Stony Brook University

Light Scalars and the KOTO Anomaly

arXiv:1911.10203 (accepted in PRL)

Sam Homiller

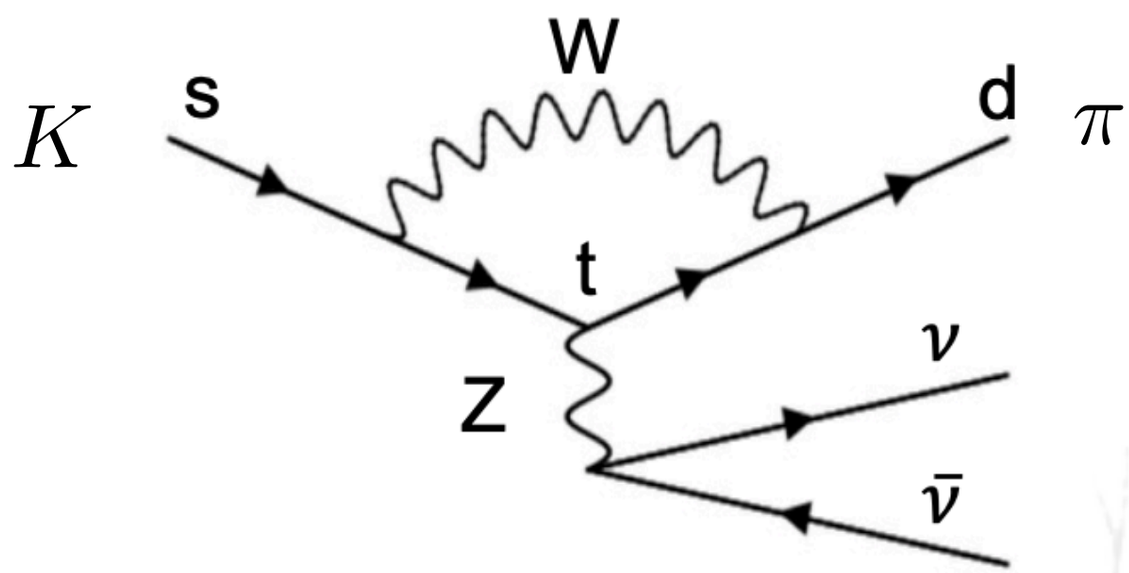
YITP, Stony Brook

In collaboration with D. Egaña-Ugrinovic and Patrick Meade

APS April Meeting, April 21, 2020

KOTO Measures Rare Kaon Decays

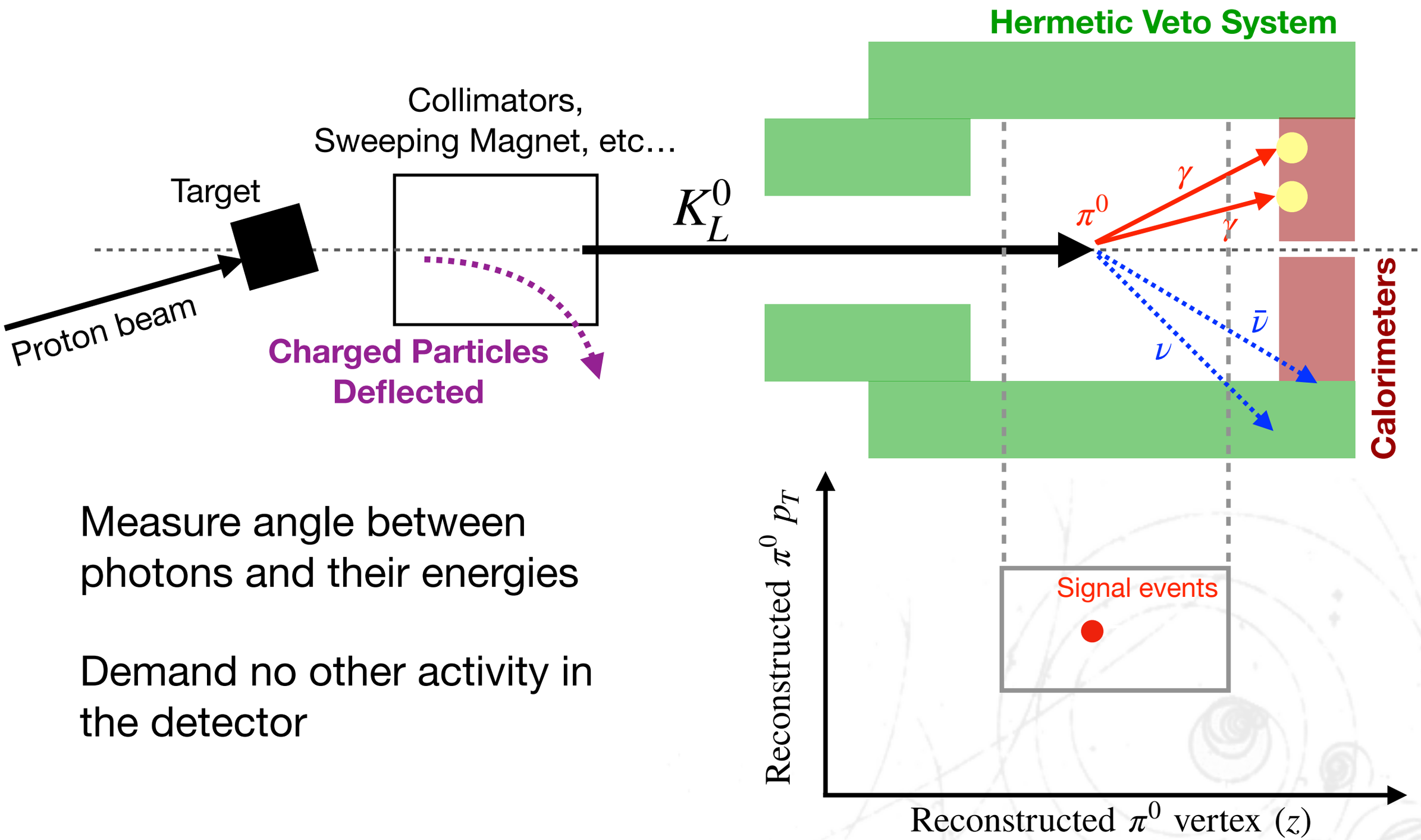
KOTO is an experiment at J-PARC searching for the rare decay of a *neutral* Kaon into a pion + neutrinos



$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (3.4 \pm 0.6) \times 10^{-11}$$

Buras et al., arXiv:1503.02693

KOTO Measures Rare Kaon Decays



Measure angle between photons and their energies

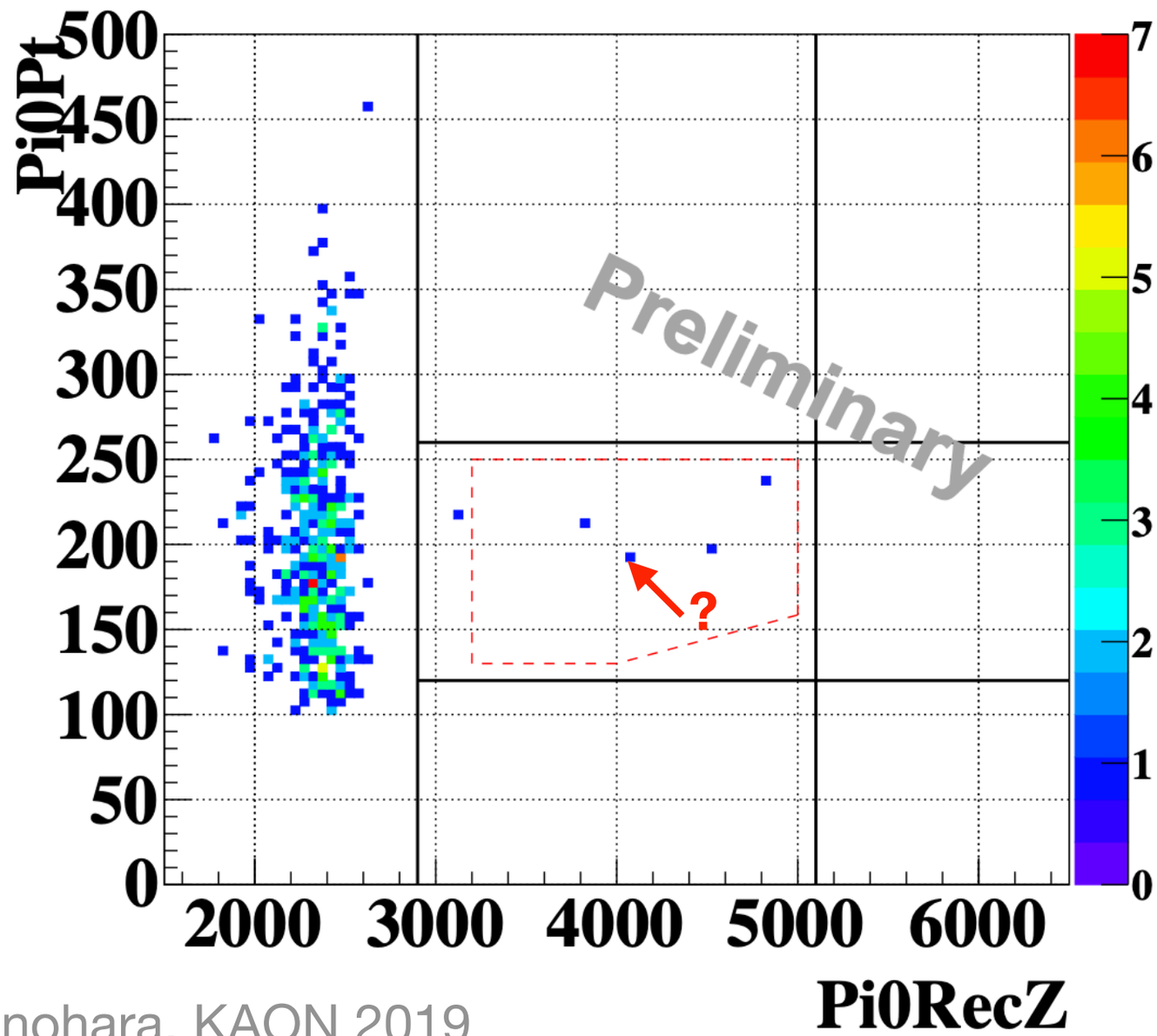
Demand no other activity in the detector

The KOTO "Anomaly"

As of Fall 2019

SM Signal + Background expectation: 0.1 ± 0.02 events

Single Event Sensitivity: 6.9×10^{-10}



Shinohara, KAON 2019

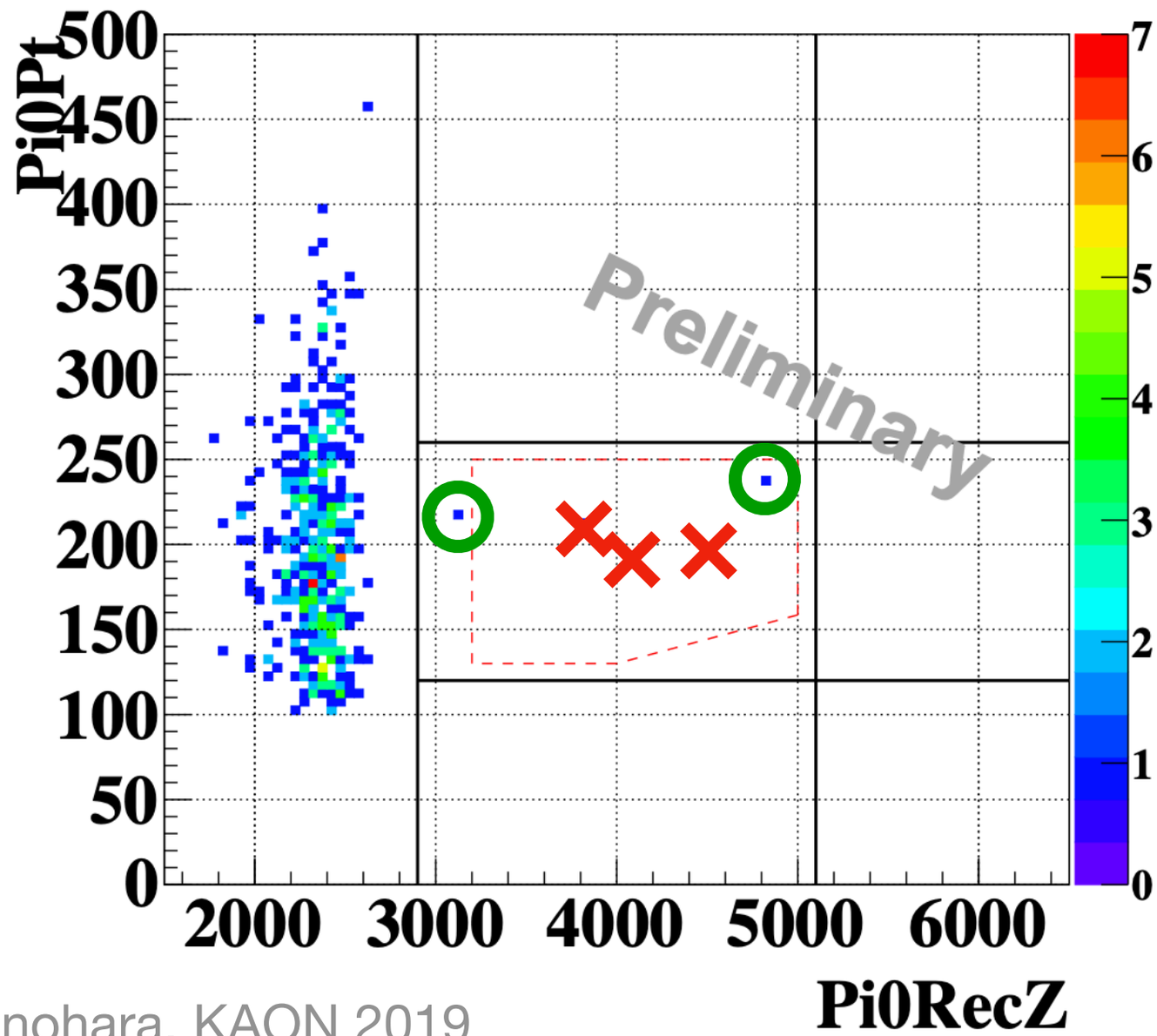
The KOTO "Anomaly"

As of Early 2020

SM Signal + Background expectation: 0.39 ± 0.08 events

Single Event Sensitivity: 7.1×10^{-10}

Including preliminary estimate of charged Kaon contamination



Shinohara, KAON 2019

Confronting the Anomaly

The 2 events are consistent with:

$$\mathrm{Br}(K_L \to \pi^0 + \mathrm{inv.})_{\mathrm{KOTO}} = 1.4^{+1.8(3.7)}_{-0.9(1.2)} \times 10^{-9}$$

Theoretical perspective: are there simple & motivated ways of explaining this result with new physics?

Yes!

The absolute *simplest*: add a scalar singlet to the SM

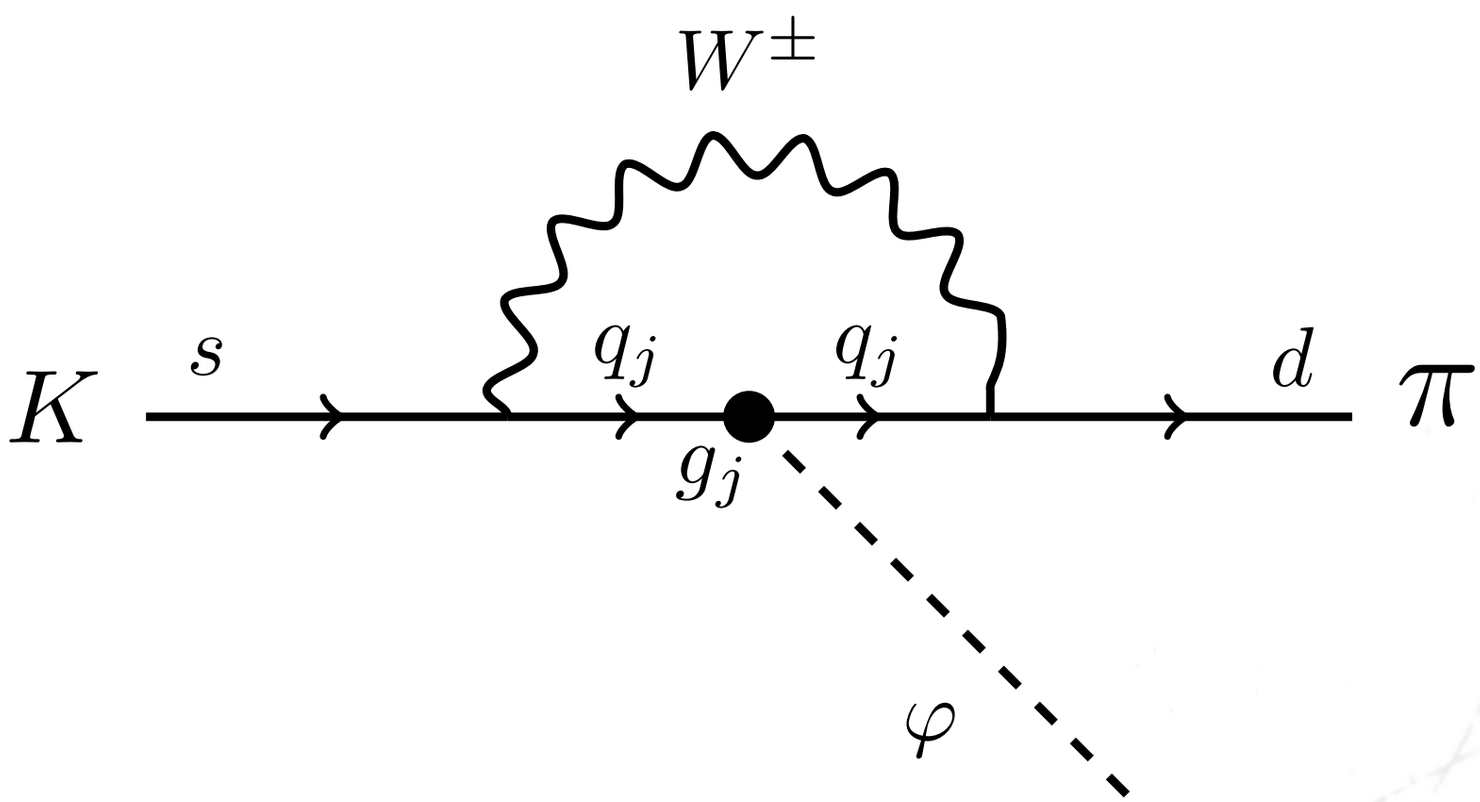
Higgs Portal Explanation of KOTO

Egana-Ugrinovic, SH, Meade [1911.10203]

Add to the SM a scalar singlet, mixing with the Higgs:

$$\zeta(H^\dagger H\varphi) \quad \rightarrow \quad \zeta\,(vh\varphi) \quad \rightarrow \quad \underline{\sin\theta} \sim \zeta v/m_h^2$$

All couplings dictated by the mixing angle



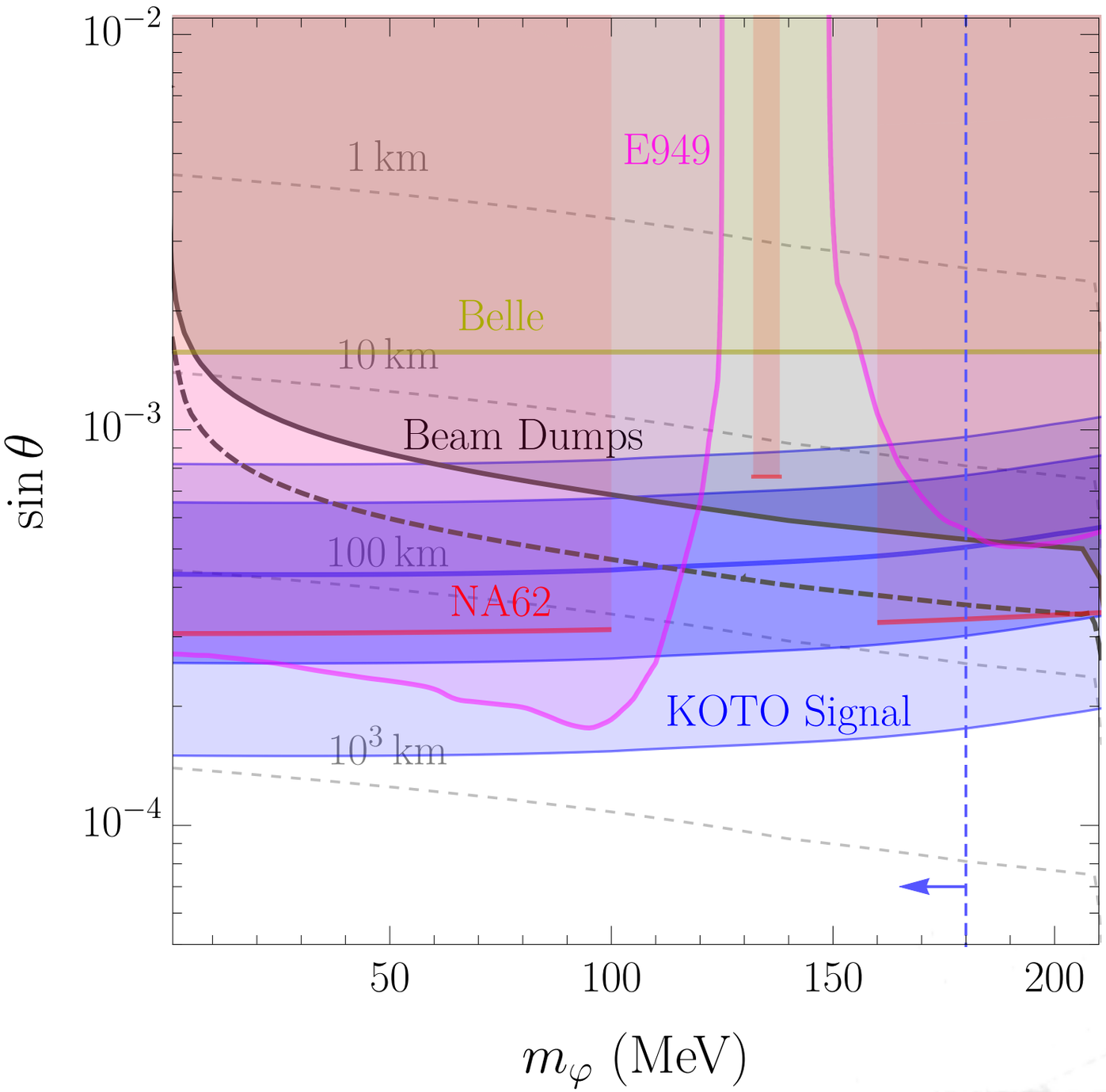
Scalar is *long lived*

⇩

escapes KOTO undetected, mimicking the neutrinos

Higgs Portal Explanation of KOTO

Egana-Ugrinovic, SH, Meade [1911.10203]

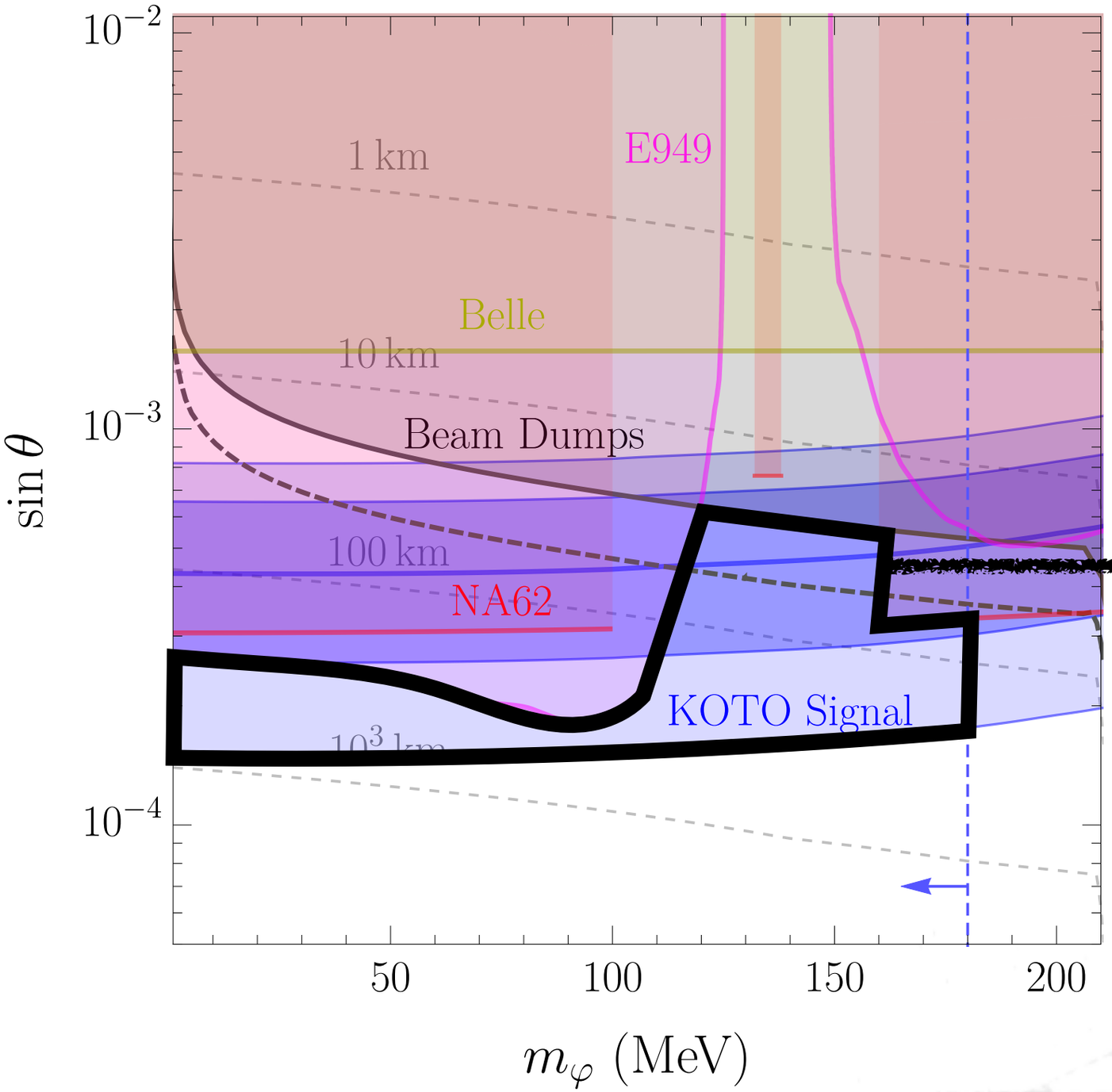


Blue: preferred KOTO region (2 events)

Dashed-gray: scalar lifetime

Higgs Portal Explanation of KOTO

Egana-Ugrinovic, SH, Meade [1911.10203]



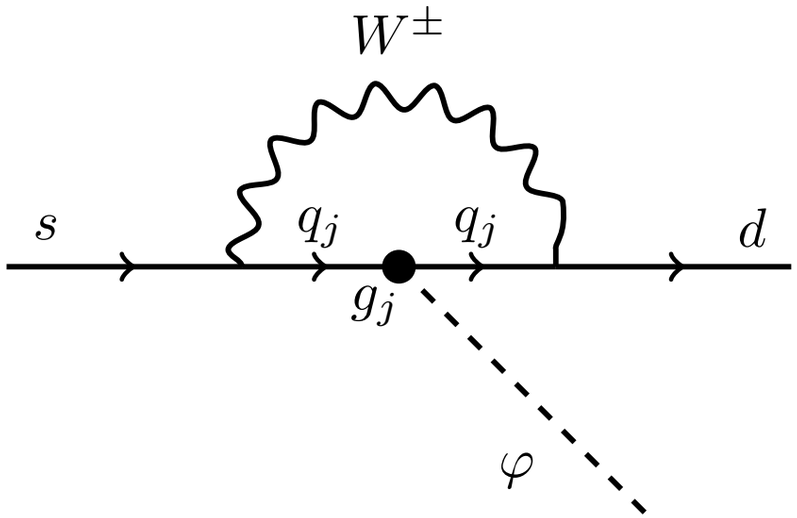
Consistent with all other bounds and explains the 2 events!

Bounds: Charged Kaon Decays

The same diagram also leads to *charged* Kaon decays:

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

(model-independent relationship:
Grossman, Nir, Phys. Lett B398, 1997, 163-168)



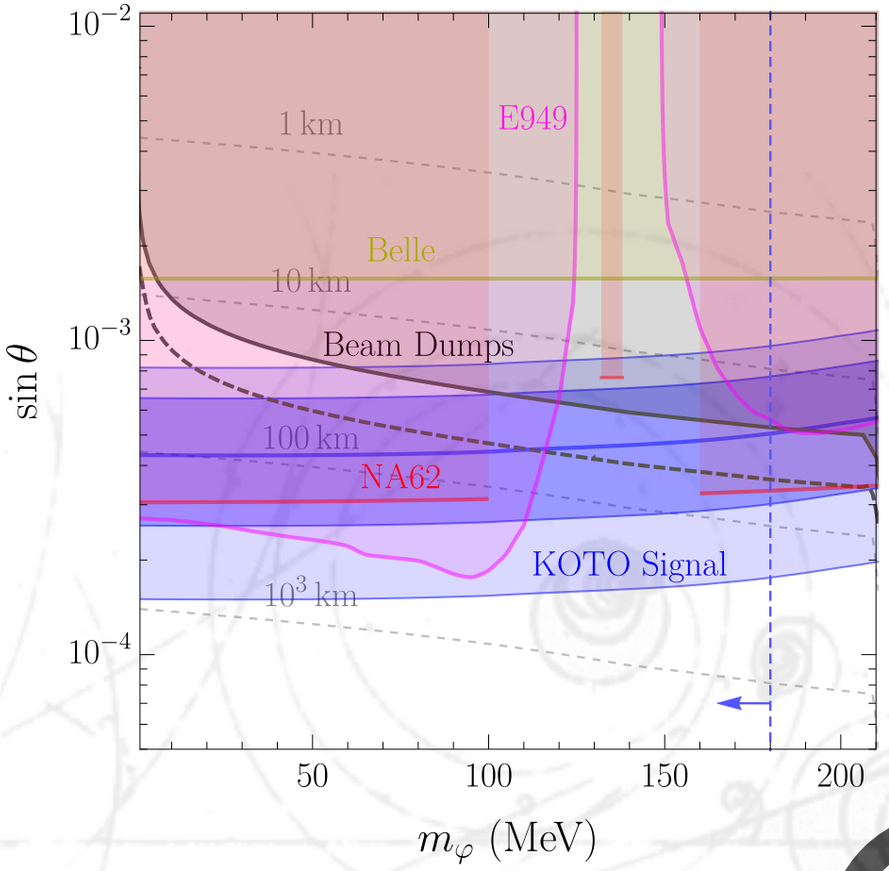
Constrained by NA62 and E949

For *charged* pions, can reconstruct the missing mass

$\Longrightarrow$ Large background when $m_\varphi \sim m_\pi$

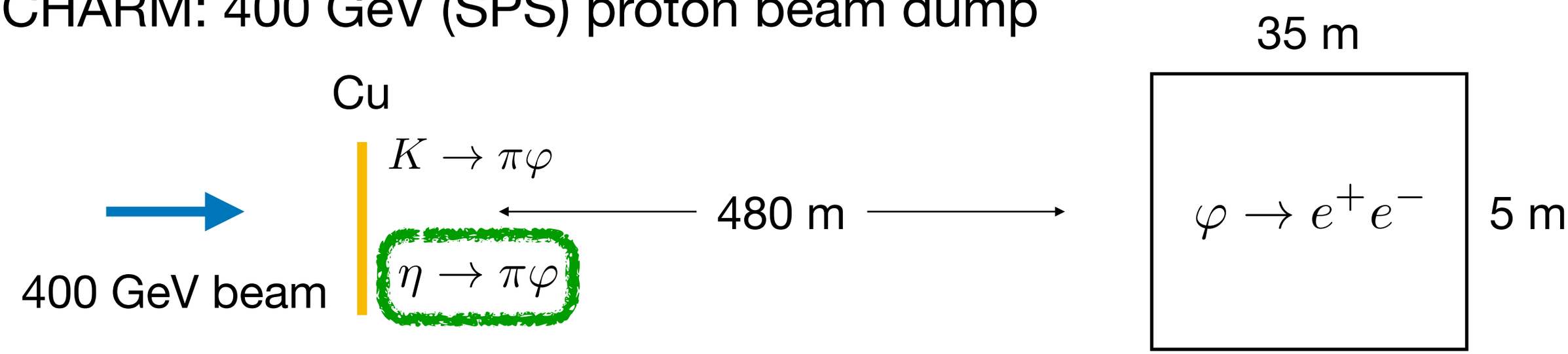
("predicted" by Hou et al., 1412.4397, 1611.09673)

"'Blessed are the Blind, for they shall see the Heavens open' ….
… So, please: Analyze, KOTO, Analyze!"



Bounds: Proton Beam Dumps

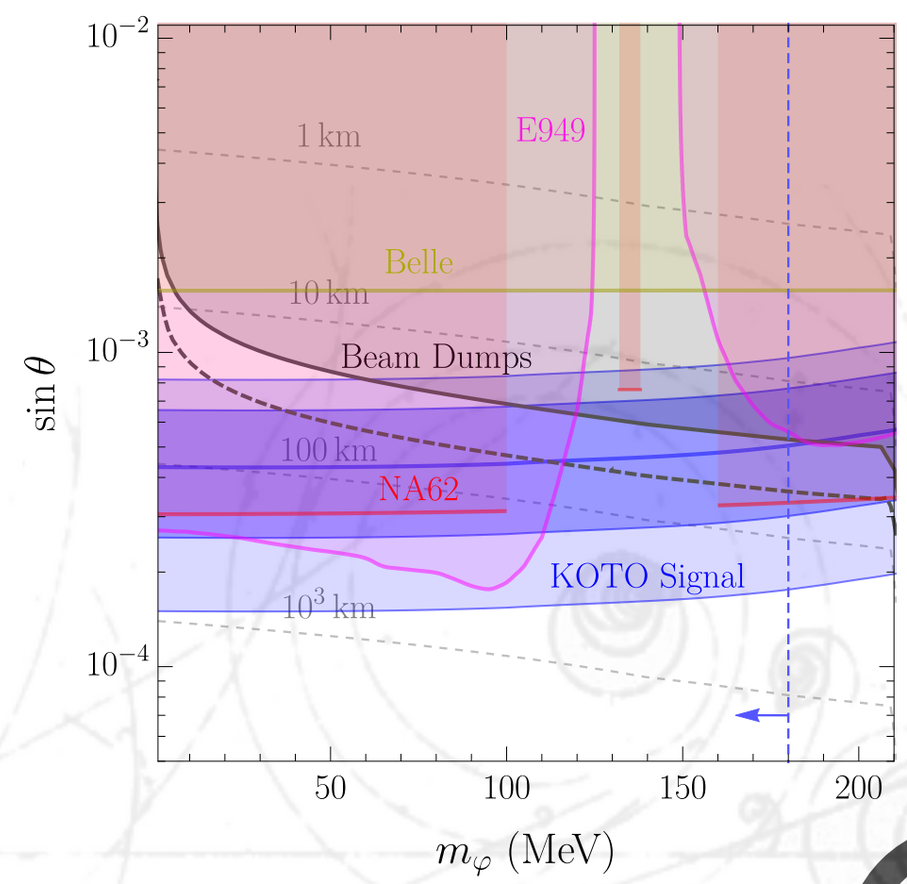
CHARM: 400 GeV (SPS) proton beam dump



Bounds cover a large portion of the window left open by NA62

Bergsma et.al., Phys. Lett., 157B, 5,6, p. 458

Beam Dumps lead to tension with "intermediate lifetime" explanations of the KOTO events

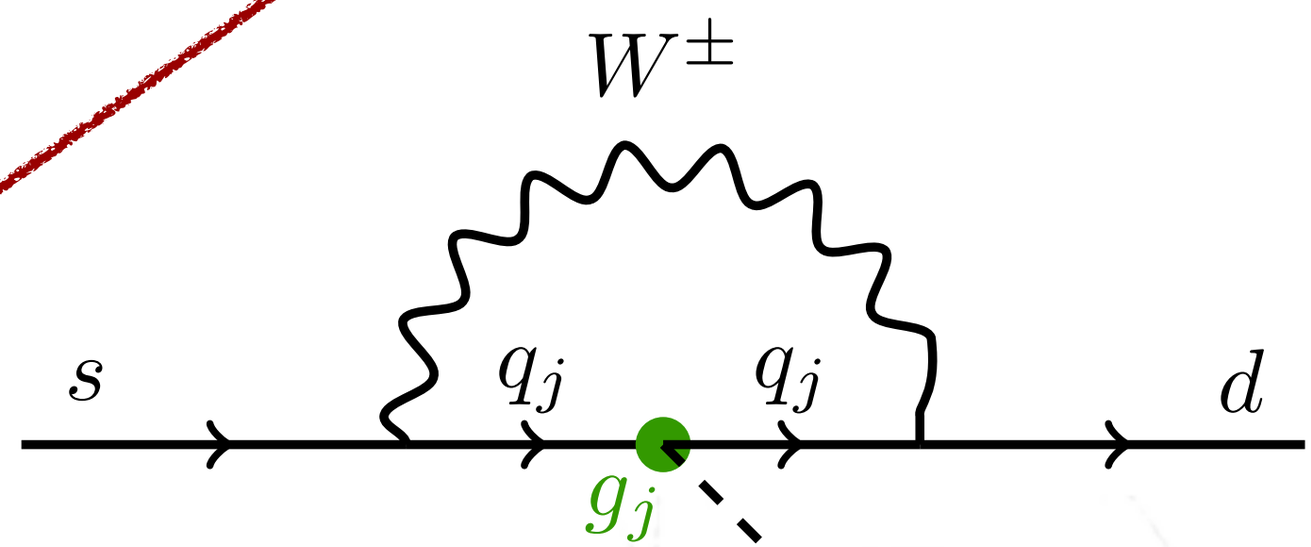


What if we change the scalar couplings?

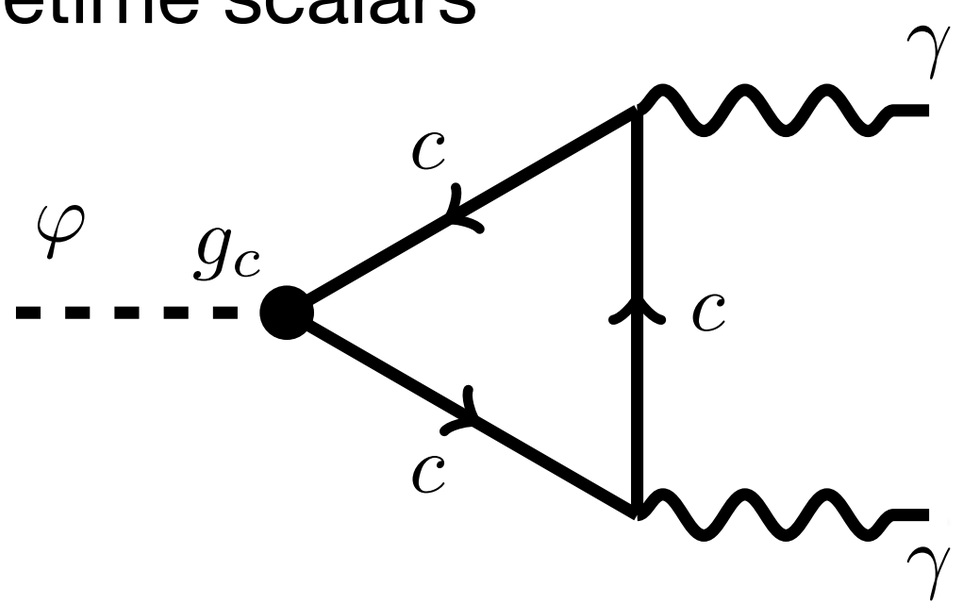
Different Flavor textures let us investigate alternative solutions to KOTO

Similar to Minimal Higgs Portal!

$$\frac{c^u_{ij}}{M}\varphi H\, Q_i \bar{u}_j \to \begin{cases} \cancel{g_u}\varphi u\bar{u} \\ g_c \varphi c\bar{c} \\ g_t \varphi t\bar{t} \end{cases}$$



Coupling predominantly to charm leads to intermediate-lifetime scalars

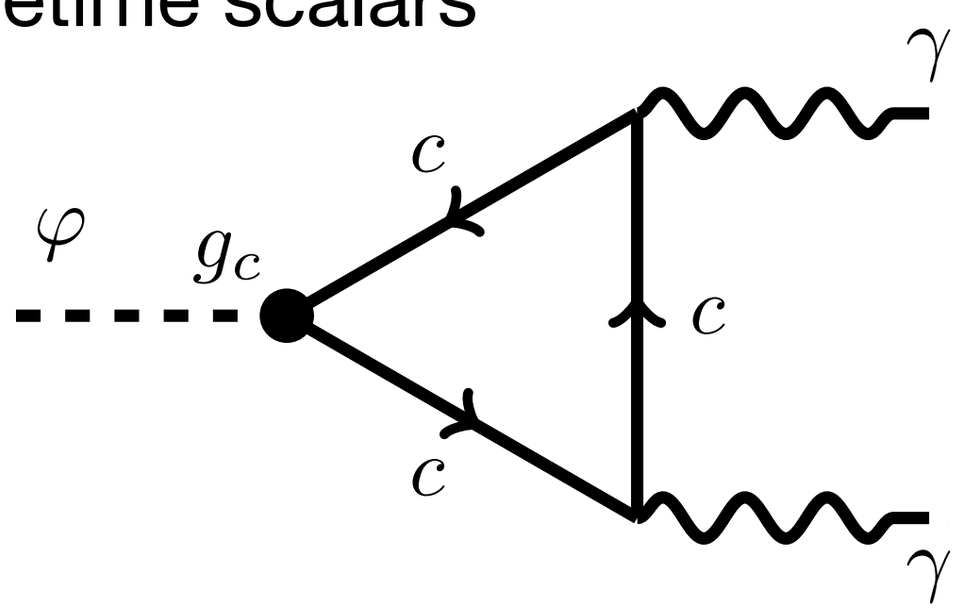


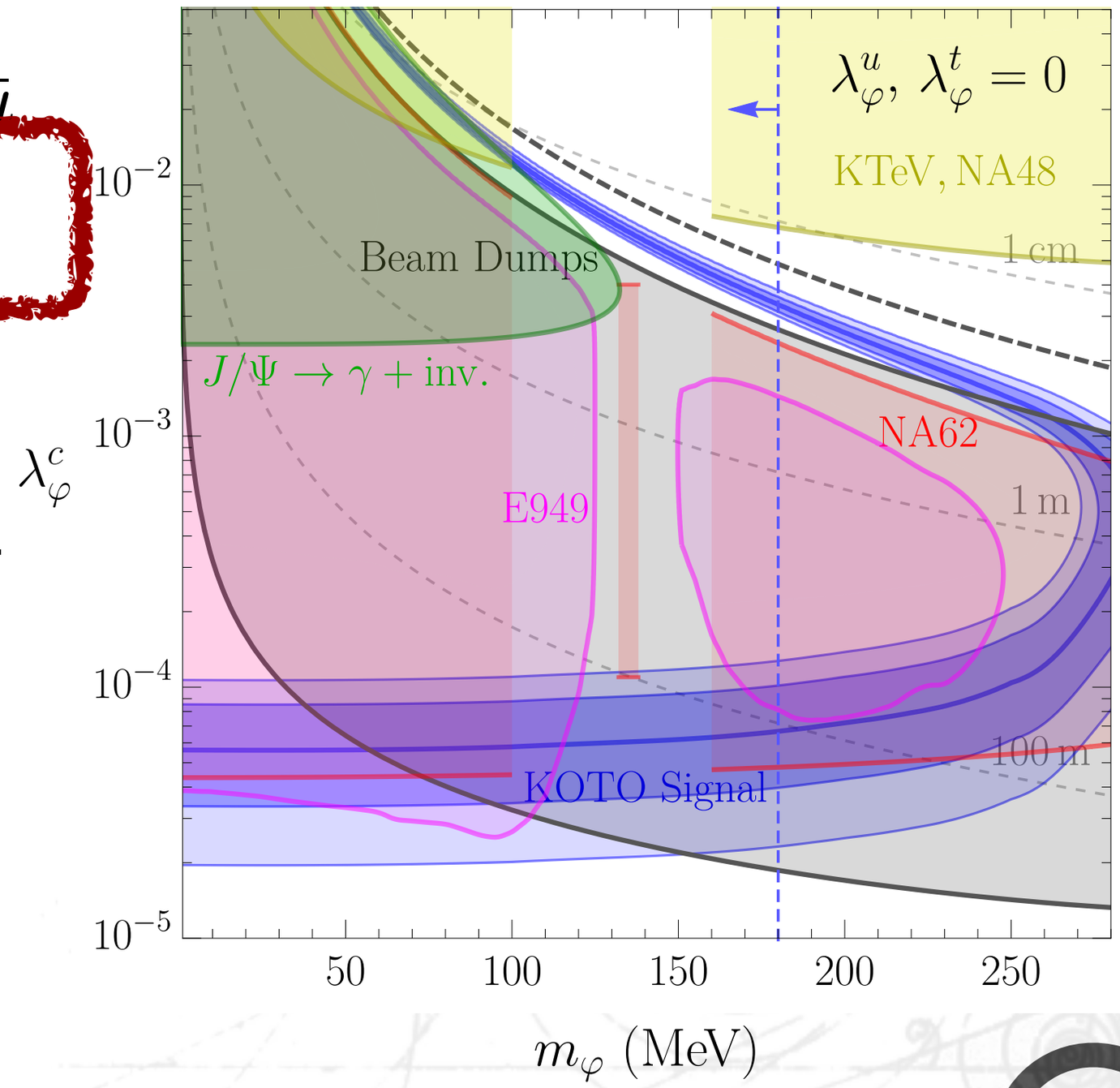
What if we change the scalar couplings?

Different Flavor textures let us investigate alternative solutions to KOTO

$$\frac{c^u_{ij}}{M}\varphi H\, Q_i \bar{u}_j \rightarrow \begin{cases} g_u \varphi u\bar{u} \\ g_c \varphi c\bar{c} \\ g_t \varphi t\bar{t} \end{cases}$$

Coupling predominantly to charm leads to intermediate-lifetime scalars





Summary

- There's a large anomaly in rare Kaon decays
- Events can be explained by the *simplest* extension of the SM
- Strongest constraints come from beam-dumps and charged Kaons
- Non-minimal solutions using a shorter lifetime can work, but are in tension with beam dump constraints

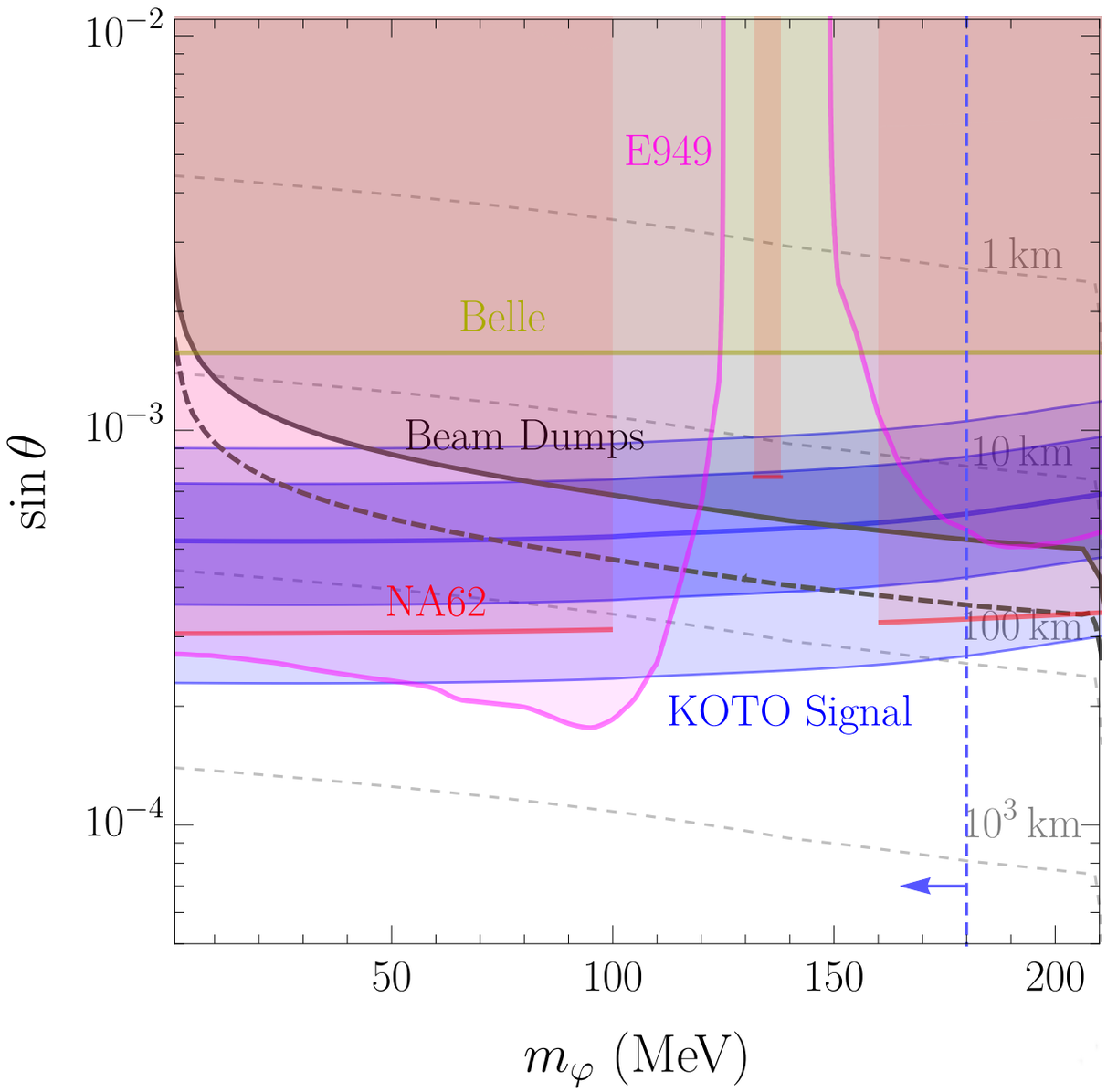
What's Next?

- Look out for KOTO final analysis (expected to finish this Summer)
- More data from 2019 KOTO Run
- New NA62 results?(Volpe, Tues. Flavor Session)
- Future LLP Experiments? (See PBC Summary: 1901.09966)

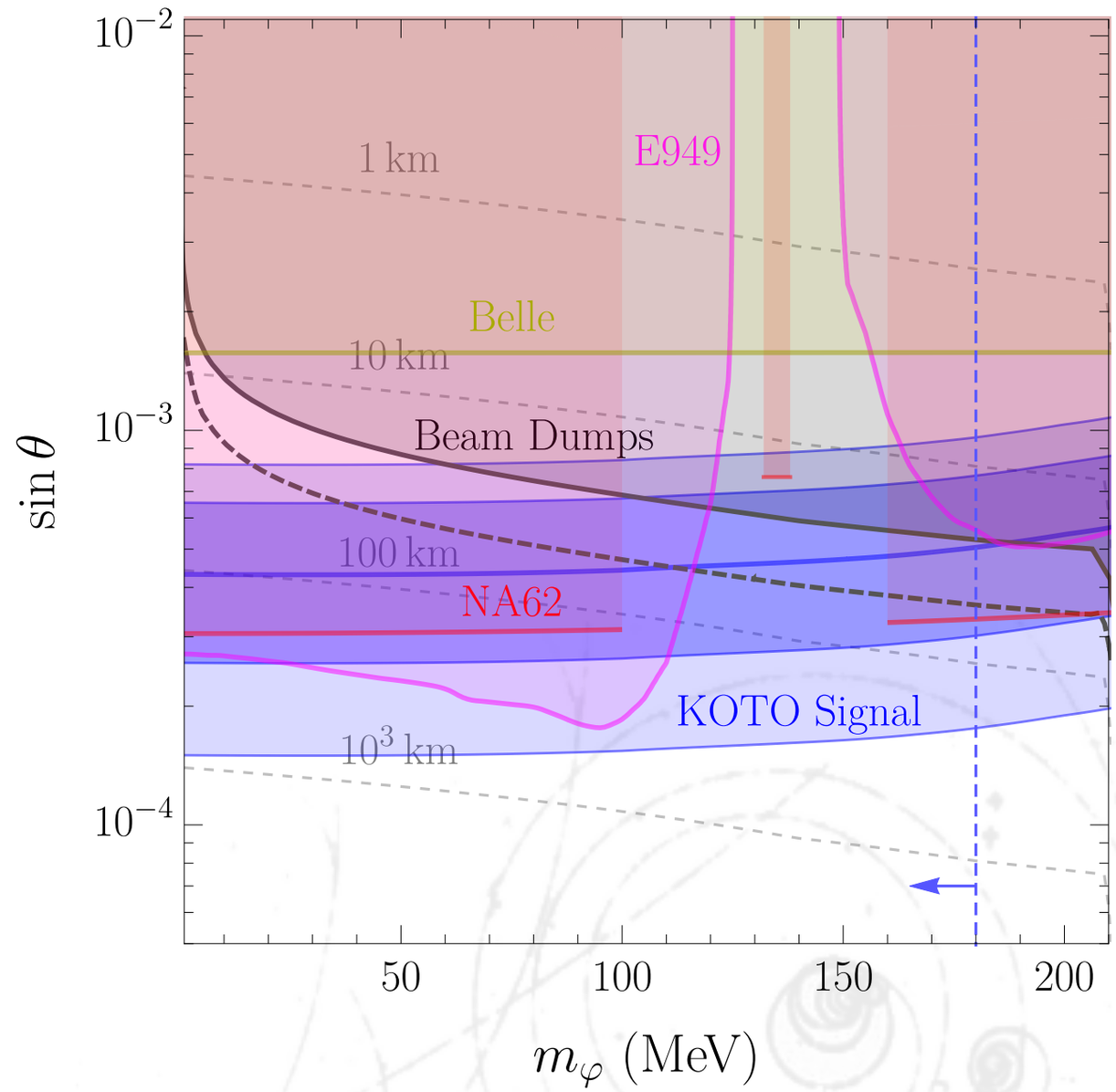
DM Implications: Pospelov, Ritz, Voloshin 0711.4866, Krnjaic, 1512.04119

Backup

2 Events vs. 3 Events

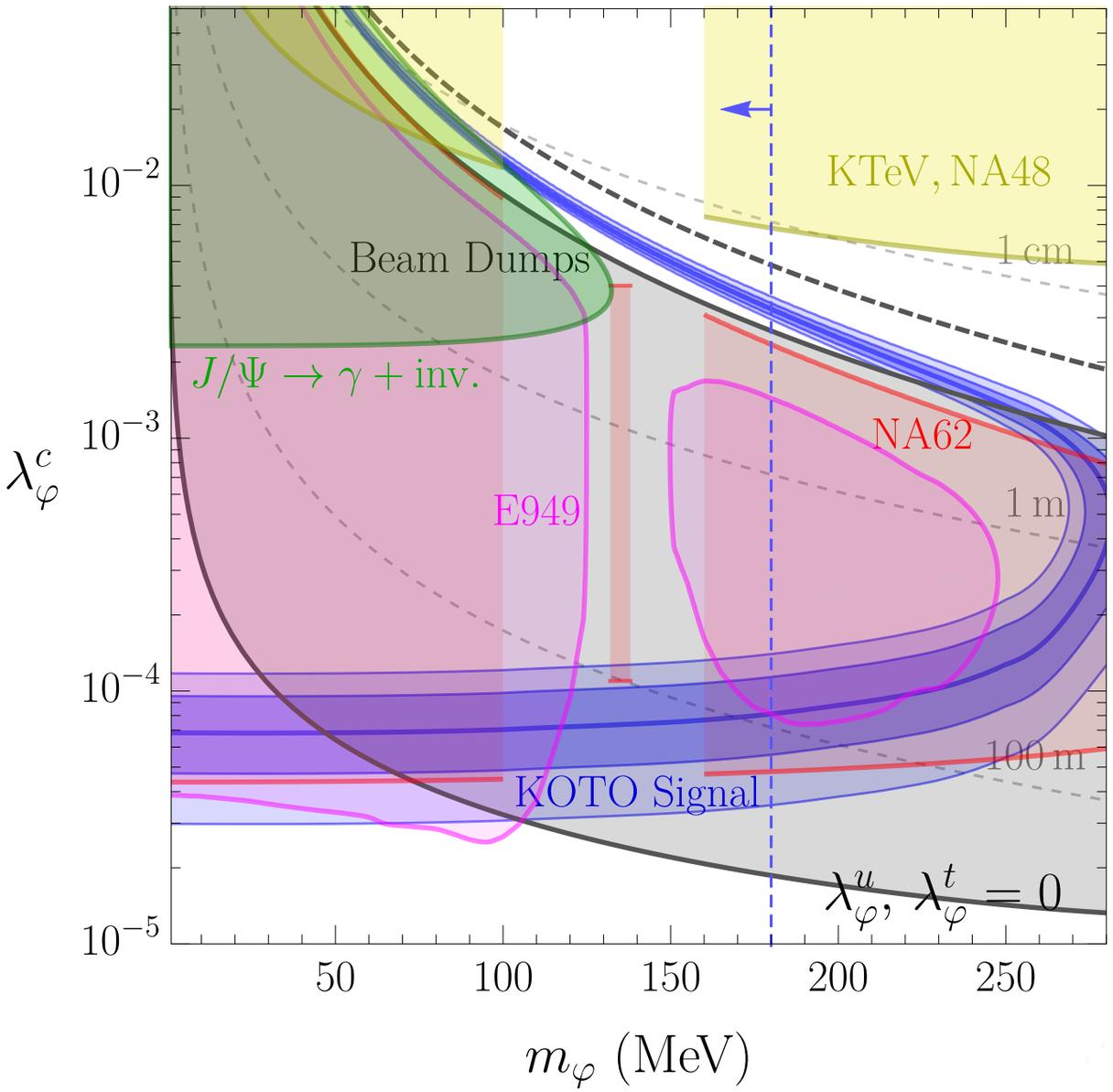


3 events

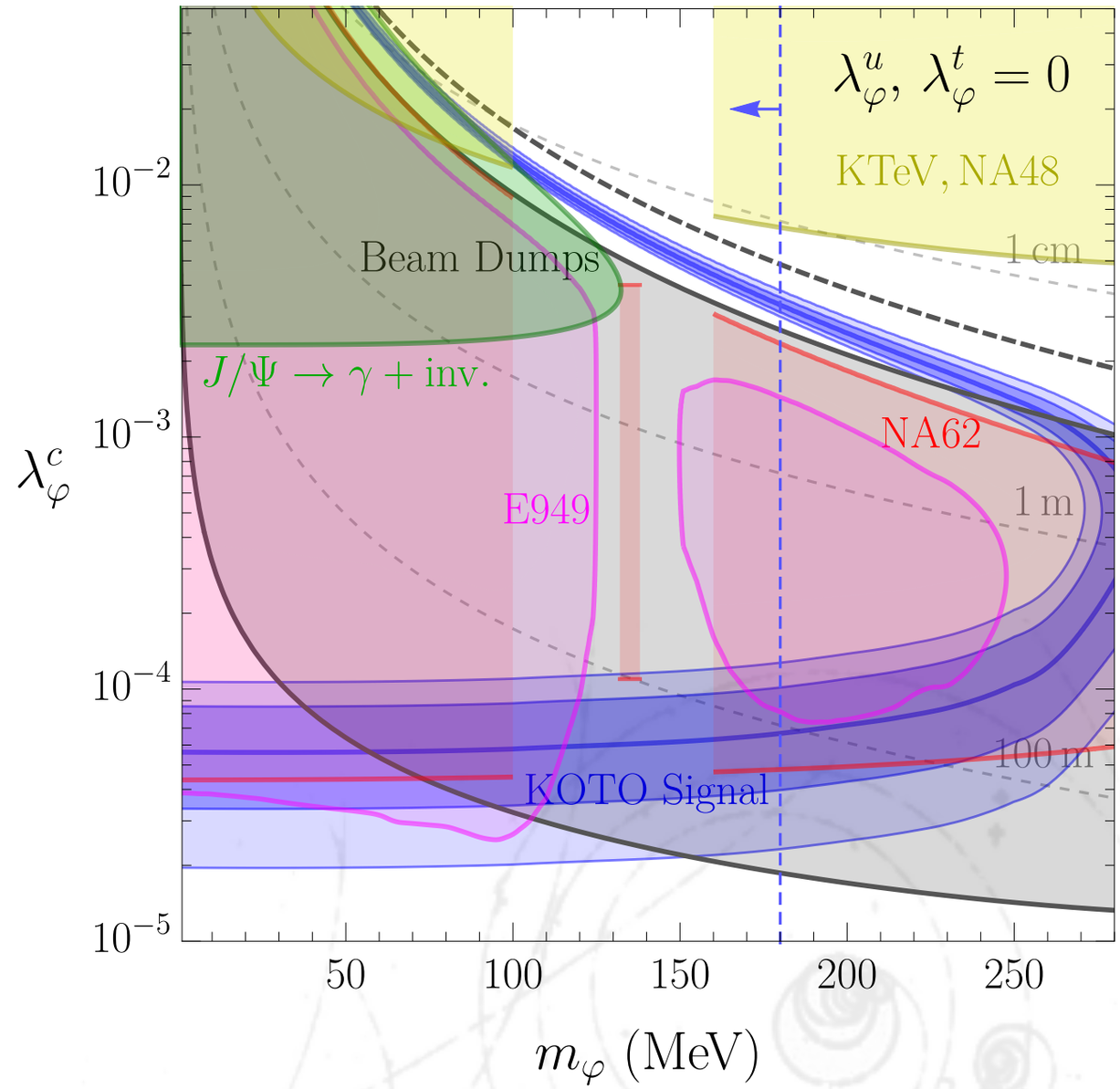


2 events

2 Events vs. 3 Events

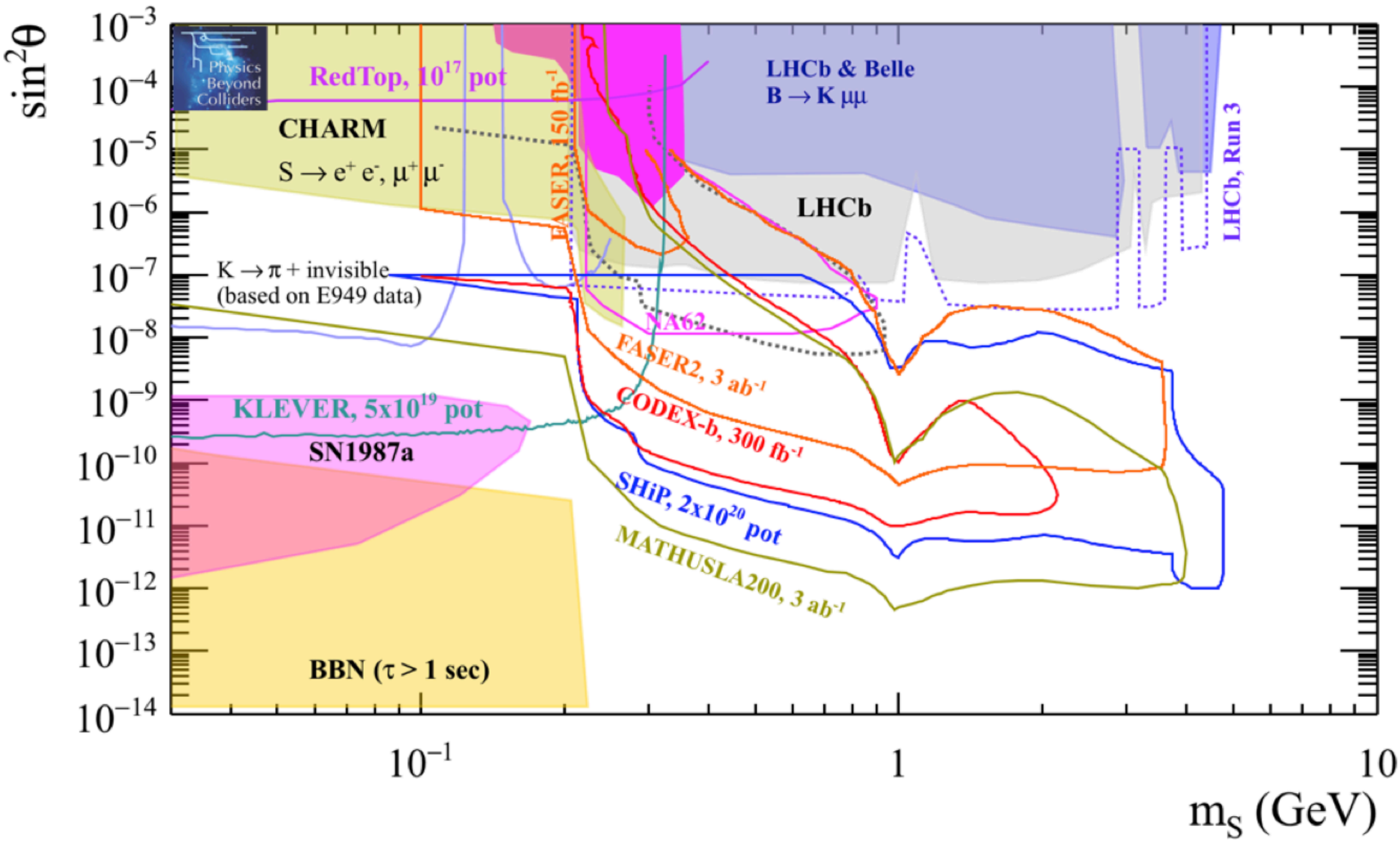


3 events



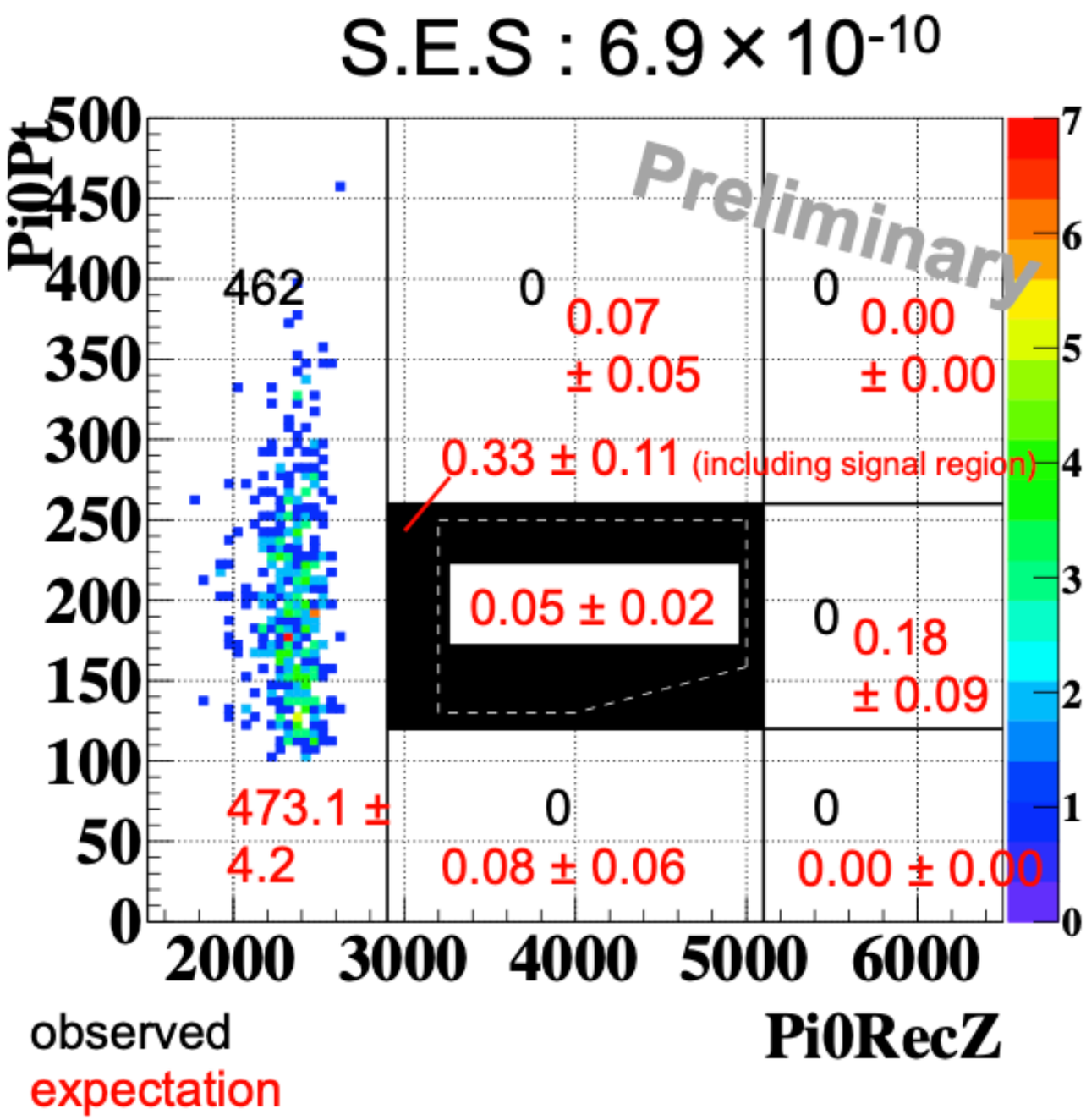
2 events

Future Constraints (PBC)



2016-2018 Background Estimation

from Satoshi Shinohara, KAON 2019



Preliminary

	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
KL2gamma	0.00 ± 0.00
Upstream π^0	0.00±0.00
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

Updated Background Estimates

As of January, 2020

from T. Nomura, J-PARC Meeting

Updated

New

source		#BG (U.L. at 90% C.L.)	#BG (U.L. at 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)	<0.04	<0.02
	Ke3 (overlapped pulse)	<0.09	<0.05
	$K_L \to 2\gamma$	0.001±0.001	0.001±0.001
	Ke3 (π^0 produced)	<0.04	<0.02
	radiative Ke3	<0.046	<0.023
	Ke4	<0.04	<0.02
	$K_L \to ee\gamma$	<0.09	<0.05
	$K_L \to \pi^+\pi^-$	<0.03	<0.02
	$K_L \to 2\gamma$ (core-like)	<0.11	<0.06
	$K_L \to 2\gamma$ (halo)	<0.19	<0.10
	Ke3 ($\pi^\pm \to \pi^0 e^\pm \nu$)	<0.01	

New

source		#BG (U.L. at 90% C.L.)	#BG (U.L. at 68% C.L.)
$K^\pm$	$K^\pm \to \pi^0\pi^\pm$	<0.01	<0.01
	$K^\pm \to \pi^0 e^\pm \nu$	**0.29±0.08**	**0.29±0.08**
	$K^\pm \to \pi^0 \mu^\pm \nu$	<0.02	<0.01
Neutron	Upstream π^0	0.001±0.001	0.001±0.001
	Hadron cluster	0.02 ±0.00	0.02 ±0.00
	CV-π^0	<0.10	<0.05
	CV-η	0.03±0.01	0.03±0.01
Total	central value	0.34(±0.08)	0.34(±0.08)

$K^\pm$	Branching ratio
$K^\pm \to \pi^0\pi^\pm$	20.7%
$K^\pm \to \pi^0 e^\pm \nu$	5.1%
$K^\pm \to \pi^0 \mu^\pm \nu$	3.4%

Updated Background Estimates

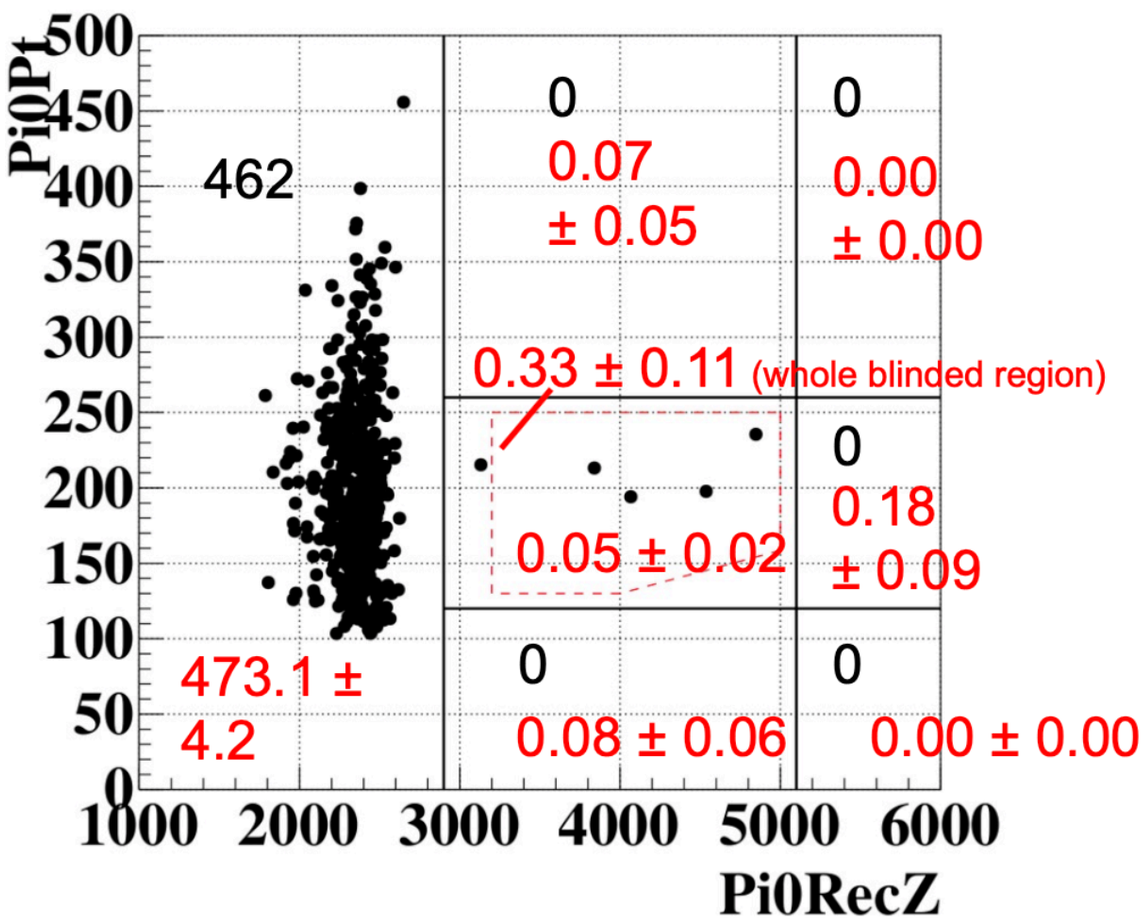
As of January, 2020

from T. Nomura, J-PARC Meeting

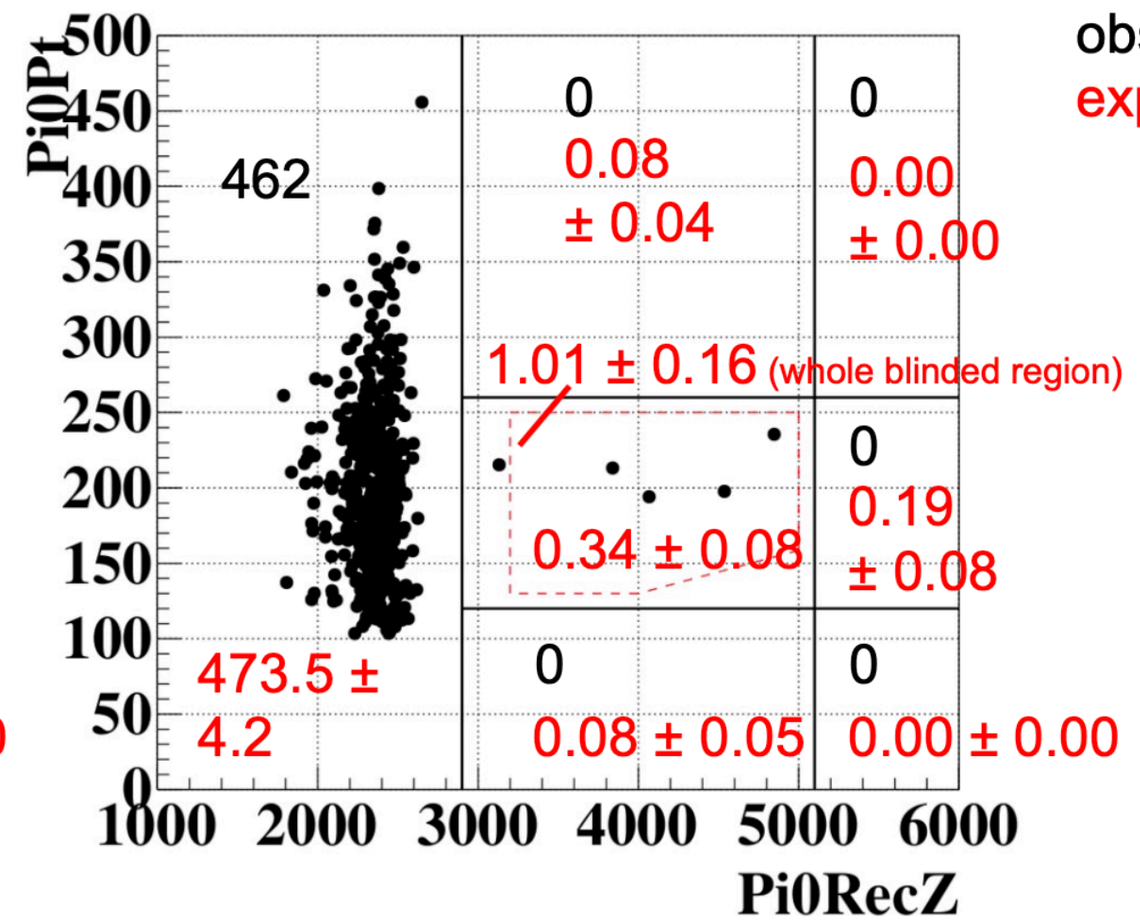
(Jan. 17, 2020)

At KAON 2019 → As of ~~today~~

S.E.S : 6.9×10^{-10}



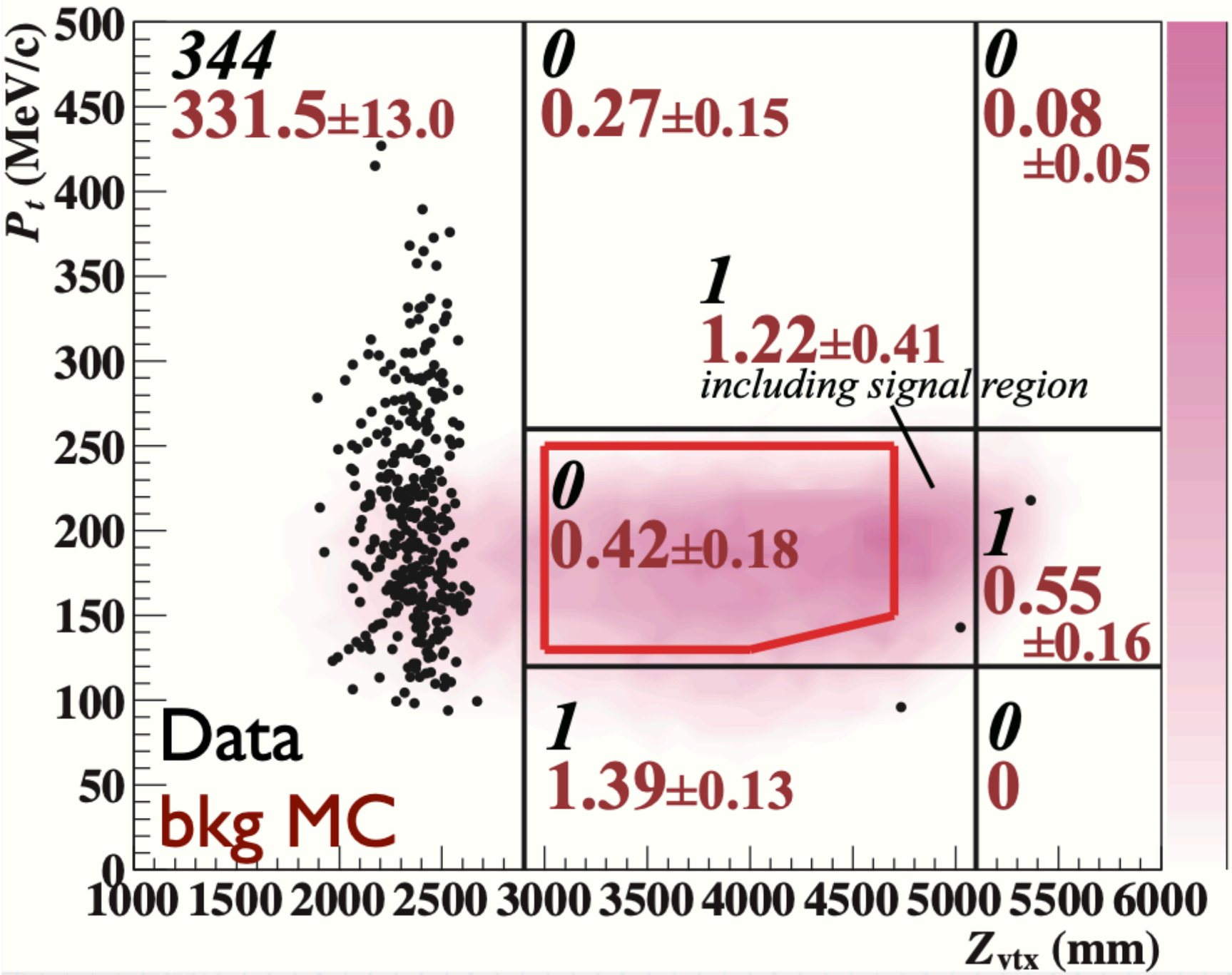
S.E.S : 7.1×10^{-10}



observed
expectation

KOTO 2015 Result

PRL **122**, 021802 (2019)



$$\mathrm{BR} < 3.0 \times 10^{-9}$$

(90% C.L.)

KOTO Runs

From Taku Yamanaka, KAON2019