New physics implications of recent data on $K \to \pi\nu\bar{\nu}$ searches

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KMI Topics
May 20, 2020, online talk

Based on
PRL124, 071801 (2020) [arXiv: 1909.11111]
with T.Okui, G.Perez, Y.Soreq, K.Tobioka

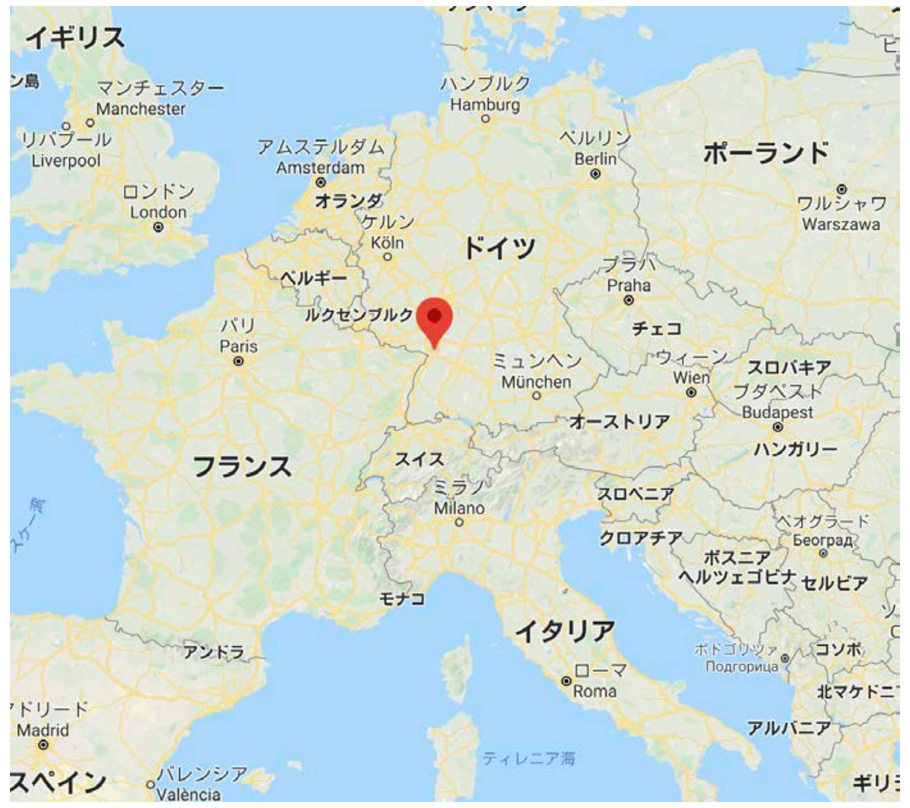
Myself

- Teppei Kitahara / 北原 鉄平
- KMI, Division of theoretical studies (基礎理論研究部門), YLC Designated Assistant Professor,

  term: 2018 October —2021 March (+2 years if pass examination)
- 2018 October—2020 March, Long term visitor at Technion pheno group in Israel
- Nagoya (E-lab) → Tokyo (Ph.D) → Karlsruhe in Germany → Technion in Israel → Nagoya (KMI)

  ↑ (KEK)
- Flavor physics, CP violation,

  Lepton physics, Dark matter



V_{us} vs unitarity

ε_K and ε'

RBC-UKQCD

$K_L \to \pi\pi$

B physics

CORRELATION

FCNC and/or CPV

$K^0 \to \mu^+\mu^-$

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

Understanding of ChPT

$K_S \to \pi^0\mu^+\mu^-$

$K_S \to \mu^+\mu^-\gamma$

$K_S \to 4\ell$

$K_S \to \pi^+\pi^-e^+e^-$

Reduce th error

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

$K \to \pi X$

V_{us} vs unitarity

ε_K and ε'

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$K_L \to \pi\pi$

Belle II

LHCb

BaBar

B physics

CORRELATION

FCNC and/or CPV

$K^0 \to \mu^+\mu^-$

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$K_S \to \pi^0\mu^+\mu^-$

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Reduce th error

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

NA62

KOTO

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

$K \to \pi X$

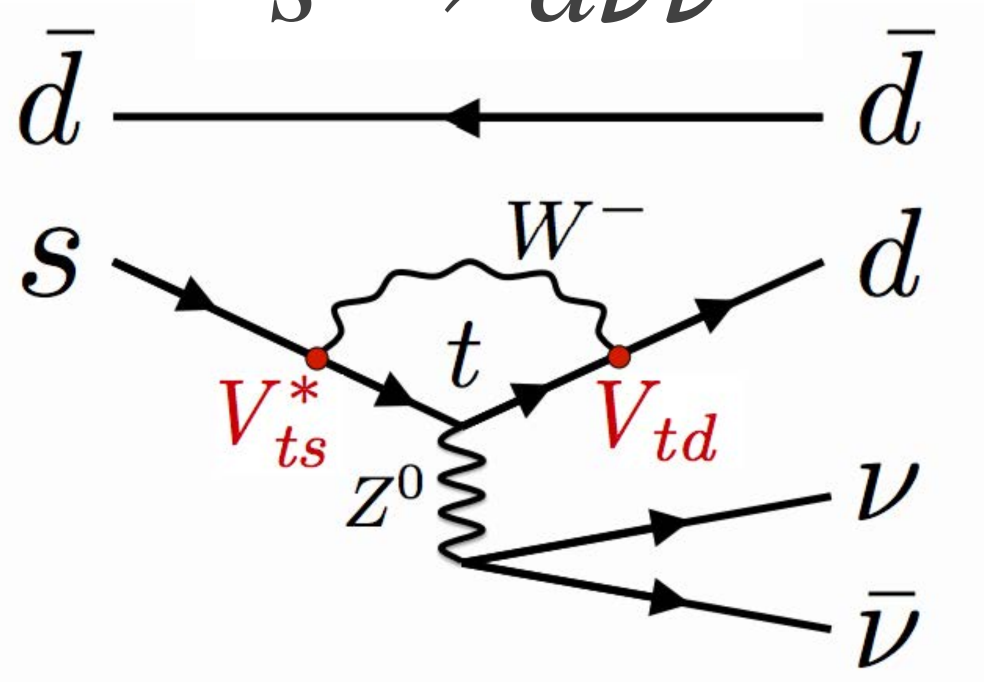
$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- Both channels are theoretical clean and significantly sensitive to short-distance contributions, **especially $K_L \to \pi^0 \nu\bar{\nu}$ is purely *CPV* decay**

  (almost) CP-odd — CP-even in SM, see Buchalla, Isidori 9806501

  - **Sensitive to CPV in NP sector**

$s \to d\nu\bar{\nu}$



loop, GIM, and small CKM

- **SM predictions:** [Buras, Buttazzo,Girrbach-Noe, Knegjens '15]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11},$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM} = (3.4 \pm 0.6) \times 10^{-11}.$$

c.f.

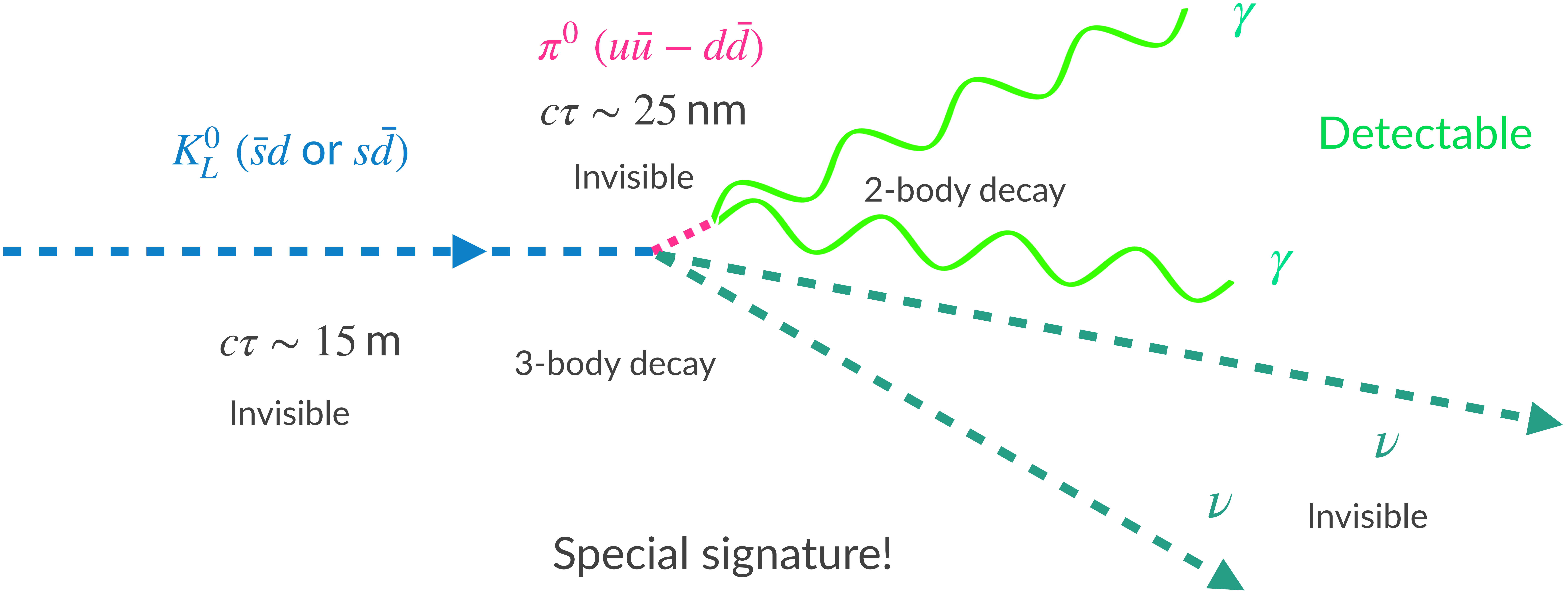
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$$

- On-going experiments:

KOTO: K_L @J-PARC — SM event is expected in ~2024

NA62: K^+ @CERN — 20 SM events are expected in 2016-18 runs

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

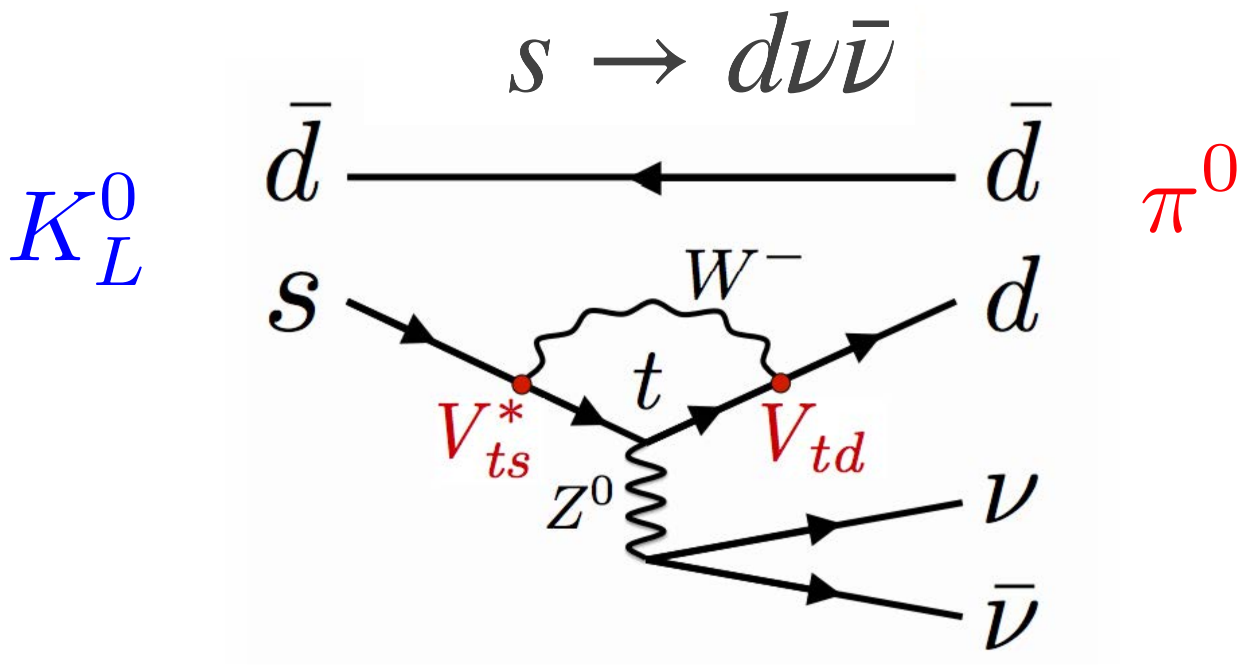


Special signature!

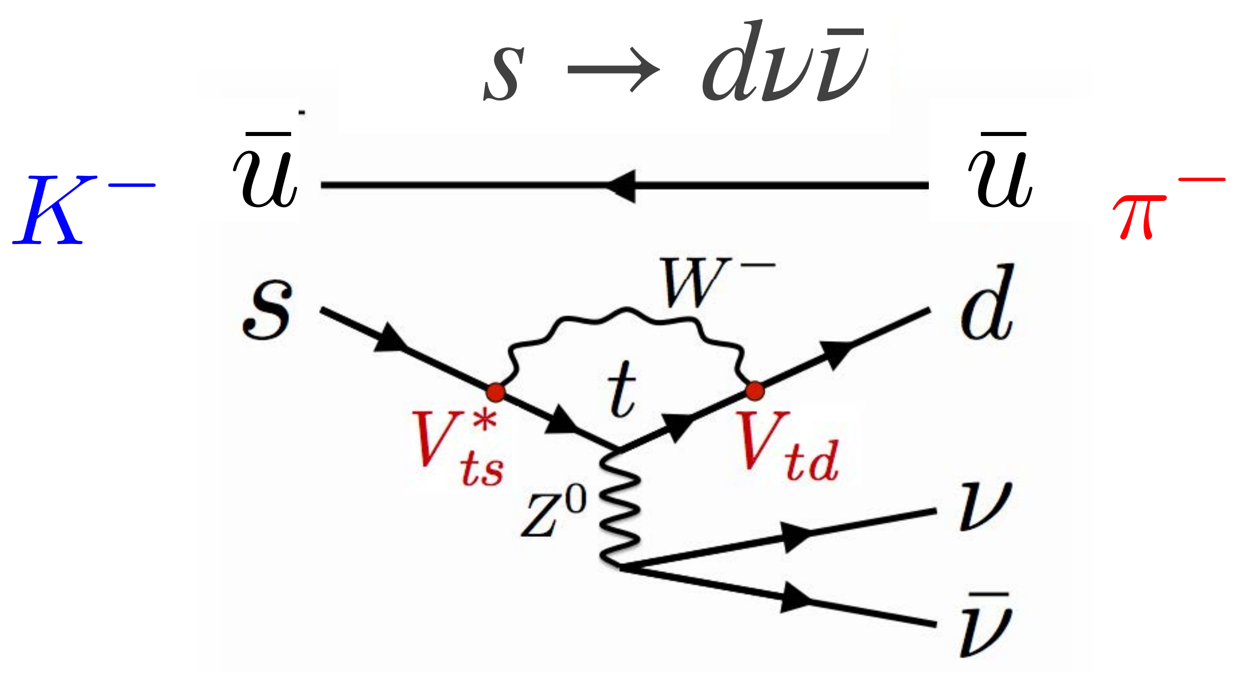
$K_L \to \pi^0 \nu\bar{\nu}$ search

- In experiments, this process looks $K_L^0 \to \pi^0 + \text{missing} \to 2\gamma + \text{missing};$ namely looks "invisible beam emits two photons with missing energy", no charged track!
- We can measure only photons' energy and positions by the elemag calorimeter;
    - We can not reconstruct the m_π^2 from two photons (!)
- In an ideal experiment, the contamination (background) only comes from $K_L^0 \to 2\gamma$ ($K^0 - \pi^0\text{mixing} + \pi^0 \to 2\gamma$): $\mathscr{B}(K_L \to 2\gamma)_{\text{exp}} = 5.47(4) \times 10^{-4}$. This BG is totally avoided by imposing large transverse missing energy.

Grossman-Nir bound (theoretical relation)



Same diagram in quark level



$$\frac{\Gamma\left(K_L \to \pi^0\nu\bar{\nu}\right)}{\Gamma\left(K^+ \to \pi^+\nu\bar{\nu}\right)} = \frac{\left|pA_{\pi^0\nu\bar{\nu}} - q\bar{A}_{\pi^0\nu\bar{\nu}}\right|^2}{\left|\sqrt{2}A_{\pi^0\nu\bar{\nu}}\right|^2} = \frac{1}{4}\left|1 - \lambda_{\pi\nu\bar{\nu}}\right|^2$$

$$= \frac{1}{4}\left(1 + |\lambda_{\pi\nu\bar{\nu}}|^2 - 2\mathrm{Re}\lambda_{\pi\nu\bar{\nu}}\right) \simeq \frac{1}{2}\left(1 - \mathrm{Re}\lambda_{\pi\nu\bar{\nu}}\right) = \sin^2\left[\frac{\mathrm{Arg}\left(\lambda_{\pi\nu\bar{\nu}}\right)}{2}\right]$$

$$A_{\pi^0\nu\bar{\nu}} = \langle\pi^0\nu\bar{\nu}|\mathcal{H}|K^0\rangle,$$

$$\bar{A}_{\pi^0\nu\bar{\nu}} = \langle\pi^0\nu\bar{\nu}|\mathcal{H}|\bar{K}^0\rangle,$$

$$\lambda_{\pi\nu\bar{\nu}} = \left(\frac{q}{p}\right)_K \frac{\bar{A}_{\pi^0\nu\bar{\nu}}}{A_{\pi^0\nu\bar{\nu}}}$$

- Grossman-Nir bound for general NP models (including $\nu_i\bar{\nu}_j$) [Grossman, Nir '97]

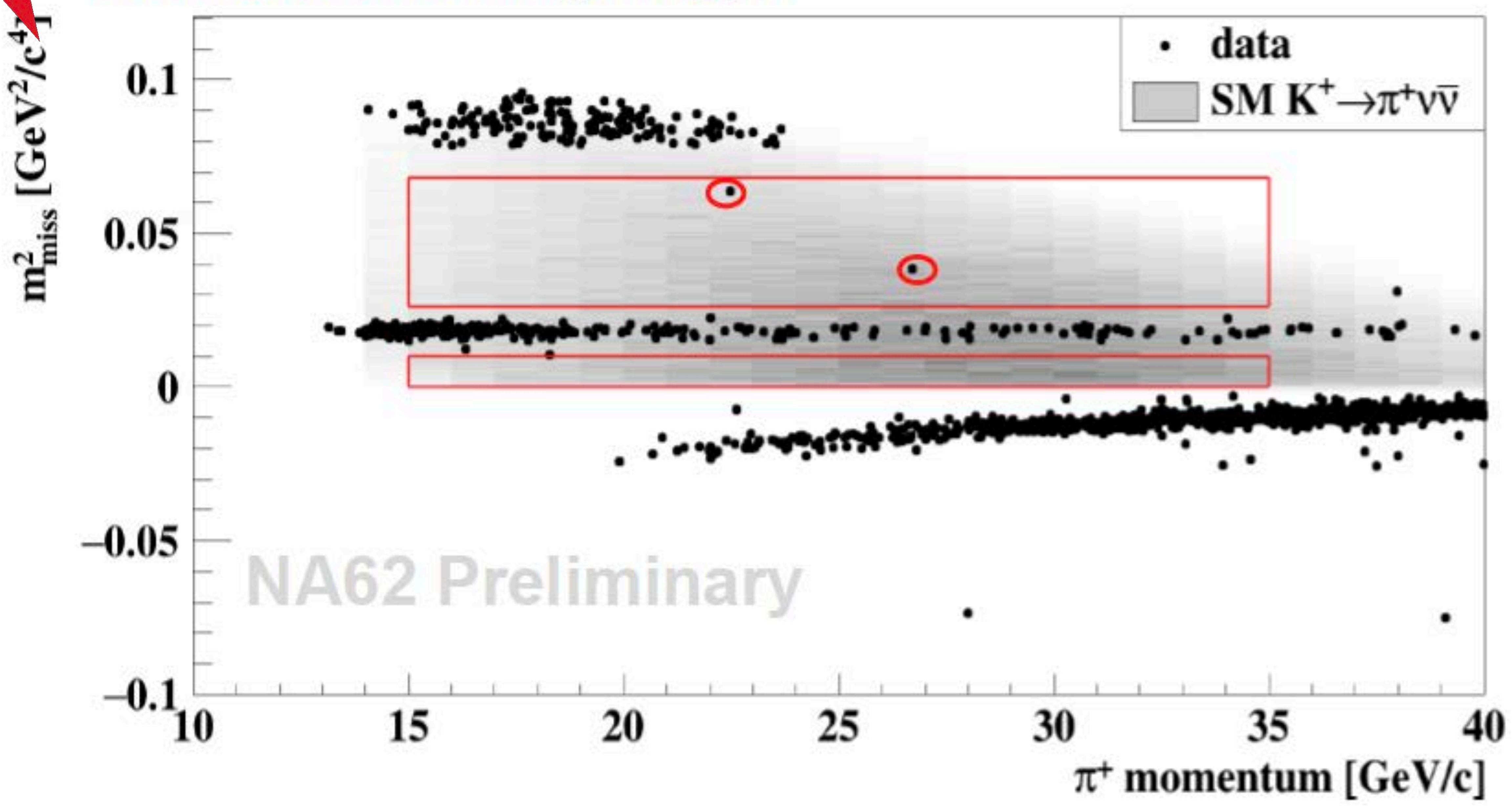
$$\mathcal{B}\left(K_L \to \pi^0\nu\bar{\nu}\right) = \left(\frac{\tau_L}{\tau^+} + \Delta_{\mathrm{IB,\,EM}}\right)\sin^2\theta\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right) \leq 4.32\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right)$$

New preliminary result@NA62

NEW

[NA62, KAON2019; 2016+17 data]

2 events observed in signal region



[BNL-E949, '09]

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) < 3.35 \times 10^{-10} \text{ at } 90\%\text{CL}$$

[NA62, FPCP2018; 2016 data]

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) < 11(14) \times 10^{-10} \text{ at } 90(95)\%\text{CL}$$

Factor 6 improved

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) < 1.85(2.44) \times 10^{-10} \text{ at } 90(95)\%\text{CL}$$

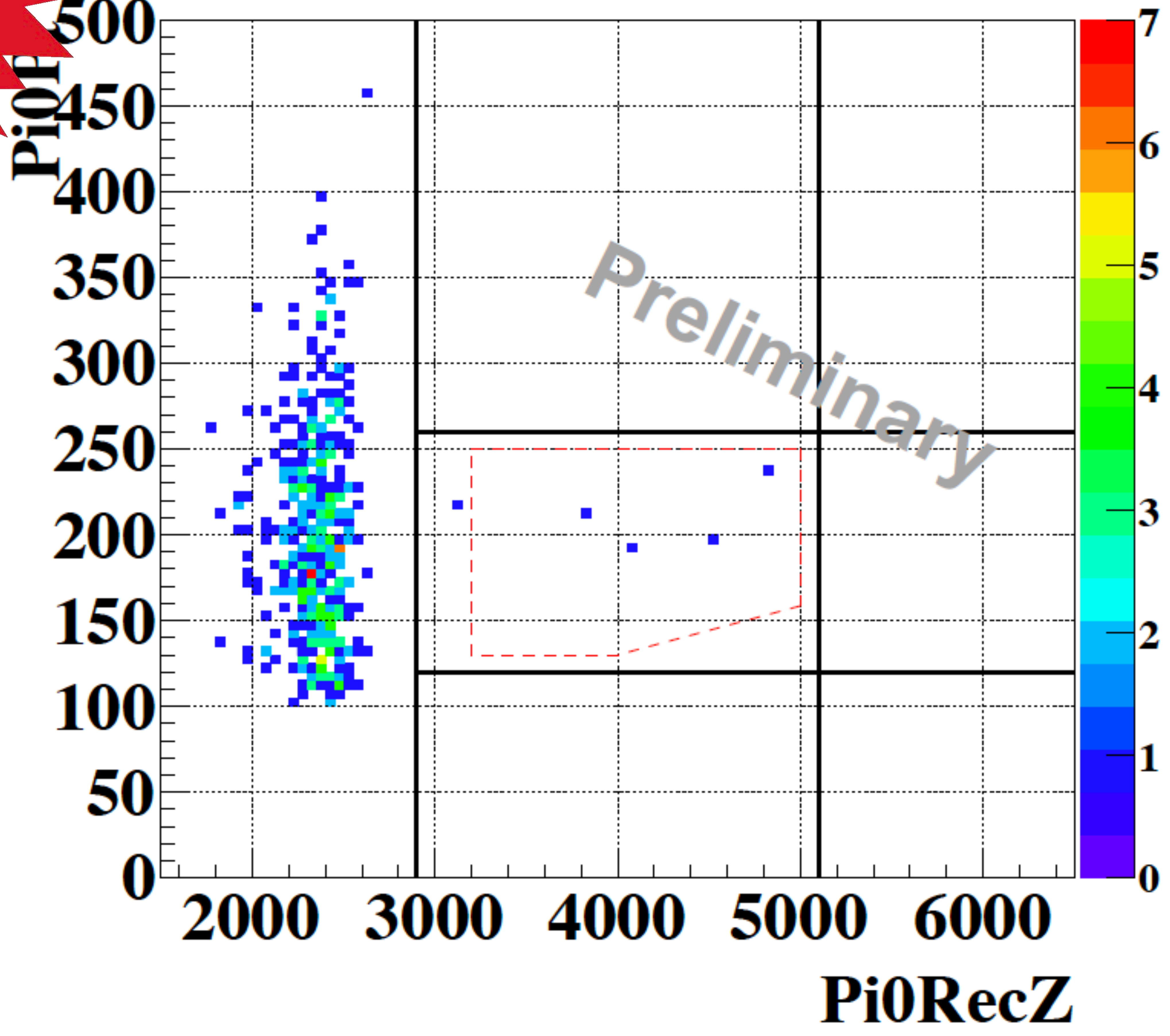
$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$$

# of events	3
Single event sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected BG	1.65±0.31
Expected SM	2.4±0.3

New data@KOTO

NEW

[KOTO, KAON2019; 2016-18 data]



[KOTO, PRL '19; 2015 data]

$$\mathcal{B}\left(K_L \to \pi^0 \nu \overline{\nu}\right) < 3.0 \times 10^{-9} \text{ at } 90\%\text{CL}$$

1 event in 4 events is suspected as a BG from an upstream activity

KOTO is planning to re-evaluate other BG sources, especially K^+/**planning a special run for BG in Feb.—Mar.**

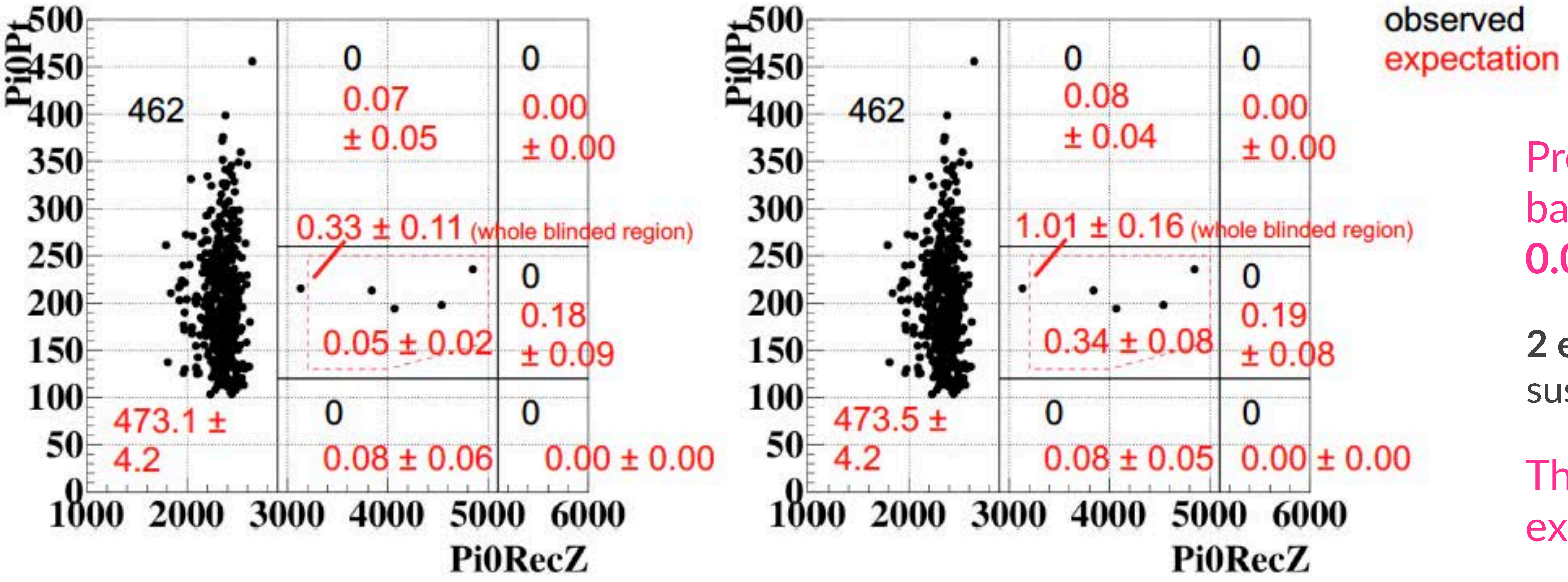
# of events	4 (3)
Single event sensitivity	~7×10^{-10}
Expected BG	0.05±0.02
Expected SM	0.05±0.01

Slide by T. Nomura
(January 17, 2020)

Revised P_T-Z plot

At KAON 2019 → As of today

S.E.S : 6.9×10^{-10} S.E.S : 7.1×10^{-10}



Preliminary improved back ground estimation
0.05 → 0.34

2 events in 4 events are suspected as a BG

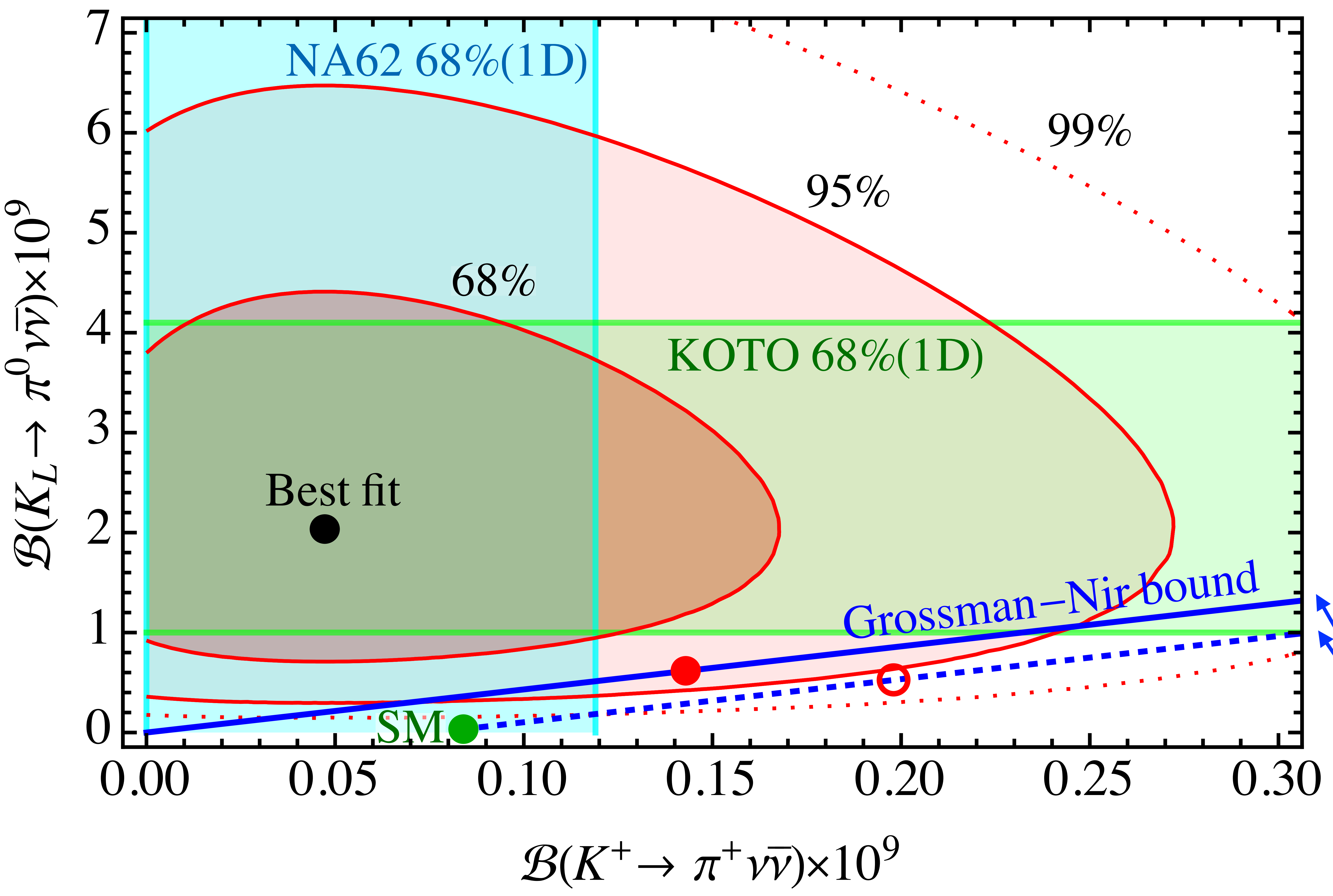
The data still could not explain the BG

* S.E.S. is also updated;
A run-dependent efficiency correction was not applied in the old value.

33

Assuming signal = 3 events in KOTO events

[TK, Okui, Perez, Soreq, Tobioka ‘20]



SM+NP w/o interference

Statistics:

Only K_L data (1d.o.f)

Best fit vs. SM ●

p-value ~ 10^{-4} ~ 3.8σ

$K_L - K^+$ plane (2d.o.f)

Best fit vs. SM ●

~ 3.4σ

NP on the GN bound (1d.o.f)

Best fit vs. Best NP ●

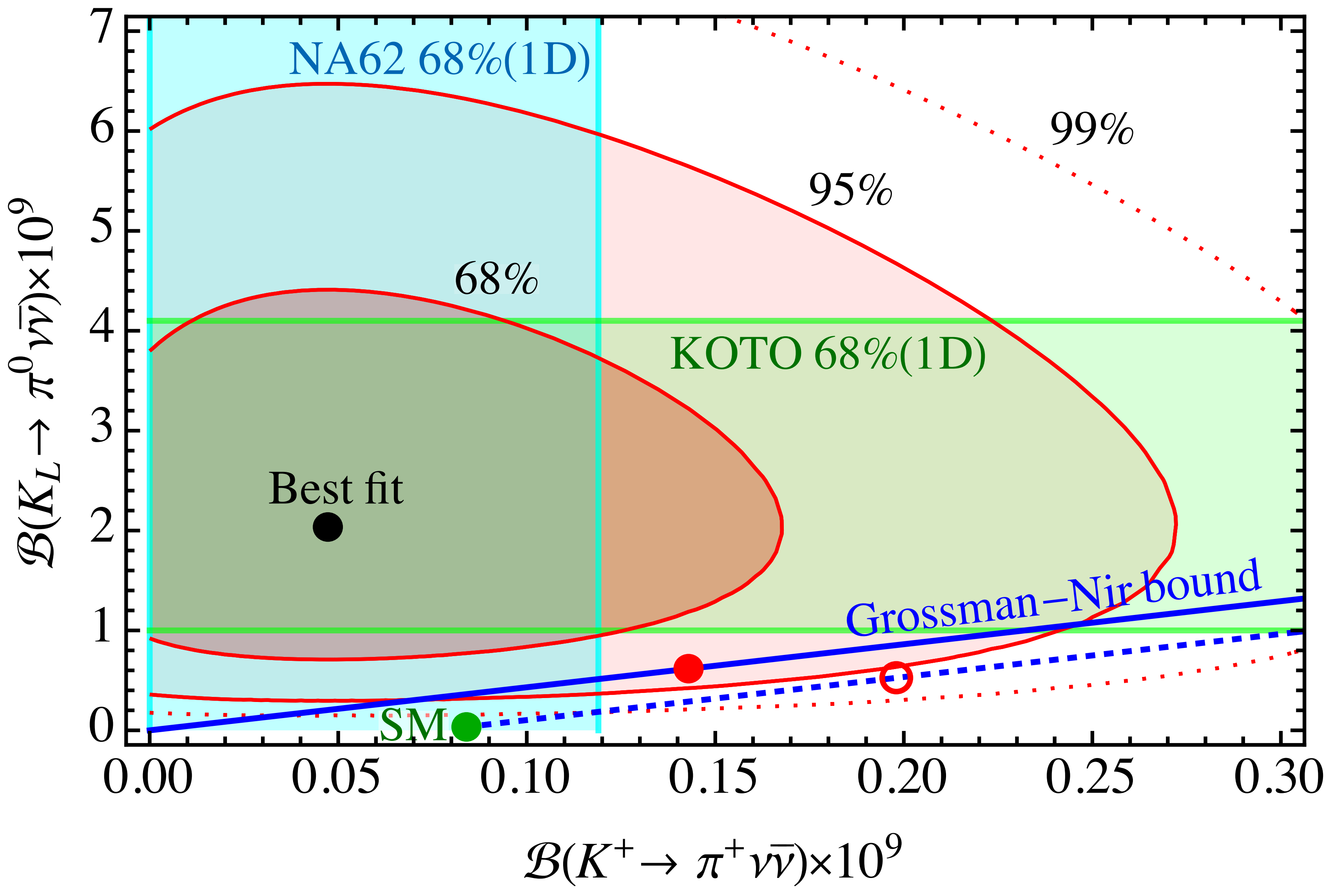
~ 2.1σ

What do we learn from data?

K_L @J-PARC — SM event is expected in ~2024

K^+ @CERN — 20 SM events are expected in 2016-18 runs

- NA62 is almost probing the SM signals. Great but no surprises.
- KOTO events are about two orders of magnitude larger than the SM [~3.8 (3.4) σ discrepancy]
- If we consider general new physics that interacts with neutrinos or stable and invisible new particles, the discrepancy can be reduced to 2.1σ (red circle)
- If the events are true, the Grossman-Nir bound has to be broken or has to be bypassed



Heavy new physics

[TK, Okui, Perez, Soreq, Tobioka '20]
[Li, Ma, Schmidt, '20]

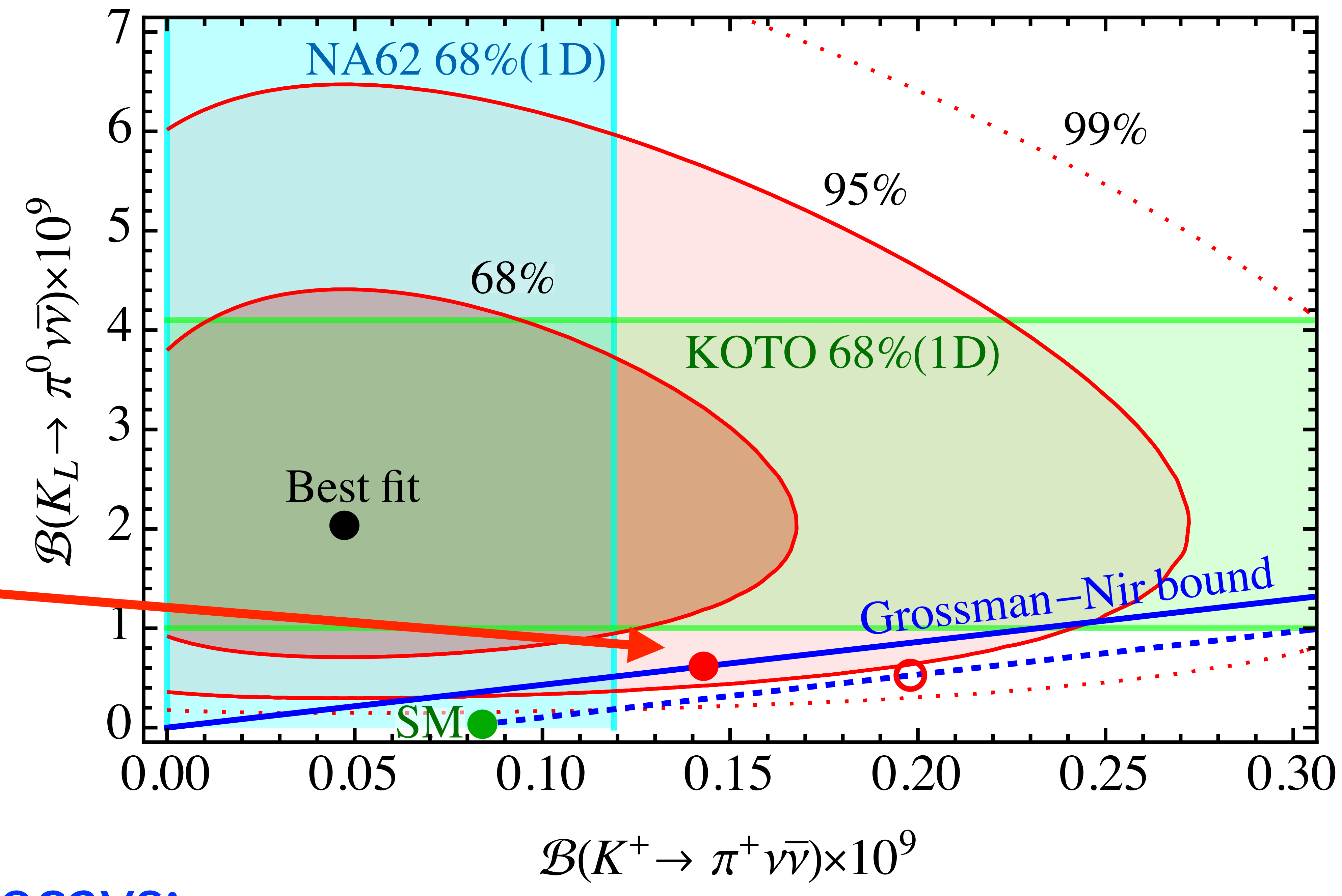
- Heavy new physics **can not** violate the Grossman-Nir bound

- Current data should be just statistical fluctuation

$$\mathcal{O}^{\nu\nu}_{S,A} = \left[\bar{Q}^2\left(\mathbf{1}_2, \sigma^i\right) Q^1\right]_{V-A}\left[\bar{L}\left(\mathbf{1}_2, \sigma^i\right) L\right]_{V-A}$$

$$\mathcal{O}^{\nu\nu}_{D} = \left(\bar{d}^2 d^1\right)_{V+A}\left(\bar{L}L\right)_{V-A}$$

$$C^{\nu\nu}_{S,D} - C^{\nu\nu}_{A} \approx \mathrm{e}^{-\mathrm{i}\frac{3}{4}\pi}/(150\,\mathrm{TeV})^2$$



- Currently no constraint.

- Correlation with (or bound from) the other CPV rare decays:

$\mathrm{BR}(K_S \to \mu\mu) < 2.4 \times 10^{-10}$ [LHCb '19]

$\mathrm{BR}(K_L \to \pi^0 ee) < 2.8 \times 10^{-10}$ [KTEV '04]

$\mathrm{BR}(K_L \to \pi^0 \mu\mu) < 3.8 \times 10^{-10}$ [KTEV '00]

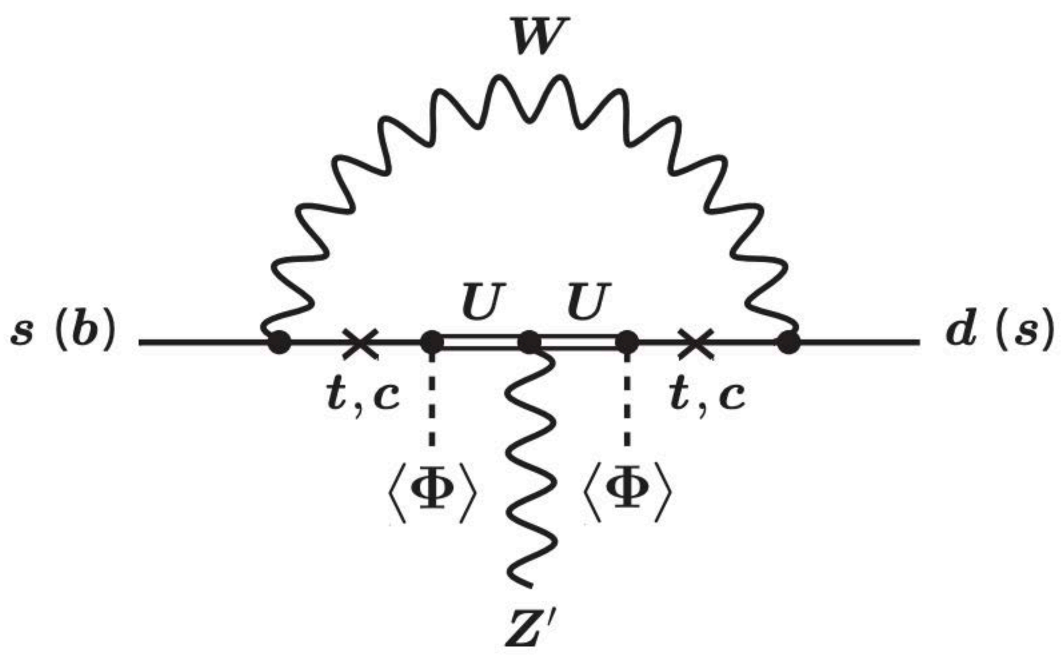
Pion mass new physics: Z'

[Fuyuto, Hou, Kohda '15]

- Consider $K_L \to \pi^0 Z'$ and $Z' \to \nu\bar{\nu}$ with $m_{Z'} \sim m_\pi$, the constraint from $K^+ \to \pi^+\nu\bar{\nu}$ is significantly loosened by the background of $K^+ \to \pi^+\pi^0$

"π^0 *blind spot*" (NA62); $116 < m_{\text{miss}} < 152\,\text{MeV}$

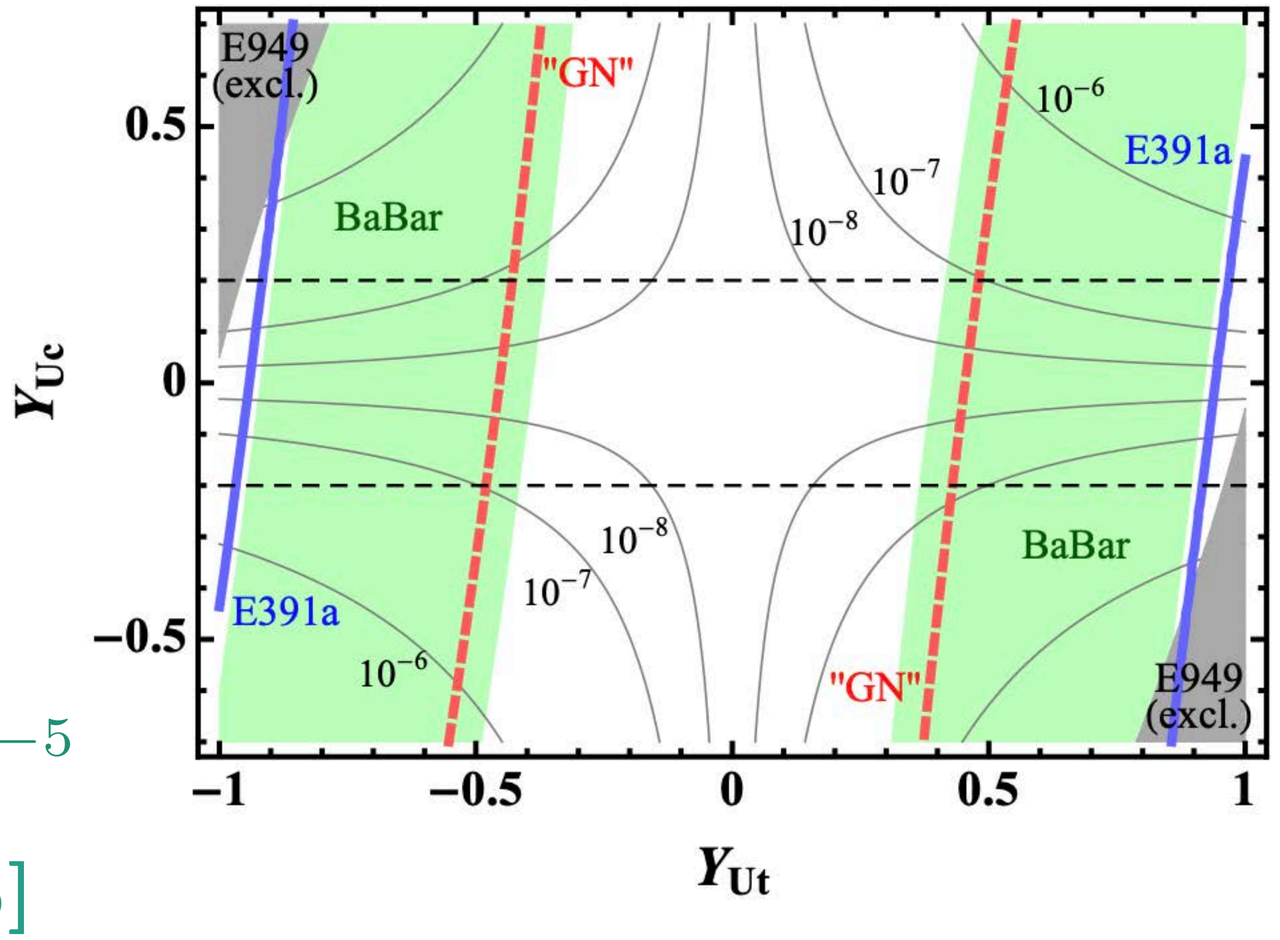
$$\mathcal{B}\left(K^+ \to \pi^+ X\right) < 5.6 \times 10^{-8} \text{ at } 90\% CL, \quad (m_X = m_{\pi^0})$$ [BNL-E949, '09]



$$\text{BR}\left(B^+ \to K^+\nu\bar{\nu}\right) = \left(0.35^{+0.6}_{-0.15}\right) \times 10^{-5}$$

[BaBar 1303.7465]

$\text{BR}\,(t \to cZ')$



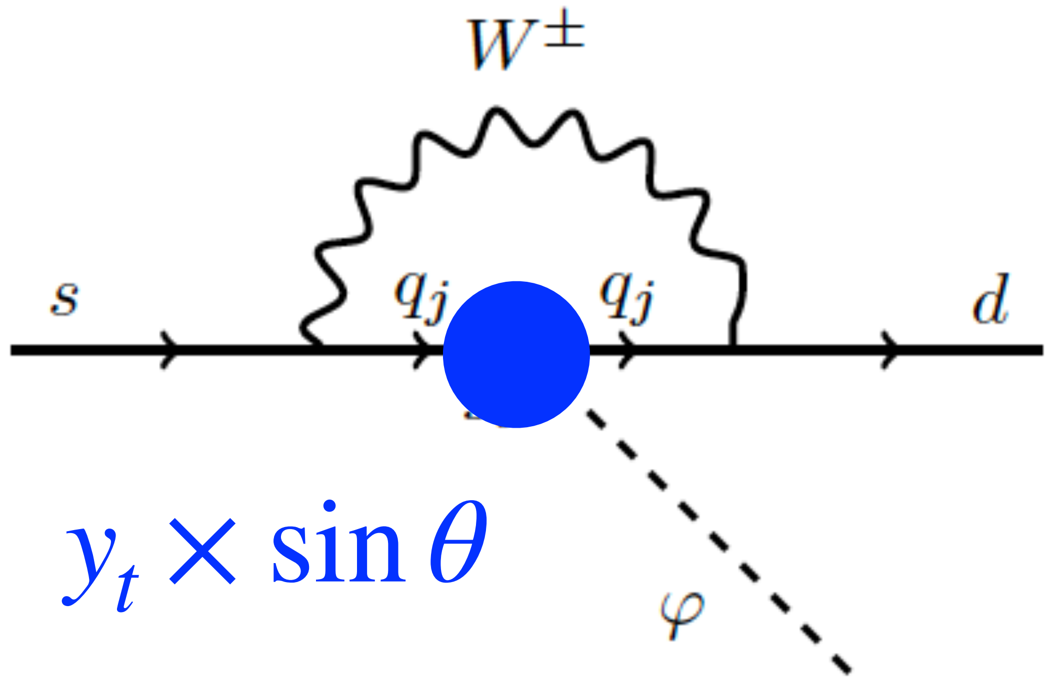
ply. Although the mass range for weakly interacting light particle emission is a bit restricted, our explicit model illustrates the potential wide-ranging impact of discovering $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \gtrsim 1.4 \times 10^{-9}$. Conversely, many measurements at B factories and the LHC could uncover correlated phenomena, which could shed light on what

Large $\mathscr{B}(K_L \to \pi^0\nu\bar{\nu})$ was already predicted in 2015

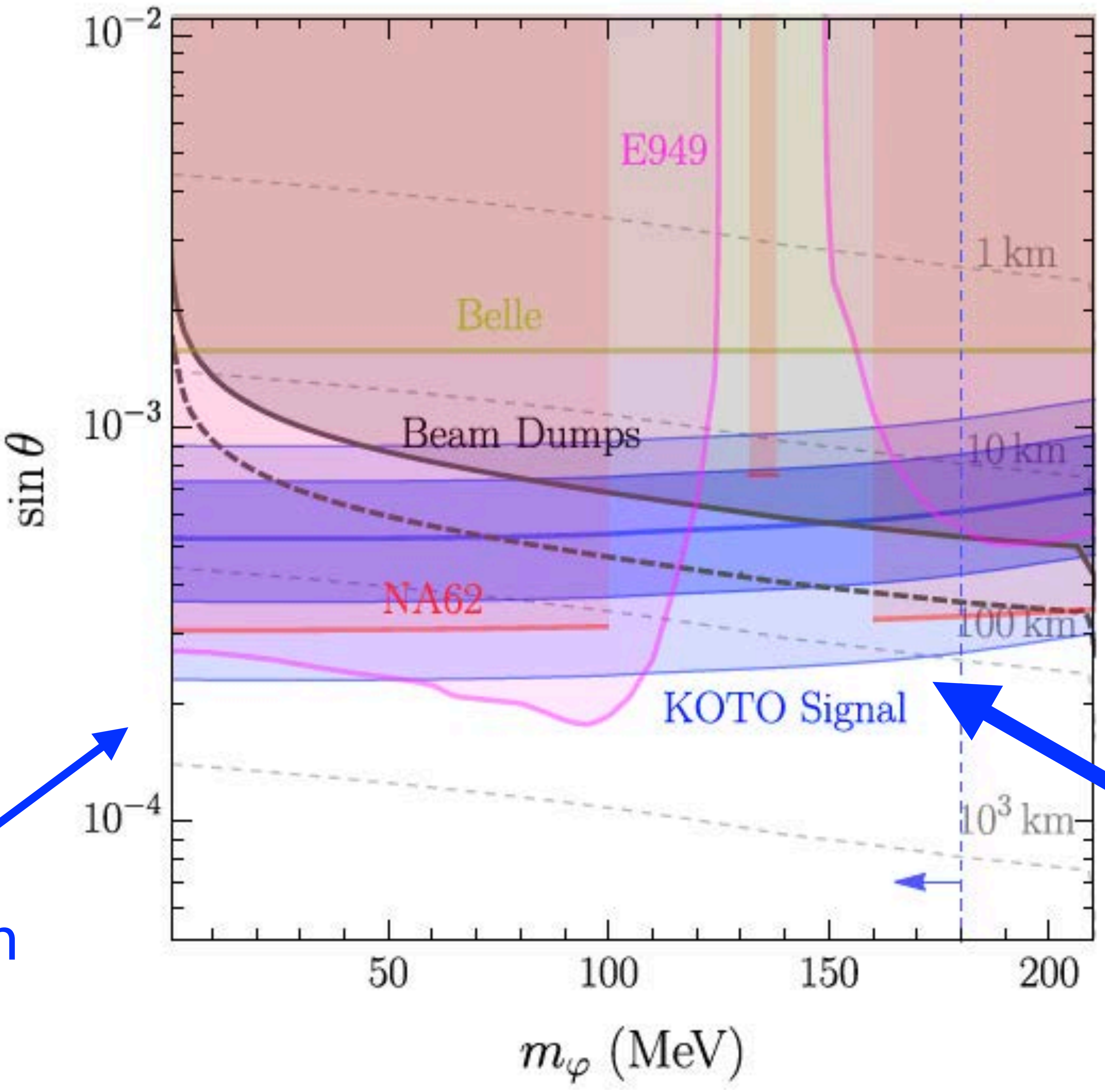
Pion mass new physics: Minimal Higgs portal

[Egana-Ugrinovic, Homiller, Meade 1911.10203], [Bhupal Dev, Mohapatra, Zhang 1911.12334]

- SM + light CP-even singlet scalar, which mixes with the SM Higgs by $\sin\theta$



$y_t \times \sin\theta$



2σ statistical fluctuation

Dashed-gray contour: $c\tau_\varphi$

φ is practically stable

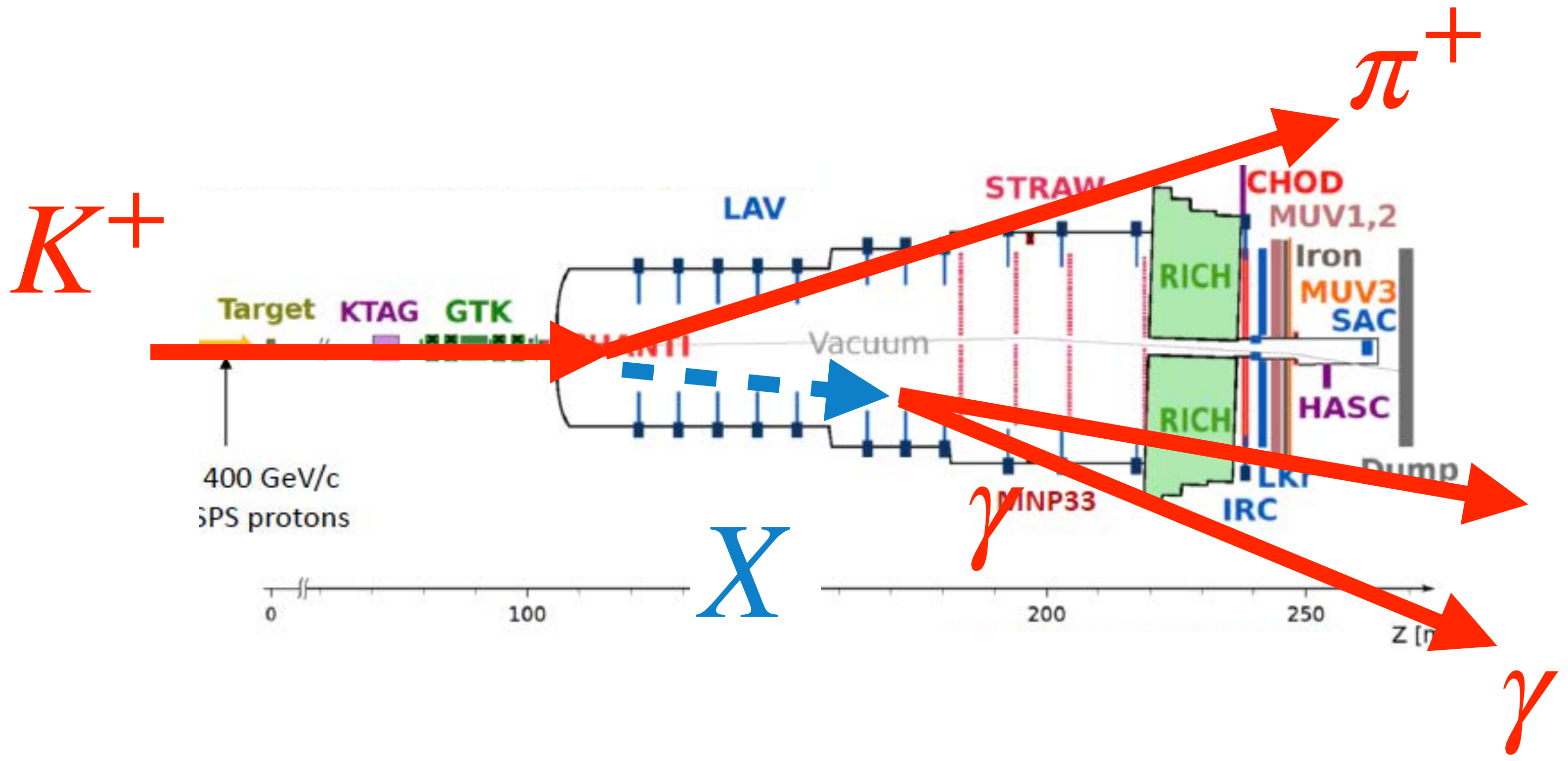
$\mathrm{BR}(\varphi \to ee) \sim 100\,\%$

"π^0 blind spot"

Unstable light new physics: $K_L \to \pi^0 X, X \to \gamma\gamma$

- X (~CP even scalar) has finite lifetime and decays into diphoton [TK, Okui, Perez, Soreq, Tobioka '20]
- $K_L \to \pi^0 X$ is CP-conserving process; CPV is not required in NP sector [Leutwyler, Shifman '90]
  - K_L: CP-odd, π^0: CP-odd

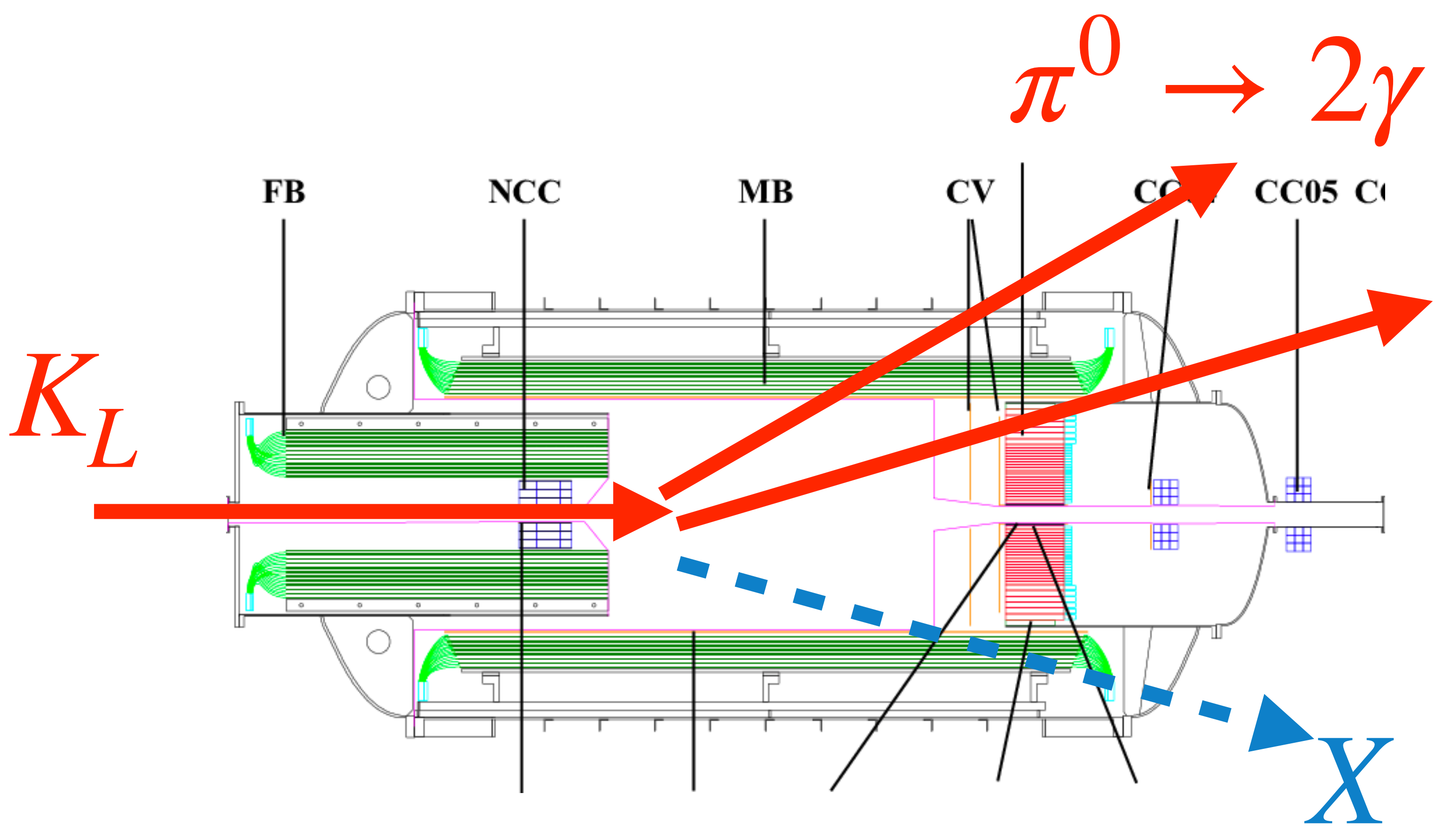
$K^+ \to \pi^+ X, X \to \gamma\gamma$ is **rejected** in the NA62 detector



NA62 detetor

L = 150 m, E = 37 GeV

X is long-lived in the KOTO detector



KOTO detetor

L = 3 m, E ~ 1.5 GeV

Unstable light new physics: $K_L \to \pi^0 X, X \to \gamma\gamma$

- Probability that X does not decay in the detector volume (= efficiency factor that X looks missing neutrinos)

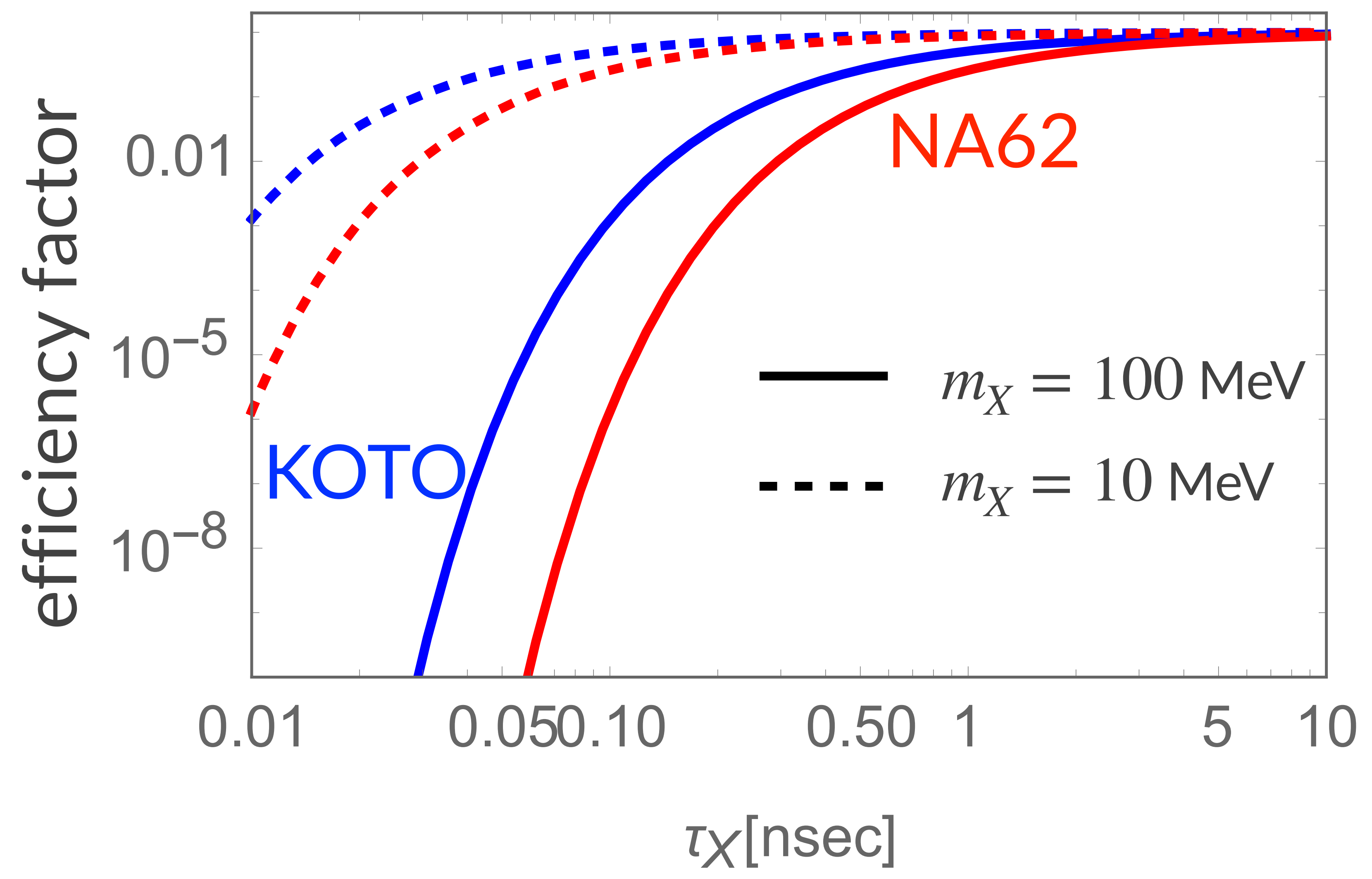
$$P = \exp(-\frac{L}{\gamma\beta\tau_X}) = \exp(-\frac{L}{(E_X/m_X)\beta\tau_X}) \simeq \exp(-\frac{Lm_X}{p_X\tau_X})$$

$$\text{(Energy scale)}^2 \gg m_X^2$$

NA62 detetor	KOTO detetor
L = 150 m, p_X = 37 GeV	L = 3 m, p_X~ 1.5 GeV

efficiency factor

$$\mathcal{B}(K \to \pi X) e^{-\frac{L}{p}\frac{m_X}{c\tau_X}}$$

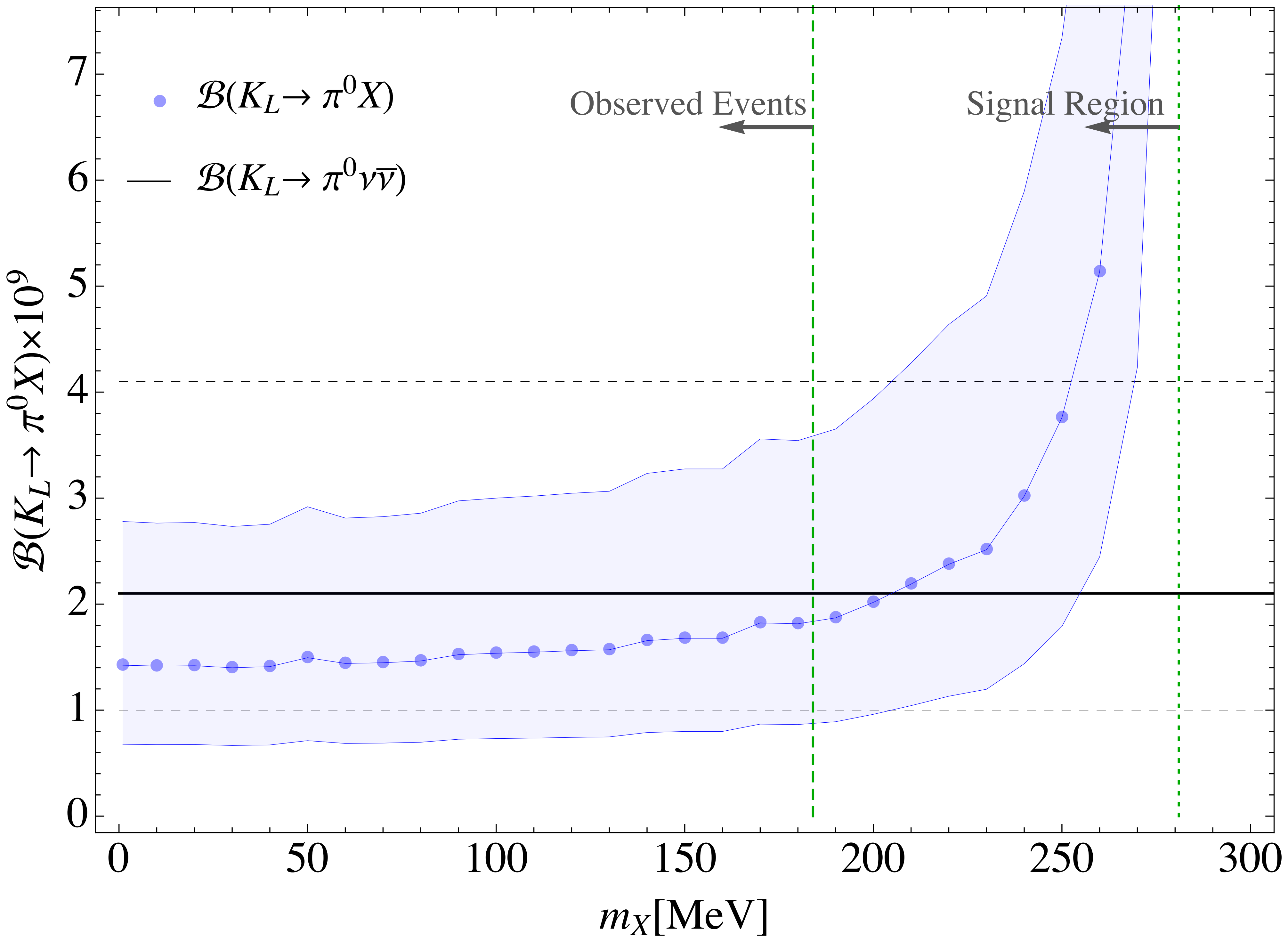


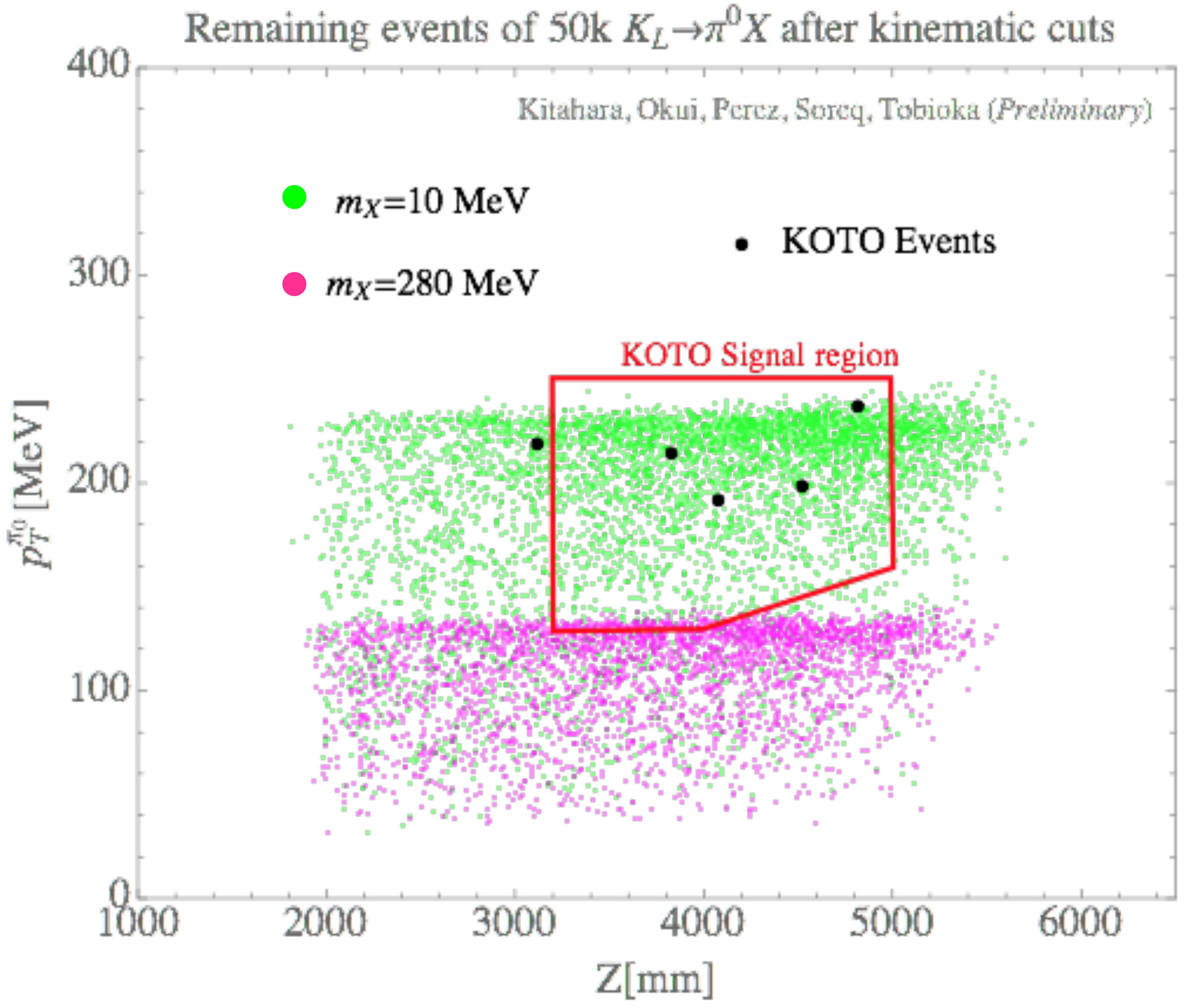
This efficiency factor can bypass GN relation

Unstable light new physics: $K_L \to \pi^0 X, X \to \gamma\gamma$

[TK, Okui, Perez, Soreq, Tobioka '20]

Required $\mathscr{B}(K_L \to \pi^0 X)$





As m_X increases, X and its pT tend to soft
(X is assumed to be stable in this plot)

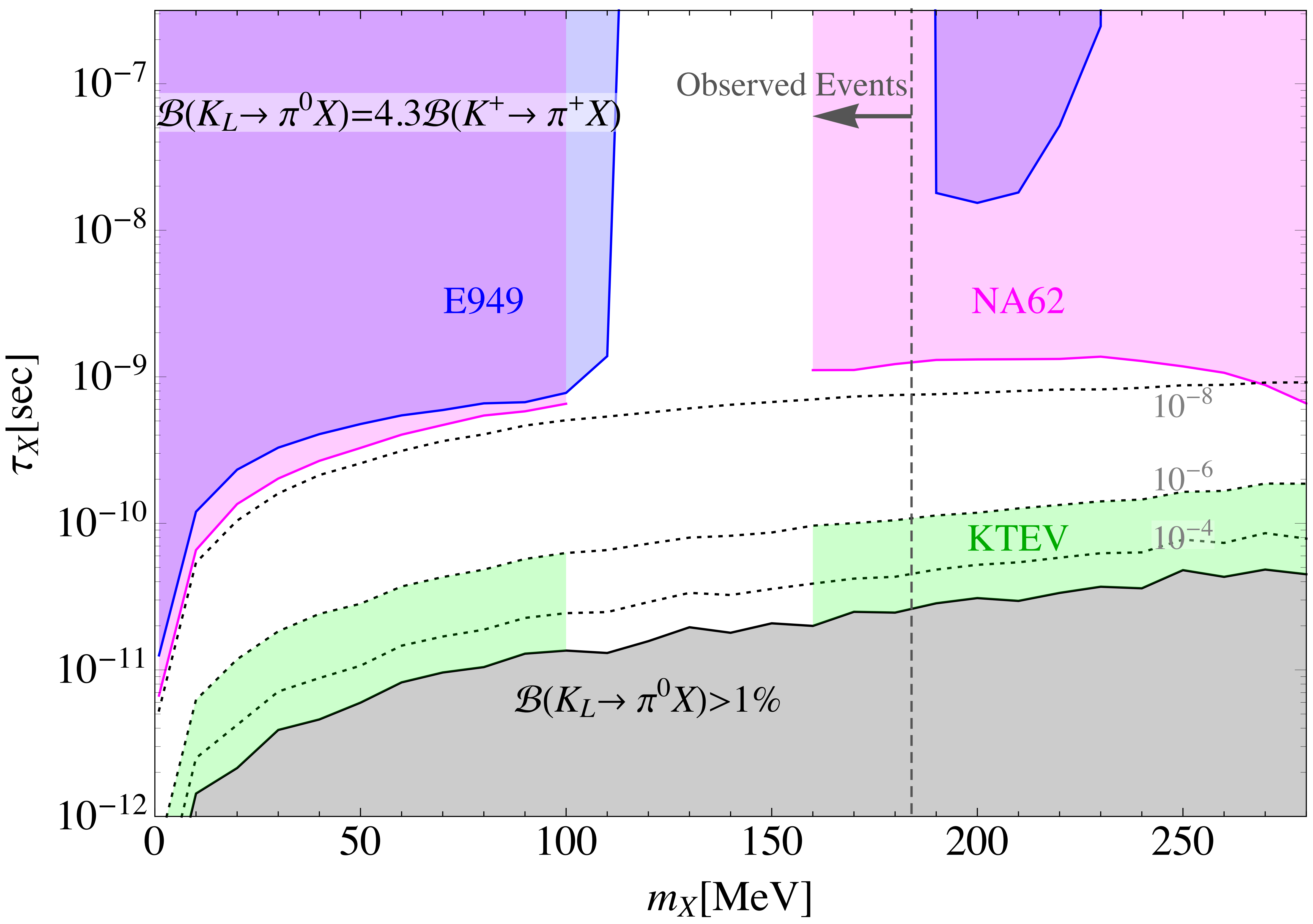
m_X = O(10)MeV is preferred in current data

Light new physics: $K_L \to \pi^0 X, X \to \gamma\gamma$

[TK, Okui, Perez, Soreq, Tobioka '20]

KOTO 3 events can be explain in white region

Colored regions are excluded



$K^+ \to \pi^+ \nu\bar{\nu}$ bound (E949@BNL)

$K^+ \to \pi^+ \nu\bar{\nu}$ bound (NA62@CERN)

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

GN bound can indeed be effectively weakened

Specific models are investigated in
Egana-Ugrinovic, Homiller, Meade 1911.10203; Liu, McGinnis, Wagner, Wang, 2001.06522

Specific model: KOTO + g-2 anomalies

[Liu, McGinnis, Wagner, Wang, 2001.06522]

- type-X 2HDM plus singlet ϕ
  (type-X: only Y_ℓ is tanβ enhanced)
- $\mathscr{B}(\phi \to ee) \simeq 1$ with n sec lifetime

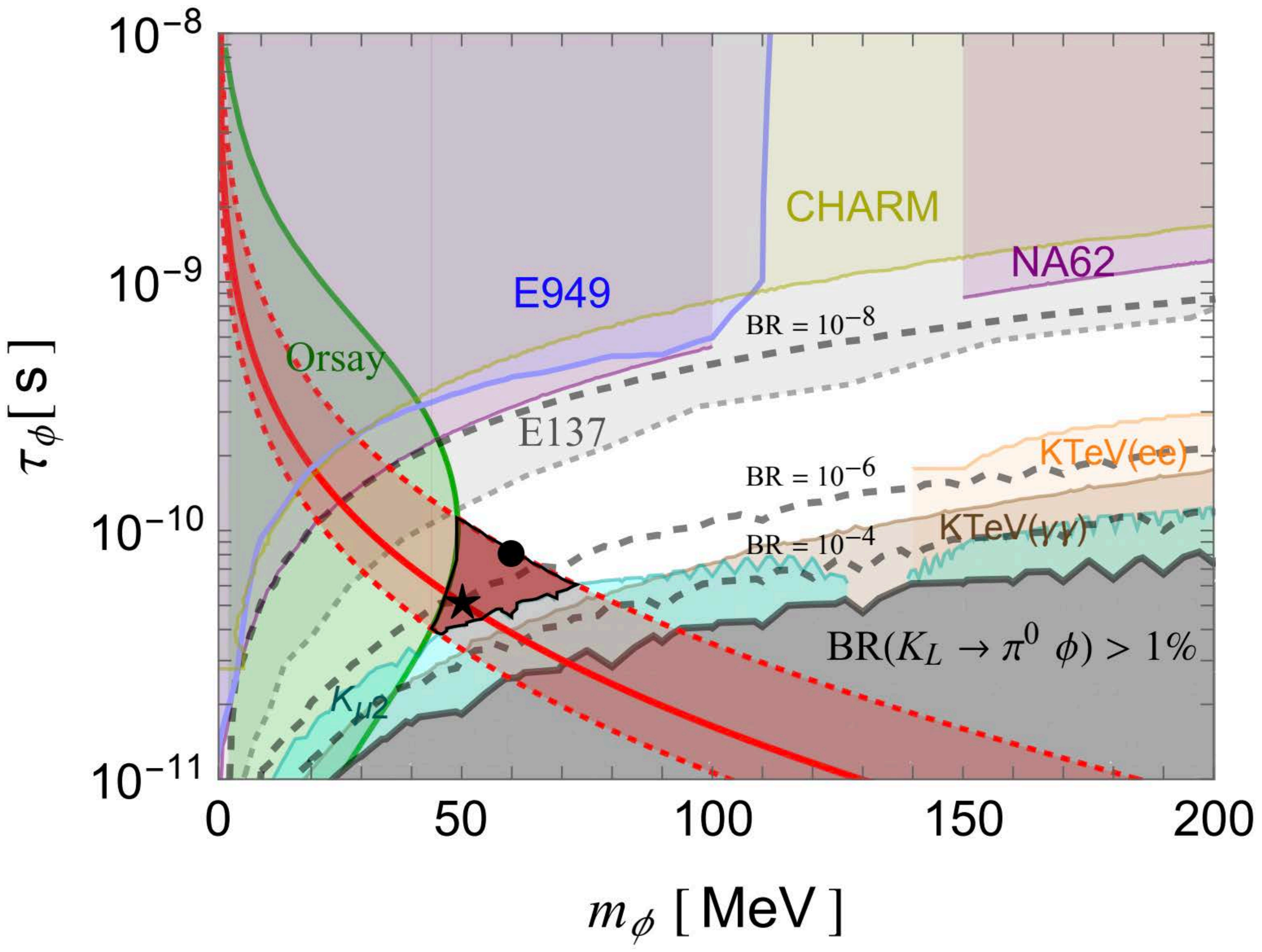
KOTO 3 events can be explain in white region

muon g-2 anomaly can be solved

Charm beam dump: $pp \to K \to \pi\phi(\to ee)$

Electron beam dump: $eN \to eN\phi(\to ee)$

Electron beam dump: $ee \to \phi(\to ee)$



Conclusions 1/2

- Interesting preliminary events were announced by KOTO experiment. If it is true, it should be a signal of new physics
- Although the Grossman-Nir bound sets the upper bound on BR($K_L \to \pi^0$ inv.), several new physics can bypass it practically
  - 100 TeV new physics with statistical fluctuation
  - "π^0 blind spot"
  - Unstable new light scalar using "lifetime gap"
- Connection to other anomaly?

Conclusions 2/2

- Very recently, several NP models that can violate the Grossman-Nir bound are proposed:
    - *Pair production of dark particles in meson decays*, Hostert, Kaneta, Pospelov, 2005.07102;
      $K_L \to X_1 X_2,\ X_2 \to \pi^0 X_1$, in Higgs/Z' portal
    - *KOTO vs. NA62 Dark Scalar Searches*, Gori, Perez, Tobioka, 2005.05170;
      $K_L \to \sigma\chi,\ \chi \to \gamma\gamma$, in strange flavor symmetry with ChPT
    - *Evading the Grossman-Nir bound with ΔI=3/2 new physics*, He, Ma, Tandean, Valencia, 2005.02942, 2002.05467 ; by dim-7 or -8 SMEFT operators
    - *Three Exceptions to the Grossman-Nir Bound*, Ziegler, Zupan, Zwicky, 2005.00451;
      $K_L \to \pi^0\phi, \pi^0\phi\phi$, in explicit isospin violating ChPT

Backup

Novel new physics interpretations [TK, Okui, Perez, Soreq, Tobioka '20]

Heavy NP *e.g.*, $\mathcal{O}_S^{\nu\nu} = (\bar{Q}^2 Q^1)_{V-A}(\bar{L}L)_{V-A}$

consider CPV in $s \to d\nu\bar{\nu}$

The Grossman-Nir bound holds

still 2.1σ tension (on the GN bound)

Pion mass NP: $K_L \to \pi^0 Z', Z' \to \nu\bar{\nu}, m_{Z'} \sim m_{\pi^0}$

"π^0 blind spot" (NA62); $116 < m_{\text{miss}} < 152\,\text{MeV}$

$\mathcal{B}\left(K^+ \to \pi^+ X\right) < 5.6 \times 10^{-8}$ at $90\%CL$, $(m_X = m_{\pi^0})$

[BNL-E949, '09]

Can explain 3 signals

Light NP: $K_L \to \pi^0 X, X \to \gamma\gamma$ New idea

Effectively go beyond the GN bound.
Key: finite lifetime, detector difference
→ "lifetime gap" appears

Can explain 3 signals

Light NP: pAu: fixed target $\to a \to \gamma\gamma$ New idea

ALP is produced at fixed target.
Key: KOTO does not distinguish $m_{\gamma\gamma}$,
$a \to \gamma\gamma$ mimics $\pi^0 \to \gamma\gamma$ with missing pT

Could explain 3 signals

A simple idea, but does not work

- Very simple idea of breaking the Grossman-Nir bound is just kinematics:

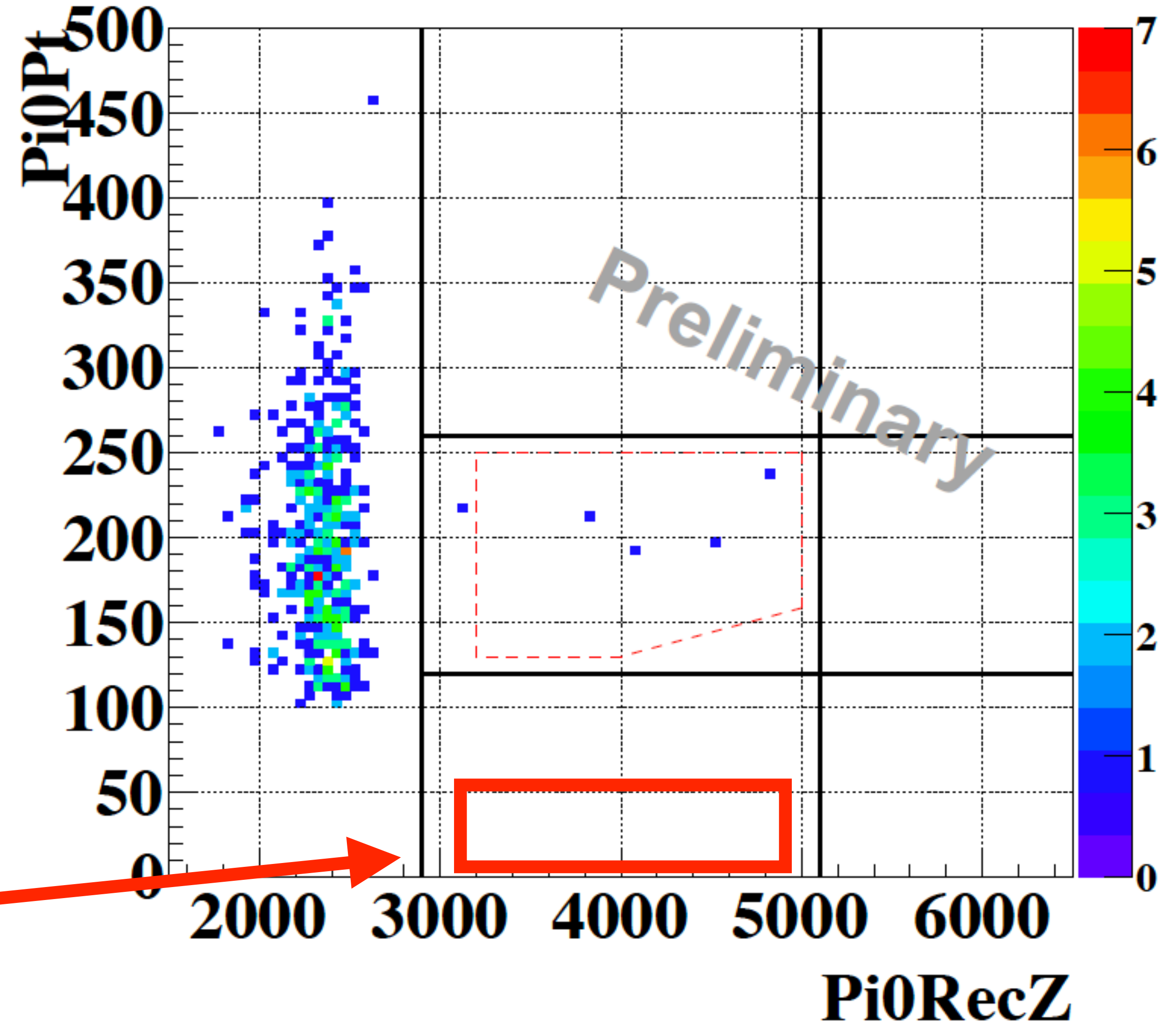
$m_{K_L} = 497.6$ MeV $\quad m_{\pi^0} = 134.9$ MeV $\quad \Delta m = 362.7$ MeV

$m_{K^\pm} = 493.6$ MeV $\quad m_{\pi^\pm} = 139.5$ MeV $\quad \Delta m = 354.1$ MeV

(Mass difference comes from the radiative corrections within the SM)

- $K_L \to \pi^0$ has a larger phase space than $K^+ \to \pi^+$
- Can new 360 MeV particle explain signals? → Impossible
- Emitted π^0 is too soft, the missing pT can not become large

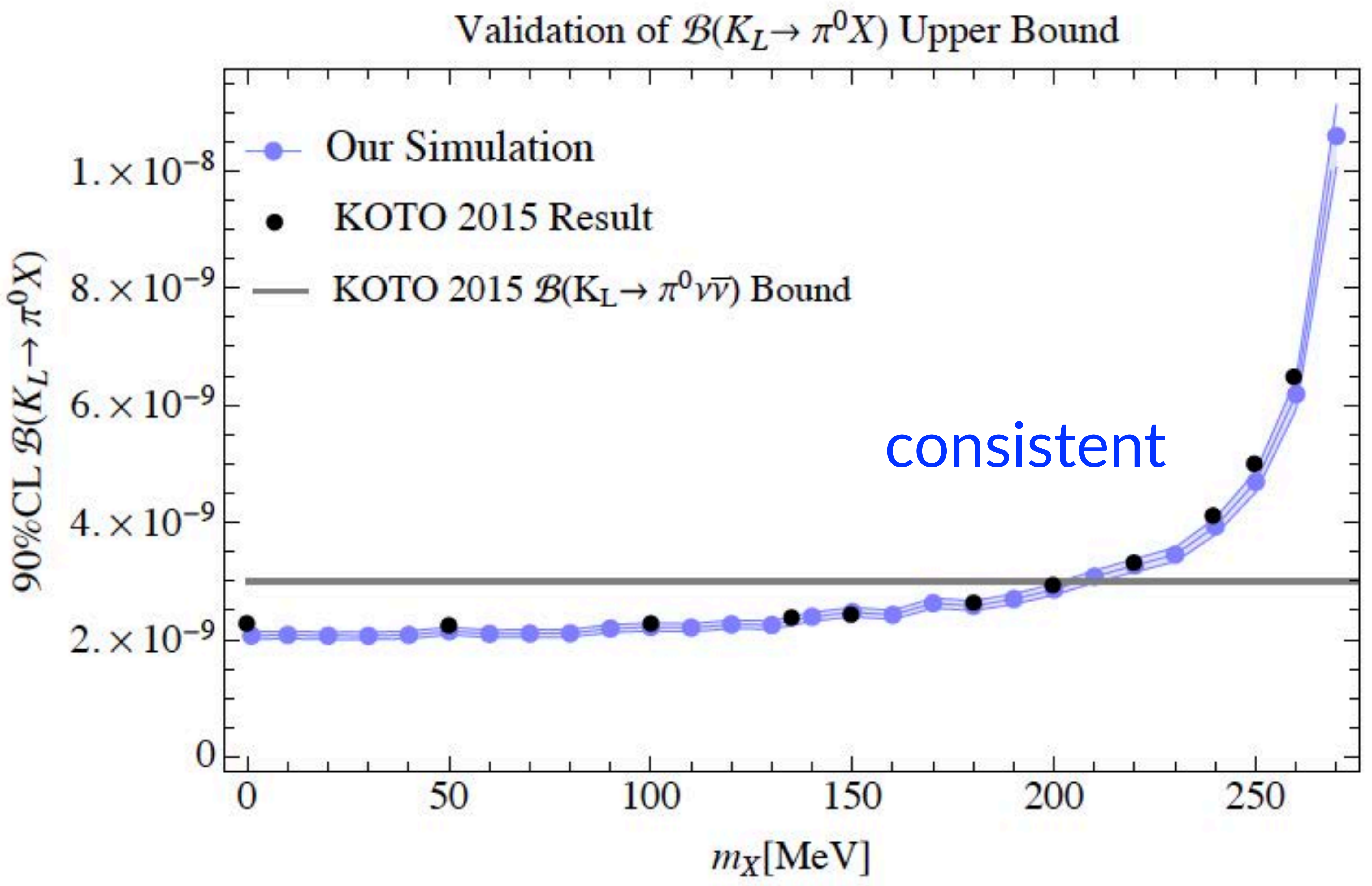
Predicted signal region [Fabbrichesi, Gabrielli, 1911.03755]



Validations

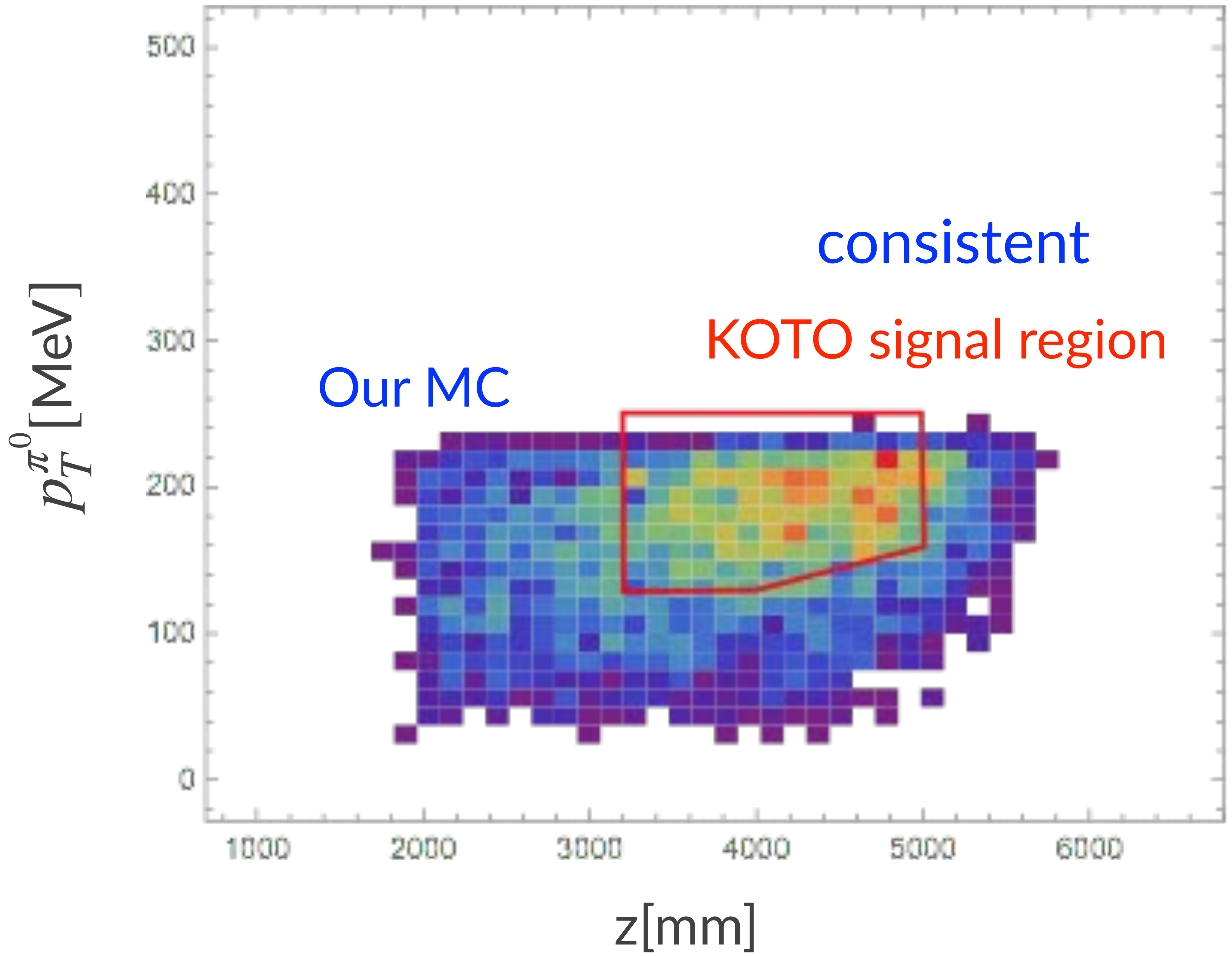
[TK, Okui, Perez, Soreq, Tobioka '20]

- We simulated efficiencies difference between $\pi^0\nu\bar{\nu}$ and $\pi^0 X$ signal (assuming stable *X*)



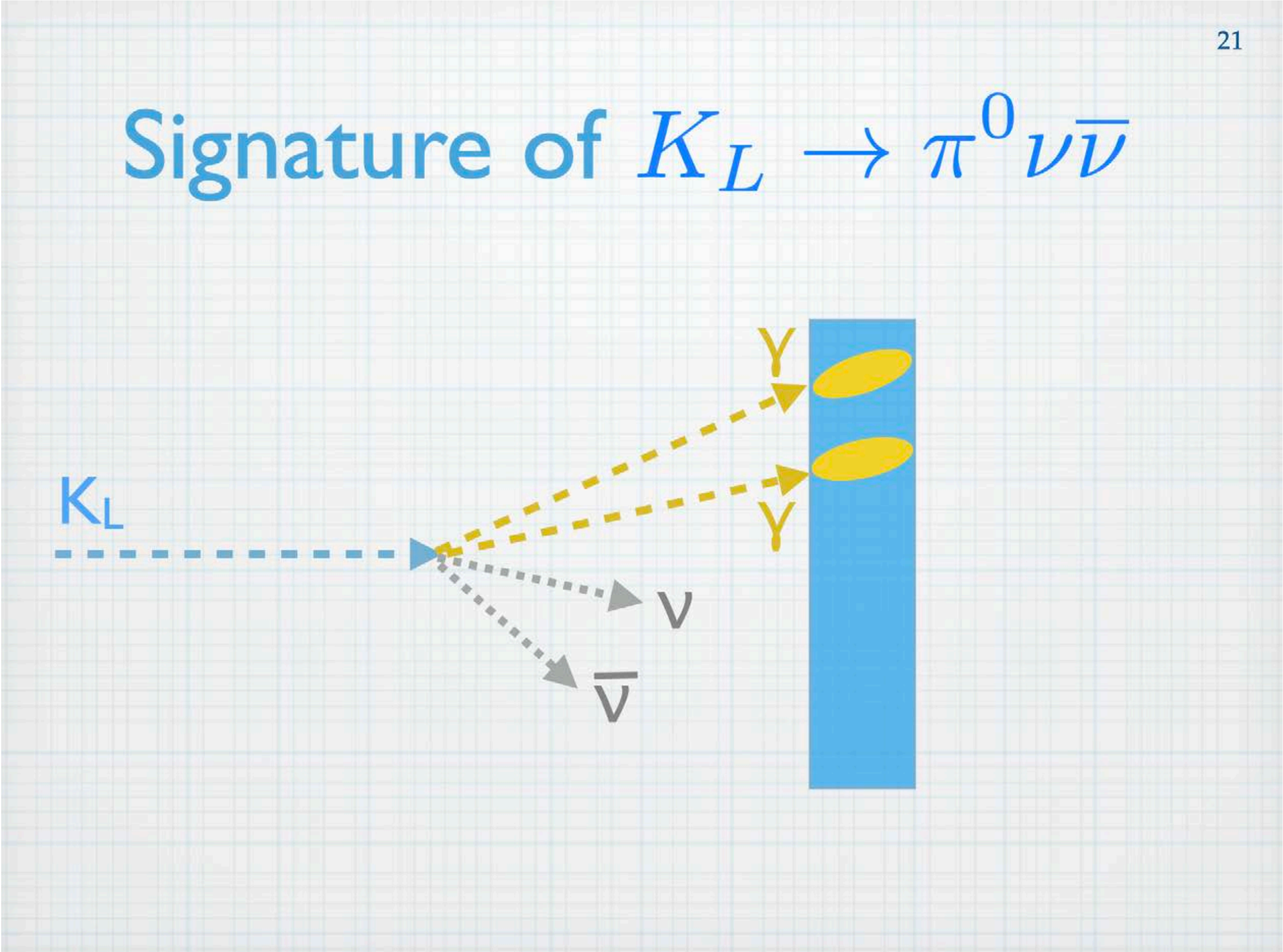
- KOTO 2015 Result [KOTO, Phys. Rev. Lett. 122, 021802 (2019)]

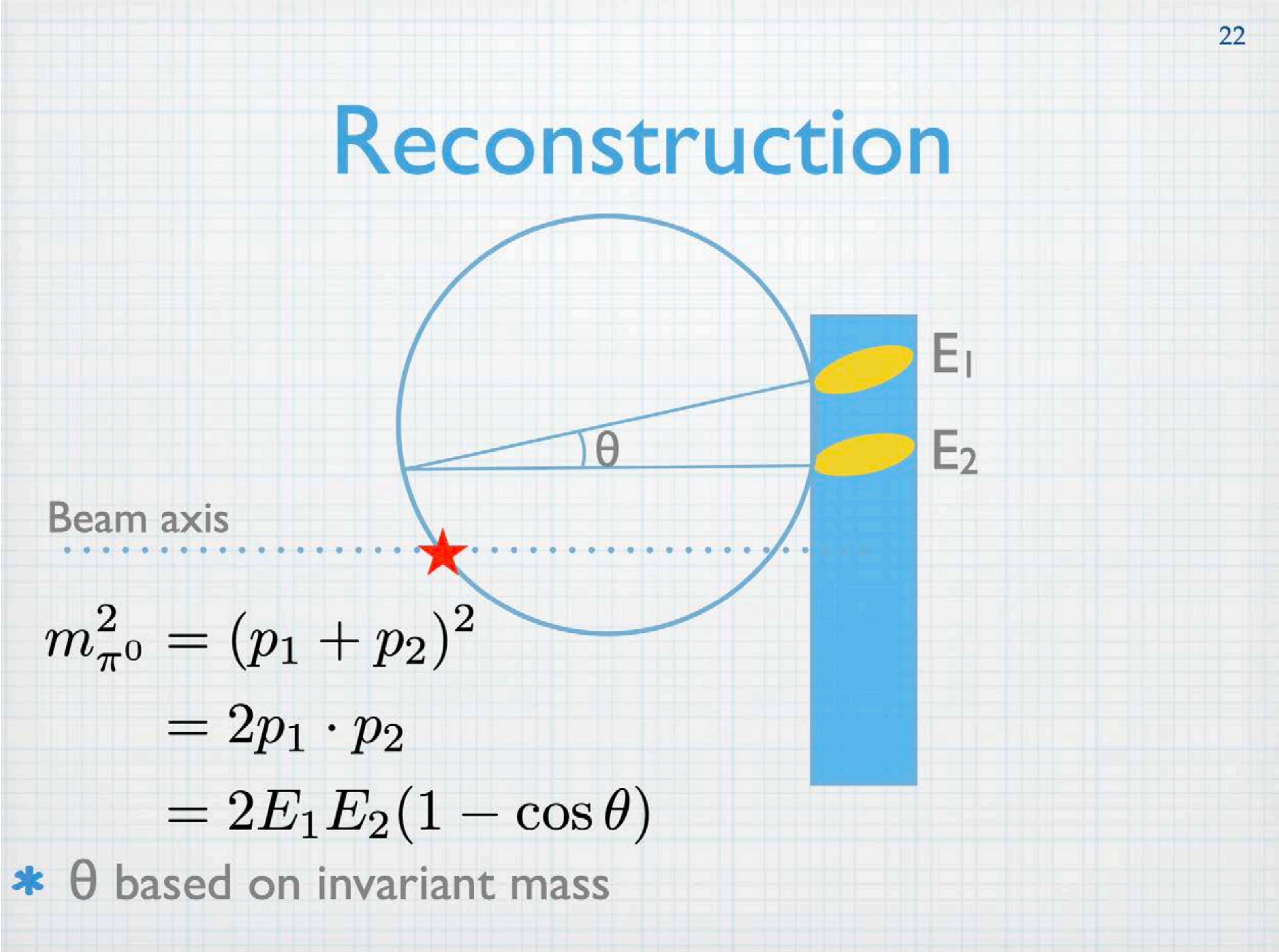
- Distribution of $\pi^0\nu\bar{\nu}$ signal

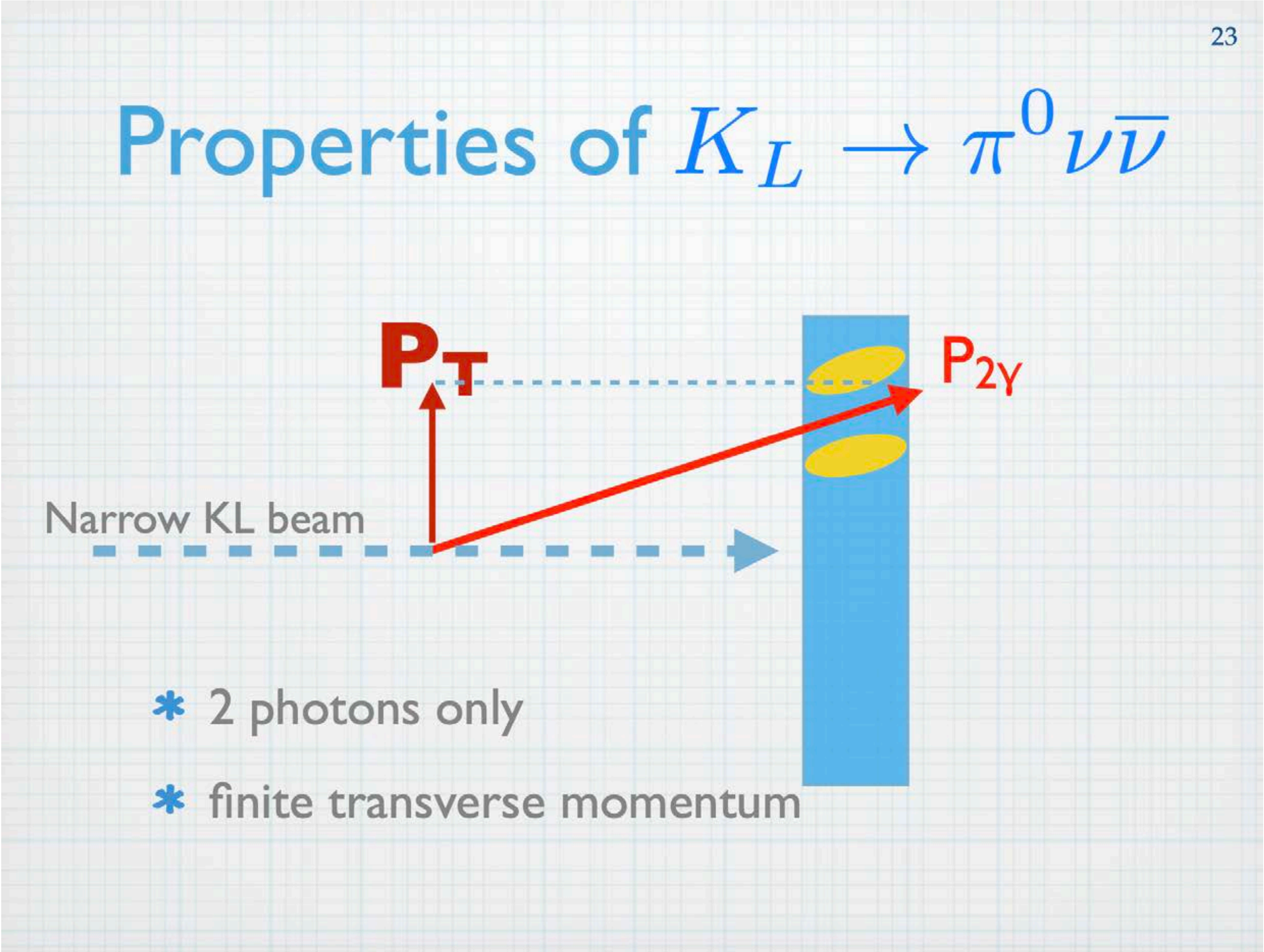


Strategy of KOTO experiment

[Figures from Yamanaka-san@FPW2019]







Initial state is neutral long-lived particle = K_L + neutron (+ ALP see later)

All particles are invisible. One can observe only photon energy

Assuming pion mass, one can reconstruct the decay point and missing pT

Require large missing pT

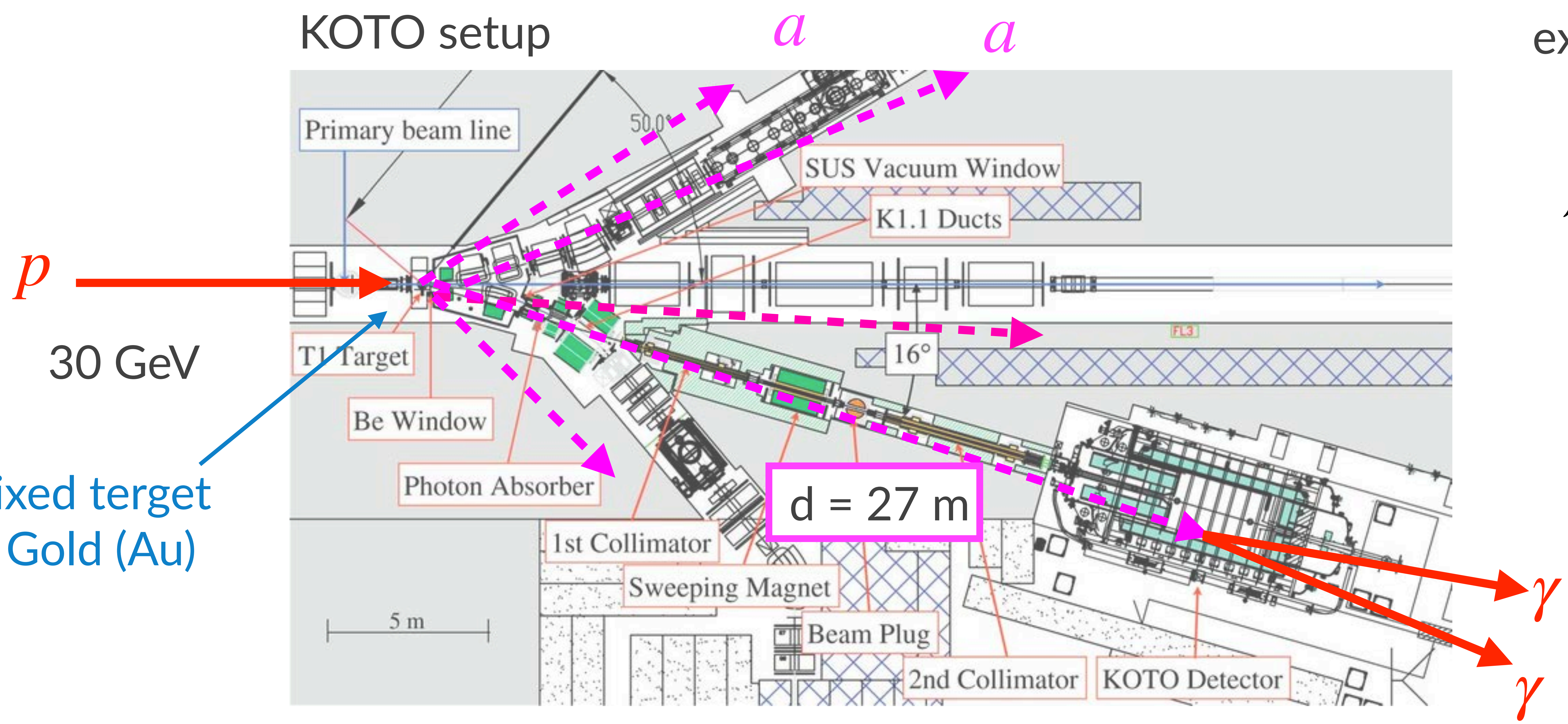
KOTO can not measure diphoton invariant mass

ALP interpretation: $pAu \to a \to \gamma\gamma$

[TK, Okui, Perez, Soreq, Tobioka '20]

- ALP (a) is produced at the fixed target and decays into $\gamma\gamma$ in the KOTO detector
- KOTO does not distinguish $m_{\gamma\gamma}$

KOTO setup



Following parameter regions can explain KOTO O(1) events

production $\pi \to a$ decay $a \to \gamma\gamma$

$$\mathcal{L}_{\rm int} = \frac{\alpha_s}{8\pi f_g} a G^a_{\mu\nu}\tilde{G}_{a\mu\nu} + \frac{\alpha_{\rm EM}}{8\pi f_\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$m_a \sim \mathcal{O}(100)\,\text{MeV} < 3m_\pi$$

$$f_g \sim f_\gamma \sim \mathcal{O}(1)\,\text{TeV}$$

$\longleftrightarrow$

$$\sin^2\theta_{a\pi} \sim 10^{-9}$$

$$\tau_a \sim \mathcal{O}(1)\,\text{nsec}$$