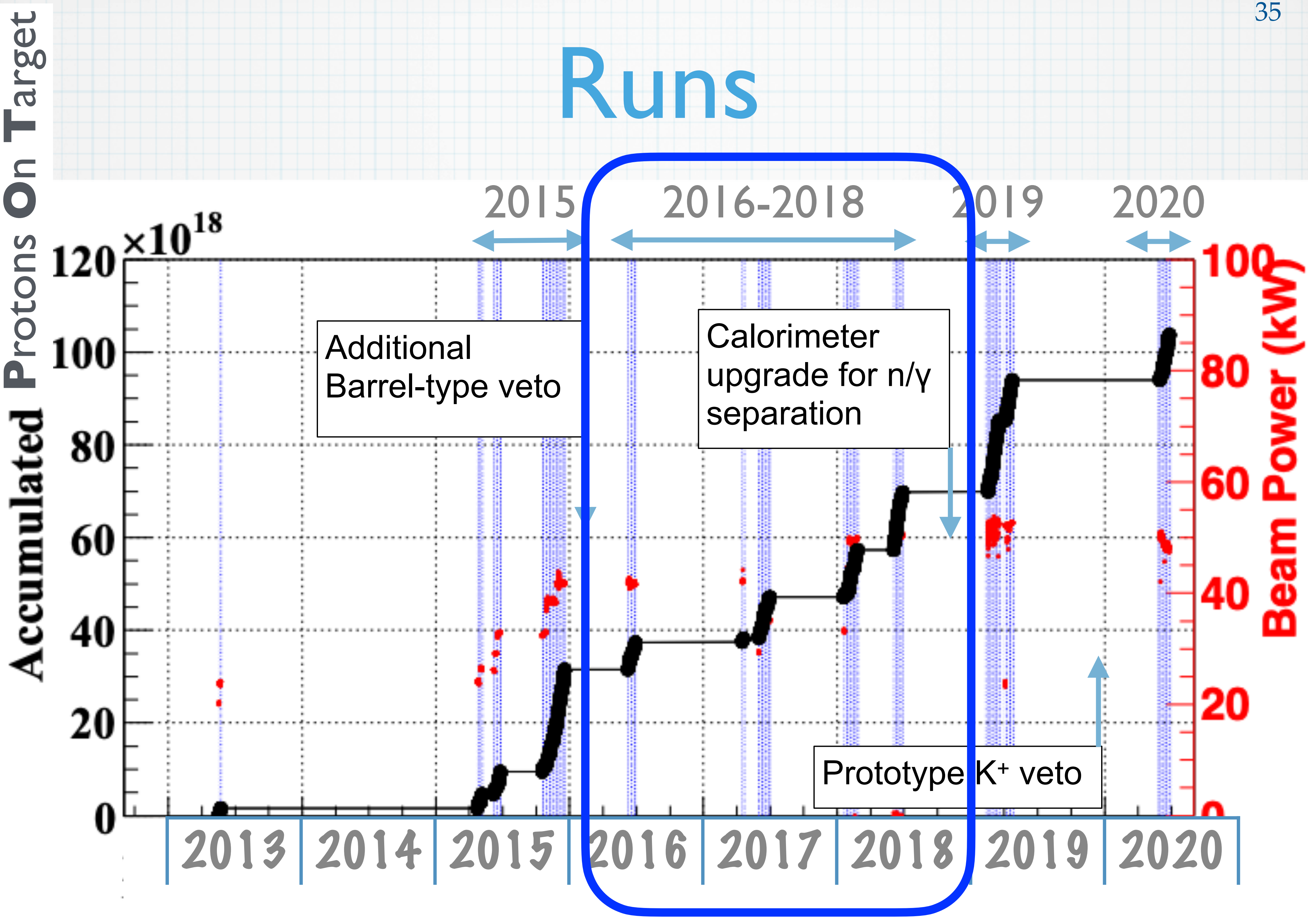
DAQ system

- 14bit FADC to record waveform and
  - to form triggers digitally
- Designed, produced by US



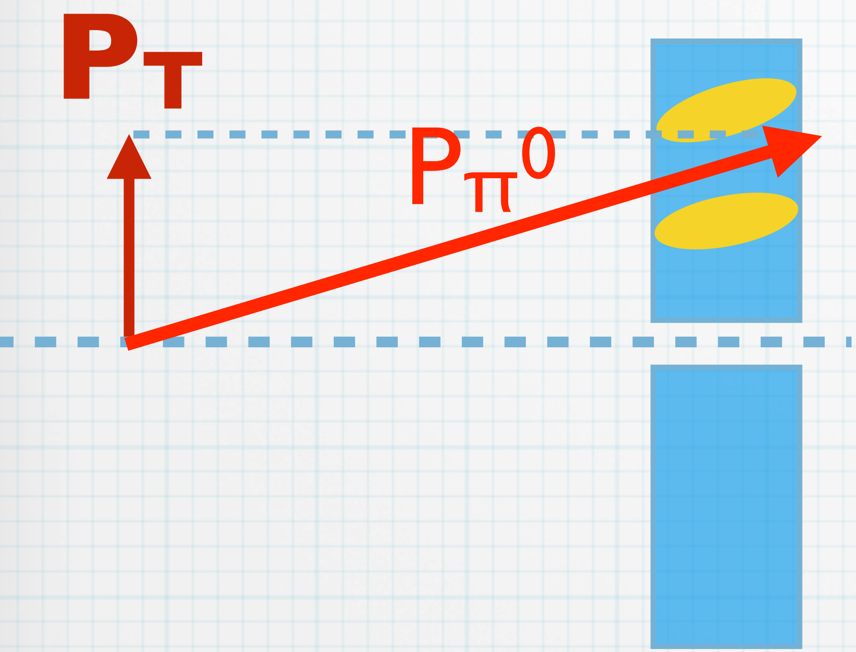


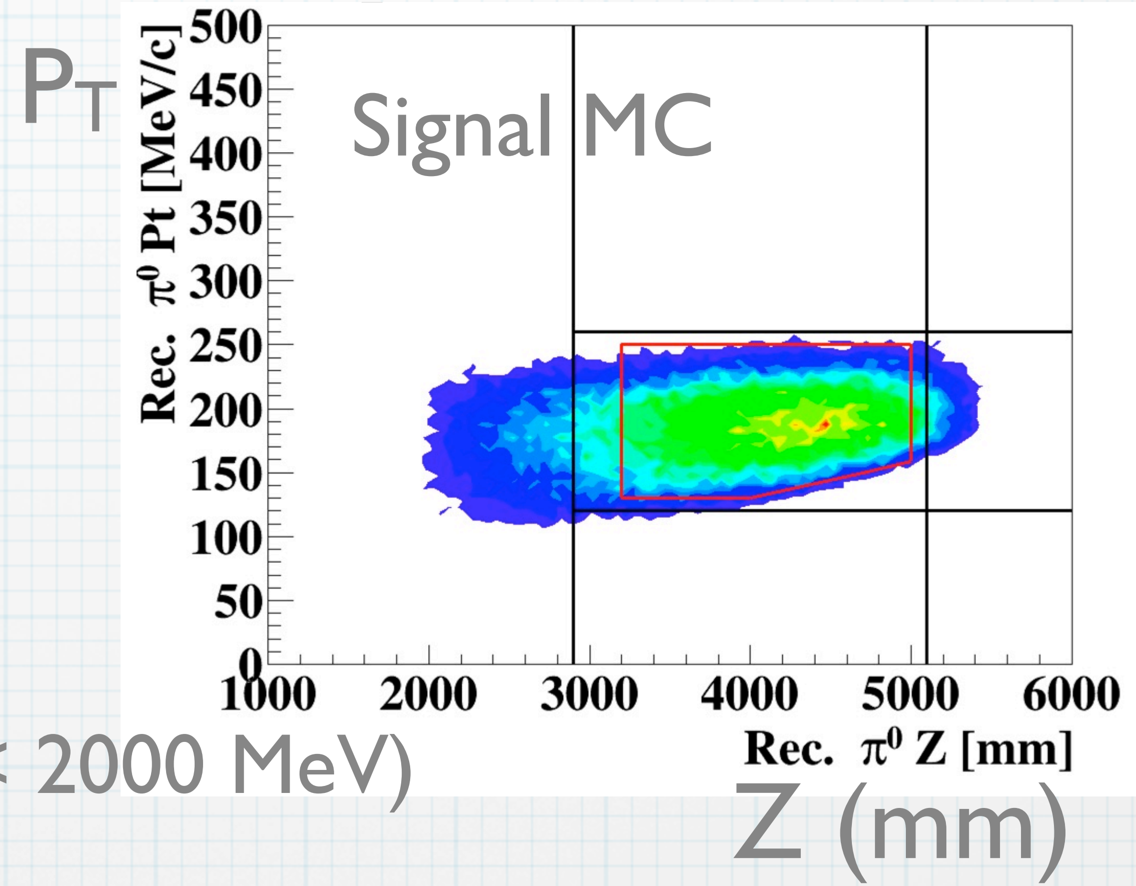
Runs



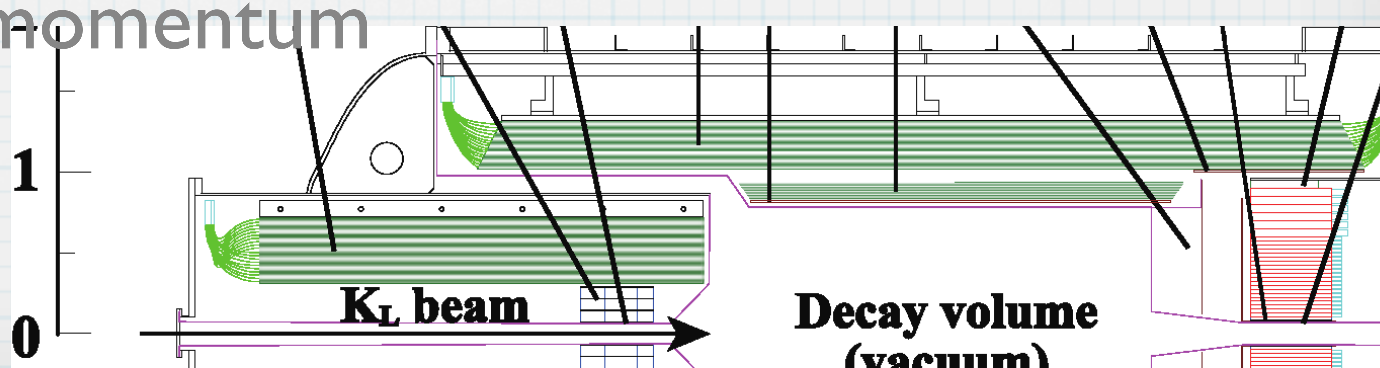
2015
2016-2018
2019
2020
Accumulated Protons On Target
×10^18
120
100
80
60
40
20
0
Beam Power (kW)
100
80
60
40
20
0
Additional
Barrel-type veto
Calorimeter
upgrade for n/γ
separation
Prototype K+ veto
2013
2014
2015
2016
2017
2018
2019
2020

Signature of $K_L \to \pi^0 \nu \bar{\nu}$

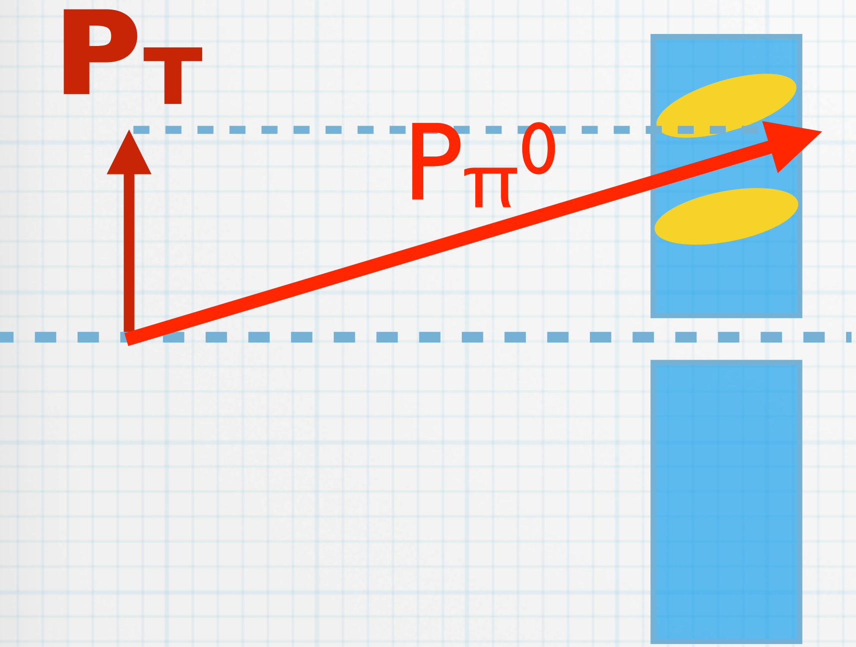


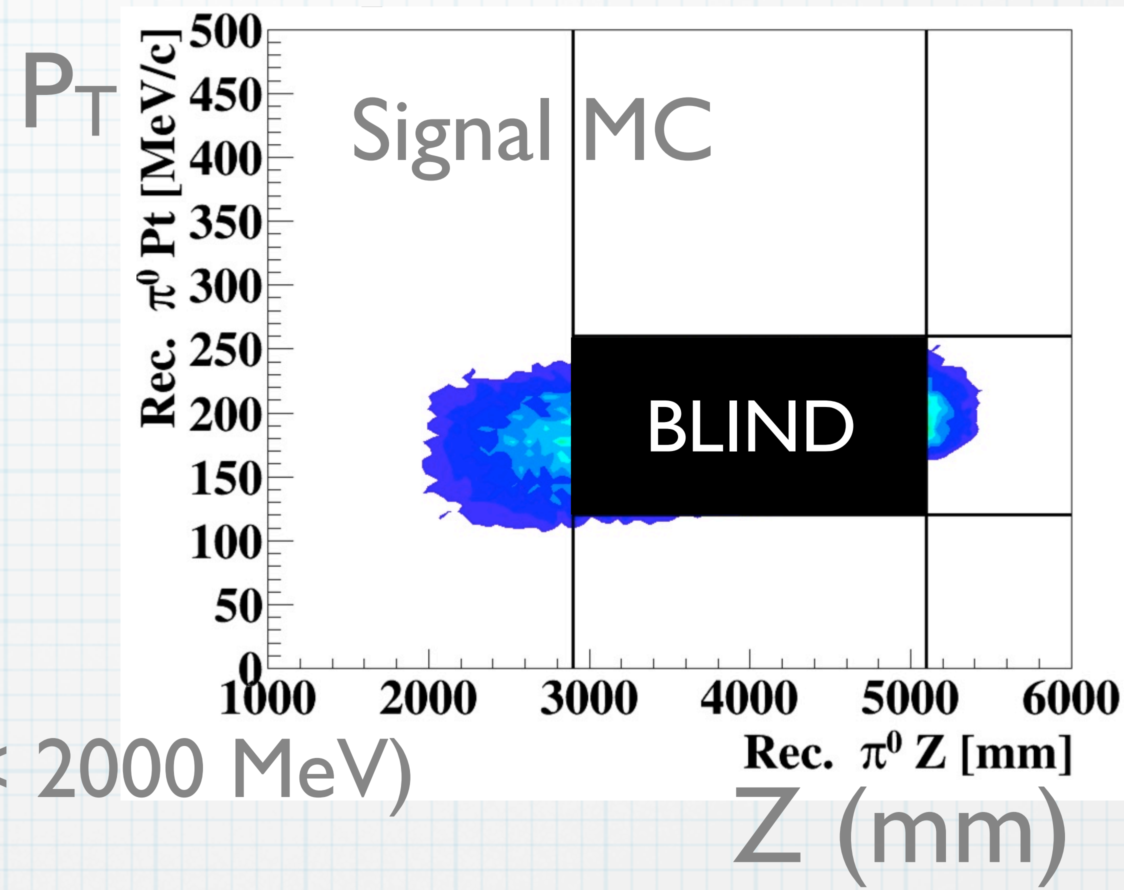


- 2 photons (100 < E_γ < 2000 MeV)
- finite transverse momentum
- $E_{2\gamma}$ > 650 MeV



Signature of $K_L \to \pi^0\nu\bar{\nu}$





- 2 photons ($100 < E_\gamma < 2000$ MeV)
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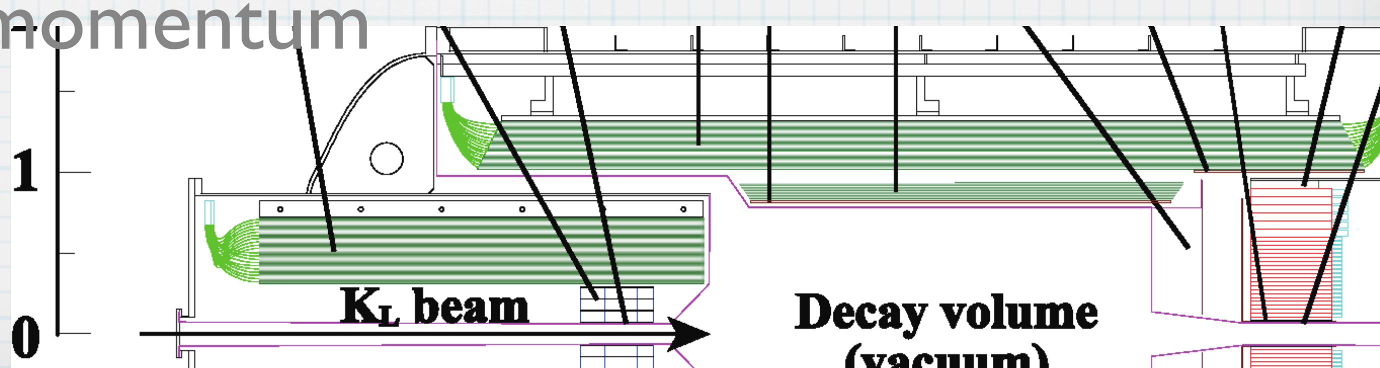


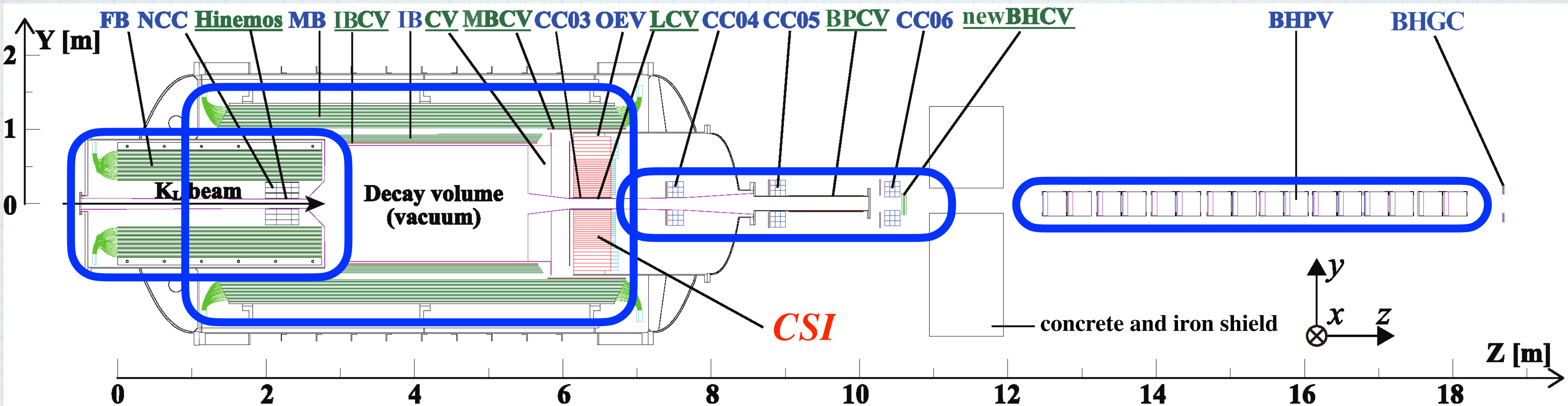
Rare decay experiment

=

Fight against backgrounds

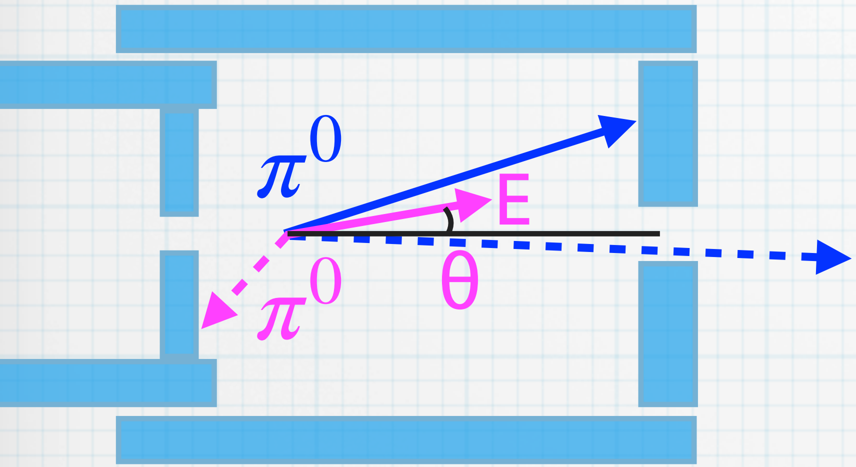
Against $K_L \to \pi^0\pi^0$ background

- No hits (> 1-3 MeV) in photon veto counters

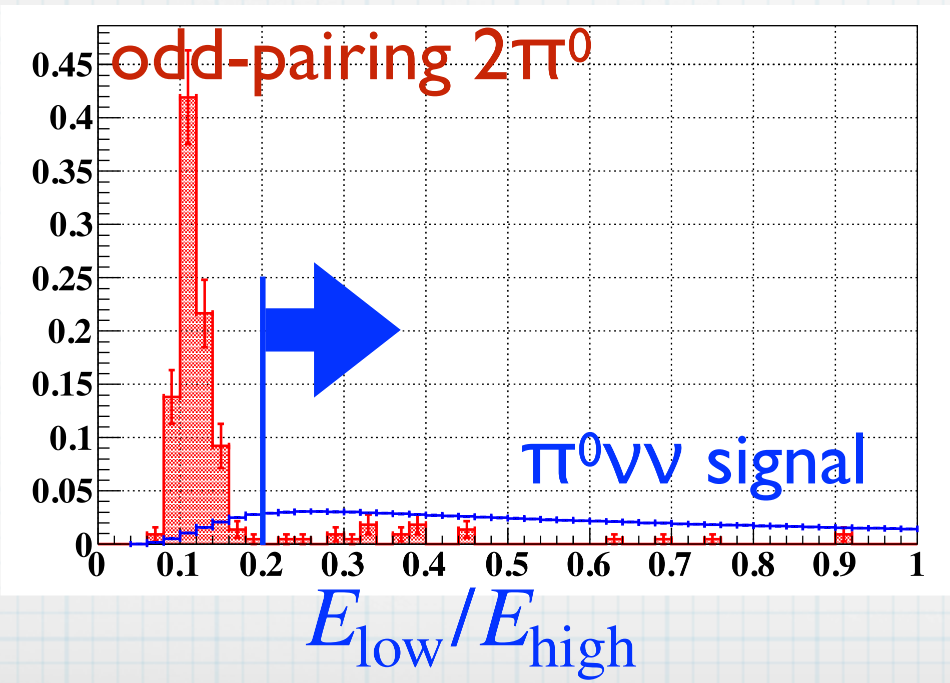


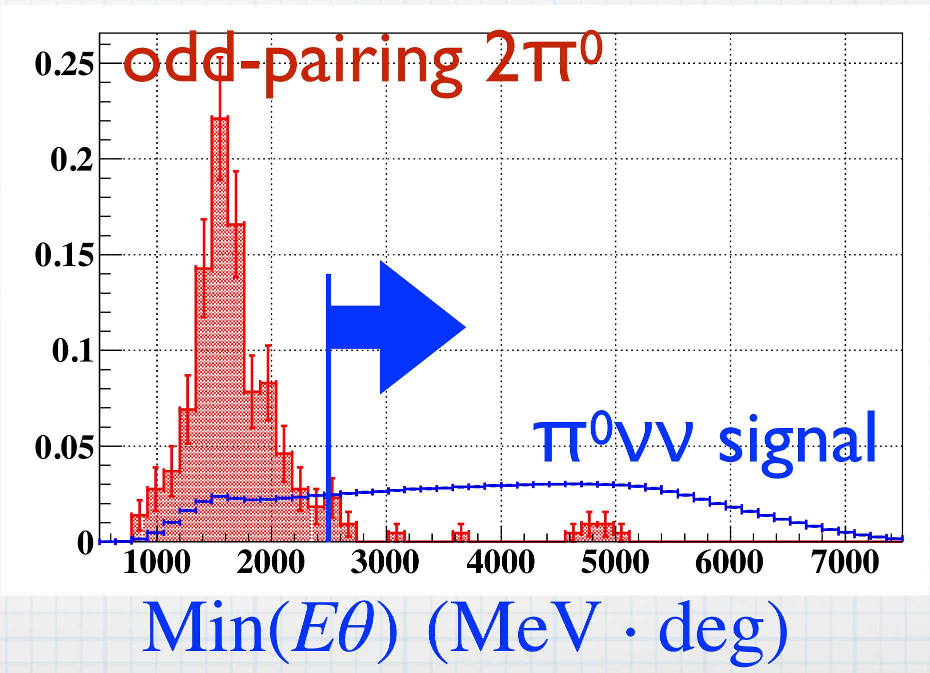
- No extra clusters or single-crystal-hits (> 3-10 MeV) in CsI calorimeter

Against odd-pairing $K_L \to \pi^0\pi^0$ background

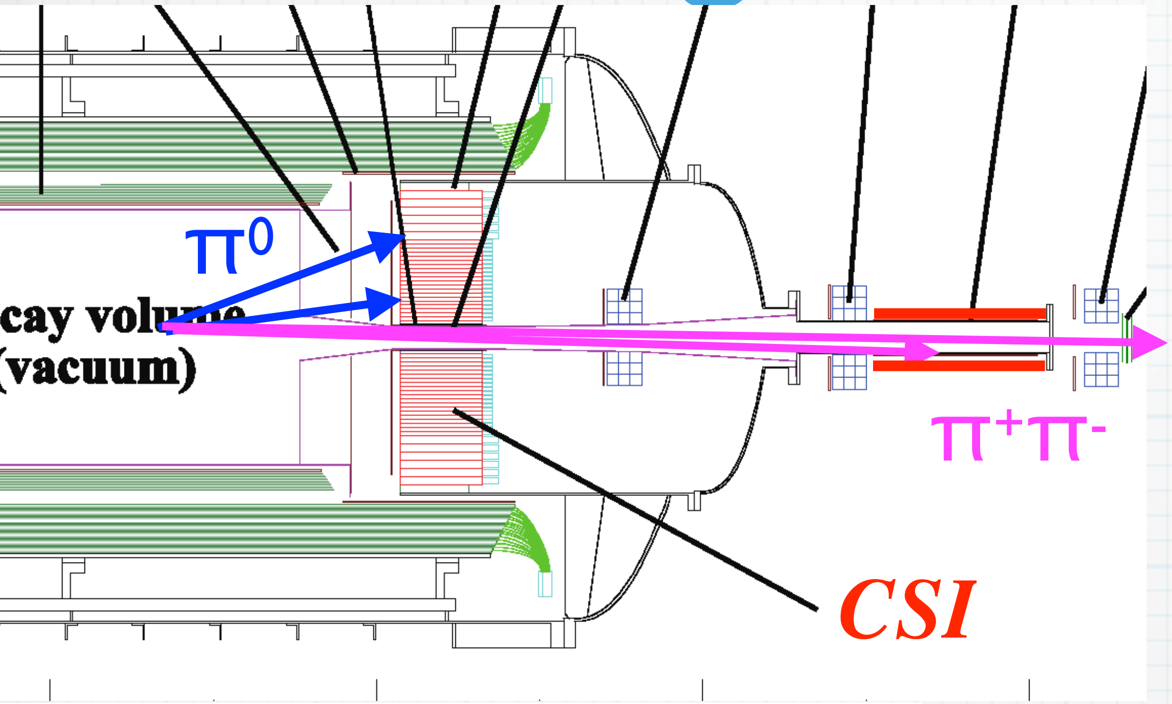


- 2γ's from different π^0
- Wrong reconstructed vertex

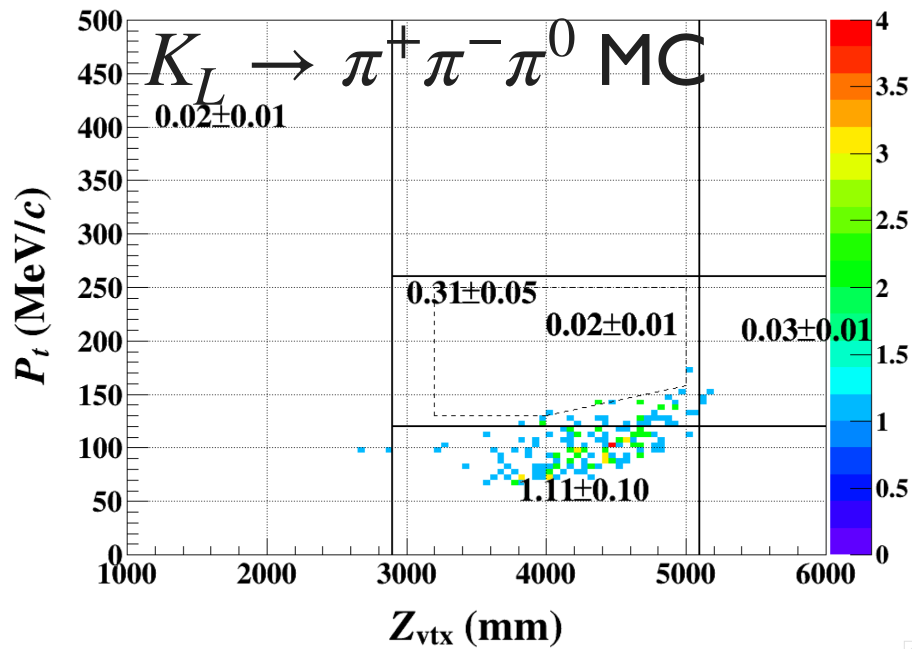




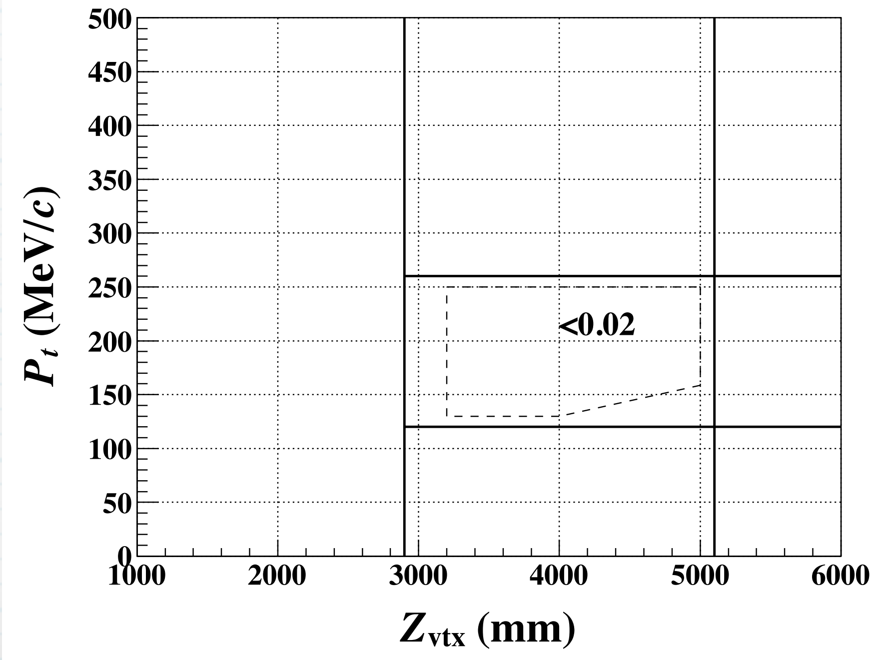
Against $K_L \to \pi^+\pi^-\pi^0$ background



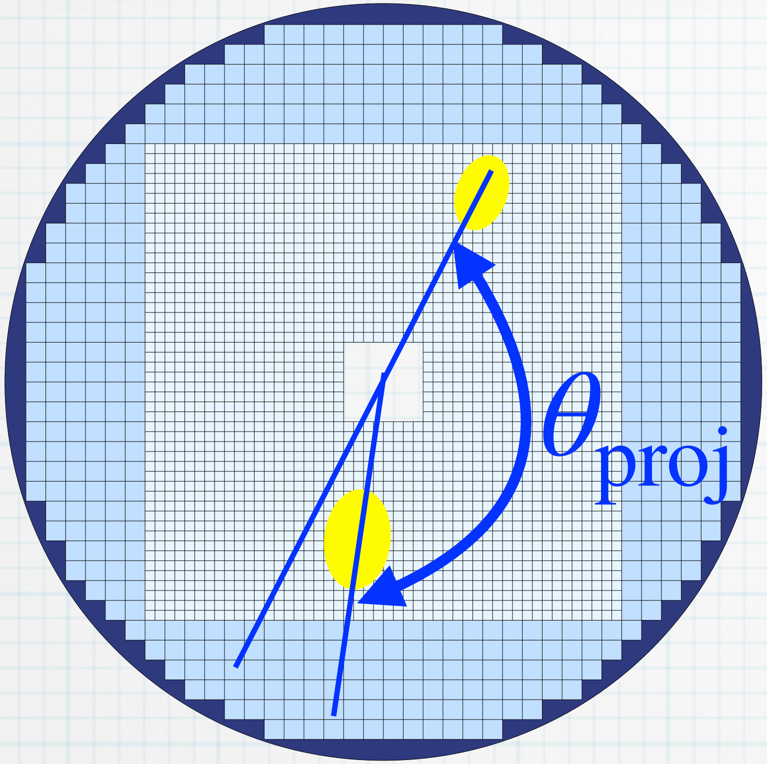
- Charged veto wrapping beam pipe
- Deep Learning cut

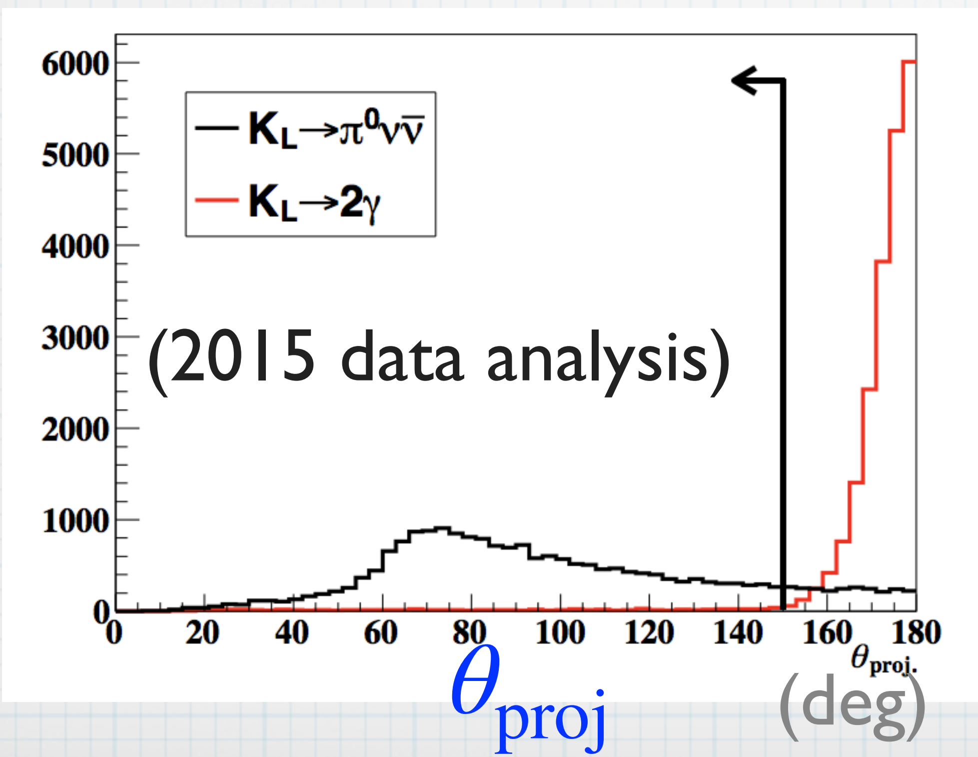


DL



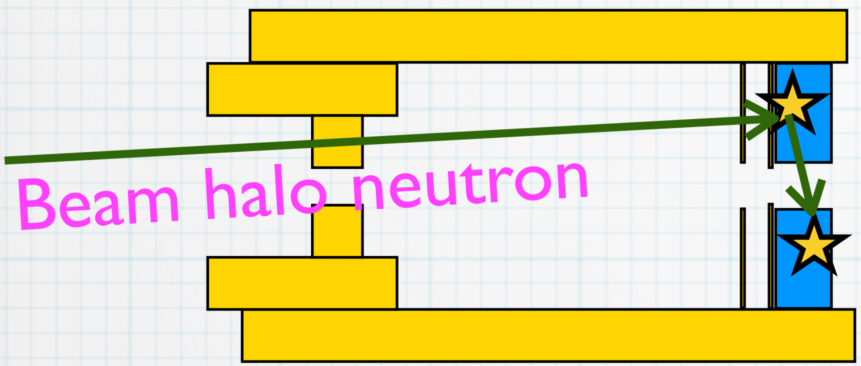
Against $K_L \to \gamma\gamma$ background

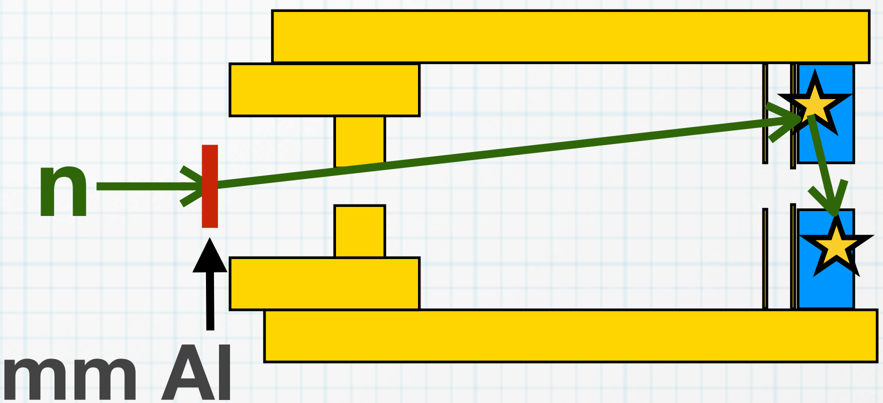


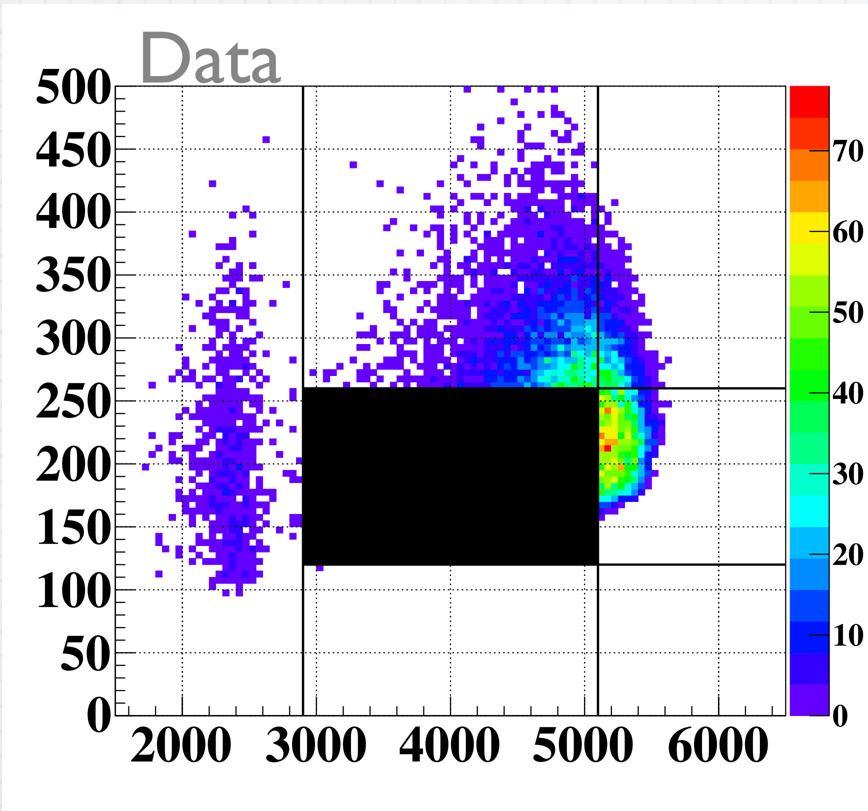


- P_T > 120 MeV/c
- $\theta_{proj} < 150°$

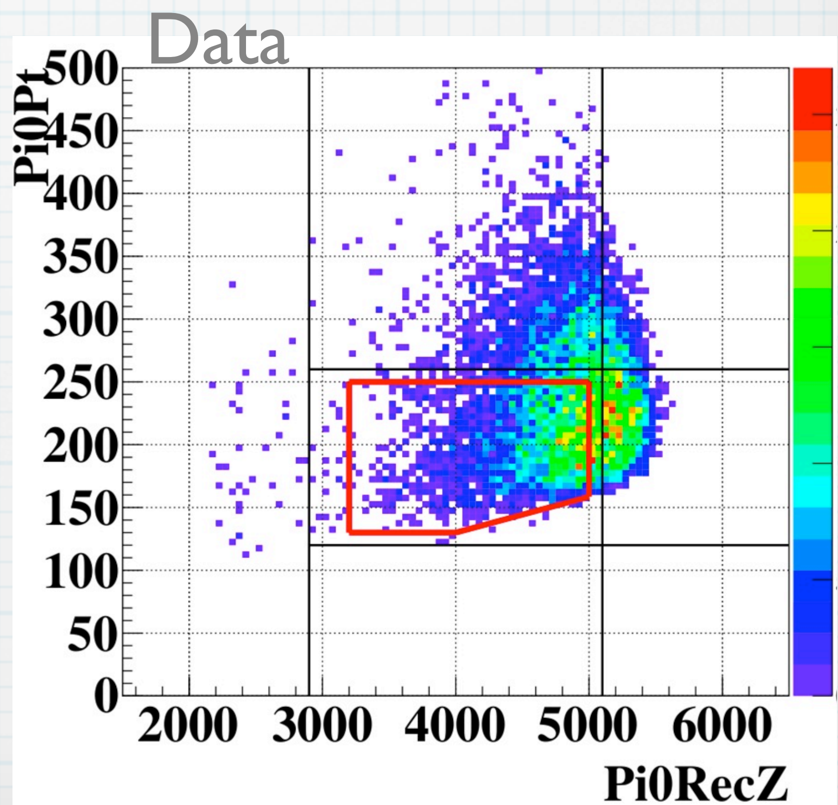
Against hadron cluster background





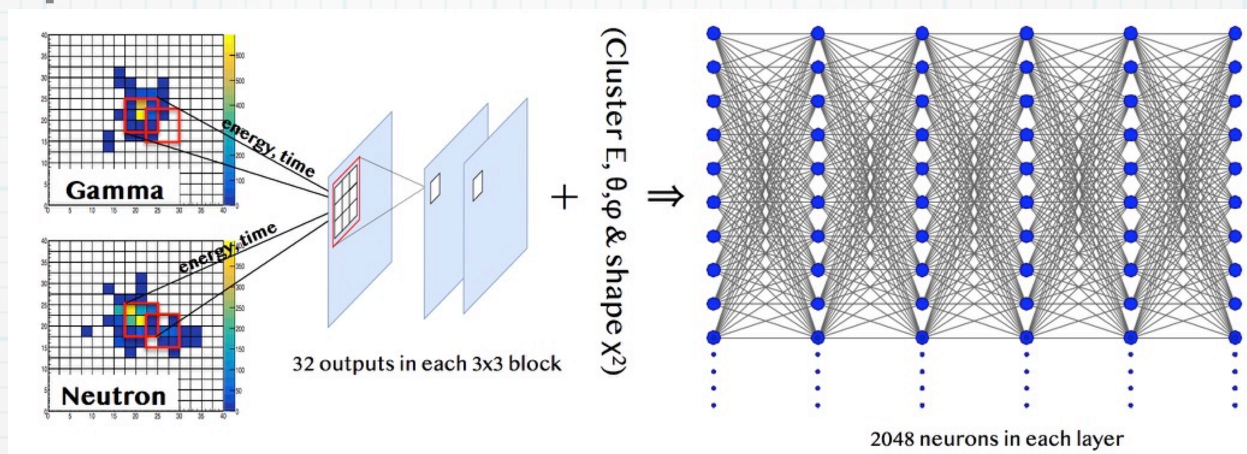


Loose cut,
w/o
neutron
cut

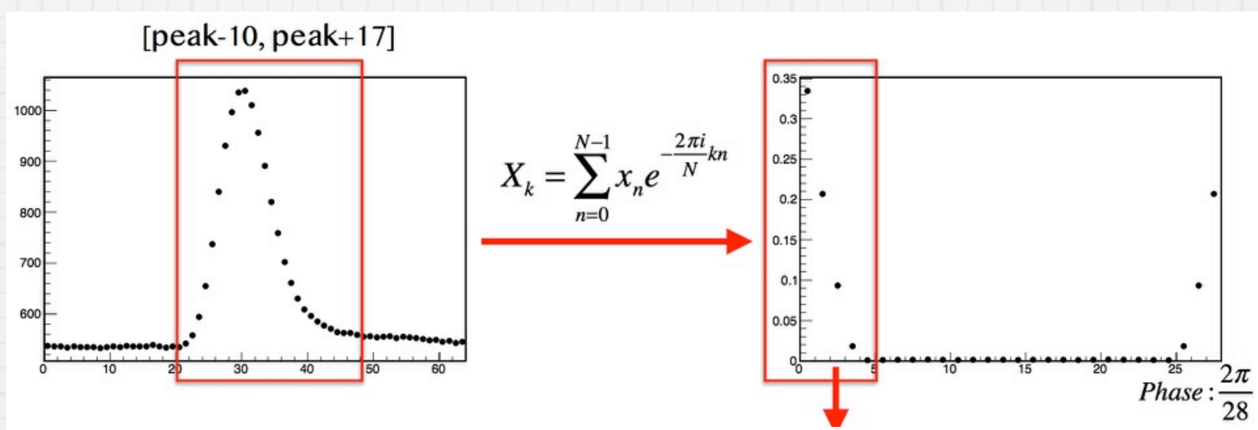


Against hadron cluster background

- Cluster shape difference: Neural Net

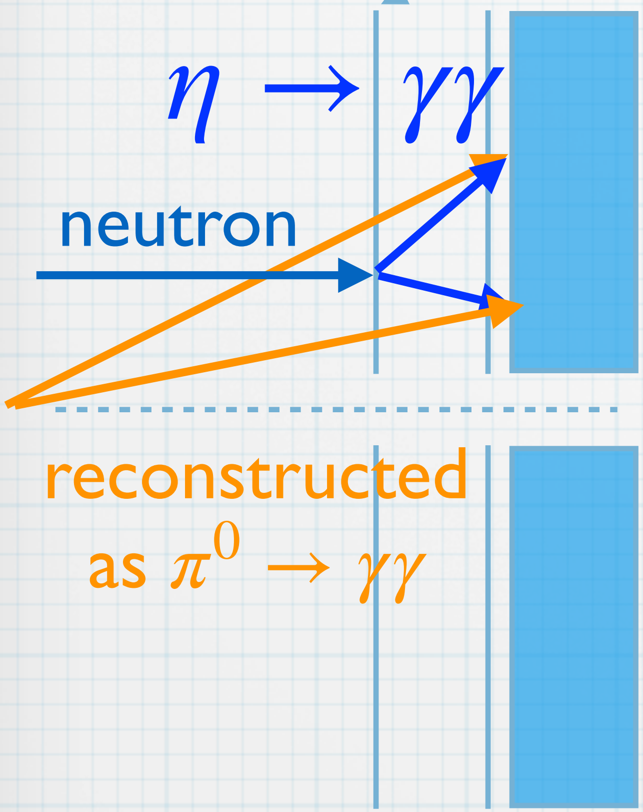


- Pulse shape difference: FFT waveform

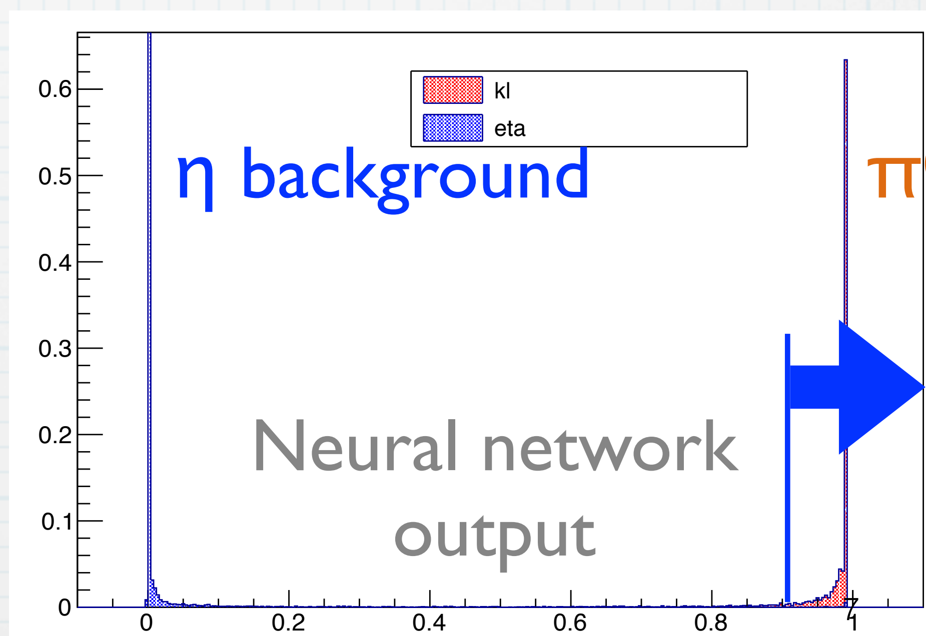


- Combined reduction: x (1.8 ± 0.2) x 10^{-6}

Against η's produced in Charged Veto

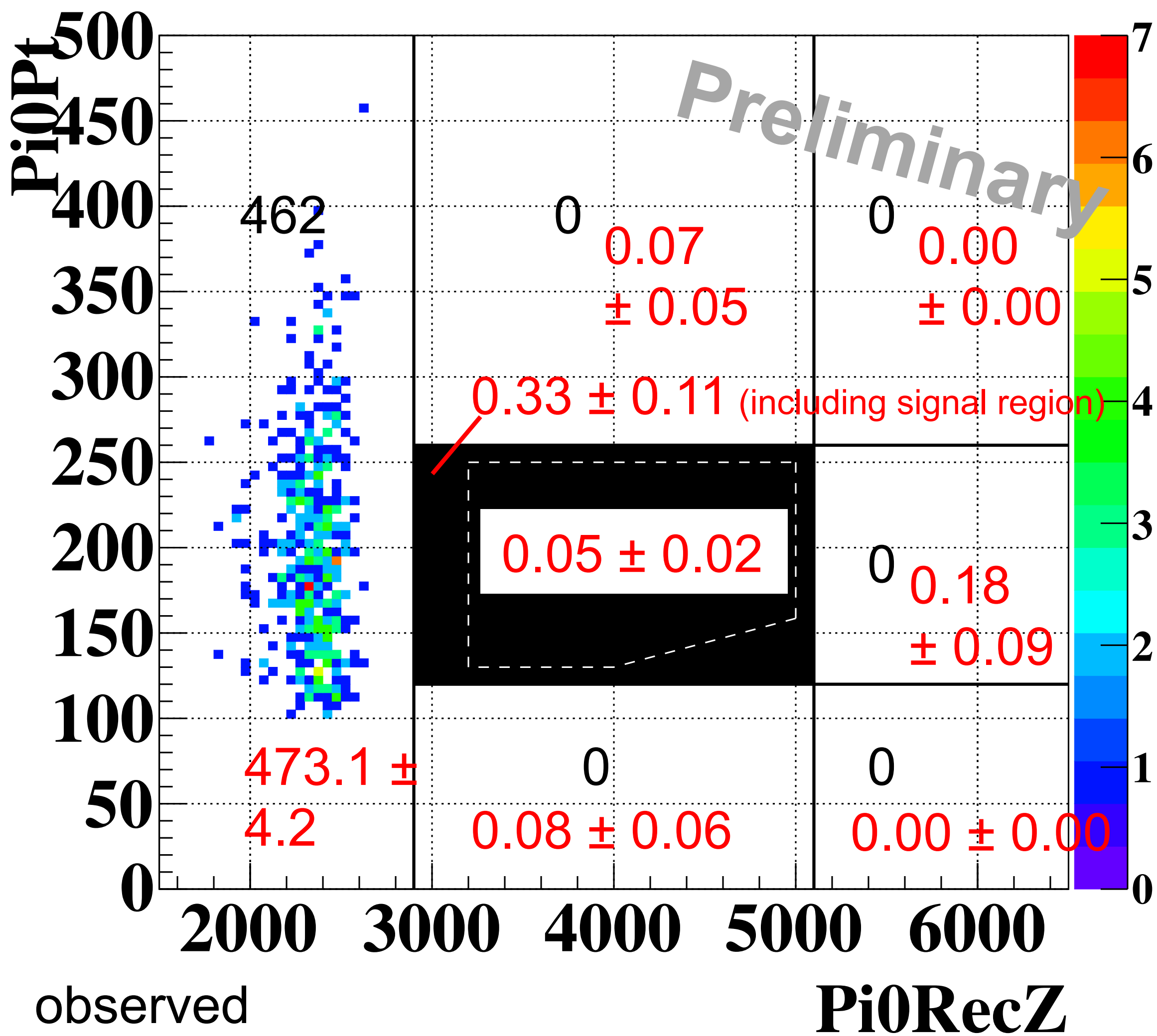


* Shower shape difference:
  * Used neural network based on energy and timing of each crystal in clusters



Background estimation at the end of Aug. 2019

S.E.S : 6.9×10^{-10}

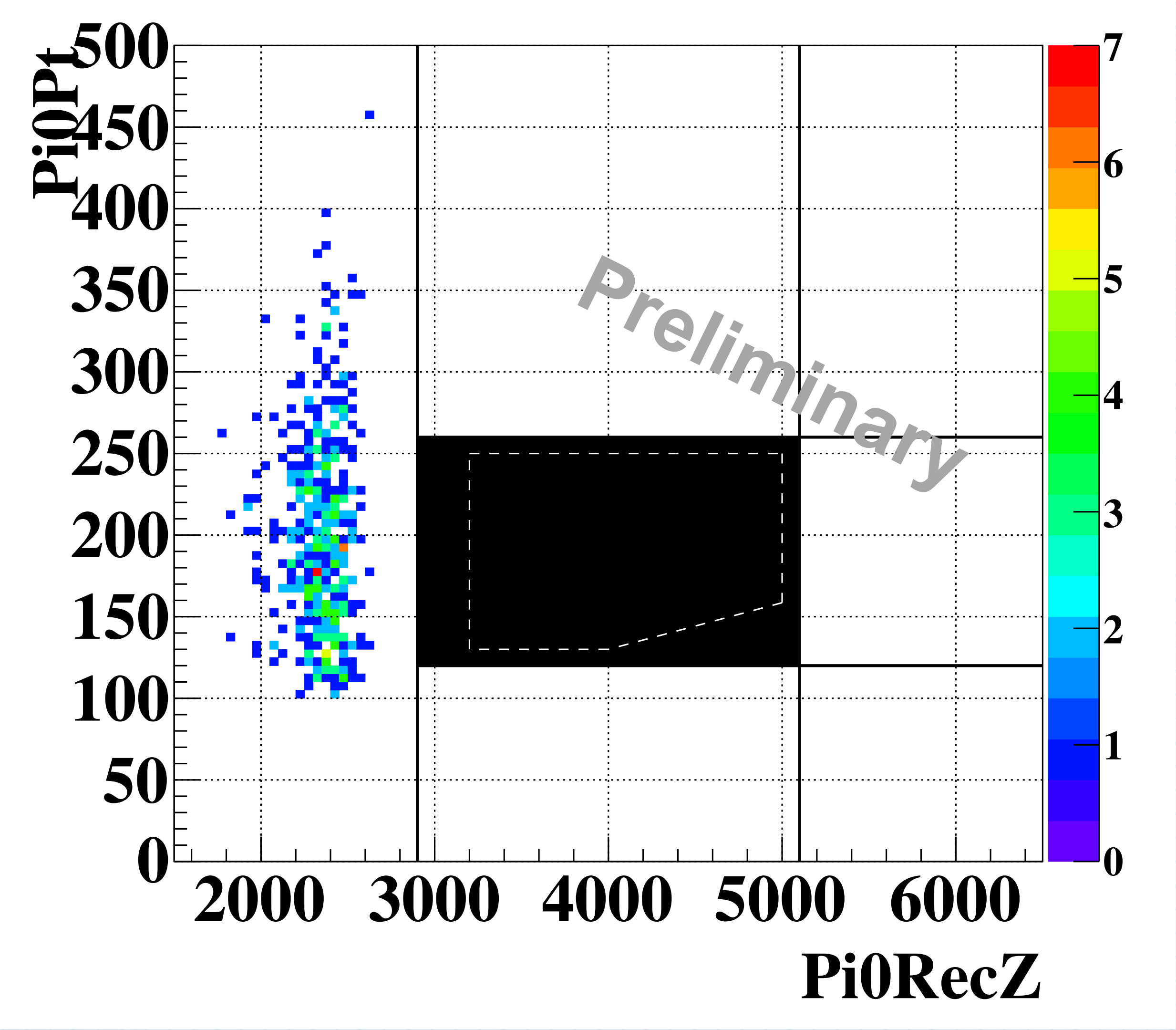


observed

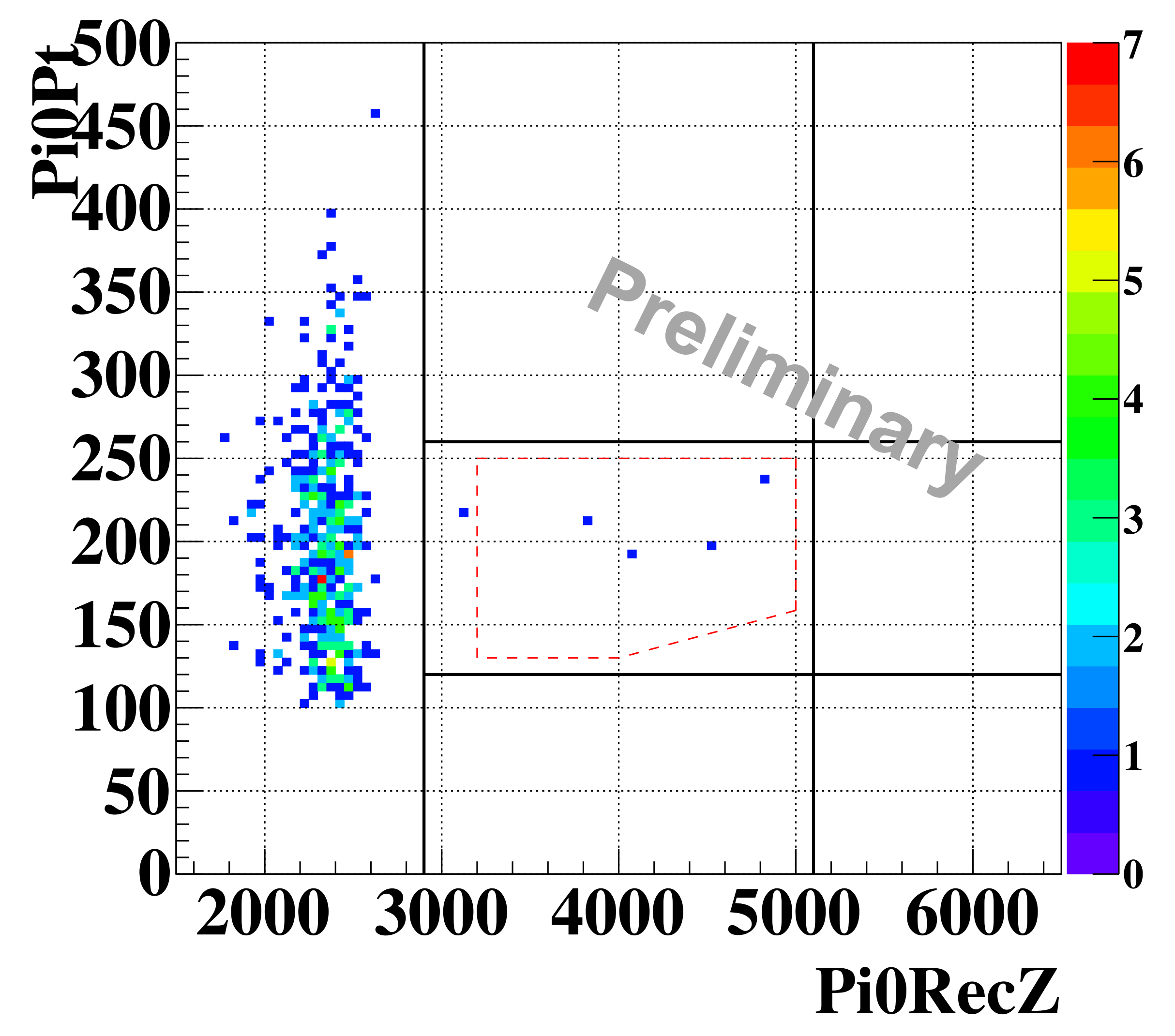
expectation

	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
KL2gamma	0.00 ± 0.00
Upstream π^0	0.00±0.00
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

Data at the end of Aug. 2019



so we opened the box…

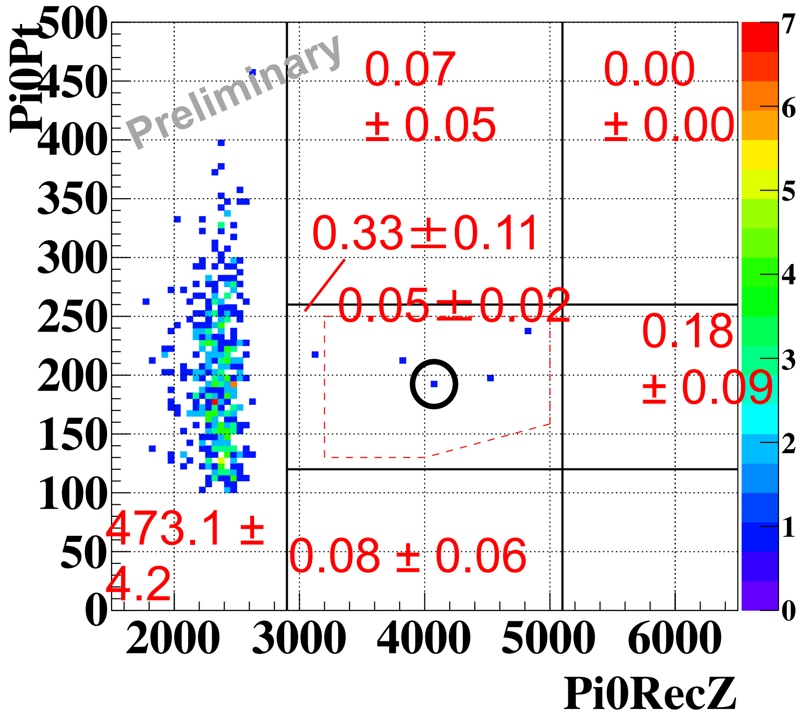


* 4 events inside the signal region

Many checks

* Event properties
  * 1 event was due to our error
* Loosened cut analysis
* Detector efficiency stabilities
* Analysis with cuts used for 2015 data
* …
* but nothing wrong

On Sep. 10, 2019.
Presented the status at the KAON 2019 Conference
by S. Shinohara



expectation

BG estimation related overlapped pulse

Preliminary

	#BG
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09

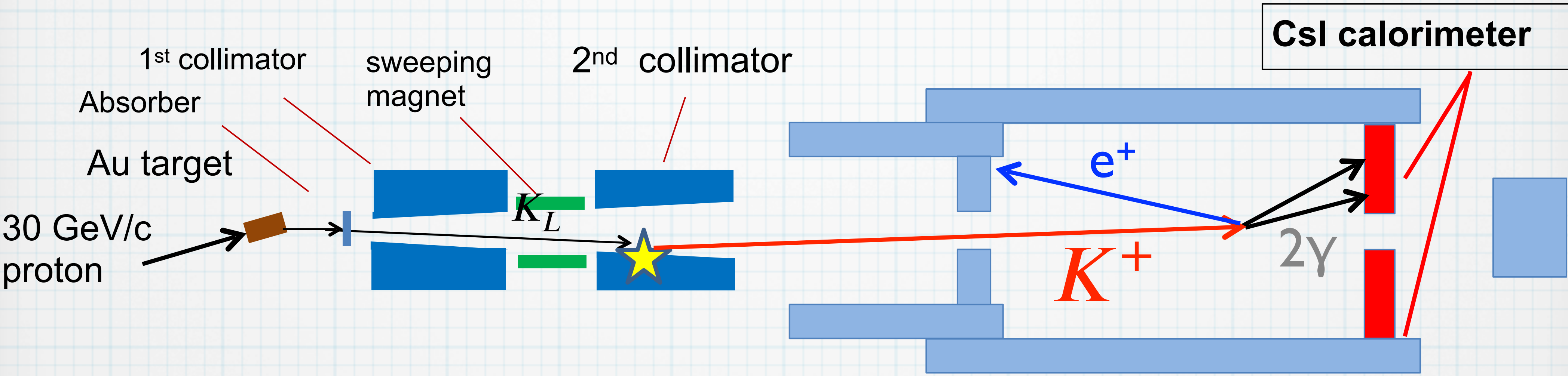
Underestimated the BG from overlapped pulse?

- Checking the properties of the other candidates
- Did we miss other background sources?
    - planning to reevaluate other BG sources

After KAON2019

- NO CHANGE IN CUTS
- Found an error in timing parameters. 4→3 events by fixing it.
- Found two new background sources, and updated background estimation

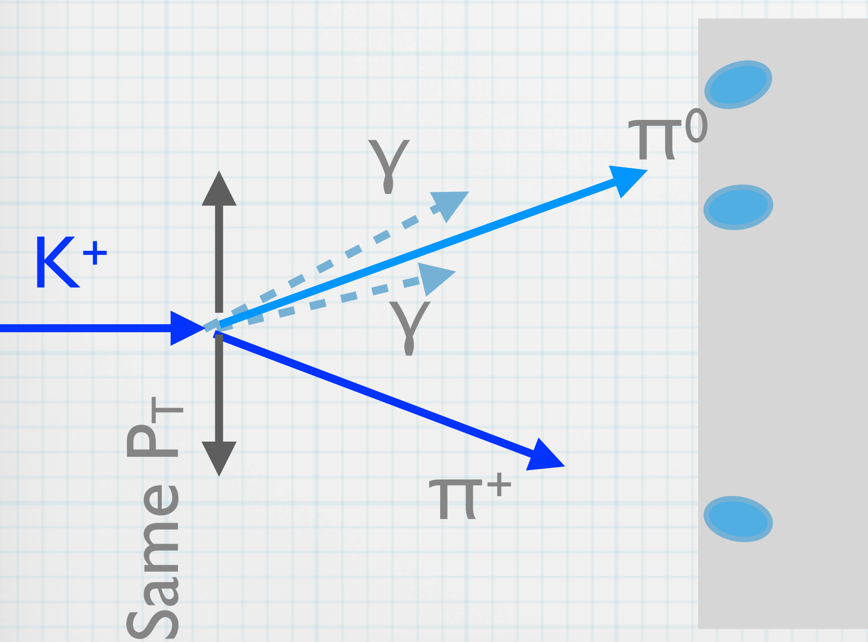
1. $K^+ \to \pi^0 e^+ \nu$ background

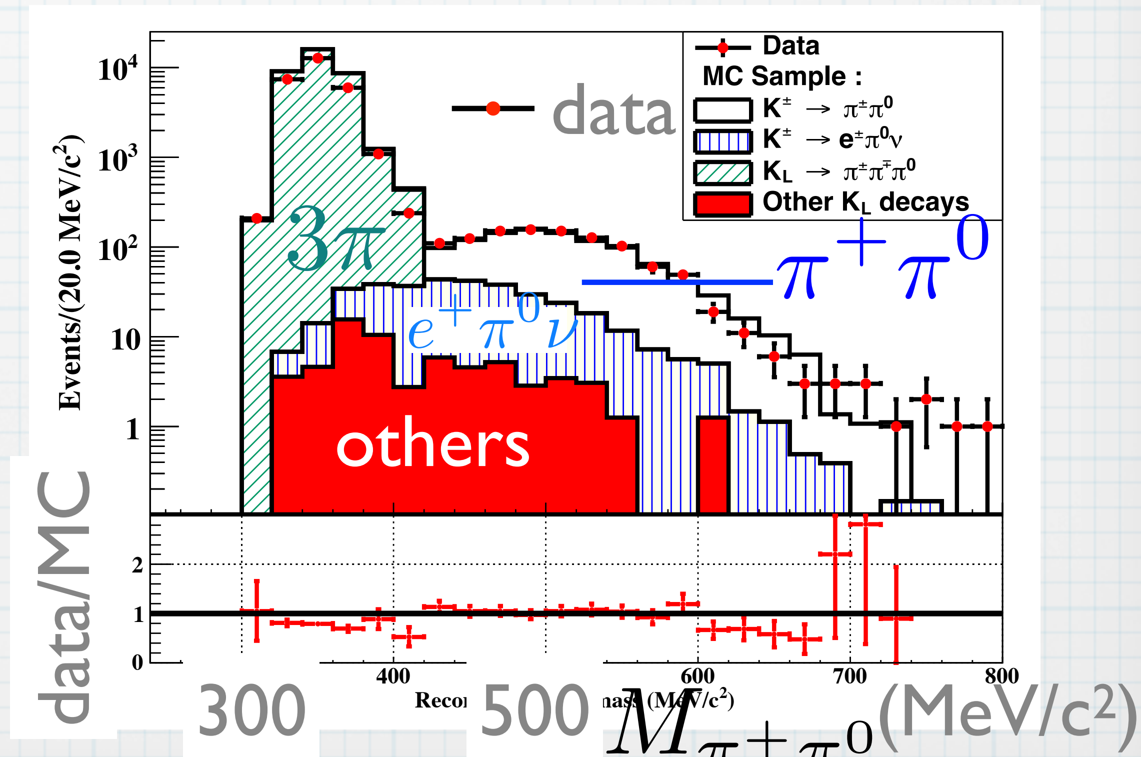


- P^*_{max} = 228 MeV/c
- Background if K^+ is produced, and e^+ is missed

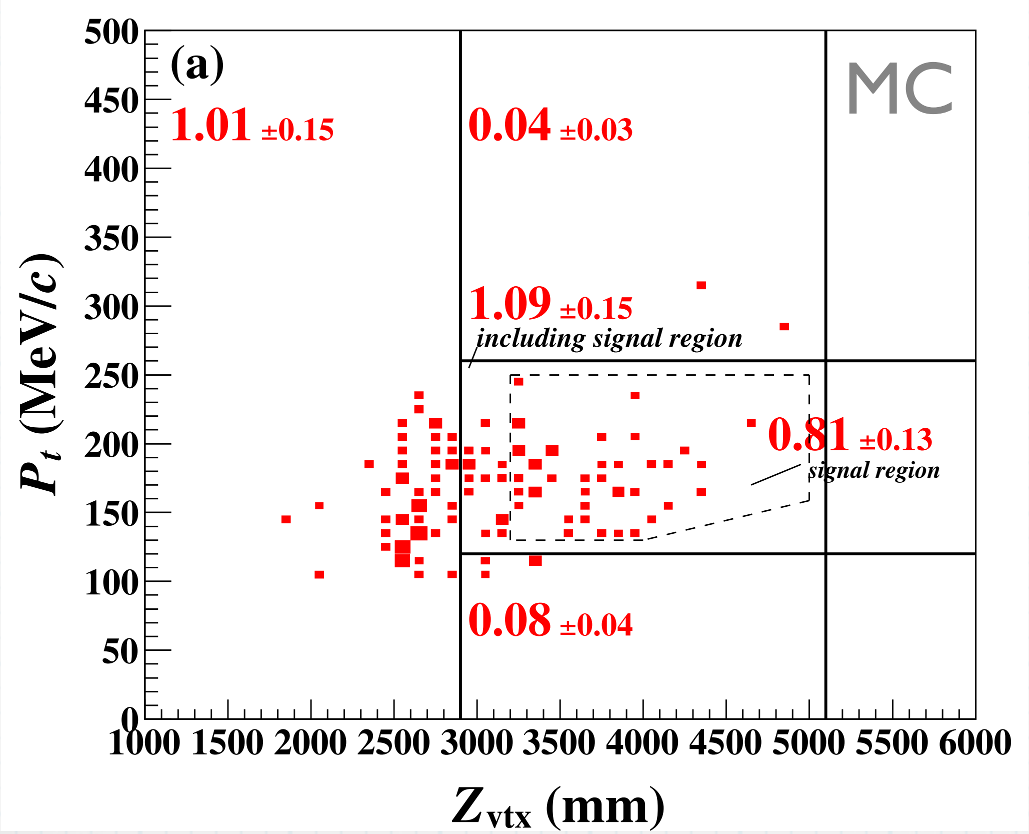
1. $K^+ \to \pi^0 e^+ \nu$ background: Yield of K⁺ in neutral beam

- In 2020, reconstructed 847 $K^+ \to \pi^+\pi^0$ events
- $K^+/K_L = (2.6 \pm 0.1) \times 10^{-5}$ in the beam

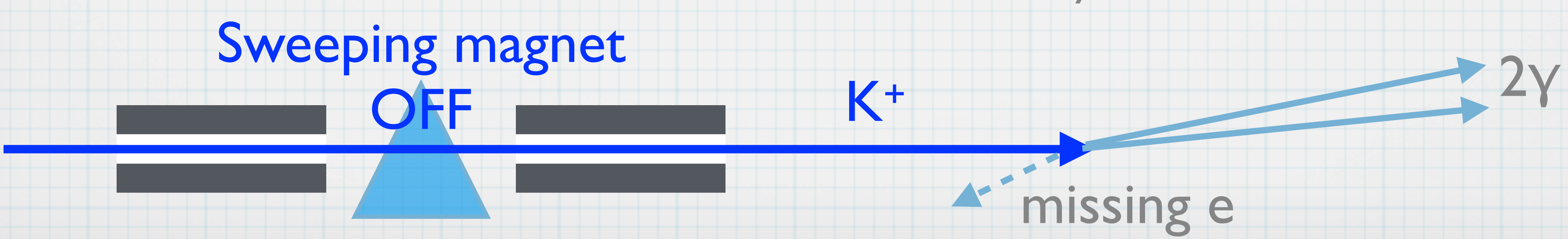




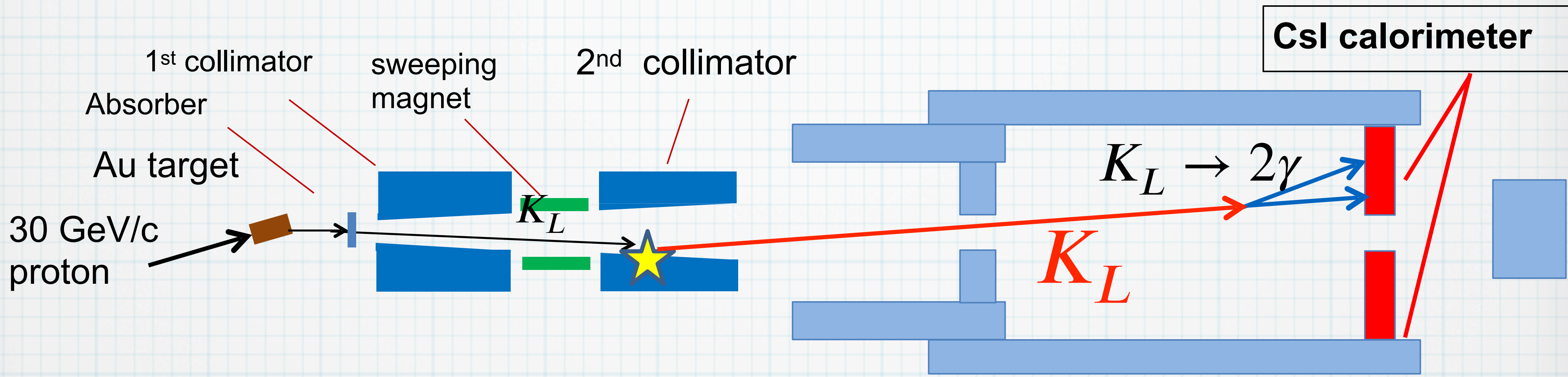
1. $K^+ \to \pi^0 e^+ \nu$ background: # of background events



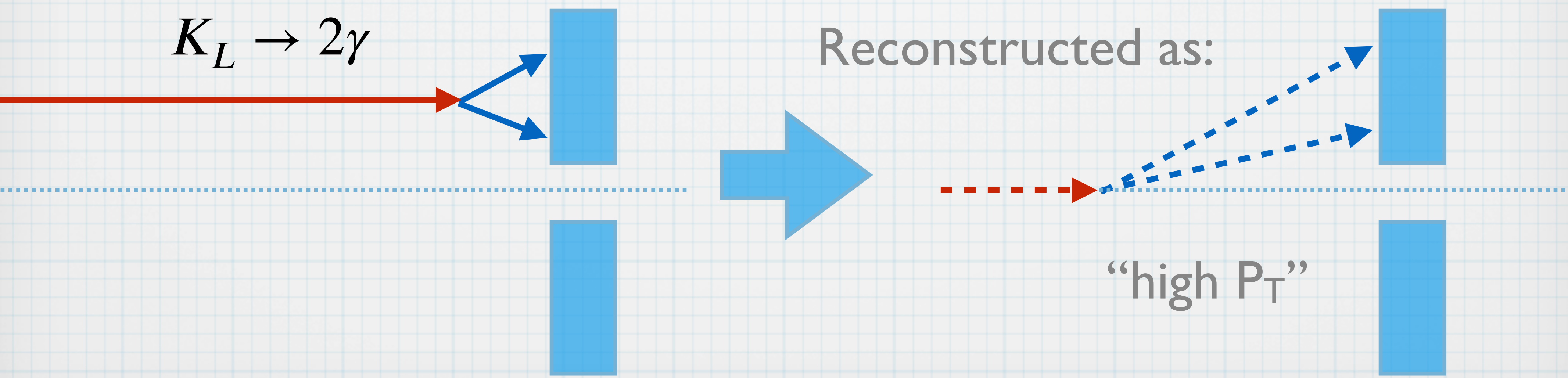
- MC: 0.81 ± 0.13 evts
- With sweeping magnet OFF, observed 27 evts (26.0 ± 3.2 expected)
- $0.87 \pm 0.13_{stat} \pm 0.21_{syst}$ evts after corr.



2. Halo $K_L \to \gamma\gamma$ background



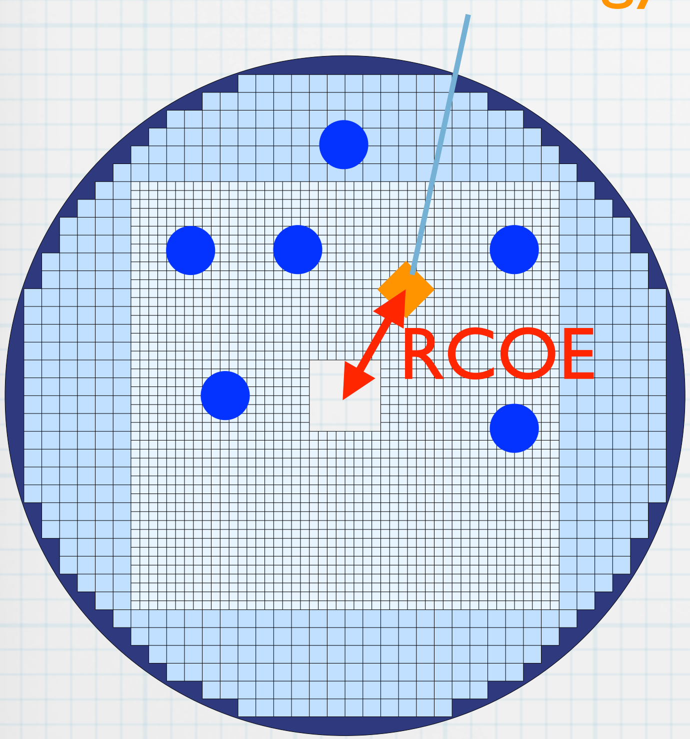
* Background if K_L in beam halo decays to 2γ

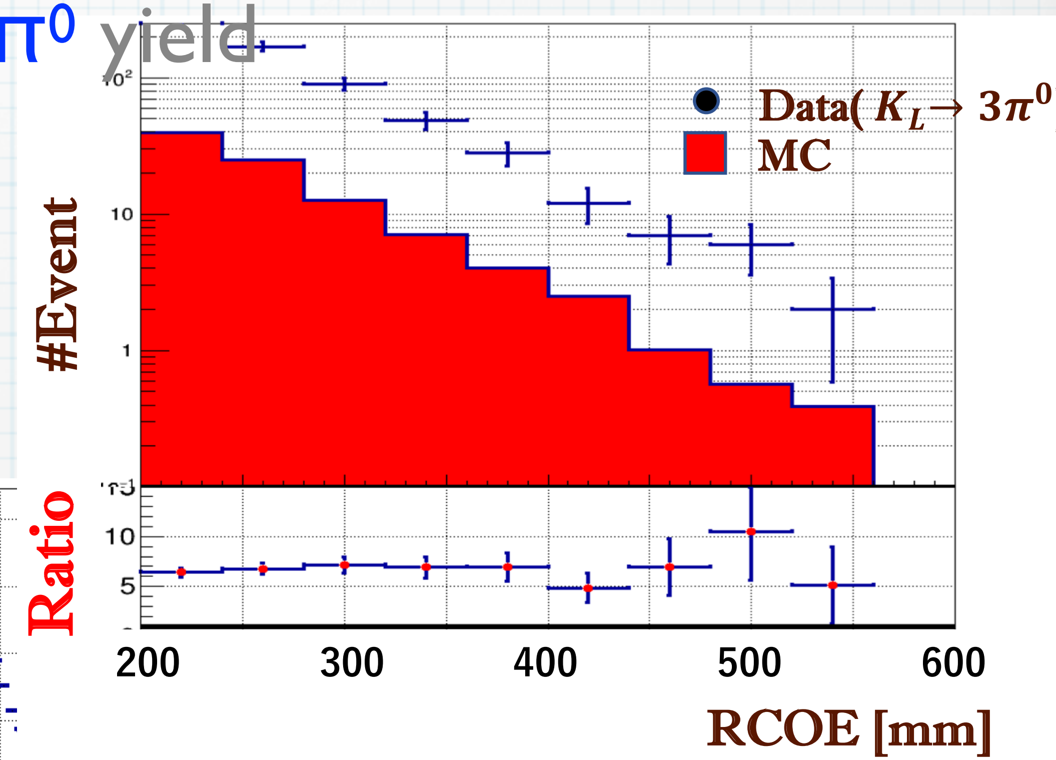


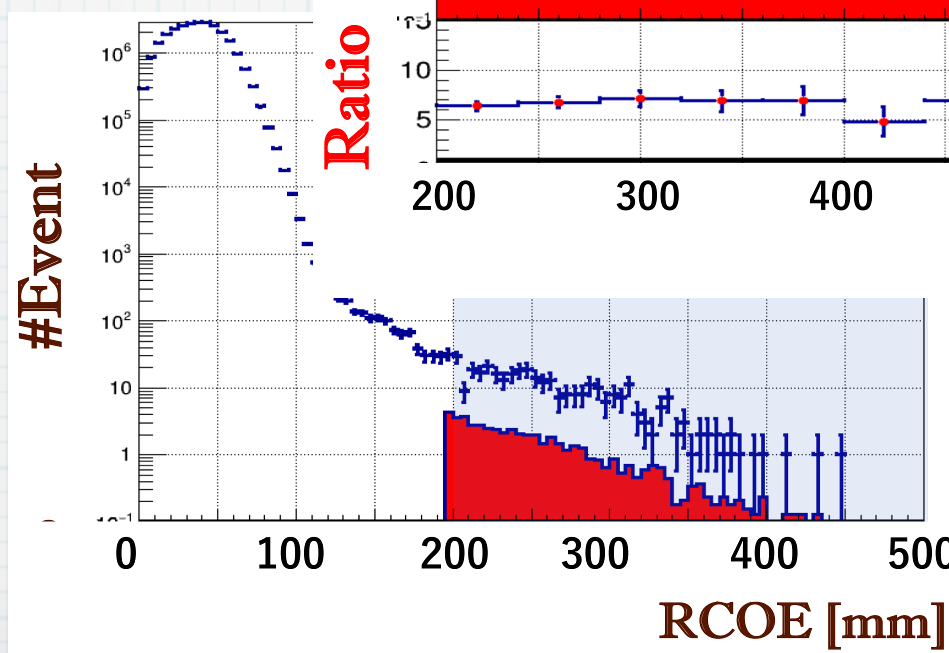
2. Halo $K_L \rightarrow \gamma\gamma$ background: Yield of halo K_L

- Measured halo $K_L \rightarrow 3\pi^0$ yield
- data: ~7x MC

Center of Energy

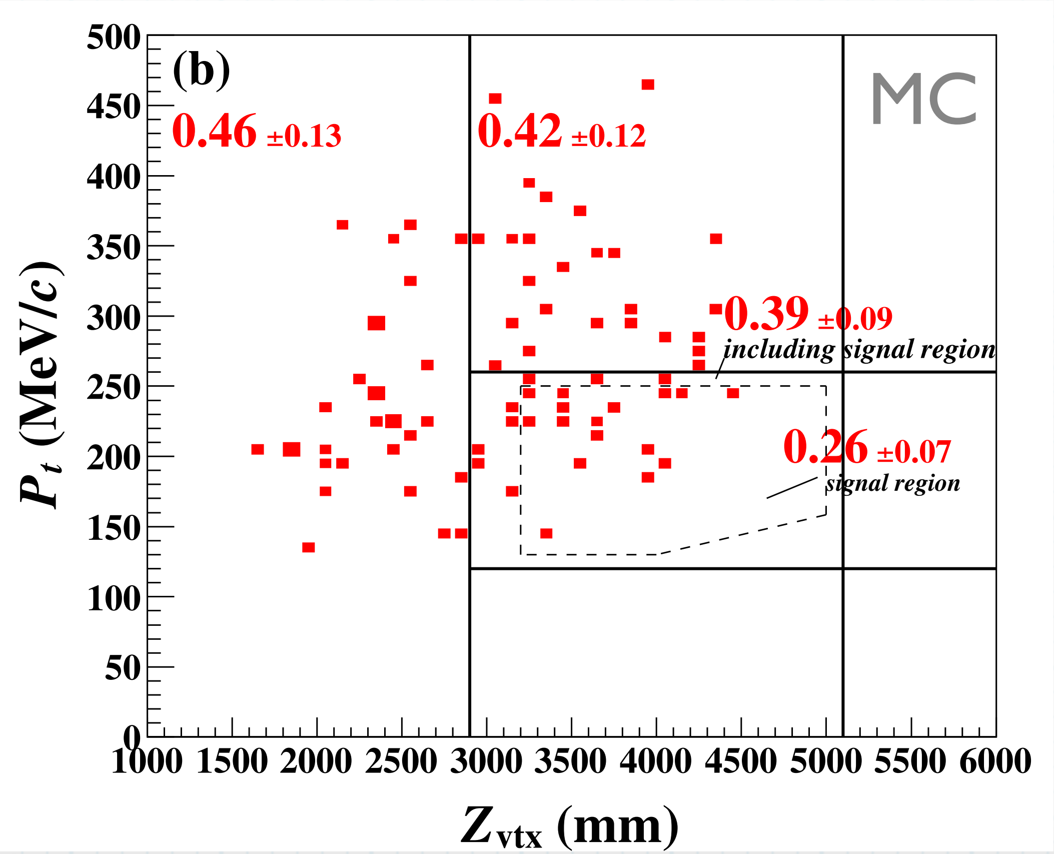






2. Halo $K_L \rightarrow \gamma\gamma$ background: # of background events

- Scaled #MC events by the data/MC ratio
- Estimated 0.26 ± 0.07 bkg events



Final Background Estimation

source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam-halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25 [a]
Neutron	Hadron-cluster	0.017 ± 0.002
	Upstream-π^0	0.03 ± 0.03
	CV-η	0.03 ± 0.01
total		1.22 ± 0.26

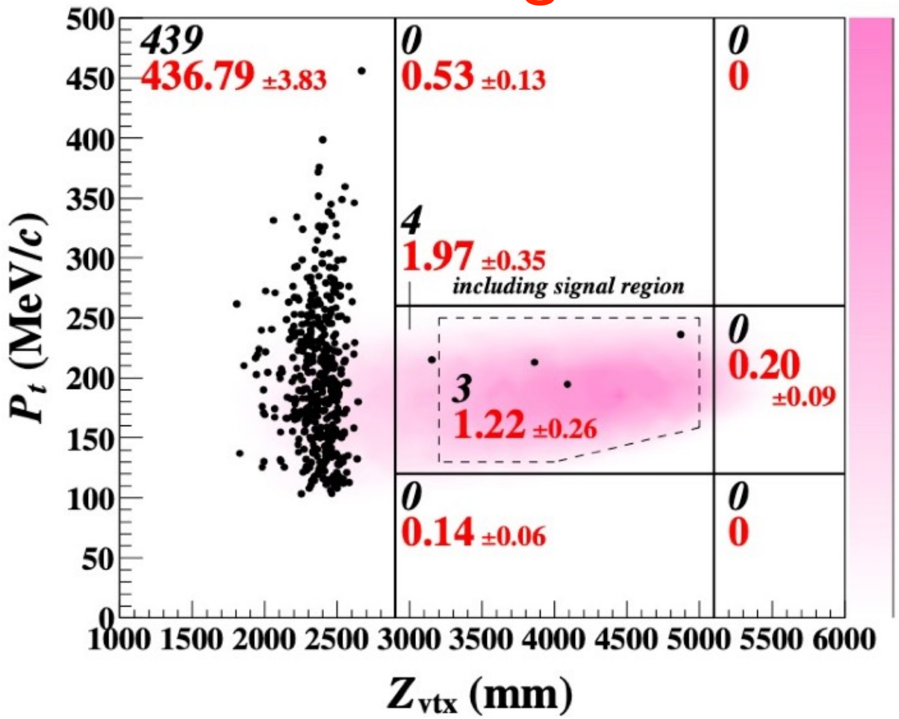
[a] Background sources studied after looking inside the blind region.

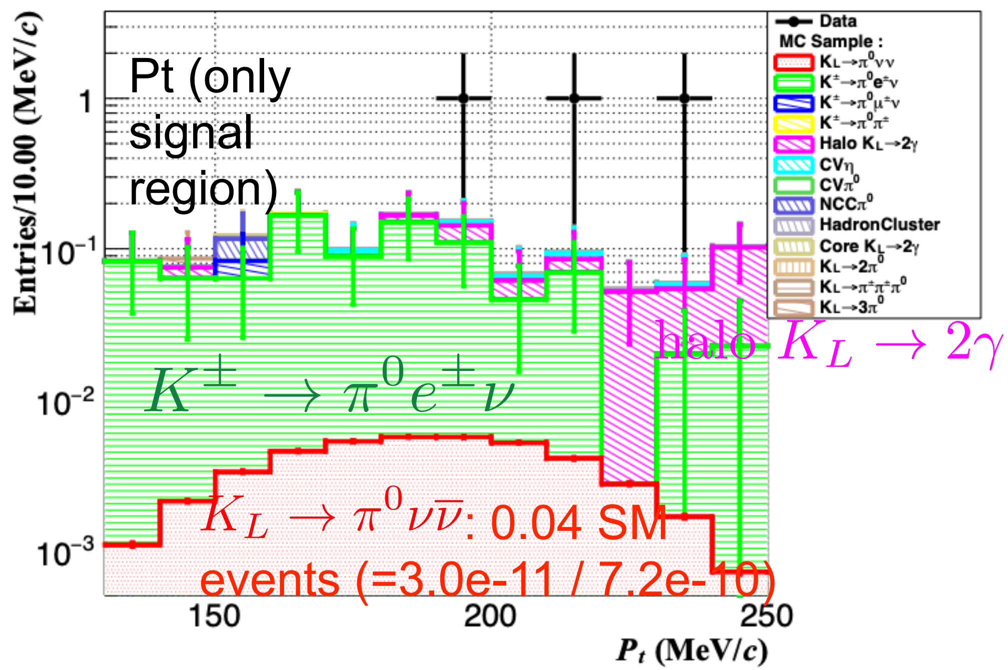
Backgrounds w/ upper limits

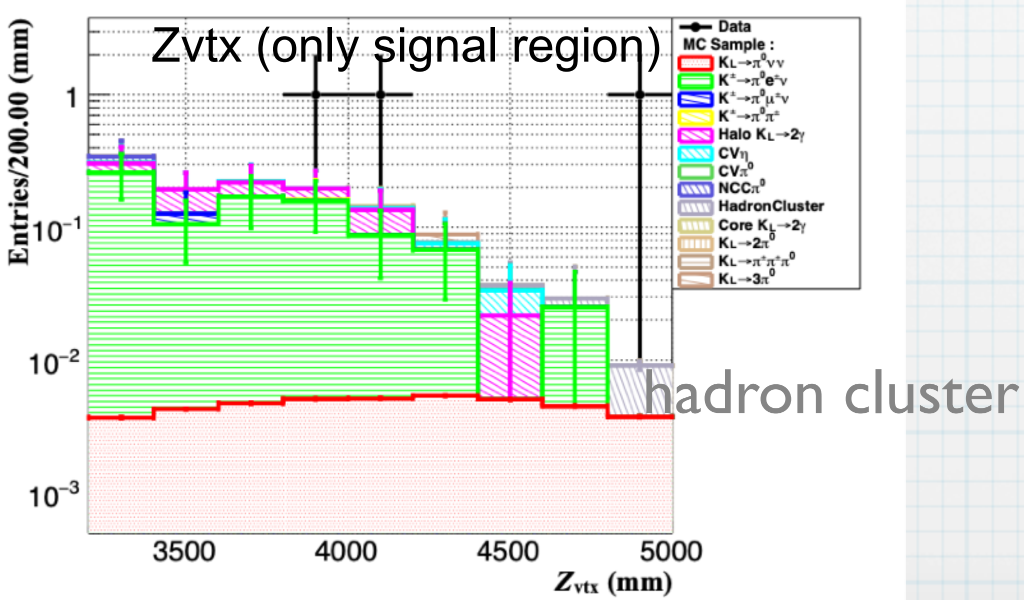
$$
\begin{array}{ll}
K_L \to \pi^{\pm} e^{\mp} \gamma \nu & < 0.05 \text{ (90\% C.L.)} \\
K_L \to \pi^{0} \pi^{\pm} e^{\mp} \nu & < 0.04 \text{ (90\% C.L.)} \\
K_L \to \pi^{\pm} \pi^{\mp} & < 0.03 \text{ (90\% C.L.)} \\
K_L \to ee\gamma & < 0.09 \text{ (90\% C.L.)} \\
K_L \to K^{\pm} e^{\mp} \nu & < 0.04 \text{ (90\% C.L.)}
\end{array}
$$

data

background MC



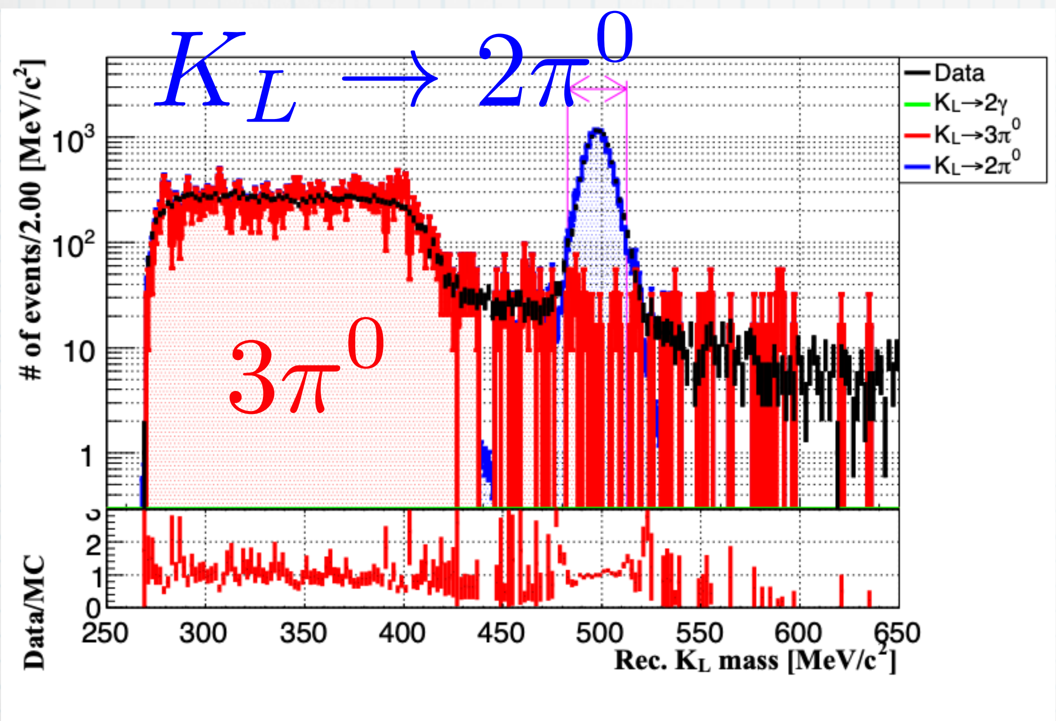


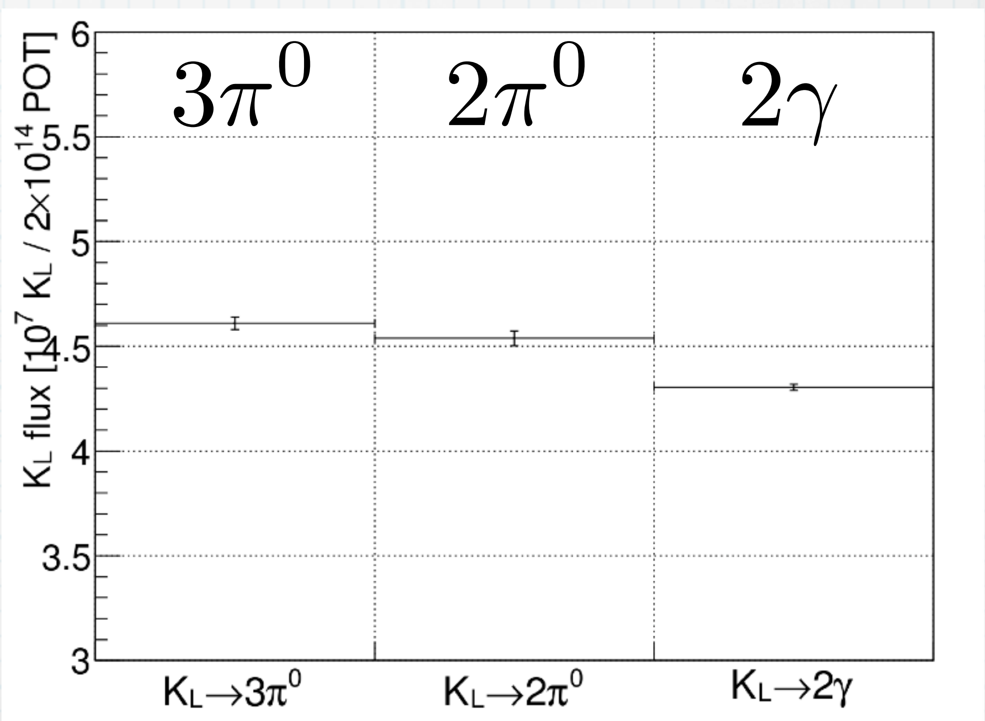


Sensitivity

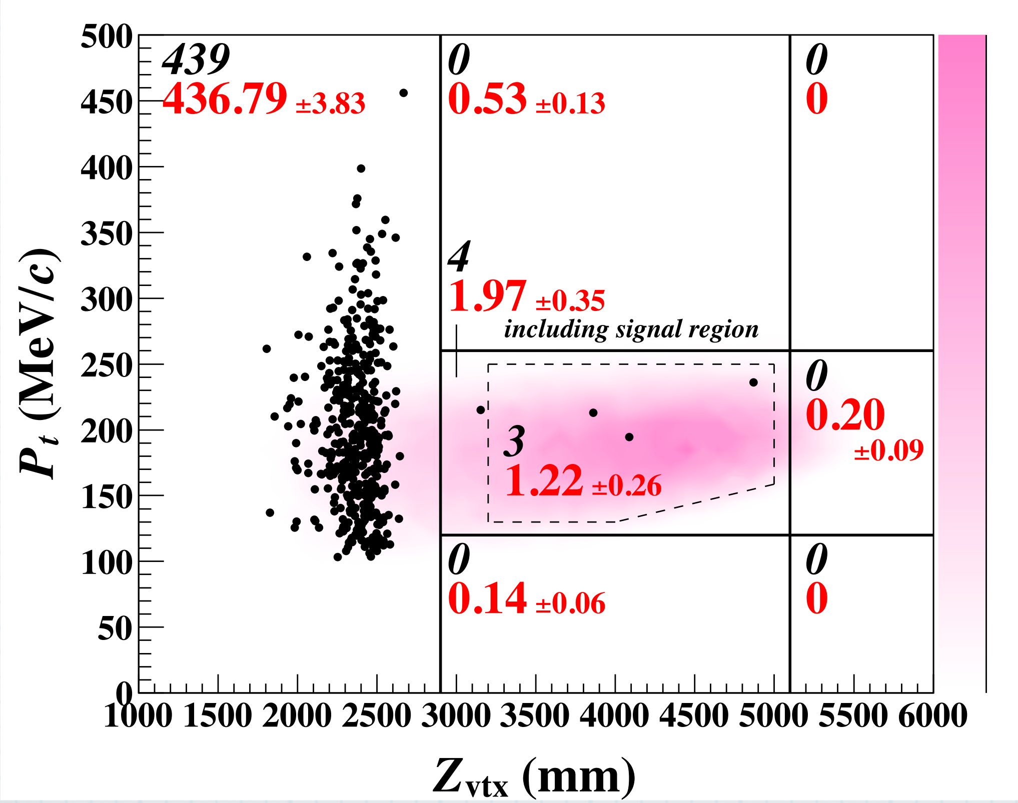
- Single Event Sensitivity: based on $K_L \to 2\pi^0$

$$SES = \frac{A_{2\pi}\ Br_{2\pi}}{A_{\rm sig}\ N_{2\pi}}$$
$$= \frac{1}{A_{\rm sig}\ N_{\rm K\ decay}}$$
$$= (7.20 \pm 0.05\ \text{stat} \pm 0.66\ \text{syst}) \times 10^{-10}$$





Final results from the 2016-2018 run



- 3 observed events @sensitivity = 7.20 x 10^{-10}
- 1.22 ± 0.26 bkg events
- BR < 4.9 x 10^{-9} (90% CL)

Final results from the 2016-2018 run

* Submitted to a journal

arXiv:2012.07571v1 [hep-ex] 14 Dec 2020

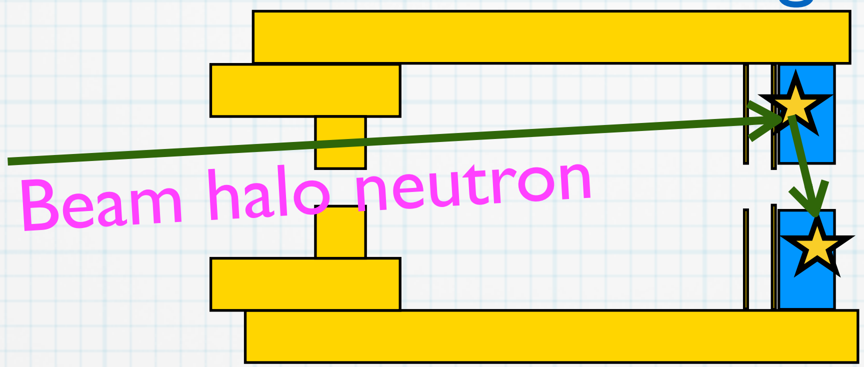
Study of the $K_L \to \pi^0 \nu \overline{\nu}$ decay at the J-PARC KOTO experiment

J. K. Ahn,[1] B. Beckford,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] M. S. Farrington,[5] K. Hanai,[6] N. Hara,[6] H. Haraguchi,[6] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[7] M. Isoe,[6] I. Kamiji,[8] T. Kato,[6] E. J. Kim,[9] J. L. Kim,[9] H. M. Kim,[9] T. K. Komatsubara,[7,10] K. Kotera,[6] S. K. Lee,[9] J. W. Lee,[6,*] G. Y. Lim,[7,10] Q. S. Lin,[5] C. Lin,[3] Y. Luo,[5] T. Mari,[6] T. Masuda,[11] T. Matsumura,[12] D. Mcfarland,[4] N. McNeal,[2] K. Miyazaki,[6] R. Murayama,[6,†] K. Nakagiri,[8,‡] H. Nanjo,[8,§] H. Nishimiya,[6] Y. Noichi,[6] T. Nomura,[7,10] T. Nunes,[6] M. Ohsugi,[6] H. Okuno,[7] J. C. Redeker,[5] J. Sanchez,[2] M. Sasaki,[13] N. Sasao,[11] T. Sato,[7] K. Sato,[6,¶] Y. Sato,[6] N. Shimizu,[6] T. Shimogawa,[14,**] T. Shinkawa,[12] S. Shinohara,[8,§] K. Shiomi,[7,10] R. Shiraishi,[6] S. Su,[2] Y. Sugiyama,[6,**] S. Suzuki,[14] Y. Tajima,[13] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[6,**] T. Toyoda,[6] Y.-C. Tung,[5,††] Q. H. Vuong,[6] Y. W. Wah,[5] H. Watanabe,[7,10] T. Yamanaka,[6] H. Y. Yoshida,[13] and L. Zaidenberg[2]
(KOTO Collaboration)

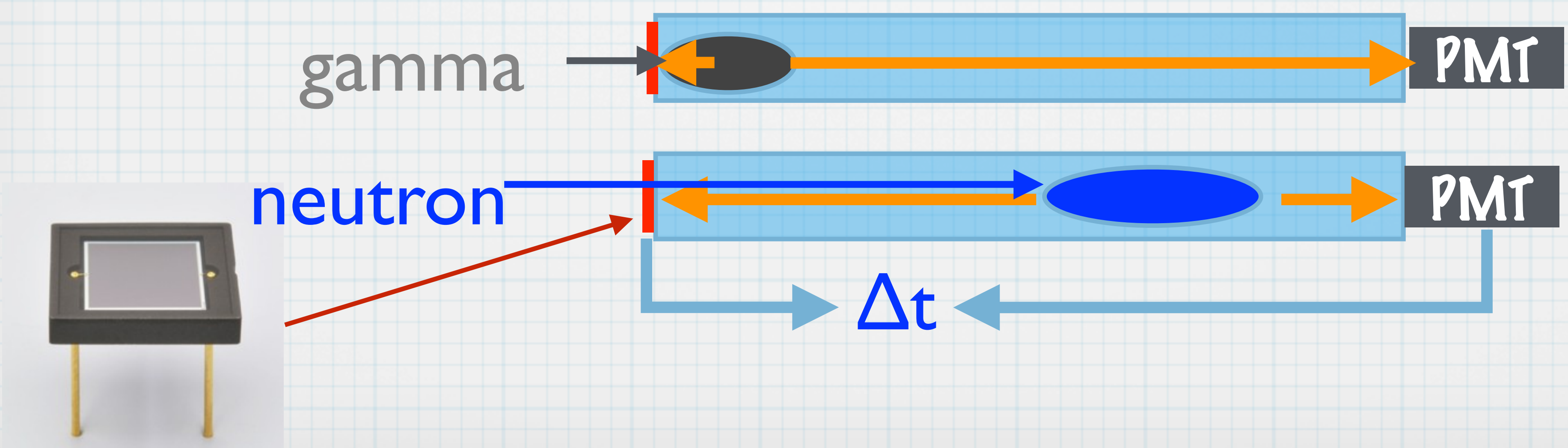
Further Background Suppression

To suppress hadron cluster background

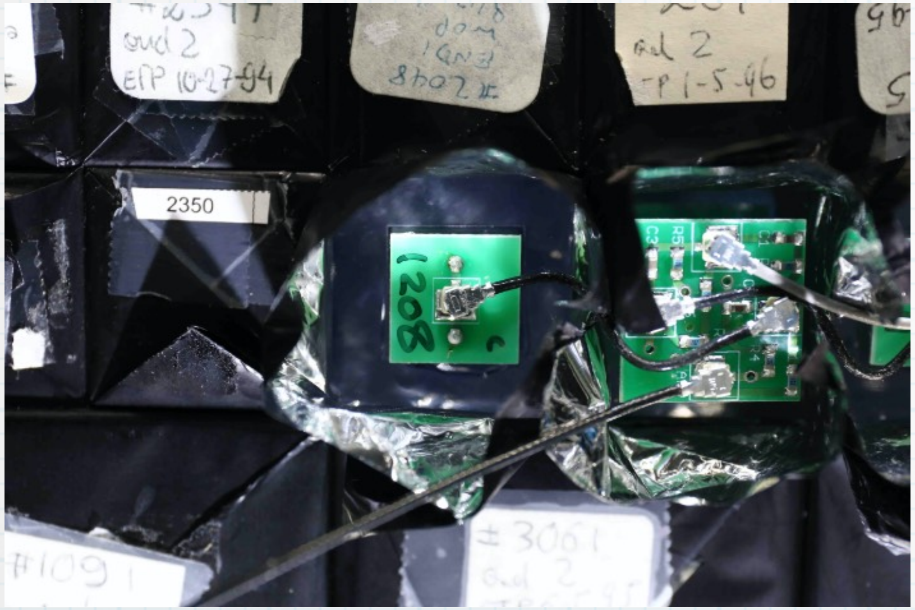
- To suppress the Hadronic background by x 0.1

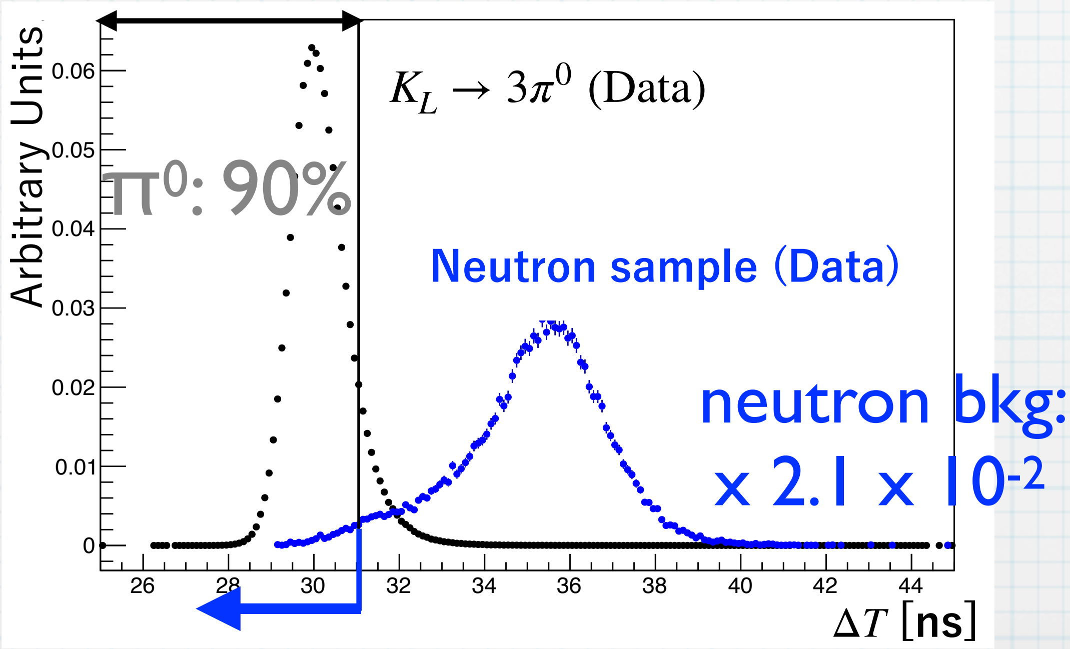


- Utilize shower depth difference



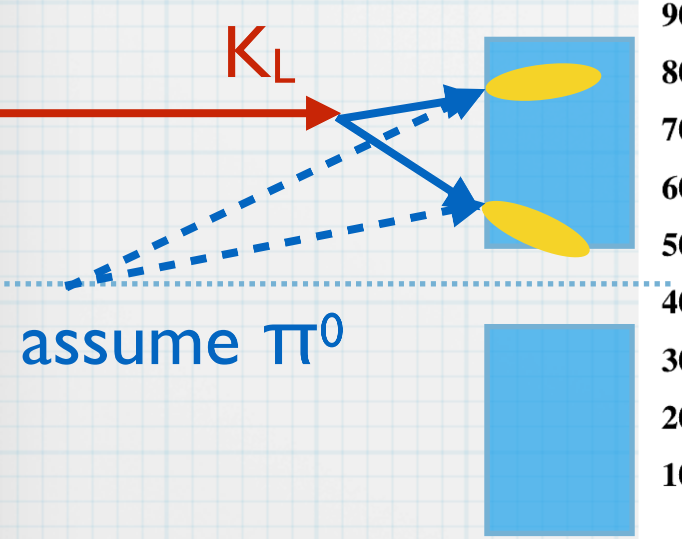
Installed in 2018

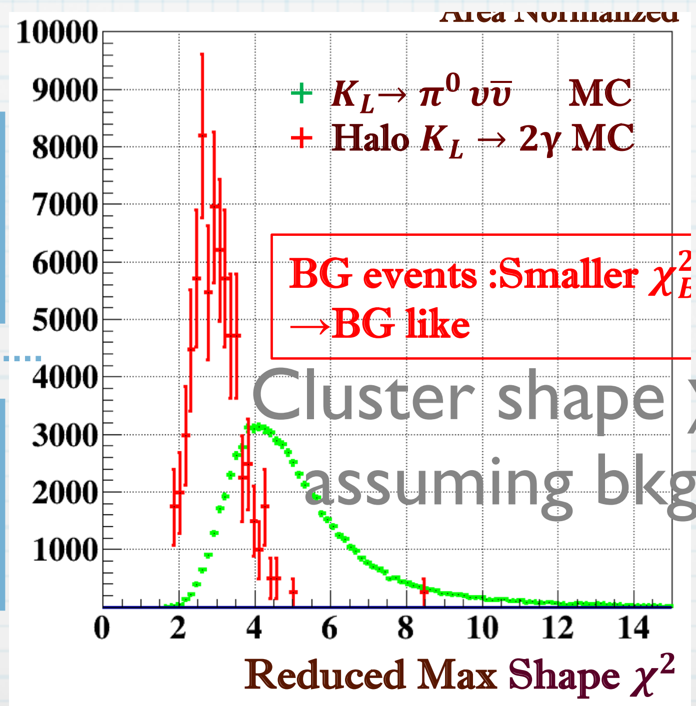


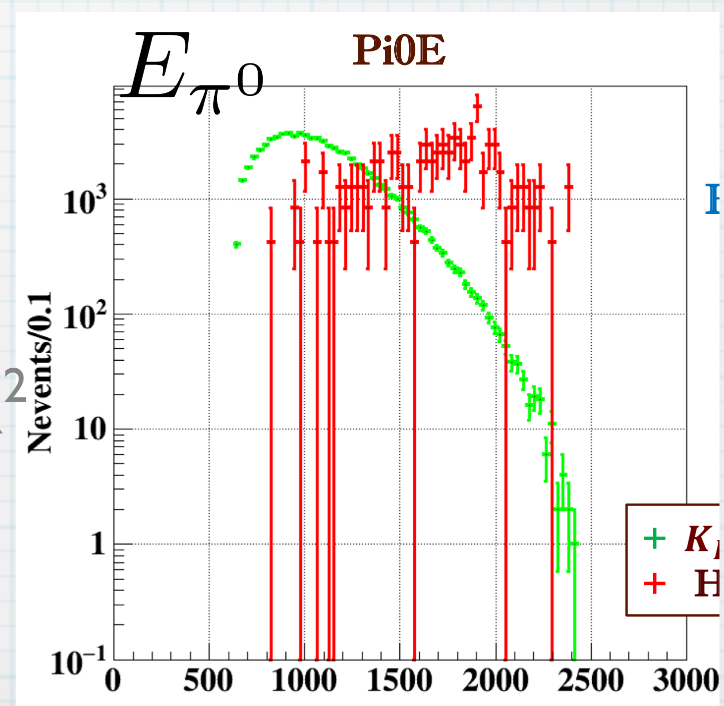


To further suppress Halo $K_L \to 2\gamma$ background

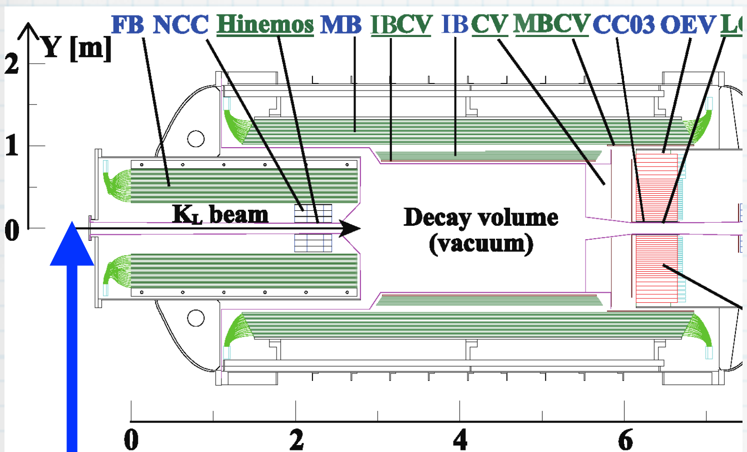
- Developing cuts on
  cluster shape and kinematic parameters
- Bkg: x0.04 (signal: x0.9) (preliminary)

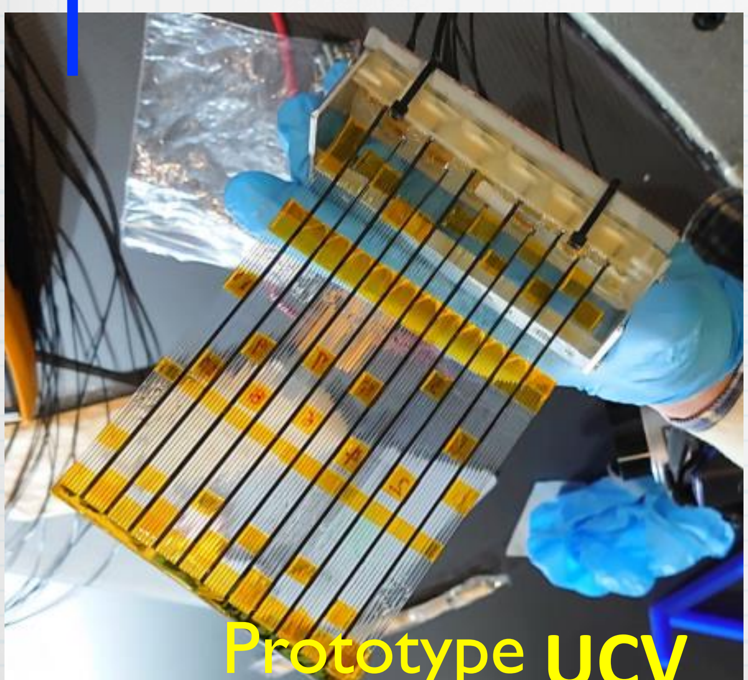




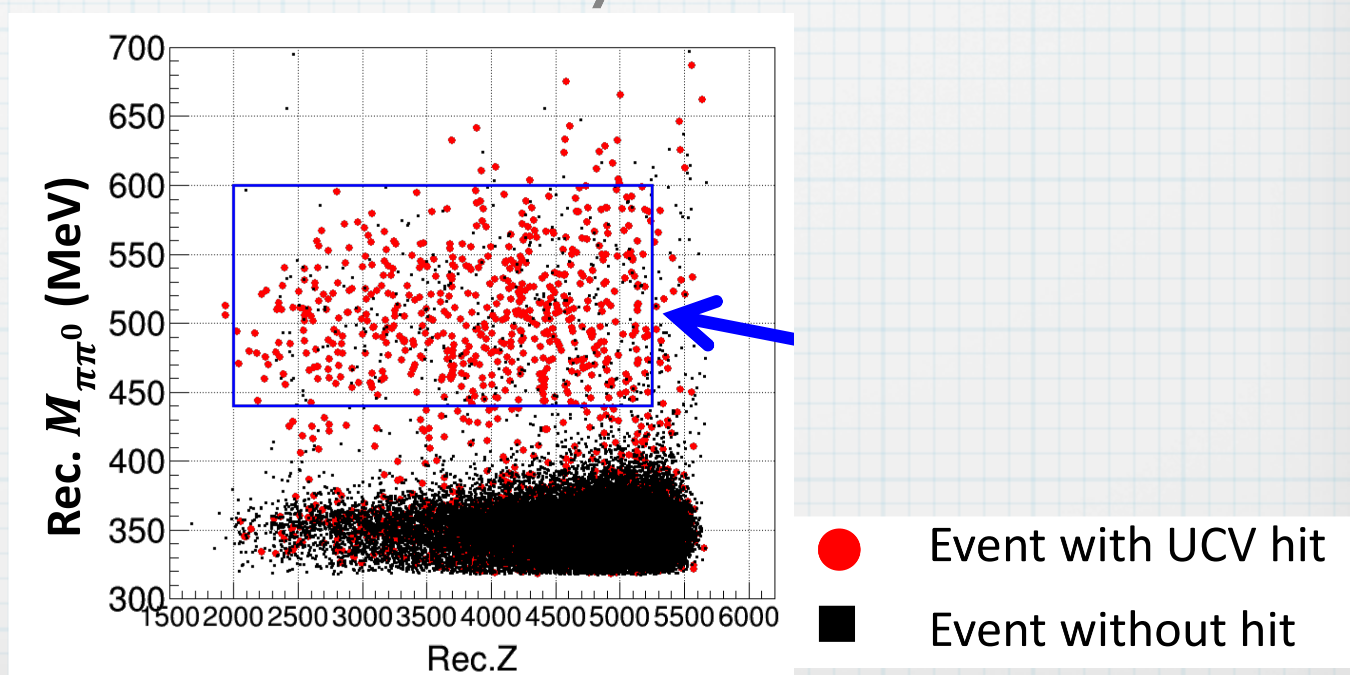


To veto K^+ in beam: Upstream Charged Veto



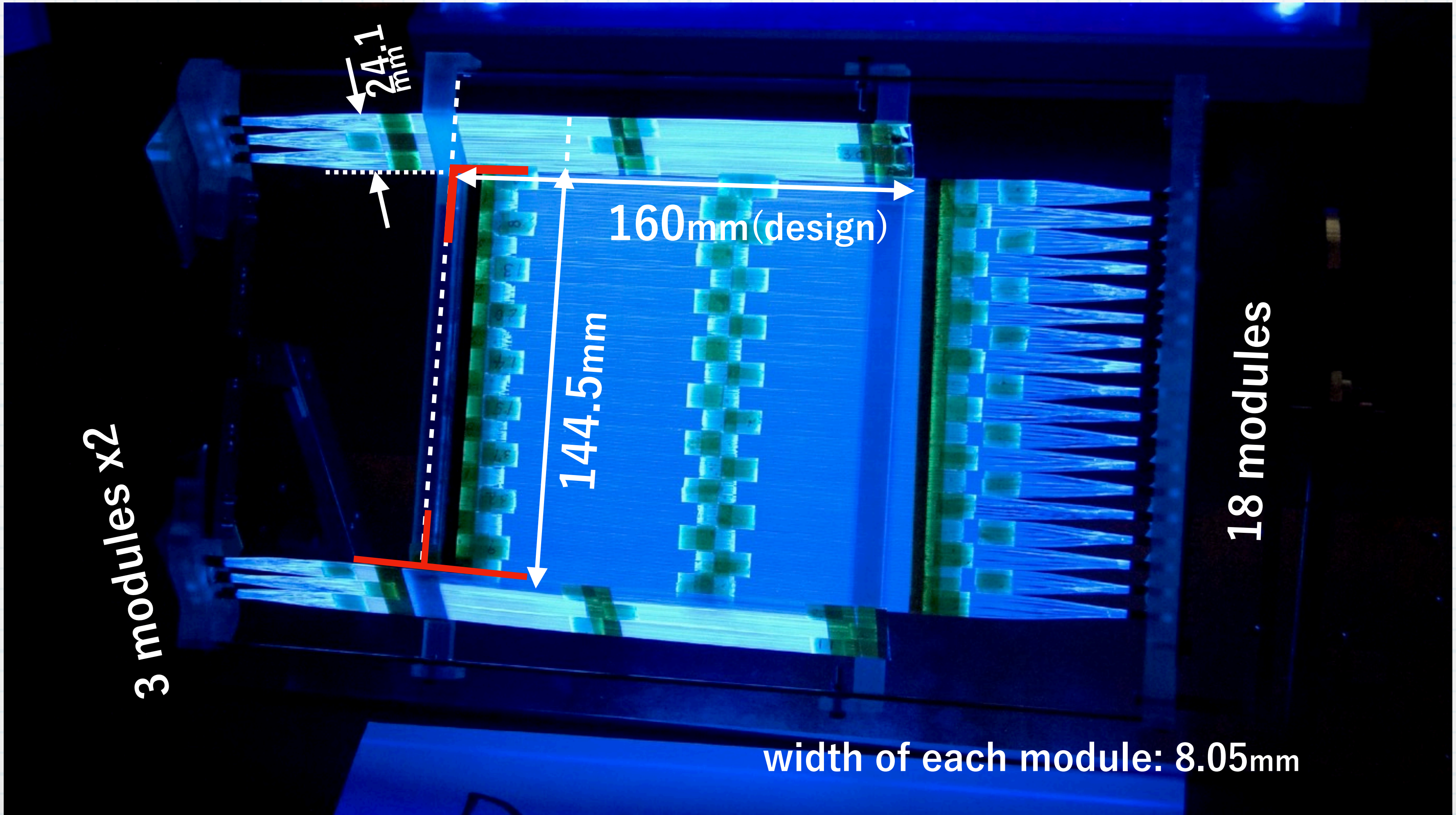


- Tested a **prototype** in 2020
- Sheet made of 1 mm square fibers read out by MPPC
- Can identify $K^+ \to \pi^+\pi^0$

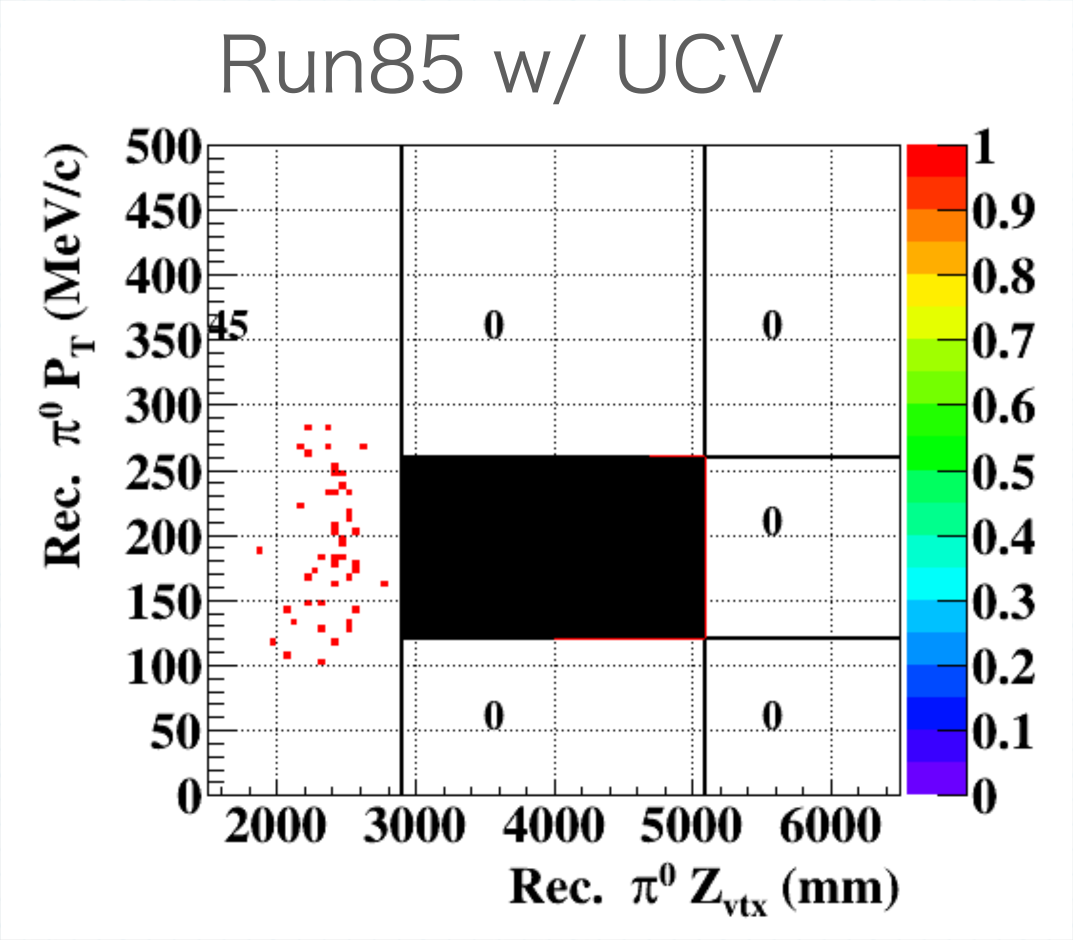


New UCV

- 0.5 mm square fibers
- Full coverage of beam and outside



Quick look at the May 2020 Run data



- Clean with prototype UCV and improved halo K_L bkg cuts
- #Background events
  - K^+: 0.05±0.01
  - halo K_L: 0.01±0.00

Beam Power

ATAC/MR_status Mar-1-2018

Mid-term plan of MR

FX: The higher repetition rate scheme : Period 2.48 s —> 1.32 s for 750 kW.
(= shorter repetition period) —> 1.16 s for 1.3 MW

SX: Mitigation of the residual activity for 100kW

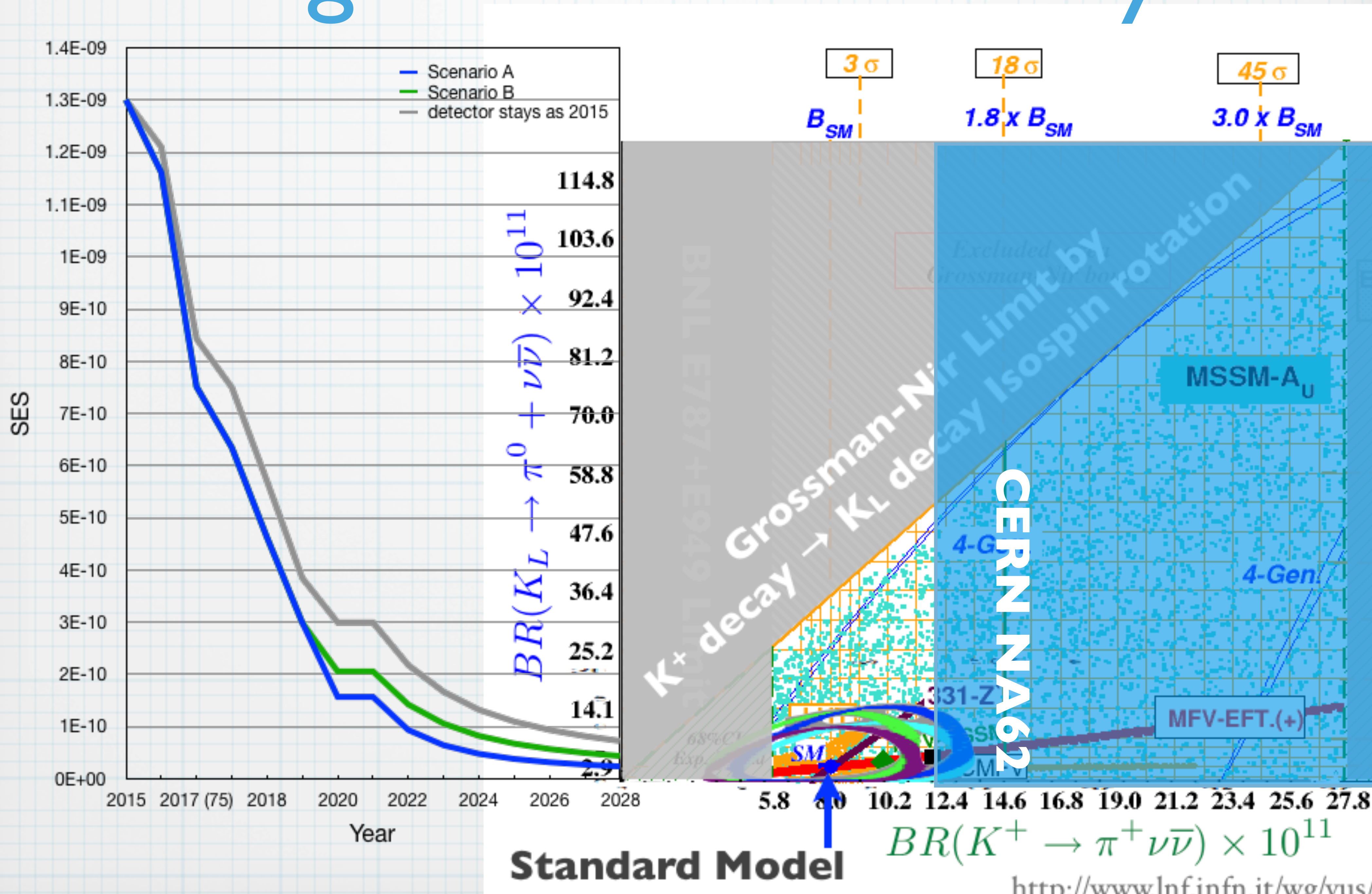
JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW]	475	>480	>480	>480		>700	800	900
SX power [kW]	50	50	50	70		> 80	> 80	> 80
Cycle time of main ma… Nev…	2.48 s	2.48 s	2.48s	2.48s		1.32 s	<1.32s	<1.32s
			…duction …n/test					
High gradient rf sys… 2nd harmonic rf syst…								
Ring collimators								
Injection system	Kicker PS improvement, Septa manufacture /test							
FX system	Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields								
Ti ducts and SX devices with Ti chamber	Ti-ESS-1	(Ti-ESS-2)						

Our assumption

	2019	2020	2021	2022	2023	2024
SX Power (kW)	50	70		80	90	100
spill cycle (s)	5.2	5.2		5.2	4.6	4.2

New Main Ring Power Supplies

Single Event Sensitivity



Summary

- BR($K_L \to \pi^0 \nu \overline{\nu}$) < 4.9 x 10^{-9} (90% CL) based on data collected in 2016-2018
- 3 observed events is consistent with the estimated 1.22 ± 0.26 background events
- The new K^+ background, halo K_L background, and old hadron-cluster background are suppressed in new data
- KOTO will improve sensitivity as the beam power is increased after 2021