Rare Kaon Decay in KOTO/KLOE-2 experiments

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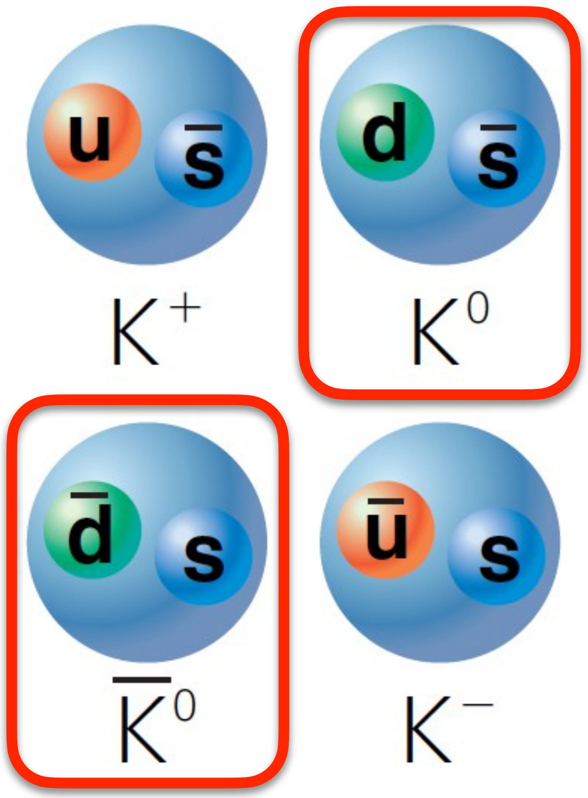
for KLOE-2 and KOTO collaborations

FPCP2021

Special thanks to Antonio Di Domenico
and the KLOE2 collaborators

Neutral Kaon



$$K_S \sim \left(\left| K^0 \right\rangle + \left| \overline{K^0} \right\rangle \right) / \sqrt{2}$$

$$K_L \sim \left(\left| K^0 \right\rangle - \left| \overline{K^0} \right\rangle \right) / \sqrt{2}$$

Quantum Superposition

~CP eigenstate

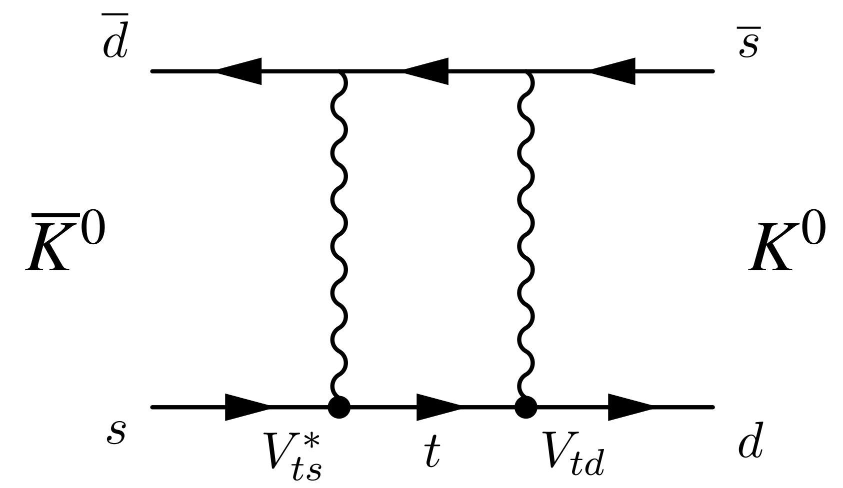
$$m(K) :\sim 0.5\,\mathrm{GeV}$$

$$\tau(K_S)\ :\ 90\,\mathrm{ps}\ (c\tau \sim 3\,\mathrm{cm})$$

$$\tau(K_L)\ :\ 51\,\mathrm{ns}\ (c\tau \sim 15\,\mathrm{m})$$

Neutral Kaon Mixing

$$i\frac{d}{dt}\begin{pmatrix}|K_0\rangle\\|\overline{K}_0\rangle\end{pmatrix}=\begin{pmatrix}H_{11} & H_{12}\\H_{21} & H_{22}\end{pmatrix}\begin{pmatrix}|K_0\rangle\\|\overline{K}_0\rangle\end{pmatrix}$$



Diagonalize

$$|K_S\rangle \propto (1+\epsilon_S)\,|K^0\rangle + (1-\epsilon_S)\,|\overline{K}^0\rangle$$

$$|K_L\rangle \propto (1+\epsilon_L)\,|K^0\rangle + (1-\epsilon_L)\,|\overline{K}^0\rangle$$

≠CP eigenstate

$$\epsilon \equiv \frac{\epsilon_S+\epsilon_L}{2}$$ off-diagonal $H_{12}-H_{21}$ ~~CP~~

$$\delta \equiv \frac{\epsilon_S-\epsilon_L}{2}$$ diagonal $H_{11}-H_{22}$

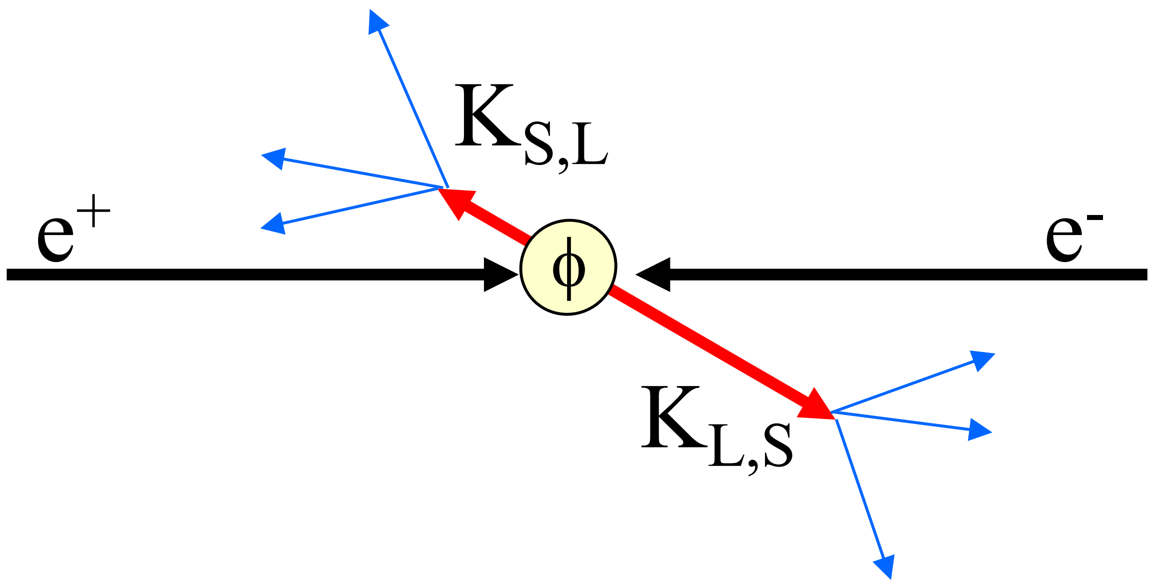
$m(K_0)-m(\overline{K}_0)$

$\Gamma(K_0)-\Gamma(\overline{K}^0)$

~~CPT~~

Recent KLOE/KLOE-2 Results / Status

Neutral Kaon at ϕ-factory



$\sigma_\phi \sim 3\mu\text{b}$

$\mathcal{B}(\phi \to K_0\overline{K}_0) \sim 34\,\%$

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\overline{K}^0(-\vec{p})\rangle - |\overline{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

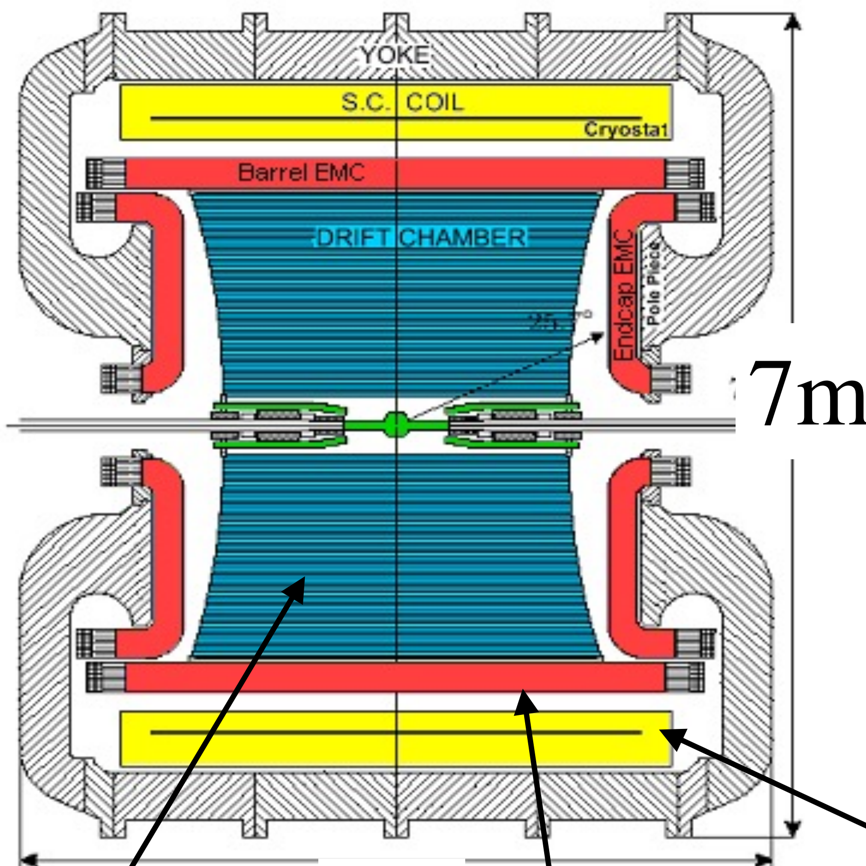
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)}\Big/\left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

Unique for
Tagged-K_S
CPT study

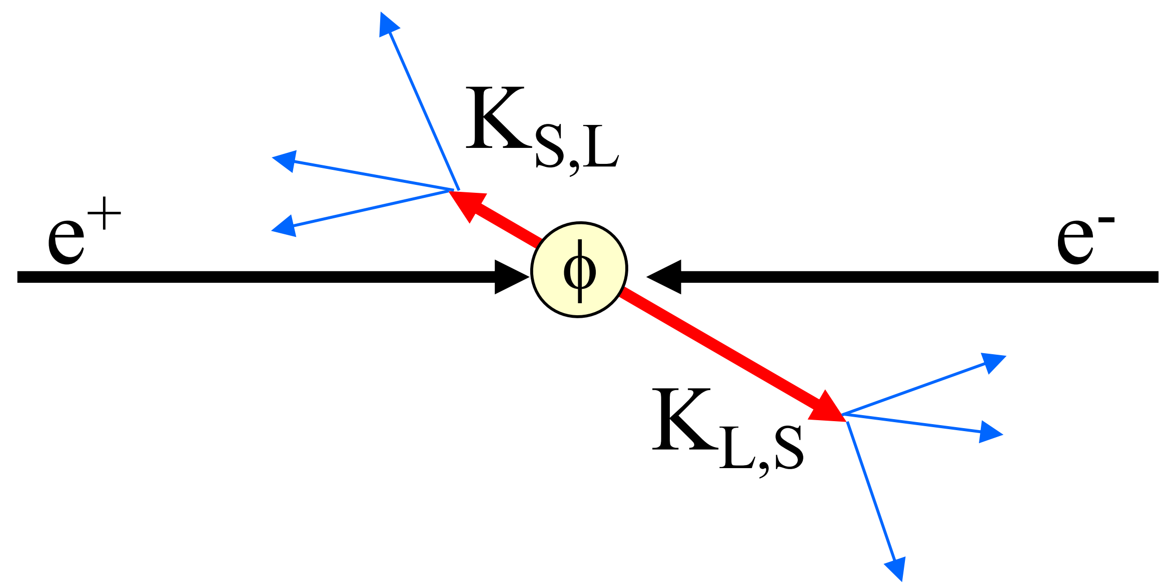
Entangled quantum antisymmetric state

KLOE Detector

KLOE detector



Tracker and Calorimeter inside magnet



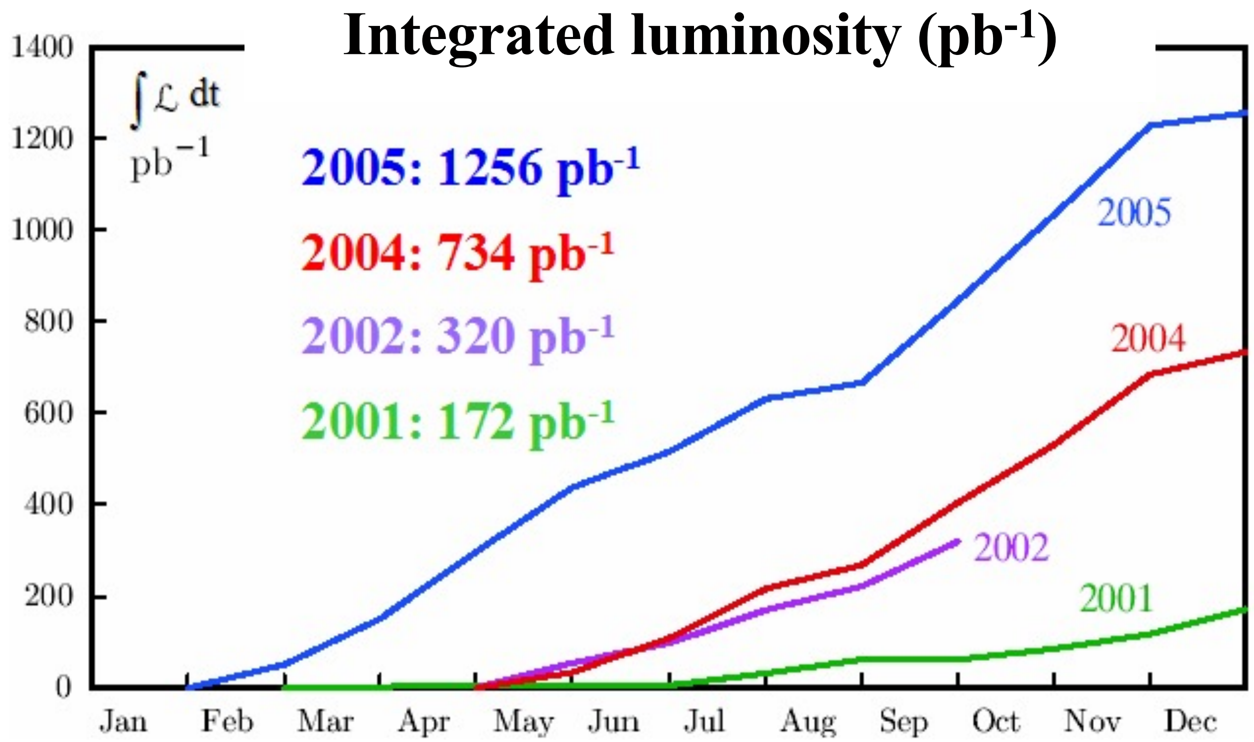
$\mathbf{p_K = 110\ MeV/c}$ $(\beta \sim 0.22)$

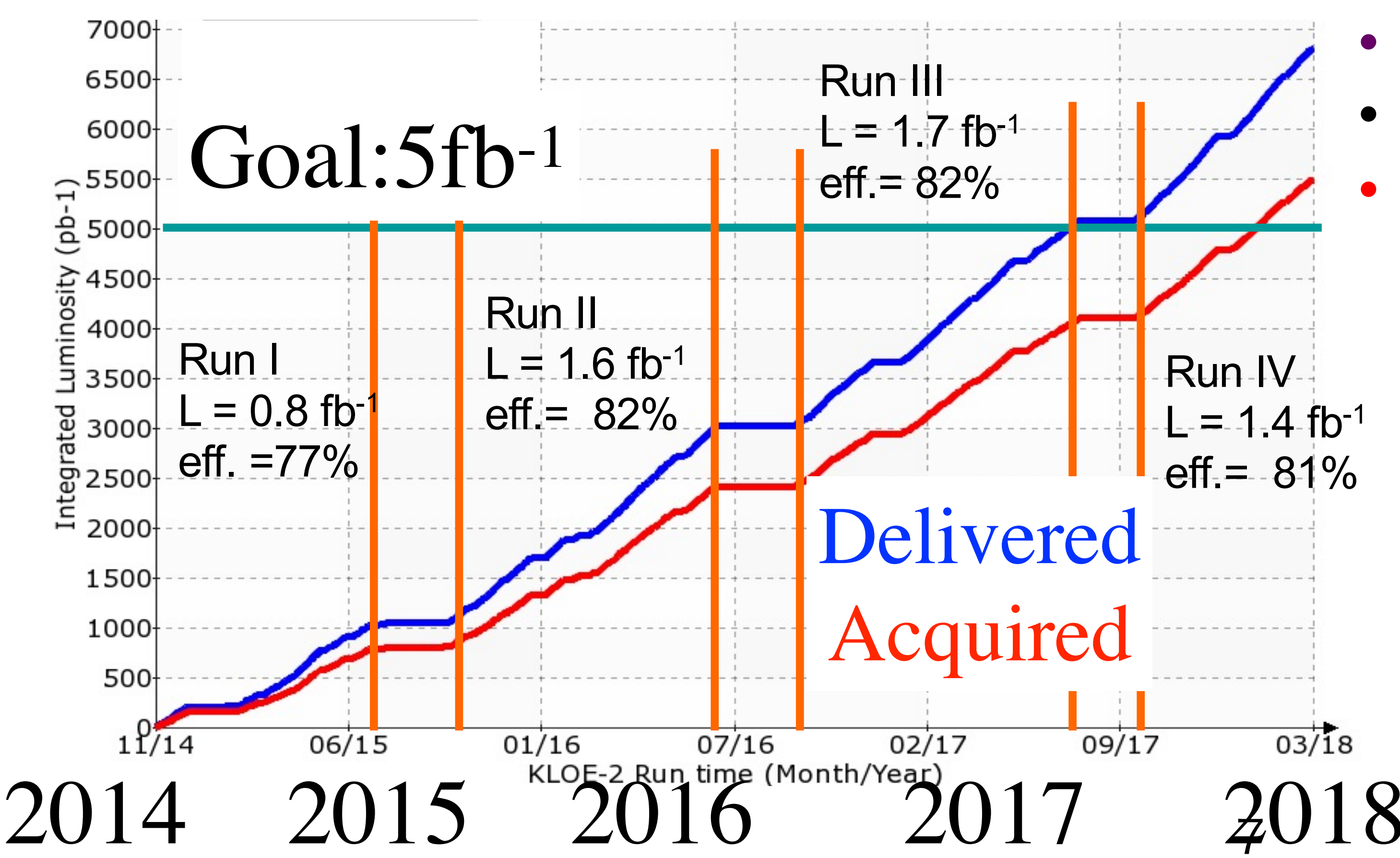
$\boldsymbol{\lambda_S = 6\ mm}$ $\boldsymbol{\lambda_L = 3.5\ m}$

charged particle : ***p*** and vertex

TOF at calorimeter

KLOE and KLOE-2 experiment at the Frascati ϕ-factory DAΦNE





- 1999: first events collected by KLOE
- 2000 – 2006: KLOE data-taking
  - ⇒ 2.5 fb^{-1}@$\sqrt{s}=M_f$
  - \+ 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV

2008 DAΦNE upgrade
2012-13 Detector upgrade

- July 2013: DAΦNE operations restarted
- November 2014: start of KLOE-2 run
- 2014 – 2018: KLOE-2 data-taking
- March 30, 2018: End of KLOE-2 data-taking
  - ⇒ 5.5 fb^{-1} collected @$\sqrt{s}=M_\phi$

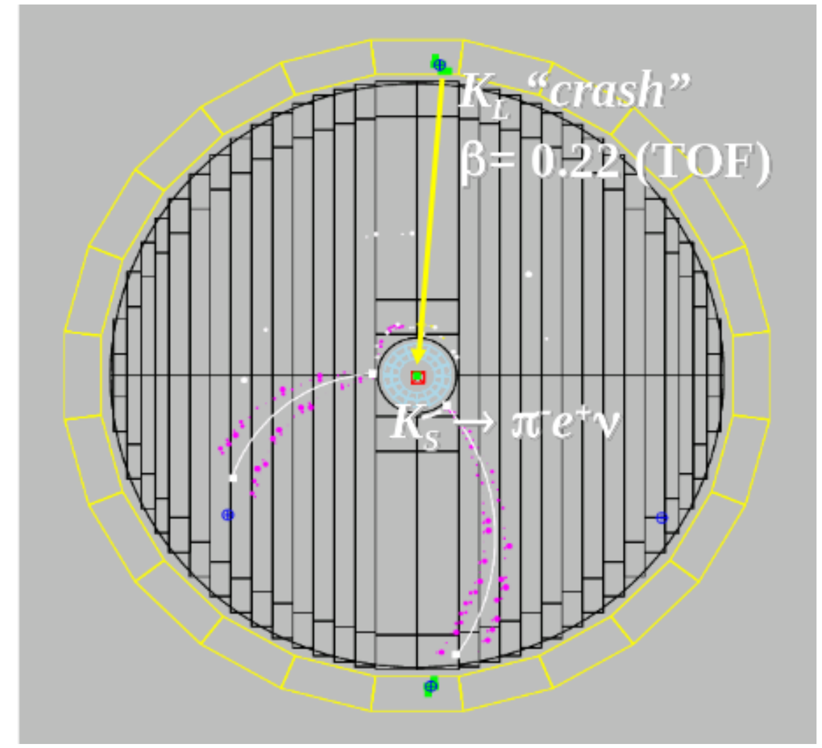
KLOE + KLOE-2 data sample:
~ 8 fb^{-1} ⇒ 2.4 × 10^{10} ϕ's produced
~ 8 x10^9 K_SK_L pairs ~ 3 x10^8 η's
⇒ the largest sample ever collected at the ϕ(1020) peak in e^+e^- collisions

Branching ratio of $K_S \to \pi\mu\nu$ decay

Analyzed 1.6 fb^{-1} (2004-2005 data)

K_L tag→ the other : K_S

K_L interaction at the calorimeter (K_L-crash)



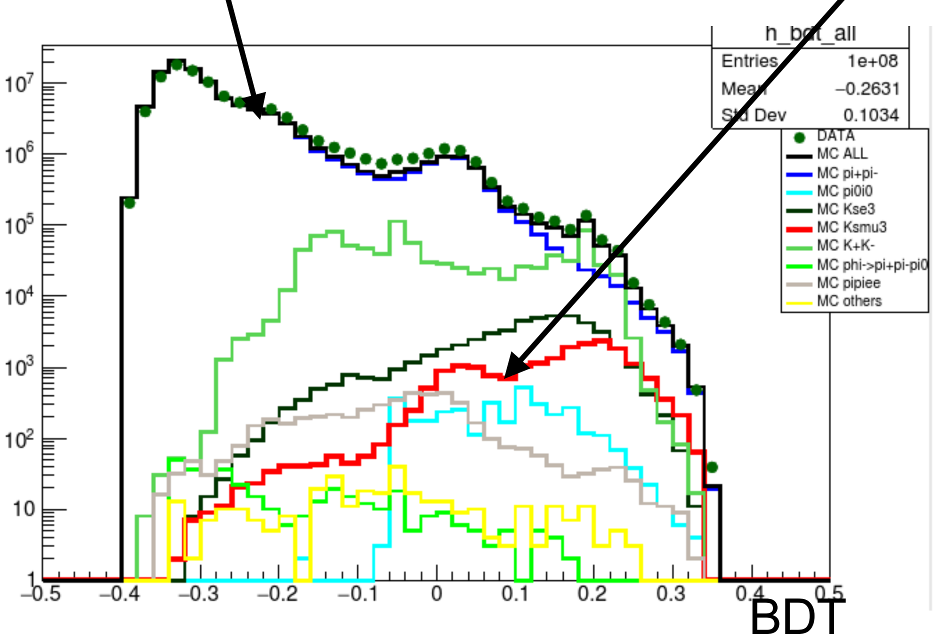
$K_S \to \pi\mu\nu$ selection

- 2 charged particles→1 vertex close to IP
- BDT : kinematics(angle, momentum, $M_{\pi\pi}$)
- Time of Flight with PID assumption

$K_S \to \pi^+\pi^-(\to \pi\mu\nu)$

$BDT > 0.180$

Signal



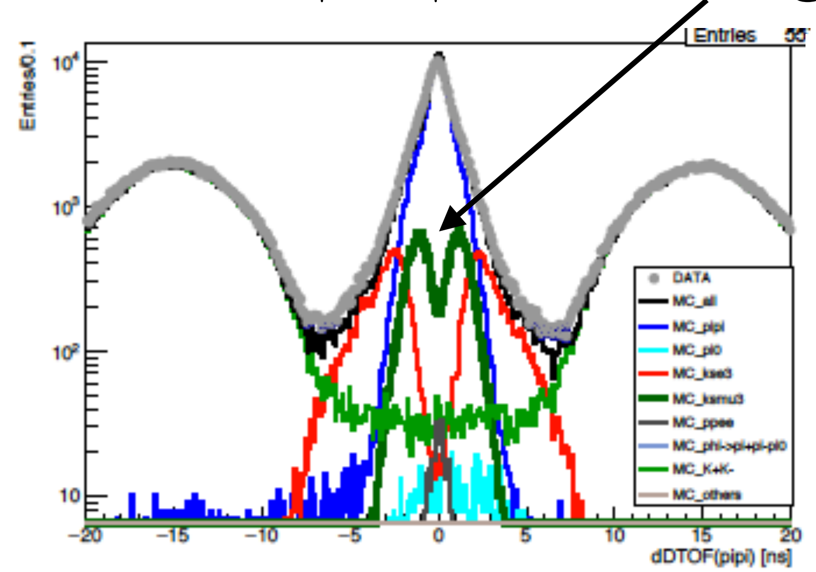
$\pi^+\pi^-$ hypothesis

$1 \text{ ns} < |\delta t_{\pi\pi}| < 3 \text{ ns}$

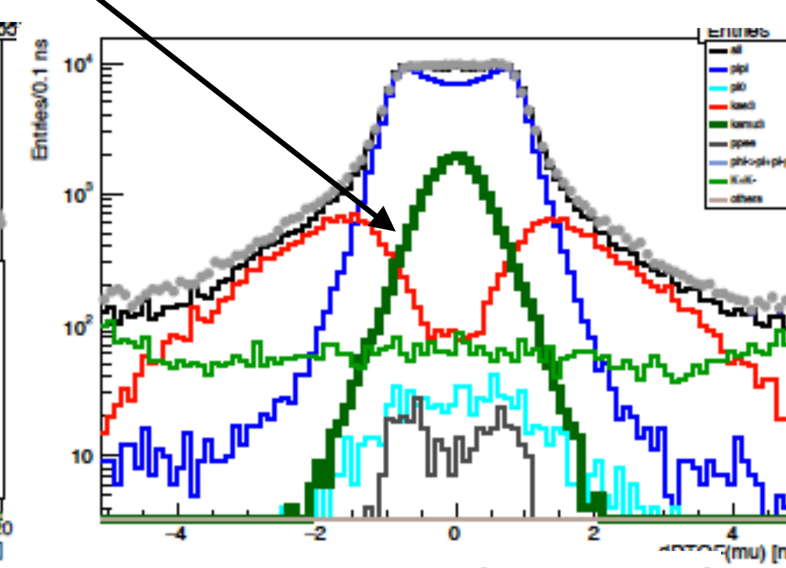
Signal

$\pi^\pm\mu^\mp$ hypothesis

$|\delta t_\mu| < 0.5 \text{ ns}$



$\delta_{\pi\pi}$



$\delta t_\mu = \min[|\delta t_{\pi\mu}|, |\delta t_{\mu\pi}|]$

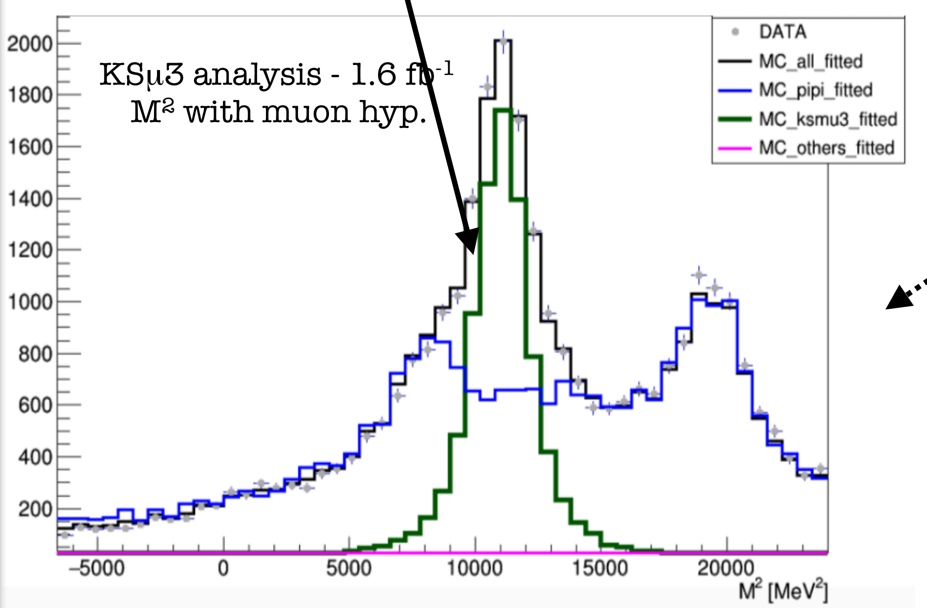
Branching ratio of $K_S \to \pi\mu\nu$ decay

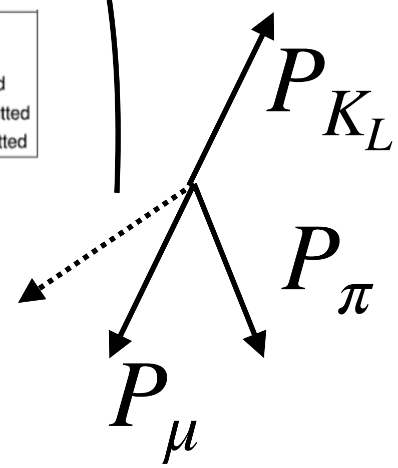
Data: $(K_L\,\text{crash}) + (K_S \to \pi\mu\nu)$

Signal count

$$m_\mu^2 = (E_{K_S,\text{tag}} - E_\pi - p_{\text{miss}})^2 - p_\mu^2$$

Signal





$m_\mu^2(\text{MeV}^2)$

$(7223 \pm 180)\ K_S \to \pi\mu\nu$ events

$\chi^2/\text{ndf} = 30/48$

Selection efficiency

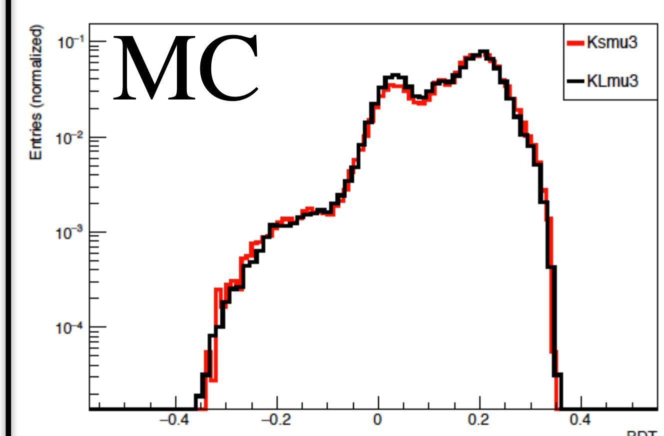
Control sample from

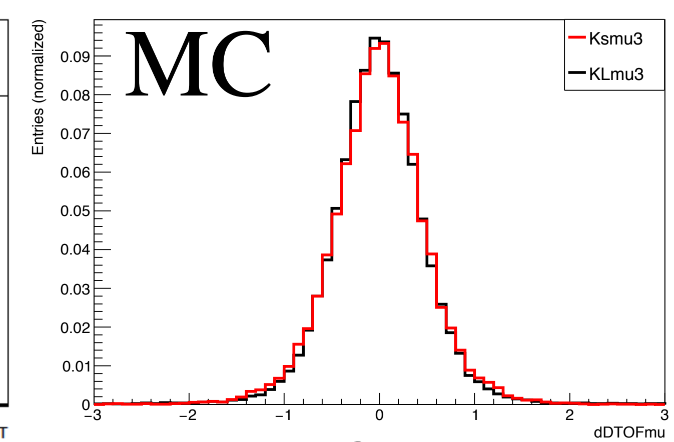
$(K_S \to \pi^+\pi^-) + (K_L \to \pi\mu\nu)$

(decay close to IP)

$\epsilon = (5.52 \pm 0.17)\ \%$

after correction on the difference between data and control sample





BDT $\qquad \delta t_\mu$

Branching ratio of $K_S \to \pi\mu\nu$ decay

Data sample: L=1.6 fb^{-1}

KLOE PLB 804 (2020) 135378 **First measurement**

$BR(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{stat} \pm 0.17_{syst}) \times 10^{-4}$

Main systematics	
TOF selection($\delta_{\pi\pi}$)	:3.0%
K_S decay ID	:1.7%
MC/Cont.Sample stat.	:0.8%
BDT selection	: 0.3%

Expected value assuming kaon-lepton coupling universality:

$BR(K_{S\mu3}) = (4.69 \pm 0.05) \times 10^{-4} = \mathcal{B}(K_S \to \pi e\nu) \times R(I_K^\ell) \times (1 + \delta_K^{\pi\mu\nu})$

using $BR(K_{Se3})$ [KLOE] and K_{Ll3} phase-space integrals ratio [KTeV] and long-distance radiative corrections.

Vus determination

$|f_+(0)V_{us}|_{KS\to\pi\mu\nu} = 0.2126 \pm 0.0046$

KLOE PLB 804 (2020) 135378

Test of lepton-flavour universality

$R_{\mu e} = [\,|f_+(0)V_{us}|_{KS\to\pi\mu\nu}\,]/[\,|f_+(0)V_{us}|_{KS\to\pi e\nu}] = 0.975 \pm 0.044$

Charge asymmetry of $K \to \pi^{\pm} e^{\mp} \nu$

$K^0 \to \pi^- e^+ \nu$ | $\overline{K}^0 \to \pi^+ e^- \overline{\nu}$

$\begin{pmatrix} d \\ \bar{s} \end{pmatrix} \longrightarrow \begin{pmatrix} d \\ \bar{u} \end{pmatrix}$

$\Delta S = \Delta Q$

$K^0 \to \pi^+ e^- \overline{\nu}$ | $\overline{K}^0 \to \pi^- e^+ \nu$

$\begin{pmatrix} d \\ \bar{s} \end{pmatrix} \longrightarrow \begin{pmatrix} u \\ \bar{d} \end{pmatrix}$

$\Delta S \neq \Delta Q$

Ratio of 4 amplitudes

3 parameters

y: $\Delta S = \Delta Q$, CPT violation

x_+: $\Delta S \neq \Delta Q$, CPT conservation

x_-: $\Delta S \neq \Delta Q$, CPT violation

Charge asymmetry of $K_S \to \pi e \nu$ and $K_L \to \pi e \nu y$

ϵ, δ

y, x_+, x_-

~~CPT~~

$\Delta S \neq \Delta Q$

$K_S \to \pi e \nu$ charge asymmetry

of events after event selection

$$M^2(e) = (E_{K_S,\text{tag}} - E_\pi - p_{\text{miss}})^2 - p_e^2$$

Fit $M^2(e)$ varying MC normalizations

Event selection efficiency

$$\epsilon^+ = (7.39 \pm 0.03)\ \%$$

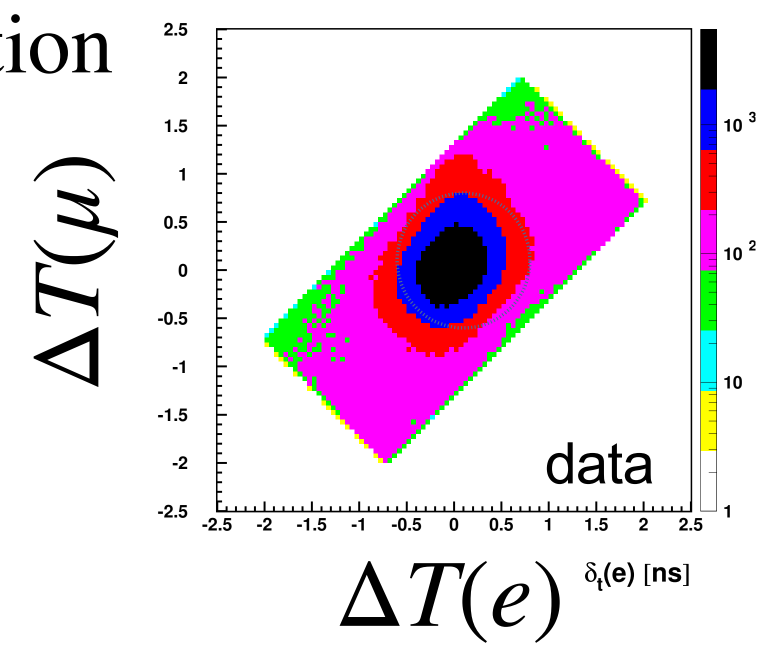
$$\epsilon^- = (7.81 \pm 0.03)\ \%$$

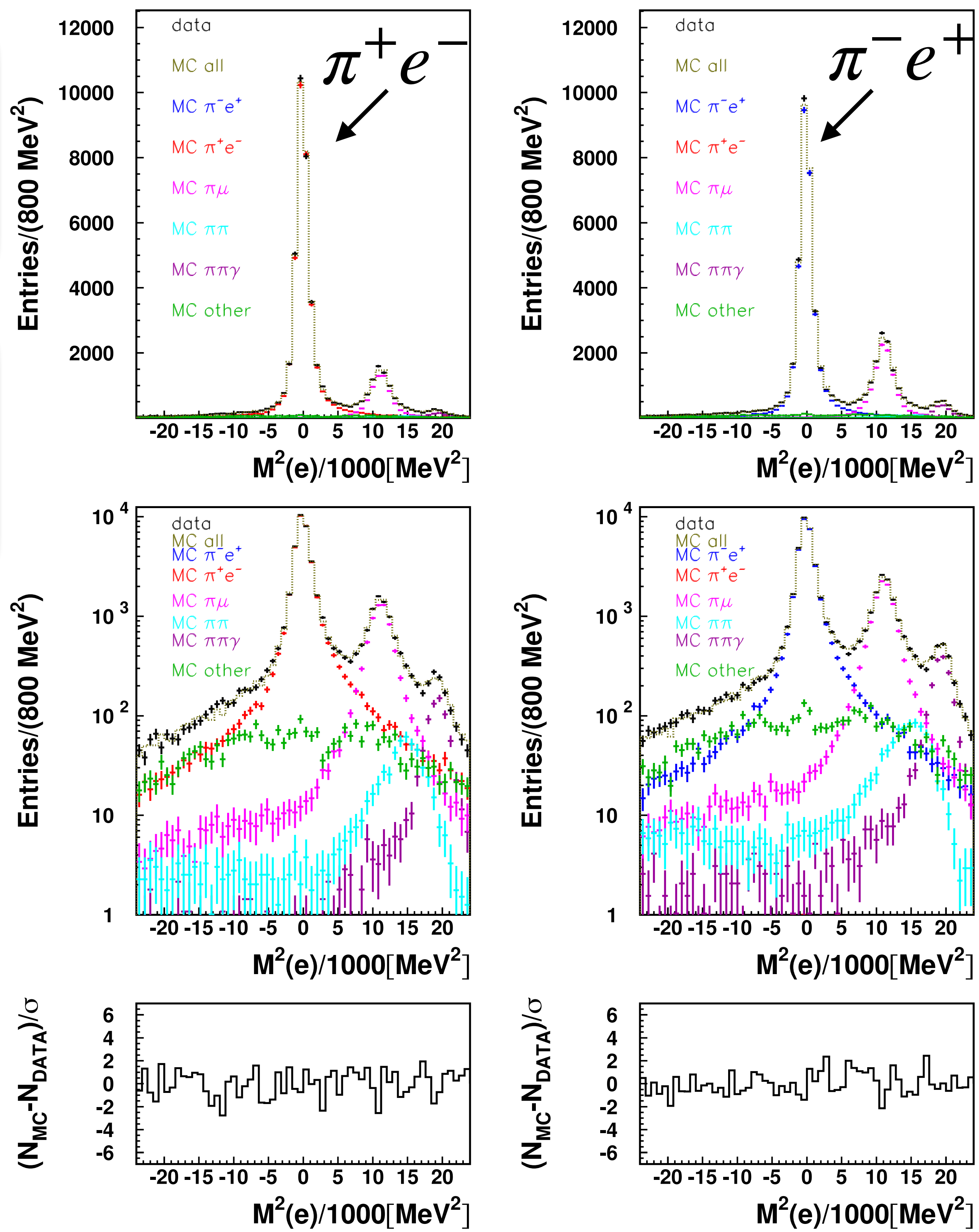
Correction with control sample from

$(K_S \to \pi^0\pi^0) + (K_L \to \pi e \nu)$

(decay close to IP)

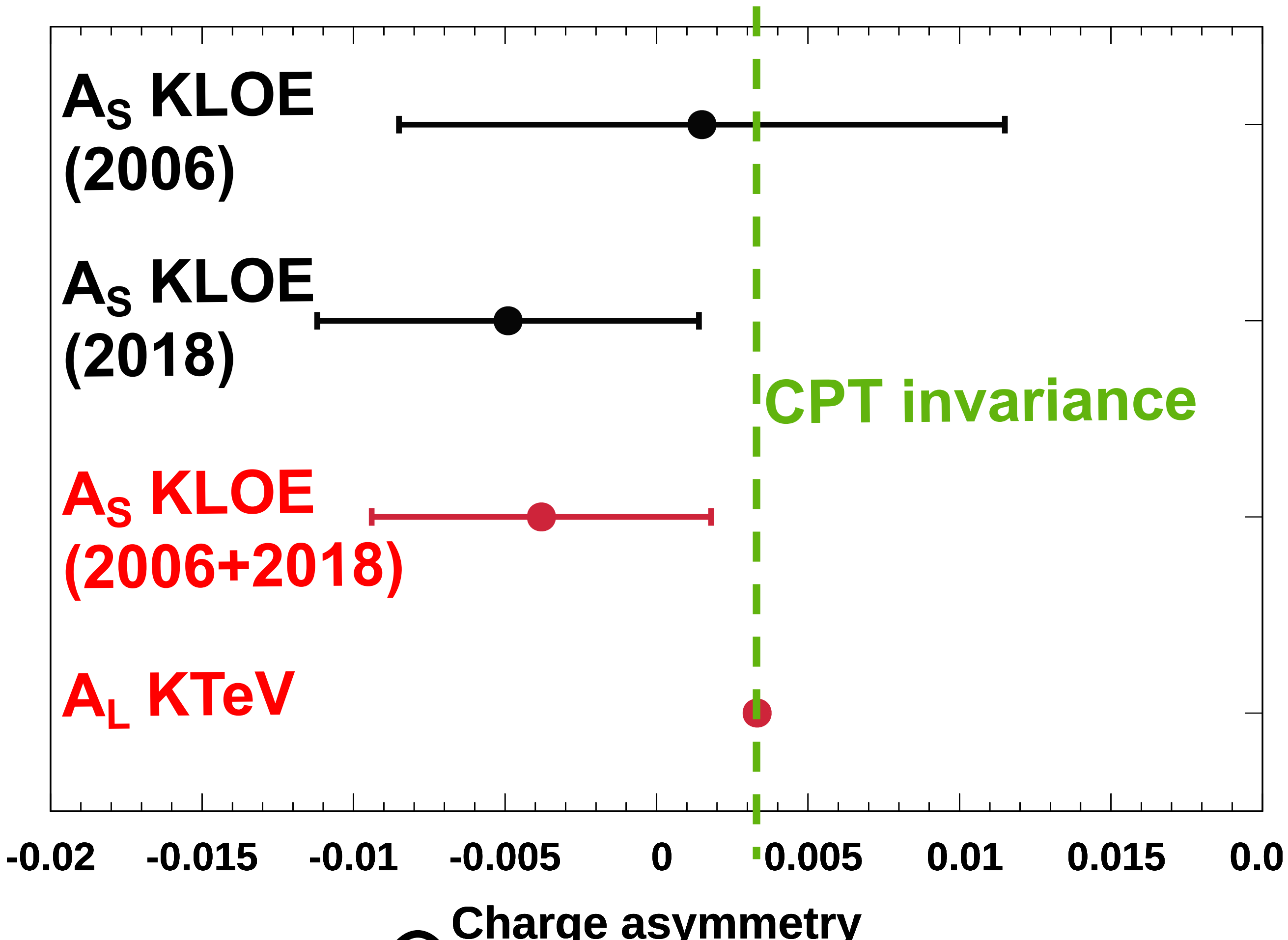
TOF selection





$\chi^2/\text{ndf} = 118/109$

$K_S \to \pi e \nu$ charge asymmetry



Data sample: L=1.6 fb^{-1}

KLOE (2018)

$$A_S = (-4.8 \pm 5.6 \pm 2.6) \times 10^{-3}$$

Combination KLOE(2006)+KLOE (2018)

$$A_S = (-3.8 \pm 5.0 \pm 2.6) \times 10^{-3}$$

JHEP 09 (2018) 21

with KLOE-2 data: $\delta A_S(\text{stat}) \to \sim 3 \times 10^{-3}$

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-2.0 \pm 1.4) \times 10^{-3}$$

CPT & $\Delta S = \Delta Q$ viol. **JHEP 09 (2018) 21**

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$

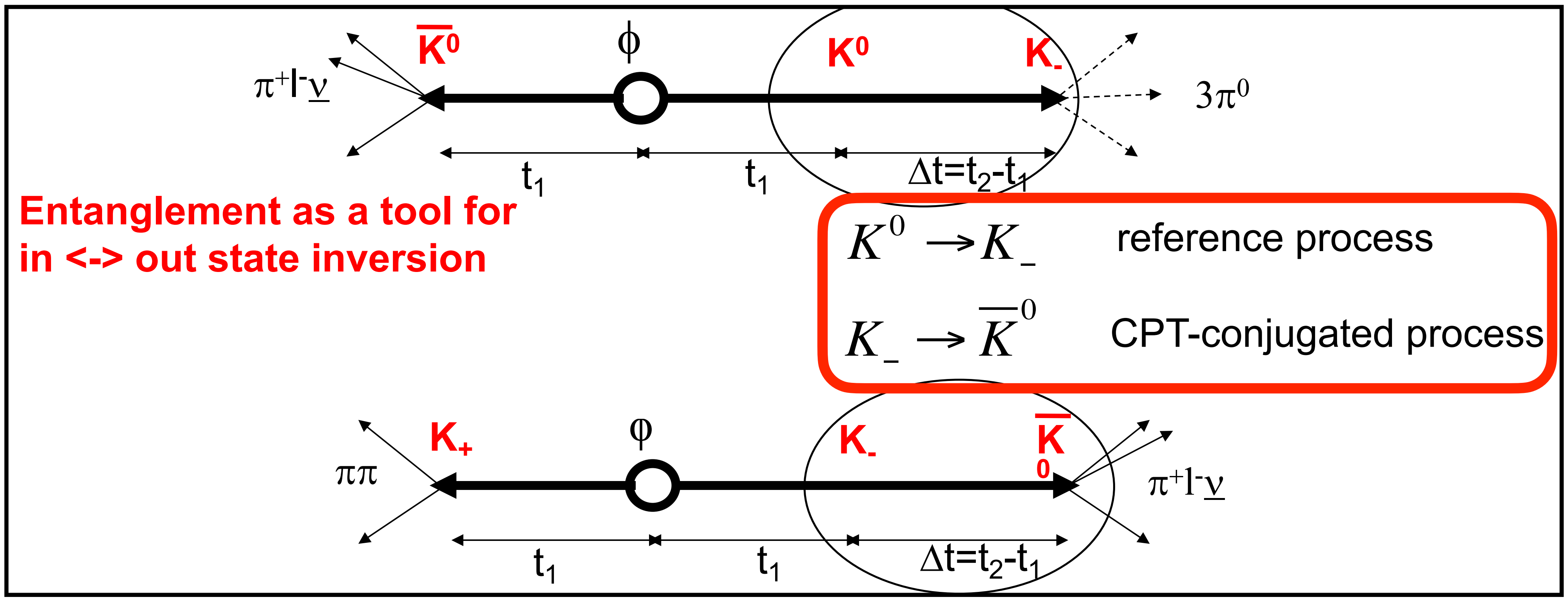
CPT viol.

input from other experiments

(A_S+A_L) => improvement of CPT test (Imδ) using Bell-Steinberger relationship.

Measurement of Br(K_{Se3}) with x4 statistics wrt previous KLOE result is in progress.

Direct test of T and CPT in neutral kaon transitions



Concept
Ncul.Phys.B 868(2013)102
JHEP 1510(2015)139

Observables of the tests (we focus on the asymptotic region):

T-violation sensitive

$$R_2^T(\Delta t) \sim \frac{I(\pi^+ e^- \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu;\ \Delta t)}$$

$$R_4^T(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \nu;\ \Delta t)}$$

CPT-violation sensitive

$$R_2^{CPT}(\Delta t) \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

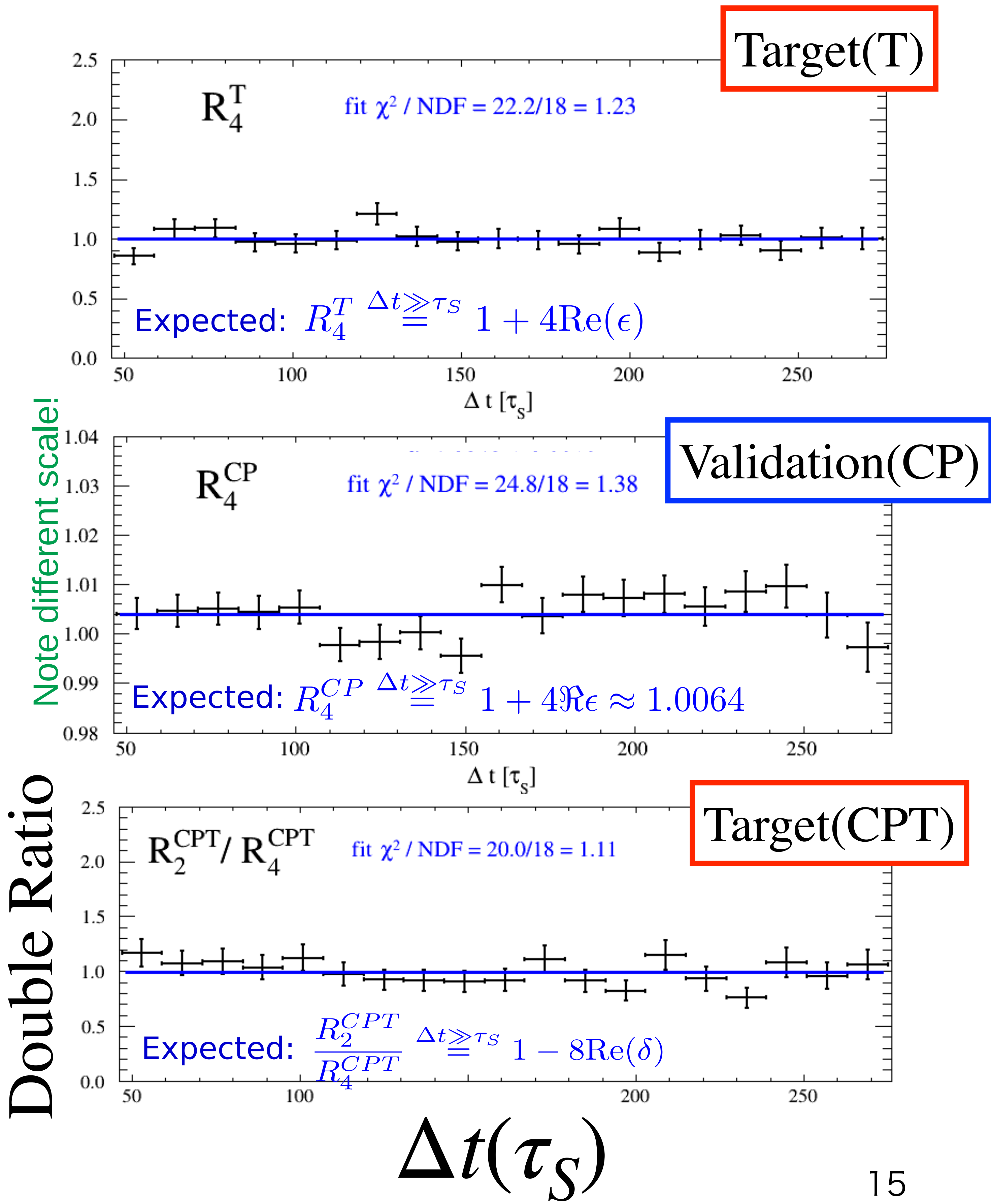
$$R_4^{CPT}(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Double ratios:

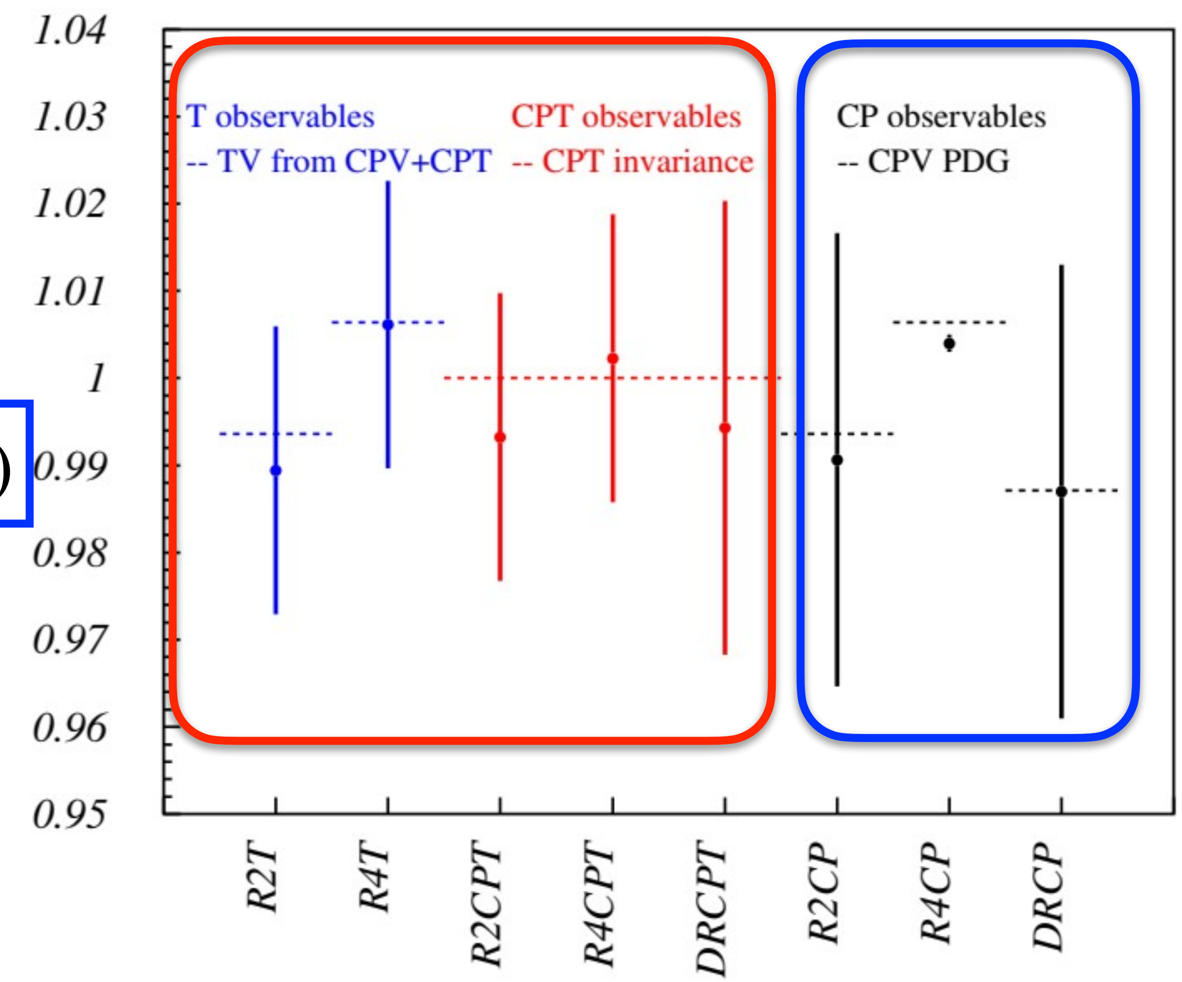
$$\text{DRCP} = \frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

Direct test of T and CPT in neutral kaon transitions



Preliminary results
(statistical uncertainty only)



First measurements

Analysis at the final stage

- Last systematic effects under study

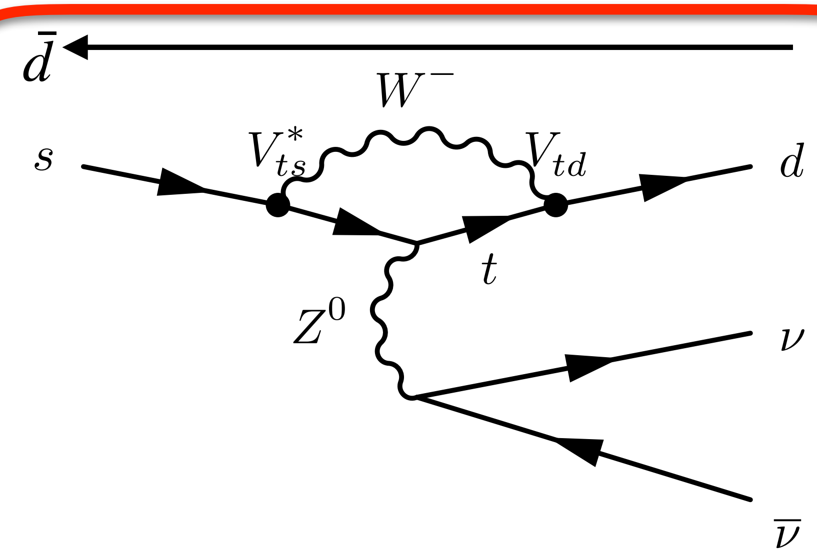
CP observable

- Consistent to known CPV
- Under control at $O(10^{-3})$

Recent KOTO Results / Prospects

$K \to \pi\nu\nu$ in SM

	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
Calculated BR (SM)	$(3.4 \pm 0.6) \times 10^{-11}$	$(8.4 \pm 1.0) \times 10^{-11}$
	Buras et al JHEP11(2015)33	
	Mainly Parameter error from CKM matrix elements	
Theoretical error	$< 2\,\%$	$< 4\,\%$
Quarks in loop	top	top > charm



Heavy t,W,Z

Weak coupling

CKM Strong suppression

$$V_{ts}^* V_{td} \sim 5 \times 10^{-4}$$

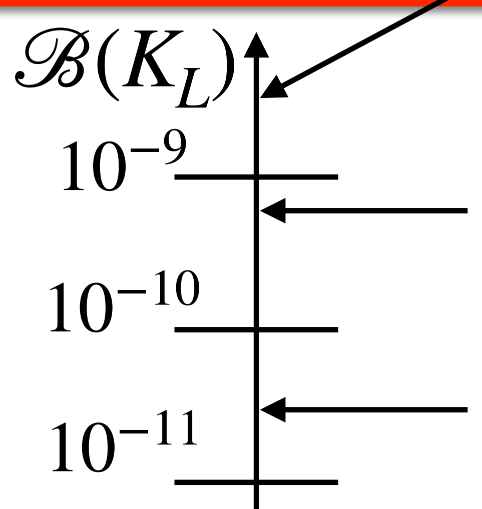
Precise and Suppressed SM process(BG)

→BSM Physics search(Signal)😀

Rare kaon decay : $K \to \pi\nu\nu$

	$K_L \to \pi^0\nu\bar{\nu}$ $\left(K_L \sim (K^0 - \bar{K}^0)/\sqrt{2}\right)$	$K^+ \to \pi^+\nu\bar{\nu}$
Amplitude	$\propto \mathscr{A}_{s\to d} - (\mathscr{A}_{s\to d})^*$	$\propto \mathscr{A}_{s\to d}$
Width	$\propto (\mathrm{Im}\mathscr{A}_{s\to d})^2$	$\propto \lvert\mathscr{A}_{s\to d}\rvert^2$
CP	**CP violating**	**CP conserving**

$\mathscr{B}$(direct meas.) $< 3.0 \times 10^{-9}$ (90 % CL) (KOTO 2015) $(10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (NA62 2021)



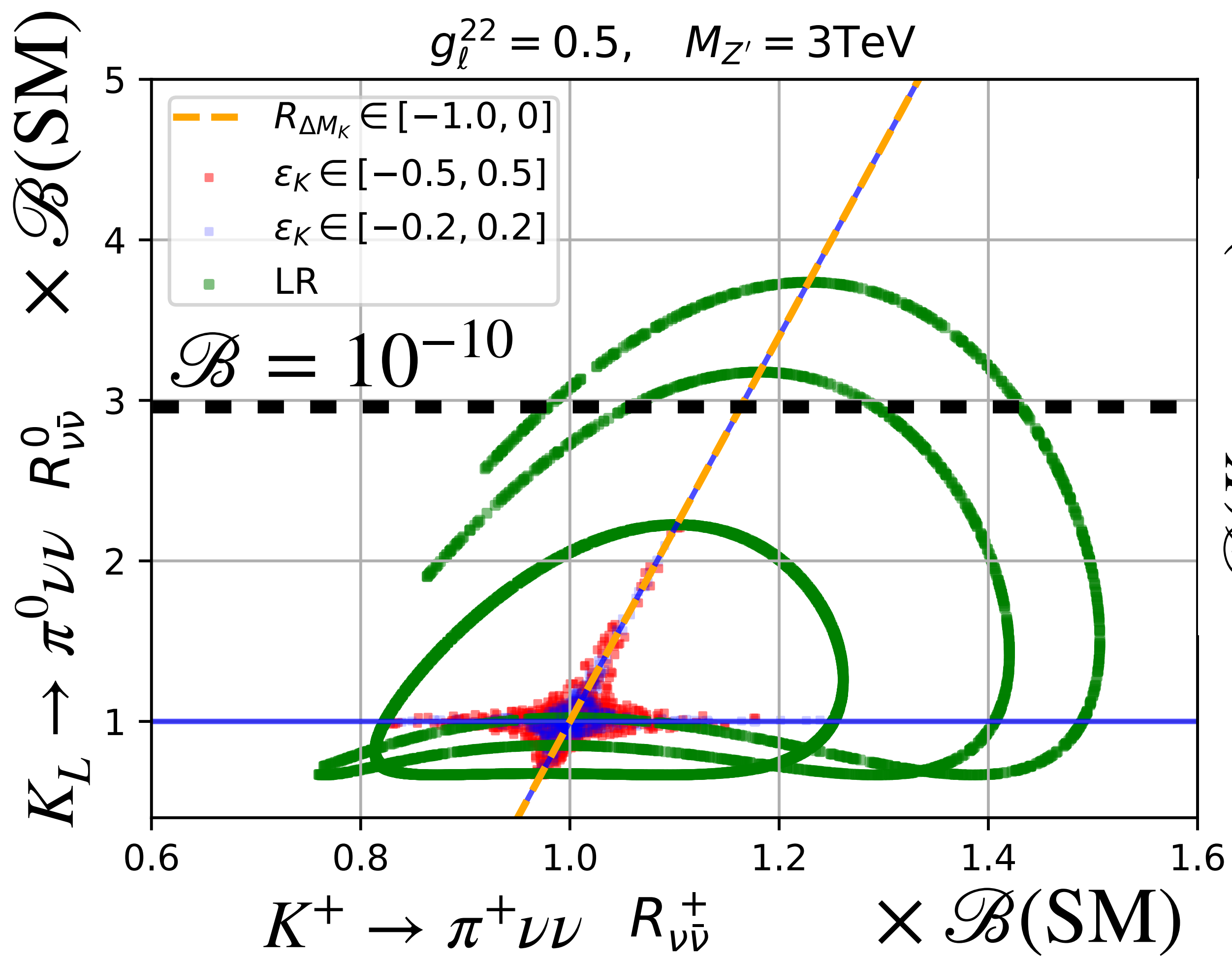
Grossman-Nir bound $\mathscr{B}_{K_L\to\pi^0\nu\bar{\nu}} < 4.4\mathscr{B}_{K^+\to\pi^+\nu\bar{\nu}}$

$\mathscr{B}$(indirect) $< 6.4 \times 10^{-10}$ (from 68 % CL meas . at NA62)

SM

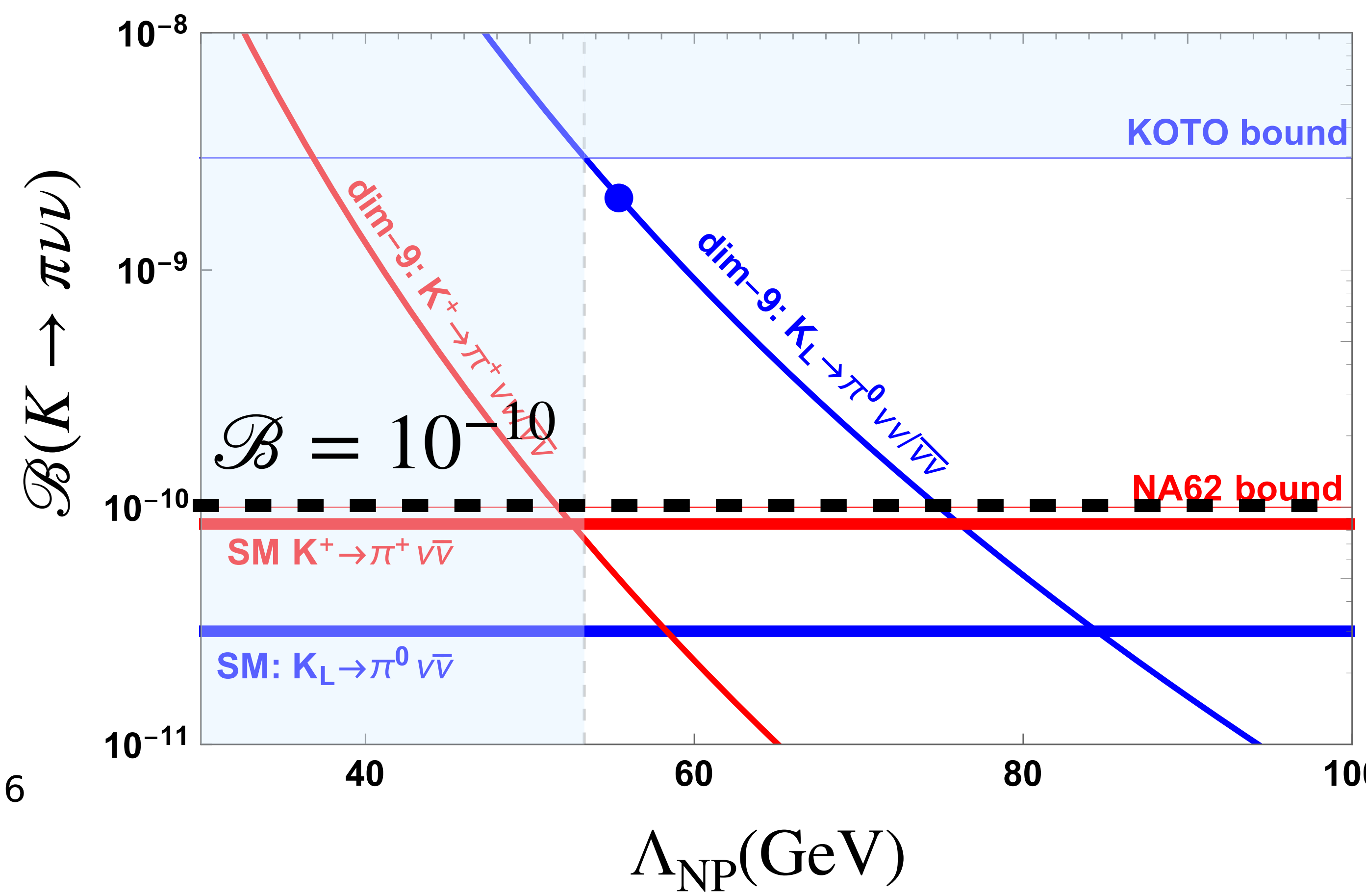
Examples of new physics contributions

JHEP12(2020)097



Flavor-violating Z' coupling

JHEP08(2020)034



Dim.9 ΔI=3/2 operator

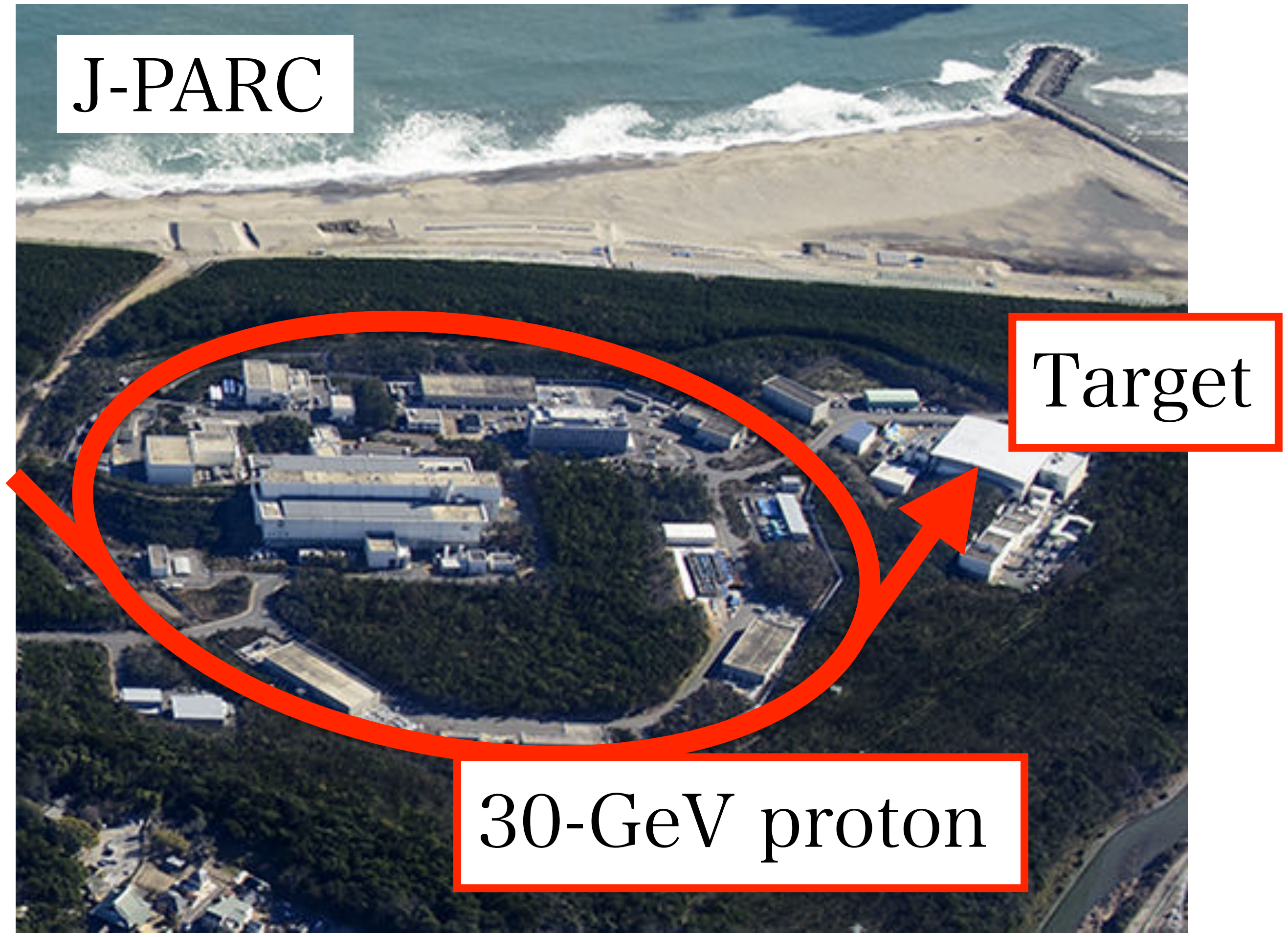
leptoquark, SUSY, charged Higgs, ν_R…

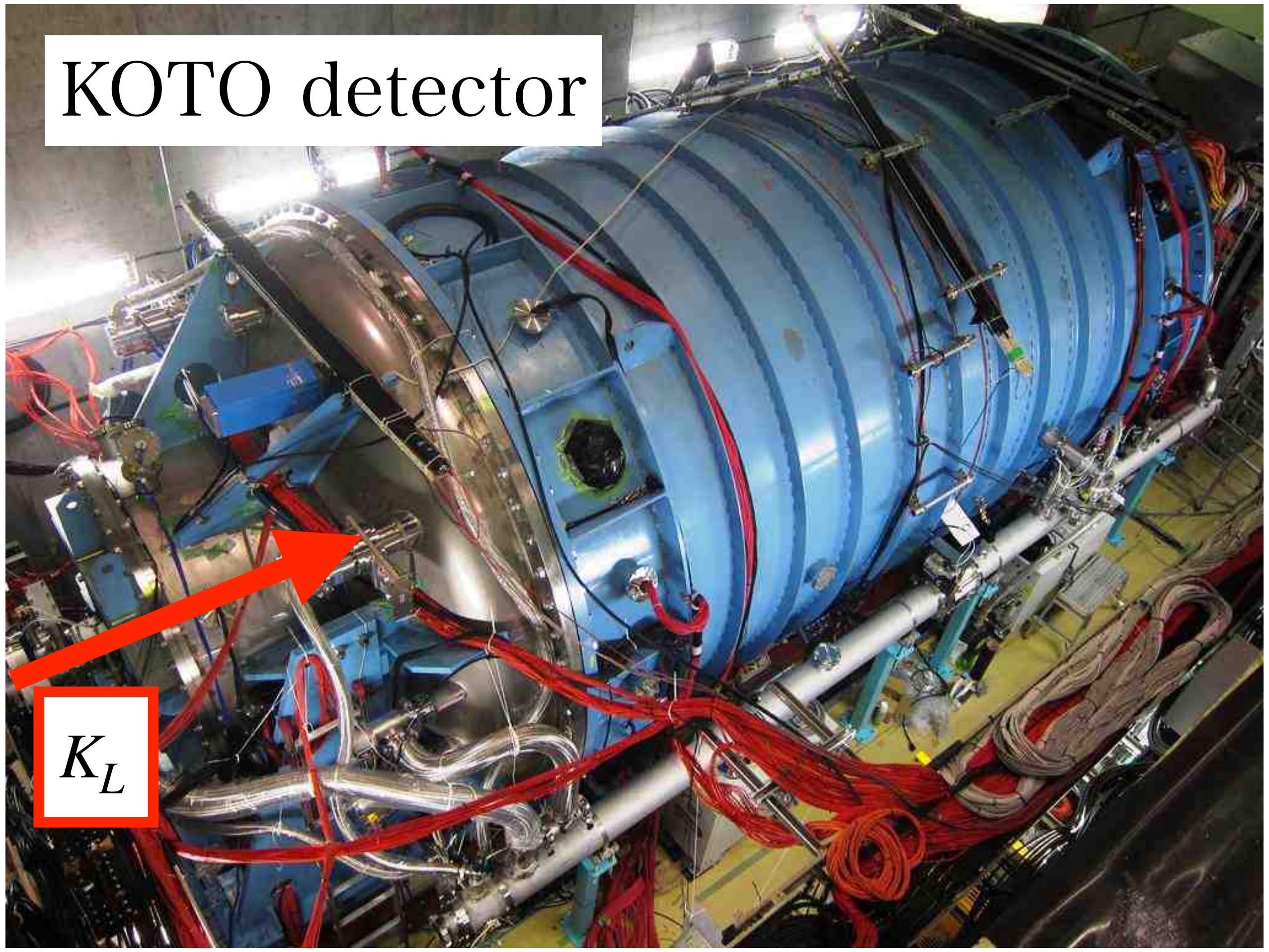
dark sector …

$K_L \to \pi^0 X$ due to loophole in $K^+ \to \pi^+ \nu\nu$ experiments(X mass / lifetime)

J-PARC KOTO experiment

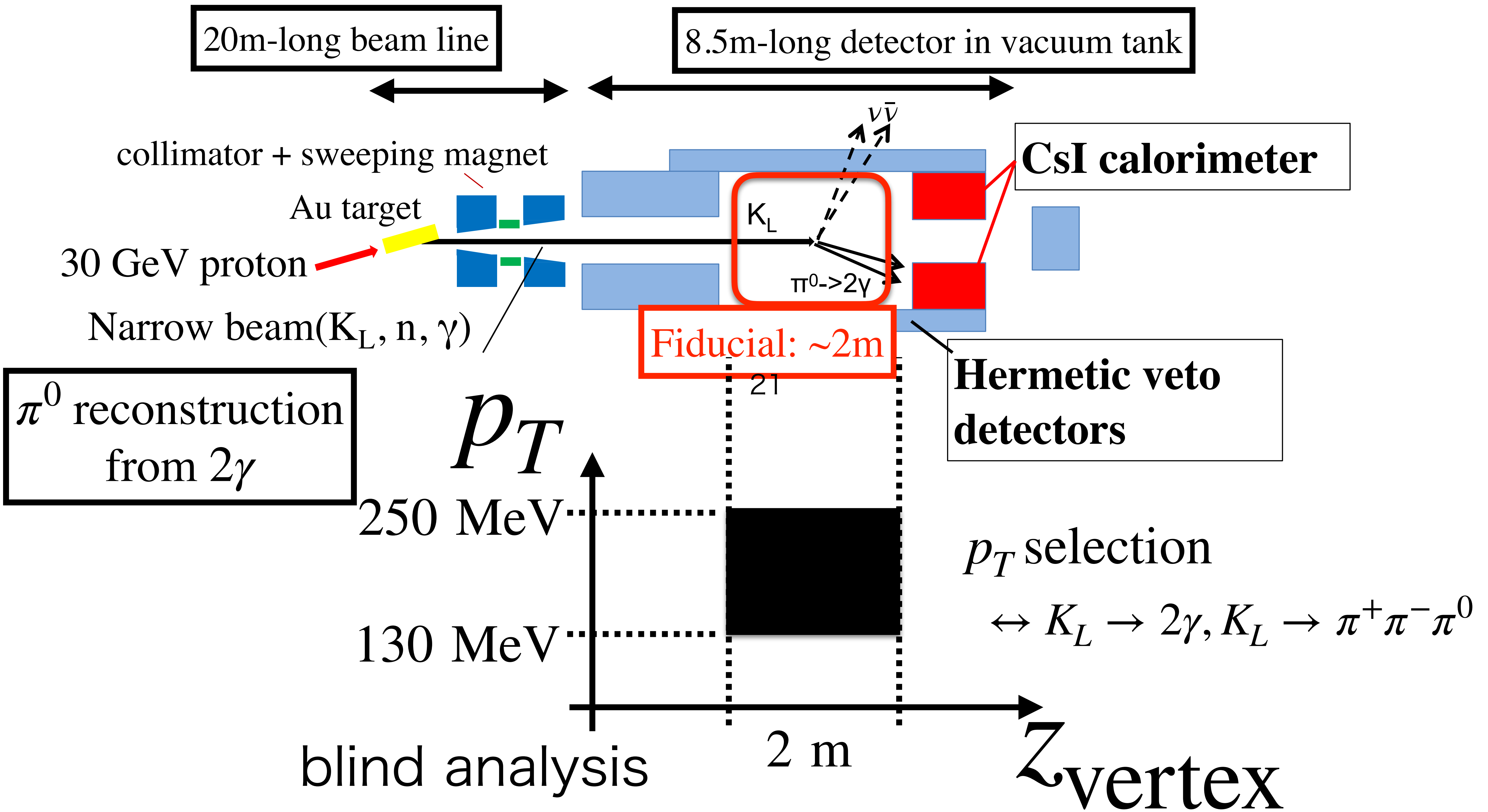
KOTO (K0 at Tokai) to search for $K_L \to \pi^0 \nu \bar{\nu}$



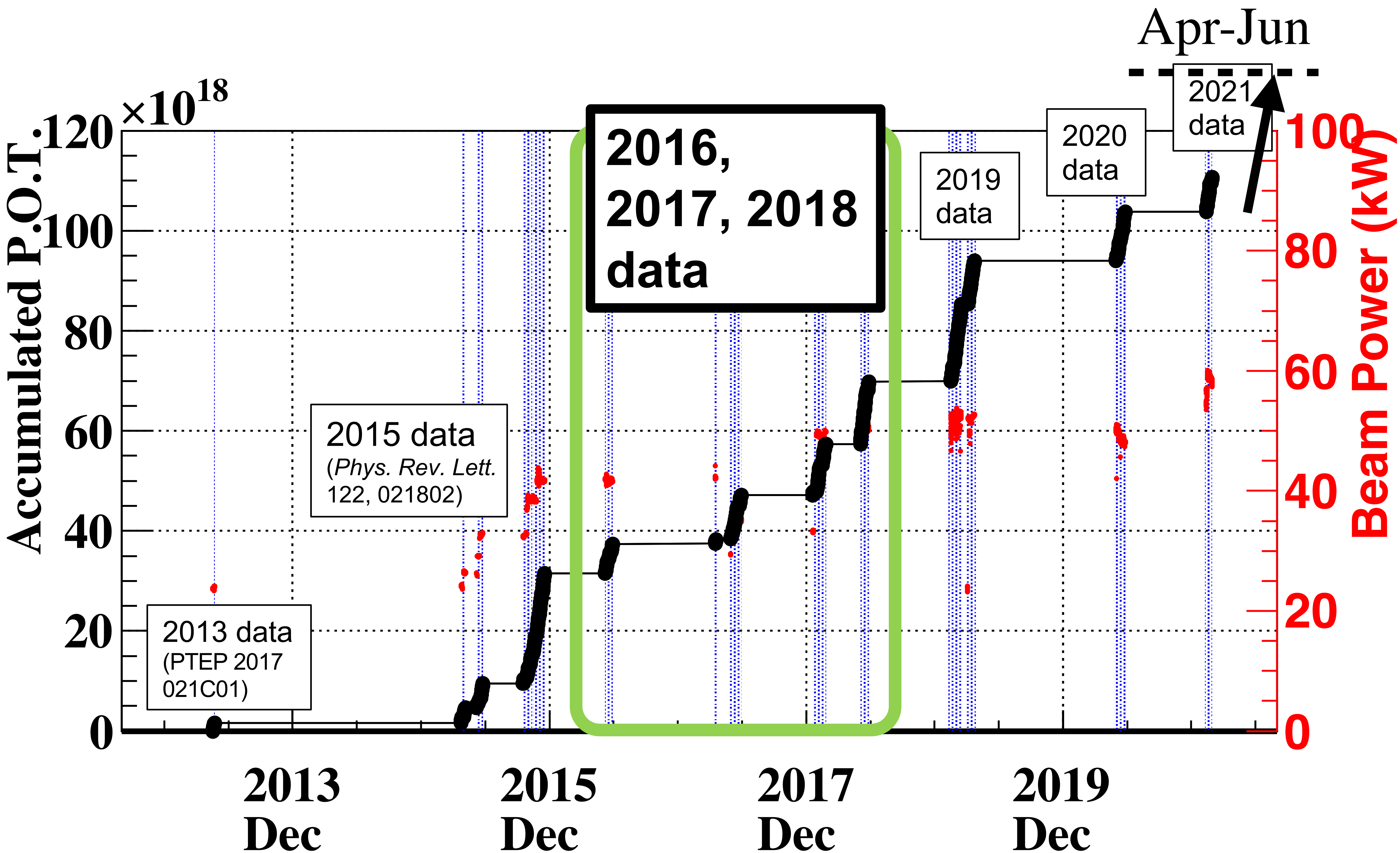


KOTO signal detection

$K_L \to \pi^0 \nu \bar{\nu} : \pi^0 (\to \gamma\gamma) +$ nothing



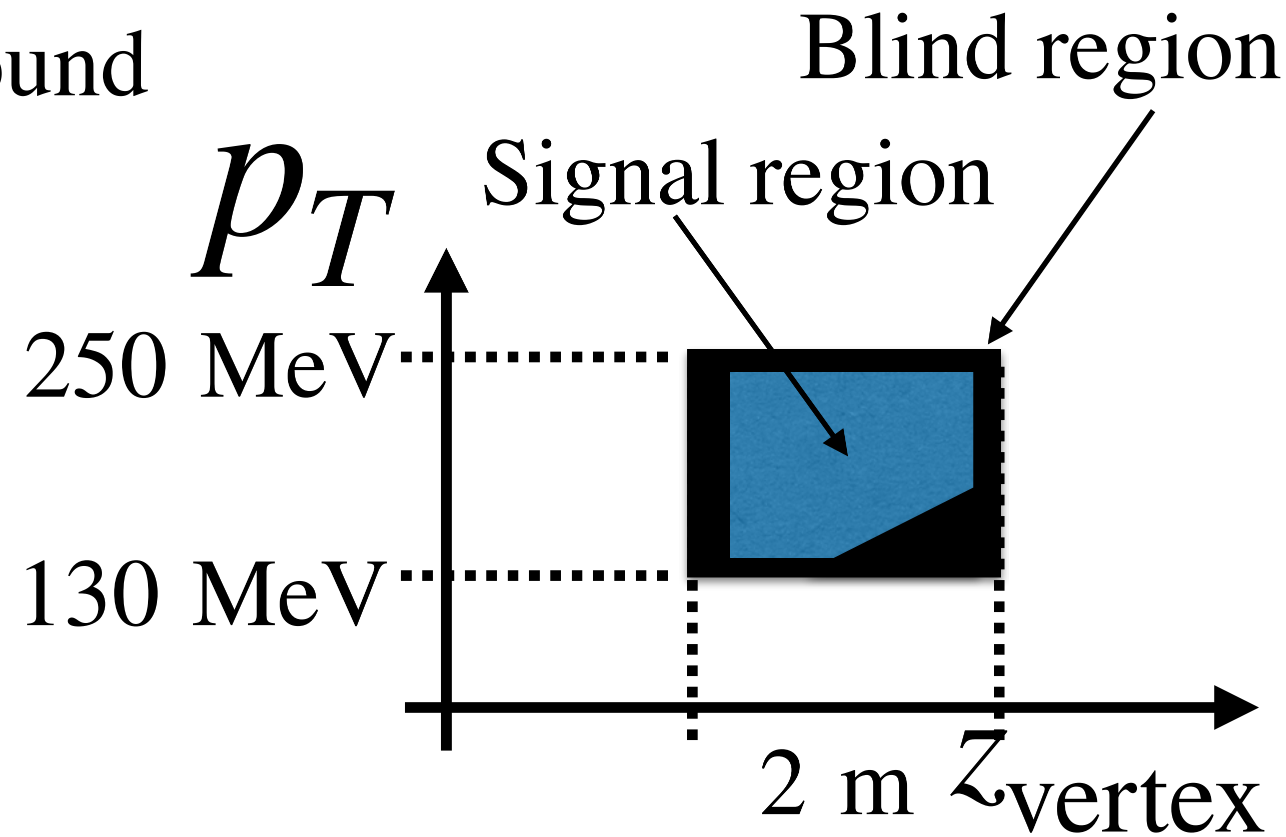
KOTO data collection



Analysis flow of 2016-18 data

Event selection to reduce background

Veto detector
γ cluster→Shower shape. etc
$\pi^0 \rightarrow$ Kinematics



\# of background → ~0
Signal acceptance (A_{sig})

Fix event selection

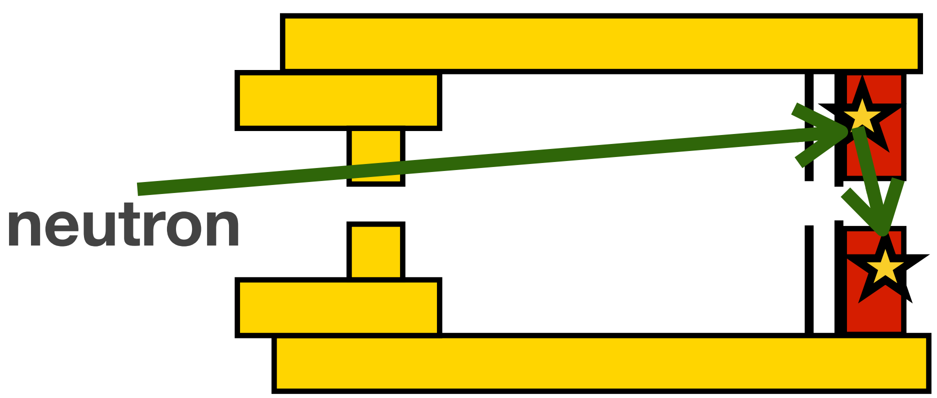
$$\text{Single Event Sensivitiy} = \frac{1}{A_{\mathrm{sig}} N_{K_L}} = \frac{1}{A_{\mathrm{sig}}} \times \frac{A_{K_L \to 2\pi^0} \mathscr{B}_{K_L \to 2\pi^0}}{N_{K_L \to 2\pi^0}}$$

Unblind → N_{sig}

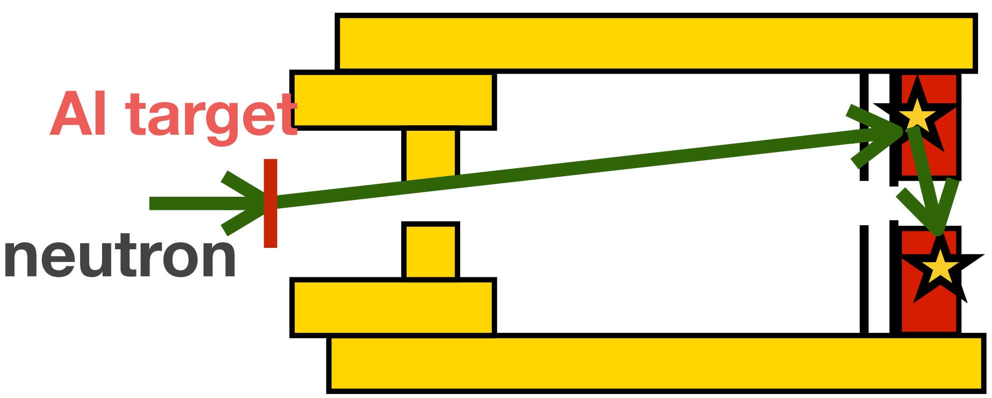
Post-unblind analysis
Keep the same event selection

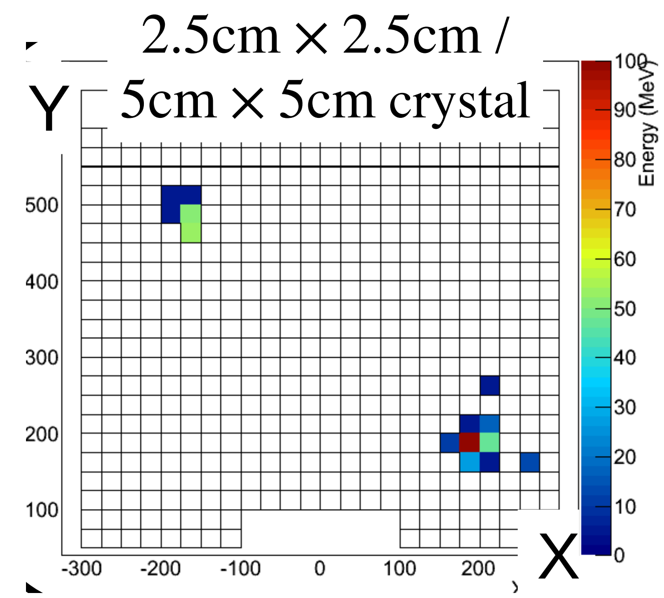
Reduction of hadron cluster background

Hadron cluster BG

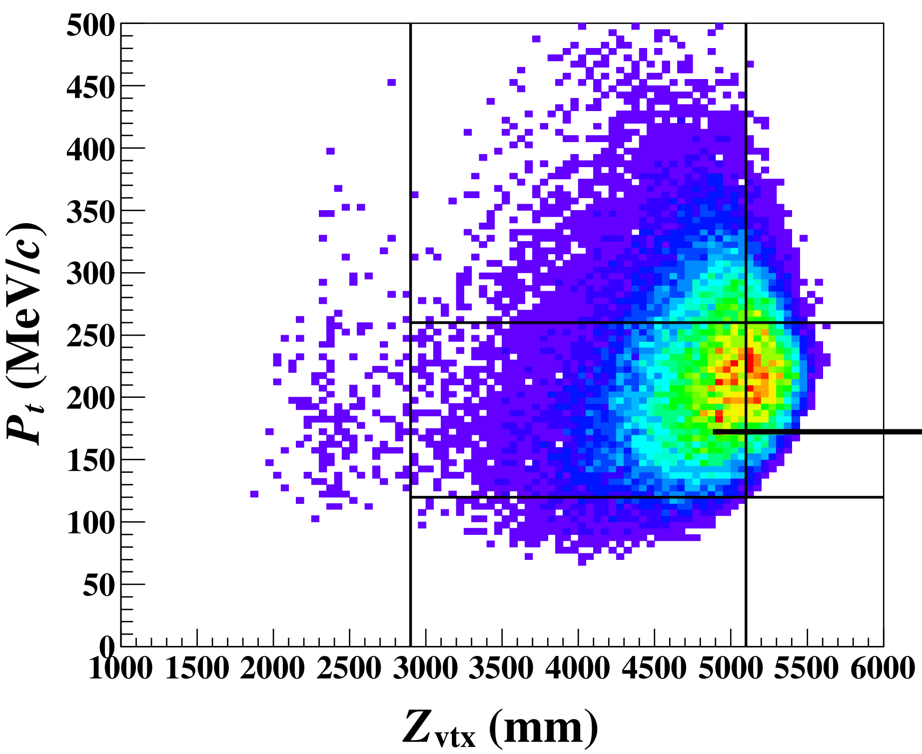


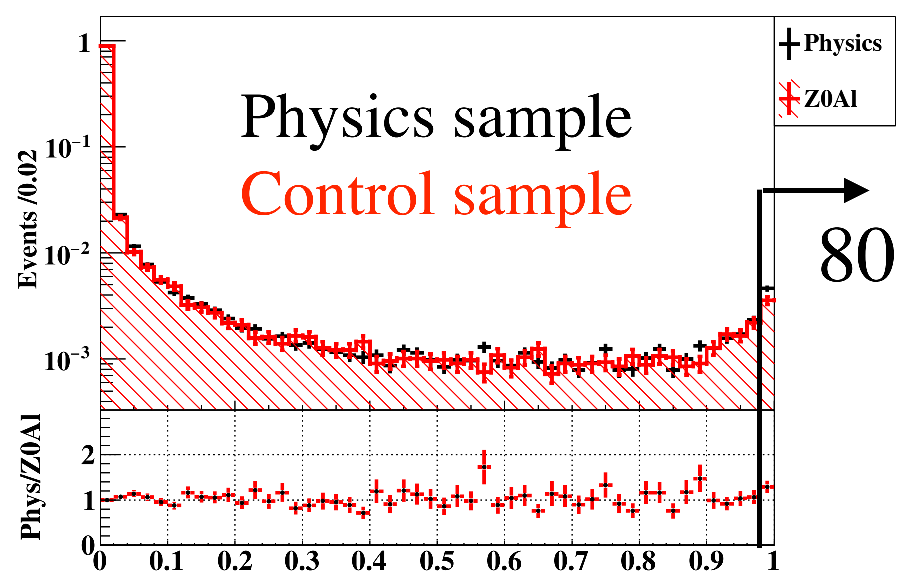
Special run to take control sample





Control sample





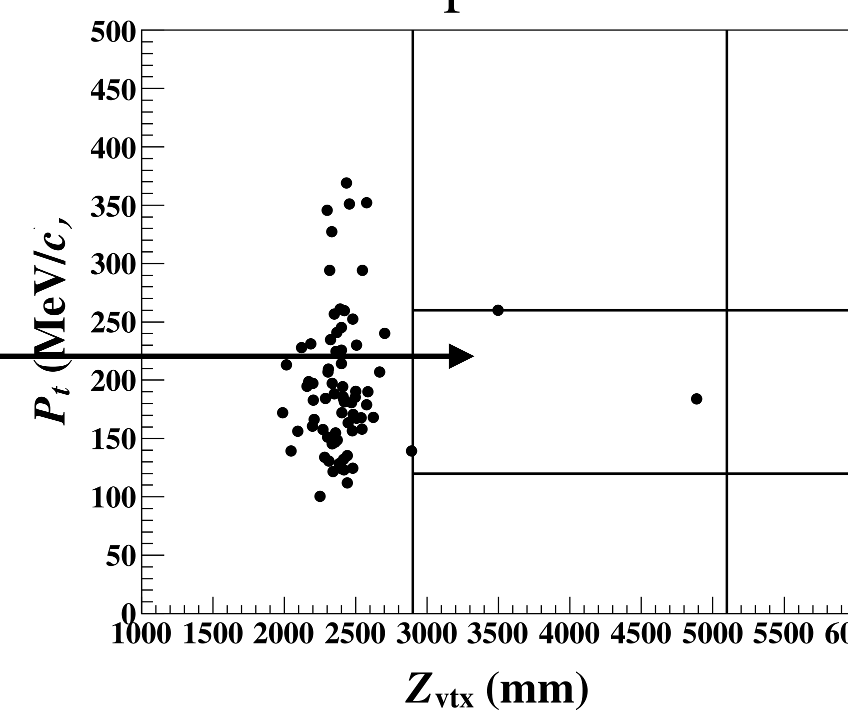
Cluster Shape Variable

80% signal acceptance

$\times (1.8 \times 10^{-6})$

(after contamination from KL decay was removed)

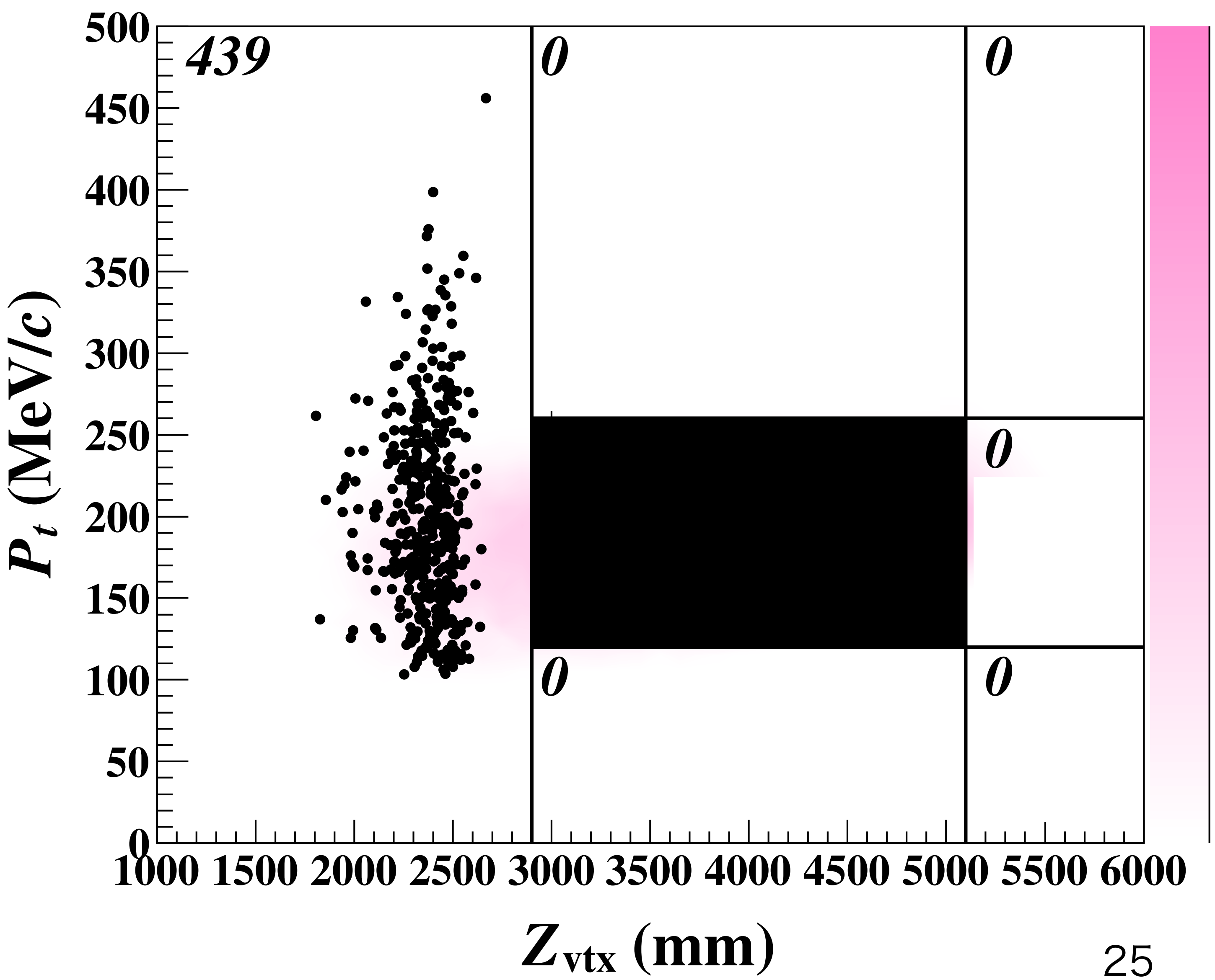
Control sample



Situation of unblinding fixing event selection

Pre-unblinding

Expected # of background in the signal region : 0.05 ± 0.02



Final result after unblinding

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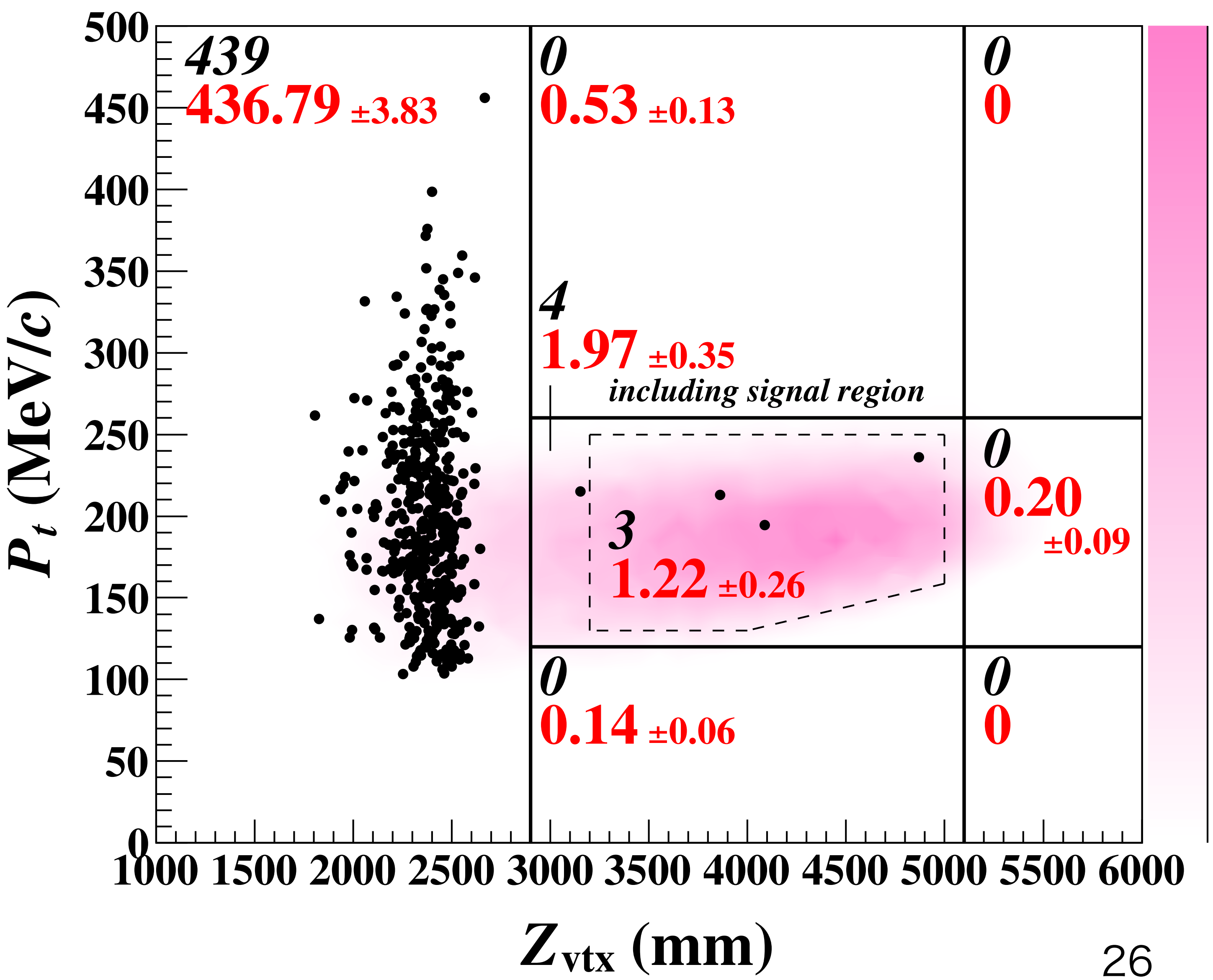
3 events observed

SES=$(7.20 \pm 0.05_{stat.} \pm 0.66_{syst.}) \times 10^{-10}$



Post-unblinding analysis

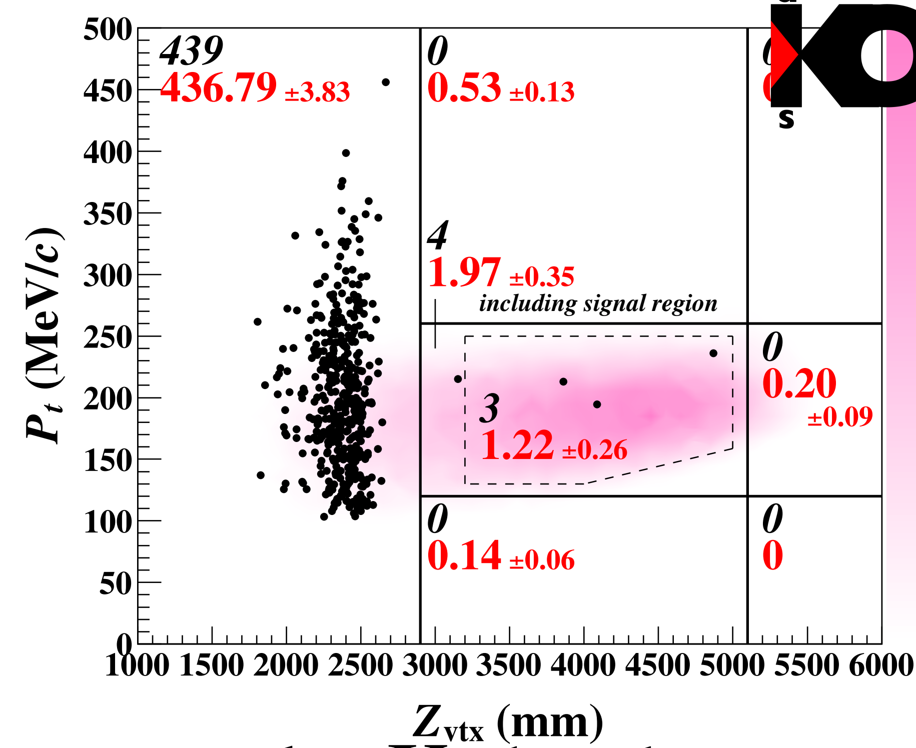
$K^{\pm}$ decay	: 0.87 ± 0.25
Halo $K_L \to 2\gamma$	: 0.26 ± 0.07
Others	: 0.09
Total	: 1.22 ± 0.26

\# of observed events is consistent to # of backgrounds

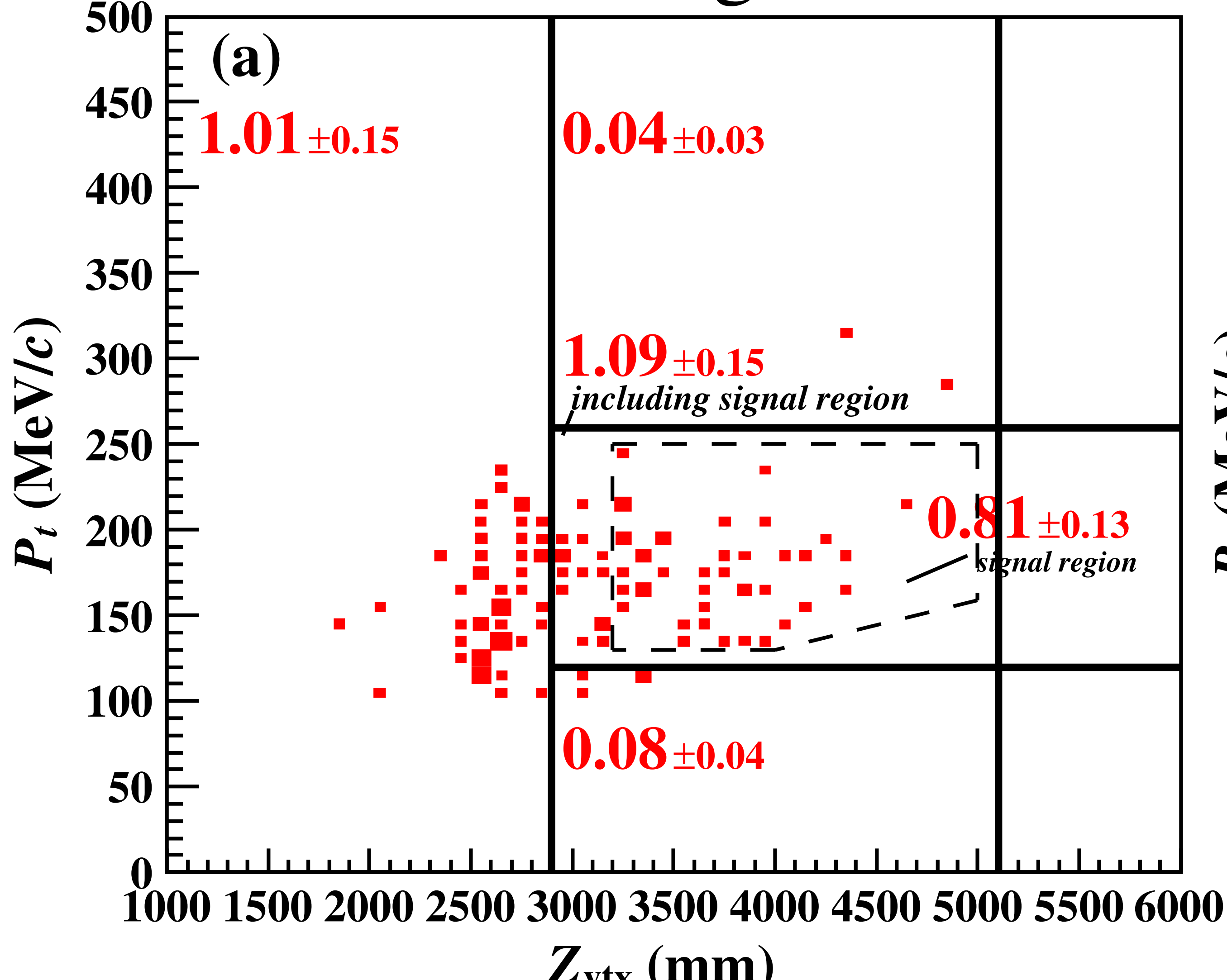
No update of the upper limit

	Number of events
$K_L \to 3\pi^0$	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]
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26

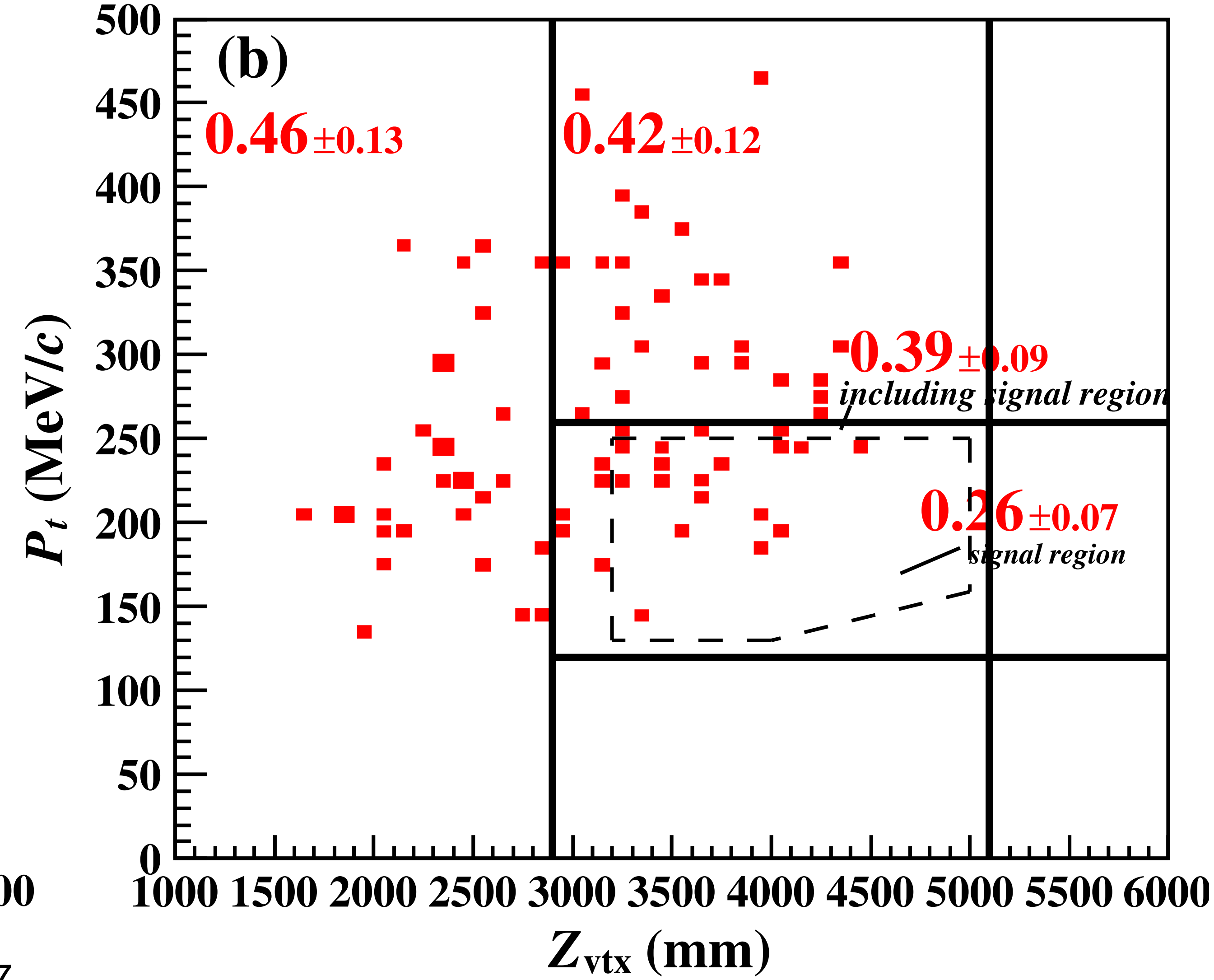
Distribution of backgrounds



$K^{\pm}$ backgrounds

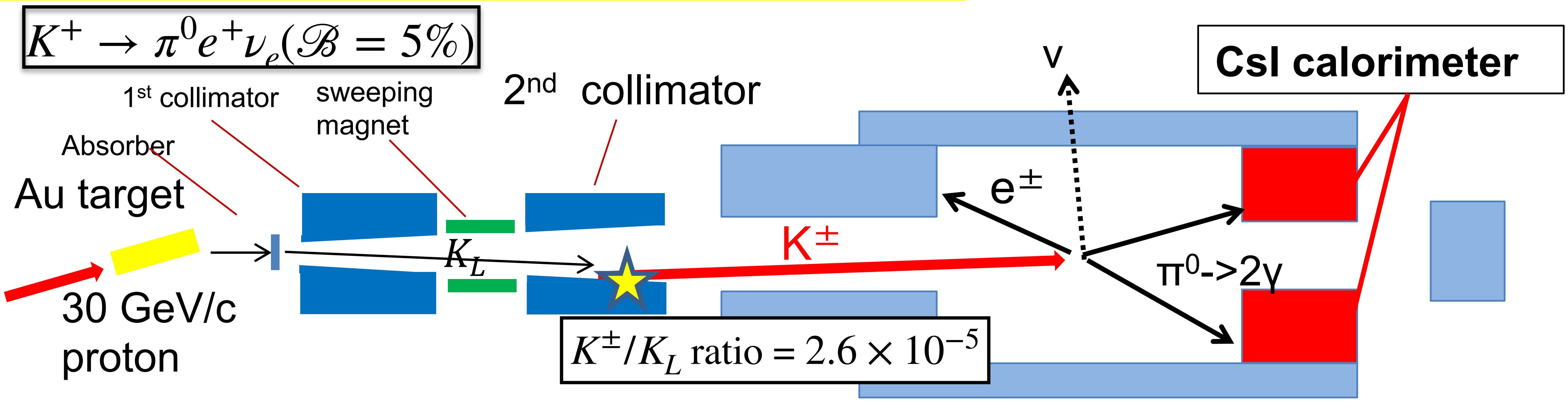


Halo K_L backgrounds

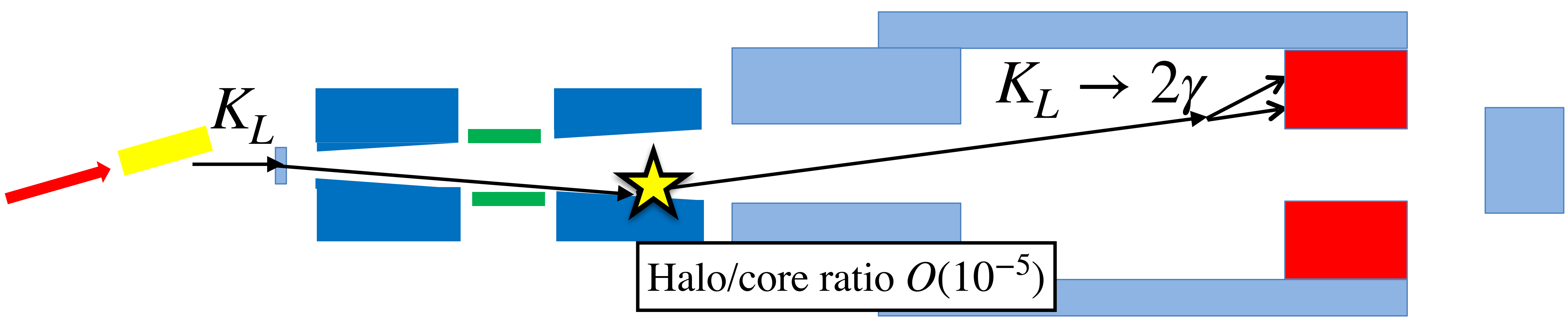


Backgrounds found in post-unblinding analysis

1.Charged K : # of BG = 0.87 / 1.22(total)



2.Halo K→2γ : # of BG = 0.26 / 1.22(total)



Evaluation of $K^{\pm}$ flux

$K^{\pm} \to \pi^0 \pi^{\pm}$

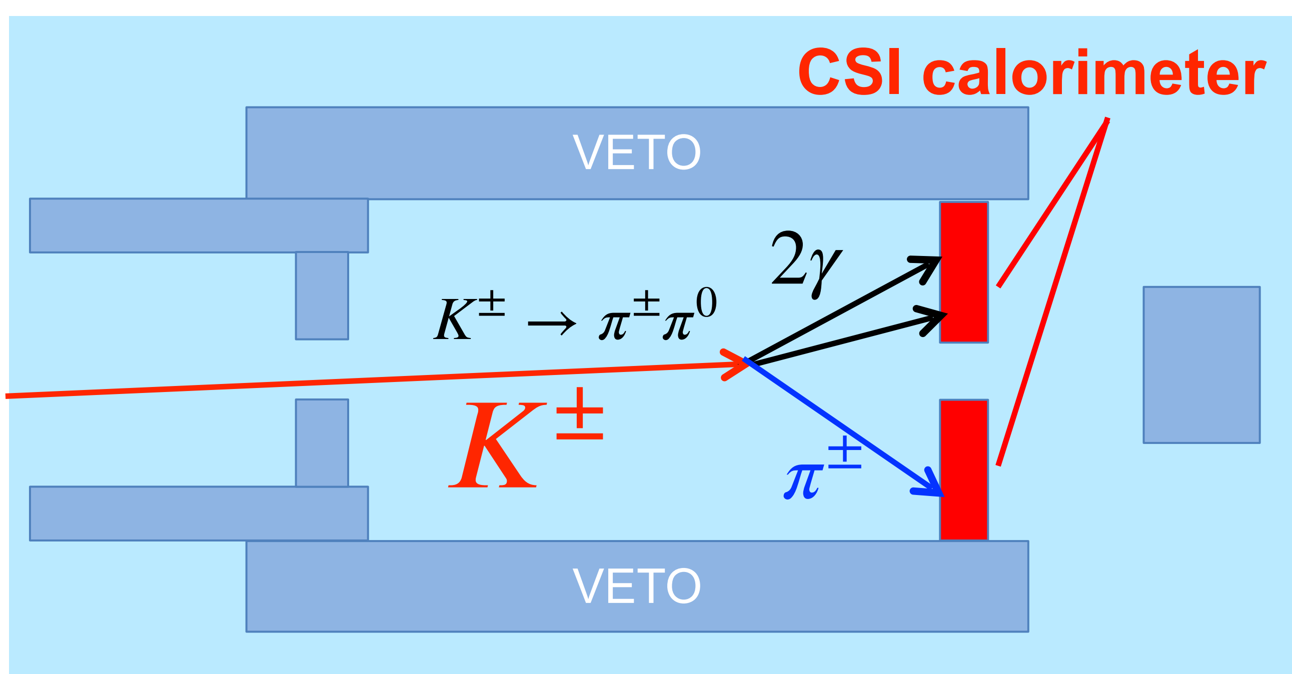
3 clusters on CSI

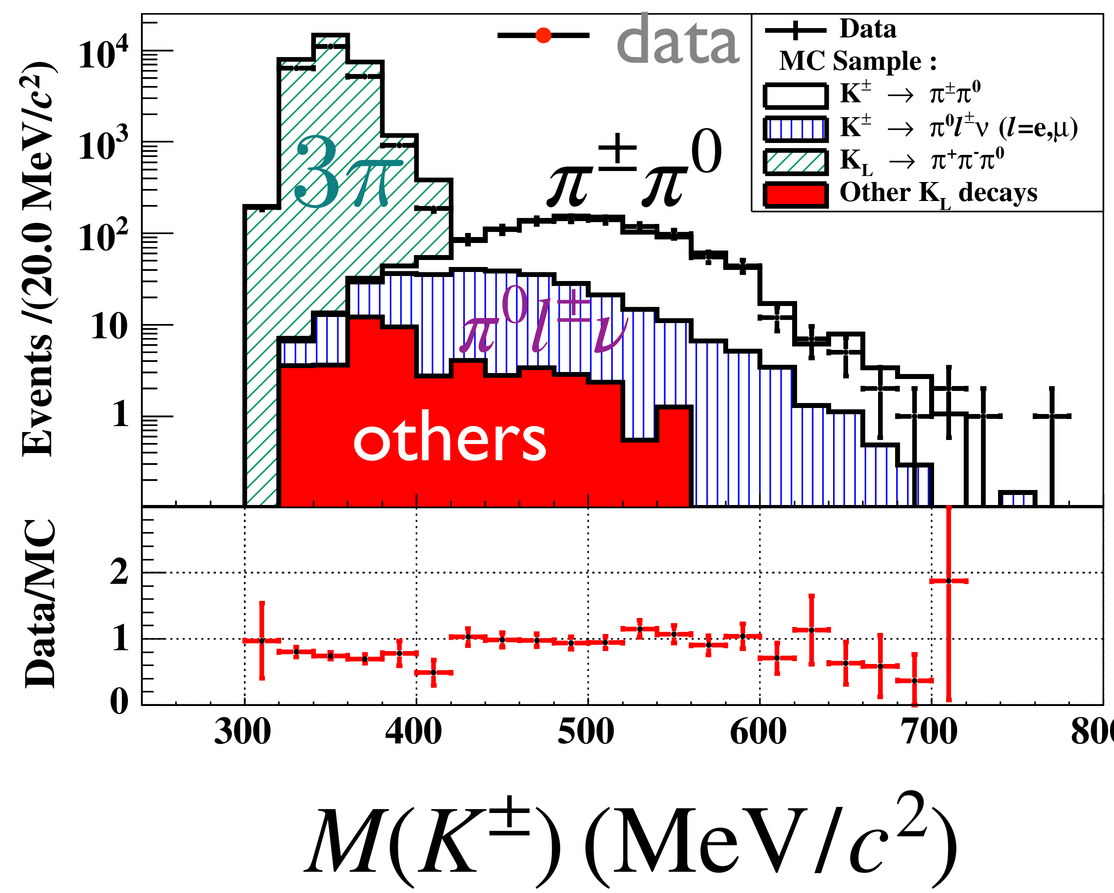
π^0 full reconstruction
$\pi^{\pm}$ momentum direction
$\mathbf{p}_T^{\pi^0} + \mathbf{p}_T^{\pi^{\pm}} = 0$

Full $\mathbf{p}^{\pi^{\pm}}$ reconstruction

$K^{\pm}$ mass from $\mathbf{p}^{\pi^0}$ and $\mathbf{p}^{\pi^{\pm}}$

$K^{\pm}$ contributions→Flux

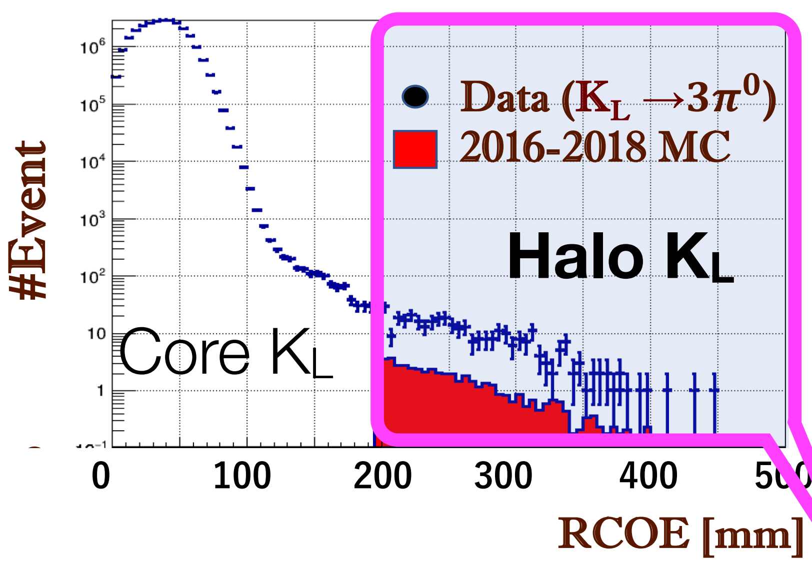


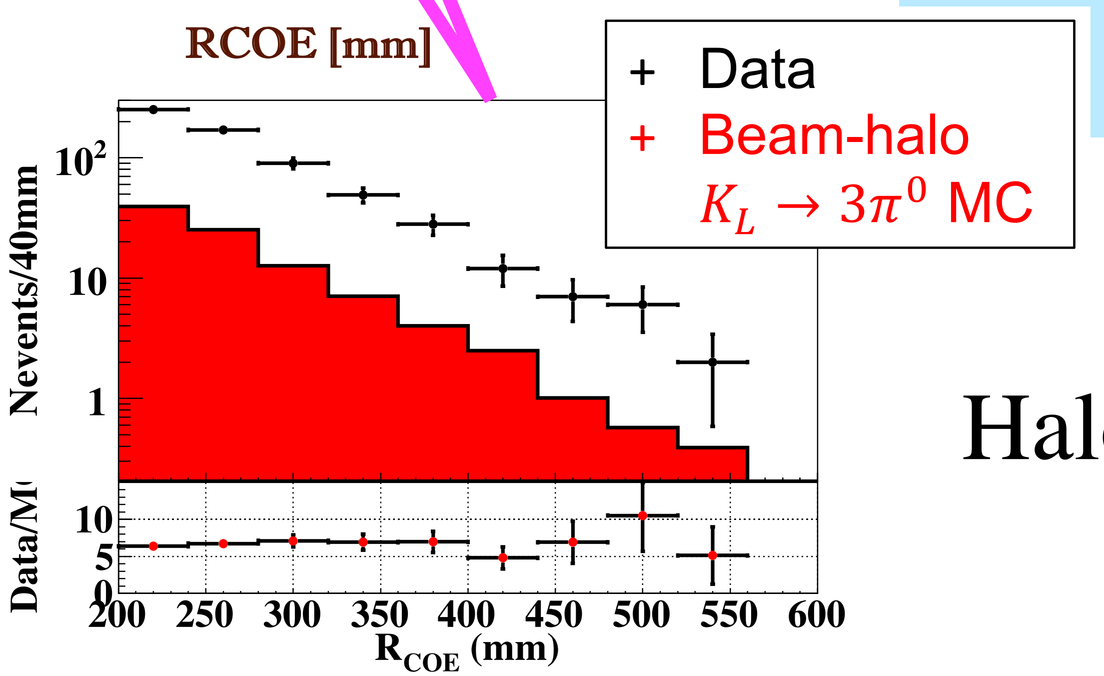


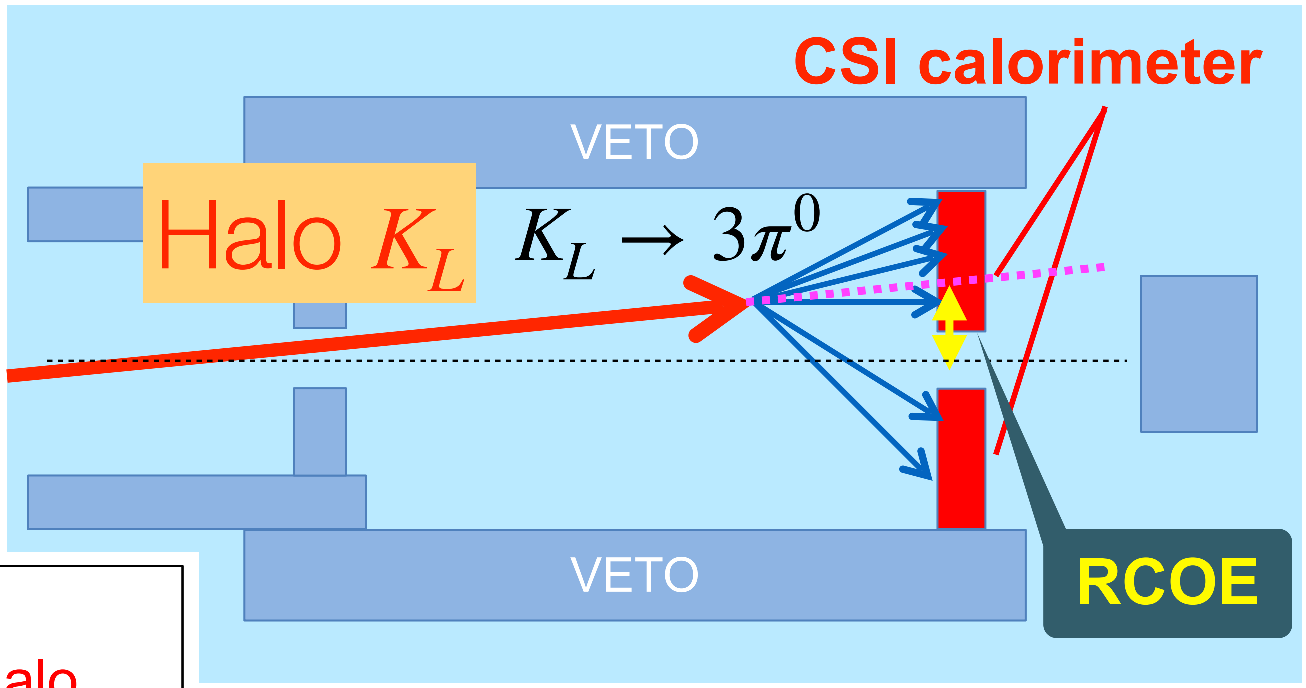
Evaluation of halo K_L flux

$K_L \to 3\pi^0$ data was used.

Center Of Energy (rCOE)



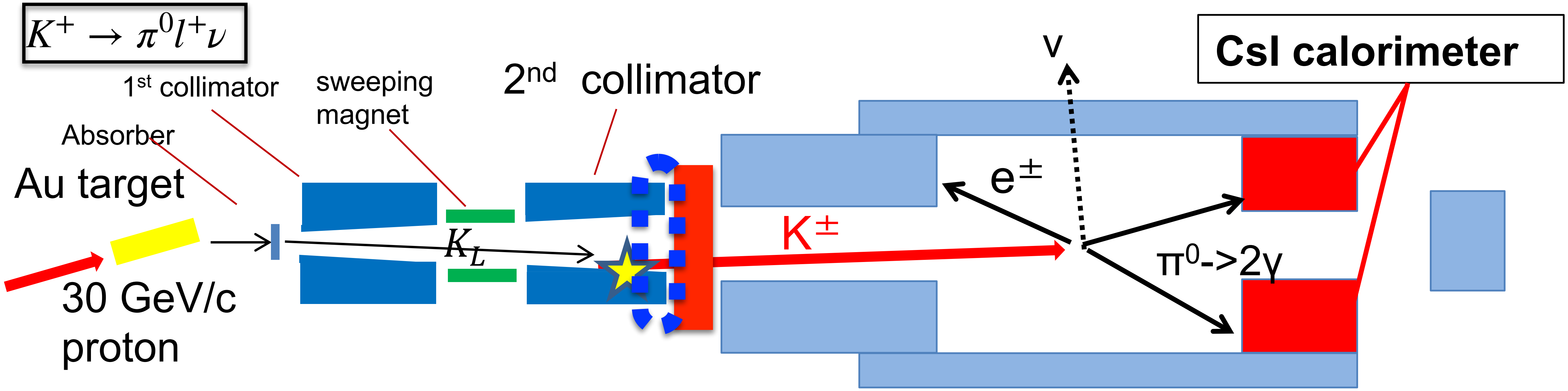




Halo K_L flux: $\sim \times 7$ of MC

Reduction of $K^{\pm}$ background

1.Charged K : # of BG = 0.84 / 1.21(total)



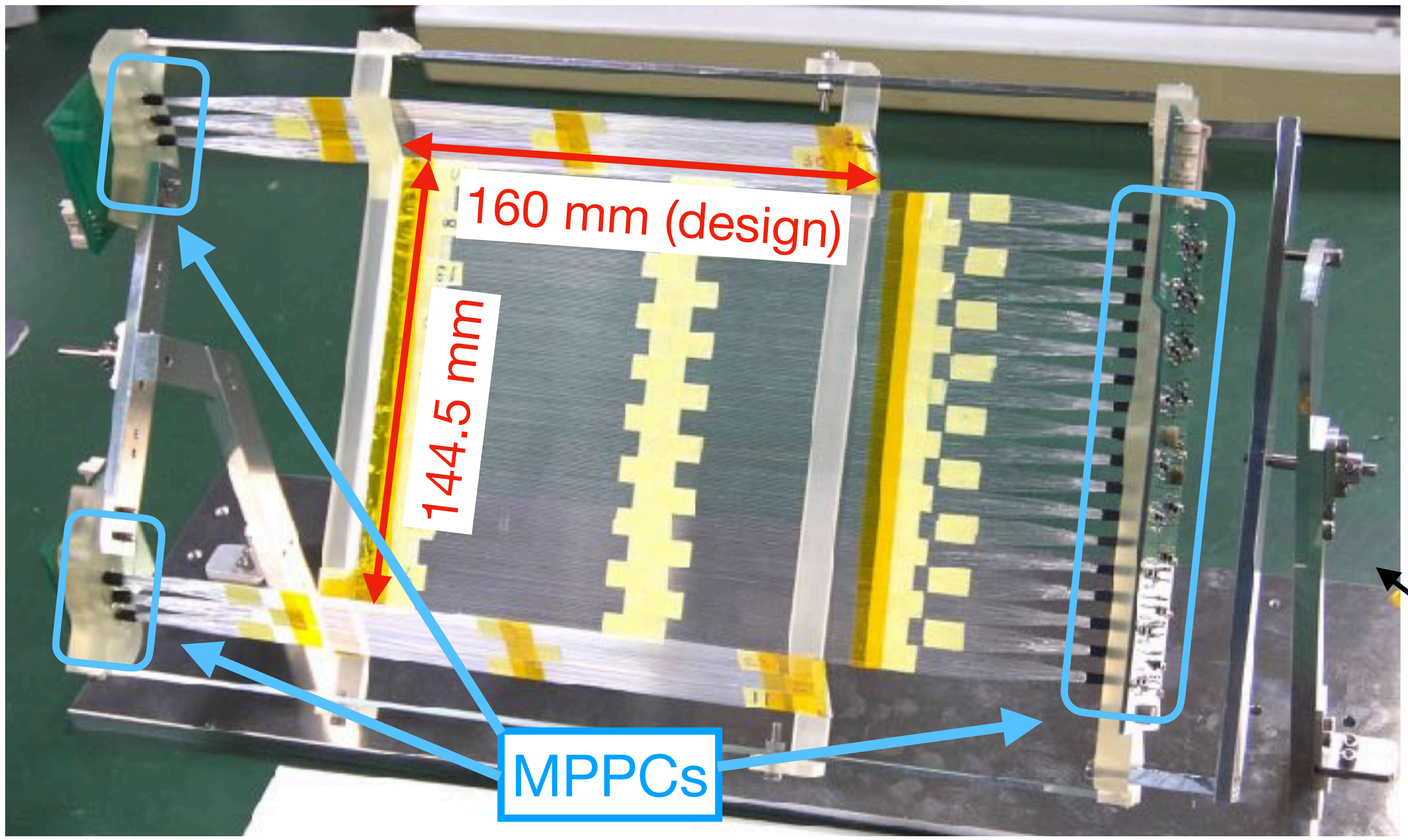
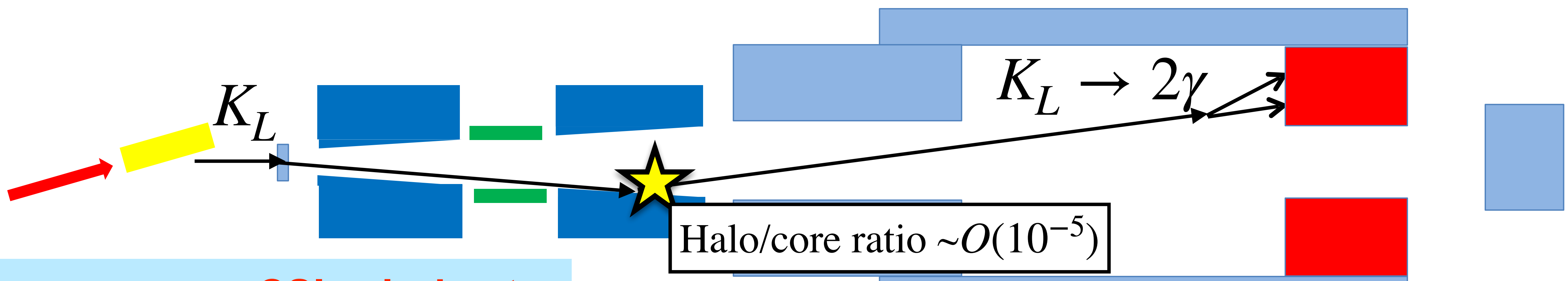


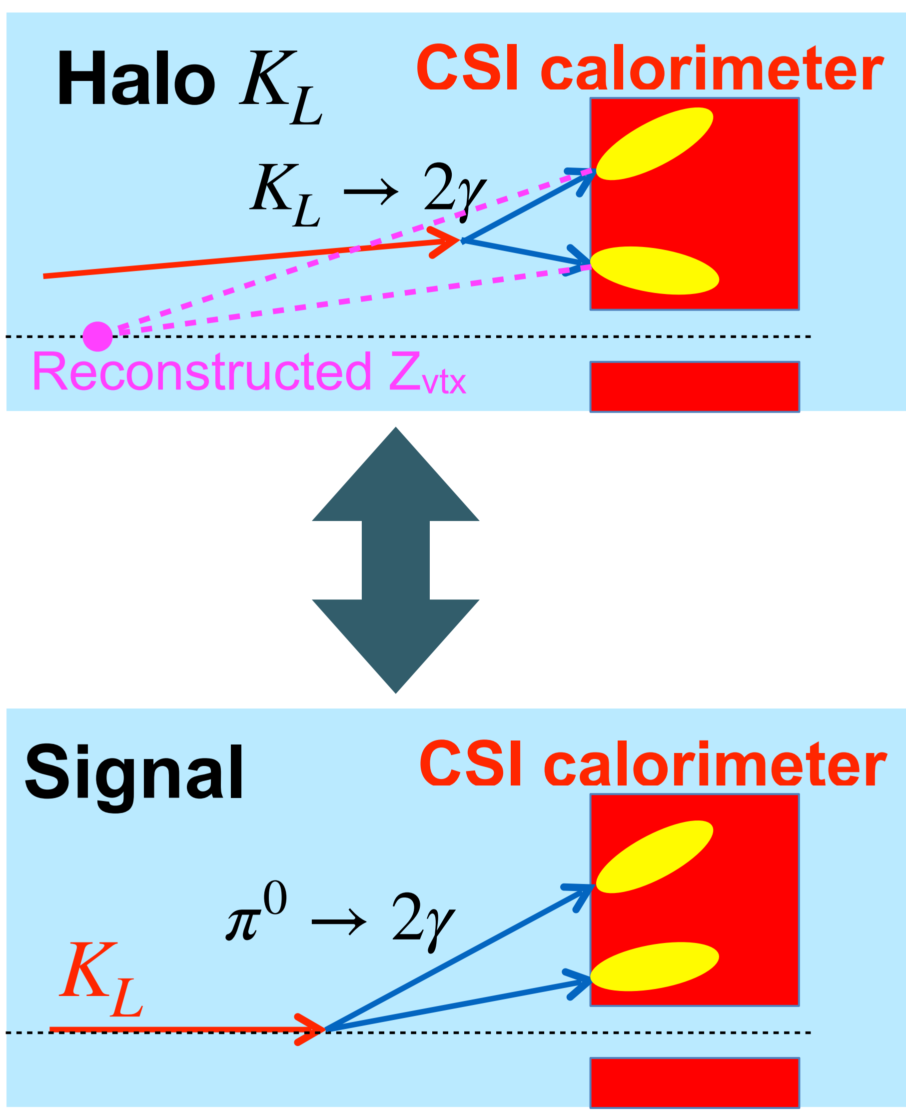
Plate with 0.5-mm square scintillating fibers to detect and veto $K^{\pm}$ in beam.

Prototype : installed in 2020.
Upgraded and used in 2021
→ × 1/20 (preliminary)

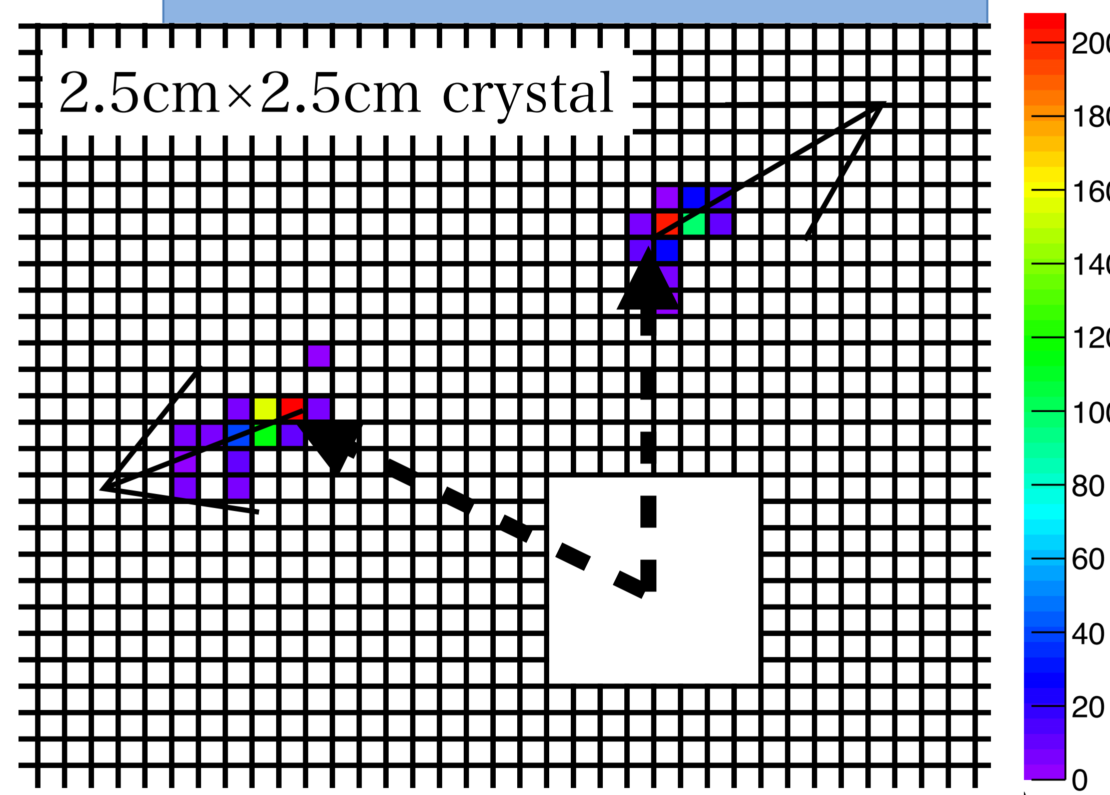
Reduction of halo K_L background

2.Halo $K \to 2\gamma$: # of BG = 0.26 / 1.22(total)





32



Shower energy and shape
~ × 1/20 (preliminary)

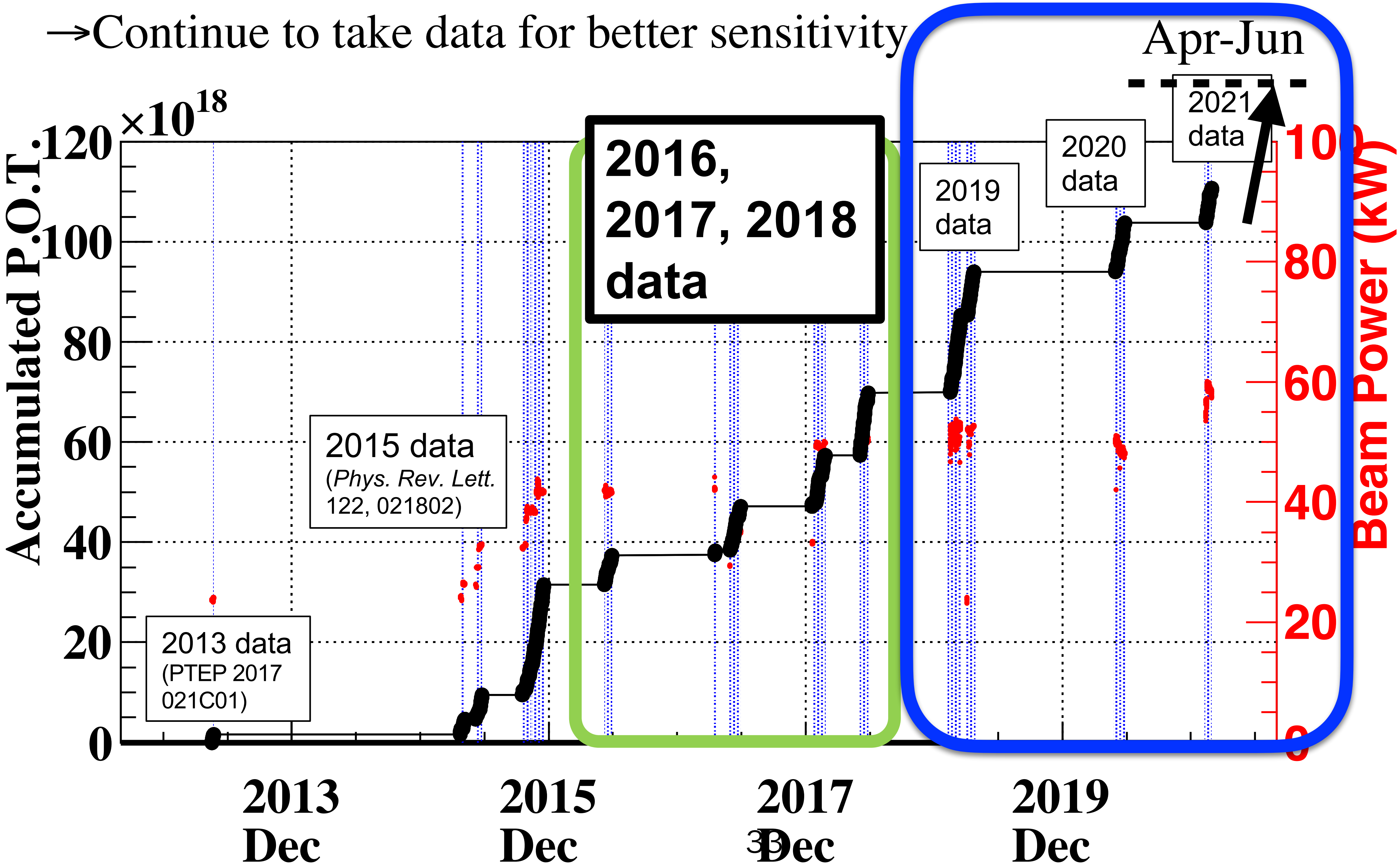
Prospects

2019-21 data : Comparable or more than 2016-18 data

Suppress background → new results

Accelerator upgrade is planned in 2021.

→Continue to take data for better sensitivity



Summary

- KLOE-2
  - Data taking was completed.
  - First measurement :$\mathcal{B}(K_S \to \pi\mu\nu) = (4.56 \pm 0.11 \pm 0.17) \times 10^{-4}$
  - Charge asymmetry in $K_S \to \pi e \nu$ provides CPT violating parameters with the decay
  - First measurements on CPT and T observables with neutral kaon transition are in progress.
- KOTO : $K_L \to \pi^0 \nu \bar{\nu}$ analysis of data taken in 2016-18
  - 3 events observed in $K_L \to \pi^0 \nu \bar{\nu}$ search at SES=7.2×10^{-10}
  - # of observed events is consistent to expected # of BG (1.22 ± 0.26)
  - Reduction of new backgrounds→ Future prospects