KOTO vs NA62

Dark Sector with Grossman-Nir bound and Beyond

Israel Joint Seminar
Israel (virtual), July 8, 2020

Kohsaku Tobioka
Florida State University

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Outline

- Introduction
  - Rare kaon decay $K \to \pi\nu\nu$
  - Observed events at KOTO, and NA62 result
- Dark Sector with Grossman-Nir bound and Beyond
  - Heavy new physics (EFT)
  - Light new physics with GN bound
  - Light new physics beyond GN bound
- Future prospects [ALP search at Kaon factories]
- Summary

Collaboration with Teppei Kitahara, Takemichi Okui, Gilad Perez, Yotam Soreq [Phys.Rev.Lett. 124 (2020) 07180, 1909.11111]
Stefania Gori, Gilad Perez [2005.05170]

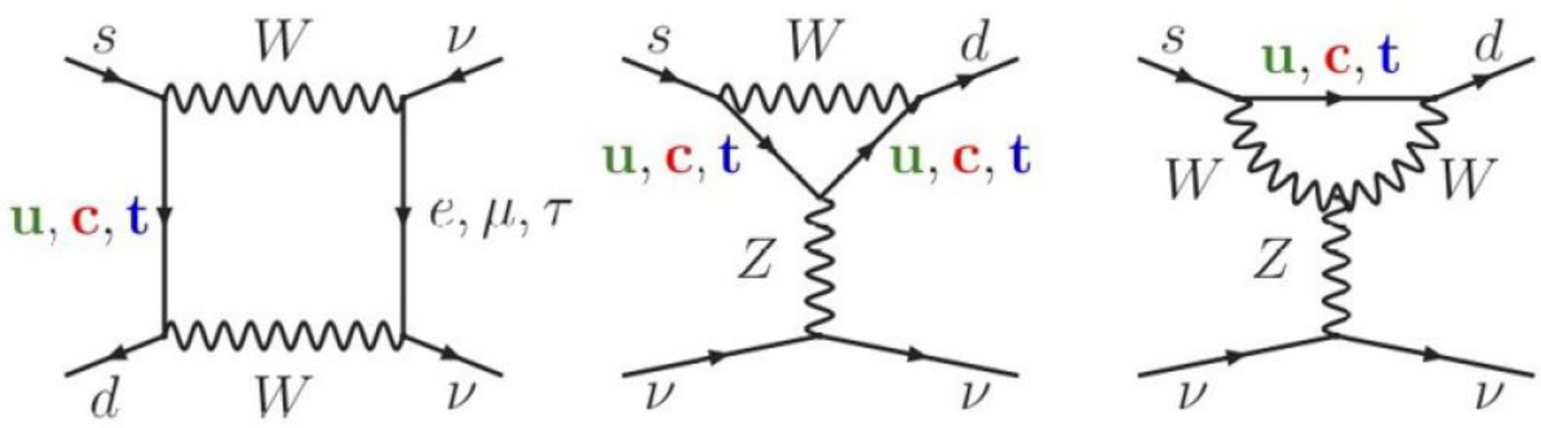
Introduction

Very Rare Kaon Decays

$$K^+ \to \pi^+ \nu\bar{\nu}$$
$$\propto |\mathcal{M}|^2$$

$$K_L \to \pi^0 \nu\bar{\nu}$$
$$\propto (\mathrm{Im}\mathcal{M})^2$$

$\mathcal{M}$ ~

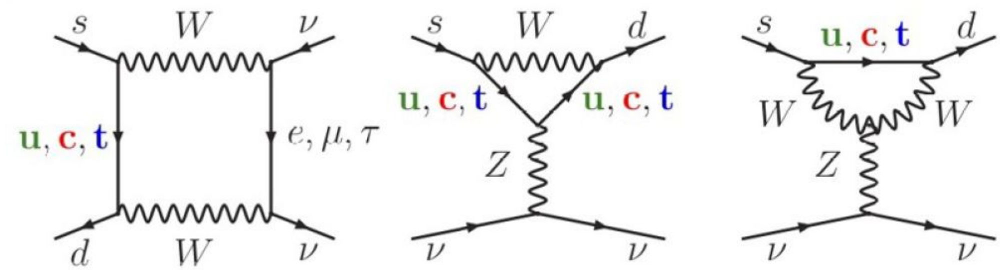


Extremely rare and precise process in SM. [Buras et al., 1503.02693]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11}$$

- **Br~10^{-11}** due to suppressions of 1loop, CKM and GIM
- Unlike LHC physics, a few events are already significant!

Grossman-Nir bound

$\mathcal{M}$ ~ 

- Br[K_L] indirectly bounded by Br[K^+] [Y. Grossman and Y. Nir ('97)]

$$\frac{\Gamma[K_L \to \pi^0 \nu\bar{\nu}]}{\Gamma[K^+ \to \pi^+ \nu\bar{\nu}]} = \frac{(\mathrm{Im}\ M)^2}{|M|^2} \leq 1$$

Isospin relation(**ΔI=1/2**)

$$\rightarrow \boxed{\frac{\mathrm{BR}[K_L \to \pi^0 \nu\bar{\nu}]}{\mathrm{BR}[K^+ \to \pi^+ \nu\bar{\nu}]} \leq 4.3}$$

Ratio of total widths
+isospin breaking

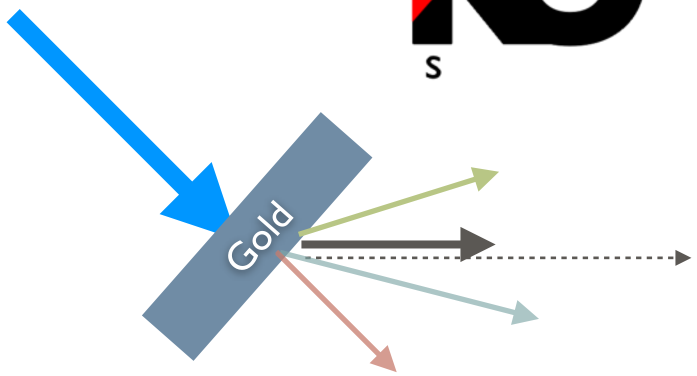
- GN bound can be generalized to new physics case

$$\rightarrow \boxed{\mathrm{BR}(K_L \to \pi^0 X) \lesssim 4.3 \mathrm{BR}(K^+ \to \pi^+ X)}$$

saturates,e.g., when X is CP-even [H. Leutwyler, M. A. Shifman('90)]

Experiments for Rare Koan Decays

JPARC KOTO

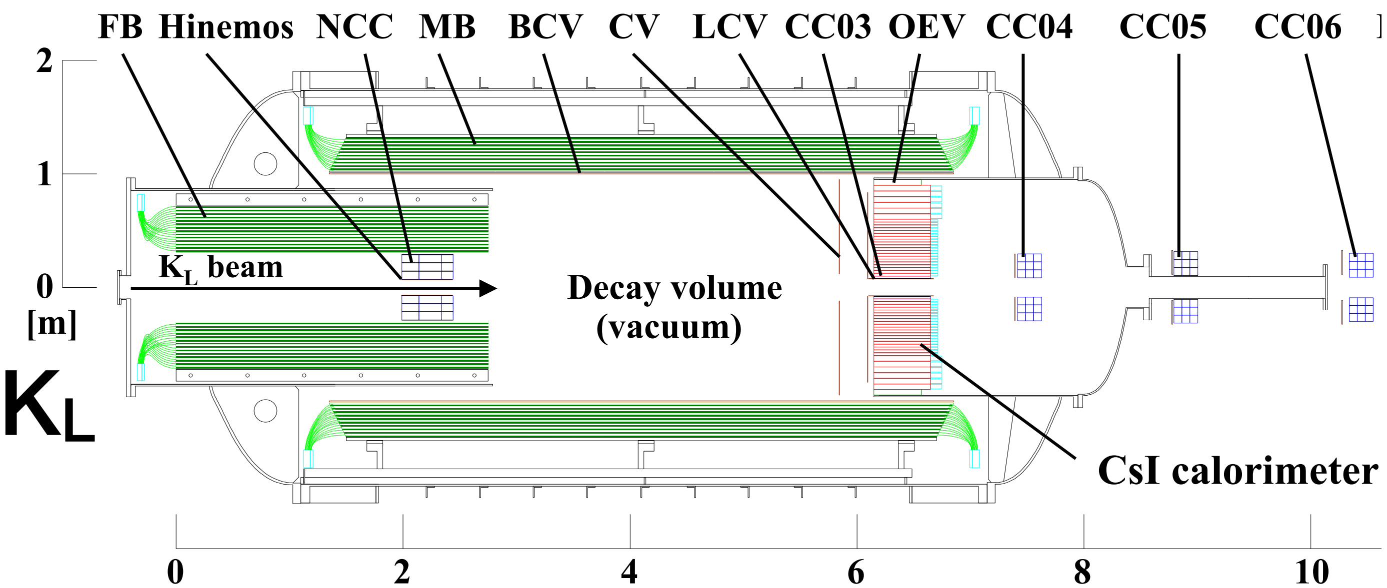


30GeV p
since 2013 (restart '15)

~2GeV K_L

~3m

Mainly ECAL

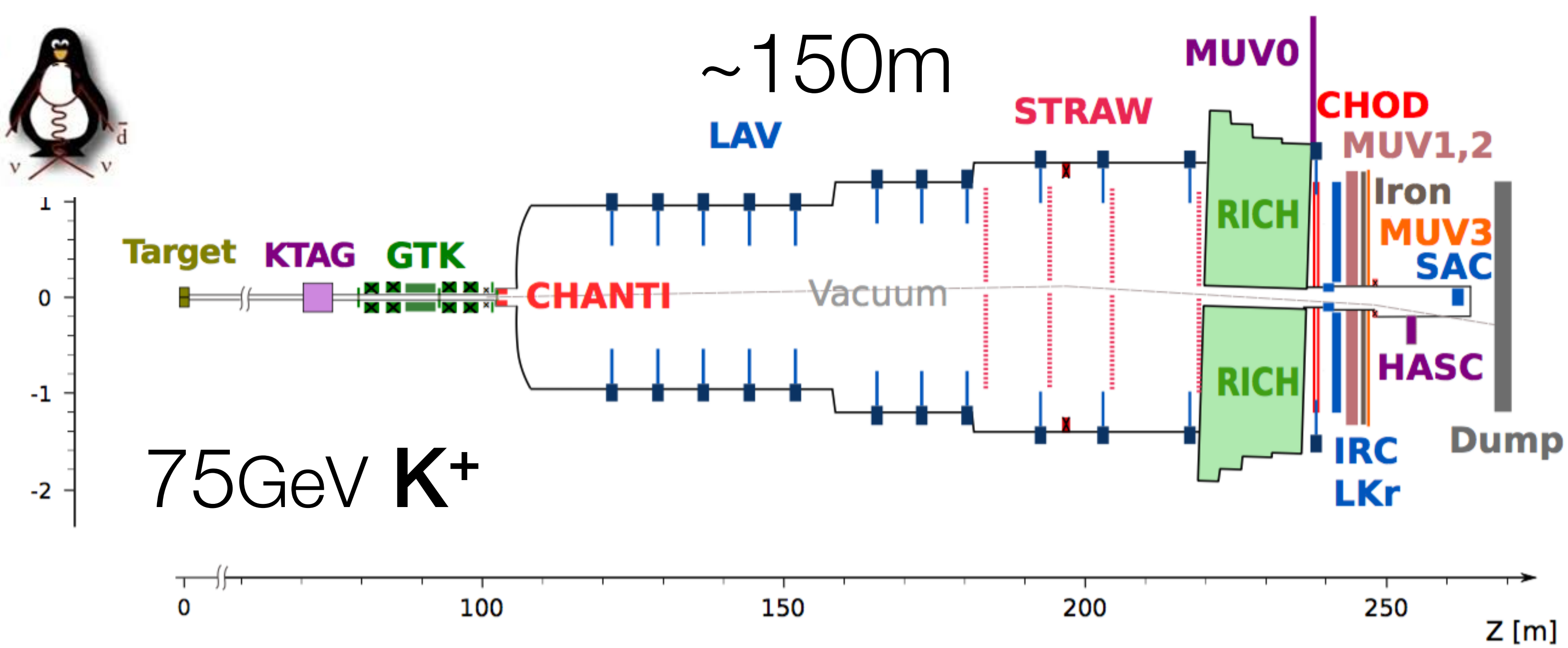


CERN NA62

400GeV p from SPS
physic run since 2015

~150m

75GeV K^+



Aim for precision Br~10^{-11} ⇒ **N_K~10^{13}** ≫ $N_{B\text{-pair,BelleII}}$~$10^{11}$!!

Reports
at KAON2019

Observed Events at KOTO

2019/9/10 KAON2019 1

Search for the rare decay $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment

Satoshi Shinohara (Osaka Univ.),
on behalf of the KOTO collaboration

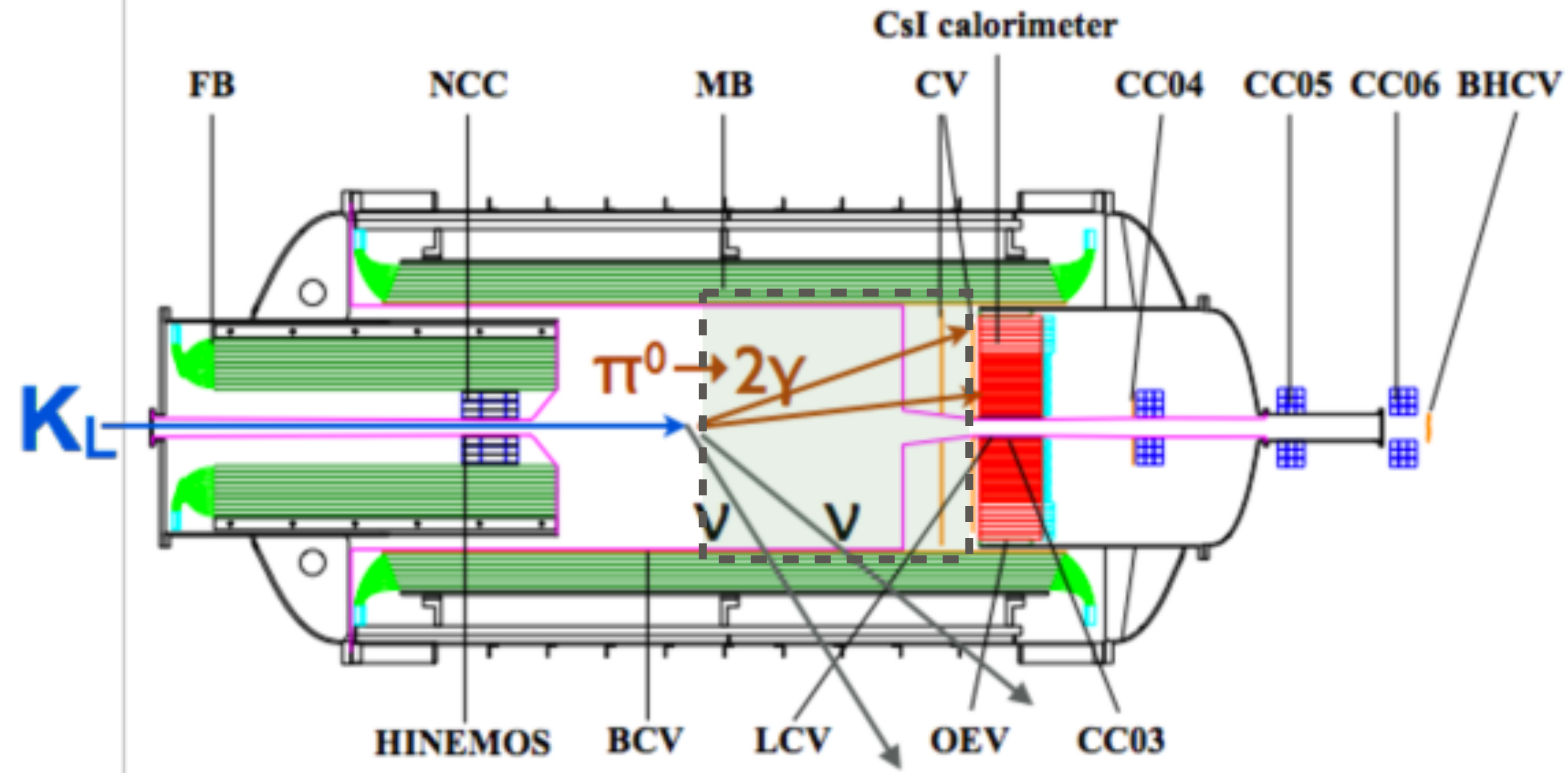
KAON2019
10-13 September 2019 University of Perugia (Italy)

https://indico.cern.ch/event/769729/contributions/3510939/attachments/1904988/3145907/KAON2019_shinohara_upload.pdf

Observed Events at KOTO

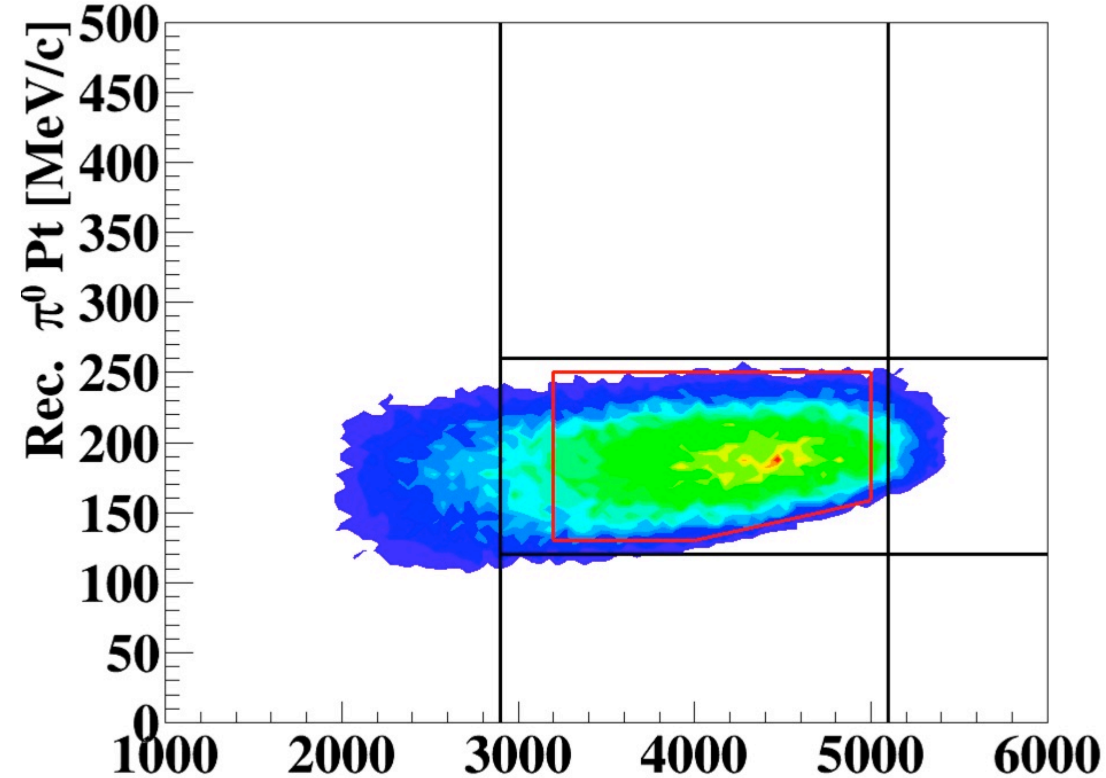
- Data until 2018
  Incoming 7×10^{12} K_L
  ~5×10^{11} K_L decays

- Two ECAL hits.
  Reconstruction assumes $\pi^0\to\gamma\gamma$.



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

Reconstructed
π^0 p_T [MeV]



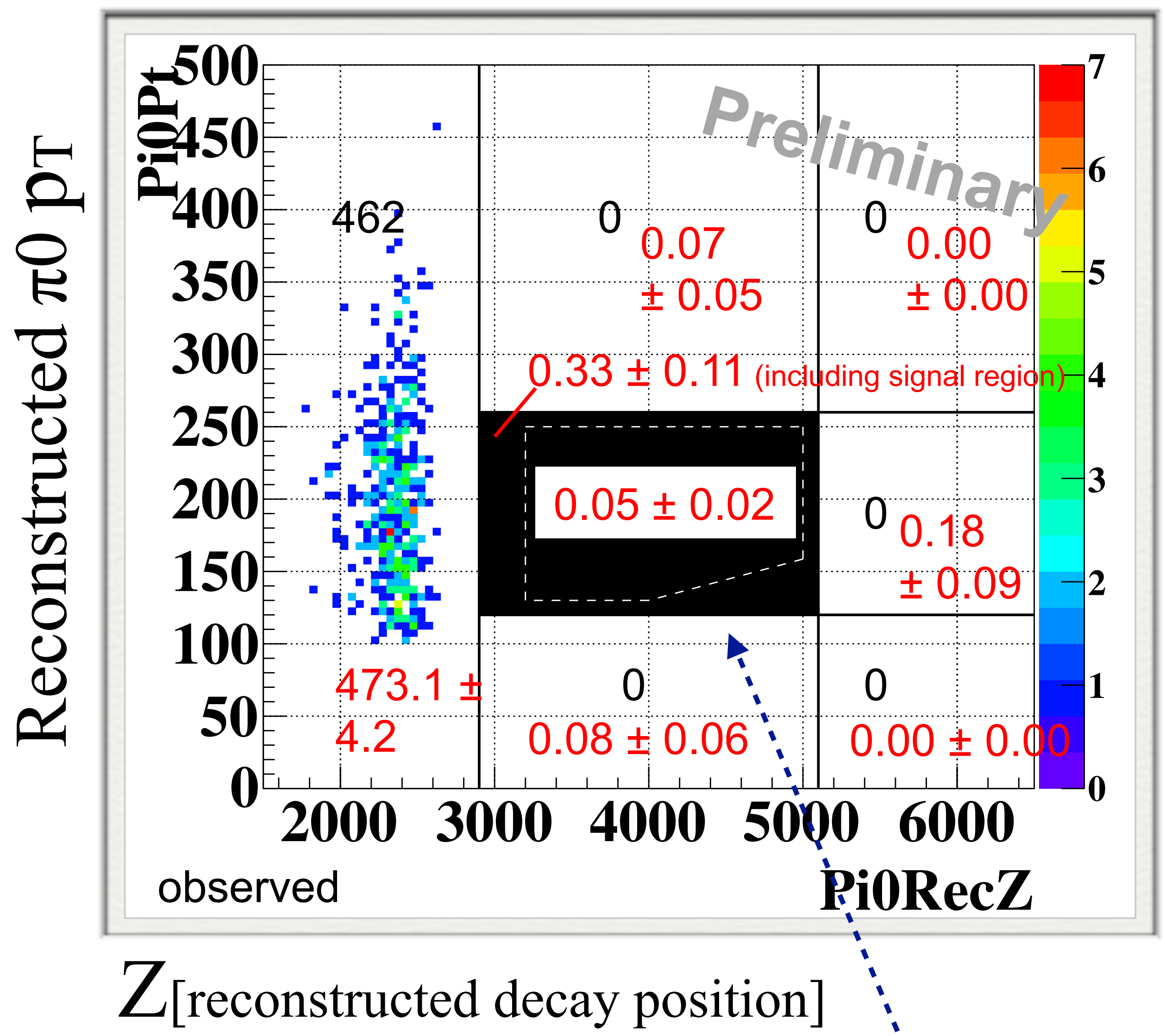
Z : reconstructed decay position

Observed Events at KOTO

Blind analysis

BG:0.05±0.02,

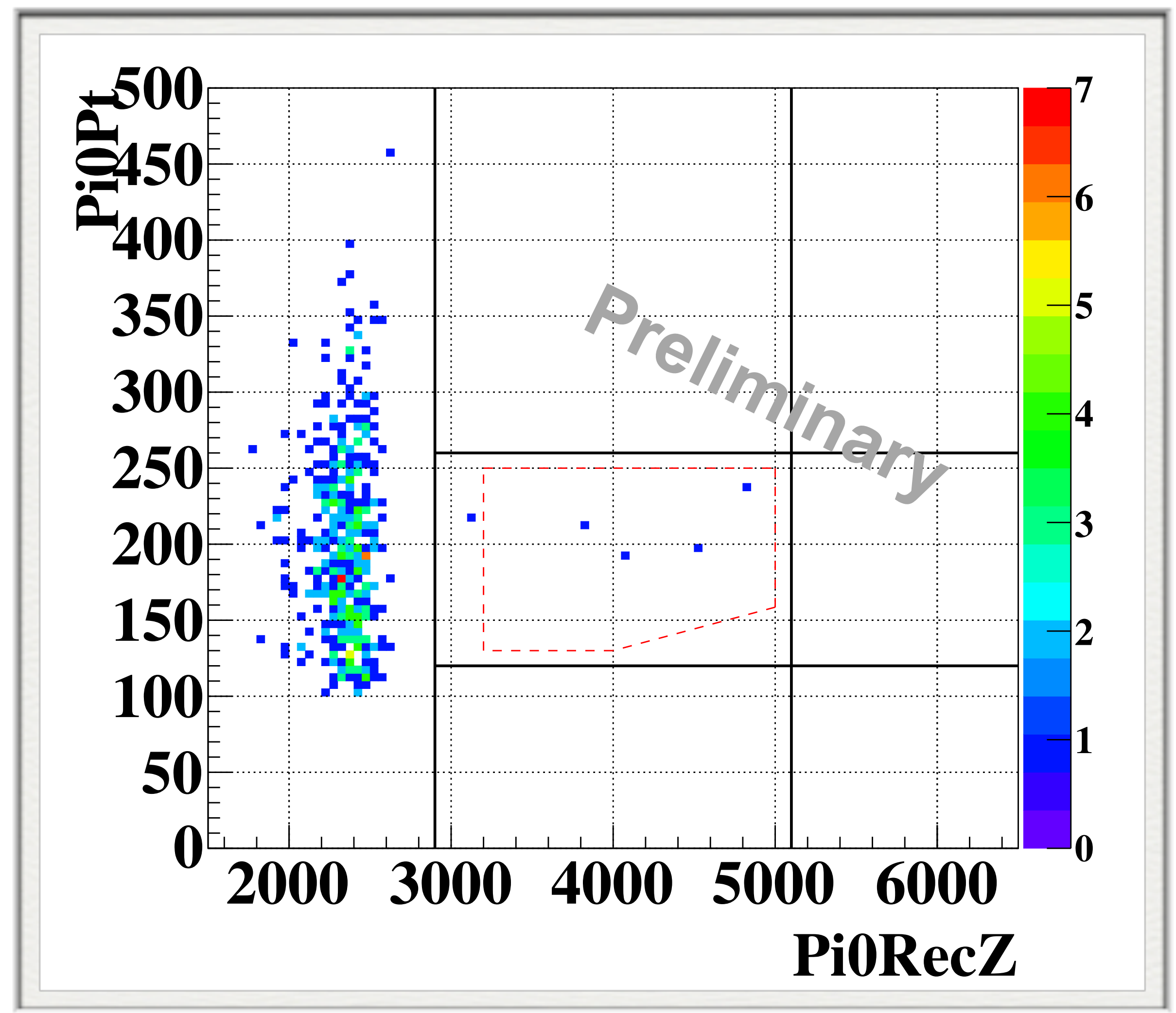
SM[$K_L \rightarrow \pi^0 \nu\nu$]0.05±0.01



signal region

[S. Shinohara, KAON2019]

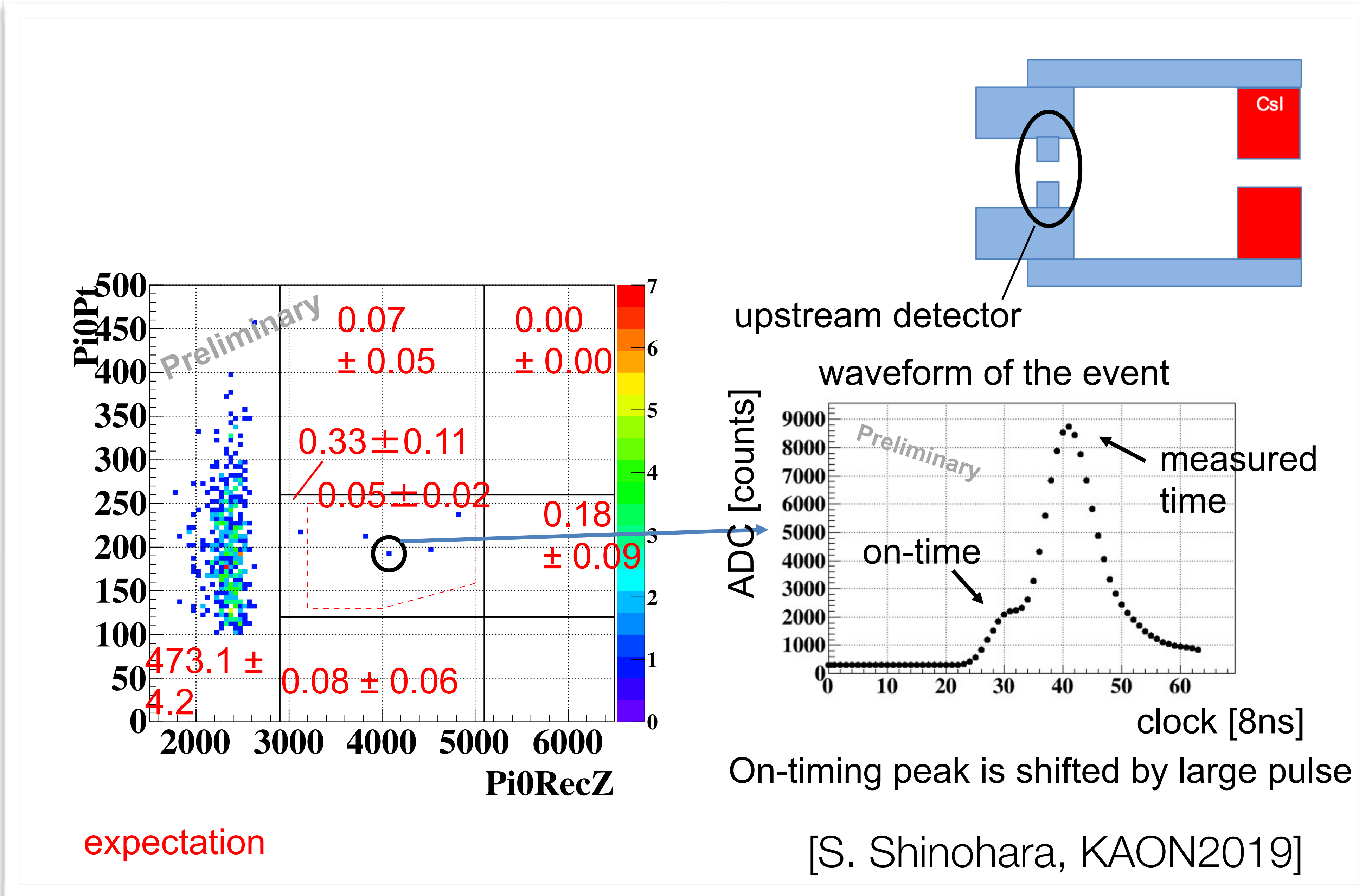
Open the box [unblinding]



4 events!

[nothing outside SR]

One event suspected as BG



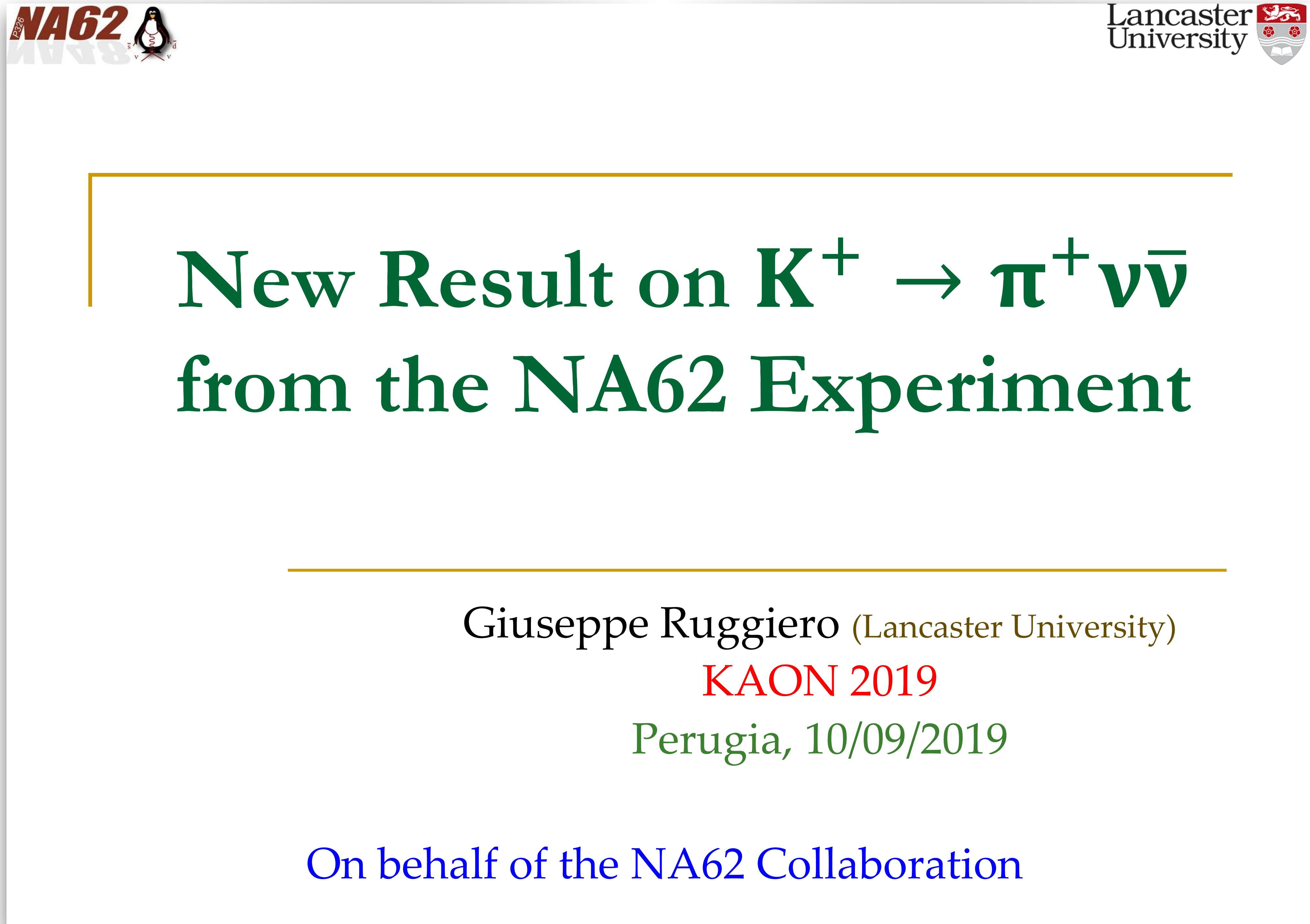
Even **3 events** ≫ **SM+BG~0.1.** *p-value*~10^{-4}

Corresponding BR

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = 2.1^{+2.0\,(+4.1)}_{-1.1\,(-1.7)} \times 10^{-9}$$

[Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

NA62 result at KAON2019



- Slightly inconsistent K^+ result reported in the same conference via GN bound

GN bound tension: KOTO vs NA62

2016+2017 Result

- 2016 and 2017 data uncorrelated

Events observed	3
Single event sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected background	1.65 ± 0.31

- Upper limits (CLs method)

Observed	Expected (background only)	CL
$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$	$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.32 \times 10^{-10}$	90%
$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \times 10^{-10}$	$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.62 \times 10^{-10}$	95%

- Two-sided 68% band: $\boxed{Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}}$

KOTO data indicates

$$\boxed{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = 2.1^{+2.0\,(+4.1)}_{-1.1\,(-1.7)} \times 10^{-9}}$$

Inconsistent with **GN bound**!

$$\frac{\mathrm{BR}[K_L \to \pi^0 \nu\bar{\nu}]}{\mathrm{BR}[K^+ \to \pi^+ \nu\bar{\nu}]} \leq 4.3$$

2D Statistical Test and GN Bound

[Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

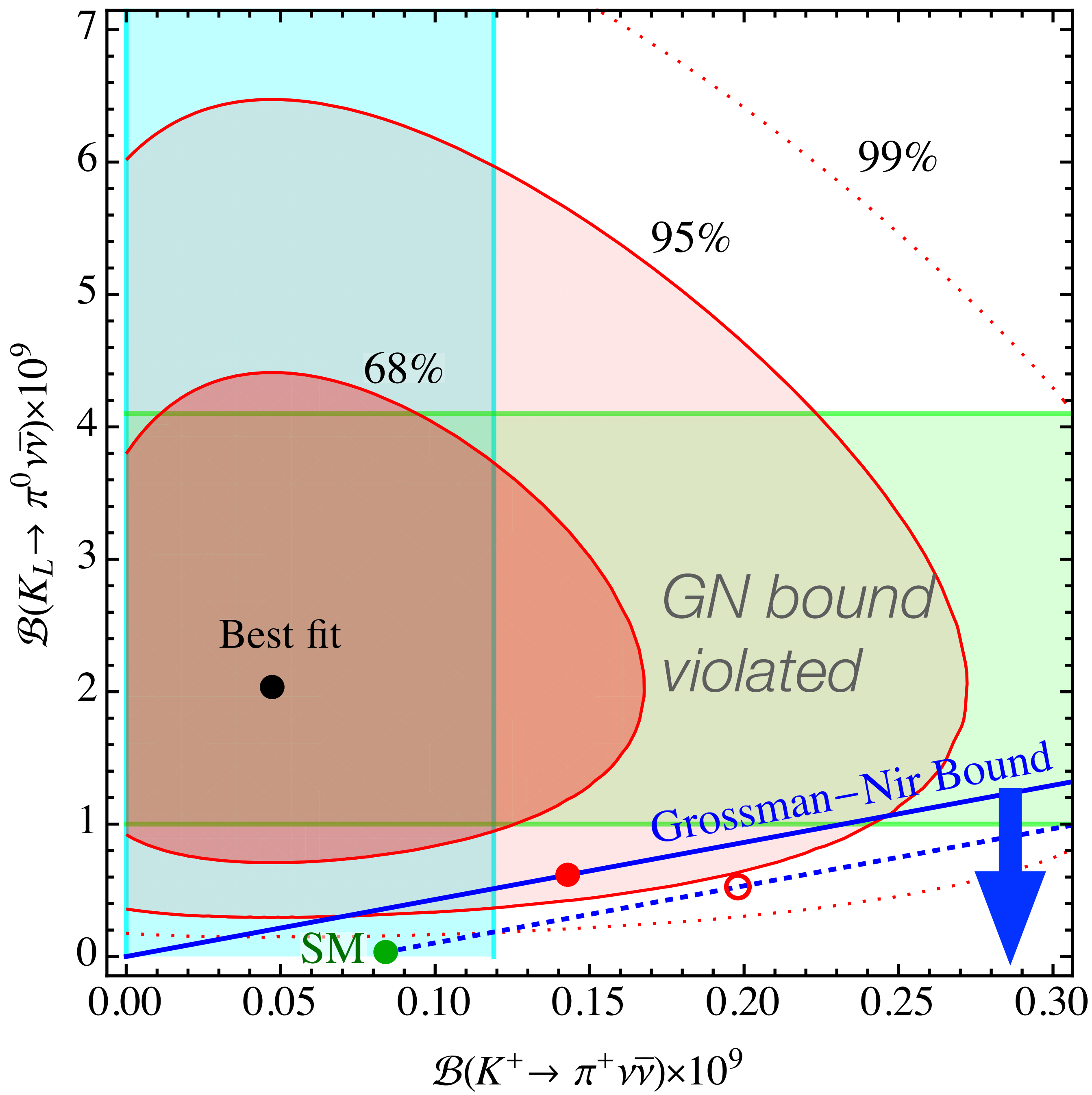
- SM point, inconsistent **3+σ**

- IF GN bound saturates [1D]

$$\frac{\mathrm{BR}[K_L \to \pi^0 \nu \bar{\nu}]}{\mathrm{BR}[K^+ \to \pi^+ \nu \bar{\nu}]} = 4.3$$

still tension of **2.1 σ**

- Violation of GN bound in $K \to \pi \nu \nu$ is very difficult.



If this is NP, ***a new light state*** is favored.

Dark Sector

with Grossman-Nir bound and Beyond

Dark Sector with Grossman-Nir bound and Beyond

- Heavy new physics

  EFT: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
  Leptoquark:R. Mandal, A. Pich [1908.11155]
  Z′: Calibbi, Crivellin, Kirk, Manzari, and Vernazza [1910.00014],
  Aebischer, Buras, Kumar [2006.01138]
  Generic neutrino interactions: Li, Ma, and Schmidt [1912.10433]
  Breaking Grossman-Nir: He, Ma, Tandean,and Valencia [2002.05467, 2005.02942]

- Light new state with GN bound

  General analysis: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
  Light dark fermions (do not work): Fabbrichesi and Gabrielli (1911.03755)
  Light scalars: Fuyuto, Hou, Kohda [1412.4397]
  Egana-Urinovic, Homiller, and Meade [1911.10203]
  Dev, Mohapatra, and Zhang [1911.12334]
  Liu, McGinnis, Wagner, and Wang (2001.06522) [muon g-2]
  Banerjee, Kim, Matsedonskyi, Perez, Safronova [2004.02899]…
  Light gauge boson: Jho, Lee, S.C. Park, Y. Park, and Tseng [2001.06572]

- Light new states violating GN bound

  M. Pospelov. Status and phenomenology of light bsm. talk Jan 20, 2019
  R. Ziegler, J. Zupan, R. Zwicky [2005.00451] S. Gori, G. Perez, KT [2005.05170],
  M. Hostert, K. Kaneta, M. Pospelov [2005.07102], W. Altmannshofer, B. V. Lehmann, S. Profumo [2006.05064]

- Exotic (not in this talk)

  Fixed target production: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
  Pionium($K_L \to \pi^0 A_{2\pi}$): P. Lichard [arXiv:2006.02969]

Heavy New Physics

Conventional solution: SM higher dim. operator due to heavy state

[Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

$$\mathcal{O}_{\rm BSM}(\psi_{\rm SM}) \supset \sum C_i \mathcal{O}_i$$ to enhance $K\to\pi\nu\nu$

$$\mathcal{O}_{\rm S} = \bar{L}\bar{\sigma}^{\mu}L\ \bar{Q}_2\bar{\sigma}_{\mu}Q_1$$

$$\mathcal{O}_{\rm T} = \bar{L}\tau^{a}\bar{\sigma}^{\mu}L\ \bar{Q}_2\tau^{a}\bar{\sigma}_{\mu}Q_1$$

$$\mathcal{O}_{\rm R} = \bar{L}\bar{\sigma}^{\mu}L\ s^{c}\bar{\sigma}_{\mu}\bar{d}^{c}$$

Best Fit

$$C_{S,R} - C_T \sim e^{-\frac{3}{4}\pi i}/(75\ \mathrm{TeV})^2$$

Lepton Universality
leads to charged lepton channels

$$K_L \to \pi^0\ell^+\ell^- \ \ (\ell = e,\mu)$$

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

bounds are BR~10^{-10}

Prescriptions

(1) neutrino is only ν_τ
(2) Impose $C_R = C_S$

K. Agashe, R. Contino, L. Da Rold, and A. Pomarol,[hep-ph/0605341

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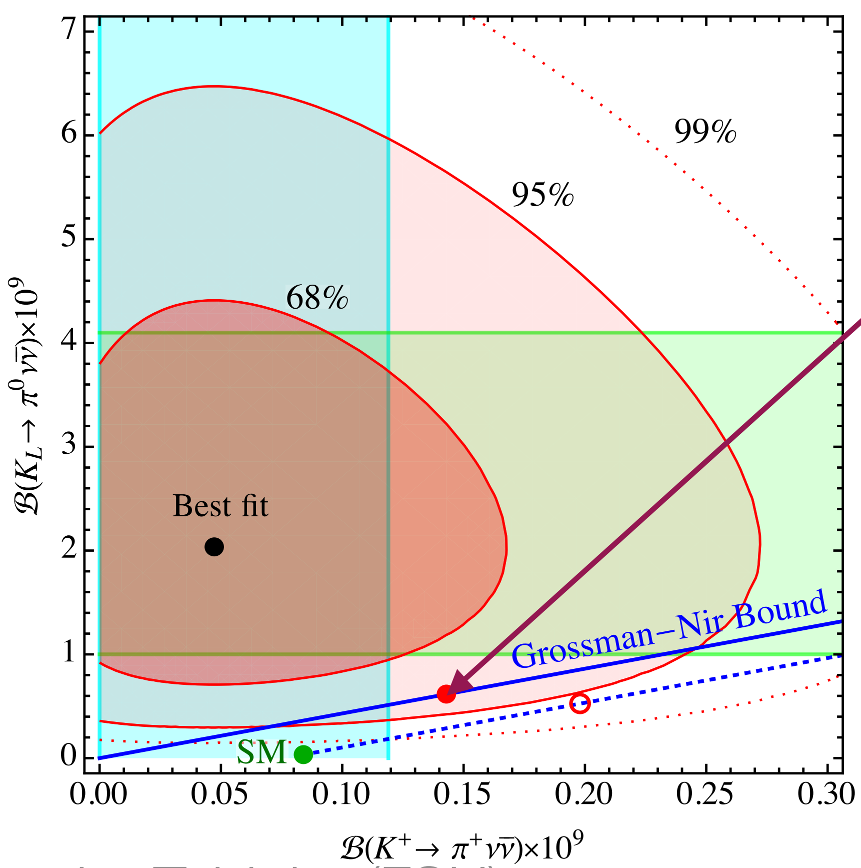
GN bound tension



Best Fit

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still **2.1σ** tension

*Operator violating GN bound starts **dimension 9(ΔI=3/2) w/ Λ~10GeV**

He, Ma, and Valencia [2002.05467]

BR[K_L]<4.3BR[K^+]→17BR[K^+]

Heavy New Physics

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GN bound tension

Best Fit

$$C_{S,R} - C_T \sim e^{-\frac{3}{4}\pi i}/(75\ \mathrm{TeV})^2$$

still **2.1σ** tension

New light state?

*Operator violating GN bound starts
dimension 9(ΔI=3/2) w/ Λ~10GeV

He, Ma, and Valencia [2002.05467]

BR[K_L]<4.3BR[K^+]→17BR[K^+]

New Light State

Light New Physics *with GN bound*

Single light particle couples to SM. [Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

$$\mathcal{O}_{\rm SM} X$$

X: SM gauge singlet
m_X<350MeV
$\mathcal{O}_{\rm SM} \supset \bar{s}d$

→

$K_L \to \pi^0 X$
$K^+ \to \pi^+ X$

Respects GN bound→**How to accommodate K^+ results**

$$\mathrm{BR}(K_L \to \pi^0 X) \lesssim 4.3 \mathrm{BR}(K^+ \to \pi^+ X)$$

Light New Physics *with GN bound*

Single light particle couples to SM.

[Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

$$\mathcal{O}_{\rm SM} X$$

X: SM gauge singlet

m_X<350MeV

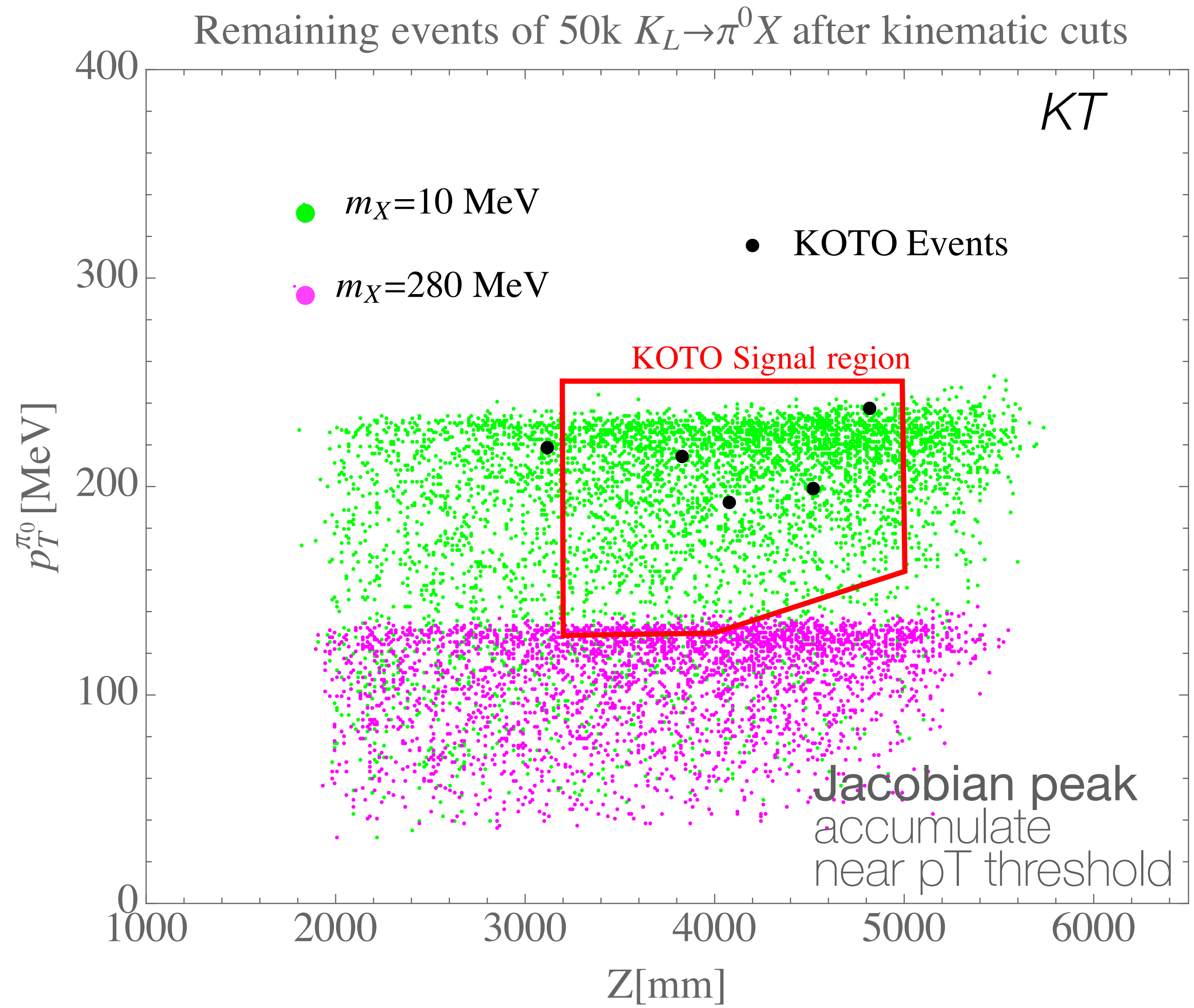
$\mathcal{O}_{\rm SM} \supset \bar{s}d$

$K_L \to \pi^0 X$

$K^+ \to \pi^+ X$

For KOTO events,

- Observed events are aligned. Prefer $K_L \to \pi^0 X$ to $K_L \to \pi^0 \nu\nu$.



Light New Physics *with GN bound*

Single light particle couples to SM. [Kitahara, Okui, Perez, Soreq, **KT** (1909.11111)]

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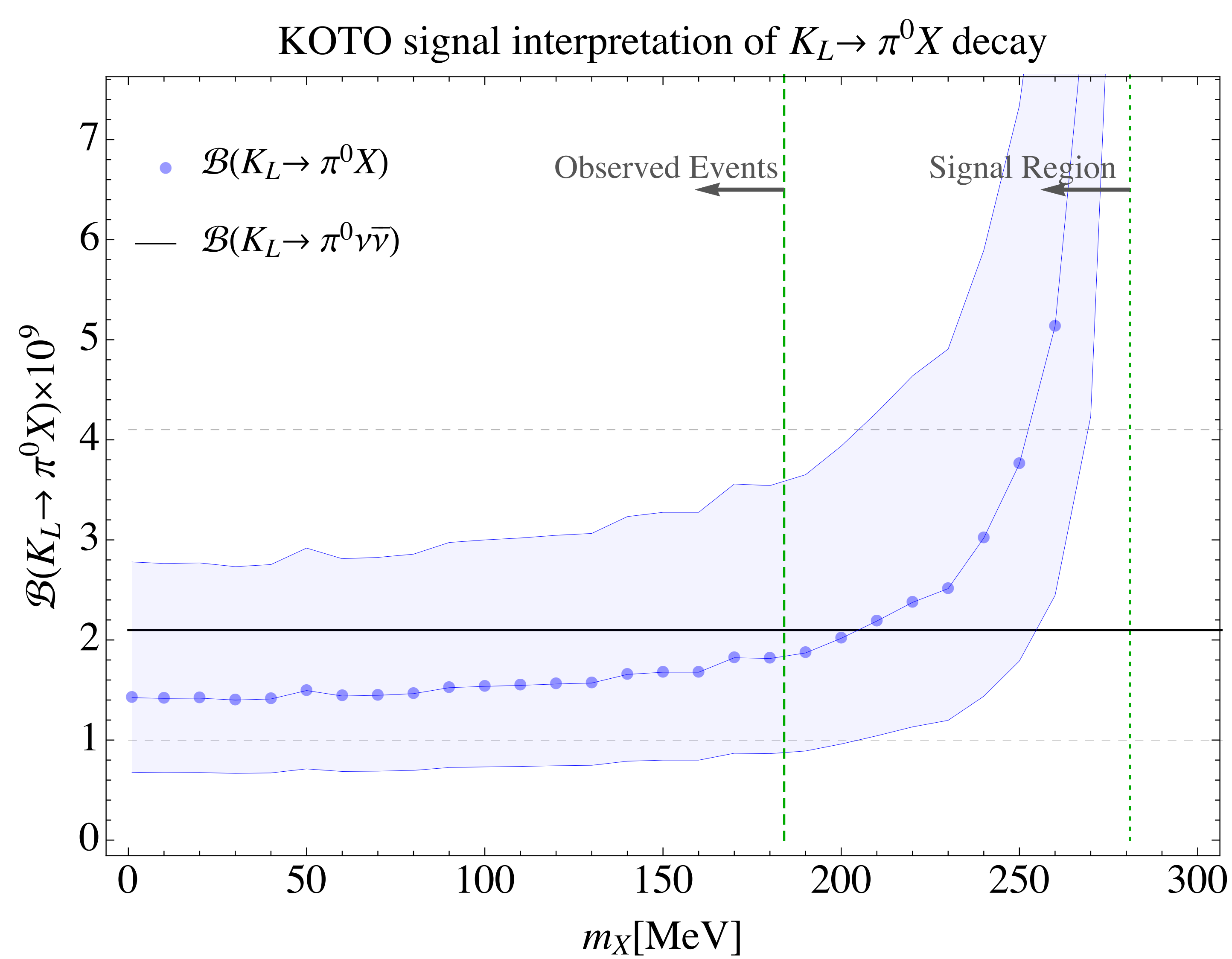
X: SM gauge singlet
m_X<350MeV
$\mathcal{O}_{\rm SM} \supset \bar{s}d$

$K_L \to \pi^0 X$
$K^+ \to \pi^+ X$

For KOTO events,

- Observed events are aligned. Prefer $K_L \to \pi^0 X$ to $K_L \to \pi^0 \nu\nu$.
- Large mX→less $p_{T,max}^{\pi 0}$. **BR~10^-9** and **m_X<180MeV** to accommodate 3 events.



Two regions compatible with K^+[NA62, E949]

- GN bound saturated [best case, X:CP even]. Require 3 events at KOTO.

$$\mathcal{B}(K_L \to \pi^0 X) = 4.3\mathcal{B}(K^+ \to \pi^+ X)$$

E949 bound [0903.0030]
NA62 $\mathcal{B}(K^+ \to \pi^+ X)^{95\%\mathrm{CL}}_{\mathrm{NA62}} = 1.6 \times 10^{-10}$

Two experimental loopholes

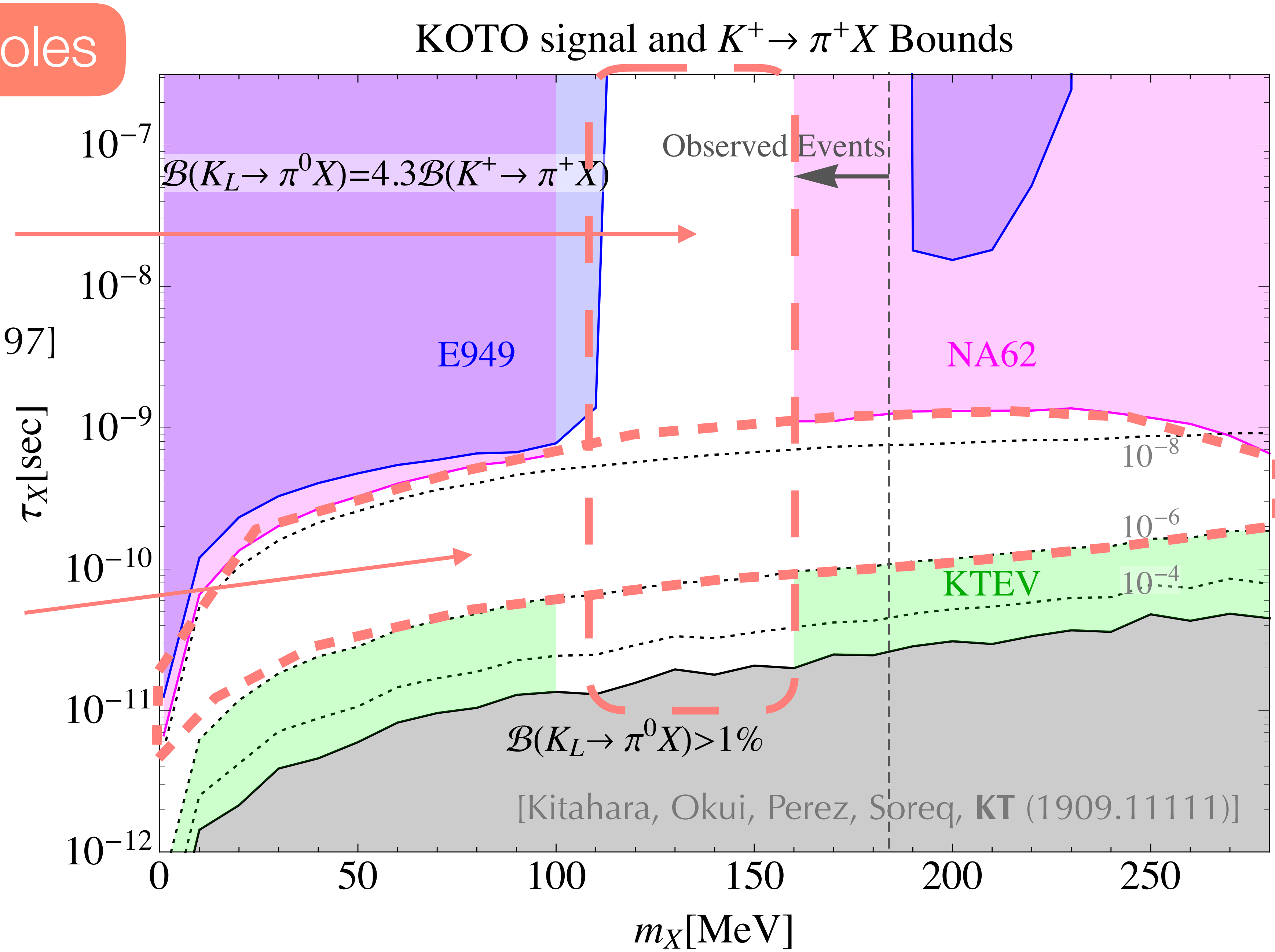
(1) $m_X \sim m_{\pi 0}$ loophole

Large $K^+ \to \pi^+\pi^0$ BG

Fuyuto, Hou, Kohda [1412.4397]

(2) Finite lifetime of X

Exploit detector size.



Two regions compatible with K^+[NA62, E949]

(1) $m_X \sim m_{\pi 0}$ loophole

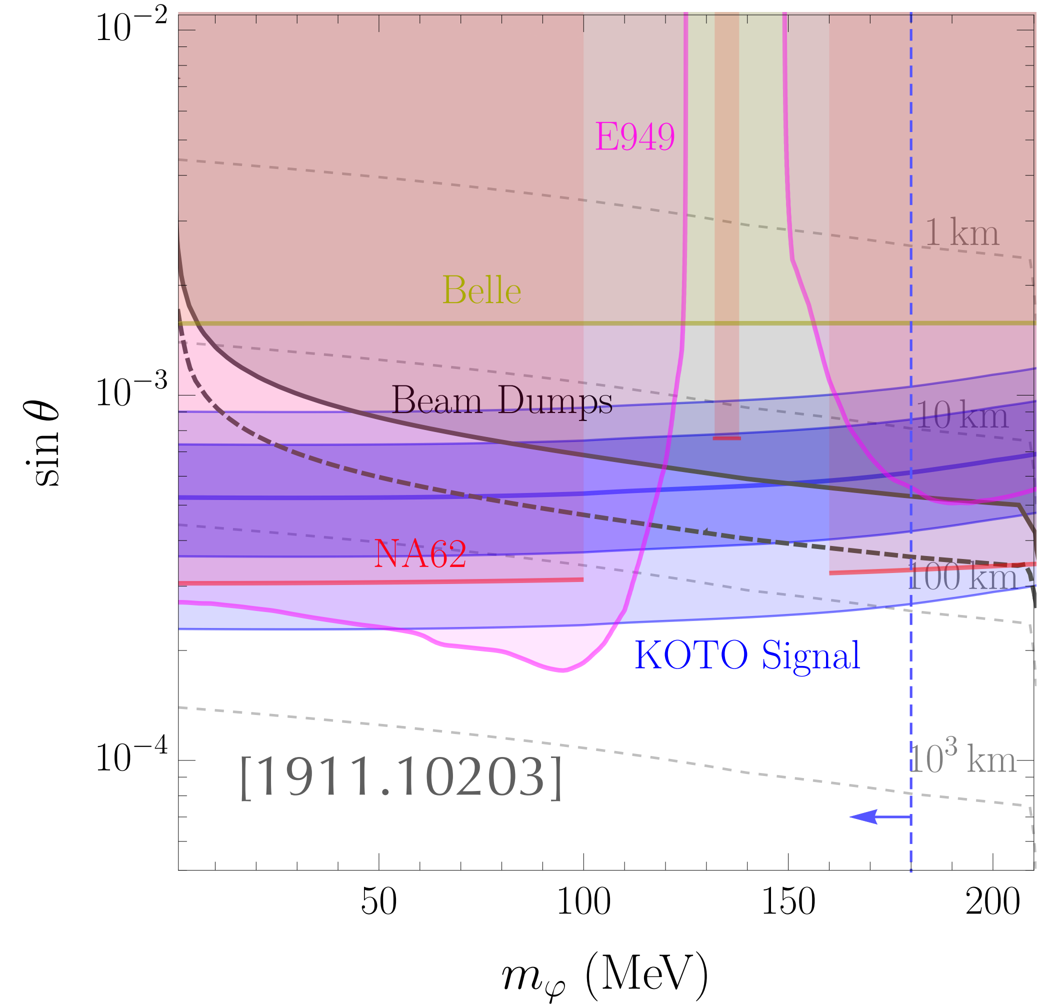
Large $K^+ \to \pi^+ \pi^0$ BG

Fuyuto, Hou, Kohda [1412.4397]

Minimal Higgs portal works.

A little tension with CHARM.

Egana-Ugrinovic, Homiller, Meade [1911.10203]



(2) Finite lifetime of X

If X is unstable (τ_X~nsec),

Some X does not decay at KOTO while all decay to $\gamma\gamma$ at NA62(E949)

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

Effective Br in each experiment as "invisible X"

Decay factor of X

$L_{\mathrm{NA62}}/p_{\mathrm{NA62}} > L_{\mathrm{KOTO}}/p_{\mathrm{KOTO}}$

NA62 is effectively larger

see also F. Kling, S. Trojanowski [2006.10630]

Dark Sector

beyond GN bound

Light New Physics violating GN (I)

With more than 2 dark sector particles, **GN bound violated**.

$$\mathcal{O}_{\rm SM} X_1 X_2$$

$X_{1,2}$: SM singlet

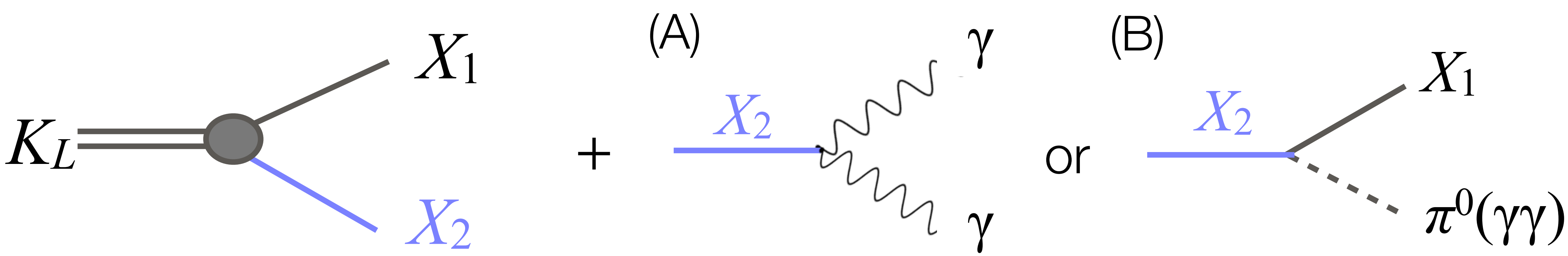
$\mathcal{O}_{\rm SM} \supset \bar{s}d$

$K_L \to X_i X_j$

$K^+ \to \pi^+ X_i X_j$

M. Pospelov [talk, Jan 2020], S. Gori, G. Perez, **KT** [2005.05170] M. Hostert, K. Kaneta, M. Pospelov [2005.07102]

- **Neutral particle (e.g., K^0, B^0) decays directly to dark sector.**
- Charged particle decays with extra SM particle (π^+) $\to 1/16\pi^2$ or forbidden.



Light New Physics violating GN (I)

With more than 2 dark sector particles, **GN bound violated**.

$$\mathcal{O}_{\rm SM} X_1 X_2$$

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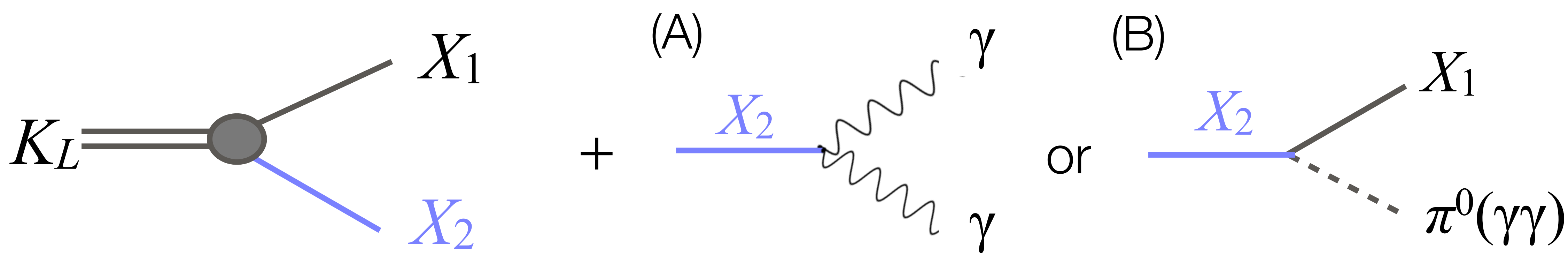
- **Neutral particle (e.g., K^0, B^0) decays directly to dark sector.**
- Charged particle decays with extra SM particle (π^+) → $1/16\pi^2$ or forbidden.



(A)E.g. ϕ carries 1/2 strange (or 2nd generation) charge [*ϕ: stable*] [2005.05170]

$$y_1 H\bar{Q}_1 s\phi^2/\Lambda^2 \qquad y_2 H\bar{Q}_2 d\phi^2/\Lambda^2$$

$$K_L \to \sigma\chi$$

Small breaking induces $\chi=\mathrm{Im}[\phi]$ decays to γγ

$$\mathcal{L}_\chi \supset \frac{\chi}{\Lambda_\chi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\chi \to \gamma\gamma$$

Another realization w/Higgs portal&Z' in [2005.07102]

Light New Physics violating GN (I)

With more than 2 dark sector particles, **GN bound violated**.

$$\mathcal{O}_{\rm SM} X_1 X_2$$

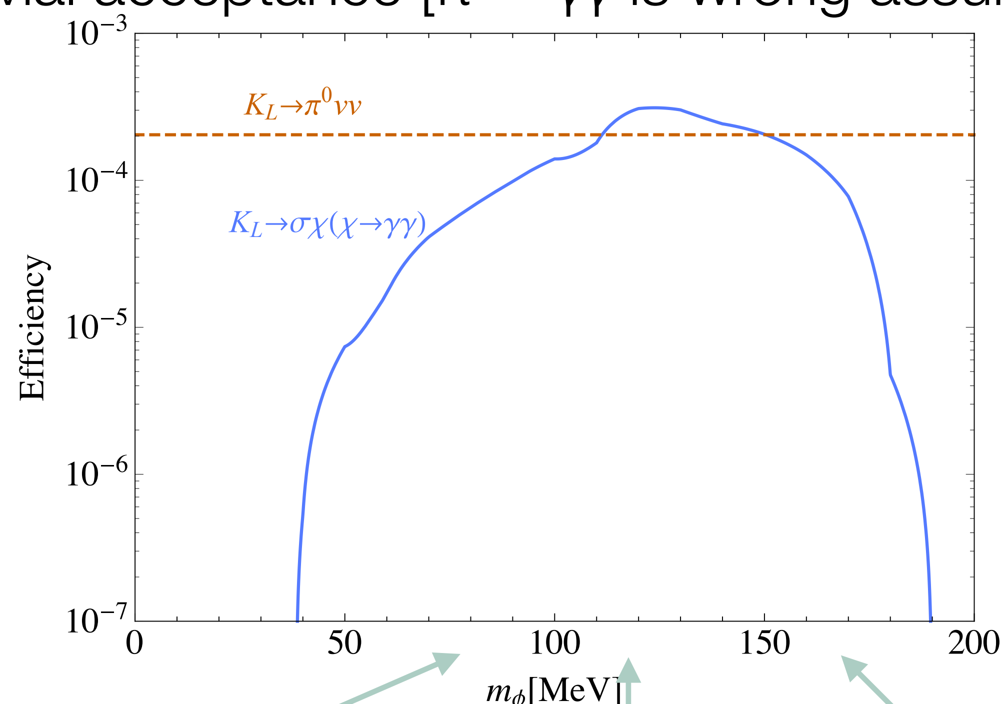
$X_{1,2}$: SM singlet

$\mathcal{O}_{\rm SM} \supset \bar{s}d$

$K_L \to X_i X_j$

$K^+ \to \pi^+ X_i X_j$

non-trivial acceptance [$\pi^0 \to \gamma\gamma$ is wrong assumption]

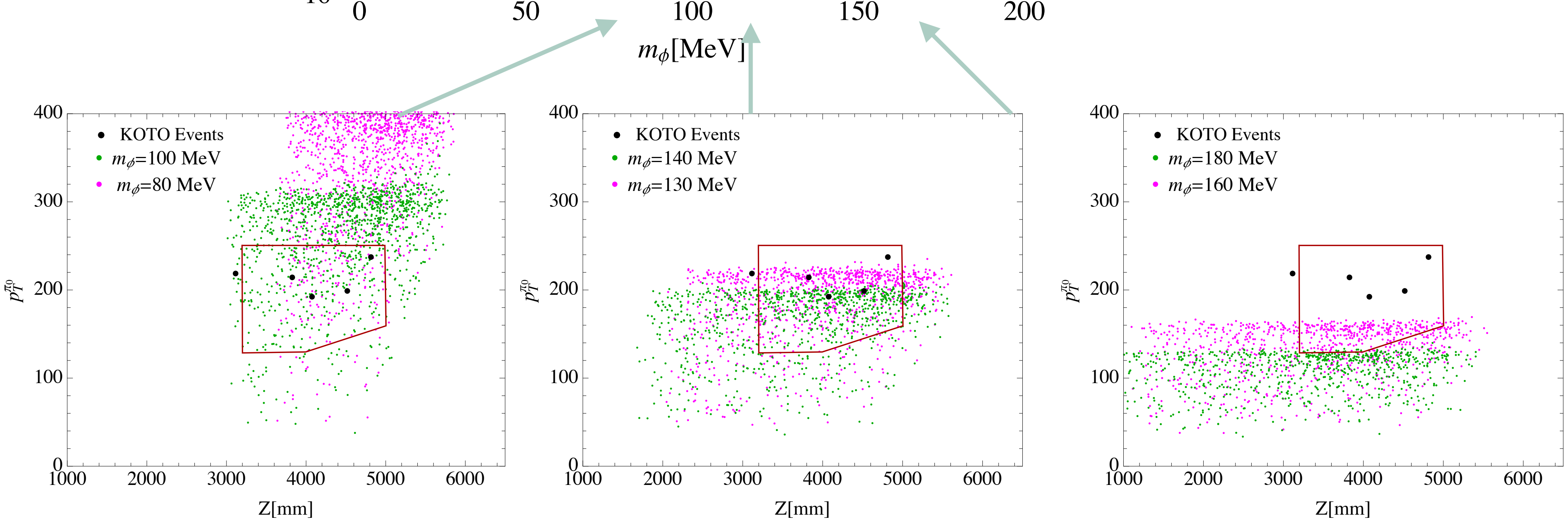


To explain KOTO events

$m_{\phi(\sigma,\chi)}$~[80GeV,140GeV]

Λ~10^7GeV (B[$K_L\to\gamma\gamma$+inv]~10^{-9})

Λ_χ~50TeV (prompt decay)



Light New Physics violating GN (II)

With more than 2 dark sector particles, **GN bound violated**.

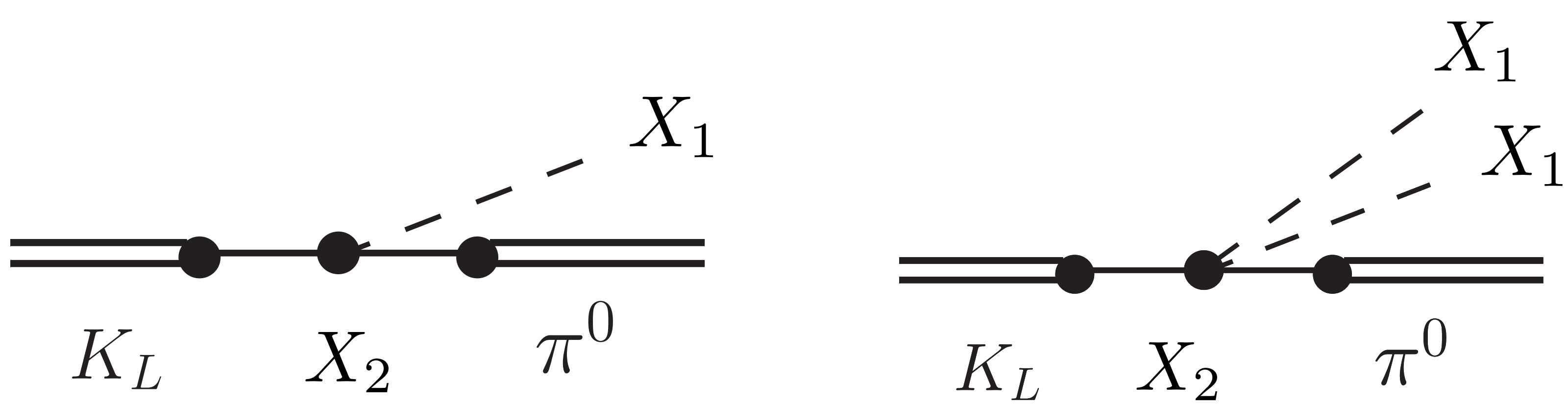
$$\mathcal{O}_{\rm SM} X_2 + \lambda m_X X_1 X_2^2, \lambda' X_1^2 X_2^2$$

$$\mathcal{O}_{\rm SM} \supset g_{sd}\bar{s}d,\ g_{dd}\bar{d}d$$

$K_L \to \pi^0 X_1 (X_1)$
$K^+ \to \pi^+ X_1 (X_1)$

R. Ziegler, J. Zupan, R. Zwicky [2005.00451]

Mixing among neutral particles: K_L, π^0, and new scalar X_2.



$m_{X2} > m_K$ but has to be light, since BR[$K_L \to \pi^0 X_1 (X_1)$] ~$(1/m_{X2})^8$.

Constrains from K-Kbar oscillation(g_{sd}), SN1987, beam dump (g_{dd})

Prospects

KOTO is investigating all the events

optimistic

pessimistic

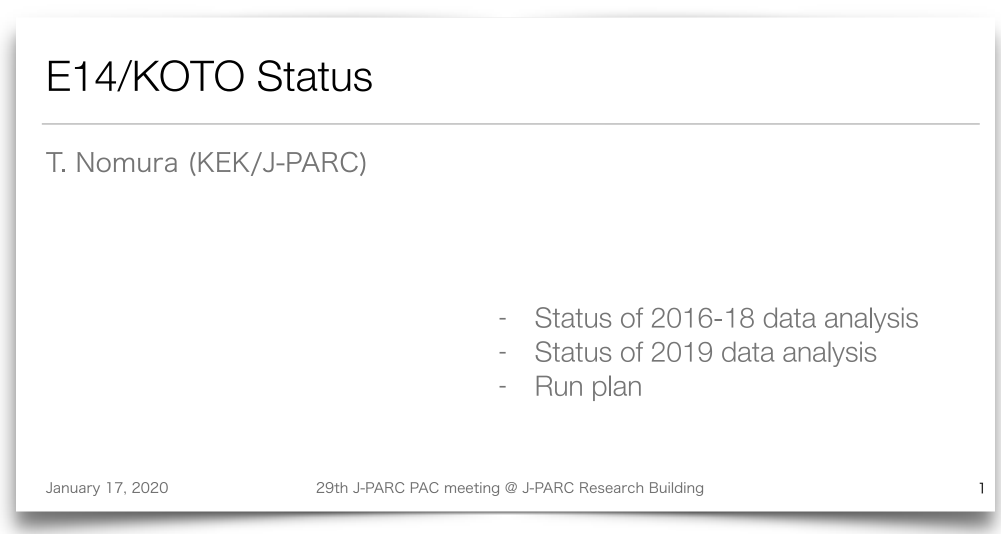
→ Current events confirmed.
GN violation indicates light new state(s)!
Search @beam dump[e^+e^-], $K^+ \to \pi^+\gamma\gamma$, KLEVER

→ Mild excess remains.
Heavy NP scenarios revive. Need more precision.

→ All the KOTO events are new BG.
SM wins. Wait for new data (<u>a few events are exciting!</u>)

talk in Jan 2020,
still preliminary.

https://kds.kek.jp/indico/event/33442/contributions/162199/attachments/128878/153930/KOTO_pac200117_v3.pdf



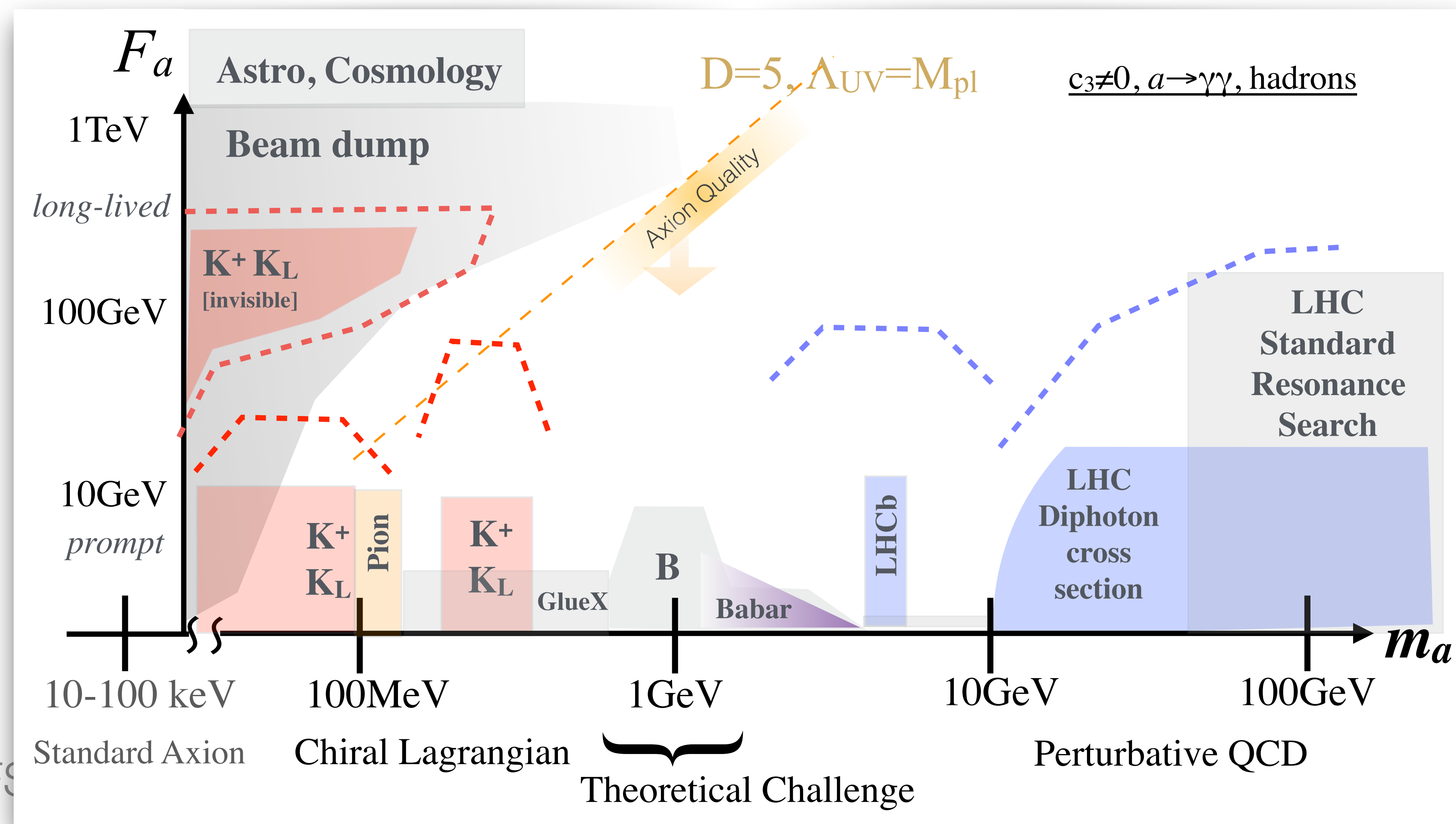
Search for Axion-like-particles via Kaon

- Consider an ALP with $\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$ for the strong CP problem
- PQ quality problem: $\Phi|\Phi|^{D-1}/\Lambda_{UV}^{D-4}$
  Global symmetry is not robust. The ALP potential ruined even by gravity.
- Large m_a and small f_a are favored

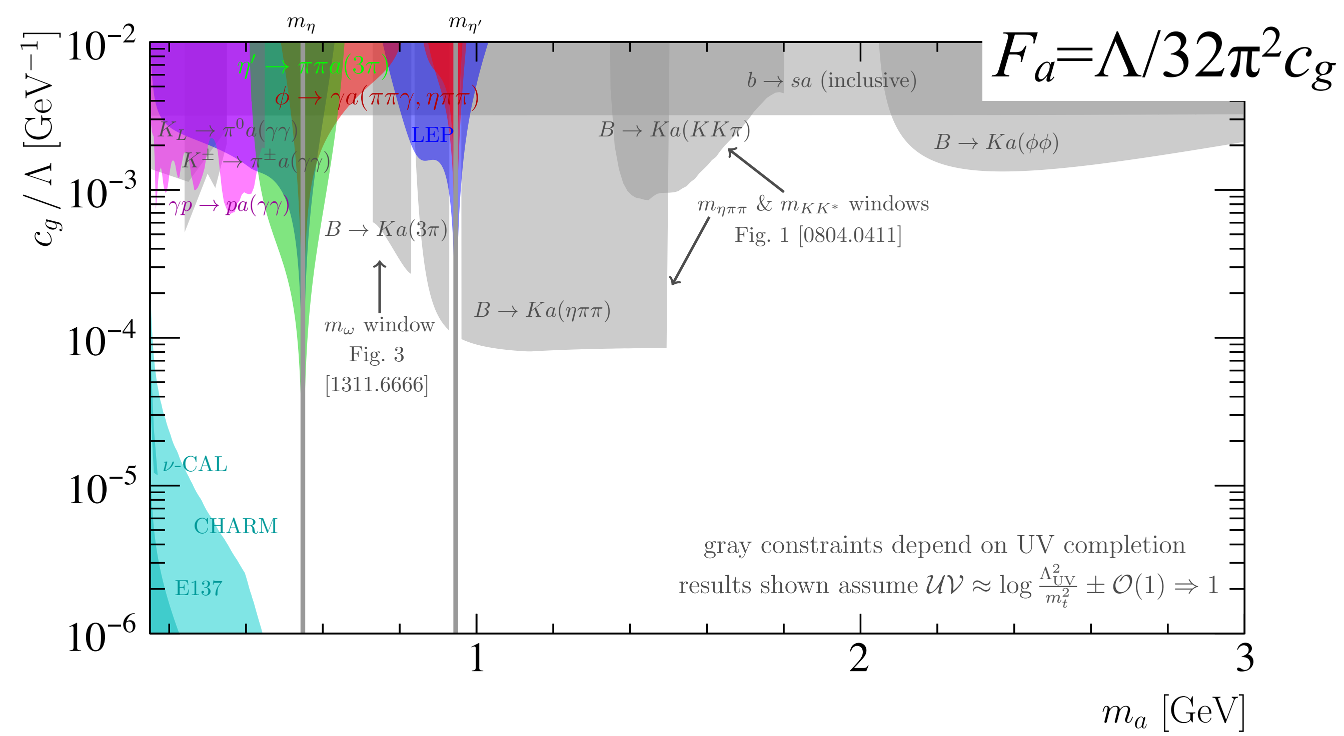
$$V(a) = m_a^2 F_a^2 \left\{1 - \cos\left(\frac{a}{F_a}\right)\right\} + \frac{F_a^2}{\Lambda_{UV}^{D-4}} \cos\left(\frac{a}{F_a} + \Delta\right)$$

$$\to \delta\bar{\theta} = \frac{\delta a_{min}}{F_a} \sim \frac{F_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}},$$

Big picture &status



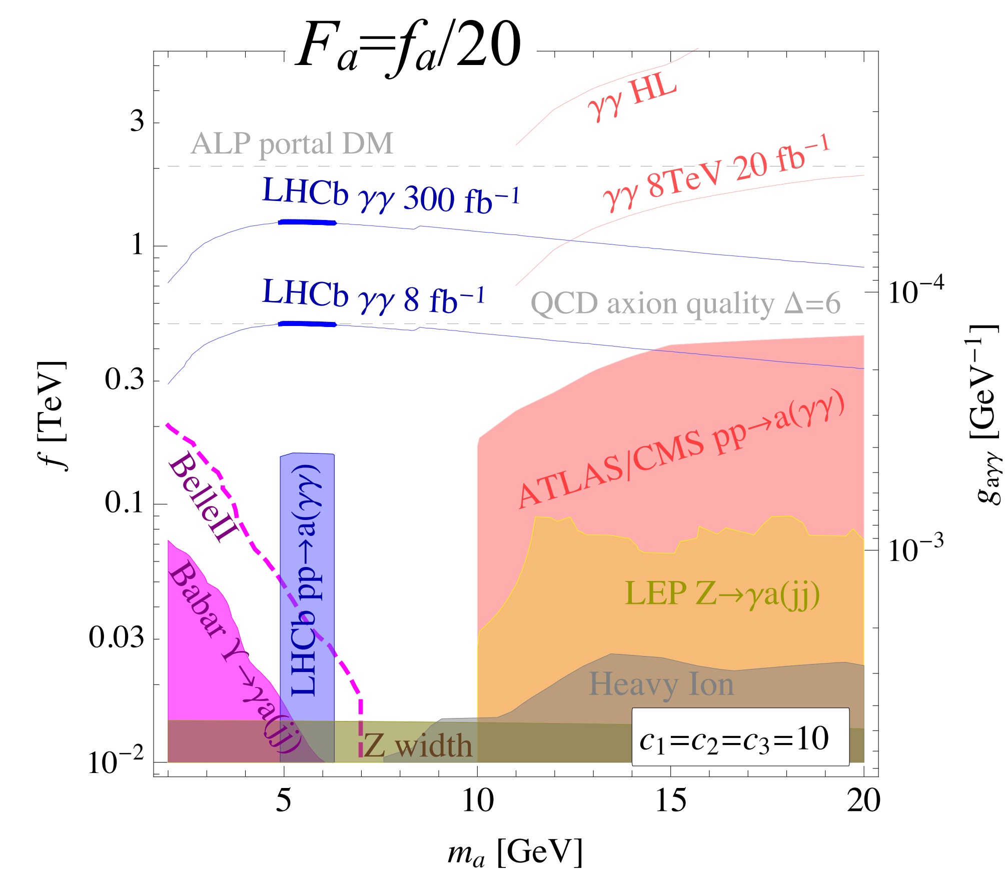
Search for Axion-like-particles via Kaon



D. Aloni, Y. Soreq, M. Williams [1811.03474, 1903.03586]

fo

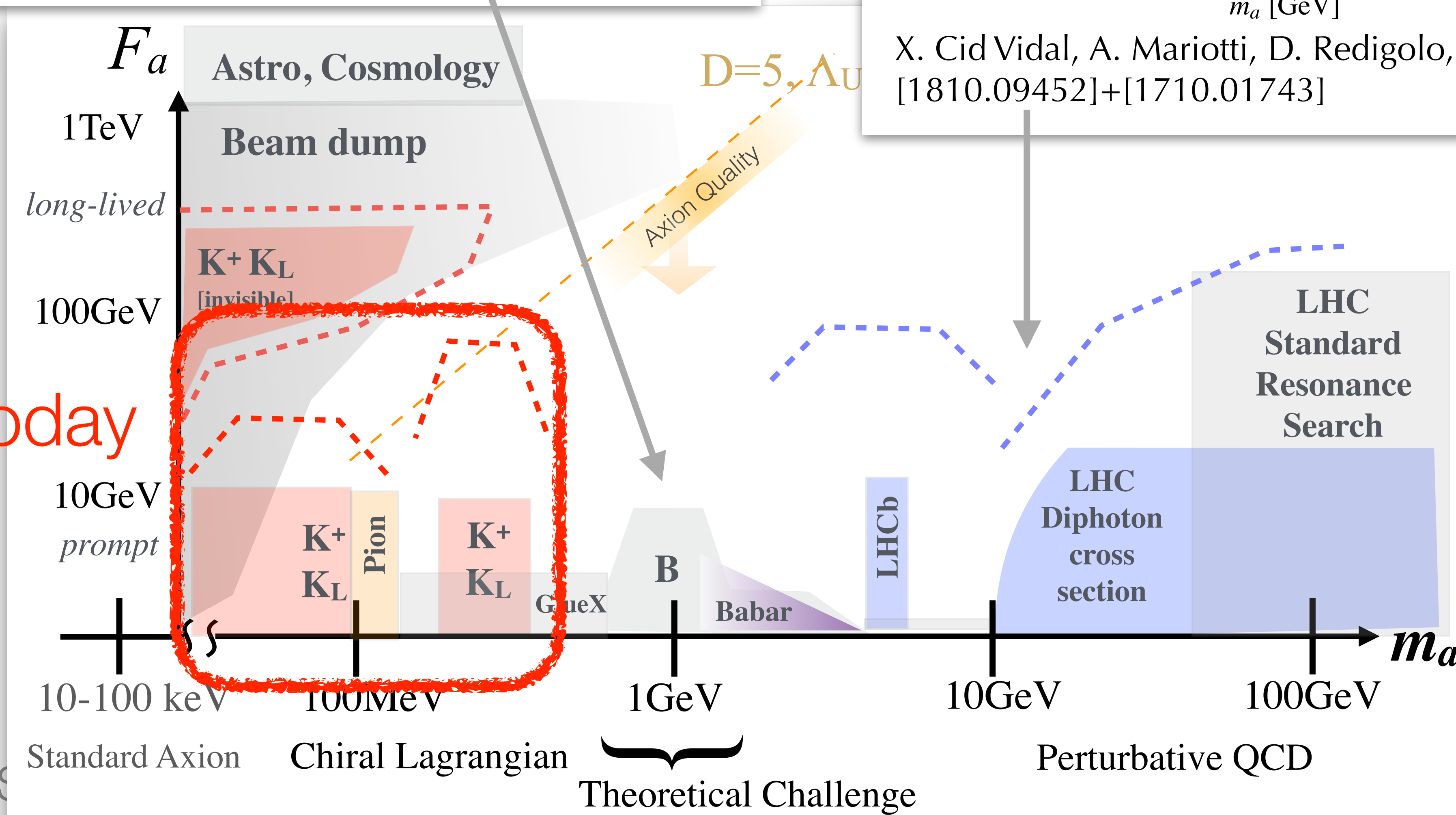
LP p



X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, **KT** [1810.09452]+[1710.01743]

Big picture &status

Today



K→πa from meson-ALP mixing

$\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$ induces axion mixing with mesons

$$\begin{pmatrix} a \\ \pi \\ \eta \end{pmatrix} \simeq \begin{pmatrix} 1 & -\frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & -\frac{K_\eta M_\eta^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} \\ \frac{K_\pi M_a^2}{M_\pi^2 - M_a^2} & 1 & 0 \\ \frac{K_\eta M_a^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{\rm phys} \\ \pi_{\rm phys} \\ \eta_{\rm phys} \end{pmatrix}$$

$$K_\pi = -\frac{F_\pi}{2F_a}(\kappa_u - \kappa_d), \quad K_\eta = -\frac{F_\pi}{\sqrt{6}F_a}(\kappa_u + \kappa_d - \kappa_s),$$

$$\delta M_{\eta a} = \sqrt{\frac{2}{3}} \frac{F_\pi}{F_a} \frac{m_u m_d m_s}{(m_u + m_d)(m_u m_d + m_d m_s + m_s m_u)} m_{\pi^0}^2$$

- Naively the production rate

$$\mathrm{BR}(K^+ \to \pi^+ a)_{\rm naive} \simeq \mathrm{BR}(K^+ \to \pi^+ \pi^0)\theta_{\pi a}^2 \frac{|\vec{p}_a|}{|\vec{p}_{\pi^0}|}$$

→not leading

"ΔI=1/2 rule" ΔI=1/2 (octet, 8_L) >> ΔI=3/2 (27plet, 27_L)

- ΔI=1/2 (octet) contribution is important, e.g. through η(')*

Weinberg('78); Bardeen, Tye('78); Antoniadis, Truong('82); Bardeen, Peccei, Yanagida('87)

$$\mathrm{Br}(K^+ \to \pi^+ a)\big|_{\text{octet enh.}} \approx \theta_{a\eta_{ud}}^2 \, 2 \frac{\Gamma_{K_s^0}}{\Gamma_{K^+}} \mathrm{Br}(K_s^0 \to \pi^+\pi^-) \frac{|\vec{p}_a|}{|\vec{p}_\pi|} D_{\pi\pi}^2$$

[1710.03764] D. Alves, N. Weiner

→still not enough

K→πa calculation update by χPT

- Naively the production rate

$$\mathrm{BR}(K^+ \to \pi^+ a)_{\mathrm{naive}} \simeq \mathrm{BR}(K^+ \to \pi^+\pi^0)\theta^2_{\pi a}\frac{|\vec{p_a}|}{|\vec{p_{\pi^0}}|}$$

- K→πη*(ΔI=1/2) contribution

$$\mathrm{Br}(K^+ \to \pi^+ a)\big|_{\text{octet enh.}} \approx \theta^2_{a\eta_{ud}}\, 2\,\frac{\Gamma_{K^0_S}}{\Gamma_{K^+}}\,\mathrm{Br}(K^0_s \to \pi^+\pi^-)\,\frac{|\vec{p}_a|}{|\vec{p}_\pi|}\,D^2_{\pi\pi}$$

- Update by χLagrangian, found octet & π-a mixing New!

$$\mathcal{L}_{\Delta S=1} = G_8 F_\pi^4 \mathrm{Tr}[\lambda_{sd} D^\mu \Sigma^\dagger D_\mu \Sigma] + G_{27} F_\pi^4 \left(L_{\mu 23} L^\mu_{11} + \frac{2}{3} L_{\mu 21} L^\mu_{13}\right) + h.c.$$

$$\to -iG_{27}F_\pi K^0\pi^0 a\left(-\frac{1}{\sqrt{2}}[2m^2_{K^0} - m^2_{\pi^0} - m^2_a]\theta_{\pi a} + \frac{1}{\sqrt{6}}[m^2_{K^0} - 2m^2_a + m^2_{\pi^0}]\theta_{\eta a}\right) + h.c.$$

$$-iG_8 F_\pi K^+\pi^- a\left(-[m^2_{\pi^+} - m^2_a]\theta_{\pi a} + \frac{2}{\sqrt{3}}[m^2_{K^+} - m^2_a]\theta_{\eta a}\right)$$

$G_{8(\Delta I=1/2)} \sim 20 \times G_{27(\Delta I=3/2)}$

accidental cancelation!

+we updated experimental constraints

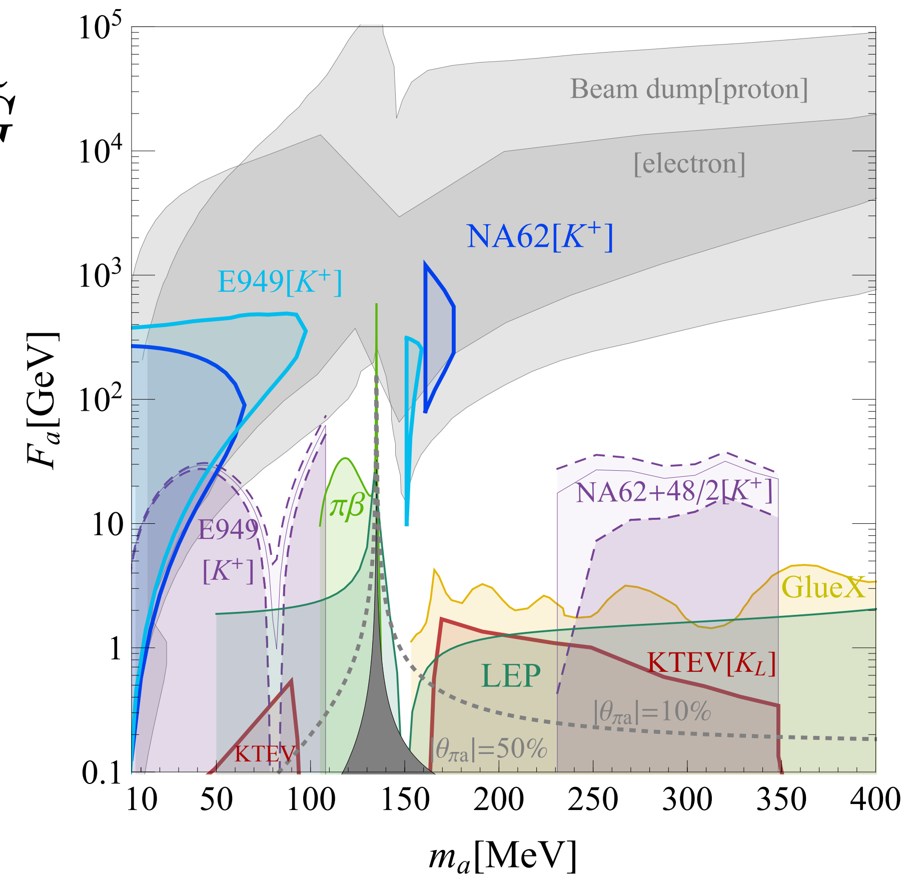
Another interesting program [ALPs]

Many new bounds and projection in S. Gori, G. Perez, **KT** [2005.05170]

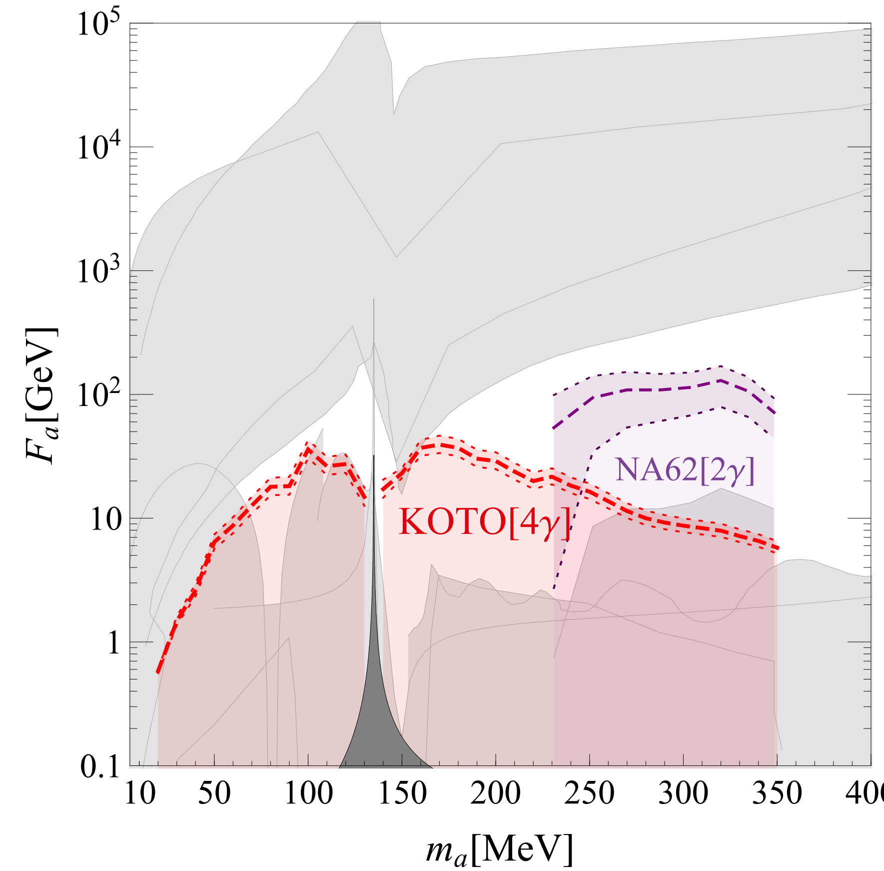
See Yotam's talk

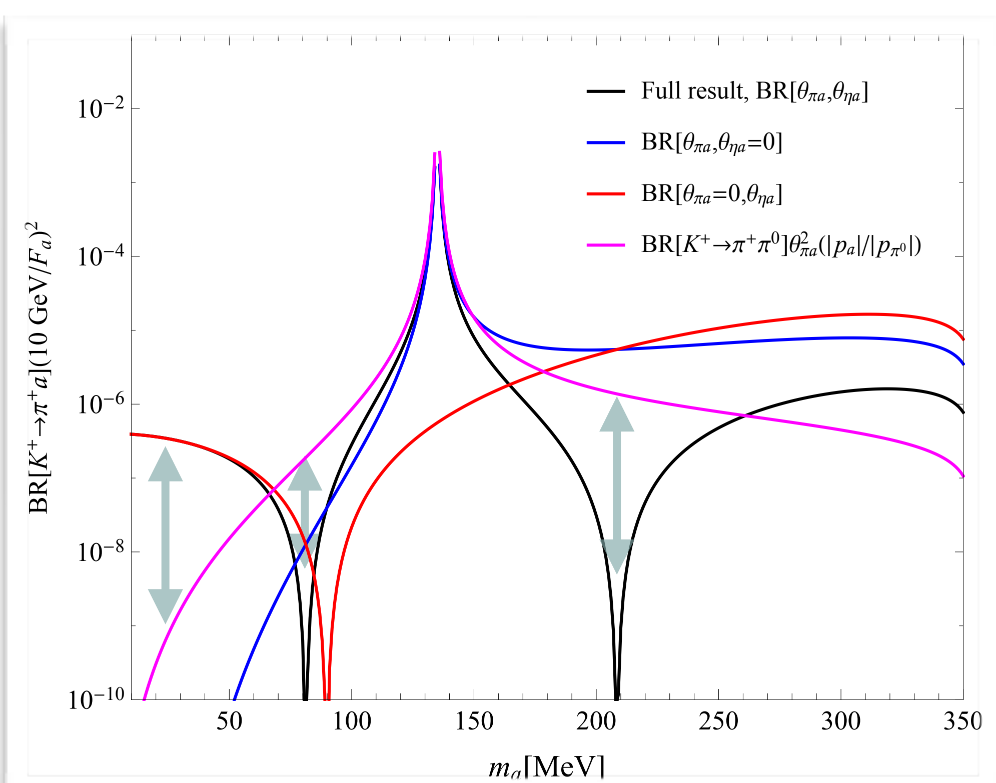
$$\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$$

Bounds



NA62&KOTO projection





- Updated calculation $K^+\to\pi^+ a$ finds uncertainty [two "octet" enhancements cancel]

Another interesting program [ALPs]

Many new bounds and projection in S. Gori, G. Perez, **KT** [2005.05170]

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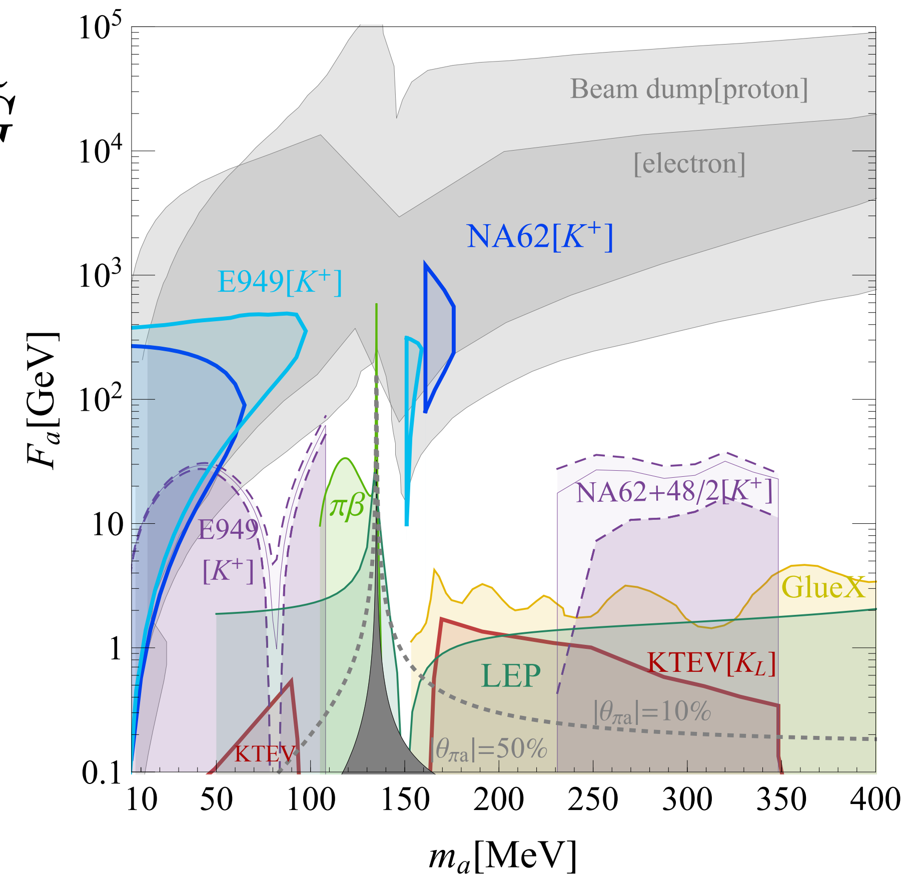
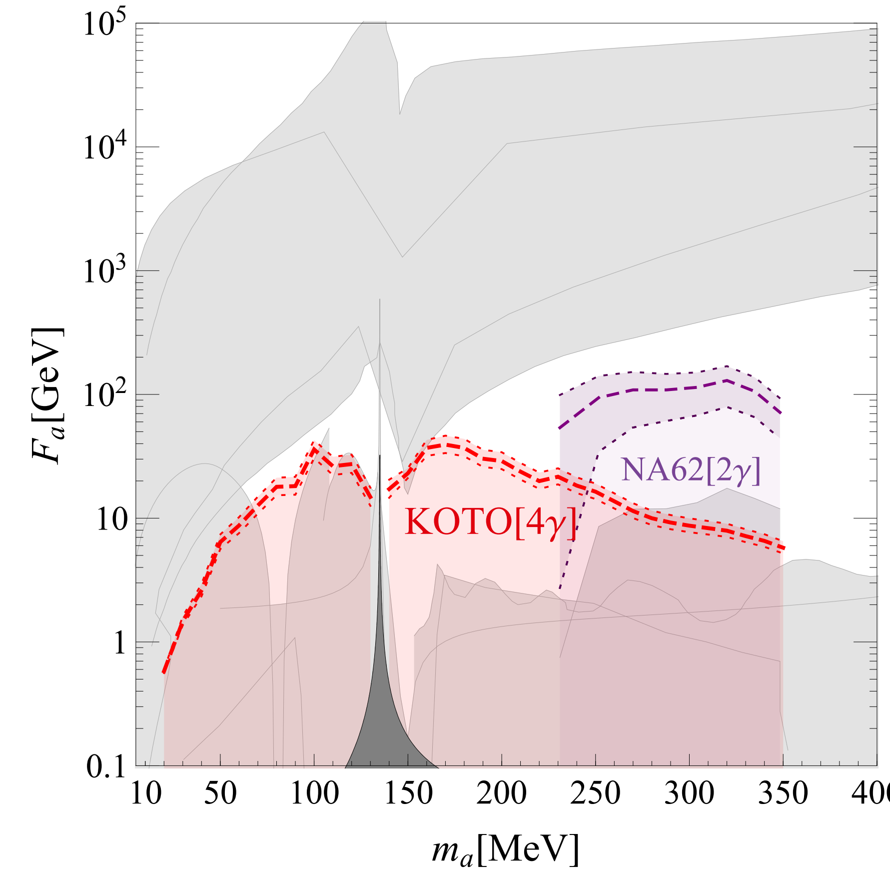
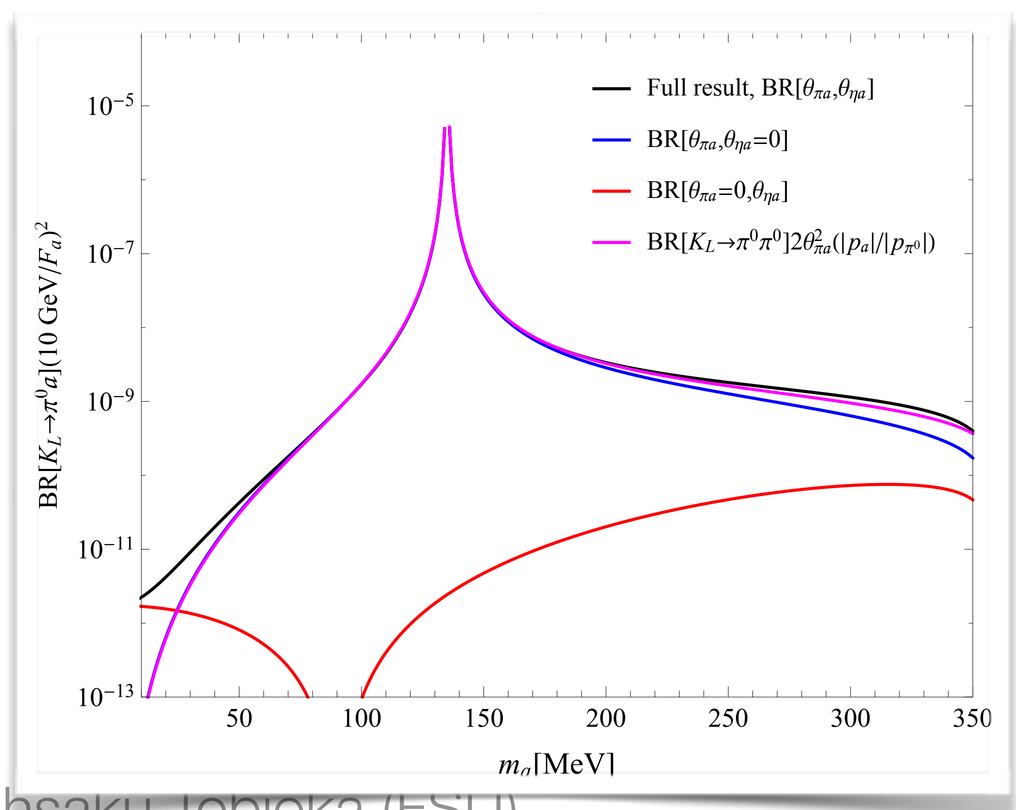
$$\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$$

Bounds



NA62&KOTO projection





- Updated calculation $K^+\to\pi^+ a$ finds uncertainty [two "octet" enhancements cancel]
- $K_L\to\pi^0 a$ is more stable, can be enhanced by two-loop without ε_K

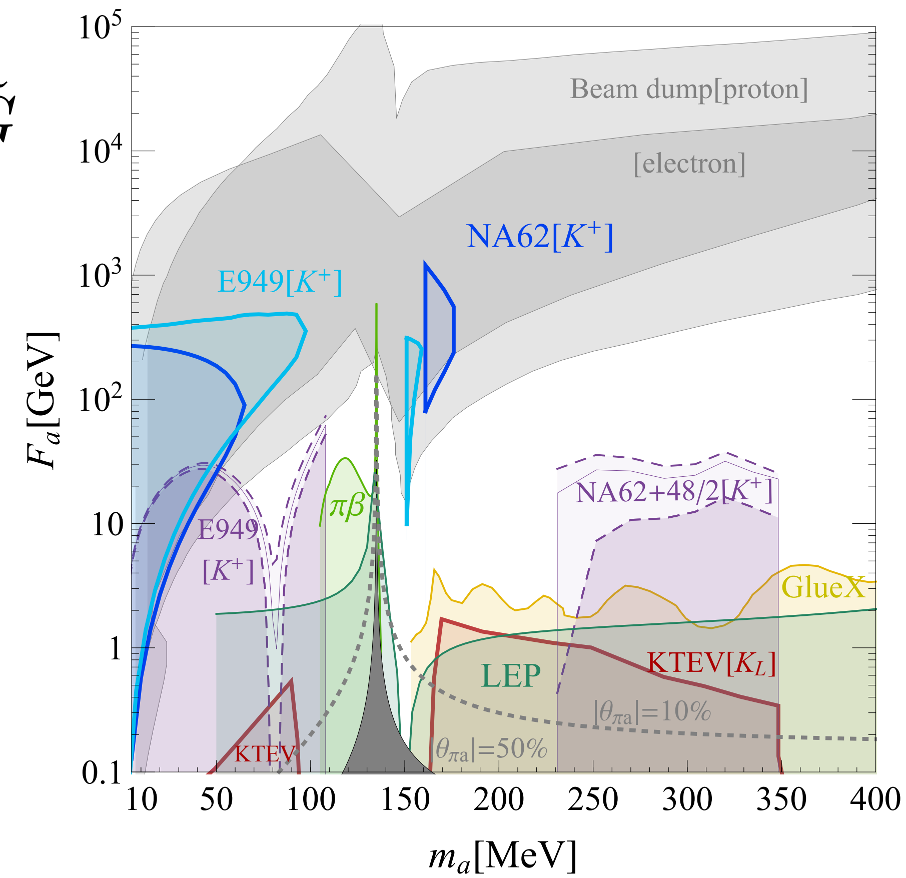
Another interesting program [ALPs]

Many new bounds and projection in S. Gori, G. Perez, **KT** [2005.05170]

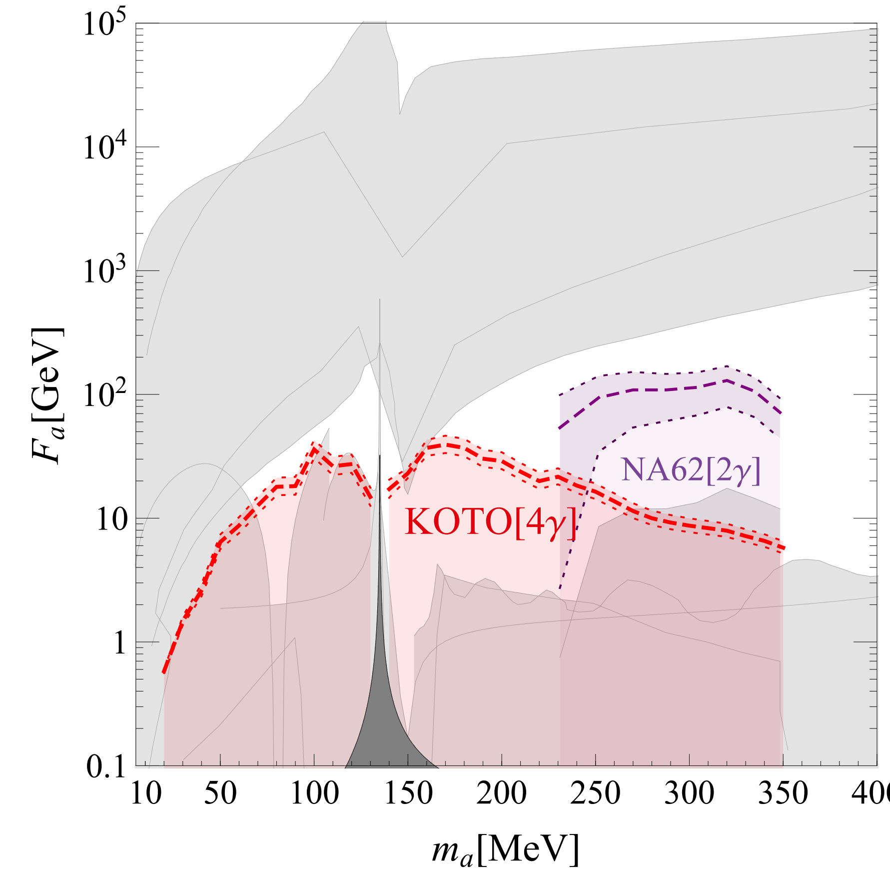
See Yotam's talk

$$\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$$

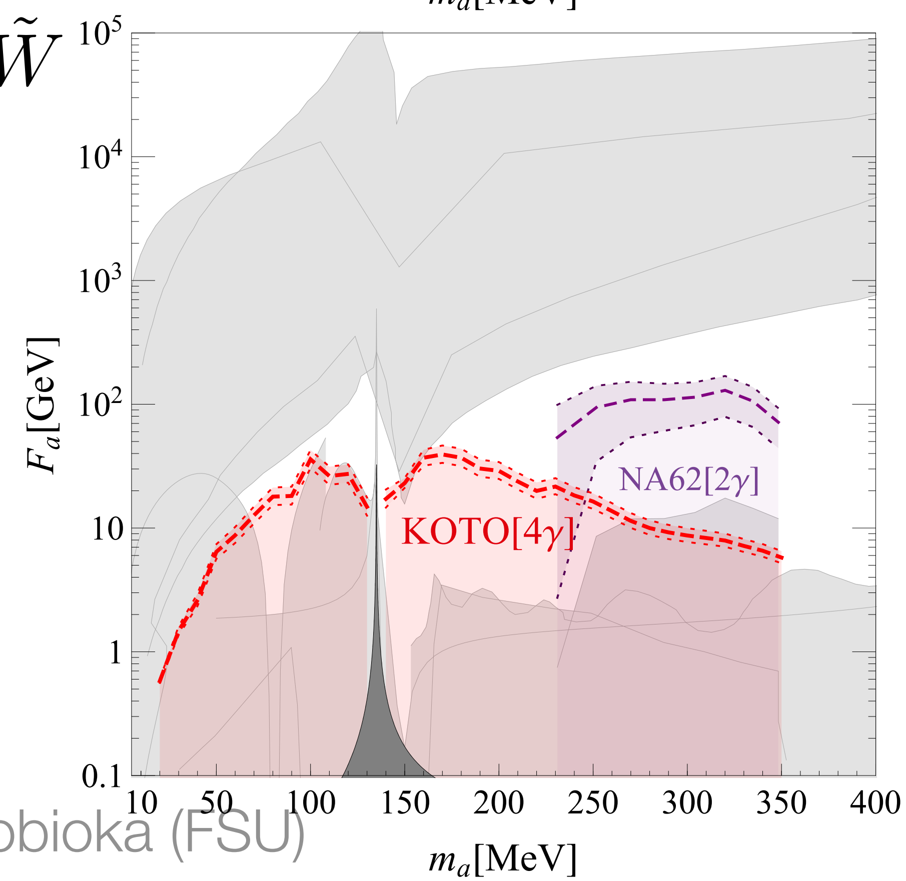
Bounds

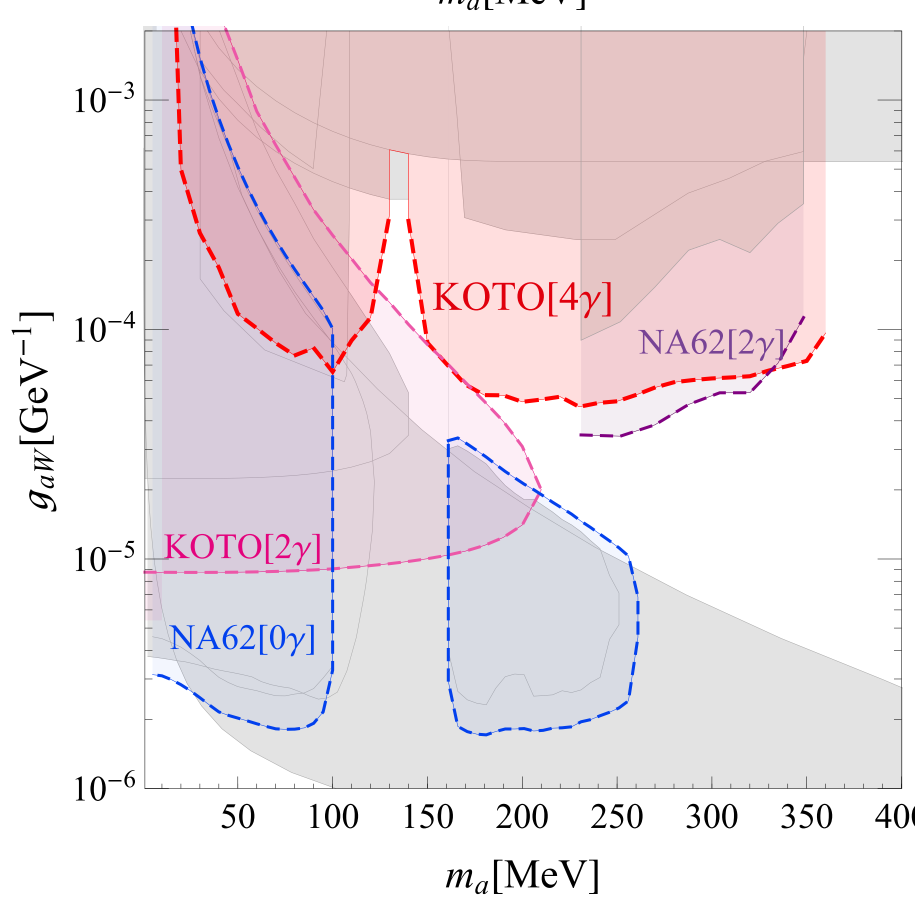


NA62&KOTO projection



$$\frac{g_{aW}}{4} a W\tilde{W}$$





Summary

(1) 3-4 events in $K_L \to \pi^0 a$@KOTO. It is more than 3σ, but still preliminary.

(2) GN bound+NA62 favors new light particle over heavy new physics.

(3) New class of models beyond GN bound. Signals from neutral mesons.

(4) Event if consistent with SM, this exercise shows how to nail down a new light state from precision measurements.

(5) KOTO&NA62 have great potential as discovery machine for $m_X < m_K$.

Axion-like Particles [$K \to \pi X(\to \gamma\gamma)$]

Higgs portal/Relaxion [$K \to \pi X(\to \text{inv})$]

Complementary to beam-dump and astrophysics.

Thank you!

Hope see you all in person.

Backup

Refine calculation and analysis

$$\frac{\alpha_s}{8\pi F_a} a G\tilde{G}$$ induces meson mixing with mesons

$$\begin{pmatrix} a \\ \pi \\ \eta \end{pmatrix} \simeq \begin{pmatrix} 1 & -\frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & -\frac{K_\eta M_\eta^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} \\ \frac{K_\pi M_a^2}{M_\pi^2 - M_a^2} & 1 & 0 \\ \frac{K_\eta M_a^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{\text{phys}} \\ \pi_{\text{phys}} \\ \eta_{\text{phys}} \end{pmatrix}$$

$$K_\pi = -\frac{F_\pi}{2F_a}(\kappa_u - \kappa_d), \quad K_\eta = -\frac{F_\pi}{\sqrt{6}F_a}(\kappa_u + \kappa_d - \kappa_s),$$

$$\delta M_{\eta a} = \sqrt{\frac{2}{3}} \frac{F_\pi}{F_a} \frac{m_u m_d m_s}{(m_u + m_d)(m_u m_d + m_d m_s + m_s m_u)} m_{\pi^0}^2$$

K→πa calculation updated by χPT

$$-iG_8 F_\pi K^+ \pi^- a \left(-[m_{\pi^+}^2 - m_a^2]\theta_{\pi a} + \frac{2}{\sqrt{3}}[m_{K^+}^2 - m_a^2]\theta_{\eta a} \right)$$

$$-iG_{27} F_\pi K^0 \pi^0 a \left(-\frac{1}{\sqrt{2}}[2m_{K^0}^2 - m_{\pi^0}^2 - m_a^2]\theta_{\pi a} + \frac{1}{\sqrt{6}}[m_{K^0}^2 - 2m_a^2 + m_{\pi^0}^2]\theta_{\eta a} \right) + h.c.$$

$$-iG_8 F_\pi K^0 \pi^0 a \left(\frac{1}{\sqrt{2}}[2m_{K^0}^2 - m_{\pi^0}^2 - m_a^2]\theta_{\pi a} + \sqrt{\frac{2}{3}}[-m_{K^0}^2 + m_a^2]\theta_{\eta a} \right)$$

$$-iG_{27} F_\pi K^+ \pi^- a \left(\frac{1}{3}[5m_{K^+}^2 + 2m_a^2 - 7m_{\pi^+}^2]\theta_{\pi a} + \frac{1}{3\sqrt{3}}[7m_{K^+}^2 - 4m_a^2 - 3m_{\pi^+}^2]\theta_{\eta a} \right)$$

Heavy New Physics (Backup)

Conventional solution: SM higher dim. operator due to heavy state

$$\mathcal{O}_{\mathrm{BSM}}(\psi_{\mathrm{SM}}) \supset \sum C_i \mathcal{O}_i$$ to enhance $K \to \pi\nu\nu$

$$\mathcal{O}_{\mathrm{S}} = \bar{L}\bar{\sigma}^{\mu} L \, \bar{Q}_2 \bar{\sigma}_{\mu} Q_1$$

$$\mathcal{O}_{\mathrm{T}} = \bar{L}\tau^{a}\bar{\sigma}^{\mu} L \, \bar{Q}_2 \tau^{a} \bar{\sigma}_{\mu} Q_1$$

$$\mathcal{O}_{\mathrm{R}} = \bar{L}\bar{\sigma}^{\mu} L \, s^{c} \tau^{a} \bar{\sigma}_{\mu} \bar{d}^{c}$$

Lepton Universality
leads to charged lepton channels

$K_L \to \pi^0 \ell^+ \ell^- \ (\ell = e, \mu)$

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

bounds are BR~10^{-10}

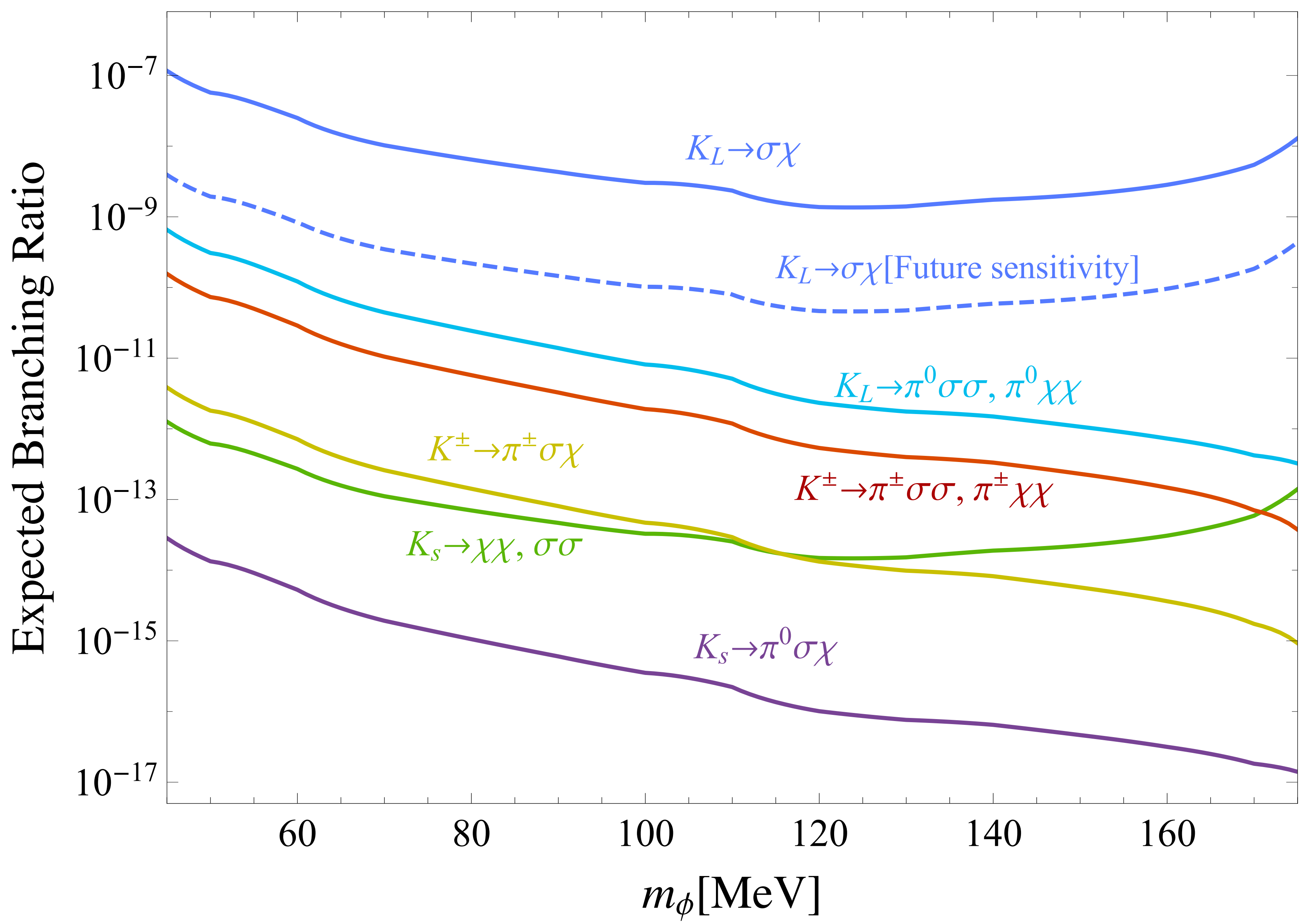
Prescriptions

(1) neutrino is only ν_τ

(2) Impose $C_R = C_S$

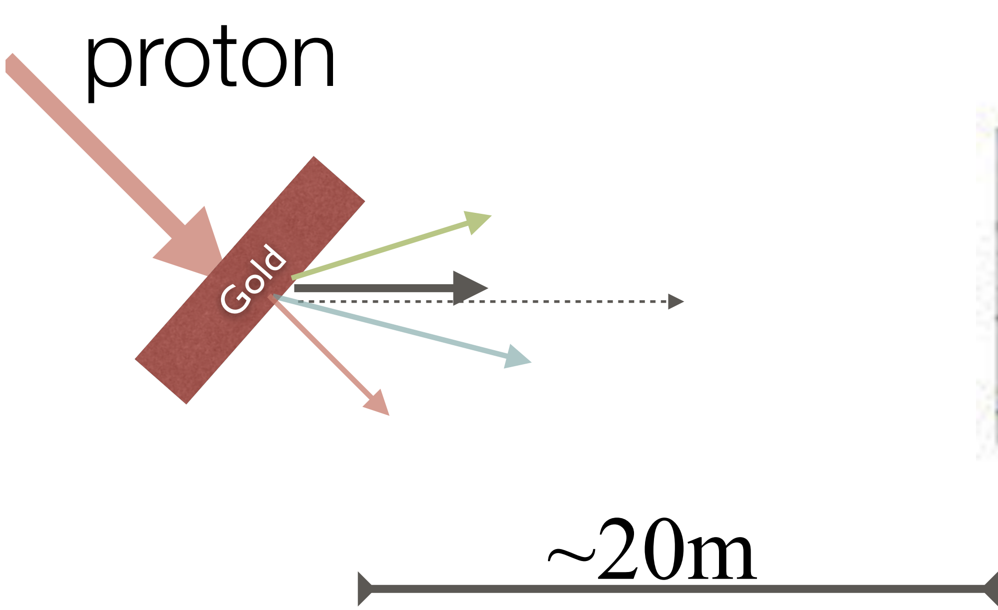
K. Agashe, R. Contino, L. Da Rold, and A. Pomarol,
[hep-ph/0605341

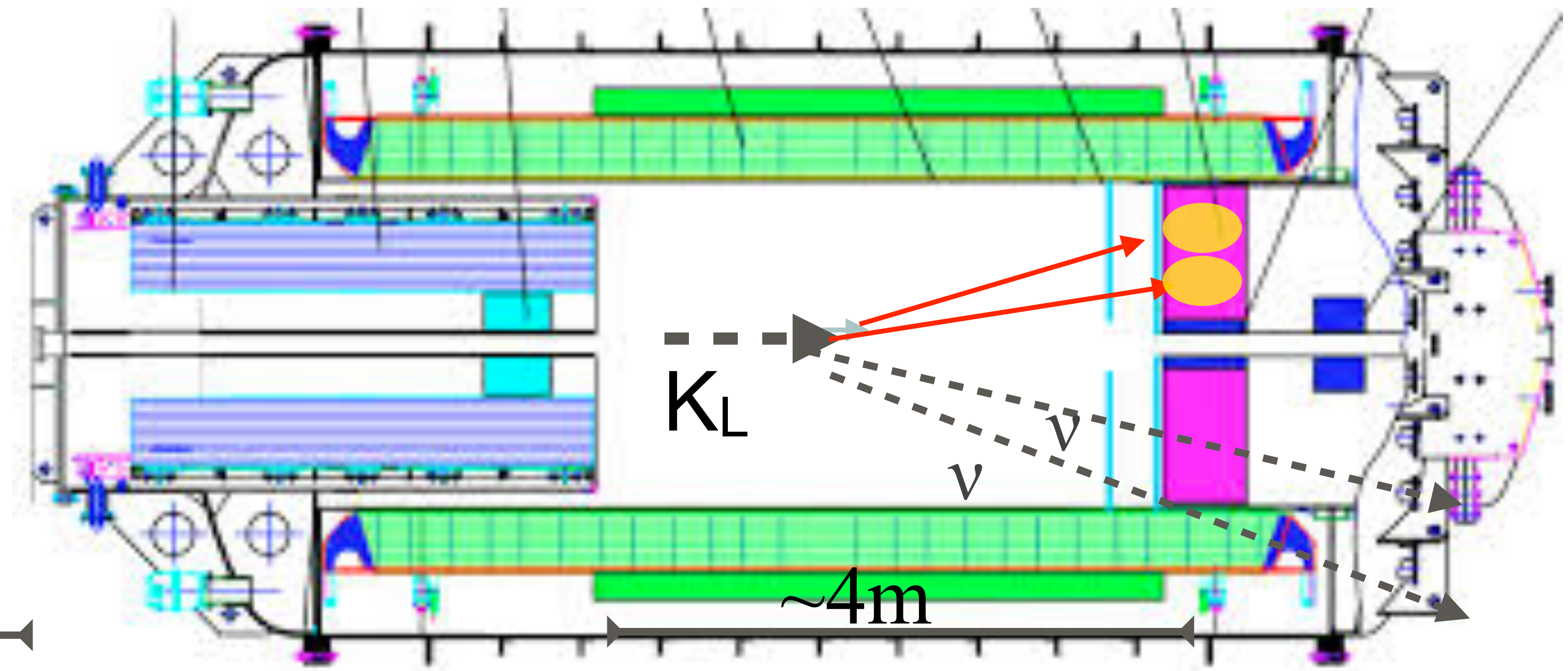
GNV scenario



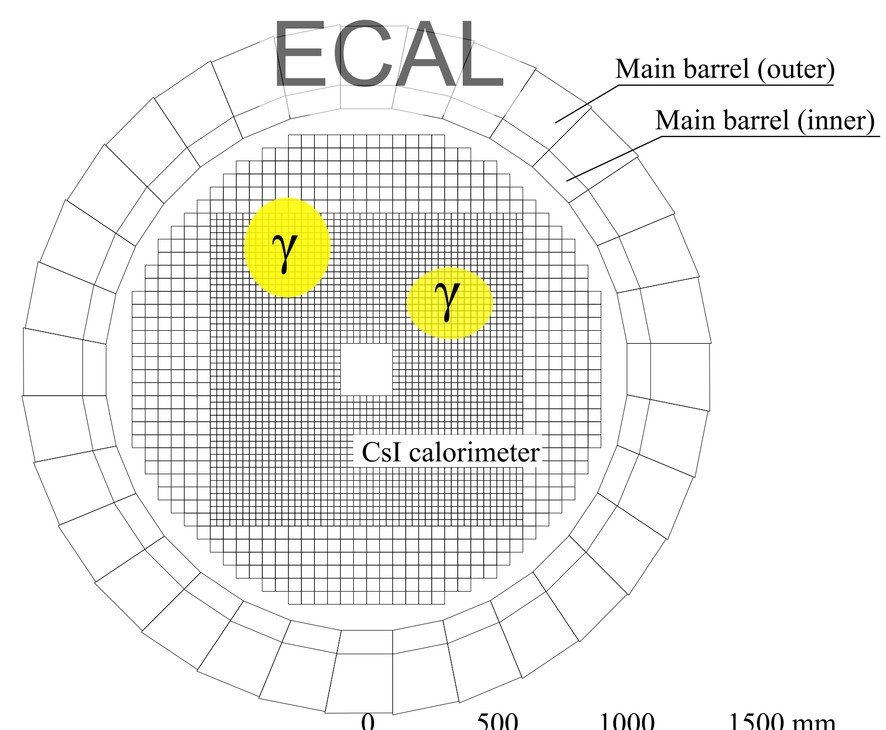
III. Exotic Particle from Fixed Target

- They do not "tag" K_L each event



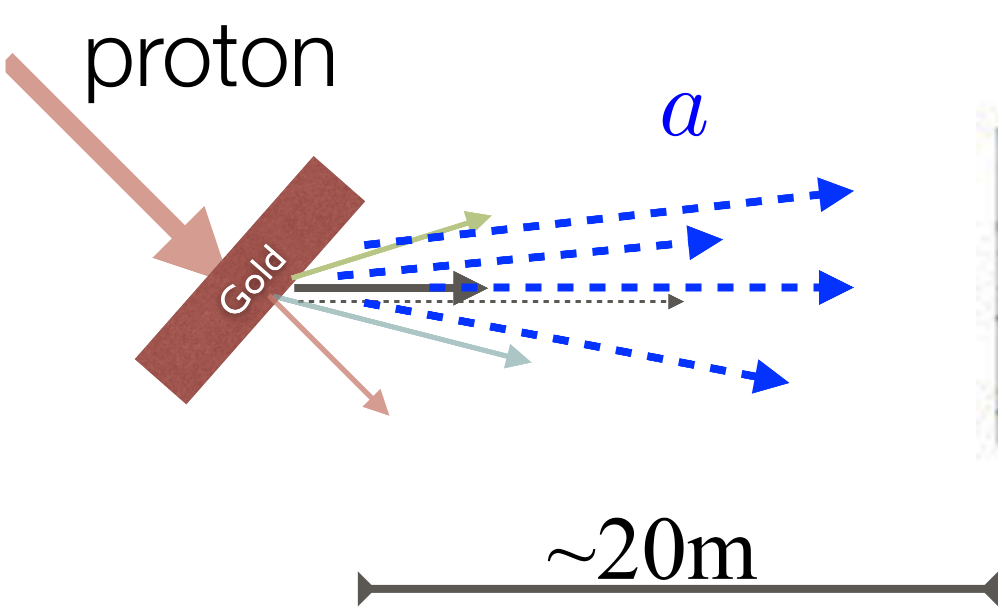


- Two γ clusters
- Asymmetry in transverse plane [evidence for $\nu\nu$]

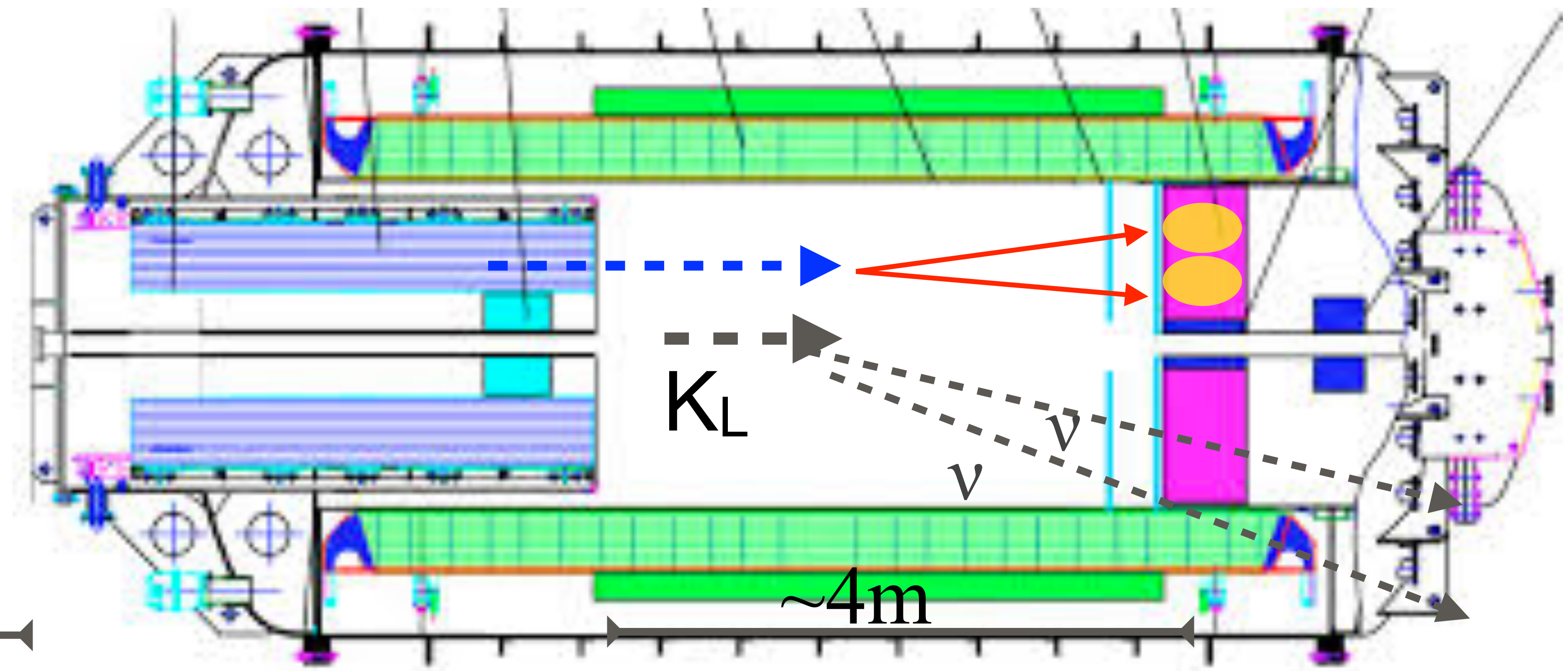


III. Exotic Particle from Fixed Target

- Two γ may not be from K_L



- They do not "tag" K_L each event



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

Neutral long-lived
axion-like particle: a

K^+ experiment insensitive

<u>Very rough estimate</u>

Lifetime: 0.1ns - 1μs
f_g~TeV if A*eff~10^{-4}

Need more precise estimates
for production and reconstruction
(if anomaly is confirmed)

BG Analysis Followup

Too striking events for KOTO [30x expected]….

Talk by Nomura Jan 17, 2020

E14/KOTO Status

T. Nomura (KEK/J-PARC)

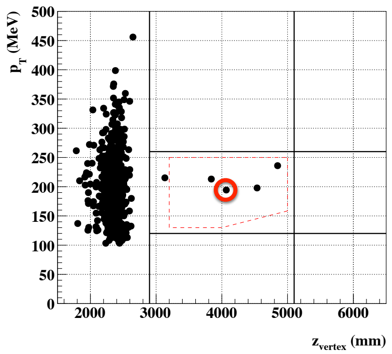
- Status of 2016-18 data analysis
- Status of 2019 data analysis
- Run plan

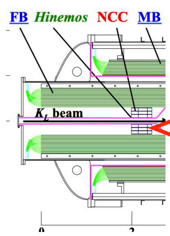
January 17, 2020 29th J-PARC PAC meeting @ J-PARC Research Building 1

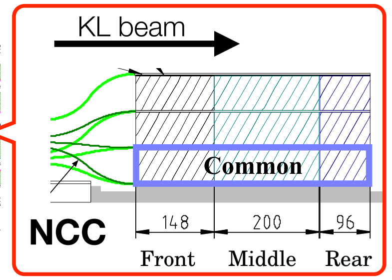
Property of Event #1

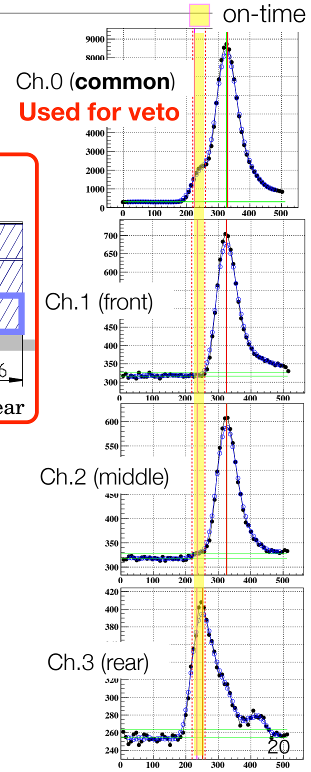
This must be accounted in our BG estimation

- Event in Run69
- **Overlapped pulse in NCC**

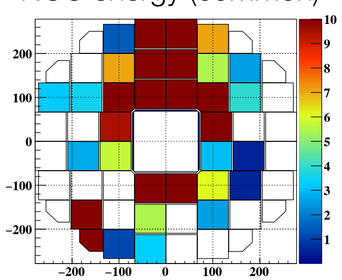






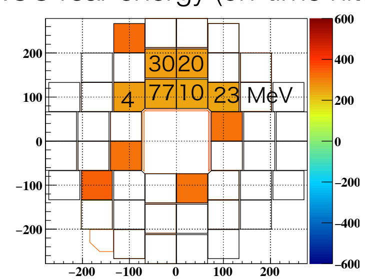


NCC energy (common)



Used for veto

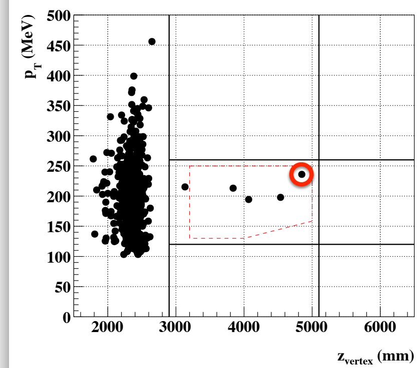
NCC rear energy (on-time hits)



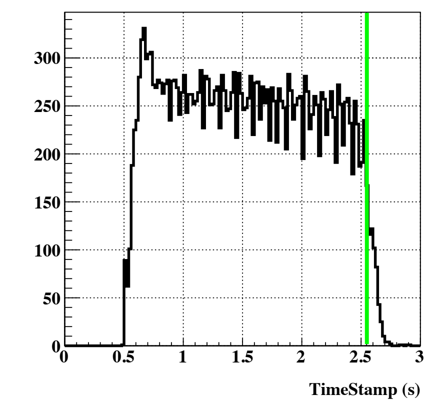
Not used for veto

Property of Event #2

- Event in Run69
- No hits in veto detectors



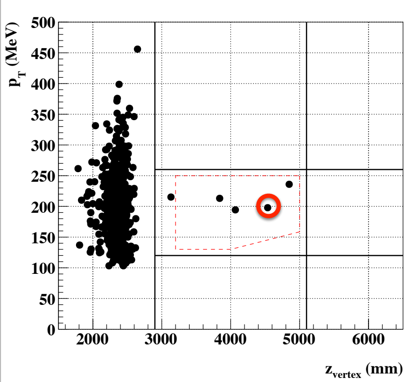
Event at the end of a spill

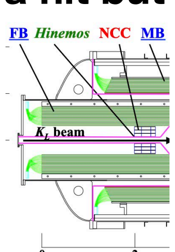


Property of Event #3

This event remained due to a mistake…

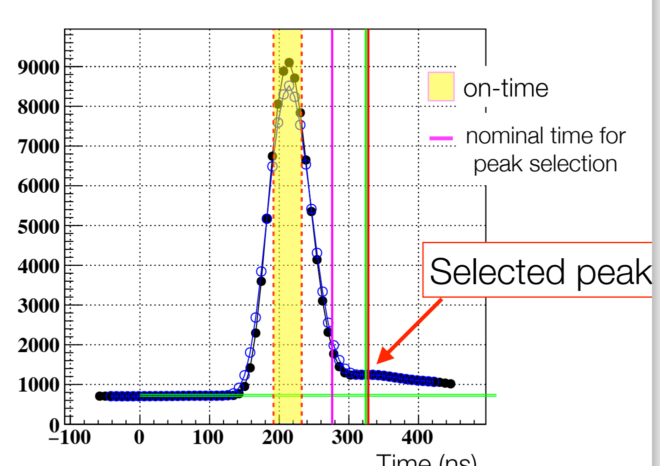
- Event in Run74
- CV hits in neighboring two strips (each less than the threshold)
- **HINEMOS (inner scintillator of NCC) had a hit but the timing was mis-measured.**





The on-time hit was lost due to a wrong parameter for peak selection in this run period.

(The large deviation existed in this detector and in this run period.)



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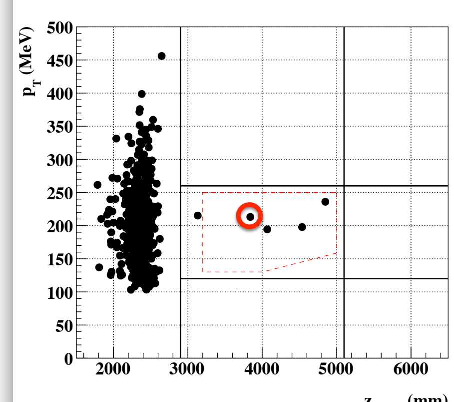
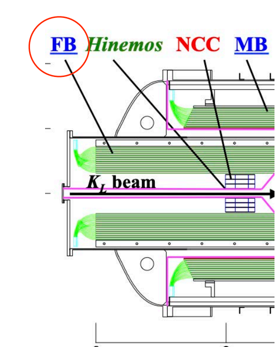
Property of Event #4

- Event in Run79
- FB hits just outside of the veto window





Official claim is not announced.

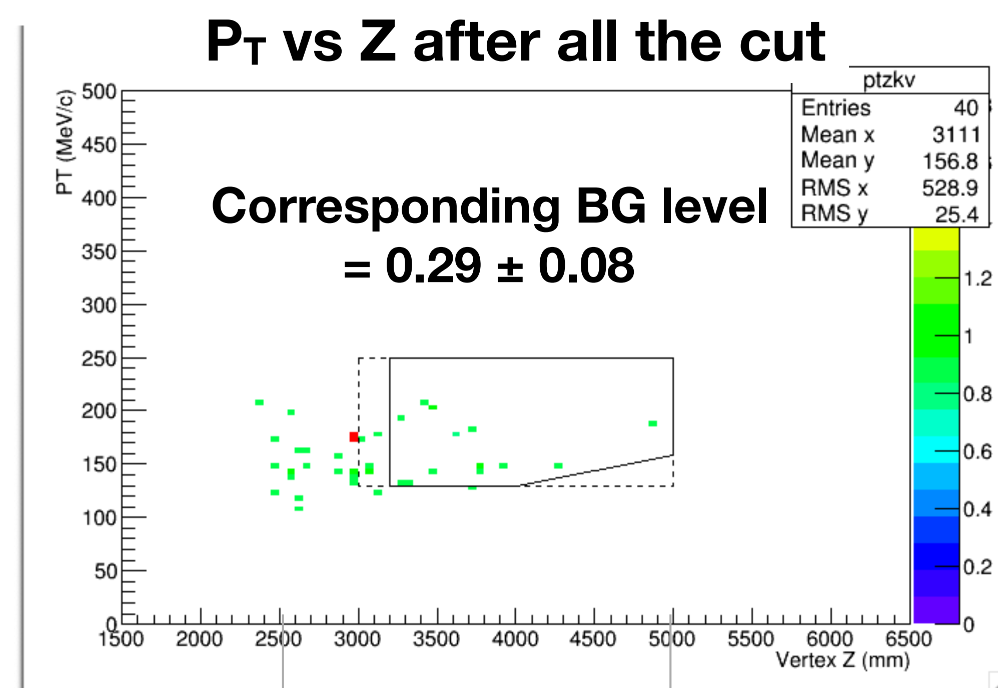
Special run in March 2020

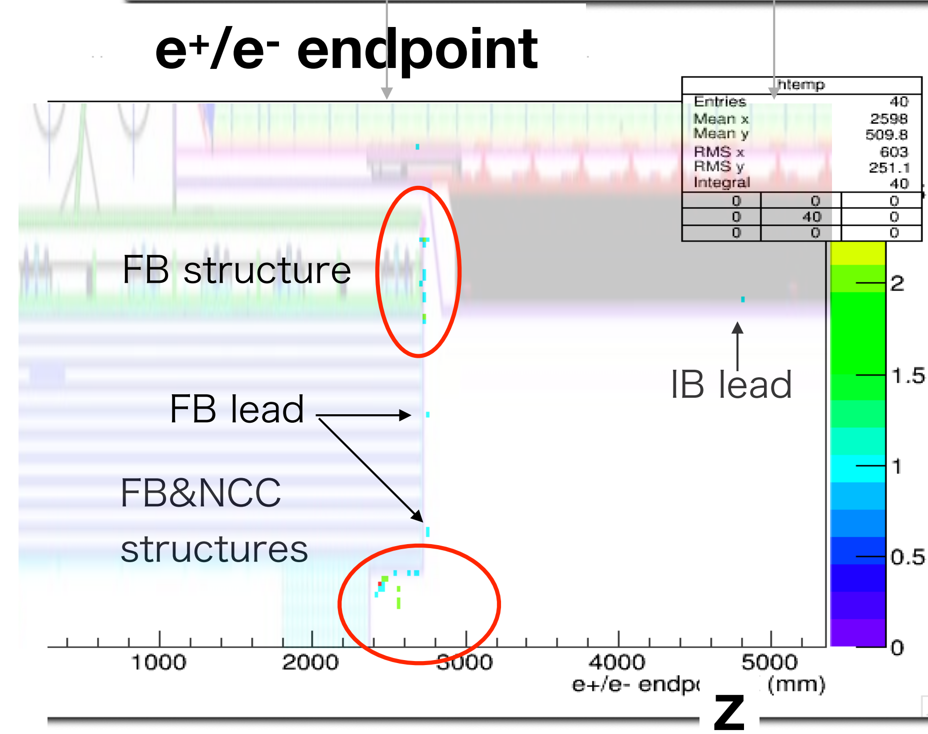
K^+ is possibly produced from detector interaction.
Measure it.

$K^\pm \to \pi^0 e^\pm \nu$ (BR=5.1%)

- π^0 can have a large P_T (P^*max=215 MeV/c)
- If $e^\pm$ goes upstream, its energy becomes low. It could be lost due to interactions with dead materials (lead in sandwich detector, support structure, etc).

The estimated number of BG relies on the $K^\pm$ flux obtained by the simulation.
We need to measure it.





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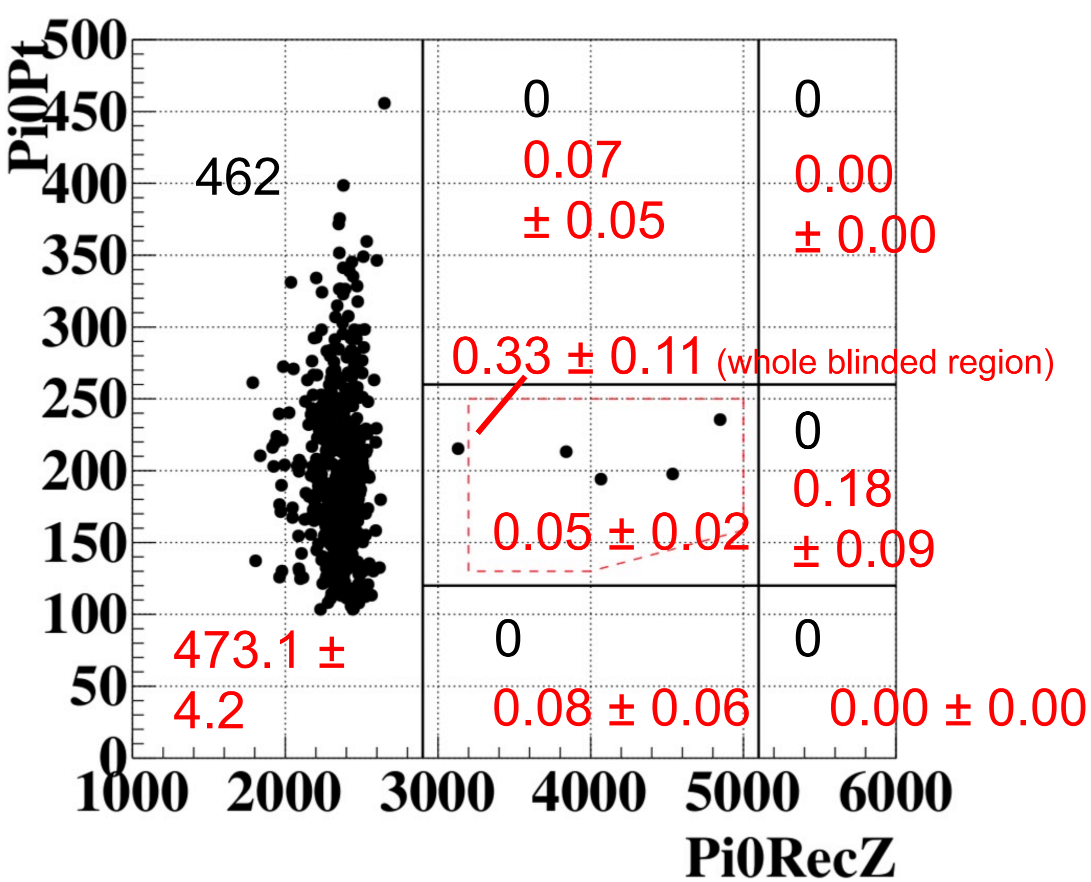
Revised P_T-Z plot

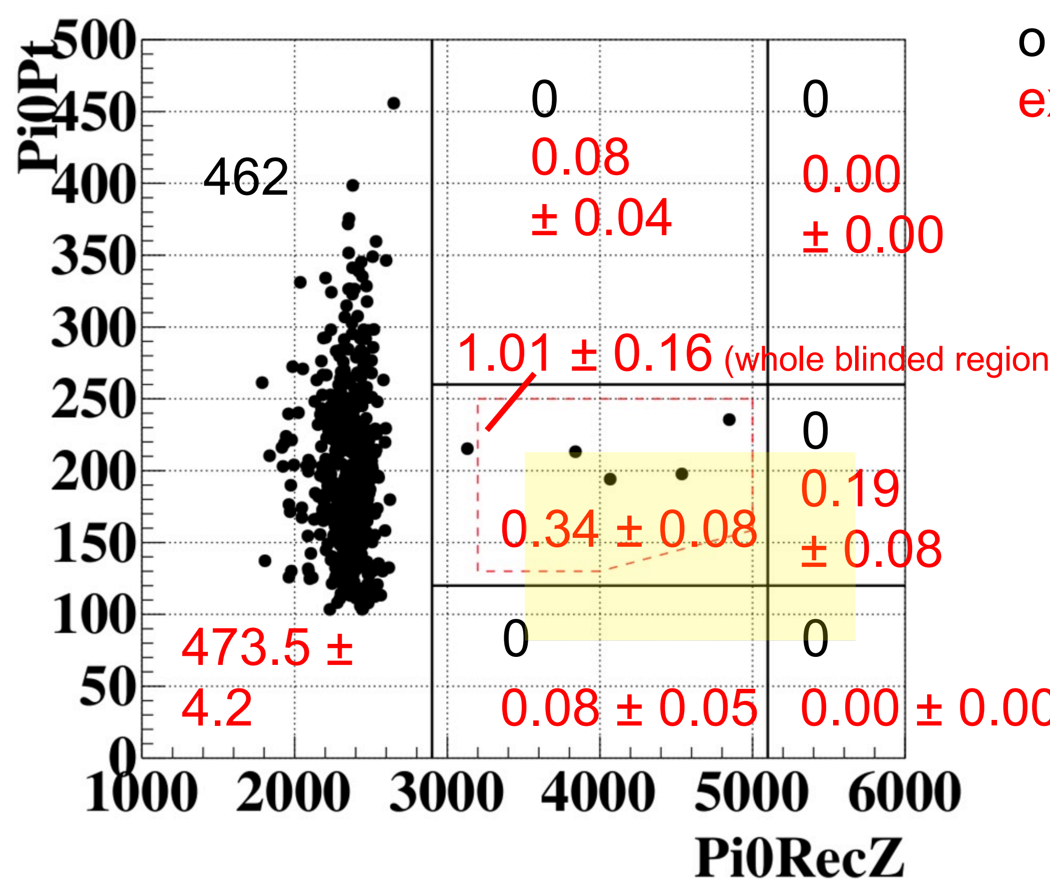
Stay Tuned!

At KAON 2019 → As of today

S.E.S : 6.9×10^{-10}

S.E.S : 7.1×10^{-10}





observed
expectation

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