K中間子による新物理探査

素粒子物理学の進展2020

YITP (virtual), Sept 2, 2020

Kohsaku Tobioka (飛岡幸作)

Florida State University

Collaboration with

Teppei Kitahara, Takemichi Okui, Gilad Perez, Yotam Soreq
[Phys.Rev.Lett. 124 (2020) 07180, 1909.11111 +updates]
Stefania Gori, Gilad Perez [2005.05170]
Gordan Krnjaic, Gustavo Marques-Tavares, Diego Redigolo
[Phys.Rev.Lett. 124 (2020) 041802, 1902.07715]

Outline

- Introduction
  - Why Kaon? Excellent probe for New Physics, FIMP
  - Rare kaon decay $K \to \pi\nu\nu$ at KOTO, and NA62

- Recent results from KAON2019 to ICHEP2020
  - NA62 results, KOTO “excess”
  - New Physics Scenarios

- Future prospects
  - Higgs Portal, Muonic Force, Axion-like-particle

History: Kaons as discovery probes of new physics

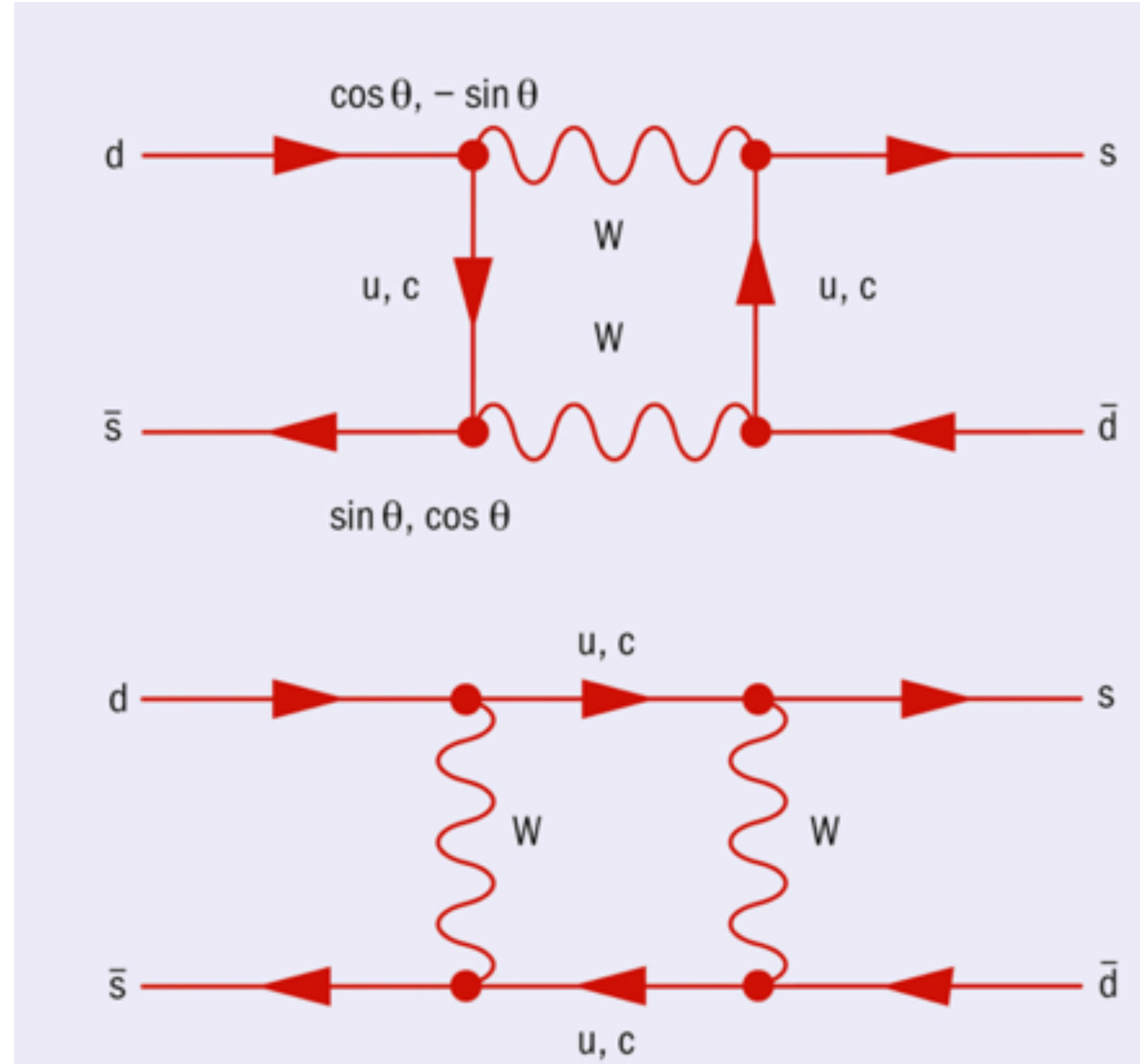
- **Charm quark**

Puzzle: $K_L \to \mu^+\mu^-$ rate too small

Glashow-Iliopoulos-Maiani (GIM) mechanism

2x2 matrix →charm as new d.o.f.

$K^0(\bar{s}d) - \bar{K}^0(s\bar{d})$ oscillation



from CERN Courier

- **CP violation**

K_L(~CP odd) $K_L \to \pi^0\pi^0\pi^0$

K_S(~CP even) $K_s \to \pi^0\pi^0$

Also observed $K_L \to \pi^0\pi^0$!!

CKM matrix [3x3 matrix with new phase]

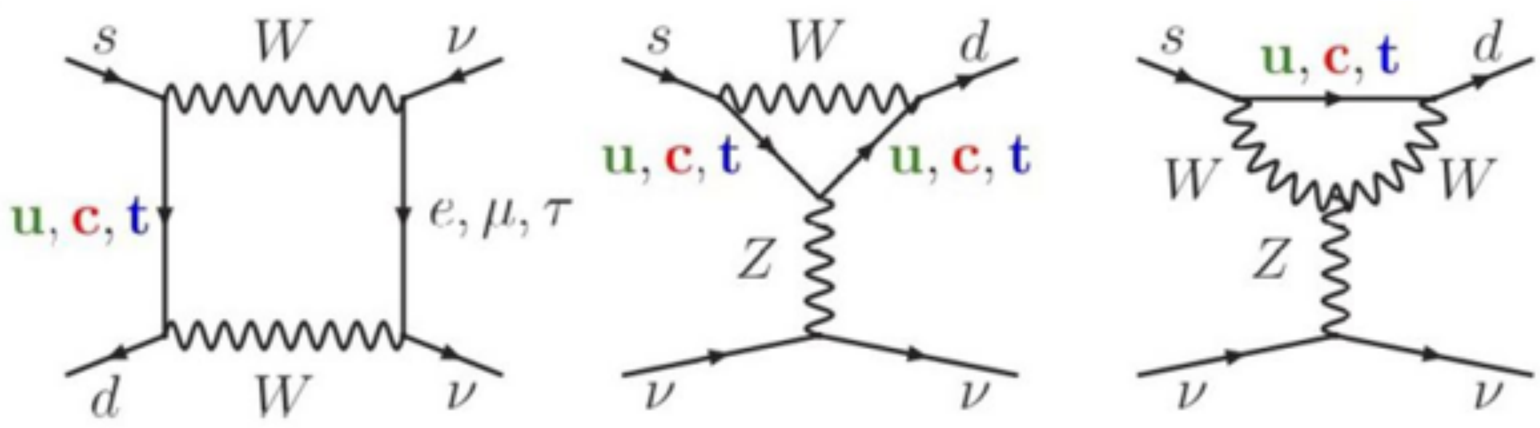

日経サイエンス

Very Rare Kaon Decays

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

$$\propto |\mathcal{M}|^2 \qquad\qquad \propto (\mathrm{Im}\mathcal{M})^2$$

$\mathcal{M}$ ~



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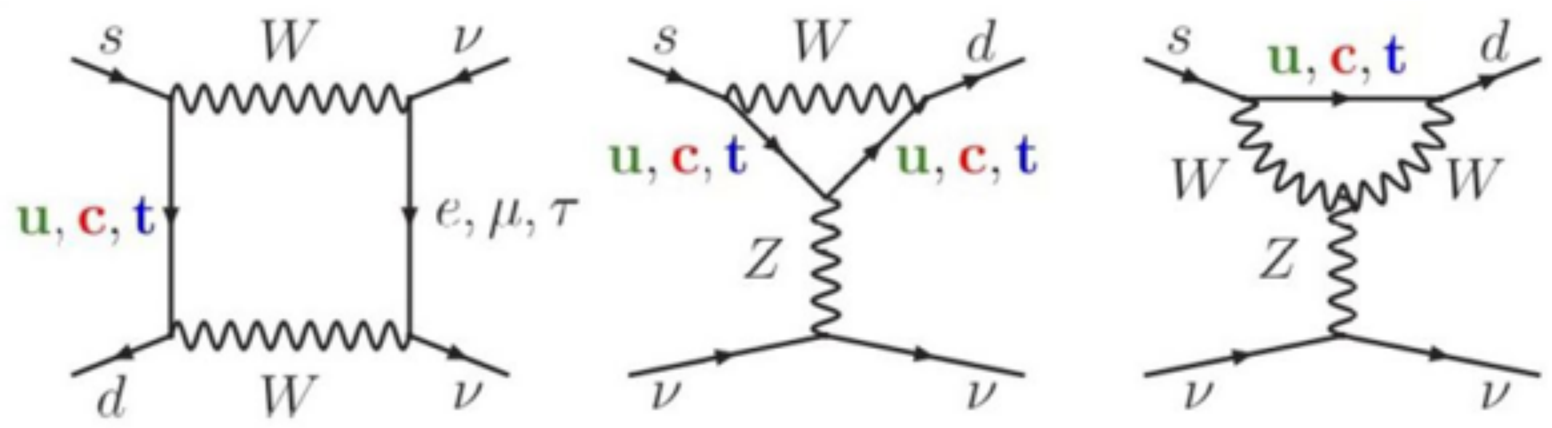
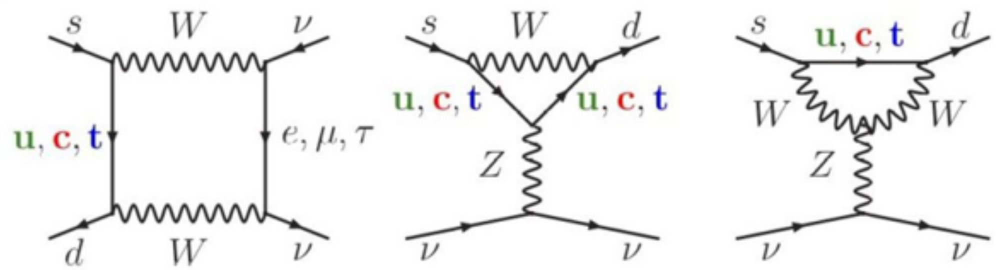


Extremely rare and precise process in SM. [Buras et al., 1503.02693]

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

- **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)]

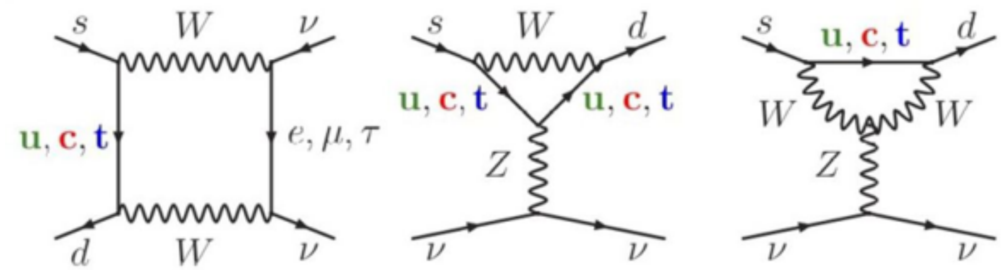
$$\frac{\Gamma[K_L \to \pi^0 \nu\bar{\nu}]}{\Gamma[K^+ \to \pi^+ \nu\bar{\nu}]} = \frac{(\mathrm{Im}\ M)^2}{|M|^2} \leq 1$$

Isospin relation(**ΔI=1/2**)

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

Ratio of total widths
+isospin breaking

Grossman-Nir bound

$\mathcal{M}$ ~ 

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

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Ratio of total widths
+isospin breaking

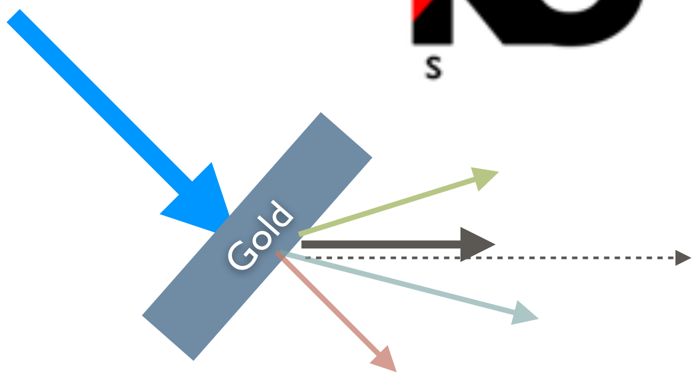
- GN bound can be generalized to new physics case

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

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

Experiments for Rare Koan Decays

JPARC KOTO



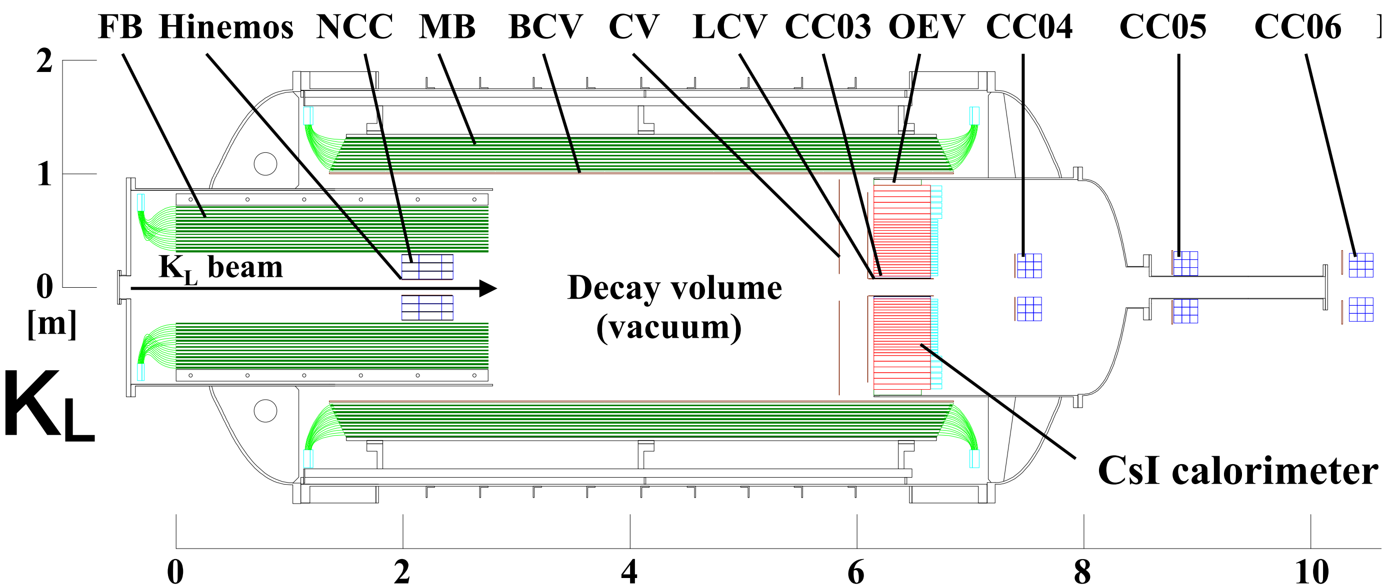
30GeV p

since 2013 (restart '15)

~2GeV K_L

~3m

Mainly ECAL



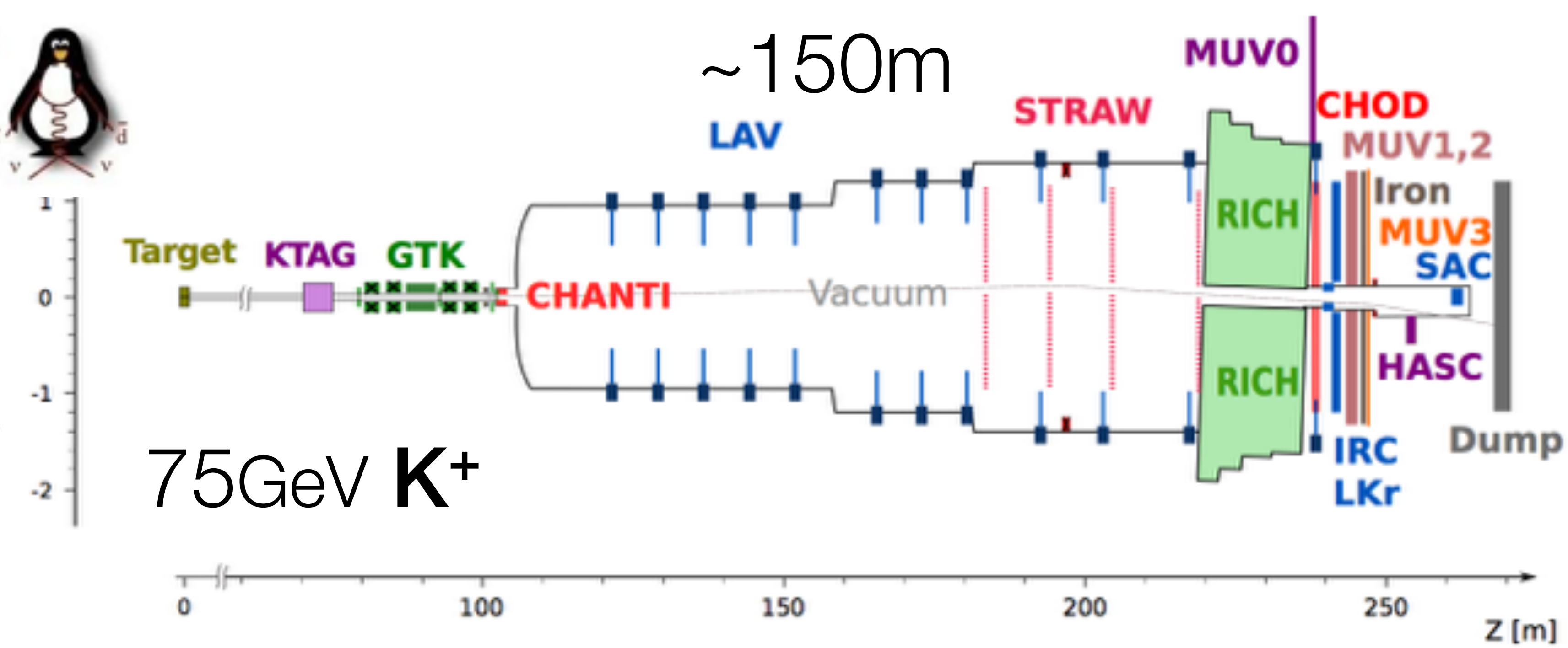
CERN NA62

400GeV p from SPS

physic run since 2015

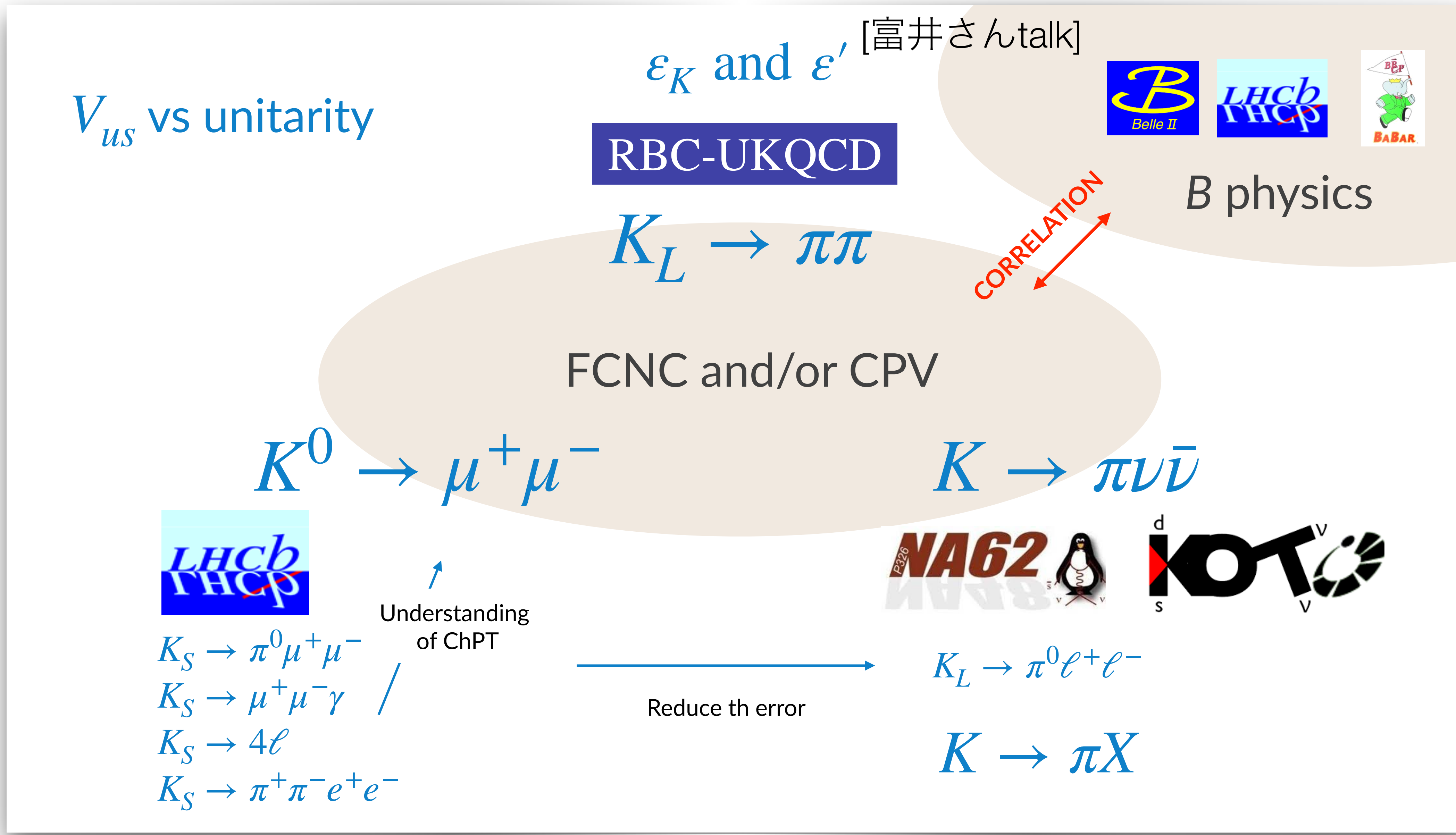
~150m

75GeV K^+



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

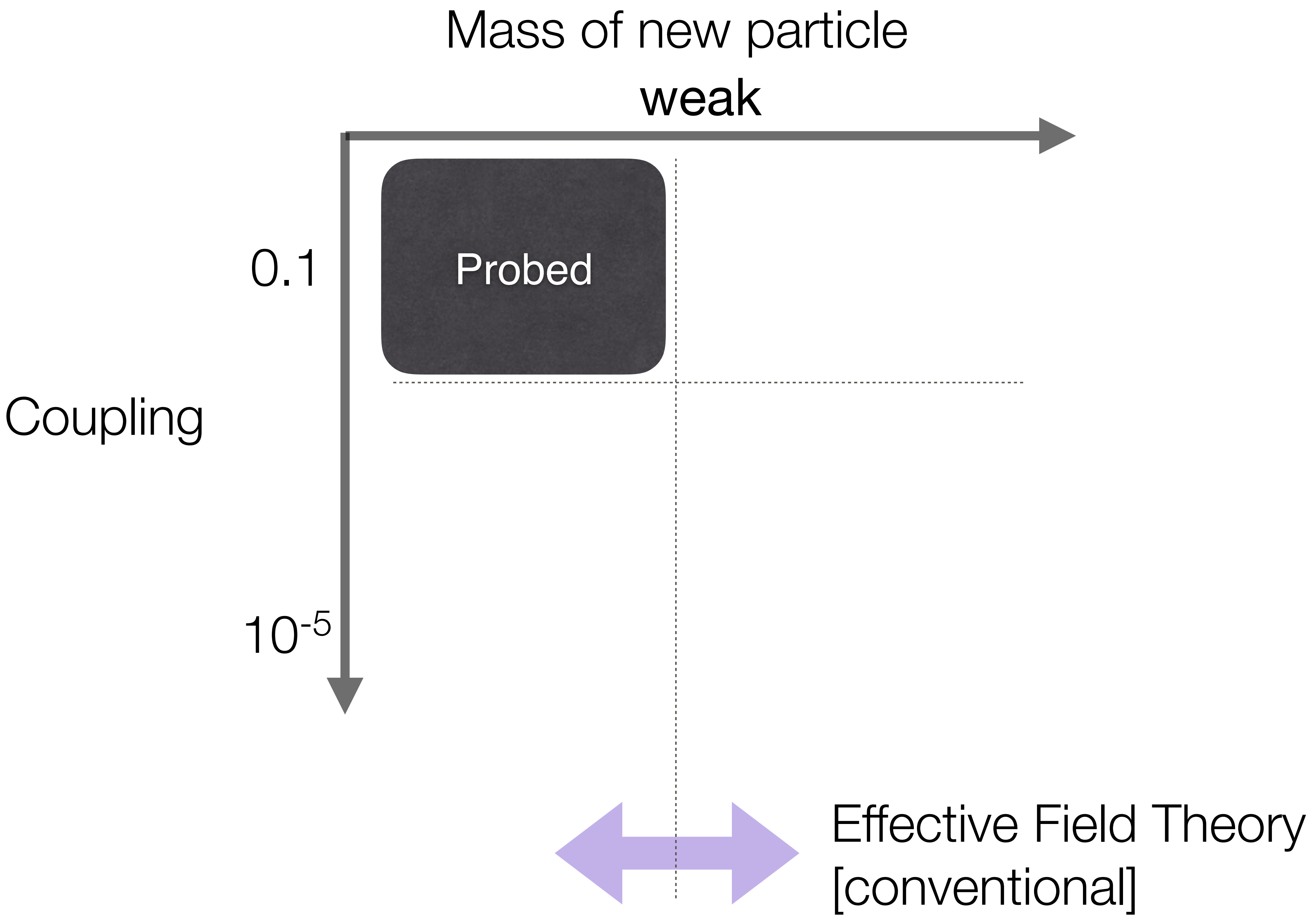
Kaon Measurements — Big Picture —



summary 北原さん

https://indico.cern.ch/event/783304/contributions/3497938/attachments/1916882/3169405/TeppeiKitahara_HC2NP.pdf

From Precision to Discovery



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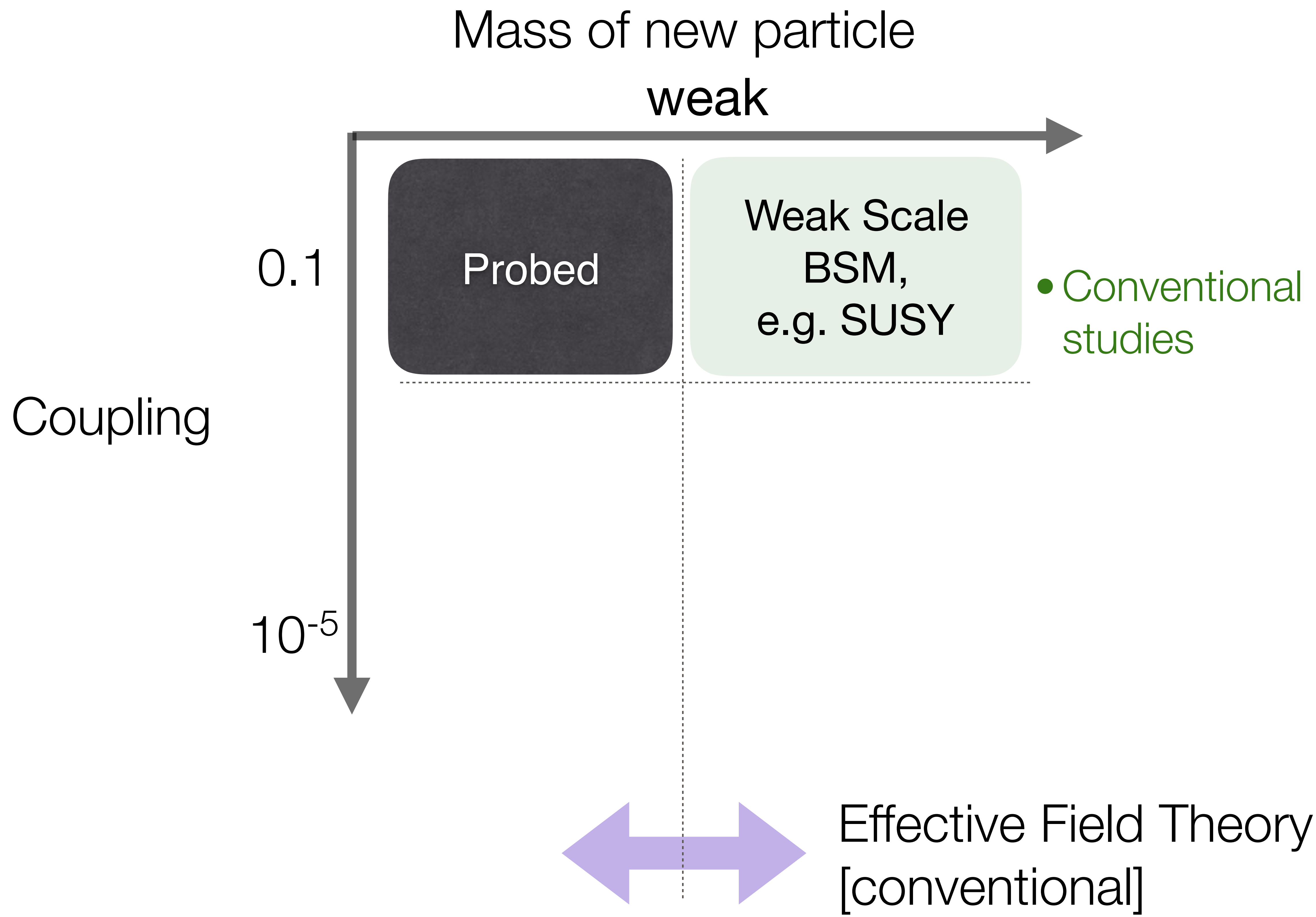

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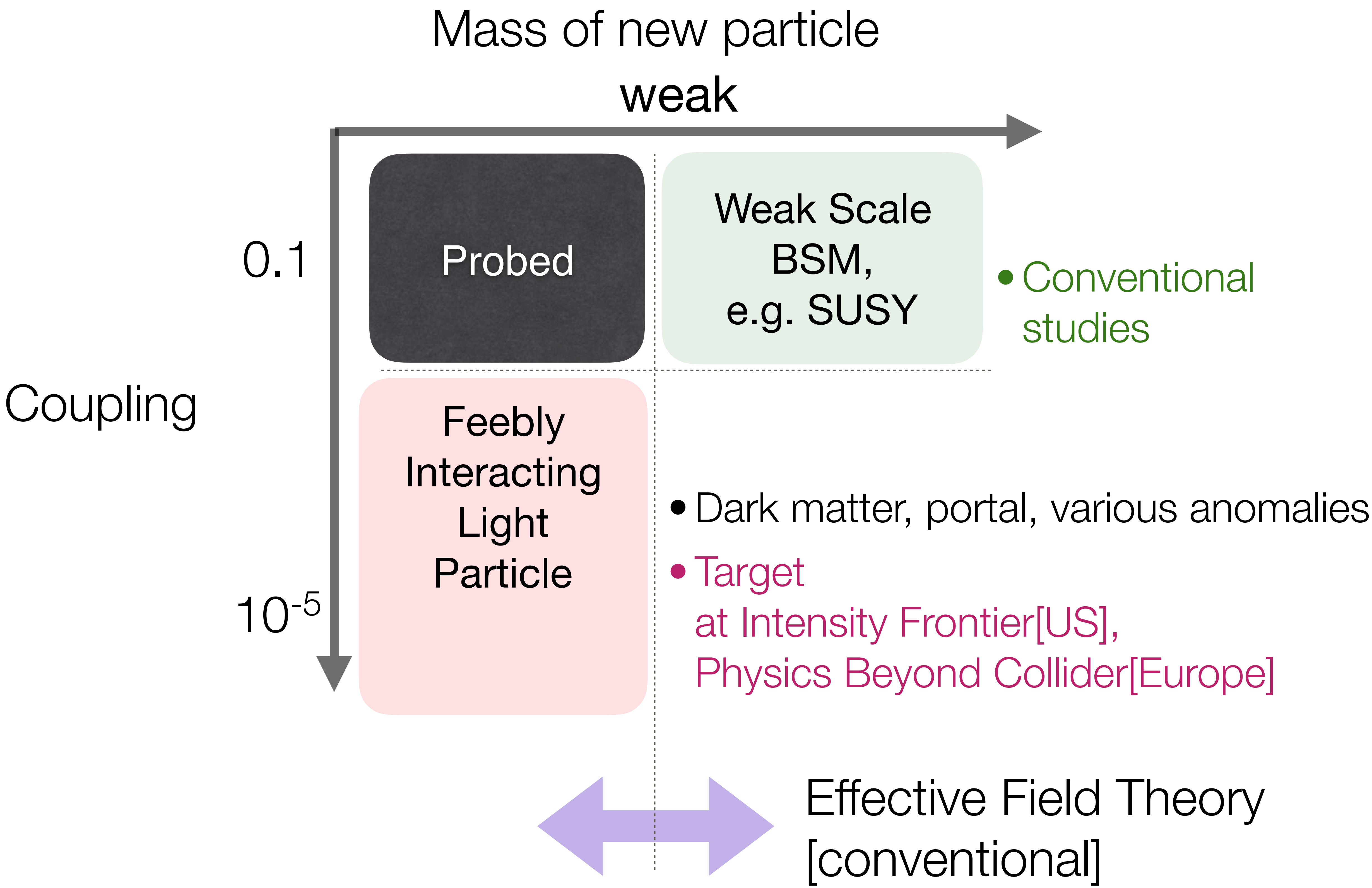

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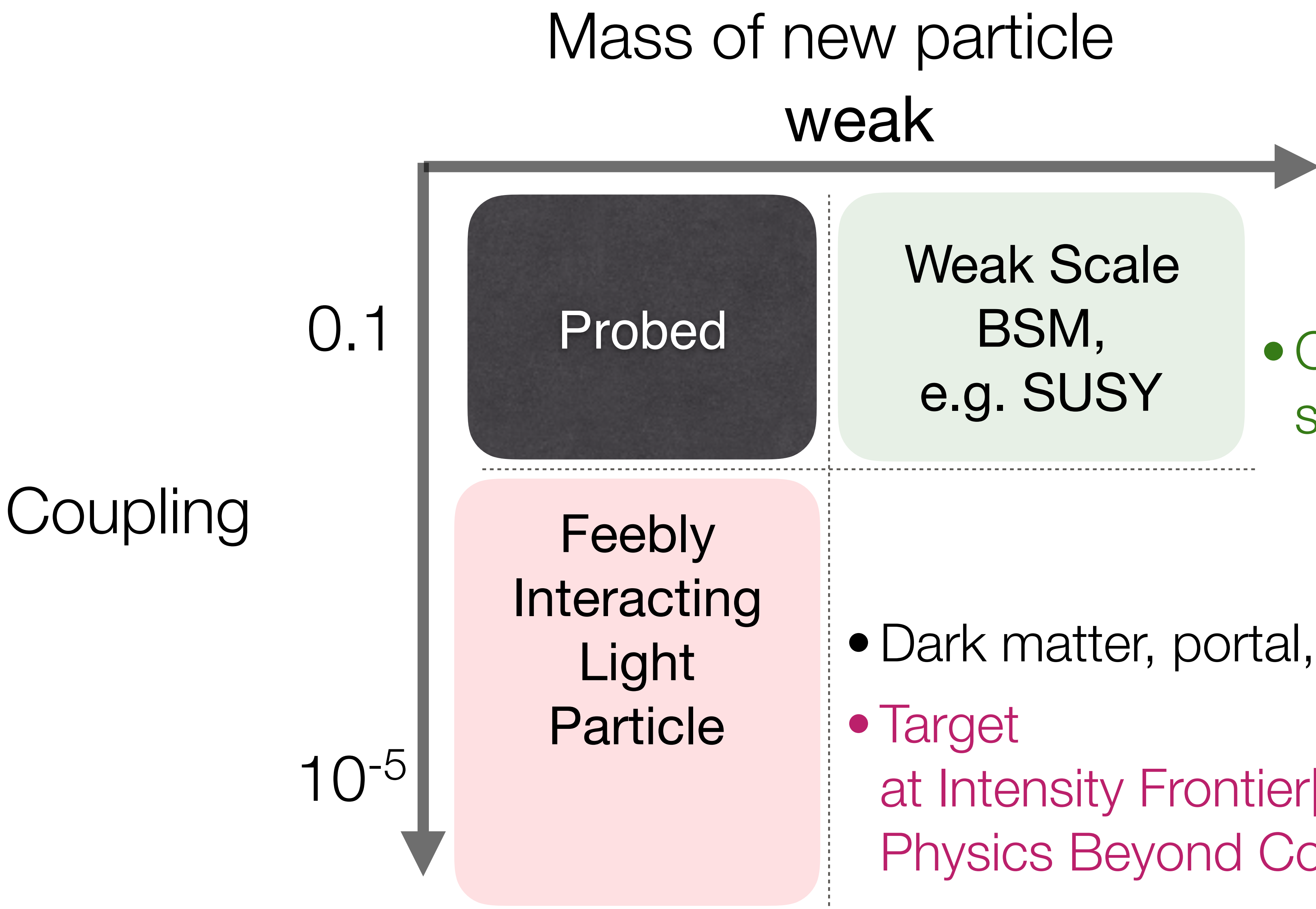
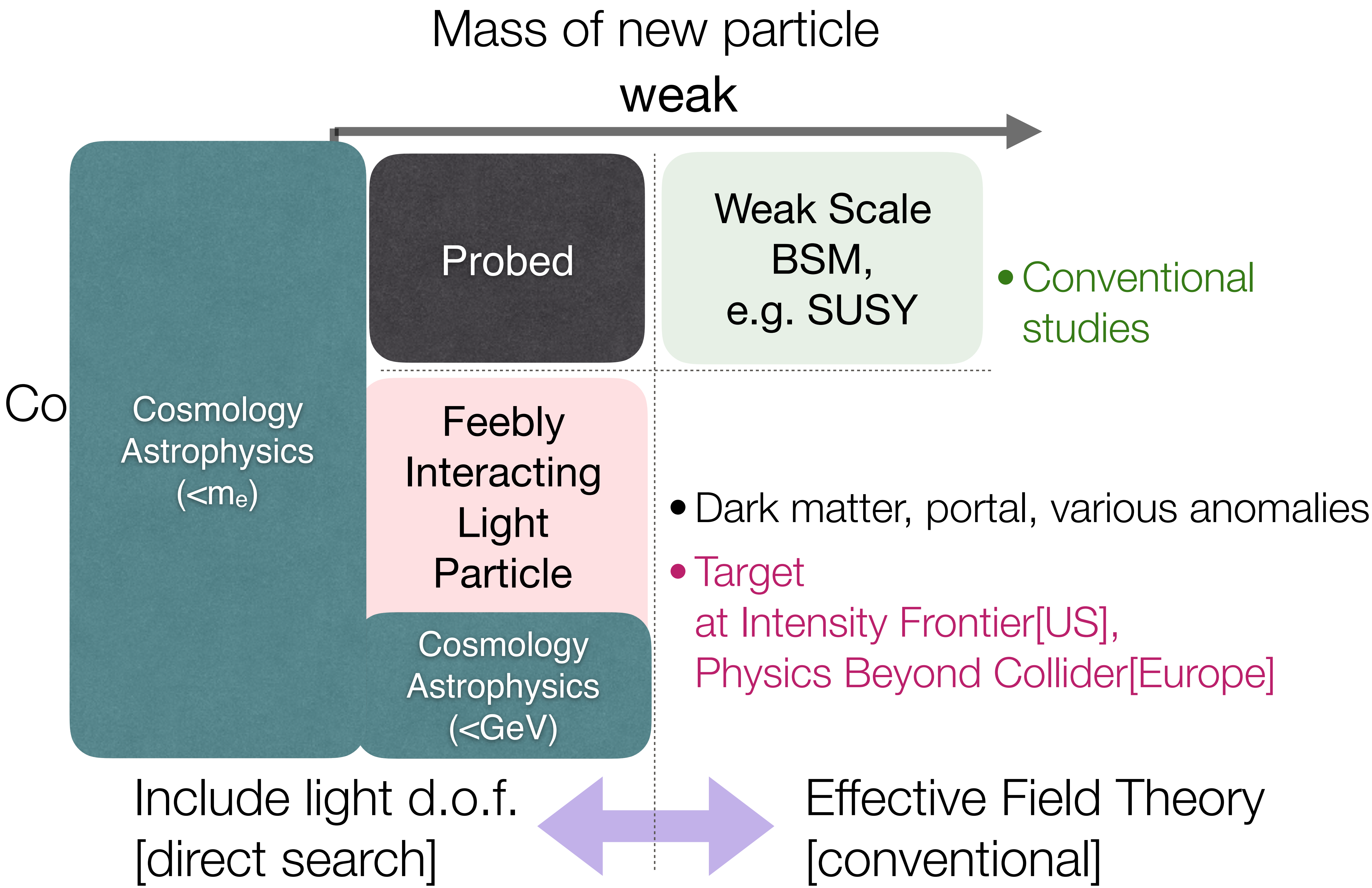


- Conventional studies

- Dark matter, portal, various anomalies
- Target at Intensity Frontier[US], Physics Beyond Collider[Europe]

Include light d.o.f. [direct search] ⟷ Effective Field Theory [conventional]

From Precision to Discovery



Same for Belle II, LHCb, ν-factrory

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NA62

CERN

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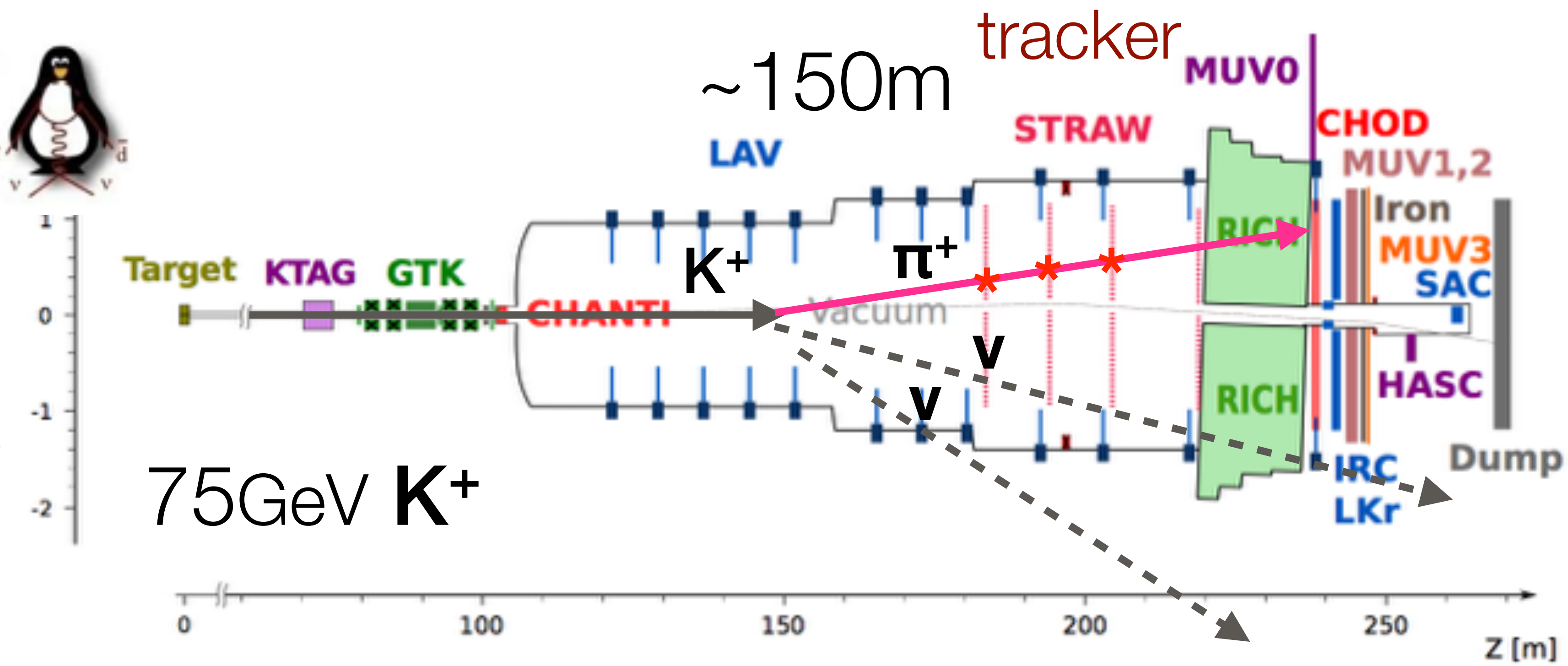
physic run since 2015



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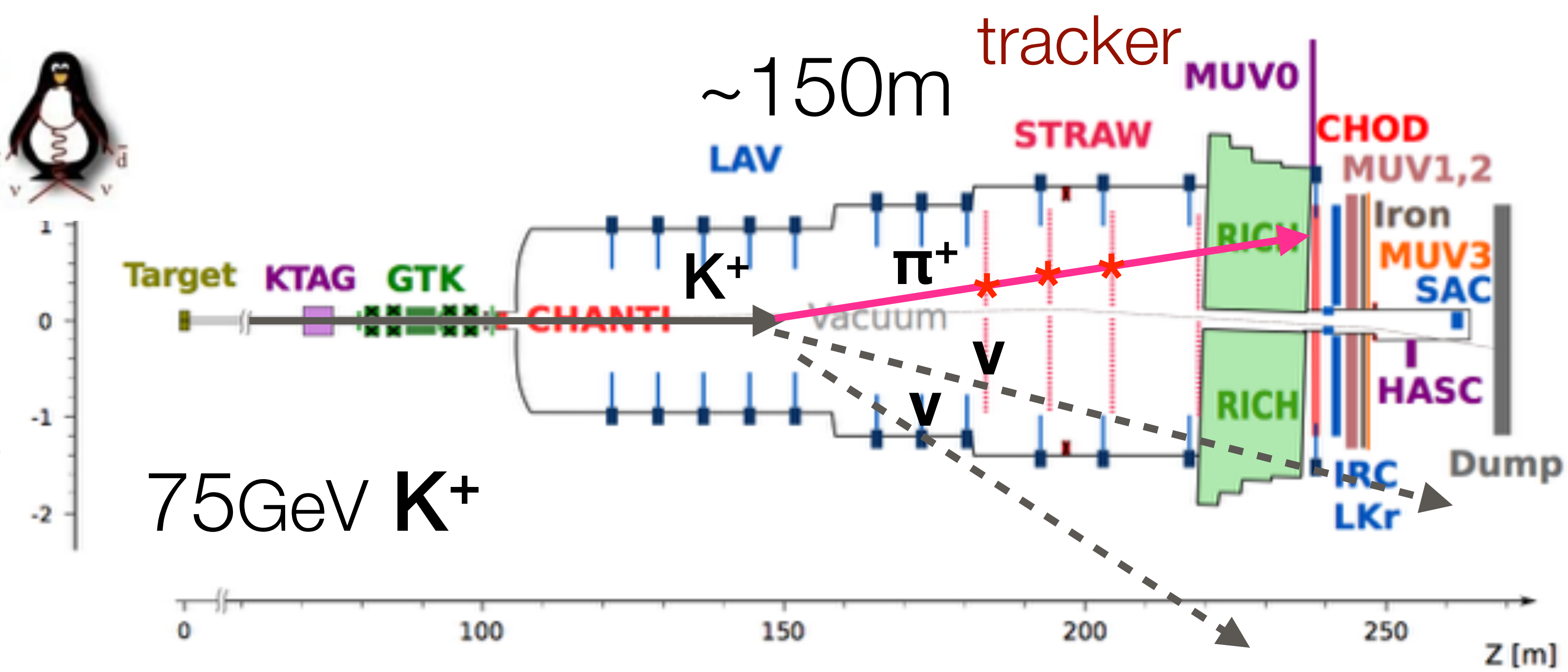

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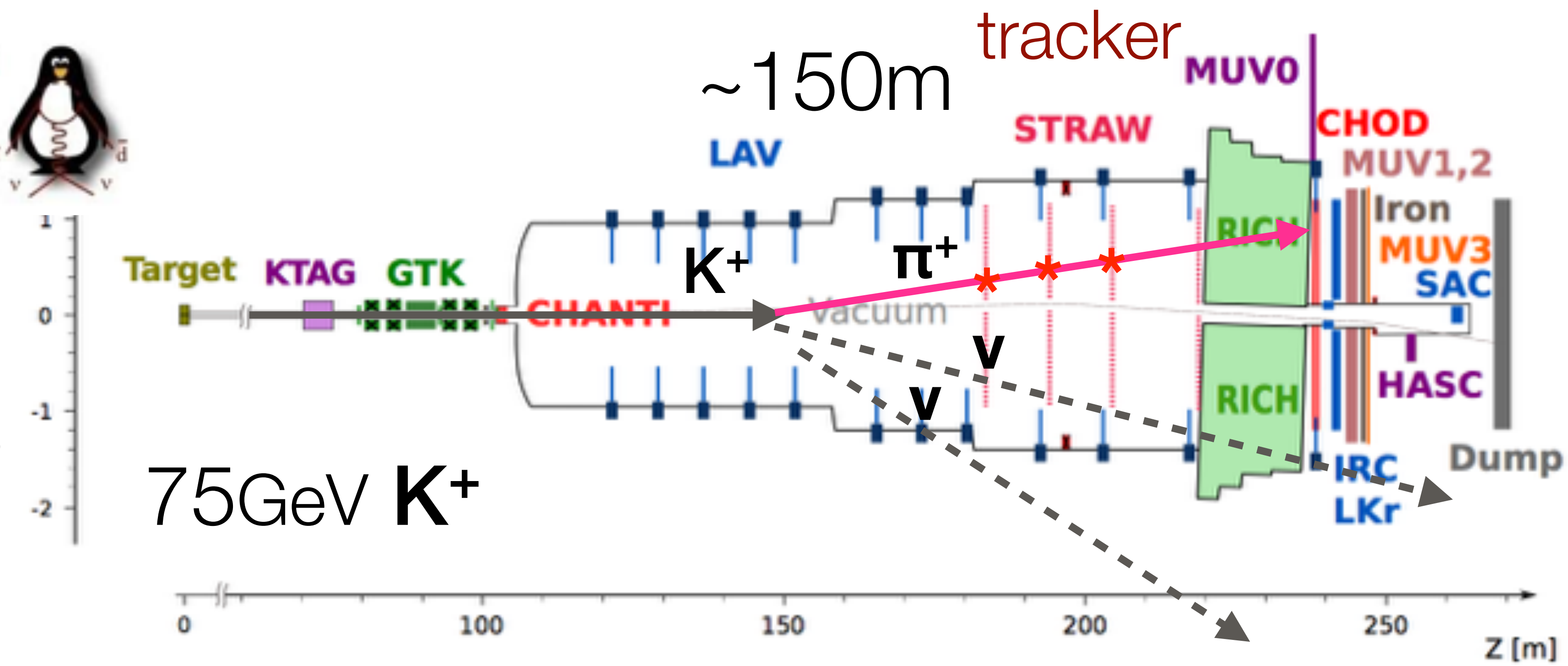

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- Currently $N_{K+} \sim 7\text{x}10^{12}$ decays

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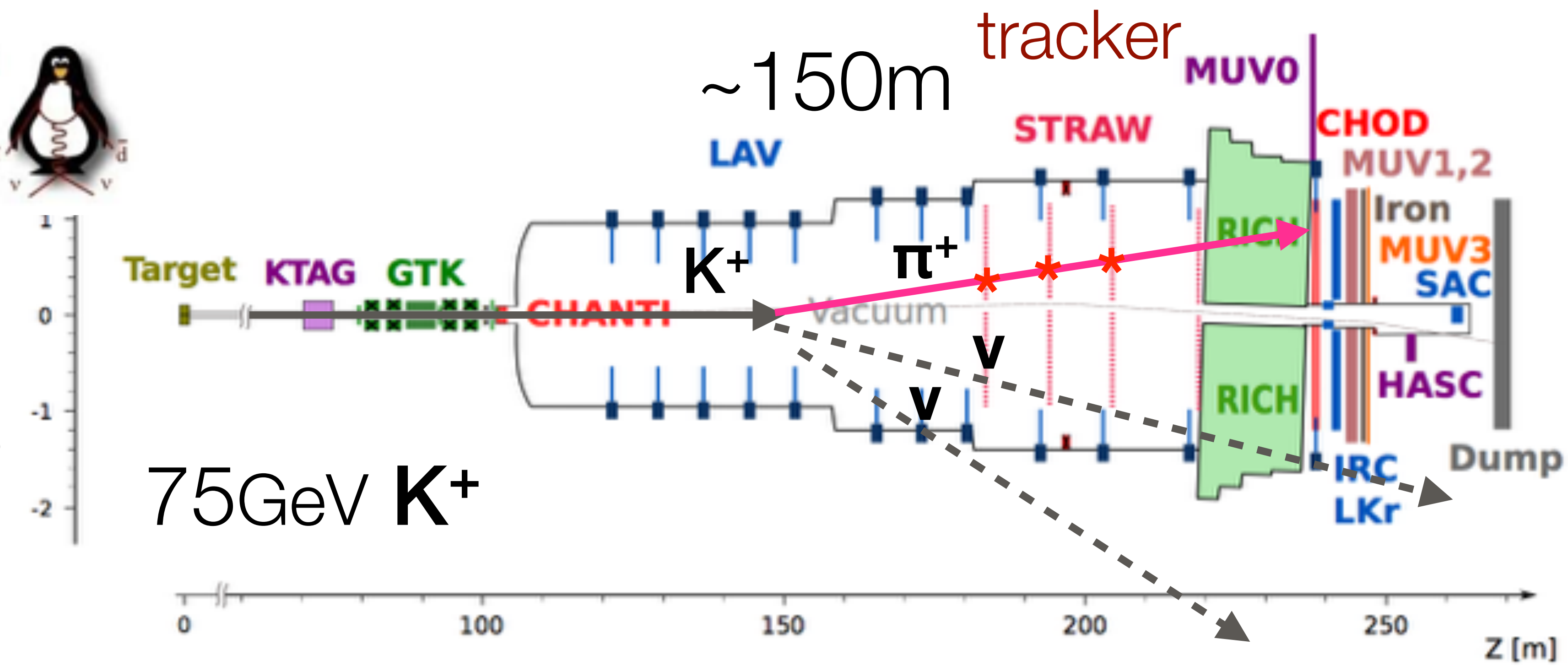

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- Currently N_{K+}~$7\text{x}10^{12}$ decays

- Trying to measure $\mathrm{BR}(K^+ \to \pi^+\nu\nu)$ with O(10%) precision

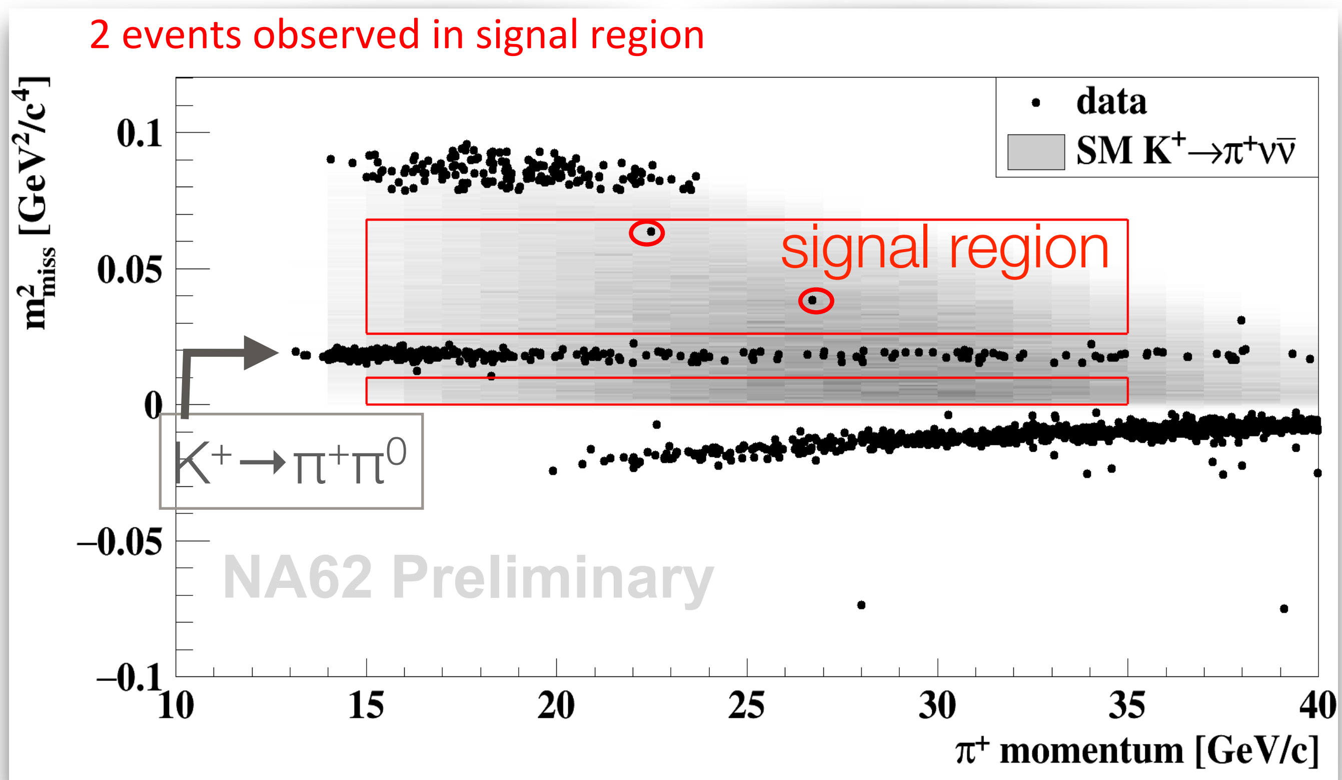
NA62

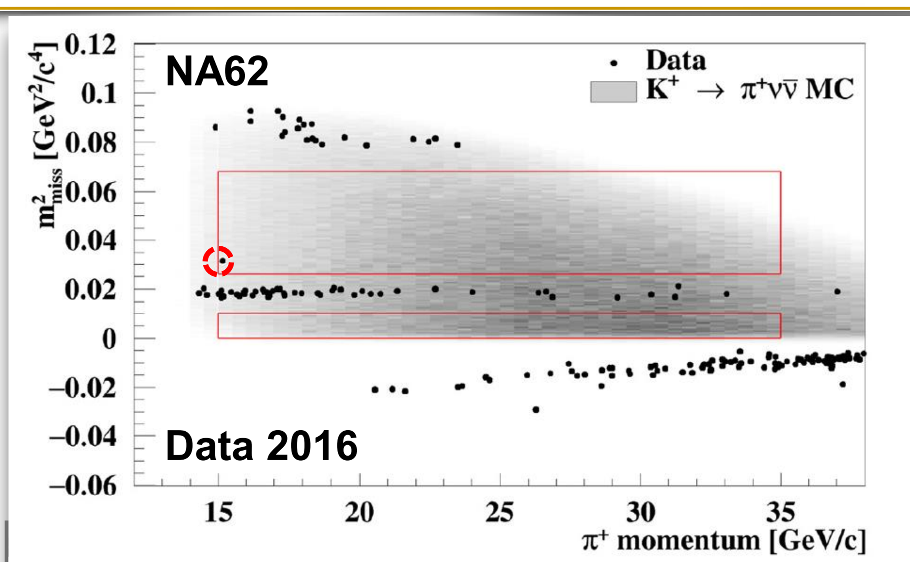
KAON2019

ICHEP2020

Obs: **3** ['16+'17, N_{K+}~2x10[12]]

BG: 1.65 (±0.31)





NA62

KAON2019	ICHEP2020
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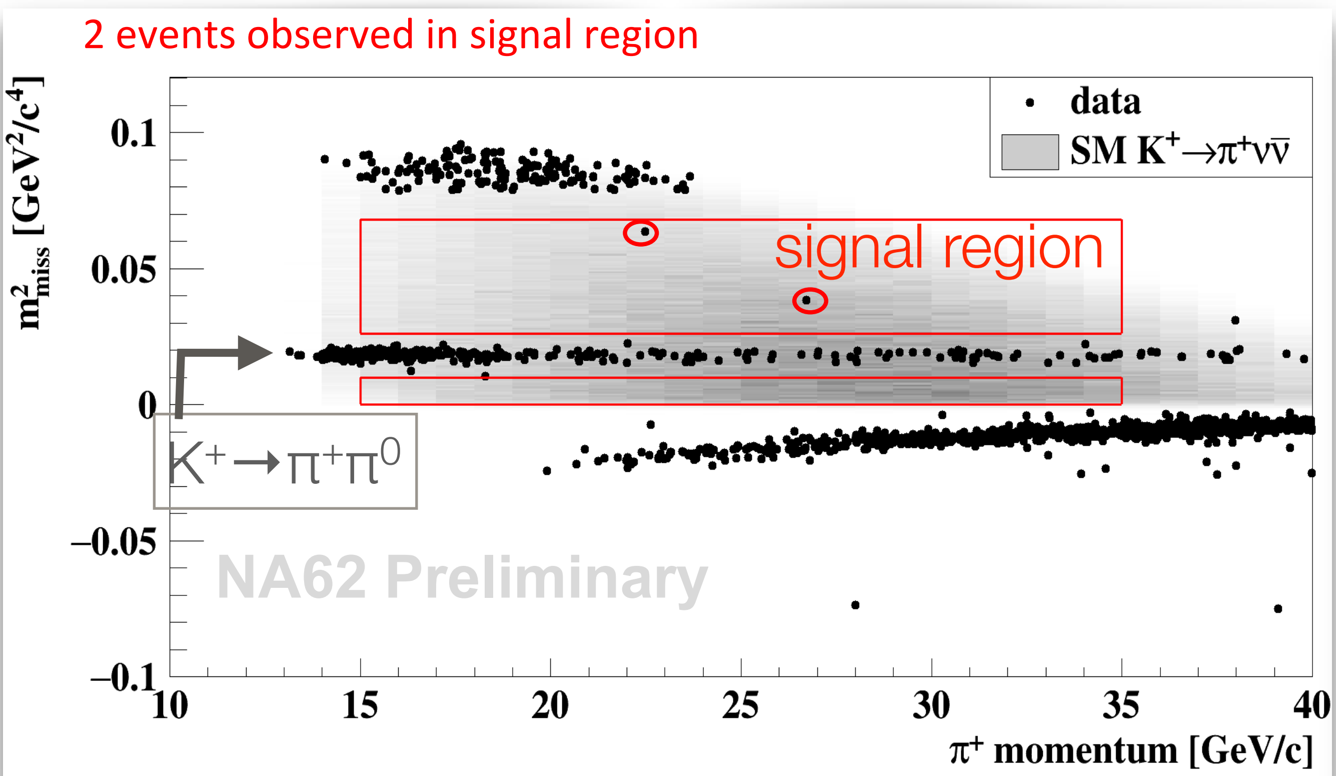

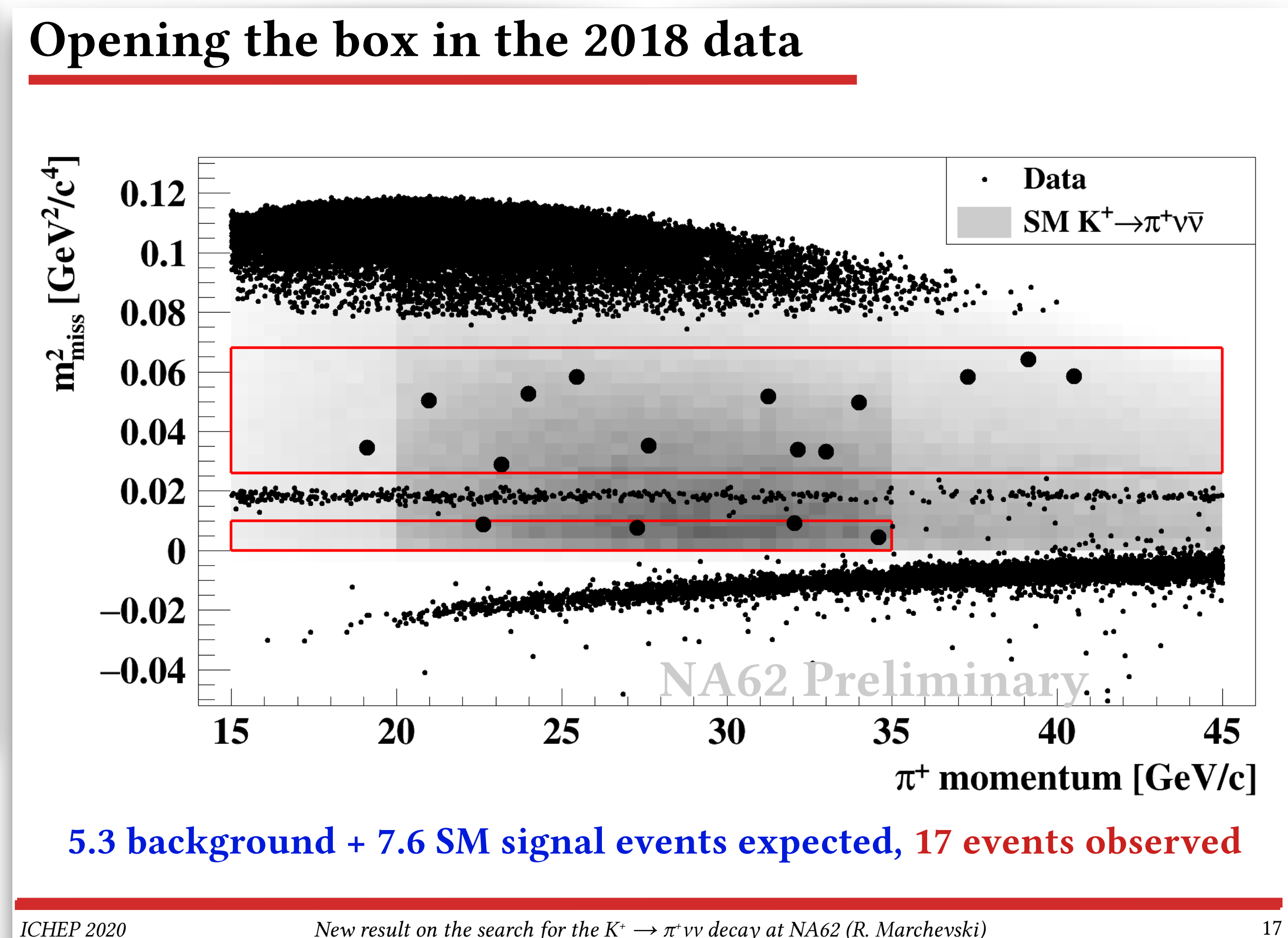

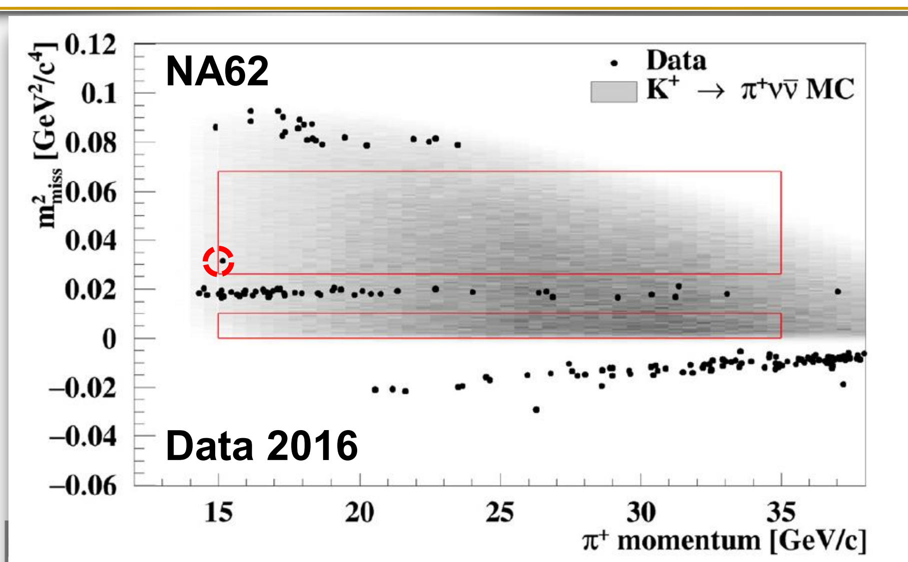

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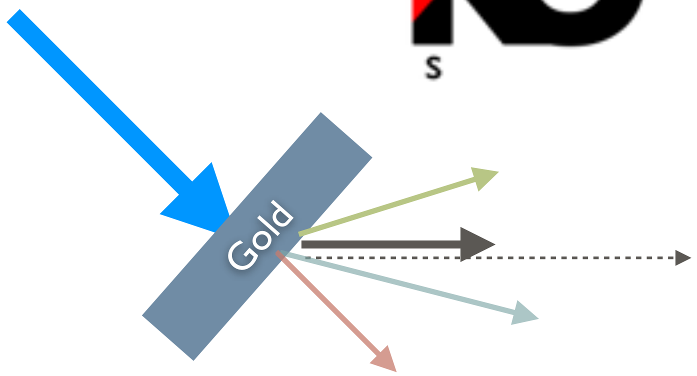
- NA62 result from the complete Run 1(2016 + 2017 + 2018)
  - Observed events: 1 (2016) + 2 (2017) + 17(2018) = 20 (Run 1)
  - Expected background ~ 0.2(2016) + 1.5(2017) + 5.3(2018) = 7 (Run 1)
  - $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$ (3.5σ significance)
  - The most precise measurement of the BR obtained so far
- The result is compatible with the SM prediction within one standard deviation

ICHEP2020
R. Marchevski

- Perform extremely well, and confirm the signal at **3.5σ!**
- Compatible with SM. More data in 2021 with LHC Run III.

KOTO

JPARC



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~2GeV K_L

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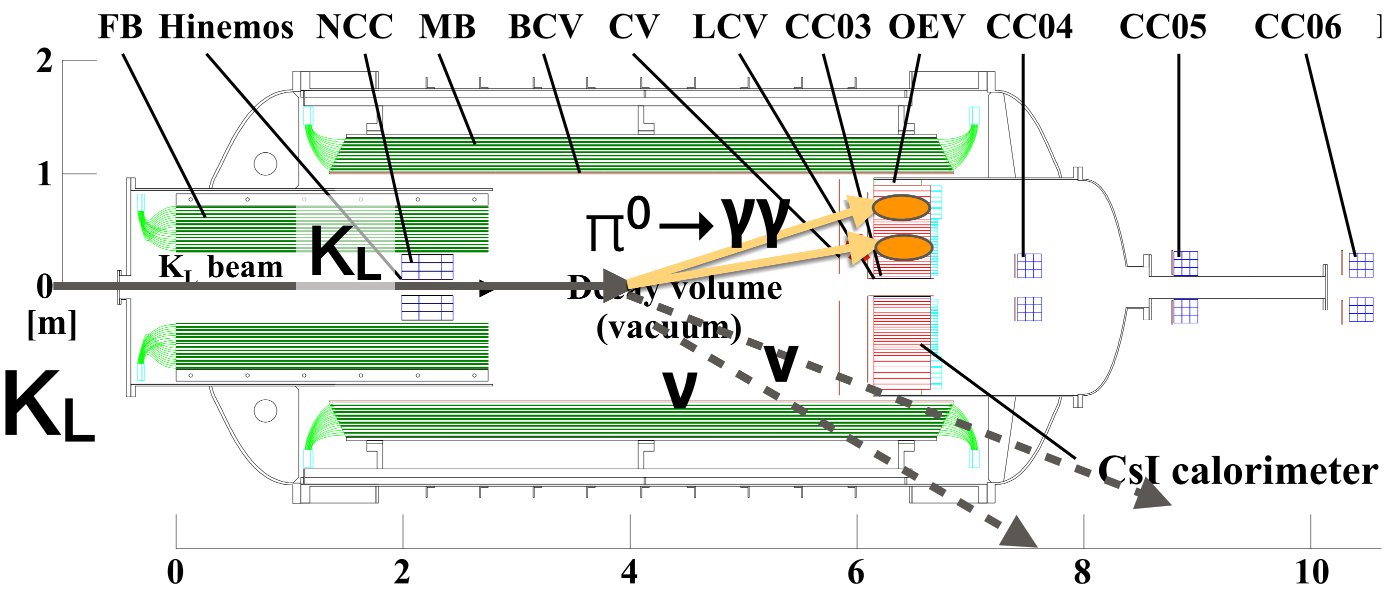
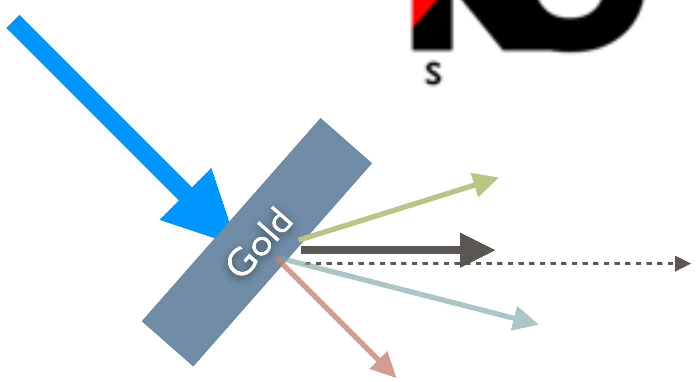


- Main signal: **2γ+missing** BG: $K_L \to 3\pi^0$, neutron

KOTO

JPARC



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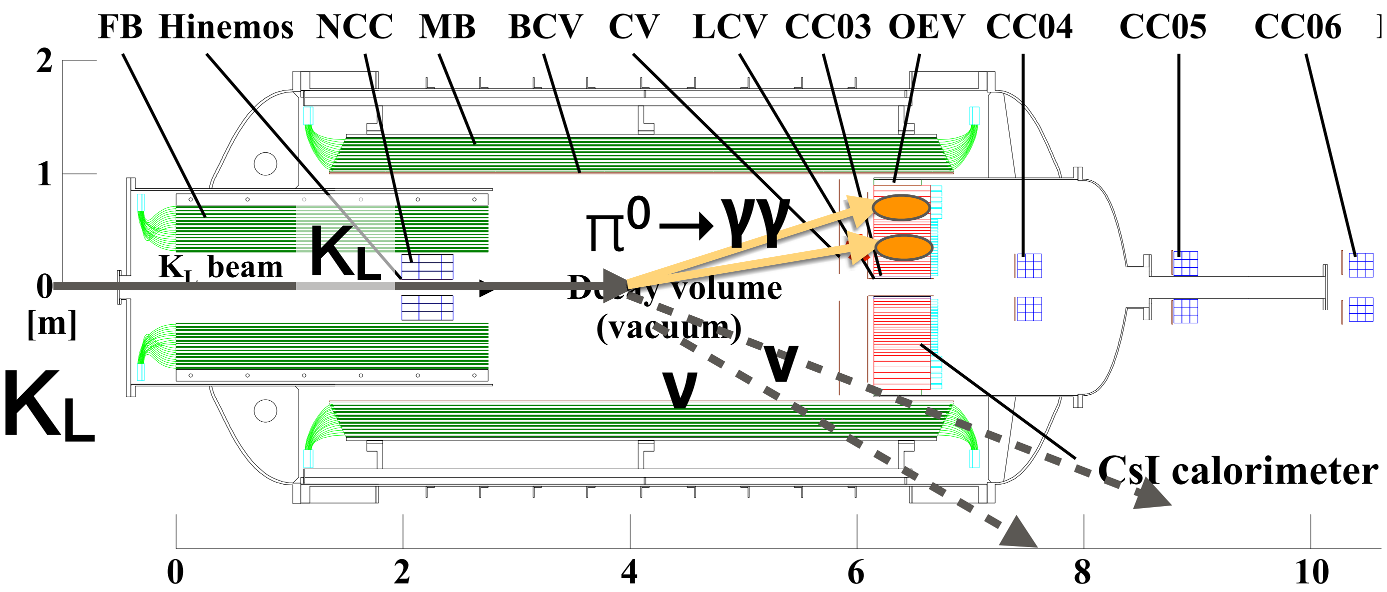

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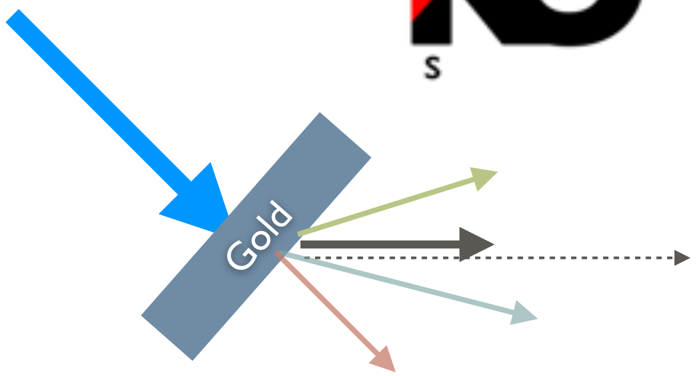

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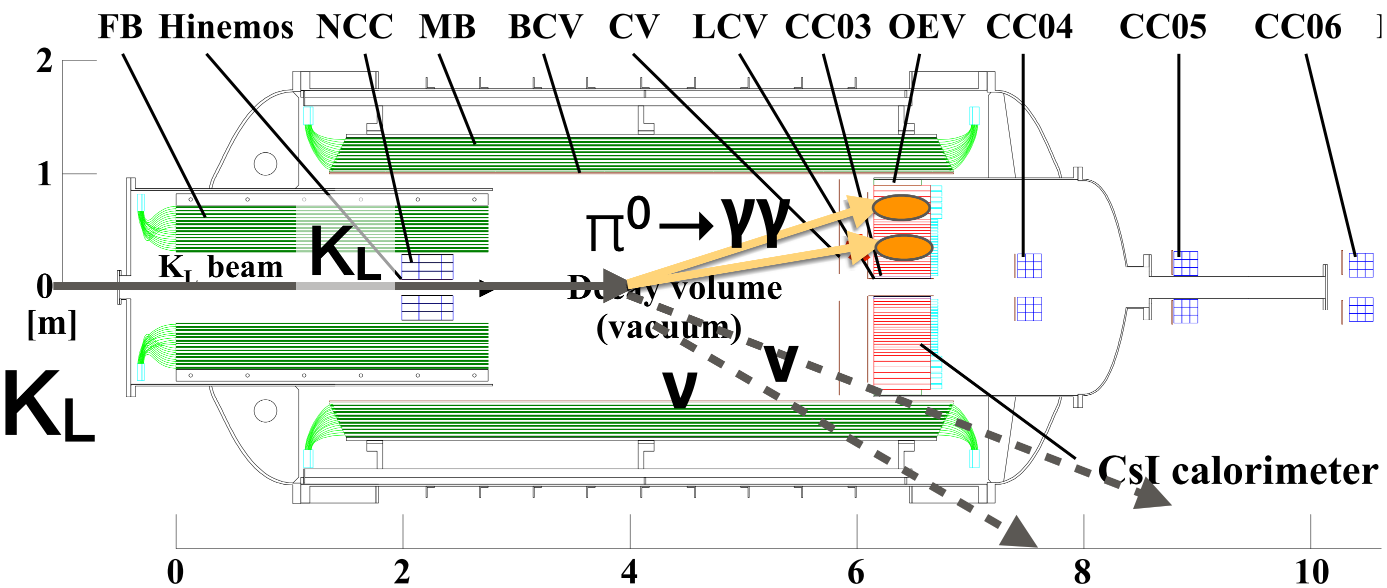

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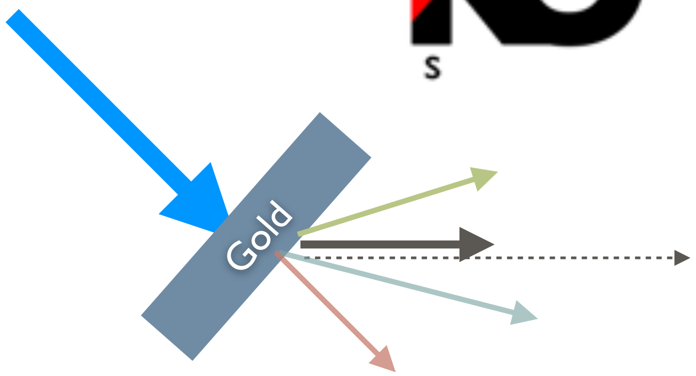

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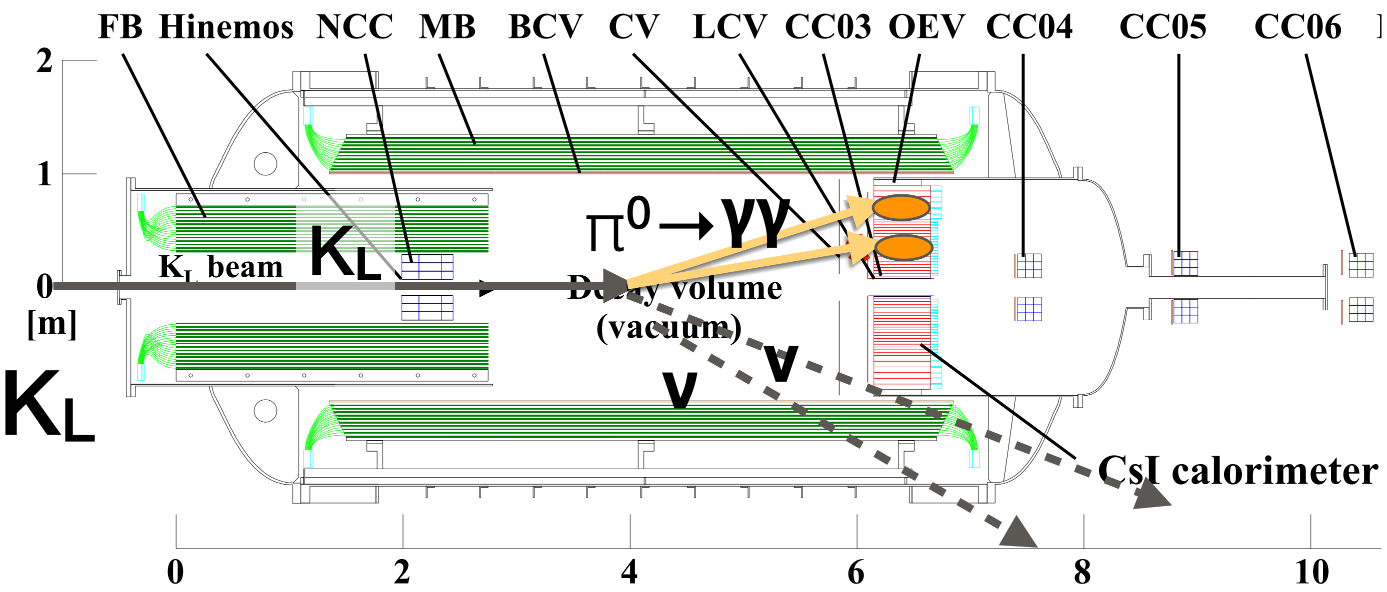

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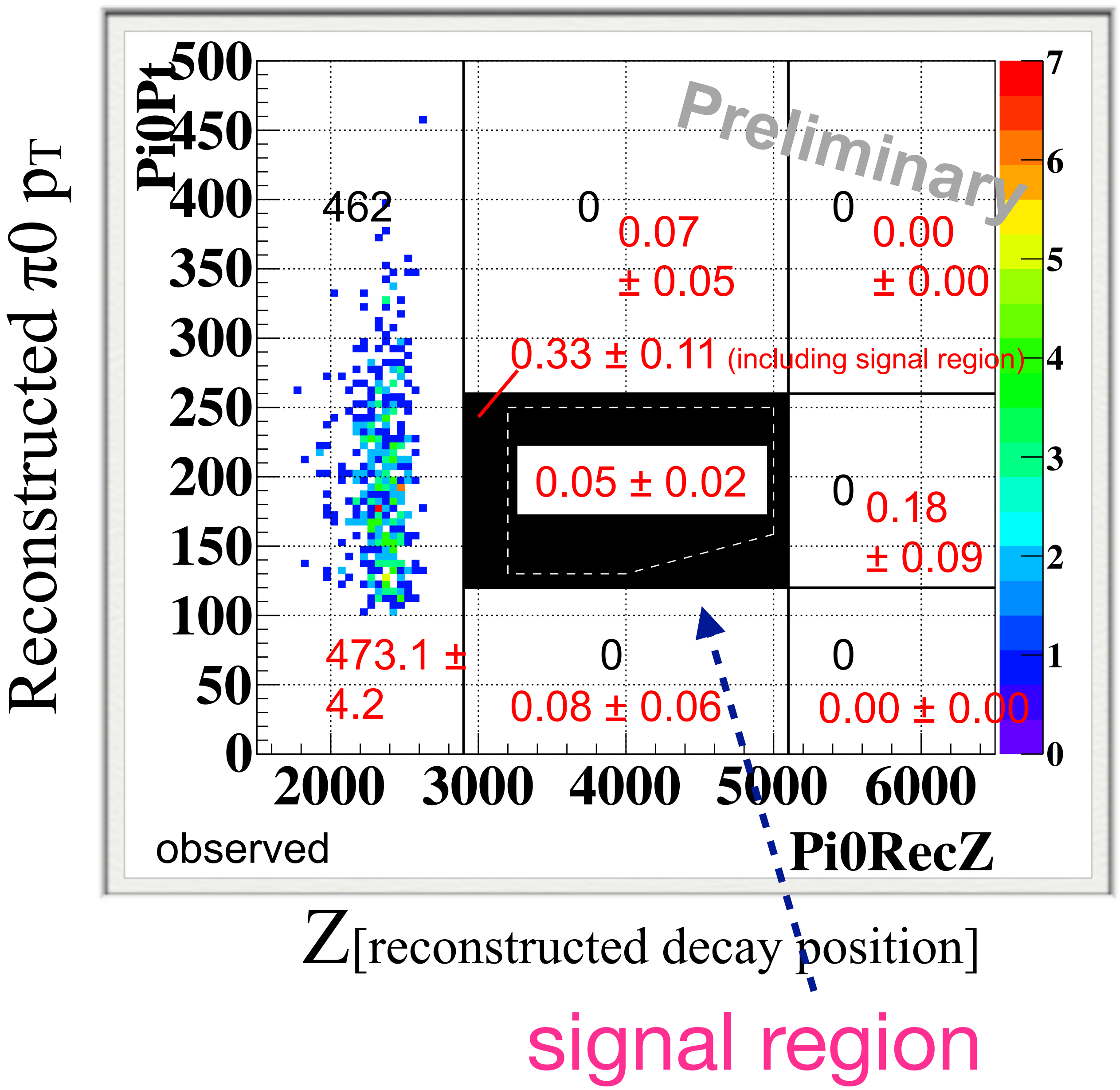
- Currently N_{KL}~6x10^{11} decays [7x10^{12} incoming]
- Trying to measure a few $K_L \to \pi^0 \nu\nu$ events

KOTO “excess”?

KAON2019 [talk by Shinohara]

Blind analysis

BG:0.05±0.02,
SM[$K_L \to \pi^0 \nu\nu$]0.05±0.01



Open the box [unblinding]

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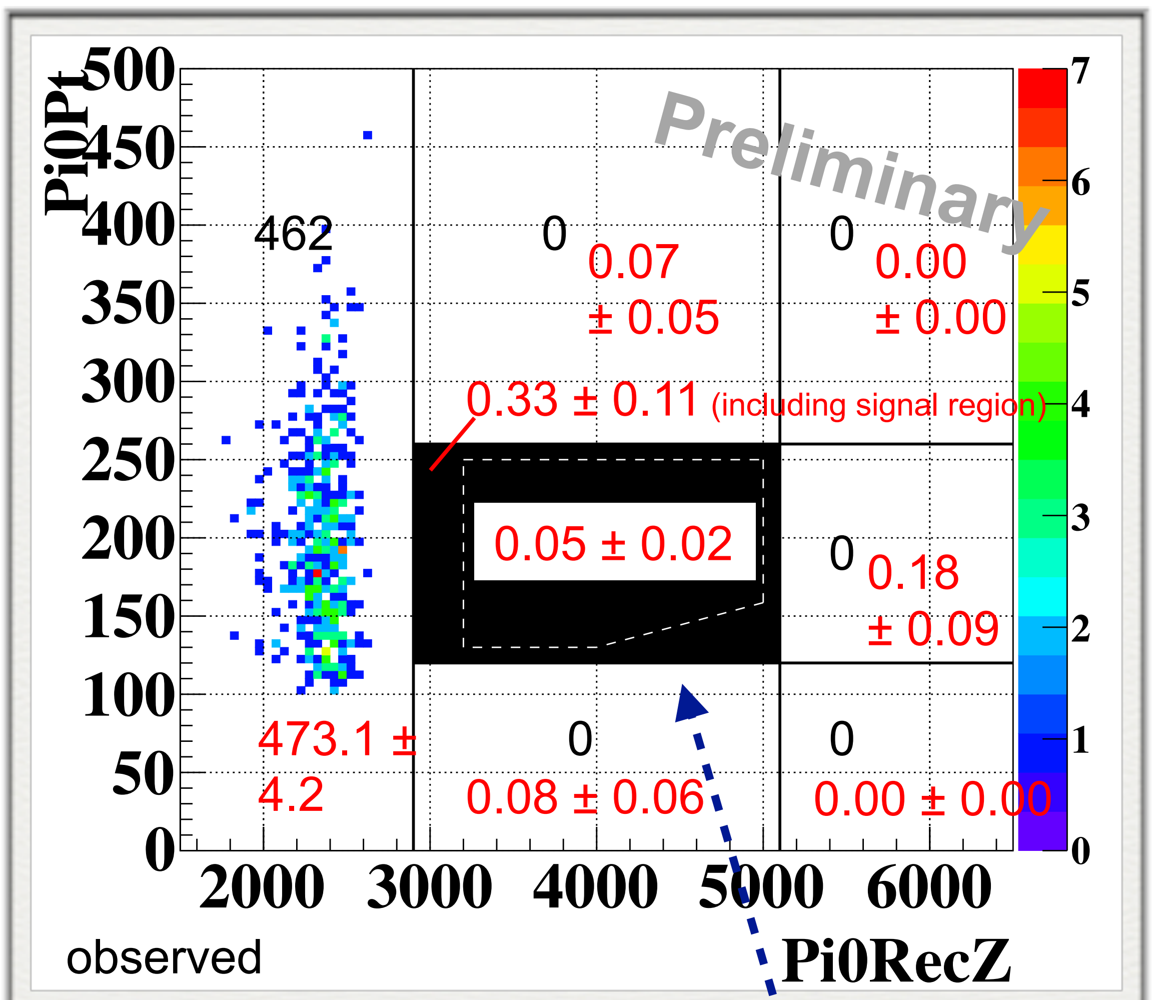
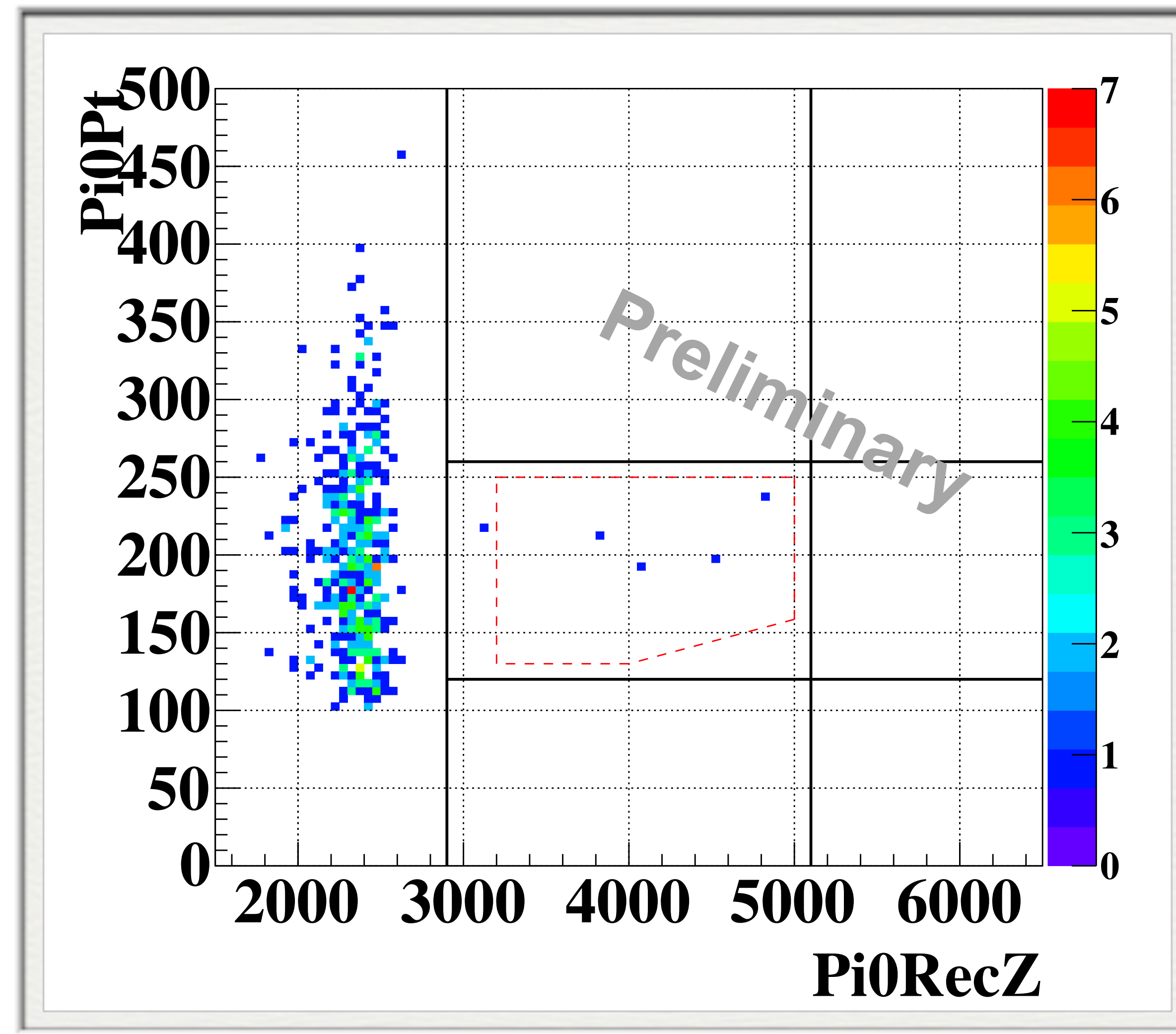
Reconstructed $\pi 0$ p_T



Z[reconstructed decay position]

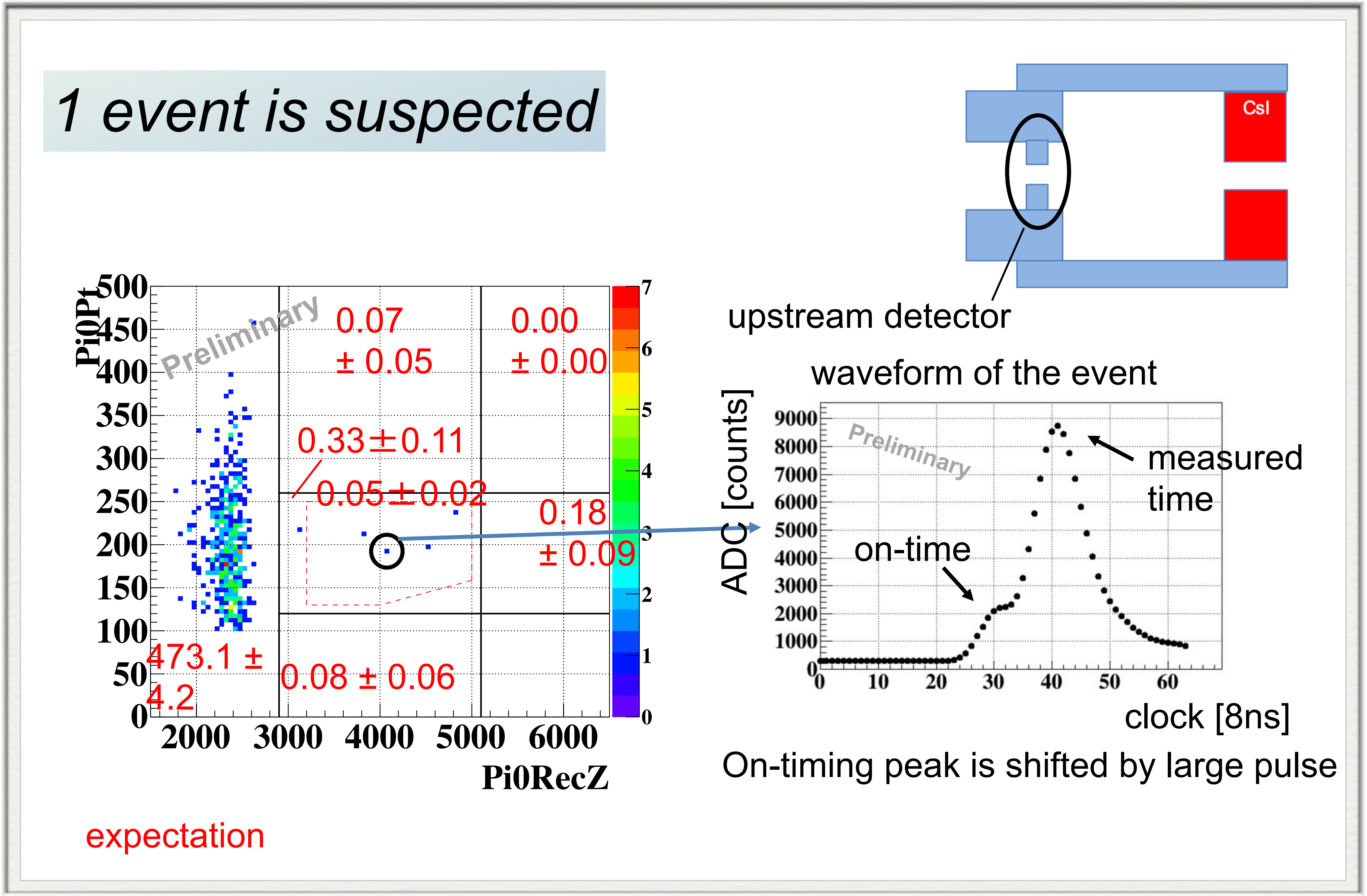
signal region

Open the box [unblinding]



4 events!
[nothing outside SR]

KOTO “excess”?

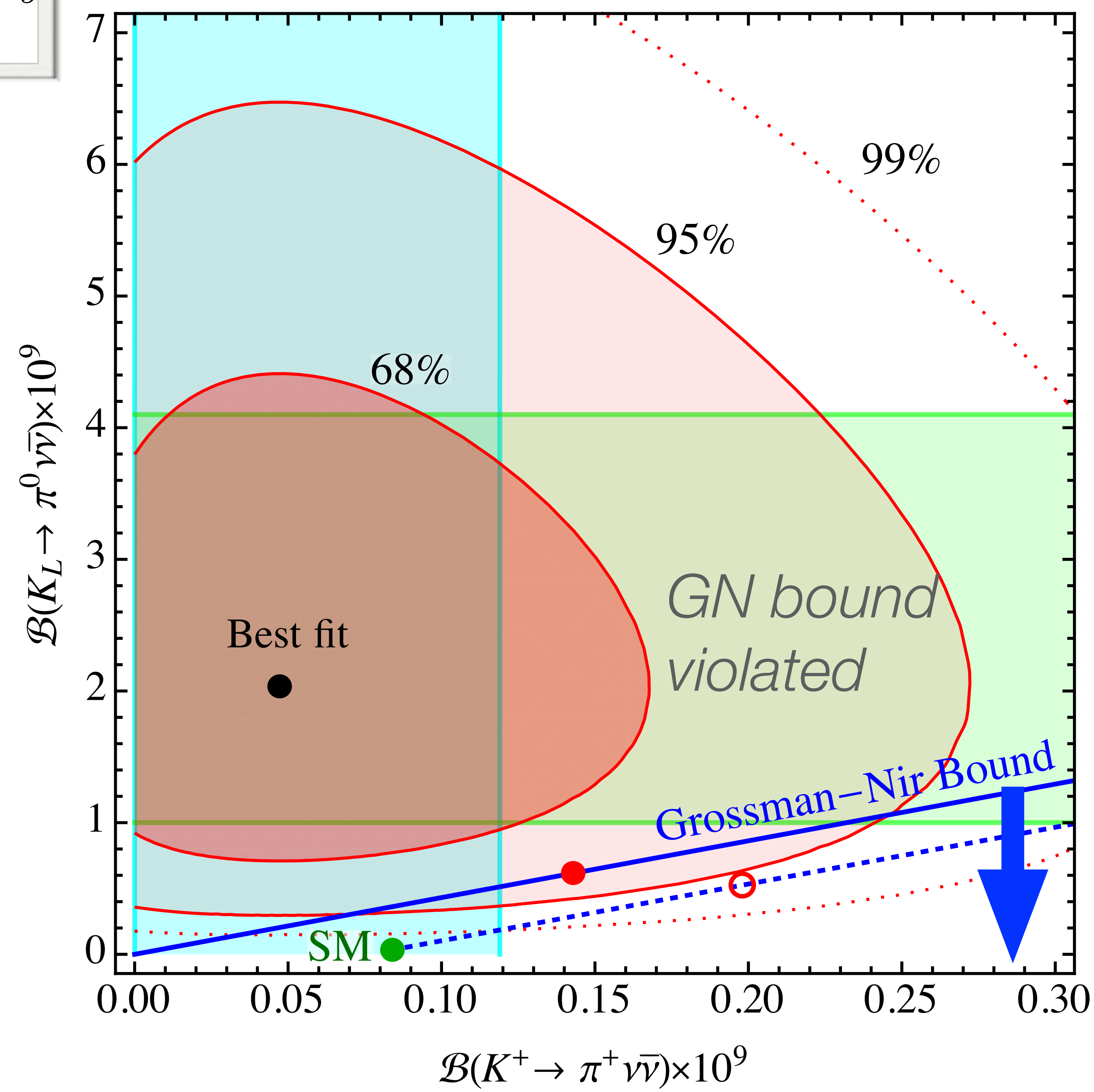


Even 3 events >> SM+BG~0.1.

Combine NA62&KOTO, KAON2019

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

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



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- SM point, inconsistent
  p-value~10^{-4} [just K_L]

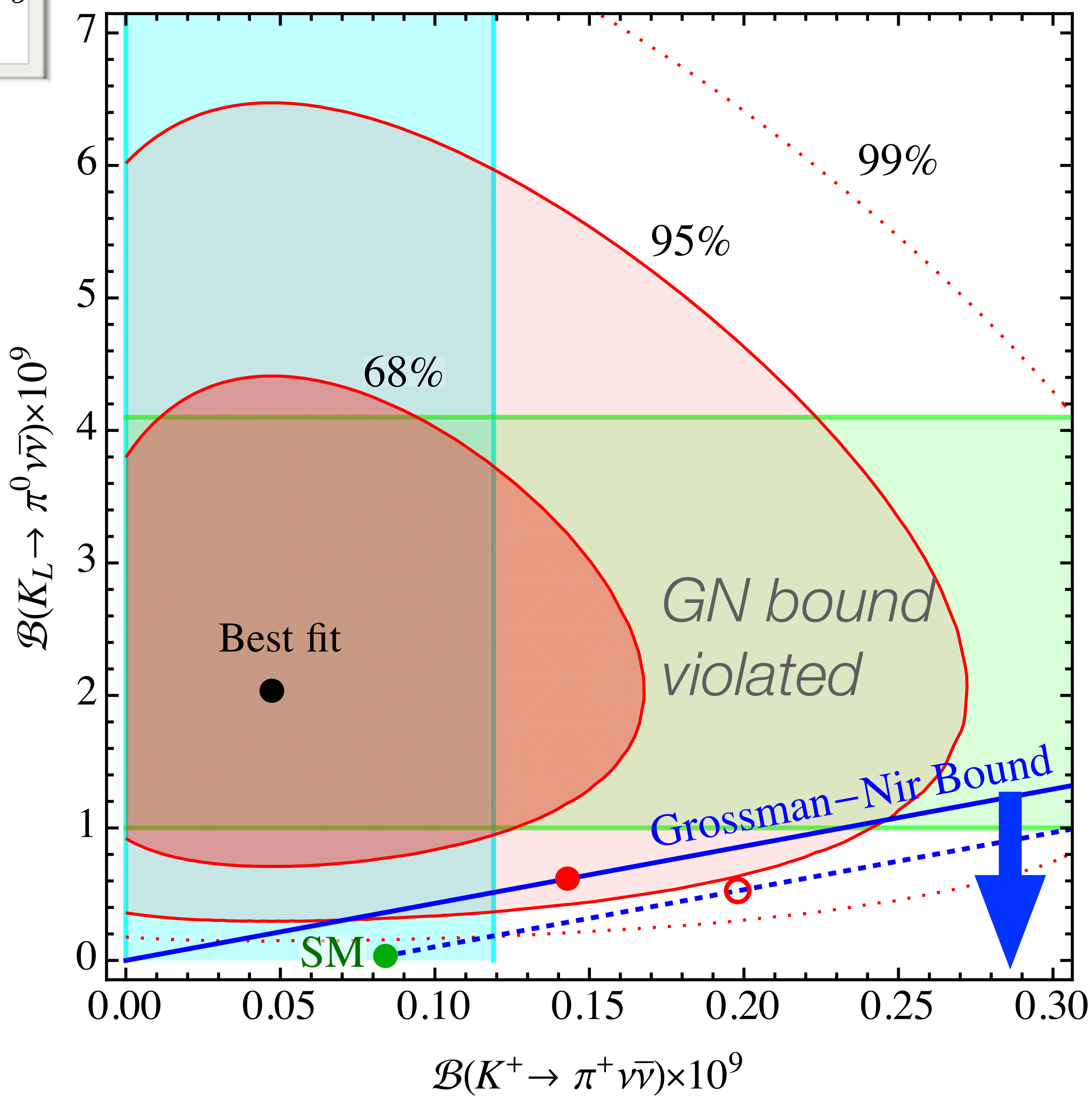
- IF GN bound saturates [1D]

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

  still tension of **2.1 σ**

- Violation of GN bound in
  $K \to \pi \nu \nu$ is very difficult.
  [heavy NP is below blue line]

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



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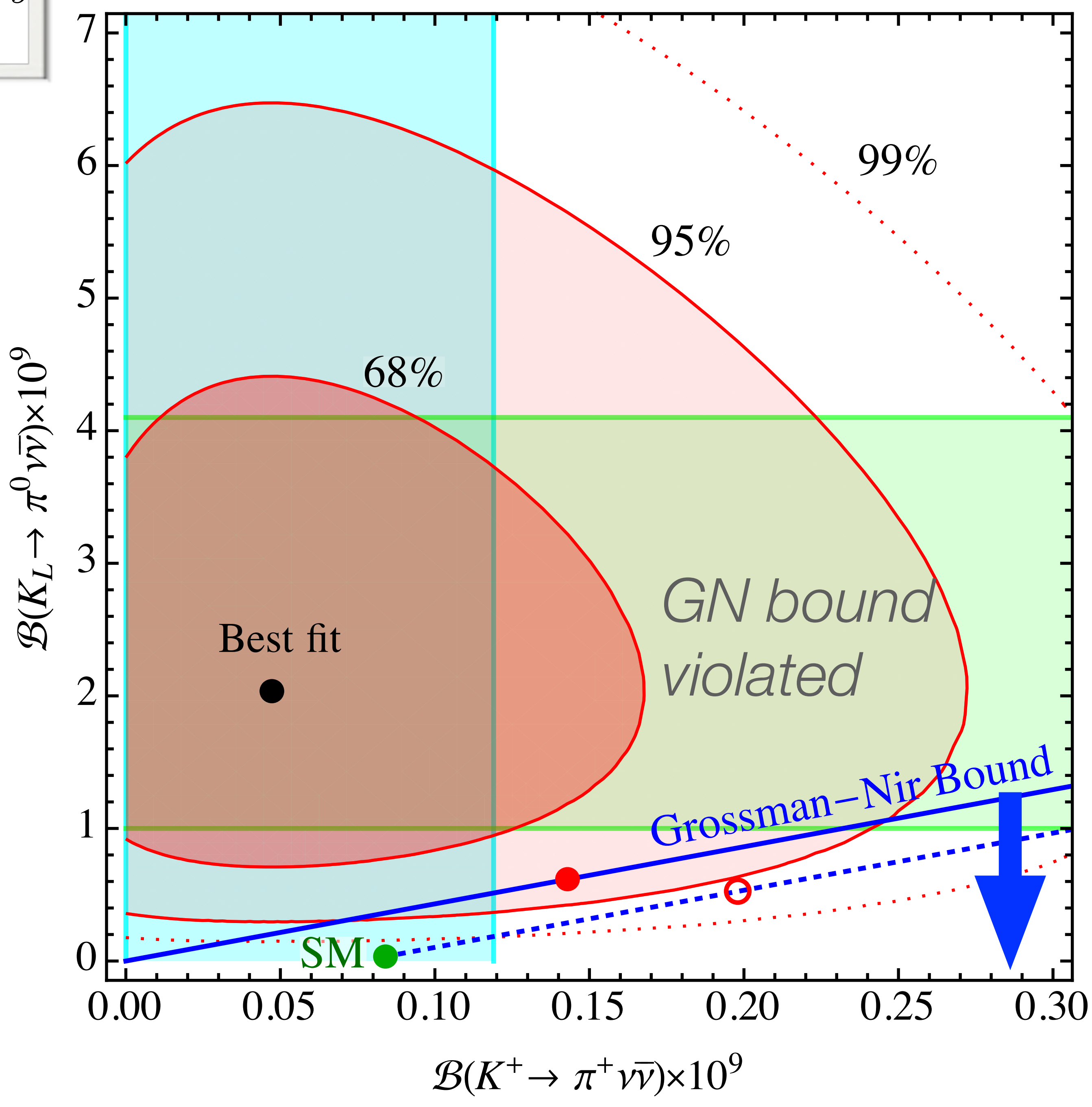


If this is NP, ***a new light state*** is favored.

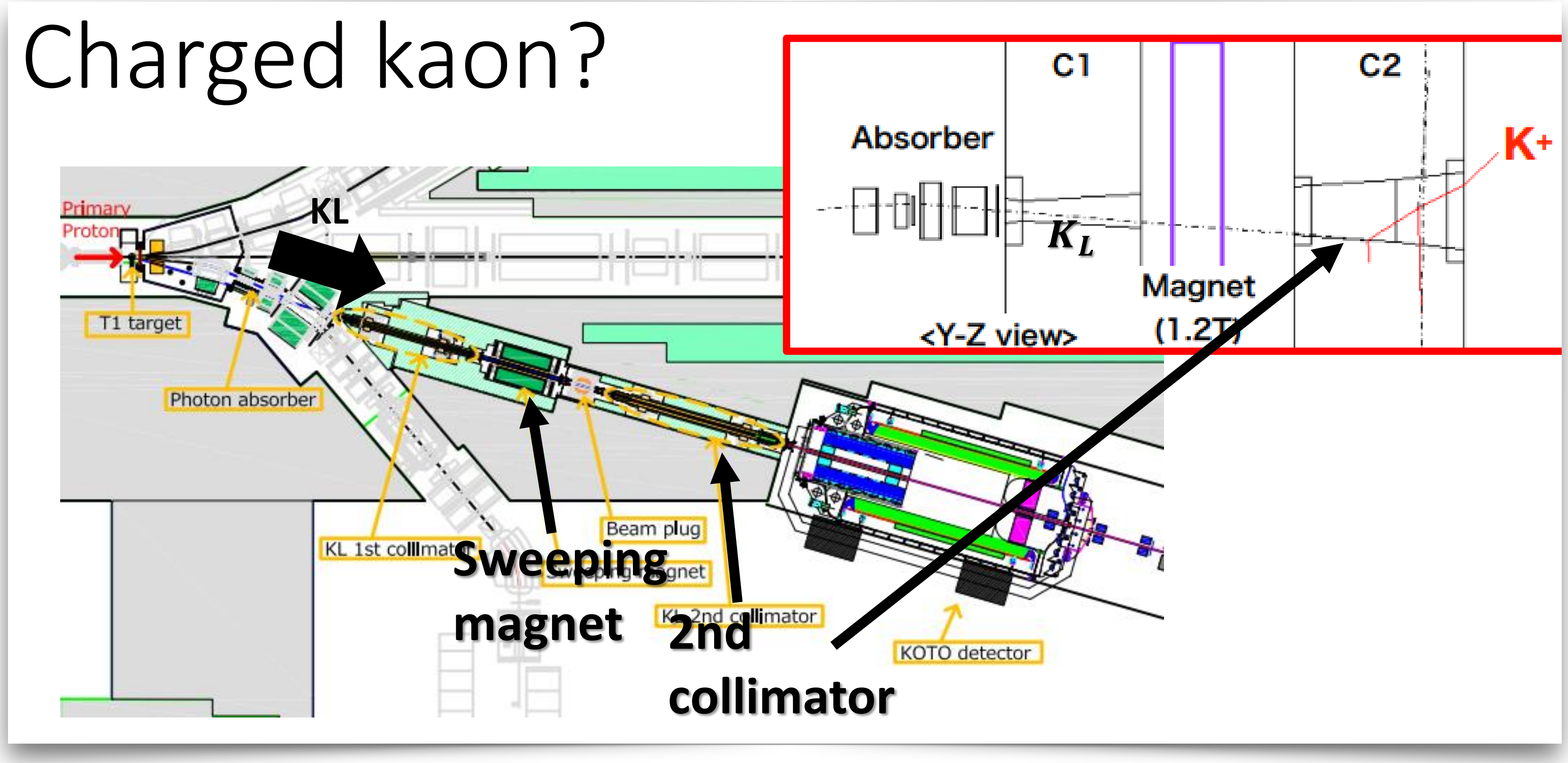
KOTO “excess”, ICHEP2020

Post-unblinding analysis found new possible BG(upstream K^+)

KAON2019

BG=**0.05**±0.02

ICHEP2020



$K_L * \text{collimator} \rightarrow K^+ \rightarrow \pi^0 e^+ \nu$ [BR~5%], $\pi^0\pi^+$

KOTO "excess", ICHEP2020

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KAON2019		ICHEP2020
BG=**0.05**±0.02	→	**0.39**±0.10
		x8 [new K^+ BG, MC]

Expected # of BGs in the signal region

	source		#BG (90% C.L.)	#BG (68% C.L.)
U	KL	$K_L \to 2\pi^0$	<0.09	<0.05
		$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
U		$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
		Ke3 (overlapped pulse)	<0.09	<0.05
		$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
N		Ke3 (π^0 production)	<0.04	<0.02
N		Ke3 (π^+ beta decay)	<0.01	<0.01
N		radiative Ke3	<0.046	<0.023
N		Ke4	<0.04	<0.02
N		$K_L \to ee\gamma$	<0.09	<0.05
N		$K_L \to \pi^+\pi^-$	<0.03	<0.02
N		$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
N		$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

	source		#BG (90% C.L.)	#BG (68% C.L.)
N	K+/-	$K^\pm \to \pi^0\pi^\pm$	0.03±0.03	0.03±0.03
N		$K^\pm \to \pi^0 e^\pm \nu$	0.30±0.09	0.30±0.09
N		$K^\pm \to \pi^0 \mu^\pm \nu$	<0.07	<0.04
	Neutron	Upstream π^0	0.001±0.001	0.001±0.001
		Hadron cluster	0.02 ±0.00	0.02 ±0.00
		CV-pi0	<0.10	<0.05
		CV-eta	0.03±0.01	0.03±0.01
	Total	central value	0.39±0.10	0.39±0.10

U: Updated from Kaon2019
N: New

talk @ichep2020

KOTO “excess”, ICHEP2020

Post-unblinding analysis found new possible BG(upstream K^+)

KAON2019 → ICHEP2020

BG=**0.05**±0.02 → **0.39**±0.10 → **1.05**±0.28

x8 [new K^+ BG, MC] [calibrate K^+ flux x3]

source		#BG (90% C.L.)	#BG (68% C.L.)
KL	$K_L \to 2\pi^0$	<0.09	<0.05
	$K_L \to \pi^+\pi^-\pi^0$	<0.02	<0.01
	$K_L \to 3\pi^0$ (overlapped pulse)	0.01±0.01	0.01±0.01
	Ke3 (overlapped pulse)	<0.09	<0.05
	$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
	Ke3 (π^0 production)	<0.04	<0.02
	Ke3 (π^+ beta decay)	<0.01	<0.01
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	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo-K)	<0.19	<0.10

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)	
K+/-	$K^\pm \to \pi^0\pi^\pm$	0.09±0.09	0.09±0.09	New
	$K^\pm \to \pi^0 e^\pm \nu$	0.90±0.27	0.90±0.27	New
	$K^\pm \to \pi^0 \mu^\pm \nu$	<0.21	<0.12	
Neutron	Upstream π^0	0.001±0.001	0.001±0.001	
	Hadron cluster	0.02 ±0.00	0.02 ±0.00	
	CV-pi0	<0.10	<0.05	
	CV-eta	0.03±0.01	0.03±0.01	
Total	central value	1.05±0.28	1.05±0.28	New

from $K^\pm$ decays

= (0.33±0.08) × uncertainties of simulation

Prediction by MC simulation

Uncertainty of flux → x 3.0

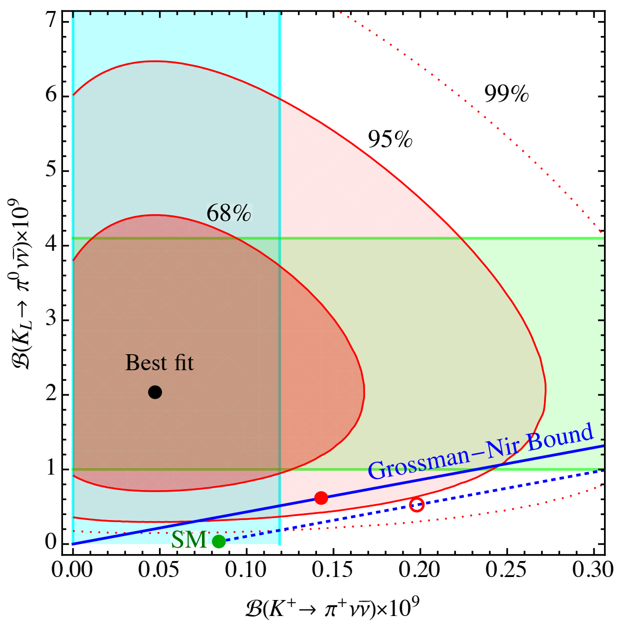
Uncertainty of the estimation of acceptance → ongoing using K^+ control sample

talk @ichep2020

It’s still tentative, let’s wait for a paper.

Combine NA62&KOTO, ICHEP2020

KOTO2019



SM: 3+σ
GN tension: 2.1σ

ICHEP2020

(A) K^+ BG based on MC

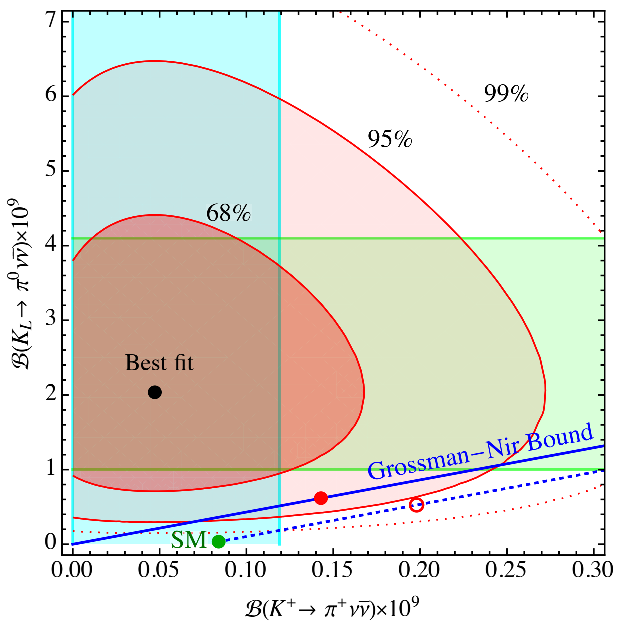
B=**0.39**±0.10

(B)K^+ BG MC **x3** [special run]

B=**1.05**±0.28

Combine NA62&KOTO, ICHEP2020

KOTO2019



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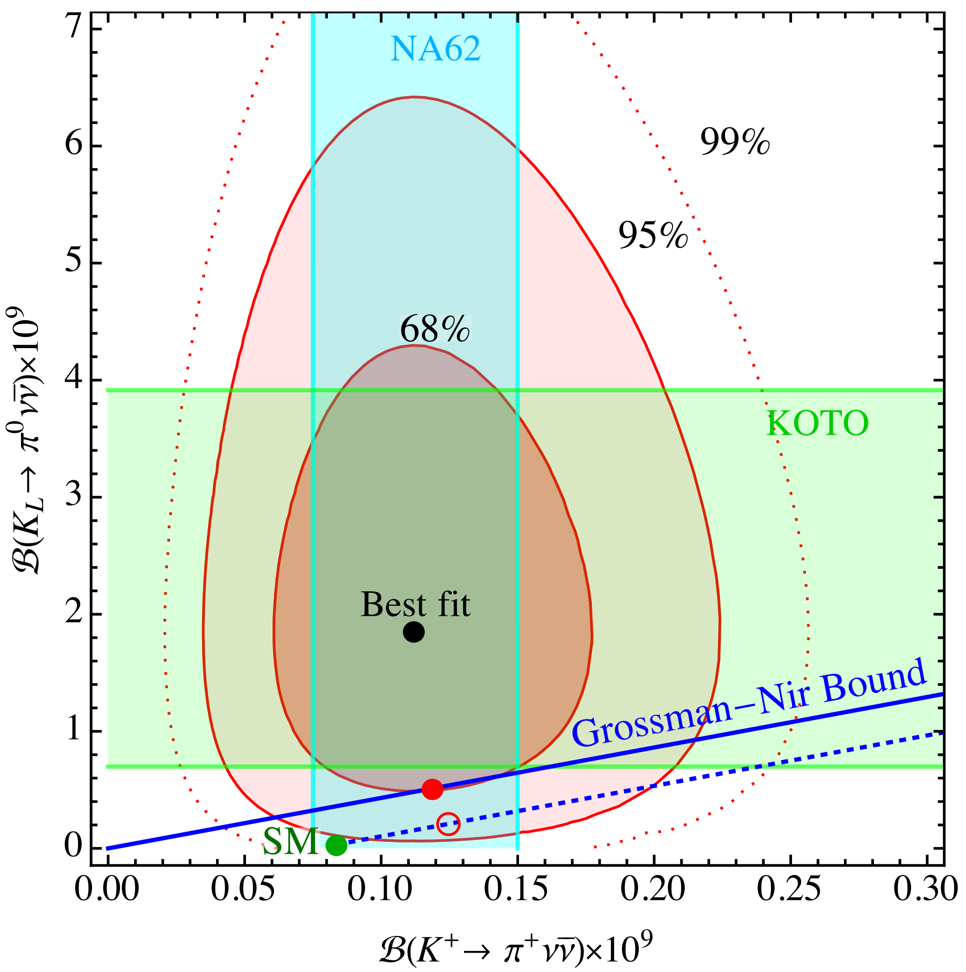


● SM: 2.6σ

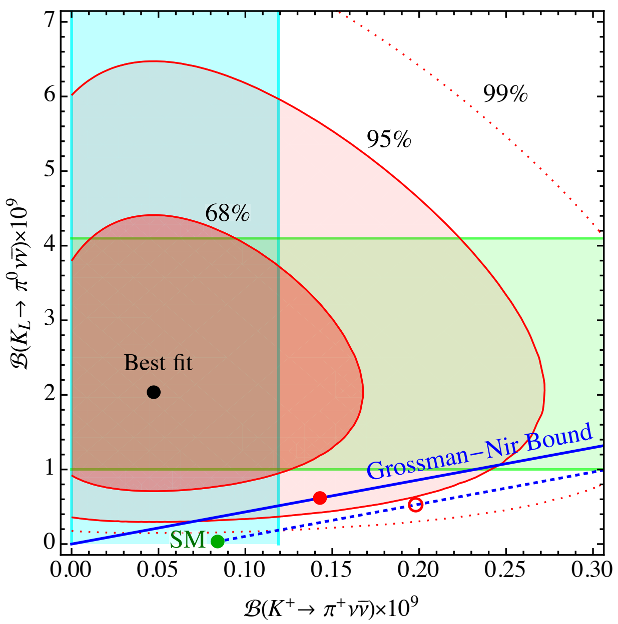
● GN tension: 1.5σ

(B)K+ BG MC **x3** [special run]

B=**1.05**±0.28

Combine NA62&KOTO, ICHEP2020

KOTO2019



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ICHEP2020

(A) K$^+$ BG based on MC

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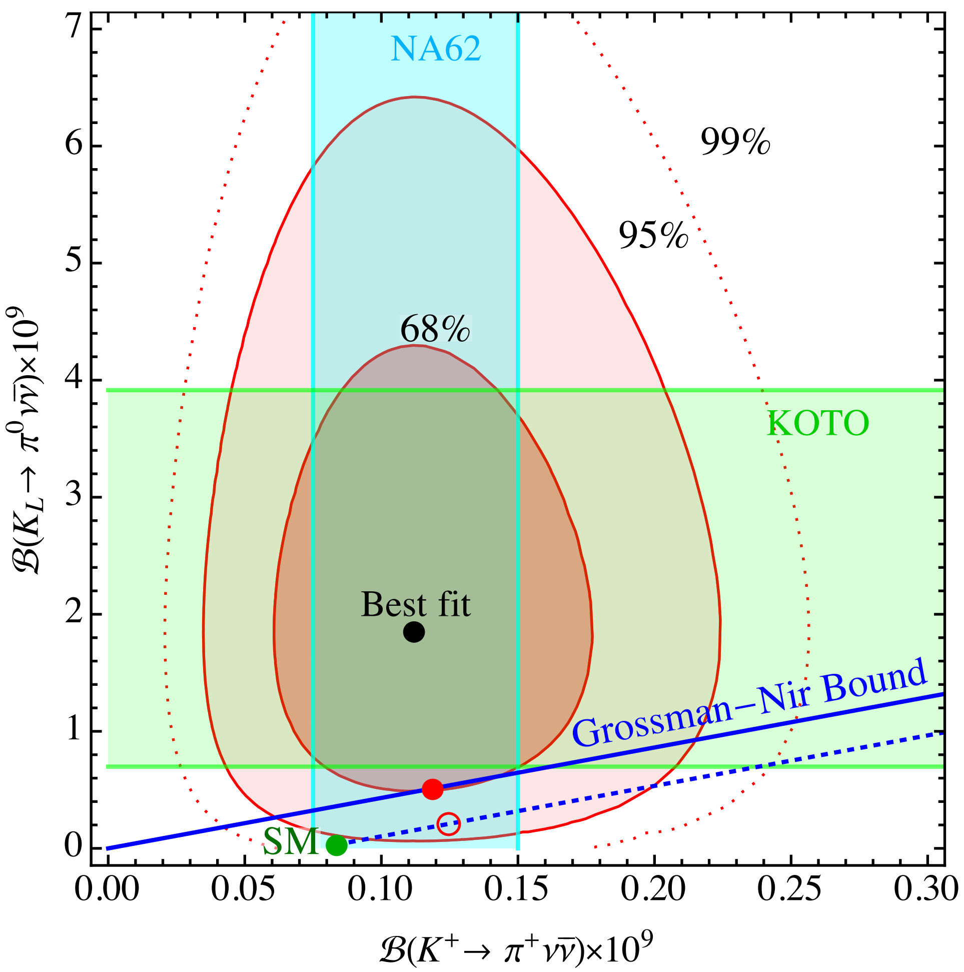
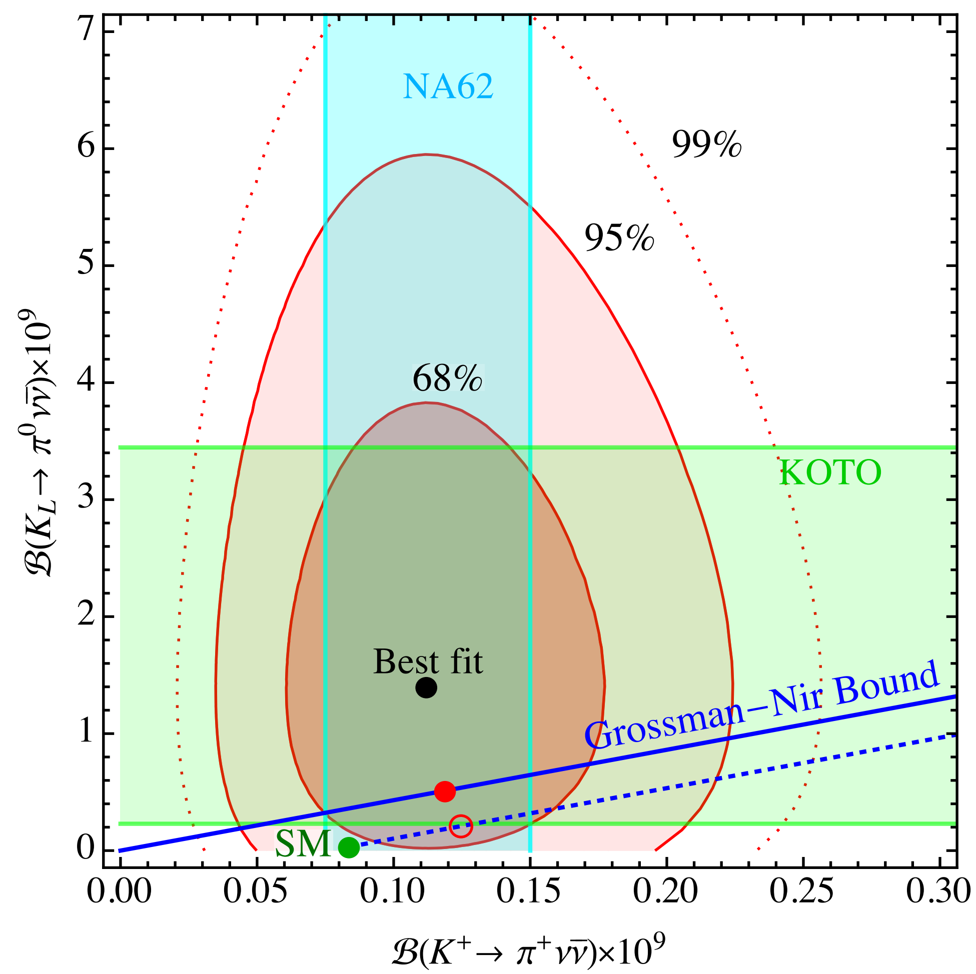


(B)K$^+$ BG MC **x3** [special run]

B=**1.05**±0.28



	(A)	(B)
● SM:	2.6σ	1.7σ
● GN tension:	1.5σ	0.9σ

References relevant to the excess

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: P. Lichard [arXiv:2006.02969]

Both heavy and light new physics compatible

Heavy NP

EFT operators for $K_L \to \pi^0 \nu\nu$

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

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

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

Best Fit

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

[1909.11111] KAON2019

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[T.Kitahara] ICHEP2020

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[T.Kitahara] ICHEP2020

Light NP

$K_L \to \pi^0 X$ X: invisible

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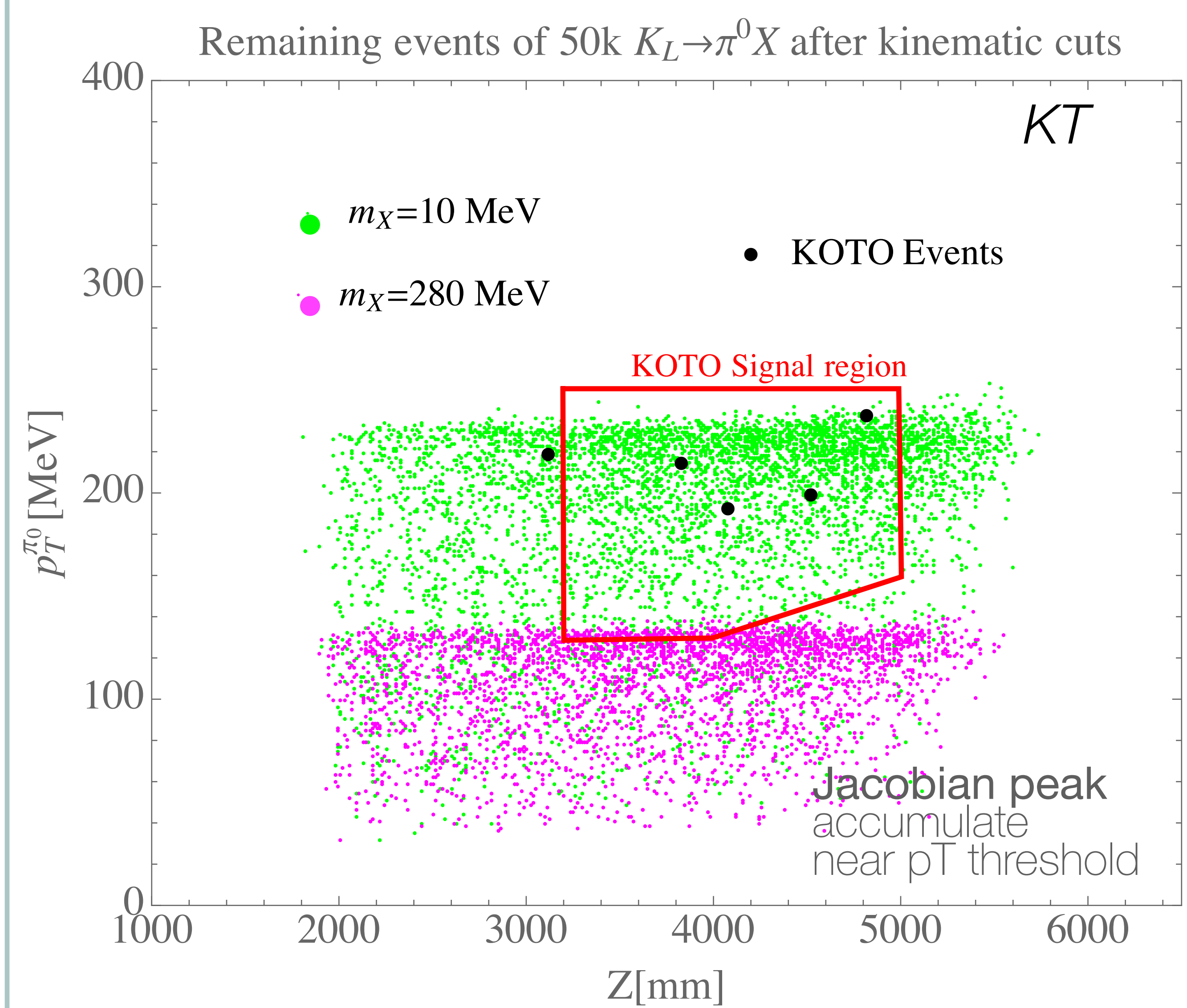

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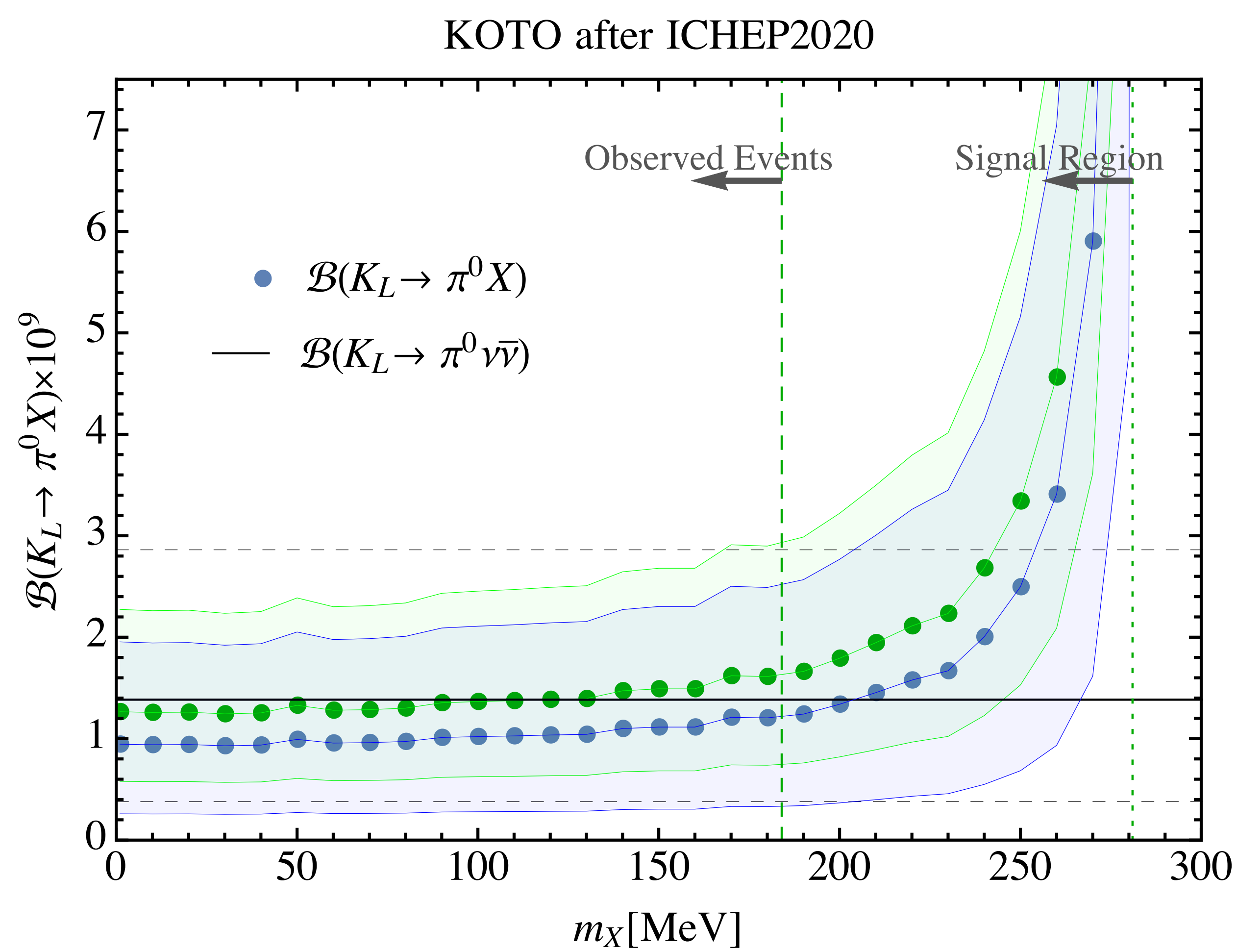

KOTO BG= **0.39**±0.10 (Green)
1.05±0.28 (Blue)

Novel Scenarios violating GN bound

- "Excess" leads to novel scenarios [K_L is the best probe of NP] Make KOTO experiment very unique!

Flavor-violating dark sector [single light state]

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

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

$K_L \to \pi^0 X$

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

Single light state, generalized GN bound still persists.

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Single light state, generalized GN bound still persists.

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

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

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

$X_{1,2}$: 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]

violate GN bound

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

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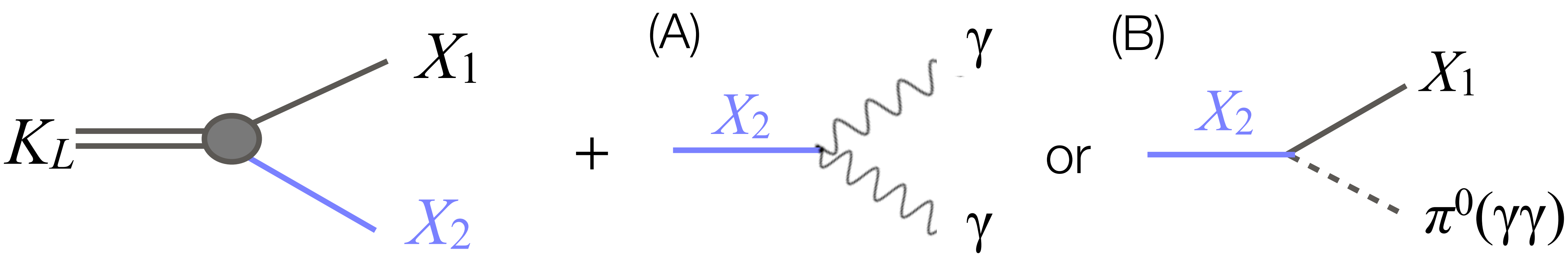
M. Pospelov [talk, Jan 2020], S. Gori, G. Perez, **KT** [2005.05170] M. Hostert, K. Kaneta, M. Pospelov [2005.07102]

violate GN bound

- **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.



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

Outline

✓ Introduction

- Why Kaon? Excellent probe for FIMP
- Rare kaon decay $K \to \pi \nu\nu$ at KOTO, and NA62

✓ Recent results from KAON2019 to ICHEP2020

- NA62 results, KOTO “excess”
- New Physics Scenarios

• Future prospects

- Higgs Portal, Muonic Force, Axion-like-particle

- Even if KOTO "excess" will be gone,
interesting opportunities for Kaon factories await

1. Higgs portal bound will be improved by $K \to \pi X$

2. Muonic Force@NA62. Timely, w/ Fermilab μ g-2, Belle II

3. ALP search @NA62&KOTO, unexplored range

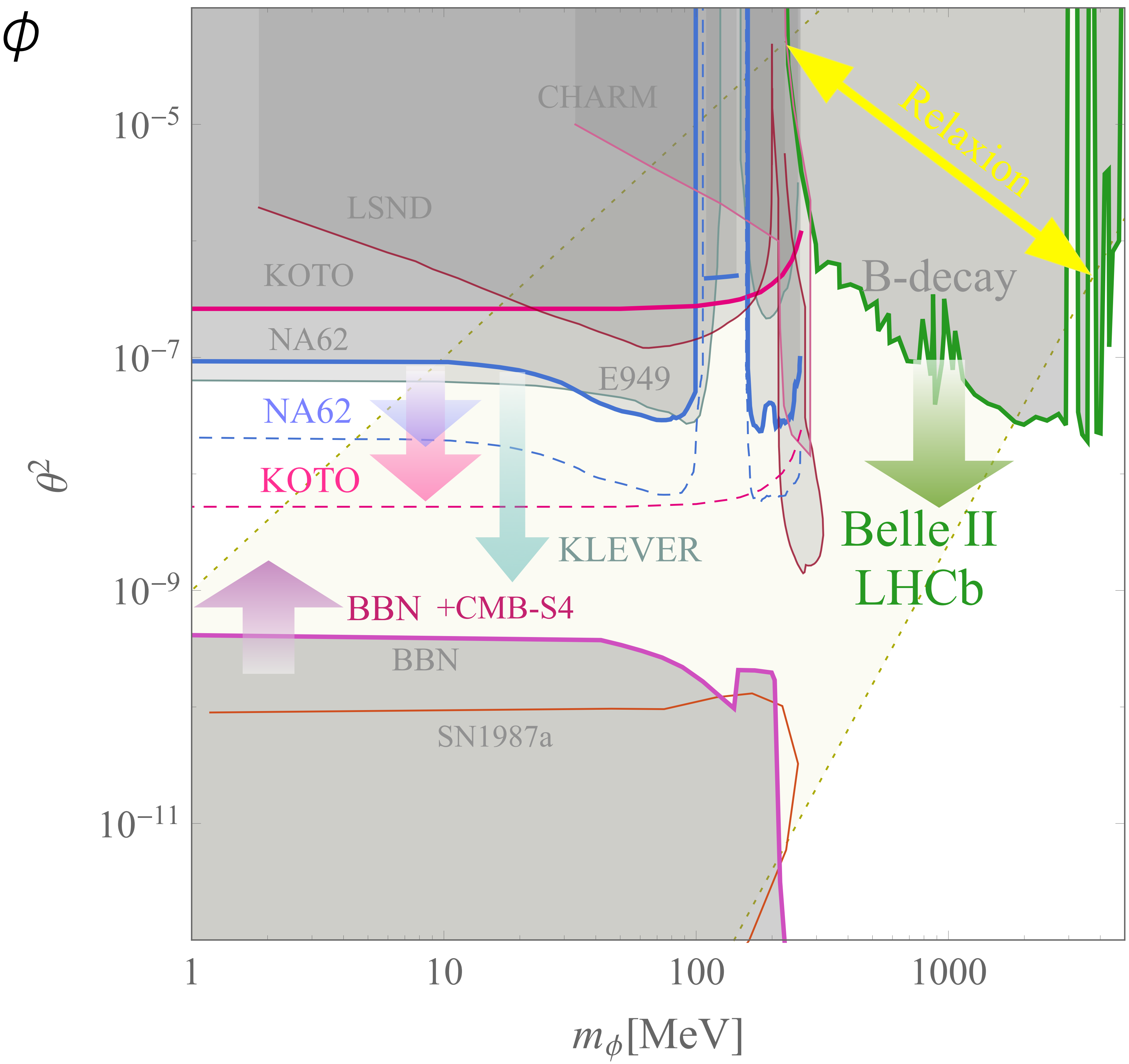
$K \to \pi X$ and Higgs Portal

- Light scalar portal ϕ to dark sector

$$A\phi|H|^2 + h.c.$$

- ϕ and Higgs mix

$$\theta \sim Av/m_h^2$$



$K \to \pi X$ and Higgs Portal

- Light scalar portal ϕ to dark sector

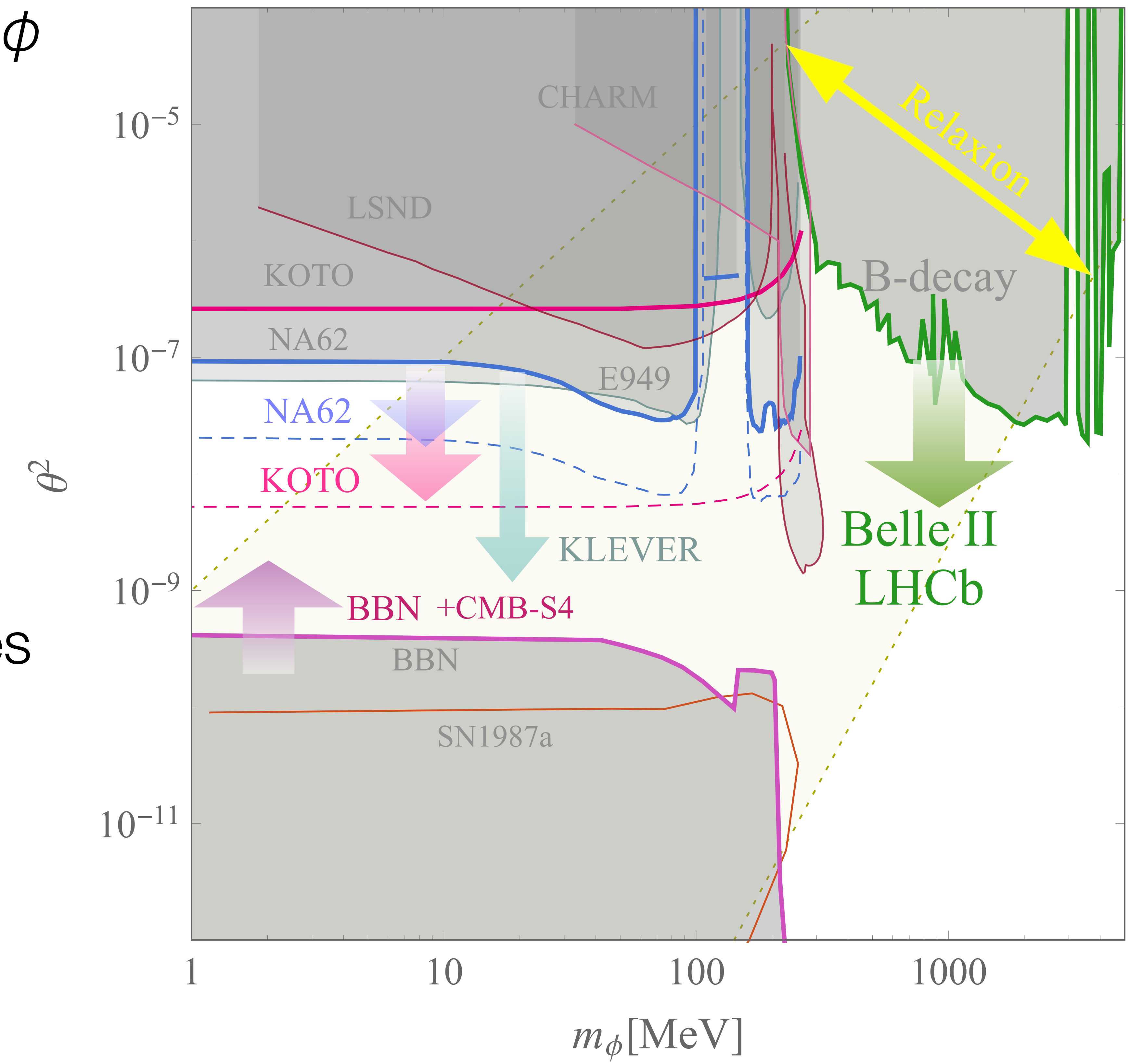
  $$A\phi|H|^2 + h.c.$$

- ϕ and Higgs mix

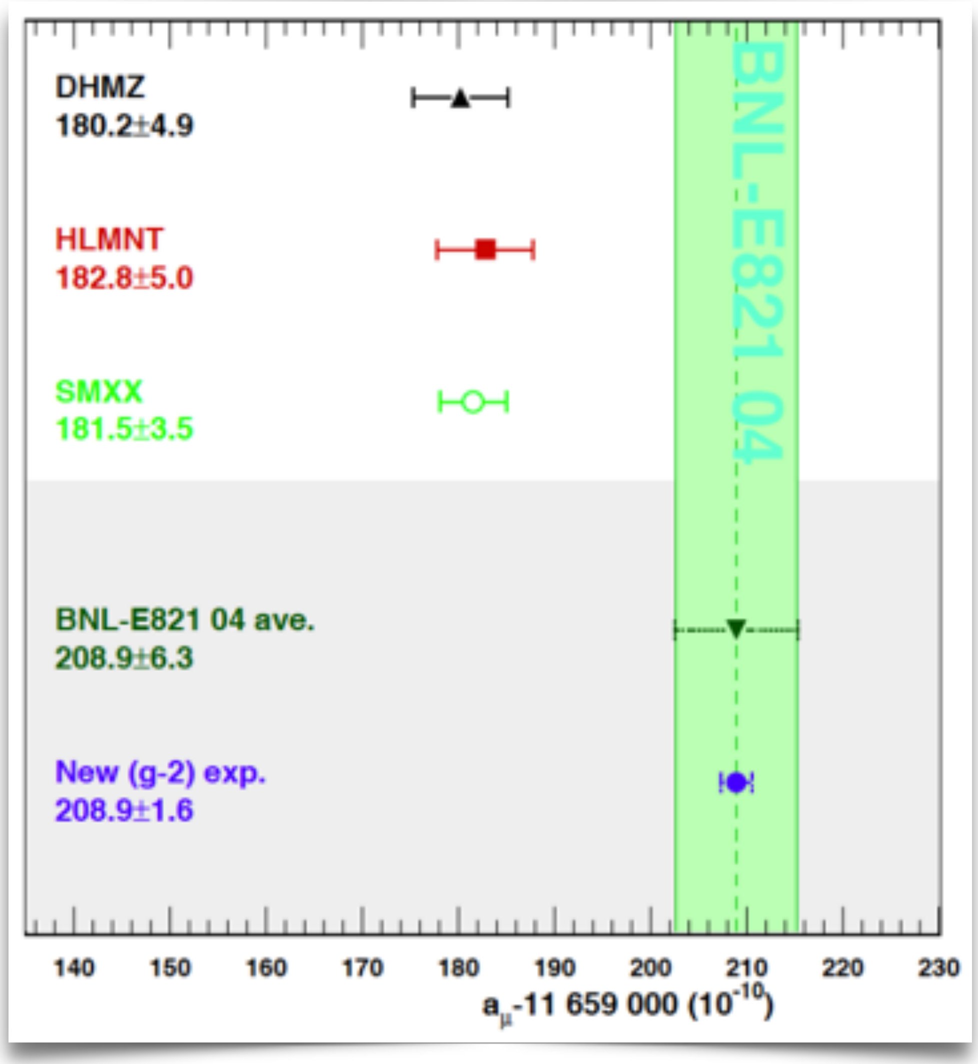
  $$\theta \sim Av/m_h^2$$

- Current $K \to \pi X$ as powerful probes

- Complimentary to B physics and cosmology



Muonic Force



$$\Delta a_\mu = (a_\mu)_{\rm exp} - (a_\mu)_{SM} = 287(63)(49) \times 10^{-11}$$

~3.5σ

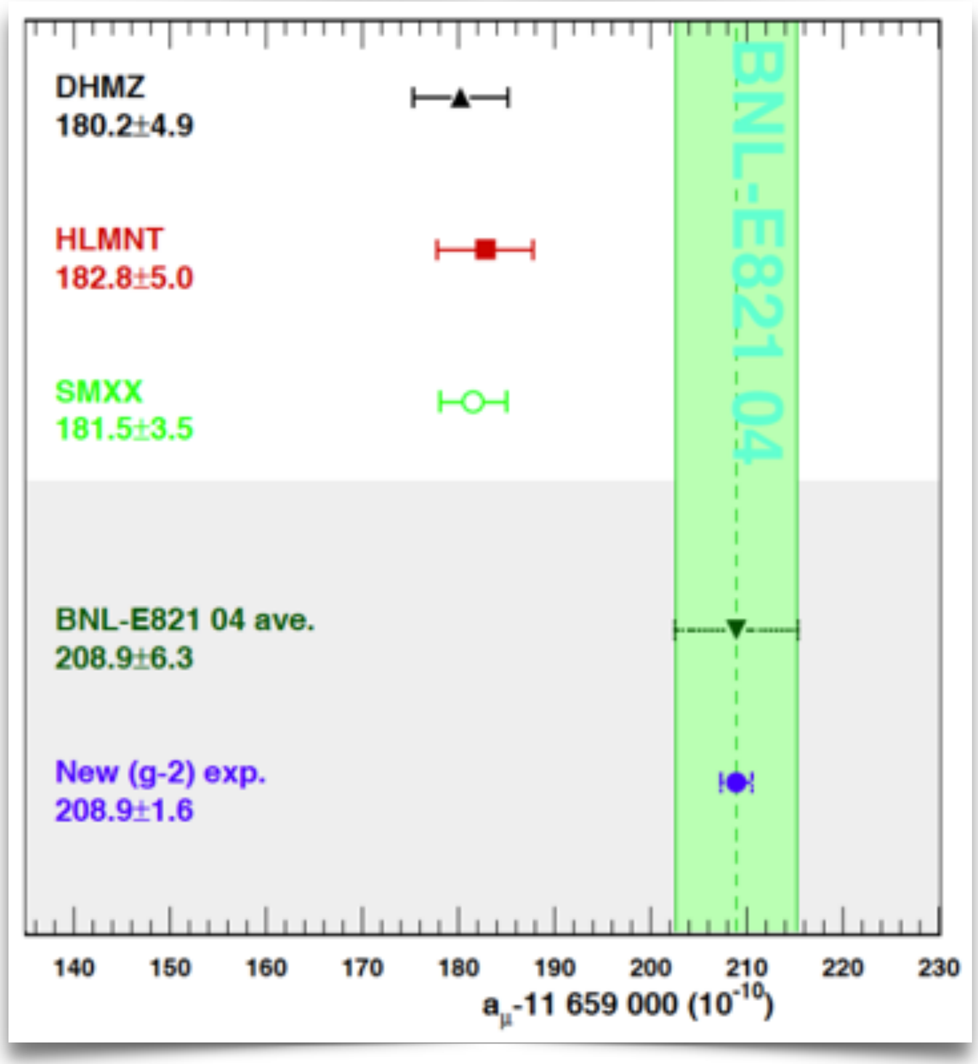
Fermilab g-2 experiment

already more data than BNL

»new result expected in 2020

In the future, J-PARC g-2 experiment

Muonic Force



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Light muonic force e.g., gauging L_μ-L_τ

S. Baek, N. Deshpande, X. He, and P. Ko, Phys.Rev. D64, 055006 (2001), arXiv:hep-ph/0104141 [hep-ph]

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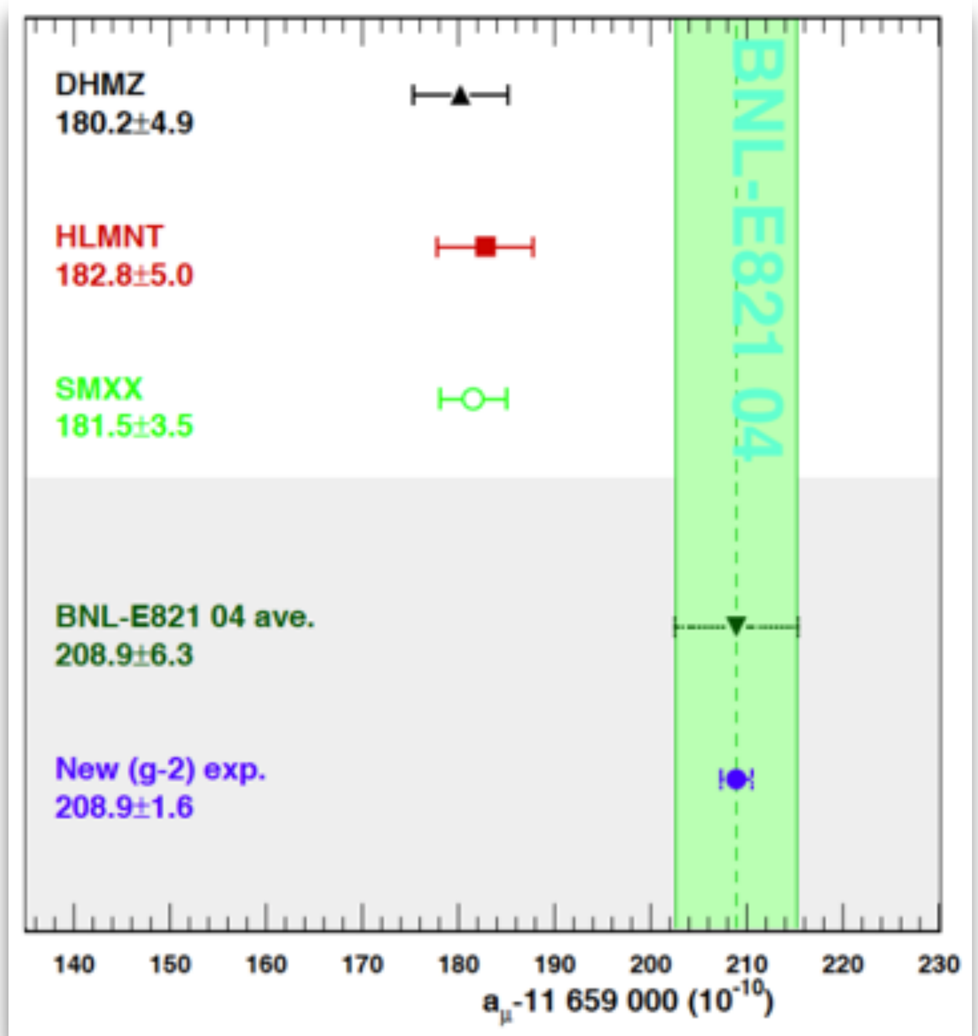

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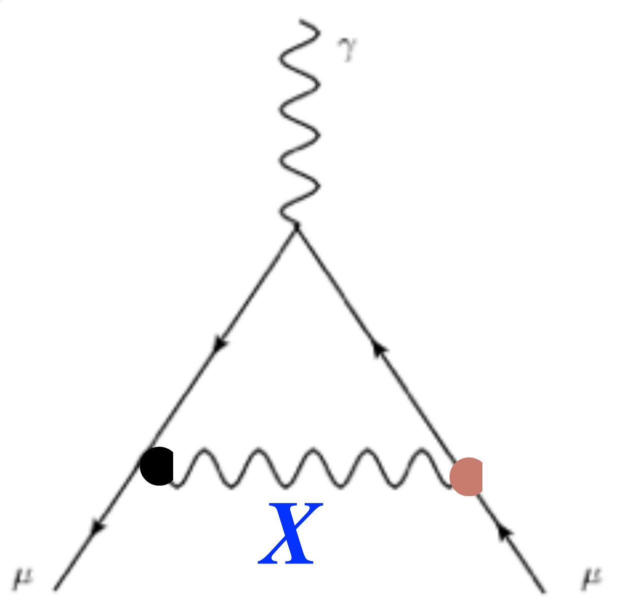

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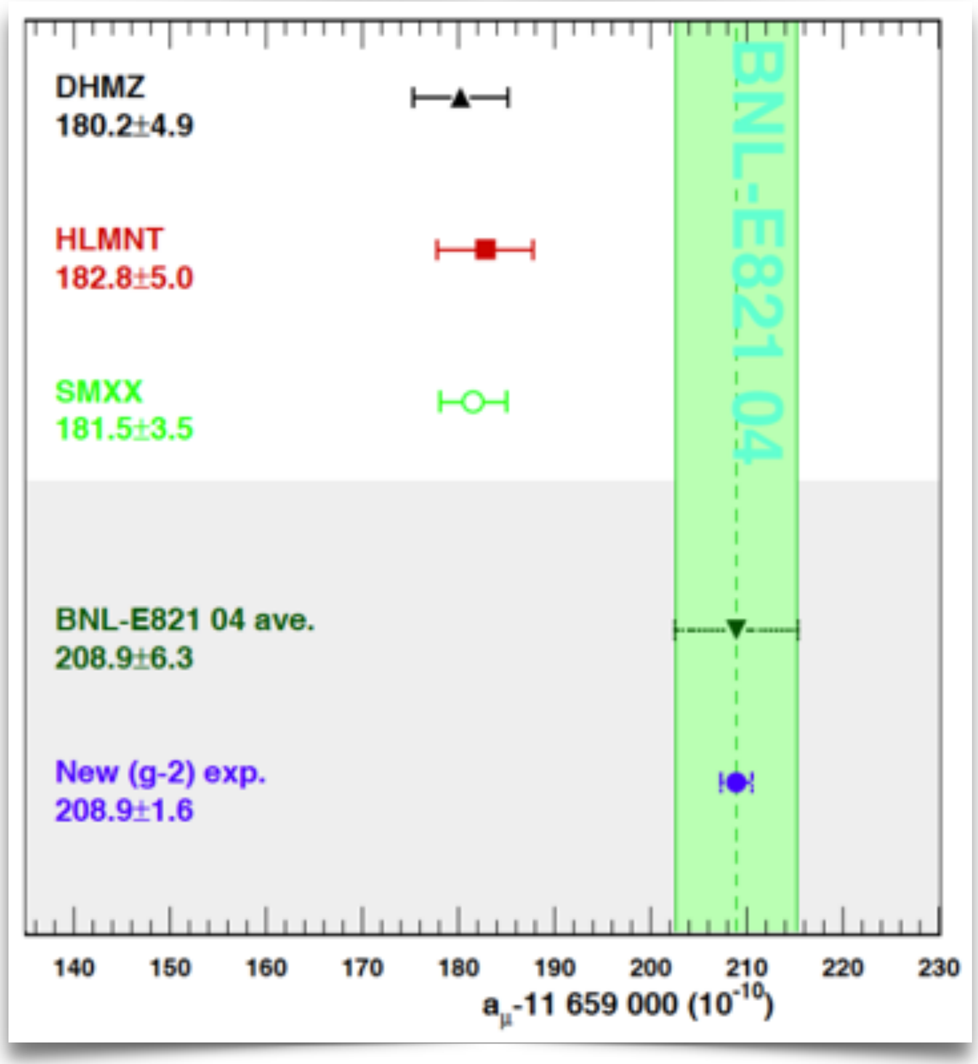

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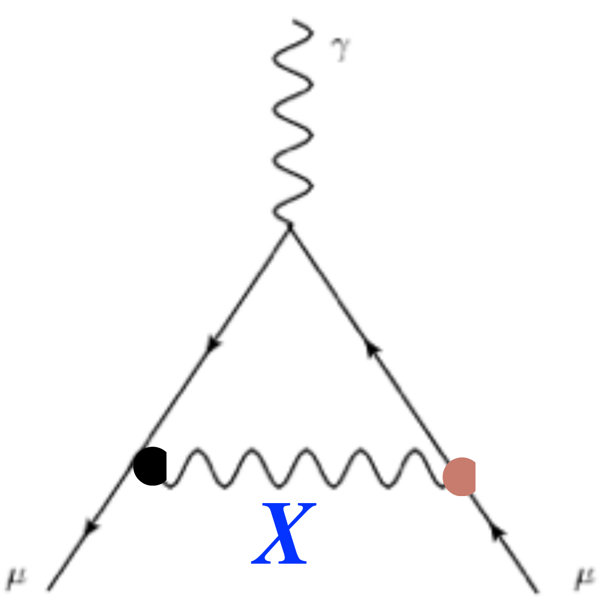
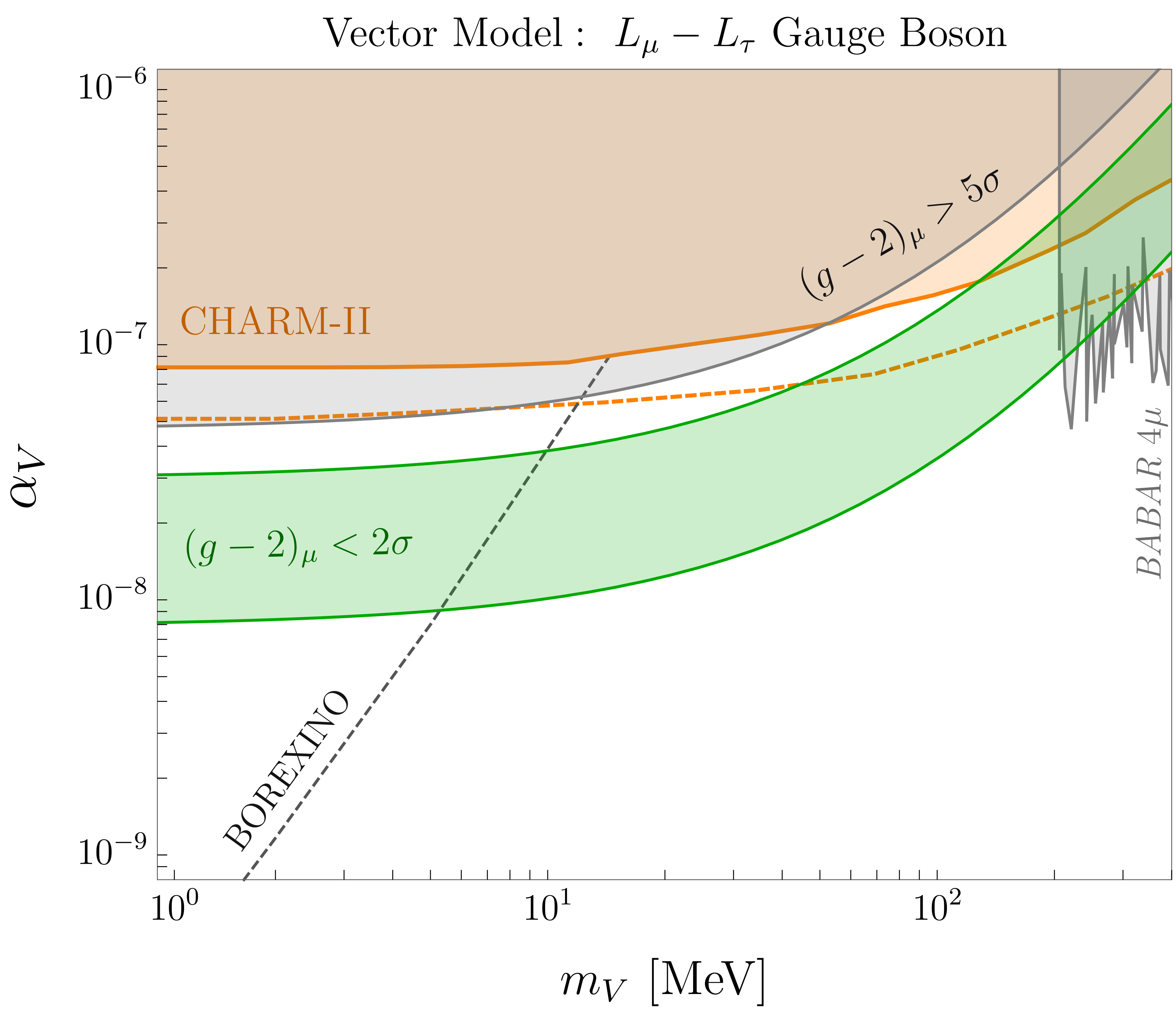
$\alpha_X \sim 10^{-8}$
$(g_X \sim 4 \times 10^{-4})$

$m_X \lesssim m_\mu$



1901.02010,1812.03829,
1804.03144, 1801.10448, …
if m_X at weak scale
[Harigaya, Igari, Nojiri, Takeuchi, Tobe,1311.0870]

Status of L_μ-L_τ gauge boson



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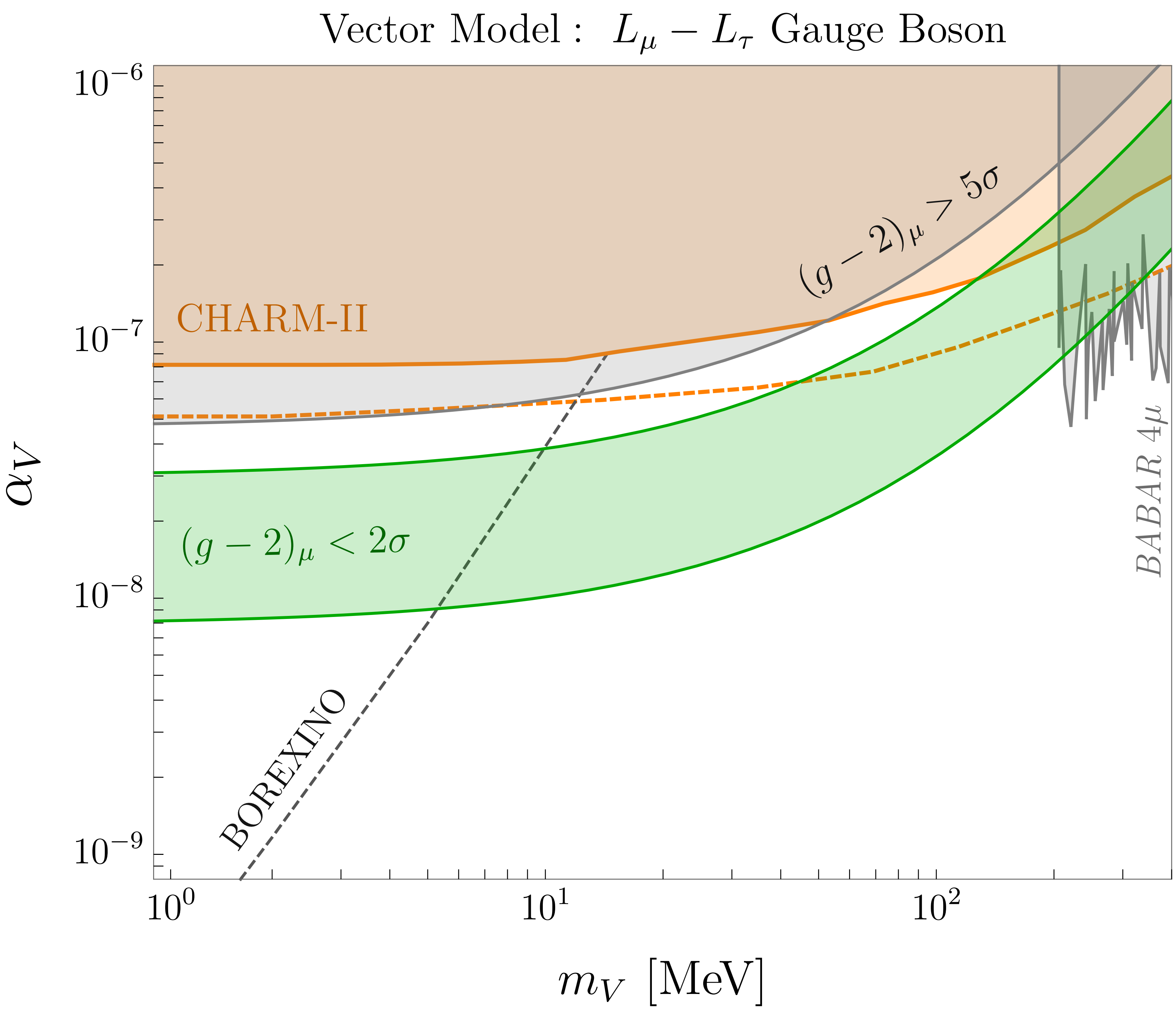

1. BaBaR (m_V>200MeV)

$$e^+e^- \to \mu^+\mu^- V(\to \mu^+\mu^-)$$

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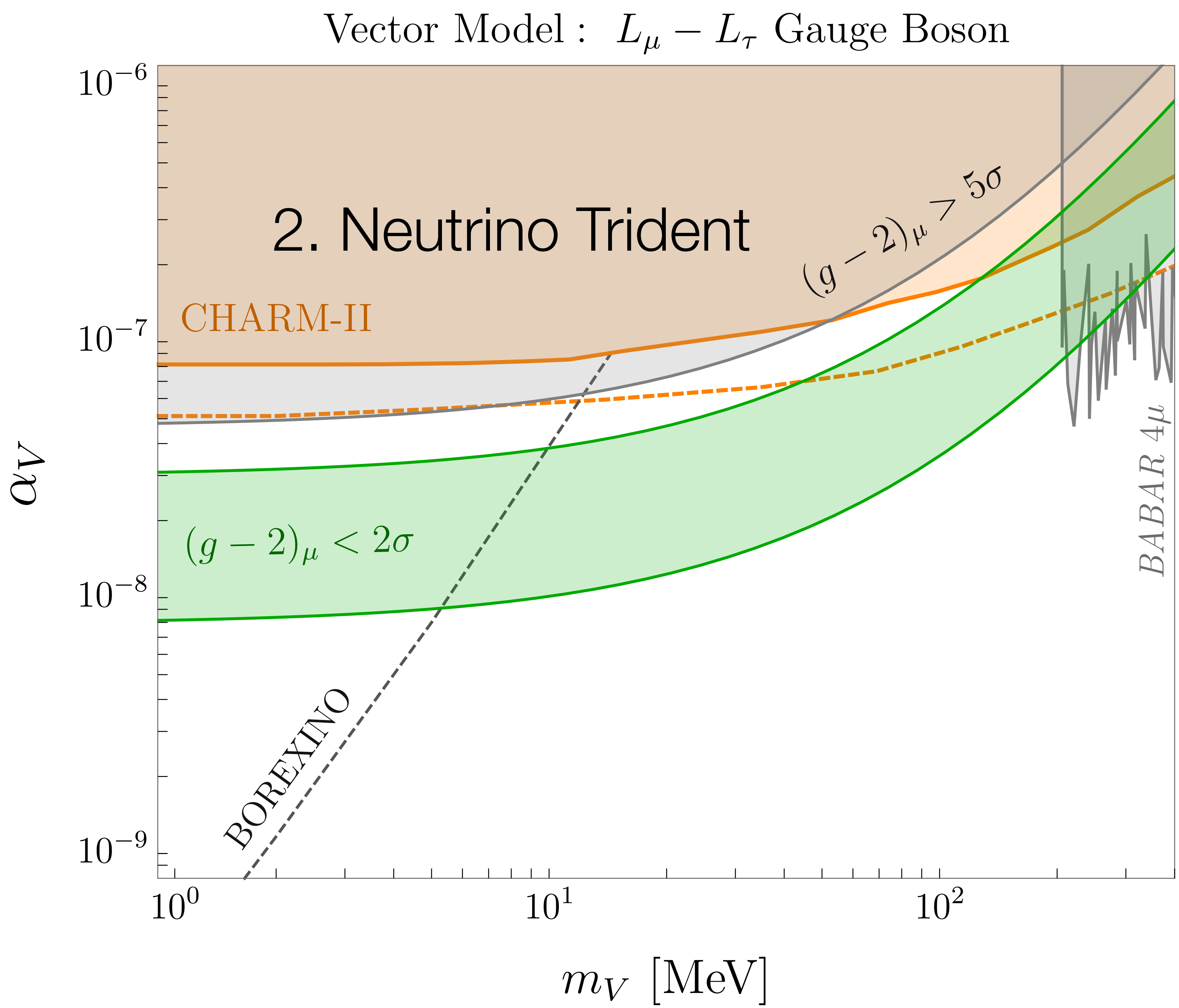

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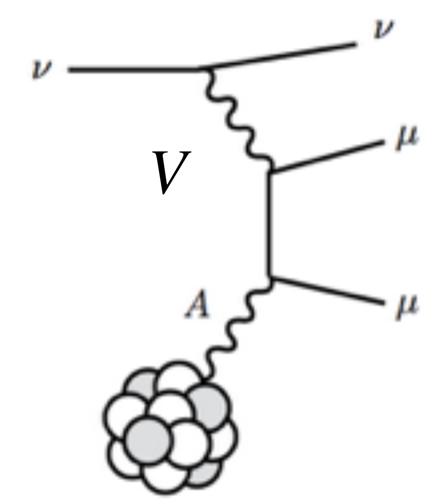

~~CCFR~~, NuTeV, Charm-II

[W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin ('14)]

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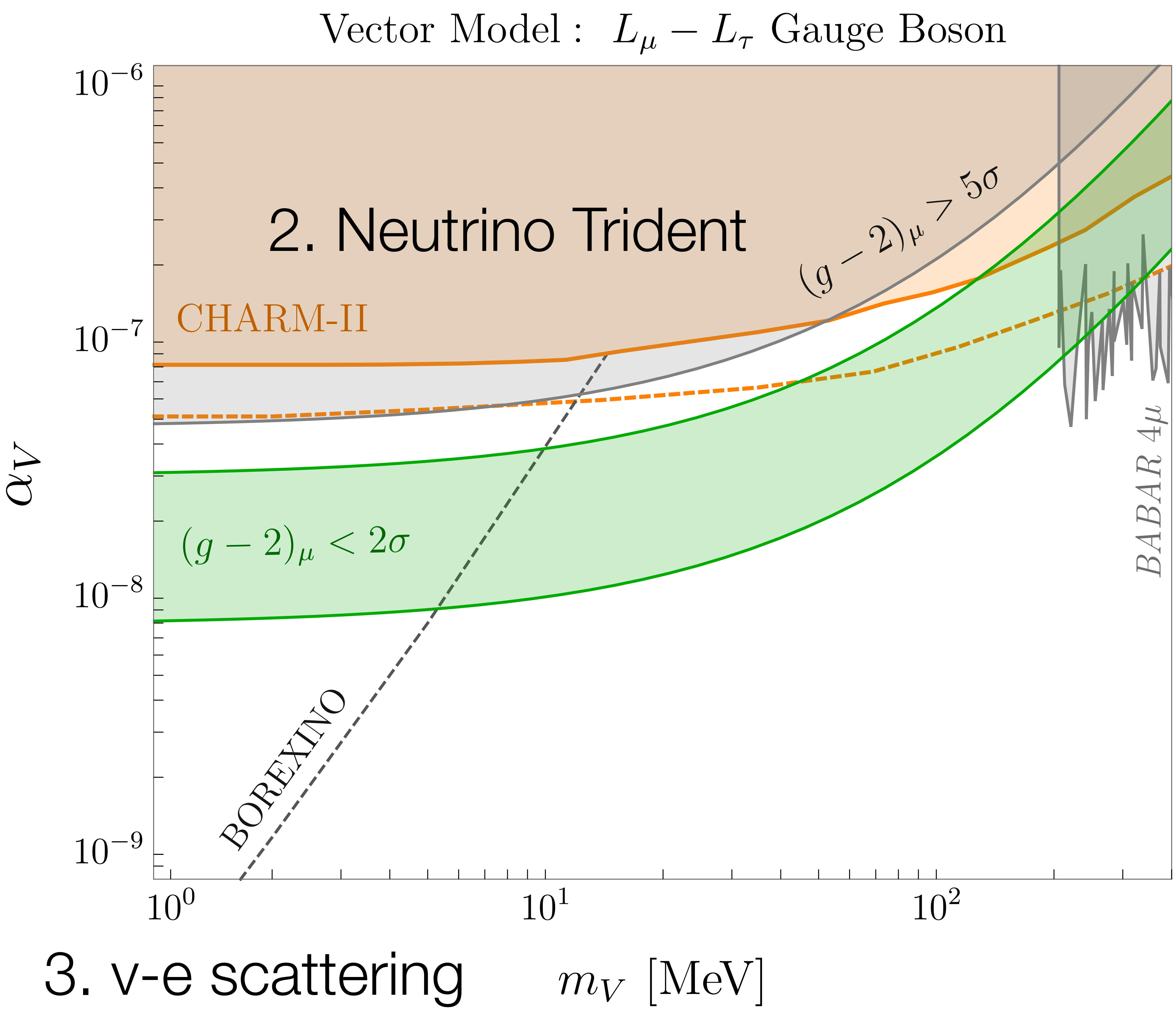

3. ν-e scattering
[solar ν+oscillation]

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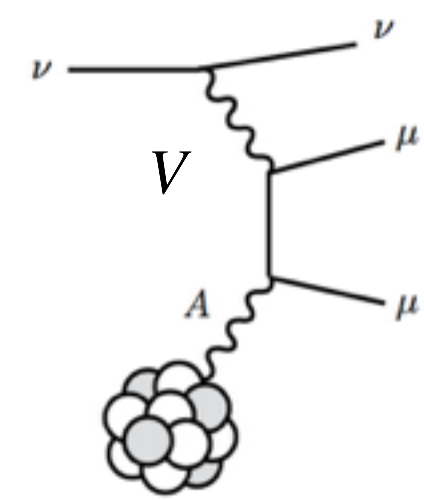
$$e^+e^- \to \mu^+\mu^- V(\to \mu^+\mu^-)$$

2.



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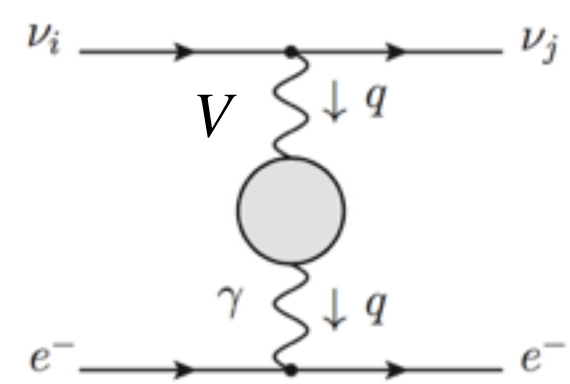
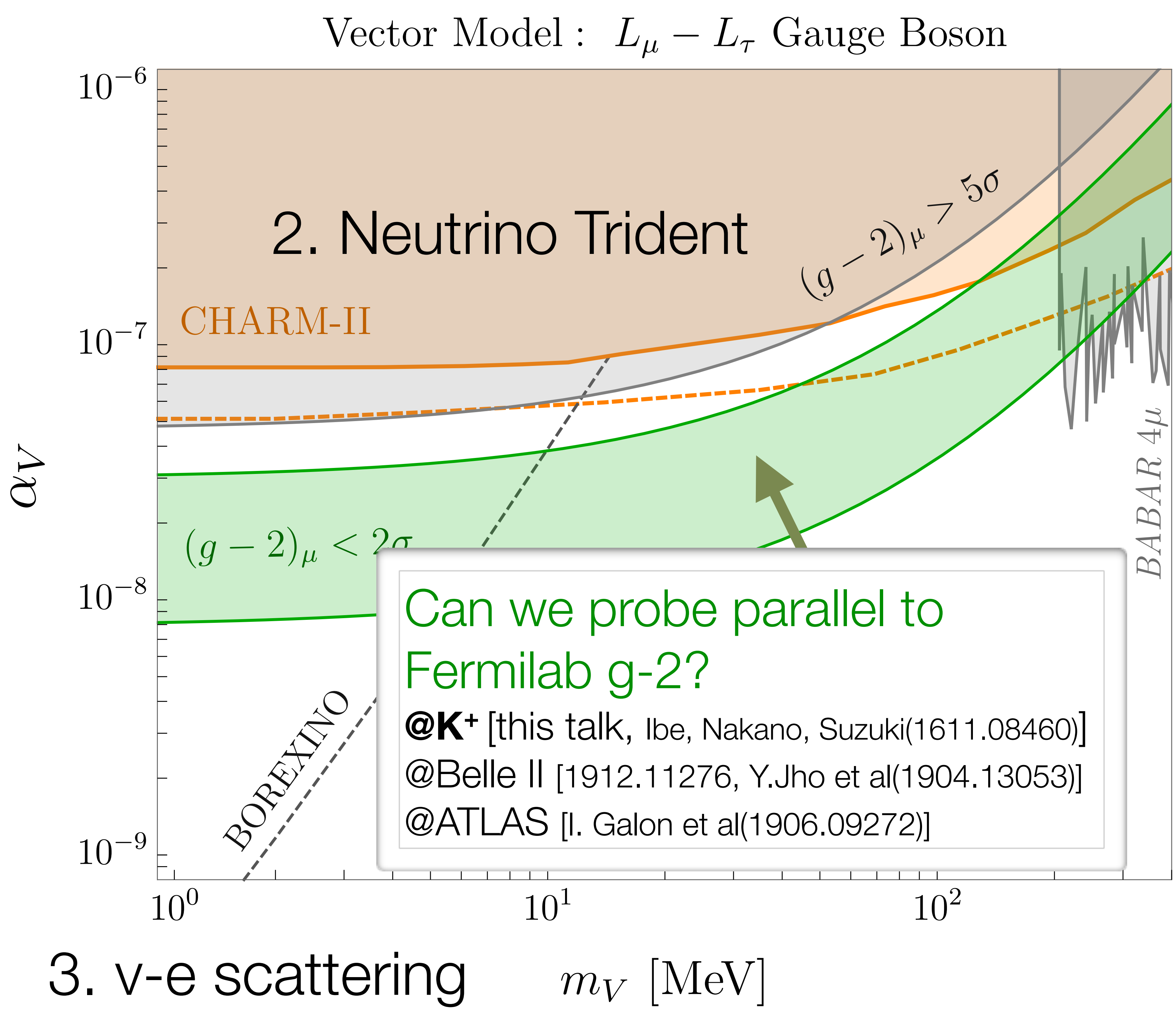
[W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin ('14)]

3.



[R. Harnik, J. Kopp, P.A. Machado('12); Y. Kaneta, T. Shimomura ('17)]

Status of L_μ-L_τ gauge boson

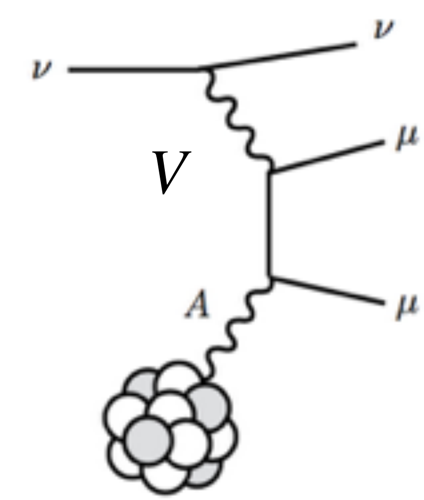


3. v-e scattering
[solar v+oscillation]

1. BaBaR (m_V>200MeV)

$$e^+e^- \to \mu^+\mu^- V(\to \mu^+\mu^-)$$

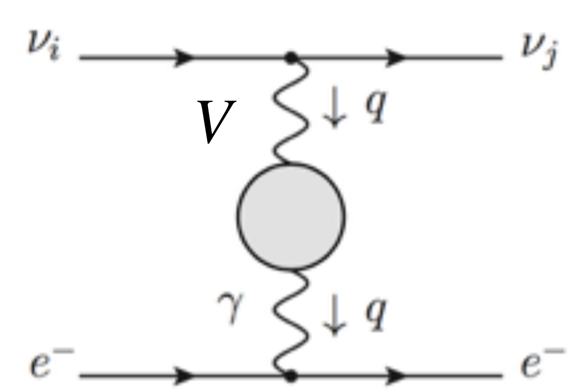
2.



~~CCFR~~, NuTeV, Charm-II

[W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin ('14)]

3.



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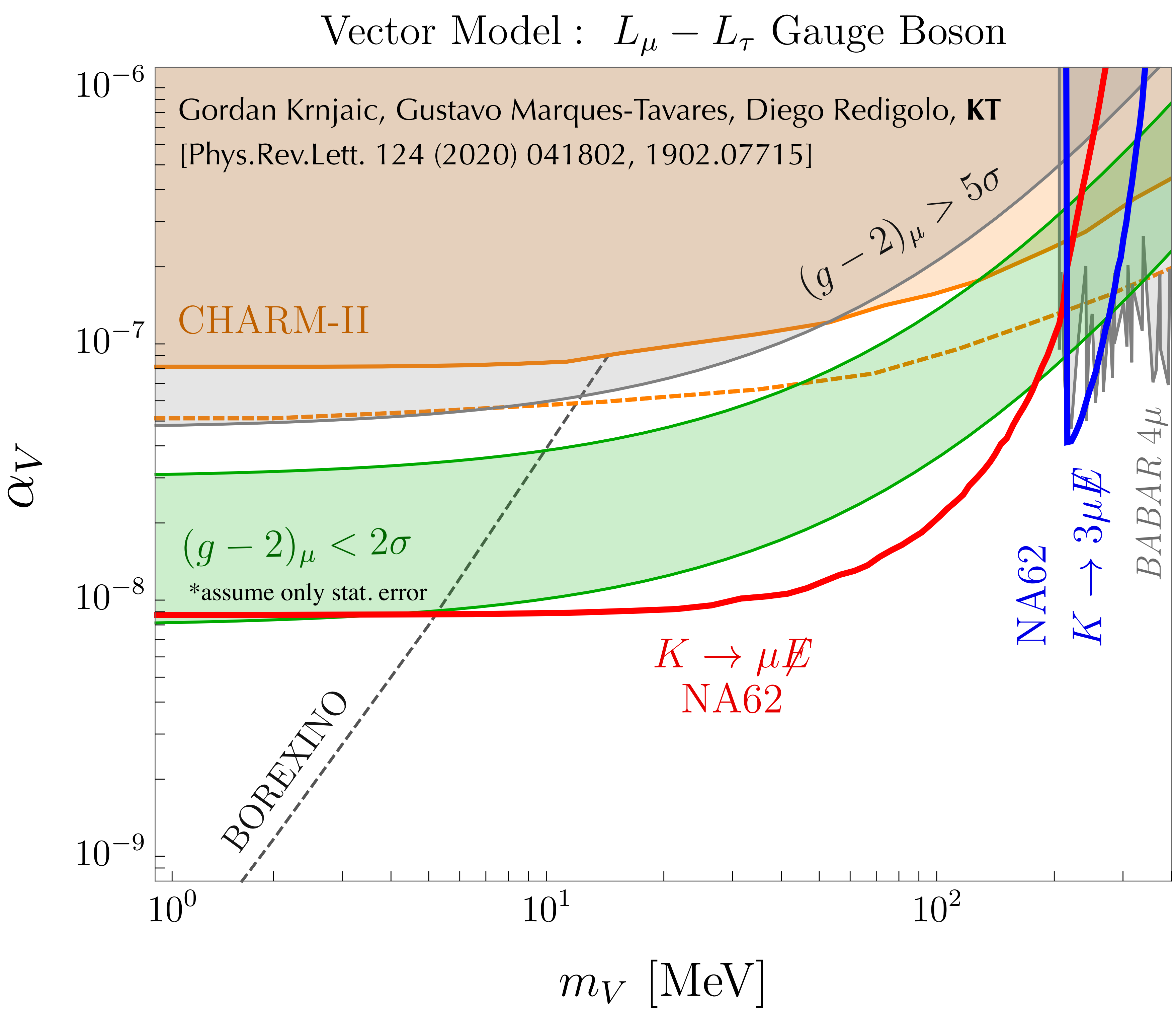
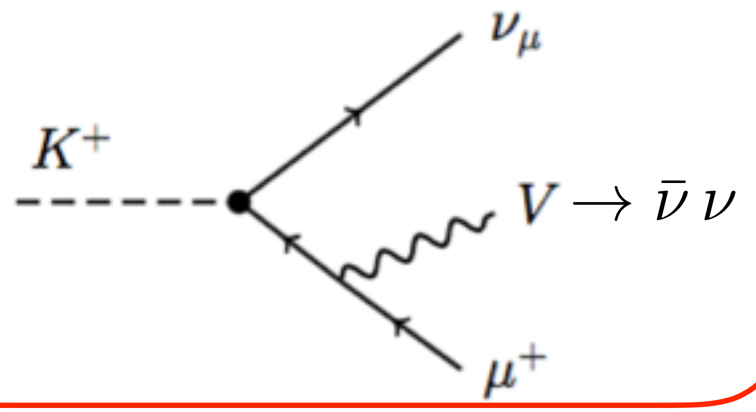
L_μ-L_τ gauge boson at NA62



signal: $K^+ \to \mu^+ + inv$



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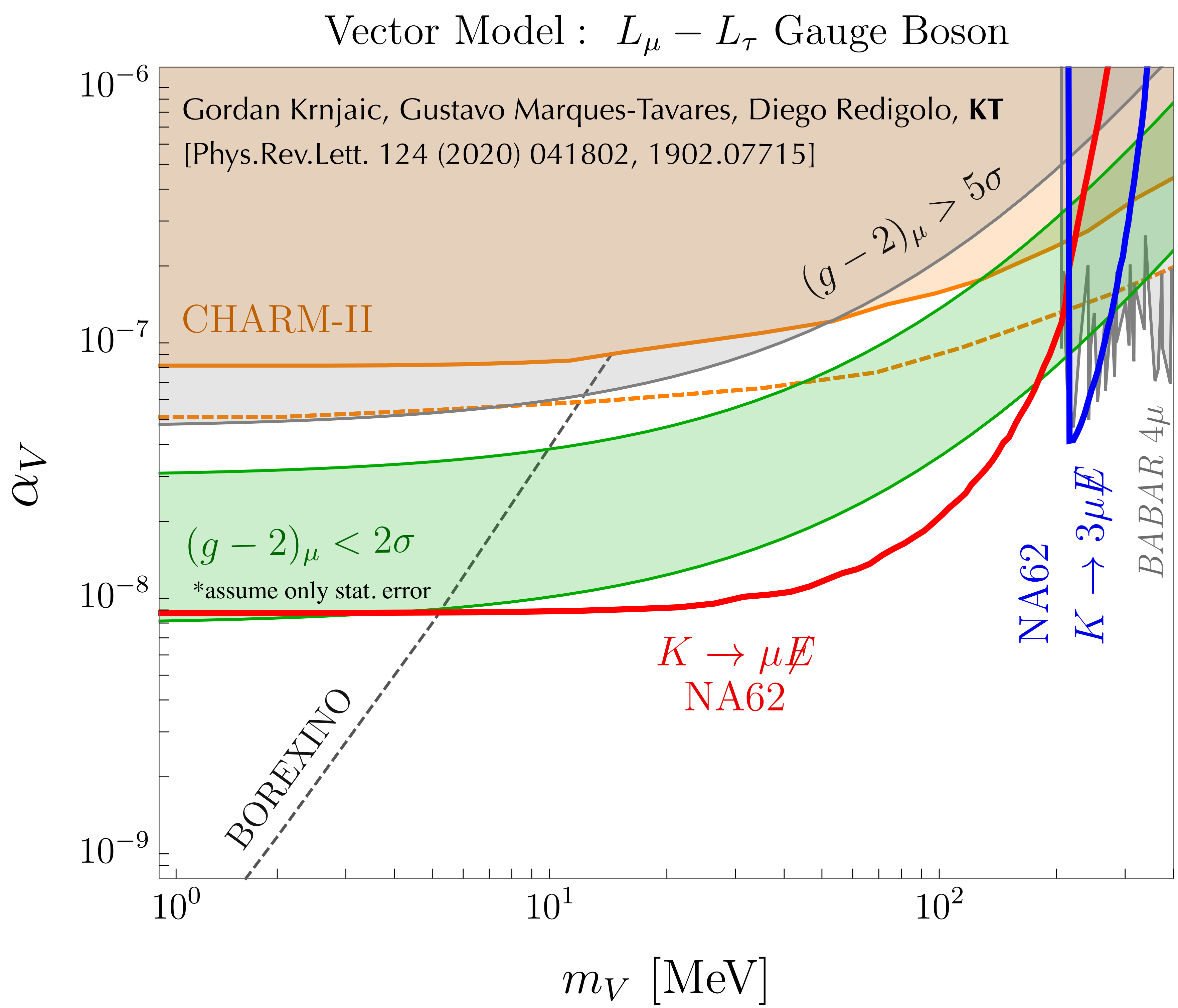

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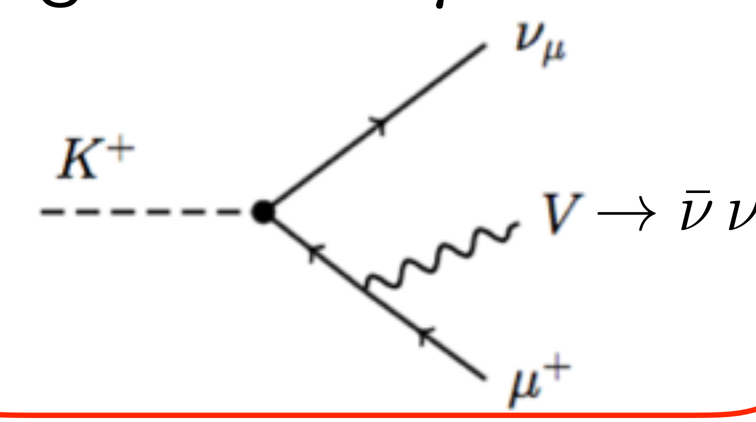
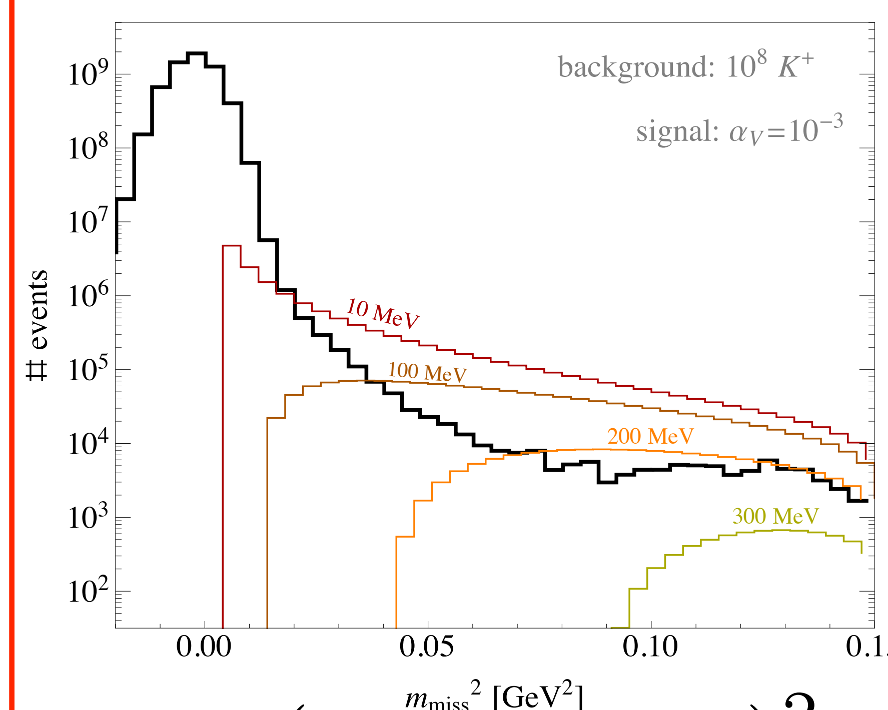


recast $K^+ \to \mu^+ N$



$$(p_{K^+} - p_{\mu^+})^2$$

BG: missed photon
halo muon

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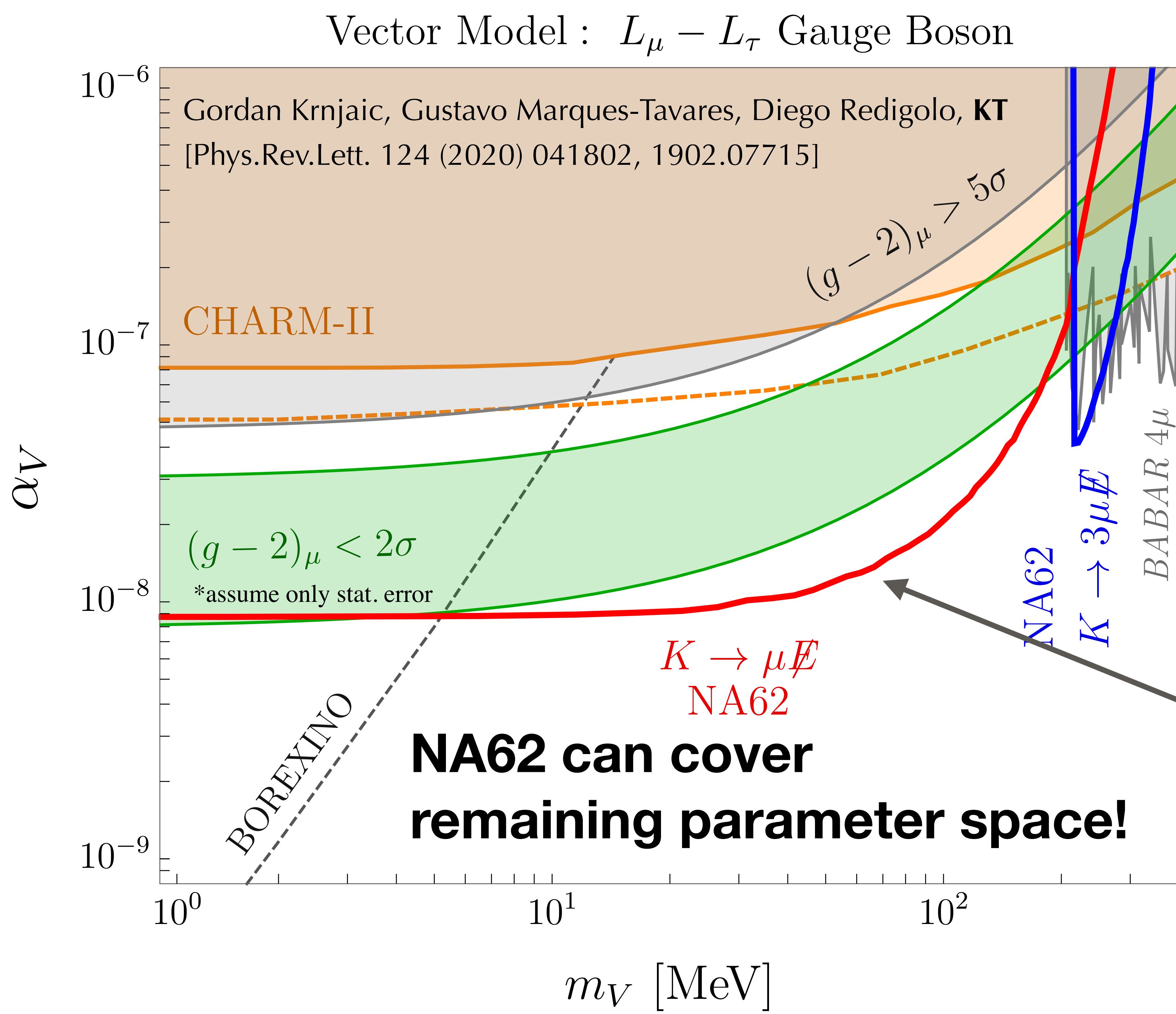

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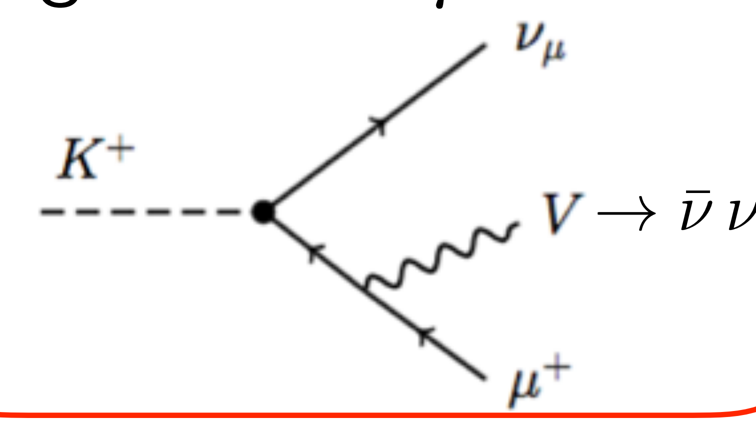

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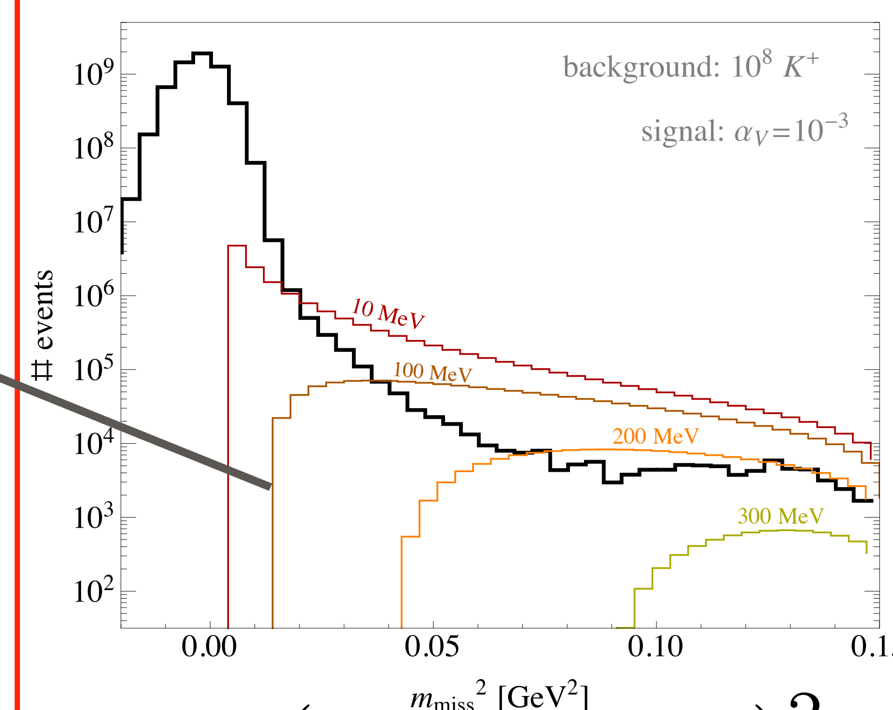

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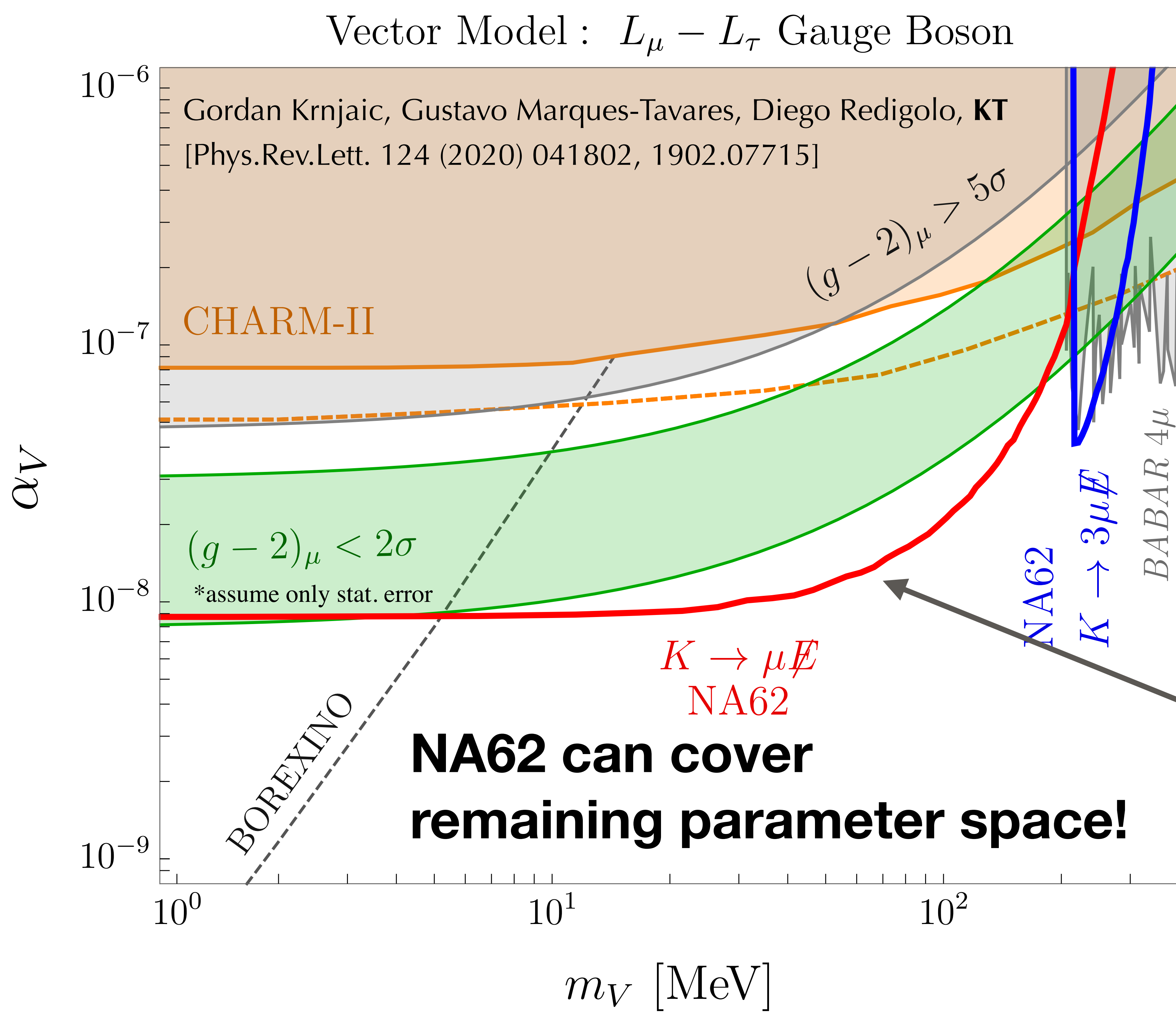

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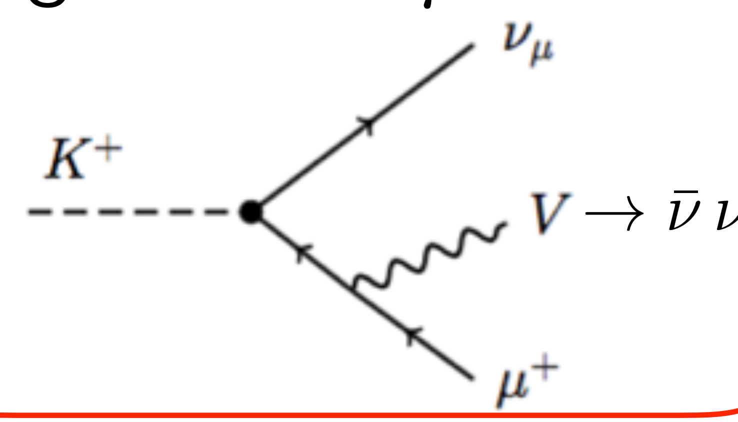

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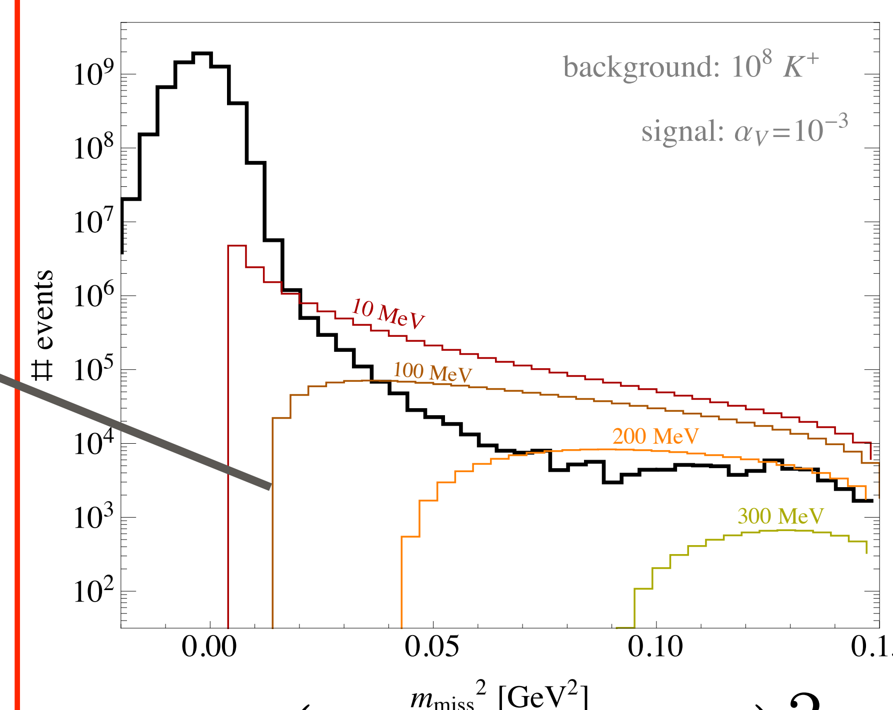

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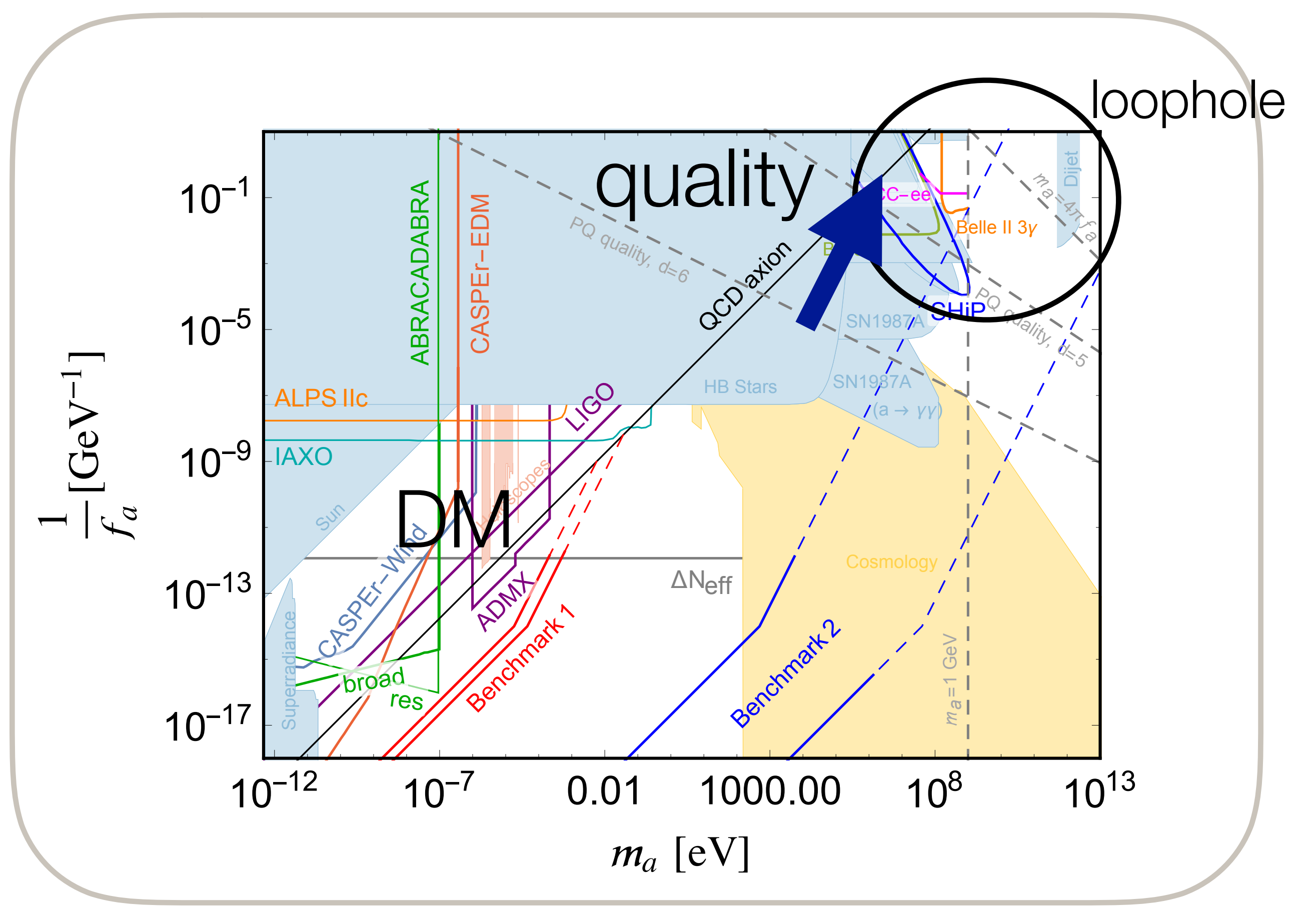
Challenges

- Remove trigger prescaling **1/400**
- Control systematics

Heavy Axion, Axion-like Particle

- Axion/ALP with MeV-GeV mass is poorly explored



P. Agrawal, K. Howe('17)

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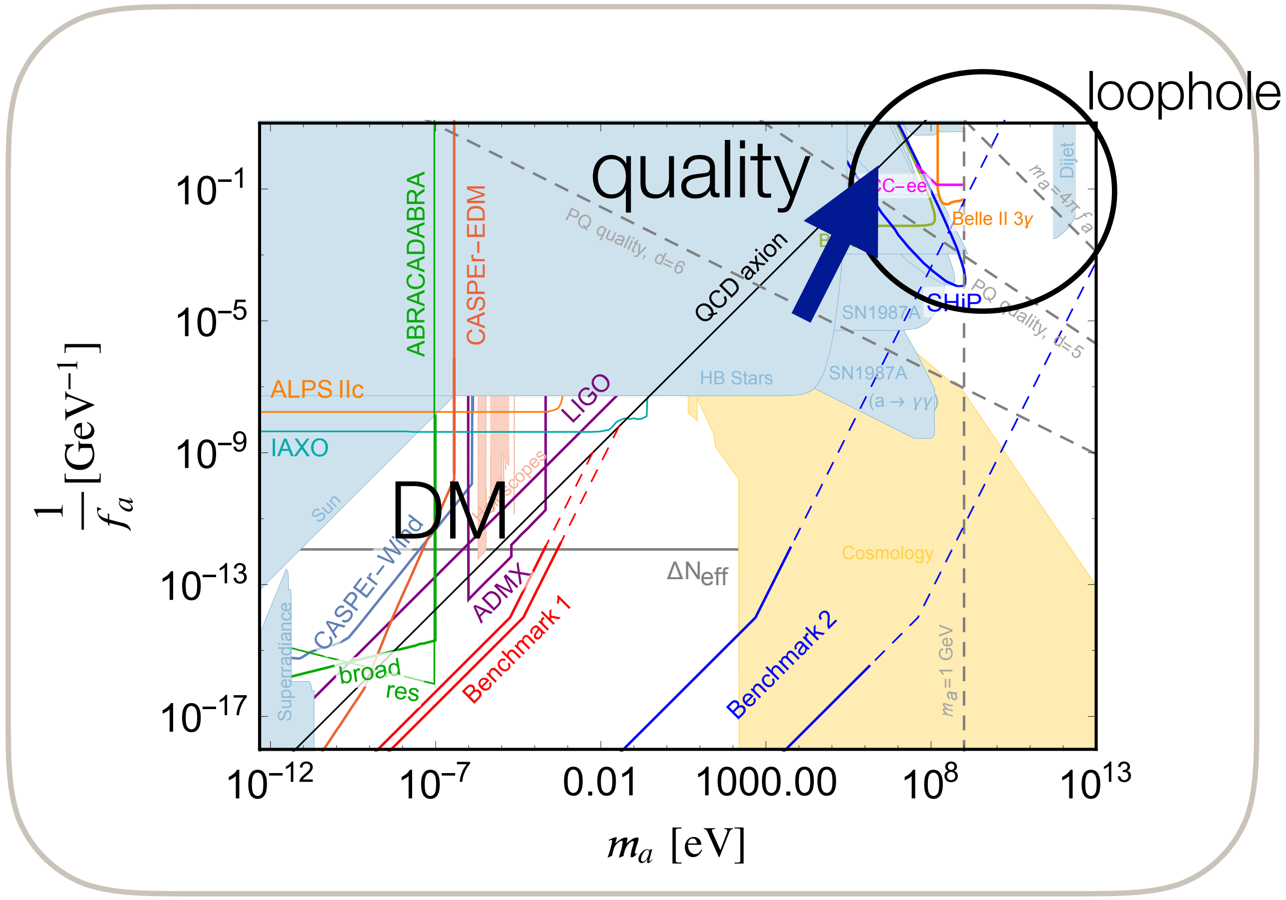

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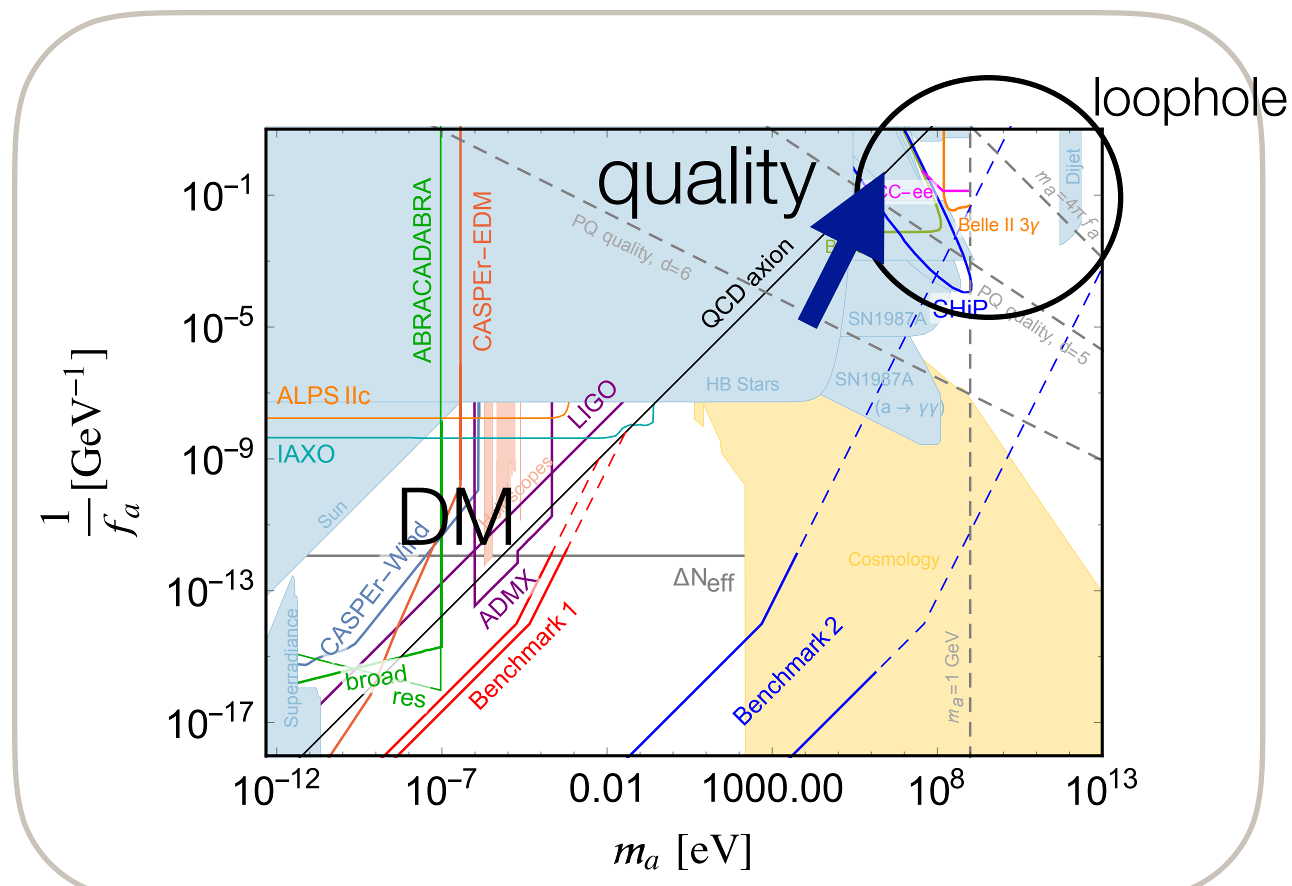

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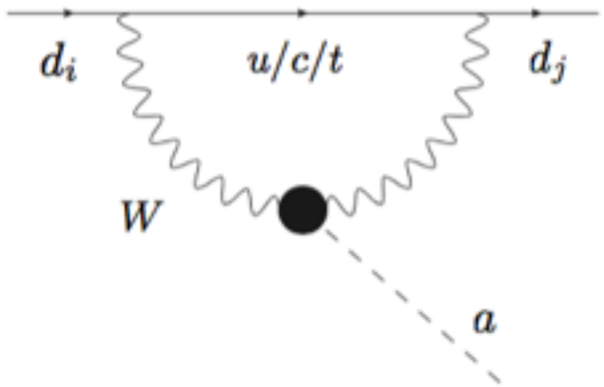

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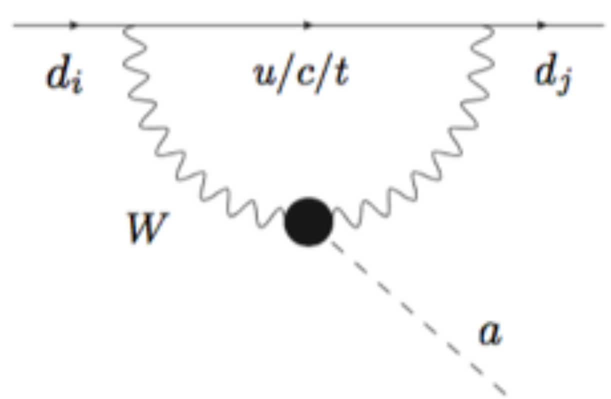
if $a \to 2\gamma$, new search at KOTO&NA62



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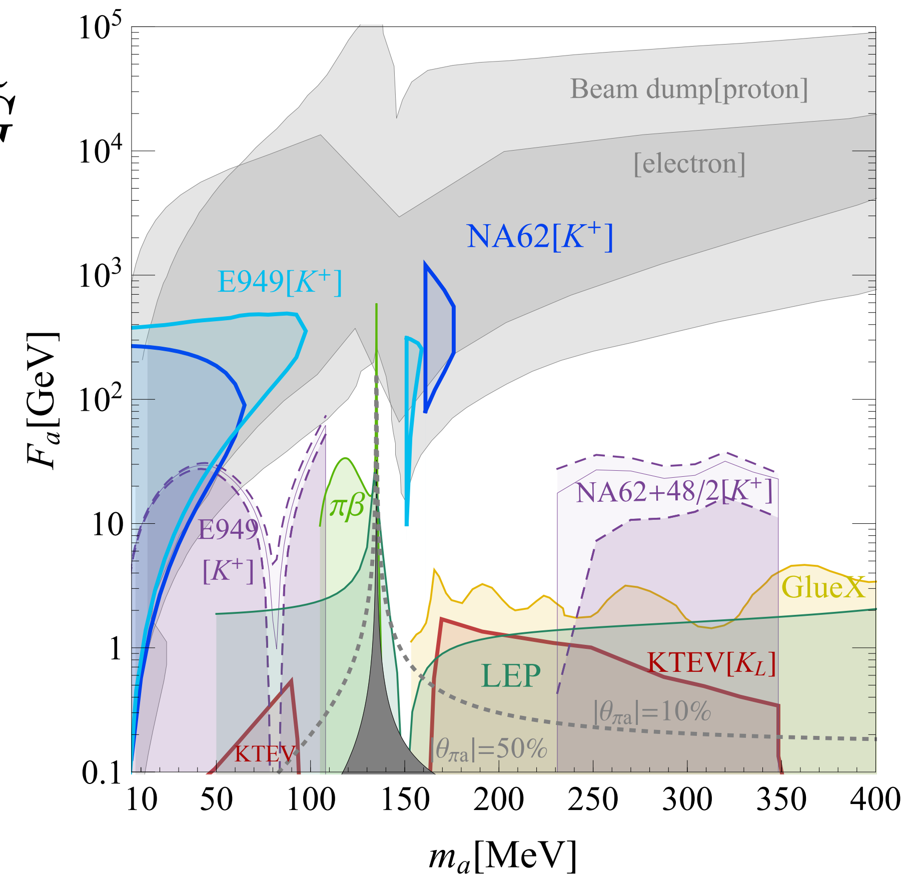
Another interesting program [ALPs]

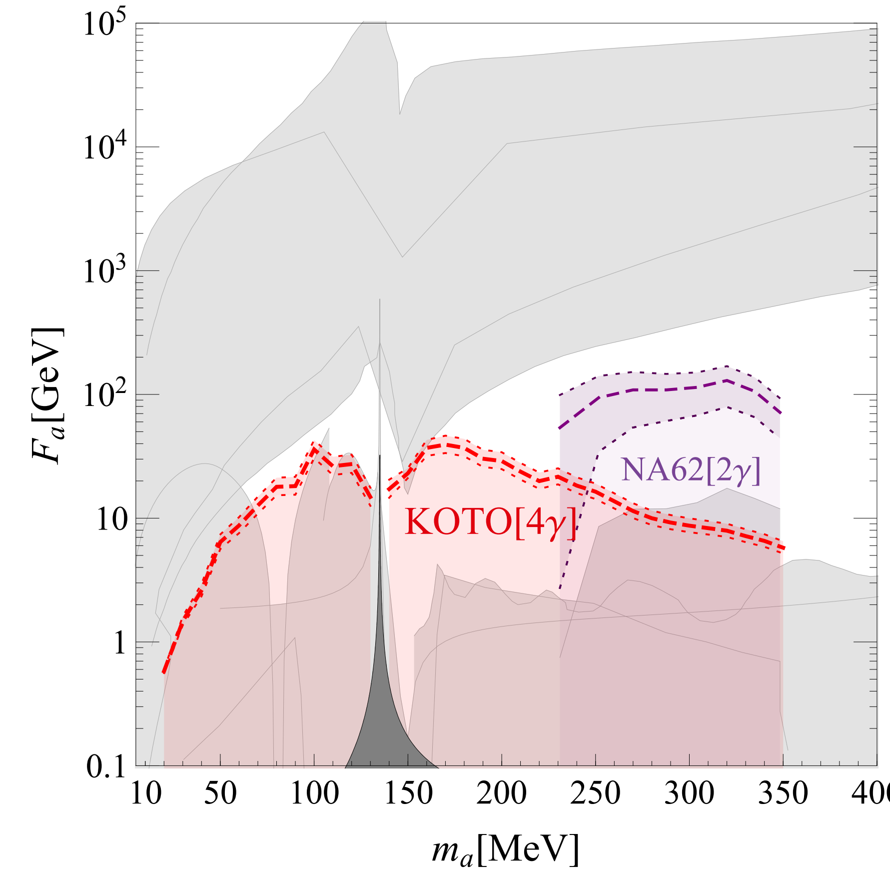
Many new bounds and projection in S. Gori, G. Perez, **KT** [2005.05170]

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

Bounds



NA62&KOTO projection



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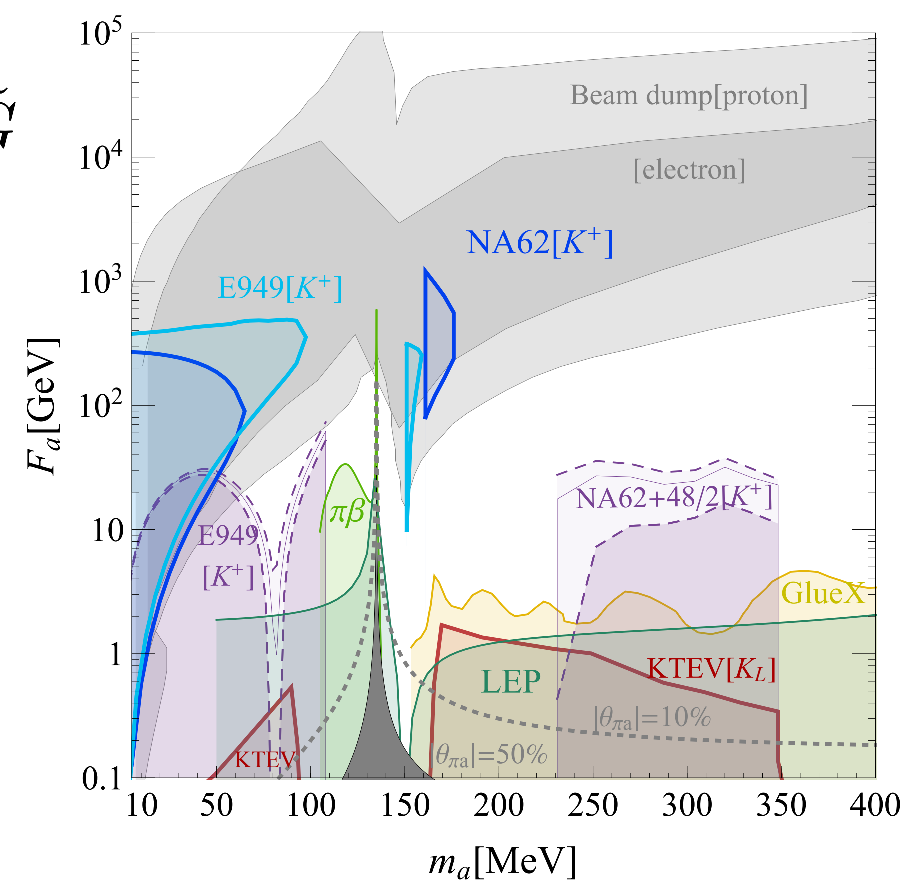

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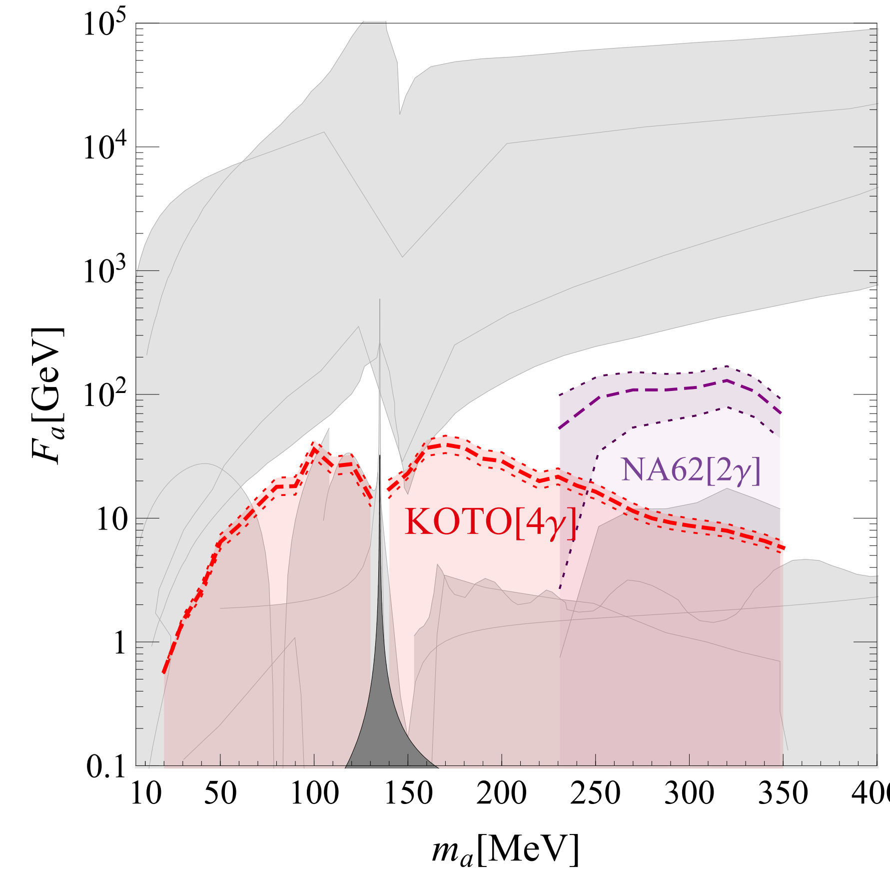

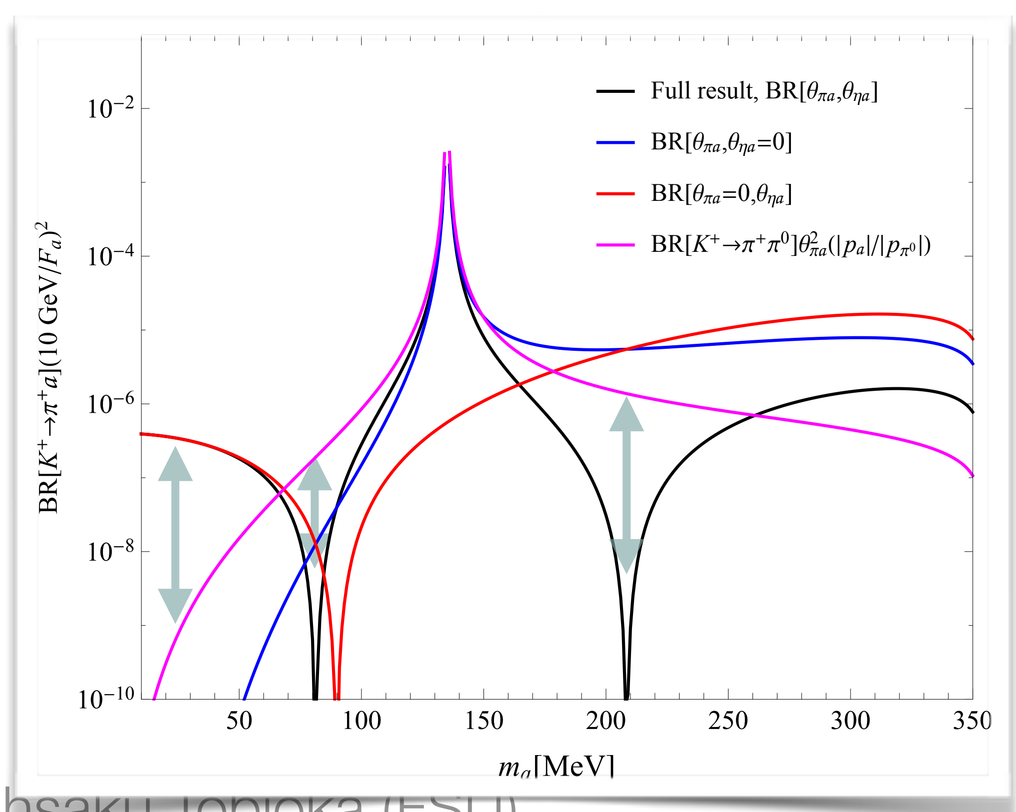

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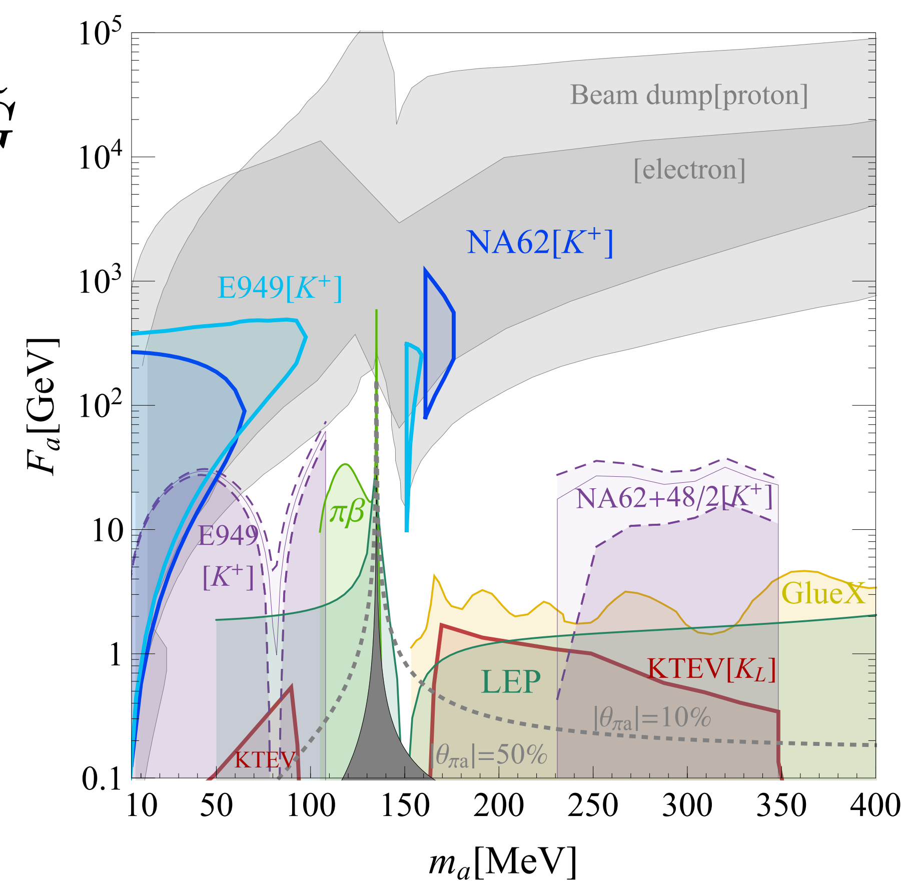

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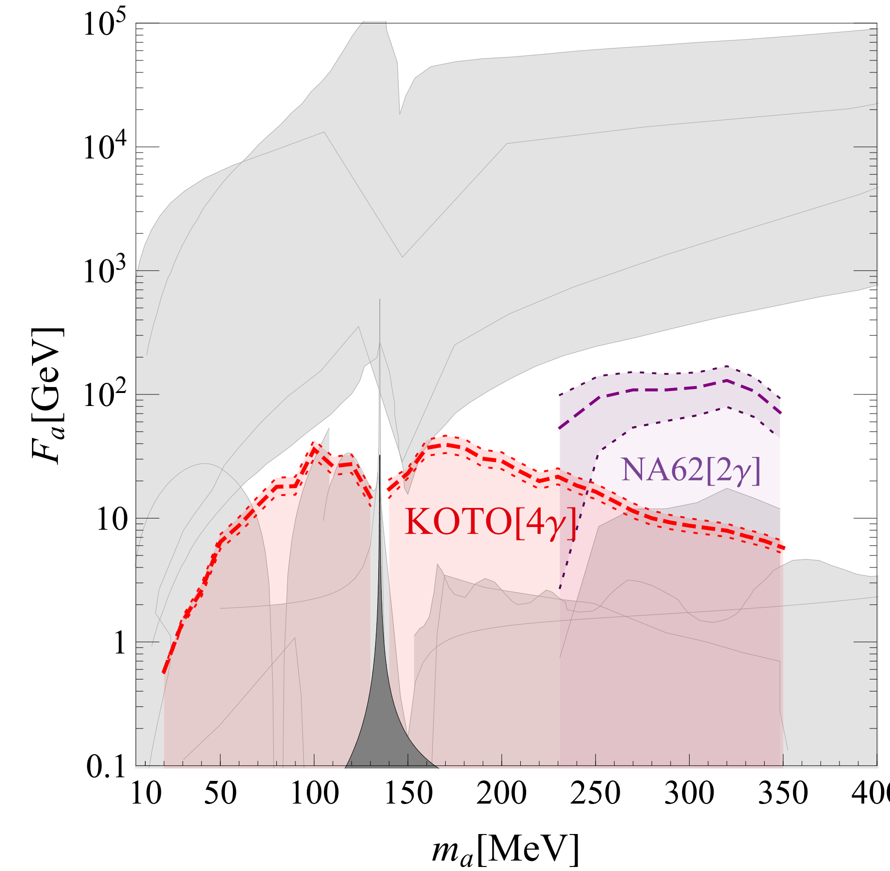

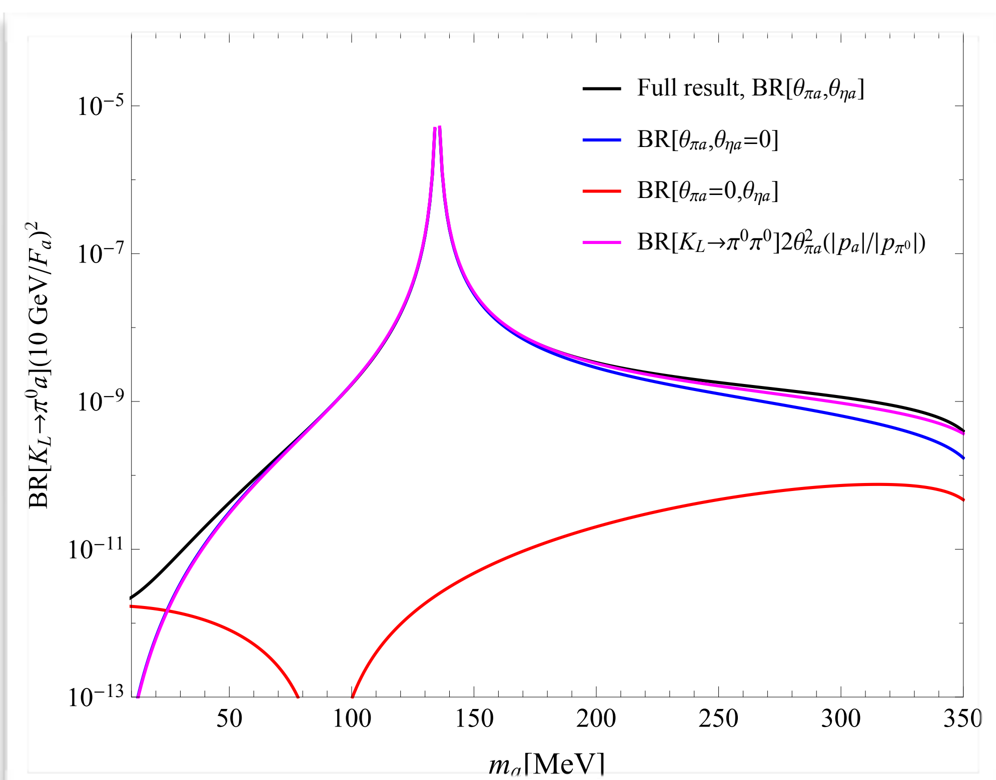

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- Updated calculation $K^+\to\pi^+ a$ finds uncertainty [two "octet(ΔI=1/2)" enhancements cancel]

- $K_L\to\pi^0 a$ is more stable, can be enhanced by two-loop without ε_K

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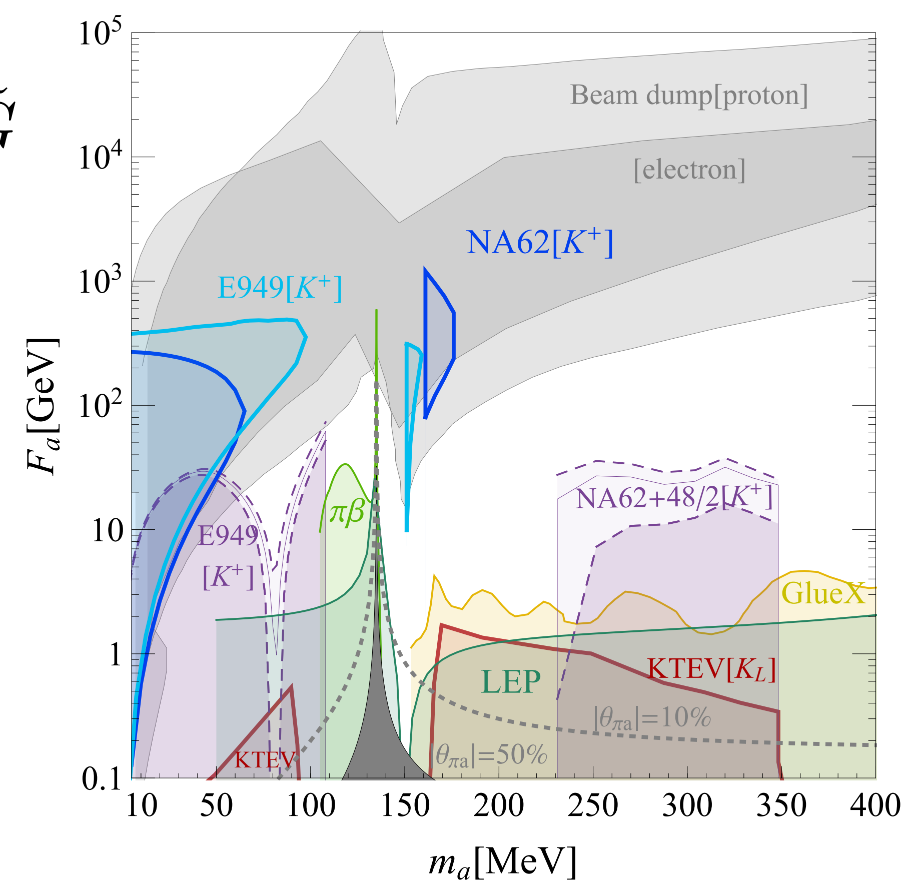

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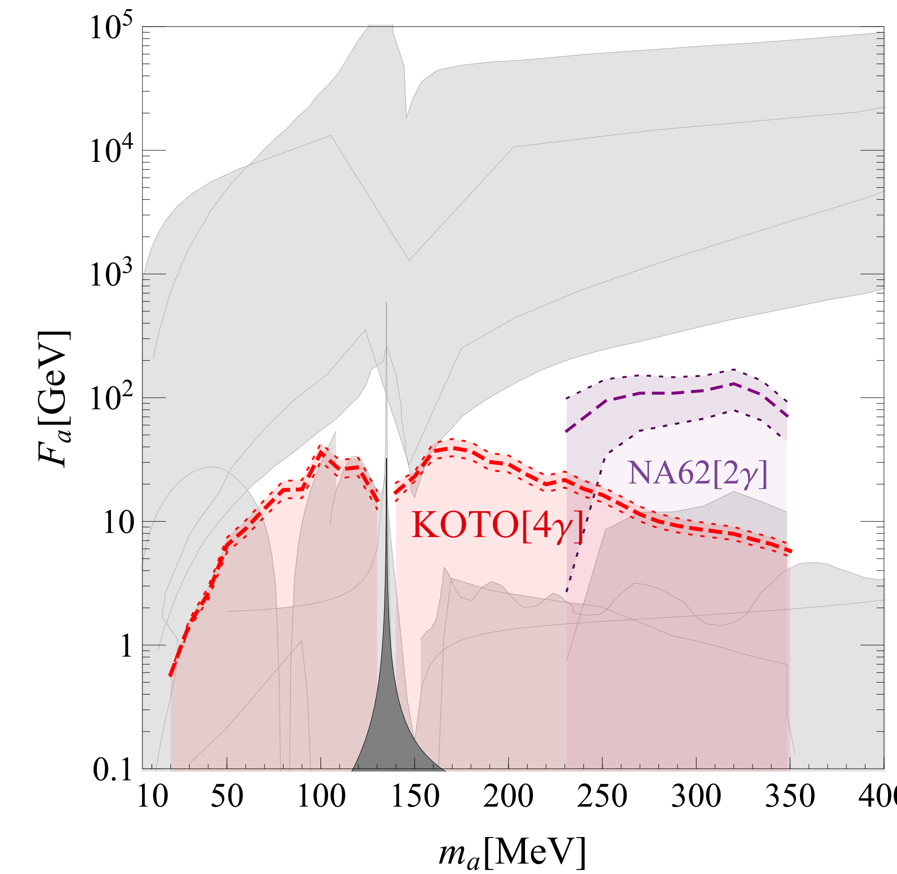
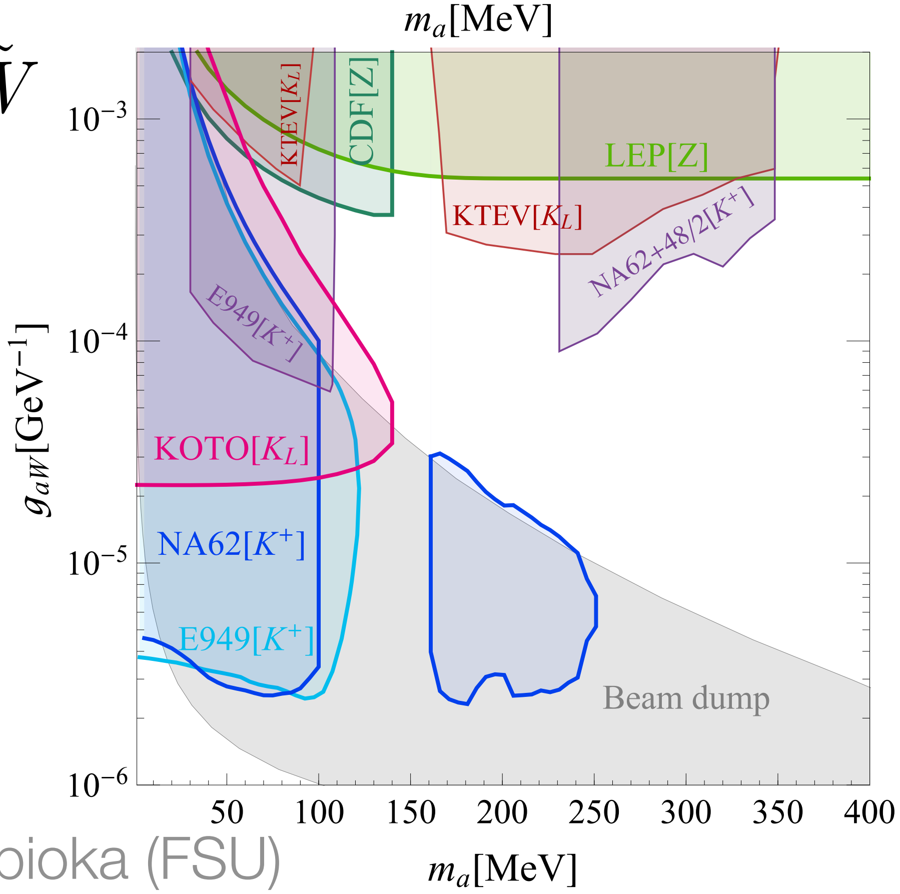
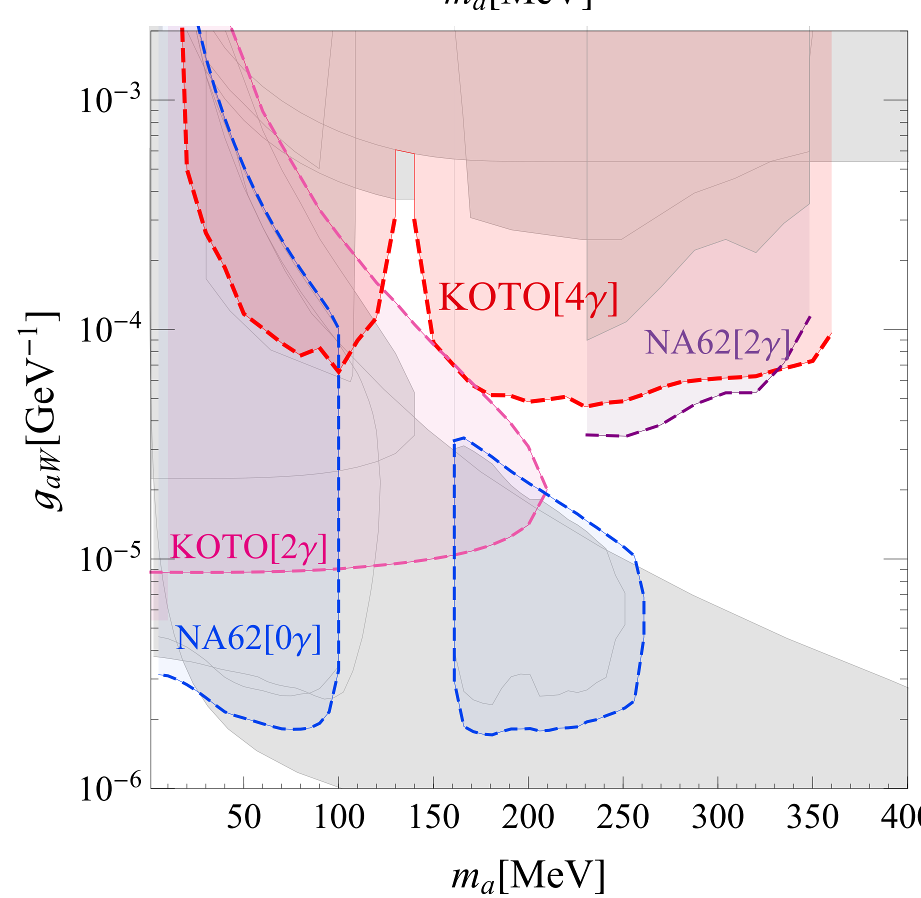


$$\frac{g_{aW}}{4} aW\tilde{W}$$





Concluding Remarks

- NA62 performs well. KOTO “excess” could be BG
  - Wait for the paper
  - If new BG is really large,
    upstream veto detector is key

- Future
  - NA62 and KOTO have opportunities for FIMP
  - Muonic force search w/ Fermila g-2
  - New ALP search with $a \to \gamma\gamma$

- New Idea?
  - Join Snowmass RF working group
    [RARE PROCESSES AND PRECISION MEASUREMENTS]

Backup

Look at Frontier Data

Rich experimental data are forthcoming, which push frontiers!

B: Belle II, LHCb
K: NA62, KOTO
ν: MicroBoone, LBNE, DUNE, T2HK
Long-lived particle: FASER, NA62++, future beam-dump

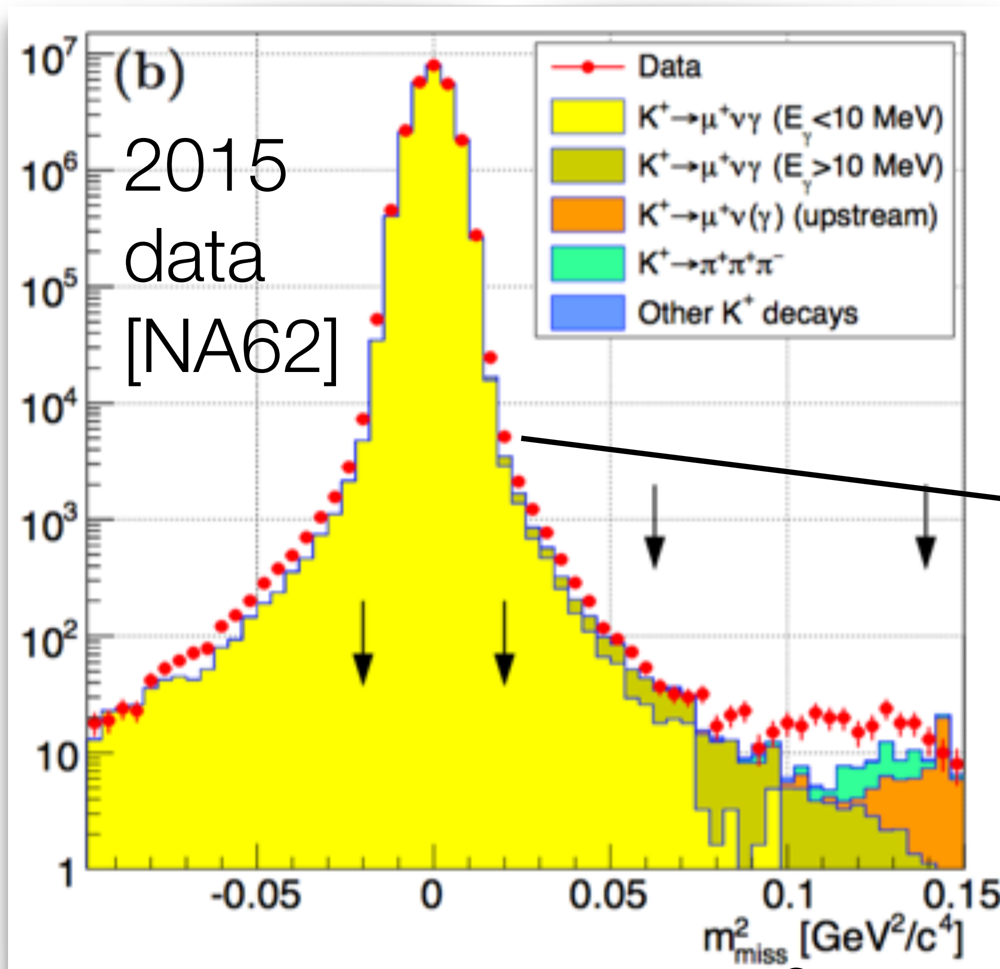
Kaon is an example
Pros: running, extremely intense, relevant to lepton and hadron.

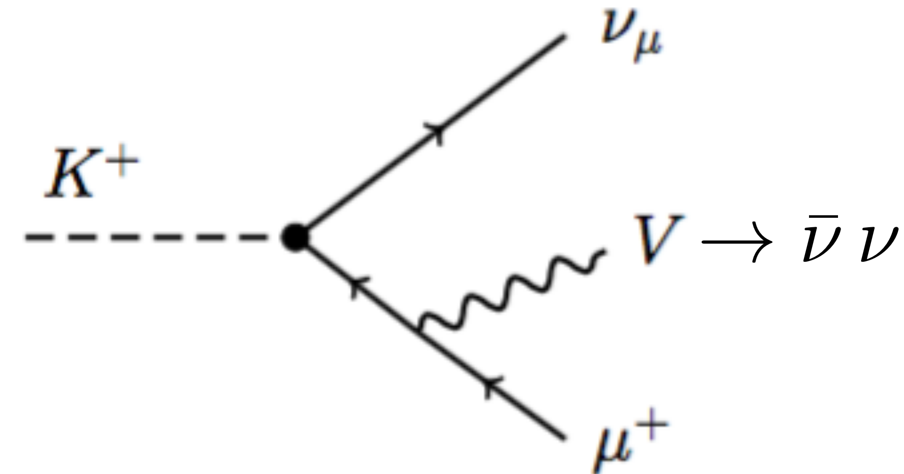
Each one is complementary to others [B-factories, beam dump]

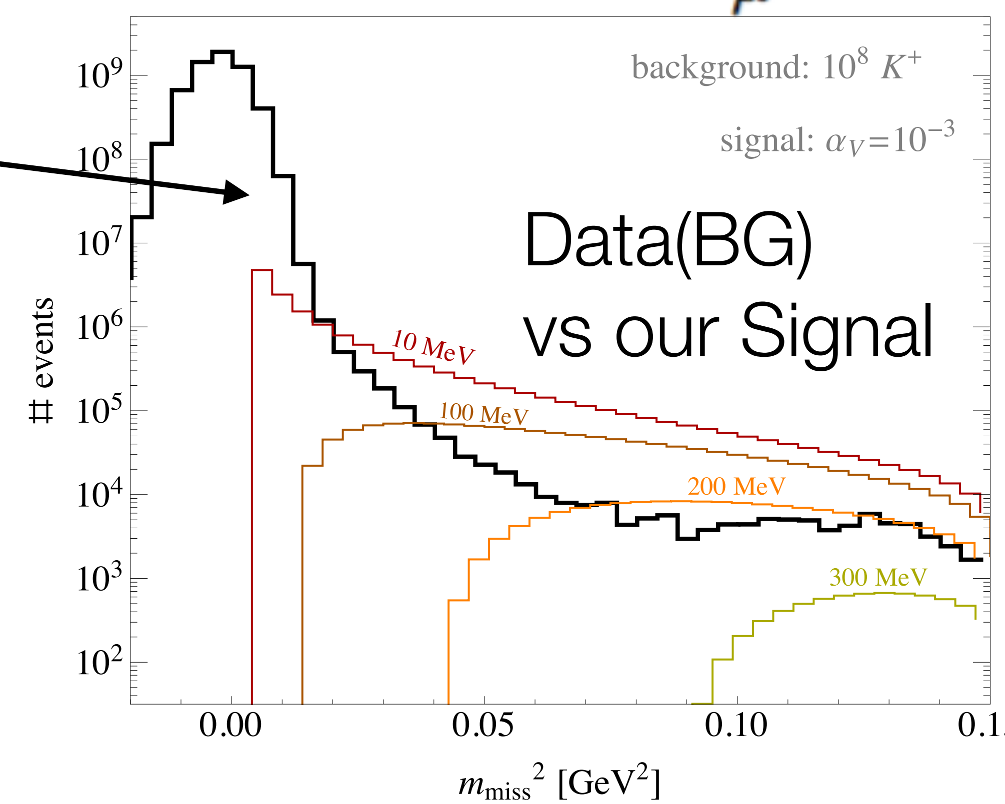
L_μ-L_τ gauge boson at NA62

[G. Krnjaic, G. Marques-Tavares, D. Redigolo, **KT ('19)**]

recast $K^+ \to \mu^+ N$







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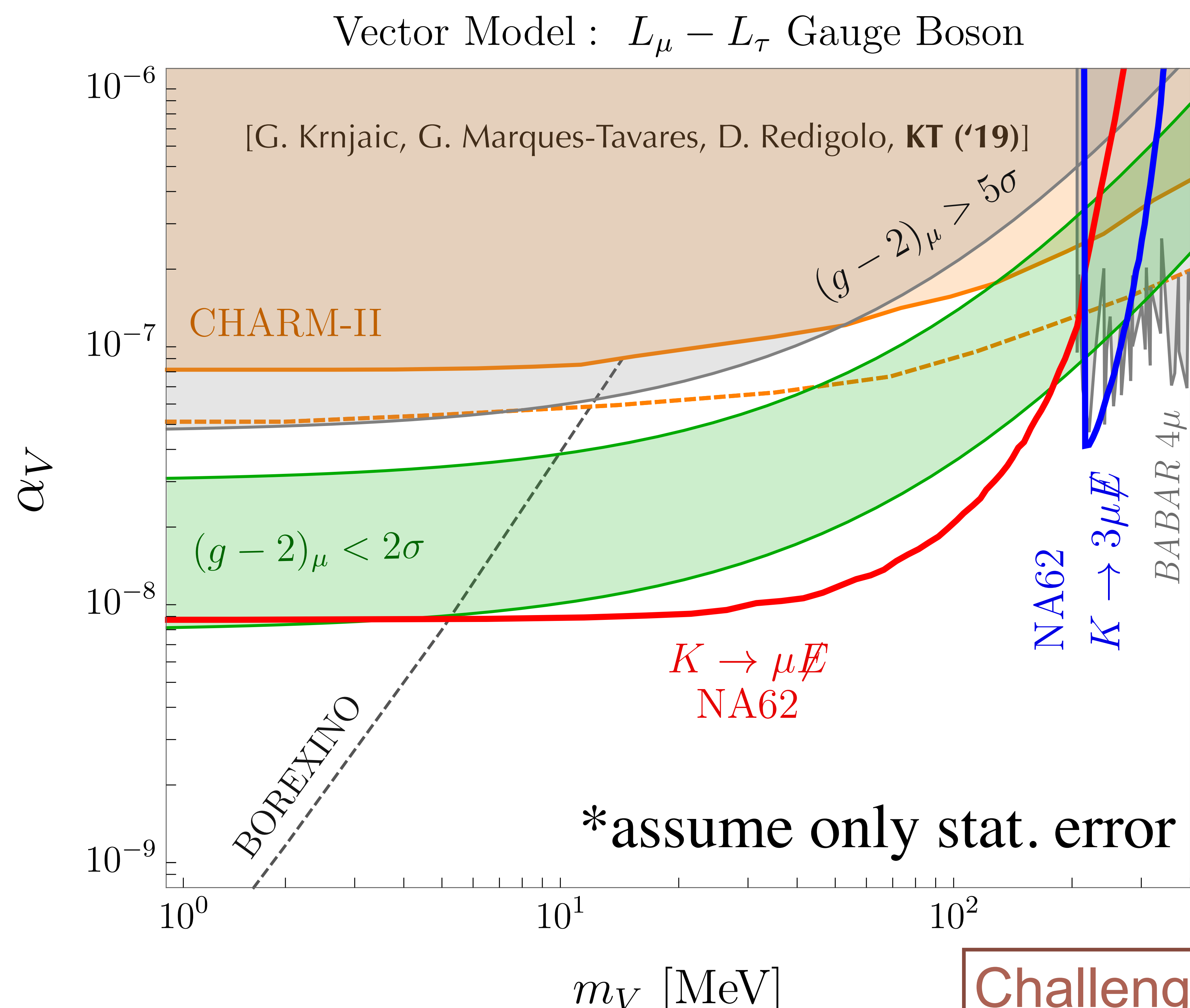

Challenges

NA62 can cover remaining parameter space!

- Remove prescaling **1/400**
- Control systematics