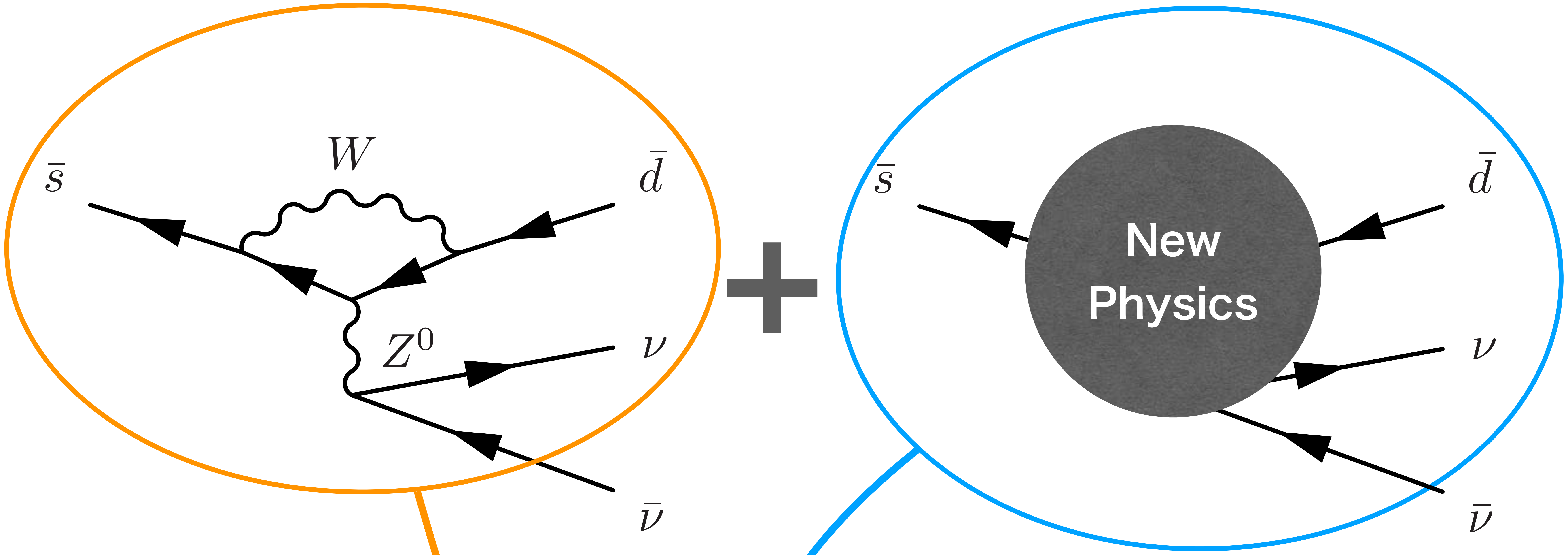
Now and future of $K \to \pi\nu\bar{\nu}$ studies

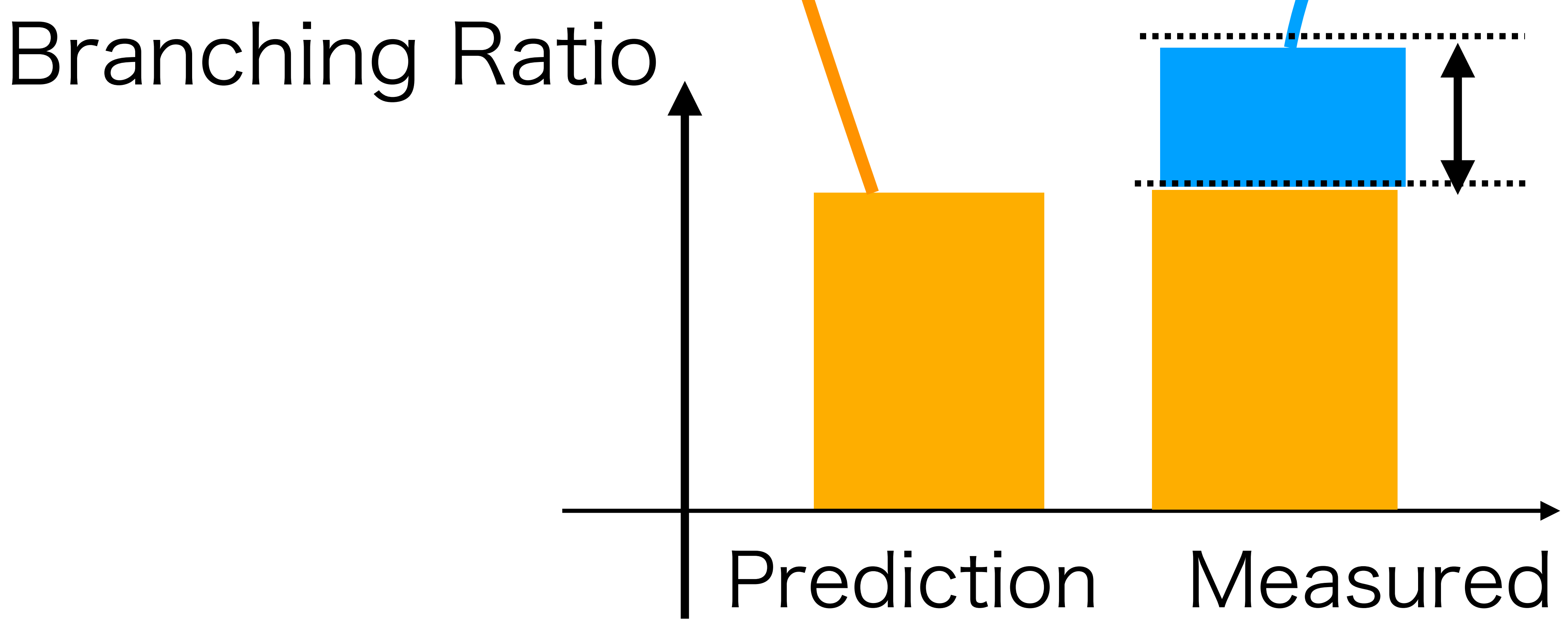
Koji Shiomi (KEK) 2026/9/3 Flavor Frontier 2026@Iwate University

New Physics search through rare decays



Heavy particles could exist in a short period due to the uncertainty principle

$$M = \frac{h}{\Delta T}$$



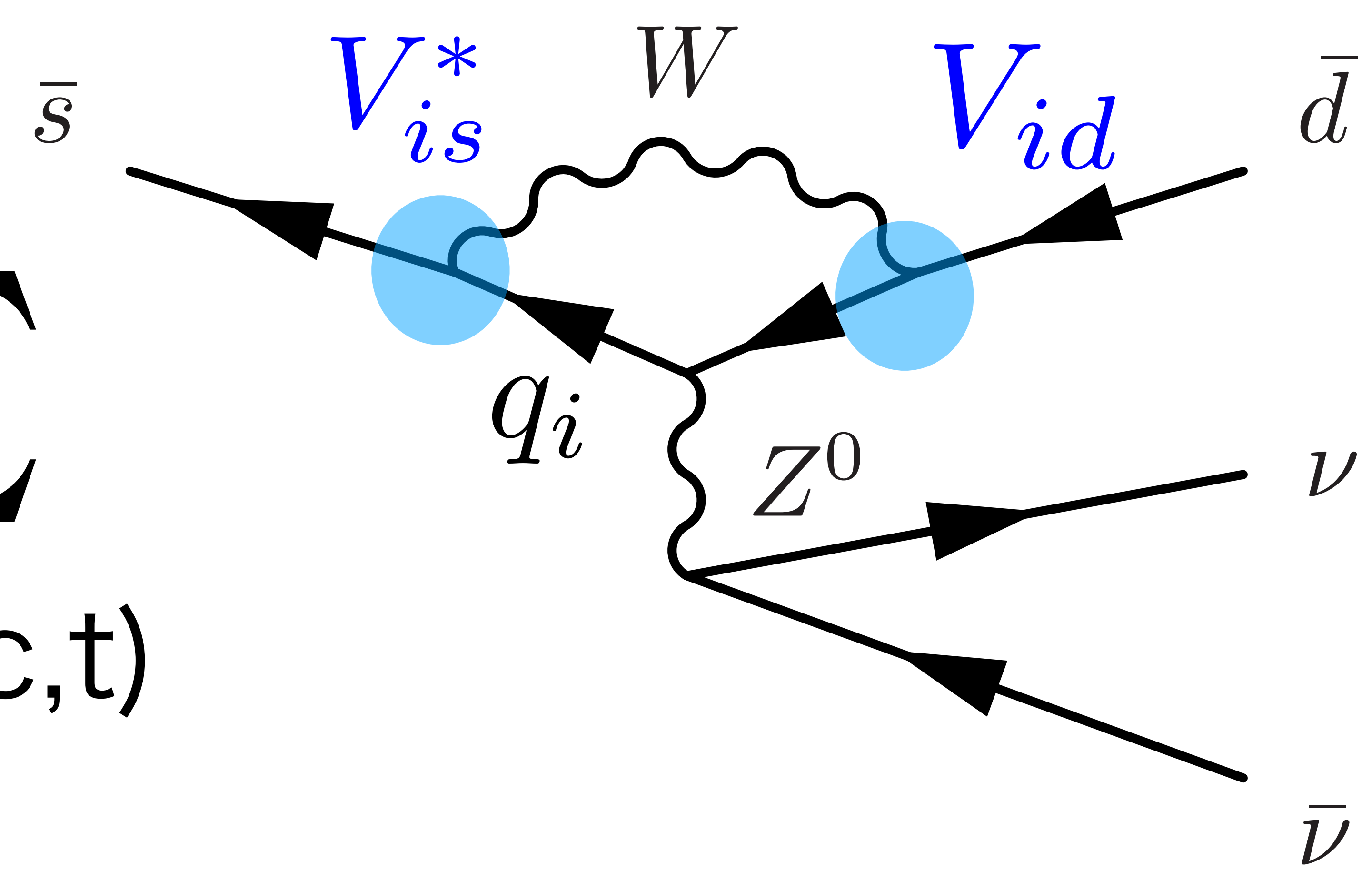
New Physics effect would **be observed as a deviation from the prediction**

Suitable physics objects

- Suppressed in the SM
- Small theoretical uncertainties

Flavor-changing neutral current in Kaon decays

$$A_{s\to d\nu\bar{\nu}} = \sum_{q_i=(u,c,t)}$$



$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \left(\begin{array}{ccc} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \boxed{\lambda^3} & \boxed{-\lambda^2} & 1 \end{array}\right) \end{array}$$

$\lambda \sim 0.23$

.s quark → u quark → d quark ∝ $V_{ud}V_{us}^{*}$ ∝ λ

.s quark → c quark → d quark ∝ $V_{cd}V_{cs}^{*}$ ∝ $-\lambda$

Suppressed by the GIM mechanism

.s quark → t quark → d quark ∝ $V_{td}V_{ts}^{*}$ ∝ λ^5 → Suppressed by the CKM strucutre

FCNC processes in Kaon decays are unique probe in search for New Physics

Reachable energy scaled via Rare Kaon decay

Very rough calculation by experimentalist

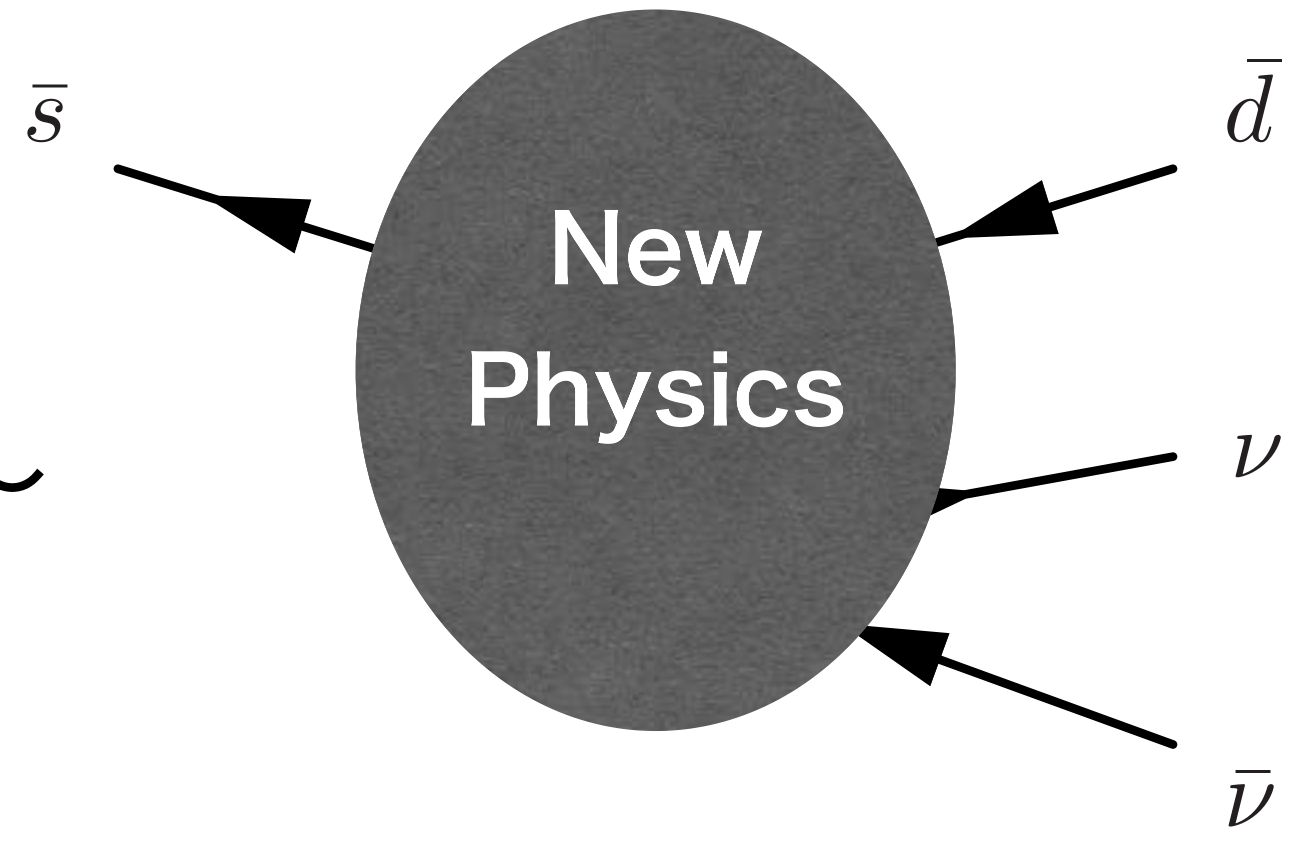
Standard Model

$$A_{s\to d\nu\bar{\nu}} \quad \sim \quad \boxed{\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin{\theta_{\rm w}}^2}\left(V_{ts}^*V_{td}\right)\cdot X_t}\left\langle\pi^0\right|\bar{s}_L\gamma^u d_L\left|K^0\right\rangle\left(\bar{\nu}_L\gamma_u\nu_L\right)$$

4x1.2x10^{-5} GeV^{-2}/√2 x 5x10^{-3}x 0.0004 x 1.5 =1.0x10^{-10} GeV^{-2}

Beyond Standard Model

$A_{\rm NP} \sim$



$$\propto \frac{C_{\rm NP}}{\Lambda^2}$$

Assume

$$A_{\rm NP} \sim A_{s\to d\nu\bar{\nu}}$$

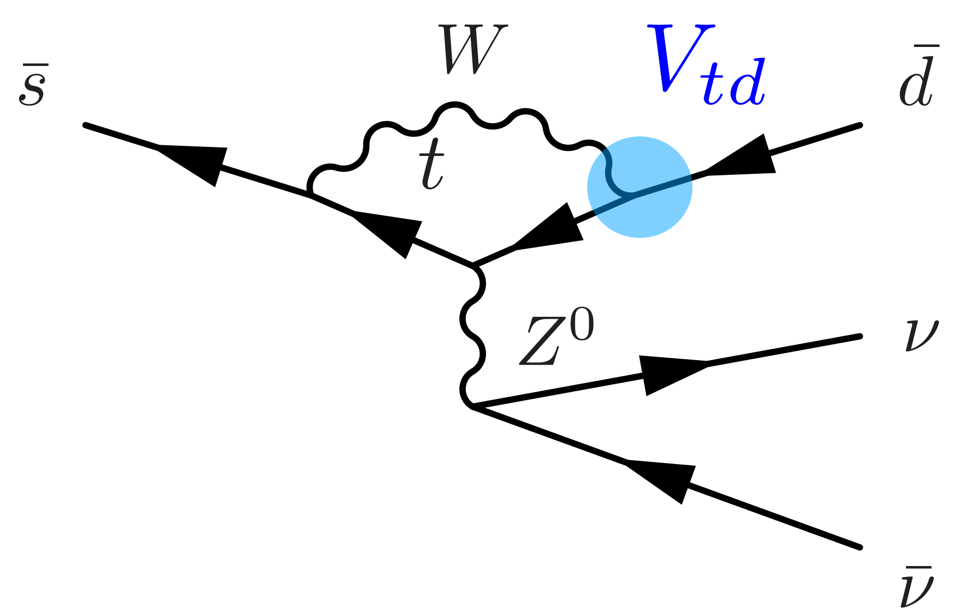
$$C_{\rm NP} \sim O(1)$$

$$\Rightarrow \boxed{\Lambda \sim 100\text{TeV}}$$

$K_L \to \pi^0 \nu \bar{\nu}$ decay in the SM

CP- CP+

$A(K_L \to \pi^0 \nu \bar{\nu}) \propto$



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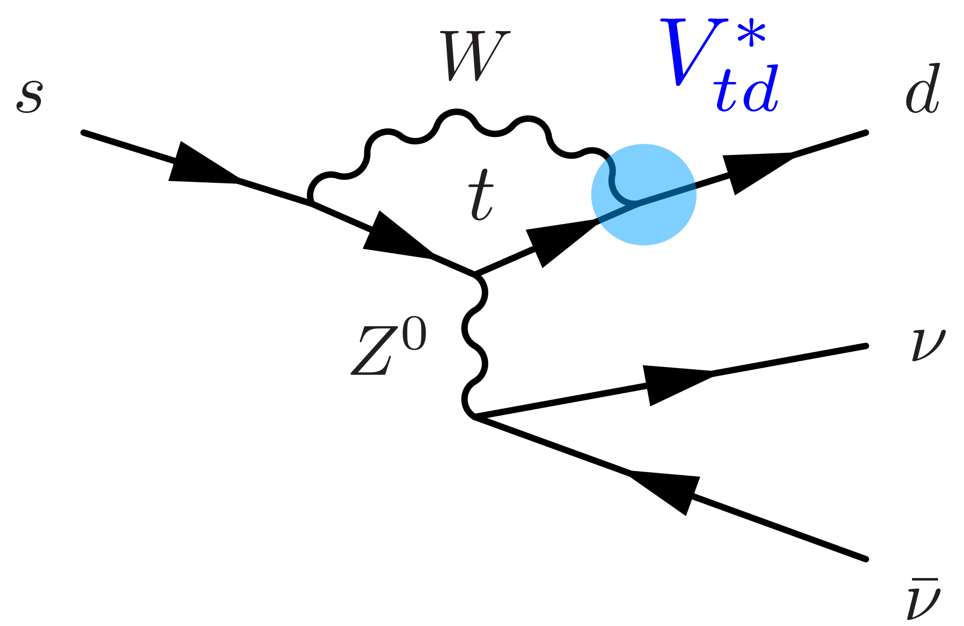


$$= A_{s\to d\nu\bar{\nu}} - A^*_{s\to d\nu\bar{\nu}}$$

~~CP~~ SD LD

$$= \frac{4G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin{\theta_{\mathrm{w}}}^2} \boxed{\Im(V_{ts}^* V_{td})} \cdot \boxed{X_t} \boxed{\langle \pi^0 |\, \bar{s}_L \gamma^u d_L \,| K^0 \rangle \, (\bar{\nu}_L \gamma_u \nu_L)}$$

Loop function for top
Precisely calculated

Extracted from
$K^+ \to \pi^0 e^+ \nu$ decay data
(Isospin symmetry)

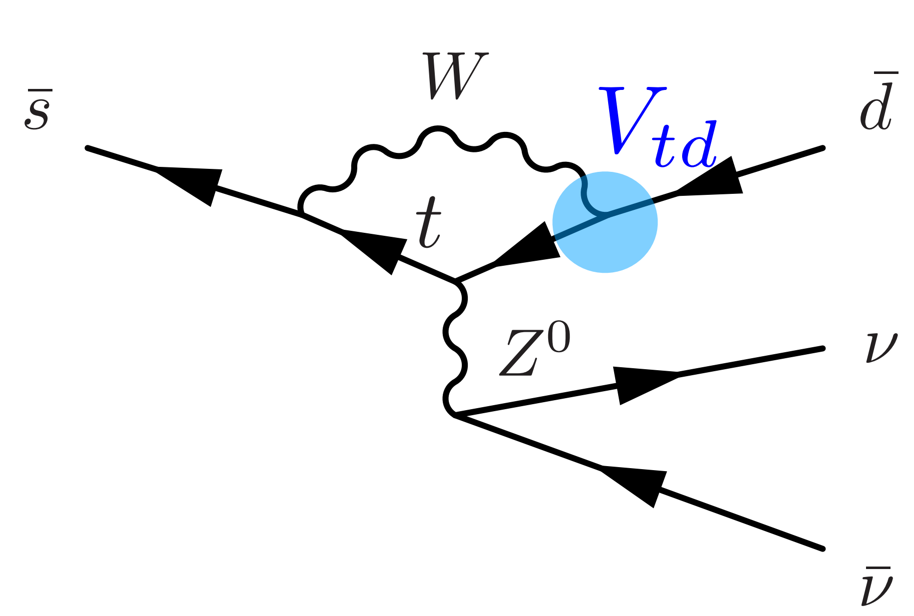
$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = 2.78(6)_{\mathrm{SD}}(2)_{\mathrm{LD}}(29)_{\mathrm{para}} \times 10^{-11}$$

主なパラメーターエラー：CKM parameters($\bar{\eta}$,A,λ), m_t

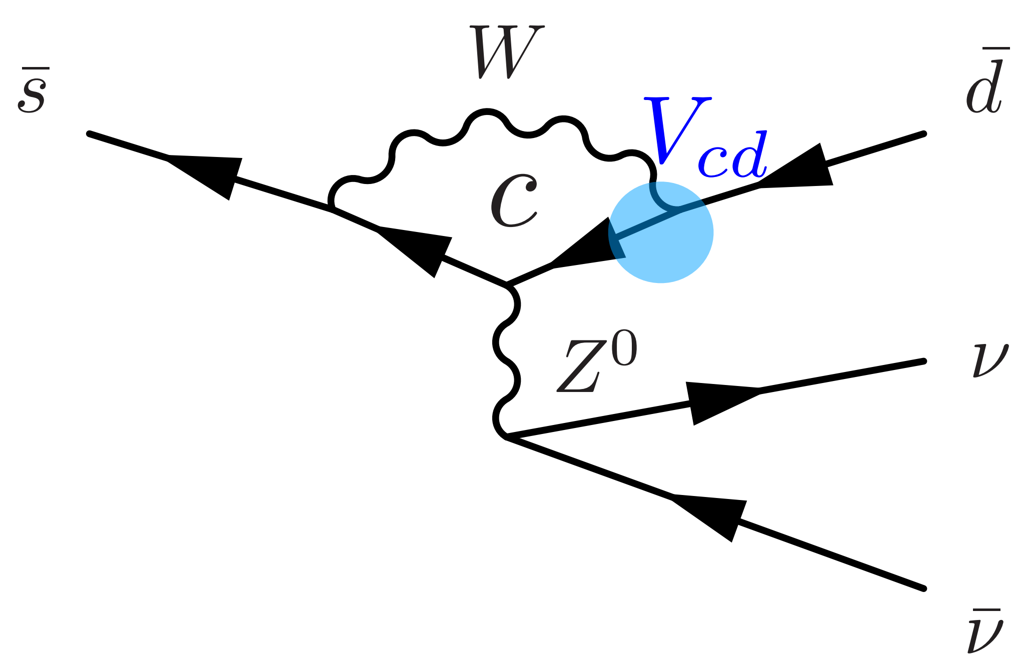
From Kaons@CERNS WS summary

$K^+ \to \pi^+\nu\bar{\nu}$ decay in the SM

$$A(K^+ \to \pi^+\nu\bar{\nu}) \propto$$



$+$



$$= \frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin\theta_{\mathrm{w}}{}^2}\Big(\overset{\lambda^5}{V_{ts}^*V_{td}}\boxed{X_t} + \overset{\lambda}{V_{cs}^*V_{cd}}\big(\boxed{X^l} + \lambda^4\boxed{\delta P^l_{c,u}}\big)\Big)\boxed{\langle\pi^+|\,\bar{s}_L\gamma^u d_L\,|K^+\rangle}(\bar{\nu}_L\gamma_u\nu_L)$$

SD

LD

LD

Loop function for top (charm)
Precisely calculated

Dimension-8 charm +
genuine light-quark long-distance contribution
(Source of theoretical uncertainties.)

Extracted from
$K^+ \to \pi^0 e^+\nu$ decay

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 8.19(17)_{\mathrm{SD}}(25)_{\mathrm{LD}}(53)_{\mathrm{para}} \times 10^{-11}$$

主なパラメーターエラー：CKM parameters($\bar{\eta}$,$\bar{\rho}$A,λ), m_t,m_c,α_s

From Kaons@CERNS WS summary

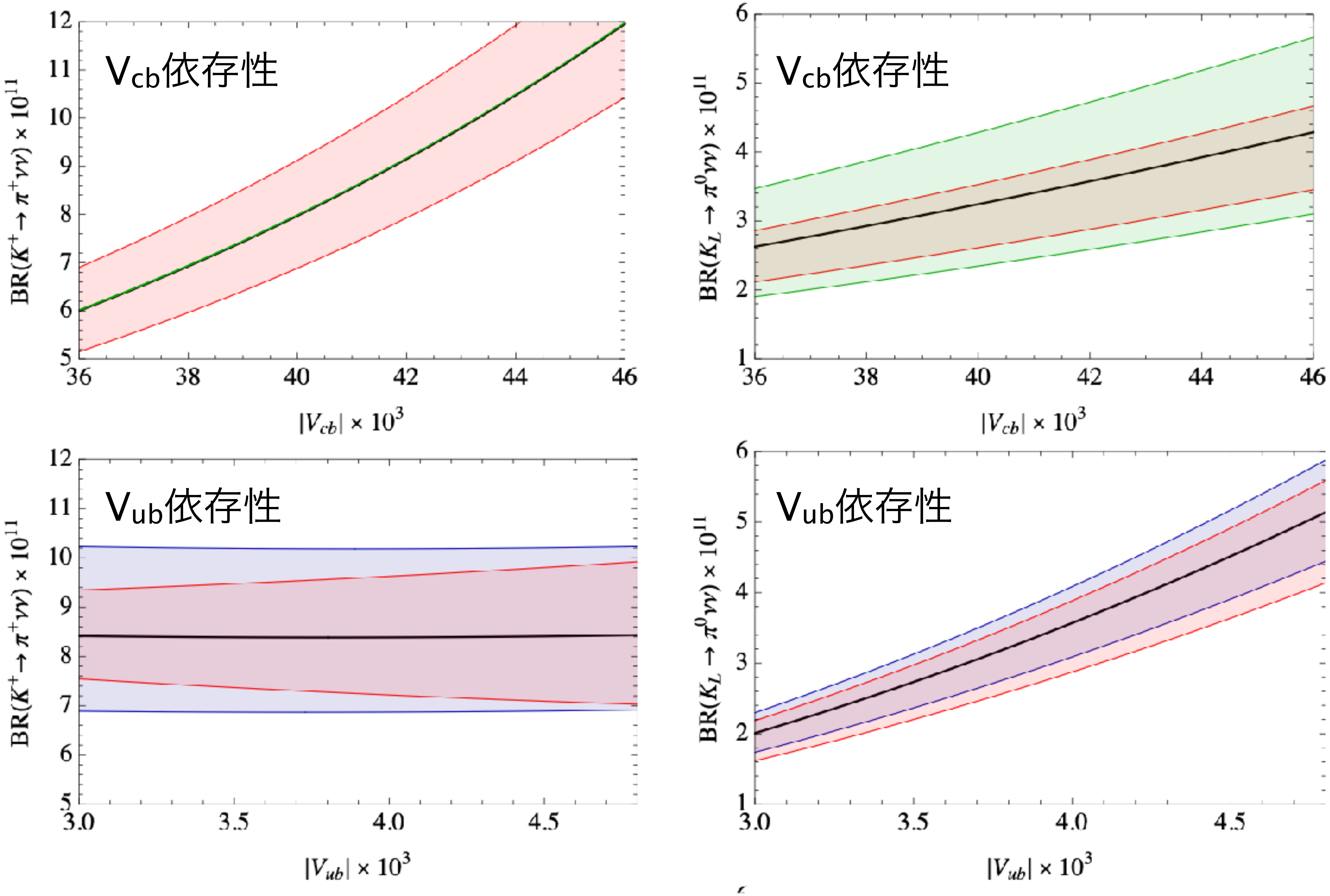
Vcb, Vub依存性

JHEP 1511 (2015) 033

$$B(K^+ \to \pi^+ \nu\bar{\nu}) \propto |V_{cb}|^{2.8}$$

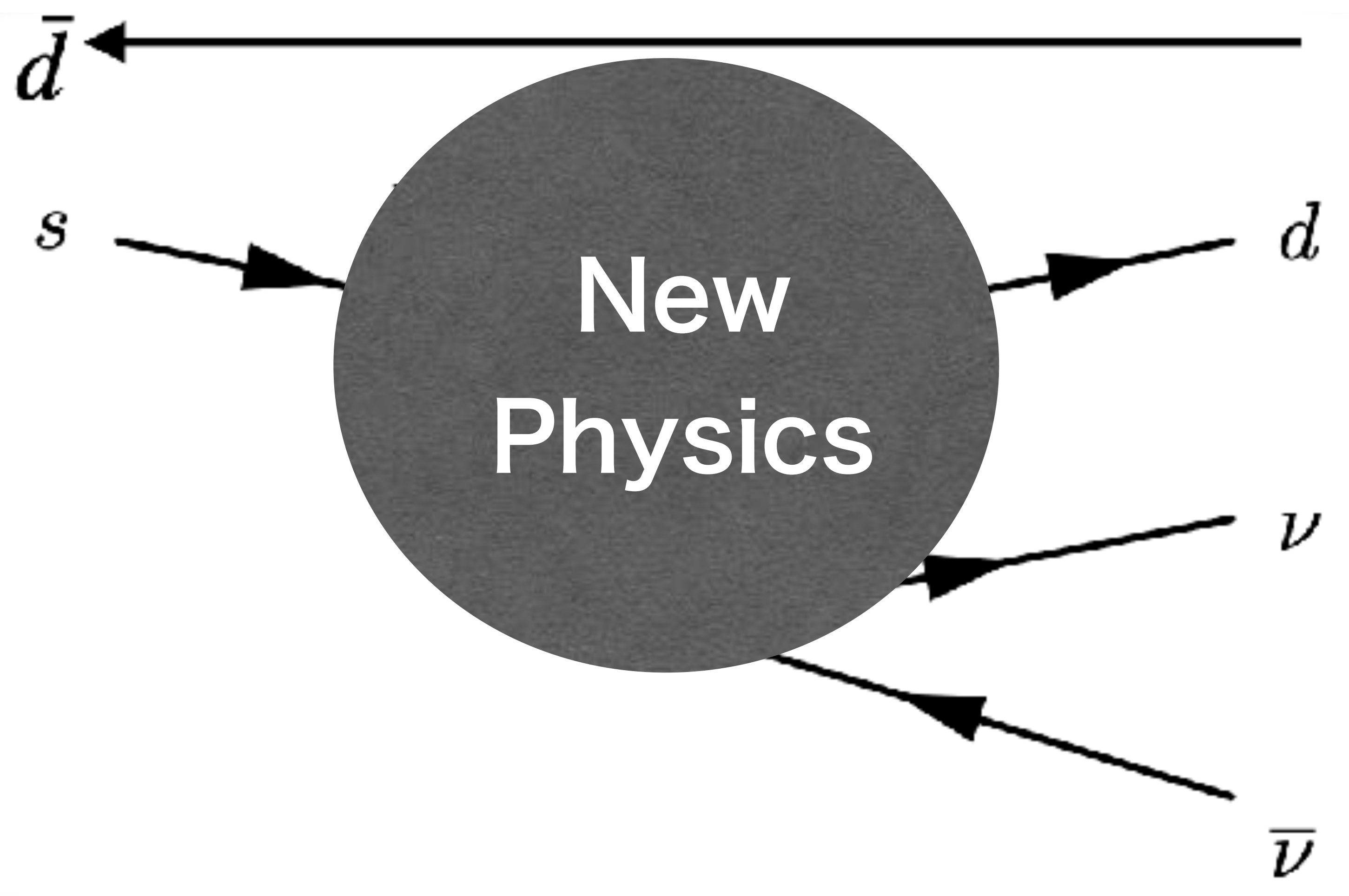
$$B(K_L \to \pi^0 \nu\bar{\nu}) \propto |V_{ub}|^2 |V_{cb}|^2$$

BR(K+→π+νν) BR(KL→π0νν)



K→$\pi\nu\nu$崩壊での新物理の見え方

新物理があると



$$\propto \frac{C_{\mathrm{NP}}}{\Lambda^2}$$

C_{NP}: ウイルソン係数

Λ: 新物理のエネルギースケール

-$K^+ \to \pi^+ \nu \nu$との相関

-C_{NP}がオーダー1の場合(generic case)

-Flavorの対称性を仮定して、Cは標準理論と同程度とする(〜$V_{td}^{*}V_{ts}$)

Correlation to $K^+ \to \pi^+\nu\bar{\nu}$

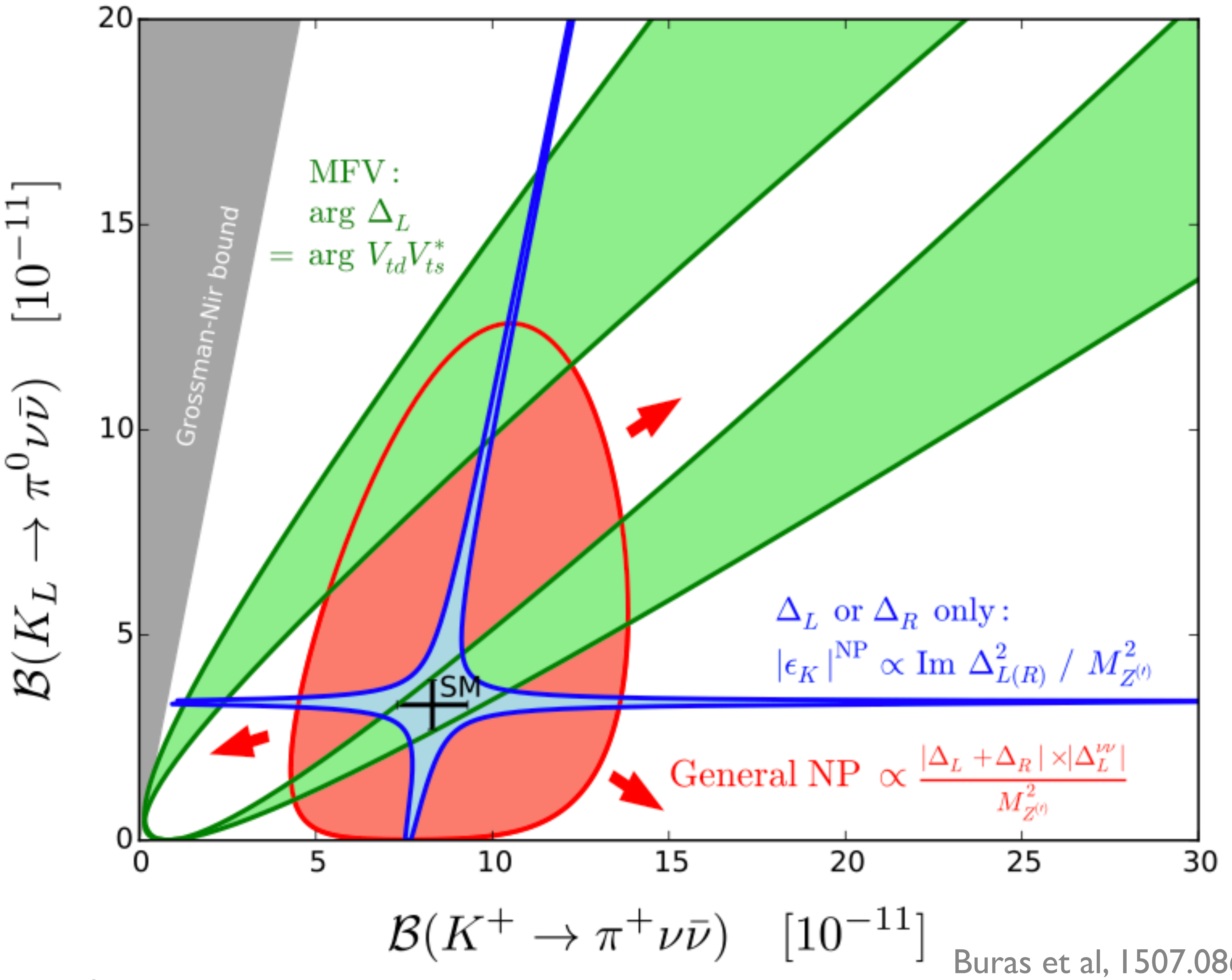
$$\Gamma(K_L \to \pi^0\nu\bar{\nu}) \propto (ImA_{s\to d})^2$$

$$\Gamma(K^+ \to \pi^+\nu\bar{\nu}) \propto |A_{s\to d}|^2$$

$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} = \frac{(ImA_{s\to d})^2}{|A_{s\to d}|^2} \leq 1$$

$$\tau_{K_L}/\tau_{K^+} \sim 4.2$$

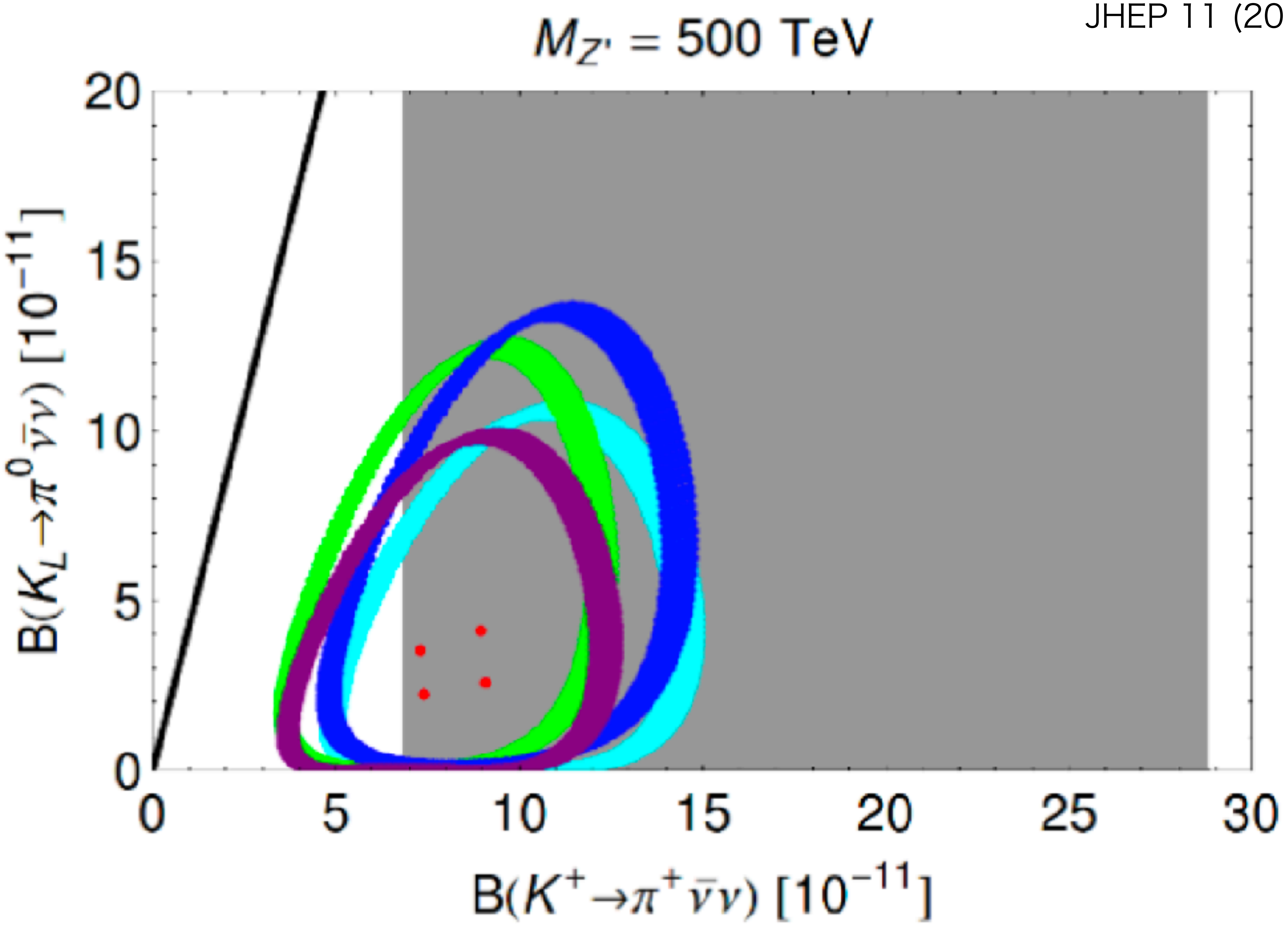
$$\frac{BR(K_L \to \pi^0\nu\bar{\nu})}{BR(K^+ \to \pi^+\nu\bar{\nu})} \leq 4.3$$ Grossman-Nir bound



Buras et al, 1507.08672

New physics scenario (Generic Model)

JHEP 11 (2014) 121



新物理の寄与C/Λ²において
C=1を仮定

500TeVの物理にも感度を持つ

New physics scenario (U(2) Flavor Symetry)

- 各Flavorの観測量に相関が生まれる。
- 第1,2世代はU(2)対称性を持つ一方、第３世代Singlet。

  ->第1,2世代にはスプリオン($\tilde{V}$)を通して結合

$$\tilde{V} = -\epsilon \begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix} \qquad q_L^3 \to q_L^3 + \tilde{V}_i q_L^i \,.$$

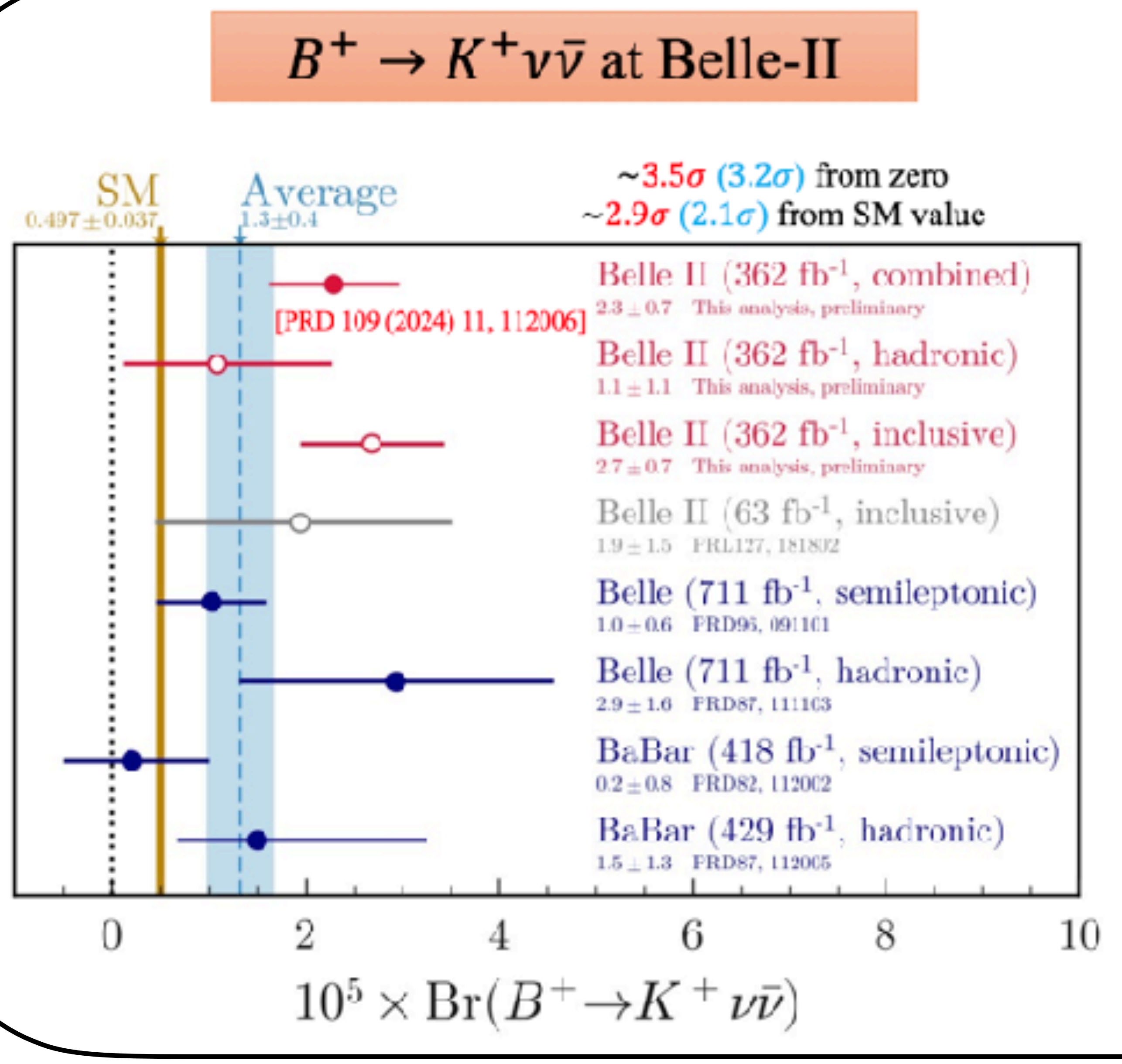
$$Y_u = y_t \begin{pmatrix} \cdot & \cdot & \square \\ \cdot & \cdot & \square \\ 0 & 0 & 1 \end{pmatrix}$$

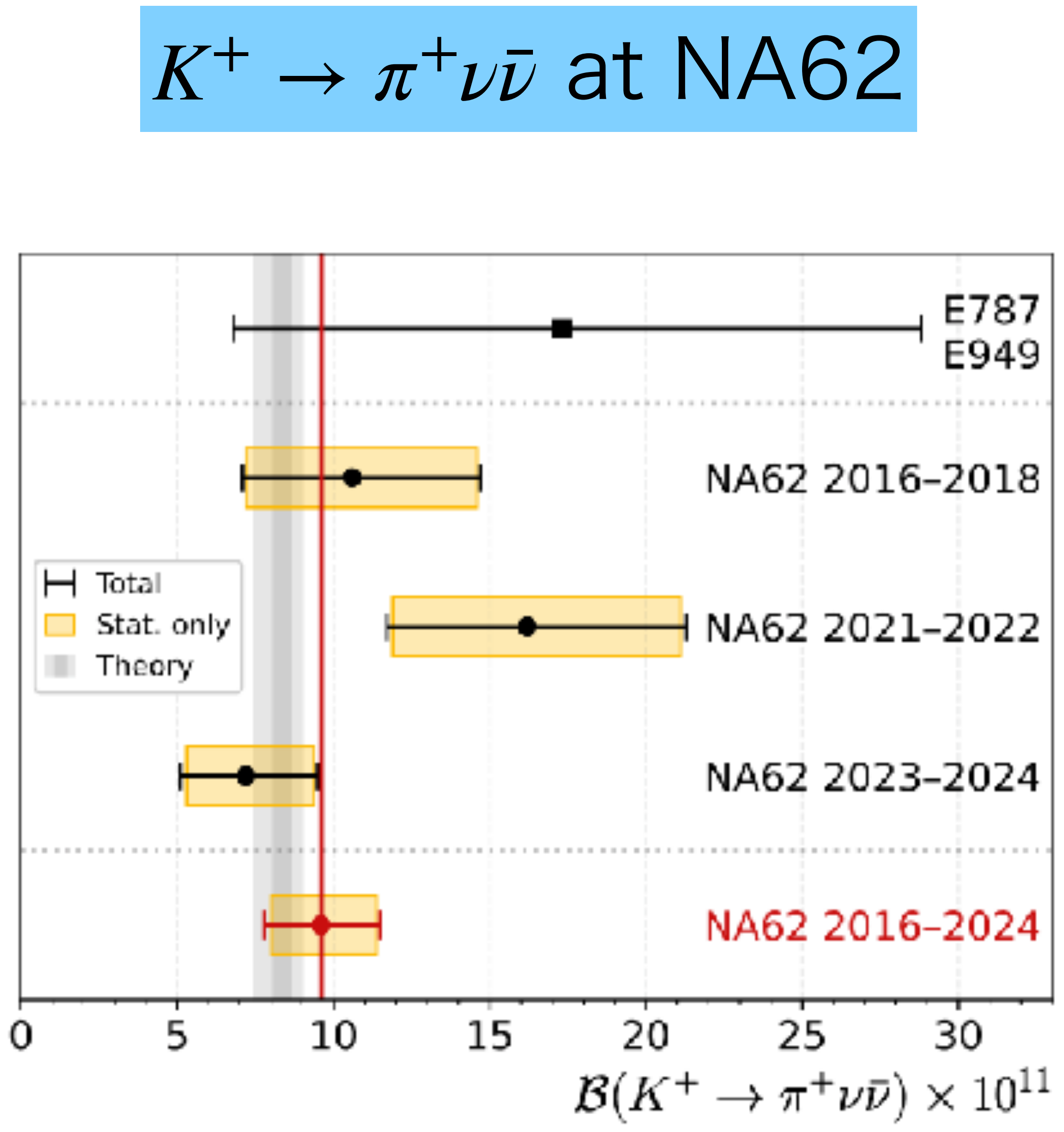
SMの計算値からのズレの予想値

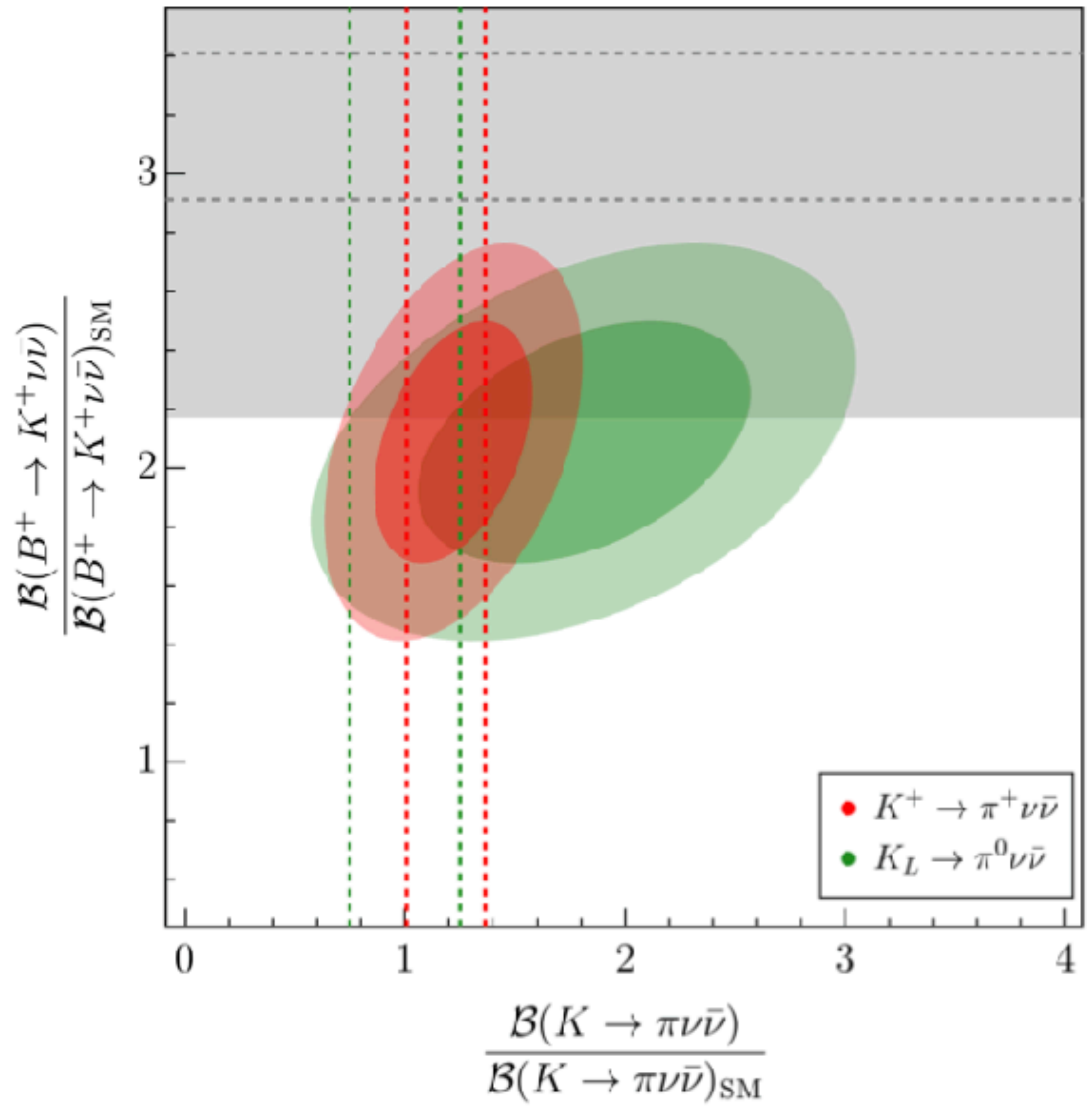
(Y軸：B+→K+ν ν, X軸:K→π ν ν)

KL→π⁰ν νに関しては予言値

arxiv 2607.24494







$\boxed{\text{KL→π⁰ν νの分岐比はSMの1.5-2倍の値を予想}}$

K→$\pi\nu\nu$ experiments at CERN and J-PARC

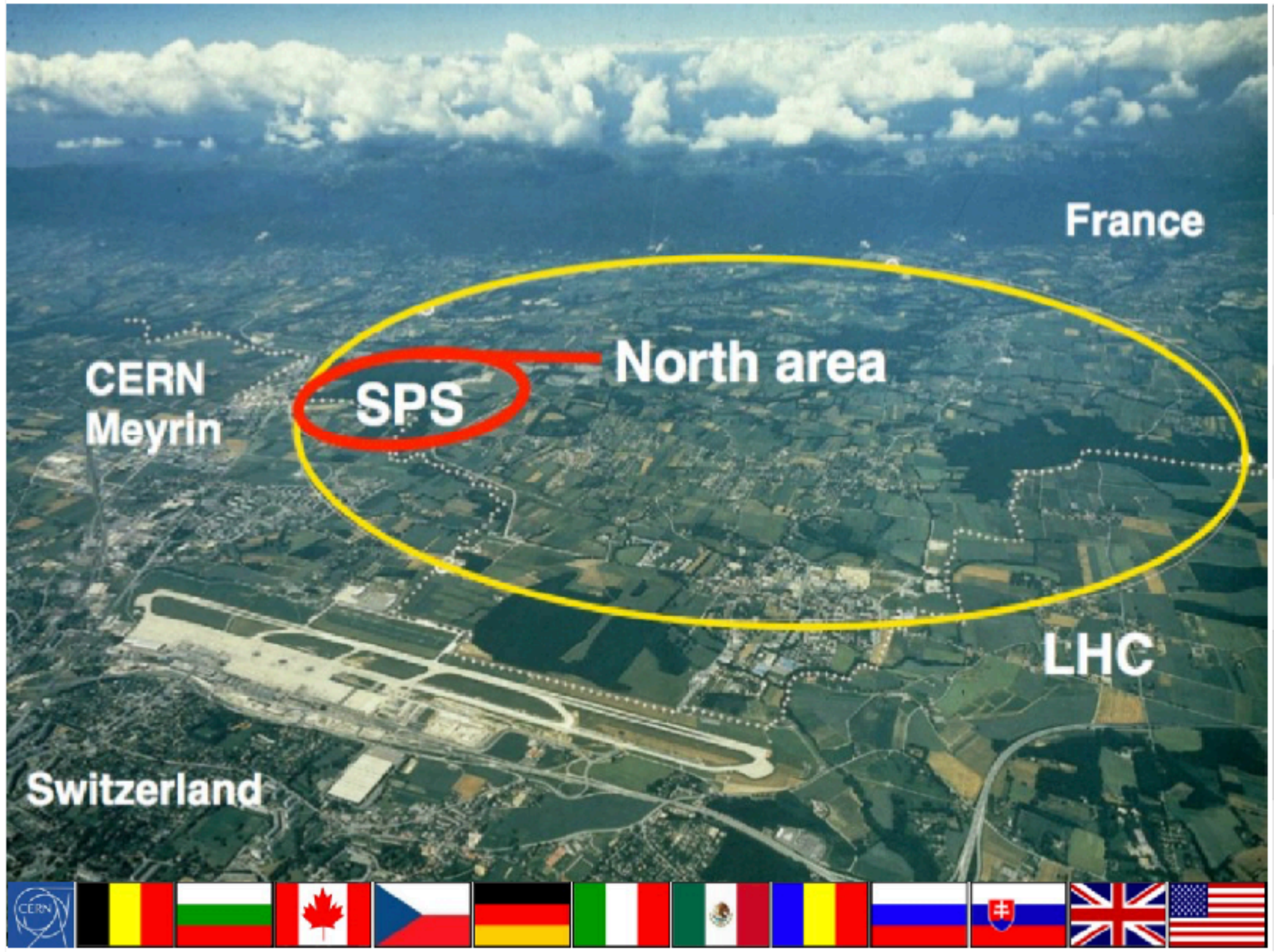
K+→π+$\nu\nu$@NA62 [Joel Swallow, ICHEP2026]

KL→π0$\nu\nu$@KOTO

KL→π0$\nu\nu$@KOTO II

NA62 experiments @ CERN

- NA62 is the last from a long traditiona of fixed-target Kaon experiments in the CERN North Area
- The primary goal is the measurement of BR$(K^+ \to \pi^+ \nu \bar{\nu})$



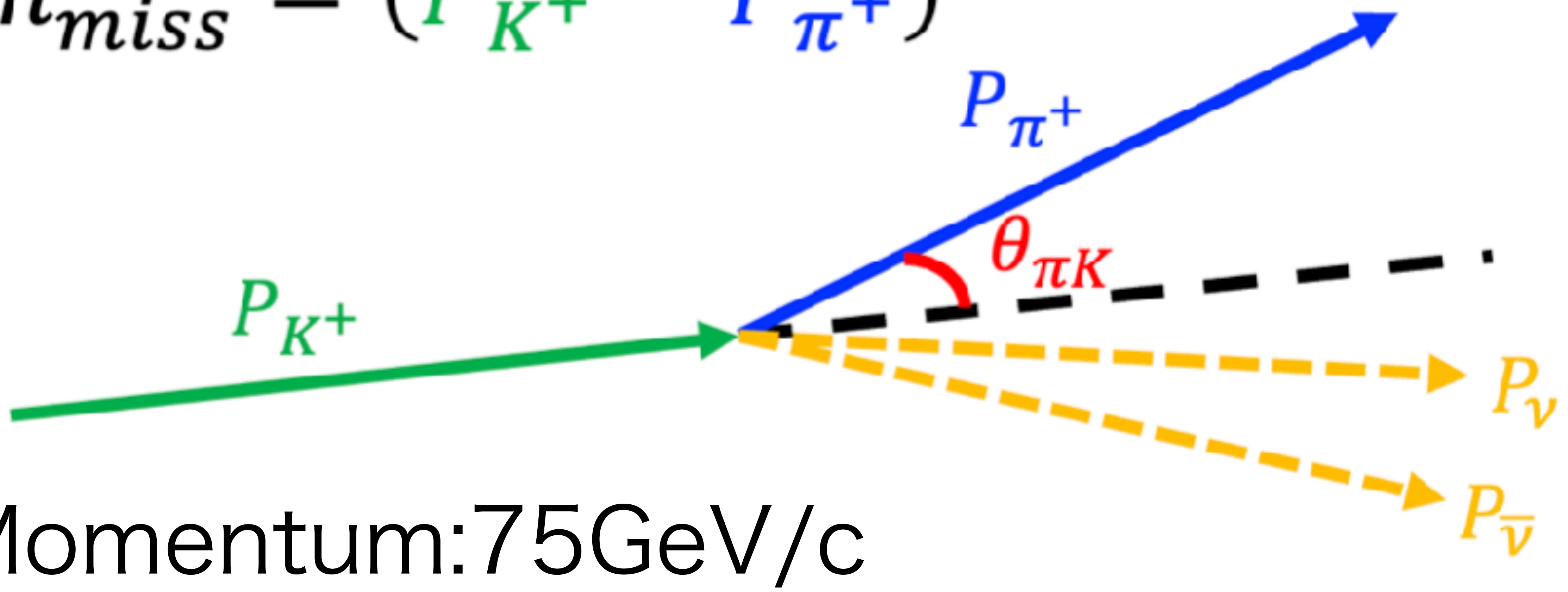
History of kaon experiments @ CERN SPS		
1982 ↓ 1993	NA31 (K_S/K_L)	Re ε'/ε
1997 ↓ 2001	NA48 (K_S/K_L)	Re ε'/ε **Discovery of direct CPV**
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV, Rare K^+/K^- decays
2007 ↓ 2008	NA62-R_K (K^+/K^-)	$R_K = \Gamma(K^\pm \to e^\pm \nu) / \Gamma(K^\pm \to \mu^\pm \nu)$, Rare K^+/K^- decays
2016 ↓ LS3	**NA62 (K^+)**	**$K^+ \to \pi^+ \nu \bar{\nu}$, Rare K^+ and π^0 decays**

~300 participants,
30 institutes
from 15 contries

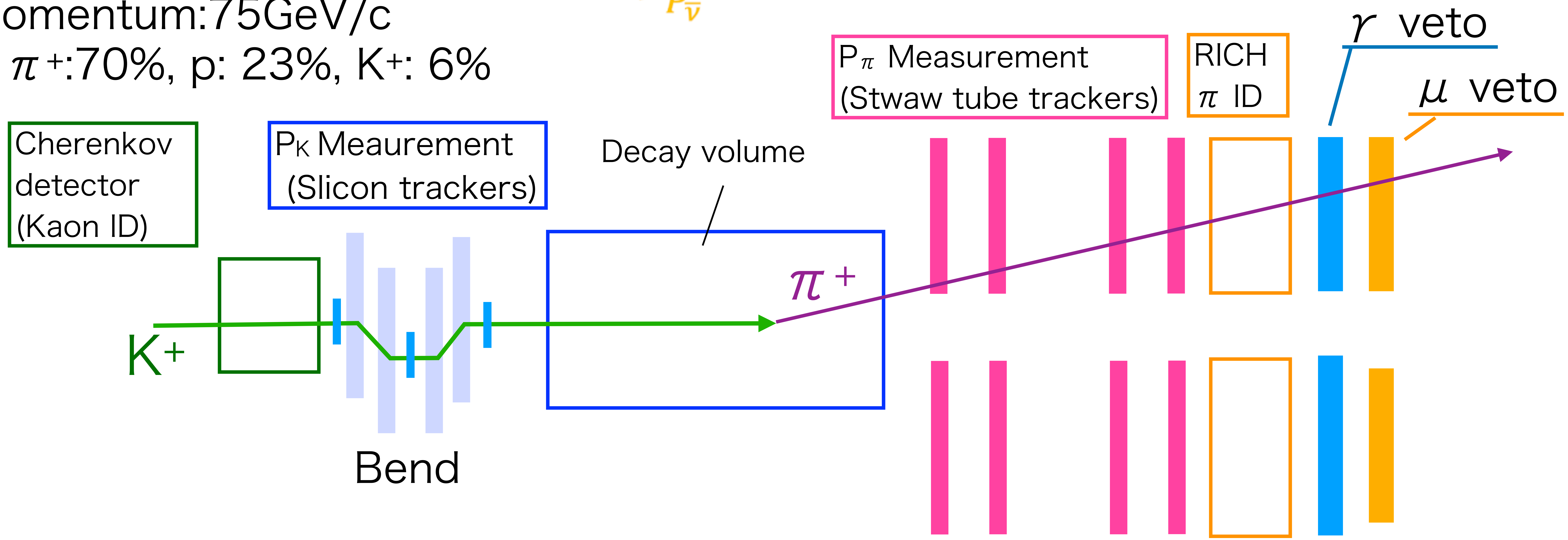
Signal identification

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$



Momentum:75GeV/c
π^+:70%, p: 23%, K^+: 6%



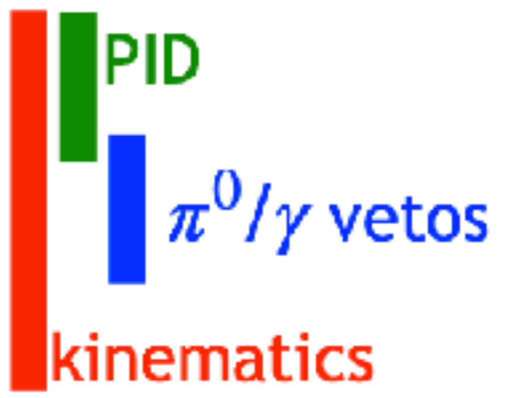
NA62 key for signal ID

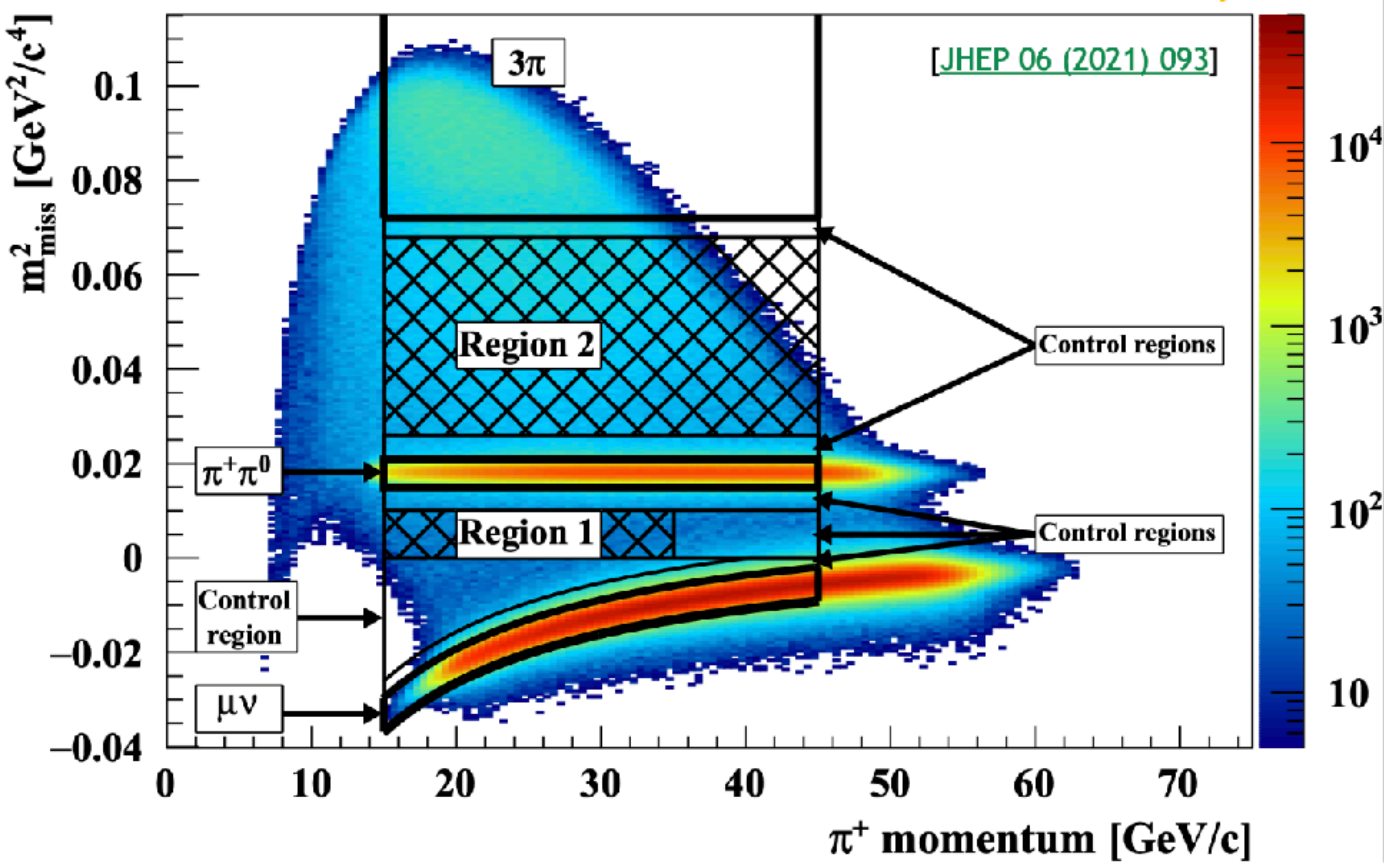
Define the signal region in m^2_{miss} vs π^+ momentum plane

NA62 Performance Keystones:

- $\mathcal{O}(100)\ ps$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- 10^7 muon rejection
  - $P(\mu^+ \text{ misID as } \pi^+) = (1.3 \pm 0.1) \times 10^{-7}$ with $\varepsilon(\pi\ \text{ID}) = 75.3\ \%$
- 10^7 rejection of π^0 from $K^+ \to \pi^+\pi^0$ decays
  - $\eta_{\pi^0} = (1.24 \pm 0.04) \times 10^{-8}$

Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\ \%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\ \%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\ \%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	8.4×10^{-11} [benchmark SM value]

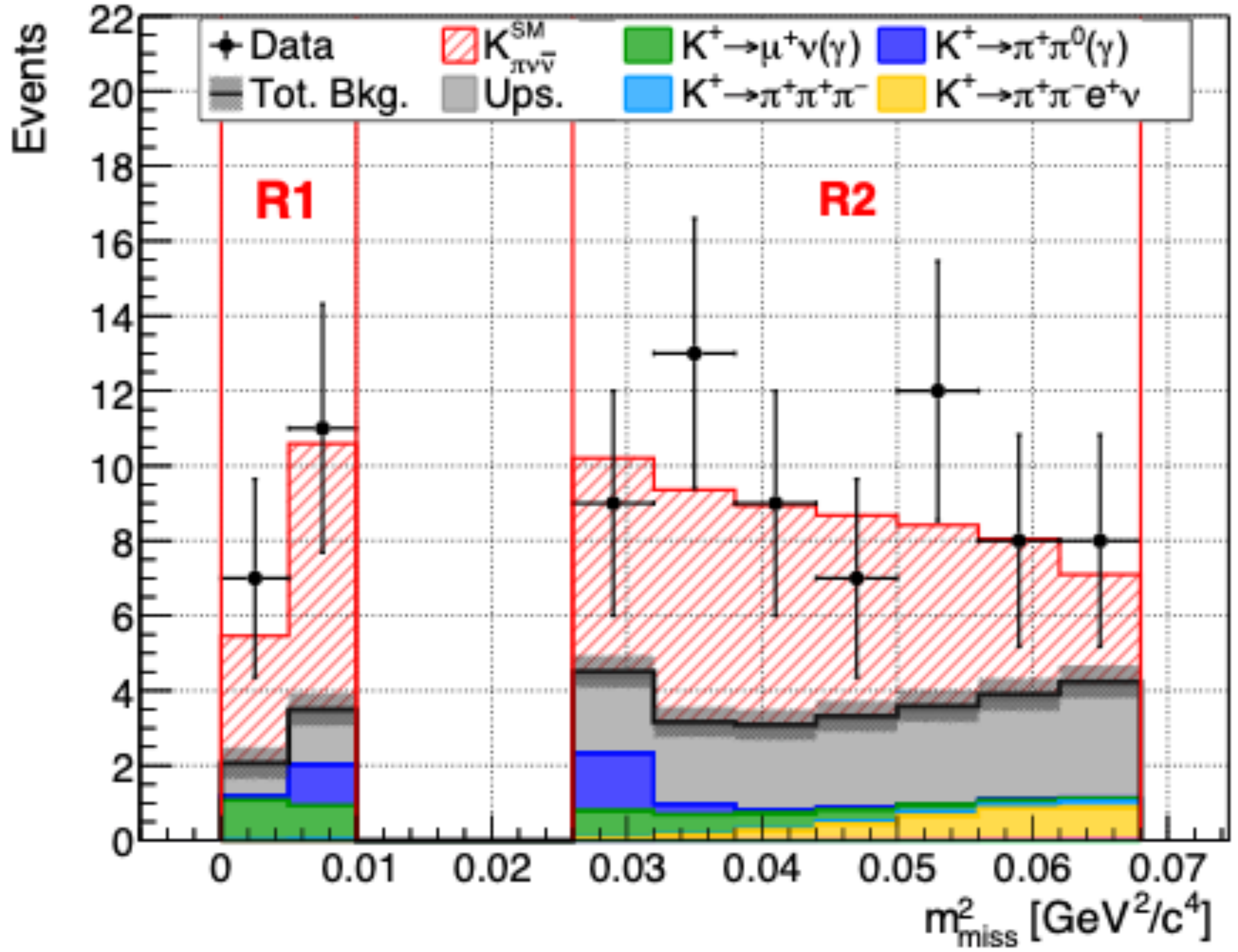




NA62 $K^+ \to \pi^+ \nu \bar{\nu}$ Latest results

arXiv:2607.16413

2016-24 data results



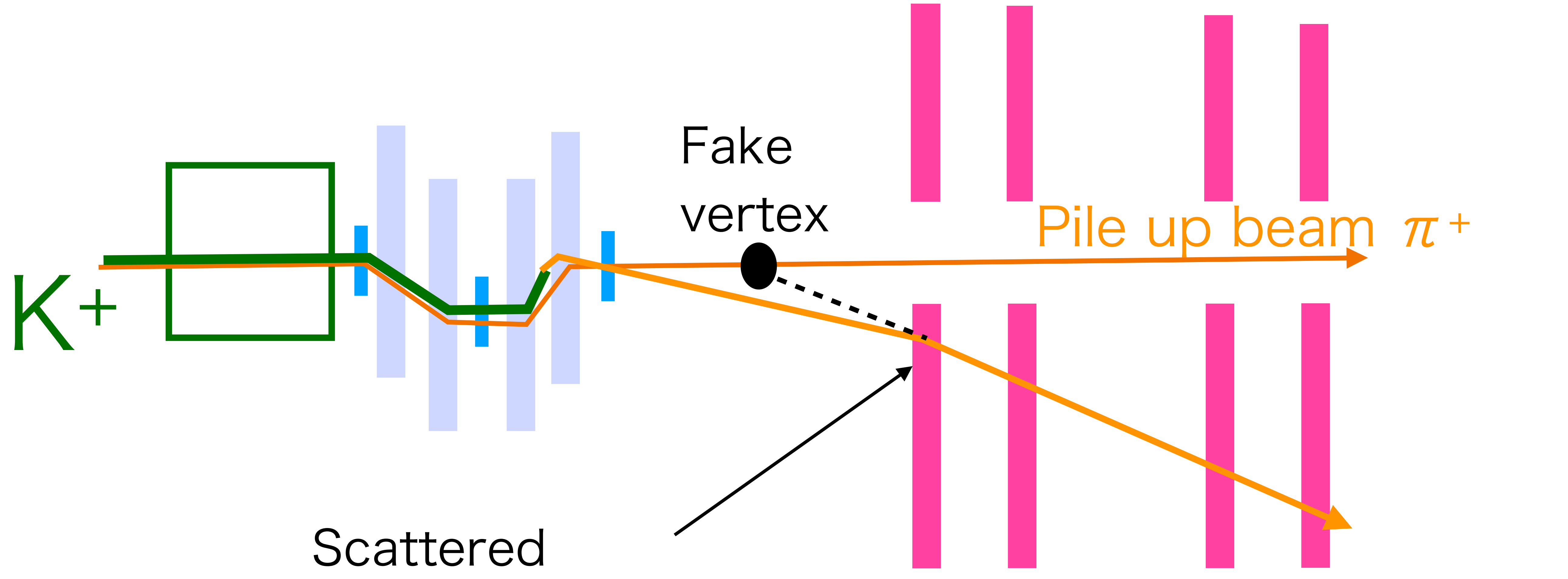
期待値：$N_{bg} = 30^{+4}_{-3}$, $N_{sig} = 43 \pm 1$

観測値：$N_{obs} = 84$

Dominant BG in the analysis is Upstream Background

-7.5 among 12 total BG for the 2023-24 dataset

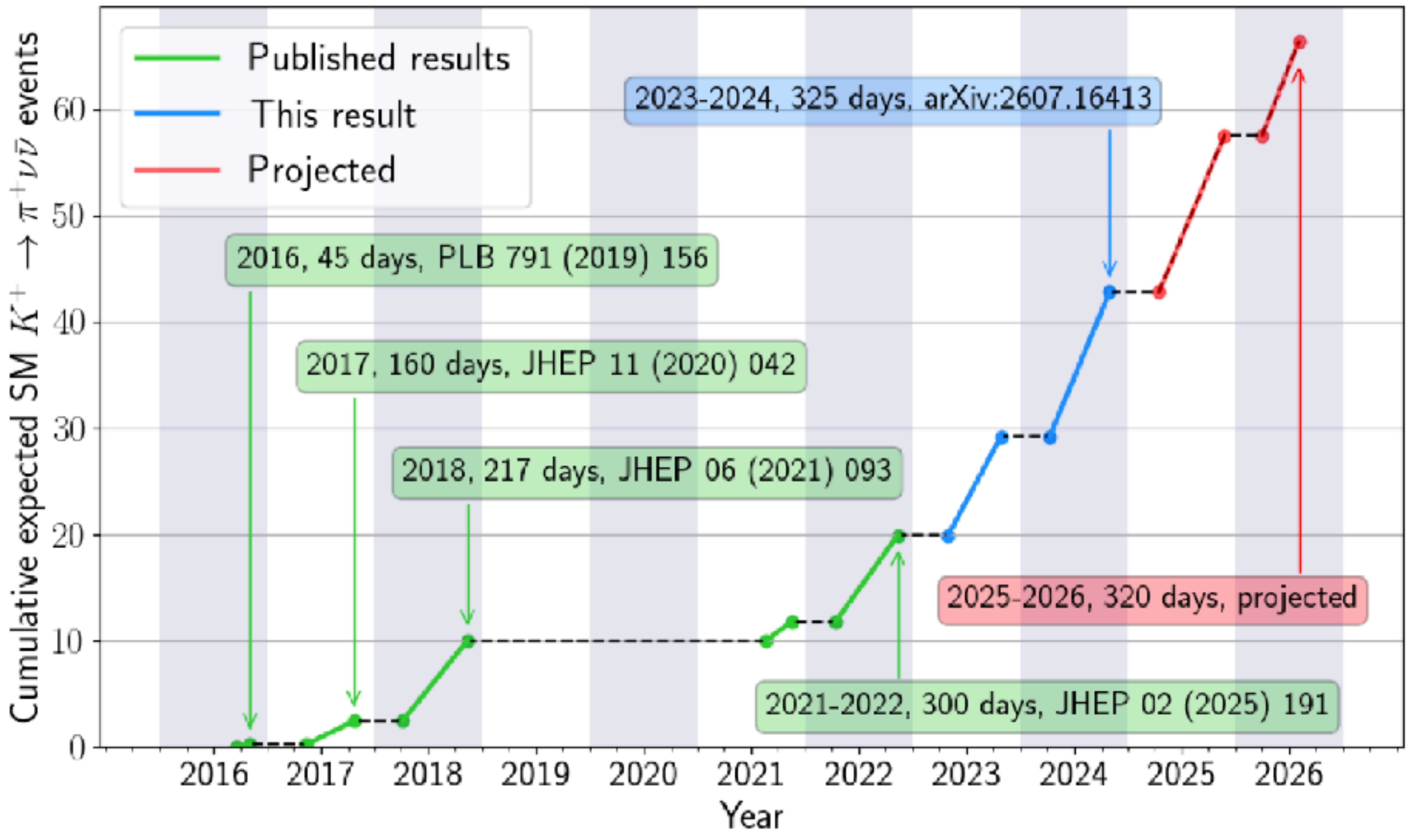
-K+ decays at upstream, and pile-up beam π^+ and π^+ produced by K+ decay leave signals on downstream counters

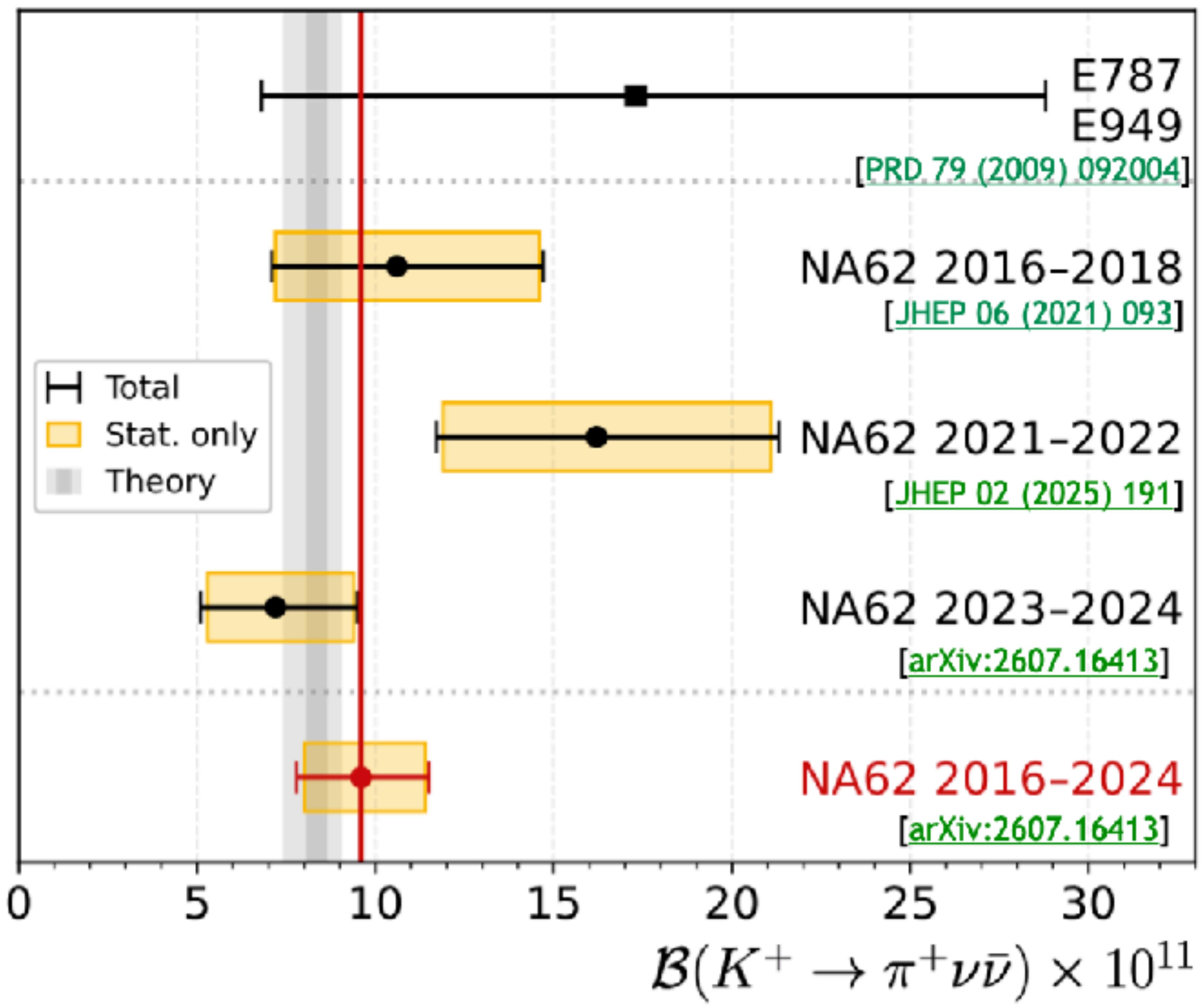


$$\mathscr{B}_{16-24}(K^+ \to \pi^+ \nu \bar{\nu}) = 9.6^{+1.9}_{-1.8} \times 10^{-11} = \left(9.6(^{+1.8}_{-1.6})_{\text{stat}}(^{+0.8}_{-0.6})_{\text{syst}}\right) \times 10^{-11}$$

NA62 $K^+ \to \pi^+ \nu \bar{\nu}$ Prospect

- Data taking was completed in August 2026.
- Final dataset(2016-2026) Projection
  - In total, more than 60 SM events are expected.
  - Expected BR uncertainty = 15%



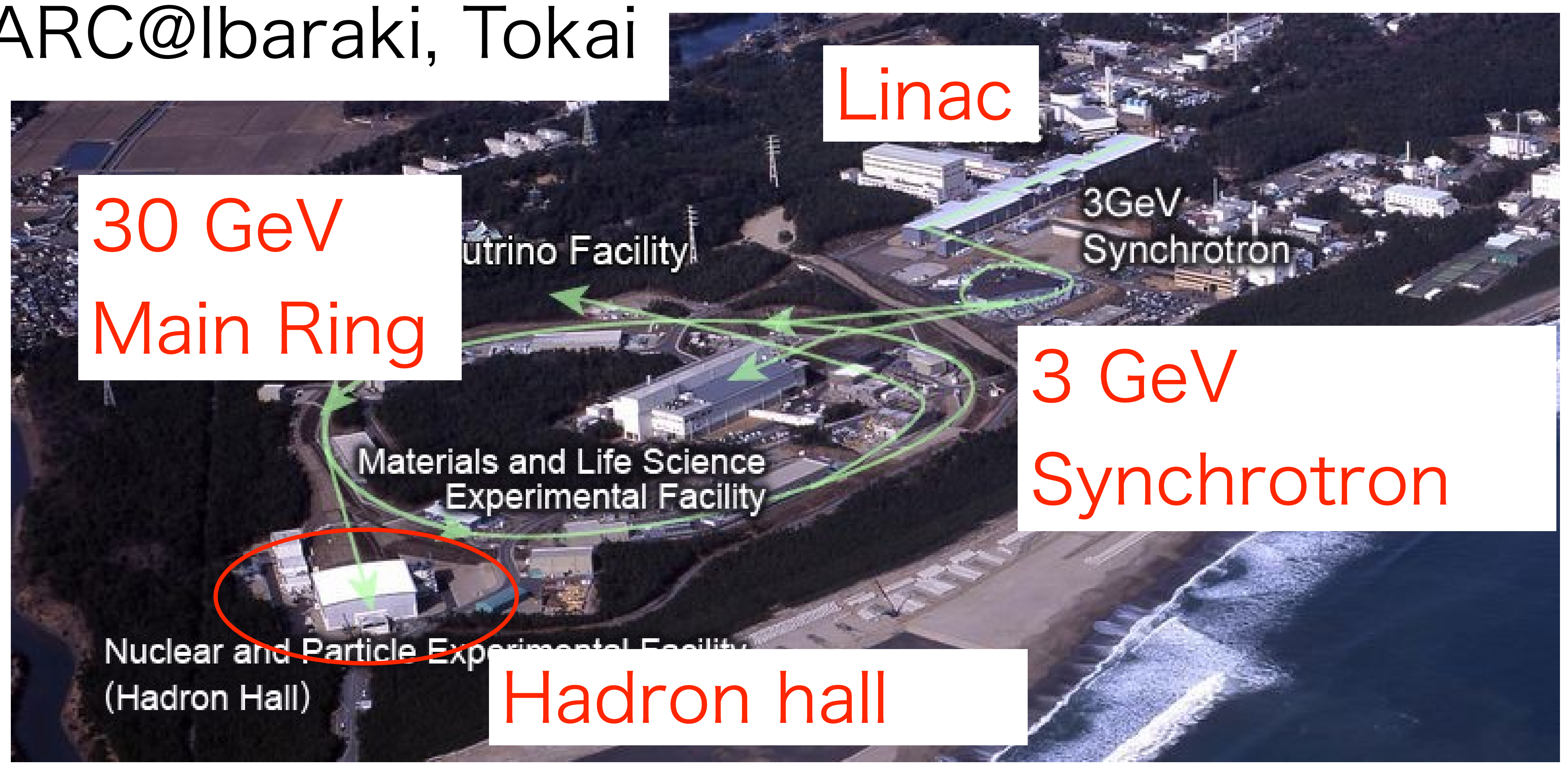


KOTO experiment @ J-PARC

KOTO=K^0 at TOkai

- Search for $K_L \to \pi^0 \nu \bar{\nu}$ decay at J-PARC
  - Aim to discover the decay mode

J-PARC@Ibaraki, Tokai



@ collaboration meeting on Dec. 19th - Dec. 21th, 2025

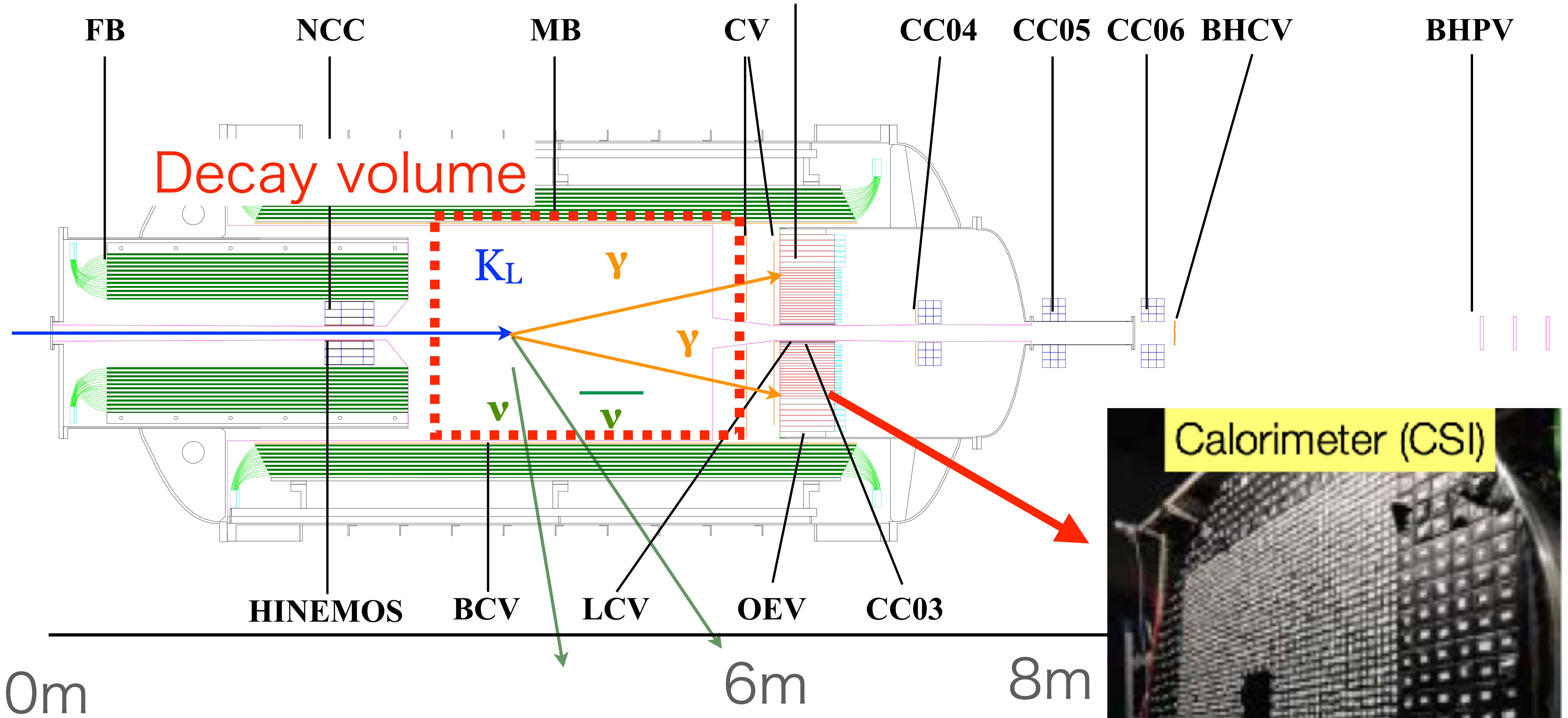

Japan

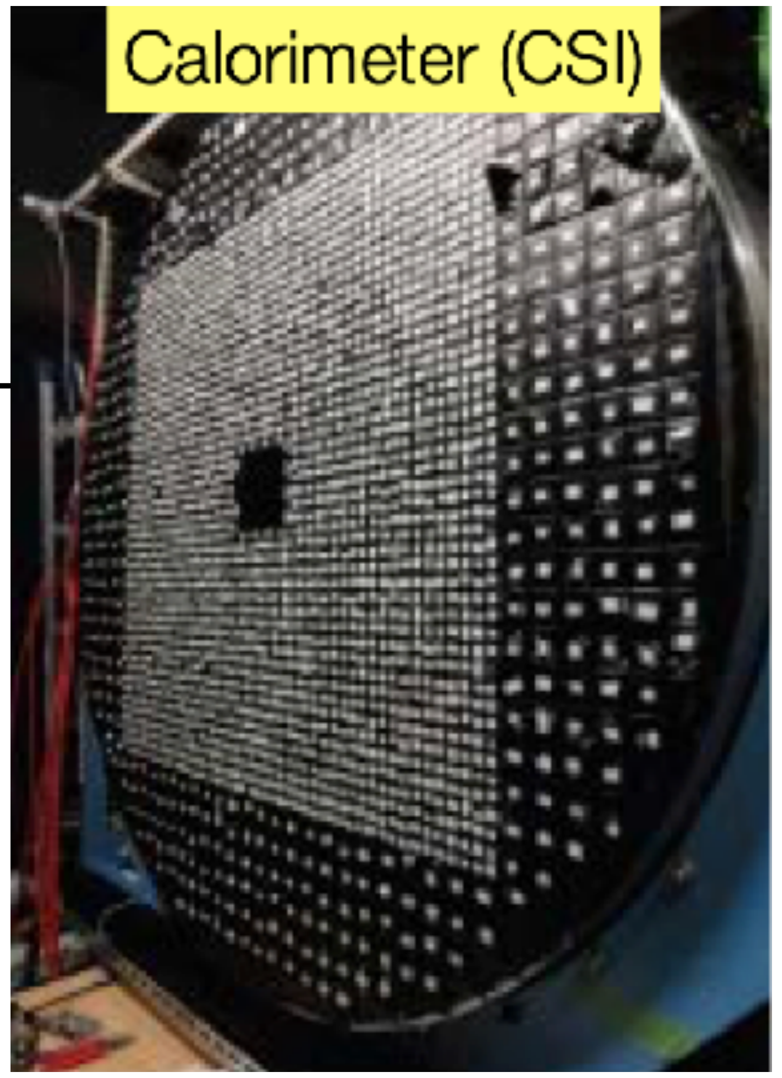

Korea

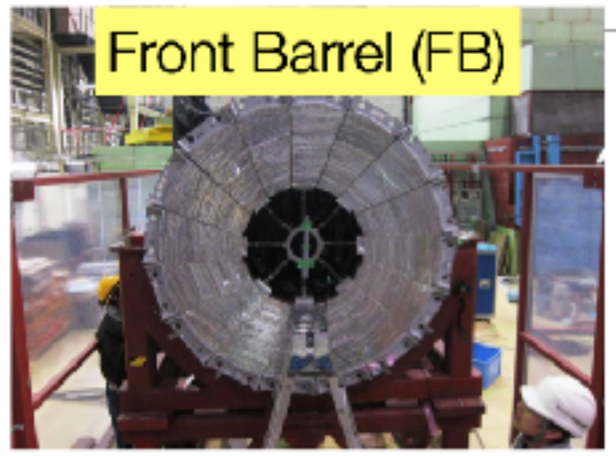

Taiwan

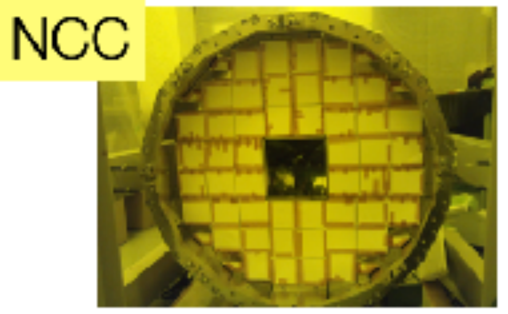

U.S.A.

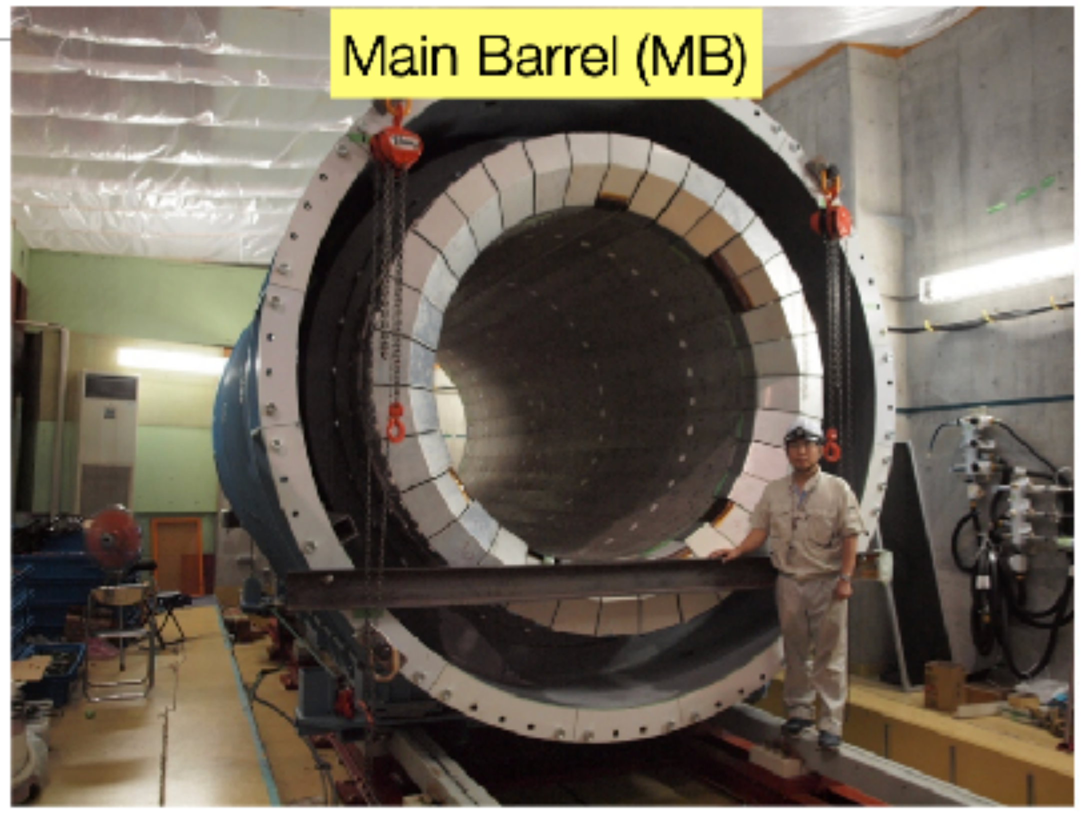
- KOTO detector
  - Calorimeter + Hermetic Veto system





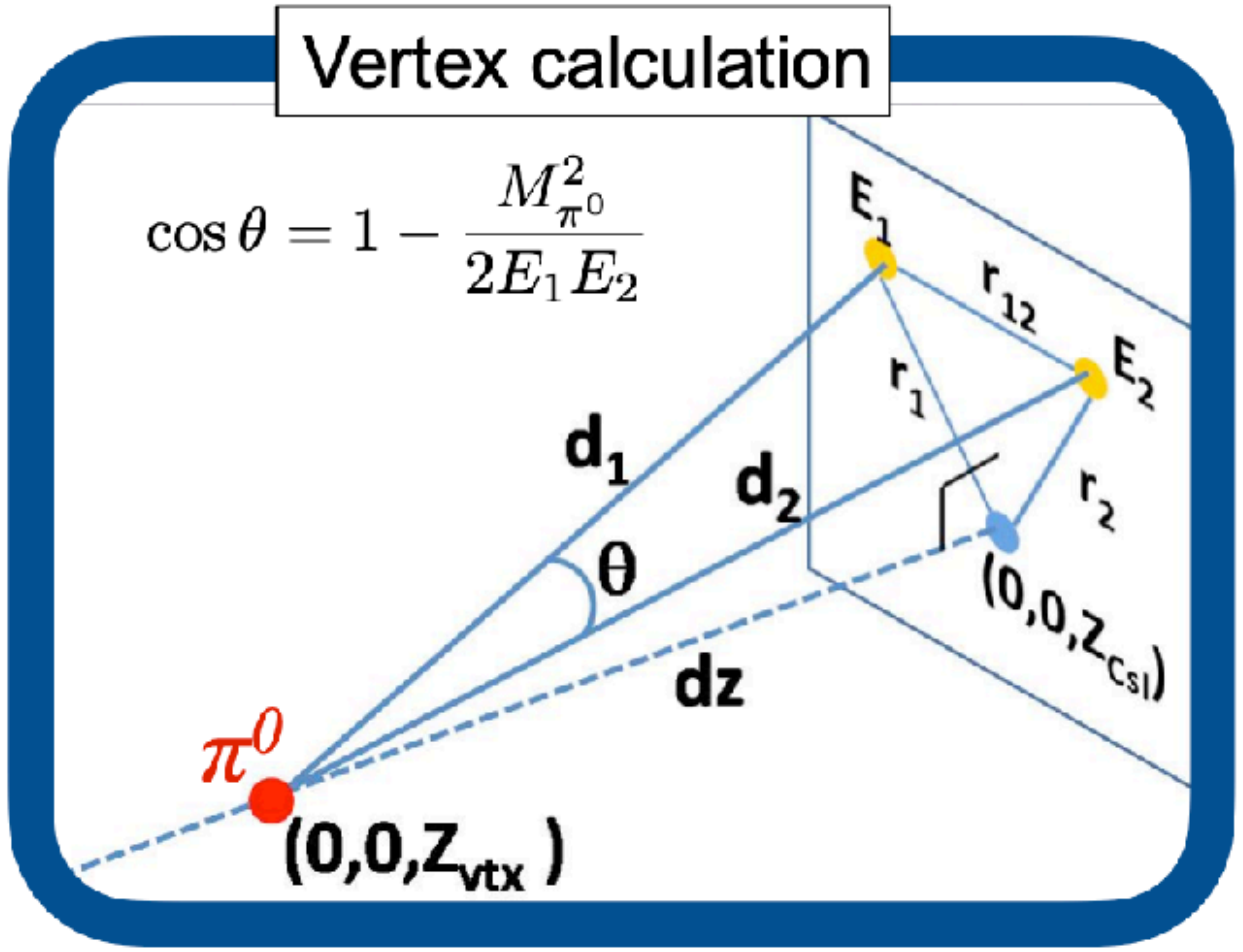


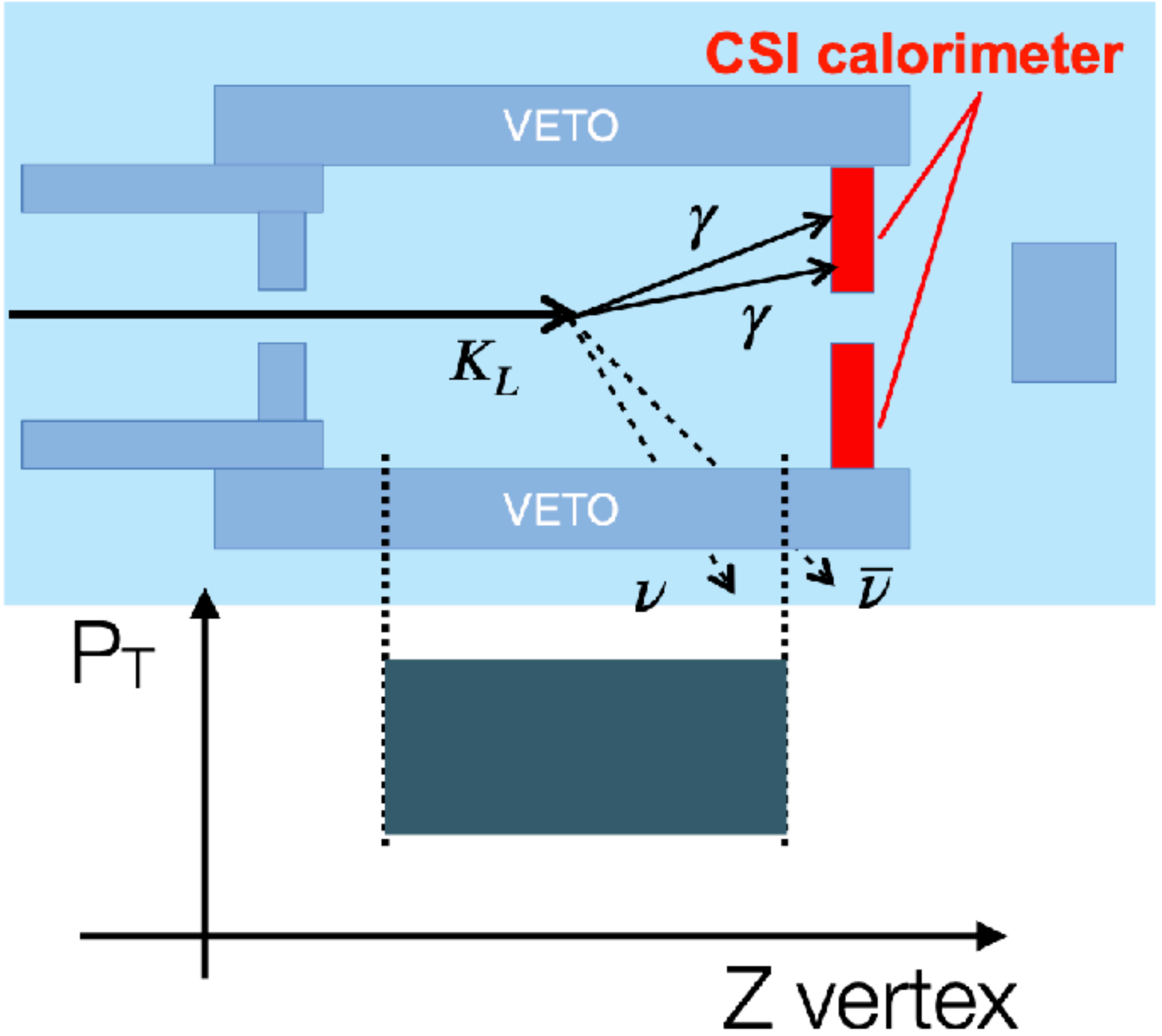




Singal Definition

- KL→$\pi^0 \nu \nu$ events
  - 2γ in the calorimeter + nothing else
  - Calculate the π^0 vertex and transverse momentum with 2γ energies and positions measured by CSI calorimeter

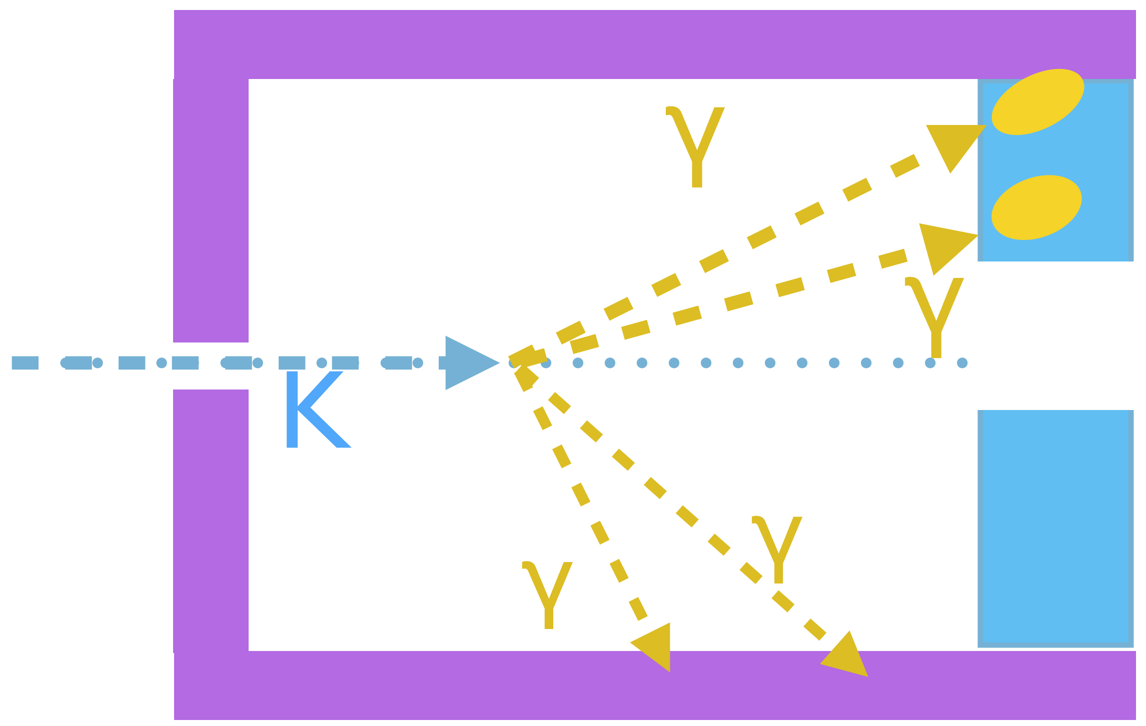




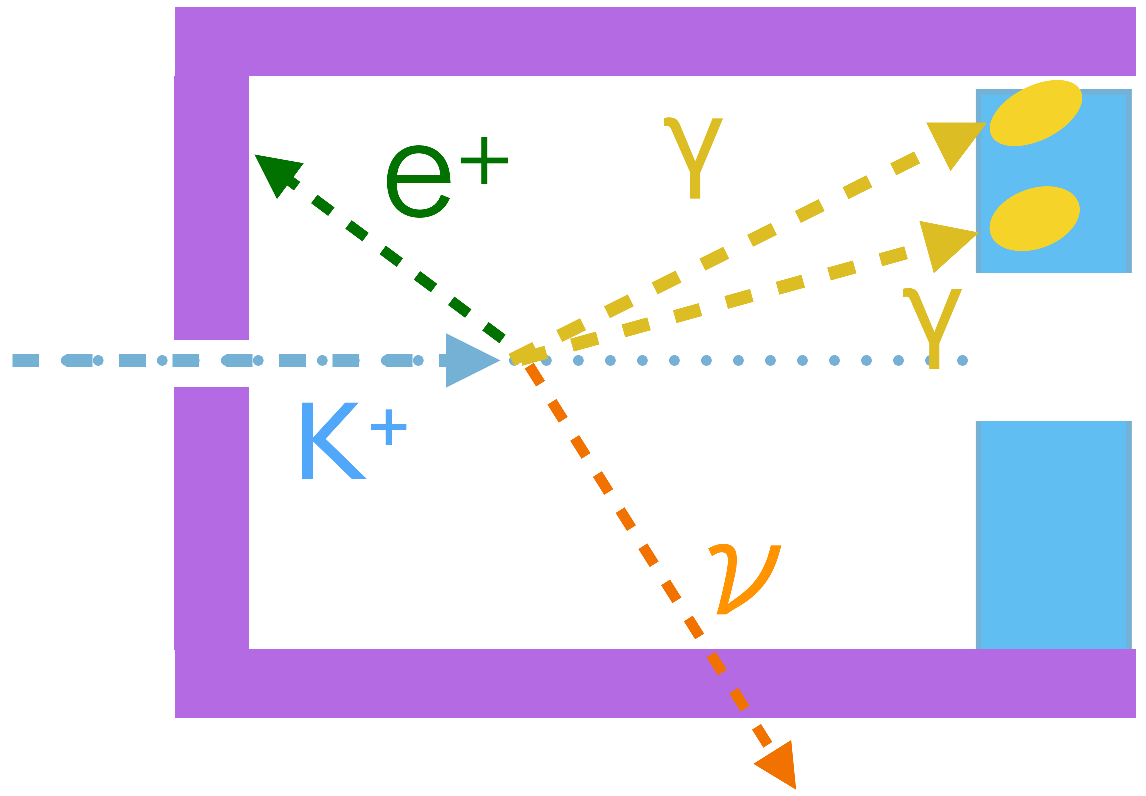
The signal region is defiend on P_T vs Z plane

Background events

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



$K^+ \to \pi^0 e^+ \nu$

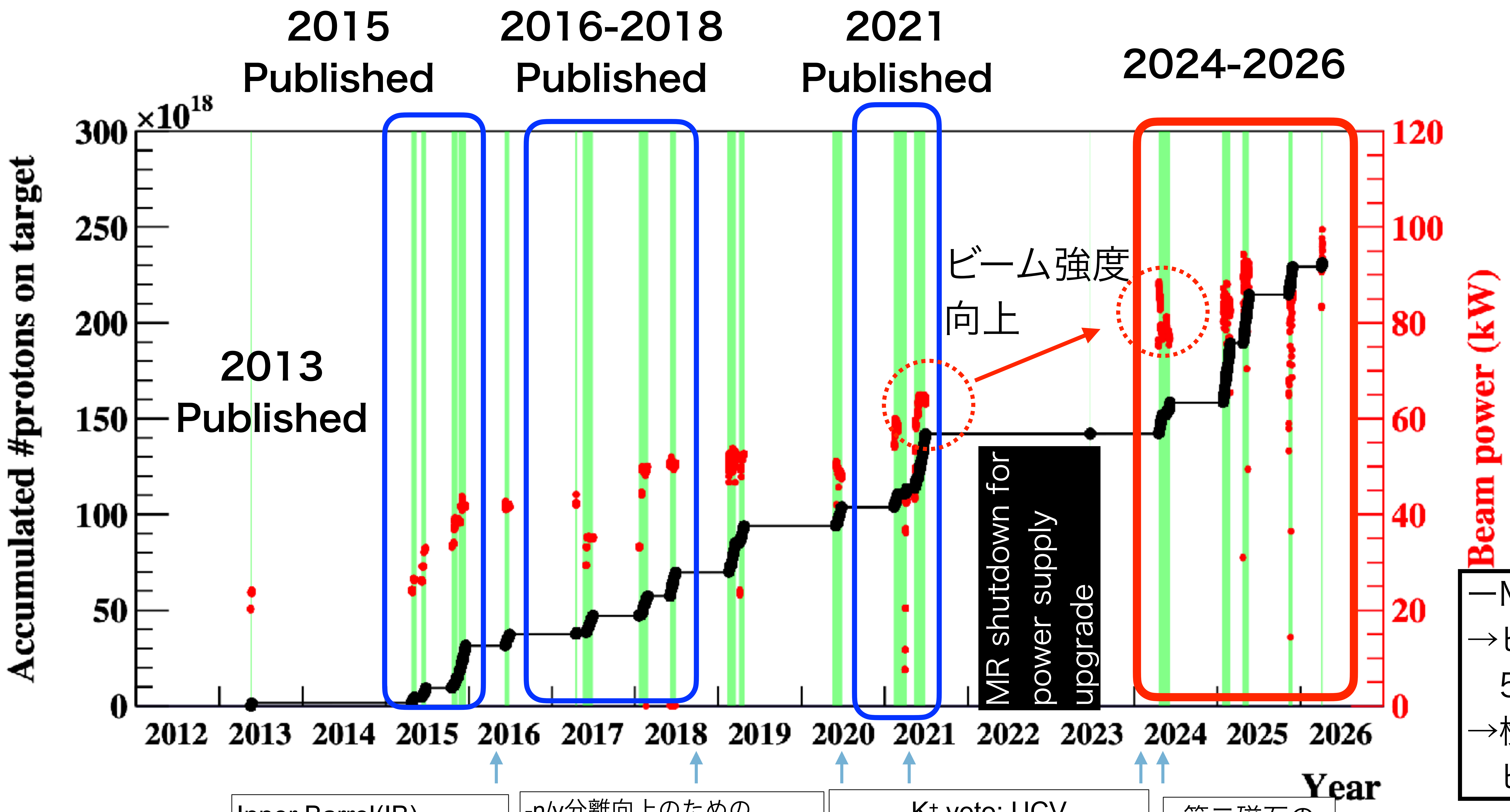


Key components to suppress BGs

-High detection efficiency for extra particles
-Minimize the K^+ flux in the neutral beam
-Minimize beam halo components and detector materials near the beam hole

Caused By Beam Halo Particles

KOTO data accumulation



検出器の改良

Inner Barrel(IB)
検出器のインストール

-n/γ分離向上のための
カロリメーター改良
-Down stream Charged veto

K± veto: UCV

1mmt | 0.5mmt | 0.2mmt

第二磁石の
インストール

ーMRの磁石の電源改良後
→ビーム繰り返し周期が
5.2s→4.2sと早くなった
→検出器レートが同じまま
ビーム強度が25%向上

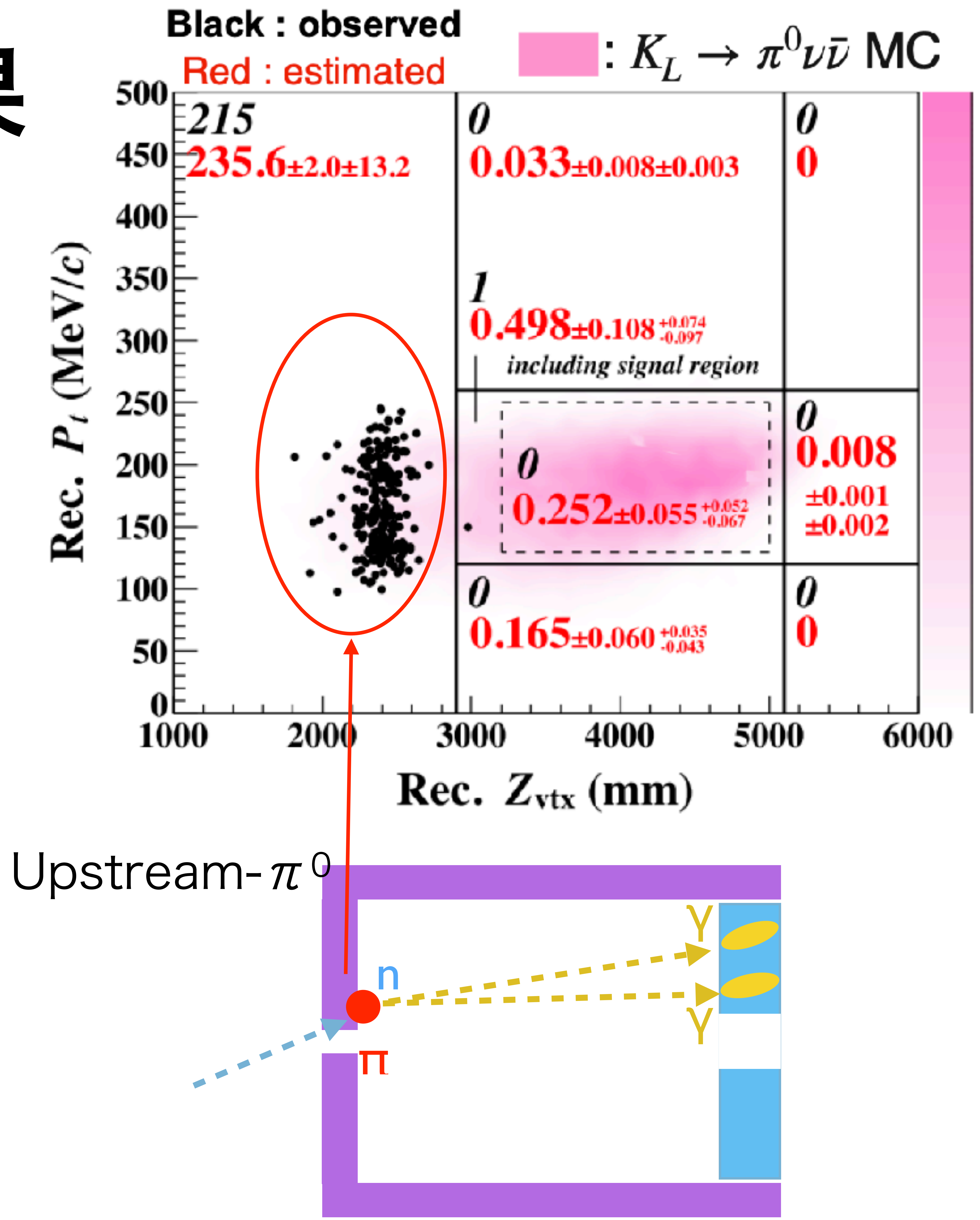
2026年4月に
100kW達成

21

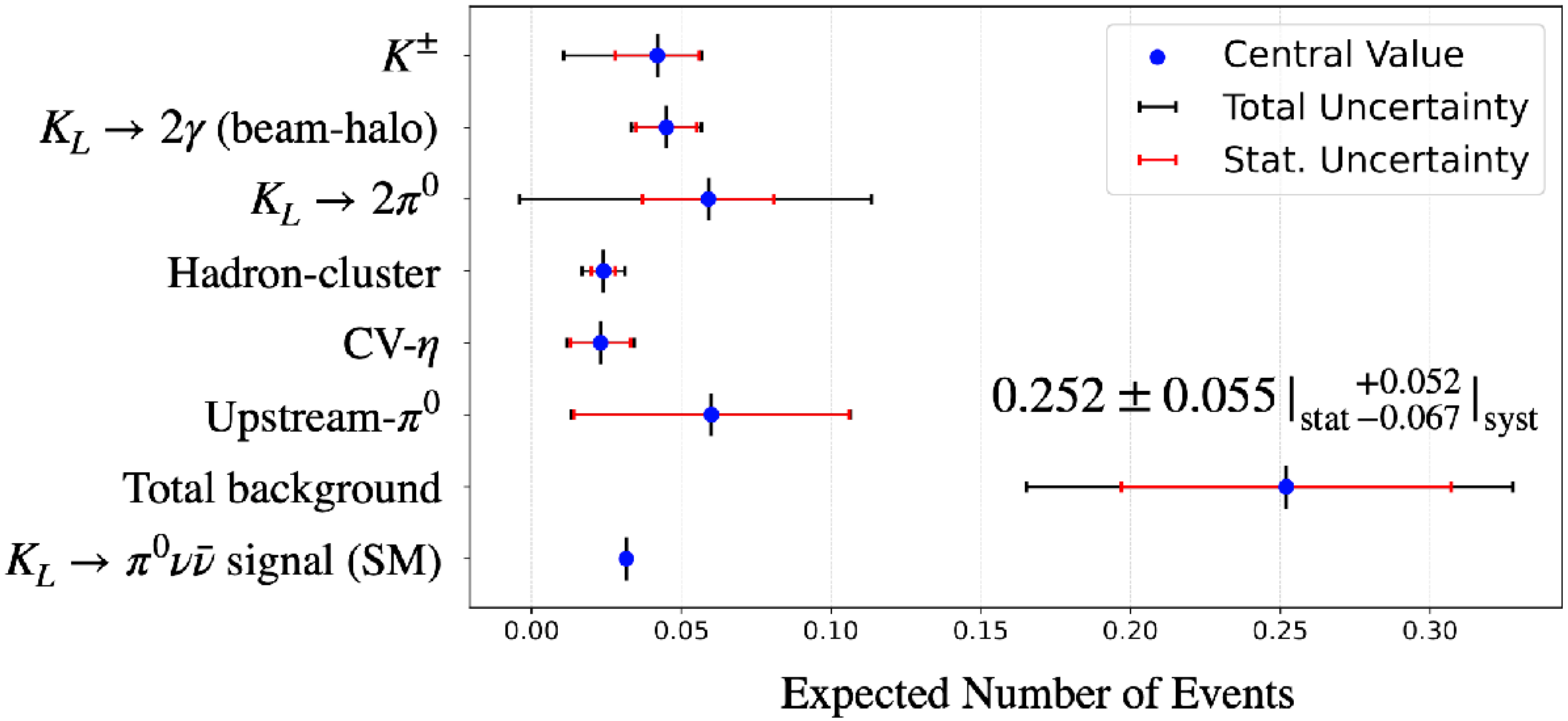
2021年データ解析の結果

Phys. Rev. Lett. 134, 081802 (2025)

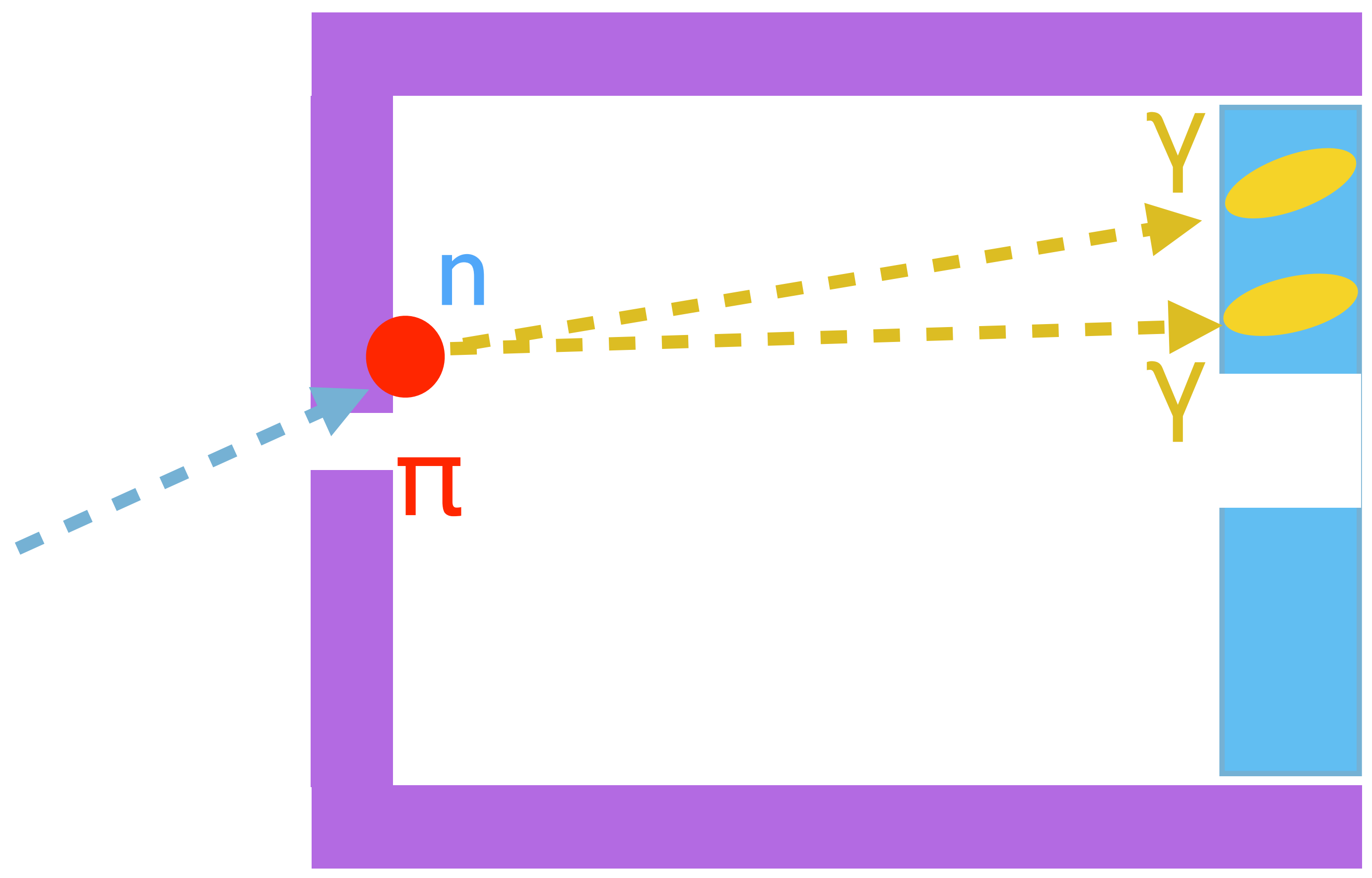
- Single Event Sensitivity(SES)
  - $(9.33 \pm 0.06_{stat} \pm 0.84_{sys}) \times 10^{-10}$
- 信号領域内では１事象も観測されず
  - $BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$(90% C.L.)



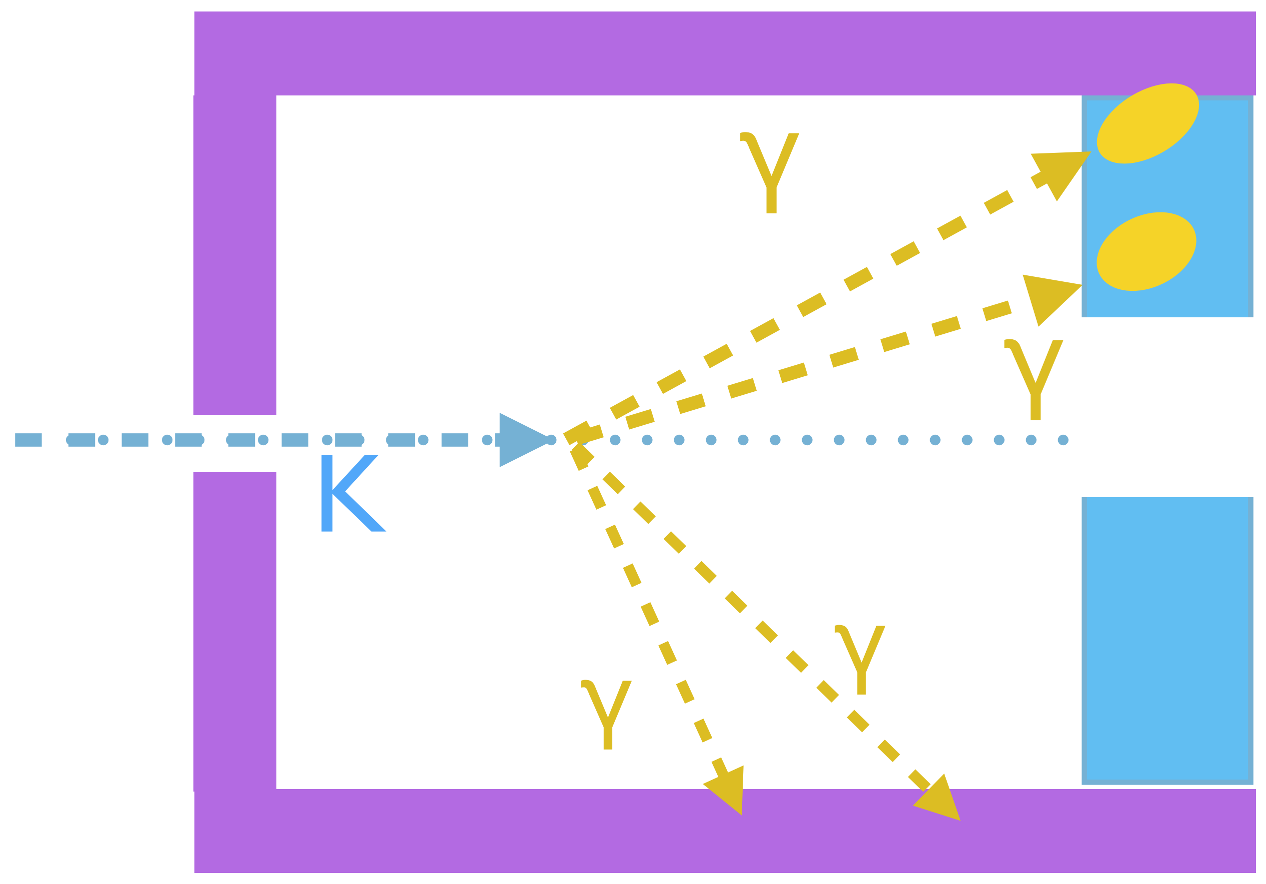
2021年データ解析での背景事象の内訳



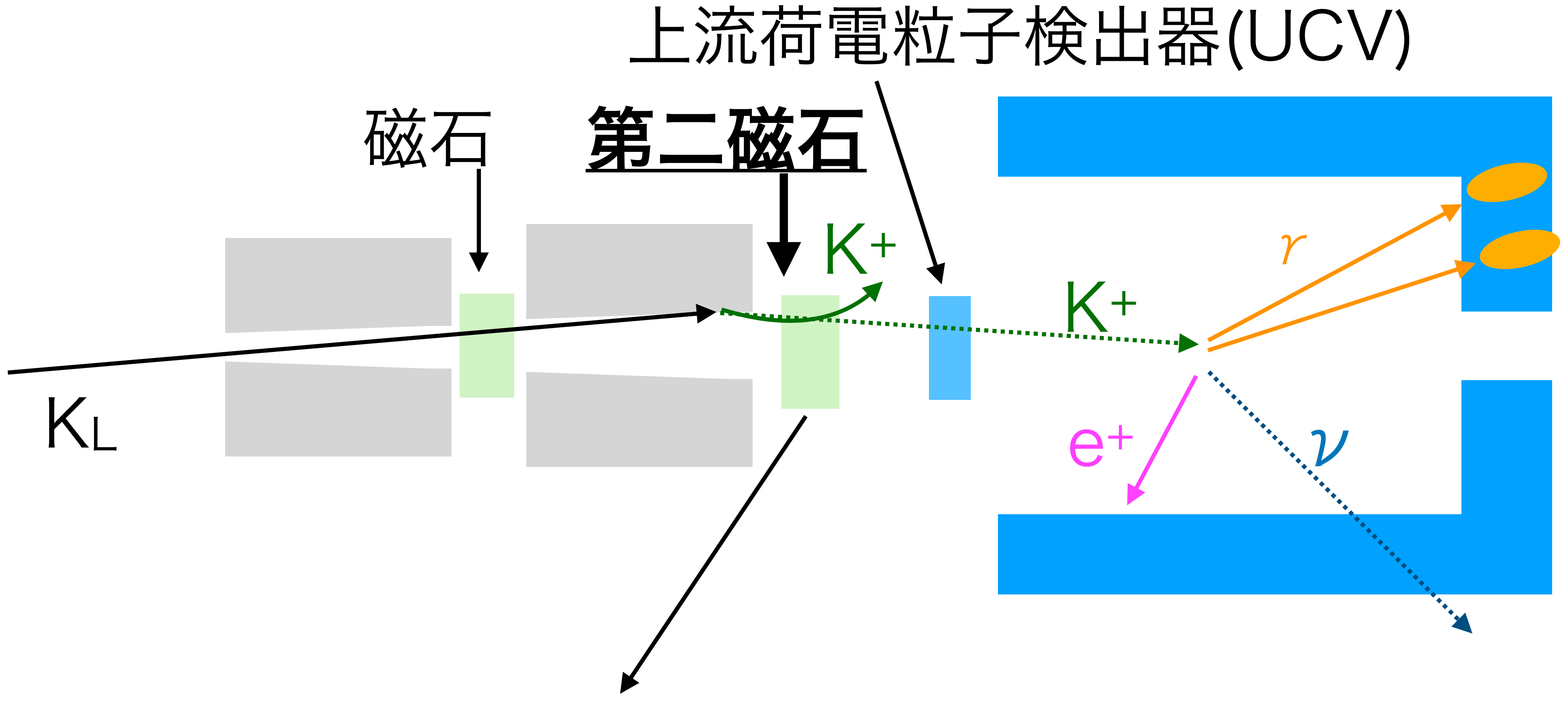
Upstream-π^0



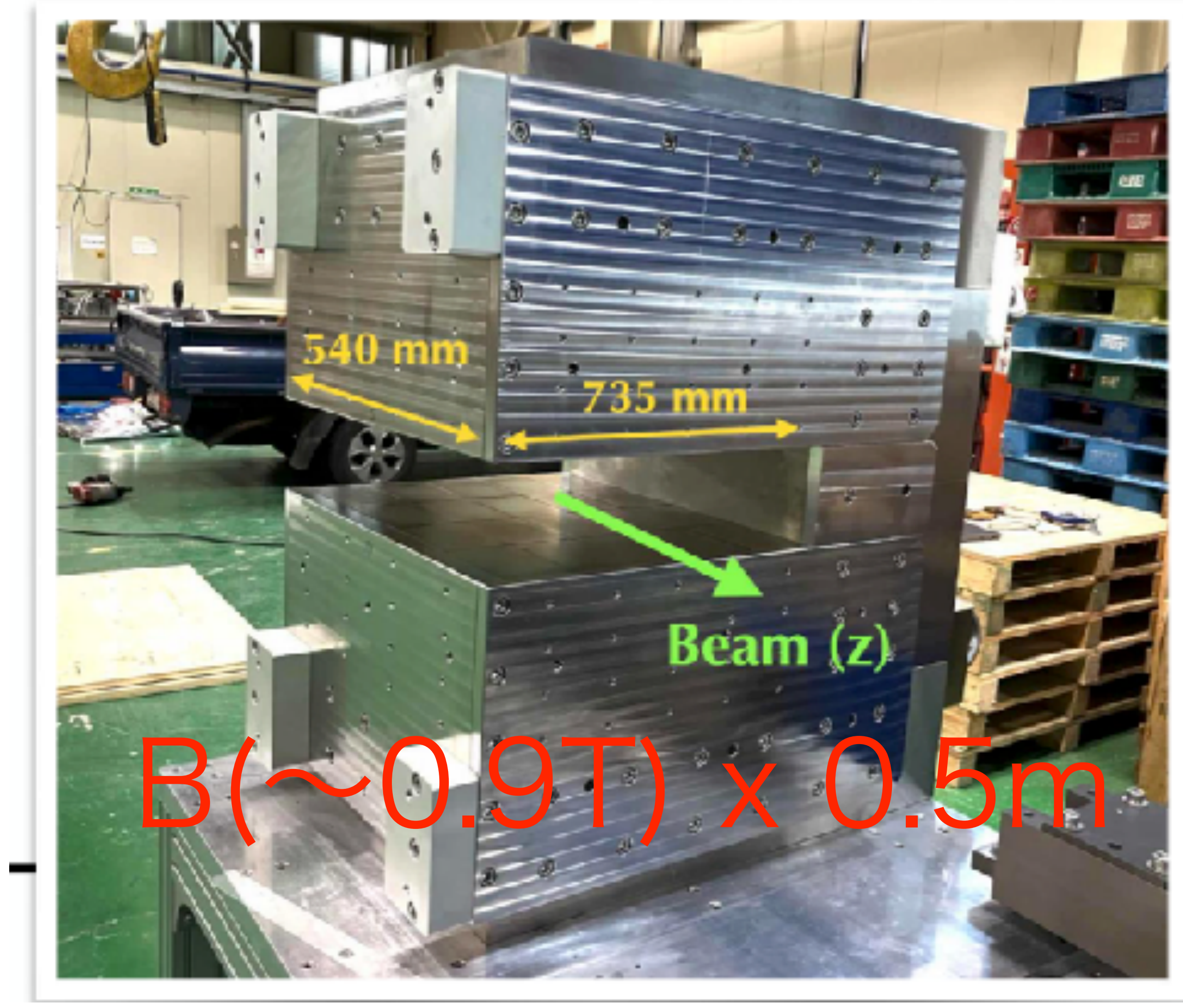
KL→2π^0



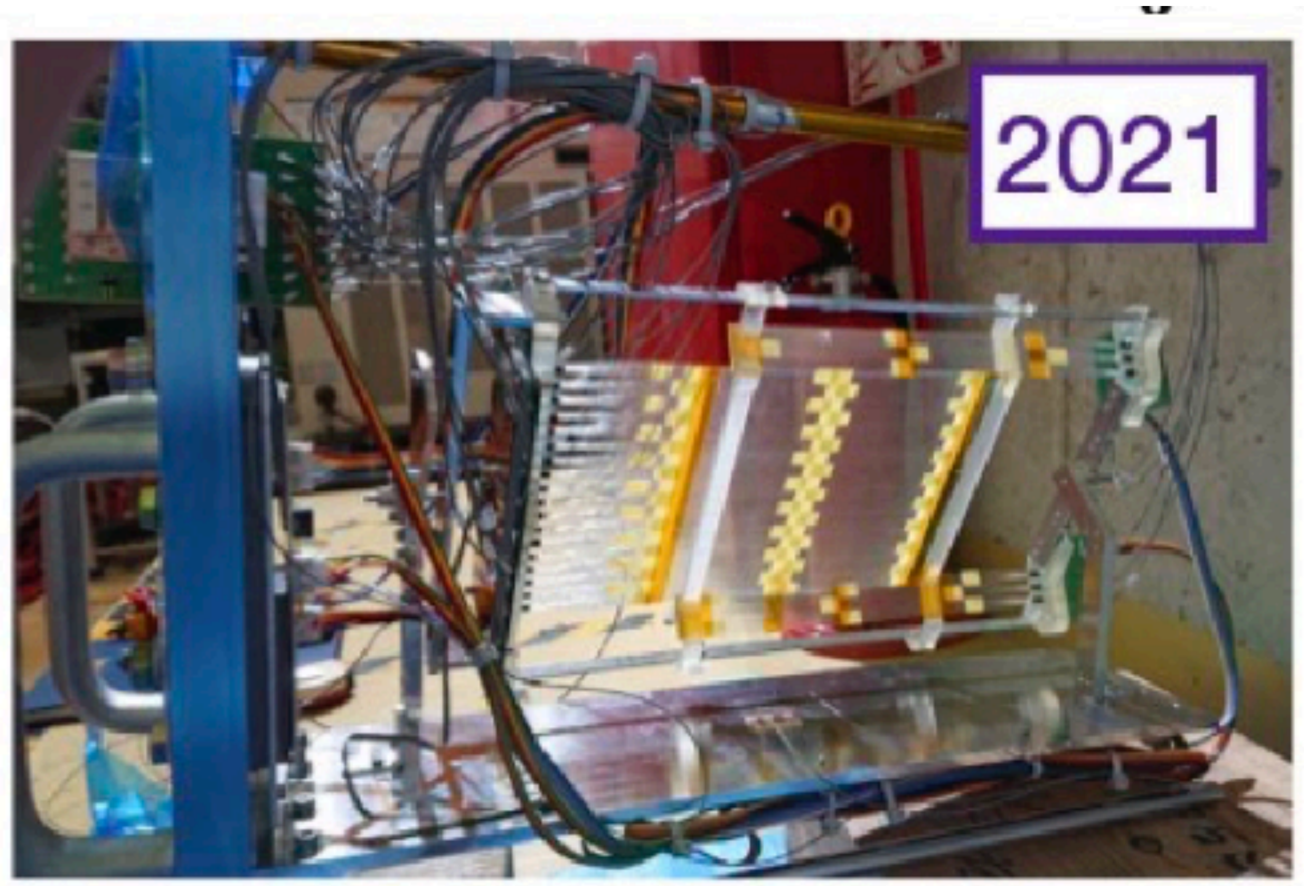
2021年以降の検出器の改良点：上流荷電粒子検出器(UCV)の改良+第二磁石



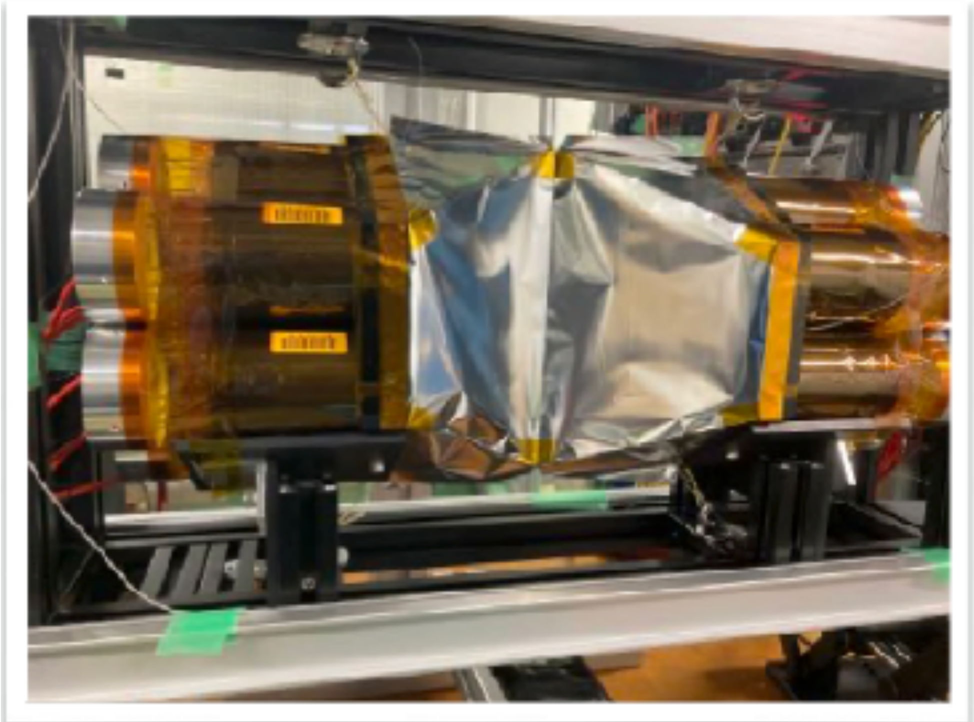
-K+ flux x1/10(MC予想)

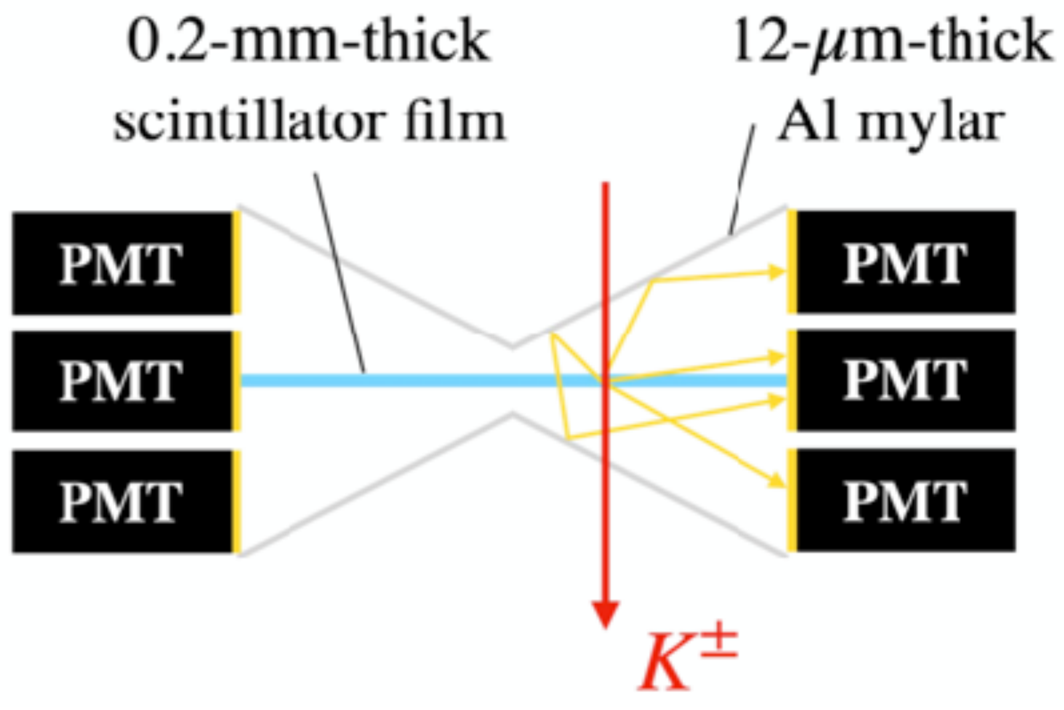


UCV (2021)



UCV (2023-)

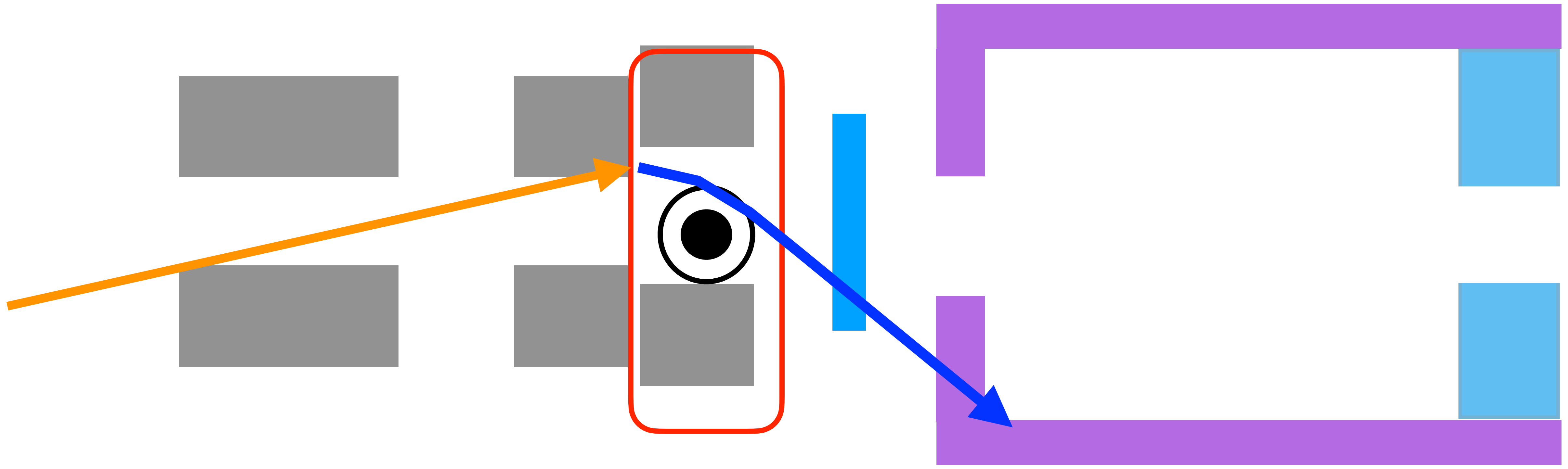




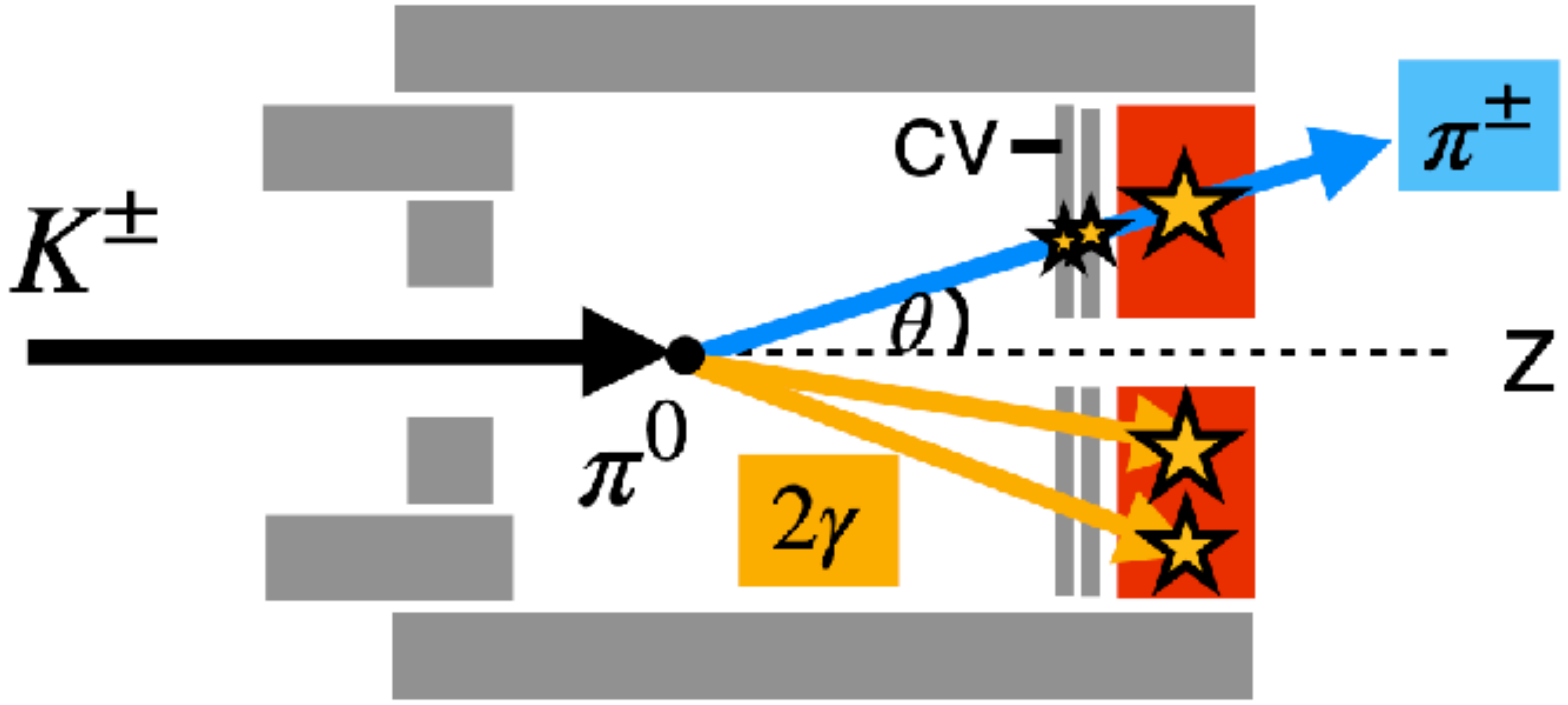
Material	0.5mmt-sq. scinti. fiber	0.2mmt scinti. Film
	→低物質量、隙間のない構造	
Readout	MPPC	PMT
	→S/Nの向上、放射線ダメージの低減	
Inefficiency	7.8%	6×10^{-4}

K+ flux estimation

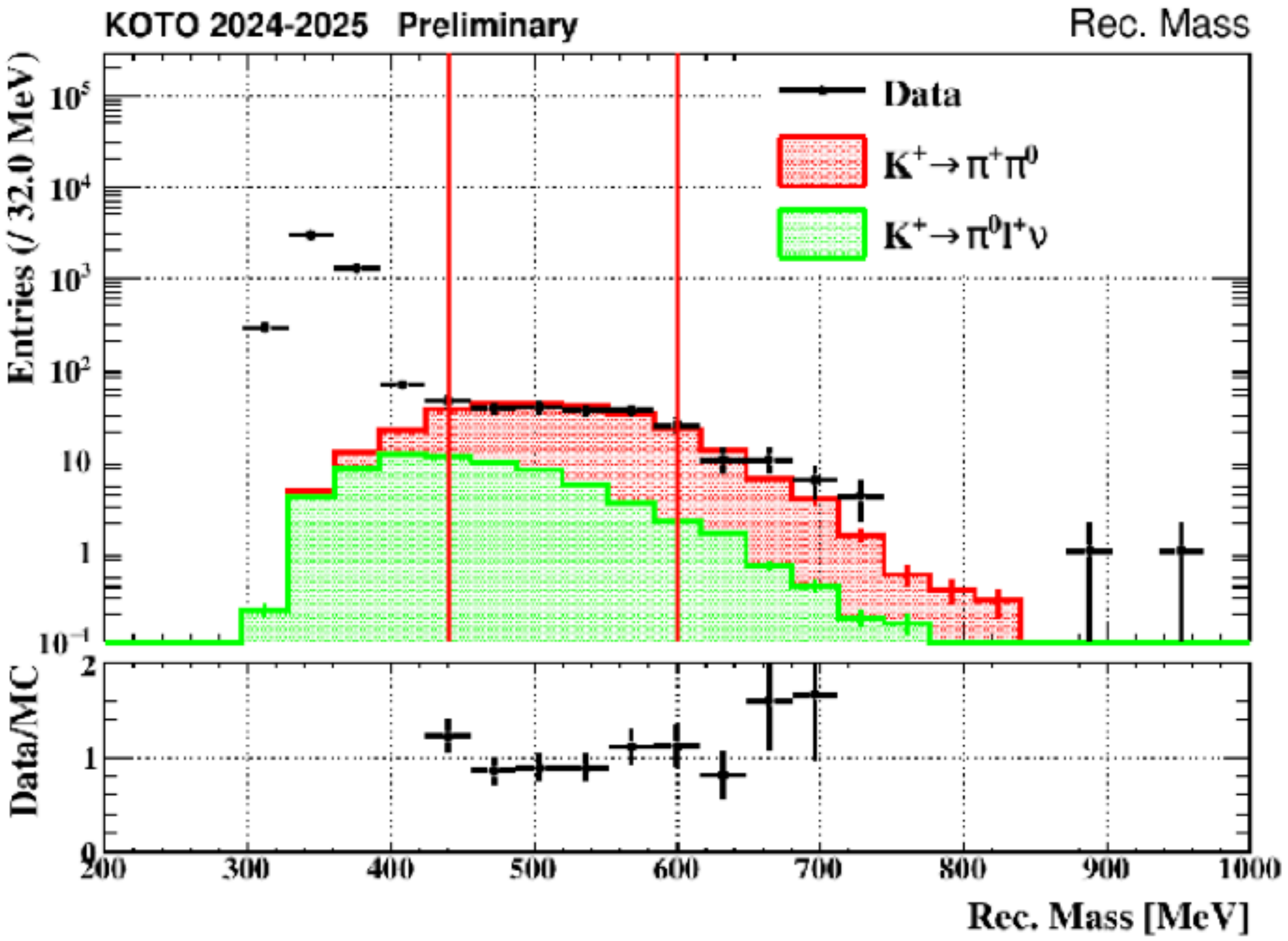
K+ flux was reduced due to the newly installed second magnet



K+ flux was evaluated by identifying the $K^+ \to \pi^+ \pi^0$



Reconstructed K+ mass distribution



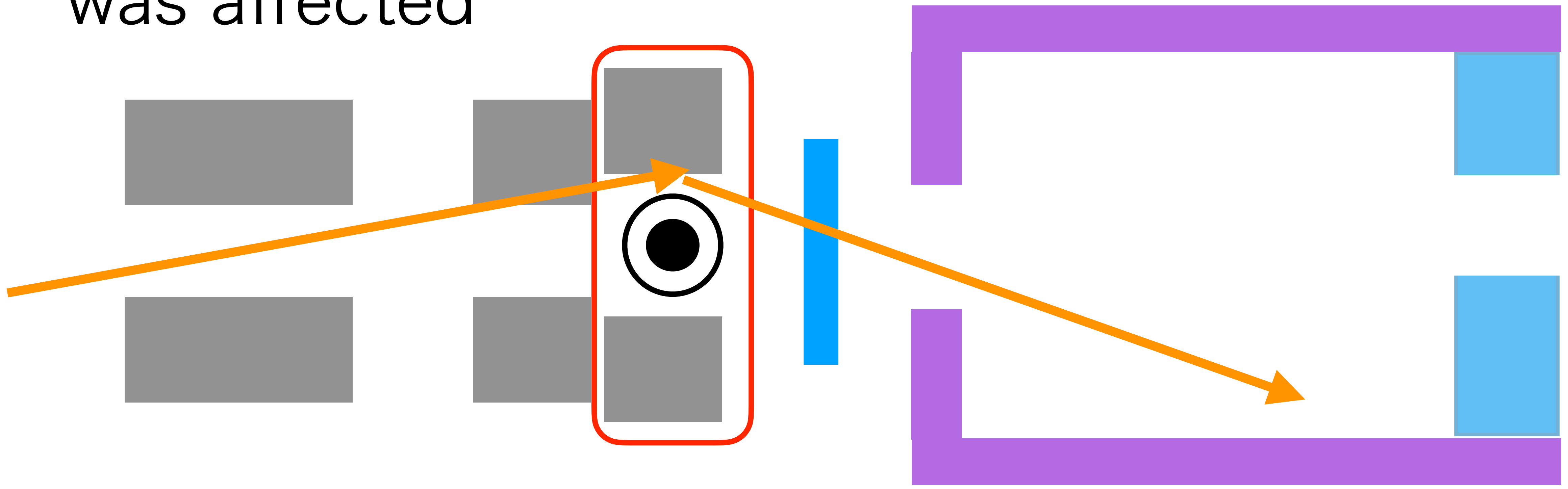
K^+/K_L flux ratio was reduced by a factor 27. (Preliminary).

Halo KL flux estimation

Source points of Halo KL

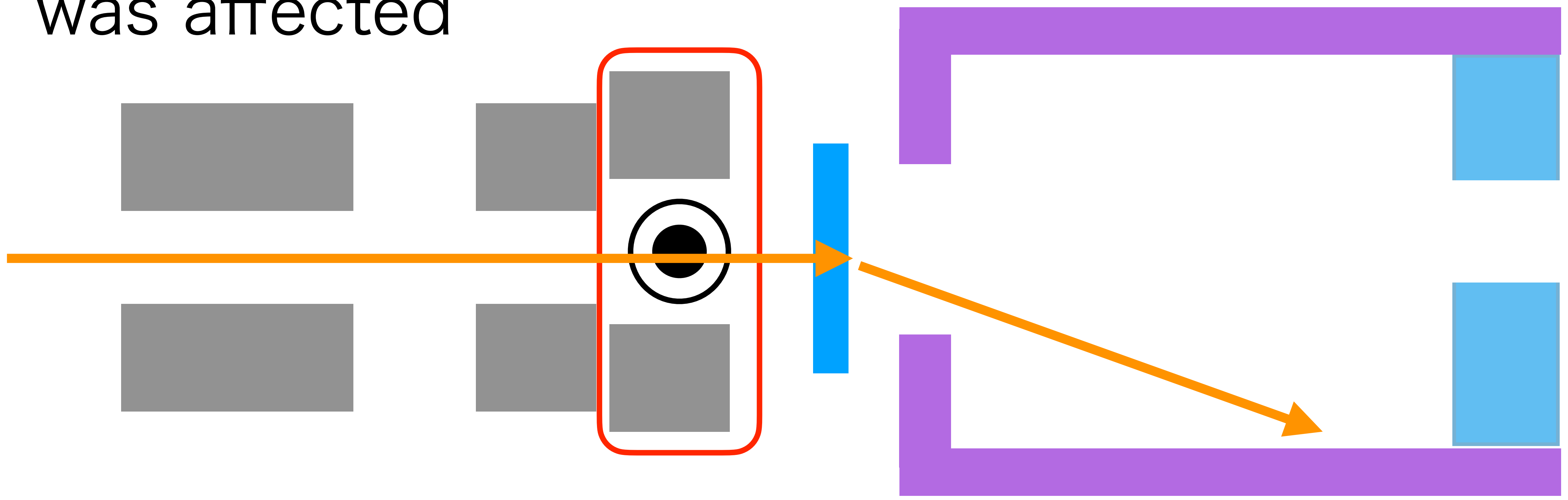
Scattered at the collimators

-Configuration change to install the second magnet was affected

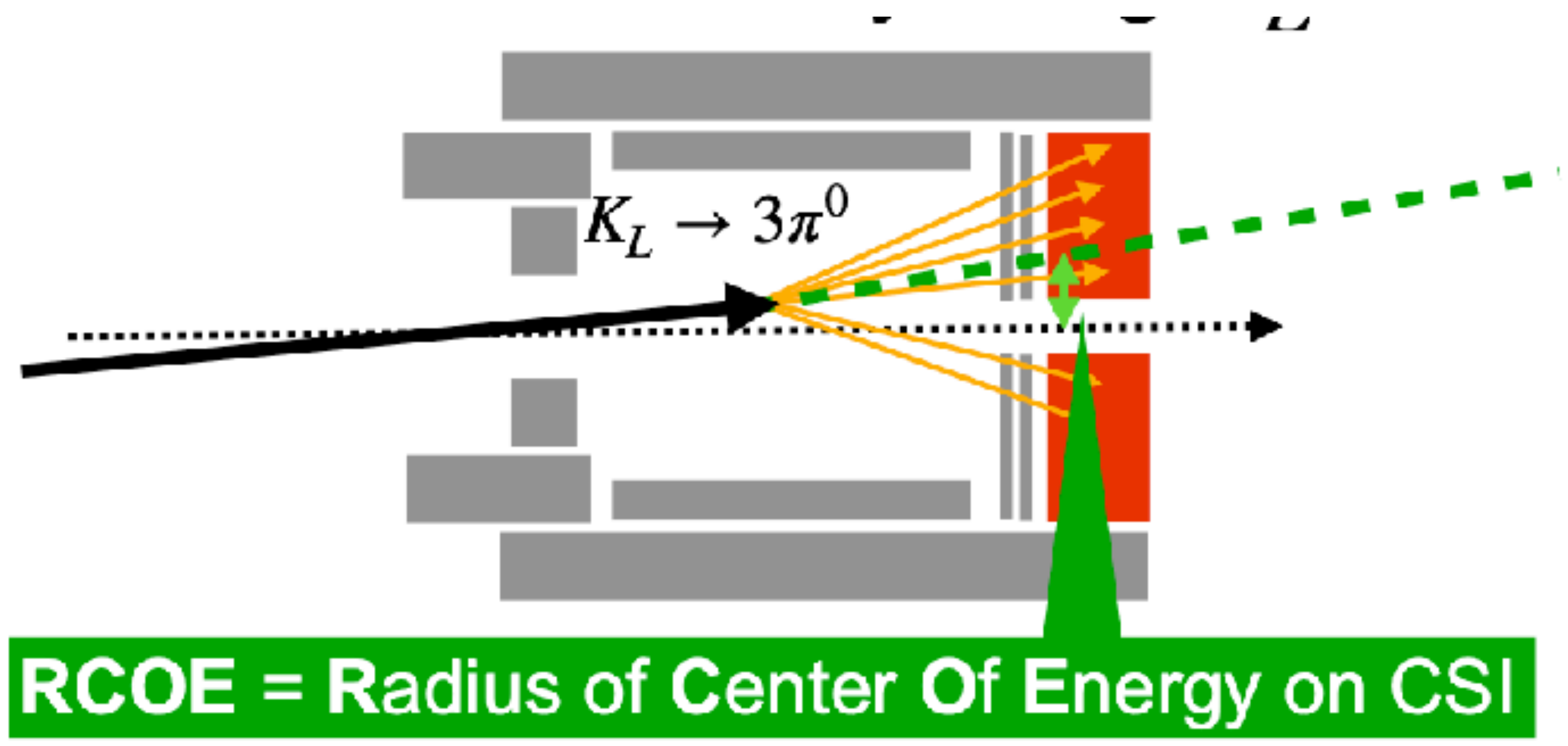


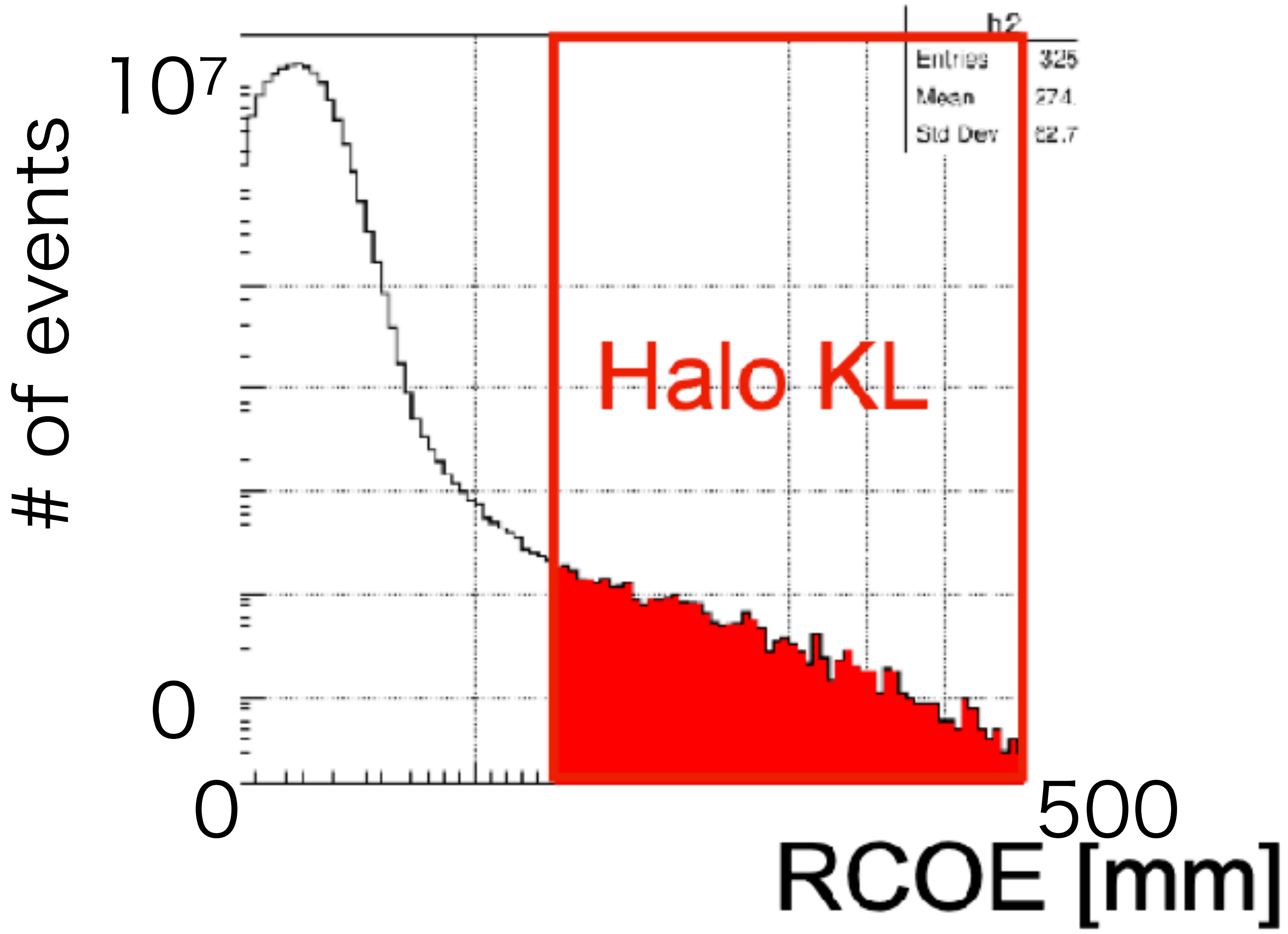
Scattered at the UCV

-The chagne of UCV thickness(0.5mm->0.2mm) was affected



Flux of Halo KL was evaluated by KL→3π^0

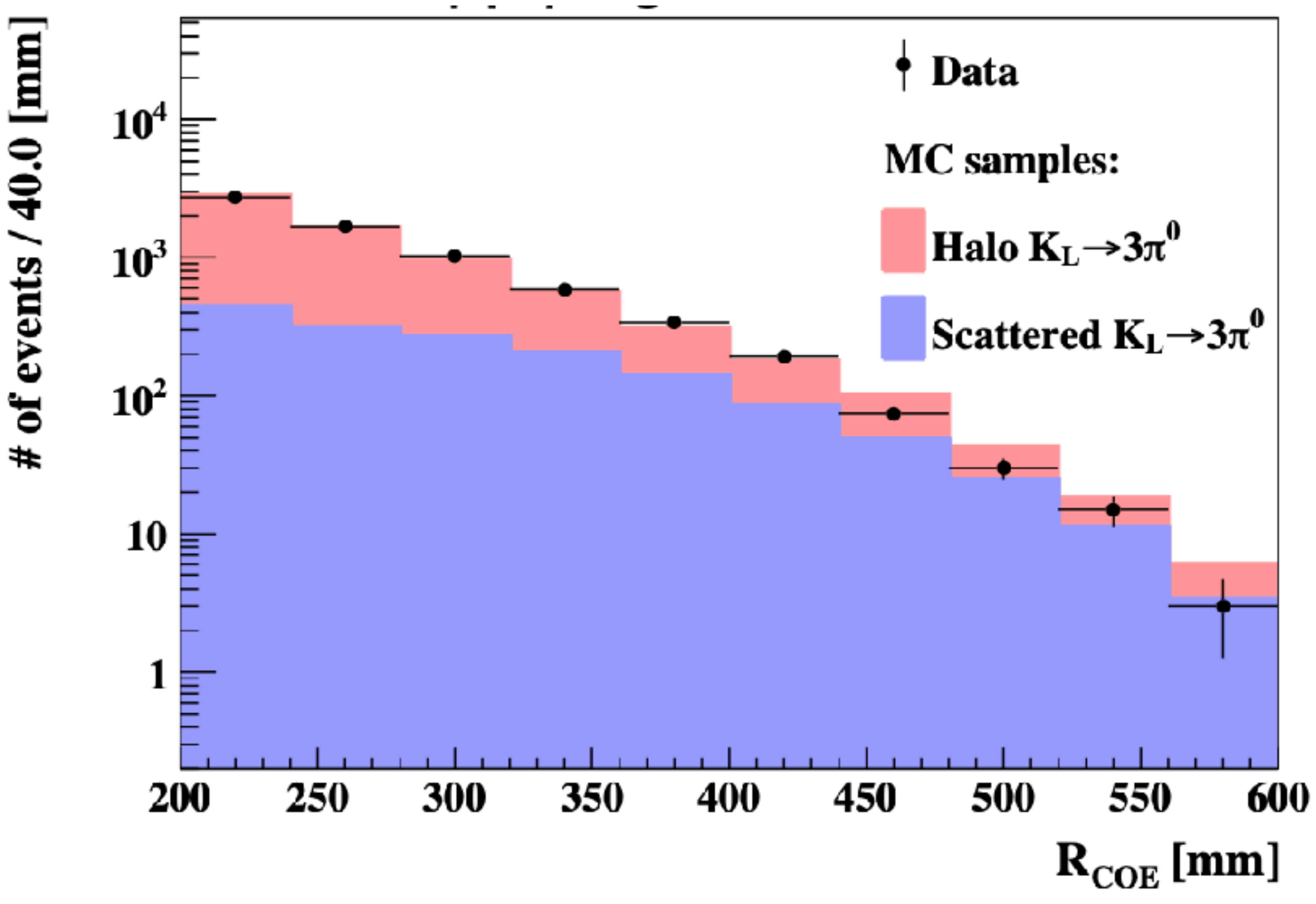




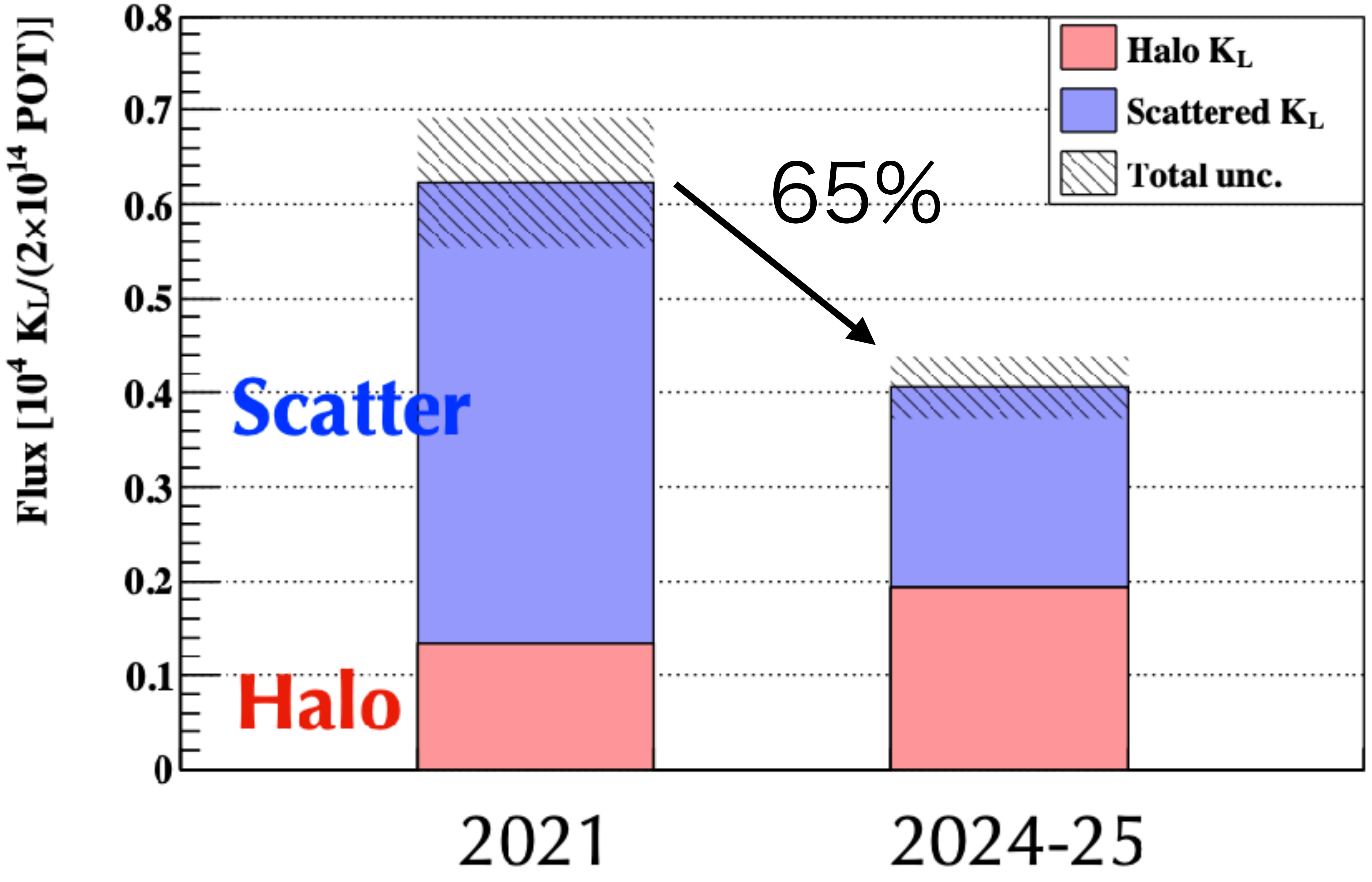
Halo KL flux estimation

Halo KL   : Scatterred at the surface of the collimators
Scattered KL: Scatterred at the UCV

Halo KL measured with
KL→3π^0 samples

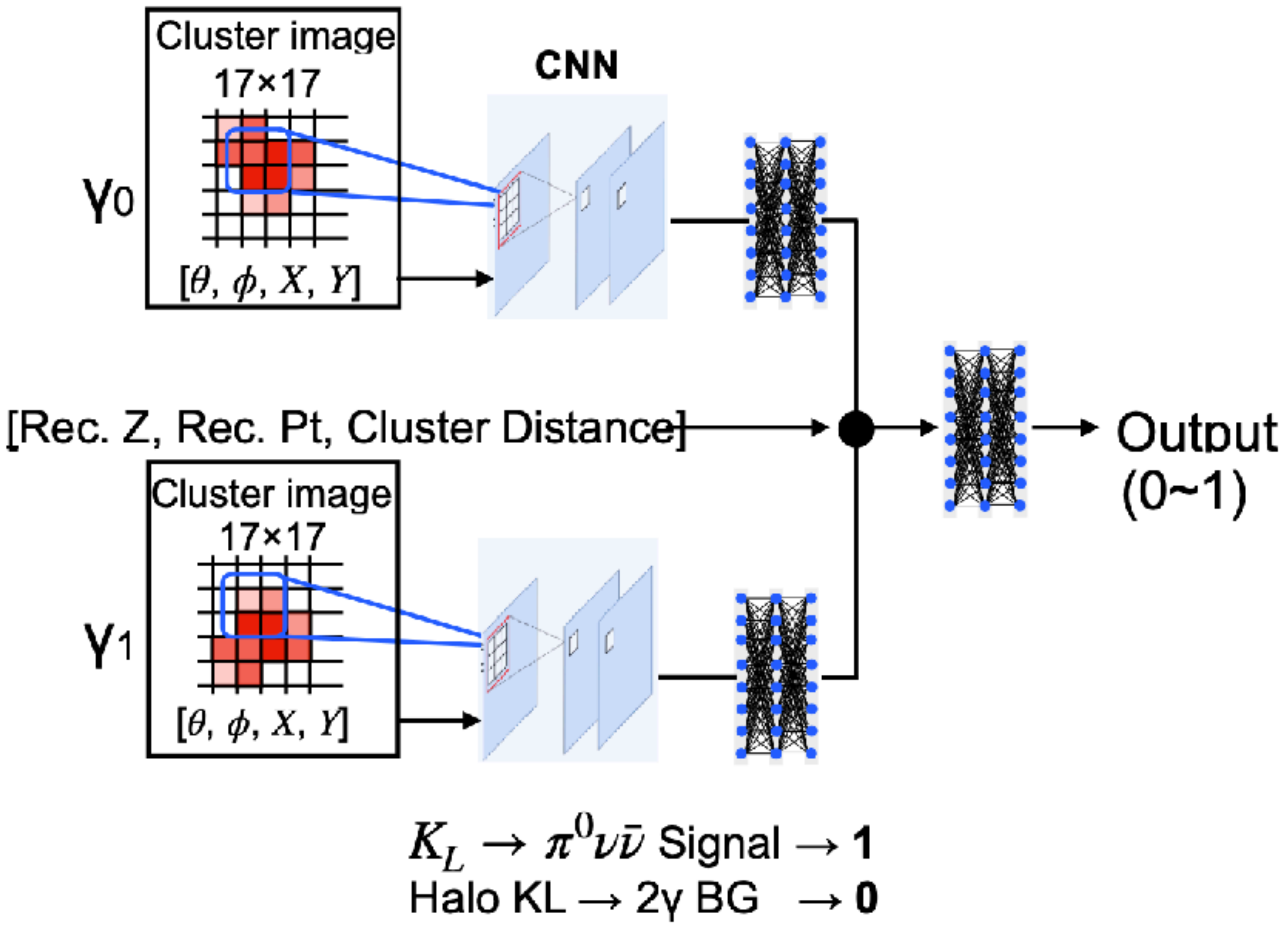


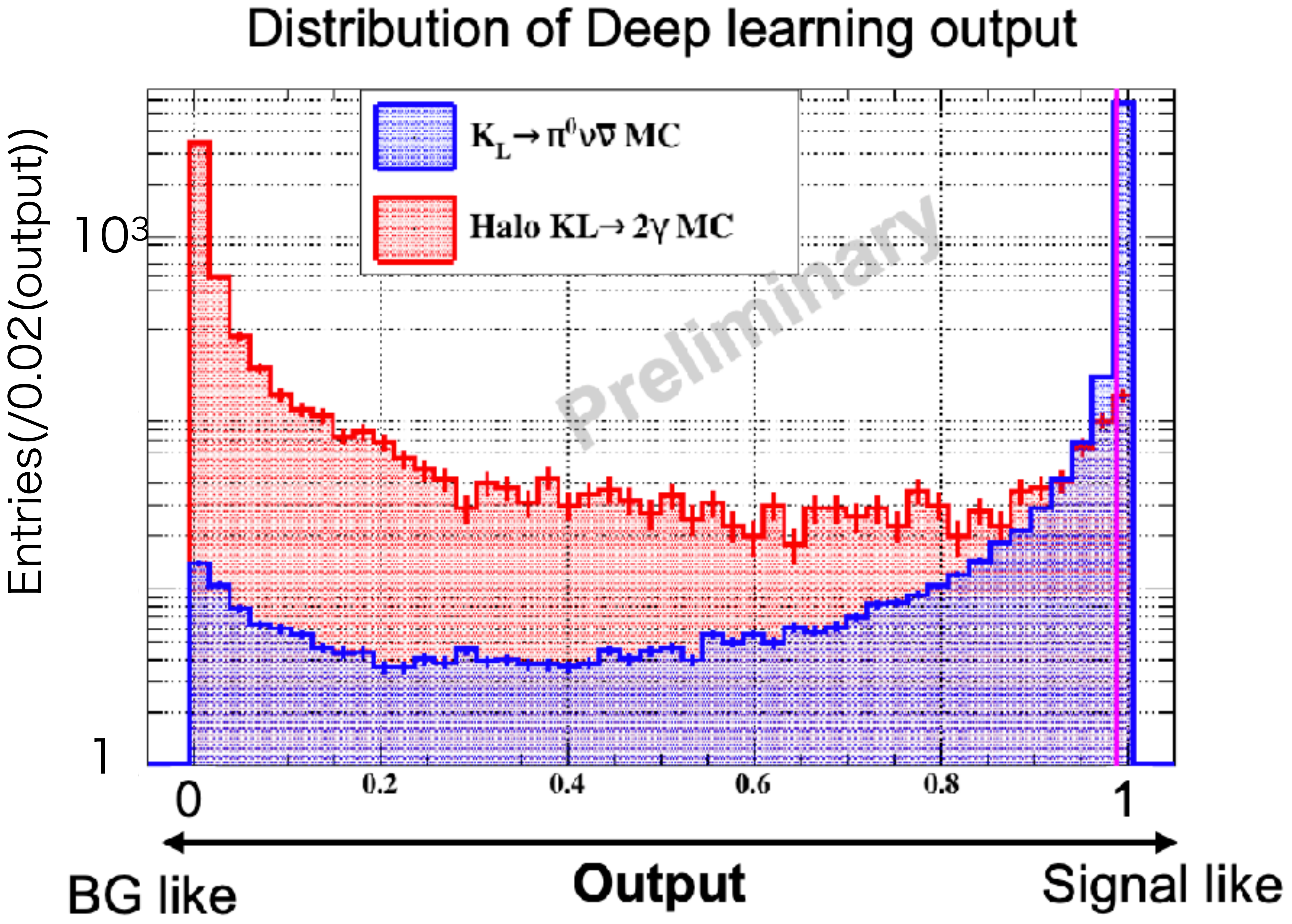
Halo KL flux



2021年以降の改良：新たな解析手法の開発

New deep learning cut against Halo $K_L \to 2\gamma$ BG

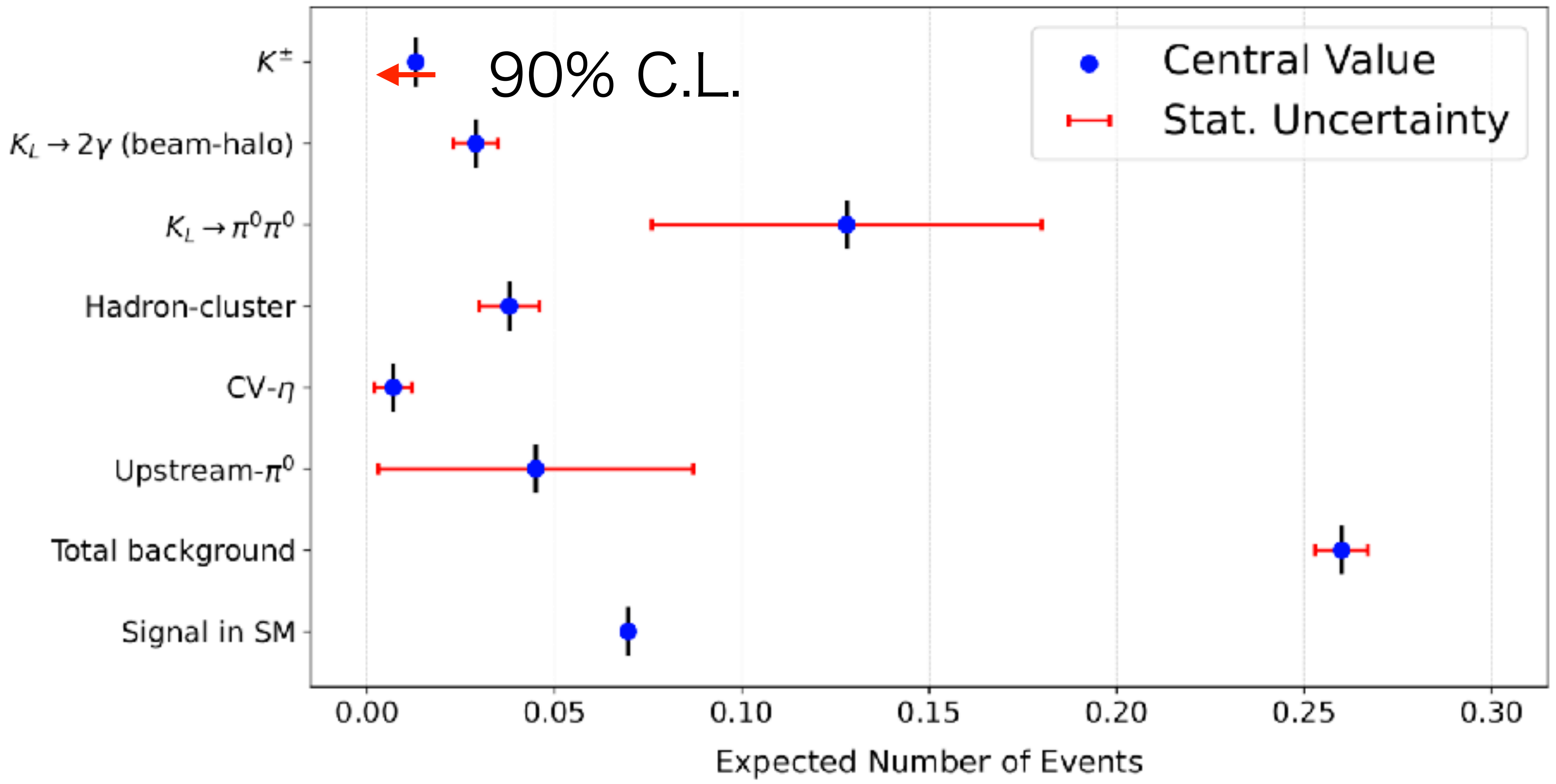




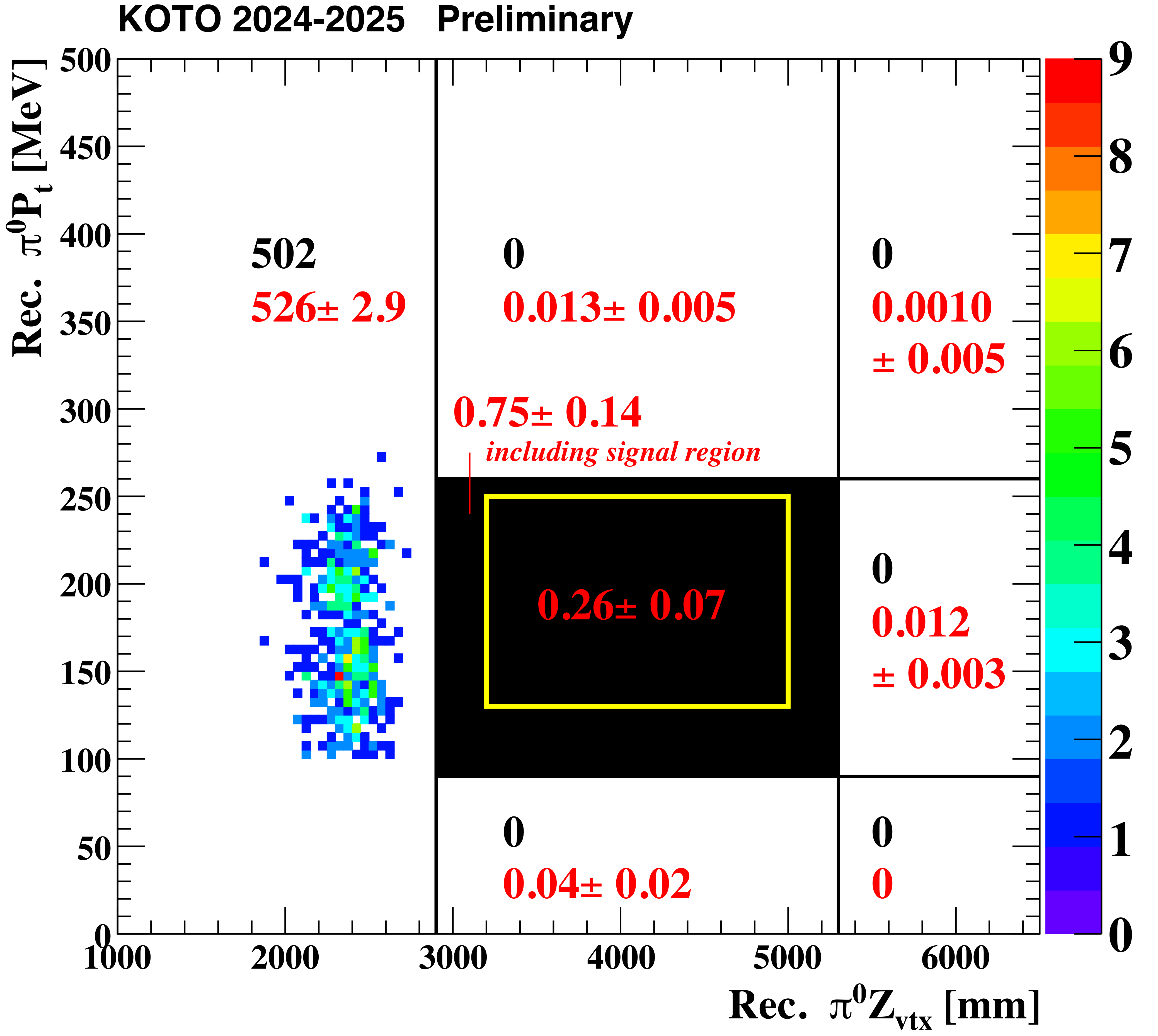
- Halo $K_L \to 2\gamma$ BG can be reduced to 4～2% with 95% signal efficiency.
  → 6 times higher rejection power than that in the previous cuts.

PT & Z distubition for 2024-2025 data set

of background events in the signal box



SES=4.22x10^{-10}



* Data taken from April 2024 to May 2025 were used for this analysis

* Only an upper limit can be obtained for K+ BG due to insufficient statistics.

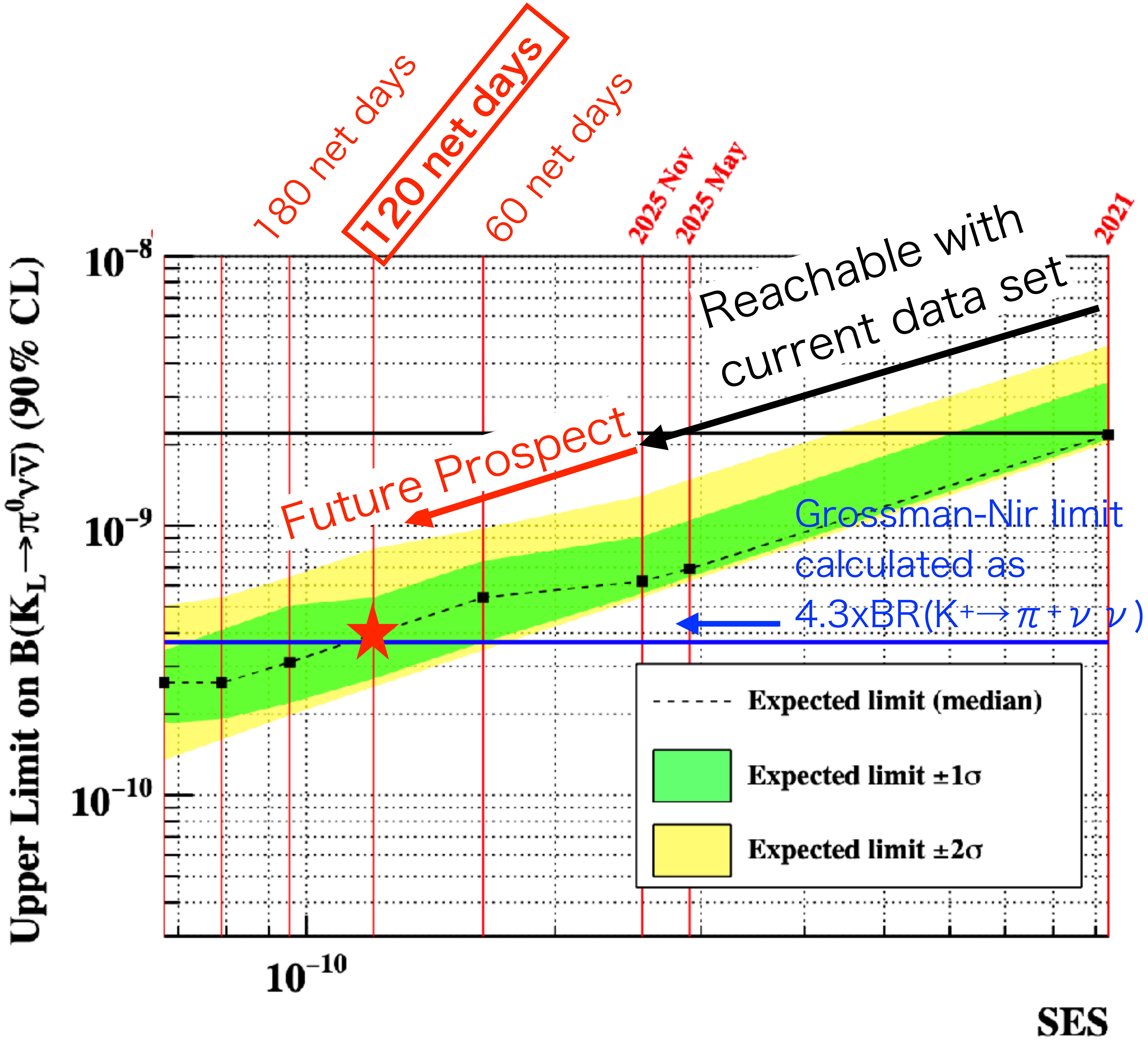
* # of hadron cluster BG is extrapolated from that in the previous analysis

* # of KL→2π0 BG will be updated based on the inefficiency measurement for the veto detectors.

# of BG events is the same as the previous run, while SES is x2

KOTO prospect

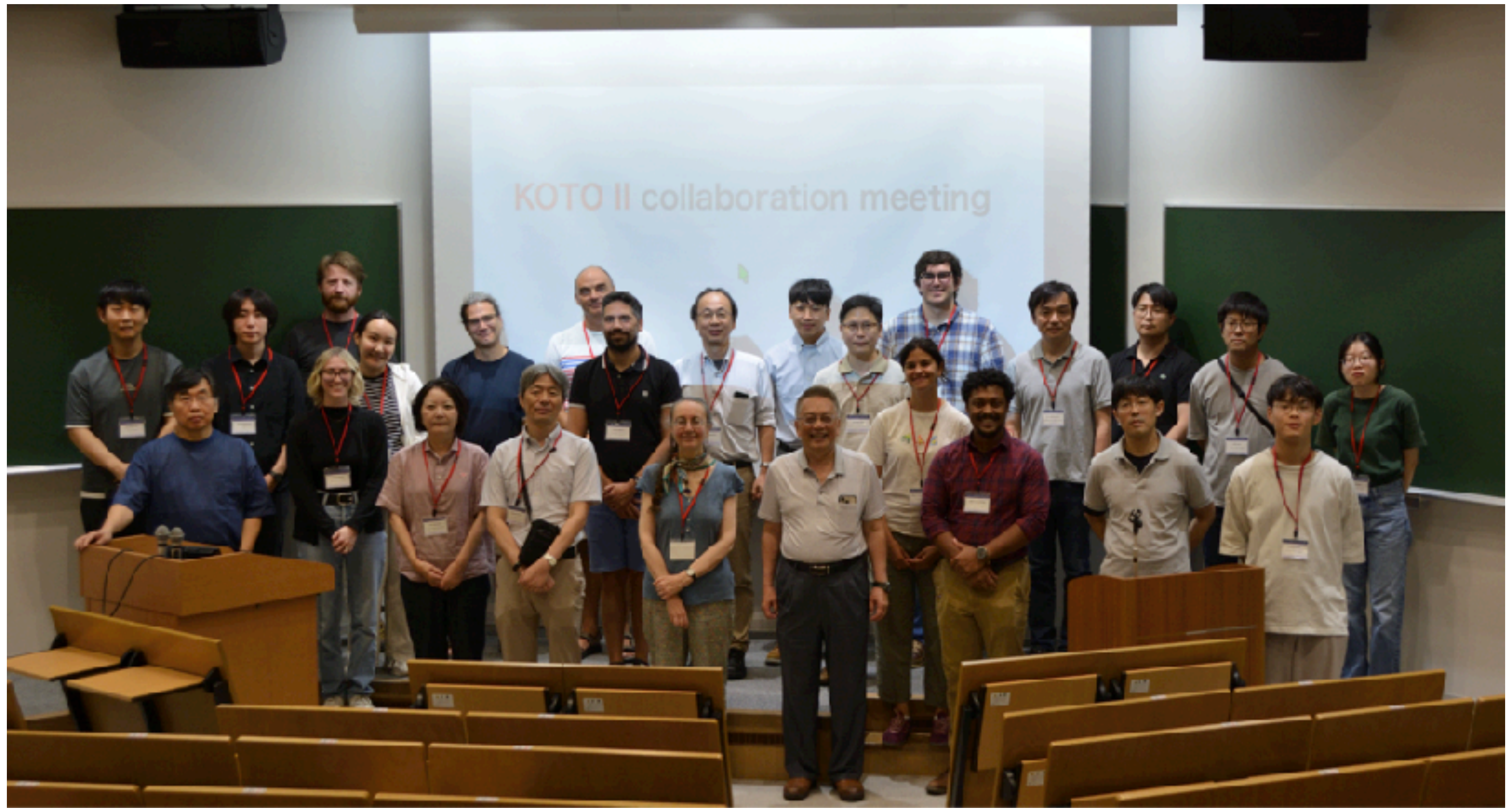
- さらに120日間のビームデータ取得で、SM分岐比を仮定したGrossman-Nir limitを超える



KOTO II @ J-PARC

To **MEASURE** $K_L \to \pi^0 \nu \nu$
(And to study $K_L \to \pi^0 l^+ l^-$ (l=e,μ) also)

KOTO II collaboration meeting at Osaka on 18-20 August 2026



- Aiming to discover $K_L \to \pi^0 \nu \bar{\nu}$ and measure the branching ratio
  - ~ 35 event/ ~ 40 background events
    - >5σ discovery of SM events
    - 25% precision of the BR measurements
  - 90% NP indication if BR>1.4xBR(SM)

The proposal (arXiv:2501.14827) was submitted to J-PARC PAC and was scientifically approved (Stage 1 approved)

Many NA62 members also join KOTO II.

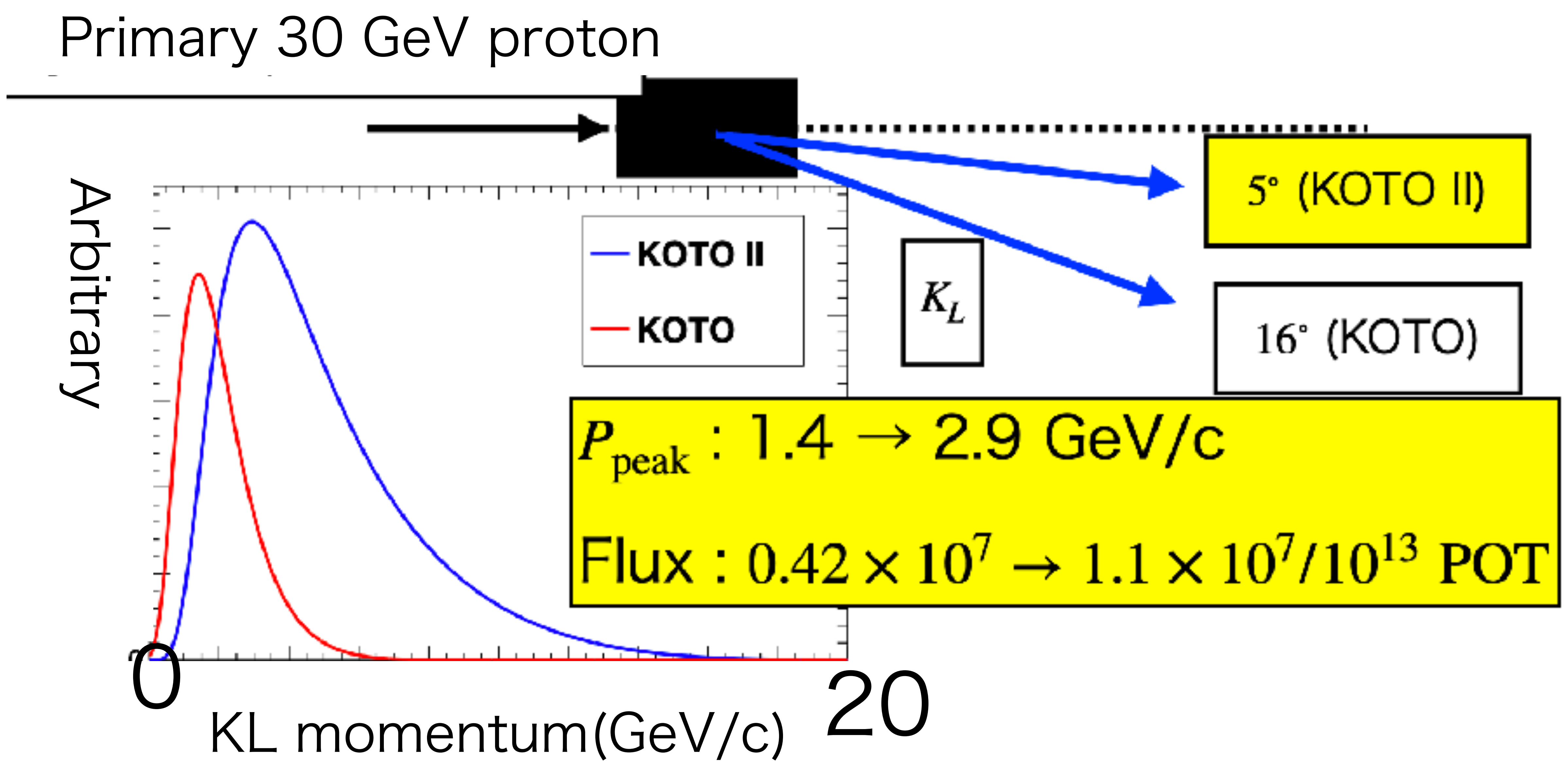
J-PARC KOTO II (E107) (scientifically approved)

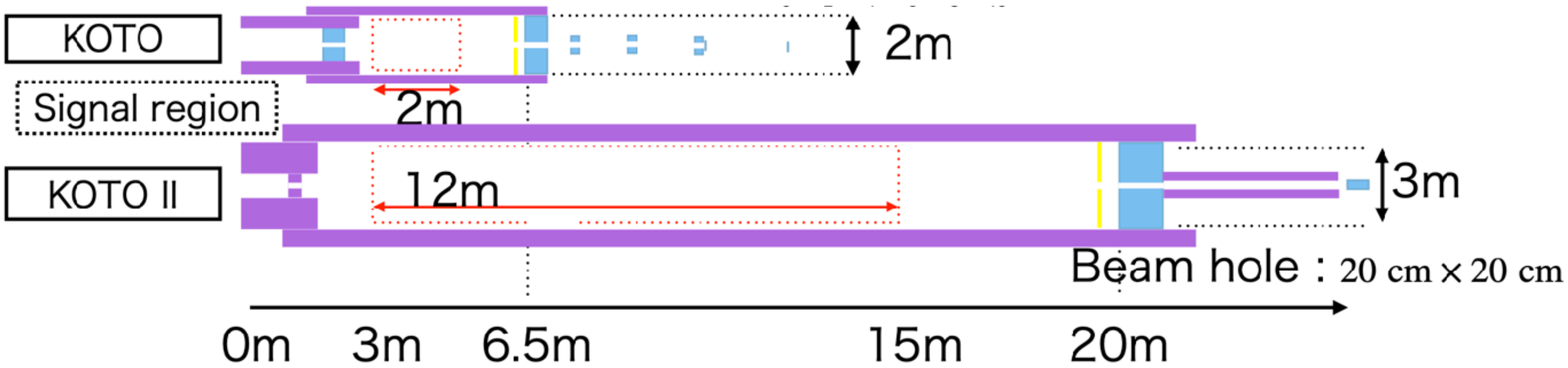
77 members + 2 observers
34 institutions, 11 countries

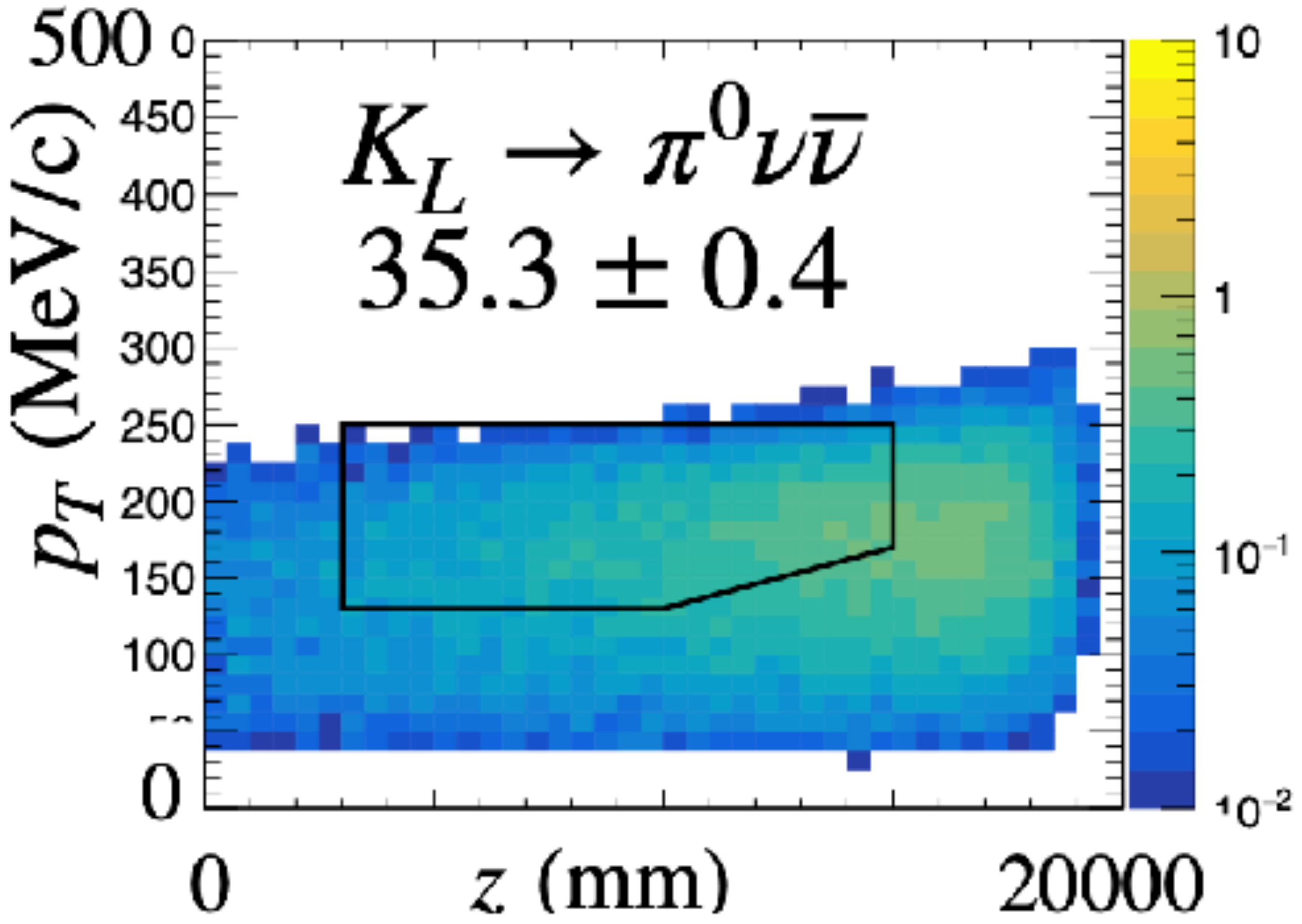
KOTO II needs significant modification(extenstion) of the experimental facility as well as construction of a new detector, which requires a large-scale budget,
KOTO II is making efforts toward realization in 2030s.

From KOTO to KOTO II to obtain x 100 sensitivity

- More K_L
  - Use forward production angle
    - x2.6 flux + **harder spectrum**
- More signal acceptance ↙ Key
  - Lnger decay volume
  - Lager calorimeter





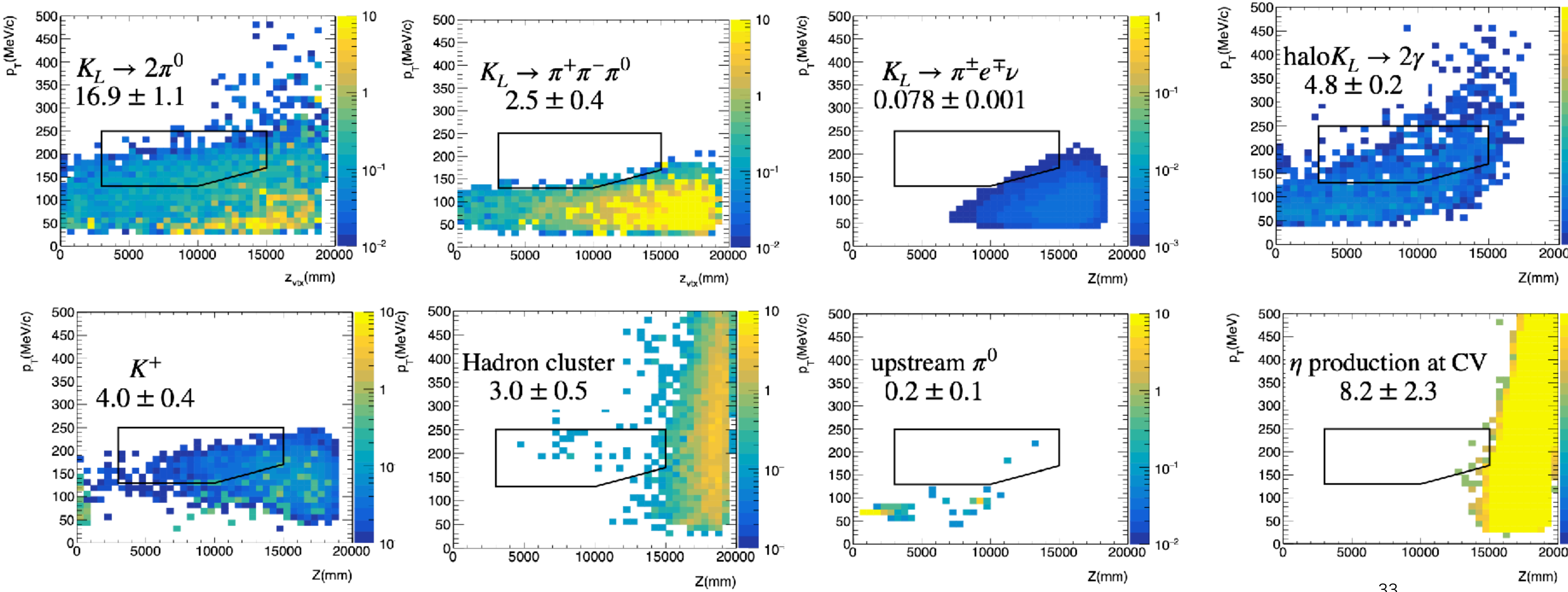


Signal/BG estimation

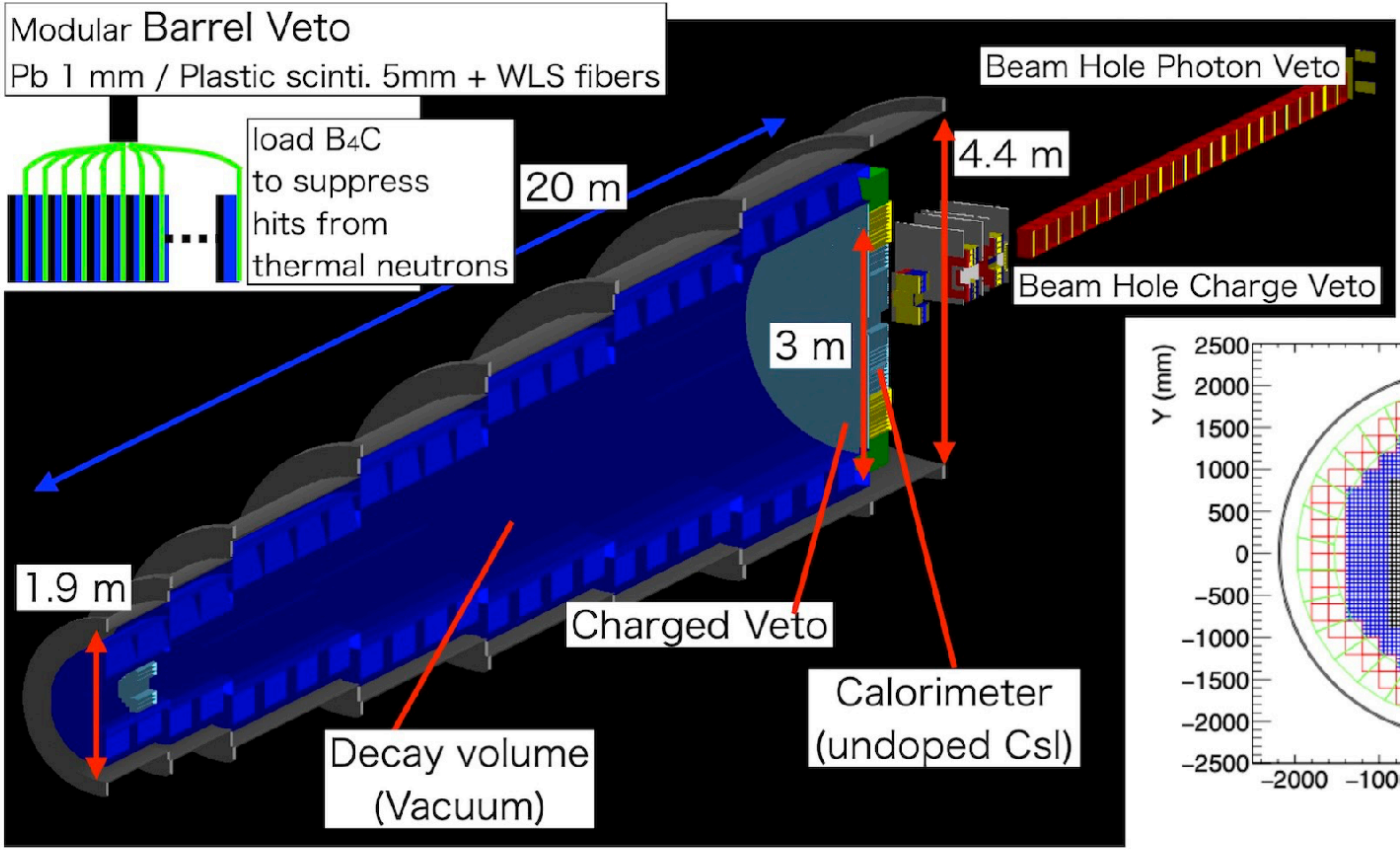
of signal events (SM) : 35
# of background events : 40

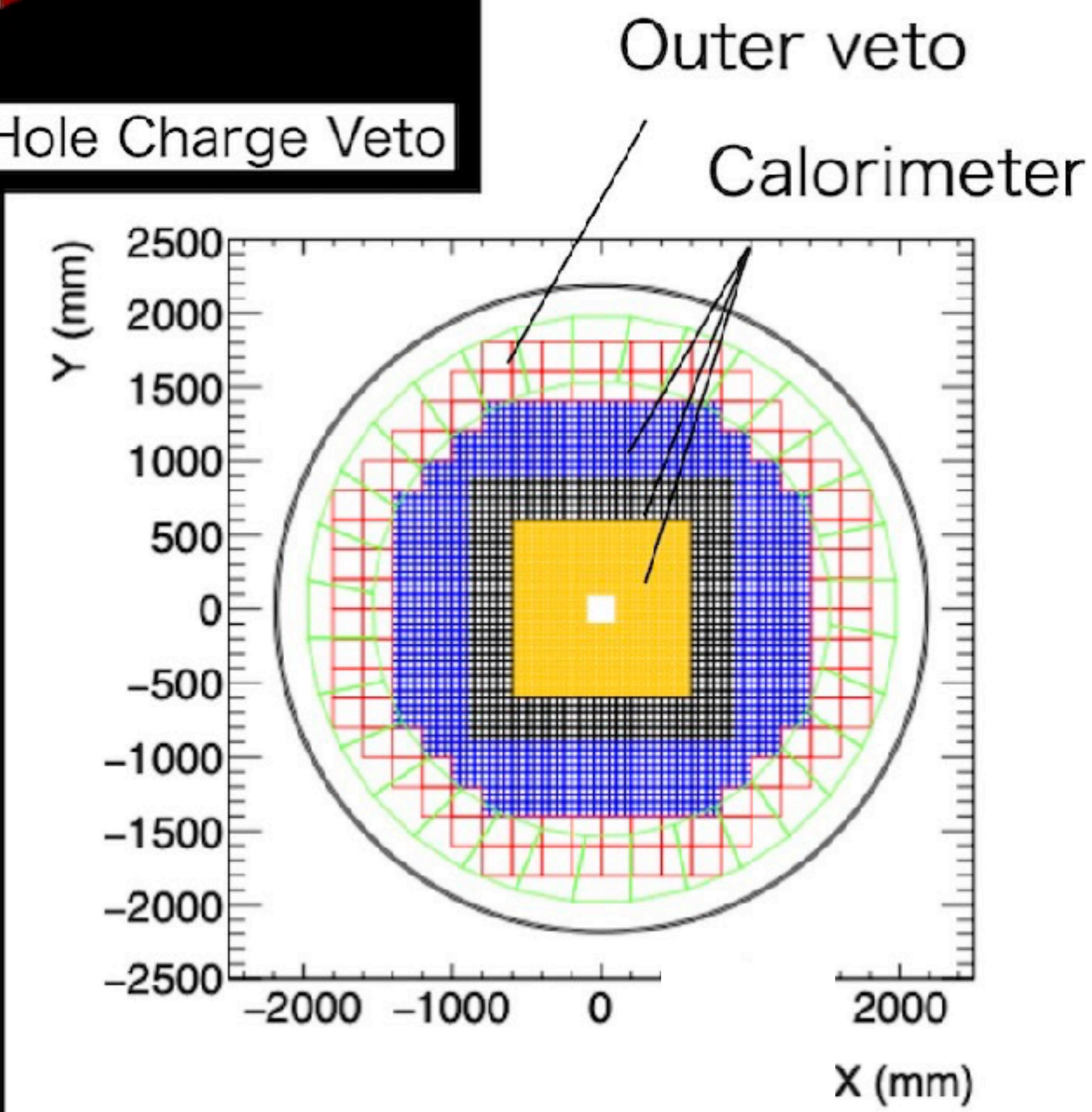
100 kW beam
3×10^7 s running time

$>5\sigma$ observation for SM value of branching ratio



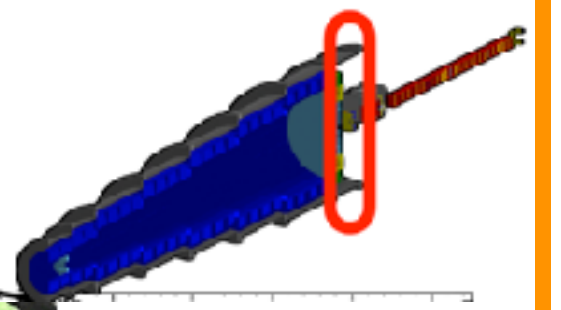
KOTO II detector (base design)





Detector R&D for KOTO II

Calorimeter prototype in outer region: Shashlyk counter



7 cm x 7cm, (Pb: 0.3 mm / Sci: 1.5 mm)x172 layers = 31 cm = $10X_0$

$\sigma_E/E = (6.91 \pm 0.04)\,\%/\sqrt{E\,(\mathrm{GeV})} \oplus (0 \pm 7)\,\%$

$\sigma_t = (50 \pm 1)\,(\mathrm{ps})/\sqrt{E\,(\mathrm{GeV})} \oplus (59 \pm 2)\,(\mathrm{ns})$ Measurement

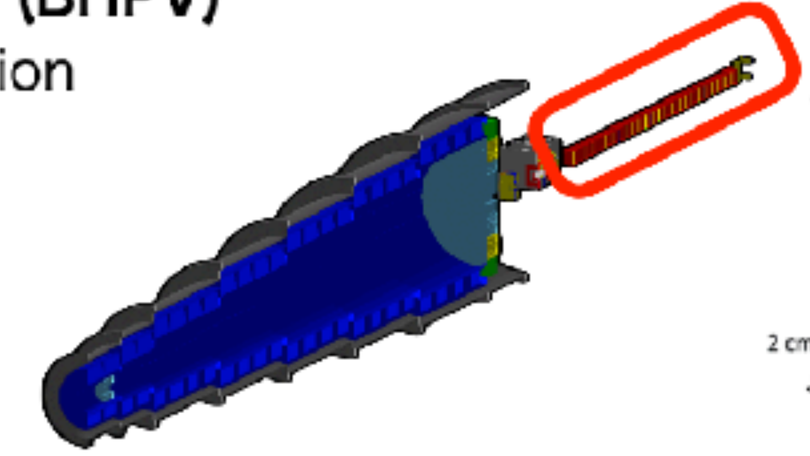
$\rightarrow 3\,\%/\sqrt{E\,(\mathrm{GeV})}$ with $27X_0$ (less leakage) Extrapolation

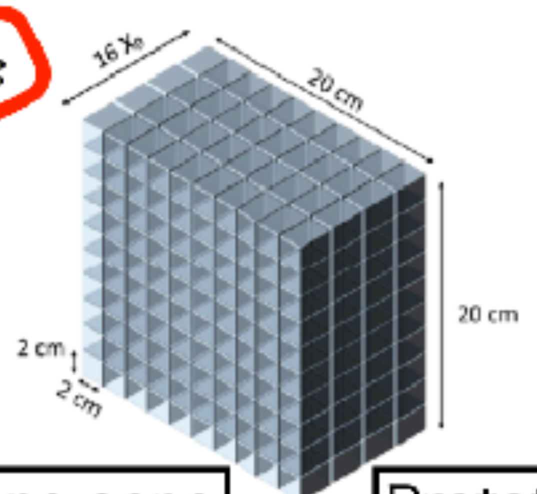
Measured resolutions meet the requirements, Depth reconstruction with both-end readout

Beam Hole Photon Veto (BHPV)

Compact Fast Crystal option

$20\ \mathrm{cm} \times 20\ \mathrm{cm} \times 16X_0$





Measurement

Electrons:

$\sigma_t \sim$ 140 ps/√E(GeV) ⊕ 95 ps

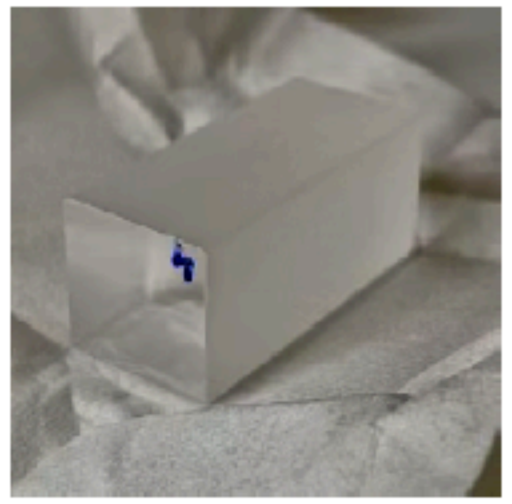
Preliminary

MIPs:

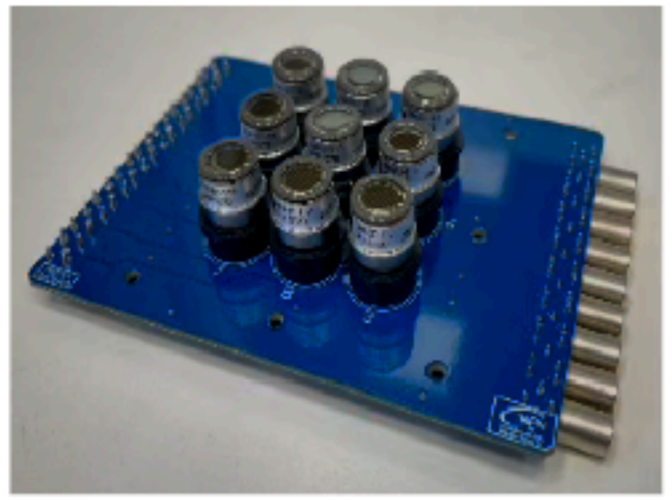
$\sigma_t \sim$ 100-130 ps

Preliminary

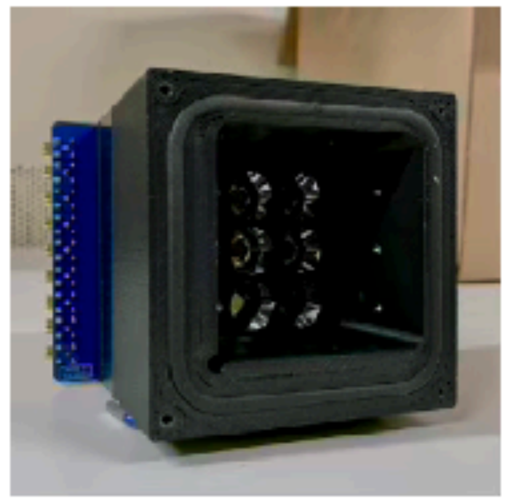
Ultra-fast PWO crystal PWO-UF



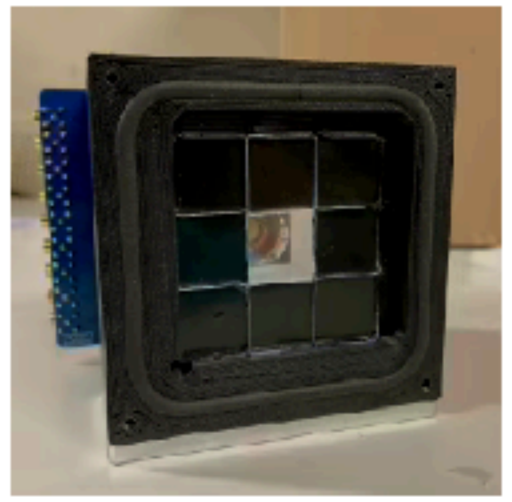
Fast Metal-channel PMTs



Winstone cone

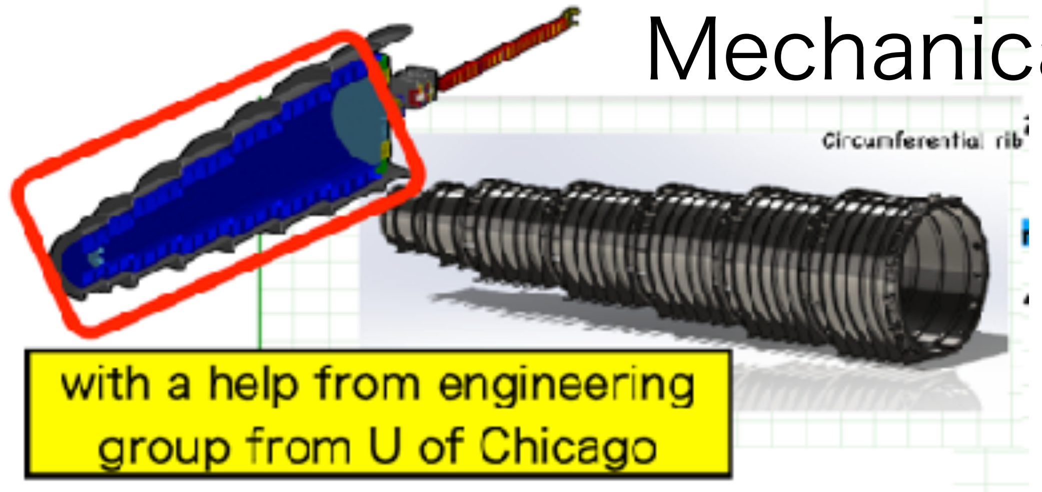


Prototype

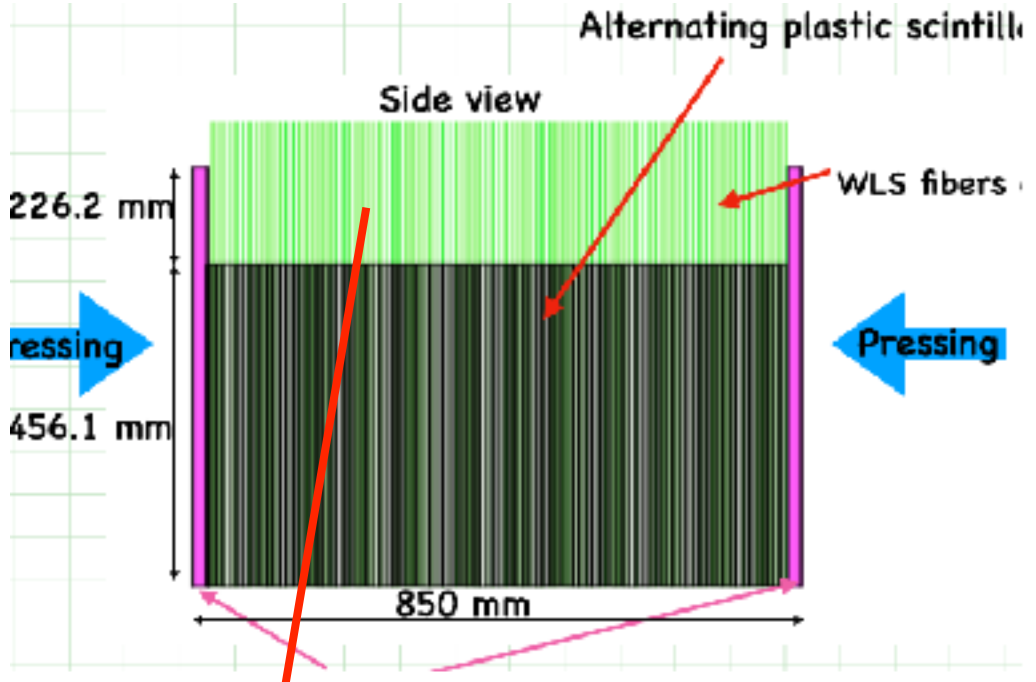


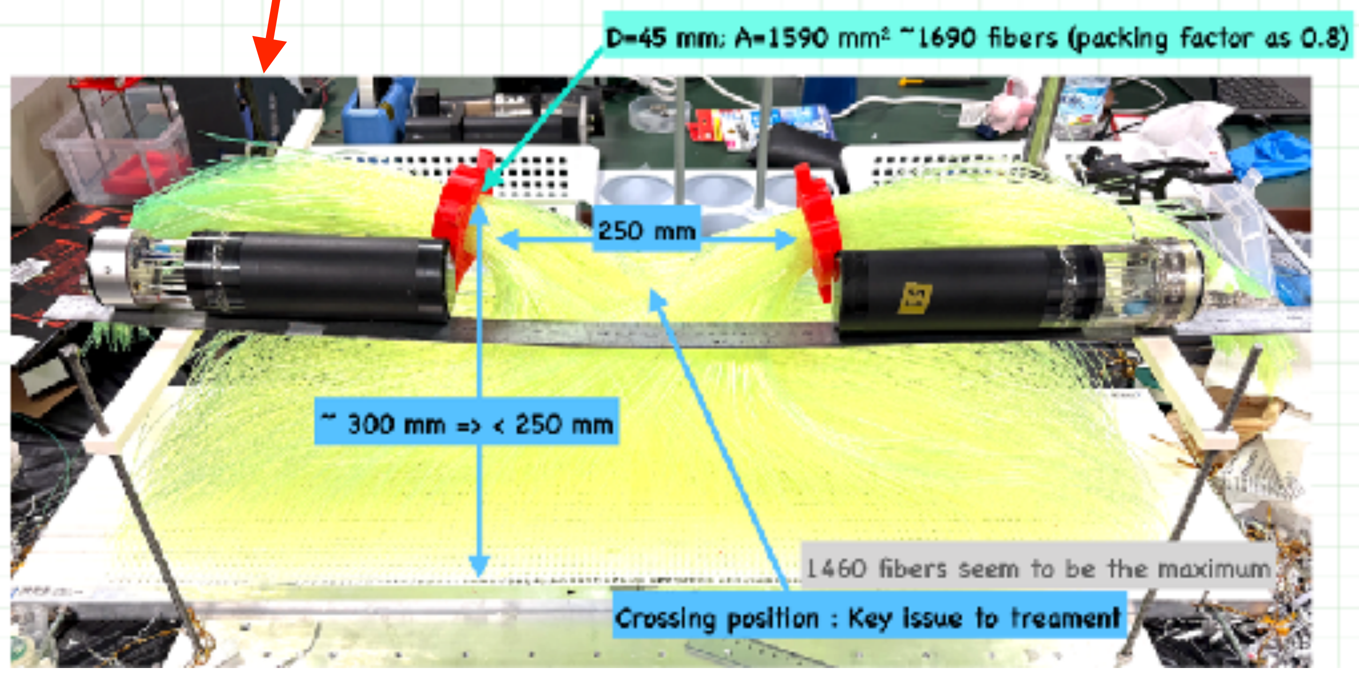
Barrel Detector

Mechanical design



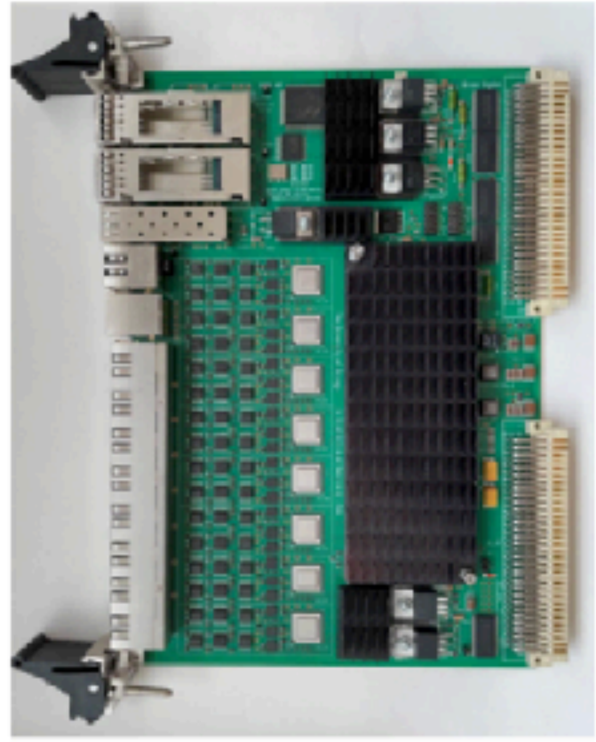
Module design

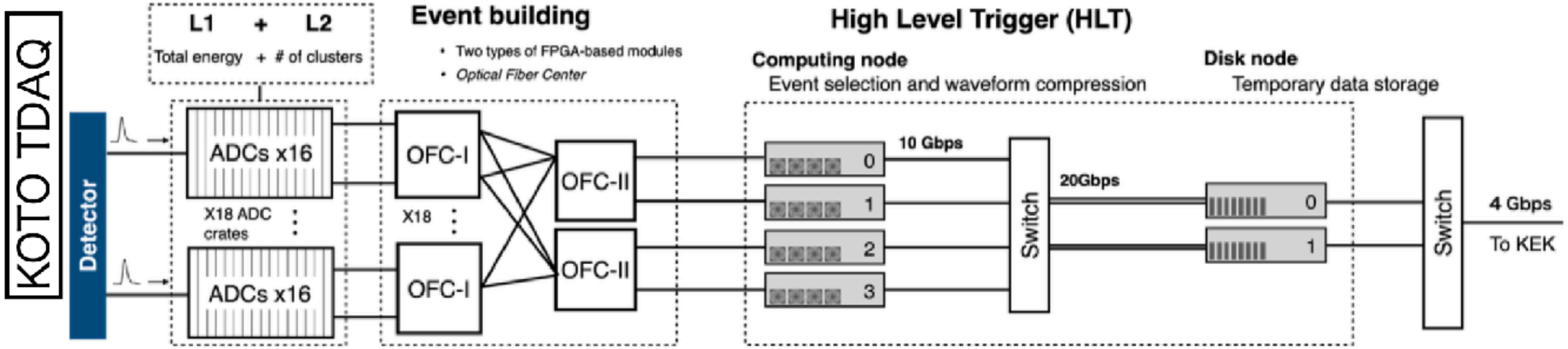


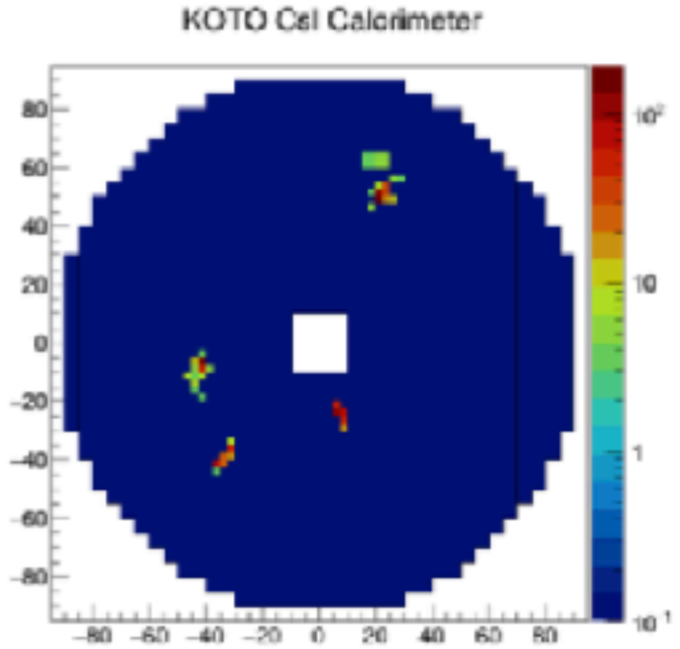


DAQ R&D for KOTO II

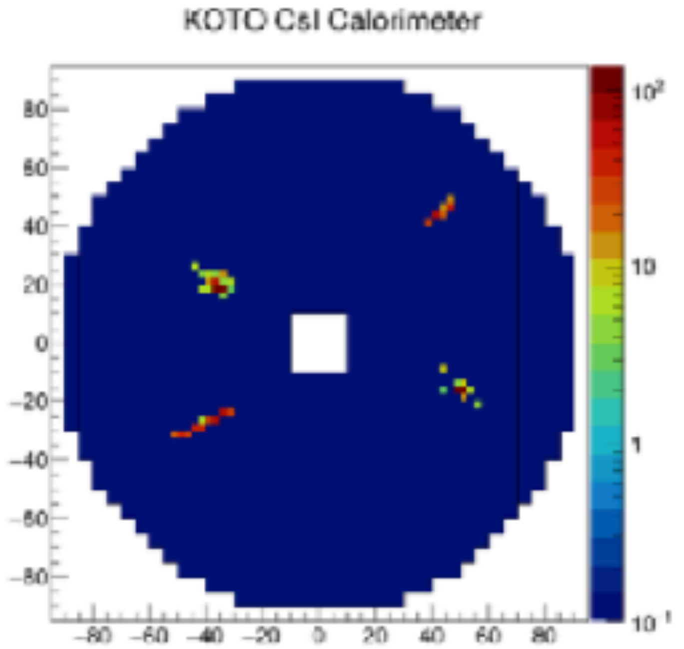
TDAQ:
base design: Level N trigger with waveform readout (as in KOTO)
ADC prototype: 16 channel, 14 bit, 500 MHz
AI trigger for cluster shape (e/π separation for example)



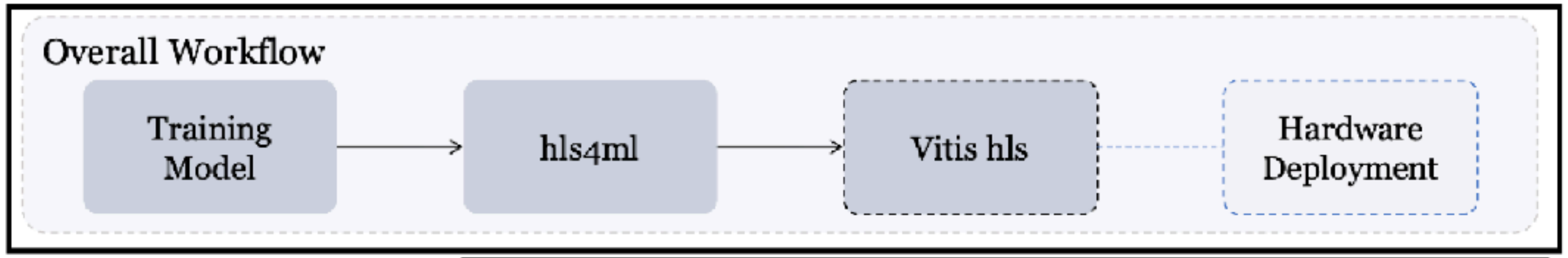




$K_L \to \pi^0 e^+ e^-$

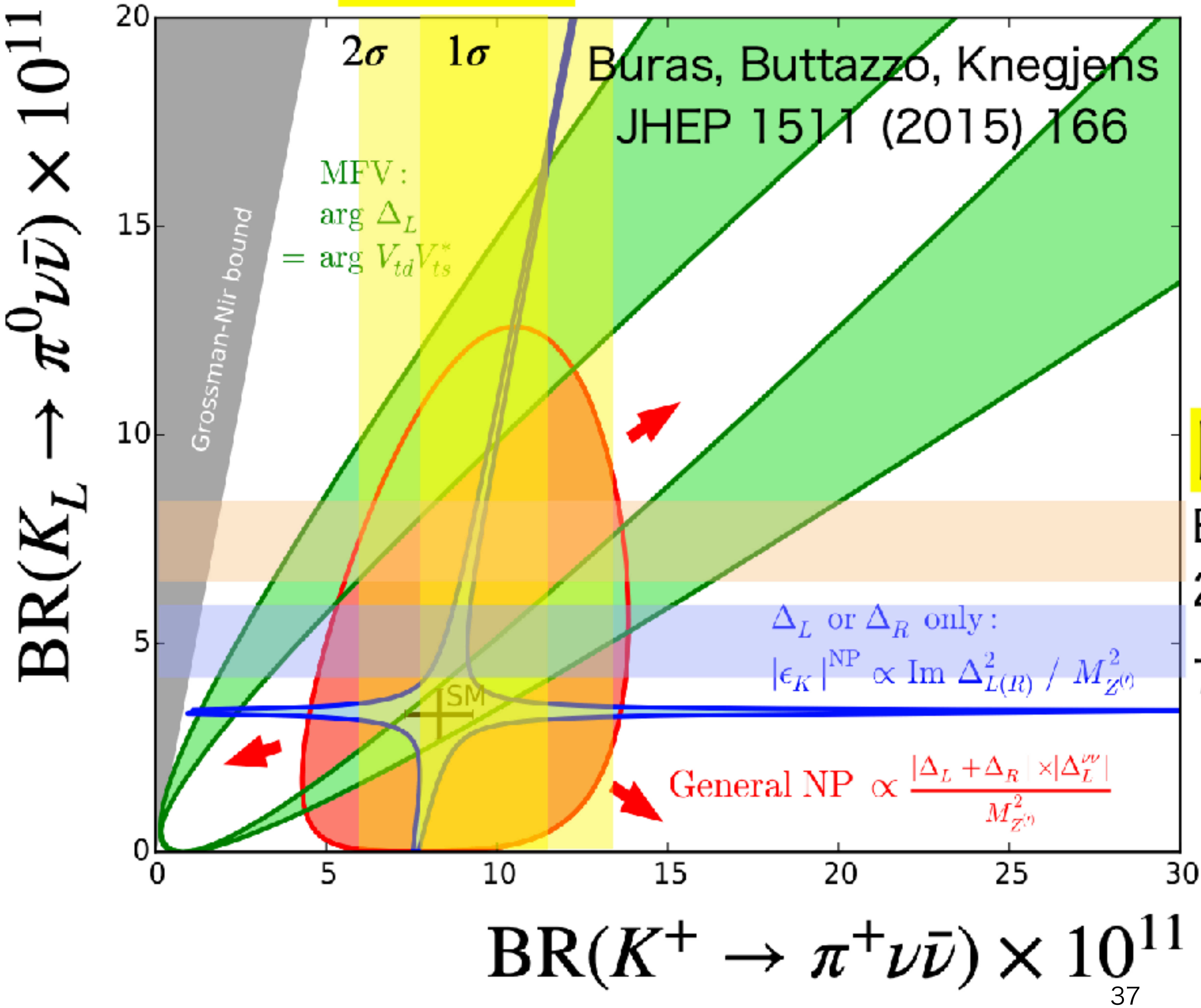


$K_L \to \pi^0 \pi^+ \pi^-$



Development with a help from KEK ITDC
Feasible according to simulations

Physics Impact of KOTO II



100-kW beam, 3×10^7 s $= 6.3\times10^{20}$ POT

SES: 8.5×10^{-13}, S/B=0.9

- 35 SM signal / 40 background events
  $\rightarrow 5.6\sigma$ observation
- $\Delta\mathcal{B}/\mathcal{B} = 25\,\%$ for SM value of $\mathcal{B}$
- 40% deviation from SM
  →90%-CL indication of NP

KOTO II

Example

250% deviation from SM

70% deviation from SM

May find NP effect

Summary

- $K \to \pi\nu\bar{\nu}$ decay provides us with a unique probe to search for New Physics.