Probing new physics in kaon rare decay

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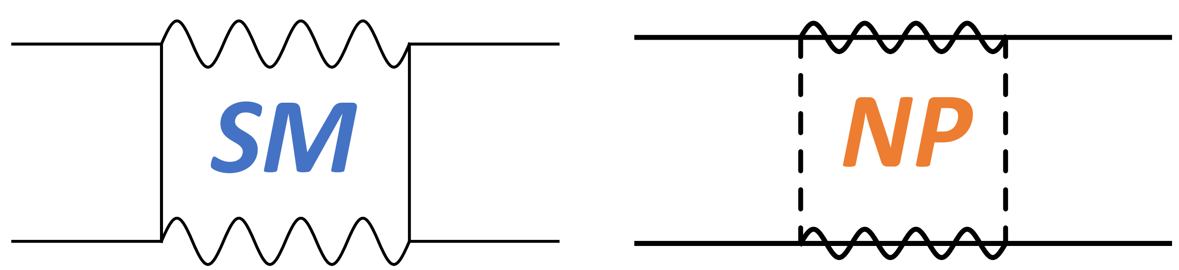
Kaon and NP

- No clear evidence of New physics so far. Intensity frontier plays an important role

- Kaon observables are sensitive to NP at a very high scale, which is not accessible at the LHC

FCNC and CP violation in Kaon system are suppressed in the SM



If $|C_{\rm NP}| \sim 1$

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \frac{1}{\Lambda_{NP}^2} \sum_i C_i \mathcal{O}_i^{\rm dim6} \qquad \Lambda_{\rm NP} \sim \begin{cases} \mathcal{O}(10^5\,{\rm TeV}) & : K^0 \\ \mathcal{O}(10^4\,{\rm TeV}) & : D^0 \\ \mathcal{O}(10^3\,{\rm TeV}) & : B_{d,s} \end{cases}$$

Kaon rare decay : $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$

- Extremely rare and precise process in SM → Golden modes

  ▶ Very rare decays **BR~10⁻¹¹** (Loop, GIM and CKM)

  ▶ Theoretically clean (Absence of virtual photon contribution, Hadronic matrix elements obtained from $BR(K_{\ell 3})$ with isospin symmetry)

SM predictions Brod, Gorbahn and Stamou [2105.02868], Buras, Buttazzo, Girbach-Noe, Knegjens [1503.02693]

$$BR(K_L \to \pi^0 \nu \bar{\nu})_{SM} = 2.59(29) \times 10^{-11}$$

$$BR(K^+ \to \pi^+ \nu \bar{\nu})_{SM} = 7.73(61) \times 10^{-11}$$

CKM error dominant

On-going experiments → Talk by Shiomi

BR(K_L) KOTO @J-PARC

will reach SM sensitivity 2025
O(100) SM events in KOTO step 2

BR(K^+) NA62 @CERN

20 SM events are expected with Run1(2016-18)
Run2(2021-2024)

$K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$ in the SM

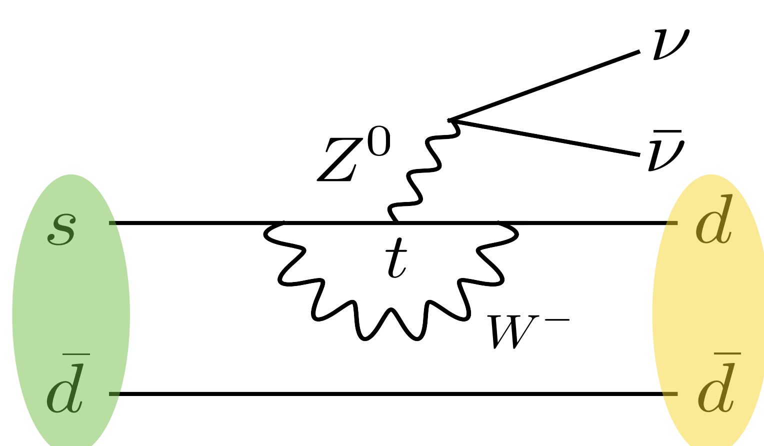
- $K_L \to \pi^0 \nu \bar{\nu}$ is CP-violating process in the SM [see e.g. Bronco, Lavoura, Silva, CP Violation]

  - Lepton flavor conserved (ν and $\bar{\nu}$ have same flavor : $\nu_i \bar{\nu}_i$) → CP eigenstate
  - V-A structure

almost CP odd K_L

$K_L \sim (K^0 - \bar{K}^0)/\sqrt{2}$

$CP\,|K^0\rangle = +\,|\bar{K}^0\rangle$



π^0

: dominant operator $\bar{\nu}\gamma^\mu(1-\gamma_5)\nu$
→ CP odd

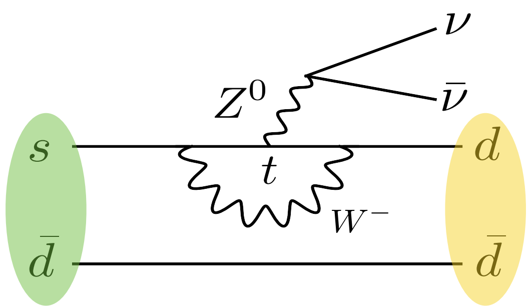
: Pseudo scalar 0^{+-}
→ CP odd

→ CP even

CP odd → CP even : CP violate

  - In the SM, CP-conserving contribution is negligible [Buchalla, Isidori, hep-ph/9806501]
  - CP-conserving effect can be induced from NP (e.g. mediated by scalar, Lepton flavor violation)

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in the SM

$X \sim$ 

+ Box contributions

$K_L \to \pi^0 \nu\nu$ $\propto F_0(\mathrm{ImX})^2$

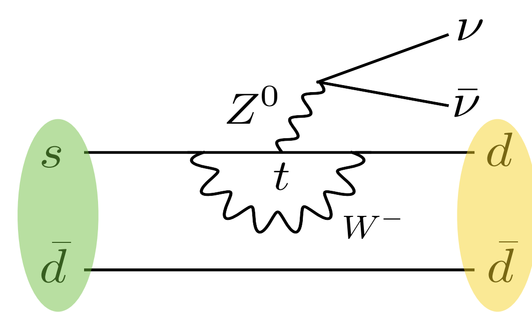
CP-violating

$K^+ \to \pi^+ \nu\nu$ $\propto F_+ |X|^2$

CP-conserving

F_0, F_+ : Form factors

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in the SM

$X \sim$  + Box contributions

$K_L \to \pi^0 \nu\nu$ $\propto F_0(\mathrm{ImX})^2$ $\propto \eta^2$

CP-violating

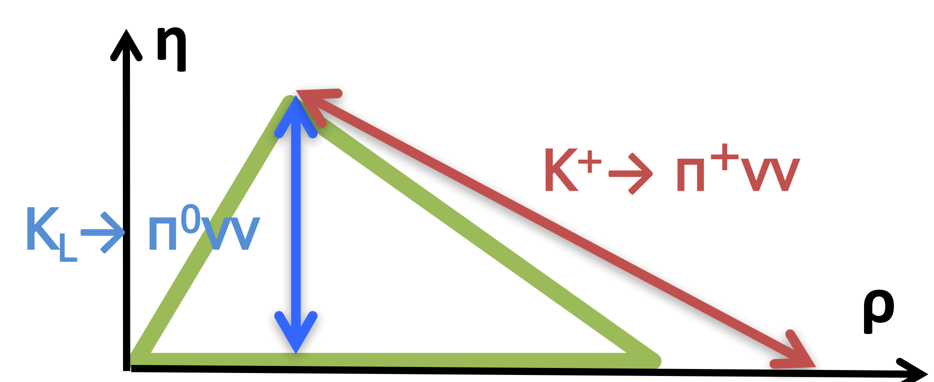
η, ρ : CKM parametr

$K^+ \to \pi^+ \nu\nu$ $\propto F_+|X|^2$ $\propto [(\bar{\rho} - \rho^0)^2 + \bar{\eta}^2]$

CP-conserving

F_0, F_+ : Form factors

- Both channel can determine the CKM unitarity triangle independently from B meson obs.



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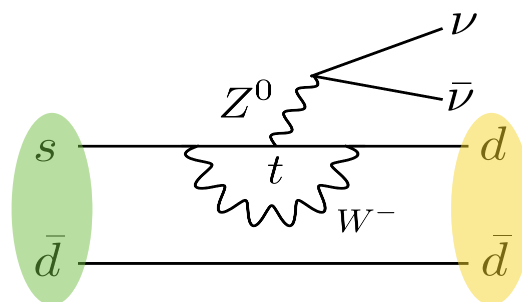
$X \sim$  + Box contributions

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CP-violating

$K^+ \to \pi^+ \nu\nu$ $\propto F_+|X|^2$

CP-conserving

isospin relation →

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

F_0, F_+ : Form factors

→ $F_0 \sim F_+$ because of isospin symmetry (ΔI=1/2)

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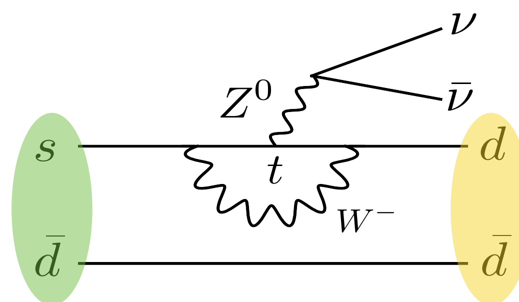
$X \sim$



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$\tau_{K_L}/\tau_{K_+} \sim 4.17$

and isospin breaking correction

F_0, F_+ : Form factors

→ $F_0 \sim F_+$ because of isospin symmetry (ΔI=1/2)

$$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} \leq 4.3$$

Grossman-Nir bound

Model-independent theoretical bound

[Grossman, Nir, hep-ph/9701313]

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in the SM+NP

- NP effects in K_L and K^+ decay are highly correlated generically

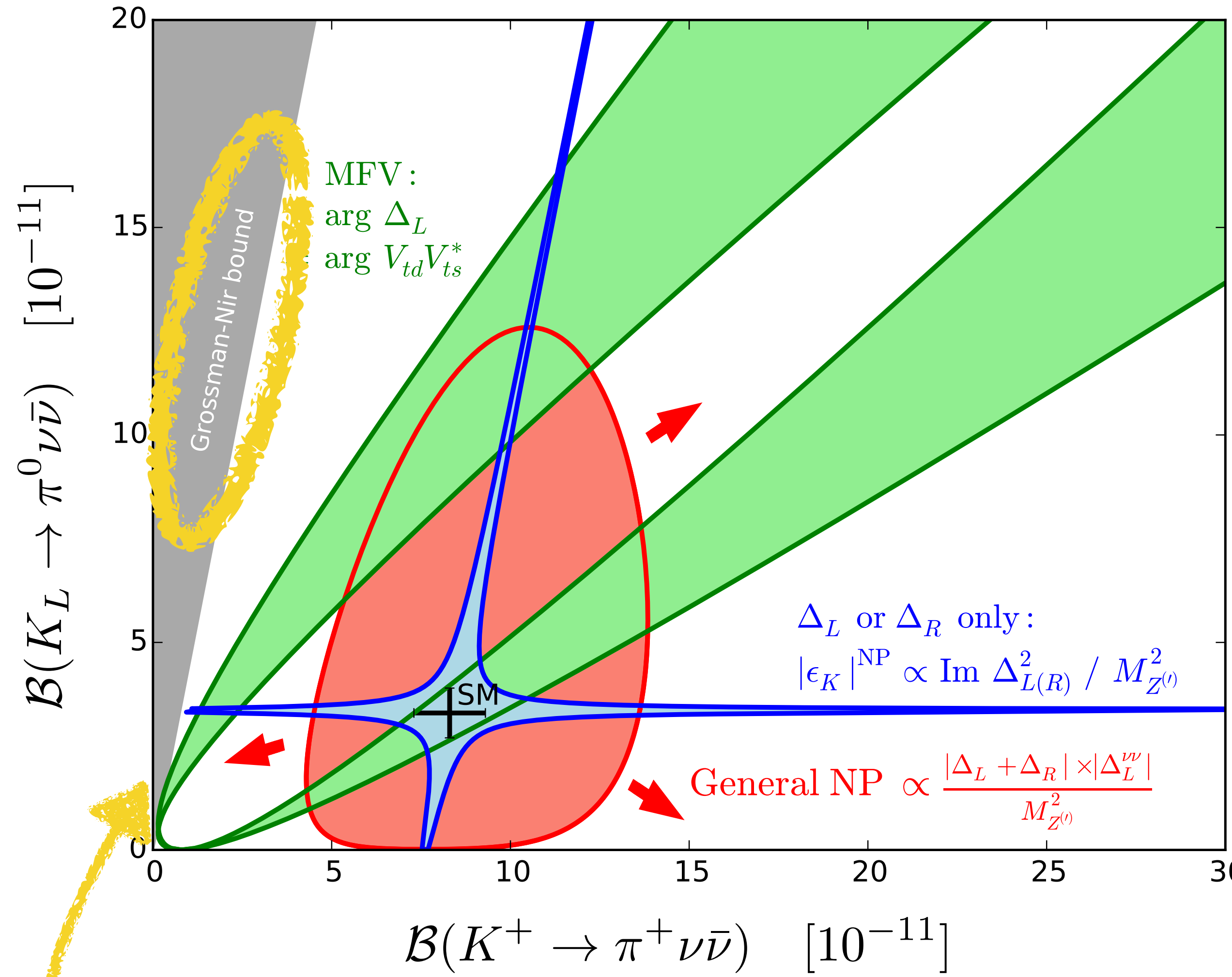
- Isospin relation (ΔI=1/2) is used

$$\frac{\langle \pi^0 | \mathcal{O}_{\Delta I=1/2} | \bar{K}^0 \rangle}{\langle \pi^+ | \mathcal{O}_{\Delta I=1/2} | K^+ \rangle} = \frac{1}{\sqrt{2}}$$

ΔI=3/2 interaction (e.g. dim9 ope) violates GN bound

- GN bound is hold for lepton flavor violating scenario : $\nu_i \bar{\nu}_j (i \neq j)$

[Buras, Buttazzo, Knegjens, 1507.08672]



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Grossman-Nir bound

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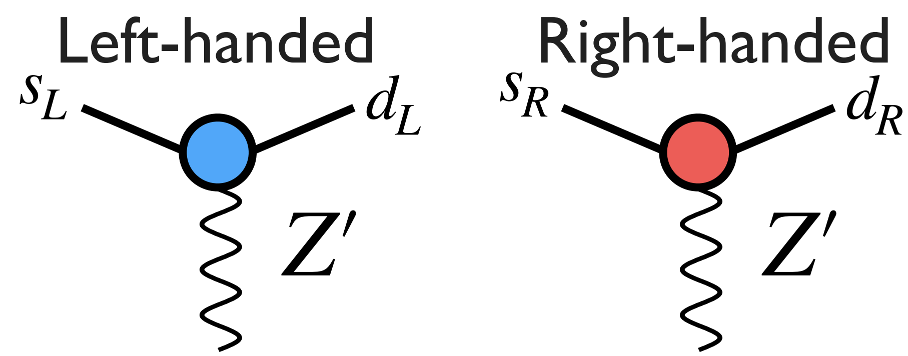
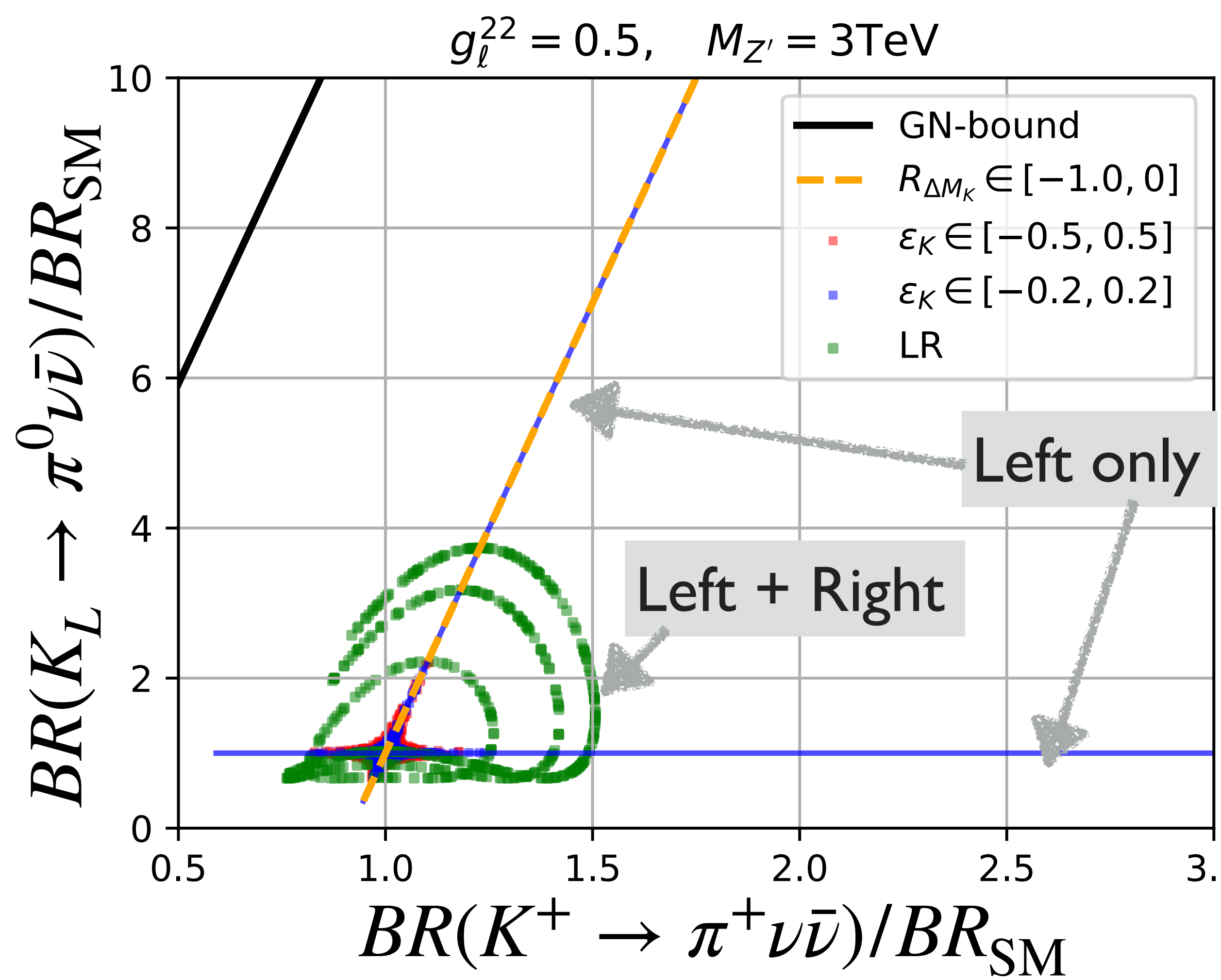
Impact of $K \to \pi\nu\bar{\nu}$ on NP

e.g.) Z' model



- Correlation btwn BR(KL) and BR(K+)

[Aebischer, Buras, Kumar, 2006.01138]



Left or Right scenario

tight constraint from ϵ_K

→strong correlation btwn BR(KL) and BR(K+)

Left + Right scenario

possible cancellation in ϵ_K

→no strong correlation

Same features in various NP model like MSSM and Randall-Sundrum models

provide model-independent test for NP at scale ~O(100 TeV)

Impact of $K \to \pi\nu\bar{\nu}$ on NP

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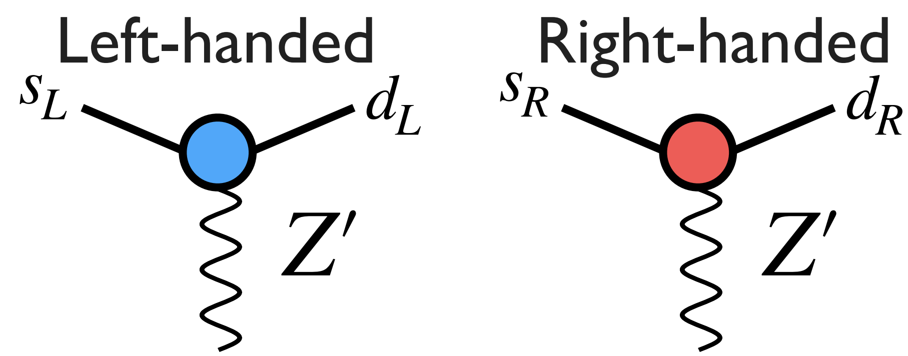
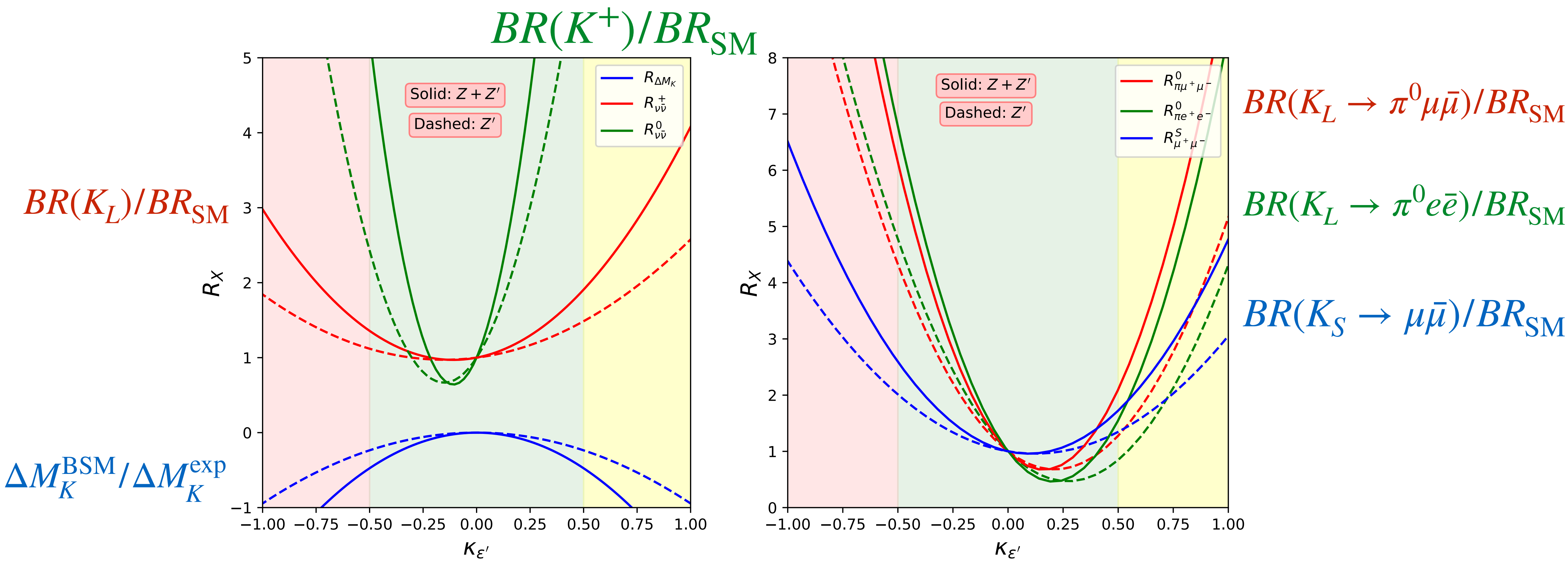


[Aebischer, Buras, Kumar, 2006.01138]

- Correlation with others



$(\epsilon'/\epsilon)_{NP} = \kappa_{\epsilon'} \cdot 10^{-3}$ (RBC-UKQCD 2020, the room left for BSM)

With improved measurements it will be possibly to select the favorite scenarios

Hot topics related to $K \to \pi\nu\bar{\nu}$ last few years

$\mathcal{O}(1)$ NP in ϵ'/ϵ ?

ϵ'/ϵ : Direct CPV in $K \to \pi\pi$

Deviation btw SM with lattice and data (2015)

→ New lattice results is consistent (2020)

KOTO "excess"?

3 events observed (2019)

~3σ tension?

→ BG consistent (2020)

Correlation, CPV

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

Dark sector search

$= K \to \pi X$

X : invisible particle

Different flavor

B anomaly

Lepton flavor universality violation
in B semi-leptonic decays (2015-)

Various NP models have been studied though not referred here

Hot topics related to $K \to \pi\nu\bar{\nu}$ last few years

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Correlation, CPV

Dark sector search

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

X : invisible particle

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in B semi-leptonic decays (2015-)

Various NP models have been studied though not referred here

Connection with B anomaly

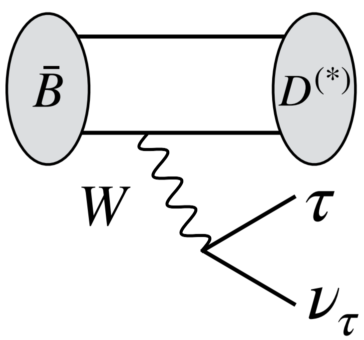
Lepton Flavor Universality Violation in semi-leptonic B decays have been reported by Belle and LHCb

$b \to c\tau\nu$ $\quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Tree-level in SM

LFUV in τ vs μ/e

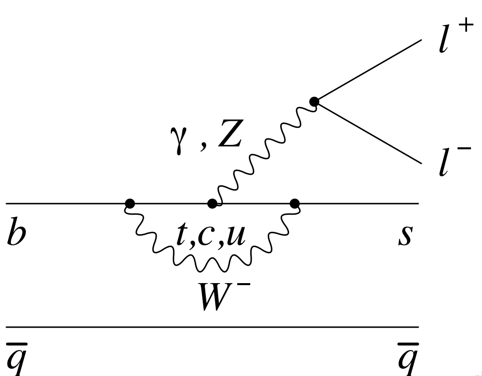


$b \to s\ell\ell$ $\quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

loop-level in SM

LFUV in μ vs e



Model independent consideration for B anomalies → NP couples to **3rd** gen. strongly

$$\text{NP in } b \to \overset{\text{3rd gen.}}{c\tau\nu_\tau} \gg \text{NP in } b \to \overset{\text{2nd gen.}}{s\mu\mu}$$

Connection with B anomaly

- Natural link with LFUV effects in B, thanks to the presence of 3rd generation leptons in the final state

3rd gen.

$$BR(K \to \pi\nu\bar{\nu}) = BR(K \to \pi\nu_e\bar{\nu}_e) + BR(K \to \pi\nu_\mu\bar{\nu}_\mu) + BR(K \to \pi\nu_\tau\bar{\nu}_\tau)$$

Connection with B anomaly

[D'Ambrosio, Iyer 1712.0812 / Fajfer, Kosnik, Silva 1802.00786/
Matsuzaki, Nishiwaki and KY 1806.02312
Gherardia, Marzoccab, Nardecchia, Romaninoa 1903.10954, etc.]

e.g.) EFT approach with flavor symmetry

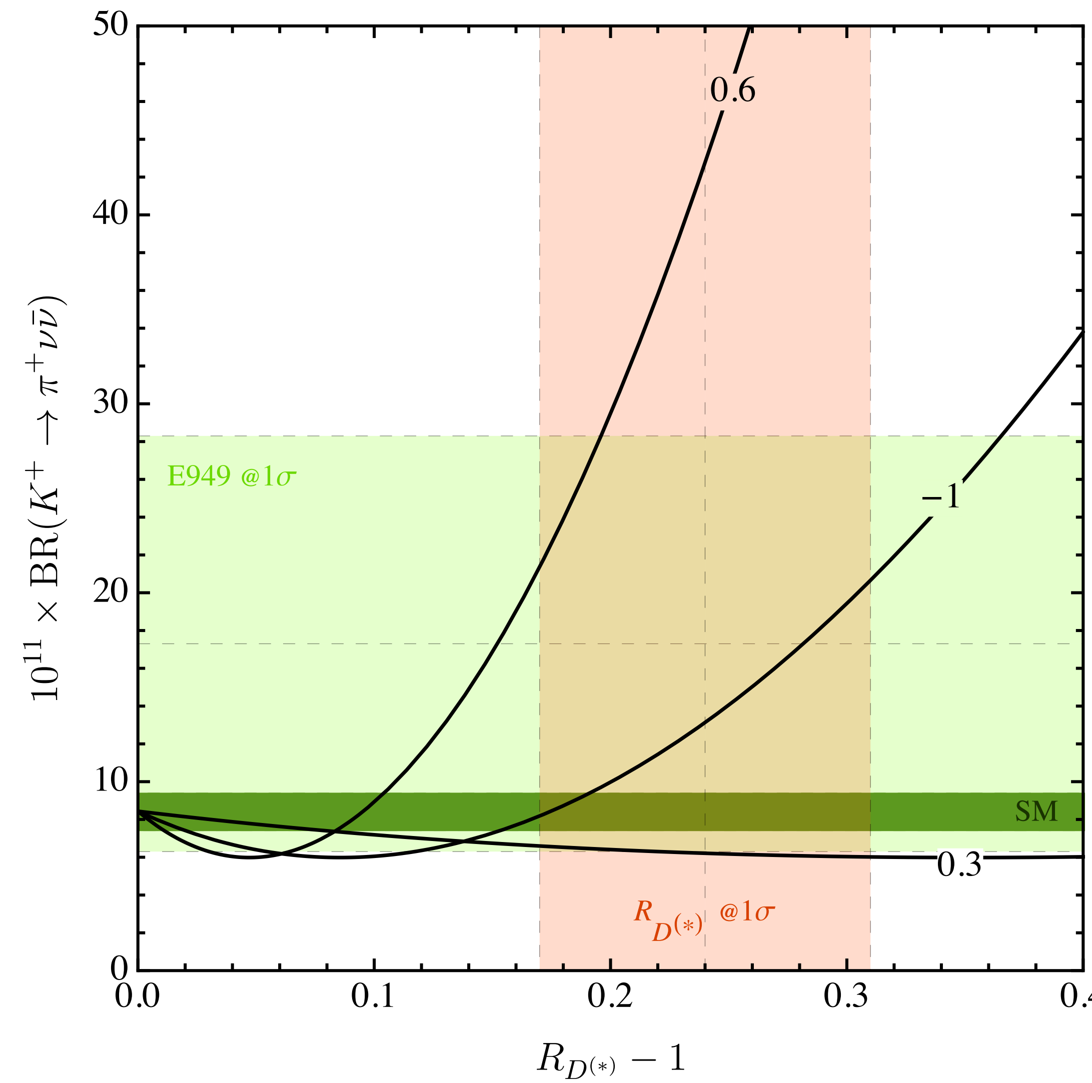
$U(2)$ flavor symmetry

B meson ⟷ Kaon

Correlation

There is strong constrain from $BR(B \to K^{(*)}\nu\bar{\nu})$, but do not exclude O(1) enhancements for $K^+ \to \pi^+\nu\bar{\nu}$

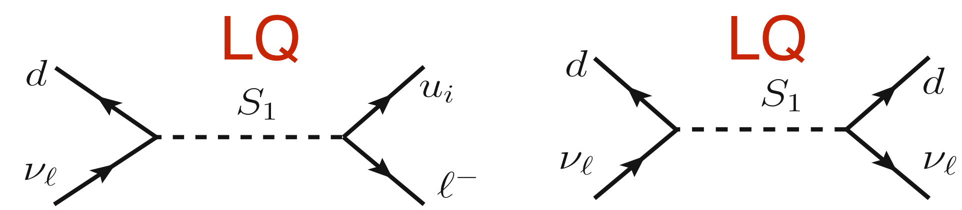
[Bordone, Buttazzo, Isidori, Monnard 1705.10729]



Connection with B anomaly

Leptoquark(LQ) solution (scalar and vector) is the best solution for B anomaly so far

LQ (GUT, Composite model, SUSY with R-parity violation)



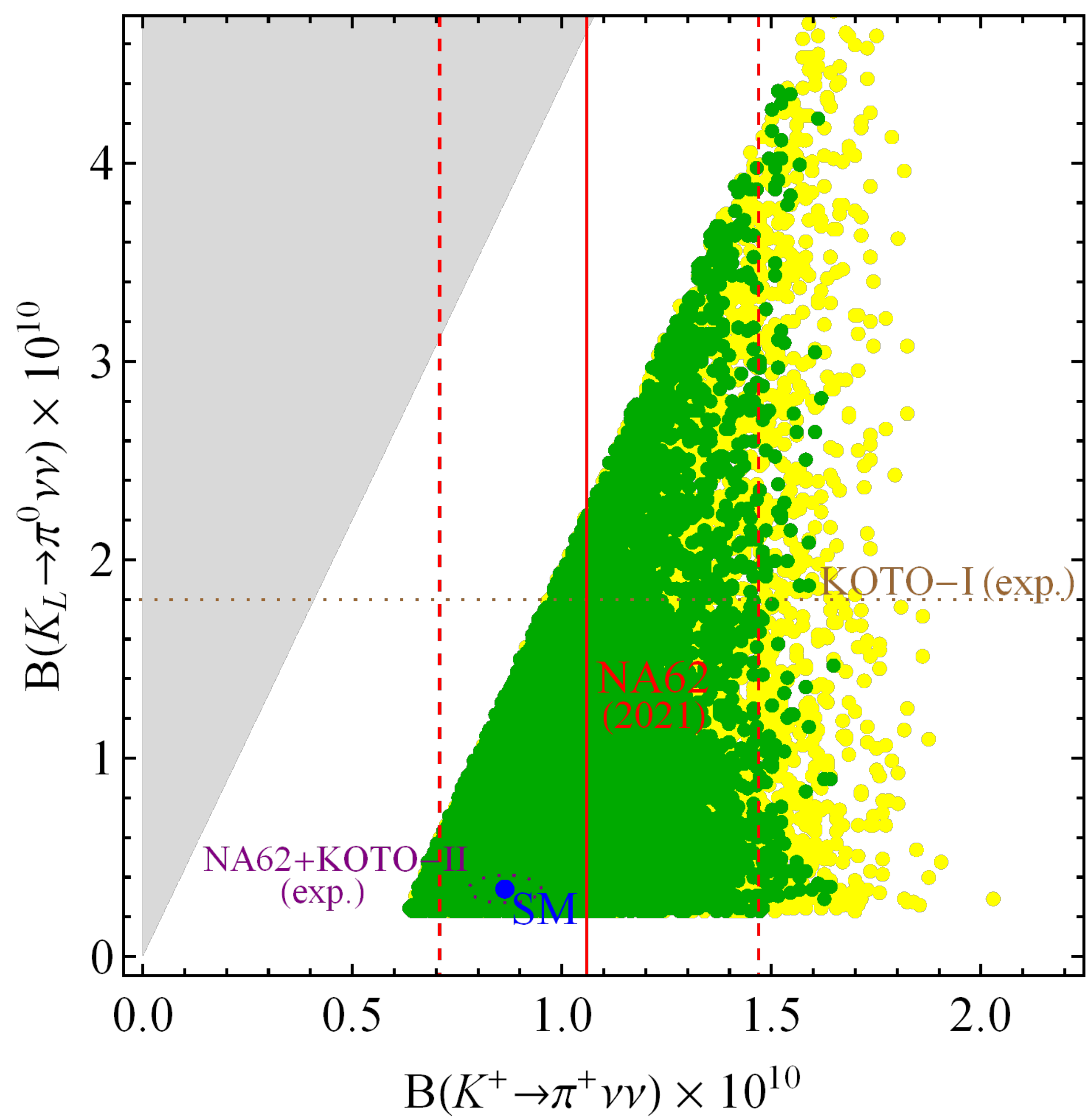
e.g.) $S_1 + S_2$ LQ model

w/o flavor symmetry

global fit at 68% (green) and 95% (yellow) CL

$BR(K_L \to \pi^0 \nu\bar{\nu})$ could potentially take values that can be probed by the end of stage 1 of the KOTO experiment

[Marzocca, Trifinopoulos, Venturini 2106.15630]



Summary

- Kaon rare decays $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ are Golden mode for NP

- Measurement $K \to \pi\nu\bar{\nu}$ will have impact on
  - CKM unitary triangle fit
  - High-scale NP
  - selection the favorite scenarios

- Hot discussions related to $K \to \pi\nu\bar{\nu}$ last few years

Lattice, Belle 2, LHCb