Models Violating Grossman-Nir Bound

2nd meeting: Searches for Hidden Sectors at Kaon and Hyperon Factories

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Section 2.7

[Teppei Kitahara, Maxim Pospelov, Matheus Hostert, Yuval Grossman, KT]

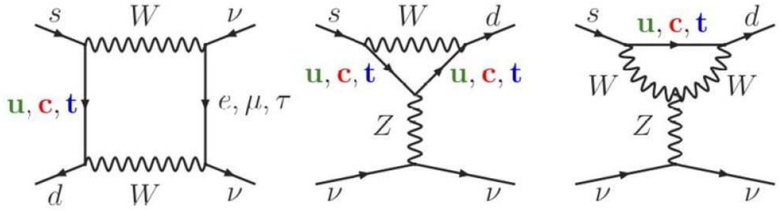
Introduction

Rare Kaon Decays and Grossman-Nir Bound

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

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

$\mathcal{M}$ ~



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!

- 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**)

$$\frac{\mathrm{BR}[K_L \to \pi^0 \nu\bar{\nu}]}{\mathrm{BR}[K^+ \to \pi^+ \nu\bar{\nu}]} \leq 4.3$$ Ratio of total widths +isospin breaking

- GN bound can be generalized to new physics case

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

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

Can we violate GN bound?

- Thanks to GN bound, K+ measurements already constraints many models
- KOTO and KLEVER will have unprecedented precision fo KL decay
- Are there interesting possibilities where NP signature primarily appears in K_L decay? (γγ+ missing channel) ==How to violate GN bound?
- Many ideas hinted by 4 events at KOTO →4 events turned out be BG.
  <u>But the ideas are relevant for the future data and KLEVER.</u>

Goal of Sec. 2.7

- Summarize the existing possibilities
- Examine other signatures of the GNV models

Two Categories

1. Violate GN bound
in the fundamental level

$$\mathrm{BR}(K_L \to \pi^0(\gamma\gamma) + inv) > 4.3\mathrm{BR}(K_L \to \pi^+ + inv)$$

- ΔI=3/2 dominance, one light dark state

  X. He et. al. [1804.07449, 2002.05467, 2005.02942]

- At least two light dark states

  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]

2. Violation effectively appears due to experimental loopholes [need one light state]

- π0 gap (K+-> pi+ X difficult)

  Fuyuto, Hou, Kohda [1412.4397]

- Lifetime gap

  Kitahara, Okui, Perez, Soreq, KT [1909.11111]

- Kinematic(Dalitz) loophole

  M. Fabbrichesi and E. Gabrielli [1911.03755]

  Marco's talk for Dark Photon section [5/10]

Fundamental violation

ΔI=3/2 dominance

- Usual kaon decays are known to be dominated by ΔI=1/2 process. One of the assumption to derive GN bound
- How about ΔI=3/2?
- SMEFT study [1804.07449]. All the quarks and neutrinos have to be present. 6 fermions-> dim 9 operators!
- NP should start from dim 9, and the corresponding scale ~GeV at most. Implausible.

From 2005.02942

$$\epsilon_{ij}\delta_{kl}(\overline{Q_o^k}\gamma_\mu Q_p^j)(\overline{d_x}\gamma^\mu u_y)\overline{L_{\{\alpha}^{ci}}L_{\beta\}}^l\,,$$
$$\epsilon_{ij}\delta_{kl}(\overline{Q_o^k}\gamma_\mu Q_p^j][\overline{d_x}\gamma^\mu u_y)\overline{L_{\{\alpha}^{ci}}L_{\beta\}}^l\,,$$
$$\epsilon_{ij}\delta_{kl}(\overline{Q_o^k}\gamma_\mu Q_p^j)(\overline{d_x}\gamma_\rho u_y)\overline{L_{[\alpha}^{ci}}\sigma^{\mu\rho}L_{\beta]}^l\,,$$
$$\epsilon_{ij}\delta_{kl}(\overline{Q_o^k}\gamma_\mu Q_p^j][\overline{d_x}\gamma_\rho u_y)\overline{L_{[\alpha}^{ci}}\sigma^{\mu\rho}L_{\beta]}^l\,,$$
$$\epsilon_{ik}\epsilon_{jl}(\overline{d_o}Q_p^i)(\overline{d_x}Q_y^j)\overline{L_{\{\alpha}^{ck}}L_{\beta\}}^l\,,$$
$$\epsilon_{ik}\epsilon_{jl}(\overline{d_o}Q_p^i][\overline{d_x}Q_y^j)\overline{L_{\{\alpha}^{ck}}L_{\beta\}}^l\,,$$
$$\epsilon_{ik}\epsilon_{jl}(\overline{d_o}Q_p^i)(\overline{d_x}\sigma_{\mu\omega}Q_y^j)\overline{L_{[\alpha}^{ck}}\sigma^{\mu\omega}L_{\beta]}^l\,,$$
$$\epsilon_{ik}\epsilon_{jl}(\overline{d_o}\sigma_{\mu\rho}Q_p^i)(\overline{d_x}\sigma_\omega{}^\rho Q_y^j)\overline{L_{[\alpha}^{ck}}\sigma^{\mu\omega}L_{\beta]}^l\,,$$

In light of KOTO 4 events

X He, X Ma, J. Tandean, G. Valencia [2005.02942]

- Replace 2 neutrinos with a new scalar singlet [dim 9→dim 7, the scale GeV→TeV]

$$\mathrm{BR}(K_L \to \pi^0 X) < \mathbf{47}\mathrm{BR}(K_L \to \pi^+ X)$$

X is singlet

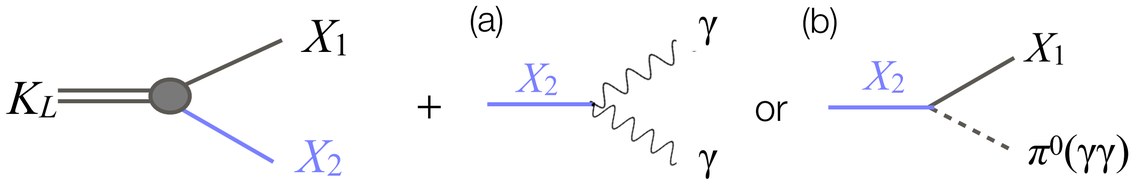
Two new light dark states

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



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

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

Small breaking induces χ=Im[ϕ] decays to γγ

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

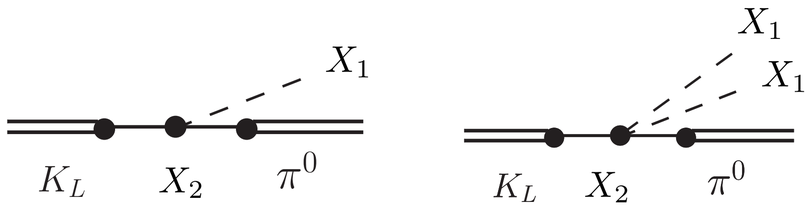
Other realization w/Higgs portal&MFV in [2005.07102]
Signature from B decay? Also X decays to electrons?

$\mathcal{O}_{\rm SM} X_2 + \lambda m_X X_1 X_2^2, \lambda' X_1^2 X_2^2$
$\mathcal{O}_{\rm SM} \supset g_{sd}\bar{s}d,\ g_{dd}\bar{d}d$

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

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

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

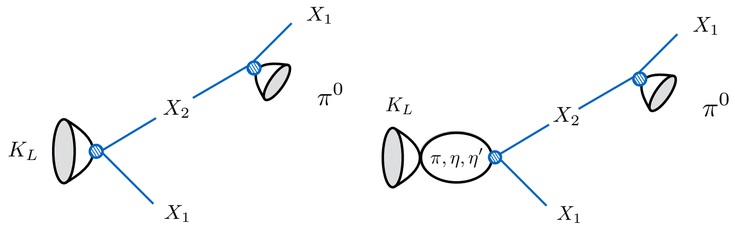


$m_{X2} > m_K$ but has to be light, since BR[$K_L \to \pi^0 X_1(X_1)$] ~$(1/m_{X2})^8$.

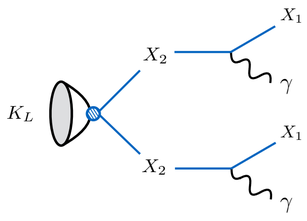
Signature is from gdd coupling?

Two new light dark states -categorization

M. Hostert, K. Kaneta, M. Pospelov [2005.07102]

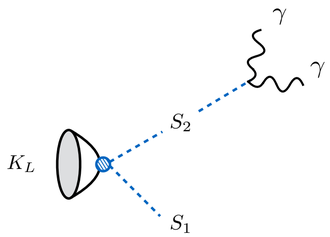


A) π^0 PRODUCTION



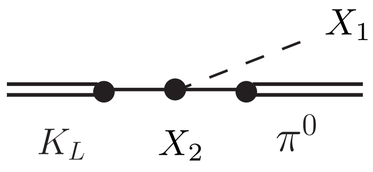
B) DIPOLE PORTAL

[S. Gori, G. Perez, **KT**]

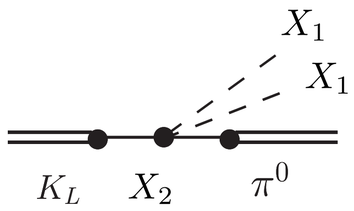


C) π^0 IMPOSTOR

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



D) Mixing, single X1



E) Mixing ,double X1

Signature based categories	A	B	C	D	E	ΔI=3/2
• γγ is from π0? [important for reconstruction]	✓			✓	✓	✓
• Is missing energy from multiple particles?	✓	✓	✓		✓	
Another category? Prediction?						

Effective violation

Lifetime and mass loopholes for K→πX

Two experimental loopholes

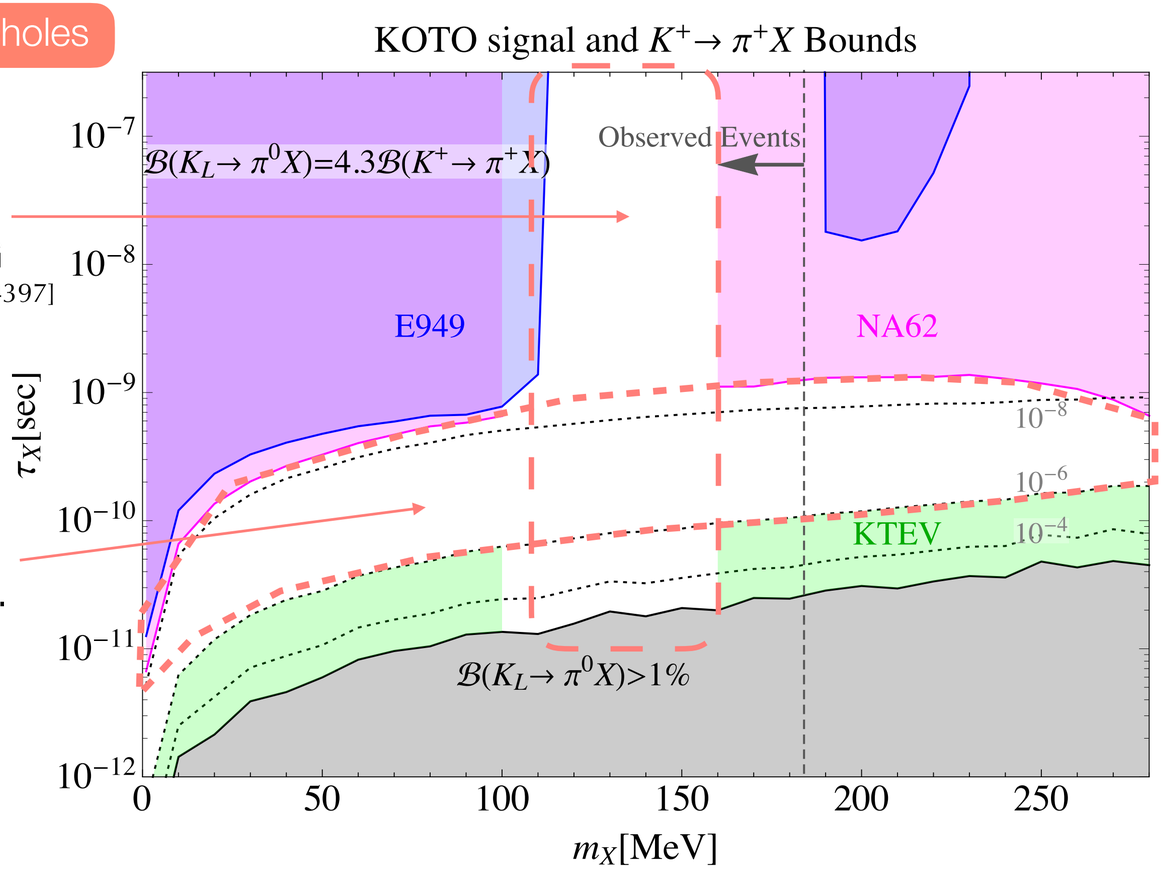
(1) $m_X \sim m_{\pi 0}$ loophole

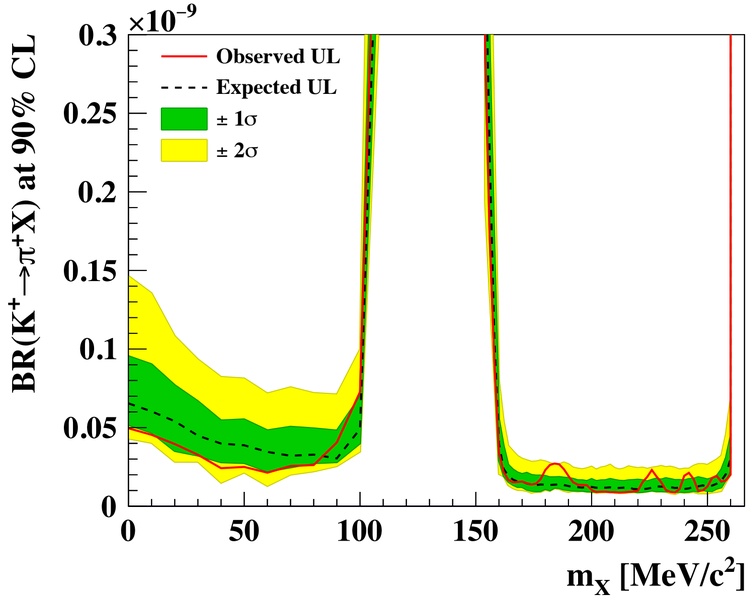
Large $K^+ \to \pi^+\pi^0$ BG

Fuyuto, Hou, Kohda [1412.4397]

(2) Finite lifetime of X

Exploit detector size.



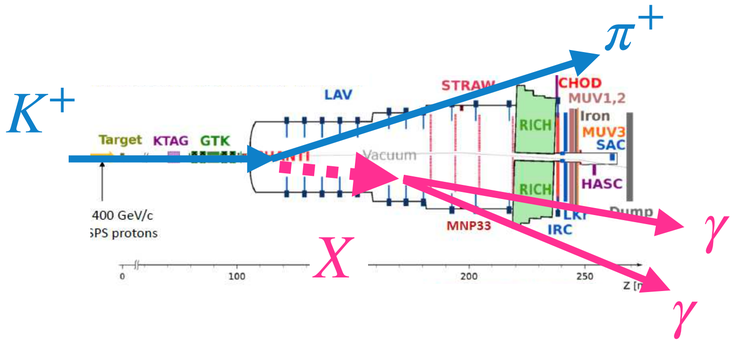


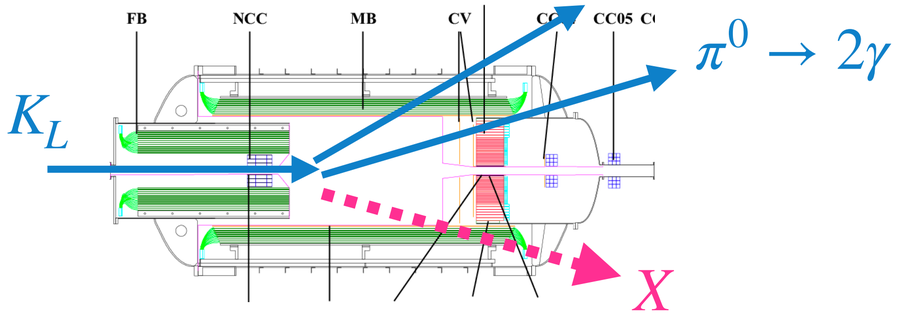
NA62 2103.15389

Effective violation of GN bound "lifetime gap"

- New particle X (CP even) decays into $\gamma\gamma$ (or e^+e^-) with finite lifetime

[TK, Okui, Perez, Soreq, Tobioka '20; Liu, McGinnis, Wagner, Wang '20; Liao, Wang, Yao, Zhang '20]





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

X seems long-lived in the KOTO detector

L = 150 m, E = 37 GeV

L = 3 m, E ~ 1.5 GeV

Effective violation of GN bound “lifetime gap”

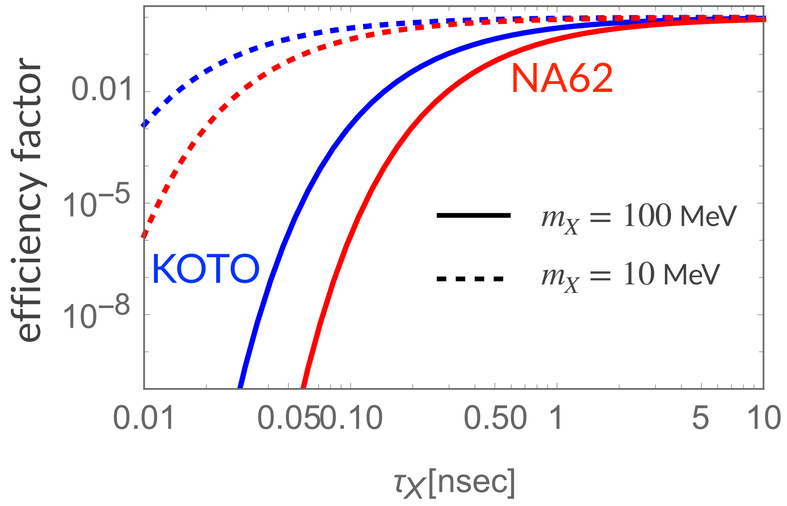
- Probability that *X* does not decay in the detector volume

  = efficiency factor that *X* looks missing neutrinos

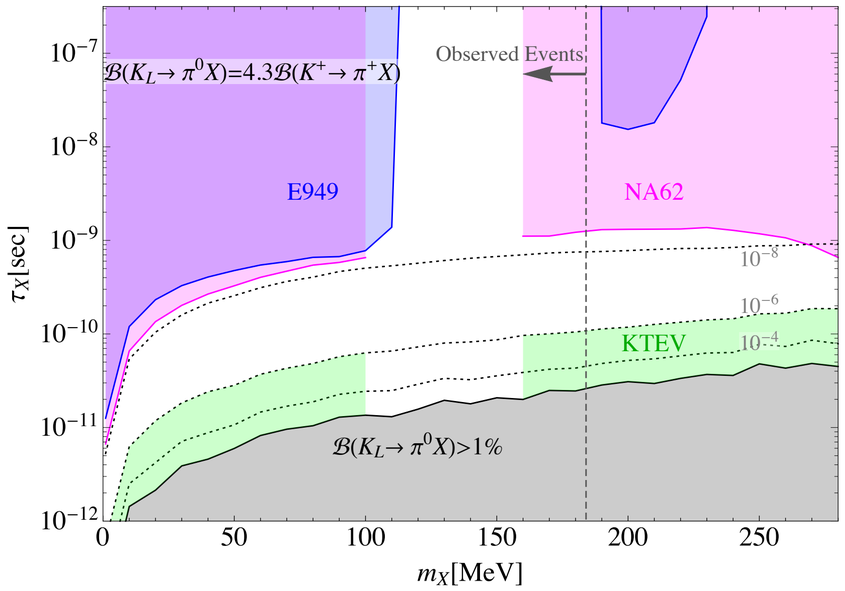
$$P = \exp(-\frac{L}{\gamma\beta\tau_X}) = \exp(-\frac{L}{(E_X/m_X)\beta\tau_X}) \simeq \exp(-\frac{Lm_X}{p_X\tau_X})$$

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

Efficiency difference
=
Effective violation of the GN bound



<Assuming 3 KOTO signals>



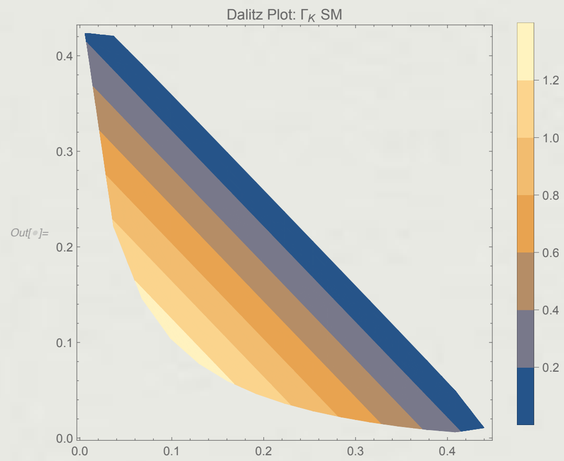
GN violation around Kinematic Distribution

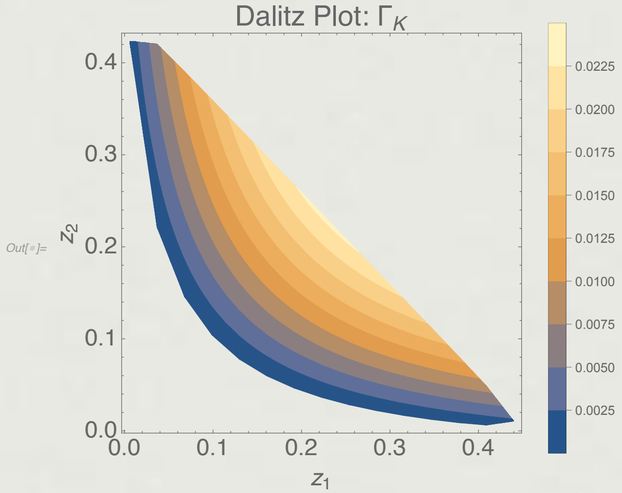
M. Fabbrichesi and E. Gabrielli [1911.03755]

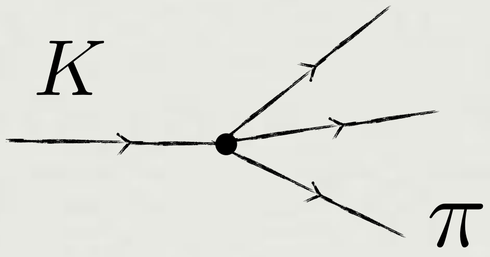
Marco's talk for Dark Photon section [5/10]

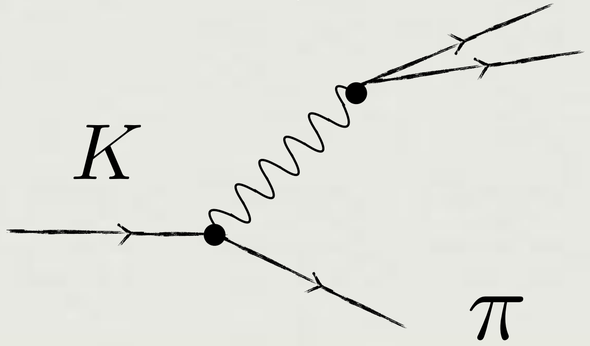
Light mediator changes missing mass distribution
Make K^+ bound less stringent

contact interaction
vs.
long distance

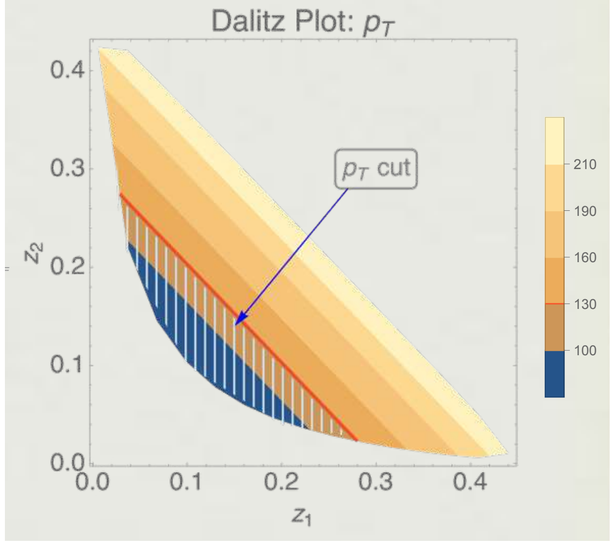








$K_L \to \pi^0 Q \bar{Q}$ KOTO



How to test?

"What we would learn, if the experiments do not find anything?"

"What would be a good target branching ratio for each signatures (such that null result is still interesting)?"

Difficult to answer these questions because we need to see signal in KL decay to set a scale.
Maybe appropriate questions for GN violating models.

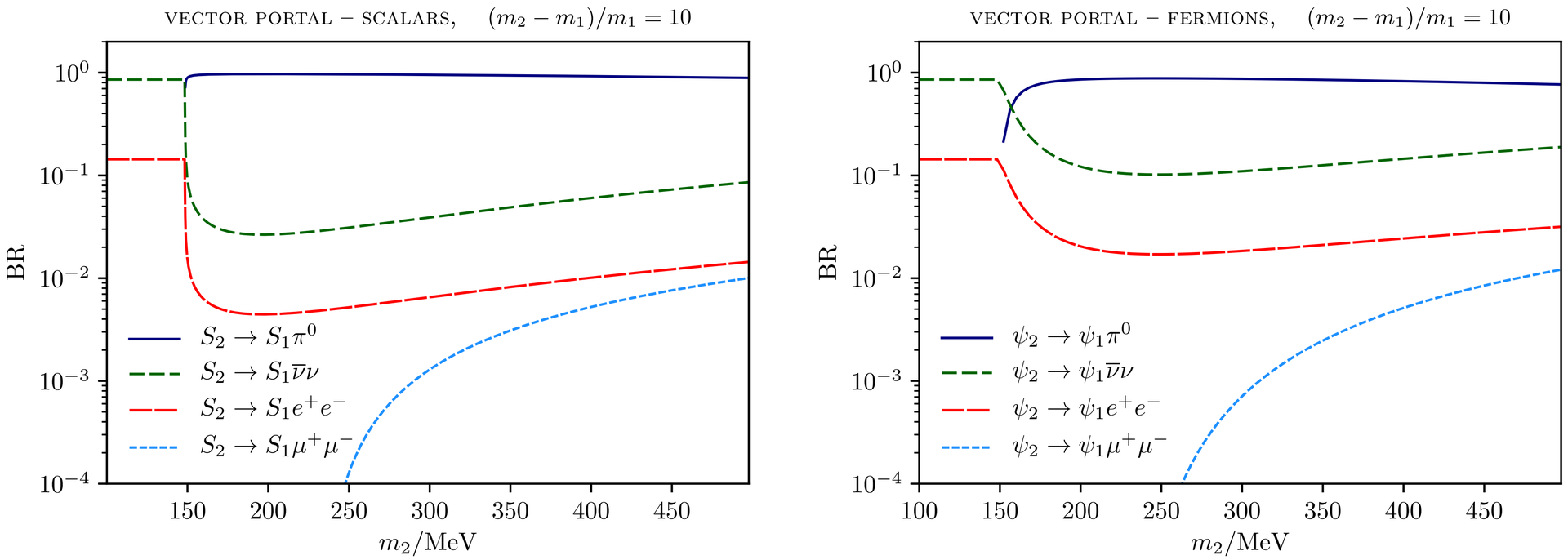
"What information from KL analysis will be useful?"

What happen if two photons are not from pi0?
For 3-body case, other kinematic distributions like massible invisible, long-distance contribution.
(2-body=single invisible is already tested.)

"How do we test the models in other signatures?"

Effective violation: $K^+ \to \pi^+$ inv. Fill pi0 gap. Simply more precise measurements will be useful.
Fundamental violation: "No sign in $K^+ \to \pi^+$ inv" is an important criteria.
Then other signature? X decay to e^+e^-? B decay (assuming MFV)? K_S physics?
$B \to K X_1 X_2 \to K \gamma \gamma$ +inv Beam dump?

Backup


VECTOR PORTAL – SCALARS, $(m_2 - m_1)/m_1 = 10$
BR
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
150
200
250
300
350
400
450
m_2/MeV
$S_2 \to S_1\pi^0$
$S_2 \to S_1\overline{\nu}\nu$
$S_2 \to S_1 e^+e^-$
$S_2 \to S_1\mu^+\mu^-$
VECTOR PORTAL – FERMIONS, $(m_2 - m_1)/m_1 = 10$
BR
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
150
200
250
300
350
400
450
m_2/MeV
$\psi_2 \to \psi_1\pi^0$
$\psi_2 \to \psi_1\overline{\nu}\nu$
$\psi_2 \to \psi_1 e^+e^-$
$\psi_2 \to \psi_1\mu^+\mu^-$