Rare Kaon Decays

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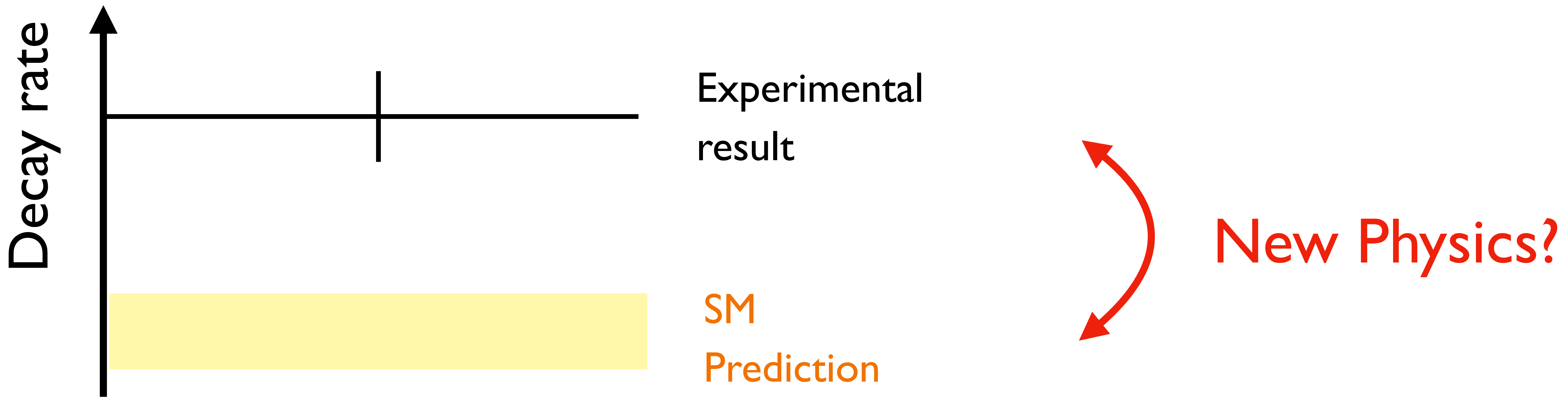
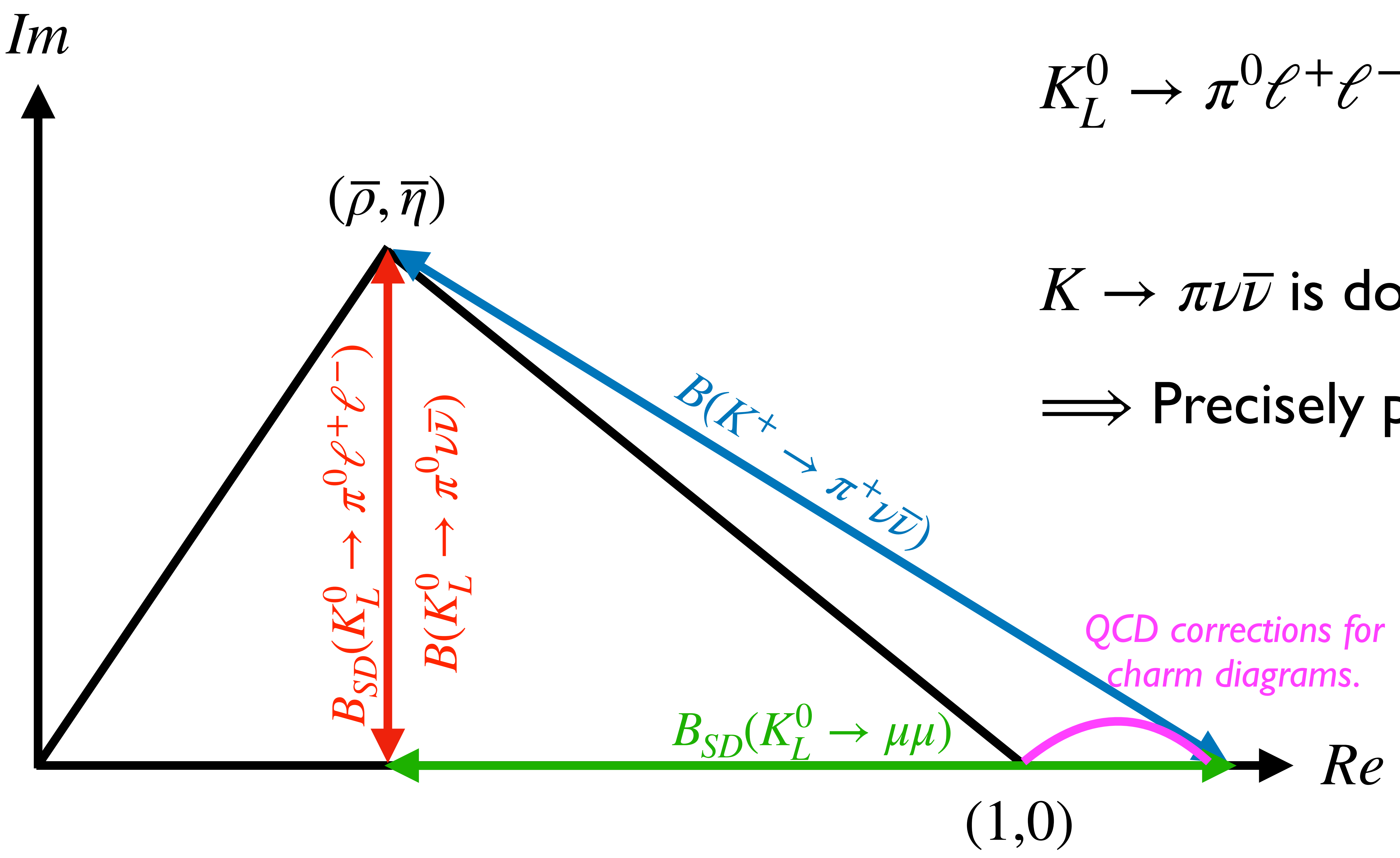
New Physics Search with Rare Kaon Decays

- Search for explicit violation in SM (e.g. Lepton flavor violating channel).
- Search for clean channels that are sensitive to SM parameters (e.g. CKM parameters).



Precise theoretical prediction → **Sensitive to New Physics**

Rare Kaon Decays with Unitarity Triangle



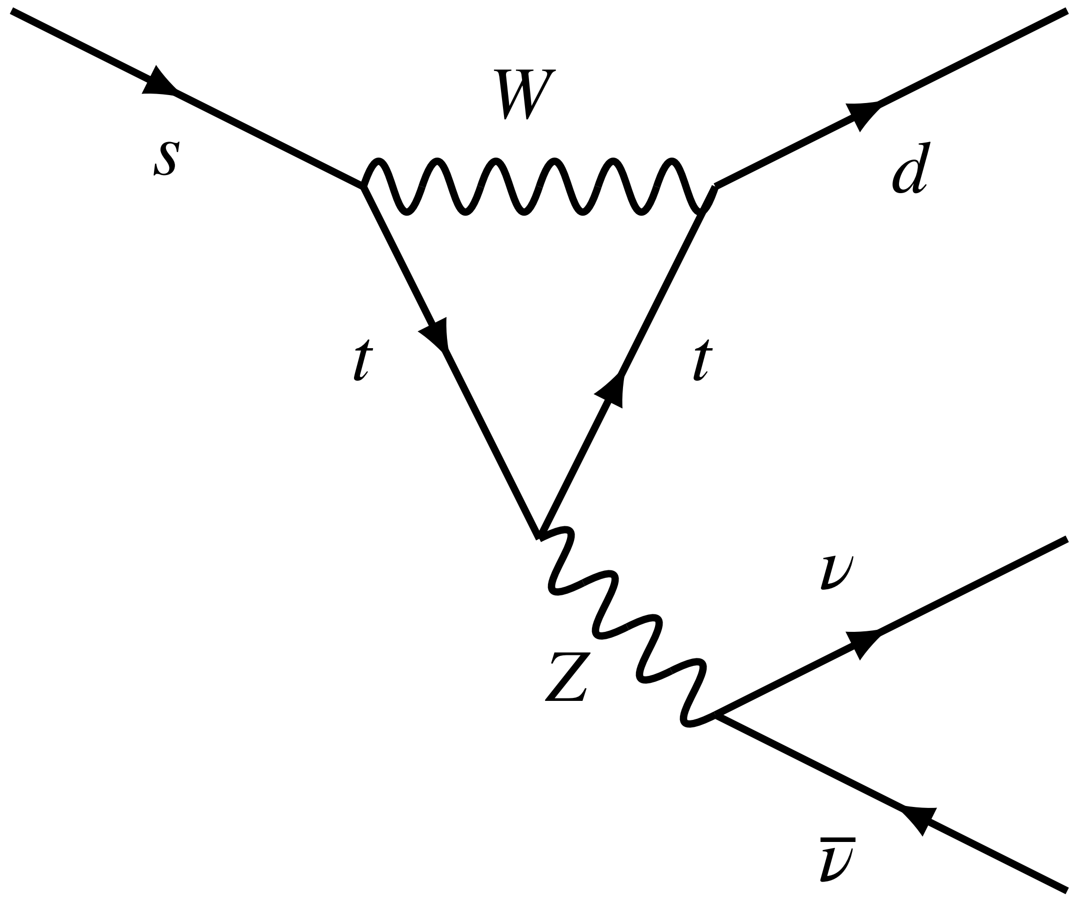
$K_L^0 \to \pi^0 \ell^+ \ell^-$ and $K_L^0 \to \mu\mu$ suffer from hadronic uncertainties.

$K \to \pi\nu\bar{\nu}$ is dominated by short-distance interactions.

$\Longrightarrow$ Precisely predicted by Standard Model.

Golden Mode $K \to \pi\nu\bar{\nu}$

Standard Model



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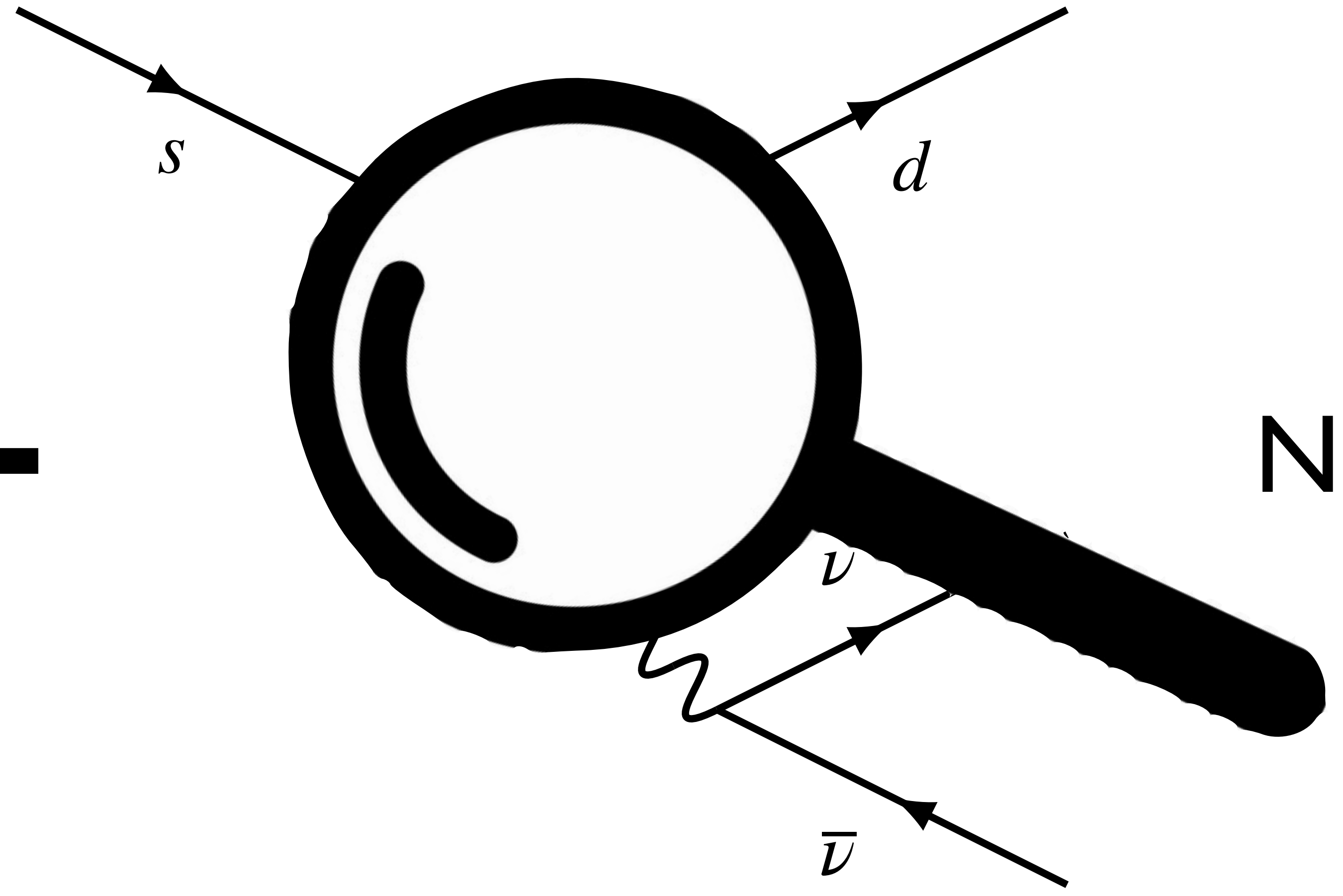


New Physics

	SM prediction	Experimental result	Experiments
$K_L^0 \to \pi^0\nu\bar{\nu}$	$(2.95 \pm 0.05) \times 10^{-11}$ arXiv:2205.01118	$< 3.0 \times 10^{-9}$ (90% C.L.) PRL 122, 021802 (2019)	KOTO
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$ arXiv:2205.01118	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$ (68% C.L.) JHEP 06 (2021) 093	NA62

New Physics Search via $K \to \pi\nu\bar{\nu}$

JHEP 1511 (2015) 033

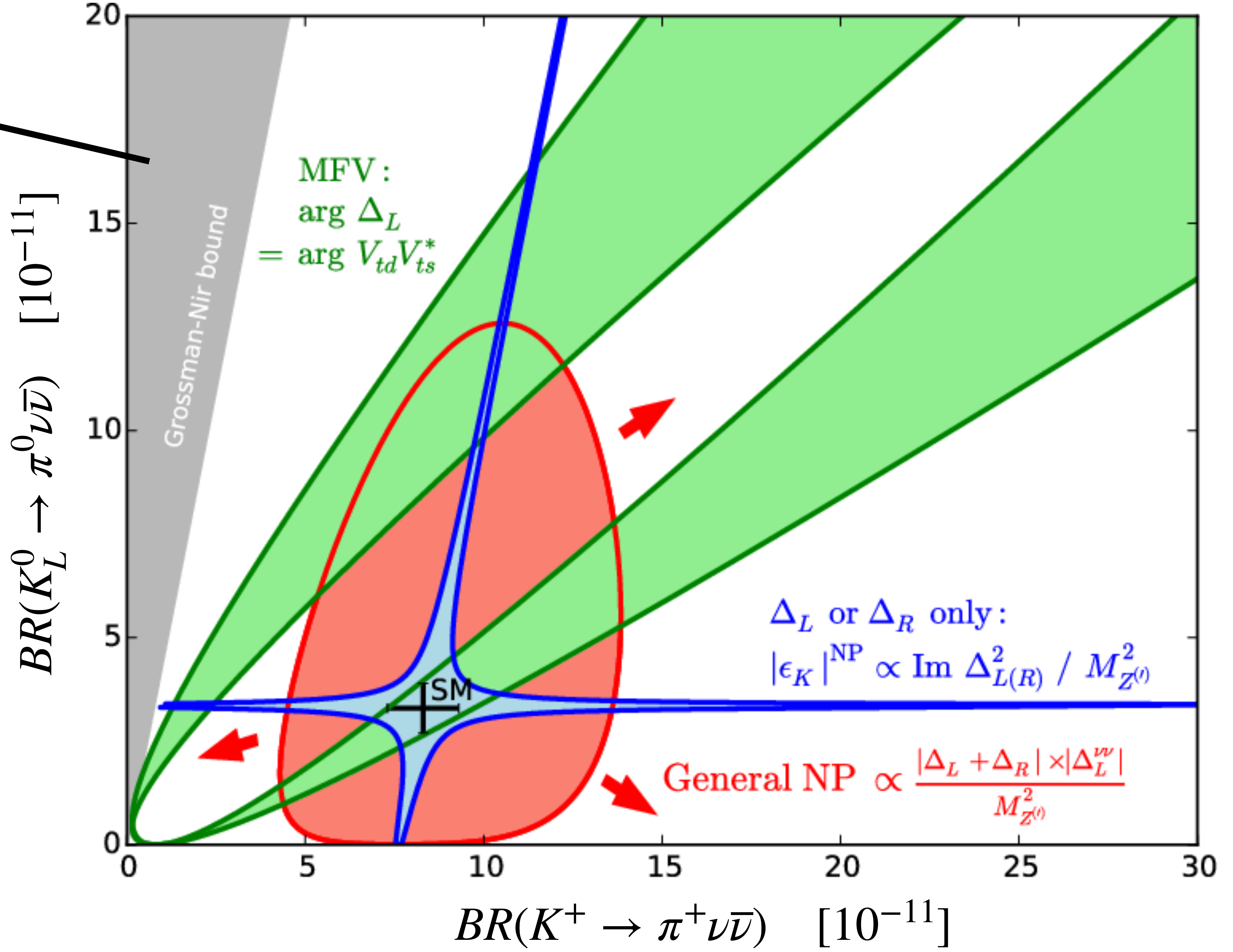
Model-independent constraint:

(Isospin symmetry in ΔI = 1/2 process)

$$B(K_L^0 \to \pi^0\nu\bar{\nu}) \leq 4.3 \times B(K^+ \to \pi^+\nu\bar{\nu})$$
$$\leq 6.3 \times 10^{-10} \quad \text{(68\% C.L.)}$$

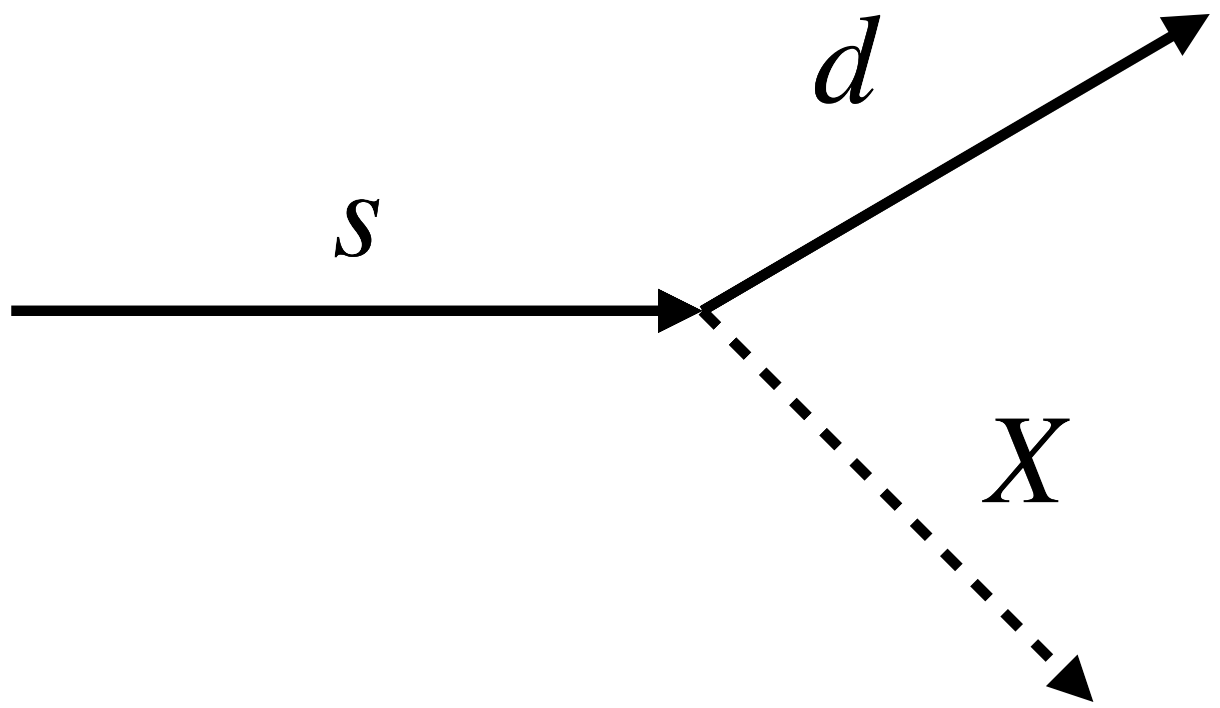
JHEP 06 (2021) 093

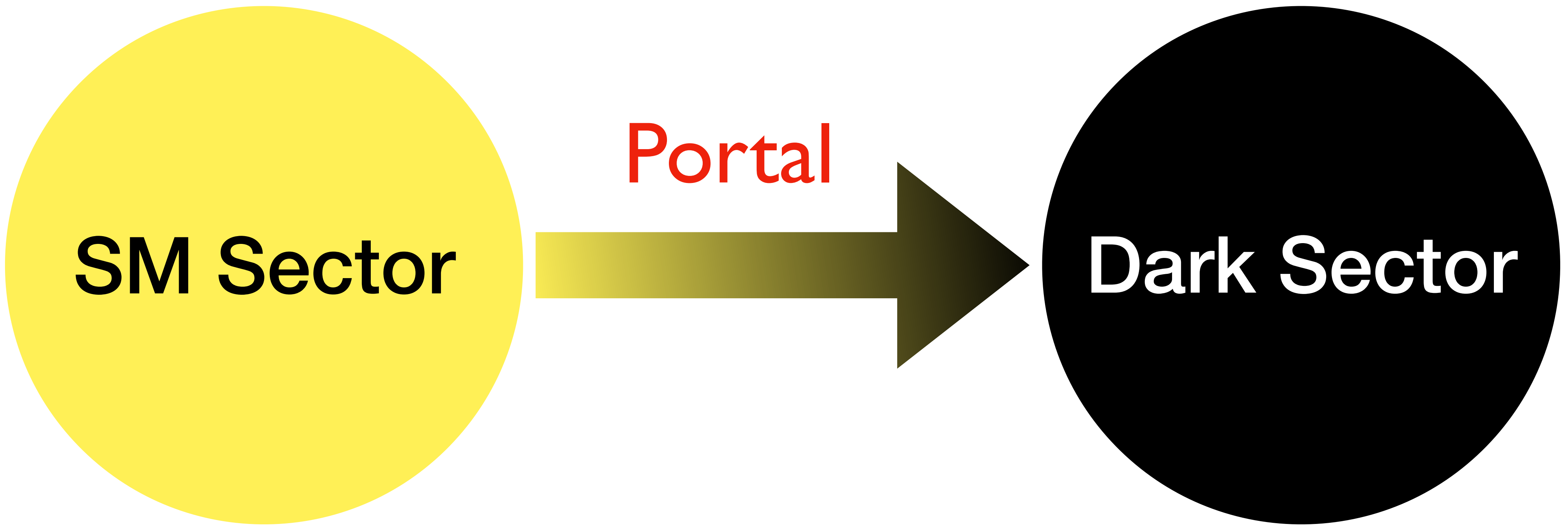
- CKM-like structure.
- LH or RH coupling dominate.
- General theories.



Probe to Dark Sector

Dark particles may feebly interact with SM particles.





$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \sum \mathcal{O}_{SM} \times \mathcal{O}_{DS}$$

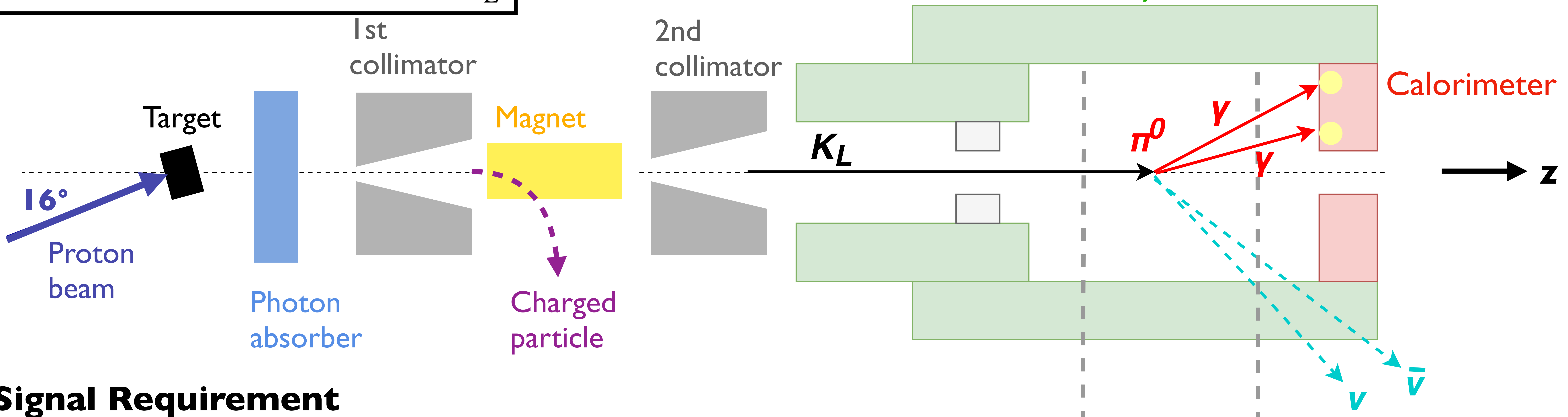
- Dark Higgs portal.
- Axion portal.
- …

J. Phys. G 47 (2020) 010501

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

KOTO at J-PARC: $K_L^0 \to \pi^0 \nu \bar{\nu}$

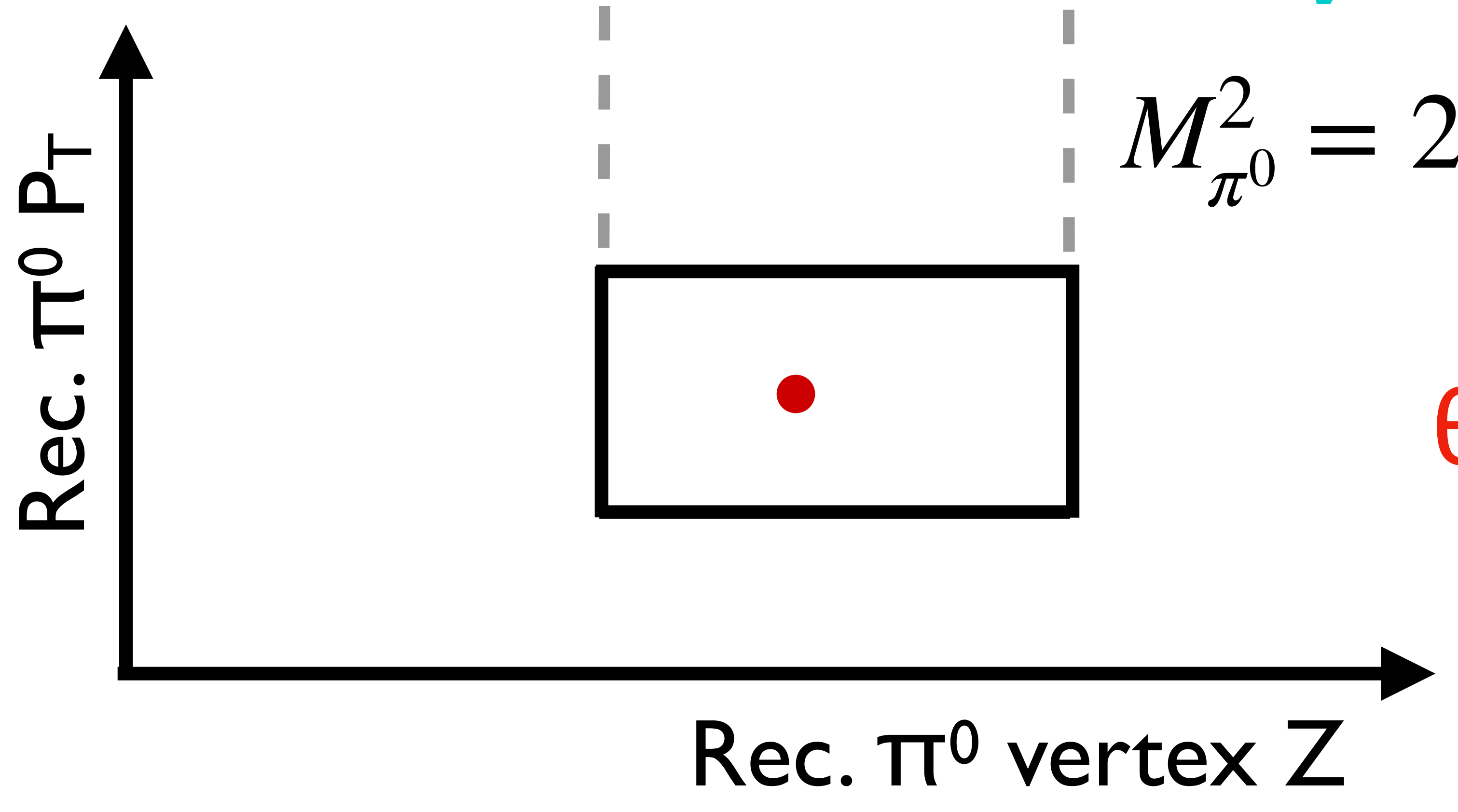
30 GeV/c proton ⟶ 1.4 GeV/c K_L



- **Signal Requirement**
  - 2γ from π^0 on calorimeter
  - Missing P_T due to neutrinos.
  - Nothing else detected
- **Blind Analysis**
  - The distribution in the signal box is inaccessible.

$$M_{\pi^0}^2 = 2E_1E_2(1 - \cos\theta_{12})$$

θ=θ(decay vertex)



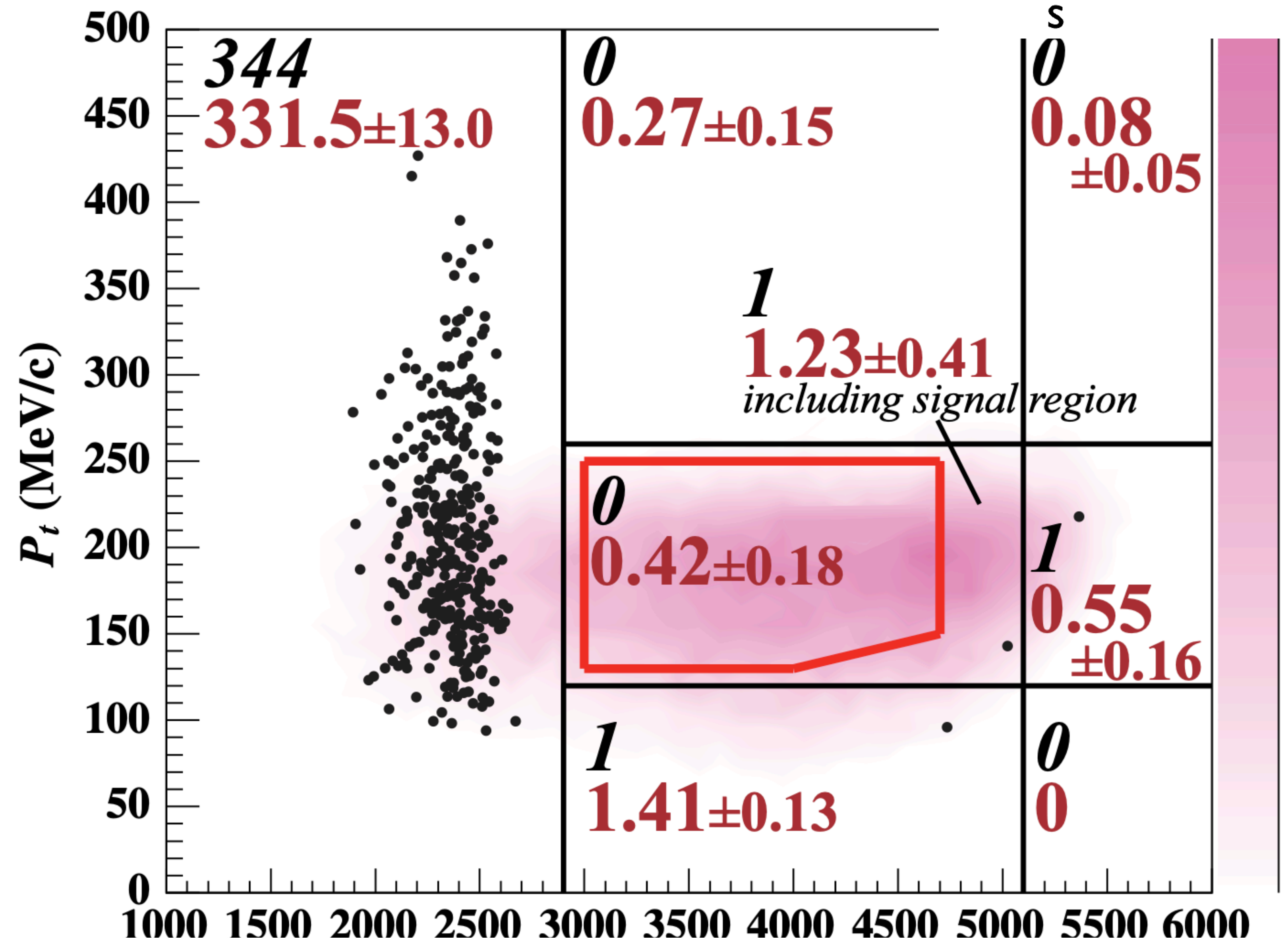
KOTO Results

Observed
Expected

2015 data result

- $S.E.S = 1.30 \times 10^{-9}$
- No event observed with 0.42 predicted BG events.
- $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ (90% C.L.)

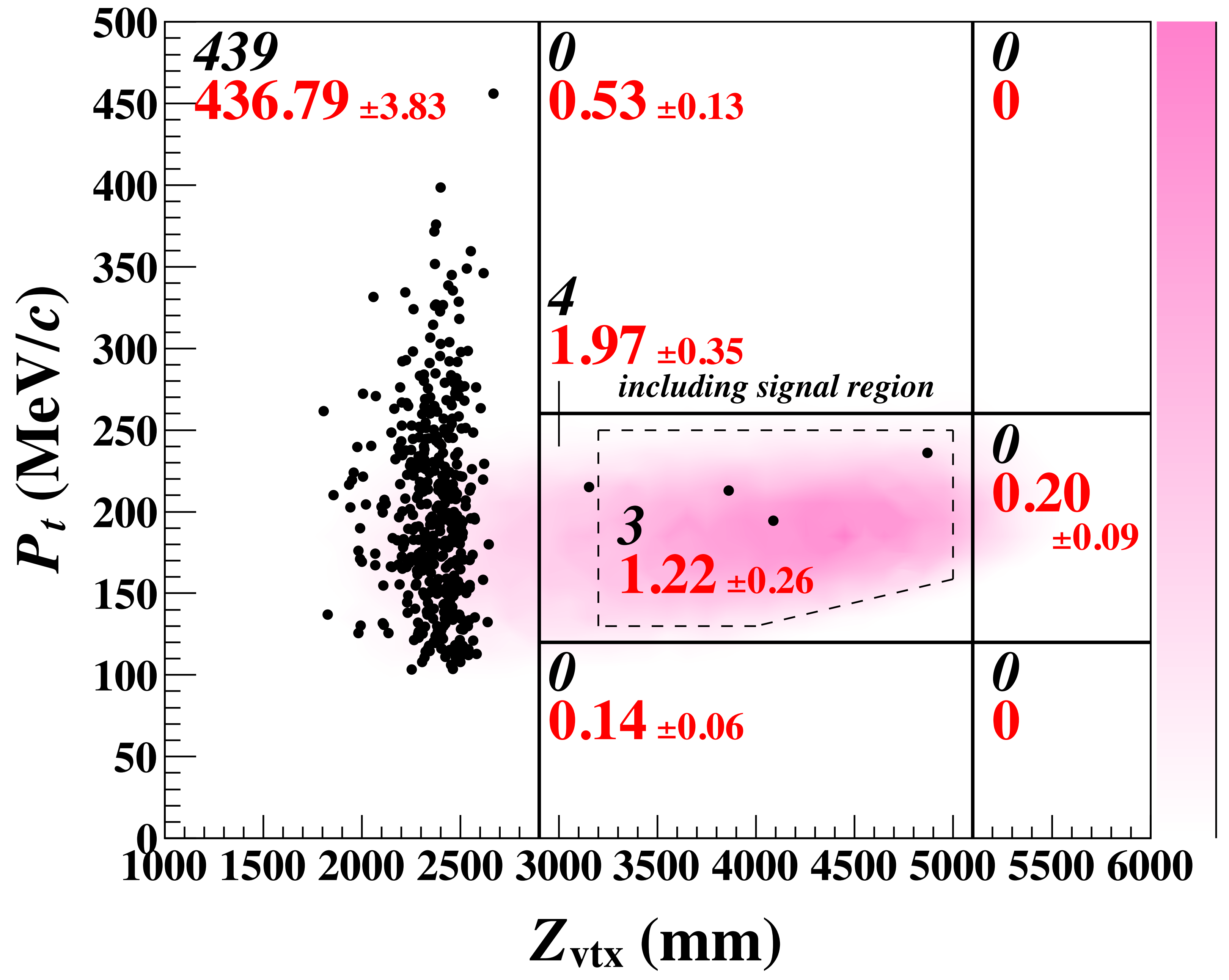
PRL 122, 021802 (2019)



2016 — 2018 data result

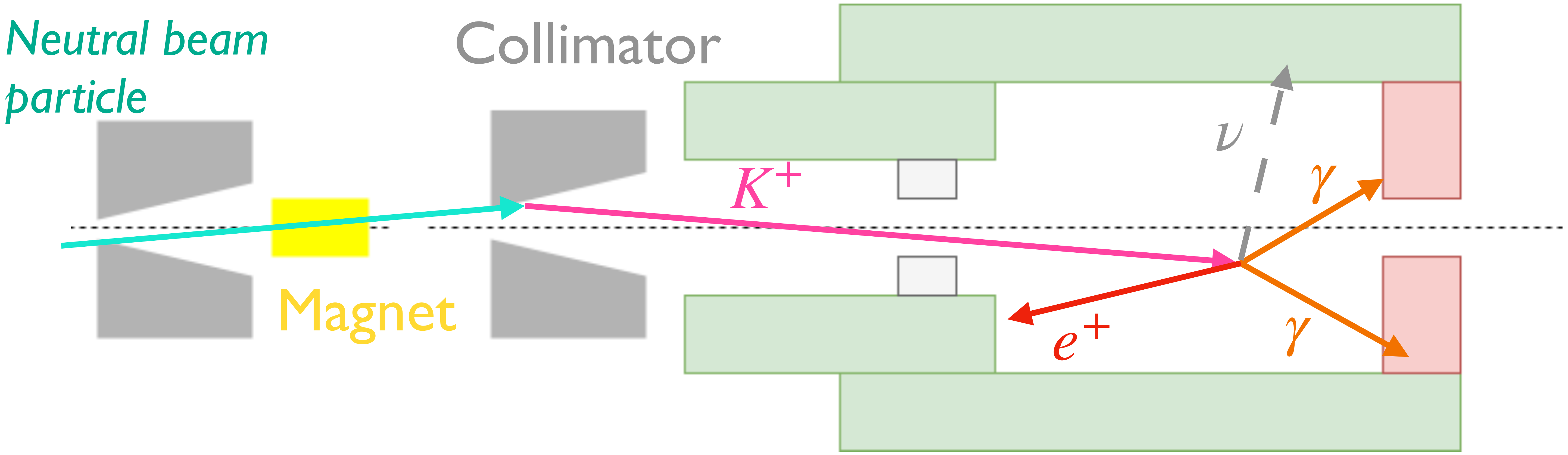
- $S.E.S = 7.20 \times 10^{-10}$
- 3 event observed with 1.22 predicted BG events.
- $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.)

PRL 126, 121801 (2021)

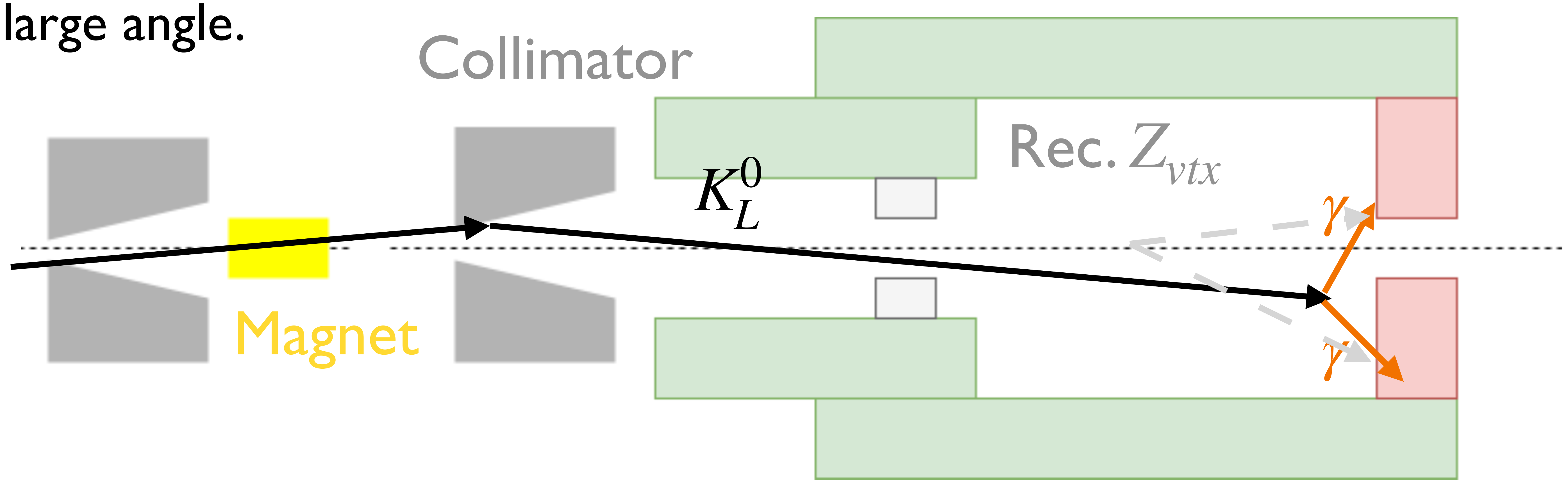


Major Background Source

- A K^+ particle is generated upstream and enters the decay region.



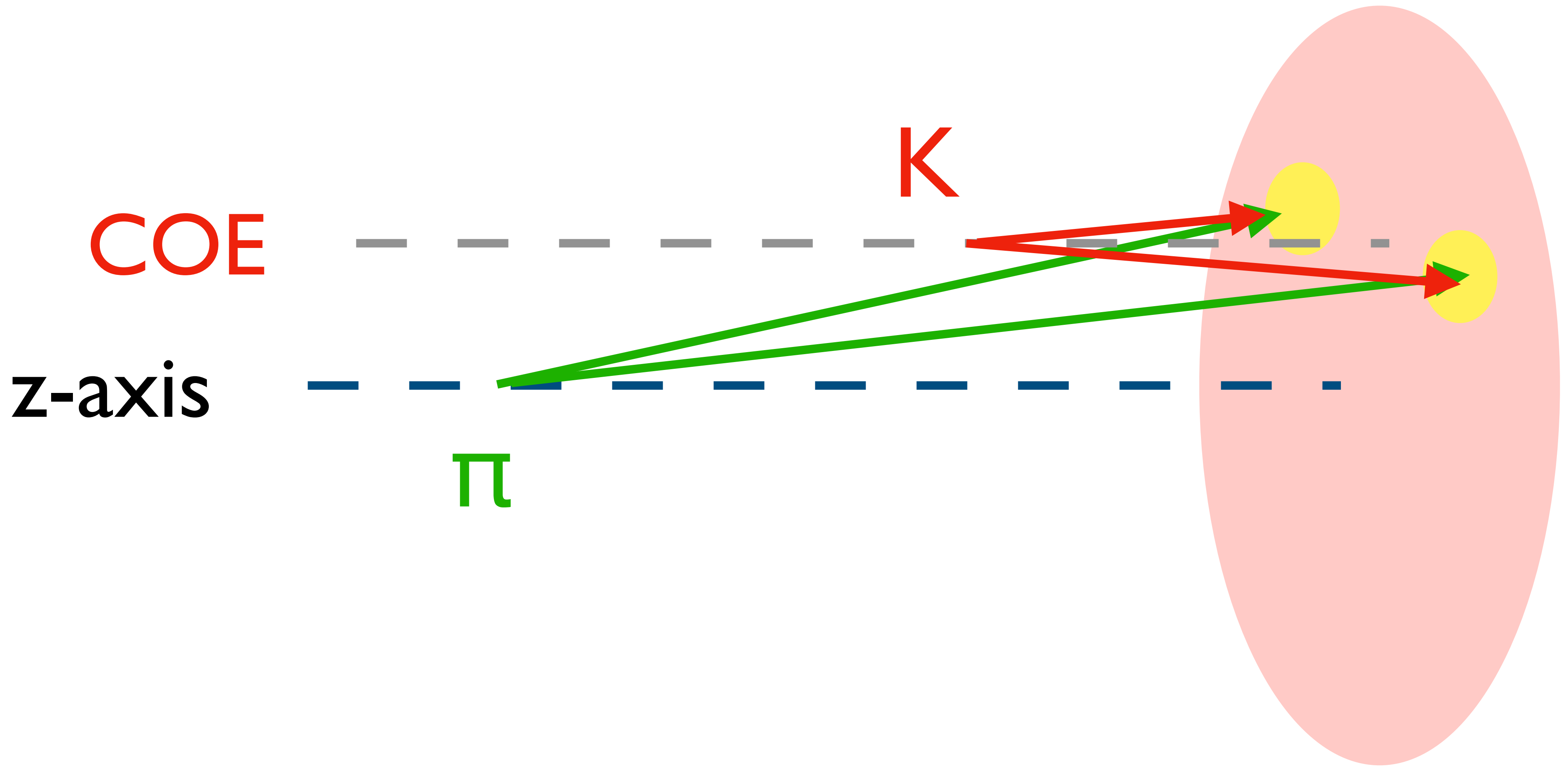
- A K_L^0 particle is scattered upstream and enters the detector at large angle.



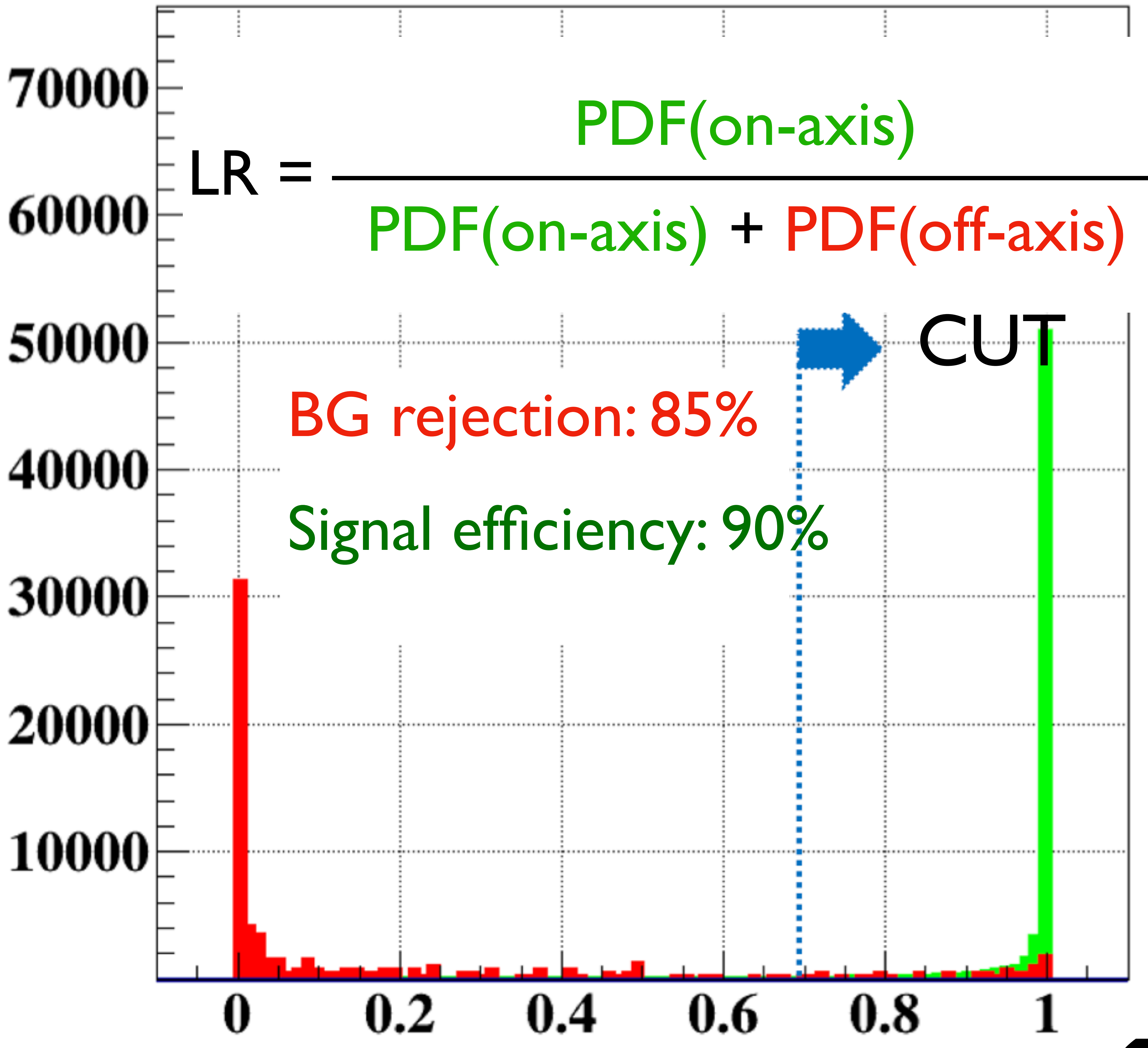
Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

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

Halo K_L Background Suppression



PDF(shower shape, incident angle)



$$LR = \frac{PDF(\text{on-axis})}{PDF(\text{on-axis}) + PDF(\text{off-axis})}$$

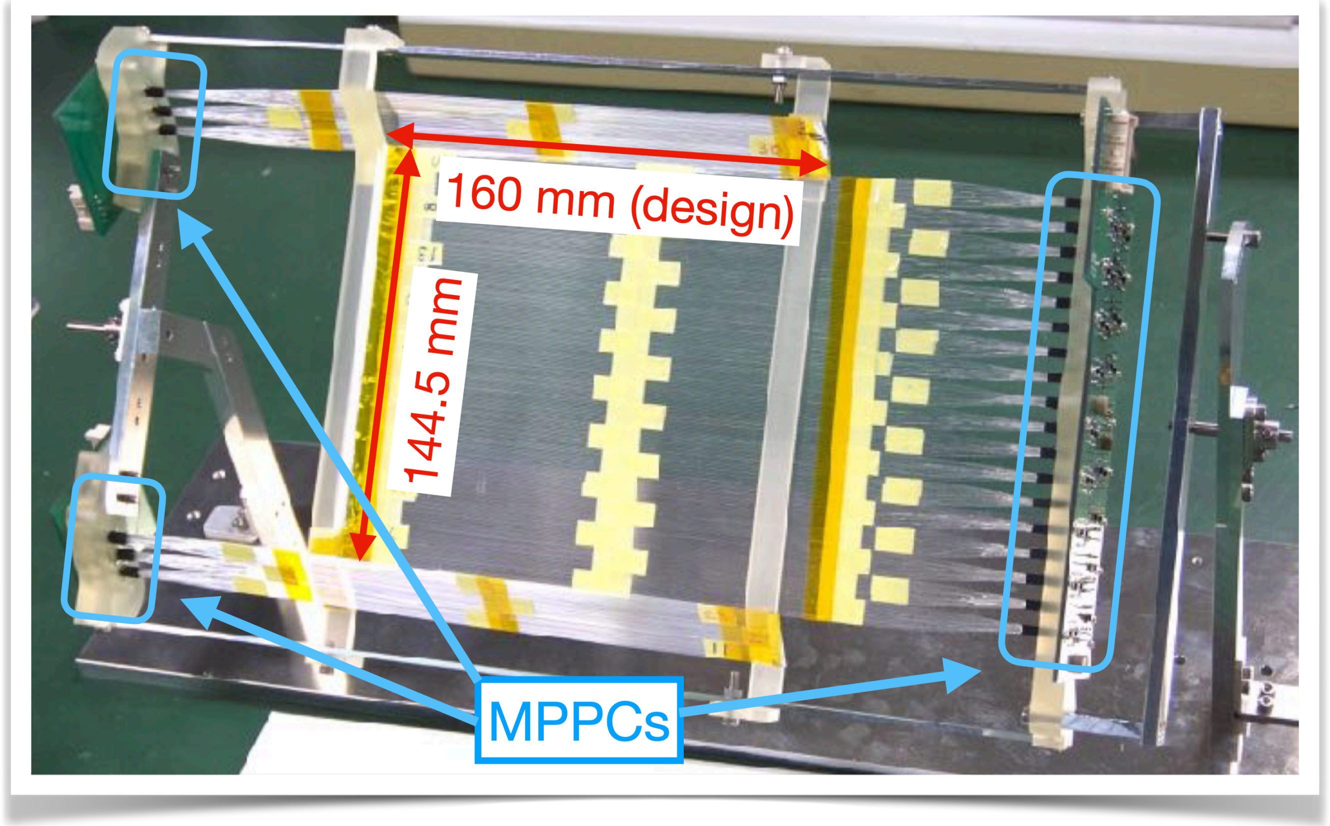
Likelihood Ratio

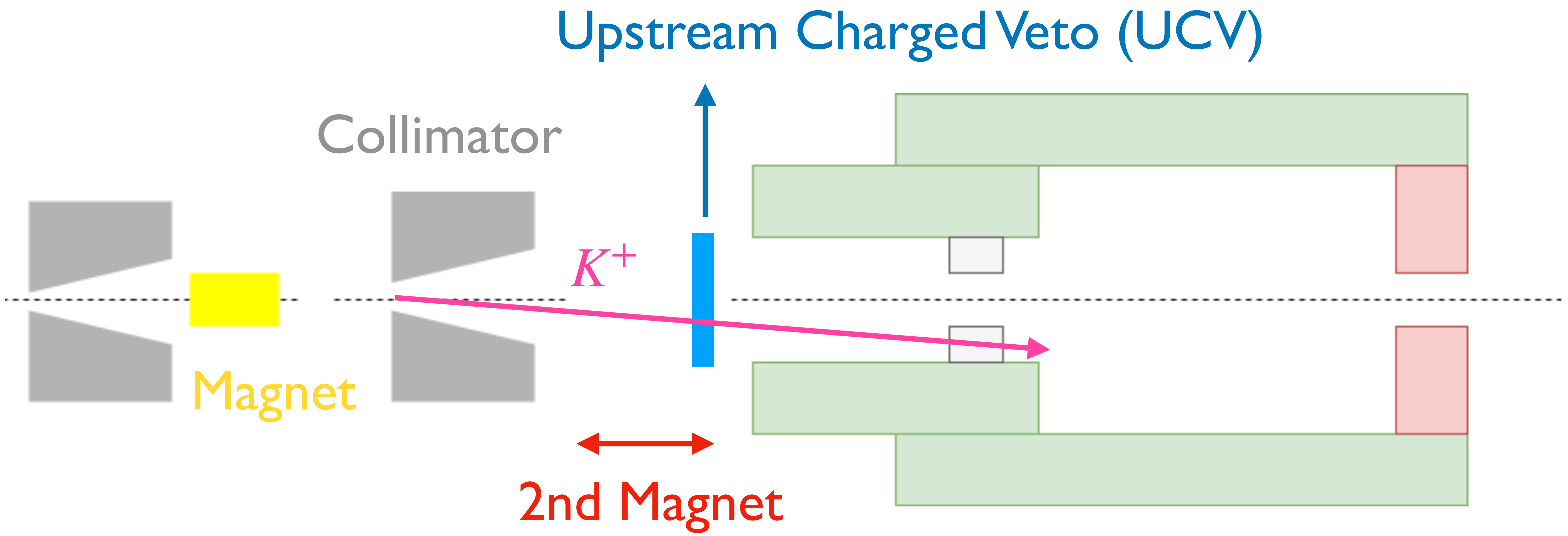
KOTO Future Upgrade

Goal: Achieve $K_L^0 \to \pi^0 \nu \bar{\nu}$ Standard Model sensitivity by the data collected till 2026.

- Beam intensity will be increased from 64kW to 100kW.
- K^+ background will be highly suppressed:
  - UCV was implemented in 2021.
  - An additional magnet will be installed in 2023.

UCV: plastic scintillator counter.

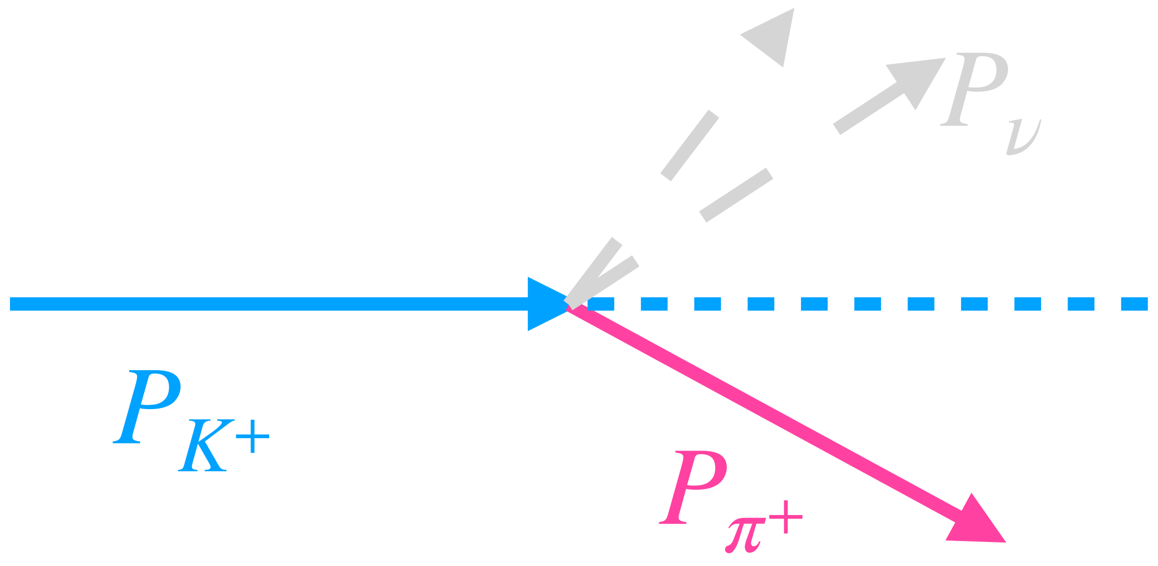




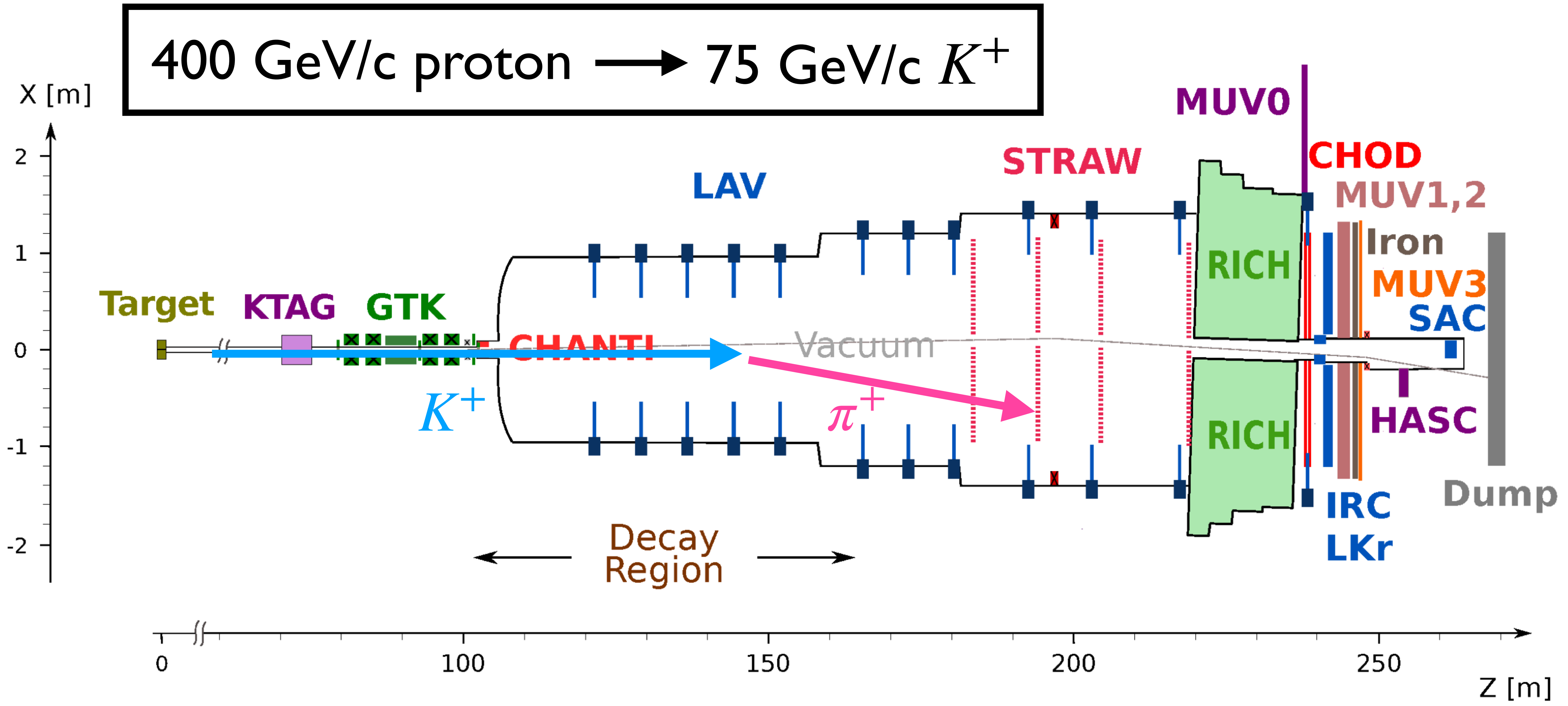
Measurement of $K^+ \to \pi^+ \nu \overline{\nu}$

NA62 at CERN: $K^+ \to \pi^+ \nu \bar{\nu}$

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



- Measure P_{K+} and P_{π^+} by tracking with magnetic field.
- Identification of K^+ and π^+.
- Nothing else detected.



JINST 12 (2017) P05025

Upstream detector (K^+).

- Differential Cherenkov for K^+ ID.
- Si pixel beam tracker.

Downstream detector (π^+).

- Momentum spectrometer.
- Photon veto.
- PID.

Analysis Strategy

Signal region is defined on

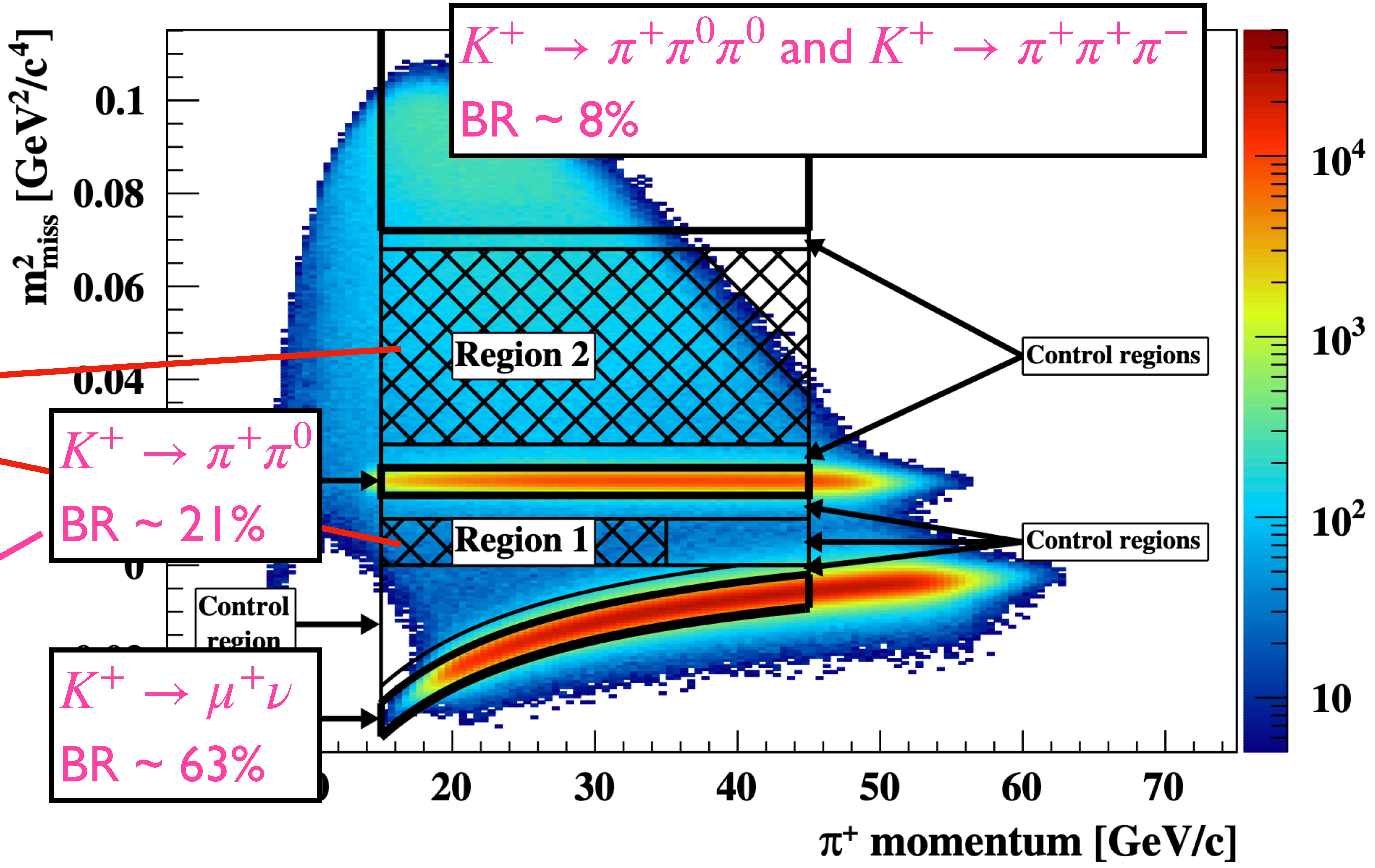
$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$ vs P_{π^+}.

$K^+ \rightarrow \pi^+ \nu \bar{\nu} \Rightarrow m_{miss} = m_{\nu\bar{\nu}}$

Blind analysis is performed.

$K^+ \rightarrow \pi^+ \pi^0 \Rightarrow m_{miss} = m_{\pi^0}$

Excluded from the signal region.

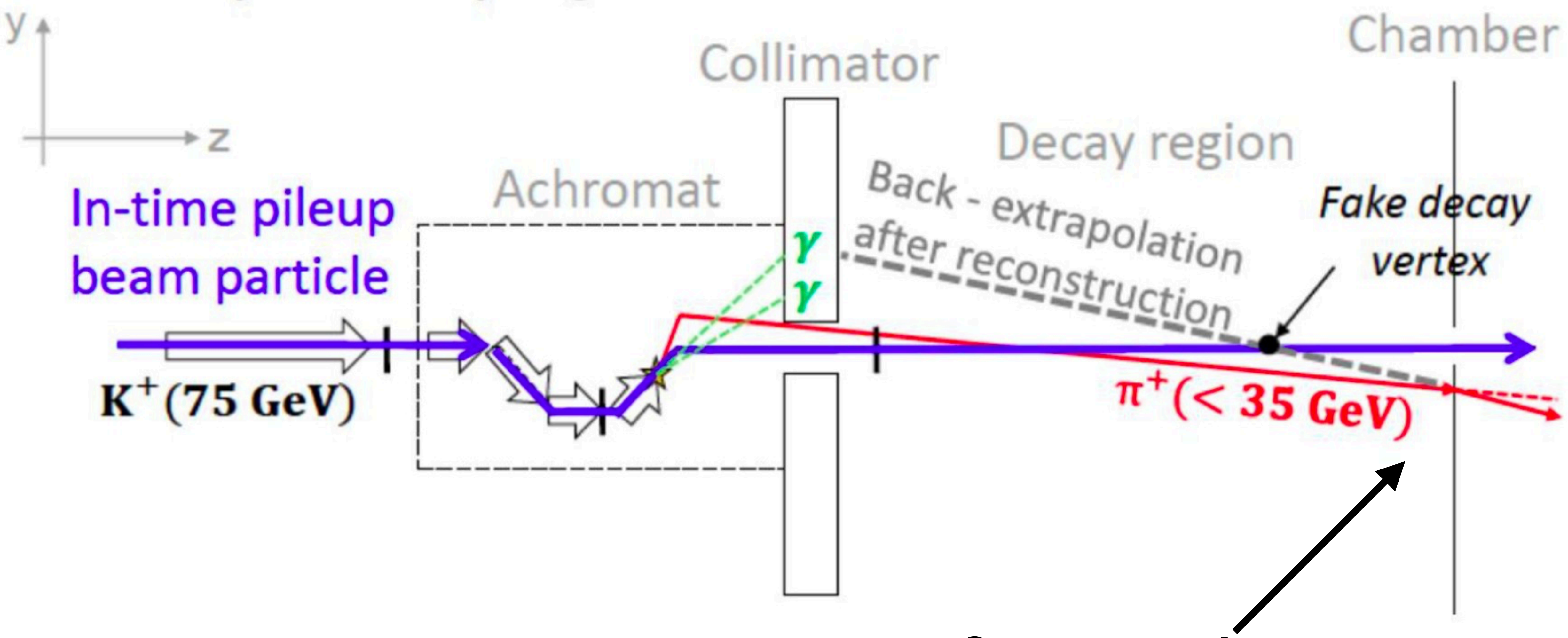


Major Background Sources

- A π^+particle generated upstream enters the decay region.
- In-time beam particle coincides with that π^+.

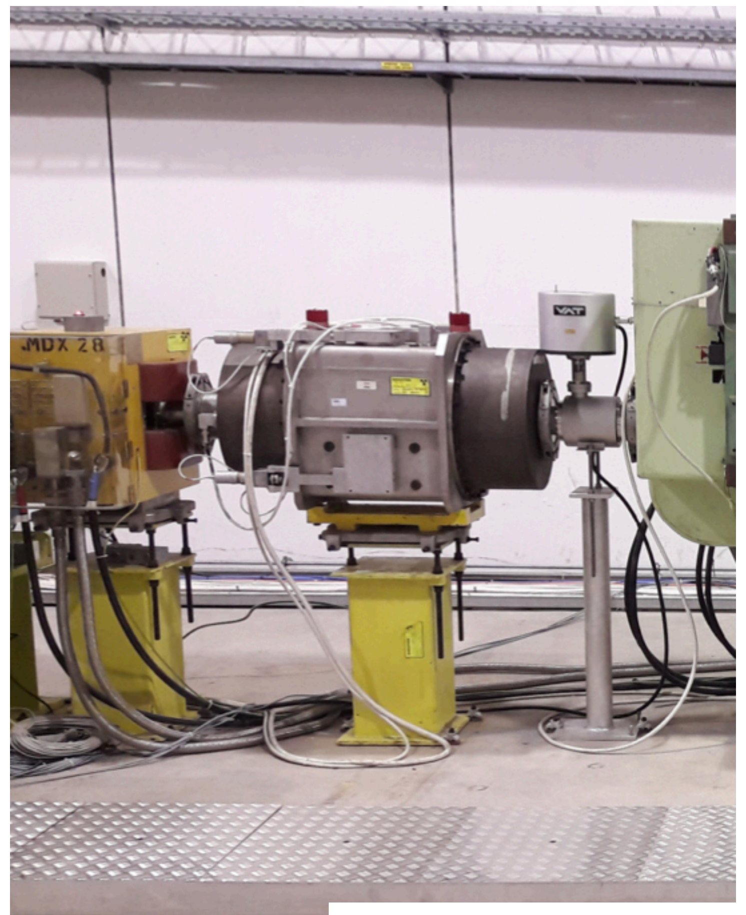
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Dominated

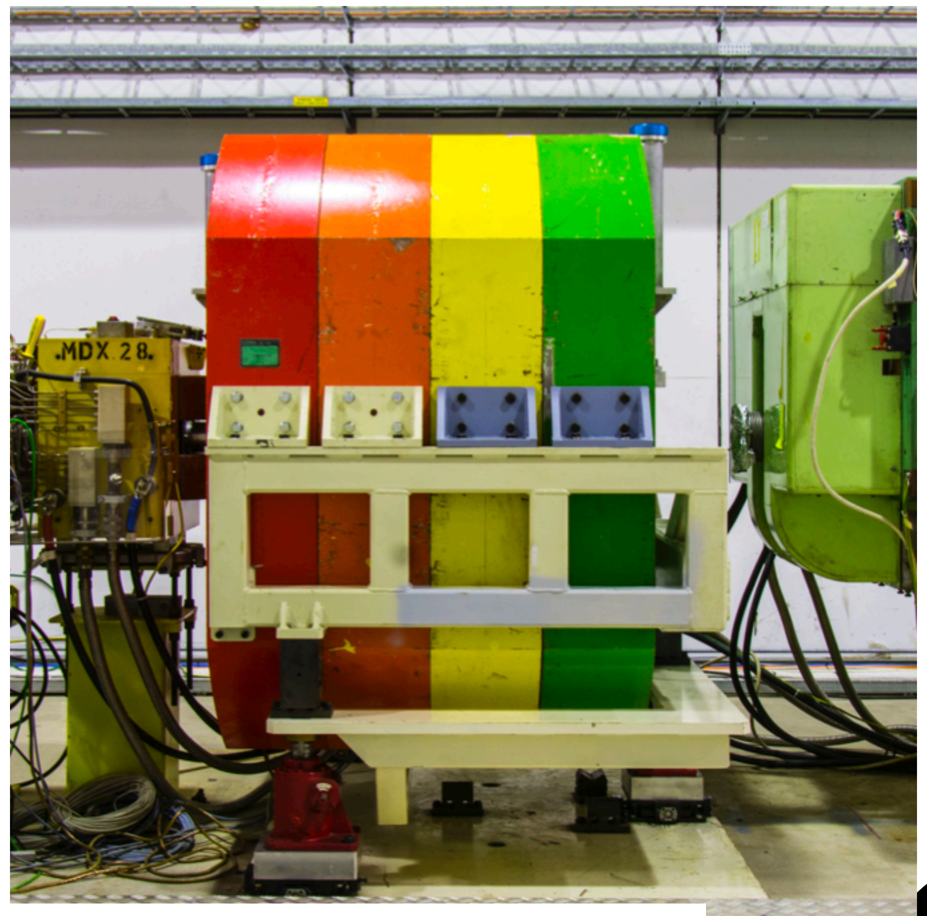


Scattered

Before 2018



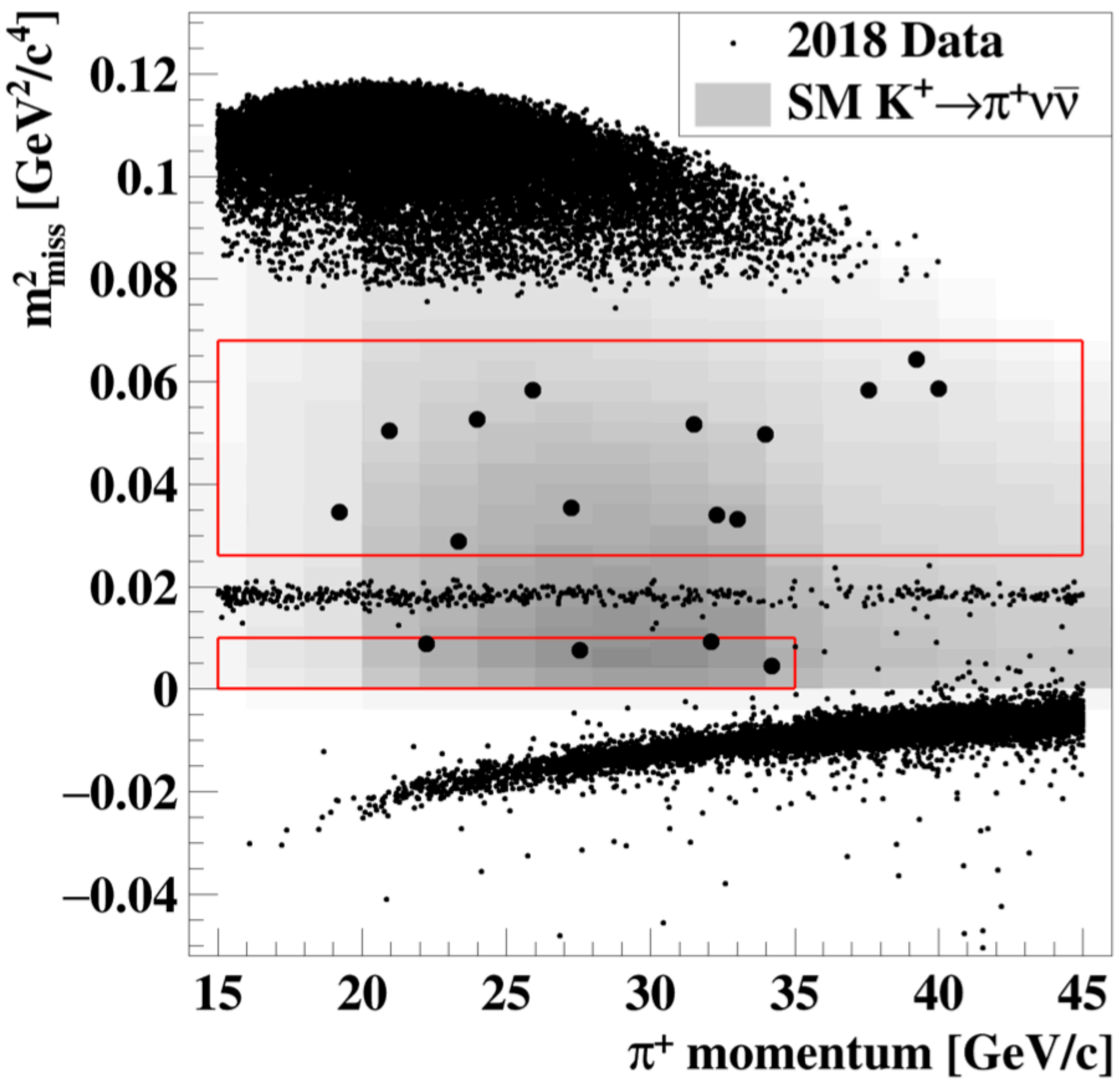
After 2018



The collimator was upgraded.

Results of NA62

2018 run result



Run	#observed	Paper
2016	1	PLB 791 (2019) 156-166
2017	2	JHEP 11 (2020) 042
2018	17	
Total	20	JHEP 06 (2021) 093

Number of predicted background = 7.0

$SES = (0.839 \pm 0.054) \times 10^{-11}$ ~ 10.0 SM events

$B(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-11}$

(68% C.L.)

Significance = 3.4 σ

NA62 Future Upgrade

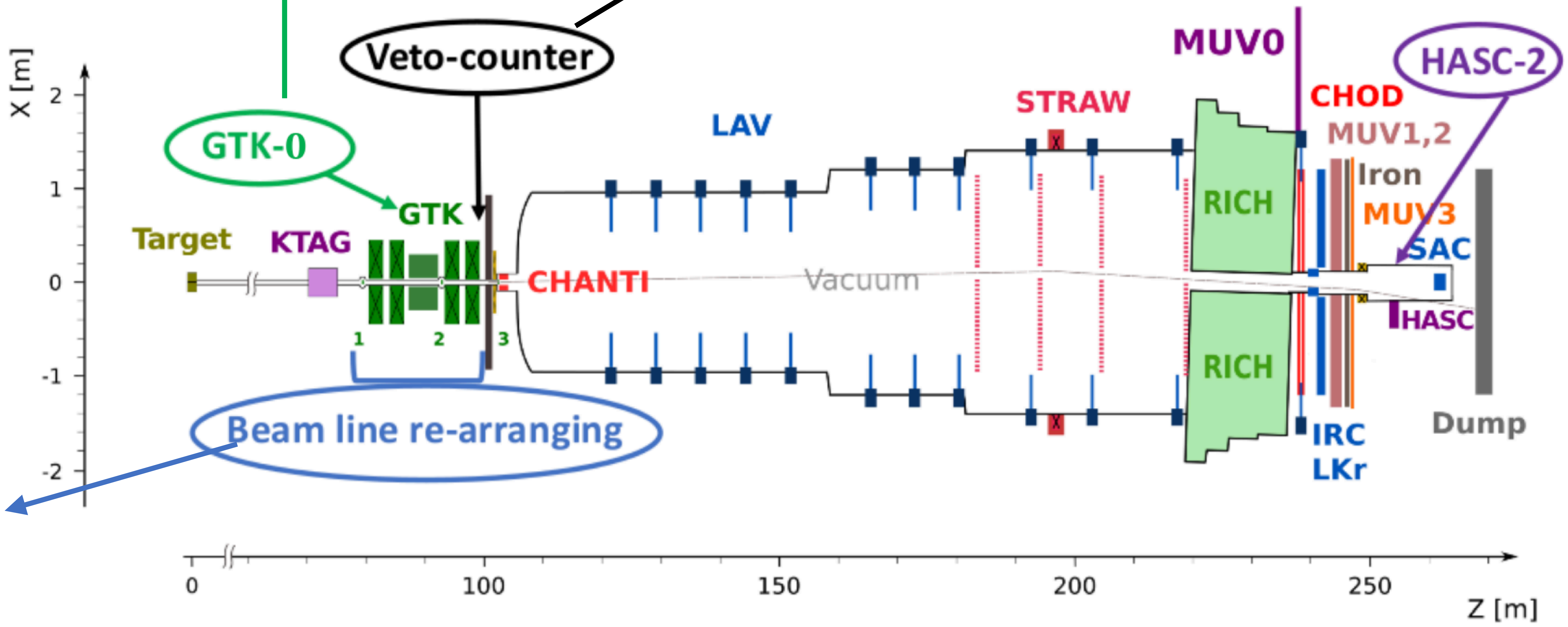
Goal: $B(K^+ \to \pi^+ \nu \bar{\nu})$ measurement with $\mathcal{O}(10\%)$ statistical precision by the 2021-2024 run.

- Expect a higher intensity beam in the future.

Add fourth GTK

Veto upstream decay products

Off-axis calorimeter to suppress $K^+ \to \pi^0 \pi^+$

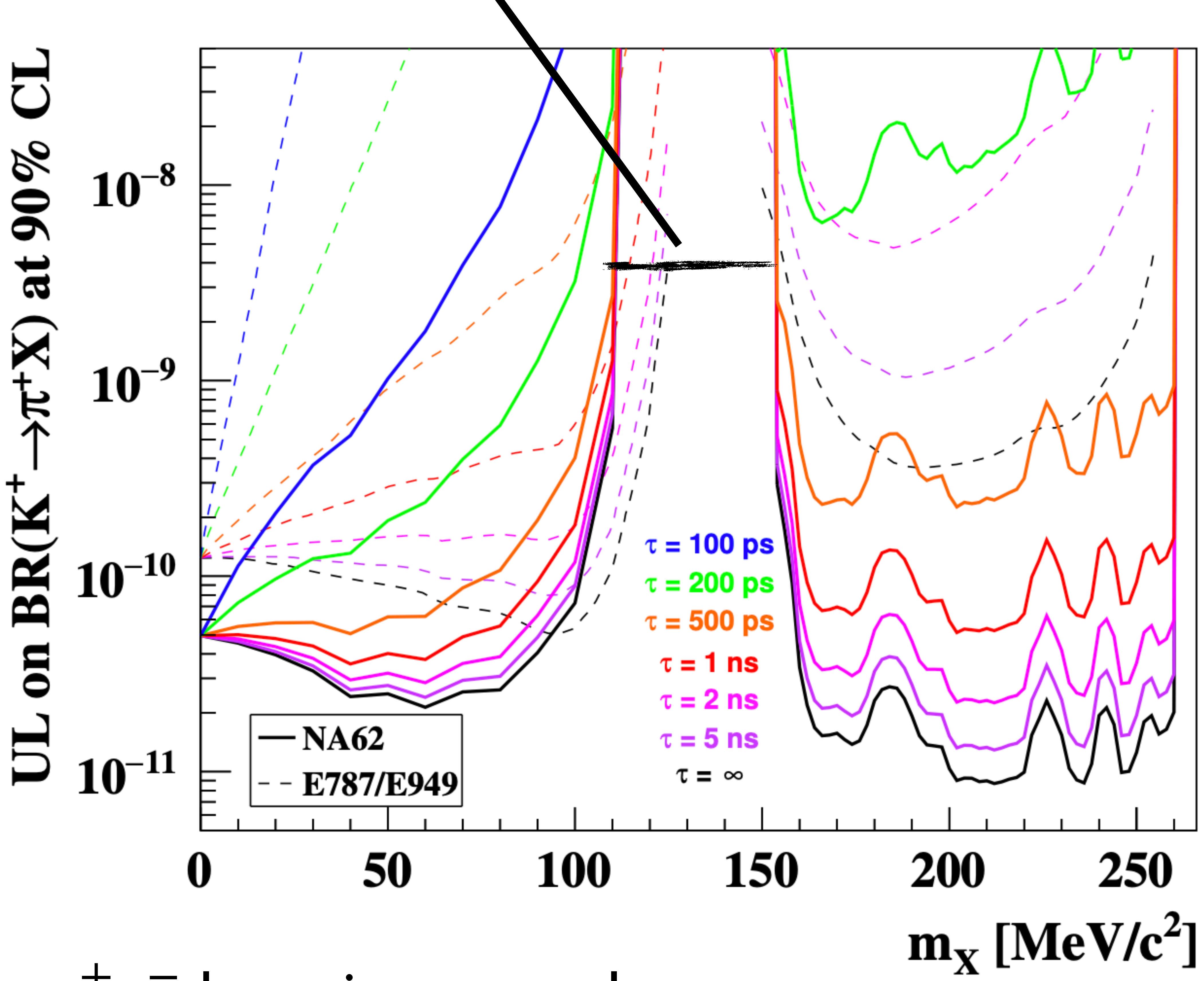


Swipe away upstream π^+

Search for Hidden Sector with $K \to \pi X$

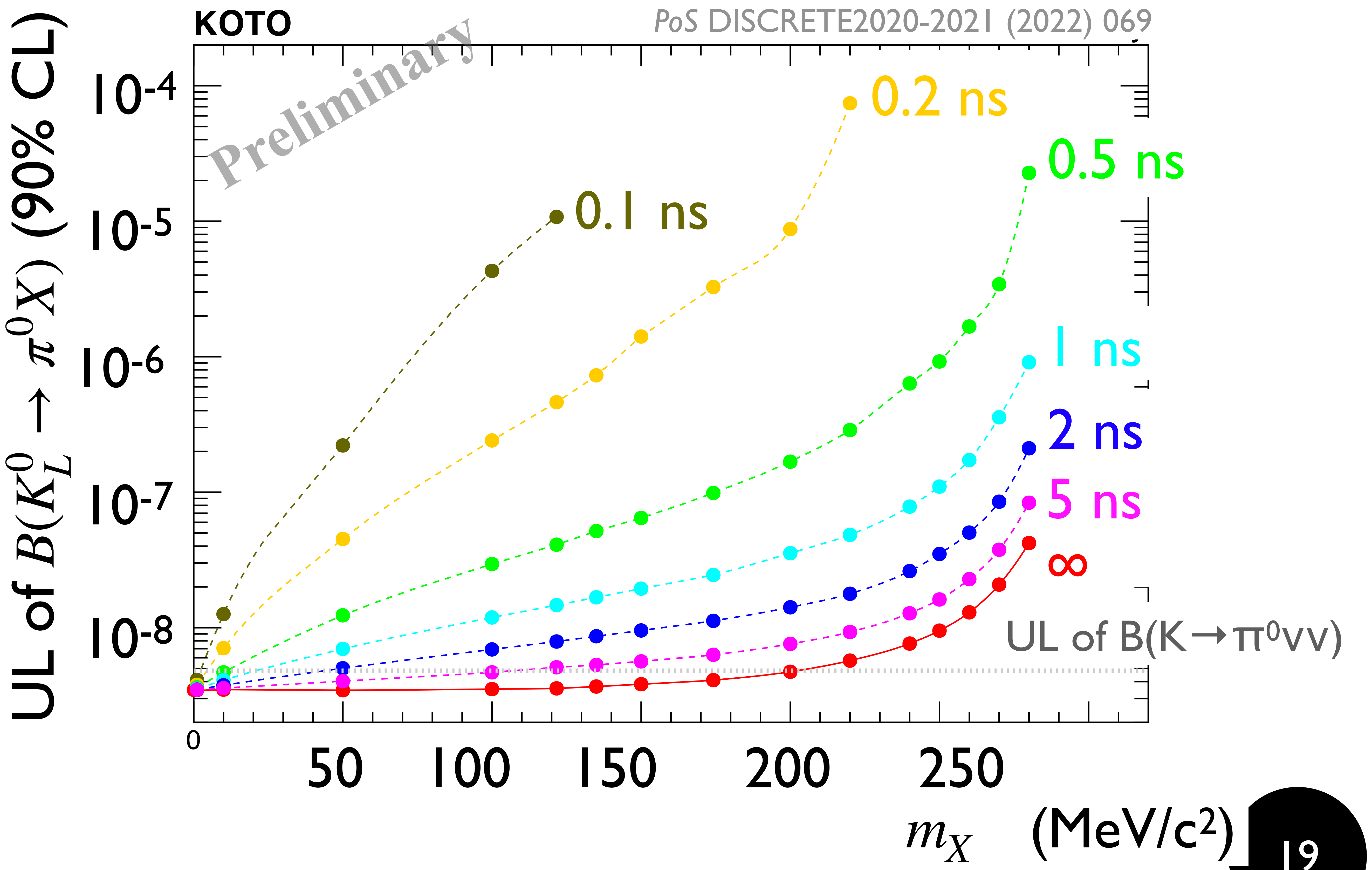
$B(K^+ \to \pi^+\pi^0, \pi^0 \to \text{invisible})$

$< 4.4 \times 10^{-9}$ (90% C.L.) *JHEP* 02 (2021) 201



$B(K_L^0 \to \pi^0 X, M_X = M_{\pi^0})$

$< 3.7 \times 10^{-9}$ (90% C.L.) (preliminary)



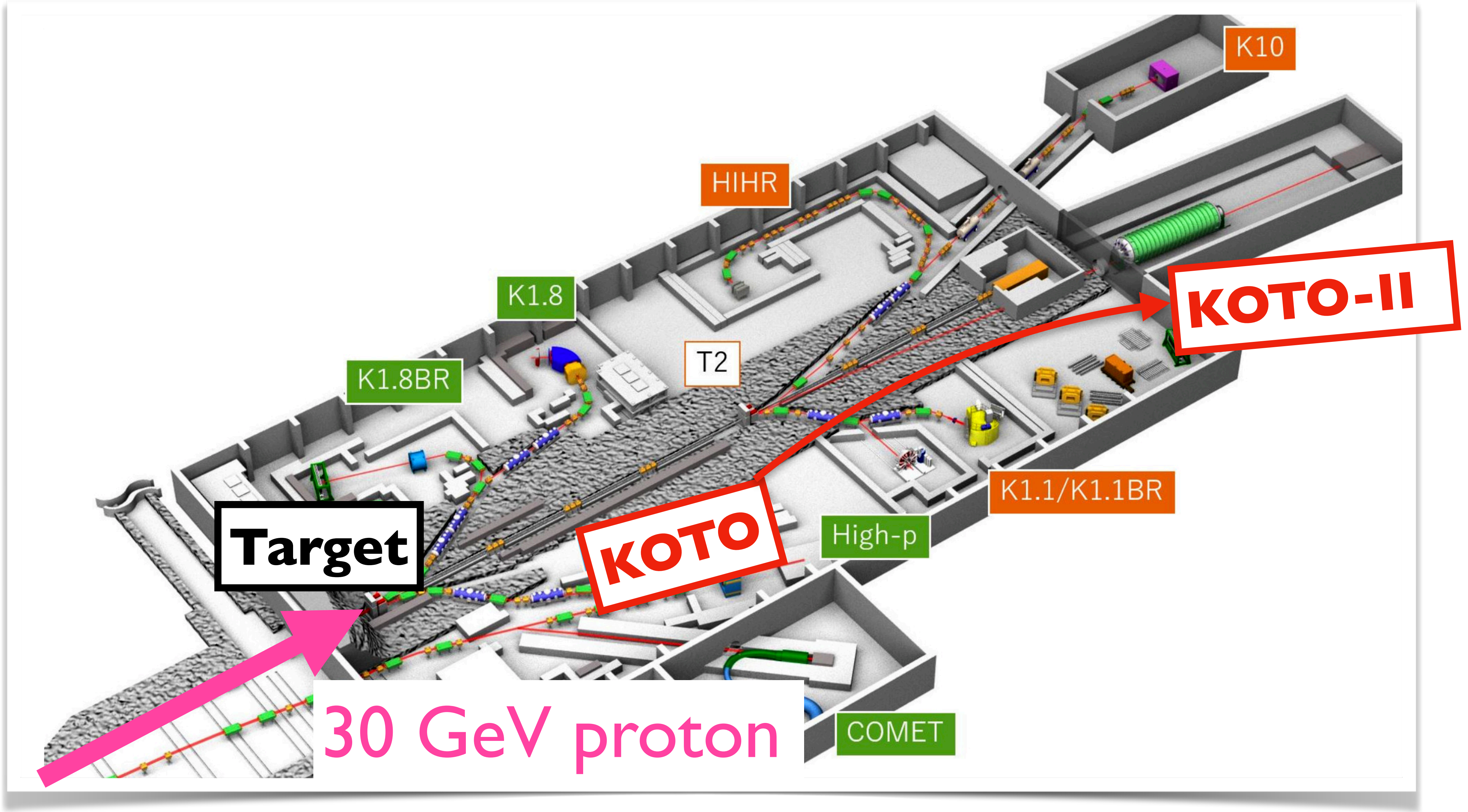
* $X \to e^+e^-$ decay is assumed.

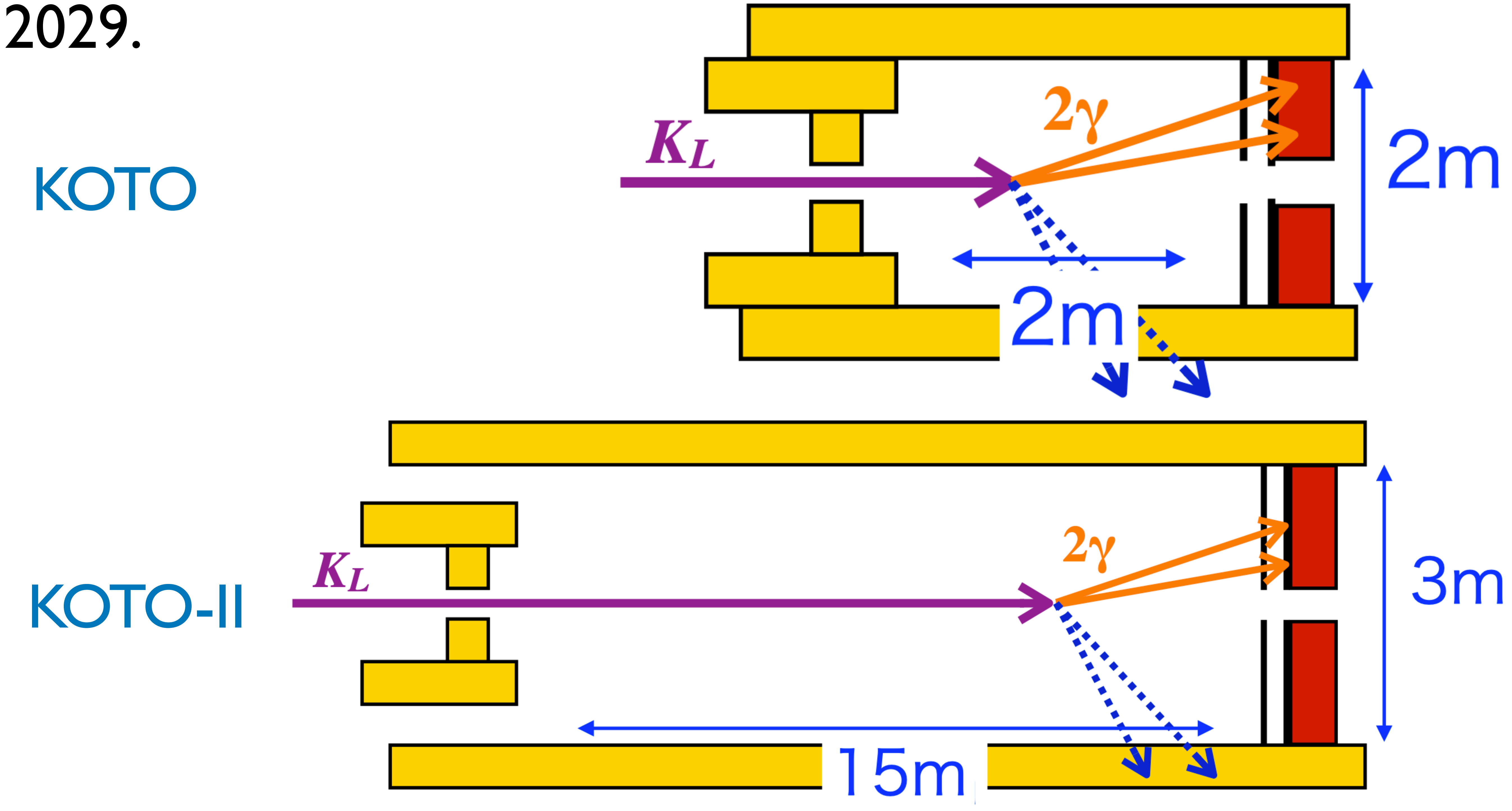
Future Kaon Experiments

KOTO Step-II

Goal: Achieve $K_L^0 \to \pi^0 \nu \bar{\nu}$ SES of $\mathcal{O}(10^{-13})$.

- Compared with KOTO: higher K_L^0 flux (KOTO x 2.4) and higher K_L^0 momentum (3 GeV/c). arXiv:2110.04462v1
- Expect 35 SM signals with 56 BG events $\longrightarrow$ $\Delta B/B \approx 27\,\%$.
- In the earliest scenario, KOTO-II starts from 2029.





KLEVER Experiment at CERN

KLEVER

arXiv:1901.03099

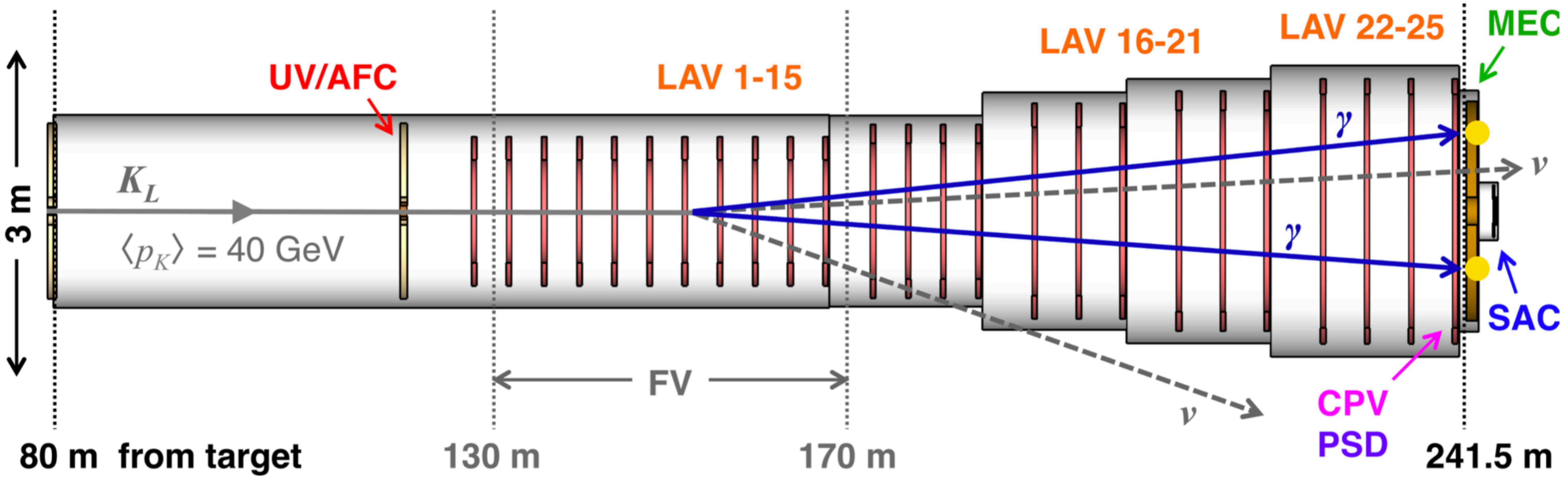
Goal: Achieve $K_L^0 \to \pi^0 \nu \bar{\nu}$ SES of $\mathcal{O}(10^{-13})$.

- Expect to collect 60 SM signals with S/B ~ 1.
- Expect 35 SM signals with 56 BG events $\longrightarrow$ $\Delta B/B \approx 20\,\%$
- The experiment is planned to start after long shutdown (2027).

400 GeV/c proton

↓

40 GeV/c K_L^0



Summary

- Rare kaon decays $K \to \pi\nu\bar{\nu}$ are the golden modes for the New Physics search.
- $K_L^0 \to \pi^0\nu\bar{\nu}$ search is performed by the KOTO experiment at J-PARC.
    - $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9}$ (90% CL) was set.
    - KOTO is scheduled to reach to the SES of $\mathcal{O}(10^{-11})$ in the future.
- $K^+ \to \pi^+\nu\bar{\nu}$ search is performed by the NA62 experiment at CERN.
    - $B(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$ (68% CL) was set.
    - NA62 is scheduled to reach the $\mathcal{O}(10\%)$ precision measurement in the future.
- The KLEVER and KOTO-2 experiments are proposed to observe 30 - 60 SM events.