August 29, 2023, Corfu' Greece

Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

Workshop on Standard Model and Beyond

Theory of rare kaon decays

Giancarlo D'Ambrosio
INFN Sezione di Napoli

Anatomy of kaon decays and prospects for lepton flavour universality violation
G. D'Ambrosio (INFN, Naples), A.M. Iyer (Indian Inst. Tech., New Delhi), F. Mahmoudi (IP2I, Lyon and CERN), S. Neshatpour (INFN, Naples) (Jun 29, 2022)
Published in: *JHEP* 09 (2022) 148, *JHEP* 09 (2022) 148 • e-Print: 2206.14748 [hep-ph]

Collaboration with David Greynat and Marc Knecht
On the amplitudes for the CP-conserving $K\pm(KS)\to\pi\pm(\pi 0)\ell+\ell-$ rare decay modes
arXiv:1812.00735 JHEP,
Matching long and short distances at order $O(\alpha s)$
in the form factors for $K\to\pi\ell+\ell-$ PLB arXiv:1906.03046

Collaboration with Crivellin,A., Kitahara, T and Nierste, U. e-Print: arXiv:1703.05786 PRD

Crivellin, A, GD, Hoferichter, M and Tunstall, L
Phys.Rev. D 2016

Collaboration with Teppei Kitahara arXiv:1707.06999 PRL

Closing in on the radiative weak chiral couplings Luigi Cappiello, Oscar Cata, GD
arXiv:1712.10270,,EPJC

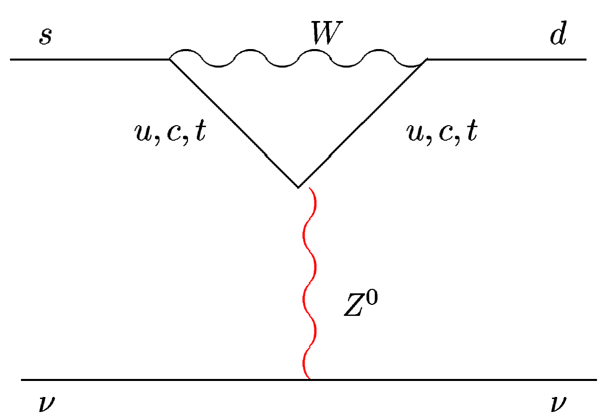
Outline

- $K \to \pi \nu\bar{\nu}$
- $K_{S,L} \to \mu\mu$
- Theory
- Lepton Flavour Universality Violation in Kaons
- Conclusions

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

Why we need KOTO NA62 HIKE

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



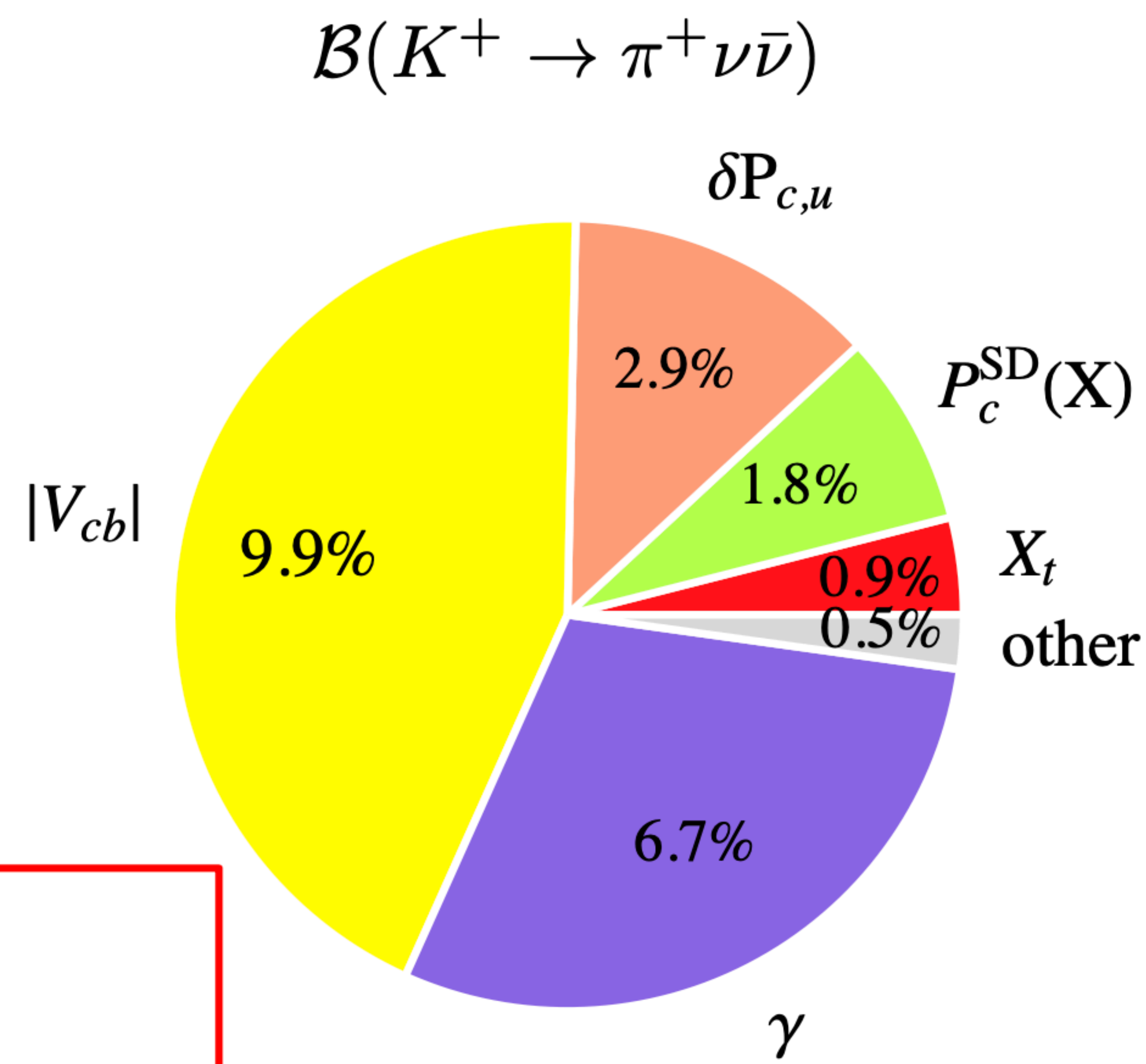
$$\sim \quad \left[A^2\lambda^5\;(1-\rho-i\eta)m_t^2 + \lambda m_c^2\right]$$

SM $\quad \underbrace{V-A\otimes V-A}_{\Downarrow}$ Littenberg

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

SM

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

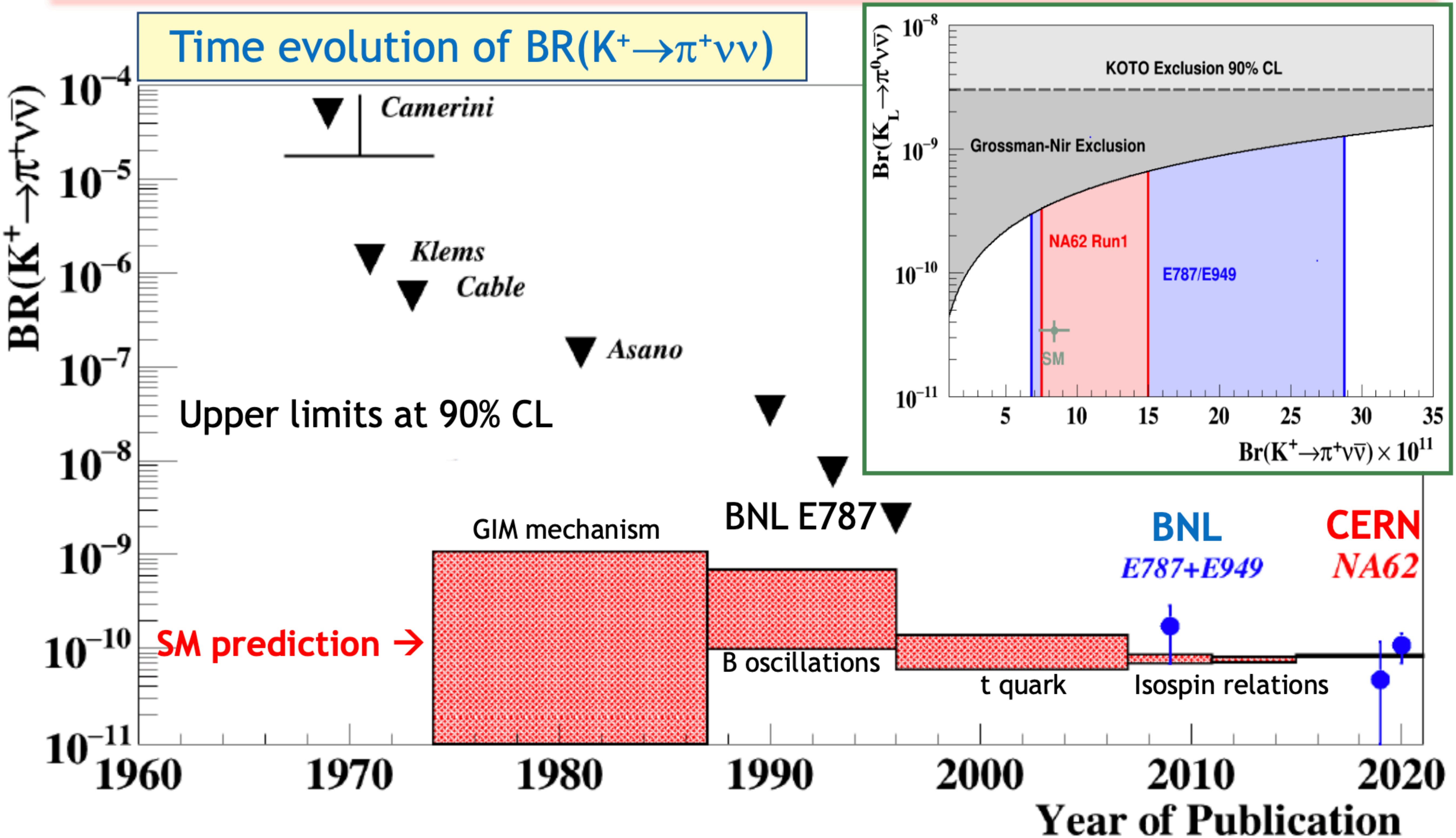


SM branching ratios:
[arXiv:2109.11032]

$K^+ \to \pi^+ \nu\nu(\gamma) = (8.62 \pm 0.42) \times 10^{-11}$

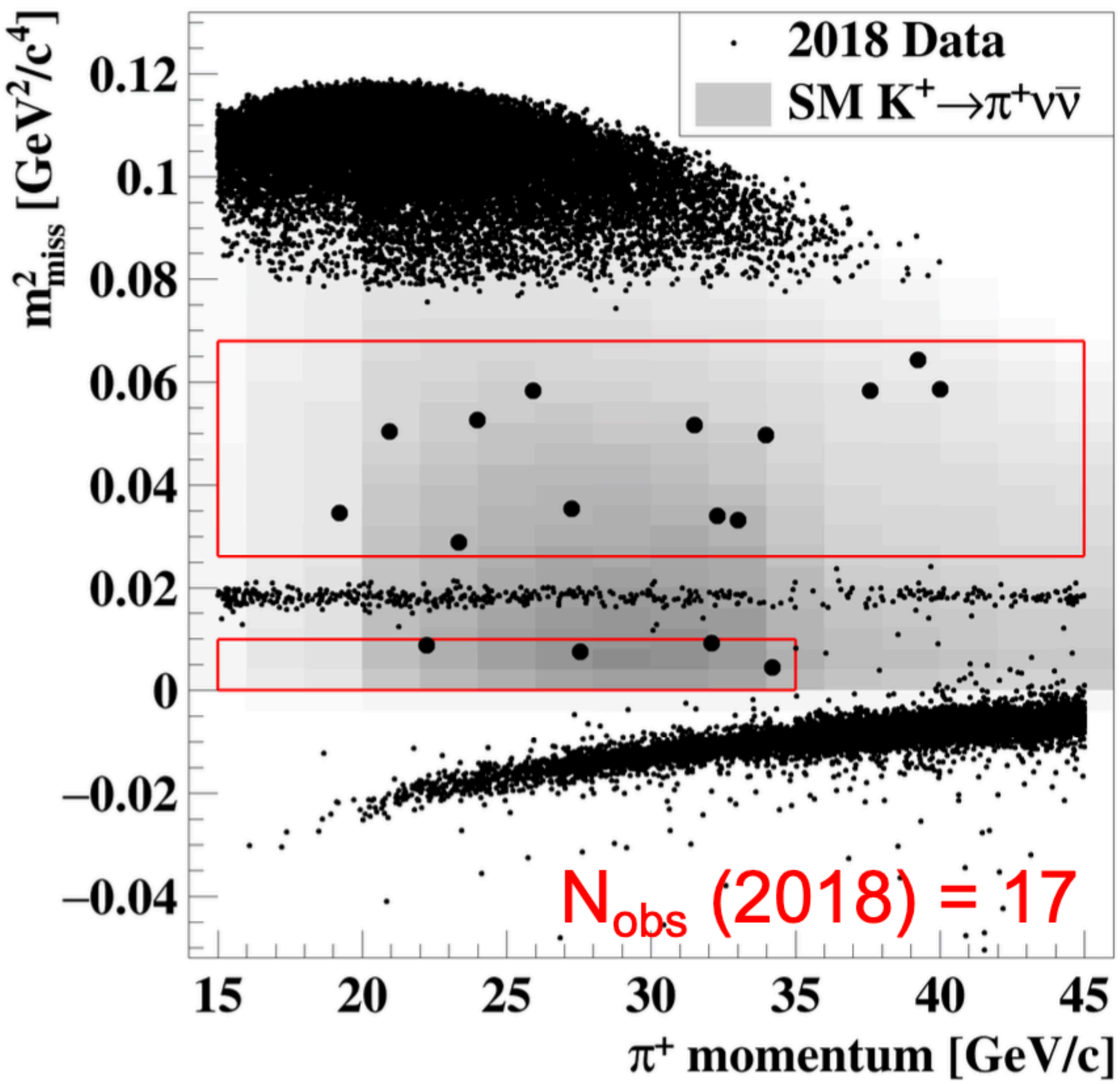
$K_L \to \pi^0 \nu\nu = (2.94 \pm 0.15) \times 10^{-11}$

History of $K^+ \to \pi^+ \nu\nu$ searches

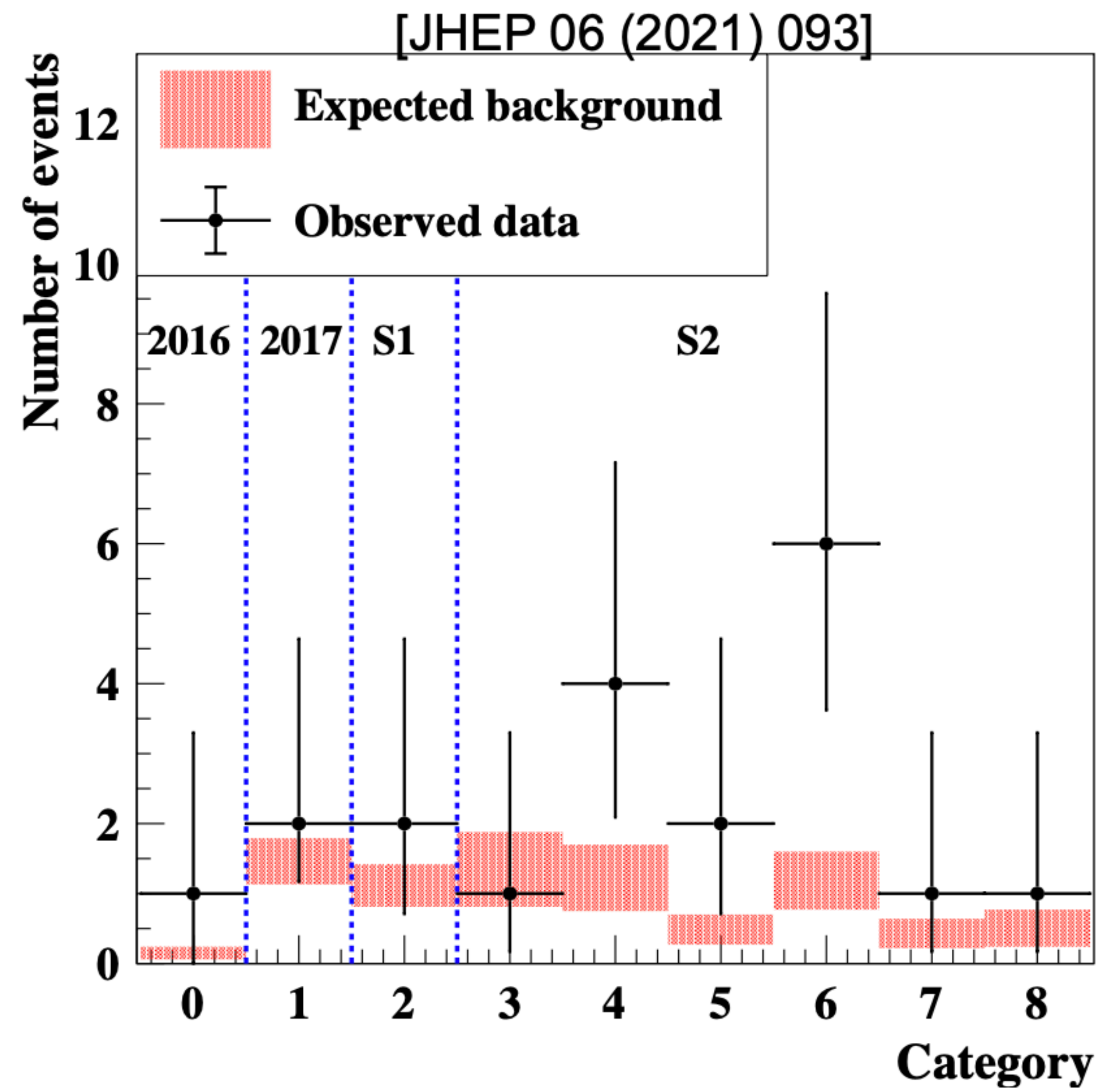


NA62 Run 2 goal: **BR($K^+ \to \pi^+ \nu\nu$)** measurement to **10–15%** precision.

NA62: $K^+ \to \pi^+ \nu \bar{\nu}$ RUN1=2016+2017+2018



[JHEP 06 (2021) 093]



N_{obs} (Run1) = 20

$$N^{exp}_{background} = 7.03^{+1.05}_{-0.82} \qquad N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

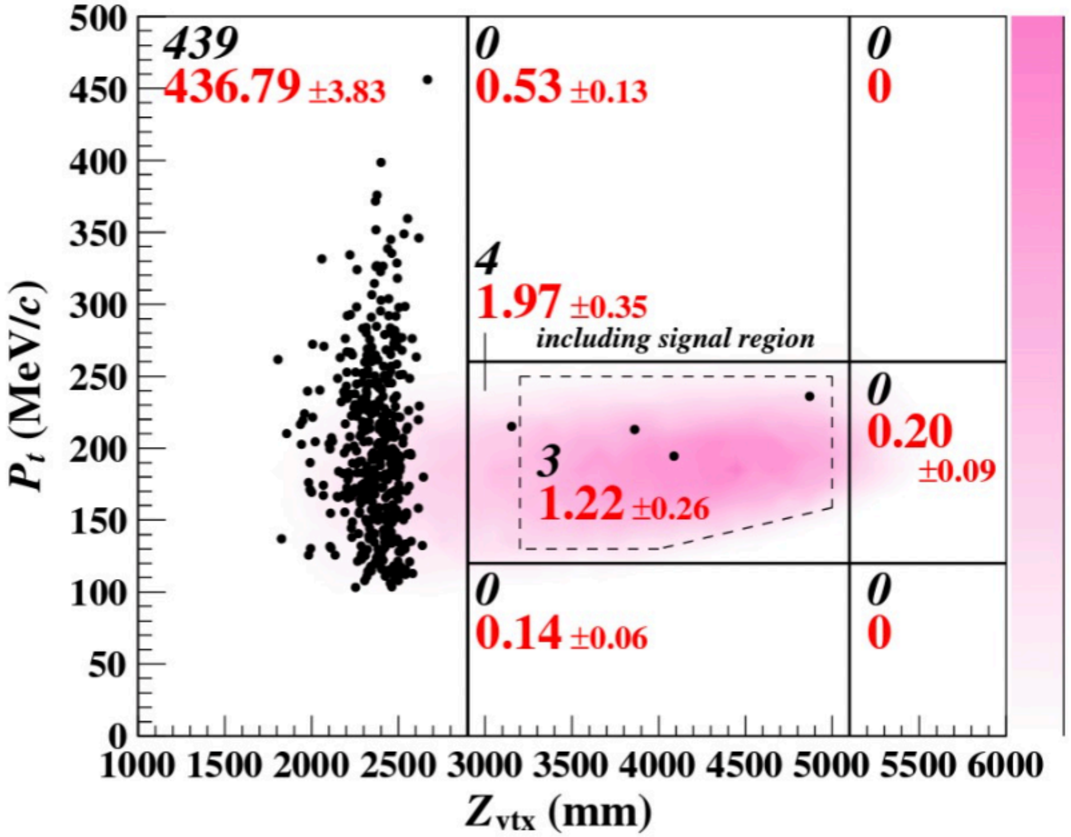
3.4σ significance

Most precise determination of the decay rate to date

Prospects: Run 2 (2021-2025) with nominal beam intensity, modified beamline and additional detectors.

Aim to measure BR($K^+ \to \pi^+\nu\nu$) at O(15%) precision by LS3

KOTO: $K^0 \to \pi^0 \nu \bar{\nu}$



Expected: 0.04 signal + 1.22 background events

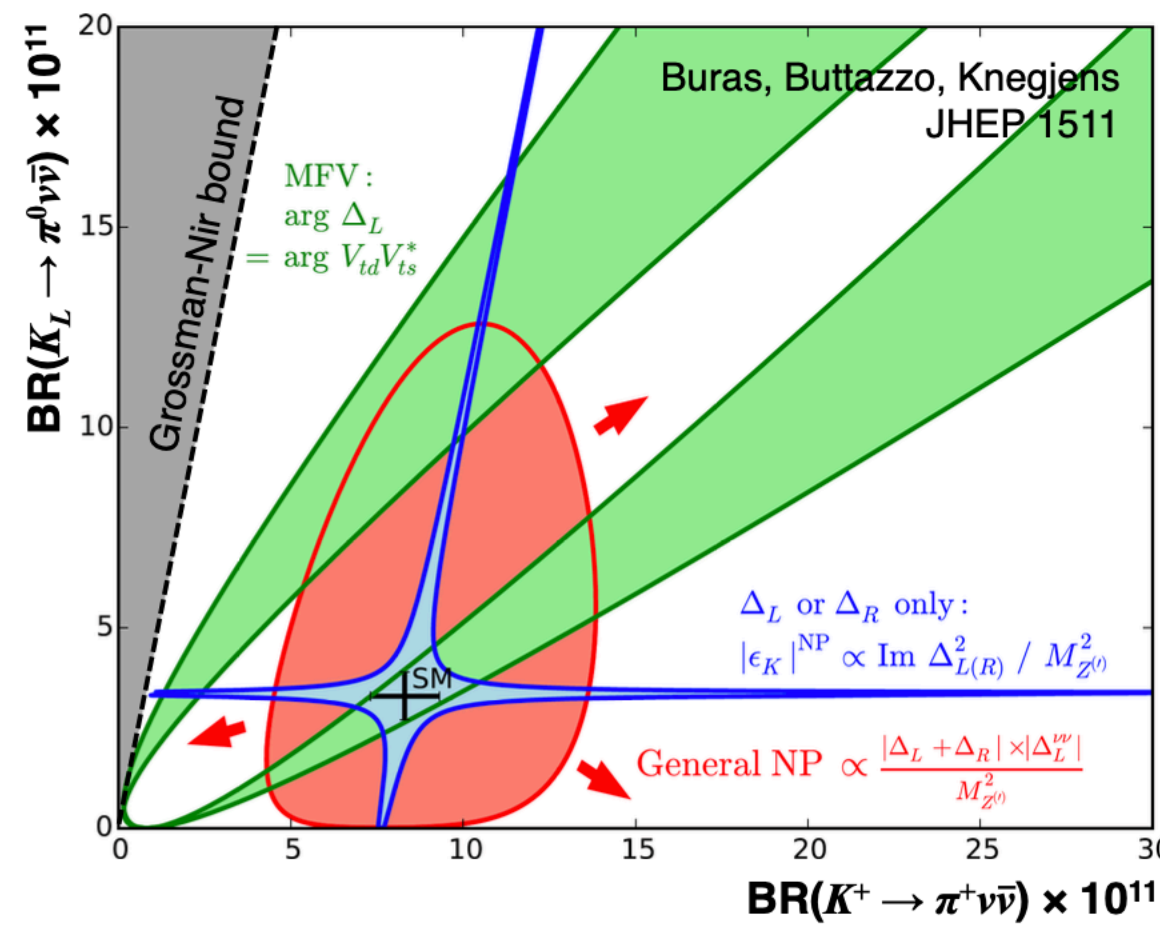
Observed: 3 events in the signal box

PRL 126 (2021) 121801

Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

Background sources studied after looking inside the blind signal region

$$\mathbf{BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}\ (90\%\ CL)}$$



Prospects:

J-PARC main ring upgrade: beam power to 80-100 kW

KOTO DAQ upgrade: event throughput x4

KOTO will collect x 11 more data, low background

Projected S.E.S. ~ O(10^{-11}) by 2026

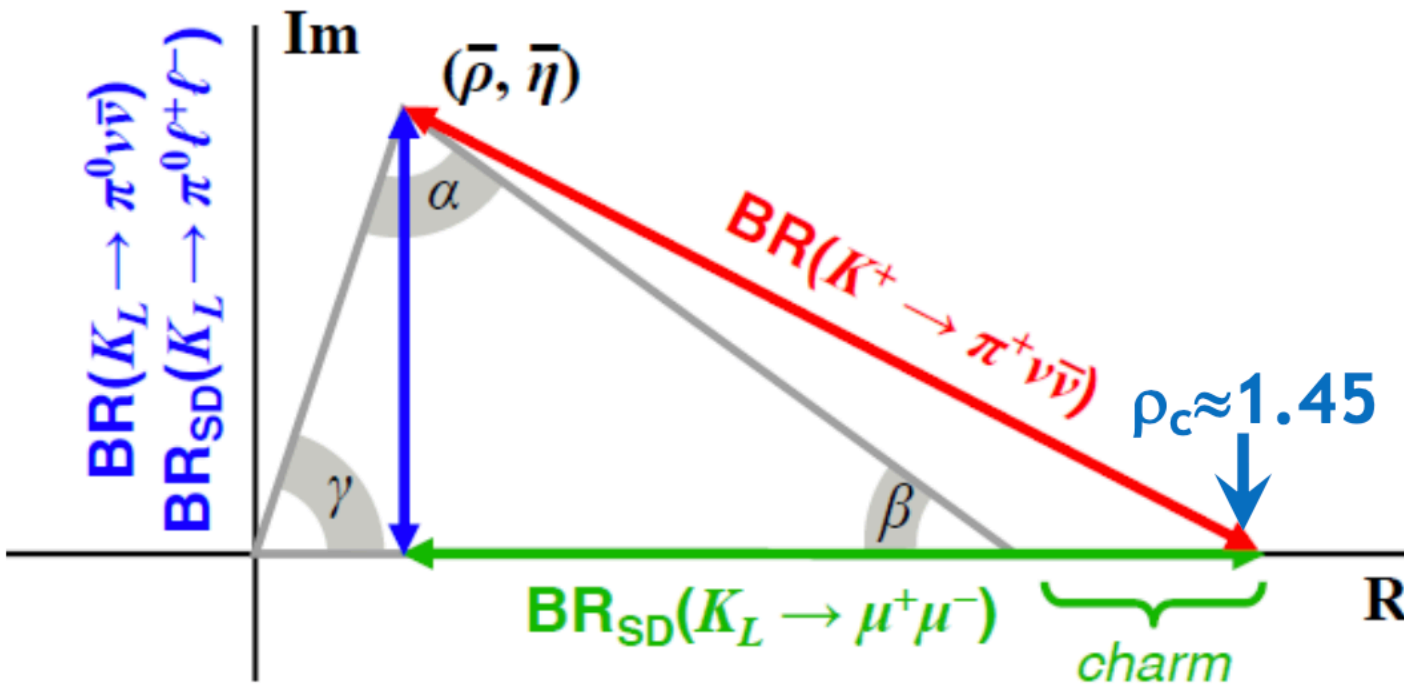
Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	**8.6±0.4**	**10.6±4.0**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	**3.0±0.2**	< 300

*Approx. error on LD-subtracted rate excluding parametric contributions

(see also arXiv:2203.09524)

- FCNC processes dominated by Z-penguin and box diagrams.
- SM rates determined by V_{CKM}, with minimal non-parametric "theory" uncertainties.
- Theory errors are being reduced *[Lattice QCD, e.g. arXiv:2203.10998]*.
- The current focus is on $K\to\pi\nu\nu$: uniquely clean theoretically.



Prospects: HIKE and KOTO-II

HIKE: multi-purpose high-intensity kaon decay-in-flight experiments proposed at CERN SPS

High-intensity beams at CERN North Area after LS3 with x 4-6 current NA62 nominal
K^+ : 2.2 x 10^{13} decays per year K_L : 3.8 x 10^{13} decays per year

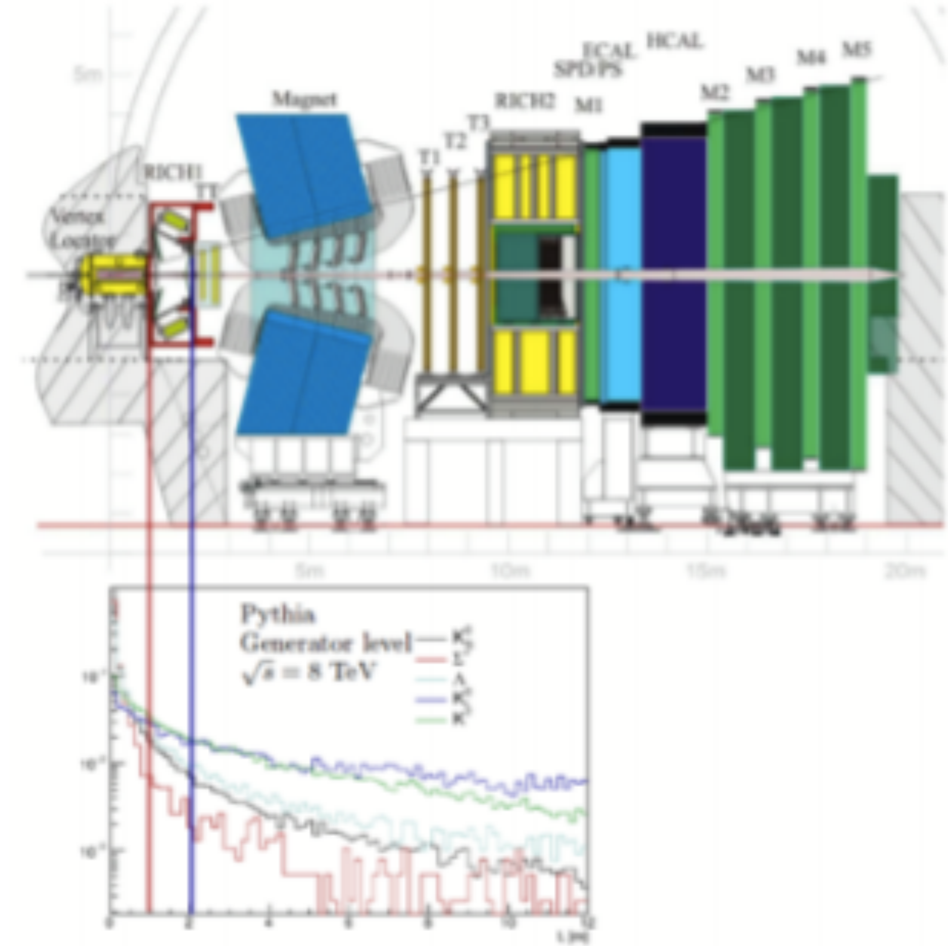
Phase 1 ($K^+ \to \pi^+ \nu\nu$ at ~5% precision), Phase 2 ($K_L \to \pi^0 l^+ l^-$ at ~20% precision)
Comprehensive program of rare kaon decays, precision measurements, searches

KOTO-II: high-beam-power experiment proposed at J-PARC Hadron Hall

Increase proton beam power > 100 kW
New neutral beamline at 5 degrees: larger K_L yield, momentum = 5.2 GeV/c
Increase fiducial volume from 2x2m to 3x12m, new detectors

60 SM events of $K_L \to \pi^0 \nu\nu$ with S/B~1 in 3 years, ~20% precision
Search for exotic particles in $K_L \to \pi^0 X$

Kaon in LHCb



- LHCb experiment has been designed for efficient reconstructions of ***b*** and ***c***
- Huge production of strangeness [$O(10^{13})/\mathrm{fb}^{-1}$ K^0_S] is suppressed by its trigger efficiency [ε~1-2%@LHC Run-I, ε~18%@LHC Run-II]
- LHCb upgrade (LS2=Phase I upgrade, LS4=Phase II upgrade) could realize high efficiency for K^0_S [ε~90%@LHC Run-III] [M. R. Pernas, HL/HE LHC meeting, Fermilab, 2018]
- In LHC Run-III and HL-LHC, we could probe the *ultra* rare decay Br~$O(10^{-11\sim-12})$

$K_S \to \mu\mu$

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST

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 electromagnetic 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

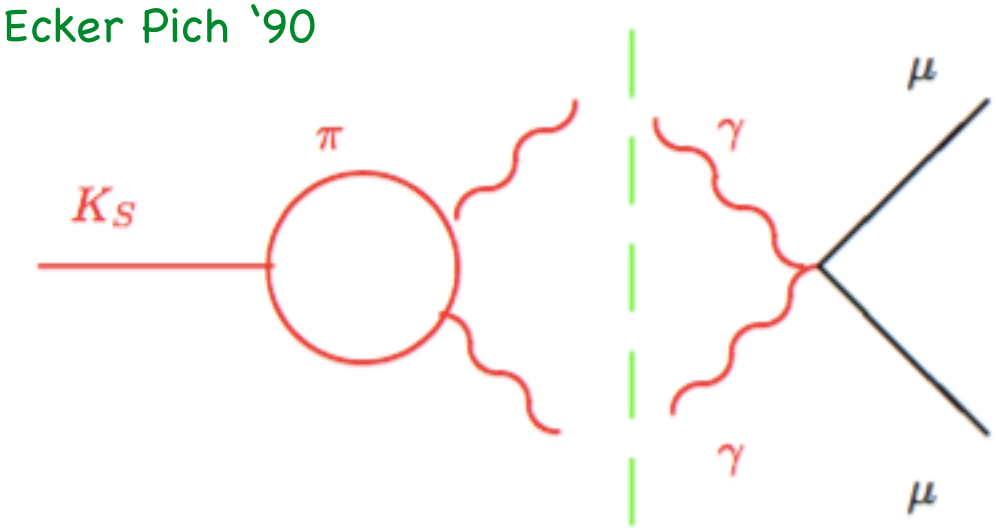
$\Gamma(K^0_S \to \mu^+\mu^-)/\Gamma_{\text{total}}$

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
$< \mathbf{2.1 \times 10^{-10}}$	90	[1] AAIJ	2020AE	LHCB
• • We do not use the following data for averages, fits, limits, etc. • •				
$< 8 \times 10^{-10}$	90	[2] AAIJ	2017BQ	LHCB
$< 9 \times 10^{-9}$	90	[3] AAIJ	2013G	LHCB
$< 3.2 \times 10^{-7}$	90	GJESDAL	1973	ASPK
$< 7 \times 10^{-6}$	90	HYAMS	1969B	OSPK

$K_S \to \mu\mu$

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

$< 2.1 \times 10^{-10} \quad 90\% CL$

$K_L \to \mu\mu$

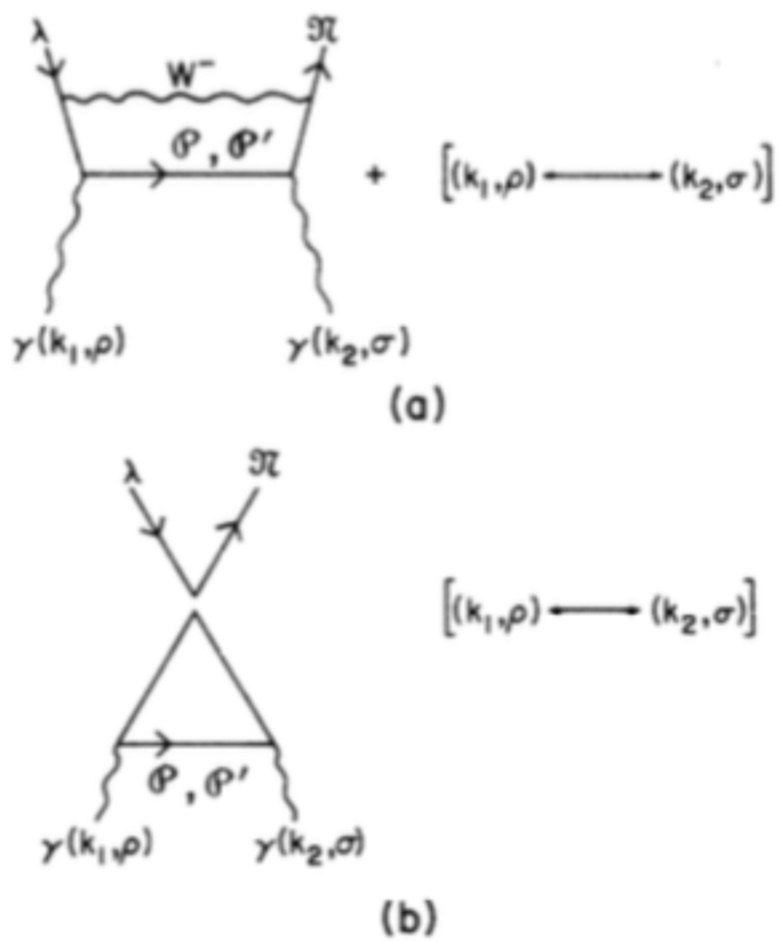


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

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

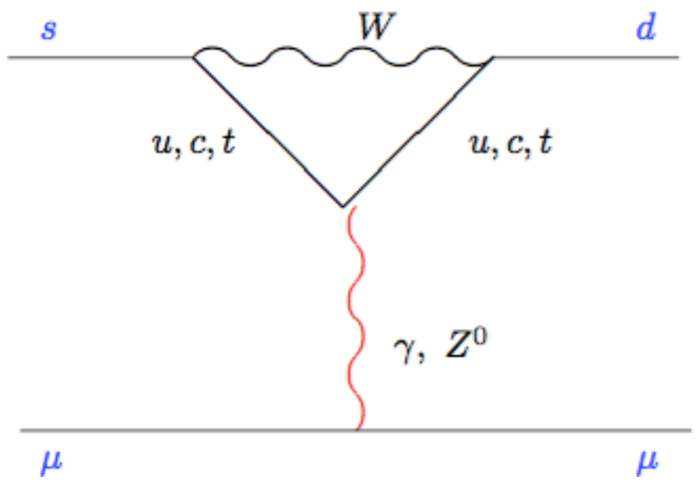
VALUE (10^{-6})	EVTS	DOCUMENT ID		TECN	COMMENT
3.48 ± 0.05	**OUR AVERAGE**				
3.474 ±0.057	6210	AMBROSE	2000	B871	
3.87 ±0.30	179	[1] AKAGI	1995	SPEC	
3.38 ±0.17	707	HEINSON	1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	1991B	SPEC	In AKAGI 19

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

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

Dispersive calculation: Re A, Im A

$K_L \to \mu\mu$



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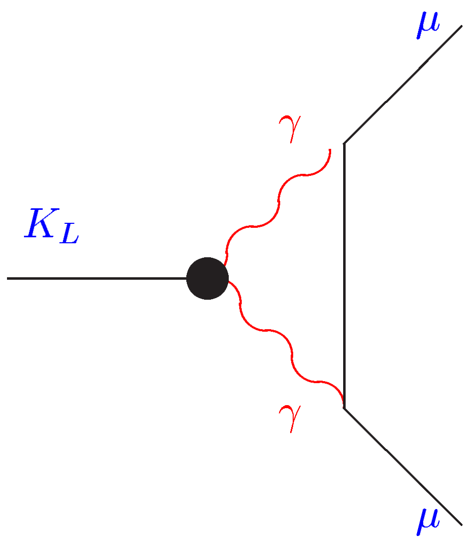


$$\frac{\Gamma(K_L \to \mu\bar{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim \quad |ReA|^2 + |ImA|^2$$

Absorptive calculation
model independent

27.14

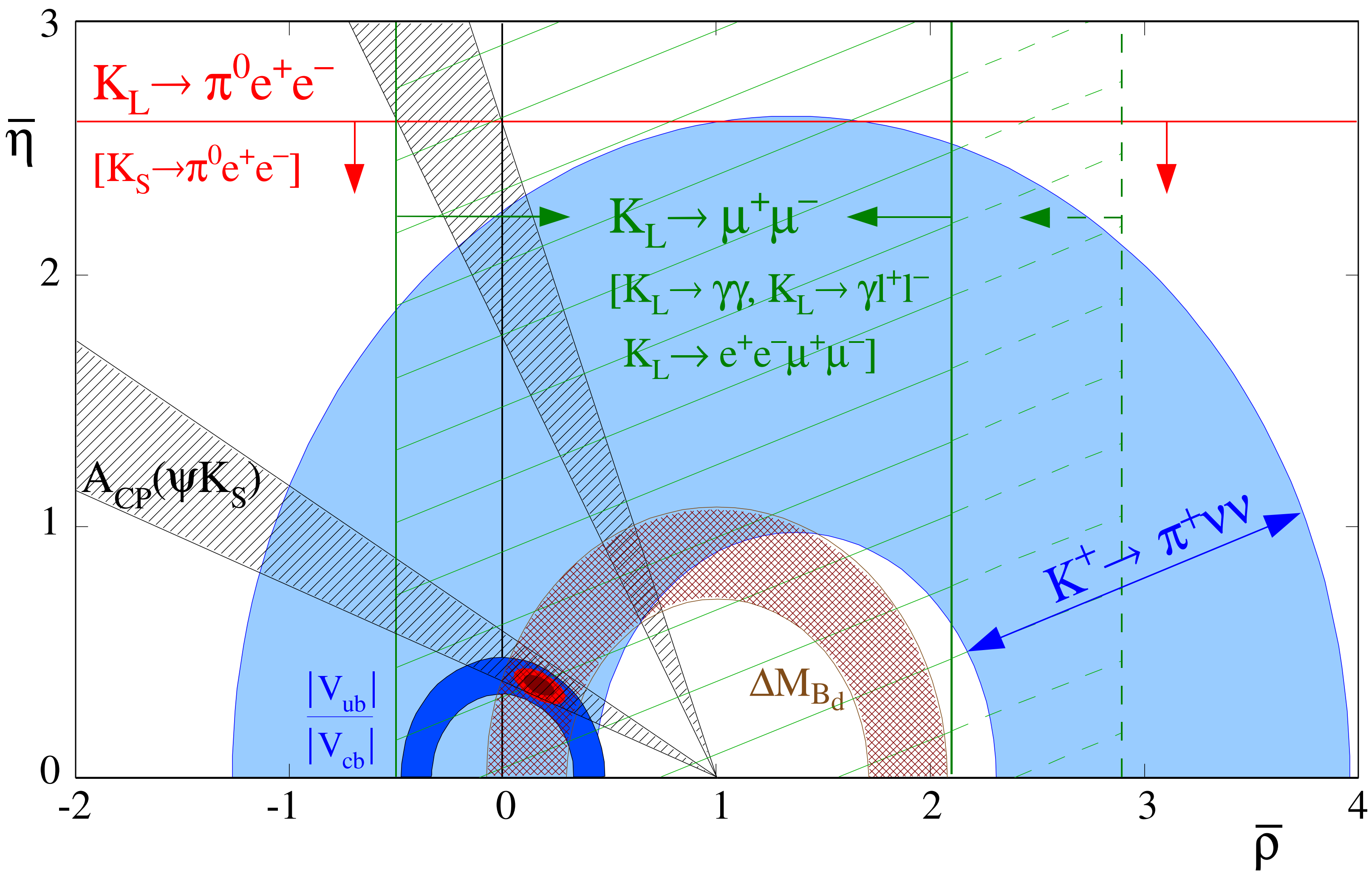
Subtracting from expt. the Absorptive contribution

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

$$|\chi_{\text{short}}^{\text{SM}}| = 1.96(1.11 - 0.92\bar{\rho})$$

Isidori Unterdorfer

$K_L \to \mu\mu$: our sign ignorance



We do not know the sign

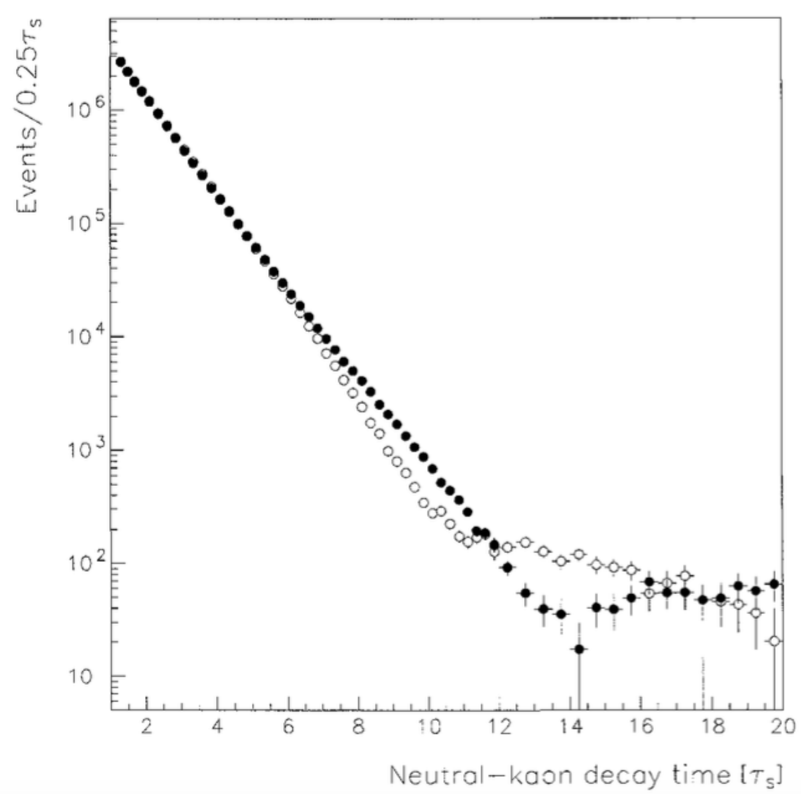
We know the sign

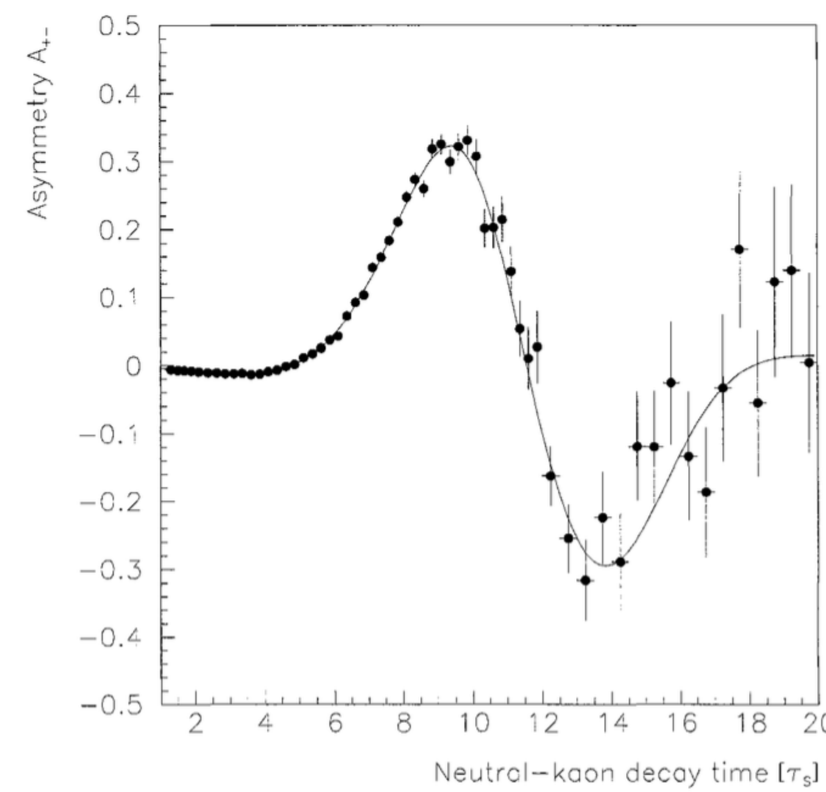
{

CPLEAR Flavor tagging

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

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





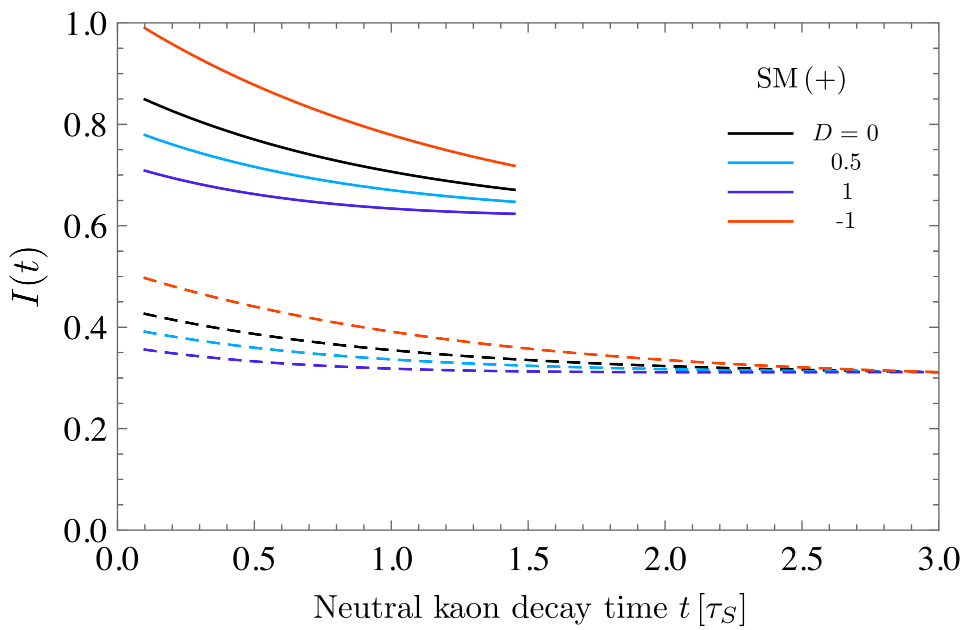
}

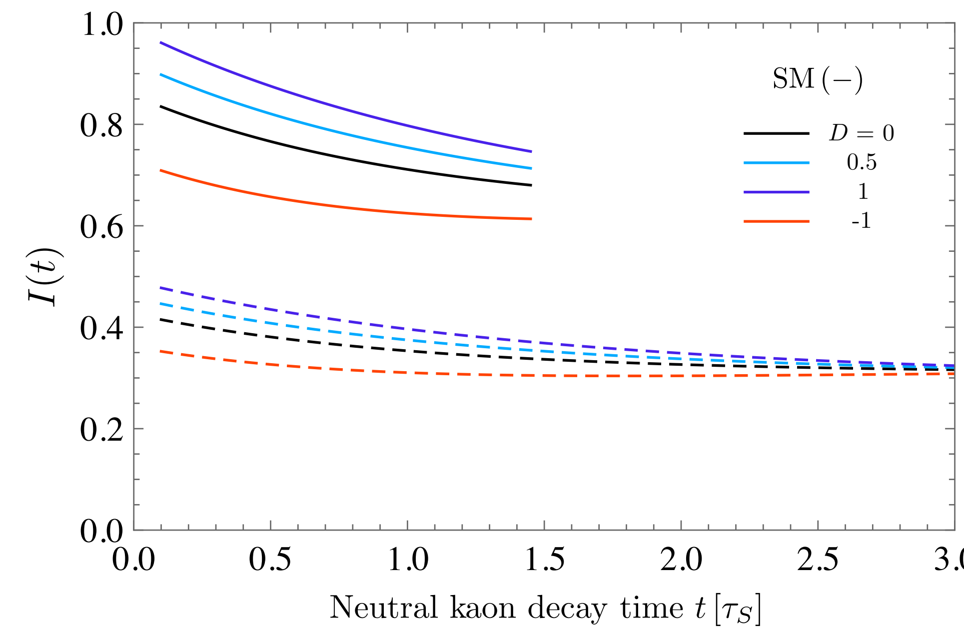
Can we study $K^0(t)$?

GD , Kitahara
1707.06999 PRL

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

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





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

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

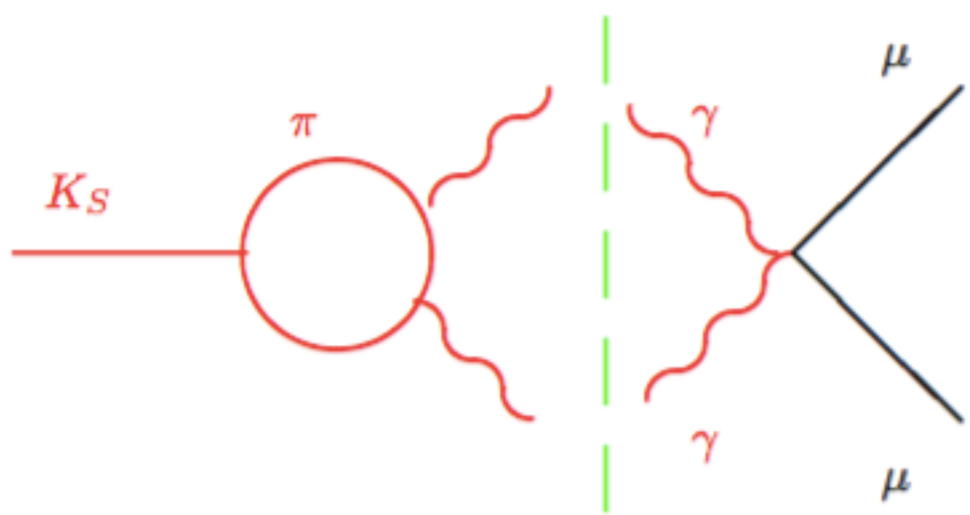
- Short distance interfering with Large CP conserving LD contribution !

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

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

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

$K_S \to \mu\mu$: how to improve the THEORY error



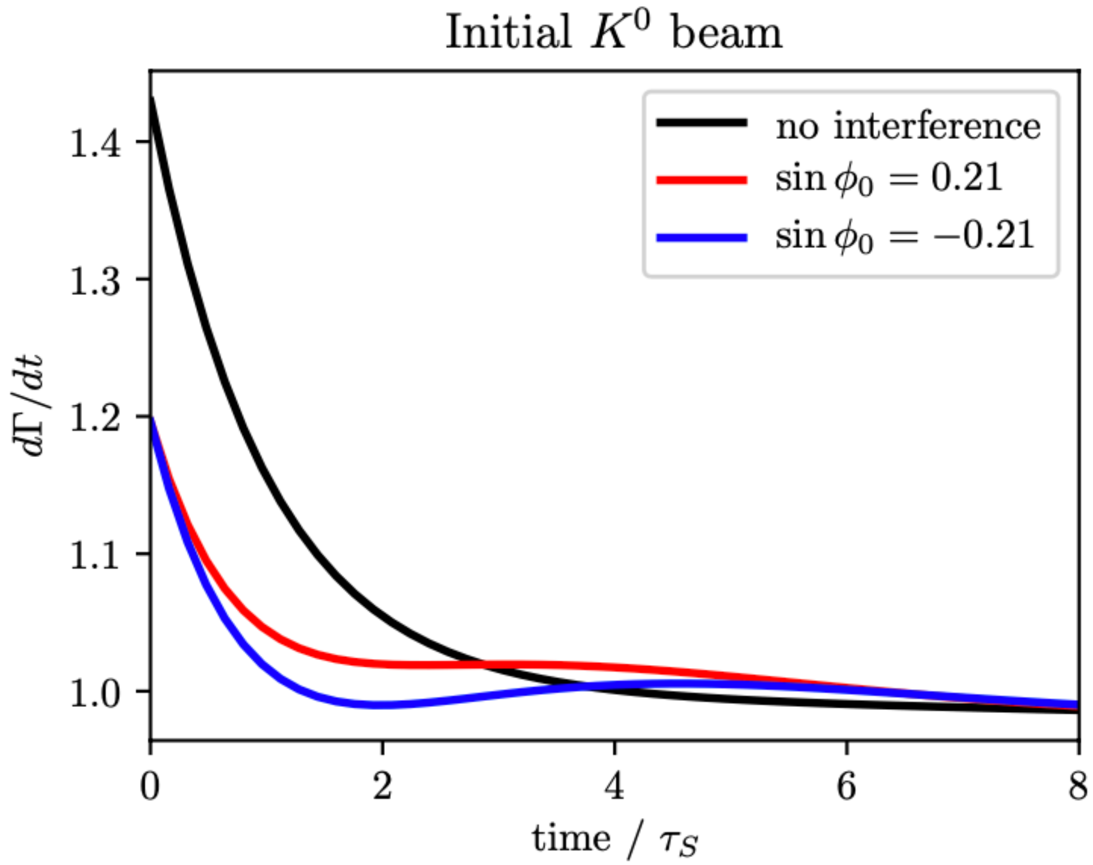
Dispersive treatment of $K_S \to \gamma\gamma$ and $K_S \to \gamma l^+ l^-$

Gilberto Colangelo, Ramon Stucki, and Lewis C. Tunstall

LD 5×10^{-12} 20% TH err

$$K_S \to \gamma\mu\mu$$
$$K_S \to \mu\mu\mu\mu$$
$$K_S \to ee\mu\mu$$
$$K_S \to \gamma\gamma$$

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



Interference terms sensitive to short-distance component!

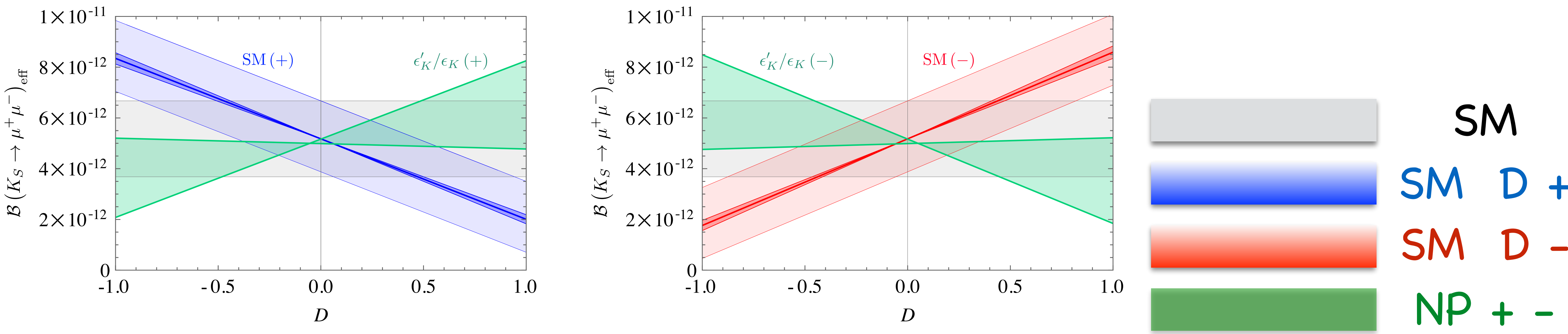
[D'Ambrosio, Kitahara 1707.06999]

$$\mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0} = \mathrm{Br}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\rm int}}{C_L}\right)^2$$

[Dery et al. 2104.06427]

Short distance window

GD , Kitahara
1707.06999 PRL

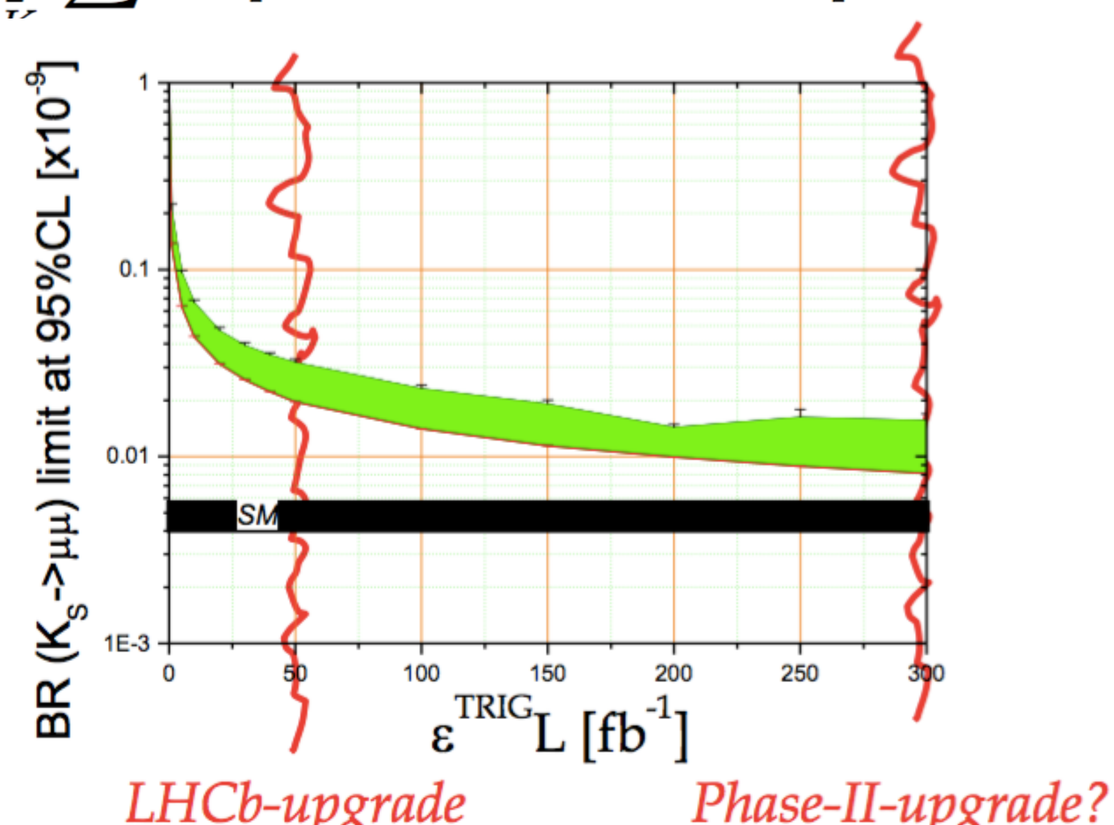


modified Z-coupling model. ϵ'_K/ϵ

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm eff}$$

$$= \tau_S \left[\int_{t_{min}}^{t_{max}} dt \left(\Gamma(K_1) e^{-\Gamma_S t} + \frac{D}{8\pi M_K} \sqrt{1 - \frac{4m_\mu^2}{M_K^2}} \sum \mathrm{Re}\left[e^{-i\Delta M_K t} \mathcal{A}(K_1)^* \mathcal{A}(K_2) \right] e^{-\frac{\Gamma_S+\Gamma_L}{2}t} \right) \varepsilon(t) \right]$$

$$\times \left(\int_{t_{min}}^{t_{max}} dt\, e^{-\Gamma_S t} \varepsilon(t) \right)^{-1},$$



Rare Kaon decay program at LHCB

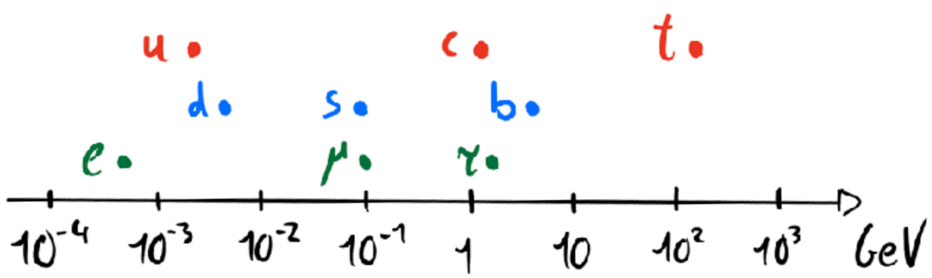
	PDG	Prospects
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	(LD)$(5.0 \pm 1.5) \cdot 10^{-12}$ NP $< 10^{-11}$
$K_S \to \mu\mu\mu\mu$	–	SM LD $\sim 2 \times 10^{-14}$
$K_S \to ee\mu\mu$	–	$\sim 10^{-11}$
$K_S \to eeee$	–	$\sim 10^{-10}$
$K_S \to \pi^0\mu\mu$	$(2.9 \pm 1.3) \cdot 10^{-9}$	$\sim 10^{-9}$
$K_S \to \pi^+\pi^-e^+e^-$	$(4.79 \pm 0.15) \cdot 10^{-5}$	SM LD $\sim 10^{-5}$
$K_S \to \pi^+\pi^-\mu^+\mu^-$	–	SM LD $\sim 10^{-14}$

Rare n Strange 2017: strange physics at LHCb

GD, Lewis Tunstall, Diego Martinez Santos,Veronika Chobanova,
Xabier Cid Vidal, Francesco Dettori, Marc-Olivier Bettler,
Teppei Kitahara,,Kei Yamamoto

Theory

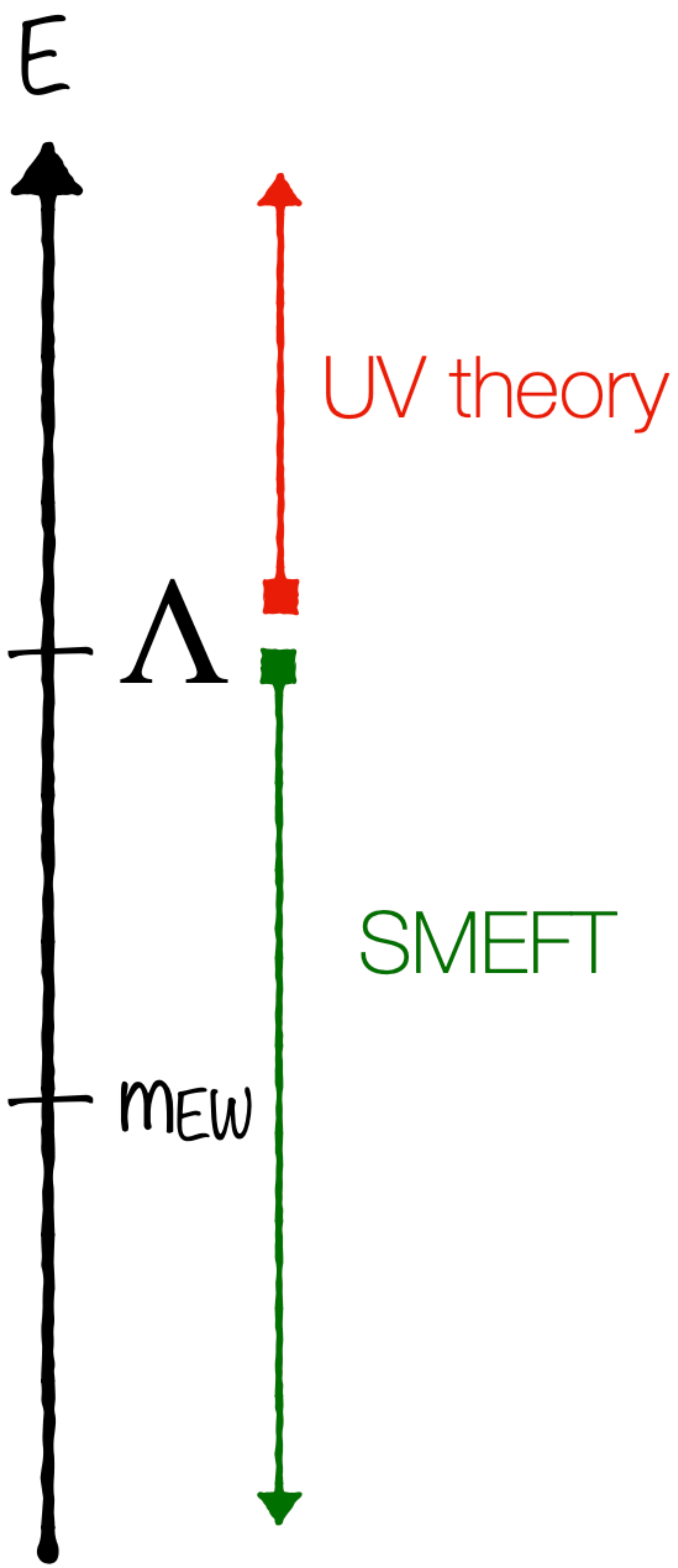
$(m_\nu \sim 10^{-11}\ \mathrm{GeV})$



	$SU(2)_L \times SU(2)_R$	$SU(3)_c$	$SU(2)_L$	Y
L_i	$(\frac{1}{2}, 0)$	1	2	$-\frac{1}{2}$
e_i	$(0, \frac{1}{2})$	1	1	-1
Q_i	$(\frac{1}{2}, 0)$	3	2	$\frac{1}{6}$
u_i	$(0, \frac{1}{2})$	3	1	$\frac{2}{3}$
d_i	$(0, \frac{1}{2})$	3	1	$-\frac{1}{3}$
H	$(0, 0)$	1	2	$\frac{1}{2}$

$$\mathcal{L}^{SM} = -\frac{1}{4}\sum_A F^A_{\mu\nu} F^{A\mu\nu} - \theta \frac{g_s^2}{32\pi^2} G^A_{\mu\nu} \tilde{G}^{A\mu\nu} + \sum_f \bar{\psi}_f i D_\mu \gamma^\mu \psi_f$$

$$+ |D_\mu H|^2 - V(H) - \left(\bar{\psi}^i_F y^{ij}_F \psi_f H + h.c. \right)$$



E
UV theory
Λ
SMEFT
mEW

Weinberg '77 EFT SM
Accidental symmetries

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d\leq 4)} + \frac{C^{(5)}}{\Lambda_K}\mathcal{O}_W + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}[\varphi_{SM}] + \mathcal{O}(\Lambda^{-4})$$

SM

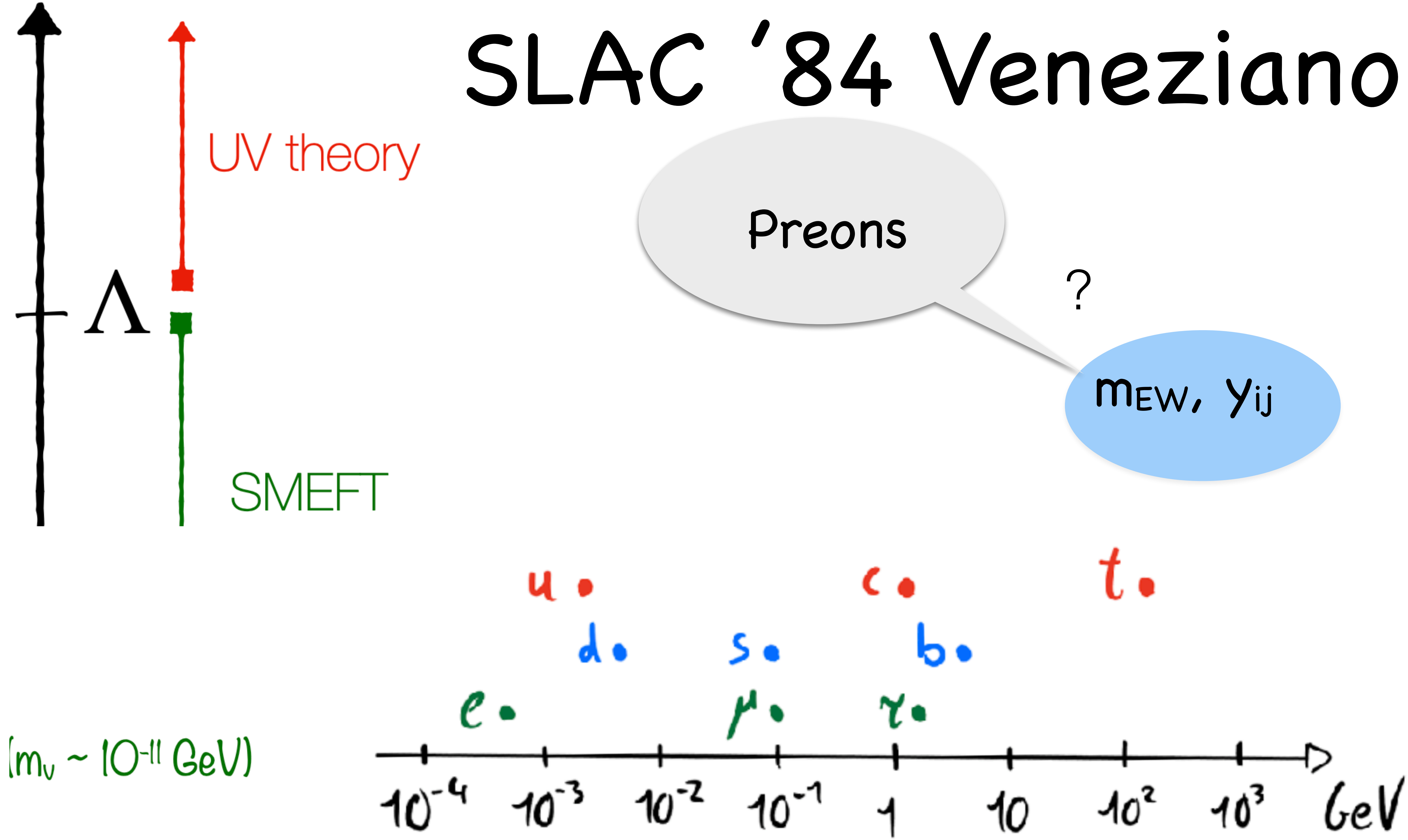
Weinberg operator
→ neutrino masses *

dim-6 SMEFT

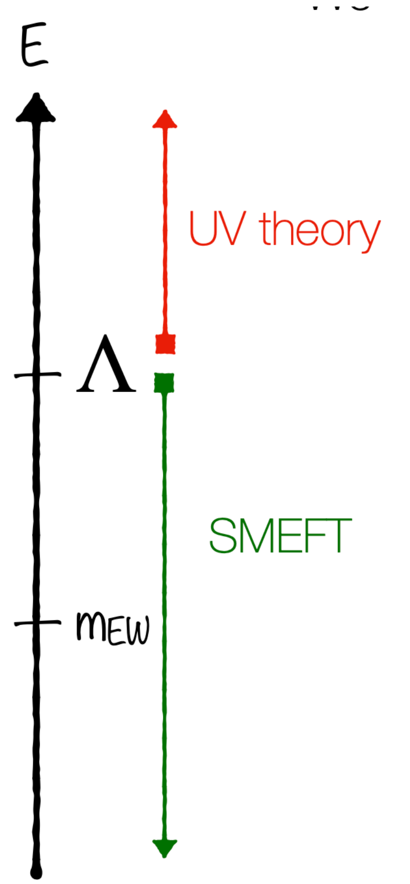
higher order effects

E.g.: Lepton Flavour Violation,
unsuppressed FCNC and CP effects,
B and L violation, etc..

SLAC '84 Veneziano

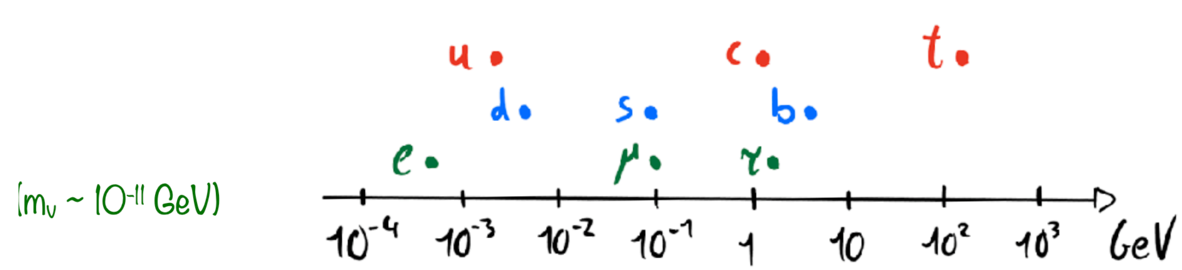


- Veneziano: maybe the solution is a two scale



y_{ij}

m_{EW}



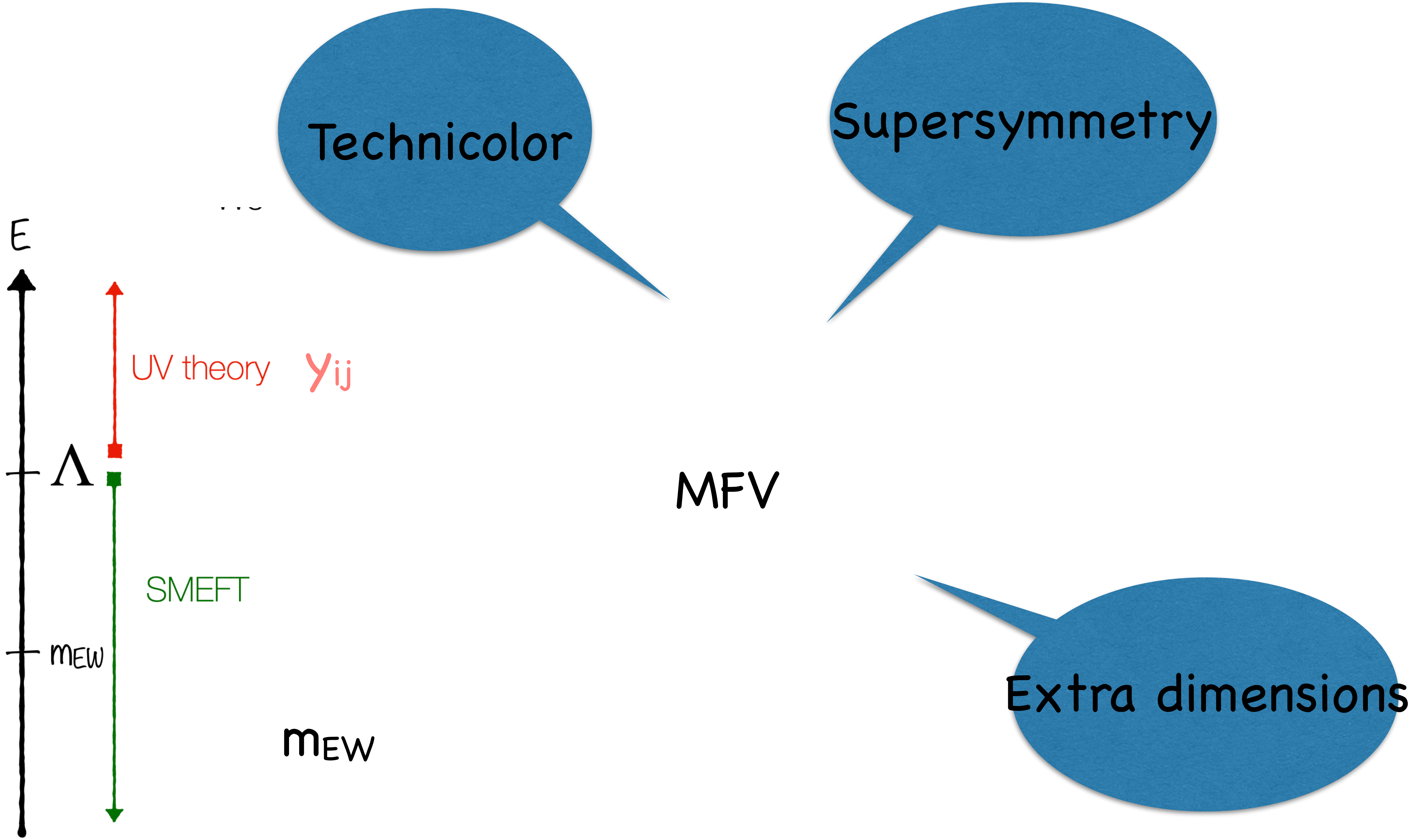
Generic Flavor structures strongly constrained

Operator	Bounds on Λ in TeV ($c_{NP}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert_D$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d \to \psi K$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s \to \psi\phi$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

Isidori Nir Perez 10

Problem already known since '86 technicolour (Chivukula Georgi) susy (Hall Randall) extra dimensions (Rattazzi Zafferoni)

Maybe there is an energy gap between the theory of flavor and the EW scale, ameliorating also a clash from the scale of the bounds in the table above and the requirement of solving the hierarchy problem



Technicolor
Supersymmetry
E
UV theory
y_{ij}
Λ
MFV
SMEFT
m_{EW}
Extra dimensions
m_{EW}

$$\mathcal{L}^{SM} = -\frac{1}{4}\sum_A F^A_{\mu\nu} F^{A\mu\nu} - \theta \frac{g_s^2}{32\pi^2} G^A_{\mu\nu} \tilde{G}^{A\mu\nu} + \sum_f \bar{\psi}_f \, i D_\mu \gamma^\mu \psi_f$$

$$+ |D_\mu H|^2 - V(H) - \left(\bar{\psi}^i_F \, y^{ij}_F \, \psi_f \, H + h.c. \right)$$

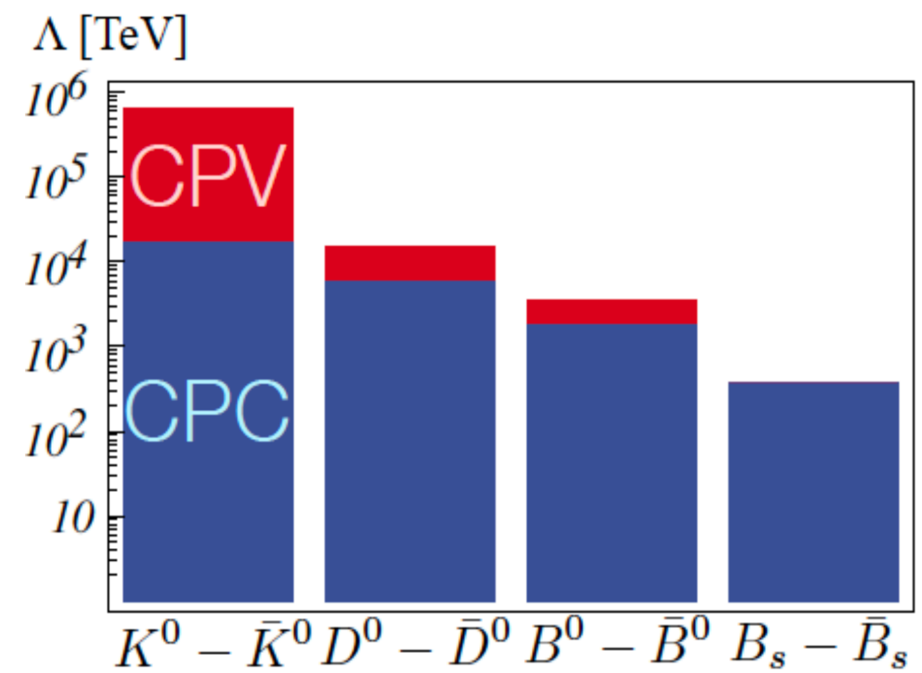
$$G_F = \overbrace{\mathrm{U}(3)_Q \otimes \mathrm{U}(3)_U \otimes \mathrm{U}(3)_D \otimes \mathrm{U}(3)_L \otimes \mathrm{U}(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

$$\boxed{\mathcal{L}^Y_{MFV} = \mathcal{L}^Y_{SM} + \mathrm{dim}\text{-}6}$$

	$su(2)_L \times su(2)_R$	$SU(3)_c$	$SU(2)_L$	Y
L_i	$(\frac{1}{2},0)$	1	2	$-\frac{1}{2}$
e_i	$(0,\frac{1}{2})$	1	1	-1
Q_i	$(\frac{1}{2},0)$	3	2	$\frac{1}{6}$
u_i	$(0,\frac{1}{2})$	3	1	$\frac{2}{3}$
d_i	$(0,\frac{1}{2})$	3	1	$-\frac{1}{3}$
H	$(0,0)$	1	2	$\frac{1}{2}$

U(3) ->U(2)

$V_{\mathrm{CKM}} \sim$ 

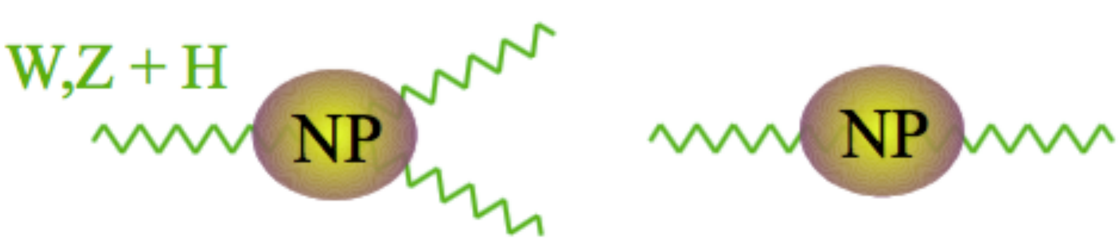


Shift of paradigma

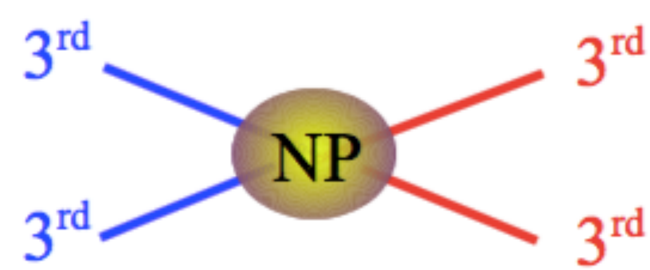
Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23

Main idea:

- Flavor non-universal interactions already at the TeV scale:
- 1^{st} & 2^{nd} gen. have small masses because they are coupled to NP at heavier scales



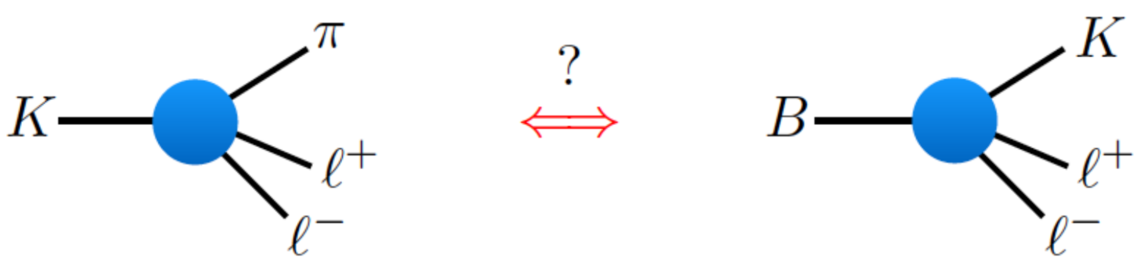
~~large (*more interesting...*)~~
small (*less interesting...*)

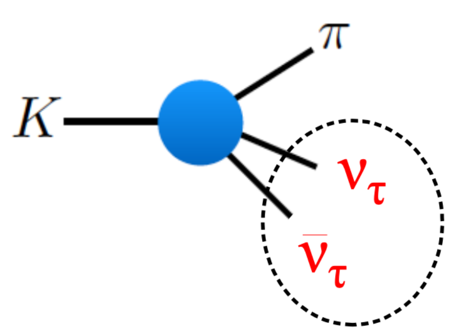


~~small (*less interesting...*)~~
large (*more interesting...*)

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 $K \rightarrow \pi\nu\nu$ *decays....*

Anatomy of kaon decays and prospects for lepton flavour universality violation

arxiv 2206.14748 GD, A.M. Iyer, F. Mahmoudi, S. Neshatpour

- Motivated by B-anomalies we study LFUV Kaon decays

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

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

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

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

$$\boxed{\delta C_L^\tau = \delta C_L^\mu}$$

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]
$\mathrm{BR}(K_L^0 \to \pi^0\nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @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]	
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			observation (CERN; long-term [58]) (we assume 100% error)
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[57]	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

arxiv 2206.14748

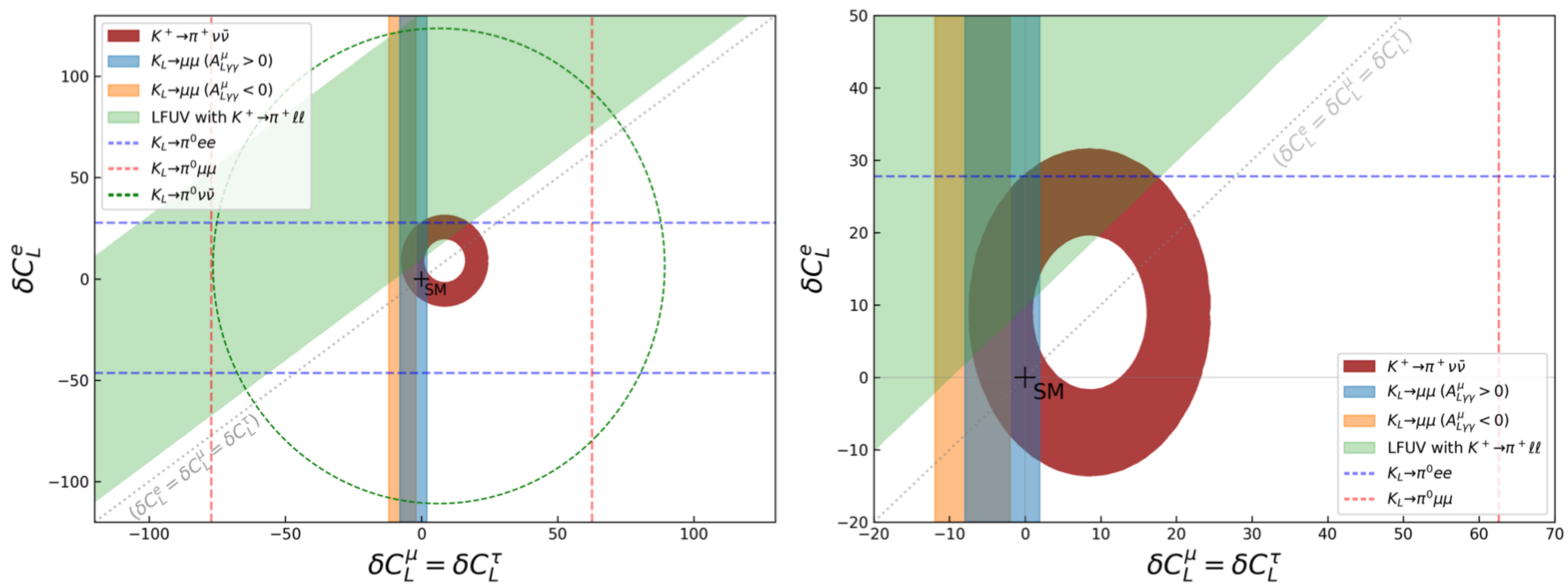
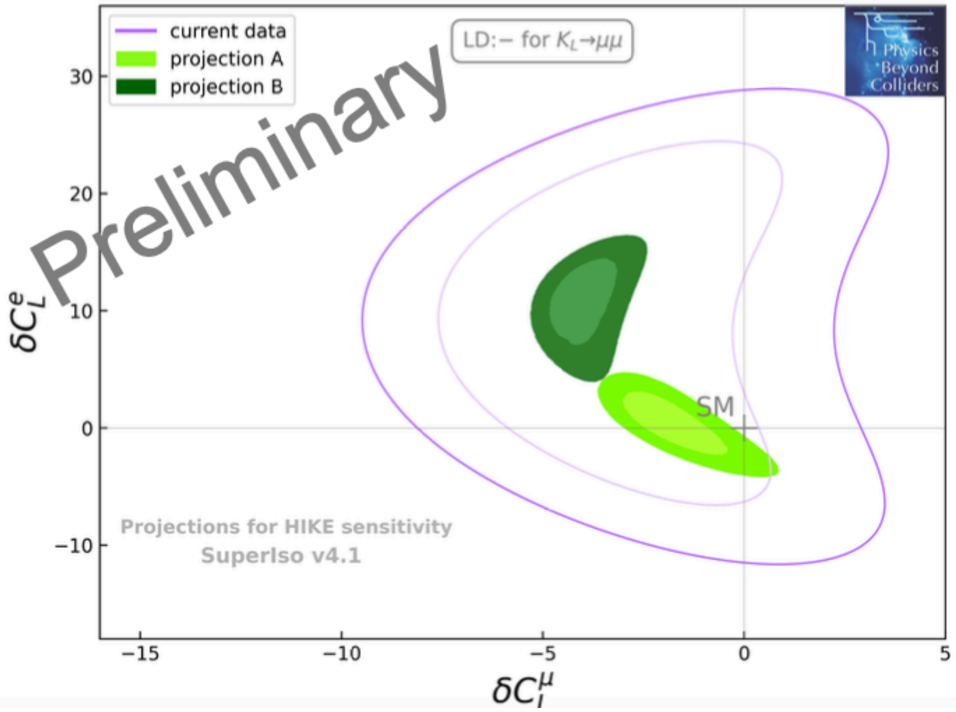
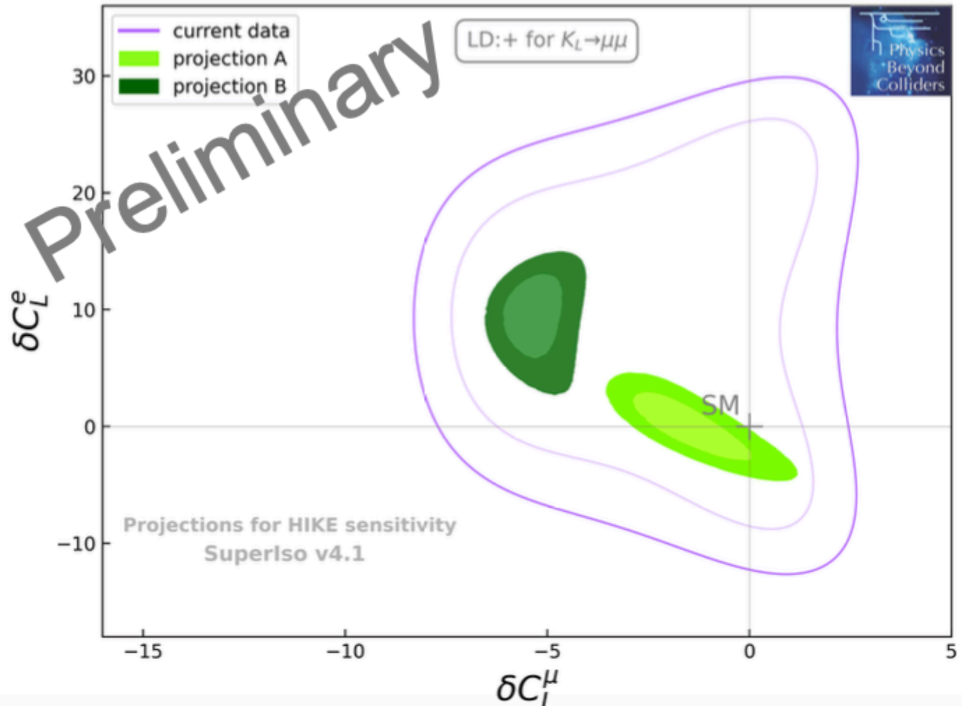


Figure 7: The bounds from individual observables. The right panel is the zoomed version of the left panel. The coloured regions correspond to 68% CL when there is a measurement and the dashed ones to upper limits at 90% CL. $K_L \to \mu\bar{\mu}$ has been shown for both signs of the long-distance contribution. 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.

Very recent development: HIKE full projections





[CERN Physics Beyond Colliders Document in preparation, and paper In preparation by D'Ambrosio, Mahmoudi, Neshatpour

Italy before 2023

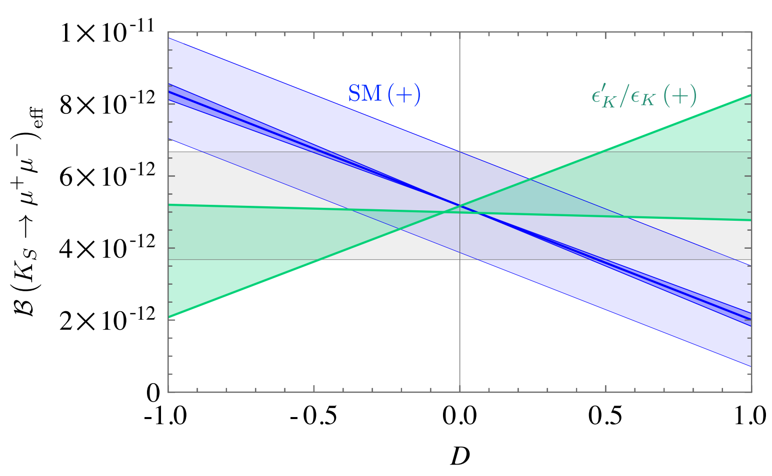
World for several millennia

Pompei

World before VII BC

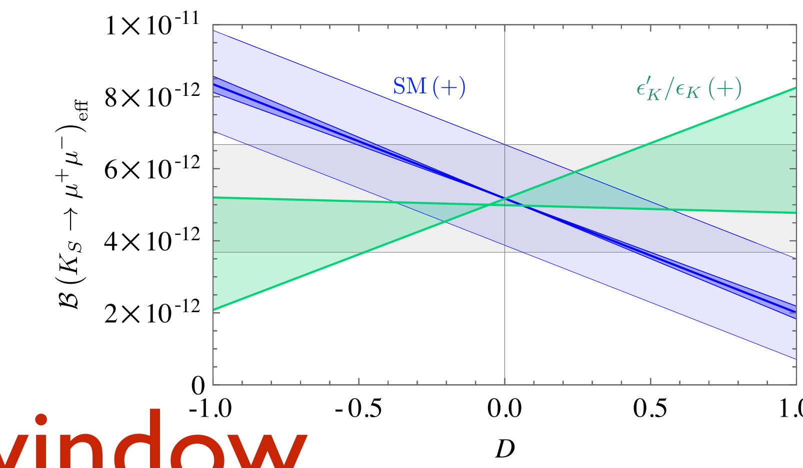
Conclusions

- Interesting new experiments and phenomenology
- Interplay with high energy experiments very important
- LHCB: $K_S \to \mu\mu$ extraordinary result: interference effect!!!Short distance window



Conclusions

- Flavour anomalies: interplay with $K\to\pi\nu\nu$ but 10% measurement needed!

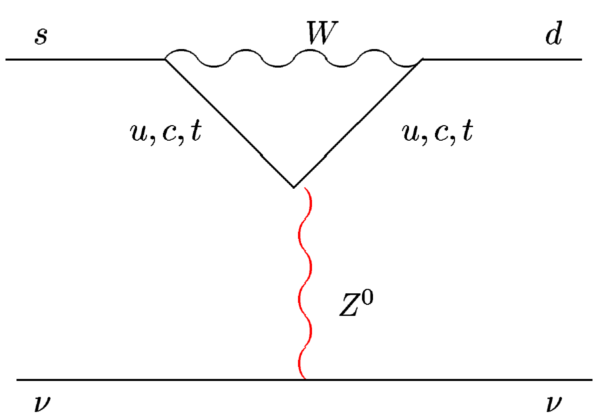


- LHCB: $K_S\to\mu\mu$ extraordinary result: interference effect!!!Short distance window
- weak chiral lagrangian
- LFUV in Kaons very useful
- Rich rare kaon program

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

Why we need KOTO and NA62

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



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

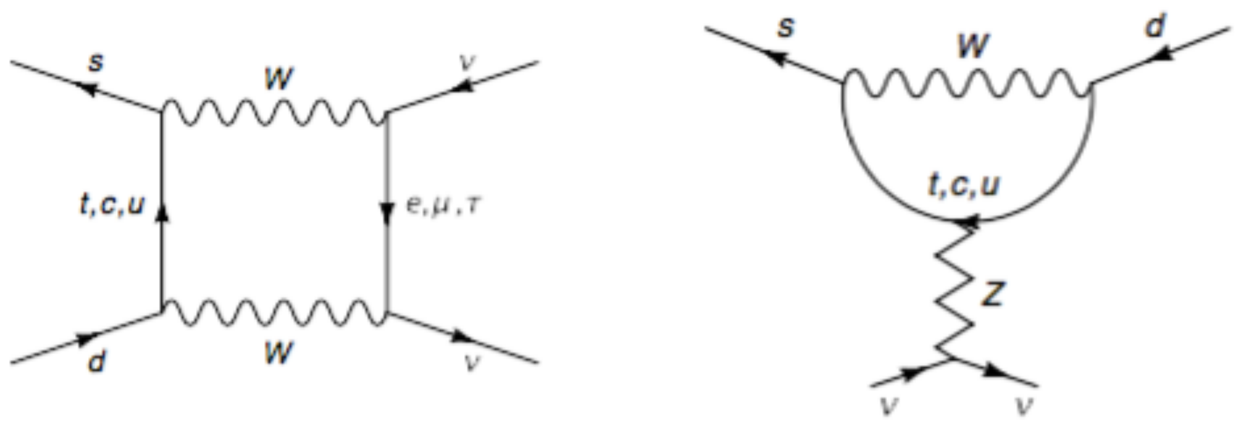
SM $\quad \underbrace{V-A \otimes V-A}_{\Downarrow}$ Littenberg

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

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

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

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

$$30\% \pm 2.5\%$$

$\downarrow$

K_{l3}

LD

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

V_{cb} nonpert QCD

$$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$$ E949

$$< 11 \cdot 10^{-10} \ 90\% \ \mathrm{CL}$$ NA62

UV sensitivity

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

Kaon Global Fit

Cristina Lazzeroni, ECFA mtg 2022

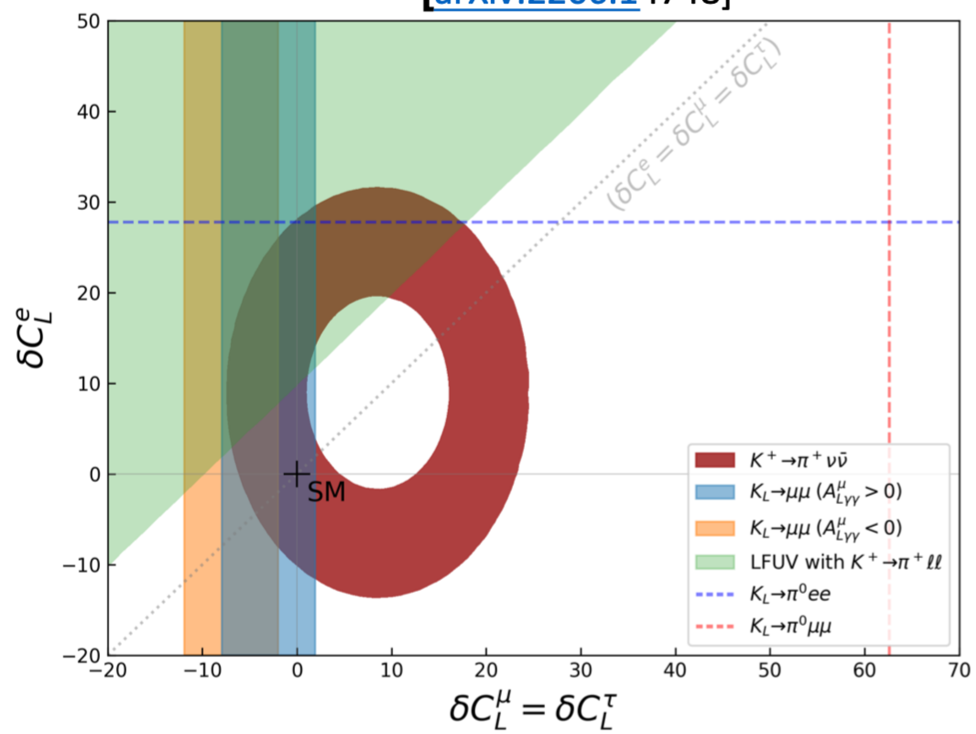
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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

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

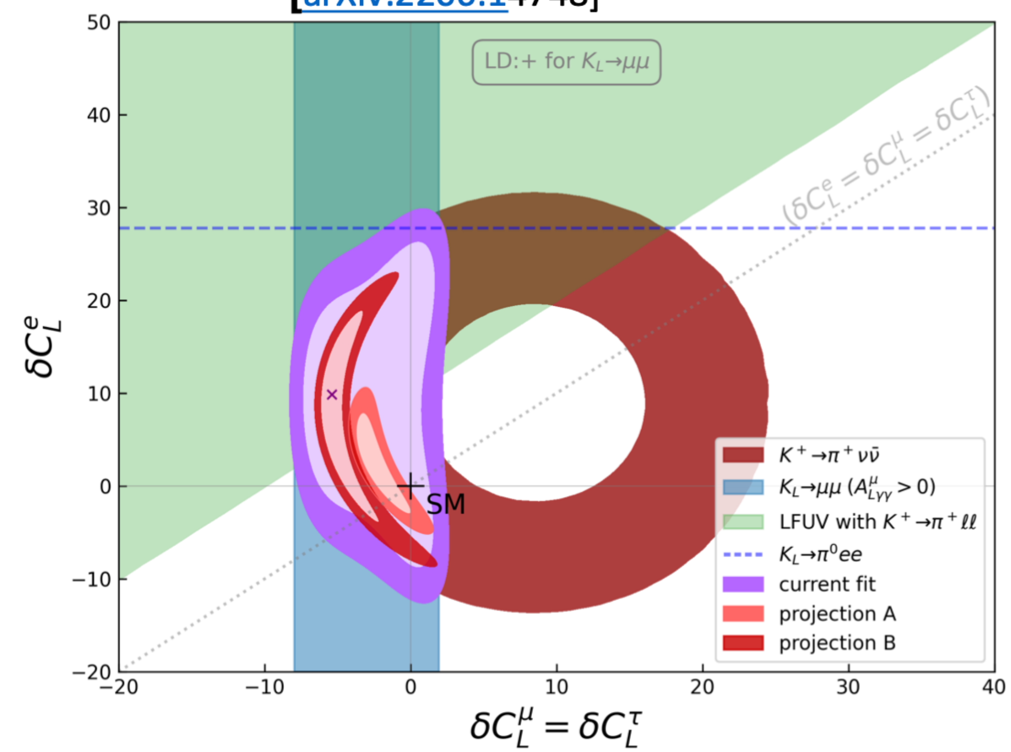
For example, recent paper with global fits to set of kaon measurements
Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

[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

Observable	SM prediction	Experimental results	Ref.	HIKE projections
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[110]	5% (Phase 1)
$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 300 \times 10^{-11}$ @90% CL	[144]	20% (Phase 3)
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.031 ± 0.017	[145, 146]	± 0.007 (Phase 1)
$\mathrm{BR}(K_L \to \mu\mu)\ (+)$	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[147]	1% (Phase 2)
$\mathrm{BR}(K_L \to \mu\mu)\ (-)$	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$			
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	[148]	Upper bound kept to current value
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[149]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[150]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

Table 5: The SM predictions, current experimental status and the expected HIKE sensitivity for the different observables. The "(+)" and "(−)" signs in the first column correspond to constructive and destructive interference of the amplitudes.

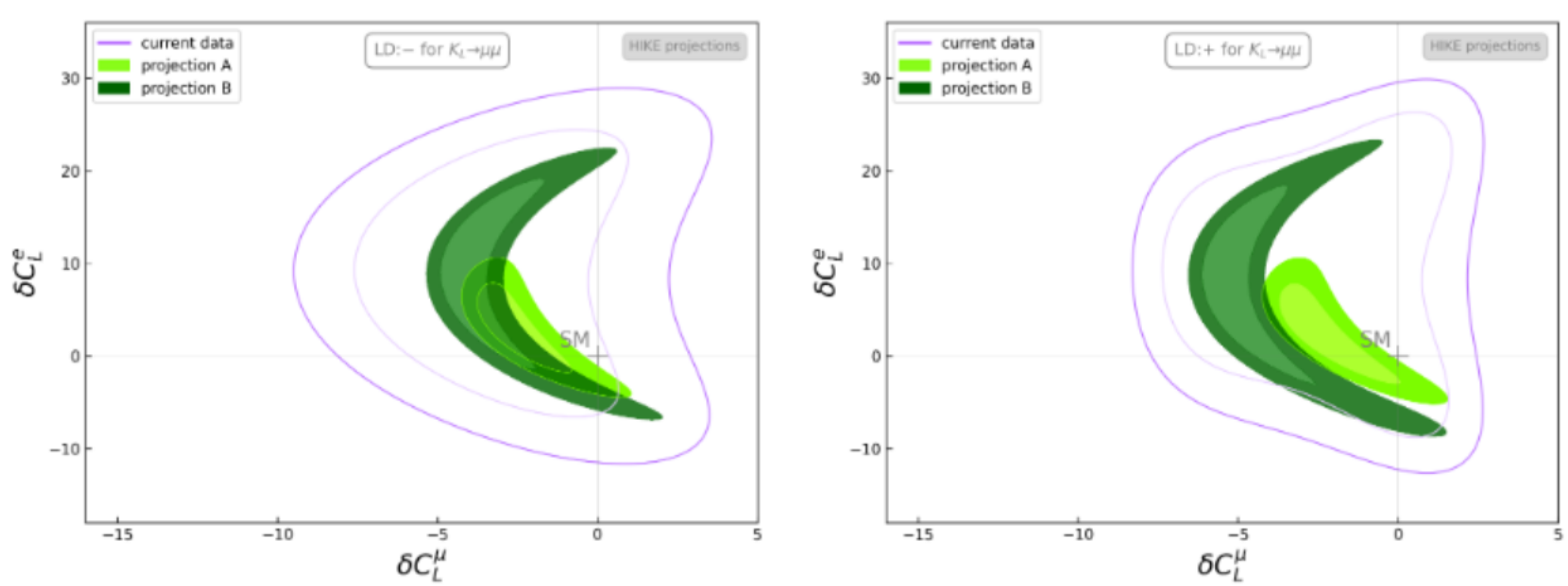


Figure 17: Global fits in the $\{\delta C_L^e, \delta C_L^\mu (= \delta C_L^\tau)\}$ plane with current data (purple contours) and the projected scenarios (green regions).

Kaons and LFUV

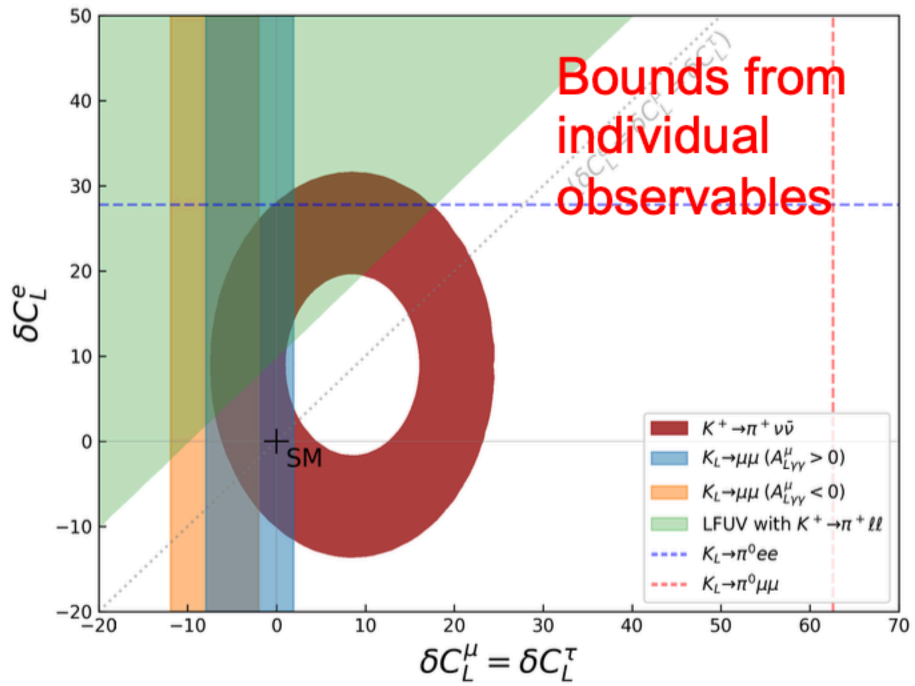
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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

Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

[arXiv:2206.14748]

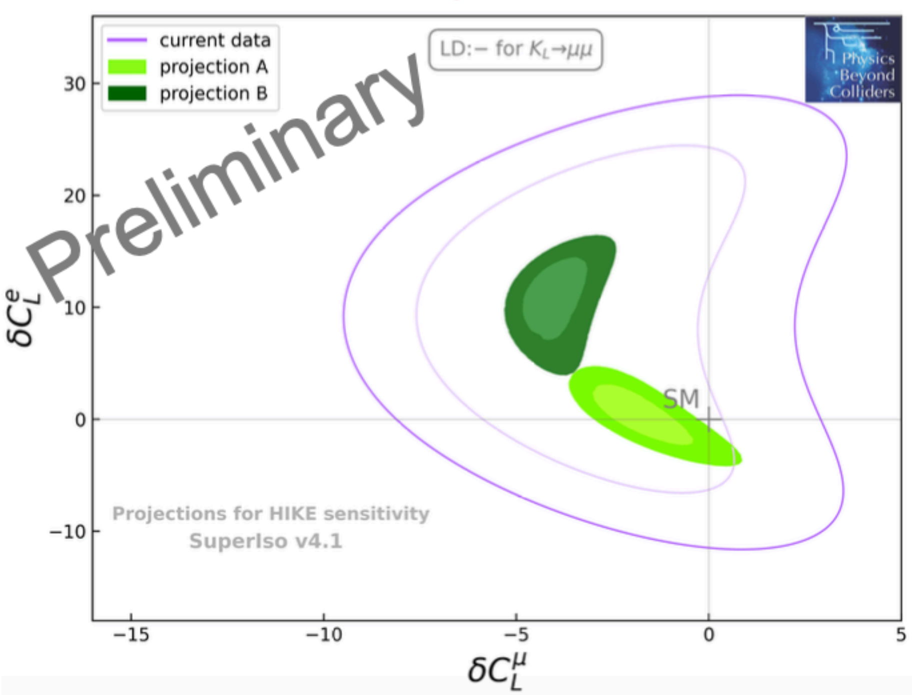
$$C_k^\ell = C_{k,{\rm SM}}^\ell + \delta C_k^\ell \qquad \delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

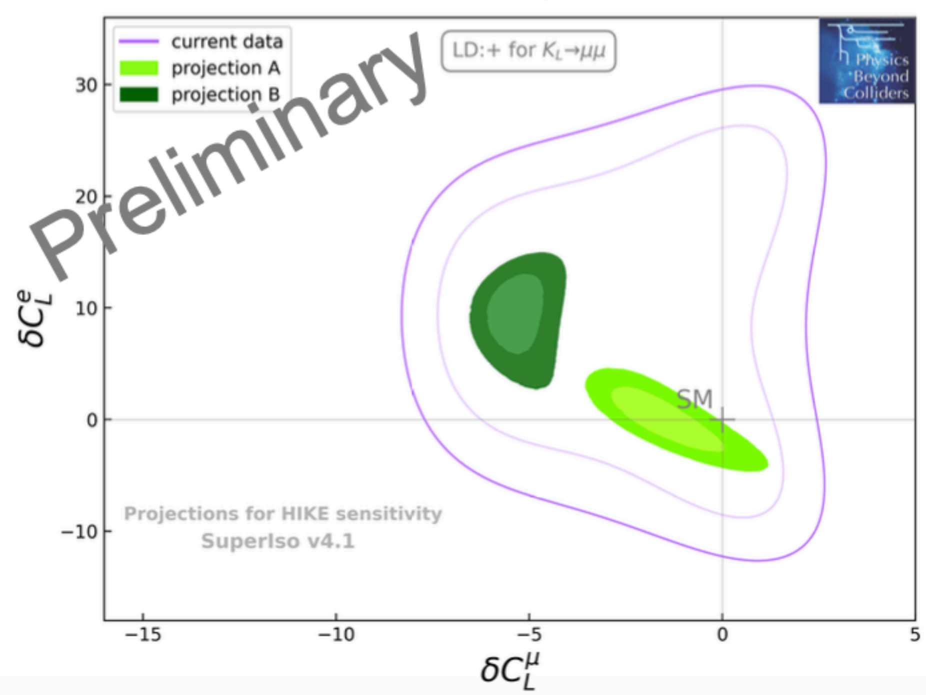


Individual measurements can be combined in a fit. Projections can be used for future experiments

Projections:
A: predicted central values for observables with only upper bound is projected to be as SM prediction; for measured ones current central values are taken.
B: central values for all observables are projected with best-fit points obtained from fits of existing data.

Very recent development: HIKE full projections





[CERN Physics Beyond Colliders Document in preparation, and paper In preparation by D'Ambrosio, Mahmoudi, Neshatpour]

$$\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yukawa}} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + Y_e^{ij}\bar{L}_L^i \phi E_R^j + \mathrm{h.c.}$$

arxiv 2206.1474

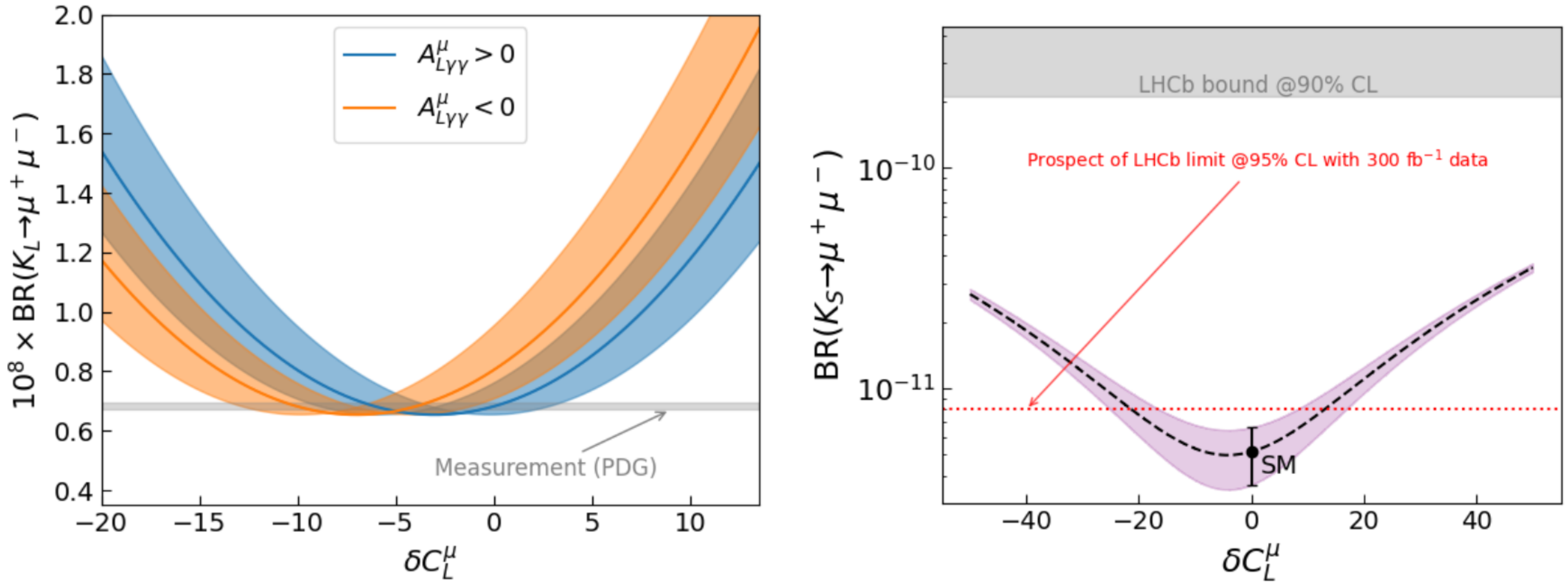
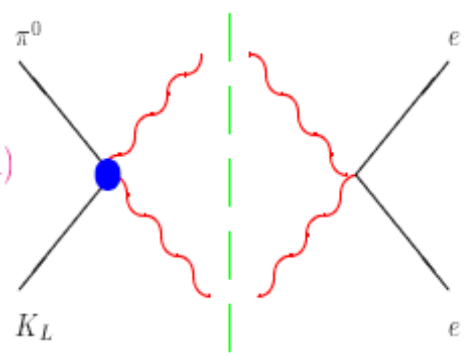


Figure 4: $\mathrm{BR}(K_L \to \mu\bar{\mu})$ as a function of $\delta C^{\mu}_{L} (\equiv \delta C^{\mu}_{9} = -\delta C^{\mu}_{10})$ assuming both possible signs for the long-distance contribution from $A^{\mu}_{L\gamma\gamma}$ on the left panel. $\mathrm{BR}(K_S \to \mu\bar{\mu})$ as a function of 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 $\mathrm{BR}(K_S \to \mu\bar{\mu})$ are from Ref. [44] and Ref. [51], respectively.

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

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

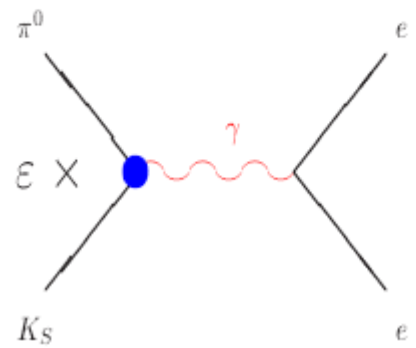
1)

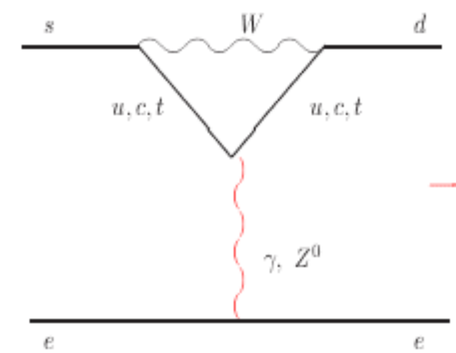


CP conserving NA48

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

V-A$\otimes$ 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

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

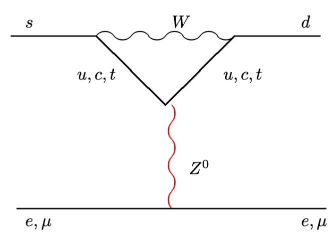
$\uparrow$ $\mathrm{B}(K_S \to \pi^0 e^+ e^-) = 4.6 a_S^2 \times 10^{-9}$

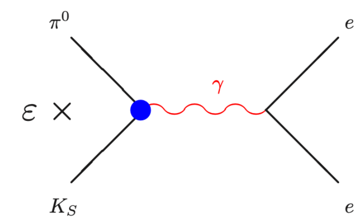
Possible large interference: $a_S < -0.5$ or $a_S > 1$; short distance probe even for a_S large

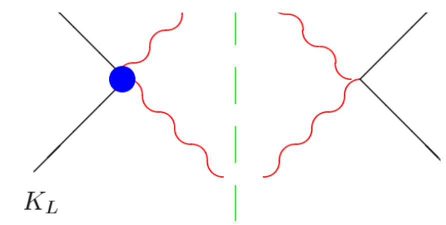
$$|2) + 3)|^2 = \left[15.3\ a_S^2 - 6.8\frac{Im\lambda_t}{10^{-4}}\ a_S + 2.8\left(\frac{Im\lambda_t}{10^{-4}}\right)^2\right] \cdot 10^{-12}$$

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

Isidori Mescia, Smith







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

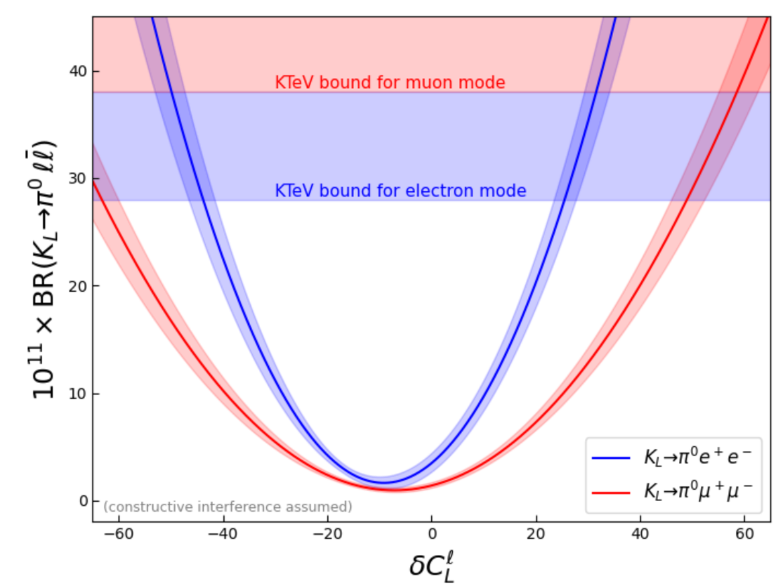
$$|a_S| \;=\; 1.20 \pm 0.20$$

	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
$\ell = e$	$(4.62 \pm 0.24)(w_{7V}^2 + w_{7A}^2)$	$(11.3 \pm 0.3)w_{7V}$	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 2206.1474

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

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



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

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

arxiv 2206.1474

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]
$\mathrm{BR}(K_L^0 \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @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]	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

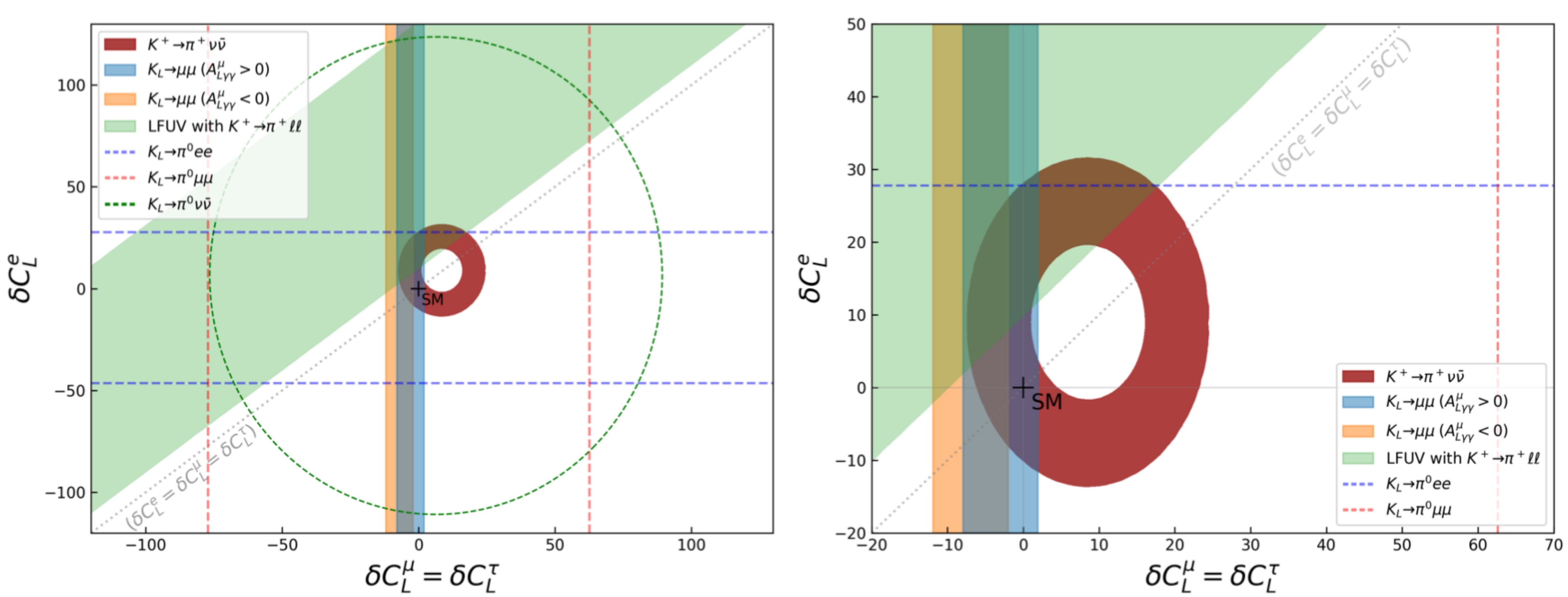


Figure 7: The bounds from individual observables. The right panel is the zoomed version of the left panel. The coloured regions correspond to 68% CL when there is a measurement and the dashed ones to upper limits at 90% CL. $K_L \to \mu\bar{\mu}$ has been shown for both signs of the long-distance contribution. 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.

Observable	SM prediction	Experimental results	Ref.	HIKE projections
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[110]	5% (Phase 1)
$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 300 \times 10^{-11}$ @90% CL	[144]	20% (Phase 3)
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.031 ± 0.017	[145, 146]	± 0.007 (Phase 1)
$\mathrm{BR}(K_L \to \mu\mu)$ (+)	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[147]	1% (Phase 2)
$\mathrm{BR}(K_L \to \mu\mu)$ (−)	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$			
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	[148]	Upper bound kept to current value
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[149]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[150]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

Table 5: The SM predictions, current experimental status and the expected HIKE sensitivity for the different observables. The "(+)" and "(−)" signs in the first column correspond to constructive and destructive interference of the amplitudes.

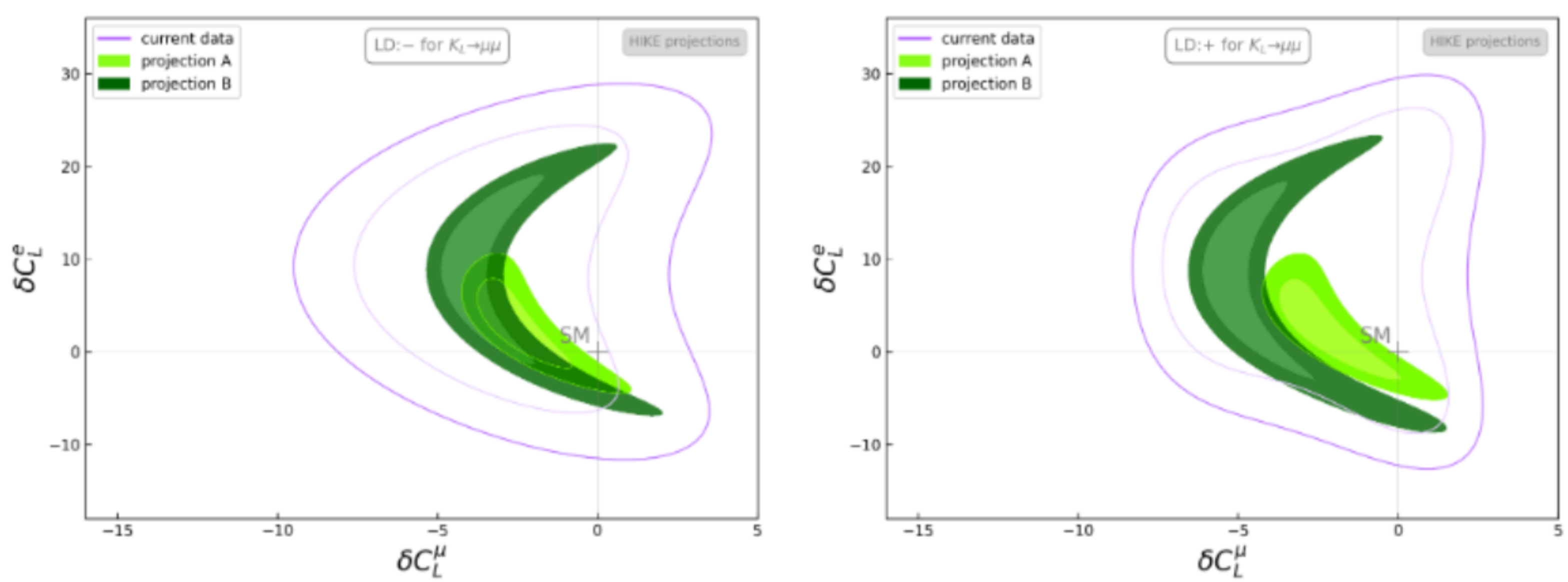


Figure 17: Global fits in the $\{\delta C_L^e, \delta C_L^\mu (= \delta C_L^\tau)\}$ plane with current data (purple contours) and the projected scenarios (green regions).

π	2π	3π	N_i	
$\pi^+\gamma^*$	$\pi^+\pi^0\gamma^*$		$N_{14}^r - N_{15}^r$	$K^+ \to \pi^+ l^+ l^-$
$\pi^0\gamma^*$ (S)	$\pi^0\pi^0\gamma^*$ (L)		$2N_{14}^r + N_{15}^r$	$K_S \to \pi^0 l^+ l^-$
$\pi^+\gamma\gamma$	$\pi^+\pi^0\gamma\gamma$		$N_{14} - N_{15} - 2N_{18}$	
	$\pi^+\pi^-\gamma\gamma$ (S)		"	
	$\pi^+\pi^0\gamma$	$\pi^+\pi^+\pi^-\gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	
	$\pi^+\pi^-\gamma$ (S)	$\pi^+\pi^0\pi^0\gamma$	"	
		$\pi^+\pi^-\pi^0\gamma$ (L)	"	
		$\pi^+\pi^-\pi^0\gamma$ (S)	$7(N_{14}^r - N_{16}^r) + 5(N_{15}^r + N_{17})$	
	$\pi^+\pi^-\gamma^*$ (L)		$N_{14}^r - N_{15}^r - 3(N_{16}^r - N_{17})$	
	$\pi^+\pi^-\gamma^*$ (S)		$N_{14}^r - N_{15}^r - 3(N_{16}^r + N_{17})$	
	$\pi^+\pi^0\gamma^*$		$N_{14}^r + 2N_{15}^r - 3(N_{16}^r - N_{17})$	
	$\pi^+\pi^-\gamma$ (L)	$\pi^+\pi^-\pi^0\gamma$ (S)	$N_{29} + N_{31}$	
		$\pi^+\pi^+\pi^-\gamma$	"	
	$\pi^+\pi^0\gamma$	$\pi^+\pi^0\pi^0\gamma$	$3N_{29} - N_{30}$	
		$\pi^+\pi^-\pi^0\gamma$ (S)	$5N_{29} - N_{30} + 2N_{31}$	
		$\pi^+\pi^-\pi^0\gamma$ (L)	$6N_{28} + 3N_{29} - 5N_{30}$	

$$\mathcal{L}_{\Delta S=1} = \mathcal{L}^2_{\Delta S=1} + \mathcal{L}^4_{\Delta S=1} + \cdots = G_8 F^4 \underbrace{\langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K\to 2\pi/3\pi} + \underbrace{G_8 F^2 \sum_i N_i W_i}_{K^+\to\pi^+\gamma\gamma,\, K\to\pi l^+ l^-} + \cdots$$

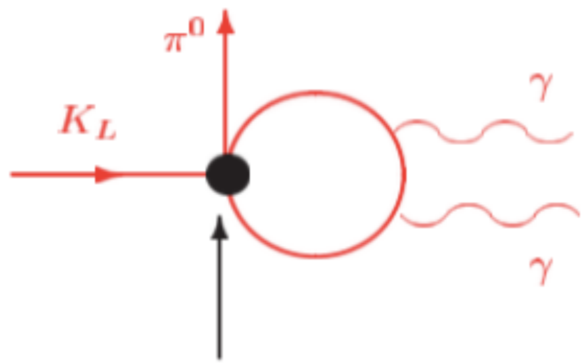
$K_L \to \pi^0\gamma\gamma$

Ecker, Pich, de Rafael; Cappiello,G.D

$O(p^4)$

CT Loop

0



G_8 from $K_S \to 2\pi$

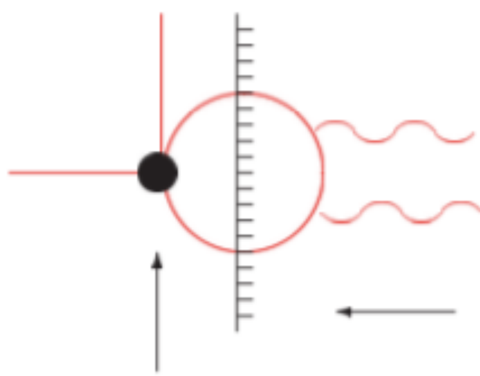
only A **But** $\frac{\Gamma(K_L\to\pi^0\gamma\gamma)_{p_4}}{\Gamma(K_L\to\pi^0\gamma\gamma)_{\exp}} \sim \frac{1}{2.5}$

3 CT′s

$F_{\mu\nu}F^{\mu\alpha}\partial_\alpha K_L \partial^\nu \pi^0$

$F^2 \ \partial K_L \partial \pi^0$

$F^2 \ m_K^2 K_L \pi^0$



Full description of unitarity cut

$A(K \to 3\pi) = a + b\ Y + c\ Y^2 + d\ X^2$

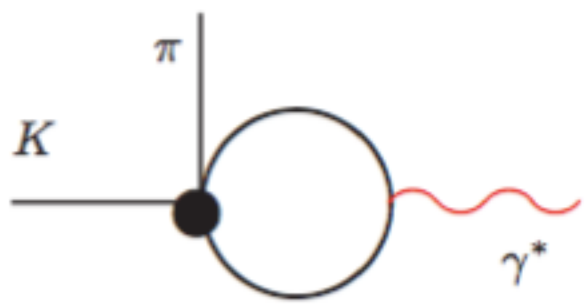
Cappiello, G.D., Miragliulo

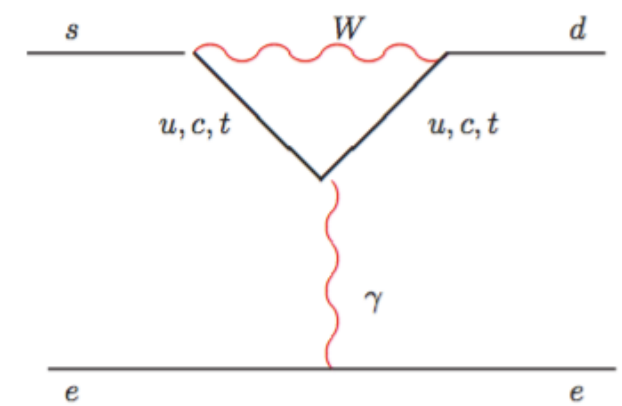
Cohen. Ecker. Pich

$$\mathcal{O}(p^4) \quad \mathrm{CHPT}:$$

Ecker, Pich, de Rafael

$$K^\pm \to \pi^\pm l \bar{l} \quad K_S \to \pi^0 l \bar{l}$$

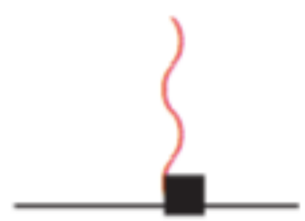




$\mathcal{O}(p^4)$

ChPT

loops +CT



Short distance

electrons and μ's in the final state

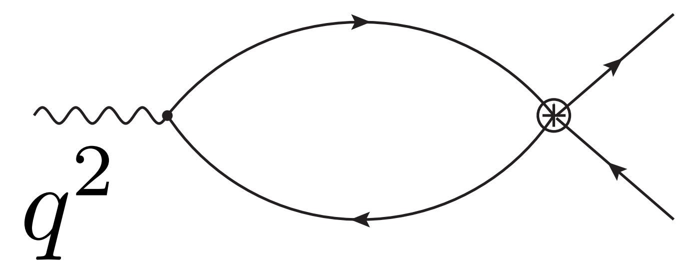
observables

$$\left\{ R = \frac{\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)}{\Gamma(K^+ \to \pi^+ e^+ e^-)} \right.$$

lepton spectrum $\quad z = \frac{q^2}{M_K^2}$

'97 Initial data inconsistency e and μ's: LFV?

General consideration ff

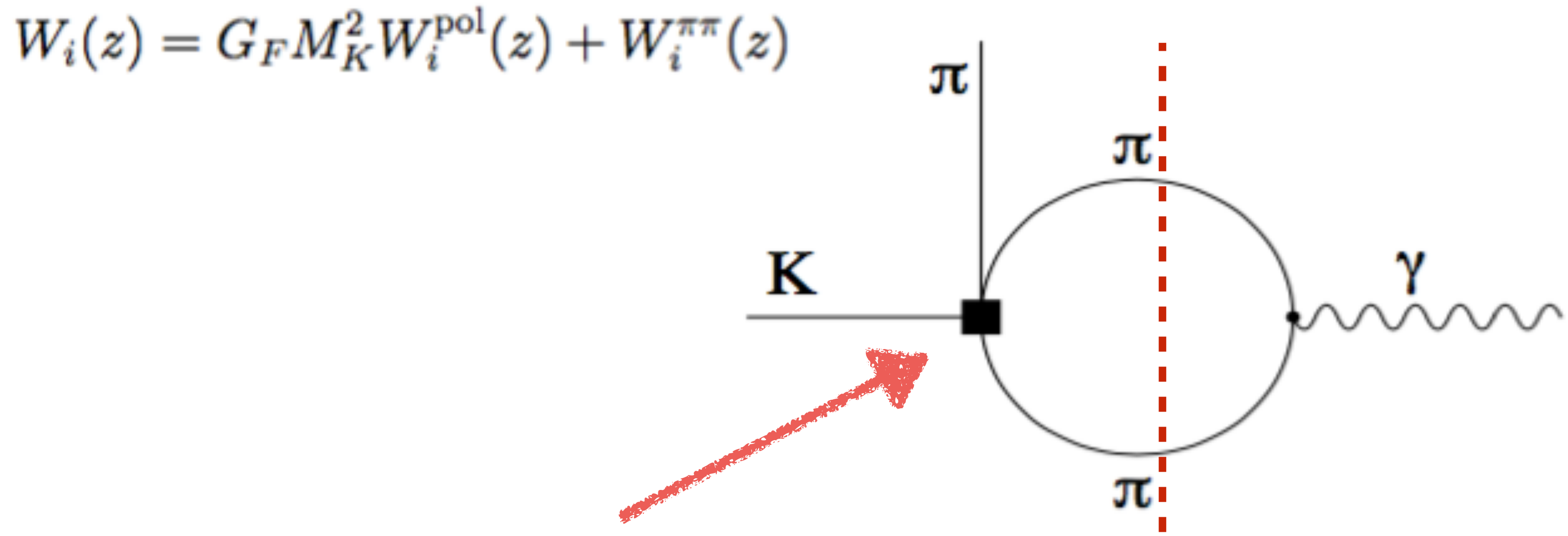


$$z = \frac{q^2}{M_K^2}$$

$$i\int d^4x e^{iqx}\langle\pi(p)|T\left\{J^\mu_{\rm elm}(x)\mathcal{L}_{\Delta S=1}(0)\right\}|K(k)\rangle = \frac{W(z)}{(4\pi)^2}\left[z(k+p)^\mu - (1-r_\pi^2)q^\mu\right]$$

$$W_i(z) = G_F M_K^2 W_i^{\mathrm{pol}}(z) + W_i^{\pi\pi}(z)$$

GD,Ecker,Isidori,Portoles



$$A(K^+ \to \pi^+\pi^+\pi^-) = \alpha_0 + \alpha_+ Y + \gamma(Y^2 + X^2/3) + \beta_+(Y^2 - X^2/3) \, ,$$

$$A(K_S \to \pi^+\pi^-\pi^0) = b_2 X - d_2 XY \, ,$$

$$s_i = (k - p_i)^2 \, , \qquad s_0 = \frac{1}{3}(s_1 + s_2 + s_3) \, , \qquad X = \frac{s_1 - s_2}{M_\pi^2} \, , \qquad Y = \frac{s_3 - s_0}{M_\pi^2} \, ,$$

$$\boxed{W_i^{\mathrm{pol}}(z) = a_i + b_i z \qquad (i = +, S)}$$

$$W_i(z) = G_F M_K^2 W_i^{\rm pol}(z) + W_i^{\pi\pi}(z)$$

$$W_i^{\rm pol}(z) = a_i + b_i z \qquad (i = +, S)$$

$$z_0 = 1/3 + r_\pi^2$$

$$\chi(z) = \frac{4}{9} - \frac{4r_\pi^2}{3z} - \frac{1}{3}(1 - \frac{4r_\pi^2}{z})G(z/r_\pi^2)$$

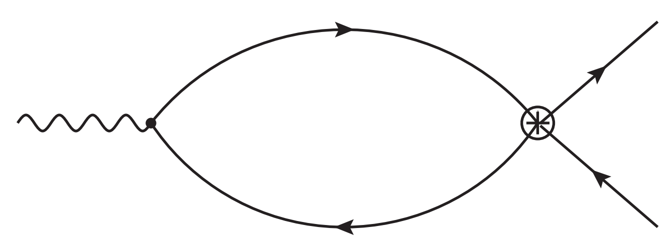
$$W_i^{\pi\pi}(z) = \frac{1}{r_\pi^2}\left[\alpha_i + \beta_i \frac{z - z_0}{r_\pi^2}\right] F(z)\ \chi(z)$$

$$F(z) = 1 + z/r_V^2$$

$K \to 3\pi$ **slopes**

$$A(K^+ \to \pi^+\pi^+\pi^-) = \quad \alpha_0 + \alpha_+ Y + \gamma(Y^2 + X^2/3) + \beta_+(Y^2 - X^2/3)\ ,$$

$$A(K_S \to \pi^+\pi^-\pi^0) = \quad b_2 X - d_2 XY \qquad ,$$



Weak chiral couplings

$K^\pm \to \pi^\pm \gamma^* :$ $\quad a_+ = -0.578 \pm 0.016$ [3, 4]

$K_S \to \pi^0 \gamma^* :$ $\quad a_S = (1.06^{+0.26}_{-0.21} \pm 0.07)$ [5, 6]

$K^\pm \to \pi^\pm \pi^0 \gamma :$ $\quad X_E = (-24 \pm 4 \pm 4)\ \mathrm{GeV}^{-4}$ [7]

$K^+ \to \pi^+ \gamma\gamma :$ $\quad \hat{c} = 1.56 \pm 0.23 \pm 0.11$ [8] .

$$\mathcal{N}_E^{(1)} \equiv N_{14}^r - N_{15}^r = \frac{3}{64\pi^2}\left(\frac{1}{3} - \frac{G_F}{G_8}a_+ - \frac{1}{3}\log\frac{\mu^2}{m_K m_\pi}\right) - 3L_9^r$$

$$\mathcal{N}_S \equiv 2N_{14}^r + N_{15}^r = \frac{3}{32\pi^2}\left(\frac{1}{3} + \frac{G_F}{G_8}a_S - \frac{1}{3}\log\frac{\mu^2}{m_K^2}\right) ;$$

$$\mathcal{N}_E^{(0)} \equiv N_{14}^r - N_{15}^r - N_{16}^r - N_{17} = -\frac{|\mathcal{M}_K| f_\pi}{2G_8} X_E ;$$

$$\mathcal{N}_0 \equiv N_{14}^r - N_{15}^r - 2N_{18}^r = \frac{3}{128\pi^2}\hat{c} - 3(L_9^r + L_{10}^r) ,$$

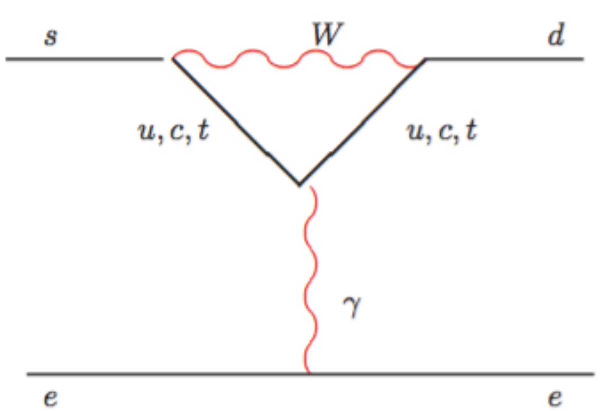
Decay mode	counterterm combination	expt. value
$K^\pm \to \pi^\pm \gamma^*$	$N_{14} - N_{15}$	$-0.0167(13)$
$K_S \to \pi^0 \gamma^*$	$2N_{14} + N_{15}$	$+0.016(4)$
$K^\pm \to \pi^\pm \pi^0 \gamma$	$N_{14} - N_{15} - N_{16} - N_{17}$	$+0.0022(7)$
$K^\pm \to \pi^\pm \gamma\gamma$	$N_{14} - N_{15} - 2N_{18}$	$-0.0017(32)$

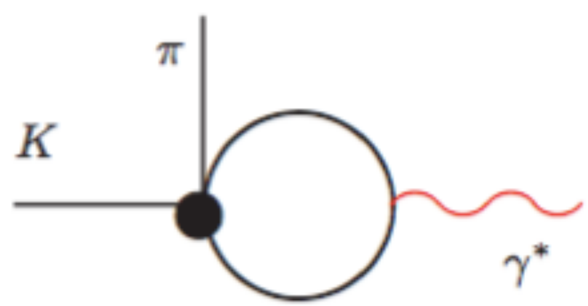
Luigi Cappiello, Oscar Cata,GD
arXiv:1712.10270,,EPJC

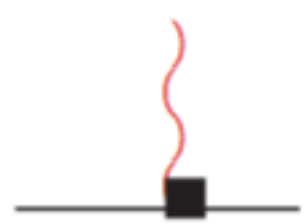
LFUV in Kaons

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

SD << LD







$$i \int d^4x e^{iqx} \langle \pi(p) | T \left\{ J^{\mu}_{\mathrm{elm}}(x) \mathcal{L}_{\Delta S=1}(0) \right\} | K(k) \rangle = \frac{W(z)}{(4\pi)^2} \left[z(k+p)^{\mu} - (1 - r_{\pi}^2) q^{\mu} \right]$$

Collaboration with Crivellin, A Hoferichter, M and Tunstall,
Phys.Rev. D 2016

LFUV: Kaons

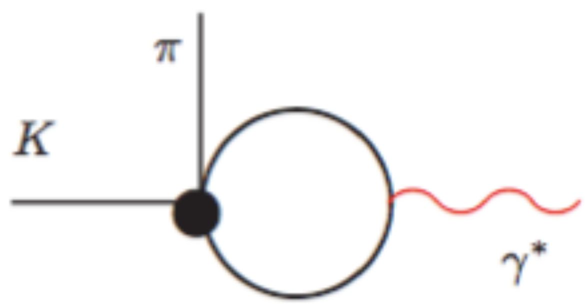
Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2

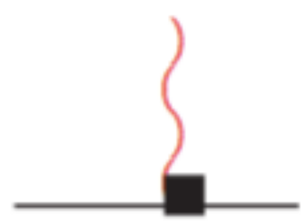
$$a_+^{\mathrm{NP}} = \frac{2\pi\sqrt{2}}{\alpha} V_{ud} V_{us}^* * C_{7V}^{\mathrm{NP}}$$

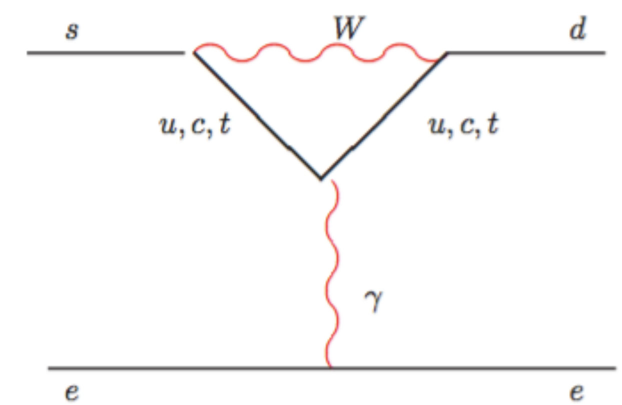
$$C_{7V}^{\mu\mu} - C_{7V}^{ee} = \alpha \frac{a_+^{\mu\mu} - a_+^{ee}}{2\pi\sqrt{2} V_{ud} V_{us}^*} \quad \stackrel{MFV}{\Longrightarrow} \quad C_{9V}^{B,\mu\mu} - C_{9V}^{B,ee} = \alpha \frac{a_+^{\mu\mu} - a_+^{ee}}{2\pi\sqrt{2} V_{td} V_{ts}^*} = -19 \pm 79$$

LHCB-NA62 PLEASE!!

High statistics: nominal # of decays 50 times greater than NA48/2







$$i \int d^4x e^{iqx} \langle \pi(p) | T \left\{ J^{\mu}_{\text{elm}}(x) \mathcal{L}_{\Delta S=1}(0) \right\} | K(k) \rangle = \frac{W(z)}{(4\pi)^2} \left[z(k+p)^{\mu} - (1 - r_{\pi}^2) q^{\mu} \right]$$

General structure of the amplitude

$$\begin{aligned}\mathcal{A}^{K\to\pi\ell^+\ell^-}(s) &= -e^2 \times \bar{\mathrm{u}}(p_-)\gamma_\rho \mathrm{v}(p_+) \times \frac{1}{s} \times i\int d^4x\, \langle \pi(p)|T\{j^\rho(0)\mathcal{L}^{\Delta S=1}_{\text{non-lept}}(x)\}|K(k)\rangle \\ &\quad -e^2 \times \bar{\mathrm{u}}(p_-)\gamma_\rho \mathrm{v}(p_+) \times \left(-\frac{G_{\mathrm{F}}}{\sqrt{2}}V_{us}V_{ud}\right) \times \frac{C_{7V}(\nu)}{4\pi\alpha}\,\langle \pi(p)|(\bar{s}\gamma^\rho d)(0)|K(k)\rangle \\ &= -e^2 \times \bar{\mathrm{u}}(p_-)\gamma^\rho \mathrm{v}(p_+)(k+p)_\rho \times \frac{W_{K\pi}(z)}{16\pi^2 M_K^2} \qquad [z \equiv s/M_K^2]\end{aligned}$$

$$W_{K\pi}(z) = W^{\mathrm{LD}}_{K\pi}(z;\nu) + W^{\mathrm{SD}}_{K\pi}(z;\nu)$$

$$j^\rho(x) = \sum_{q=u,d,s} e_q(\bar{q}\gamma^\rho q)(x) \qquad \mathcal{L}^{\Delta S=1}_{\text{non-lept}}(x) = \left(-\frac{G_{\mathrm{F}}}{\sqrt{2}}V_{us}V_{ud}\right) \times \sum_{I=1}^{6} C_I(\nu)Q_I(x;\nu)$$

$$\nu\frac{dC_{7V}(\nu)}{d\nu} = \frac{\alpha}{\alpha_s(\nu)}\sum_{J=1}^{6}\gamma_{J,7V}(\alpha_s)C_J(\nu)$$

E. Witten, Nucl. Phys. B 122, 109 (1977)
F. J. Gilman, M. B. Wise, Phys Rev D 21, 3150 (1980)
C. Dib et al., Phys Lett B 218, 487 (1989); Phys Rev D 39, 2639 (1989)
J. Flynn, L. Randall, Nucl Phys B 326, 31 (1989) [Nucl Phys B 334, 580 (1990)]
A. J. Buras et al., Nucl Phys B 423, 349 (1994)

Predicting $a_+,\ b_+$? Going beyond the low-energy expansion

requires an unsubtracted dispersion relation

$$W(z)|_{\pi\pi} = \frac{1}{\pi}\int_0^\infty dx \frac{\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi}}{x - zM_K^2 - i0}$$

with

$$\frac{\mathrm{Abs}\, W(s/M_K^2)|_{\pi\pi}}{16\pi^2 M_K^2} = \theta(s - 4M_\pi^2) \times \frac{s - 4M_\pi^2}{s}\lambda_{K\pi}^{-1/2}(s) \times F_V^{\pi *}(s) \times f_1^{\pi^+\pi^-\to K^+\pi^-}(s)$$

Then a_+ and b_+ are given by spectral sum rules

$$G_F M_K^2 a_+|_{\pi\pi} = W(0)|_{\pi\pi} = \frac{1}{\pi}\int_0^\infty \frac{dx}{x}\,\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi}$$

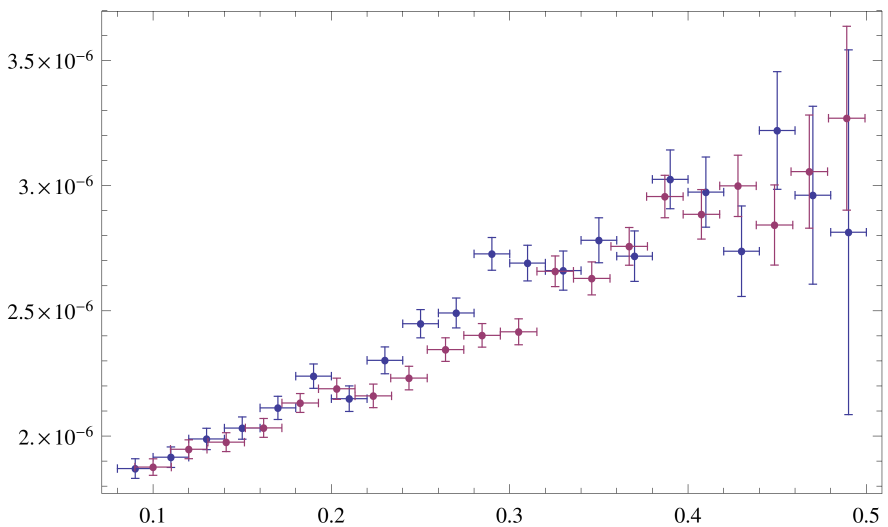
and

$$\begin{aligned} G_F M_K^2 b_+|_{\pi\pi} &= W'(0)|_{\pi\pi} - \frac{1}{60}\left(\frac{M_K^2}{M_\pi^2}\right)^2\left(\alpha_+ - \beta_+\frac{s_0}{M_\pi^2}\right) \\ &= \frac{M_K^2}{\pi}\int_0^\infty \frac{dx}{x^2}\,\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi} - \frac{1}{60}\left(\frac{M_K^2}{M_\pi^2}\right)^2\left(\alpha_+ - \beta_+\frac{s_0}{M_\pi^2}\right) \end{aligned}$$

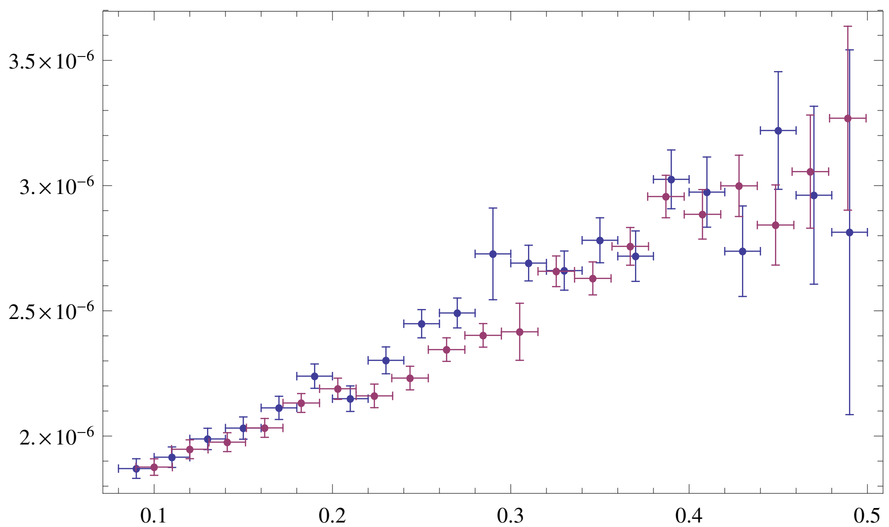
requires $F_V^{\pi *}(s)$ and $f_1^{\pi^+\pi^-\to K^+\pi^-}(s)$ beyond low-energy expansion

Combined fit (e^+e^-)

$\beta_+ \cdot 10^8$	a_+	b_+	$\chi^2/\mathrm{d.o.f}$
-3.96	$+0.483$	$+1.632$	86.7/39
	-0.598	-0.678	48.8/39
-2.88	$+0.489$	$+1.630$	60.4/39
	-0.592	-0.680	45.4/39
-1.80	$+0.495$	$+1.629$	74.8/39
	-0.585	-0.682	42.8/39



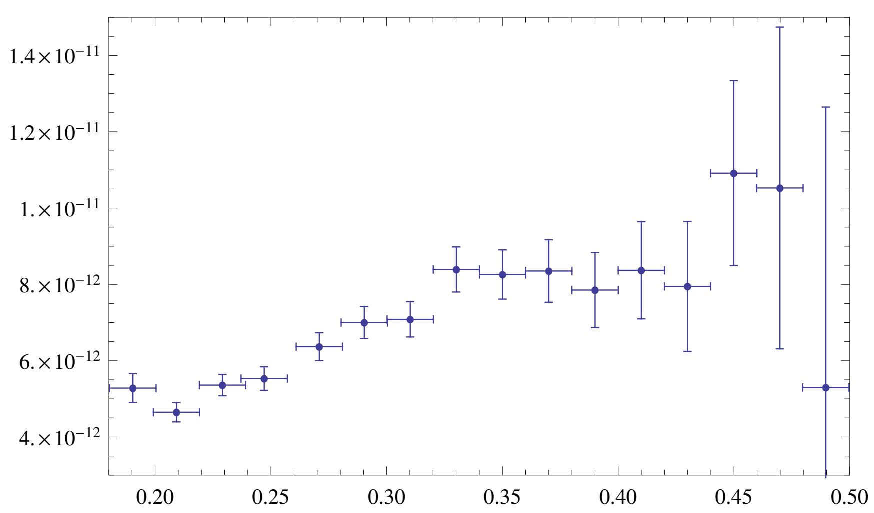
$\longrightarrow$



NA48/2 + E865

Fit to NA48/2 data ($\mu^+\mu^-$)

$\beta_+ \cdot 10^8$	a_+	b_+	χ^2/d.o.f
-3.96	$+0.372$	$+2.102$	11.9/15
	-0.611	-0.746	15.9/15
-2.88	$+0.384$	$+2.081$	12.1/15
	-0.598	-0.768	15.2/15
-1.80	$+0.397$	$+2.060$	12.4/15
	-0.585	-0.790	14.5/15



NA48/2

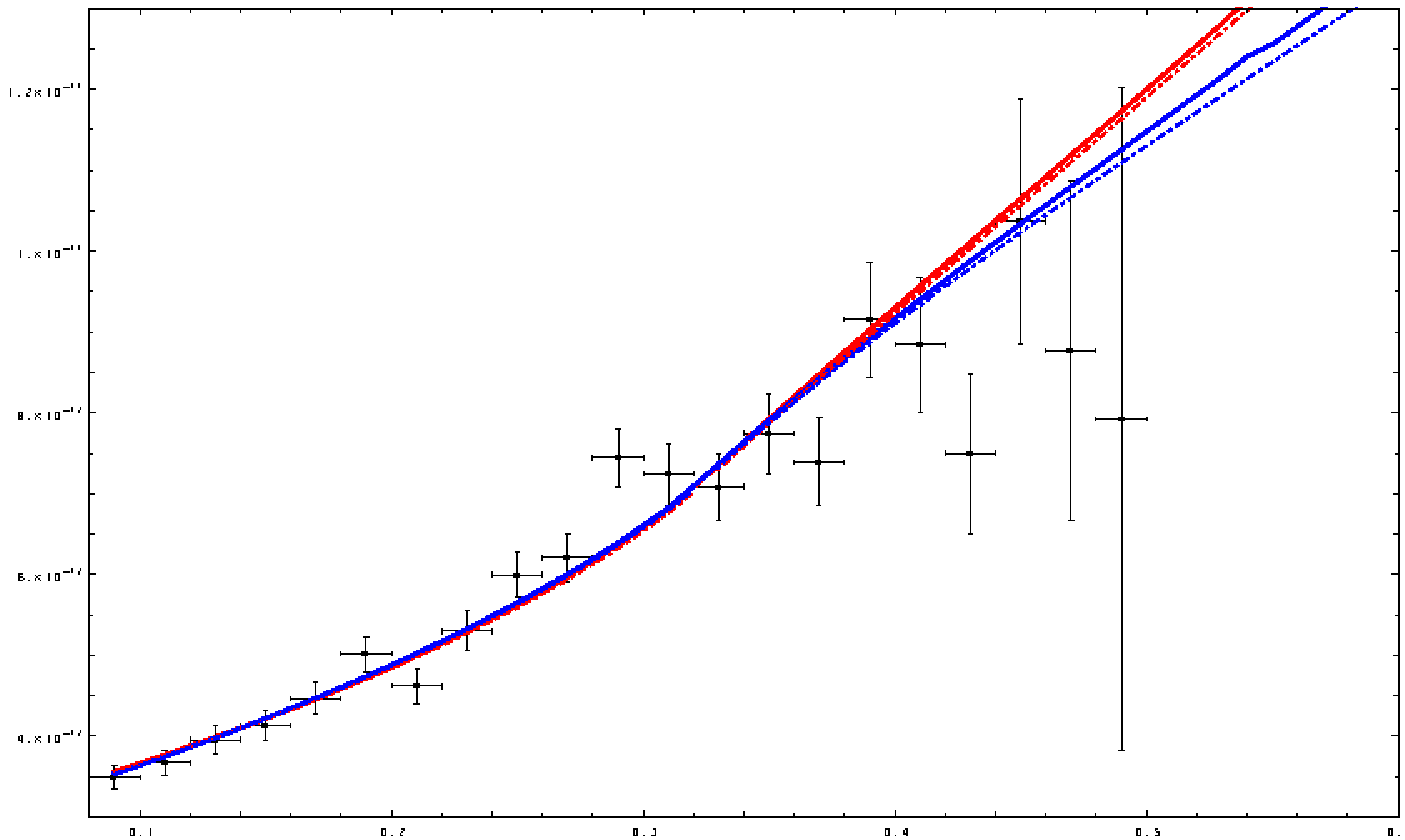
As in the NA48/2 data for the e^+e^- channel, the data show a slight preference for the positive solution

Robustness of determinations of a_+ and b_+

Impact of remaining two-loop contributions, not contained in $W_{\text{BOL}}(z)$

Predictions for a_+ and b_+?

Comparing $W_{2\mathrm{loop}}(z)$ and $W_{\text{BOL}}(z)$



solid lines: $|W_{2\mathrm{loop}}(z)|^2$ full two loops

dash-dotted lines $|W_{\text{BOL}}(z)|^2$

red curves: $a_+ = -0.585, b_+ = -0.779, \beta_+ = -2.88 \cdot 10^{-8}$

blue curves: $a_+ = -0575, b_+ = -0.779, \beta_+ = -0.99 \cdot 10^{-8}$

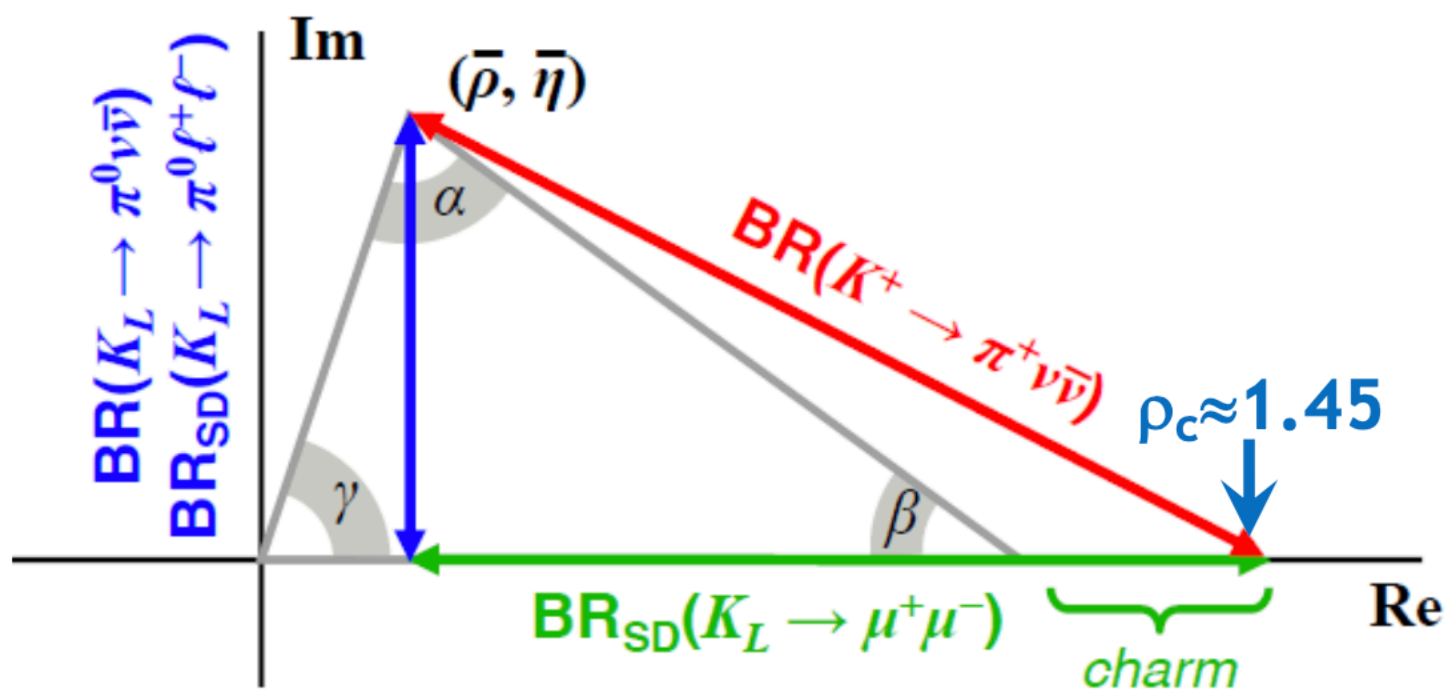
Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	**8.6±0.4**	**10.6±4.0**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	**3.0±0.2**	< 300

*Approx. error on LD-subtracted rate excluding parametric contributions

(see also arXiv:2203.09524)

- FCNC processes dominated by Z-penguin and box diagrams.
- SM rates determined by V_{CKM}, with minimal non-parametric "theory" uncertainties.
- Theory errors are being reduced *[Lattice QCD, e.g. arXiv:2203.10998]*.
- The current focus is on $K\to\pi\nu\nu$: uniquely clean theoretically.



Kaons and LFUV

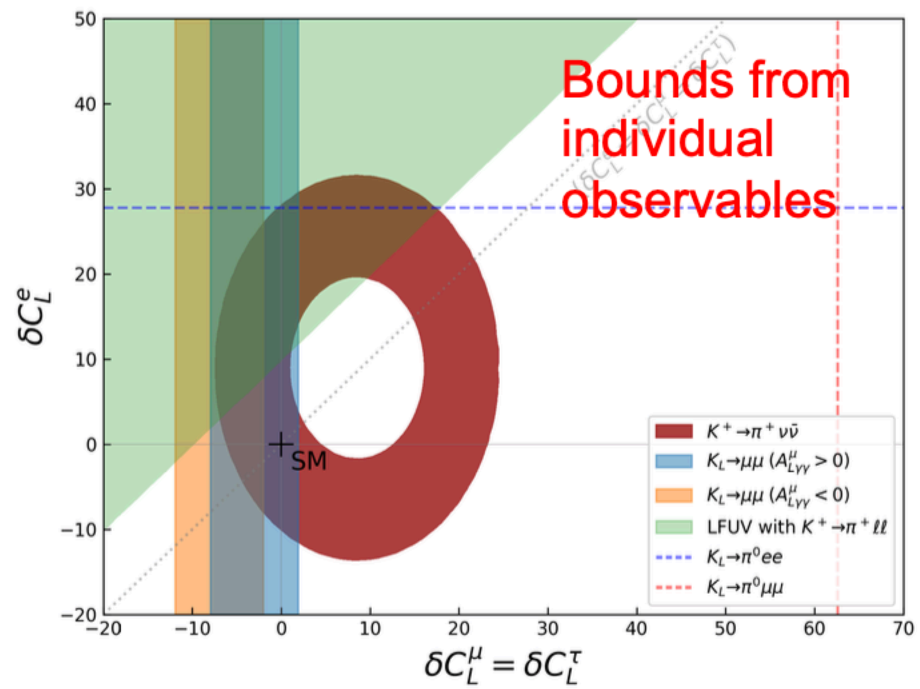
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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

Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

[arXiv:2206.14748]

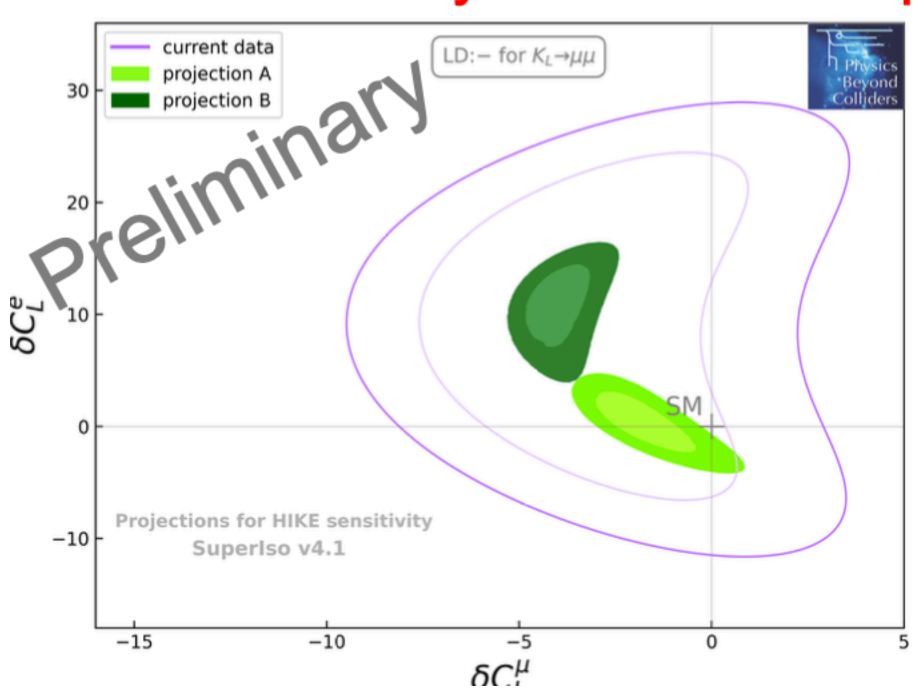
$$C_k^\ell = C_{k,\text{SM}}^\ell + \delta C_k^\ell \qquad \delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

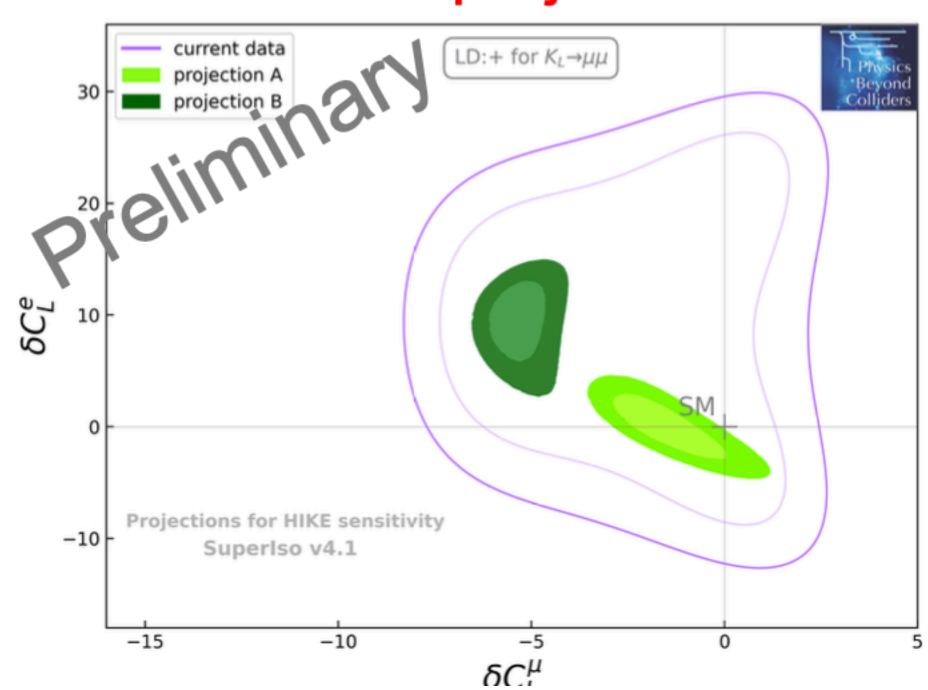


Individual measurements can be combined in a fit. Projections can be used for future experiments

Projections:
A: predicted central values for observables with only upper bound is projected to be as SM prediction; for measured ones current central values are taken.
B: central values for all observables are projected with best-fit points obtained from fits of existing data.

Very recent development: HIKE full projections





[CERN Physics Beyond Colliders Document in preparation, and paper In preparation by D'Ambrosio, Mahmoudi, Neshatpour]

HIKE Phase 2: sensitivity

- Decay BRs in the Standard Model (assuming constructive interference):

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 e^+ e^-) = \left(15.7|a_S|^2 \pm 6.2|a_S|\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right) + 2.4\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right)^2\right) \times 10^{-12} = 3.54^{+0.98}_{-0.85} \times 10^{-11},$$

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 \mu^+ \mu^-) = \left(3.7|a_S|^2 \pm 1.6|a_S|\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right) + 1.0\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right)^2 + 5.2\right) \times 10^{-12} = 1.41^{+0.28}_{-0.26} \times 10^{-11}$$

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

[Isidori, Smith, Unterdorfer, EPJ C36 (2004) 57]
[Mescia, Smith, Trine, JHEP 08 (2006) 88]

- SM signal yields and backgrounds in **5** years of operation:

Mode	N_S	N_B	$N_S/\sqrt{N_S+N_B}$
$K_L \to \pi^0 e^+ e^-$	70	83	5.7
$K_L \to \pi^0 \mu^+ \mu^-$	100	53	8.1

- Sensitivity to the CKM parameters
  (assuming an improved $|a_S|$ measurement with $K_S \to \pi^0 \ell^+ \ell^-$ at LHCb):

$$\left.\frac{\delta({\rm Im}\lambda_t)}{{\rm Im}\lambda_t}\right|_{K_L\to\pi^0 e^+ e^-} = 0.33, \qquad \left.\frac{\delta({\rm Im}\lambda_t)}{{\rm Im}\lambda_t}\right|_{K_L\to\pi^0 \mu^+ \mu^-} = 0.28.$$

Predicting $a_+,\ b_+$? Going beyond the low-energy expansion

requires an unsubtracted dispersion relation

$$W(z)|_{\pi\pi} = \frac{1}{\pi}\int_0^\infty dx \frac{\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi}}{x - zM_K^2 - i0}$$

with

$$\frac{\mathrm{Abs}\, W(s/M_K^2)|_{\pi\pi}}{16\pi^2 M_K^2} = \theta(s-4M_\pi^2) \times \frac{s-4M_\pi^2}{s}\lambda_{K\pi}^{-1/2}(s) \times F_V^{\pi *}(s) \times f_1^{\pi^+\pi^-\to K^+\pi^-}(s)$$

Then a_+ and b_+ are given by spectral sum rules

$$G_F M_K^2 a_+|_{\pi\pi} = W(0)|_{\pi\pi} = \frac{1}{\pi}\int_0^\infty \frac{dx}{x}\,\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi}$$

and

$$\begin{aligned} G_F M_K^2 b_+|_{\pi\pi} &= W'(0)|_{\pi\pi} - \frac{1}{60}\left(\frac{M_K^2}{M_\pi^2}\right)^2\left(\alpha_+ - \beta_+\frac{s_0}{M_\pi^2}\right) \\ &= \frac{M_K^2}{\pi}\int_0^\infty \frac{dx}{x^2}\,\mathrm{Abs}\, W(x/M_K^2)|_{\pi\pi} - \frac{1}{60}\left(\frac{M_K^2}{M_\pi^2}\right)^2\left(\alpha_+ - \beta_+\frac{s_0}{M_\pi^2}\right) \end{aligned}$$

requires $F_V^{\pi *}(s)$ and $f_1^{\pi^+\pi^-\to K^+\pi^-}(s)$ beyond low-energy expansion

Predicting $a_+,\ b_+$? Going beyond the low-energy expansion

Simple approach: unitarize both using the inverse amplitude method

T. N. Truong, Phys Rev Lett 61, 2526 (1988)

A. Dobado et al, Phys Lett B 235, 134 (1990)

T. Hannah, Phys Rev D 55, 5613 (1997)

A. Dobado, J. R. Pelaez, Phys Rev D 56, 3057 (1997)

J. Nieves et al., Phys Rev D 65, 036002 (2002)

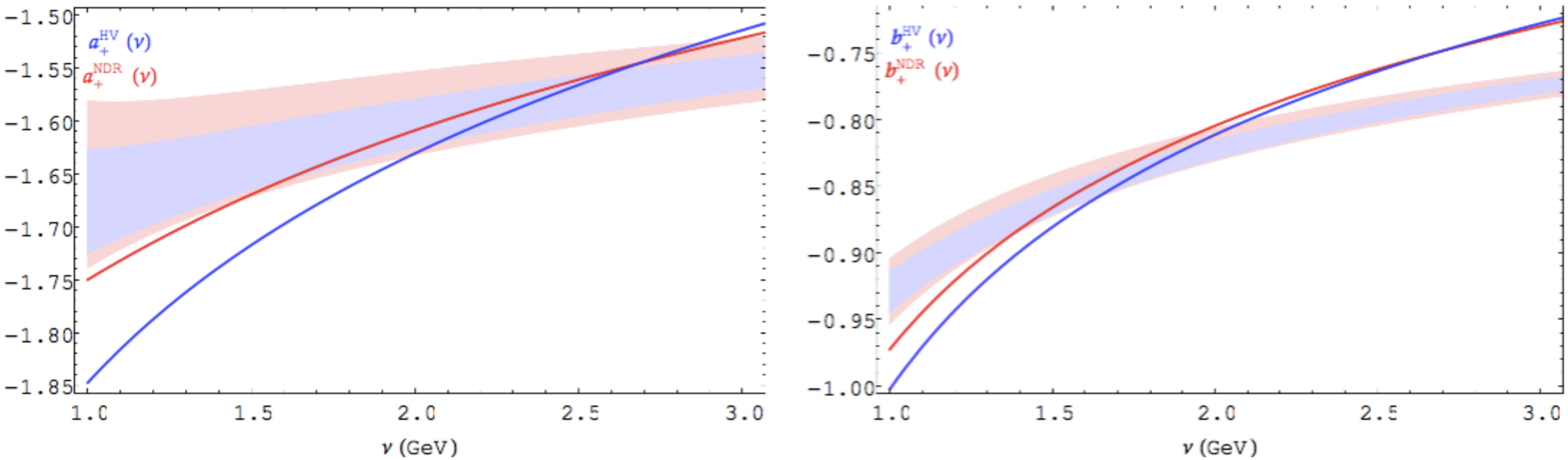
$$a_+|_{\pi\pi} = -(1.574^{+0.003}_{-0.020}) \qquad b_+|_{\pi\pi} = -(0.622^{+0.012}_{-0.017}) \qquad \text{for } \beta_+ = -0.85 \cdot 19^{-8}$$

note: position of the ρ resonance much too low for $\beta_+ = -2.88$... (phase goes through $\pi/2$ at $s \sim M_\rho^2/2$!)

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

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

Matching LD and SD at NLO



Results

$$BR(K^+ \to \pi^+ \nu \overline{\nu}) < 11 \times 10^{-10} \text{ @ } 90\% \; CL$$

$$BR(K^+ \to \pi^+ \nu \overline{\nu}) < 14 \times 10^{-10} \text{ @ } 95\% \; CL$$

- One event observed in Region 2
- Full exploitation of the CLs method in progress
- The results are compatible with the Standard Model
- For comparison: $BR(K^+ \to \pi^+ \nu \overline{\nu}) = 28^{+44}_{-23} \times 10^{-11} \text{ @ } 68\% \; CL$

$$BR(K^+ \to \pi^+ \nu \overline{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K^+ \to \pi^+ \nu \overline{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

Prospects

- Processing of 2017 data on-going
  - ~ 20 times more data than the presented statistics
  - Expected reduction of upstream background
  - Methods to improve the reconstruction efficiency under study
- 2018 data taking under way
  - Further mitigation of the upstream background is expected
  - Processing in parallel with data taking
  - Final 2018 reprocessing expected beginning 2019
- Expect ~ 20 SM events from the 2017+2018 data sample. The analysis of this sample should provide:
  - Input to the European Strategy for Particle Physics
  - Solid extrapolation to the ultimate sensitivity of NA62 achievable after LS2

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

$$B(K_L) = (3.14 \pm 0.17 \pm 0.06) \times 10^{-11}$$ TH

$$B(K_L) < 2.6 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$ E391a

Model-independent bound, based on SU(2) properties
dim-6 operators for $\bar{s}d\bar{\nu}\nu$ Grossman Nir

$$B(K_L) \le \frac{\tau_L}{\tau_+} \times B(K^{\pm})_{\mathrm{E949}} \le 1.4 \times 10^{-9} \quad \text{at } 90\% C.L.$$

UV sensitivity

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