Istituto Nazionale di Fisica Nucleare

Workshop on status and perspectives of physics at high intensity
9 Nov 2022, 09:00 → 11 Nov 2022, 18:00
LNF, 9th November 2022

Physics of rare Kaon decays (Theory)

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Outline

- $K \to \pi\nu\nu$
- $K_{S,L} \to \mu\mu$
- $K \to \pi\ ee$
- arxiv:2206.14748 Lepton flavour violation in kaons

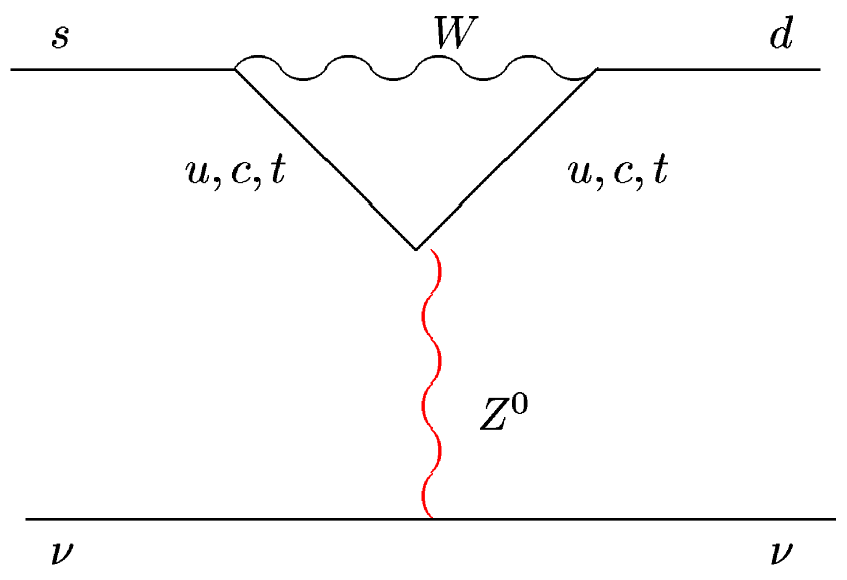
With A. Iyer, F. Mahmoudi, S.Neshatpour

e-Print: 2206.14748 [hep-ph] t JHEP

$K \to \pi\nu\overline{\nu}$

why we need HIKE and KOTO-2

$$A(s \to d\nu\overline{\nu})_{\mathrm{SM}} \sim \overline{s}_L\gamma_\mu d_L \quad \overline{\nu}_L\gamma^\mu\nu_L \quad \times \left[\sum_{q=c,t} V^*_{qs}V_{qd}\, m_q^2\right]$$



$$\sim \quad \left[A^2\lambda^5\ (1-\rho-i\eta)m_t^2 + \lambda m_c^2\right]$$

SM $\underbrace{V-A\otimes V-A}$ Littenberg

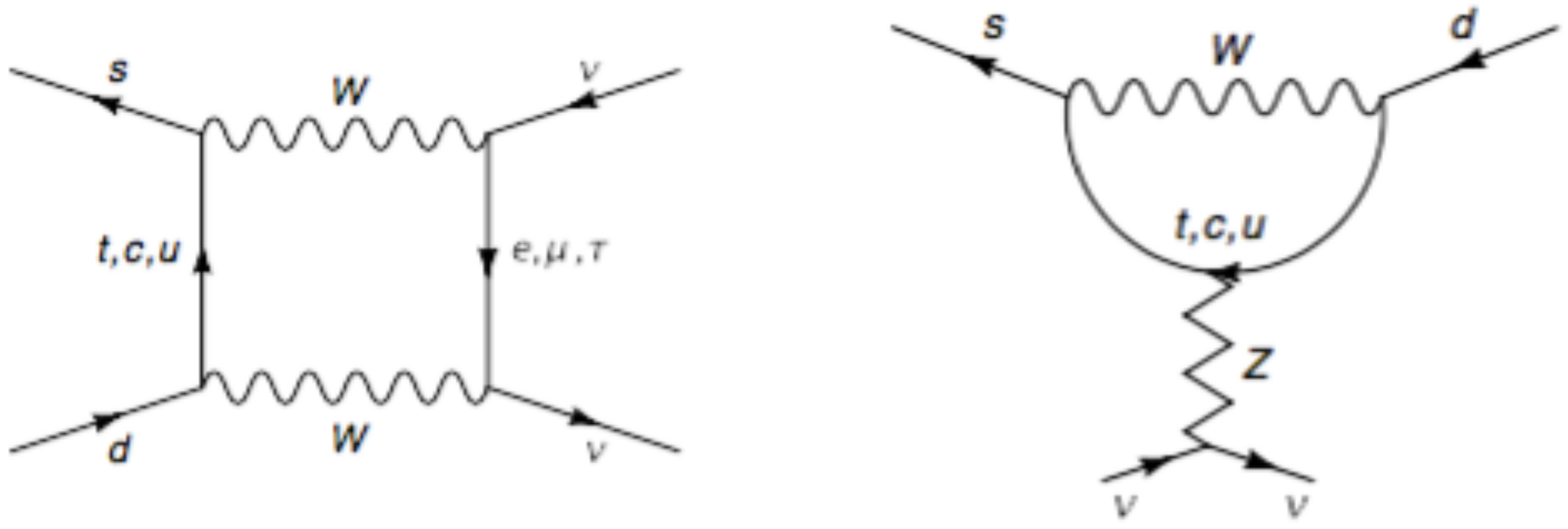
$\Downarrow$

$$\Gamma(K_L \to \pi^0\nu\overline{\nu}) \quad \begin{cases} \text{CP violating} \\ \Rightarrow\ J = A^2\lambda^6\eta \\ \text{Only } top \end{cases}$$

SM

Buchalla and Buras,
hep-ph/9308272, Buras et al,
1503.02693.

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



Misiak, Urban; Buras, Buchalla; Brod, Gorbhan, Stamou`11, Straub

$\lambda_q = V_{qd}{}^* V_{qs}$

$$\mathcal{B}(K^+) \sim \kappa_+ \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} \left(P_c + \delta P_{c,u} \right) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X_t \right)^2 \right]$$

$\kappa_+ \downarrow K_{l3}$

$30\% \pm 2.5\%$

LD

$$\mathcal{B}(K^\pm) = (8.82 \pm 0.8 \pm 0.3) \times 10^{-11}$$

TH

V_{cb} nonpert QCD

UV sensitivity

$$\mathcal{L} \sim \frac{1 - 0.3\, i}{(180\ \text{TeV})^2} (\overline{s}_L \gamma_\mu d_L \overline{\nu}_L \gamma^\mu \nu_L)$$

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

Gorbhan KAON2022

Computations

NNLO — Buras/Gorbahn/Haisch/Nierste:hep-ph/0508165, Buras/Gorbahn/Haisch/Nierste:hep-ph/0603079, Gorbahn/Haisch:hep-ph/0411071

Isospin breaking — Mescia/Smith:0705.2025

Non-perturbative effects — Isidori/Mescia/Smith:hep-ph/0503107

Measurement

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\text{exp}} = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$ — NA62: 2103.15389

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\text{exp}} \leq 3.0 \times 10^{-9}$ — KOTO: 1810.09655

SM prediction — **Brod/Gorbahn/Stamou: 2105.02868**

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\text{SM}} = (7.7 \pm 0.6) \times 10^{-11}$

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\text{SM}} = (2.6 \pm 0.3) \times 10^{-11}$

- arxiv 2206.14748

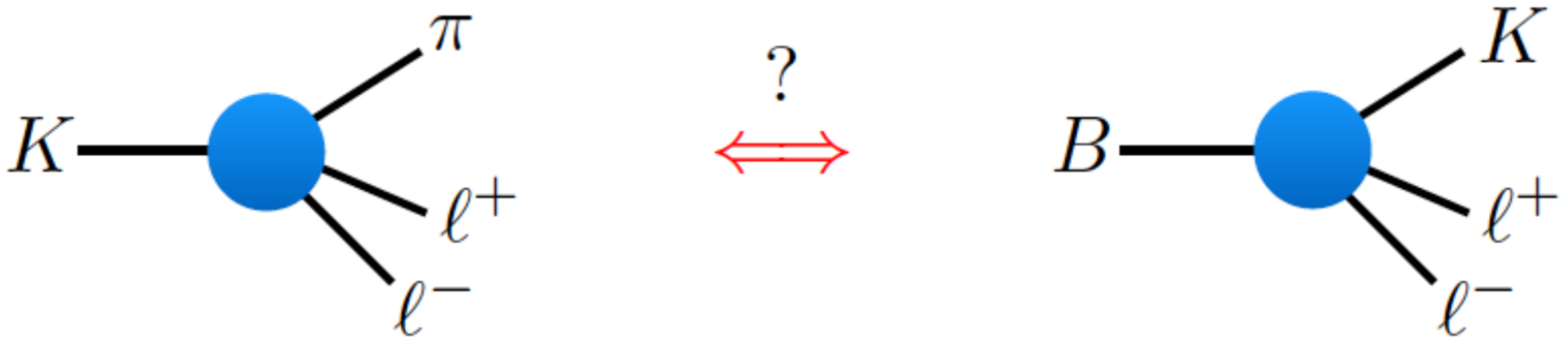
$$\text{BR}(K^+ \to \pi^+\nu\bar{\nu})^{\text{SM}} = (7.86 \pm 0.61) \times 10^{-11},$$

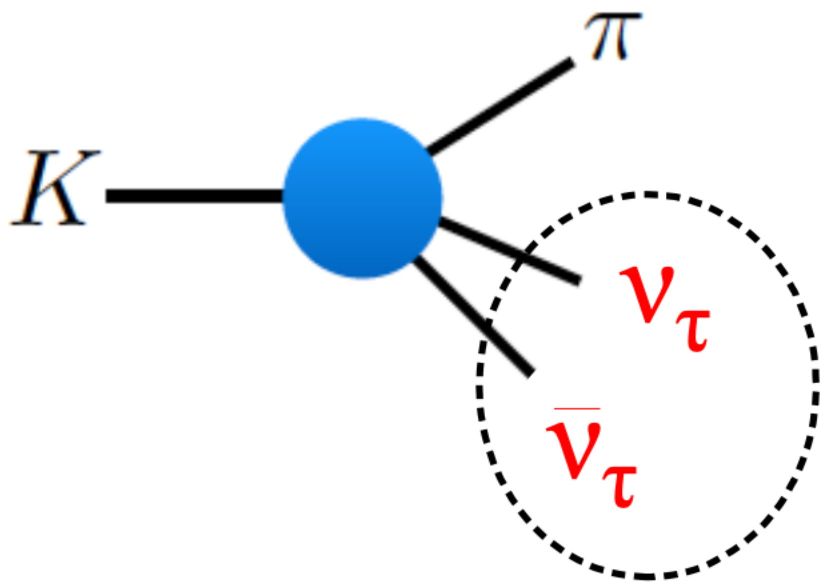
$$\text{BR}(K_L \to \pi^0\nu\bar{\nu})^{\text{SM}} = (2.68 \pm 0.30) \times 10^{-11}.$$

G.D. Iyer Nazila Neshtapour

▶ Lepton Flavor Universality

Example-II: *neutral currents, $\mu^+\mu^-$ vs. e^+e^-*





Access to 3rd gen. leptons as in R(D) & R(D*)

...but a potential more promising effect could appear in our beloved $K \to \pi\nu\nu$ decays....

▶ *SM, BSM, & "non-standard BSM" in $K \to \pi\nu\nu$*

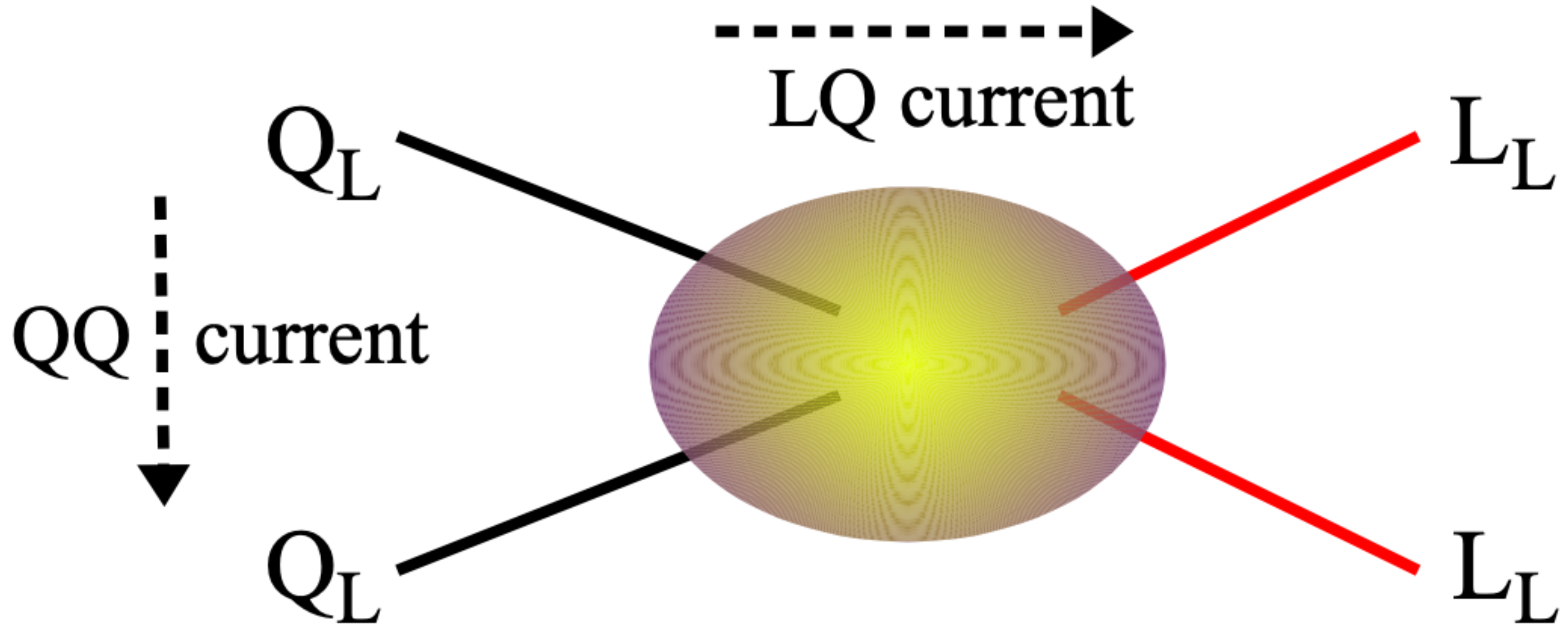
But what I find even more interesting, is the natural link with LFU effects in B-physics, thanks to the presence of 3rd generation leptons in the final state

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

SM like

few % deviation as in $b \to s\mu\mu$

possible O(1) deviation from SM expected also in $b \to s\tau\tau$



Explicit (UV) models:

- LQ (composite) mediators
  Barbieri, GI, Pattori, Senia '16
- Z',W' (composite) mediators
  GI *et al.* - work in prog.

Anatomy of kaon decays and prospects for lepton flavour universality violation

GD, A.M. Iyer, F. Mahmoudi, S. Neshatpour

arxiv 2206.14748

- Motivated by B-anomalies we study LFUV Kaon decays

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell \,,$$

- $$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)\,,$$

$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

$$\delta C_L^\tau = \delta C_L^\mu$$

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

arxiv 2206.14748

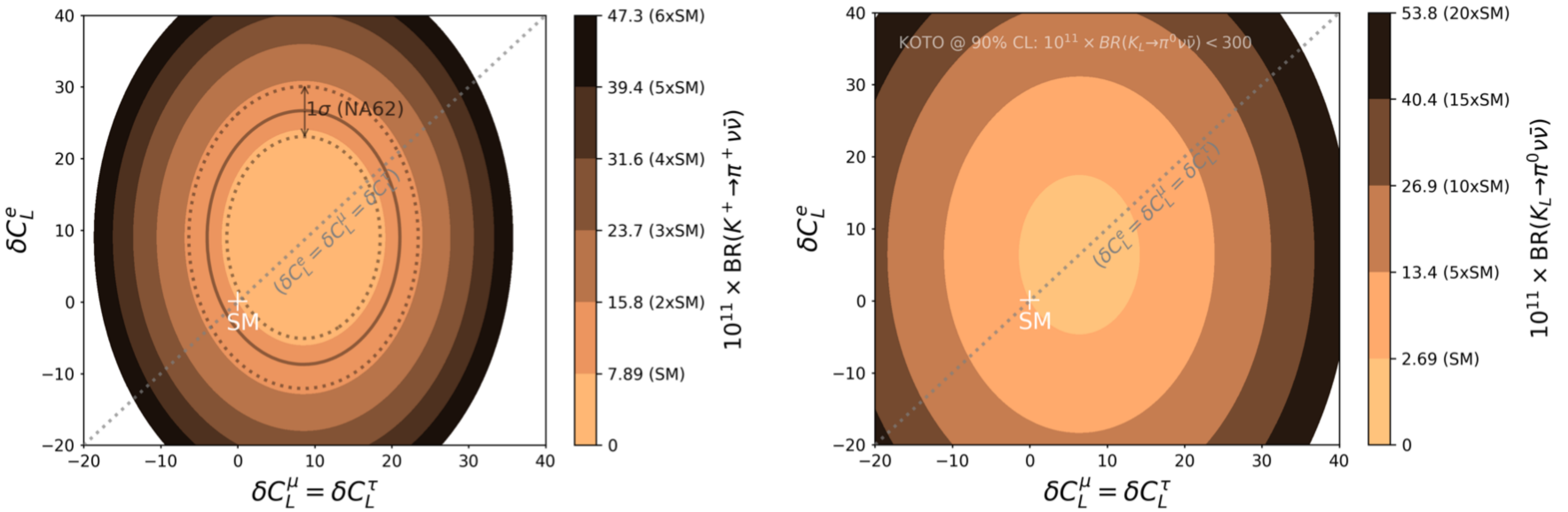
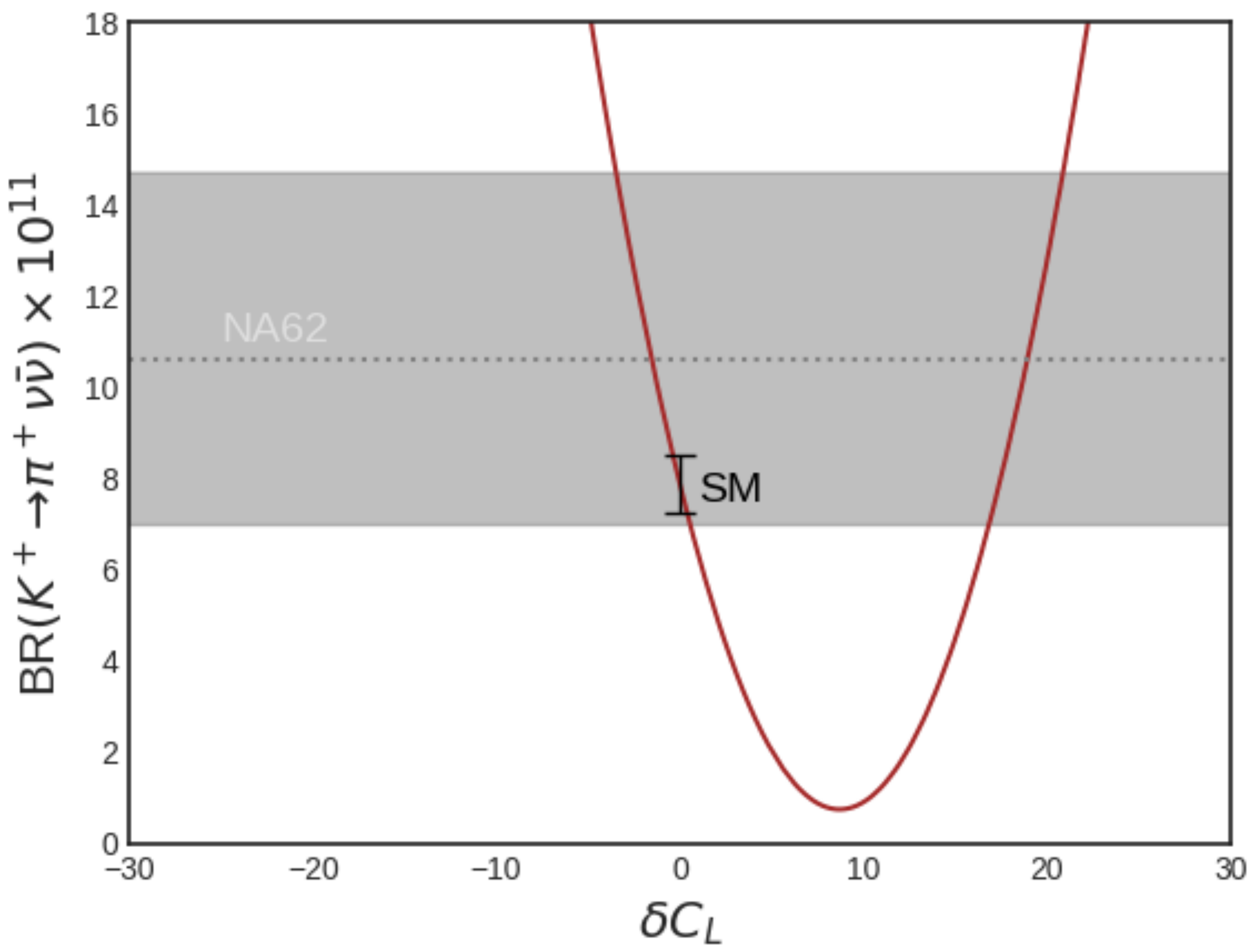


Figure 1: BR($K^+ \to \pi^+ \bar{\nu}\nu$) (left) and BR($K_L \to \pi^0 \bar{\nu}\nu$) (right) as a function of δC_L^e and $\delta C_L^\mu = \delta C_L^\tau$. The dotted grey line represents the lepton flavour universality scenario. In the left plot, the brown solid (dotted) line corresponds to the measured central value (1σ experimental uncertainty) by NA62 [15]. In the right plot, the upper bound on BR($K_L \to \pi^0 \bar{\nu}\nu$) is not visible for the scanned values.



$$K_{L,S} \to \mu\mu$$

$K_L \to \mu\mu$

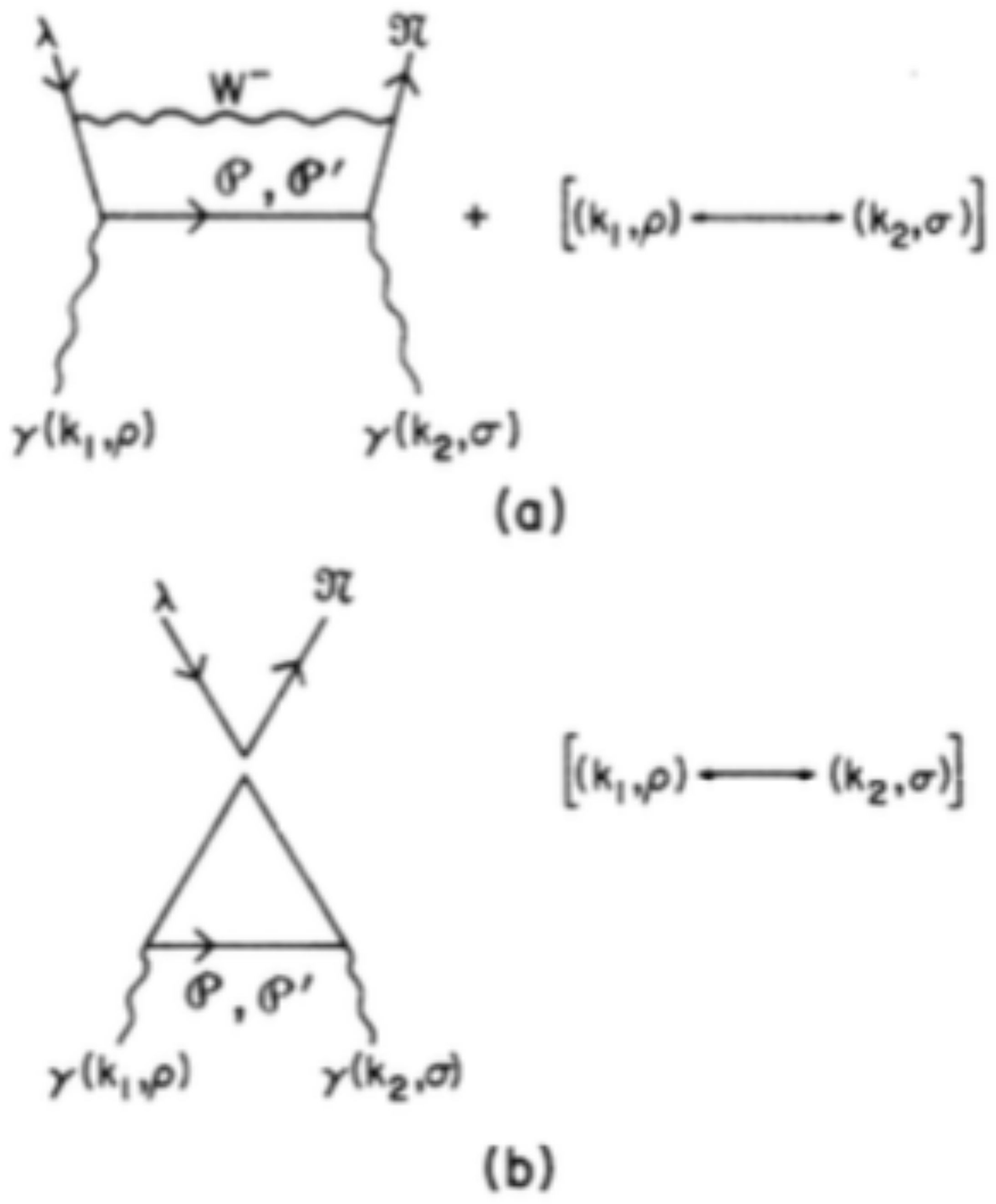


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

$\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-)$

VALUE (10^{-6})	EVTS	DOCUMENT ID		TECN	COMMENT
3.48 ± 0.05	**OUR AVERAGE**				
3.474 ±0.057	6210	AMBROSE	2000	B871	
3.87 ±0.30	179	[1] AKAGI	1995	SPEC	
3.38 ±0.17	707	HEINSON	1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	1991B	SPEC	In AKAGI 1995

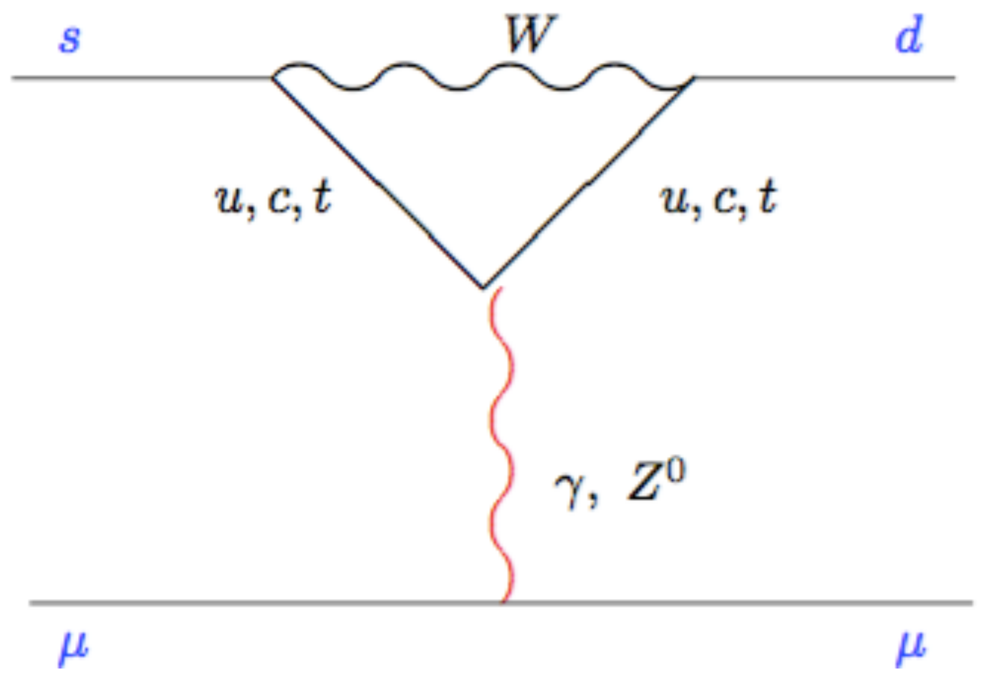
$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\text{exp}} = (6.84 \pm 0.11) \times 10^{-9}$$

$K_L \to \gamma\gamma\,|_{\text{exp}}$ known

Dispersive calculation: Re A, Im A

$K_L \to \mu\mu$

Isidori Unterdorfer
GD Isidori Portoles



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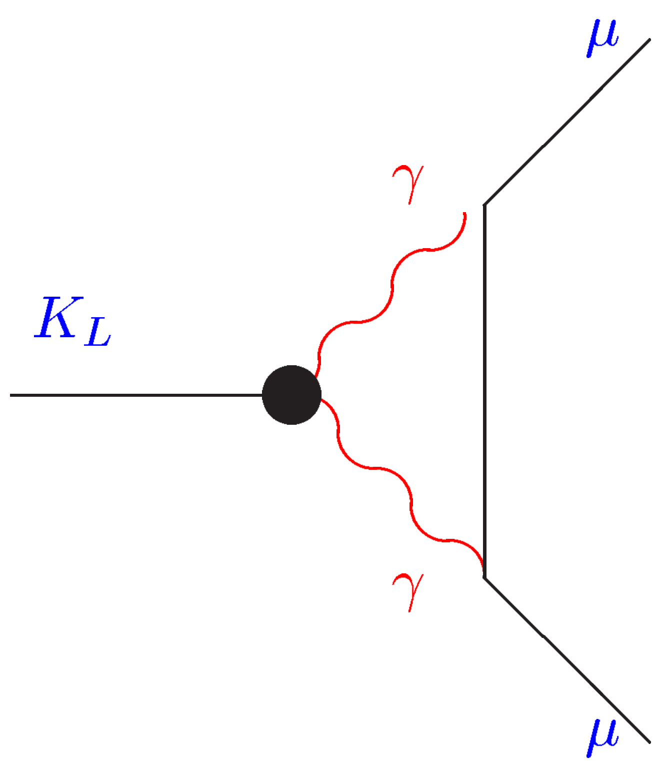

$$\frac{\Gamma(K_L \to \mu\bar{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim$$

$$|ReA|^2 + |ImA|^2$$

Absorptive calculation
model independent

$$27.14$$

Subtracting from expt. the Absorptive contribution

$$0.98 \pm 0.55 = |ReA|^2 = (\chi_{\gamma\gamma}(M_\rho) + \chi_{\rm short} - 5.12)^2$$

$$|\chi^{\rm SM}_{\rm short}| = 1.96(1.11 - 0.92\bar{\rho})$$

$K_S \to \mu\mu$

KAON2022 LHCB

$BR(K_S \to \mu\mu) < 2.1 \times 10^{-10}$
@ 90% CL

Run1 data (3 fb^{-1})

$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$
90%, 95% CL
factor 11 improvement

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST 1974

Rare decay modes of the K mesons in gauge theories

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National Accelerator Laboratory, Batavia, Illinois 60510‡
(Received 4 March 1974)

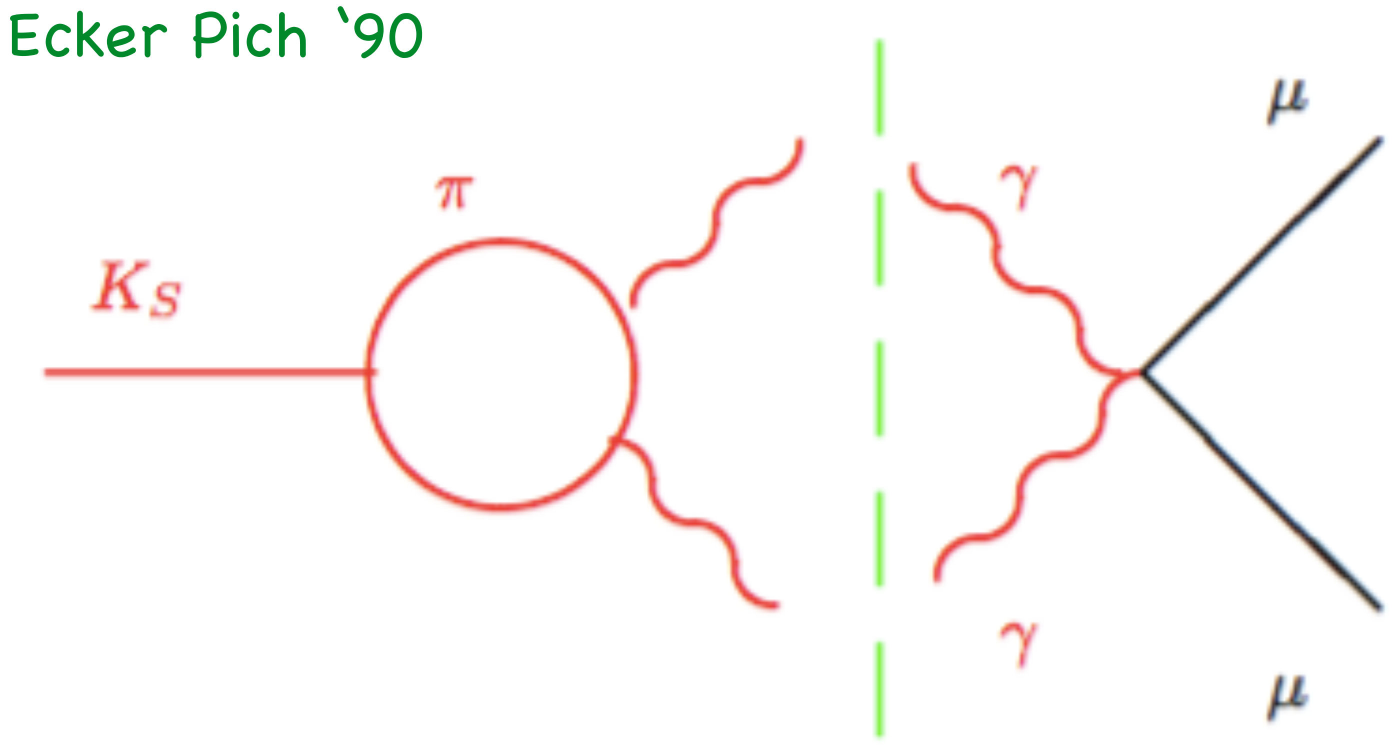
Rare decay modes of the kaons such as $K \to \mu\bar{\mu}$, $K \to \pi\nu\bar{\nu}$, $K \to \gamma\gamma$, $K \to \pi\gamma\gamma$, and $K \to \pi e\bar{e}$ are of theoretical interest since ~~here we are observing higher-order weak and electro-~~ magnetic interactions. Recent advances in unified gauge theories of weak and electromagnetic interactions allow in principle unambiguous and finite predictions for these processes. The above processes, which are "induced" $|\Delta S| = 1$ transitions, are a good testing ground for the cancellation mechanism first invented by Glashow, Iliopoulos, and Maiani (GIM) in order to banish $|\Delta S| = 1$ neutral currents. The experimental suppression of $K_L \to \mu\bar{\mu}$ and nonsuppression of $K_L \to \gamma\gamma$ must find a natural explanation in the GIM mechanism which makes use of extra quark(s). The procedure we follow is the following: We deduce the effective interaction Lagrangian for $\lambda + \mathfrak{N} \to l + \bar{l}$ and $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$ in the free-quark model; then the appropriate matrix elements of these operators between hadronic states are evaluated with the aid of the principles of conserved vector current and partially conserved axial-vector current. We focus our attention on the Weinberg-Salam model. In this model, $K \to \mu\bar{\mu}$ is suppressed due to a fortuitous cancellation. To explain the small K_L-K_S mass difference and nonsuppression of $K_L \to \gamma\gamma$, it is found necessary to assume $m_{\mathcal{P}}/m_{\mathcal{P}'} \ll 1$, where $m_{\mathcal{P}}$ is the mass of the proton quark and $m_{\mathcal{P}'}$ the mass of the charmed quark, and $m_{\mathcal{P}'} < 5$ GeV. We present a phenomenological argument which indicates that the average mass of charmed pseudoscalar states lies below 10 GeV. The effective interactions so constructed are then used to estimate the rates of other processes. Some of the results are the following: $K_S \to \gamma\gamma$ is suppressed; $K_S \to \pi\gamma\gamma$ proceeds at a normal rate, but $K_L \to \pi\gamma\gamma$ is suppressed; $K_L \to \pi\nu\bar{\nu}$ is very much forbidden, and $K^+ \to \pi^+\nu\bar{\nu}$ occurs with the branching ratio of $\sim 10^{-10}$; $K^+ \to \pi^+ e\bar{e}$ has the

VALUE (10^{-9})	CL%	DOCUMENT ID		TECN
< 9	90	[1] AAIJ	2013G	LHCB
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 0.032 \times 10^4$	90	GJESDAL	1973	ASPK
$< 0.7 \times 10^4$	90	HYAMS	1969B	OSPK

[1] AAIJ 2013G uses 1.0 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV. They obtained $B(K^0_S \to \mu^+\mu^-) < 11 \times 10^{-9}$ at 95% C.L.

$K_S \to \mu\mu$

Ecker Pich '90



No CP conserving Short Distance due to Furry Theorem

Gaillard Lee

LD 5×10^{-12} 30% TH err

Short Distance

SM $10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$

NP few 10^{-11} allowed

LHCB

$< 8 \times 10^{-10}$ 90%CL

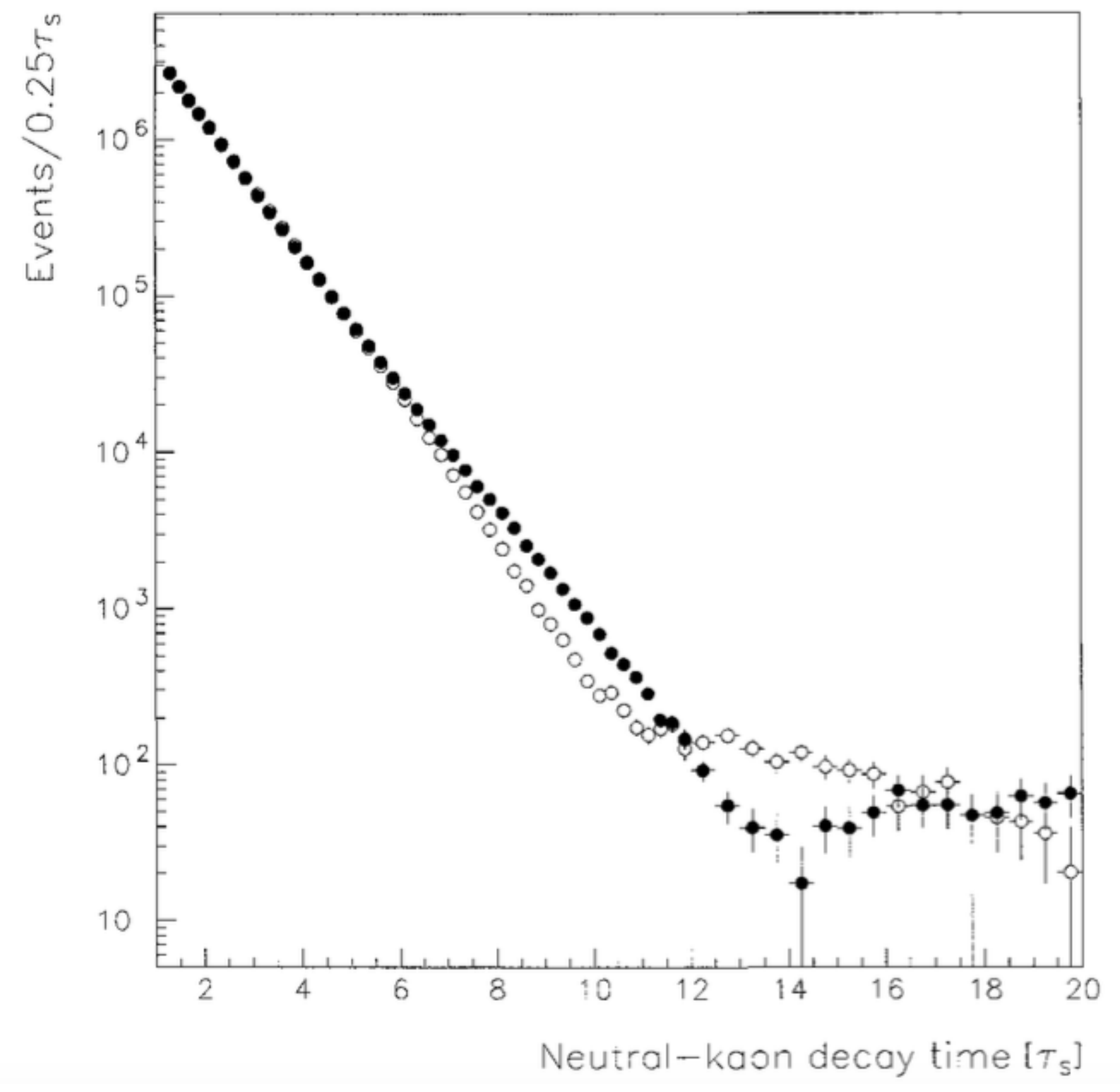
2.1×10^{-10}

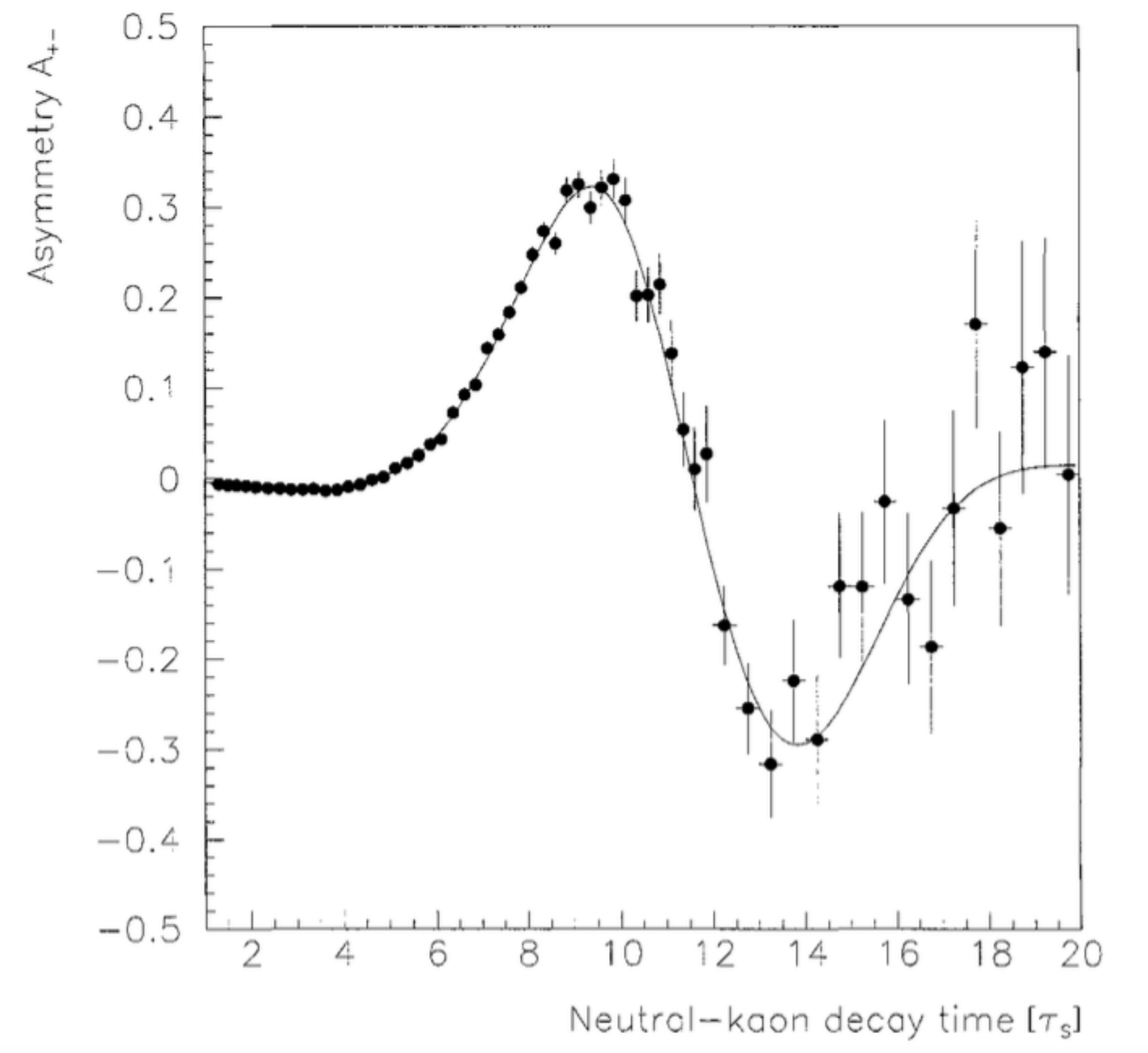
{

CPLEAR Flavor tagging

$$p\bar{p} \to \begin{array}{l} K^-\pi^+K^0 \\ K^+\pi^-\overline{K}^0 \end{array}$$

$$\frac{R(\tau)}{\overline{R}(\tau)} \propto (1 \mp 2\mathrm{Re}(\varepsilon_L))(e^{-\Gamma_S\tau} + |\eta_{+-}|^2 e^{-\Gamma_L\tau} \pm 2|\eta_{+-}|e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\tau}\cos(\Delta m\tau - \phi_{+-}))$$





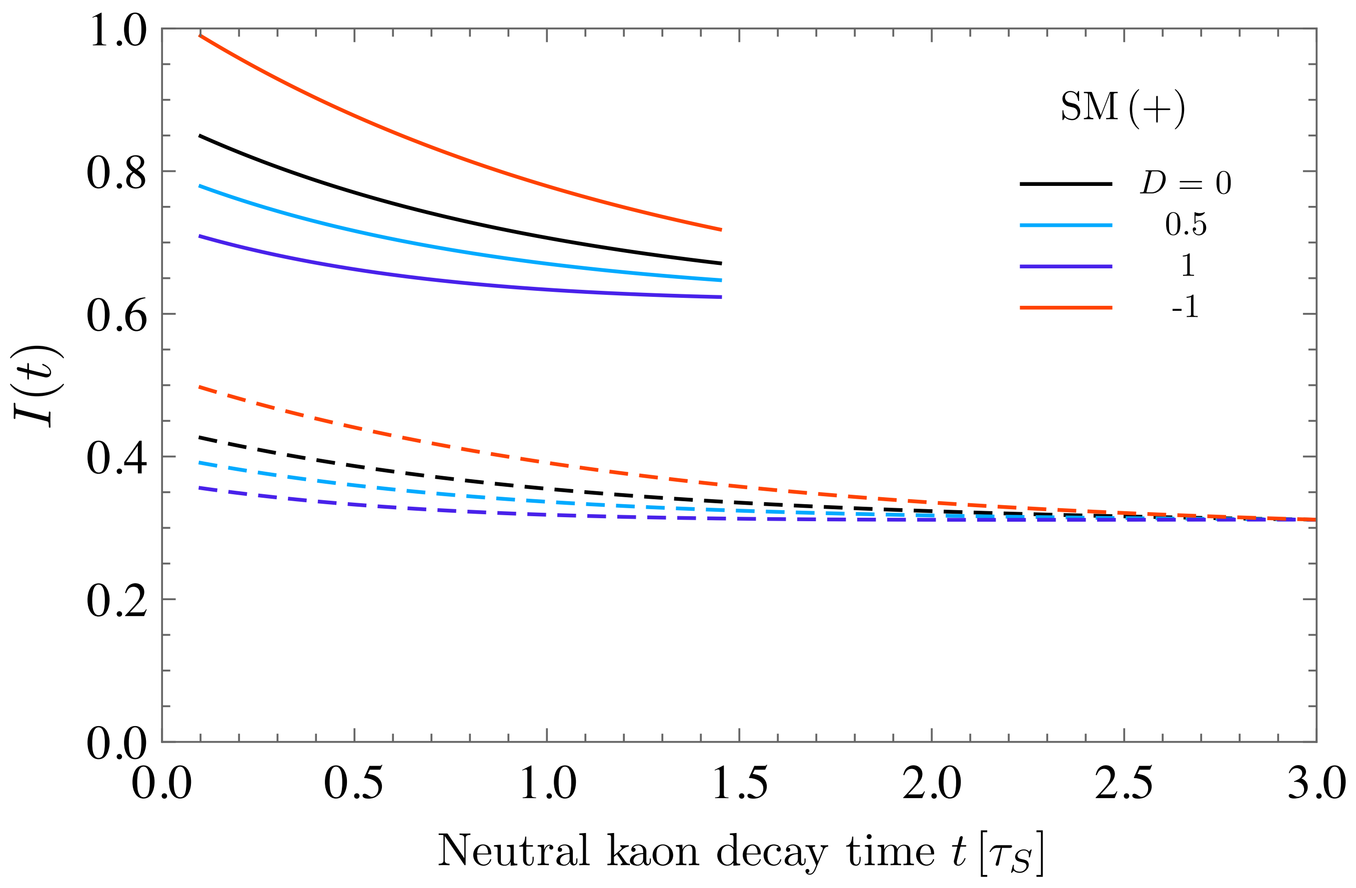
}

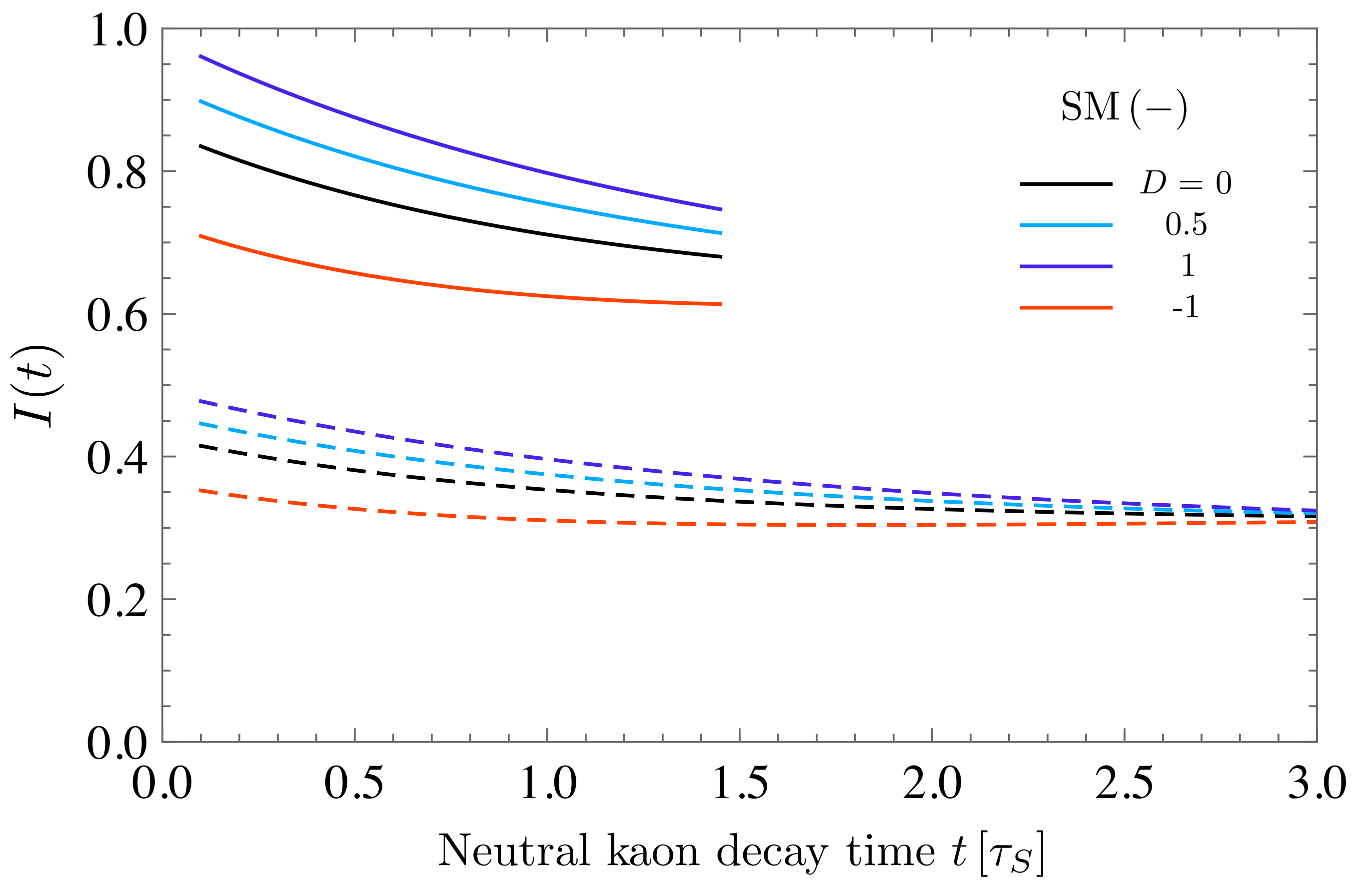
Can we study $K^0(t)$?

GD , Kitahara
1707.06999 PRL

$$pp \to K^0 K^- X$$

$$pp \to K^{*+} X \to K^0 \pi^+ X$$





$$|\overset{(-)}{K}{}^0(t)\rangle = \frac{1}{\sqrt{2}(1 \pm \bar{\epsilon})} \left[e^{-iH_S t} \left(|K_1\rangle + \bar{\epsilon}|K_2\rangle \right) \pm e^{-iH_L t} \left(|K_2\rangle + \bar{\epsilon}|K_1\rangle \right) \right]$$

$$D = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

- Short distance interfering with Large CP conserving LD contribution !

- We may be able to study the time evolution of K^0 by tracking the associated particles (K^-)

$$\sum_{\text{spin}} \mathcal{A}(K_1 \to \mu^+\mu^-)^* \mathcal{A}(K_2 \to \mu^+\mu^-)$$

$$\sim \text{Im}[\lambda_t] y'_{7A} \left\{ A^{\mu}_{L\gamma\gamma} - 2\pi \sin^2\theta_W \left(\text{Re}[\lambda_t] y'_{7A} + \text{Re}[\lambda_c] y_c \right) \right\}$$

arxiv 2206.14748

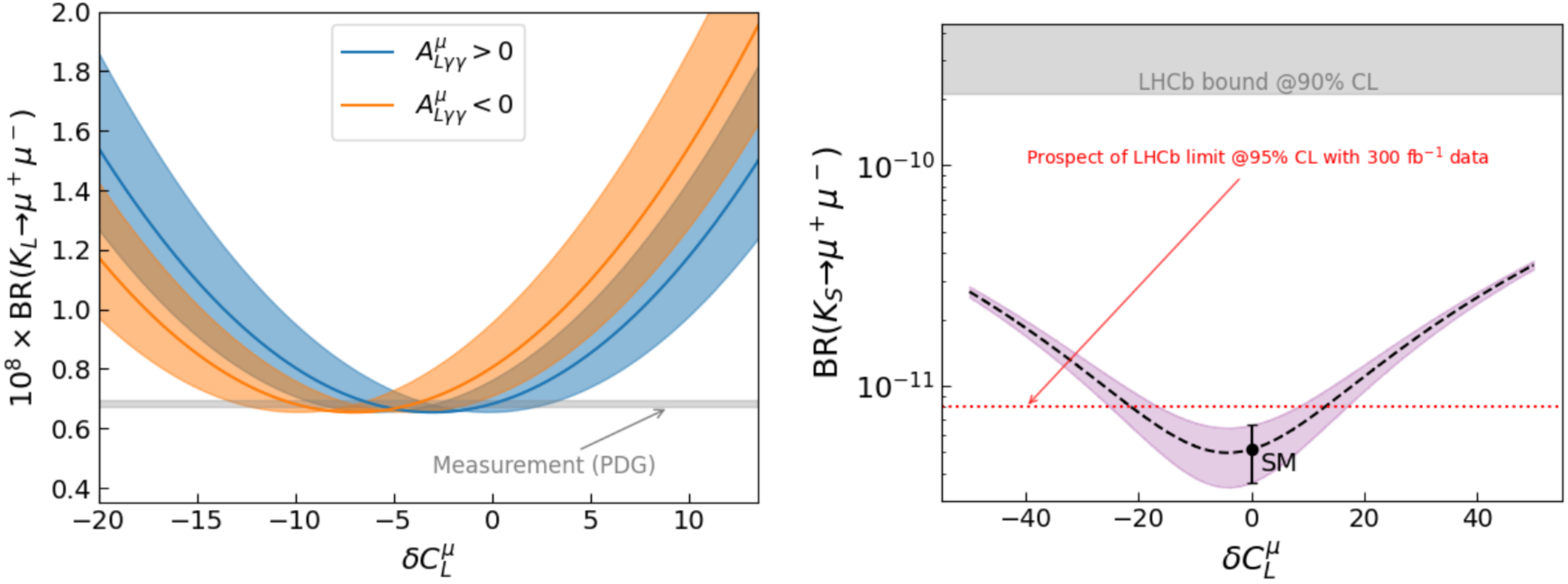
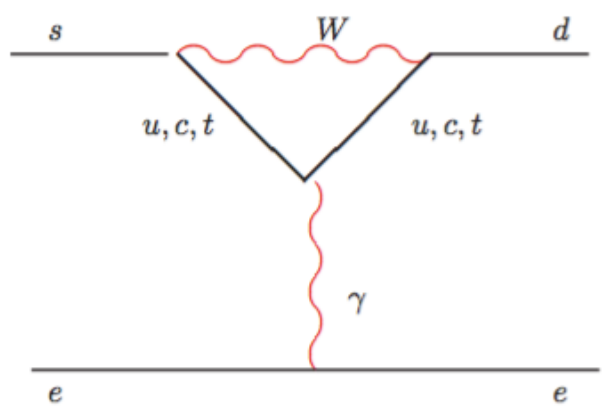


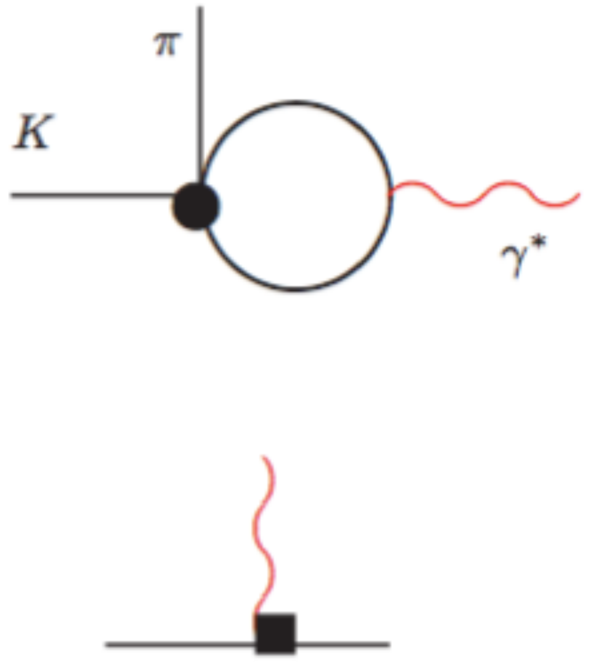
Figure 4: $BR(K_L \to \mu\bar{\mu})$ as a function of $\delta C^\mu_L (\equiv \delta C^\mu_9 = -\delta C^\mu_{10})$ assuming both possible signs for the long-distance contribution from $A^\mu_{L\gamma\gamma}$ on the left panel. $BR(K_S \to \mu\bar{\mu})$ as a function of NP contributions in δC^μ_L on the right panel. In the left (right) panel, the grey band indicates the experimental measurement (upper limit) while the coloured bands correspond to the theoretical uncertainties. The LHCb bound and prospect for $BR(K_S \to \mu\bar{\mu})$ are from Ref. [44] and Ref. [51], respectively.

LFUV in Kaons

$$\frac{\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)}{\Gamma(K^+ \to \pi^+ e^+ e^-)}$$

SD << LD





$$A_V^{K^+\to\pi^+\gamma^*} = -\frac{G_f \alpha}{4\pi} V_+(z) \bar{u}_l(p_-)(\gamma_\mu k^\mu + \gamma_\mu p^\mu) v_l(p_+)$$

GD,Ecker,Isidori,Portoles

$$V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)$$

a_+ and b_+ **Short distance**

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\,[V_{td} V_{ts}^* (C_9^\mu - C_9^e)]$$

Crivellin,GD, Hofrichter, Tunstall

Historical progression			
Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865 [32]
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2 [33]
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2 [34]

Current situation			
Channel	a_+	b_+	Reference
ee	-0.561 ± 0.009	-0.694 ± 0.040	comb. [42]
$\mu\mu$	-0.592 ± 0.015	-0.699 ± 0.058	NA62 [16]

Table 1: Summary of the estimation of vector form factors for $K^+ \to \pi^+ \ell\bar{\ell}$. The left panel gives the historical progression and the right panel gives the current status.

NA62

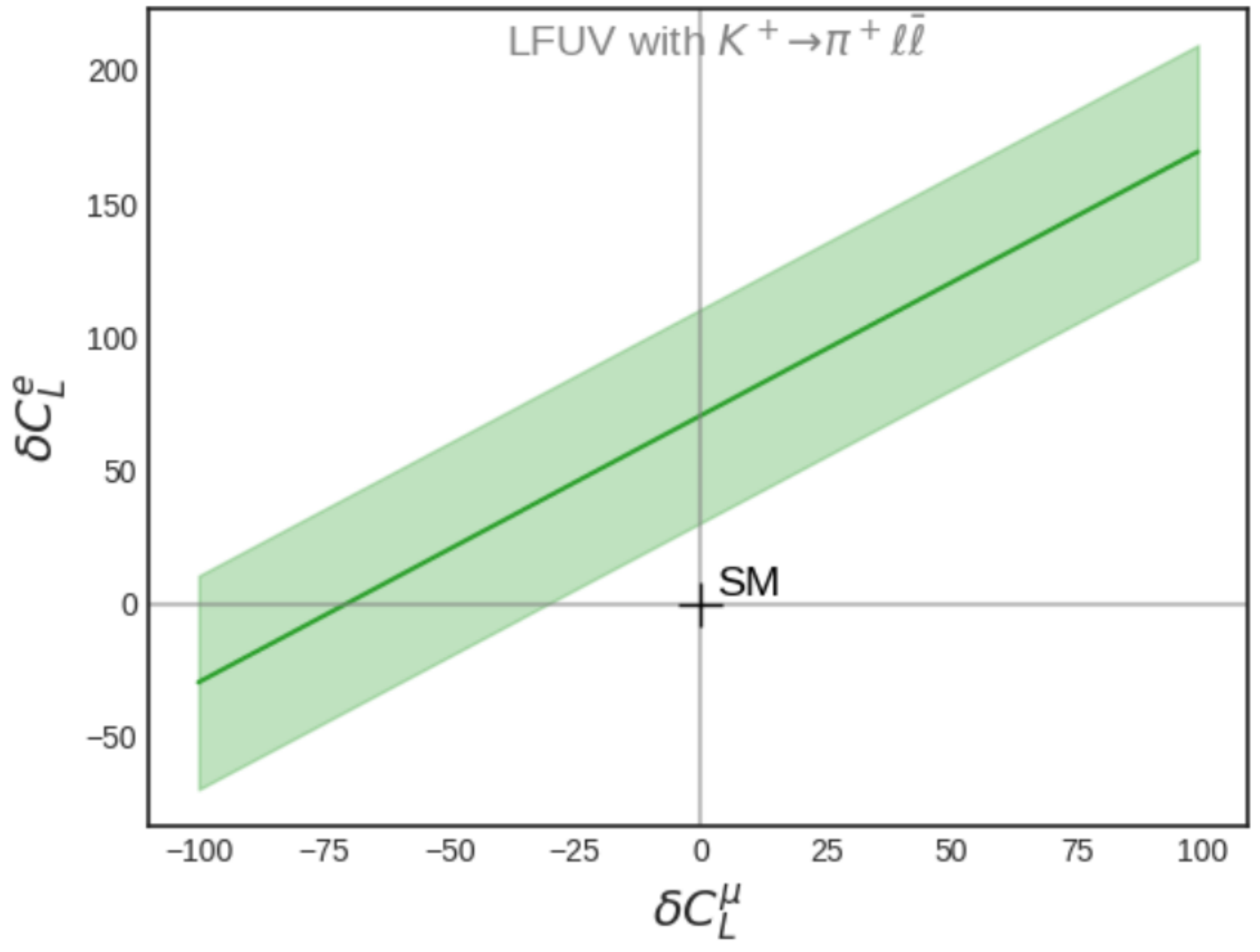
Measurement of the rare decay $K^+ \to \pi^+\mu^+\mu^-$ at the NA62 experiment

Newly published: arXiv:2209.05076

Michal Koval
michal.koval@cern.ch

KAON2022

$$a_+ = -0.575 \pm 0.013, \ b_+ = -0.722 \pm 0.043$$



arxiv 2206.14748

Figure 2: Region consistent with the estimation of the LFUV variable in $K^+ \to \pi^+ \ell\bar{\ell}$ decays.

Physica **96A** (1979) 327–340 © *North-Holland Publishing Co.*

PHENOMENOLOGICAL LAGRANGIANS*

STEVEN WEINBERG
Lyman Laboratory of Physics, Harvard University
and
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA

The most general such Lagrangian is an infinite series of operators of higher and higher dimensionality[9])

$$\mathscr{L} = -\tfrac{1}{2}g_2 D_\mu \boldsymbol{\pi} \cdot D^\mu \boldsymbol{\pi} - \tfrac{1}{4}g_4^{(1)}(D_\mu \boldsymbol{\pi} \cdot D^\mu \boldsymbol{\pi})^2 - \tfrac{1}{4}g_4^{(2)}(D_\mu \boldsymbol{\pi} \cdot D_\nu \boldsymbol{\pi})(D^\mu \boldsymbol{\pi} \cdot D^\nu \boldsymbol{\pi}) + \cdots, \tag{2}$$

K->pi ll

$$a_+ = -0.575 \pm 0.013, \; b_+ = -0.722 \pm 0.043$$

Expt.

$$a_+ = -1.58 + \begin{cases} -0.10 \div +0.03 & \text{NDR} \\ -0.14 \div +0.07 & \text{HV} \end{cases}$$

$$b_+ = -0.76 + \begin{cases} -0.04 \div +0.03 & \text{NDR} \\ -0.07 \div +0.03 & \text{HV} \end{cases}$$

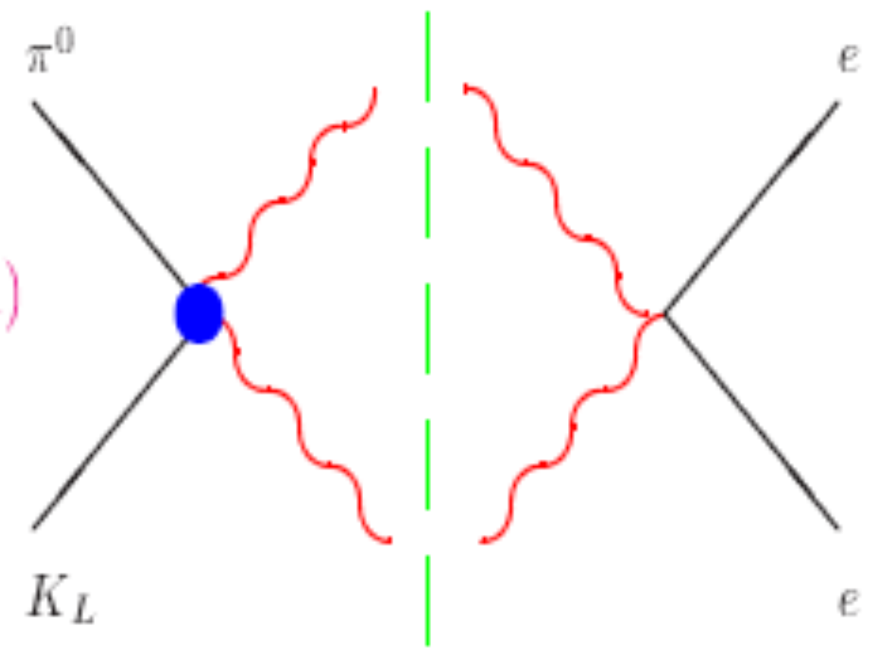
Matching short distance

GD. ,Greynat, Knecht

$K_L \to \pi^0 e^+ e^-$: summary

$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10}$ at 90% CL KTeV

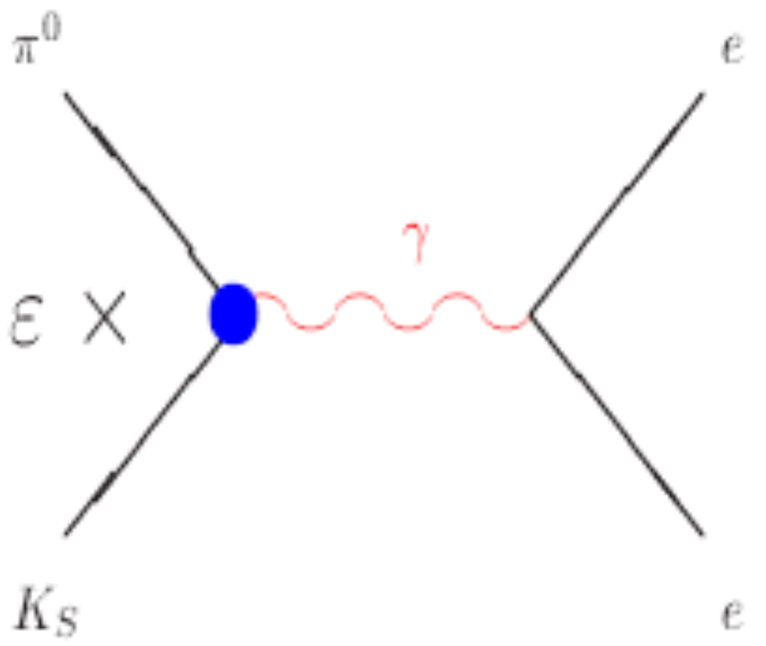
1)

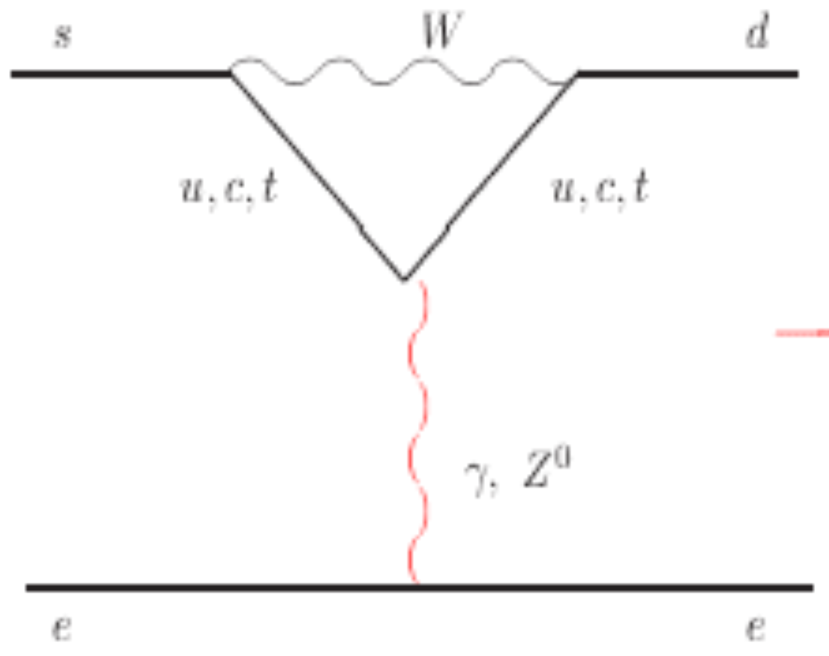


CP conserving NA48

$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$

V-A⊗ V-A $\Rightarrow \langle \pi^0 e^+ e^- | (\bar{s}d)_{V-A} (\bar{e}e)_{V-A} | K_L \rangle$ violates CP

2) $\varepsilon \times$ 

$+$ 3) 

$\longrightarrow$ Im λ_t

$\lambda_t = V_{td} V_{ts}^*$

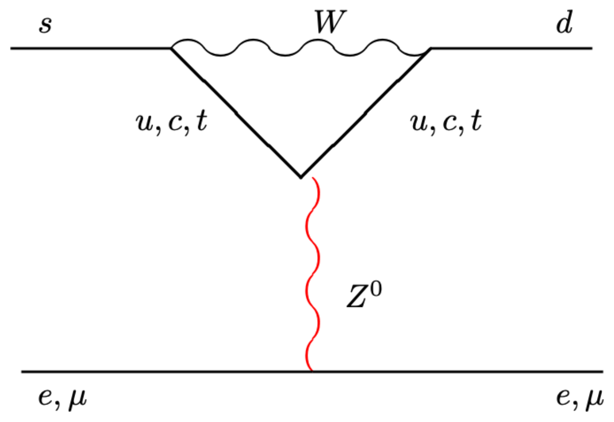
$\uparrow$ $\mathrm{B}(K_S \to \pi^0 e^+ e^-) = 4.6 a_S^2 \times 10^{-9}$

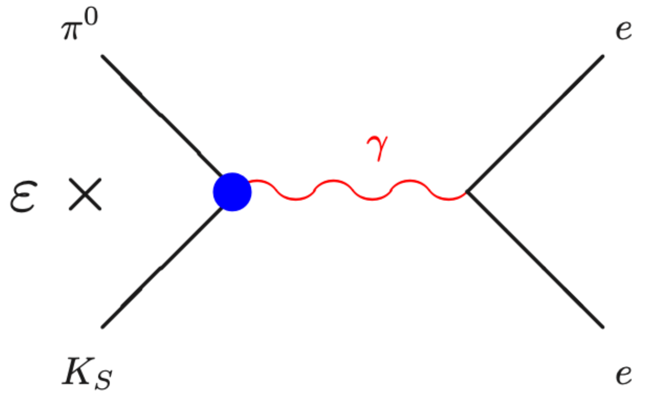
Possible large interference: $a_S < -0.5$ or $a_S > 1$; short distance probe even for a_S large

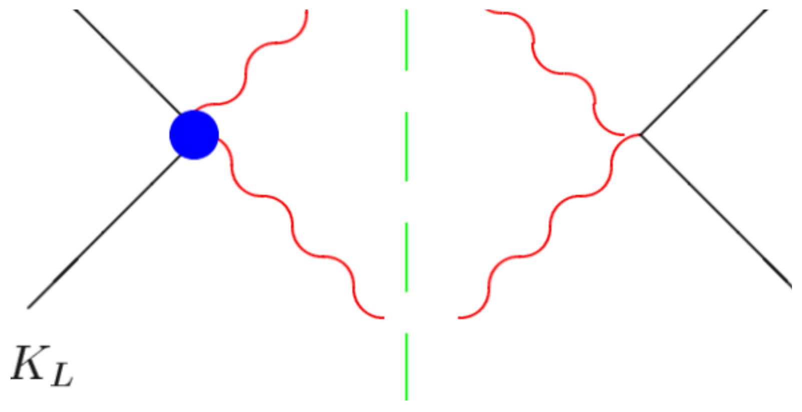
$$|2) + 3)|^2 = \left[15.3\ a_S^2 - 6.8 \frac{Im \lambda_t}{10^{-4}}\ a_S + 2.8 \left(\frac{Im \lambda_t}{10^{-4}} \right)^2 \right] \cdot 10^{-12}$$

$$[17.7 \pm \quad 9.5 + \quad 4.7] \quad \cdot 10^{-12}$$

Isidori Mescia, Smith







$$\mathrm{BR}(K_L \to \pi^0 \ell\bar{\ell}) = \left(C^{\ell}_{\rm dir} \pm C^{\ell}_{\rm int}|a_S| + C^{\ell}_{\rm mix}|a_S|^2 + C^{\ell}_{\gamma\gamma}\right) \cdot 10^{-12}$$

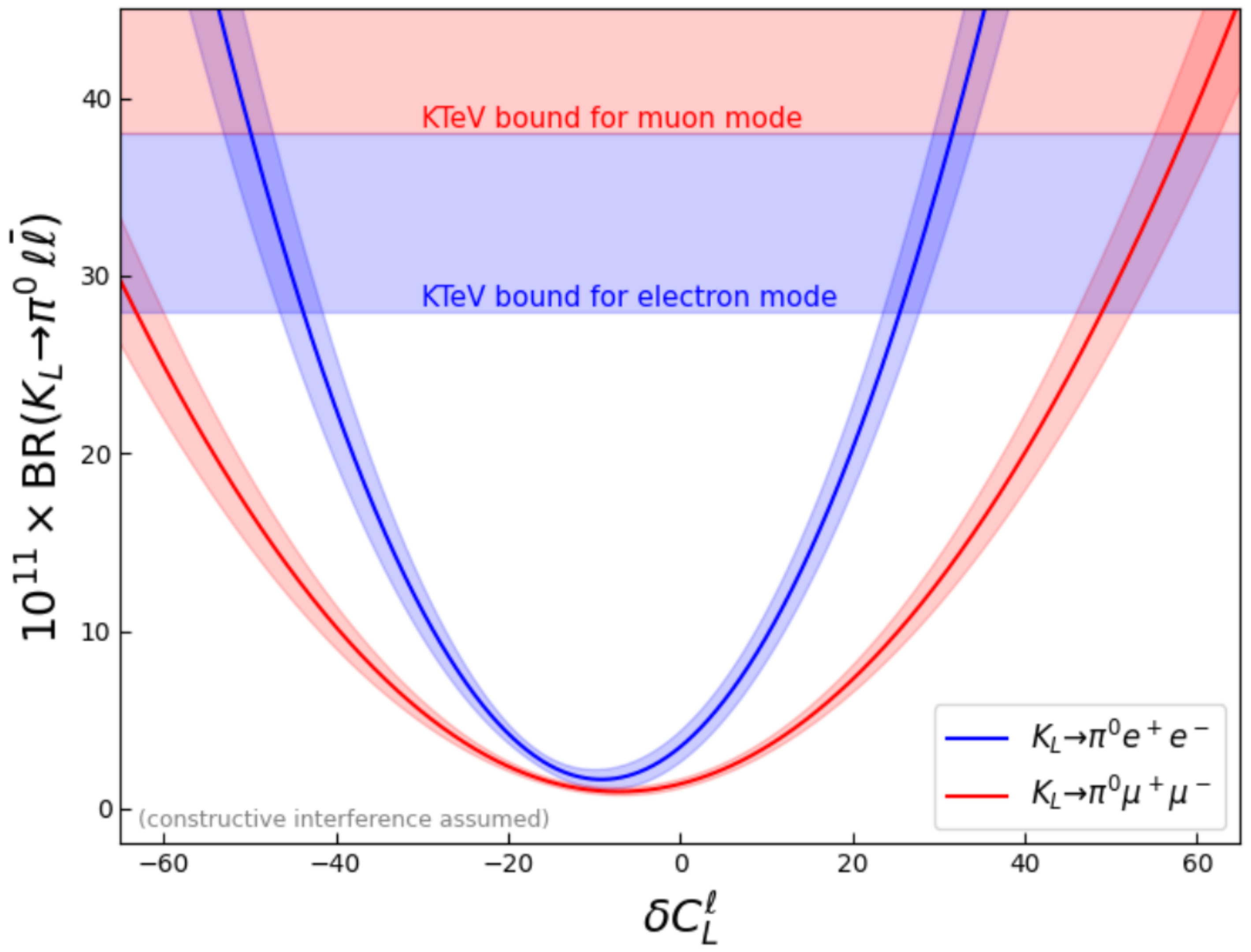
$$|a_S| = 1.20 \pm 0.20$$

	$C^{\ell}_{\rm dir}$	$C^{\ell}_{\rm int}$	$C^{\ell}_{\rm mix}$	$C^{\ell}_{\gamma\gamma}$
$\ell = e$	$(4.62 \pm 0.24)(w_{7V}^2 + w_{7A}^2)$	$(11.3 \pm 0.3)w_{7V}$	14.5 ± 0.5	≈ 0
$\ell = \mu$	$(1.09 \pm 0.05)(w_{7V}^2 + 2.32 w_{7A}^2)$	$(2.63 \pm 0.06)w_{7V}$	3.36 ± 0.20	5.2 ± 1.6

arxiv 2206.14748

$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 e\bar{e}) = 3.46^{+0.92}_{-0.80}\,(1.55^{+0.60}_{-0.48}) \times 10^{-11}$$

$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 \mu\bar{\mu}) = 1.38^{+0.27}_{-0.25}\,(0.94^{+0.21}_{-0.20}) \times 10^{-11}$$



$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 e\bar{e}) < 28 \times 10^{-11} \quad \text{at 90\% CL}$$

$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 \mu\bar{\mu}) < 38 \times 10^{-11} \quad \text{at 90\% CL}$$

arxiv 2206.14748

Observable	SM prediction	Exp results	Ref.	Experimental Err. Projections
$\mathrm{BR}(K^+ \to \pi^+\nu\nu)$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[15]	10%(@2025) 5%(CERN; long-term) [58]
$\mathrm{BR}(K^0_L \to \pi^0\nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL	[17]	20%(CERN; long-term [58]) 15% (KOTO [61])
$\mathrm{LFUV}(a^{\mu\mu}_+ - a^{ee}_+)$	0	-0.031 ± 0.017	[16, 42]	± 0.007 (assuming ± 0.005 for each mode)
$\mathrm{BR}(K_L \to \mu\mu)$ (+)	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[43]	experimental uncertainty kept to current value
$\mathrm{BR}(K_L \to \mu\mu)$ (−)	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$			
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	[44]	$< 8 \times 10^{-12}$ @95% CL (CERN; long-term [51])
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[56]	observation (CERN; long-term [58]) (we assume 100% error)
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[57]	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

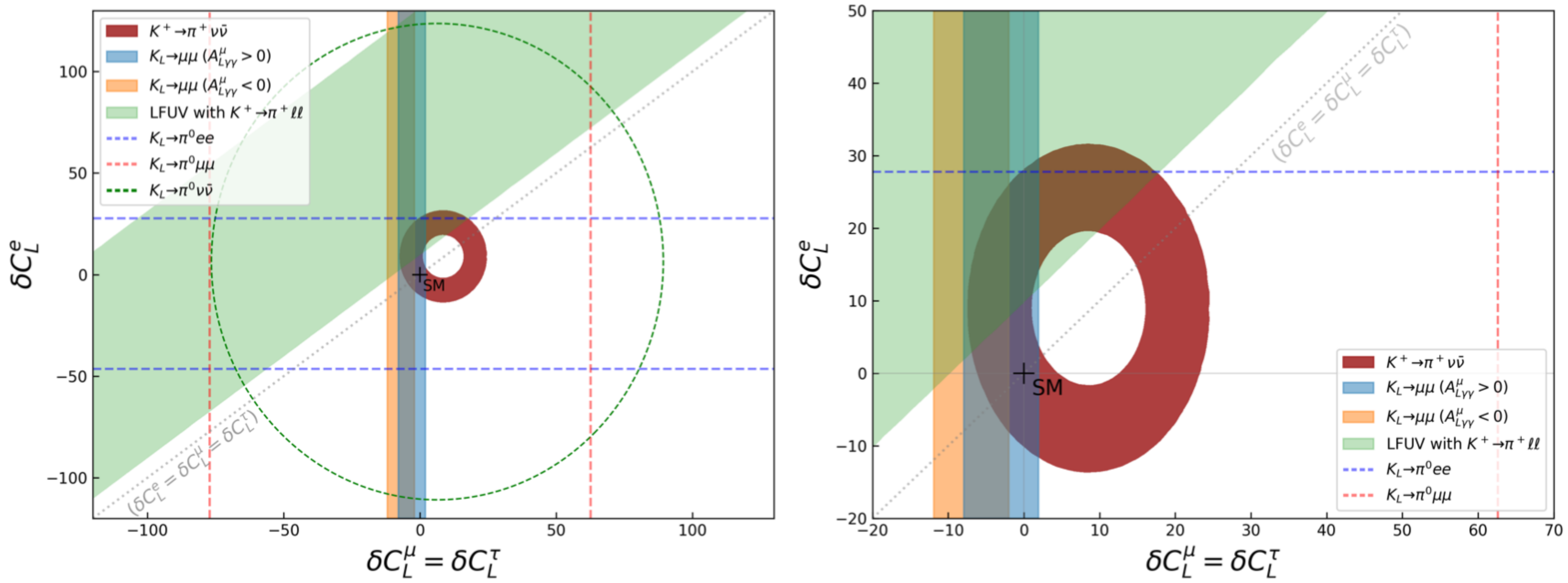


Figure 7: The bounds from individual observables. The right panel is the zoomed version of the left panel. The coloured regions correspond to 68% CL when there is a measurement and the dashed ones to upper limits at 90% CL. $K_L \to \mu\bar{\mu}$ has been shown for both signs of the long-distance contribution. For $K_L \to \pi^0 e\bar{e}$ and $K_L \to \pi^0 \mu\bar{\mu}$, constructive interference between direct and indirect CP-violating contributions has been assumed.

Cristina Lazzeroni, ECFA mtg 2022

Kaon Global Fit

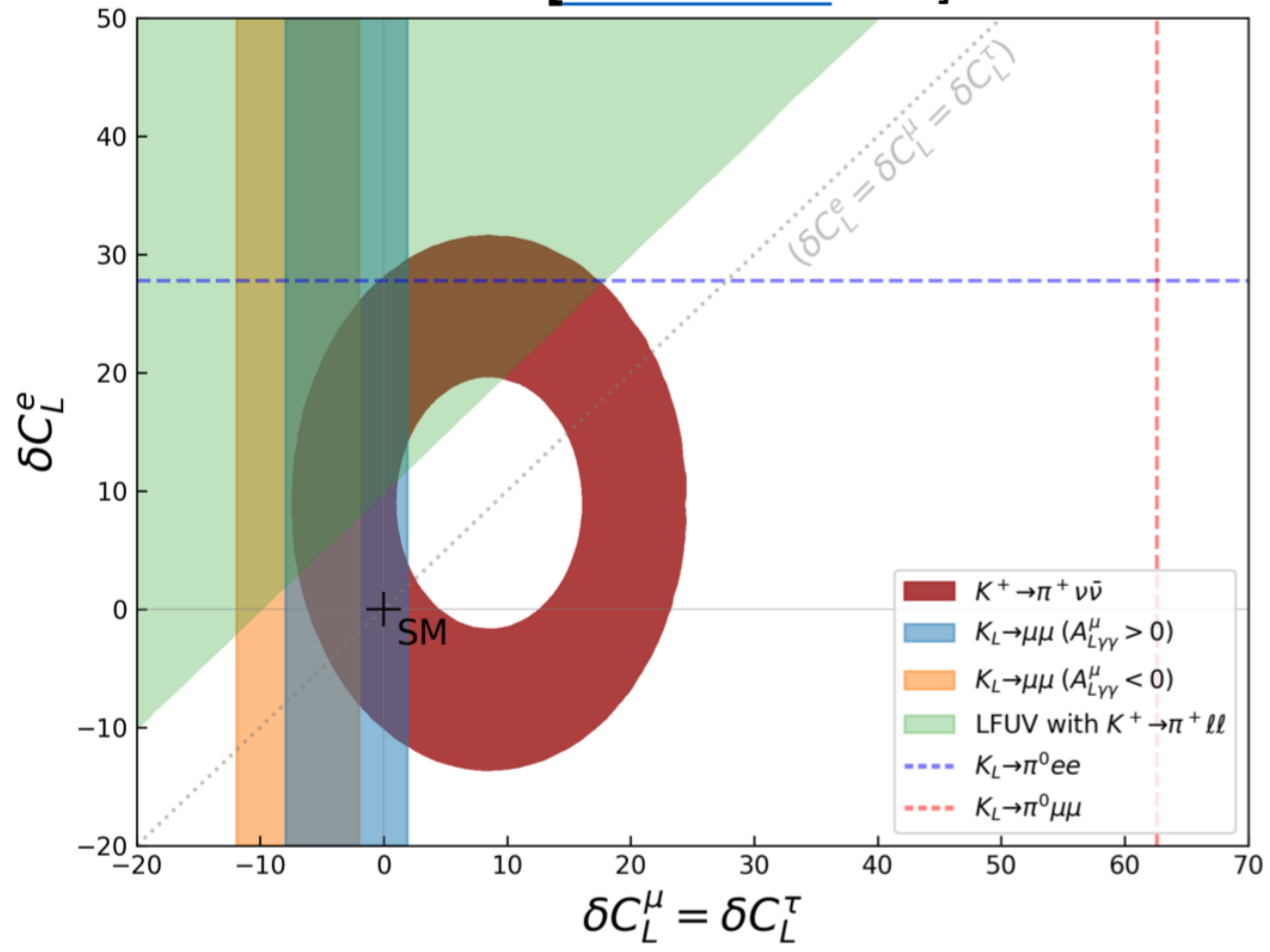
For example, recent paper with global fits to set of kaon measurements
Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

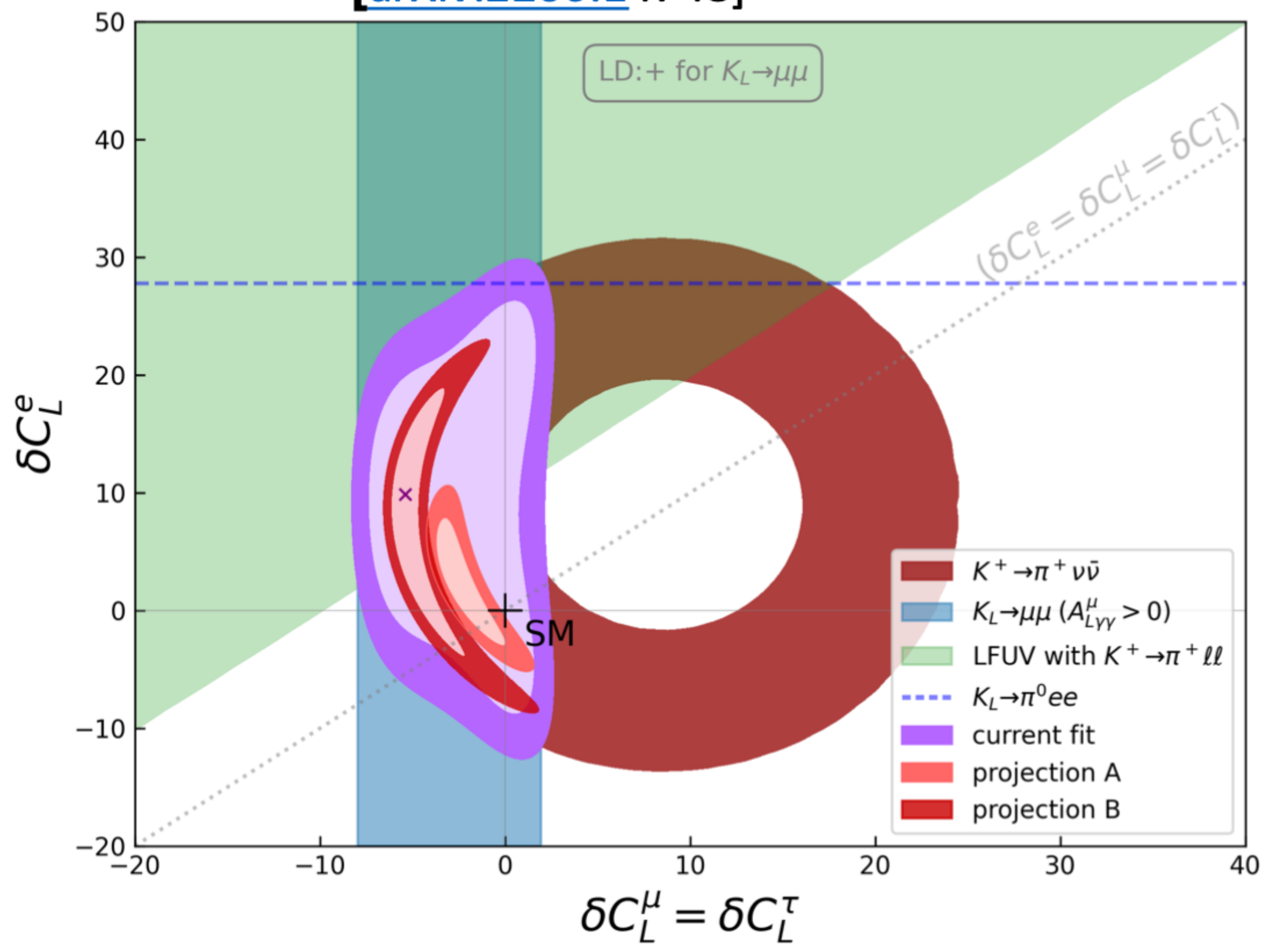
$$C_k^\ell = C_{k,\text{SM}}^\ell + \delta C_k^\ell$$

[arXiv:2206.14748]



Bounds from individual observables.
Coloured regions are 68%CL measurements
Dashed lines are 90%CL upper limits

[arXiv:2206.14748]



With projections: central value for existing measurements kept the same, A upper bounds extrapolated to central value consistent with SM, B central value of all observables is projected to the best-fit points obtained from fits to existing data

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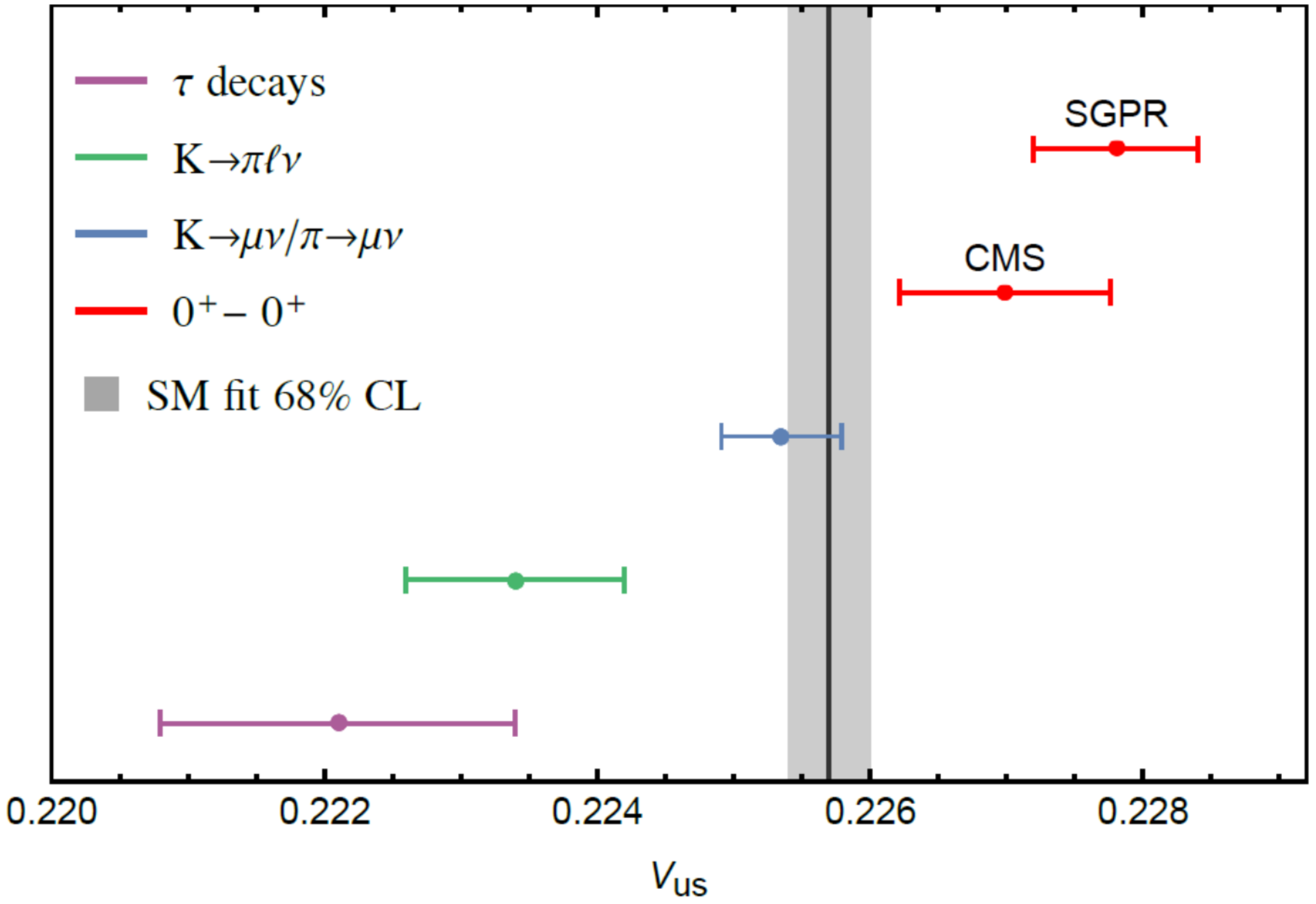
Cabibbo Angle Anomaly

Slide from talk by
Andreas Crivellin
La Thuille 2022

Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity



CMS, SGPR: radiative corrections

$$|V_{ud}^2|+|V_{us}^2|+|V_{ub}^2|=0.9985\pm0.0005,\ |V_{ud}^2|+|V_{cd}^2|+|V_{td}^2|=0.9970\pm0.0018$$

Deficits in 1th row and column CKM unitarity

K->3pi fit/K-lifetimes to be remeasured

arxiv 2209.02143

G.D. Knecht Neshtapour

amplitude coefficient	Devlin et *al.* (Ref. [3])	Kambor et *al.* (Ref. [4])	Bijnens et *al.* (Ref. [5])	Our scaled fit	SF
α_1	91.4 ± 0.24	91.71 ± 0.32	93.16 ± 0.36	92.80 ± 0.64	2.9
α_3	-7.14 ± 0.36	-7.36 ± 0.47	-6.72 ± 0.46	-7.45 ± 0.79	3.2
β_1	-25.83 ± 0.41	-25.68 ± 0.27	-27.06 ± 0.43	-26.46 ± 0.22	1.6
β_3	-2.48 ± 0.48	-2.43 ± 0.41	-2.22 ± 0.47	-2.50 ± 0.29	1.6
γ_3	2.51 ± 0.36	2.26 ± 0.23	2.95 ± 0.32	2.78 ± 0.10	1.0
ζ_1	-0.37 ± 0.11	-0.47 ± 0.15	-0.40 ± 0.19	-0.11 ± 0.03	1.7
ζ_3	—	-0.21 ± 0.08	-0.09 ± 0.10	-0.05 ± 0.03	1.8
ξ_1	-1.25 ± 0.12	-1.51 ± 0.30	-1.83 ± 0.30	-1.20 ± 0.13	1.7
ξ_3	—	-0.12 ± 0.17	-0.17 ± 0.16	0.10 ± 0.10	1.6
ξ'_3	—	-0.21 ± 0.51	-0.56 ± 0.42	-0.07 ± 0.16	1.8
χ^2/dof	12.8/3	10.3/2	5.4/5	5.18/5 (30.66/5)	

Needed also for various SM Kaon assessments

Conclusions

- Zupan, Kaon physics: Flavour tests and (possible) light sector test
- Nice complementarity with B-physics /anomalies

Back-up

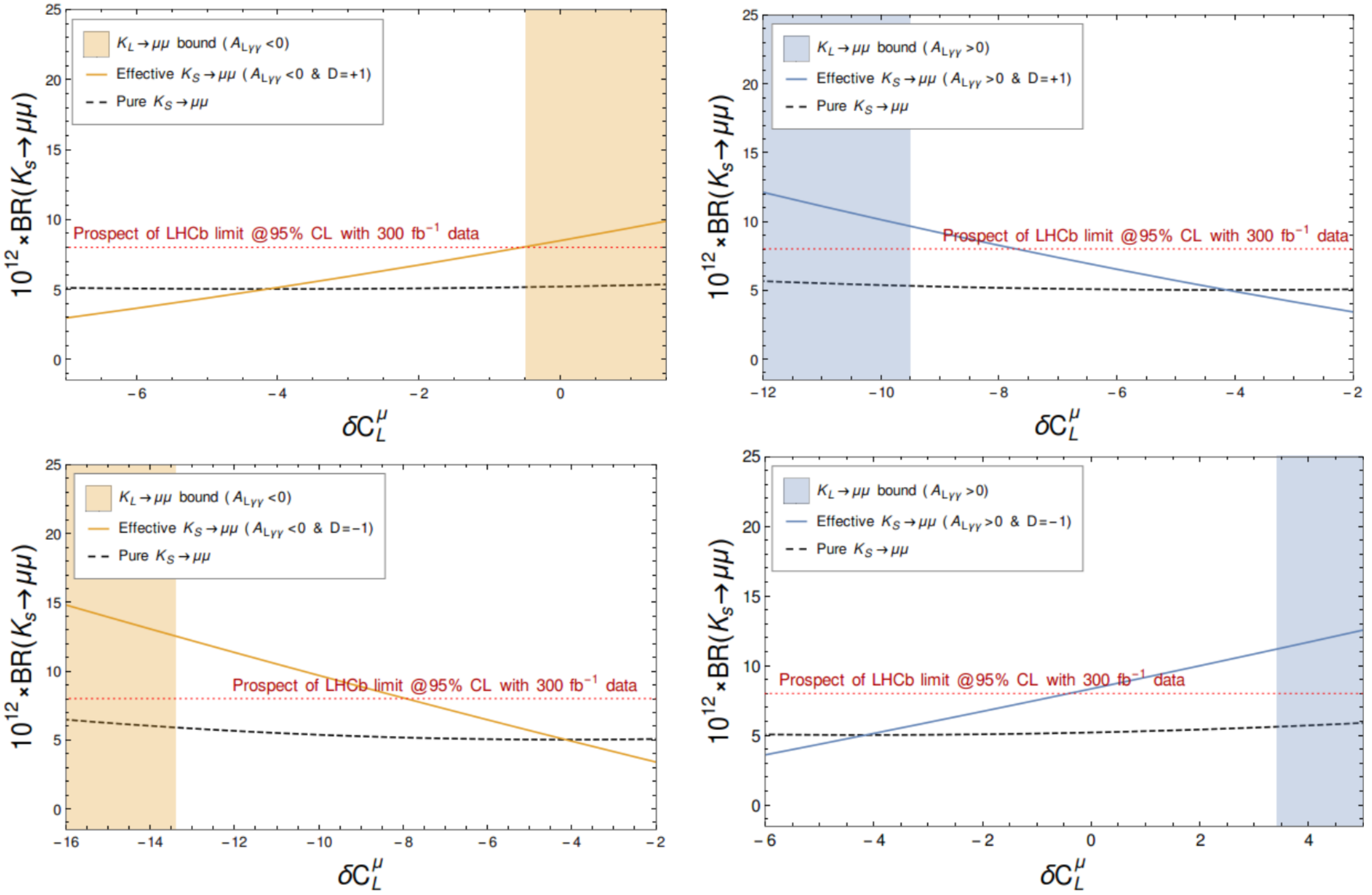


Figure 5: The impact of the interference of $K_L \to \mu\bar{\mu}$ on the effective branching fraction of $K_S \to \mu\bar{\mu}$. The left and the right panels correspond to negative and positive signs for $A_{L\gamma\gamma}$, respectively. The upper and lower panels correspond to dilution factor $D = +1$ and $D = -1$, respectively.

$K \to \pi\nu\bar{\nu}$ in the Standard Model

- 2105.02868 Standard Model Prediction

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= 7.73(16)_{SD}(25)_{LD}(54)_{para.} \times 10^{-11}\,, \\ \mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) &= 2.59(6)_{SD}(2)_{LD}(28)_{para.} \times 10^{-11}\,. \end{aligned}$$

- will update [preliminary numerics:]

$$\begin{aligned} \mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) &= 8.25(11)_{SD}(25)_{LD}(57)_{para.} \times 10^{-11}\,, \\ \mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) &= 2.83(1)_{SD}(2)_{LD}(30)_{para.} \times 10^{-11}\,. \end{aligned}$$

- NA62 collaboration
  $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+3.4}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$
- JPARC-KOTO has $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \leq 3.0 \times 10^{-9}$

Other interesting issues

KAON2022

09:00	**Radiative Kaon Decays**	*Filippo Mazzetti*	
	Osaka University, Toyonaka Campus, Nambu Hall	09:00 - 09:25	
	Measurement of structure dependent radiative K+ ->e+ nu gamma decays using stopped positive kaons		
	Suguru Shimizu		
10:00	**Measurement of the radiative decay Ke3g at the NA62 experiment**	*Mauro Piccini*	
	Osaka University, Toyonaka Campus, Nambu Hall	09:50 - 10:15	
	Study of the rare decay K+ -> pi+ gamma gamma at the NA62 experiment	*Artur Shaikhiev*	
	Osaka University, Toyonaka Campus, Nambu Hall	10:15 - 10:40	
	CANCELED: Measurement of the K+ → π0 μ+ νμ γ decay with OKA setup	*Victor Kurshetsov*	
	Osaka University, Toyonaka Campus, Nambu Hall	10:40 - 10:41	
	Coffee Break		
11:00	*Osaka University, Toyonaka Campus, Nambu Hall*	10:41 - 11:10	
	Radiative modes $K\to\pi\gamma^*\gamma^{(*)}$ and the $K\to\pi4e$ decay	*Tomas Husek*	
	Osaka University, Toyonaka Campus, Nambu Hall	11:10 - 11:35	
	Measurement of the rare decay K+ -> pi+ mu+ mu- at the NA62 experiment	*Michal Koval*	
	Osaka University, Toyonaka Campus, Nambu Hall	11:35 - 12:00	
12:00	**RD Search for KS(L)-> μμμμ at the LHC**	*Miguel Fernández Gómez*	
	Osaka University, Toyonaka Campus, Nambu Hall	12:00 - 12:25	
	First measurement of the K± → π0 π0 μ± ν decay	*Anna Korotkova*	
	Osaka University, Toyonaka Campus, Nambu Hall	12:25 - 12:50	

LHCB

$K_S \to \mu^+\mu^-\mu^+\mu^-$, search for instance Dark photons and Standard Model

Forward backward asymmetry $K^\pm \to \pi^\pm\mu^+\mu^-$ NA62

extract SD from $K^+ \to \pi^+\pi^0 e^+ e^-$ NA62

Arxiv 1112.5184

Historical progression			
Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865 [32]
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2 [33]
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2 [34]

Current situation			
Channel	a_+	b_+	Reference
ee	-0.561 ± 0.009	-0.694 ± 0.040	comb. [42]
$\mu\mu$	-0.592 ± 0.015	-0.699 ± 0.058	NA62 [16]

Table 1: Summary of the estimation of vector form factors for $K^+ \to \pi^+\ell\bar{\ell}$. The left panel gives the historical progression and the right panel gives the current status.

$$a_+ = -0.575 \pm 0.013, \; b_+ = -0.722 \pm 0.043$$

$$a_+ = -1.58 + \begin{cases} -0.10 \div +0.03 & \text{NDR} \\ -0.14 \div +0.07 & \text{HV} \end{cases}$$

$$b_+ = -0.76 + \begin{cases} -0.04 \div +0.03 & \text{NDR} \\ -0.07 \div +0.03 & \text{HV} \end{cases}$$

Matching short distance