Annihilating kaons into a dark sector at the KOTO experiment

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In collaboration with

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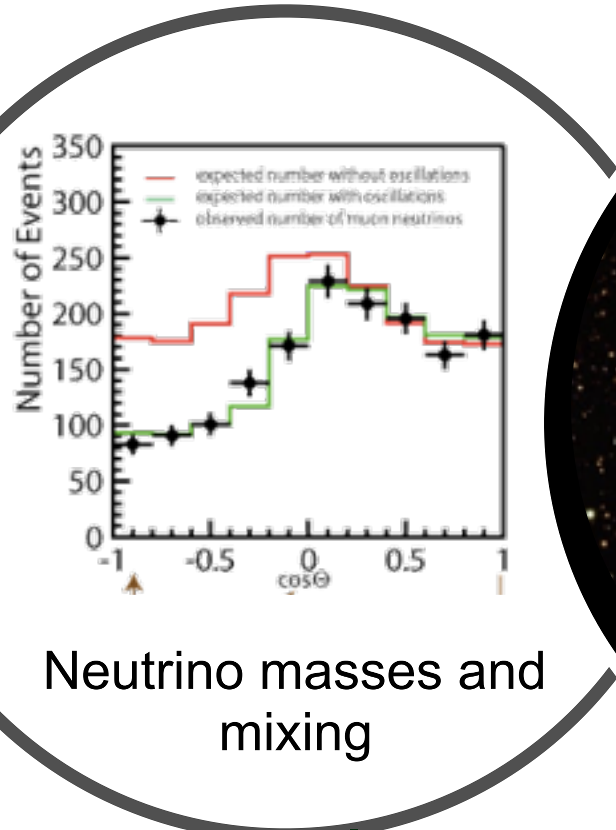
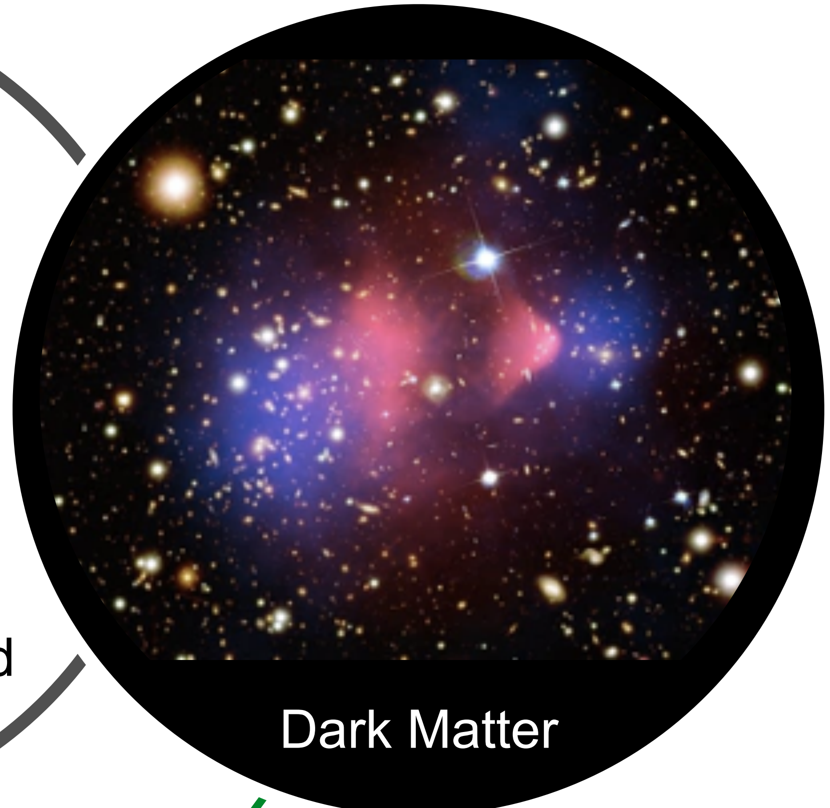
arXiv: 2005.07102

Outline

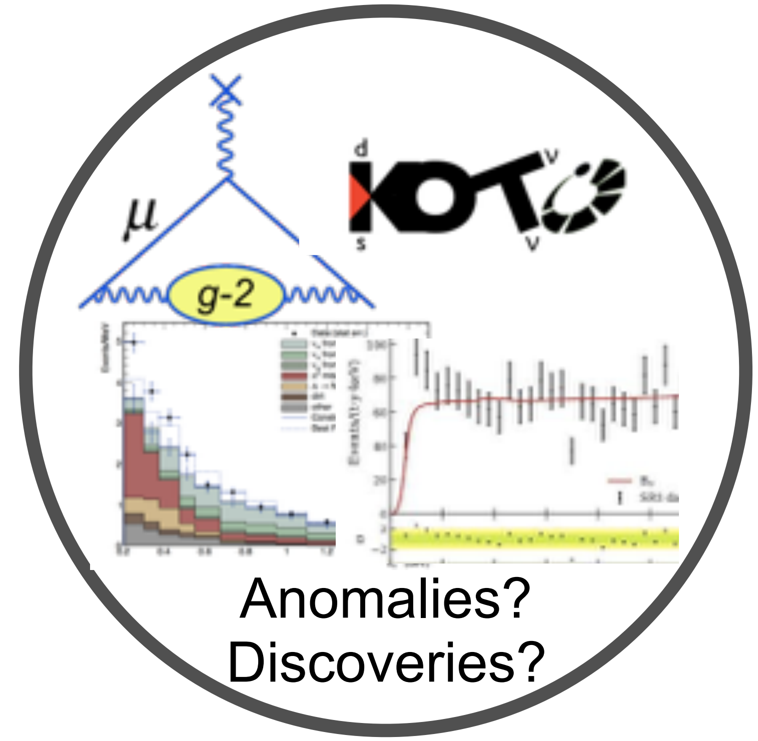
- New $K \to \pi\overline{\nu}\nu$ results — *an excess at KOTO*?
- Completely annihilating K_L into dark states
- Possible connections to Dark Matter

Exciting times in HEP





? ? ?



New particles in our Universe (a dark sector?)

New models and hypotheses

Broad and highly sensitive experimental landscape

Exciting times in HEP

Time to explore

G. Raffelt, 9712538

Where do we expect the largest strain on the SM?

RARE and/or CLEAN observables

High Energies
- Colliders (LHC)
- UHE-neutrinos (IceCube, ANITA)

Weak Decays
- NA62
- KOTO
- B factories

ν Sector
- (new) oscillations
- Solar
- Scattering
- Beta decays

Precision
- $(g-2)_\mu$
- $\nu - e$
- APV

Missing Energy
- B-factories (Belle-II, BESS-III)
- NA64
- LDMX

Displaced Vertices
- Beam dumps (SeaQuest, DUNE)
- FASER
- B-factories

*Not an exhaustive list

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- Colliders (LHC)
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Weak Decays
- NA62
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- B factories

e.g, $K \to \pi \bar{\nu} \nu$

Extremely rare and well-understood process!

Displaced Vertices
- Beam dumps (SeaQuest, DUNE)
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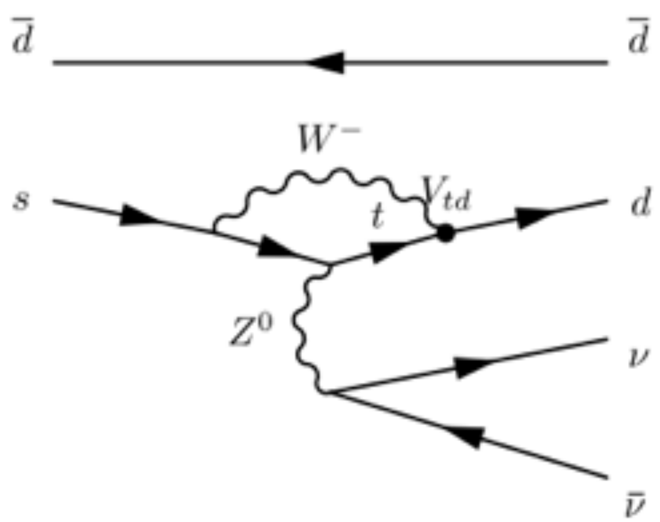
FCNC loops, CP-violating & GIM suppressed $s \to d$



Robust SM predictions:

$$\mathrm{BR}\left(\mathrm{K}^+ \to \pi^+ \overline{\nu} \nu\right) = (0.84 \pm 0.10) \times 10^{-10},$$
$$\mathrm{BR}\left(\mathrm{K_L} \to \pi^0 \overline{\nu} \nu\right) = (0.34 \pm 0.06) \times 10^{-10}.$$

A. J. Burjas et al, , JHEP11, 033 (2015)

Negligible long-distance contributions. Theoretically, a very clean process.

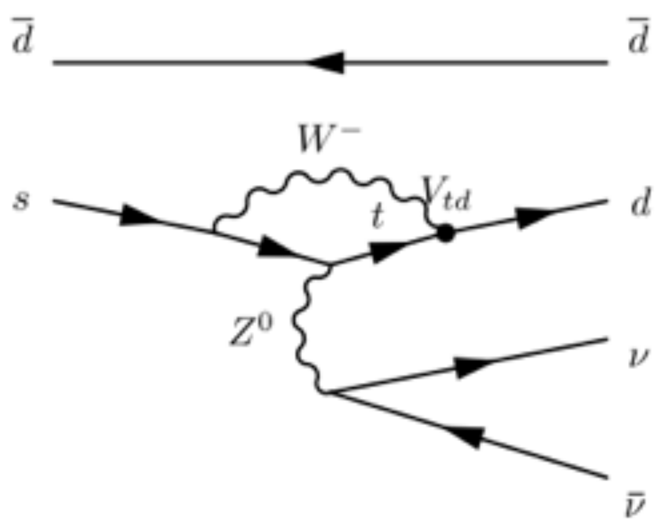
Grossman-Nir Bound

Simply Isospin + total lifetime
(QED corrections are small.)

$$\mathrm{BR}\left(\mathrm{K_L} \to \pi^0 \overline{\nu} \nu\right) < 4.4 \times \mathrm{BR}\left(\mathrm{K}^+ \to \pi^+ \overline{\nu} \nu\right).$$

Y. Grossman, Y. Nir, PLB 398 (1997) 163-168

FCNC loops, CP-violating & GIM suppressed $s \to d$



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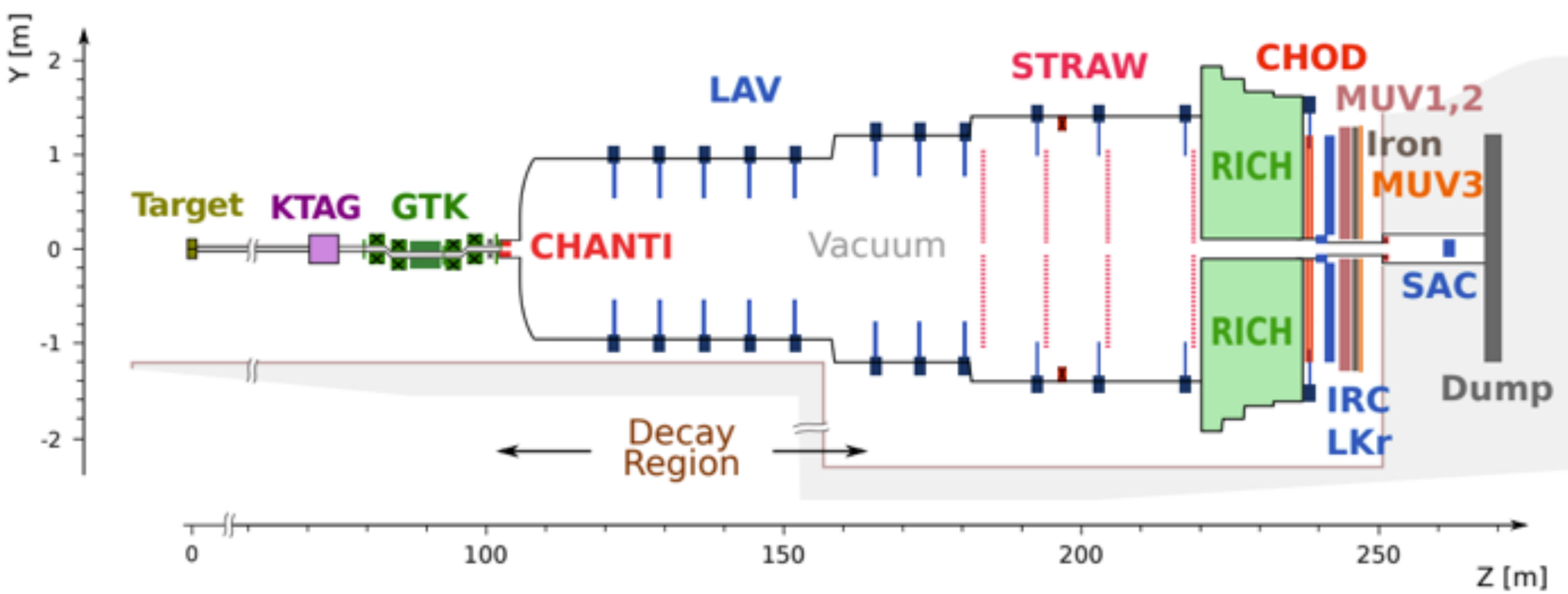
Negligible long-distance contributions. Theoretically, a very clean process.

	past	*current*	*future*
K^+	*E787/E949* *(40 - 60% measurement)*	***NA62 (2016/17 data)*** ***BR < 1.85e-10 @ 90 C.L.***	*NA62 (full)* *towards 10%*
K_L	*KOTO (2015 data) @ J-PARC* *BR < 3e-9 @ 90 C.L.*	***KOTO (2016/18) unblinding*** ***in progress***	*KOTO (2019 data)* *(S.E.S. ~ 2x SM BR by 2024)* *KLEVER @ CERN (?)*

NA62 @ CERN



Kaon decay-in-flight

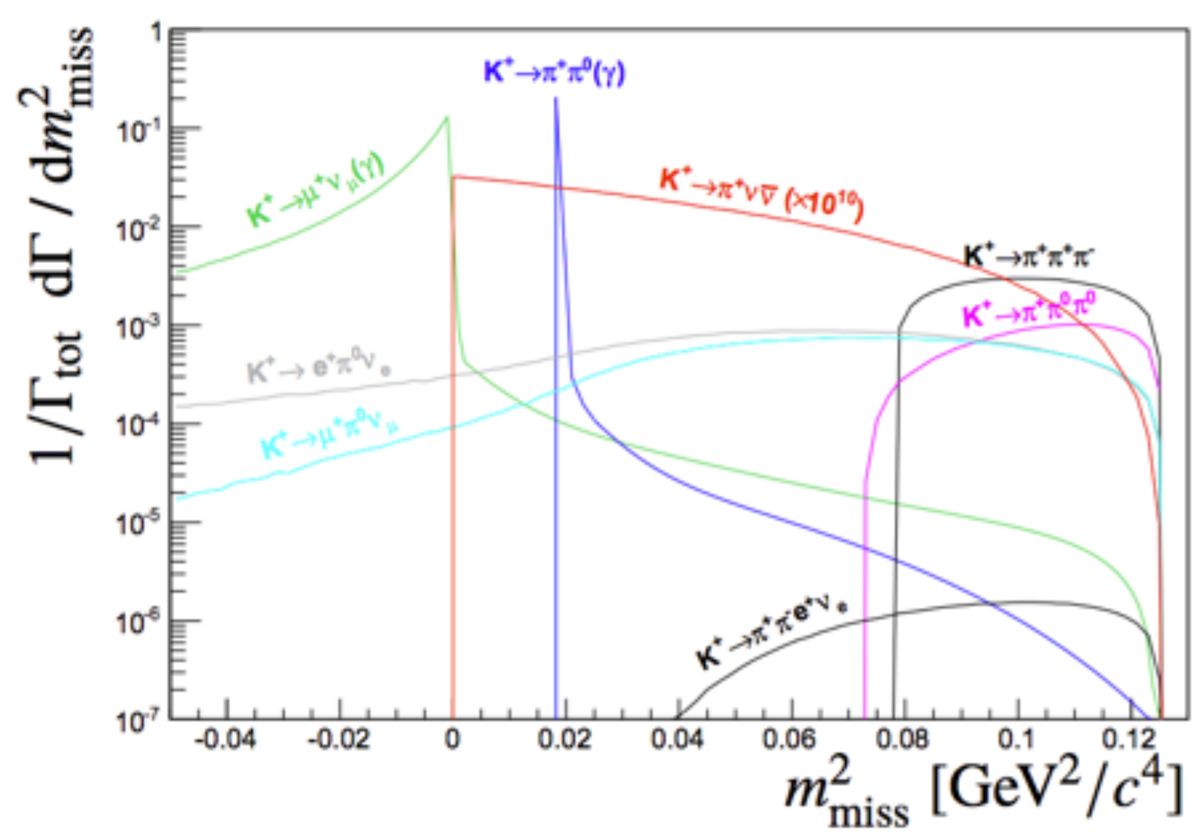
75 GeV/c kaons

$$m^2_{\text{miss}} = (p_{K^+} - p_{\pi^+})^2$$

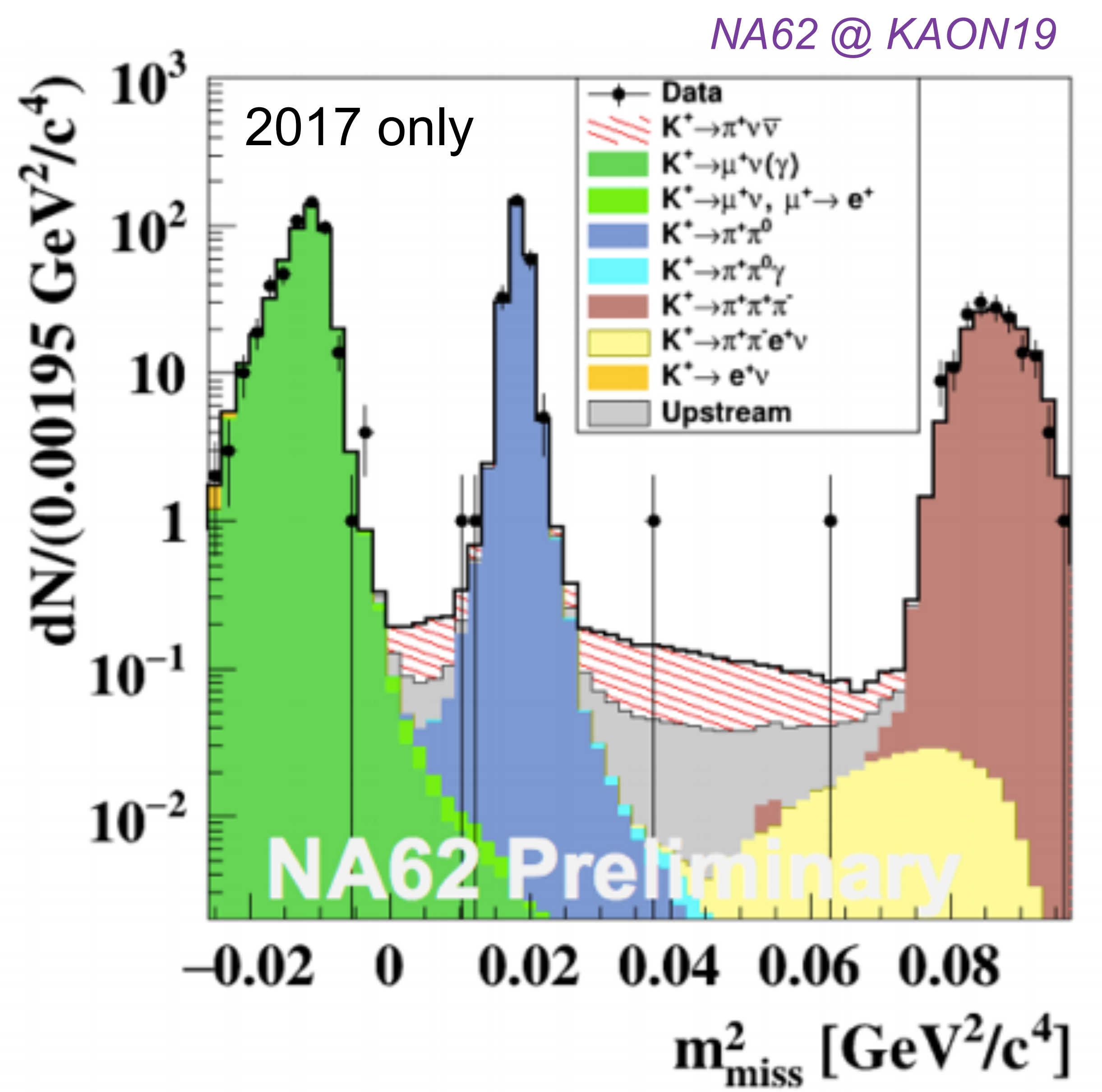
2016 (1.2×10^{11} K^+ decays) analysed

2017 (2×10^{12} K^+ decays) analysed

2018 (4×10^{12} K^+ decays) in progress



NA62 results presented @ KAON19



Double-sided 1 sigma region

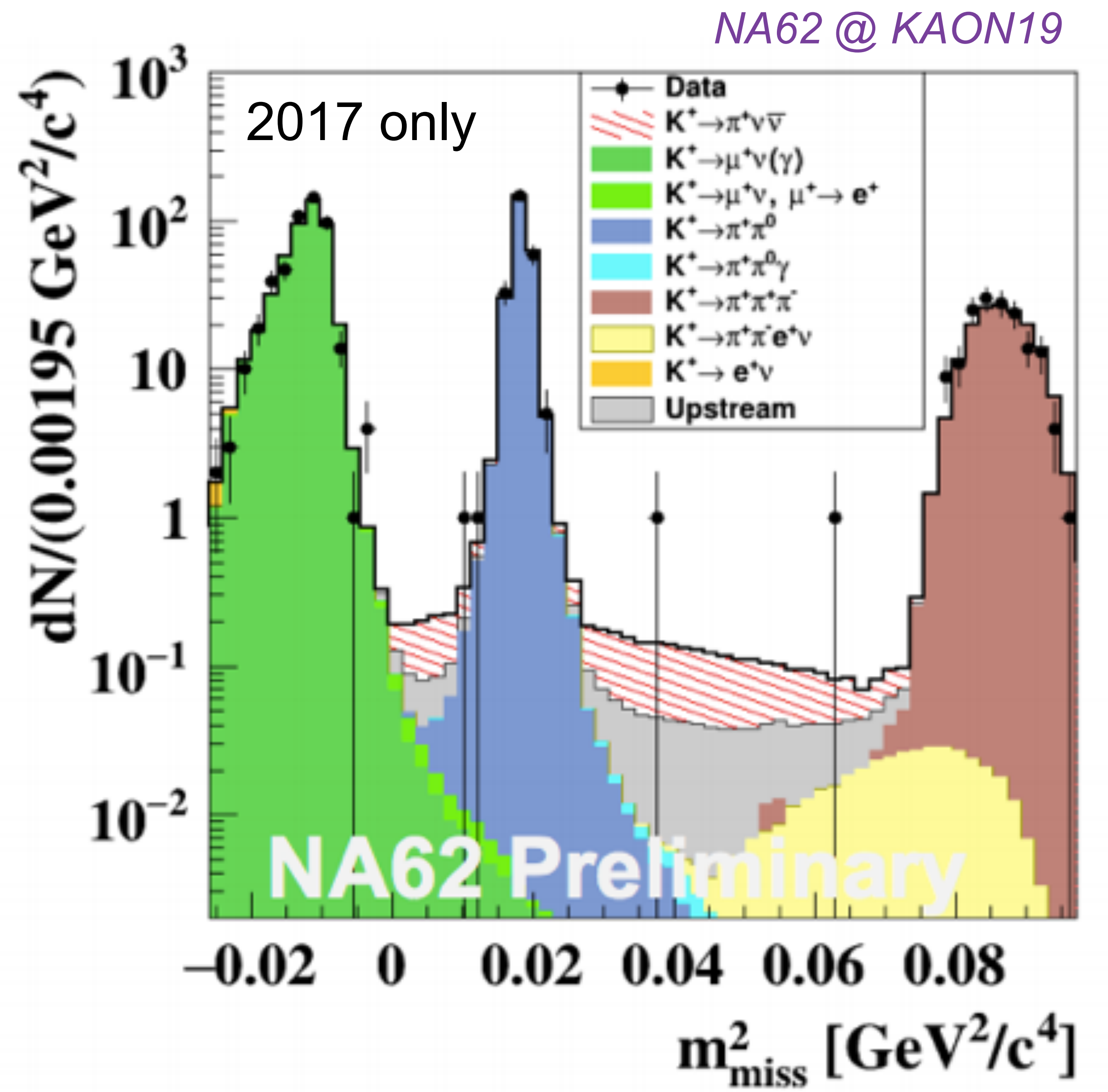
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$$

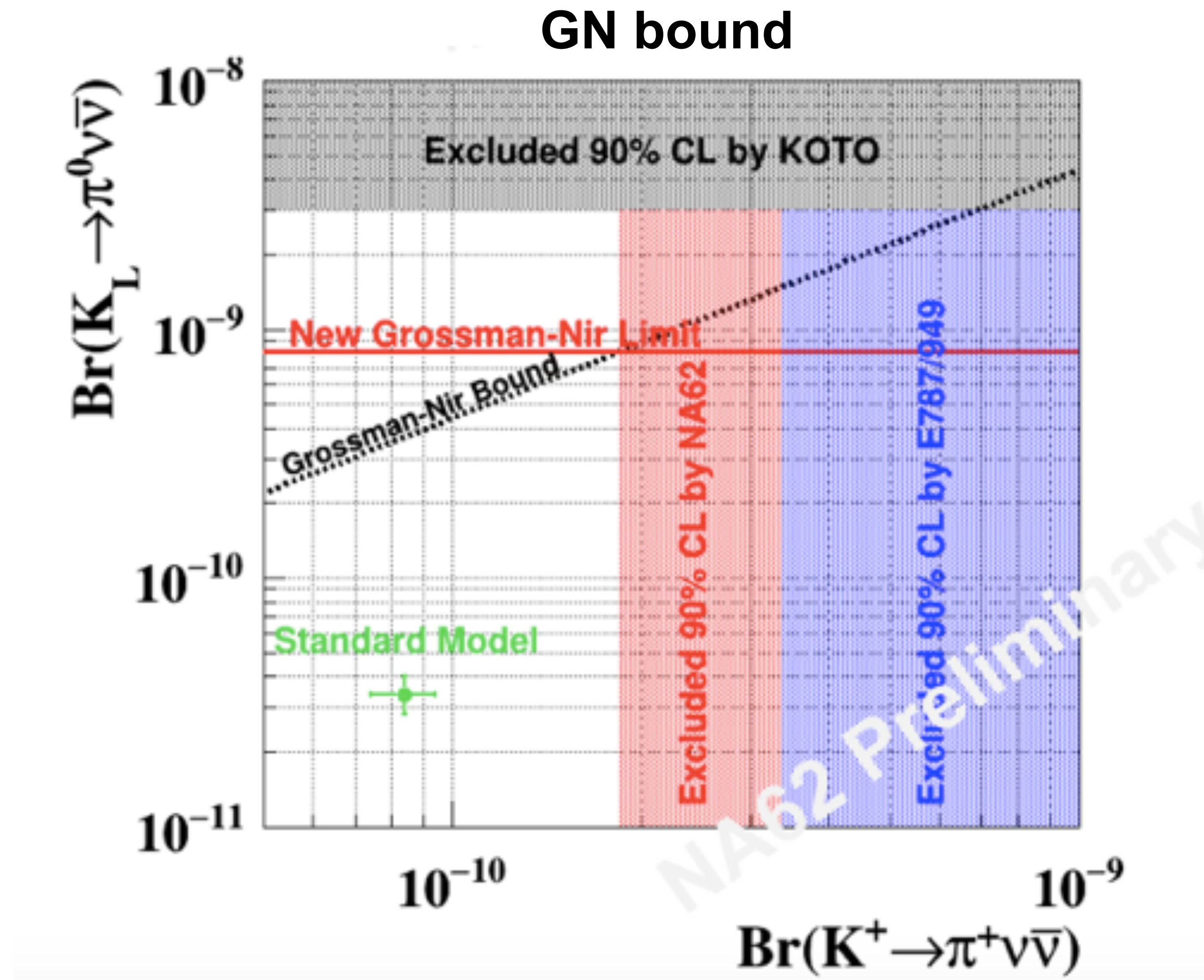
__Full 2016+2017 dataset:__

3 *candidate events with*

2.4 *signal prediction and* ***1.65 ± 0.31*** *background*

NA62 results presented @ KAON19





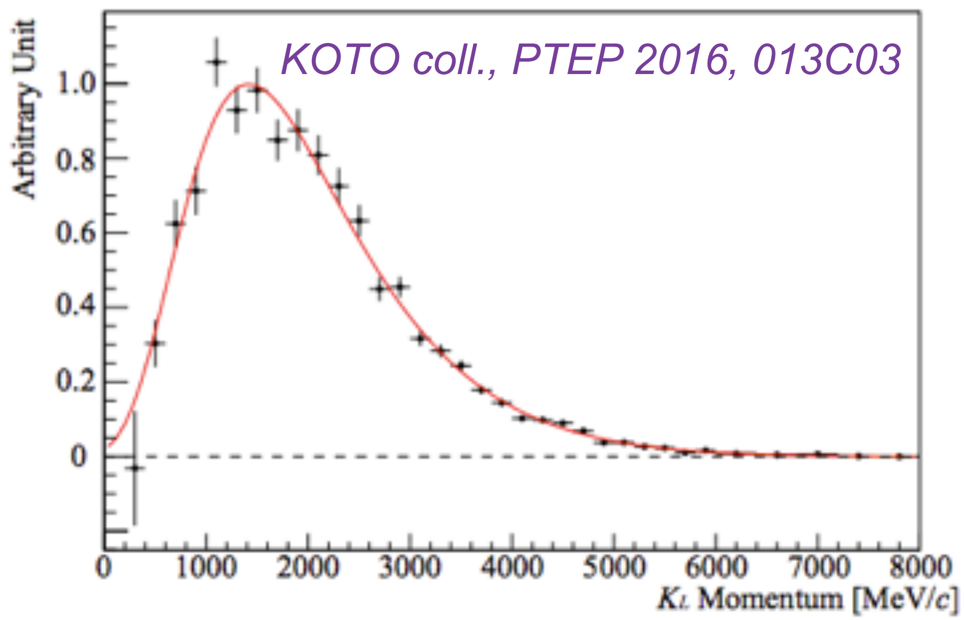
Double-sided 1 sigma region

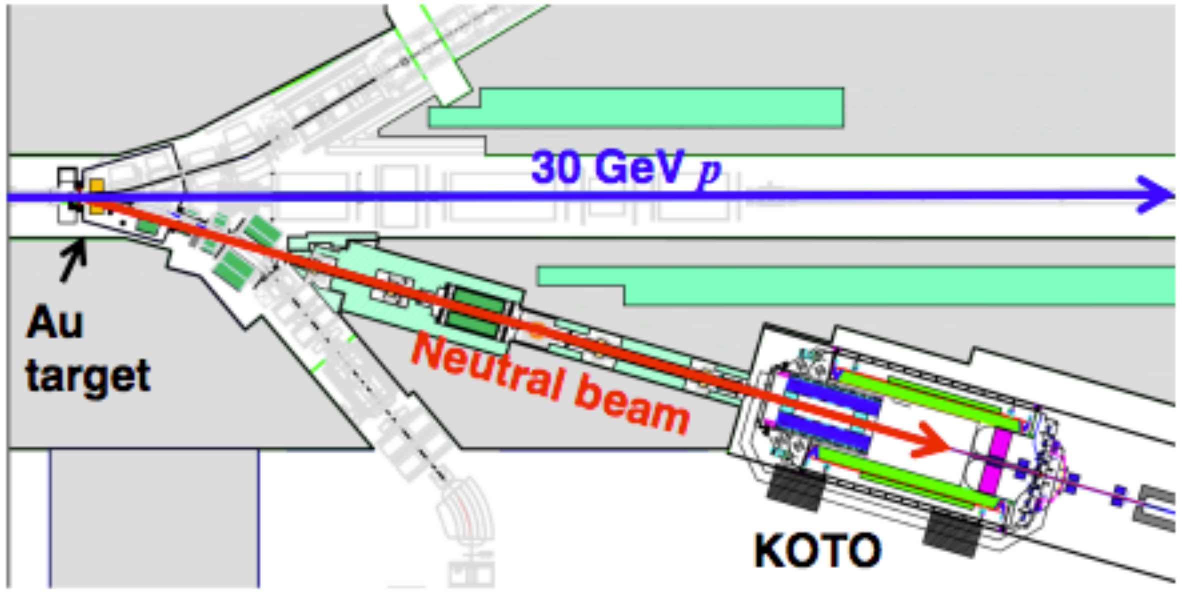
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$$

GN bound at 90% C.L.

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 8.14 \times 10^{-10}$$

KOTO @ J-PARC (beam)





Future experiments for rare kaon decays – C. Lazzeroni and M. Moulson –

2015: $\sim 4.7 \times 10^{12}\ K_L$ at beam exit

KOTO coll., PRL 122, 021802 (2019)

2016-18: $\sim 7.1 \times 10^{12}\ K_L$ at beam exit

KOTO @ KAON19

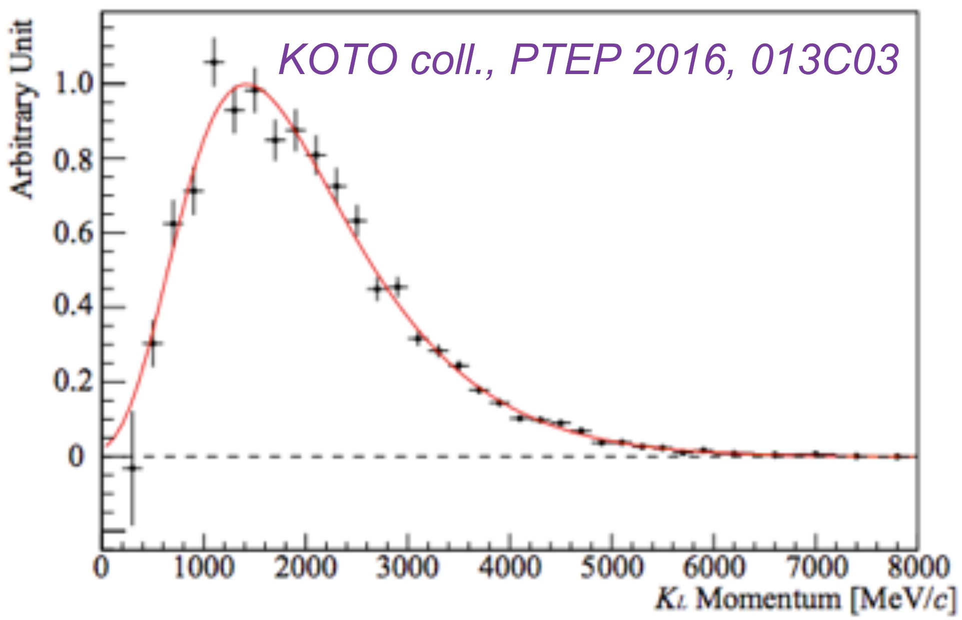
30 GeV protons

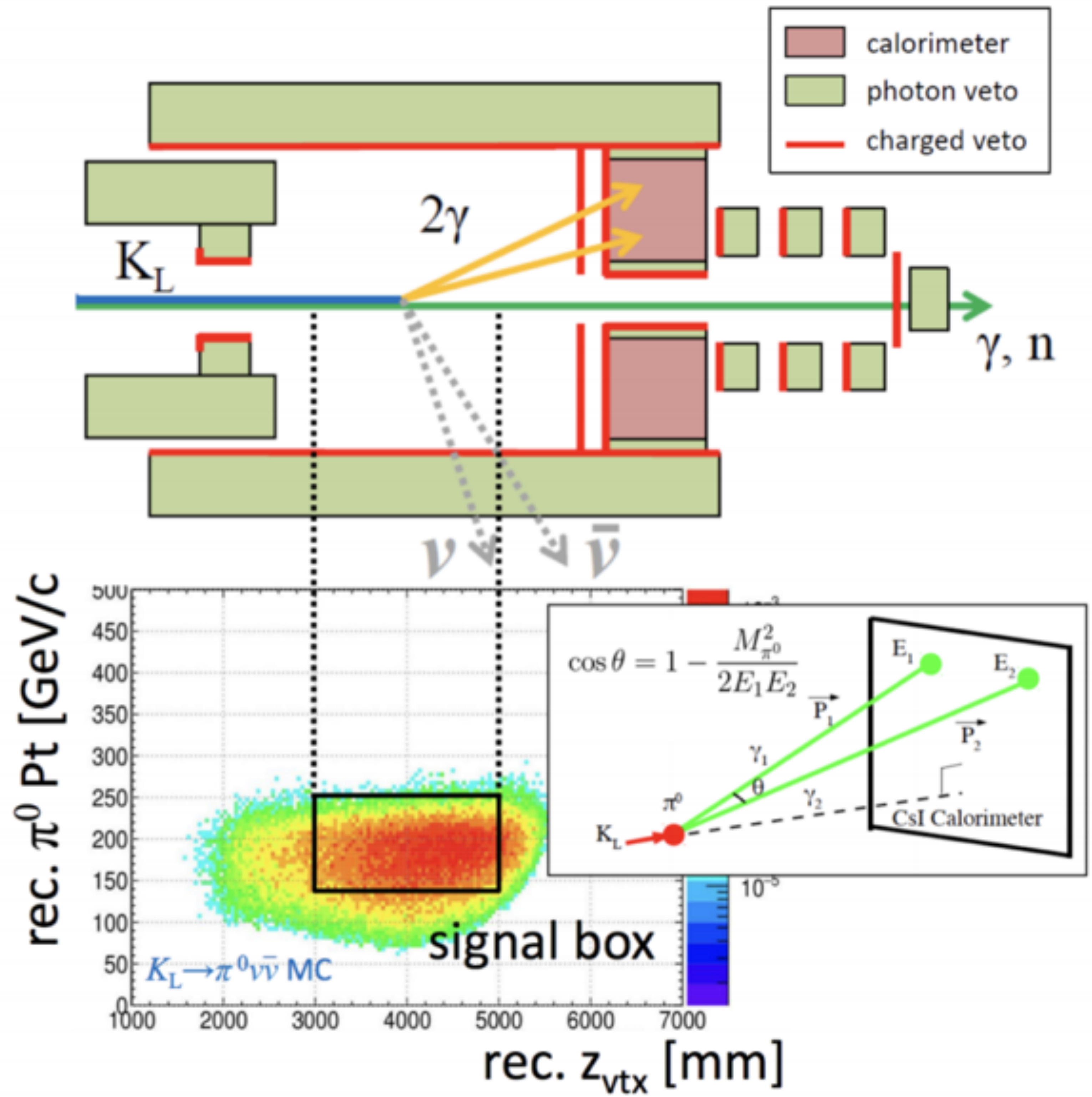
16 degrees off-axis neutral kaon beam

6x (7x) more neutrons (photons) than kaons

except to reconstruct position of incidence of gammas on ECAL surface.

KOTO @ J-PARC (detector and analysis)





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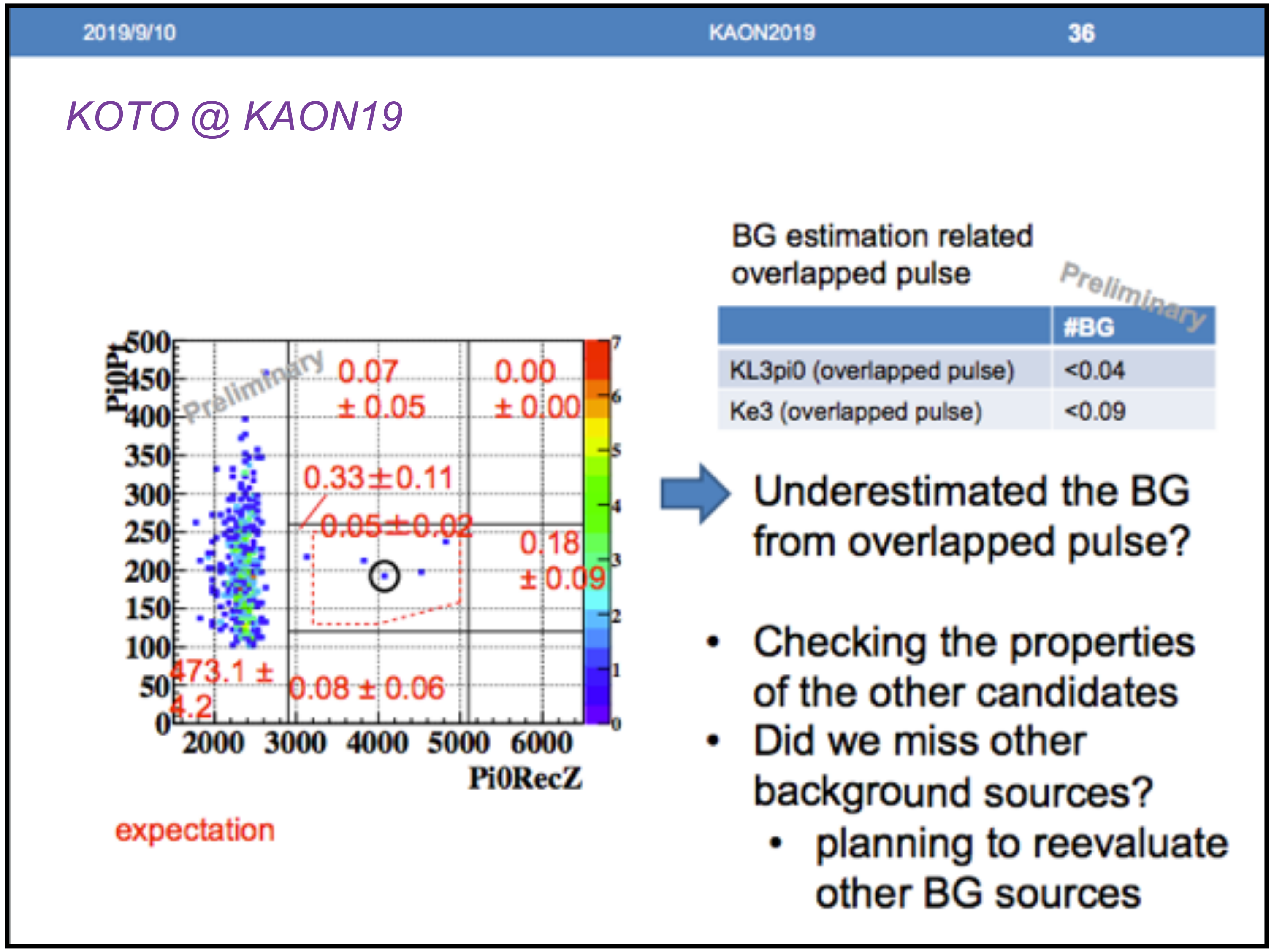
KOTO coll., PRL 122, 021802 (2019)

2016-18: $\sim 7.1 \times 10^{12}\ K_L$ at beam exit
KOTO @ KAON19

- hermetic charge and γ vetoes
- **large *rec* PT**
- decay region *rec* $Zvtx$
- **pencil beam → assumes (x,y)=(0,0**
- No 3-momenta directly measured*

**except to reconstruct position of incidence of gammas on ECAL surface.*

KOTO unblinding @ KAON19



4 "observed" events

0.05 ± 0.02 backgrounds

1 event attributed to overlapped pulse bkg

3 events still under study

If taken seriously, implies $\mathrm{BR}\left(\mathrm{K_L} \to \pi^0 \overline{\nu}\nu\right) = \left(2.1^{+4.1}_{-1.7}\right) \times 10^{-9}$

(unofficial BR)

Mild tension ($\gtrsim 1\sigma$) with NA62 (GN) bound…. **but 60x larger BR than the SM prediction**

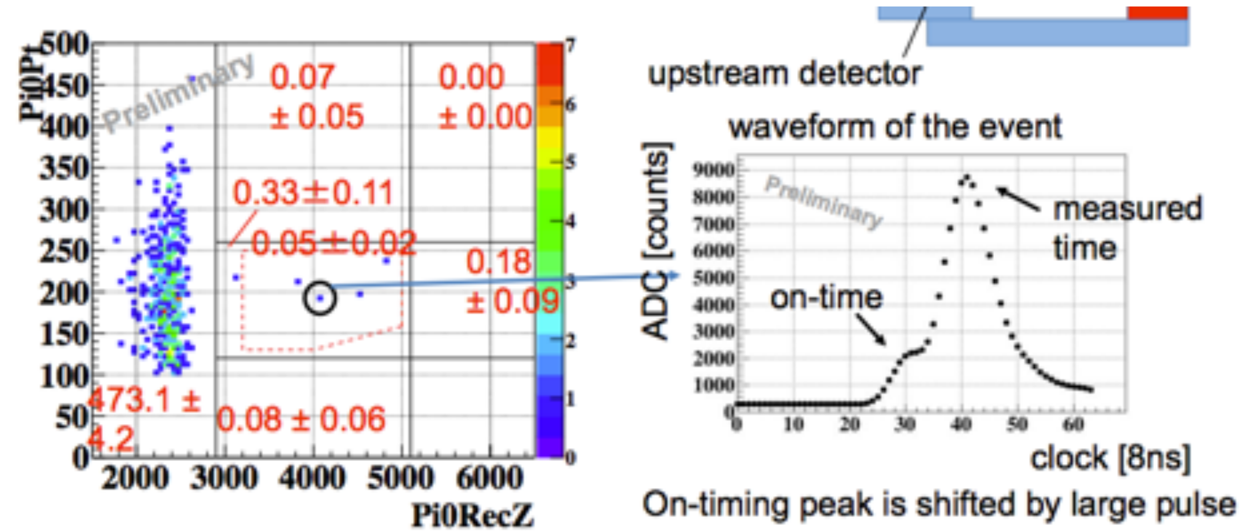
@KAON19
by KOTO collaboration

Why?

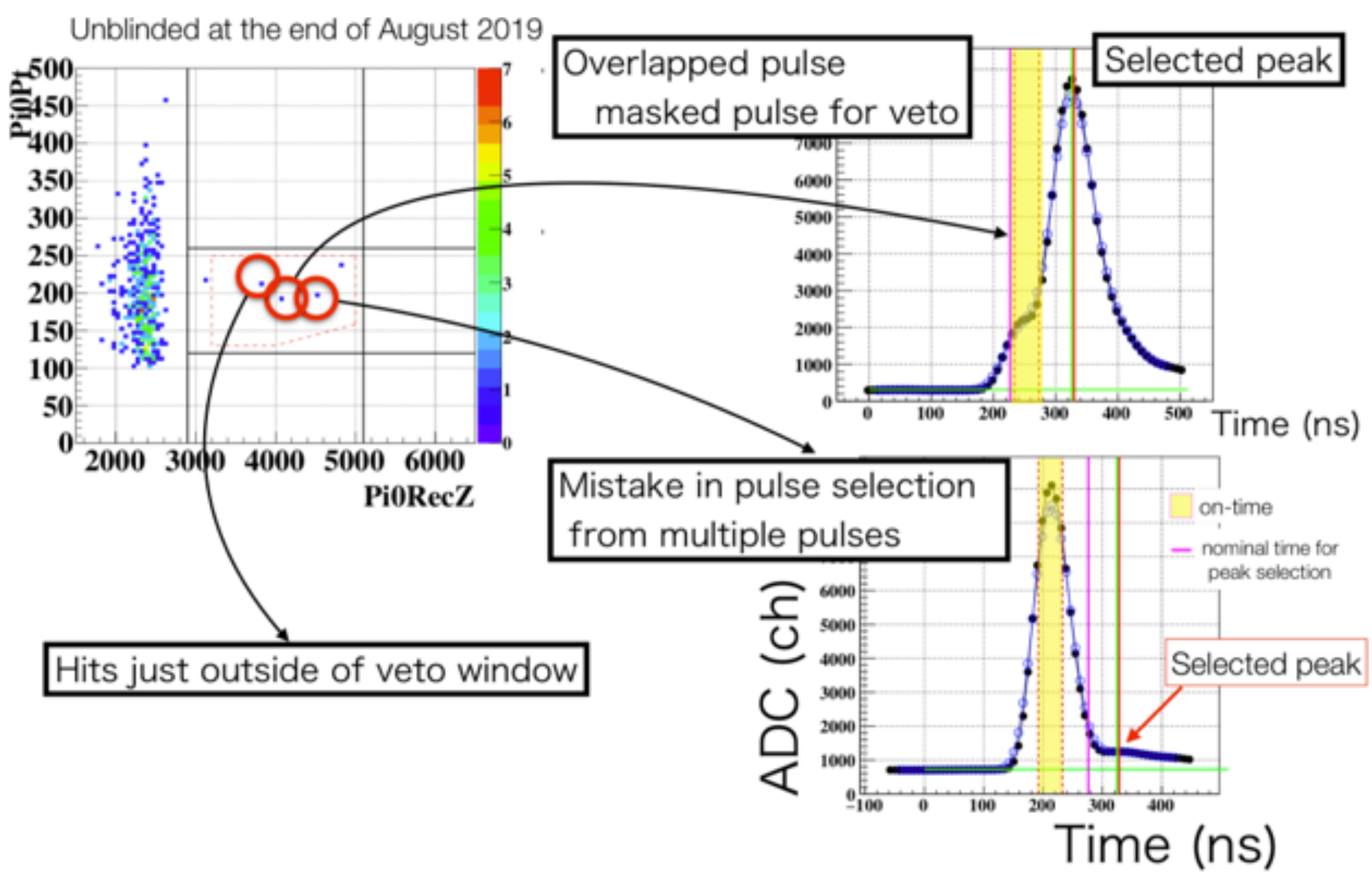
- In blind analysis, the standard way is to give a result regardless of the contents inside the signal box.
- However, the number of events in the signal box was beyond our reasonable expectation.
- To be scientifically correct, we decided to do further checks on the events, detector status, and background estimations before announcing a result.
- To be honest to the scientific community, we should not hide the fact that we had opened the signal box.
- To be scientifically correct and to be honest, at the KAON2019 Conference, we showed the events and explained exactly what had happened.

KOTO further checks reported@ FCPC (Jun, 2020)

Box-opening → *3 candidates*



After more checks → *1 candidate?*

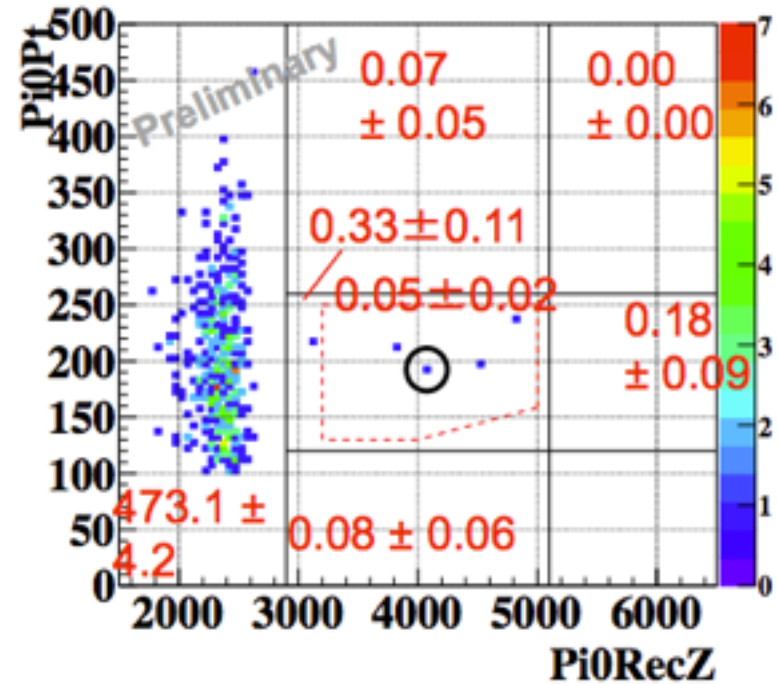


KOTO further checks reported@ FCPC (Jun, 2020)

Box-opening →

	#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 *

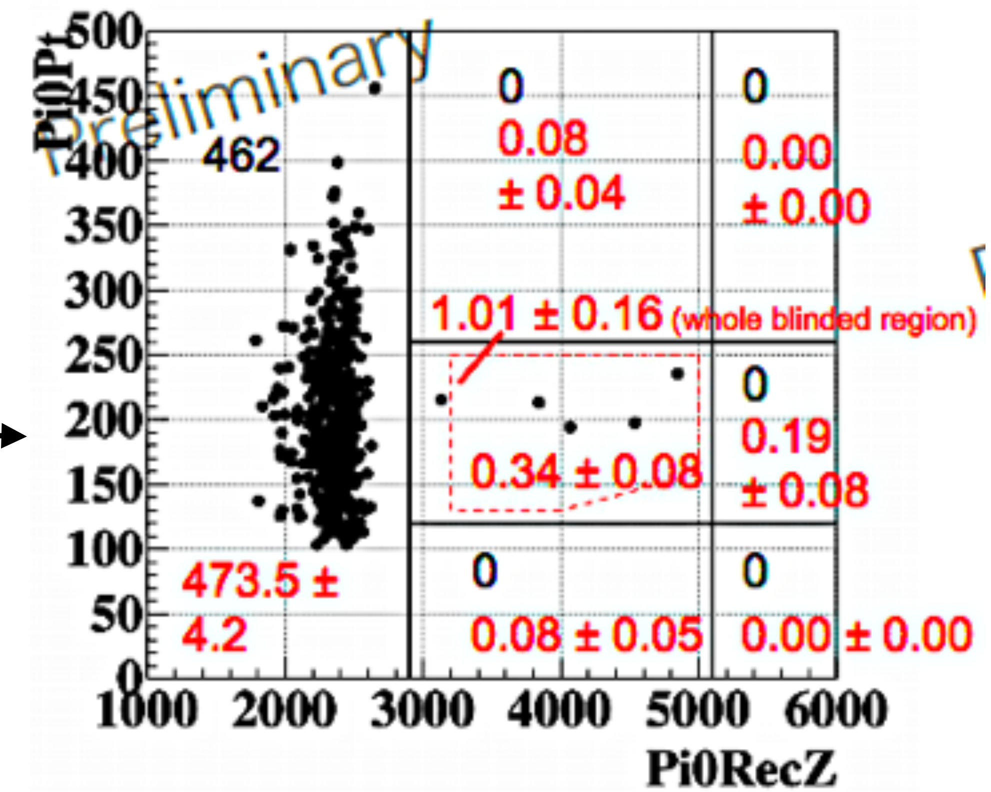
S.E.S : 6.9×10^{-10}



After more checks →

	#BG
$K_L \to 2\pi^0$	<0.09 *
$K_L \to 3\pi^0$+ accid.	<0.04
Ke3 + accid.	<0.09
Hadron cluster	0.02±0.00
CV-η	0.03±0.01
$K^\pm \to \pi^0 e^\pm \nu$	**0.29±0.08** *
Total	0.34±0.08 *

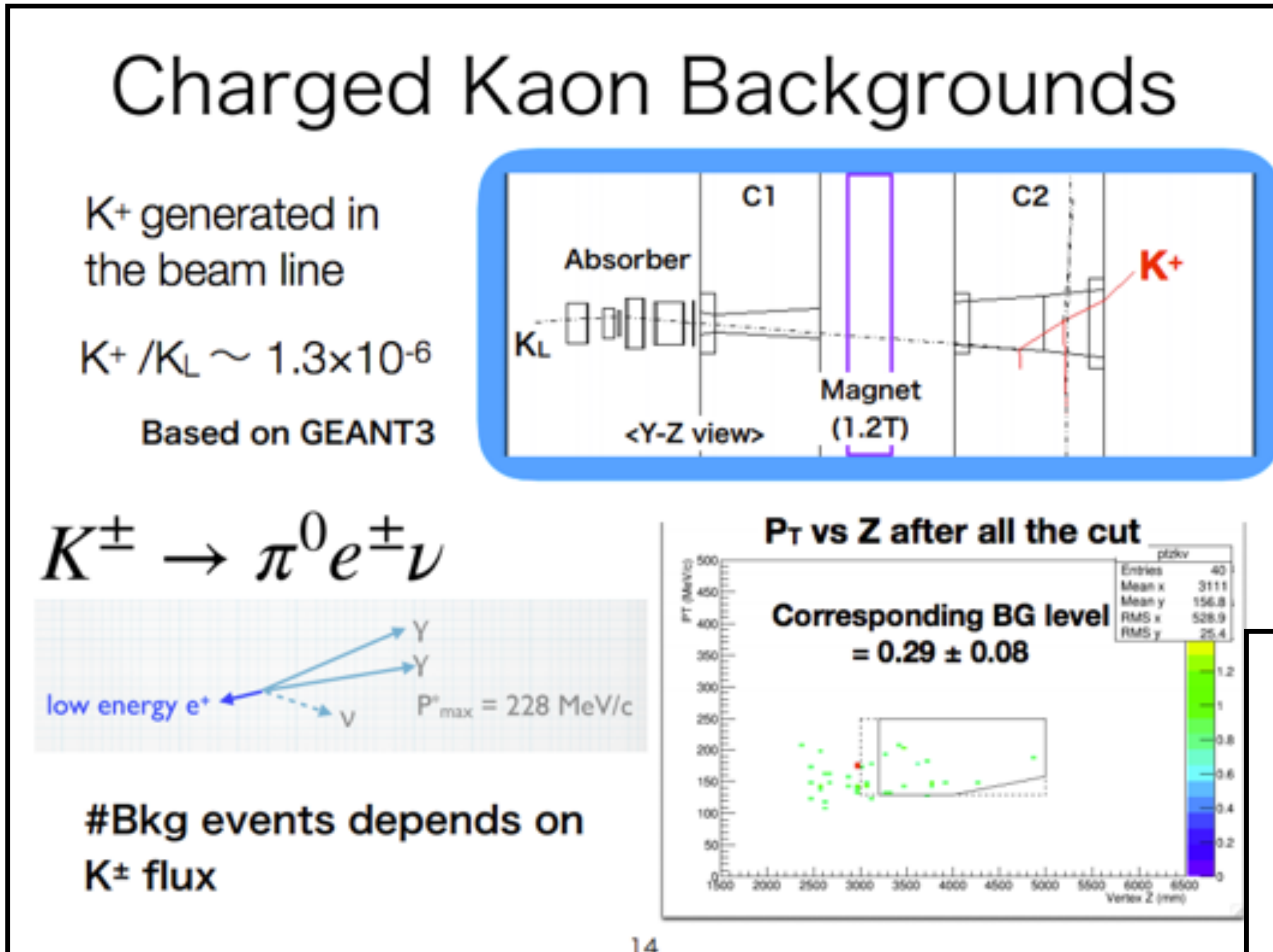
S.E.S : 7.1×10^{-10}



*** change**

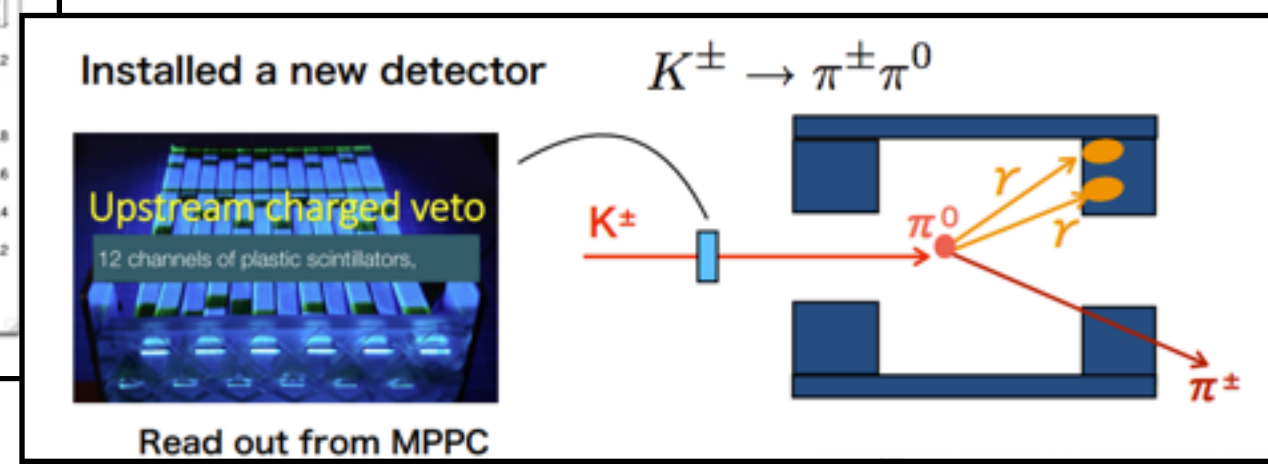
extra channels investigated, but negligible.

KOTO further checks reported@ FCPC (Jun, 2020)



KOTO @ FCPC (2020)

New source of background is being measured.



Analysis still in progress, but new checks **suggest**

1 observed event w/
0.34 ± 0.08 bkg

On the theory side…

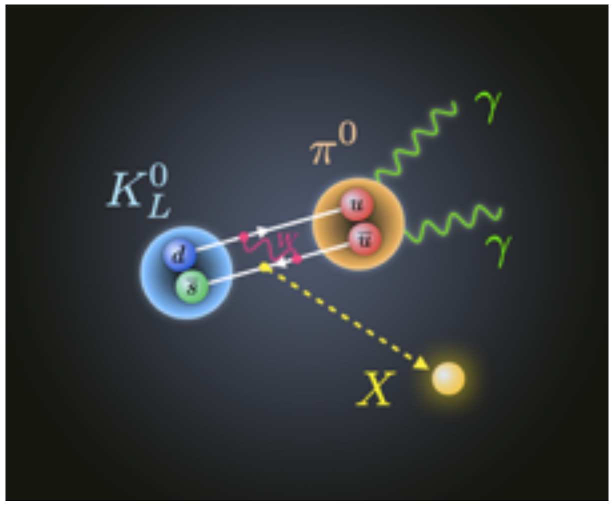
Several explanations put forward

T. Kitahara et al, PRL124.071801, + citing refs.

Fooling the Grossman-Nir bound:

1. Emission of invisible light particles (X) alongside a pi0 ($K \to \pi X \text{ or } \pi XX$)
   A. Particle X may decay **visibly** at NA62, but be stable at KOTO (tension w/ beam dumps)
   B. Particle X is truly **invisible**, and may fake background kinematics at NA62.
2. Long-lived a produced at the target decaying inside detector ($a \to \gamma\gamma$, **unrelated to kaons**!)
3. Isospin breaking from **heavy new mediators** and light scalars.
4. **Pair production of dark states (this talk)**
   see also, R. Ziegler, 2005.00451, S. Gori et al, 2005.05170

A minimal singlet scalar

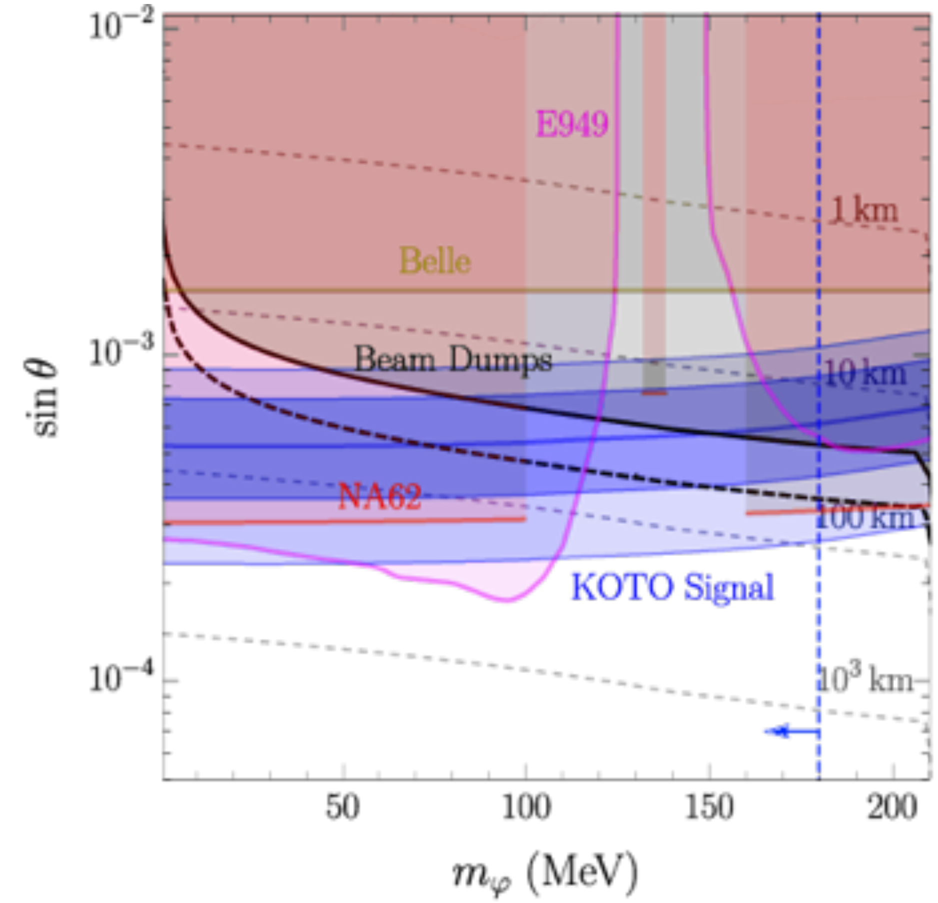


K. Tobioka/Florida State University

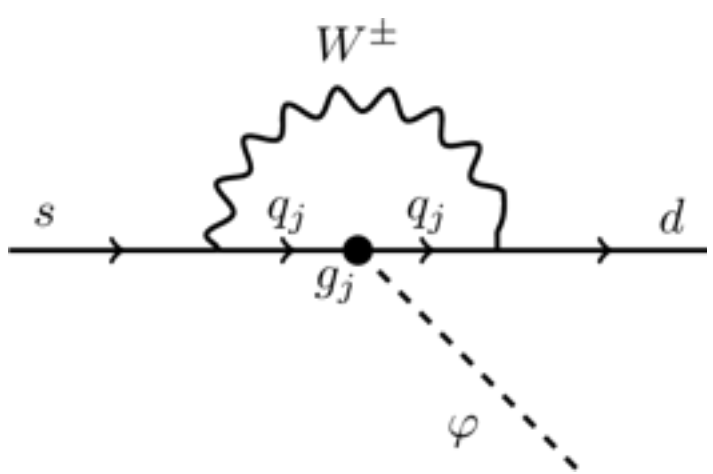
$$K \to \pi X$$

w/ X invisible

D. Egana-Ugrinovic et al, PRL 124 19, 191801 (2020)



Minimal model w/ singlet scalar: $\mathcal{L} \supset \lambda |H|^2 |\varphi|^2$



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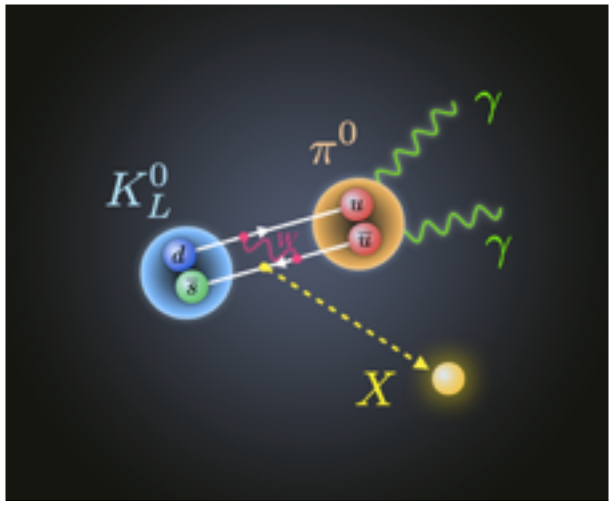

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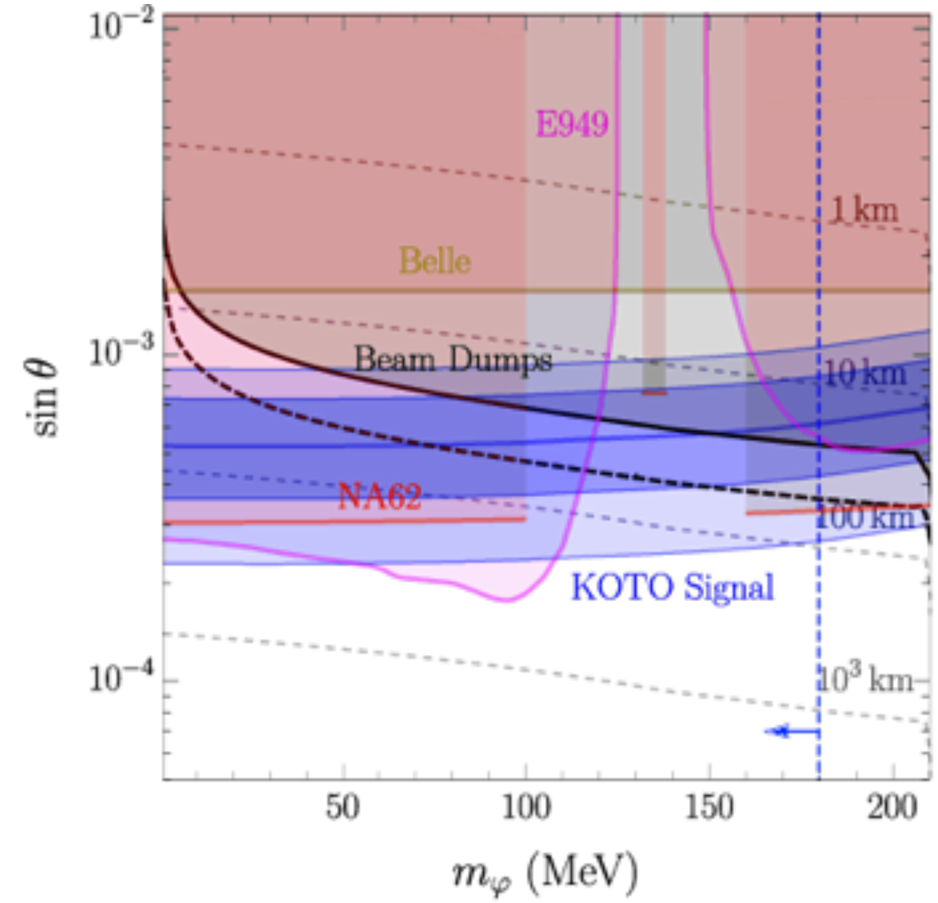

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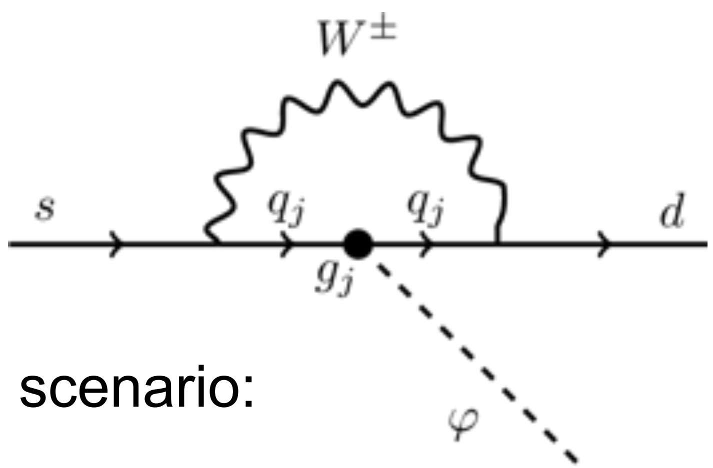

Most studied scenario:

T. Kitahara et al, PRL 124, 071801 (2020)
D. Egana-Ugrinovic et al, PRL 124 19, 191801 (2020)
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Y. Jho et al, JHEP 04 (2020) 197
J. Liu et al, JHEP 04 (2020) 197
J. Cline et al, JHEP 05 (2020) 039
+ many others.

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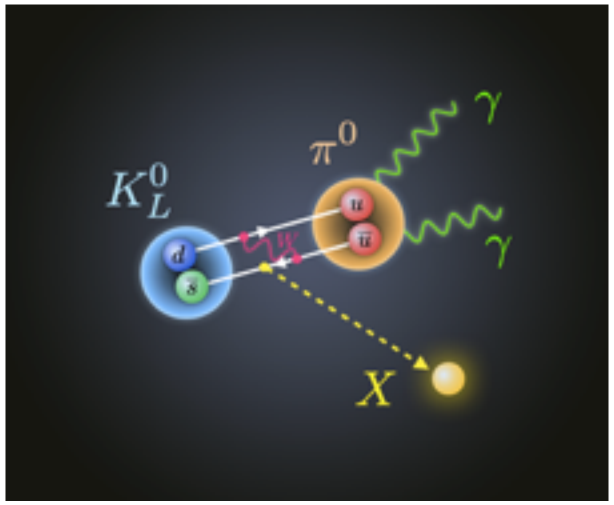

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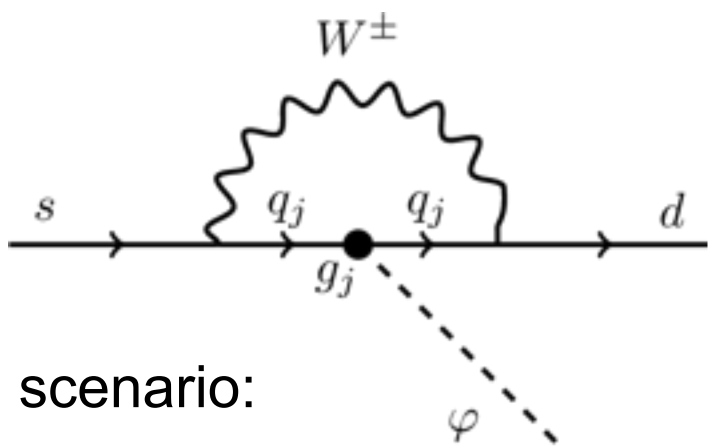

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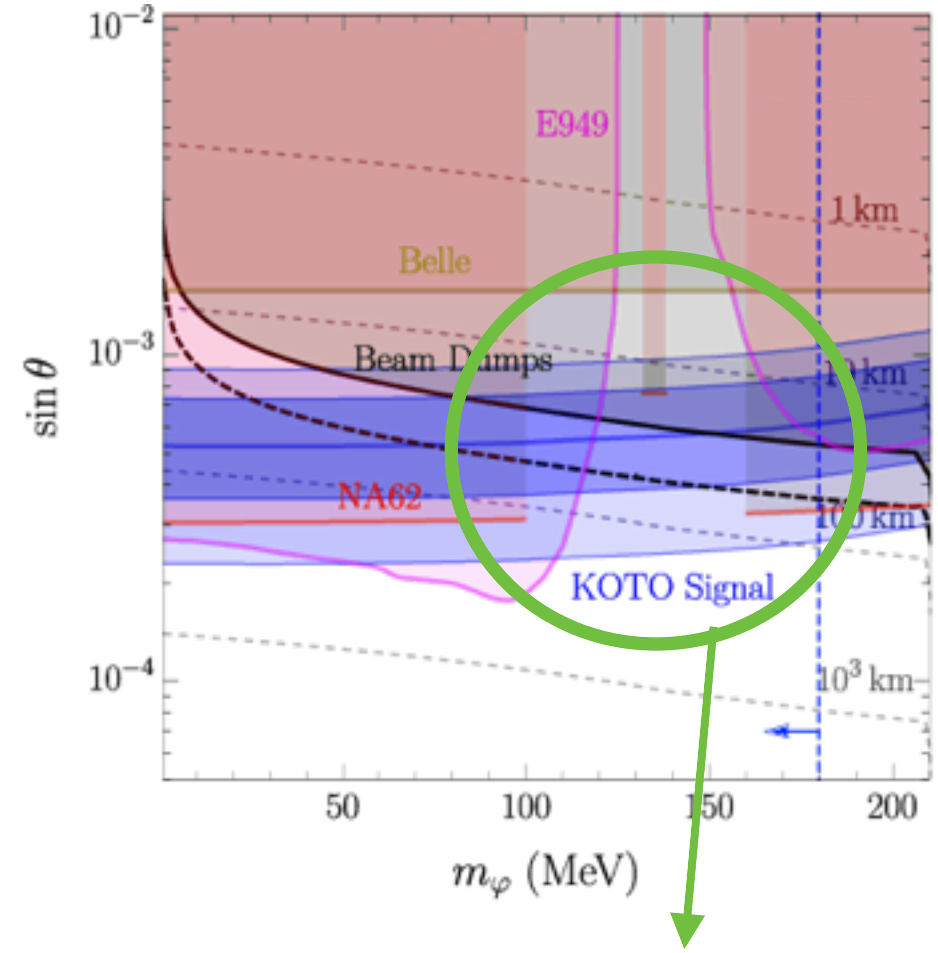

1) $m_\varphi \sim m_\pi$ hides under bkgs at NA62

$$K^+ \to \pi^0 \varphi \sim K^+ \to \pi^+ \pi^0 (\gamma)$$

2) Beam dump constraints do not even apply when scalar is invisible, eg., $\varphi \to$ long-lived HNLs

*P. Ballett, **MH,** S. Pascoli, PRD 101 (2020) 11, 115025*

K LONG GONE: THE COMPLETE ANNIHILATION OF KAONS

Pair production of dark particles in K and B meson decays

$$K, B \to X_1 + X_2 + Y_{\rm SM}$$

SM singlets

Dark states that are weakly coupled to matter,

If X_1 is stable, it may be a dark matter candidate.

Pair production of dark particles in K and B meson decays

$$K, B \to X_1 + X_2 + Y_{\rm SM}$$

SM singlets

1. Y_{SM} may be $\varnothing$ for <u>neutral</u> mesons (2-body) vs Y_{SM} charged for <u>charged</u> mesons (3-body).

charge conservation.

Pair production of dark particles in K and B meson decays

$$K, B \to X_1 + X_2 + Y_{\mathrm{SM}}$$

SM singlets

1. Y_{SM} may be $\varnothing$ for <u>neutral</u> mesons (2-body) vs Y_{SM} charged for <u>charged</u> mesons (3-body).

2. If X_1 and X_2 <u>stable</u>, very weak bounds ($\mathcal{B}(K_L \to \overline{\nu}\nu) < 6.3 \times 10^{-4}$)

S, N. Gninenko, PRD91 (2015) 1,015004

Pair production of dark particles in K and B meson decays

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3. If X_2 <u>unstable</u>, still challenging, but may produce $\pi^0, \ell^+\ell^-, \gamma\gamma, \ldots$

Meson → dark sector → back to SM.

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3. If X_2 <u>unstable</u>, still challenging, but may produce $\pi^0, \ell^+\ell^-, \gamma\gamma, \ldots$

4. Note the f_B/m_B suppression in 2-body B decays. Instead, $B \to K X_1 X_2$ may be relevant as $|V_{tb}^* V_{ts}| \gg |V_{ts}^* V_{td}|$

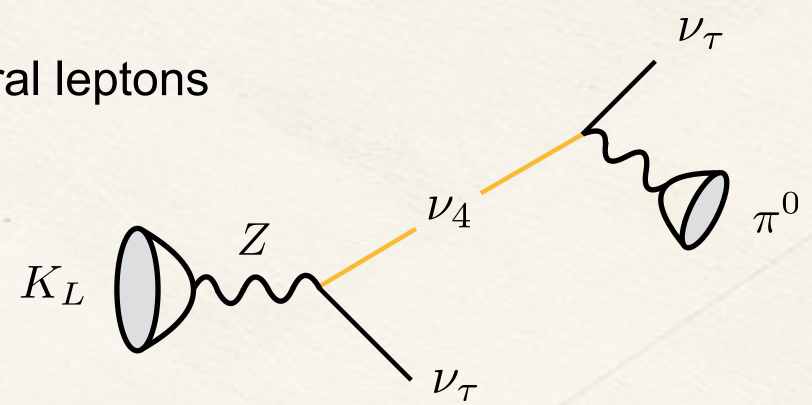
Are there models for these scenarios, and would them be able to contribute to the signal

$$K_L \to \pi^0 \overline{\nu}\nu \text{ ?}$$

Sketching an idea

SM FCNC loops generate $K_L \to \overline{\nu}\nu$, but BR → 0 as m_ν → 0.

“Type-I Seesaw” heavy neutral leptons



$\mathrm{BR}\,(K_L \to \nu_\tau \nu_4) \approx |U_{\tau 4}|^2\, 4.6 \times 10^{-9}$ for m_4 ~ 400 MeV

e.g., only tau-4 mixing *A. Abada et al, PRD 95, 075023 (2017)*

Dominant BR: $\nu_4 \to \nu_\tau \pi^0$ w/ $c\tau^0_{\nu_4} \approx \dfrac{20\,\mathrm{cm}}{|U_{\tau 4}|^2}$

BR ~ few x 10 $^{-11}$ once the constraints on the mixing are included

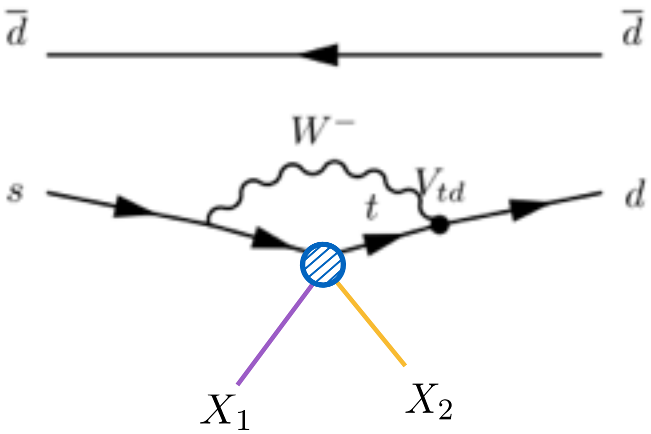
Lesson: *search for models with new* ***100’s of MeV states*** *and* ***weak-strength couplings to SM FCNC loops.***

Generic features of our study

<u>Mediator scale (e.g., 10 GeV) >> meson masses:</u>
integrate out vector/scalar mediator.

$$O^V_{sd} = g^V_{sd}(\bar{s}_L\gamma_\mu d_L) \times J^\mu_X; \qquad O^S_{sd} = g^S_{sd} m_s (\bar{s}_R d_L) \times J_X$$

Dark current contains products of X_1 and X_2 particles,
depending purely on the dark sector.



Assumptions:

- SM-like FCNC
- Minimal Flavour Violation *ansatz*

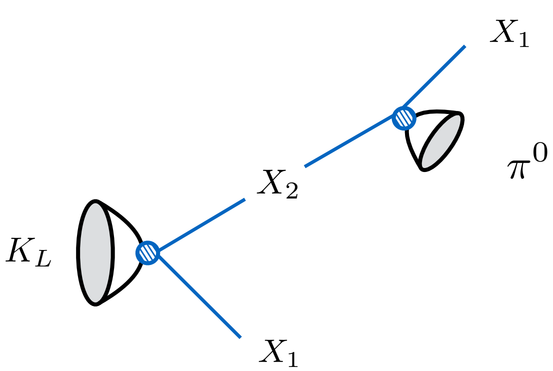
$$g^V_{sd}(\bar{s}_L\gamma_\mu d_L) \subset a\bar{Q}_L Y_U Y_U^\dagger \gamma_\mu Q_L; \qquad g^S_{sd} m_s(\bar{s}_R d_L) \subset b\bar{D}_R M_D^\dagger Y_U Y_U^\dagger Q_L.$$

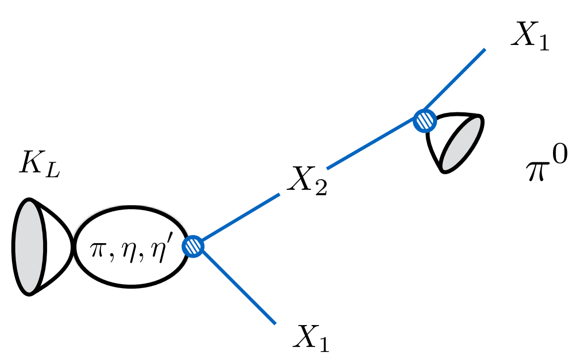
In practice, for some constants a and b, we have:

$$\langle 0|O^V_{sd}|K_L\rangle \propto a\mathrm{Re}(y_t^2 V_{ts}^* V_{td} + y_c^2 V_{cs}^* V_{cd}), \quad \langle 0|O^S_{sd}|K_L\rangle \propto b\mathrm{Im}(y_t^2 V_{ts}^* V_{td} + y_c^2 V_{cs}^* V_{cd}),$$
$$\langle \pi^0|O^V_{sd}|K_L\rangle \propto a\mathrm{Im}(y_t^2 V_{ts}^* V_{td} + y_c^2 V_{cs}^* V_{cd}), \quad \langle \pi^0|O^S_{sd}|K_L\rangle \propto b\mathrm{Re}(y_t^2 V_{ts}^* V_{td} + y_c^2 V_{cs}^* V_{cd}).$$

Generic features of our study

A) π^0 production





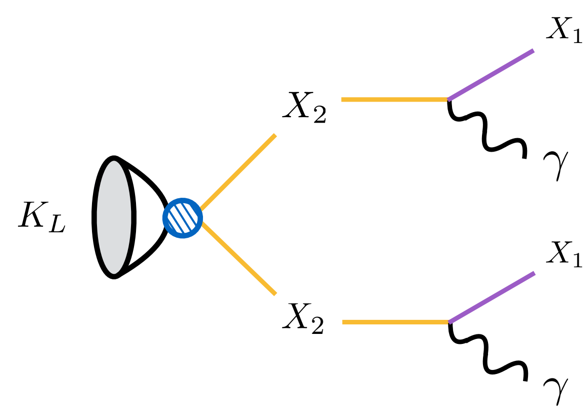
(a) *(b)*

a) Z-Z' mixing for production and decay

b) Production via long-distance ΔS = 1 operators in the SM, and flavour diagonal NP couplings.

Same coupling in prod. controls decay.

B) dipole portal



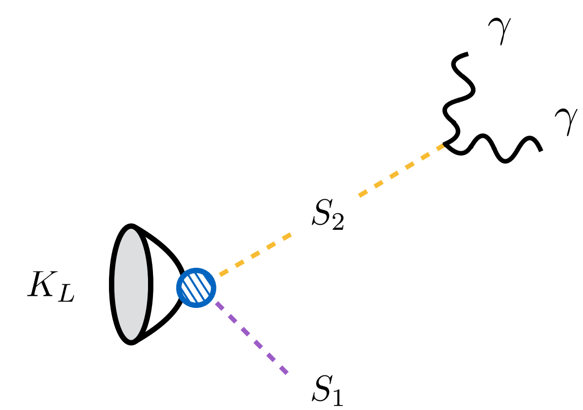
Production via Z-Z' mixing

Decay via mag moment:

$$\mathcal{L} = \frac{\mu}{2}\,\overline{\psi_1}\sigma_{\mu\nu}\psi_2\,F^{\mu\nu}$$

Uncorrelated photons.

C) π^0 impostor



Production via Higgs portal

Decay via eff coupling to photons:

$$\lambda_\Psi \overline{\Psi} i\gamma_5 \Psi S_2$$

$$\mathcal{L}_{eff} = \frac{\alpha\lambda_\Psi}{4\pi m_\psi} S_2 F_{\mu\nu}\tilde{F}_{\mu\nu},$$

Different inv mass.

A simple higgs portal example

Consider 1 heavy scalar S3, and two light scalars S1, S2, all real:

$$\mathcal{L} \supset \mu\, H^\dagger H S_3 + \mu_S\, S_1 S_2 S_3$$

In most Higgs portals models, one will automatically generate a prediction for H → inv.

$$\mathrm{BR}(K_L \to S_1 S_2) = 2 \times 10^{-8} \times \frac{\Gamma_{h\to S_1 S_2}/\Gamma_h^{SM}}{0.1} \left(\frac{10\,\mathrm{GeV}}{m_{S_3}}\right)^4 \quad ✓$$

Pair production is large enough… now how to obtain the signal?

Pion production scenario (A)

Take, e.g., Type-II 2HDMs $\quad \mathcal{L}_\Phi = \lambda^\Phi i(\Phi^\dagger H - H^\dagger \Phi) S_1 S_2 + y_d^\Phi (\overline{d_L} d_R \Phi^0 + \overline{d_R} d_L (\Phi^0)^*)$

$$\Gamma_{S_2 \to S_1 \pi^0} = \frac{1}{c\tau_{S_2}} \simeq \frac{1}{3.5\,\mathrm{m}} \times \left(\frac{y_d^\Phi \lambda^\Phi}{10^{-3}}\right)^2 \left(\frac{\mathrm{TeV}}{m_A}\right)^4 \frac{300\,\mathrm{MeV}}{m_2} \times \lambda^{1/2}(1, y_1^2, y_\pi^2)$$

Using a vector portal for pair production

$F_{\mu\nu} X_{\mu\nu}$

kinetic mixing

Kinematically mixed vector contributes via *photon-penguin:*

$\overline{s_L} \gamma^\mu d_L \times \partial^\nu F_{\mu\nu}$ vanishes as $\overline{s_L} \gamma^\mu d_L \to p_K^\mu$ and $\partial^\mu \partial^\nu F_{\mu\nu} = 0$

Hypercharge mixing is suppressed by $(mZ'/mZ)^2$ and is also leading to no enhacement.

Mass mixing, on the other hand, leads to large Z-Z' mixing:

" $\varepsilon_Z m_Z^2 X_\mu Z^\mu$ "

mass mixing

$$\mathcal{L} \supset g_X X^\mu i \left(H^\dagger \overleftrightarrow{D}_{\mu Z} H \right) \xrightarrow{\text{EWSB}} \varepsilon_Z m_Z^2 X_\mu Z^\mu, \quad \text{with} \quad \varepsilon_Z = \frac{g_X v}{m_Z}.$$

effective coupling to NC + arbitrary dark sector

$$\mathcal{L} \supset \frac{\varepsilon_Z g}{2 \cos \theta_W} J_\mu^{\text{NC}} Z'^\mu + g_X Z'_\mu \left(c_V \overline{\psi_2} \gamma^\mu \psi_1 + c_A \overline{\psi_2} \gamma^\mu \gamma_5 \psi_1 + \text{h.c.} \right)$$

Gx ~ Gf , as expected.

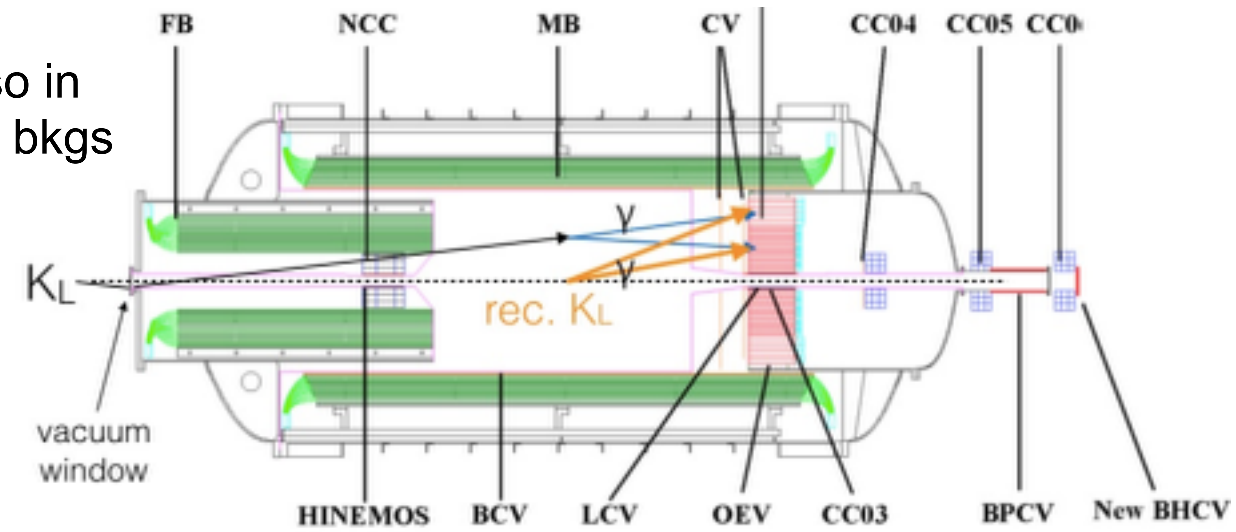
$$\text{BR} \left(K_L \to \psi_1 \psi_2 \right)_{\text{D}} = 3 \times 10^{-7} \left(\frac{G_X}{G_F} \right)^2 [\ldots \text{mass ratios} \ldots] \; \checkmark$$

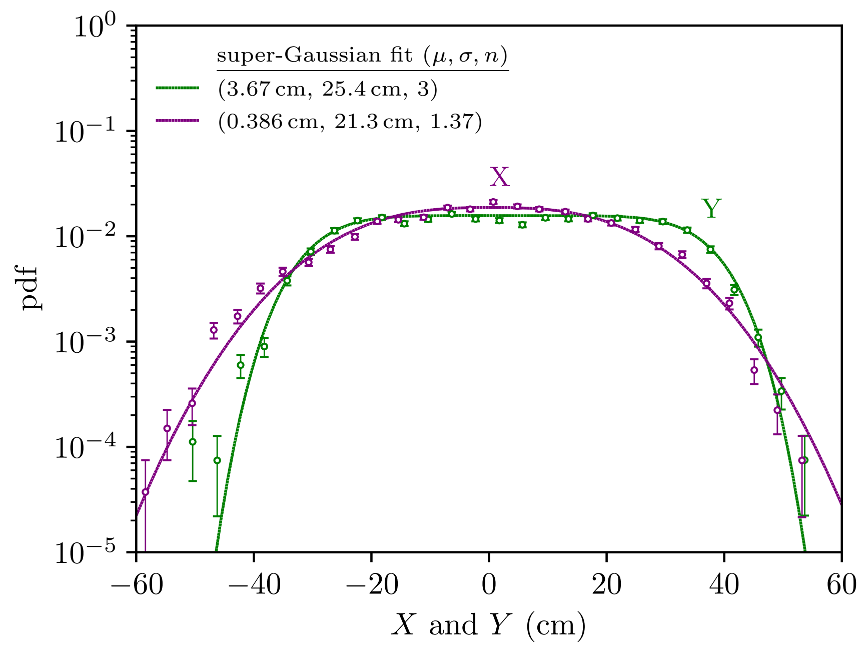
$$\frac{G_X}{\sqrt{2}} = \frac{\varepsilon_Z g \, g_X}{4 c_W m_{Z'}^2}$$

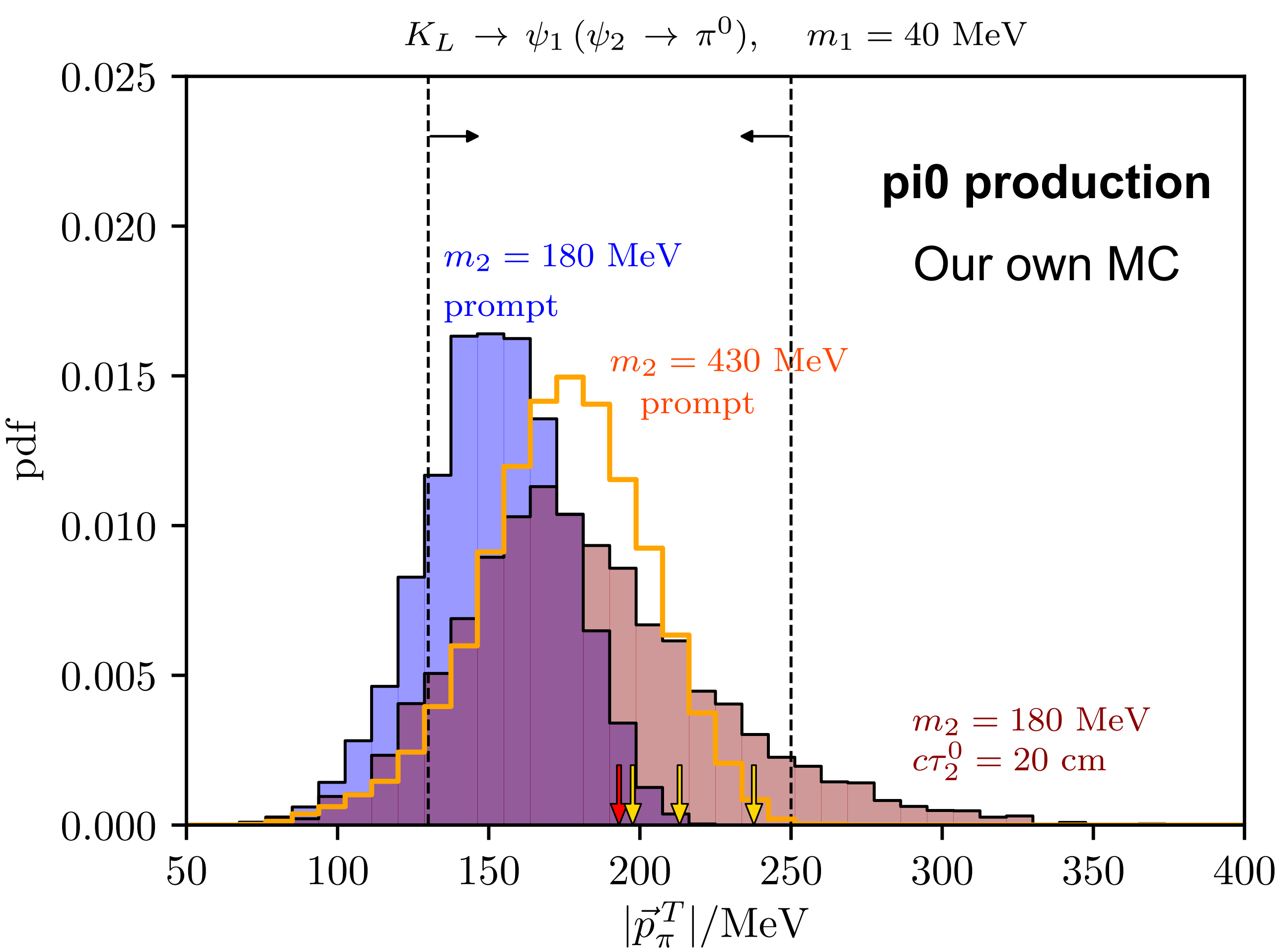
Kinematics — point 1

Signal reconstruction assumes decay has happened exactly along the beam.

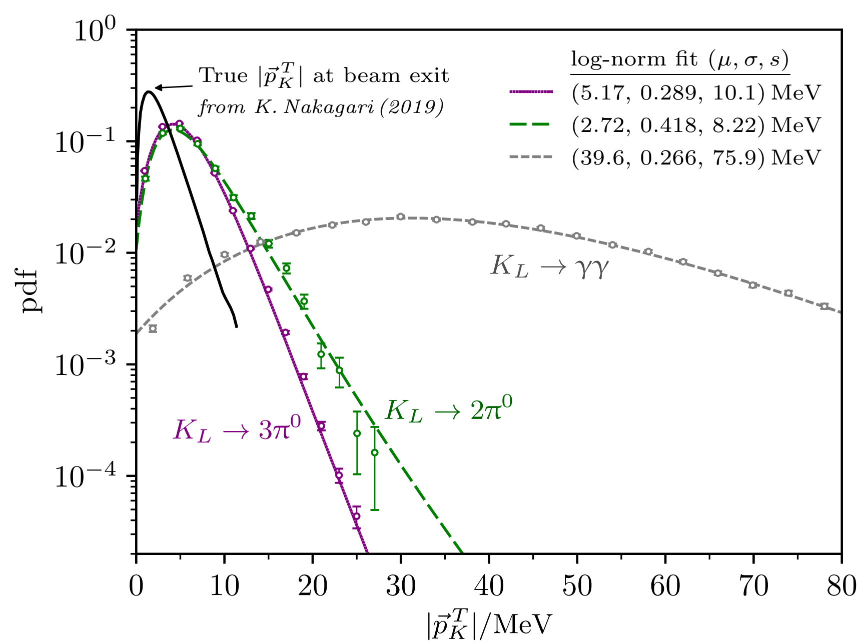
Present also in scattered KL bkgs







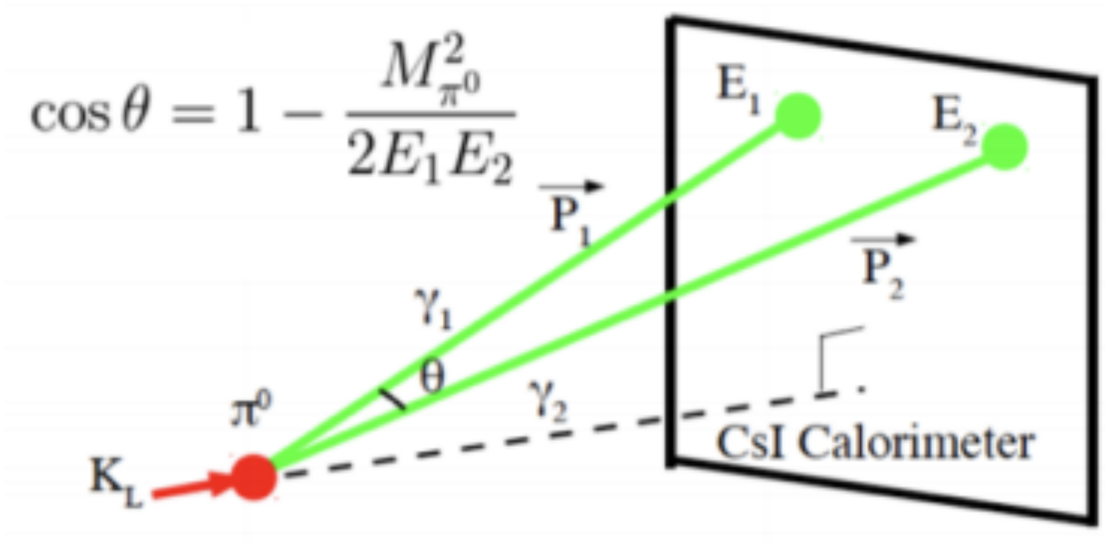
Need to understand beam size & its spread in momentum.

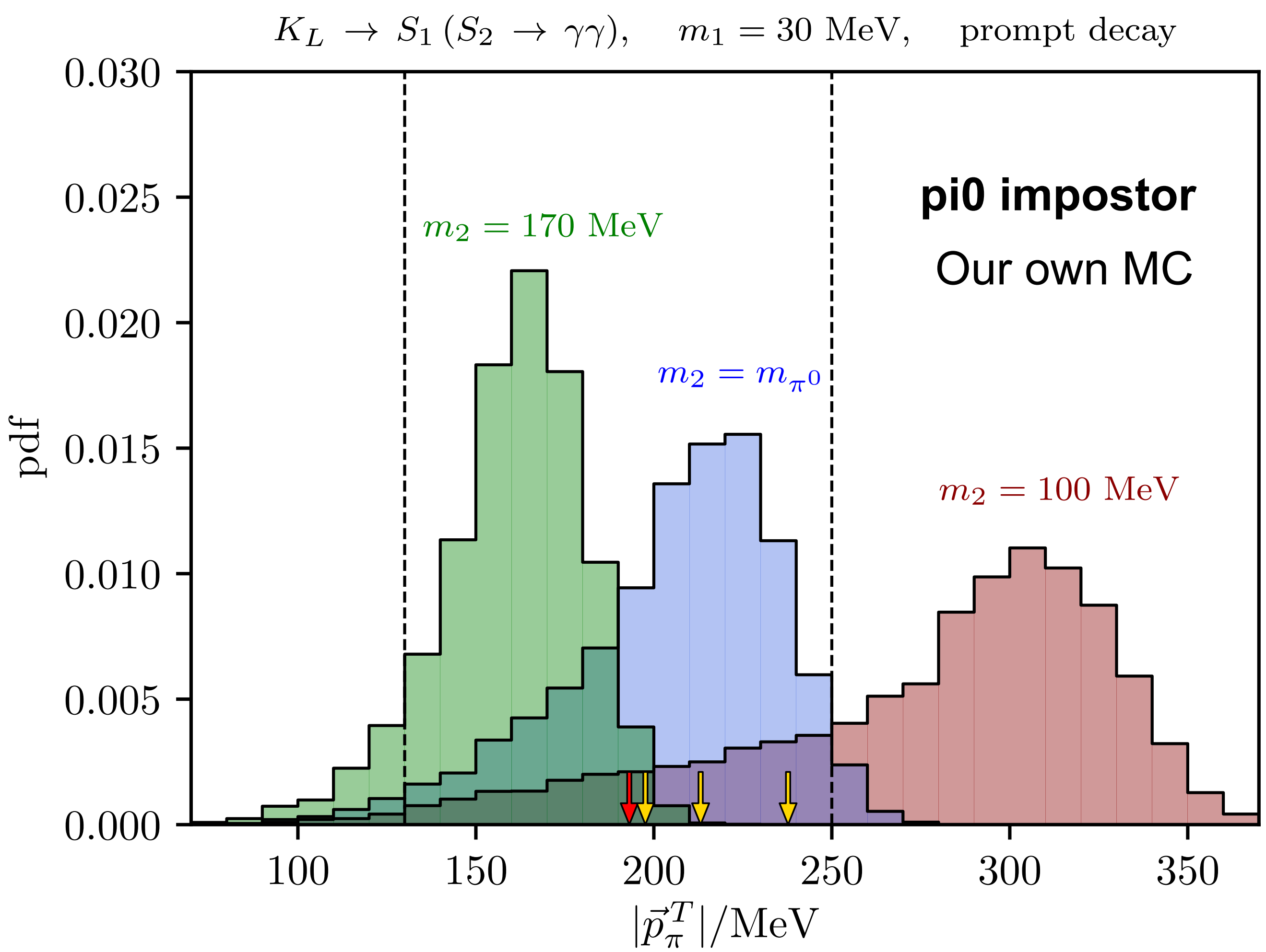


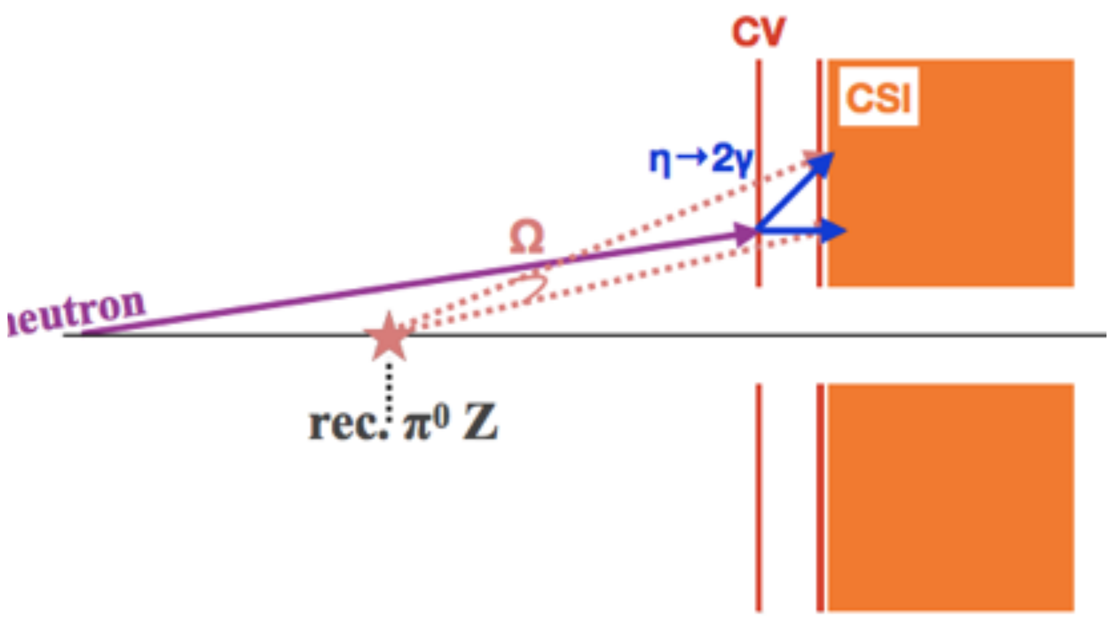
Kinematics — point 2

Signal reconstruction assumes photons with a pi0 invariant mass

Not satisfied in dipole (B) or pion impostor (C) cases.

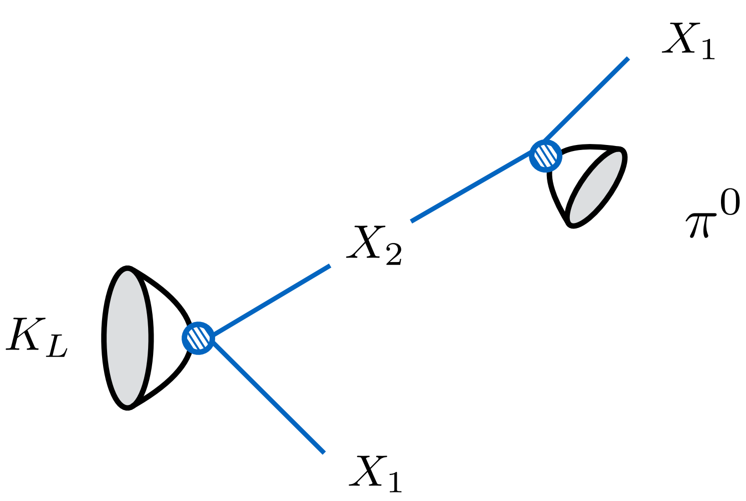




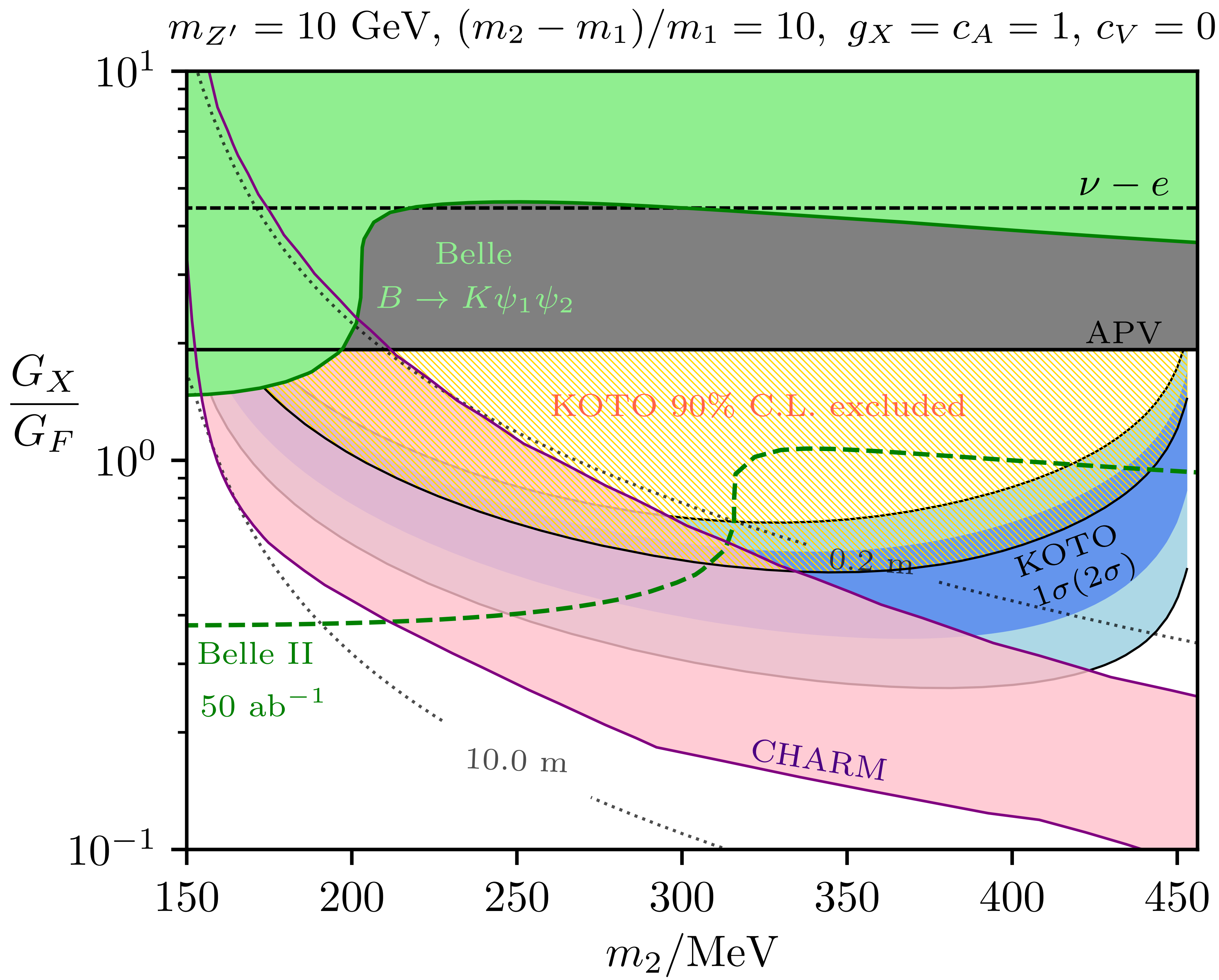


Present also in CV-eta bkgs

Results



Heavier dark state may also decay invisibly to neutrinos (BR ~ 10%)



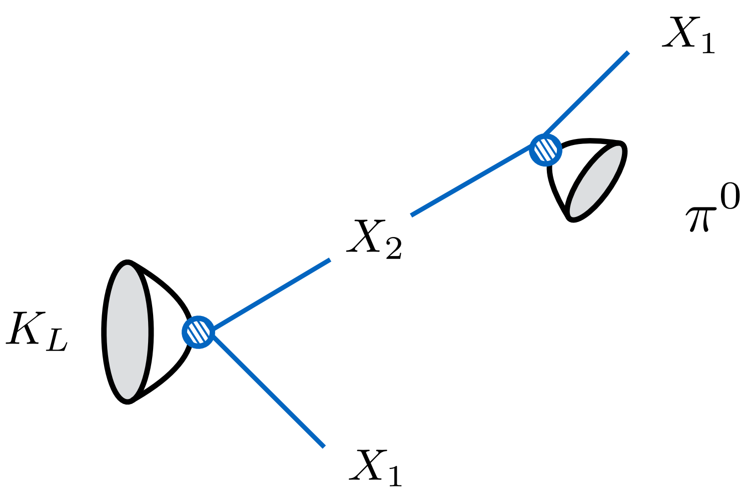
Belle @ 90 C.L.

$$\mathrm{BR}(B \to K\nu\overline{\nu}) < 1.6 \times 10^{-5}$$

Phys.Rev.D 96 (2017) 9, 091101

All plots assume same efficiency as SM KL decays

Results



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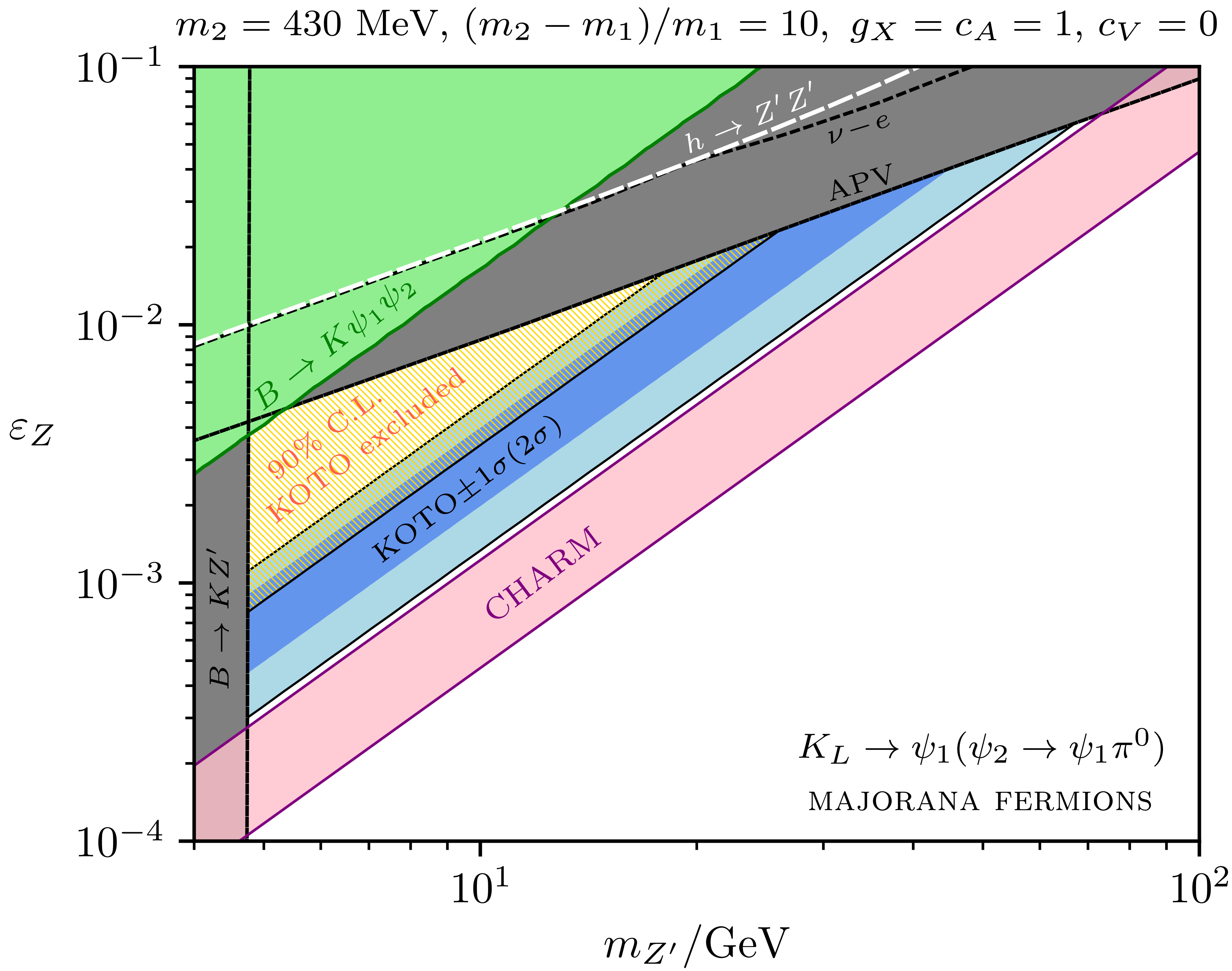


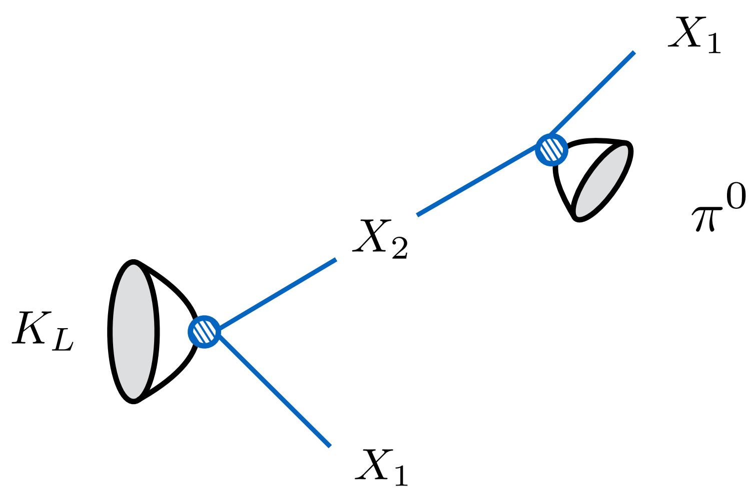
Belle @ 90 C.L.

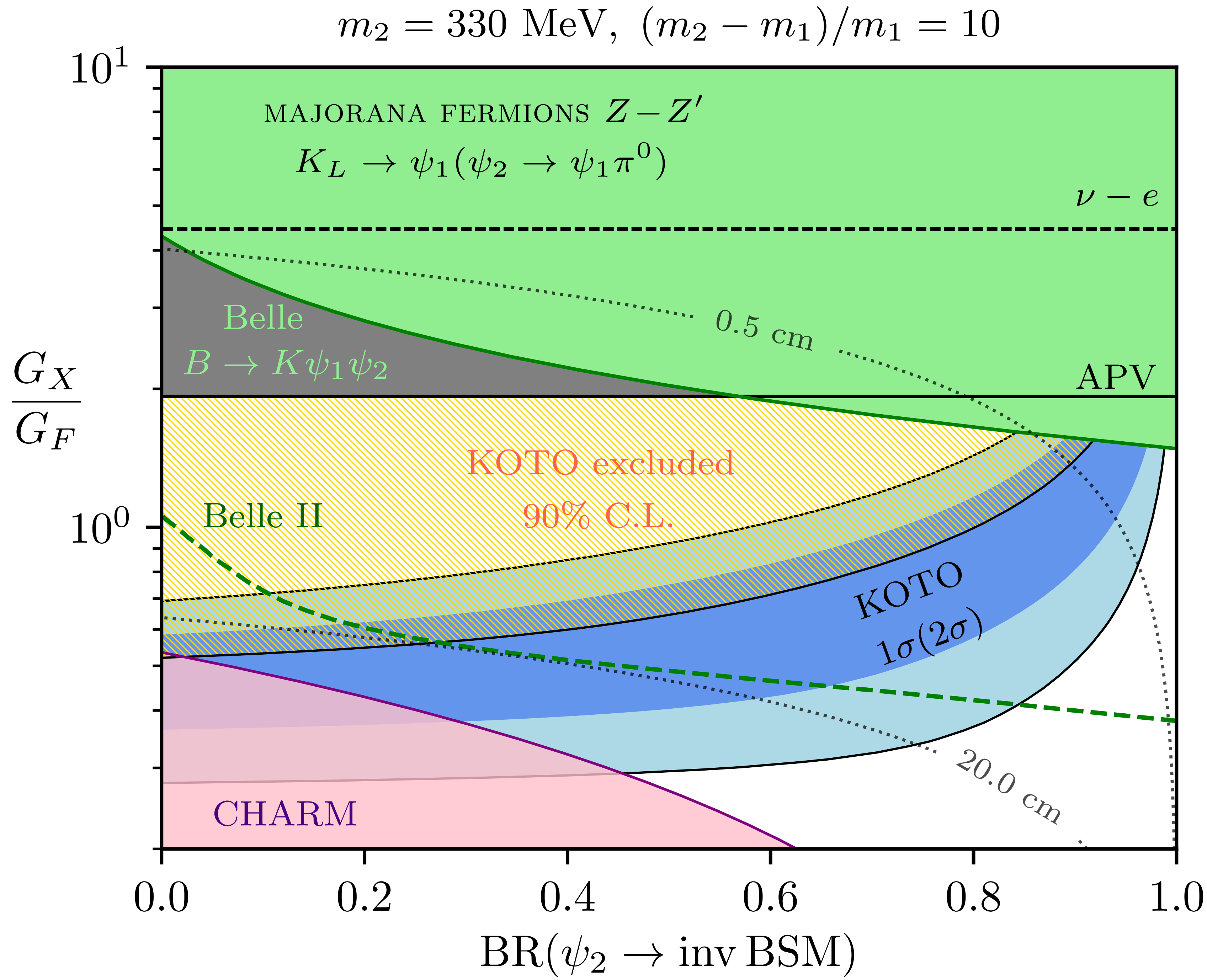
$$\mathrm{BR}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$

Phys.Rev.D 96 (2017) 9, 091101

KOTO sets leading constraints on parameter space, especially if X2 are short-lived.

Results





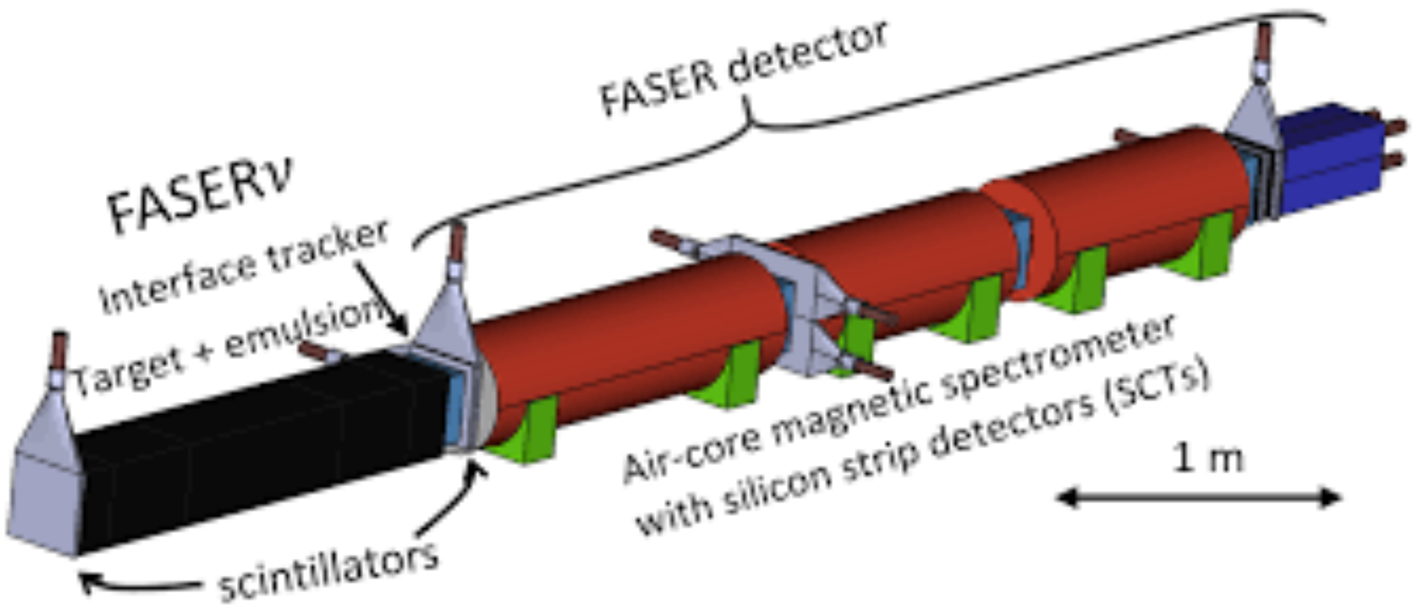
Belle @ 90 C.L.

$$\mathrm{BR}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$

Phys.Rev.D 96 (2017) 9, 091101

But beam dump constraints can be alleviated if new dark decays exist **(relaxed assumption about inv BR)**

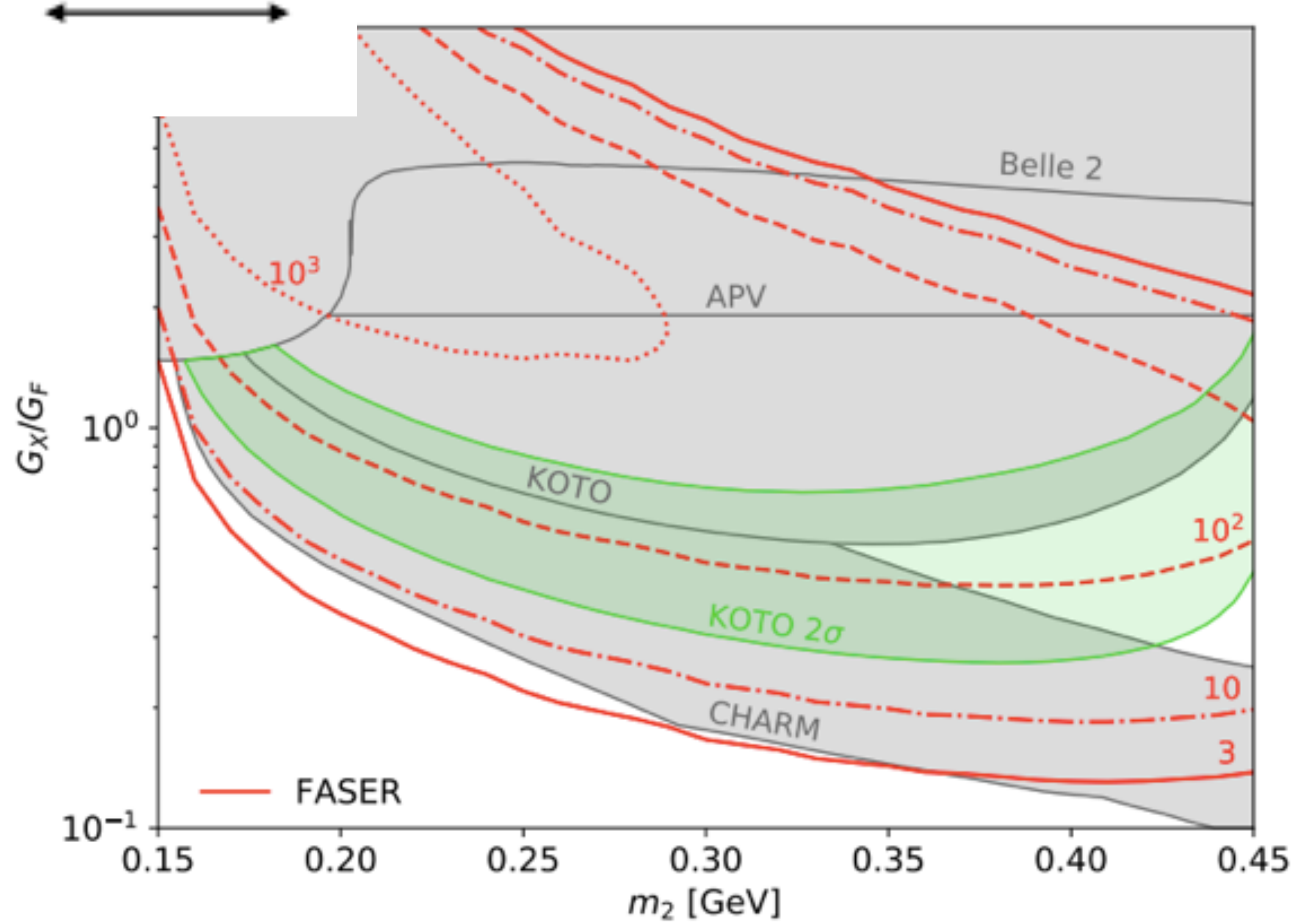
Future tests at beam dump facilities (FASER)



$$\textbf{FASER:}\ \Delta = 1.5\ \text{m},\ R = 10\ \text{cm},\ \mathcal{L} = 150\ \text{fb}^{-1},$$
$$\textbf{FASER HL:}\ \Delta = 1.5\ \text{m},\ R = 10\ \text{cm},\ \mathcal{L} = 3\ \text{ab}^{-1},$$
$$\textbf{FASER 2:}\ \Delta = 5\ \text{m},\ R = 1\ \text{m},\quad \mathcal{L} = 3\ \text{ab}^{-1}.$$

Searching for new particles produced in the forward direction at the LHC.

Event contours at **FASER 2**



F. Kling & S. Trojanowski, 2006.10630

Dark Matter connection

1. In all models, except pion impostor (C), X1 is stable and can be DM candidate
2. Thermal equilibrium is guaranteed (weak-strength interactions with SM)
3. Unfortunately, X1 weak-strength couplings to SM at 10's and 100's MeV scale is not sufficient to achieve correct relic density — additional annihilation channels required.

↓

Secluded annihilation into light unstable particles + **velocity dependence** to avoid CMB limits

$$\text{Fermionic dark matter :} \quad \psi_1 + \overline{\psi_1} \to \phi + \phi \to \text{ SM}, \quad m_\phi < m_1$$

p-wave annihilation fermions -> scalars

$$\mathcal{L} \supset \; y_\phi \phi \overline{\psi_1} \psi_1 .$$

$$\sigma \mathrm{v} = \mathrm{v}^2 \frac{3 y_\phi^4}{64 \pi m_1^2} F(m_\phi^2/m_1^2) \simeq 1\,\mathrm{pbn} \times c \times \frac{\mathrm{v}^2}{0.1} \times \left(\frac{y_\phi}{0.01}\right)^4 \left(\frac{100\,\mathrm{MeV}}{m_1}\right)^2$$

new scalar decays via higgs portal coupling ($\theta^2 \sim 10^{-9}$)

Dark Matter connection

1. In all models, except pion impostor (C), X1 is stable and can be DM candidate
2. Thermal equilibrium is guaranteed (weak-strength interactions with SM)
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$\downarrow$

Secluded annihilation into light unstable particles + **velocity dependence** to avoid CMB limits

$$\text{Bosonic dark matter}: \quad S_1 + S_1 \to \phi + \phi \to \text{ SM}, \quad m_\phi > m_1.$$

"**Forbidden" annihilation** scalars -> scalars (otherwise, s-wave and no v-dependence)

$$\mathcal{L} \supset \lambda_\phi S_1^2 \phi^2$$

$$\sigma \mathrm{v} = \frac{\lambda_\phi^2}{32\pi E_1^2} \times \sqrt{1 - m_\phi^2/E_1^2}.$$ suppressed by $\exp(-2\Delta m/T)$

R.T. D'Agnolo and J. Ruderman, PRL. 115, 061301 (2015)

new scalar decays via higgs portal coupling ($\theta^2 \sim 10^{-9}$)

Dark Matter connection

1. In all models, e … te
2. Thermal equili …
3. Unfortunately, … le is not sufficient to achieve cor …

Broad range of parameters that predict DM.

Existence of new scalar is motivated as the real part of scalar that generates mass splitting between X1 and X2

For further connections between KOTO & DM see W. Altmannshofer et al, 2006.05064

Secluded annihilat … oid CMB limits

Bosonic … $> m_1.$

"**Forbidden** … v-dependence)

$$\sigma \mathrm{v} = \frac{\lambda_\phi^2}{32\pi E_1^2} \times \sqrt{1 - m_\phi^2/E_1^2}.$$

suppressed by $\exp(-2\Delta m/T)$

R.T. D'Agnolo and J. Ruderman, PRL. 115, 061301 (2015)

new scalar decays via higgs portal coupling ($\theta^2 \sim 10^{-9}$)

CONCLUSIONS

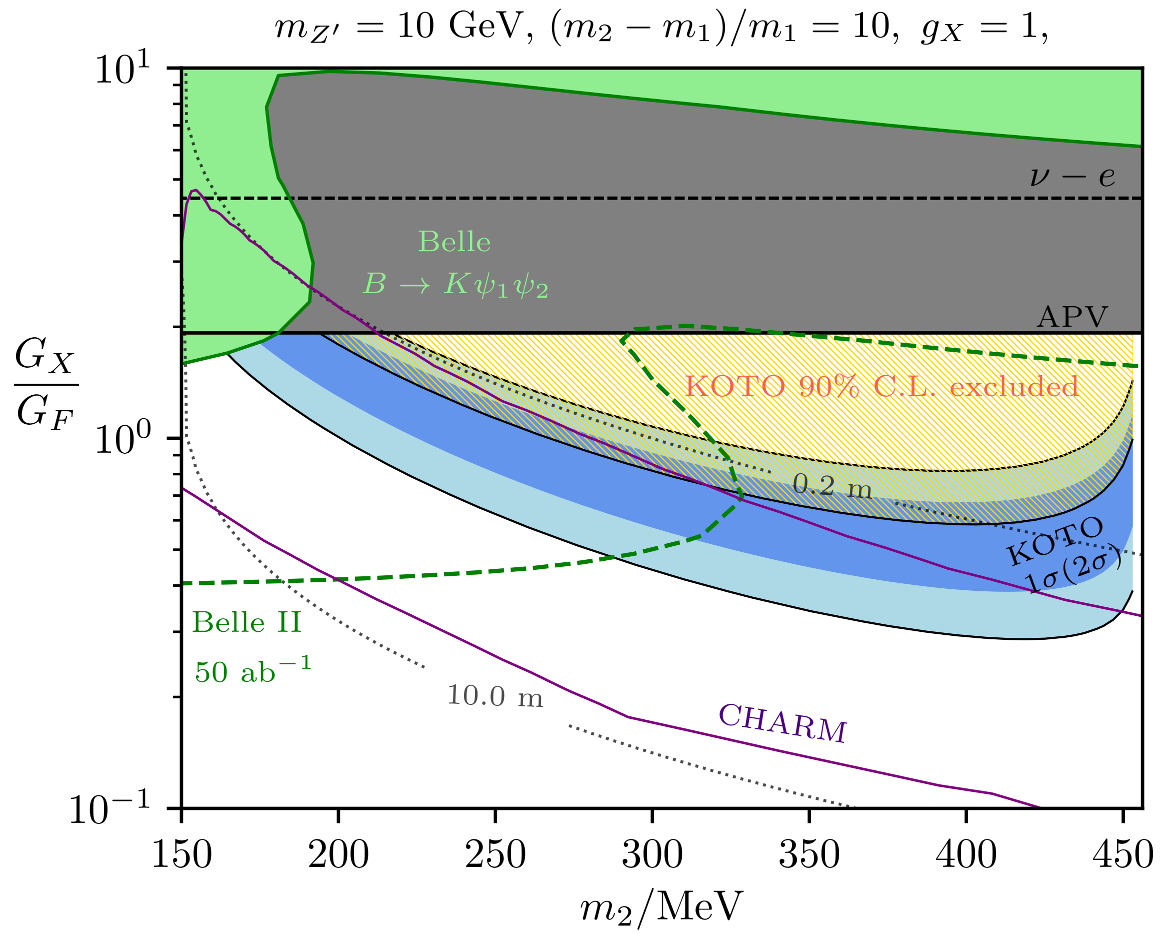
- *Hints from the* ***KOTO****? — possible violation of GN bound?* ***Still waiting final results.***
- ***New loophole to avoid GN:*** *pair production of dark states*
    - *Scalar portals typically require new (DS - SM) interactions, but are possible.*
    - *Vector portals require ONE coupling combination ~* $g_X \varepsilon_Z$
    - *Achieve large pT by mis-reconstruction.*
- *Very* ***testable scenario*** *— beam dumo exps and* $B \to K \not{E}$
- *Proposed a few connections to* ***dark matter****, but all in non-minimal realisations.*

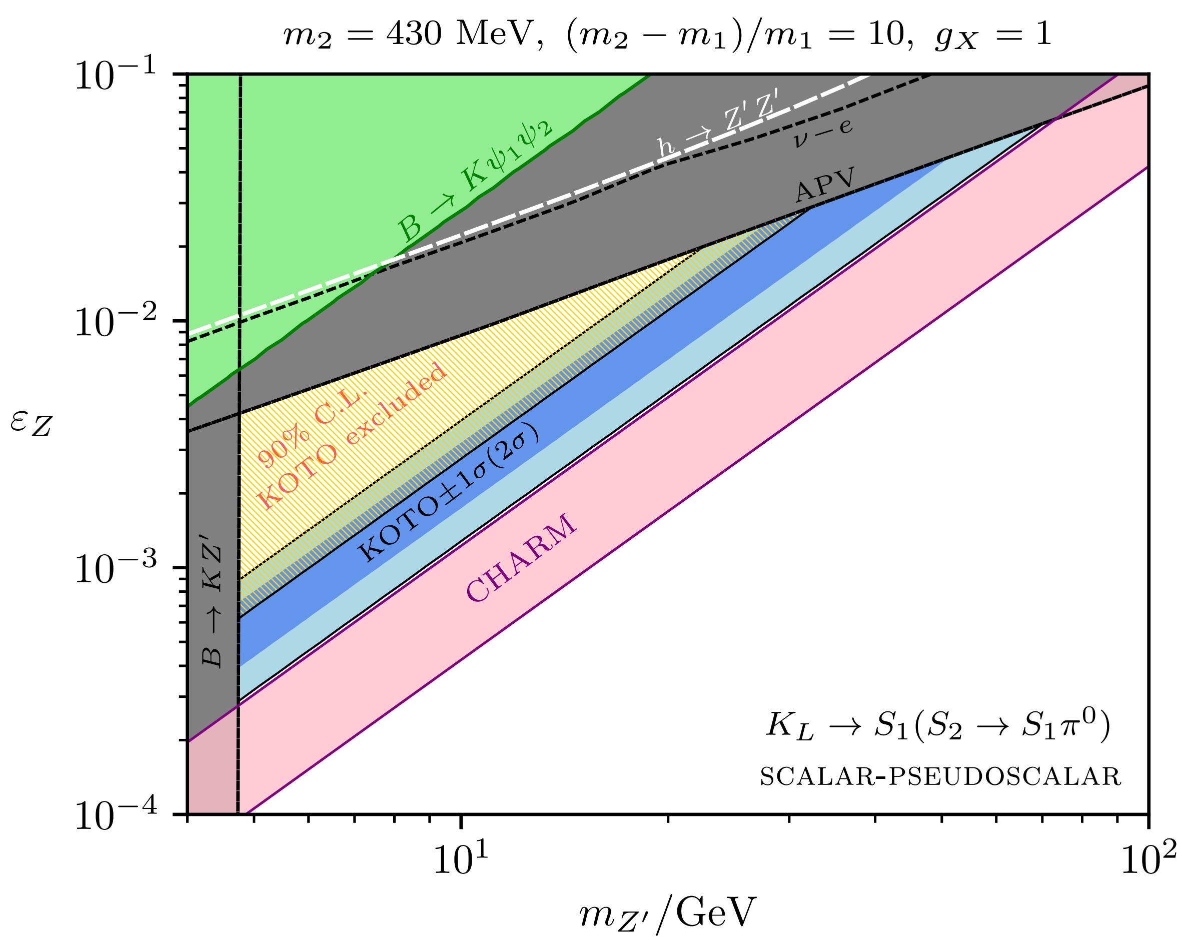
Thank you!

Appendix

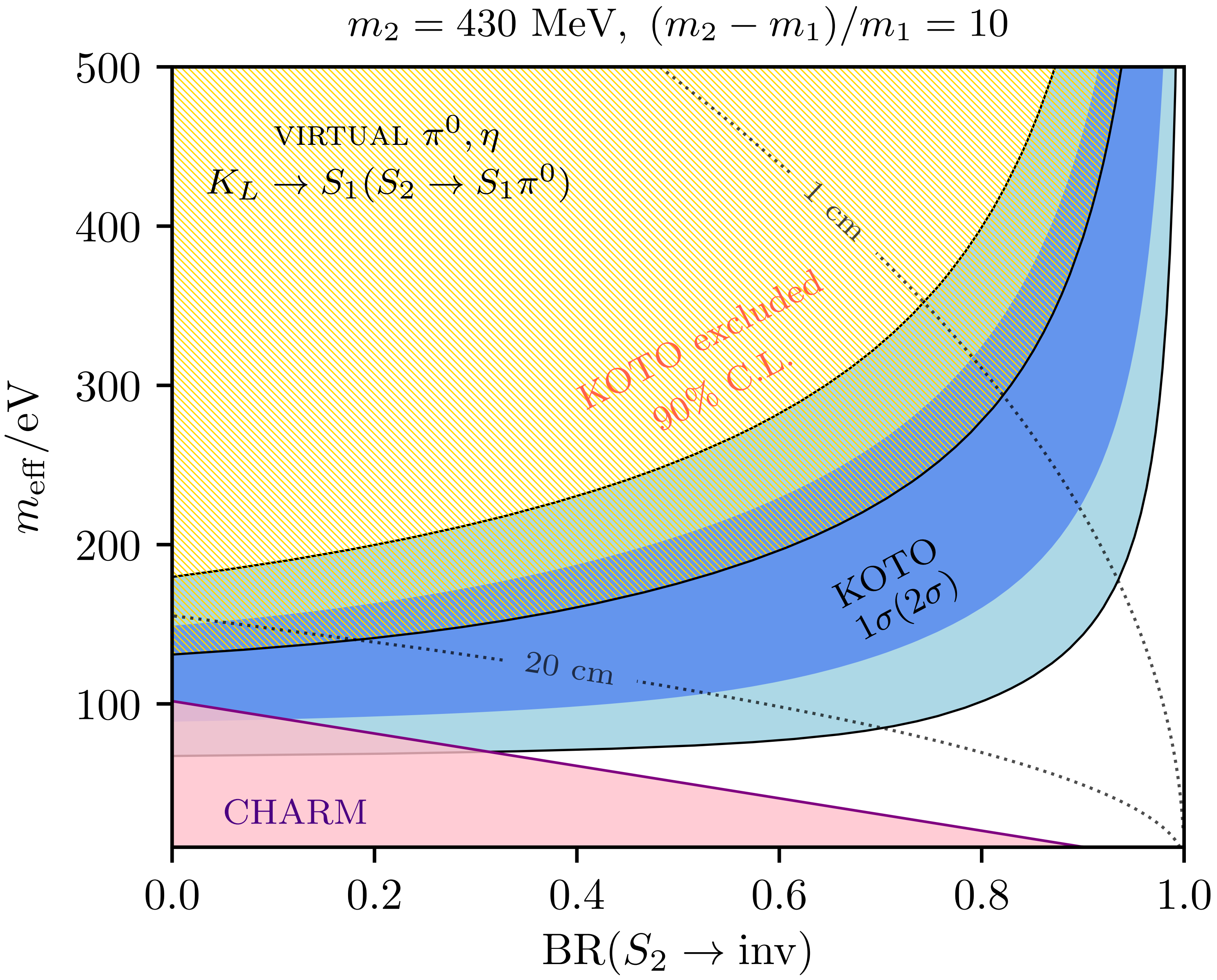
Scalar-pseudoscalar production via Z-Z' mixing

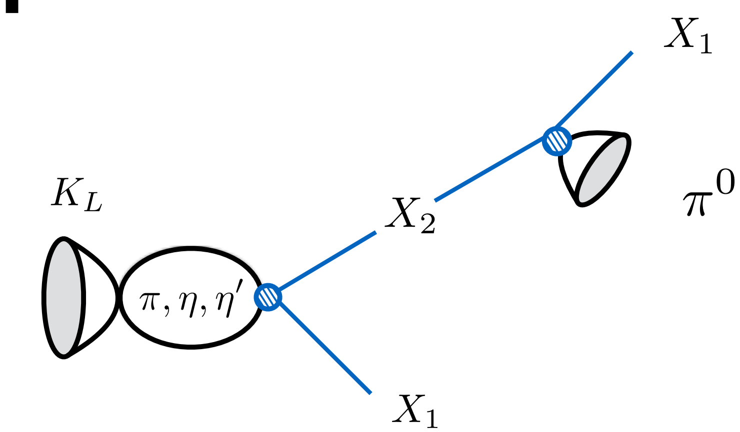
$$\mathcal{L}_S \supset g_X Z'_\mu J^\mu_S = g_X Z'_\mu (S_2 \partial^\mu S_1 - S_1 \partial^\mu S_2),$$





Virtual (pi0,eta)-mediated dark state production





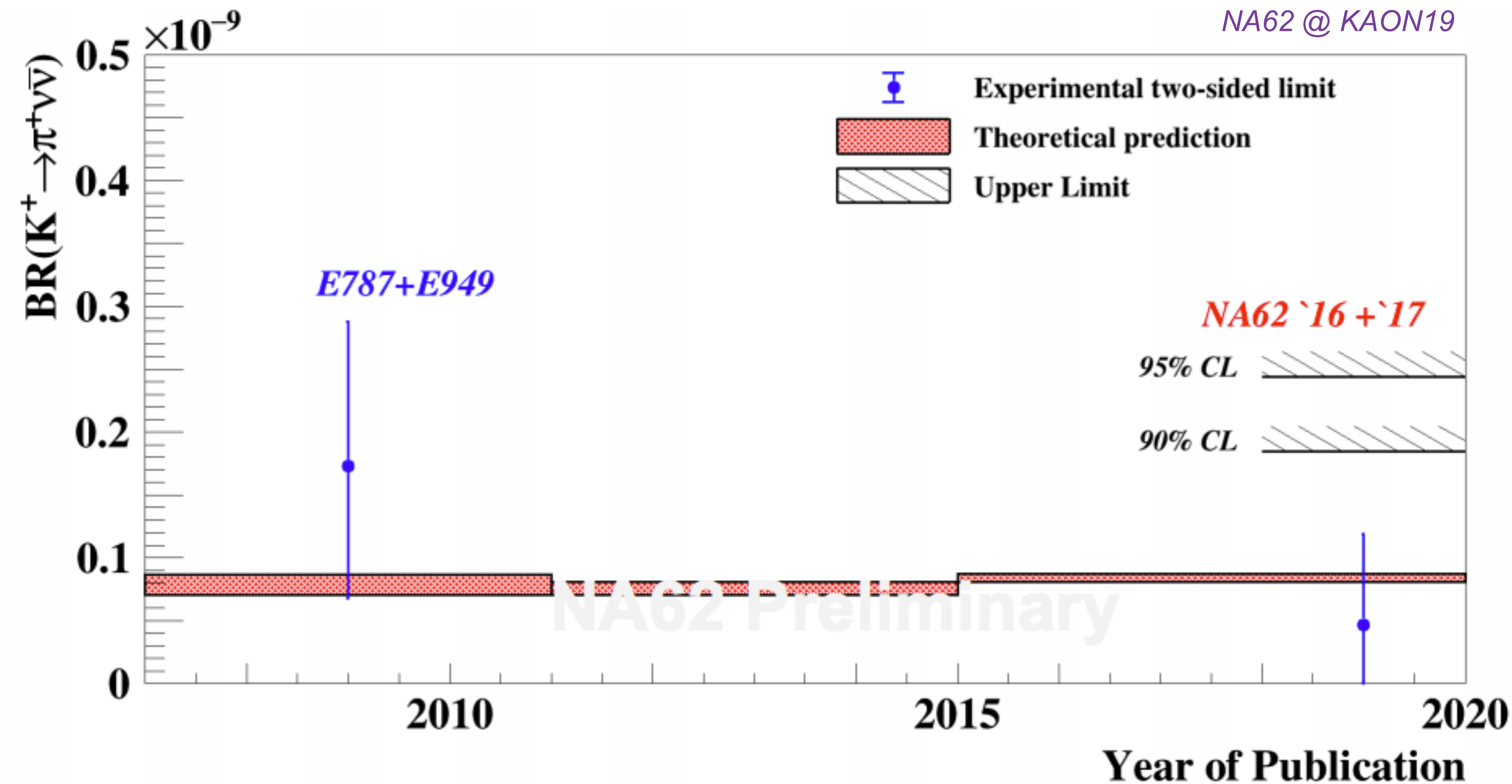
Type-II 2HDM

$$\mathcal{L} = m_{eff} S_1 S_2 \left(\pi^0 + \eta \times \frac{2}{\sqrt{3}} \times \frac{y_s^{\rm SM}}{y_d^{\rm SM}}\right)$$

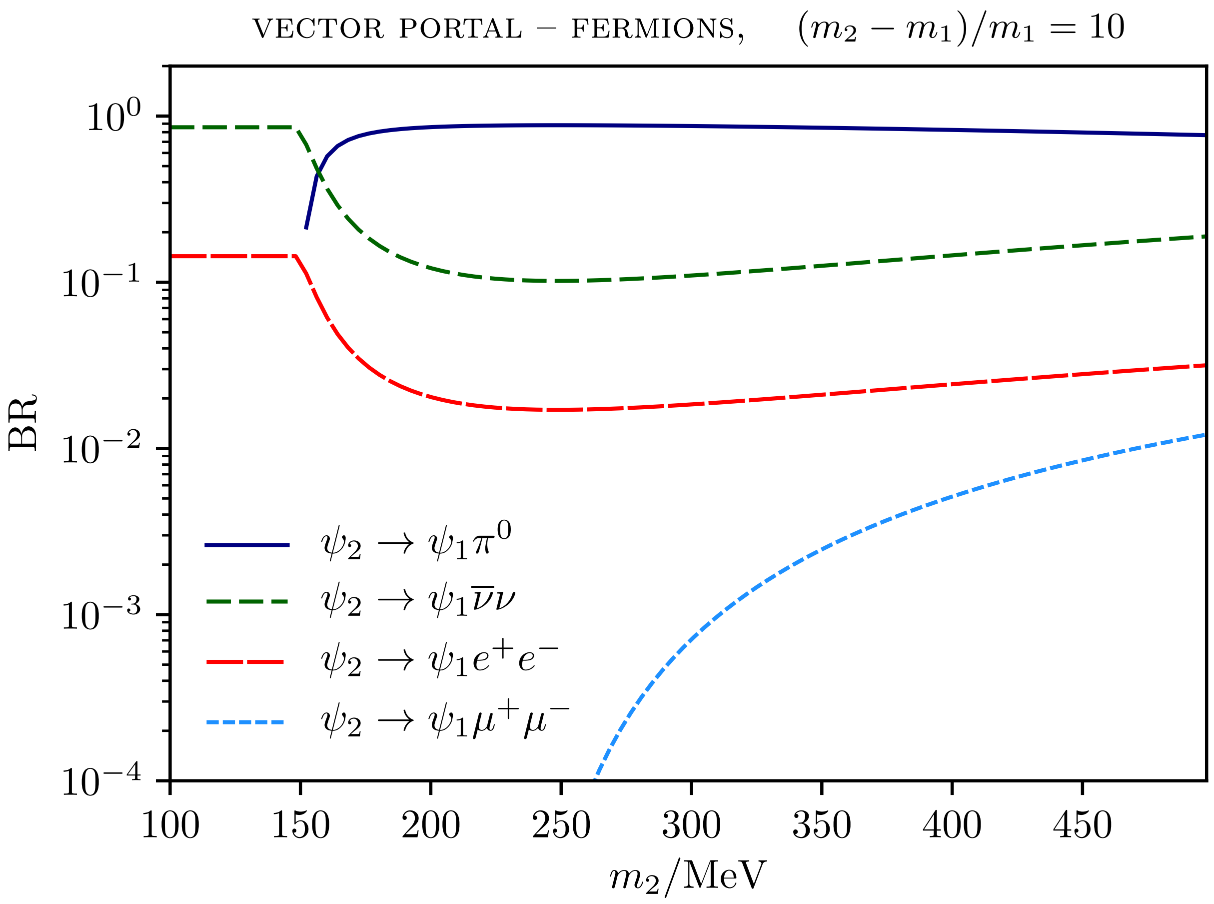
$$m_{eff} = y_d^\Phi \lambda^\Phi \times \frac{v\langle \bar{q}q\rangle}{\sqrt{2}F_\pi m_A^2},$$

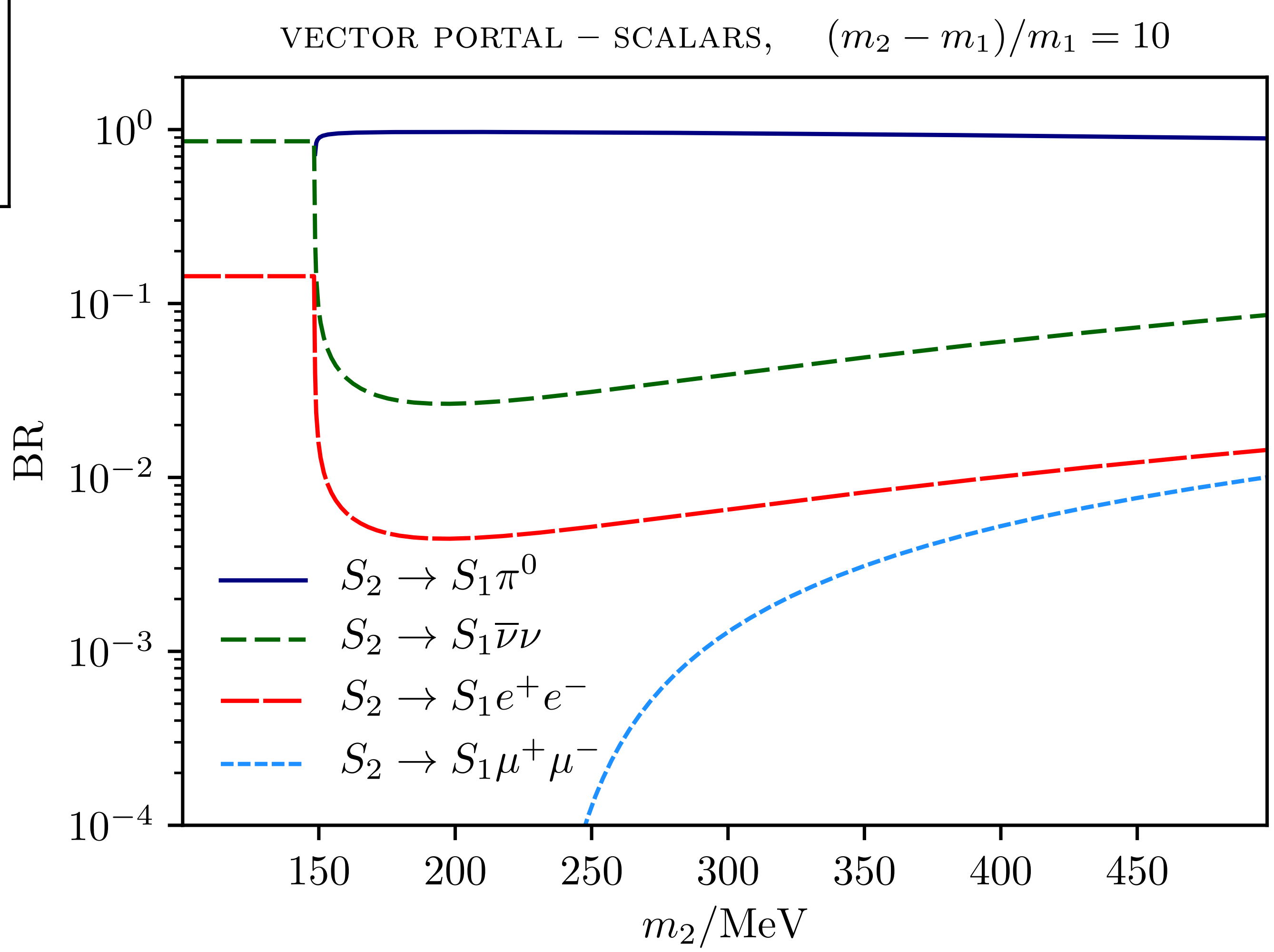
$$\mathrm{BR}(K_L \to S_1 S_2) = 9 \times 10^{-9} \times \left(\frac{m_{eff}}{100\,\mathrm{eV}}\right)^2 \lambda^{1/2}(1, r_1^2, r_2^2),$$

NA62 compared with previous measurements



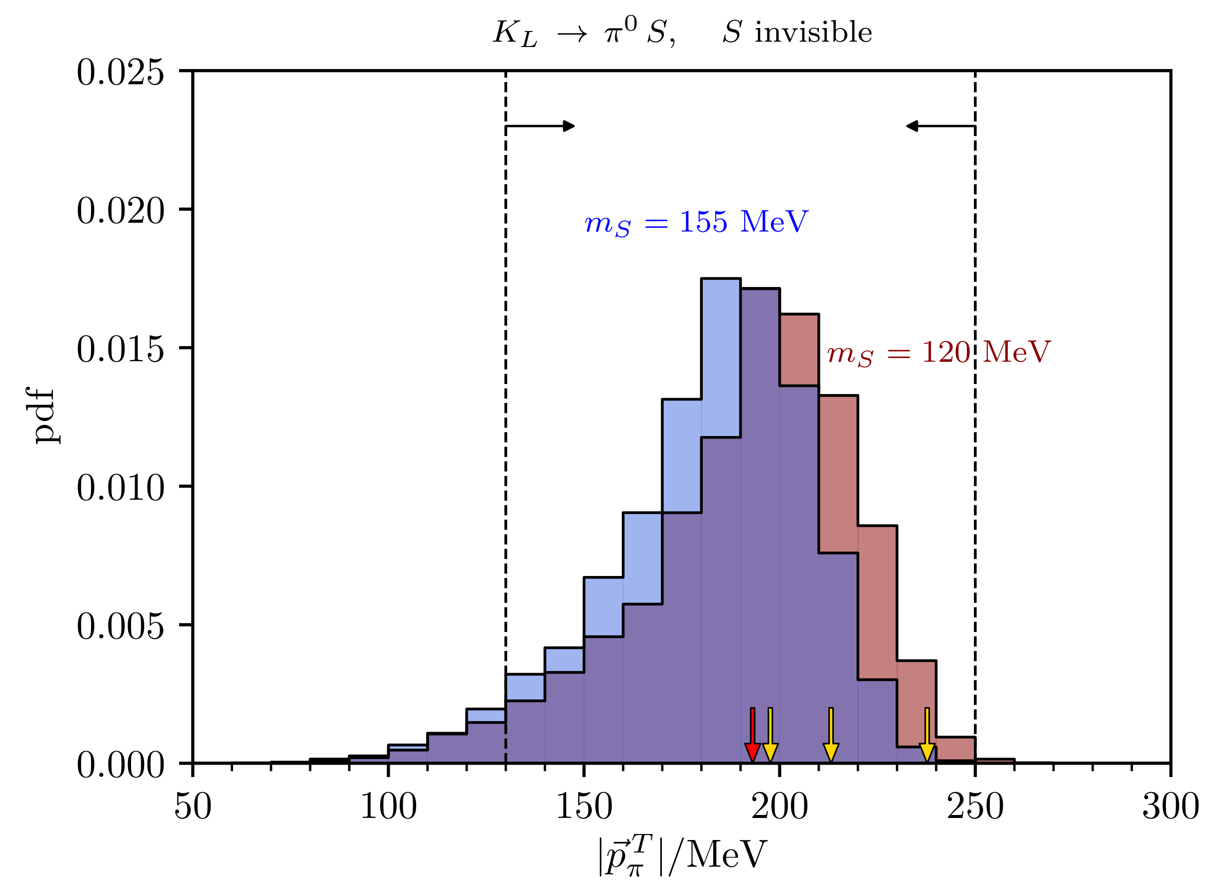
Branching ratios in vector portal model



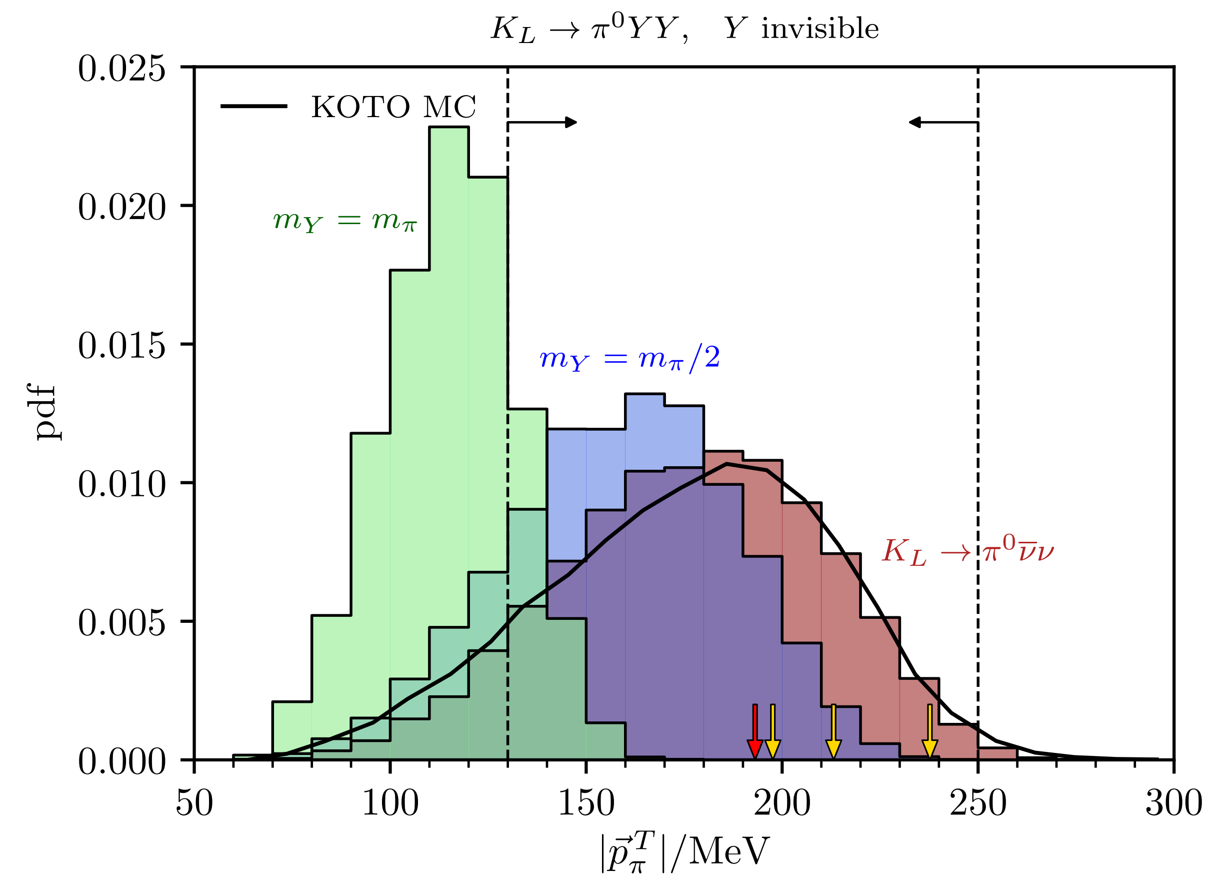


Revisiting other scenarios and validation

Singlet scalar



Two invisible majorana fermions



Dipole distributions