PHENO 2020

FROM THE INFRARED TO THE ULTRAVIOLET

PAIR PRODUCTION OF DARK PARTICLES IN MESON DECAYS

IN COLLABORATION WITH

MAXIM POSPELOV & KUNIO KANETA

APPEARING SOON (2005.XXXX)

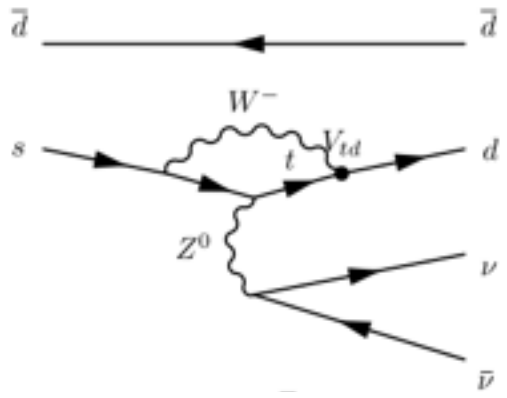
LATEST TOPICS IN PARTICLE PHYSICS

UNIVERSITY OF MINNESOTA

Matheus Hostert
University of Minnesota
& Perimeter Institute

PERIMETER INSTITUTE

FCNC: short-distance, loop-level, CP-violating, GIM suppressed process.



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

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

Grossman-Nir bound
(isospin & lifetime)

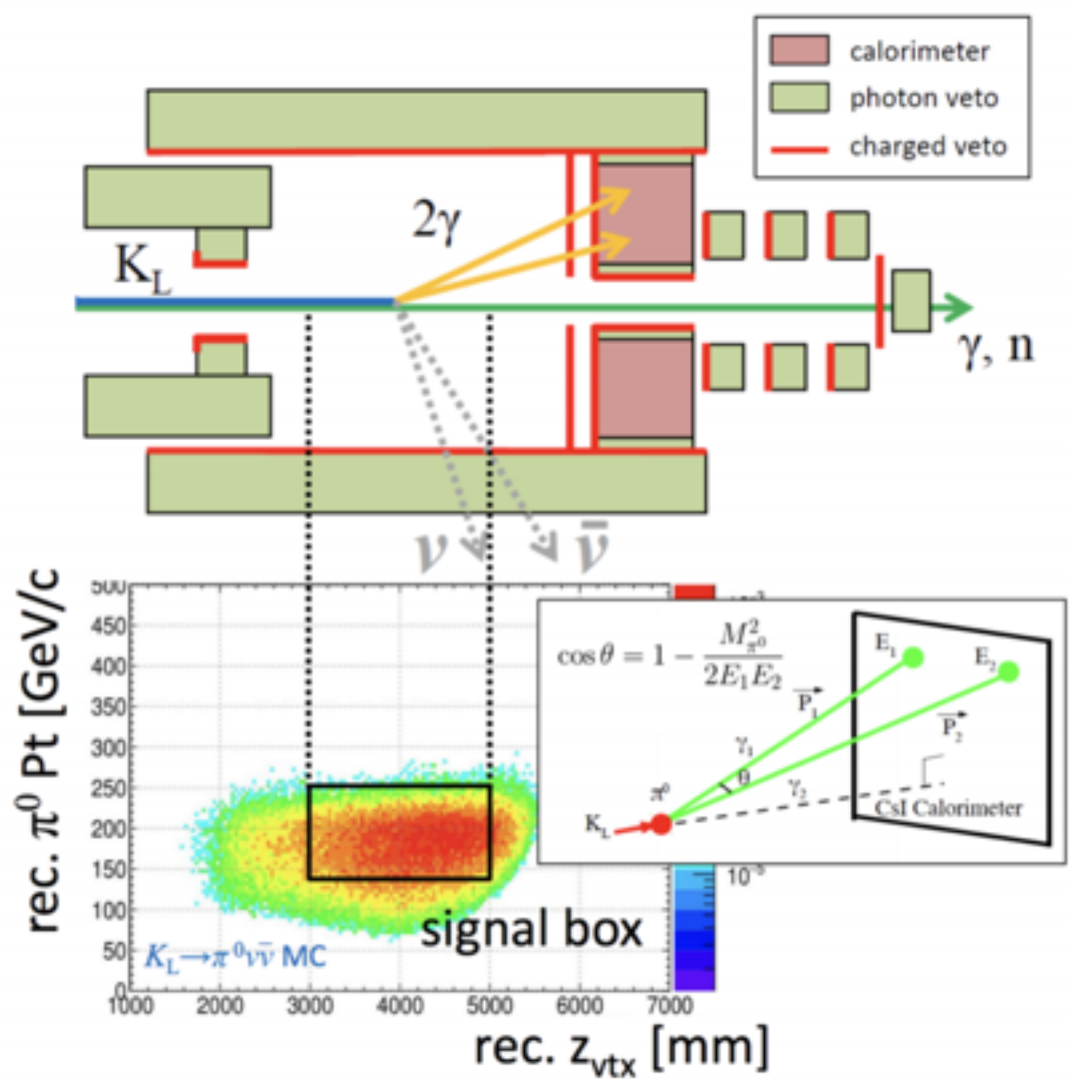
$$\mathrm{BR}\left(\mathrm{K_L} \to \pi^0\overline{\nu}\nu\right) < 4.4 \times \mathrm{BR}\left(\mathrm{K}^+ \to \pi^+\overline{\nu}\nu\right).$$

	past	current	future
K^+	**Measured** @ E787/E949 (40 - 60%)	NA62(2016/17 data) < 1.85e-10 @ 90 C.L.	NA62(all) towards 10%
K_L	KOTO(2015 data) @ J-PARC BR < 3e-9	KOTO(2016/18) unblinding **4 events** **< 1 expected backgrounds**	KOTO(2019 data) + KOTO *Gen.*2 202(?) KLEVER @ CERN

KOTO

- hermetic C and γ vetoes
- large *rec* P_T
- decay region *rec* Z_{vtx}
- pencil beam → assumes (x,y)=(0,0)

No 3-momentum is directly measured*

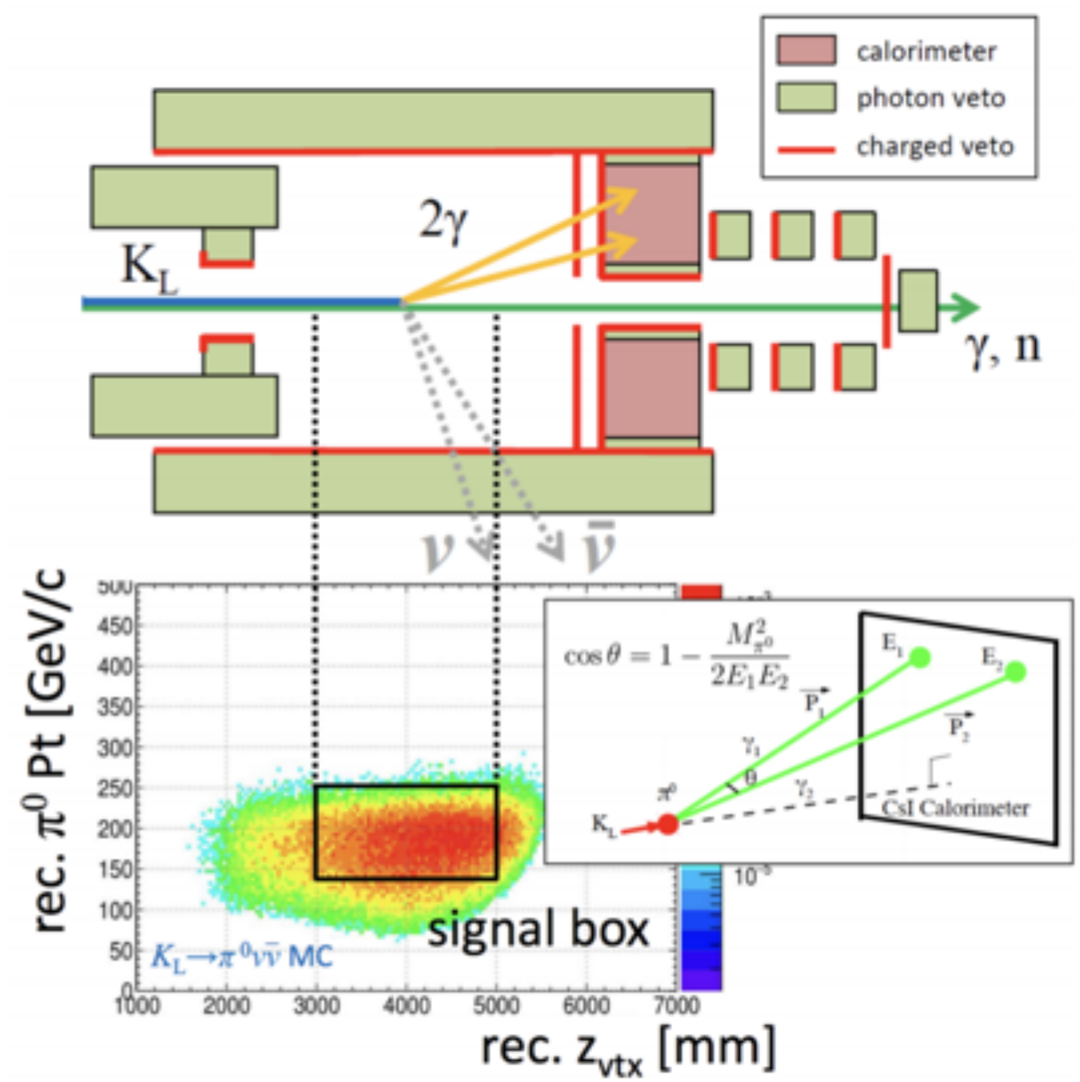


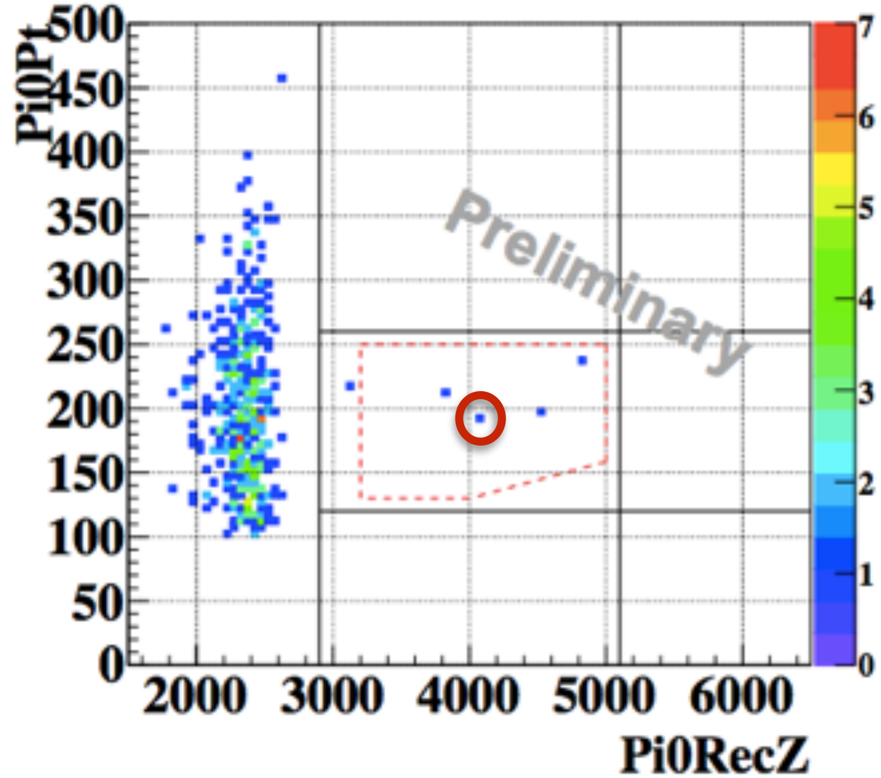
*except to reconstruct position of incidence of gammas on ECAL surface.

KOTO

- hermetic C and γ vetoes
- large *rec* P_T
- decay region *rec* $Zvtx$
- pencil beam → assumes (x,y)=(0,0)

No 3-momentum is directly measured*





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 π⁰	0.00±0.01
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

1 event attributed to overlapped pulse bkg,
3 events still under study, awaiting publication

S. Shinohara for KOTO coll. @ KAON2019

If confirmed → 60x larger BR than in the SM

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

(unofficial BR)

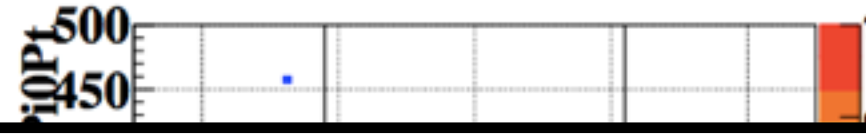
T. Kitahara et al, PRL 124, 071801 (2020)

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

KOTO

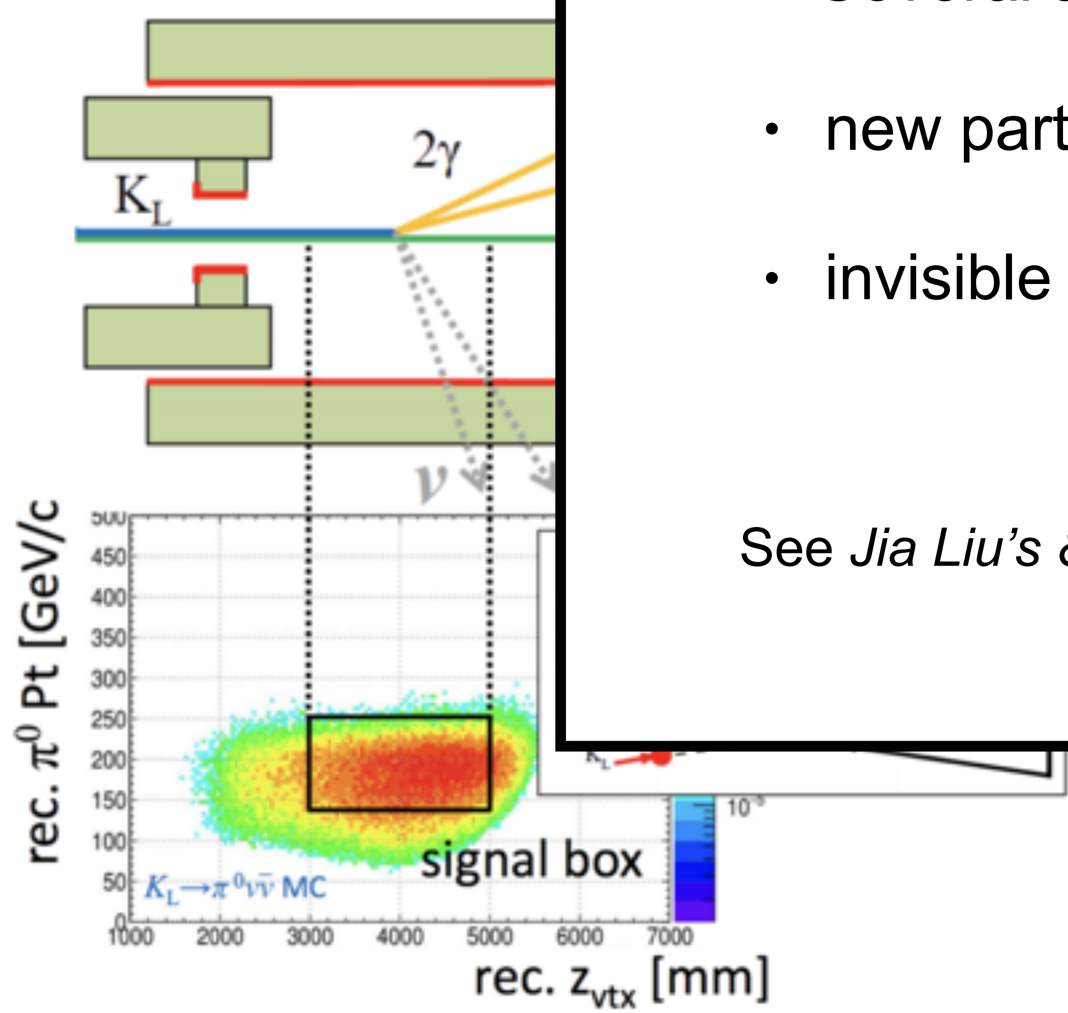
- hermetic C and γ vetoes
- large *rec* P_T
- decay region *rec* ...
- pencil beam → as...

No 3-momentum ...



Preliminary

	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
...pi0 ...rlapped ...e)	<0.04
... (overlapped ...e)	<0.09
...gamma	0.00 ± 0.00
...tream π^0	0.00±0.01
...ron cluster	0.02 ±0.00
...pi0	<0.10
...eta	0.03±0.01
...l	0.05±0.02



If true, grossly violates GN bound

Several alternative discussed so far:

- new particles produced at the target
- invisible X production

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

See *Jia Liu's & Samuel Homiller's* slides from today!

... pulse bkg,
...g publication

...ON2019

...n in the SM

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

(unofficial BR)

T. Kitahara et al, PRL 124, 071801 (2020)

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

We want to revisit **pair** production of dark sector particles in K and B meson decays.

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

SM singlets (dark states)

1) Y_{SM} may be ∅ for neutral mesons (2-body) vs Y_{SM} charged for charged mesons (3-body).

- If X_1 and X_2 stable, very weak bounds (BR < $O(10^{-4})$ for K_L).
- If X_2 unstable, still challenging, but may produce $\pi^0, \ell^+\ell^-, \gamma\gamma, \ldots$
- Note the f_B/m_B suppression in 2-body B decays. Instead $B \to K X_1 X_2$ may be relevant as $|V_{tb}^* V_{ts}| \gg |V_{ts}^* V_{td}|$.

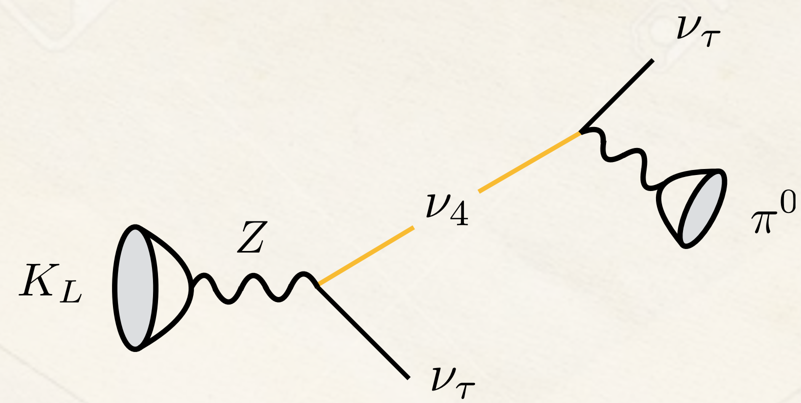
Can pair production w/ $X_2 \to$ pi0-like signatures enhance the rate for

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

A neutrino *sanity check*:

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

… but rate is much enhaced for “Type-I Seesaw” HNL



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

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

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

Once the constraints on the mixing are included:

BR ~ few x 10^{-11} (not too far from SM!) and tens of meters lifetimes.

Can expect larger enhancements for 10’s of GeV-scale mediators & purely “dark” pairs.

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

Higgs portal: Real scalars w/ $\mathcal{L} \supset \mu\, H^\dagger H S_3 + \mu_S\, S_1 S_2 S_3$

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

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

Vector portal: Require mixing w/ SM Z^0 boson (*mass mixing*)*:

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

effective coupling to NC + dark sector

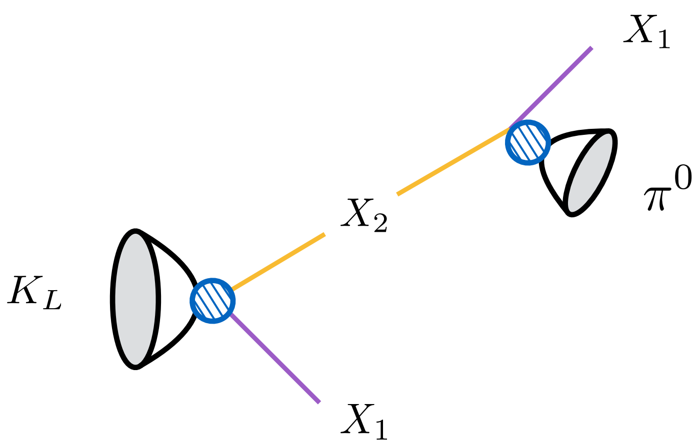
$$\mathcal{L} \supset \frac{\varepsilon_Z g}{2\cos\theta_W} J^{\mathrm{NC}}_\mu Z'^\mu + g_X Z'_\mu \left(c_V \overline{\psi_2}\gamma^\mu \psi_1 + c_A \overline{\psi_2}\gamma^\mu\gamma_5\psi_1 + \mathrm{h.c.}\right)$$

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

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

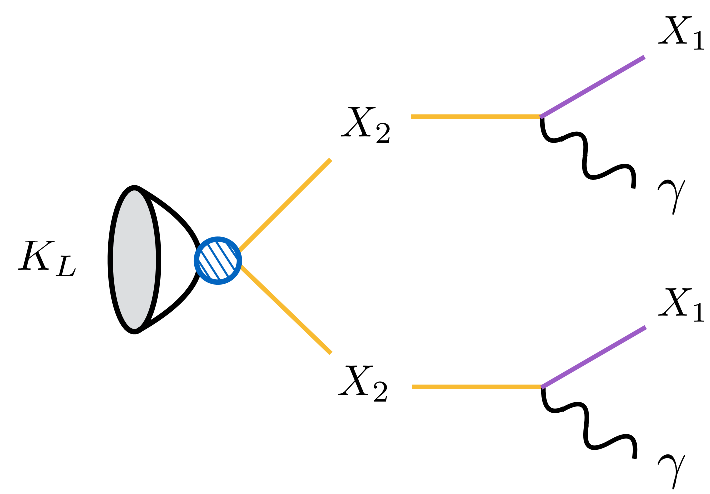
* "dark photons" can only couple through $(m_{Z'}/m_Z)^2$ hypercharge coupling or much suppressed photon penguins.

Three distinct possibilities to fake a $K_L \to \pi^0 \overline{\nu}\nu$ signature



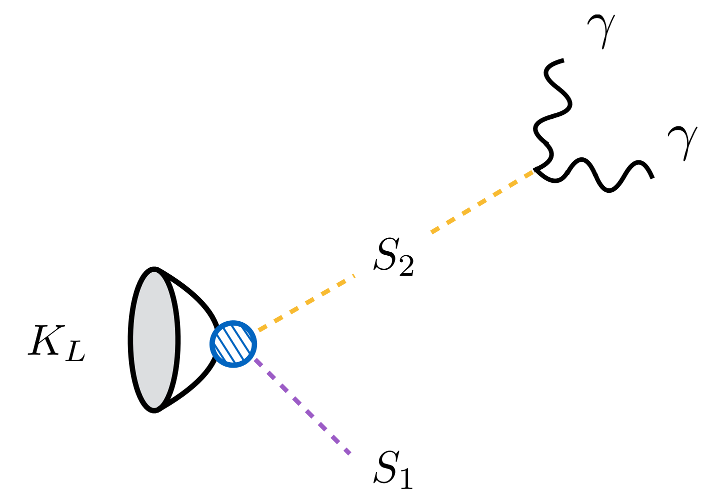
A) π^0 production

Z-Z' mixing for decay
(same as production)



B) dipole portal

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



B) π^0impostor

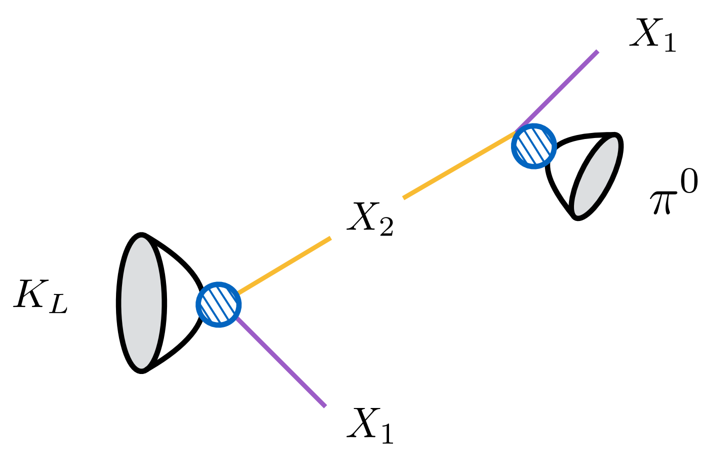
$$\lambda_\Psi \overline{\Psi} i\gamma_5 \Psi S_2$$

↓

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

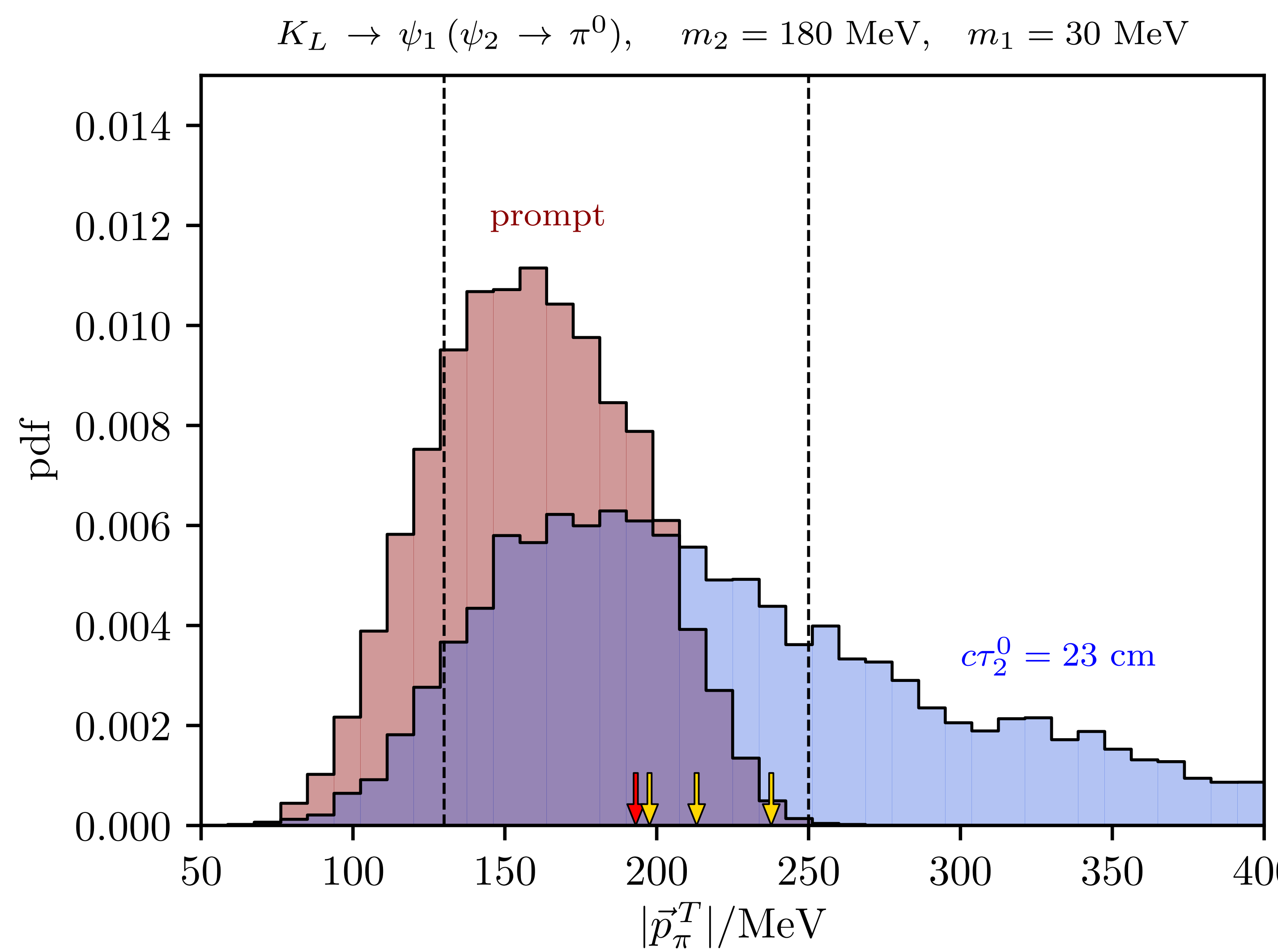
* note that "dark photons" can only couple through $(mZ'/mZ)^2$ hypercharge coupling or much suppressed photon penguins.

At KOTO, such events are reconstructed as



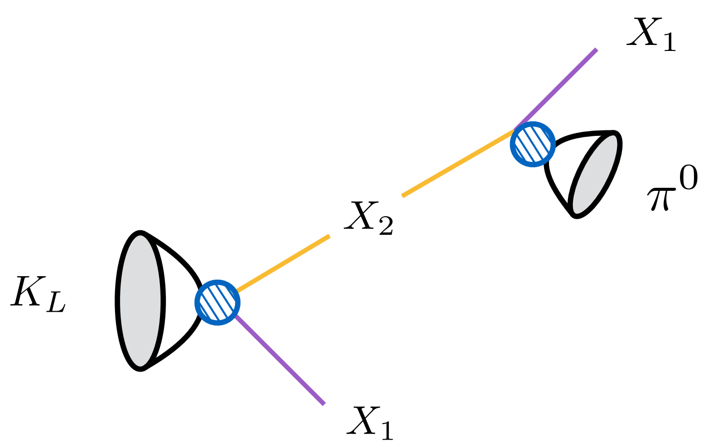
A) π^0 **production**

Z-Z' mixing for decay
(same as production)



Analysis assumes decay occurs along the center of the beam:
— mis-reconstruction of pT —

* note that "dark photons" can only couple through (mZ'/mZ)² hypercharge coupling or much suppressed photon penguins.

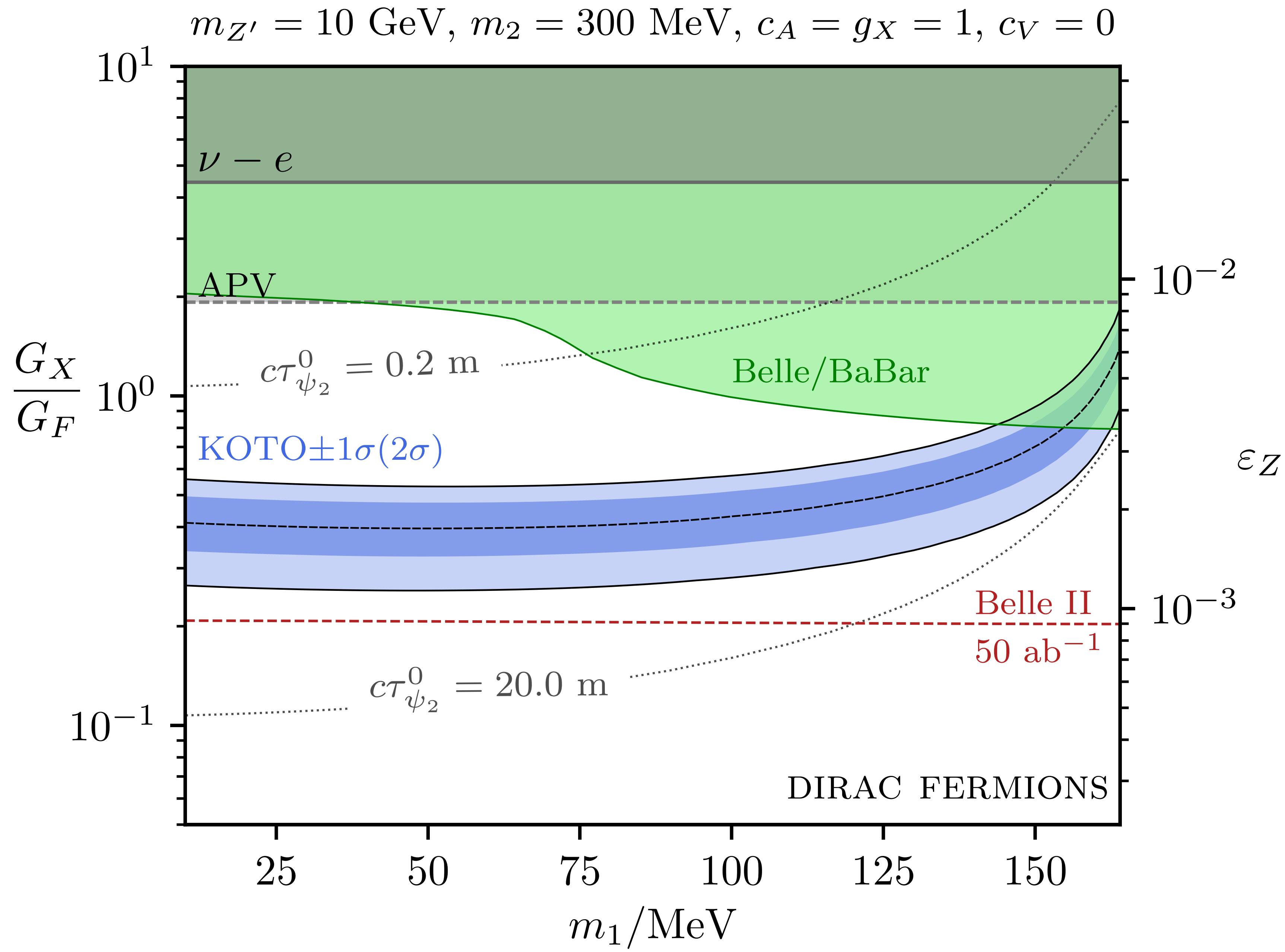


Heavier dark state may also decay invisibly (BR ~ 10%)

Belle @ 90 C.L.

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

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



Belle-II at full luminosity with 10% measurement of

$$B \to K\not{E}$$

is sensitive to our hypothesis (at 1σ)

CONCLUSIONS

- Enormous progress in K,B missing energy decays.
- Hints from the KOTO? — possible violation of GN bound?
  - **New loophole to avoid GN:** pair production of dark states
    - Scalar portals typically require new (DS - SM) interactions, but possible.
    - Vector portals require ONE coupling combination ~ $g_X \varepsilon_Z$
    - Achieve large pT by mis-reconstruction.
  - Very **testable scenario** — explored predictions for $B \to K \not{E}$
  - Many other scenarios for pair production, e.g., via $K_L - \pi^0, K_L - \eta$ mixing, etc.

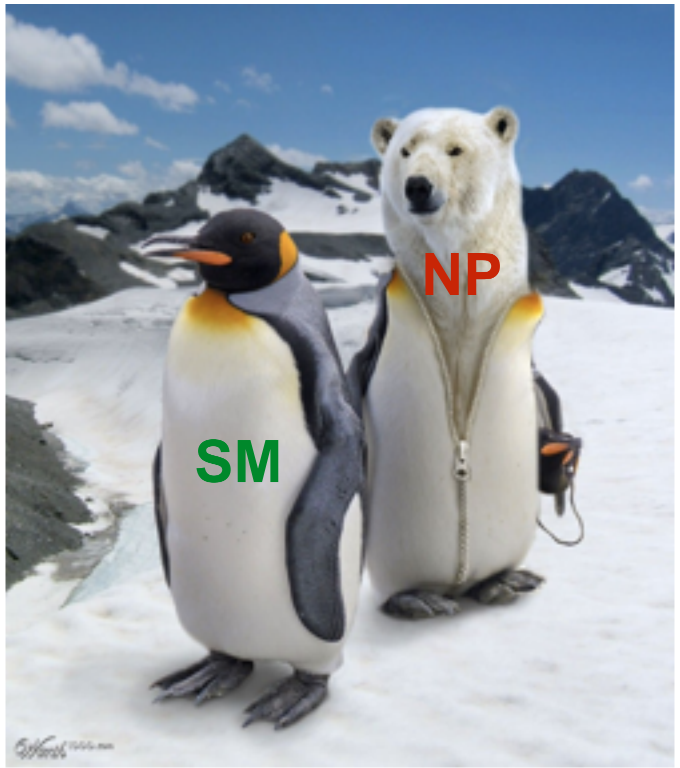
Stay tuned!

Appendix

Mediator scale >> meson masses:
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 mechanism for 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:

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