Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

2nd Flavour Physics conference in Lyon

Flavor physics: recent theoretical developments in Kaon decays

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INFN Sezione di Napoli

arXiv:1707.06999

arXiv:1711.11030

arXiv:1703.05786

arXiv:1712.10270

arXiv:1712.08122

Outline

- Flavour issues
- $K \to \pi \nu \nu$
- K-anomalies: ε'
- $K_{S,L} \to \mu\mu$
- weak counterterms

Anomalies in Kaons

Footprints of LQs: from B to K rare decays

Luiz Vale Silva **Svjetlana Fajfer and Nejc Koˇsnik**

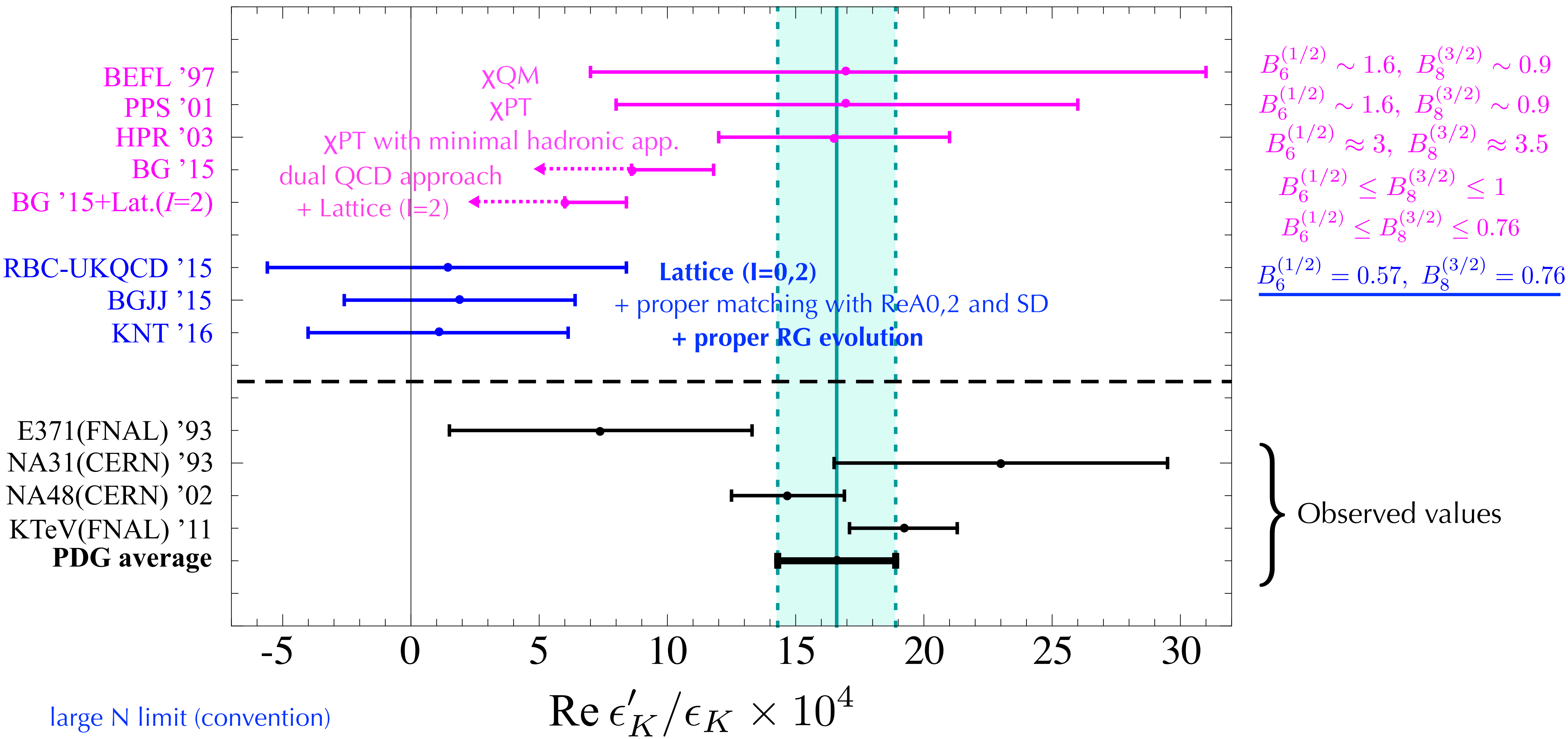
Correlation with different flavor sectors

$\Lambda_{NP}^{b\to c,s} \sim \mathcal{O}(1, 100)$ TeV $\Rightarrow$ direct searches,
low-energy precision observables

GIM suppression and CKM suppression:

$$\mathcal{L}_{\rm eff} \supset -\frac{1-0.3\,i}{(180\ \mathrm{TeV})^2}(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_L\gamma^\mu\nu_L) + \mathrm{h.c.}$$

Current situation of $\epsilon'_K/\epsilon_K \propto \mathrm{Im}A_0 - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)\mathrm{Im}A_2$



large N limit (convention)

$$B_6^{(1/2)} = B_8^{(3/2)} = 1$$

dual QCD prediction

$$B_6^{(1/2)} \leq B_8^{(3/2)} < 1,\ B_8^{(3/2)} = 0.8$$

	Exp.	χPT	dual QCD	Lattice (I=0,2)
$\left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)$	22.45 ± 0.05	~ 14	16.0 ± 1.5	31.0 ± 11.1

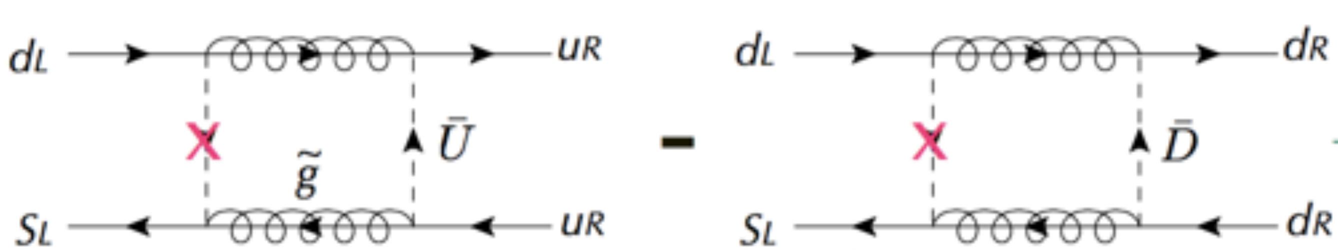
Kitahara,Nierste, Tremper PRL 16

ϵ' from isospin breaking

Kagan Neubert,99, Grossman, Kagan Neubert,99

$$\frac{\epsilon'_K}{\epsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|_{\rm exp}} \frac{\omega_{\rm exp}}{({\rm Re}A_0)_{\rm exp}} \left(-{\rm Im}A_0 + \frac{1}{\omega_{\rm exp}}{\rm Im}A_2\right) \quad \text{where} \quad \frac{1}{\omega} \equiv \frac{{\rm Re}A_0}{{\rm Re}A_2} = 22.46\ ({\rm exp.})$$

Assuming a discrepancy 2.9 sigmas from SM



$\rightarrow$ EW penguin(Q_8)

$m_{\bar{U}} \neq m_{\bar{D}} \rightarrow$ contribute to ${\rm Im}A_2$

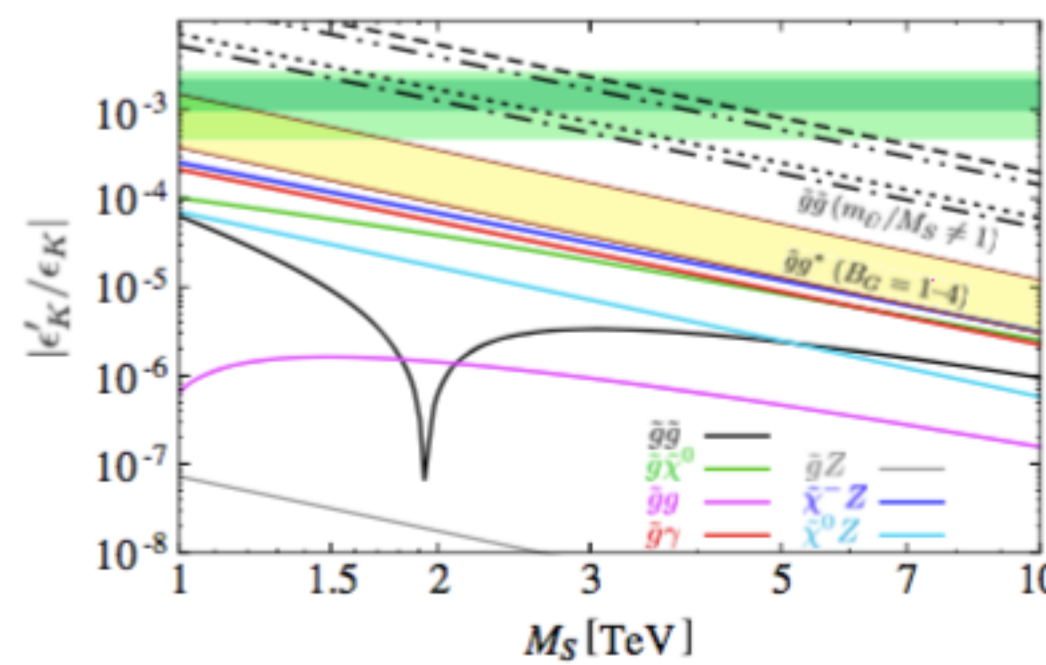


FIG. 3. Individual supersymmetric contributions to $|\epsilon'_K/\epsilon_K|$

Models solving ε'/ε anomaly

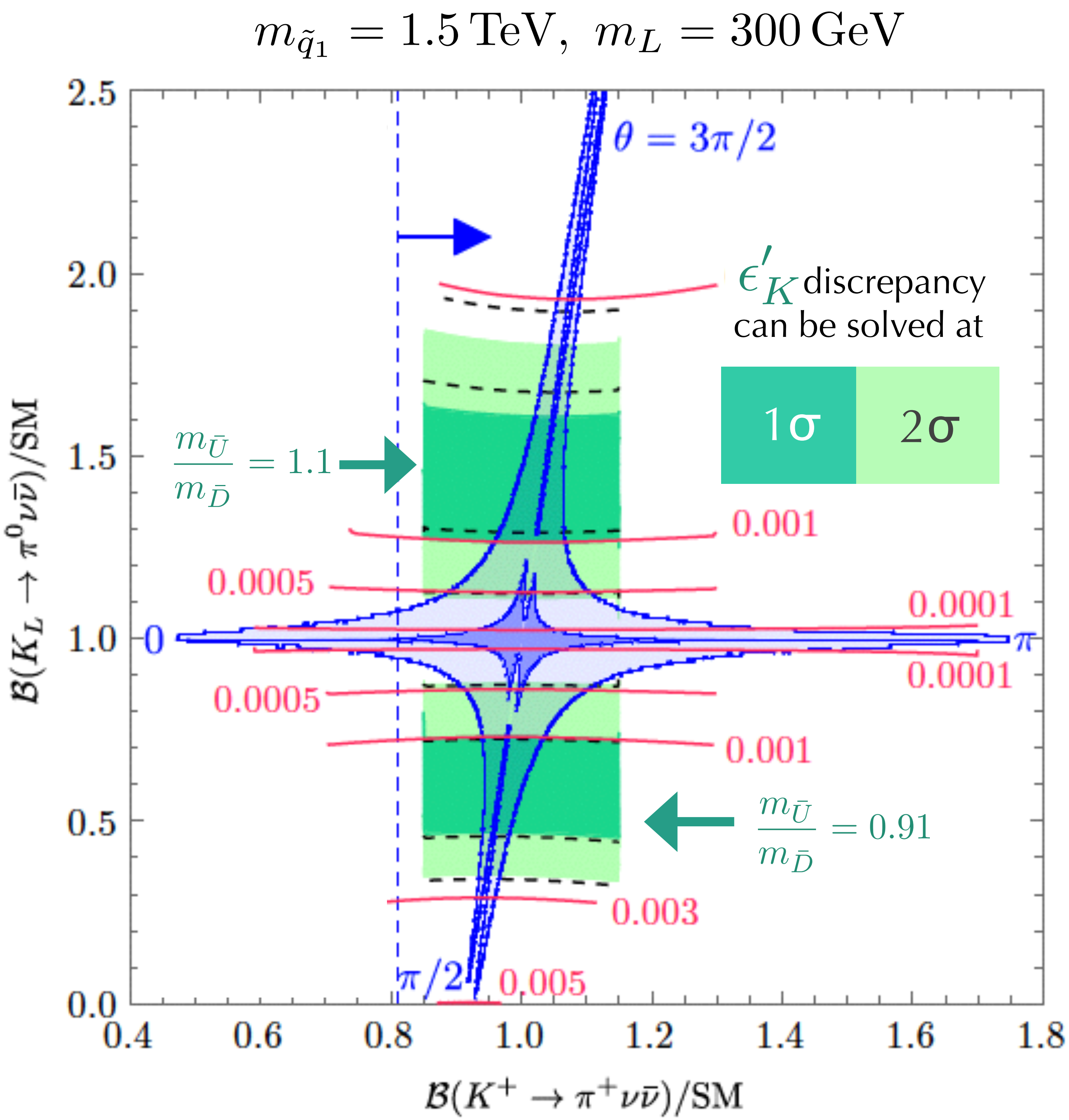
- Several new physics models have been studied to explain ε'/ε anomaly

MSSM	-- chargino Z penguin	*[M. Endo, S. Mishima, D. Ueda and KY, PLB762(2016)493]*
	-- gluino Z penguin	*[M. Tanimoto and KY, PTEP(2016)no.12,123B02]*
	-- gluino box	*[T.Kitahara, U.Nierste and P.Tremper, PRL117(2016)no.9, 091802 A.Crivellin, G.D'Ambrosio, T.Kitahara and U.Nierste, 1703.05786]*
Vector-like quarks		*[C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]*
Little Higgs Model with T-parity		*[M.Blanke, A.J.Buras and S.Recksiegel, EPJ.C76 (2016)no.4,182]*
331 model		*[A.J.Buras and F.De Fazio, JHEP1603(2016)010 & JHEP1608 (2016) 115]*
Right handed current		*[V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB 767 (2017) 1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]*

- Different implications (correlations & predictions) for other observables appear depending on models $\Rightarrow$ Possibility of model discriminations

B(K→πνν)

[Crivellin, D'Ambrosio, **TK**, Nierste, '17]



more than 10% mass shift of the gluino mass from $M_3 \simeq 1.45 M_S$ is possible in light of the constraint from ϵ_K

1-10 % mass shift of the gluino mass is possible

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})/\mathrm{SM} \lesssim 2\,(1.2)$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})/\mathrm{SM} \lesssim 1.4\,(1.1)$

for a fine-tuning at the 1(10)% level

- $m_{\bar{U}}/m_{\bar{D}}$ determines a position of the green band
- Positive ϵ'_K predicts a strict correlation

$$\mathrm{sgn}\left[\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) - \mathcal{B}^{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu})\right] = \mathrm{sgn}\left[m_{\bar{U}} - m_{\bar{D}}\right]$$

$$\mathrm{sgn}\left[m_{\bar{U}} - m_{\bar{D}}\right] \xrightarrow{\epsilon'_K} \arg\left[m^2_{Q12}\right]$$

$$\downarrow$$

$$\mathrm{sgn}\left[\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) - \mathcal{B}^{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu})\right]$$

Interplay with B-anomalies

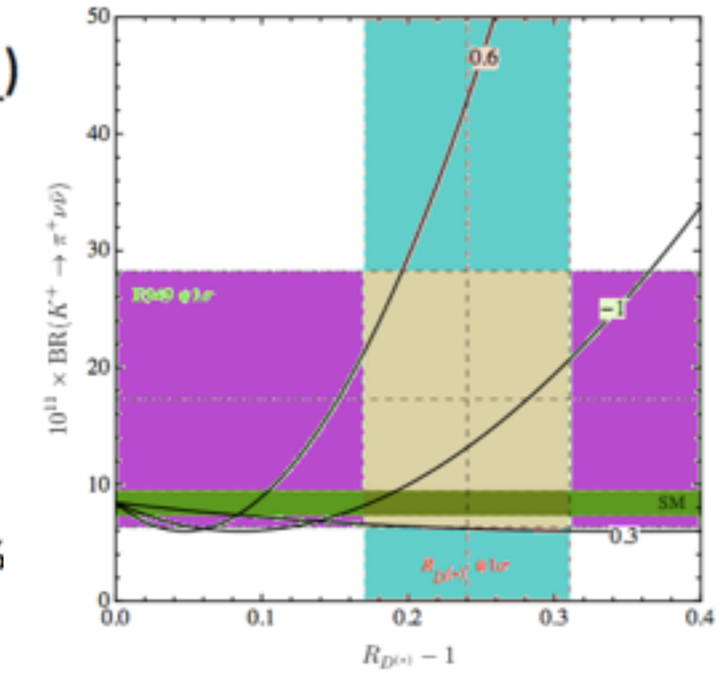
Bordone, Buttazzo, Isidori, Monnard

NP is coupled only to the left-handed third generation flavour-singlets (q_{3L} and l_{3L})

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu\sigma^a q_{3L})(\bar{\ell}_{3L}\gamma^\mu\sigma^a\ell_{3L}) - \frac{c_{13}}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu q_{3L})(\bar{\ell}_{3L}\gamma^\mu\ell_{3L})$$

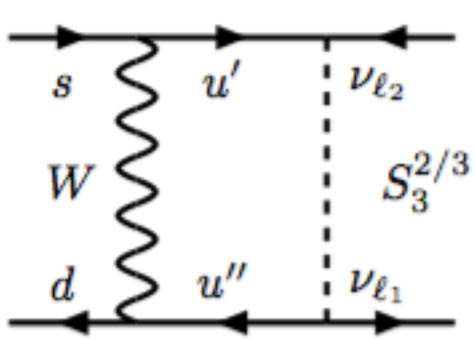
The interference of NP (weak interaction triplets) with the SM amplitude is always destructive.

The suppression could be as large as 30% relative the SM value.

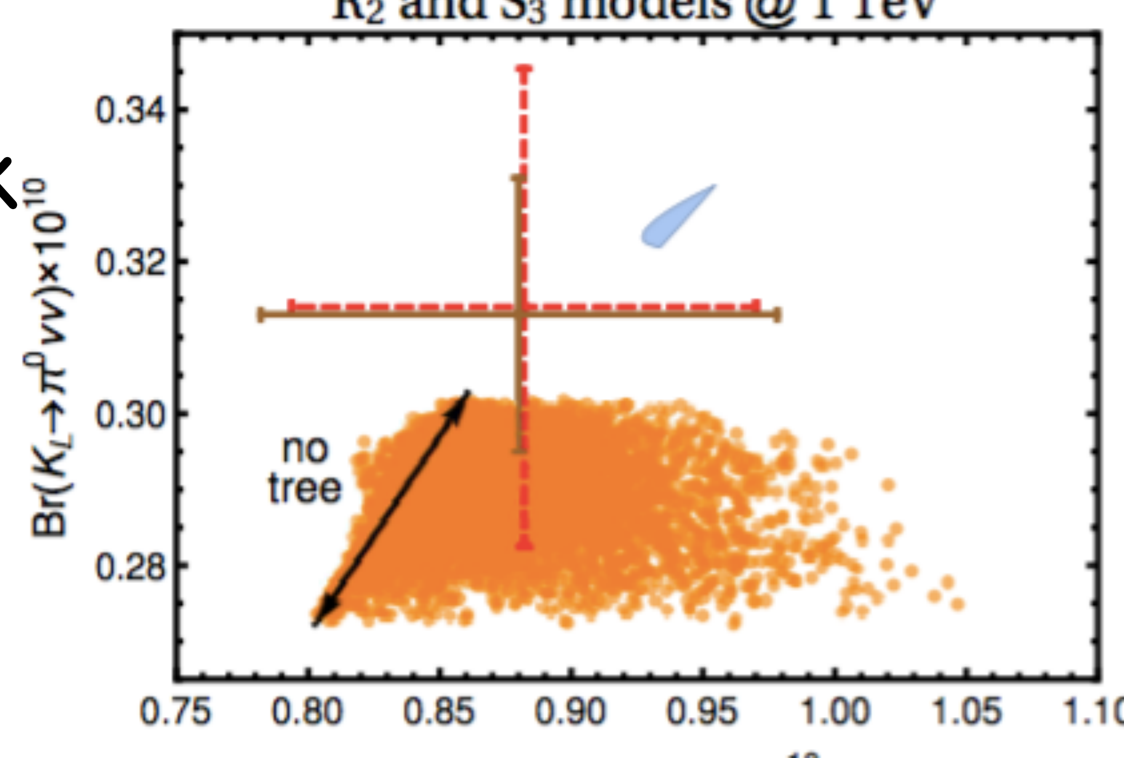


S. Fajfer N. Koˇsnik, L. Vale Silva

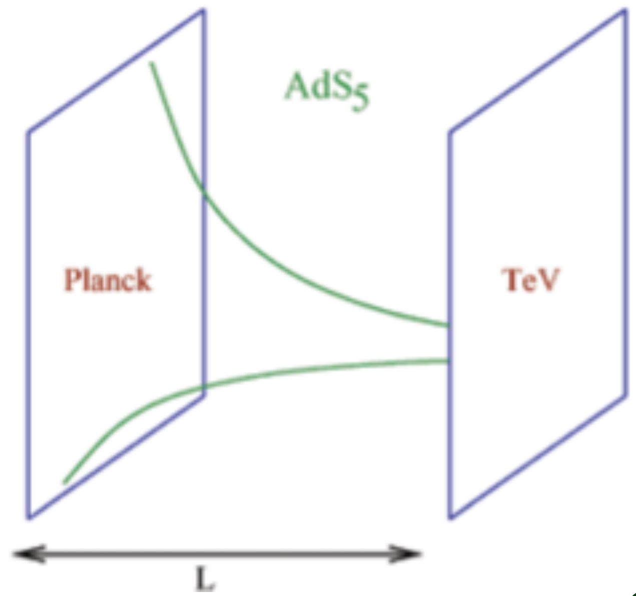
Scalar/triplet leptoquark



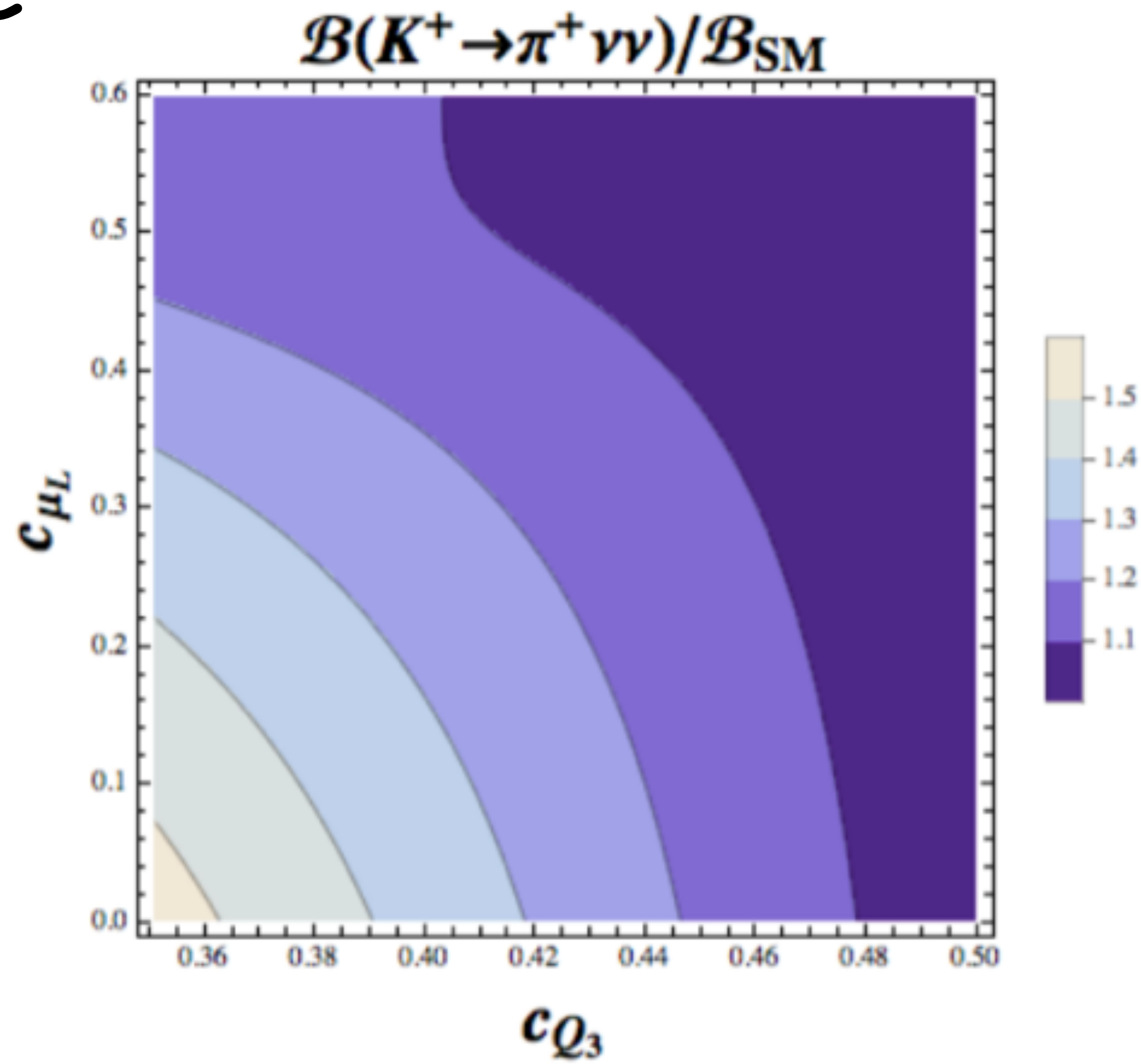
(a) *Box diagram (Box).*



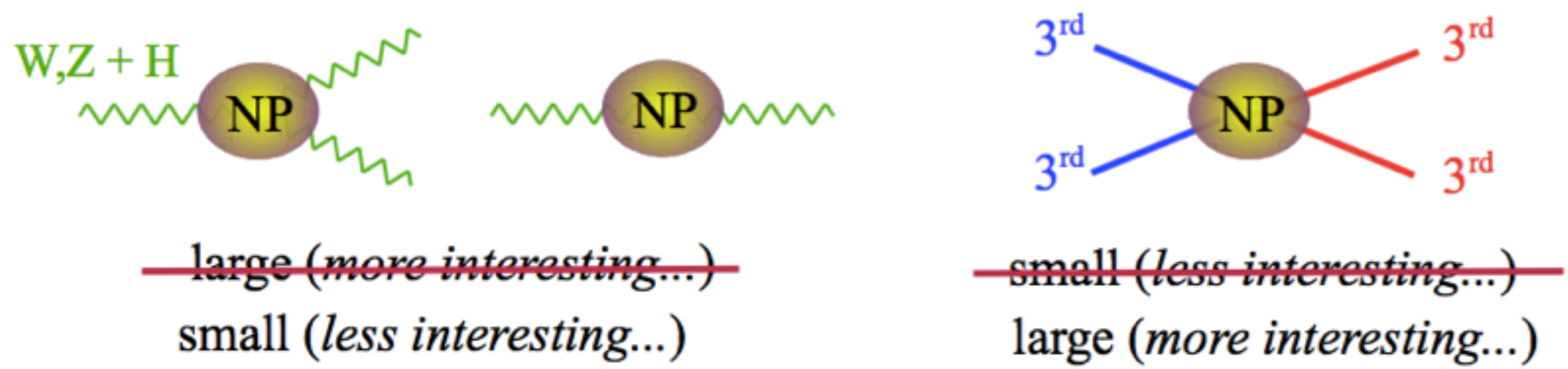
EW vs flavor scale



GD,Iyer



[*a possible shift of parading in model-building*] G. Isidori



Javier Fuentes-Martín

M. Bordone, C. Cornella and G. Isidori

Rare Kaon decay program

$K_L \to \mu\mu$

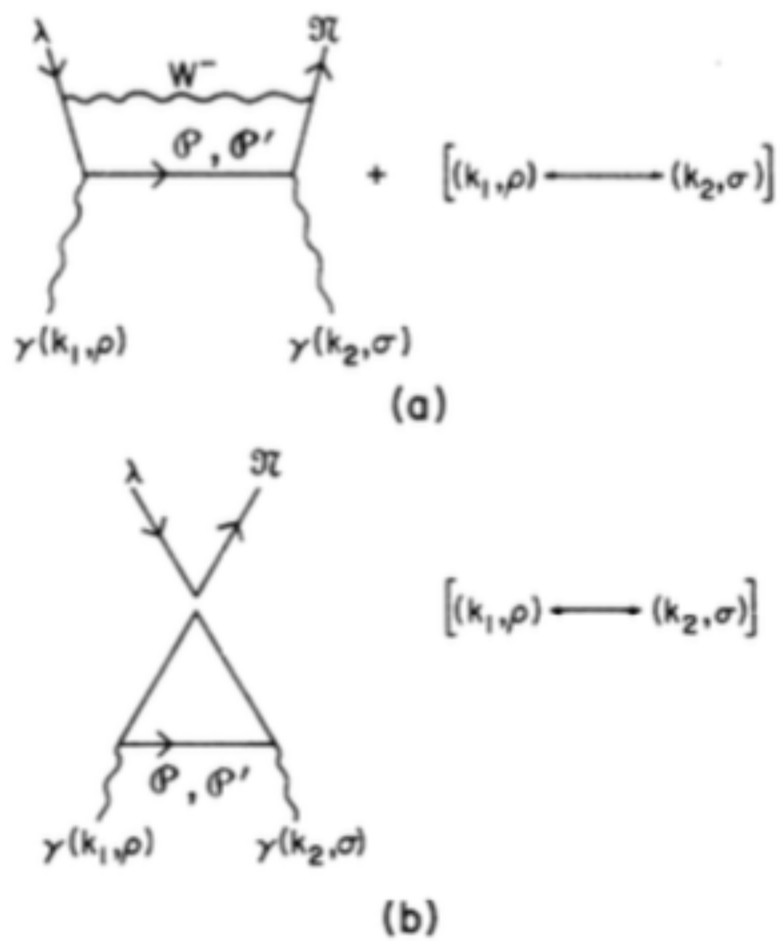


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

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

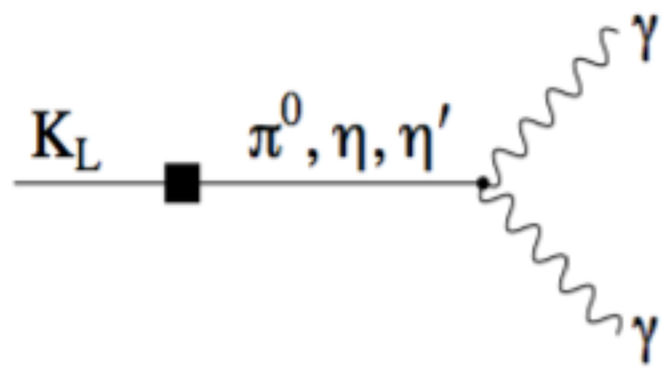
VALUE (10^{-6})	EVTS	DOCUMENT ID		TECN	CO
3.48 ± 0.05	**OUR AVERAGE**				
3.474 ±0.057	6210	AMBROSE	2000	B871	
3.87 ±0.30	179	[1] AKAGI	1995	SPEC	
3.38 ±0.17	707	HEINSON	1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	1991B	SPEC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

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

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

Dispersive calculation: Re A, Im A

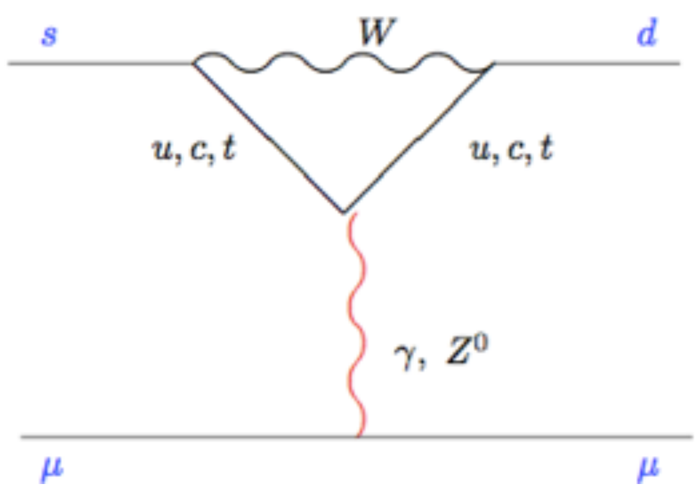
We do not know the sign of $A(K_L \to \gamma\gamma)$



$$A(K_L \to 2\gamma_\perp)_{O(p^4)} = A(K_L \to \pi^0 \to 2\gamma_\perp) + A(K_L \to \eta_8 \to 2\gamma_\perp)$$
$$= A(K_L \to \pi^0)A(\pi^0 \to 2\gamma_\perp)\left[\frac{1}{M_K^2 - M_\pi^2} + \frac{1}{3}\cdot\frac{1}{M_K^2 - M_8^2}\right] \simeq 0$$

Kaon Decays in the Standard Model
Vincenzo Cirigliano (Los Alamos), Gerhard Ecker, Helmut Neufeld (Vienna U.), Antonio Pich, Jorge Portoles, refs therein

$K_L \to \mu\mu$



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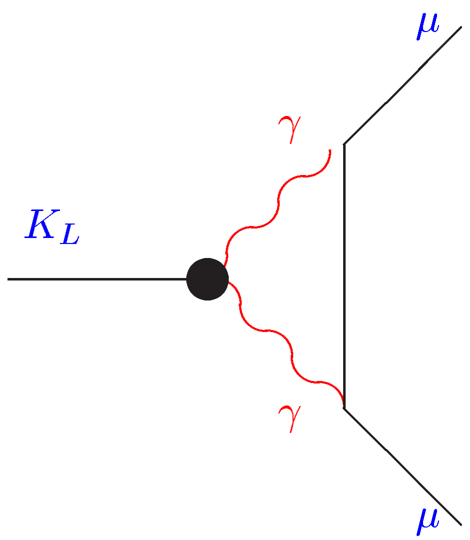

$$\frac{\Gamma(K_L \to \mu\bar{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim \quad |ReA|^2 + |ImA|^2$$

Absorptive calculation model independent

$$27.14$$

Subtracting from expt. the Absorptive contribution

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

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

$K_S \to \mu\mu$

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST 1

Rare decay modes of the K mesons in gauge theories

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(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 $\lambda+\bar{\mathfrak{N}}\to l+\bar{l}$ 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

Run1 data (3 fb^{-1})

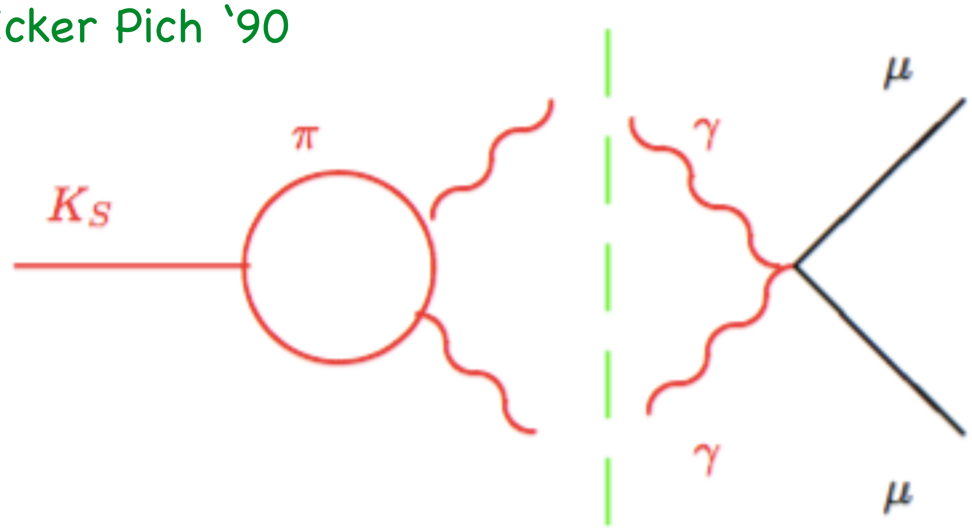
$\mathcal{B}(K^0_S\to\mu^+\mu^-) < 0.8(1.0)\times10^{-9}$
90%, 95% CL
factor 11 improvement

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. • • •				
$< 0.032\times10^4$	90	GJESDAL	1973	ASPK
$< 0.7\times10^4$	90	HYAMS	1969B	OSPK

[1] AAIJ 2013G uses 1.0 fb^{-1} of pp collisions at $\sqrt{s}=7$ TeV. They obtained B($K^0_S\to\mu^+\mu^-$) $< 11\times10^{-9}$ 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

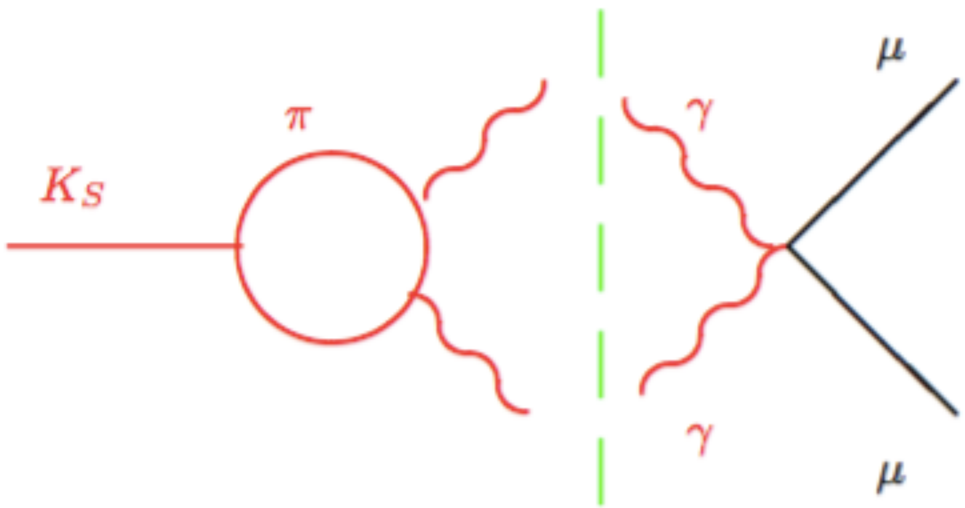
SM $10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$

NP few 10^{-11} allowed

LHCB

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

$K_S \to \mu\mu$: 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

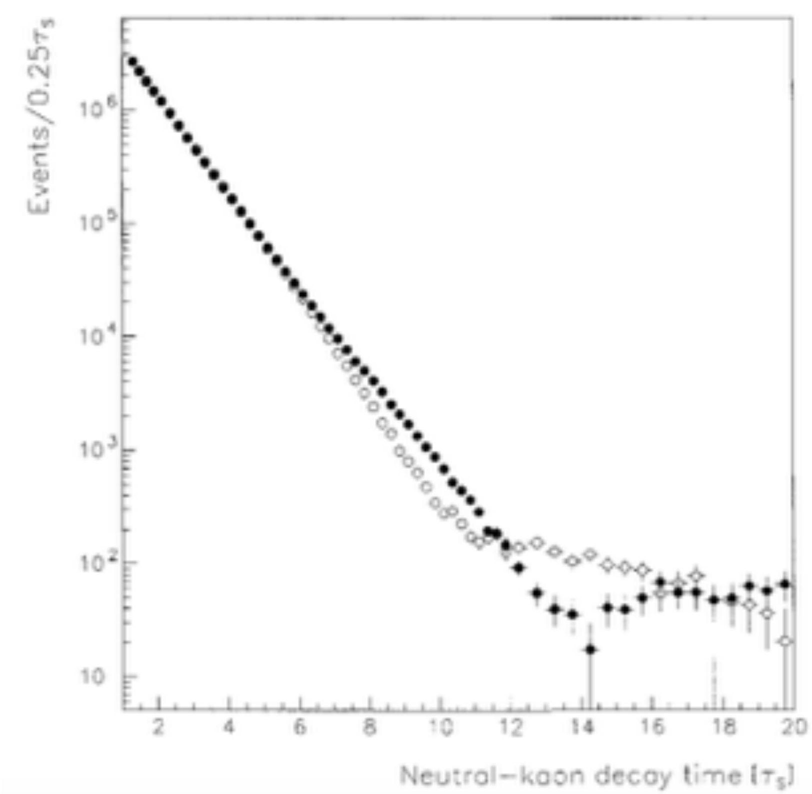
$$K_S \to \gamma\mu\mu$$
$$K_S \to \mu\mu\mu\mu$$
$$K_S \to ee\mu\mu$$
$$K_S \to \gamma\gamma$$

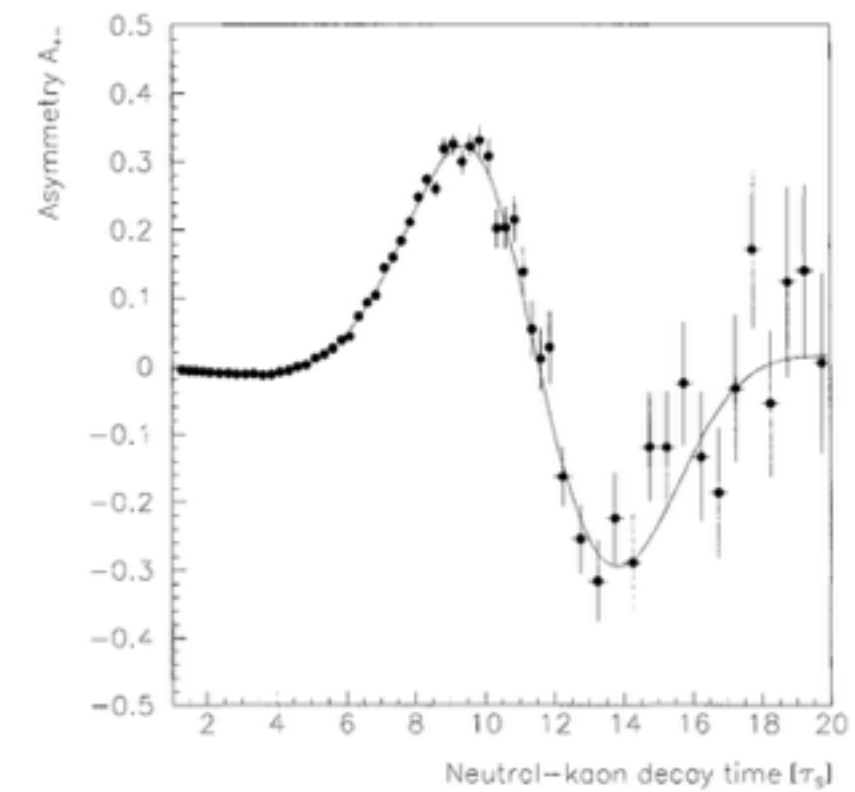
{

CPLEAR Flavor tagging

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

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





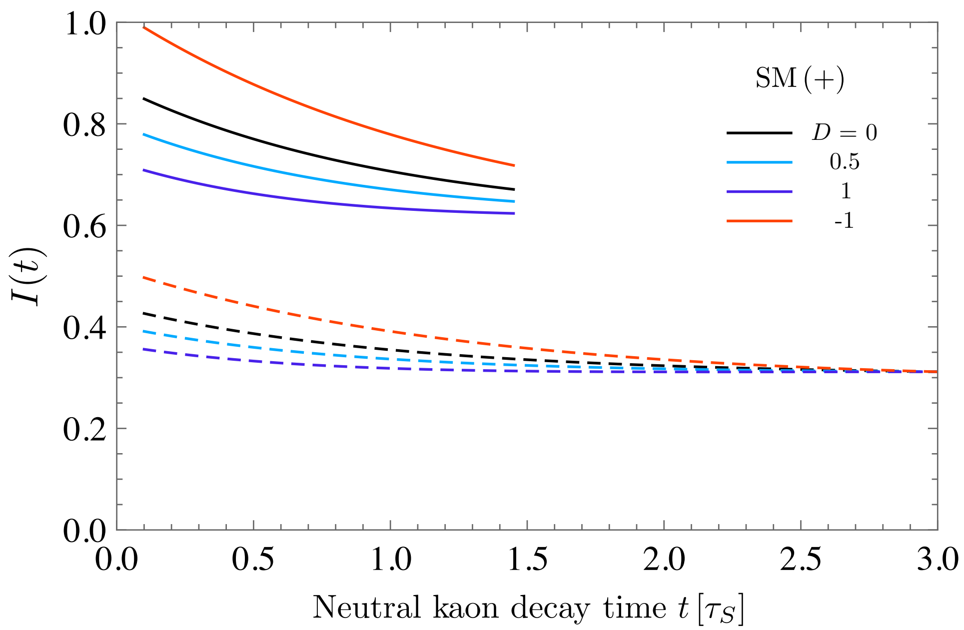
}

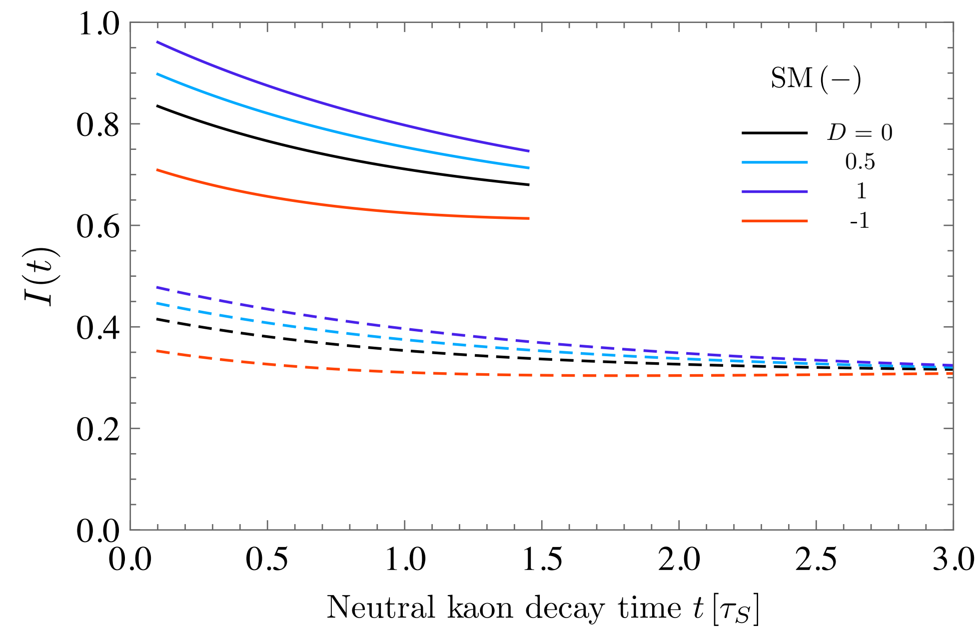
Can we study $K^0(t)$?

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 !

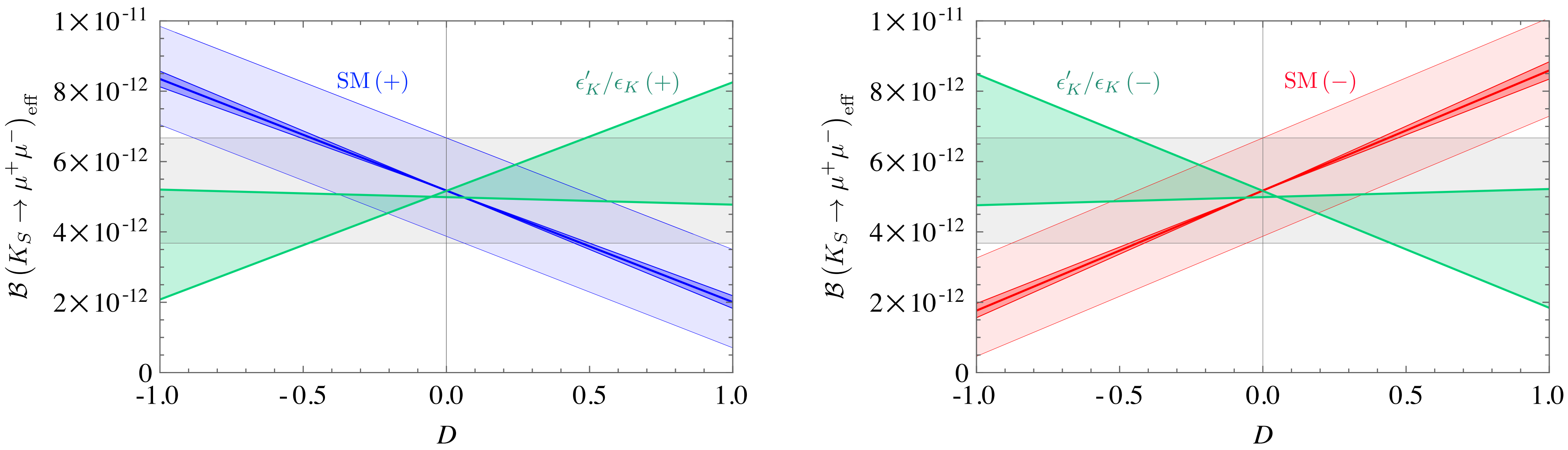
- We may be able to study the time evolution of K^0 by tracking the associated particles (K^-)

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

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

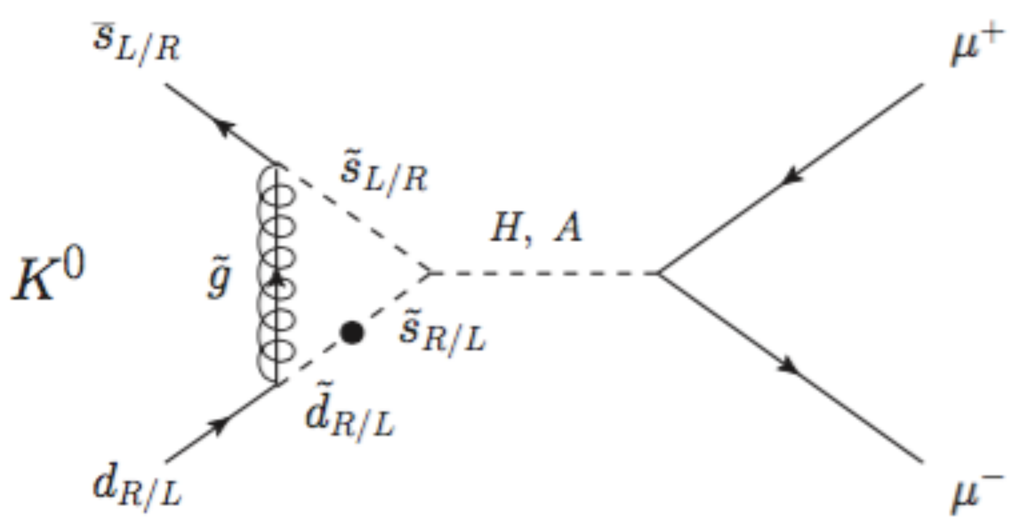
GD , Kitahara
1707.06999 PRL

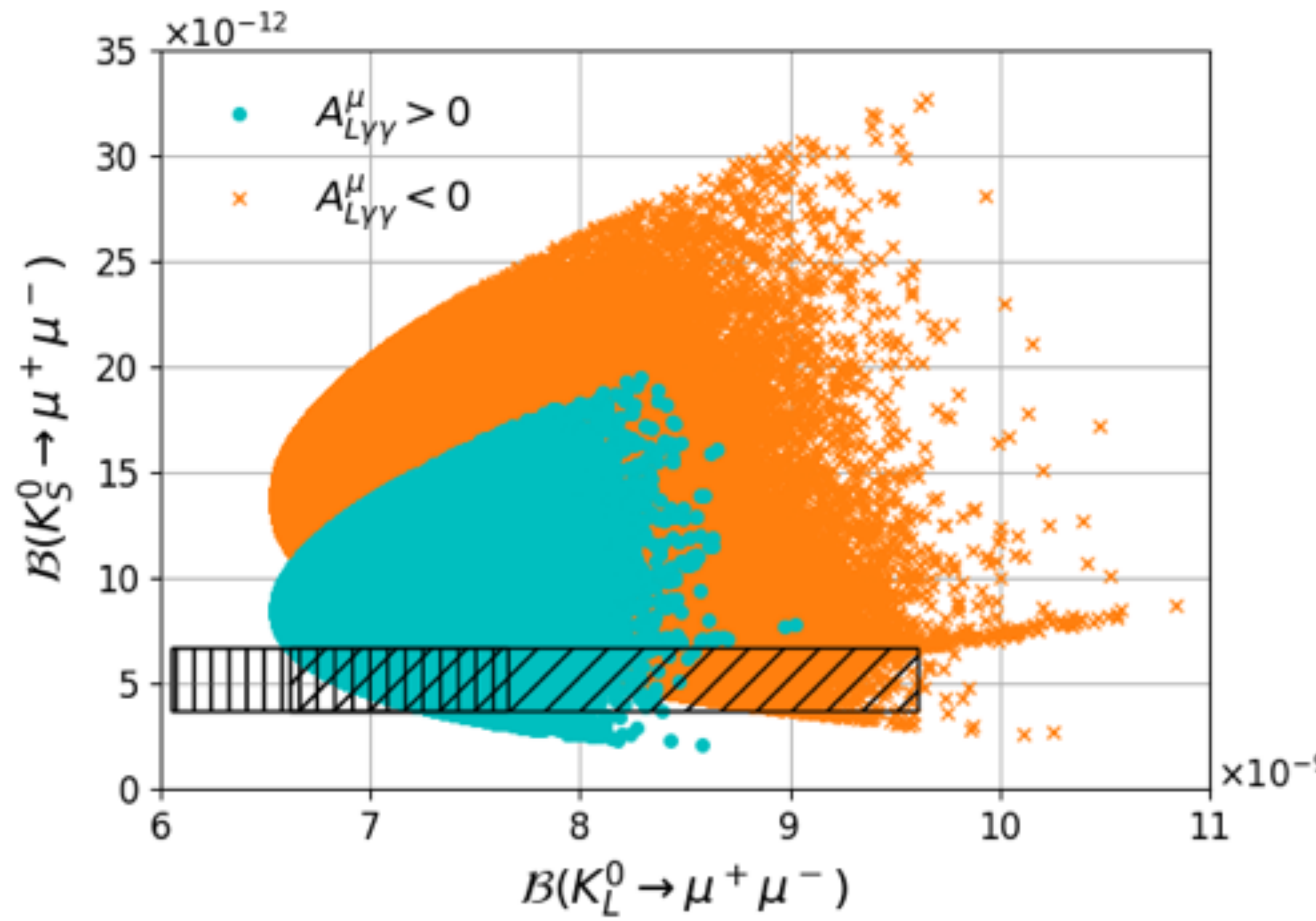
Short distance window



$$\mathcal{B}(K_S\to\mu^+\mu^-)_{\rm eff}$$
$$=\tau_S\left[\int_{t_{min}}^{t_{max}}dt\left(\Gamma(K_1)e^{-\Gamma_S t}+\frac{D}{8\pi M_K}\sqrt{1-\frac{4m_\mu^2}{M_K^2}}\sum_{\rm spin}{\rm Re}\left[e^{-i\Delta M_K t}\mathcal{A}(K_1)^*\mathcal{A}(K_2)\right]e^{-\frac{\Gamma_S+\Gamma_L}{2}t}\right)\varepsilon(t)\right]$$
$$\times\left(\int_{t_{min}}^{t_{max}}dt\,e^{-\Gamma_S t}\,\varepsilon(t)\right)^{-1},$$

Collaboration with Teppei Kitahara, Isabel Fernández Suárez, Miriam Lucio Martínez, Diego Martínez Santos, Veronika Georgieva Chobanova arXiv:1711.11030, JHEP





Miriam Lucio

QCD and EFT

Chiral Perturbation theory

χPT effective field theory approach based on two assumptions

- π's Golstone bosons of $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$ — $SU(3)_L \times SU(3)_R$ symm. $\mathcal{L}_{QCD}$ $m_q = 0$
- (chiral) power counting There is a small expansion parameter $p^2/\Lambda^2_{\chi SB}$

$\Lambda_{\chi SB} \simeq 4\pi F_\pi \sim 1.2$ GeV

Chiral sym. breaking through dim. parameter F_π, χ related to

$\langle 0|J_{5\mu}|\pi\rangle$, $\langle 0|\bar{q}_L q_R|0\rangle$

$F_\pi \approx 93$ MeV

$$\mathcal{L}_S = \mathcal{L}_S^2 + \mathcal{L}_S^4 + \cdots = \frac{F_\pi^{\ 2}}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U \chi^\dagger \rangle}^{\pi \to l\nu,\ \pi\pi \to \pi\pi,\ K \to \pi..} + \overbrace{\sum_i L_i O_i}^{K \to \pi..} + \cdots$$

Fantastic chiral prediction

$A_{\pi\pi} \sim (s - m_\pi^2)/F_\pi^2$

L_i Gasser Leutwyler coeff determined from expts.
O_i p^4 operator

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

Vector Meson Dominance in the strong sector

Ecker, Gasser, de Rafael, Pich

L_i	L_i expts	V	A	Total (Scalar incl.)	Total QCD rel. incl.
L_1	0.4 ± 0.3	0,6	0	0,6	0,9
L_2	1.4 ± 0.3	1,2	0	1,2	1,8
L_3	-3.5 ± 1.1	-3,6	0	-3,0	-4,9
L_4	-0.3 ± 0.5	0	0	0	0
L_5	1.4 ± 0.5	0	0	1,4	1,4
L_6	-0.2 ± 0.3	0	0	0	0
L_7	-0.4 ± 0.2	0	0	-0,3	-0,3
L_8	0.9 ± 0.3	0	0	0,9	0,9
L_9	6.9 ± 0.7	6,9	0	6,9	7,3
L_{10}	-5.5 ± 0.7	-10	4	-6,0	-5,5

QCD inspired relations relations

$$F_V = 2G_V = \sqrt{2} f_\pi$$

$$F_A = f_\pi$$

$$M_A = \sqrt{2} M_V$$

KSFR: $G_V = \sqrt{2}\ F_\pi$
determined by dominance of pion, V,A to recover QCD short distance constraints

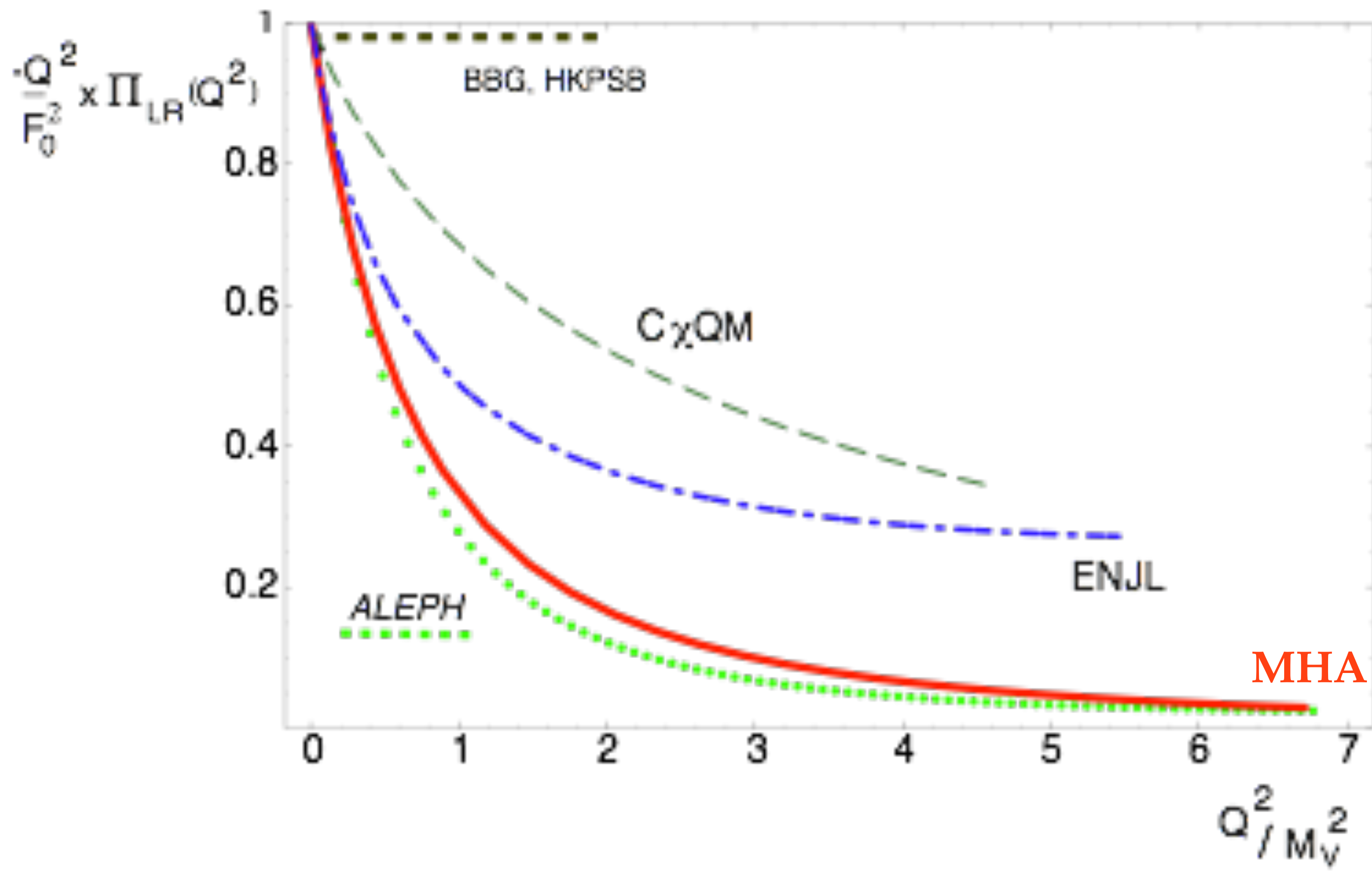
$$L_1^V = \frac{L_2^V}{2} = -\frac{L_3^V}{6} = \frac{G_V^2}{8M_V^2}, \qquad L_9^V = \frac{F_V G_V}{2M_V^2}, \qquad L_{10}^{V+A} = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2}$$

QCD inspired relations relations

$$L_1^V = L_2^V/2 = -L_3^V/6 = L_9^V/8 = -L_{10}^{V+A}/6 = f_\pi^2/(16M_V^2)$$

Minimal Hadronic Ansatz (MHA)

- Traditional wisdom: low energy VERY WELL approximated by π's ,V,A
- Short distance: QCD
- A good interpolation among the two regimes is sufficient for a good description of the correlators



De Rafael

π	2π	3π	N_i
$\pi^+\gamma^*$	$\pi^+\pi^0\gamma^*$		$N_{14}^r - N_{15}^r$
$\pi^0\gamma^*$ (S)	$\pi^0\pi^0\gamma^*$ (L)		$2N_{14}^r + N_{15}^r$
$\pi^+\gamma\gamma$	$\pi^+\pi^0\gamma\gamma$		$N_{14} - N_{15} - 2N_{18}$
	$\pi^+\pi^-\gamma\gamma$ (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)	$6N_{28} + 3N_{29} - 5N_{30}$

$$
\begin{aligned}
K^{\pm} \to \pi^{\pm}\gamma^{*} : &\quad a_{+} = -0.578 \pm 0.016 \ [3,\ 4] \\
K_S \to \pi^{0}\gamma^{*} : &\quad a_S = (1.06^{+0.26}_{-0.21} \pm 0.07) \ [5,\ 6] \\
K^{\pm} \to \pi^{\pm}\pi^{0}\gamma : &\quad X_E = (-24 \pm 4 \pm 4) \ \mathrm{GeV}^{-4} \ [7] \\
K^{+} \to \pi^{+}\gamma\gamma : &\quad \hat{c} = 1.56 \pm 0.23 \pm 0.11 \ [8] \ .
\end{aligned}
$$

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

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

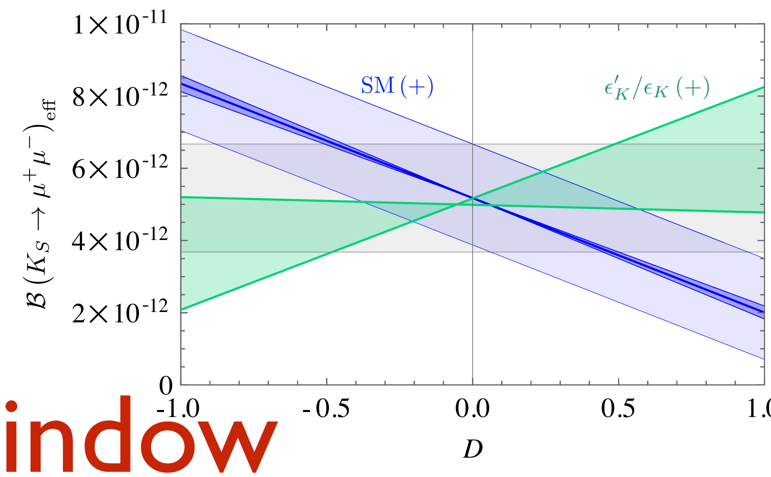
$$
\mathcal{N}_E^{(0)} \equiv N_{14}^r - N_{15}^r - N_{16}^r - N_{17} = -\frac{|\mathcal{M}_K| f_\pi}{2G_8} X_E \ ;
$$

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

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

Conclusions

- Flavour anomalies: interplay with K->π***νν*** but 10% measurement needed!



- LHCB: K_S->μμ extraordinary result: interference effect!!!Short distance window

- weak chiral lagrangian

- LFUV in Kaons very useful

- Rich rare kaon program

Back up

Correlation with different flavor sectors

$\Lambda_{NP}^{b\to c,s} \sim \mathcal{O}(1, 100)$ TeV $\Rightarrow$ direct searches,
low-energy precision observables

GIM suppression and CKM suppression:

$$\mathcal{L}_{\rm eff} \supset -\frac{1-0.3\,i}{(180\ \text{TeV})^2}(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_L\gamma^\mu\nu_L) + \text{h.c.}$$

Svjetlana Fajfer and Nejc Koˇsnik Luiz Vale Silva

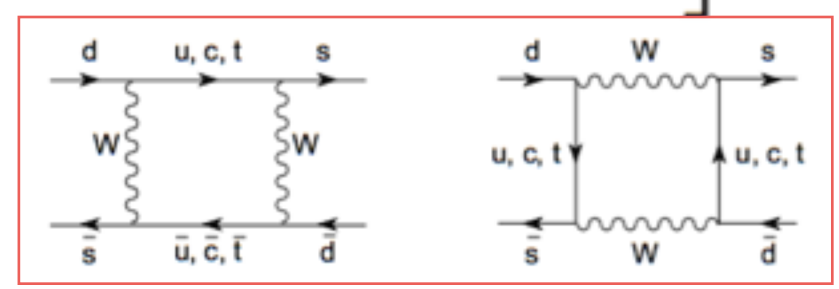
Flavour Problem

- the SM Yukawa structure

$$\mathcal{L}_{SM}^{Y} = \bar{Q} Y_D D H + \bar{Q} Y_U U H_c + \bar{L} Y_E E H + \text{h.c.}$$

FCNC

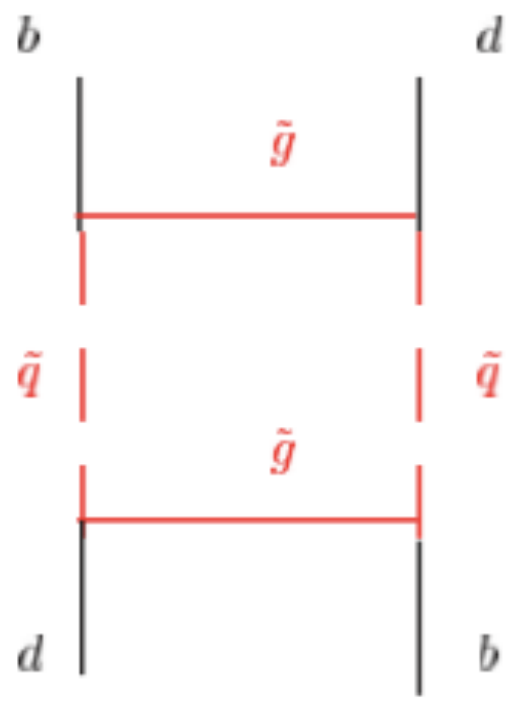
$$\mathcal{H}_{\Delta F=2}^{SM} \sim \frac{G_F^2 M_W^2}{16\pi^2} \left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right] + \text{charm}$$



- Supersymmetry must be broken

$$-\mathcal{L}_{soft} = \tilde{Q}^\dagger m_Q^2 \tilde{Q} + \tilde{L}^\dagger m_L^2 \tilde{L} + \tilde{\bar{U}} a_u \tilde{Q}\, H_u + \ldots$$

- $m_Q^2, m_L^2, a_u, \ldots$ matrices in flavour space additional (to $Y_{u,d,l}$) non-trivial structures



$$\mathcal{H}^{\tilde{g}}_{\Delta F=2} \sim \frac{\alpha_s^2}{9M^2_{\tilde{Q}}} \left[(\delta_{12}^{LL})^2 \; (\bar{s}_L \gamma_\mu d_L)^2 + \cdots \right]$$

δ_{12}^{LL} departure from identity matrix m^2_Q

Gabrielli Masiero
Silvestrini

$$K - \bar{K} \Longrightarrow \quad \frac{(\delta_{12}^{LL})^2}{M^2_{\tilde{Q}}} \leq \frac{1}{(100\text{TeV})^2} \Longrightarrow \text{Naturalness?}$$

obey some Flavour symmetry so that GIM is realized

$$m^2_Q \sim I$$

$$\mathcal{L}_{\Delta F=2} = \frac{C}{\Lambda^2_{MFV}} \left[\frac{(V^*_{td} m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V^*_{td} m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right]$$

Traditional solution

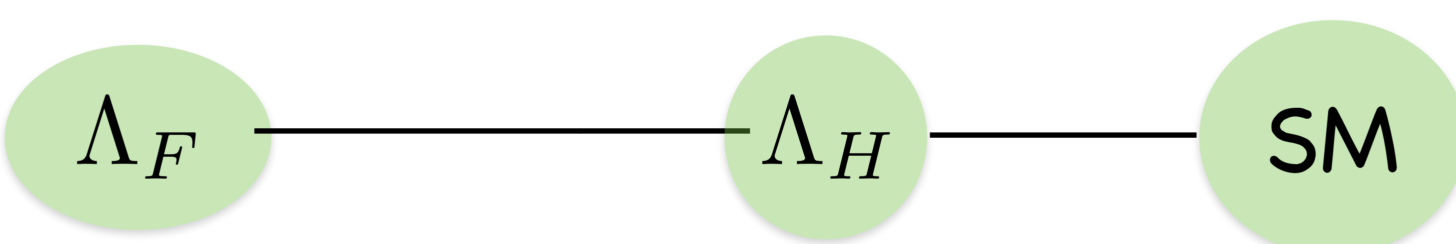
Problem already known since '86 technicolour, (Chivukula Georg

susy (Hall Randall)

extra dimensions (Rattazzi Zafferoni)

G.D.,Giudice,Isidori,Strumia; A. Buras, Gambino,Silvestrini

Scale New Physics, stabilizing EW scale, Λ_H <<scale of the dynamical understanding of Flavor



$$\Lambda_H << \Lambda_F$$

CP violation in $K \to 2\pi$

$$A(K_L \to \pi^+\pi^-) \propto \epsilon + \epsilon'$$

$$A(K_L \to \pi^0\pi^0) \propto \epsilon - 2\epsilon'$$

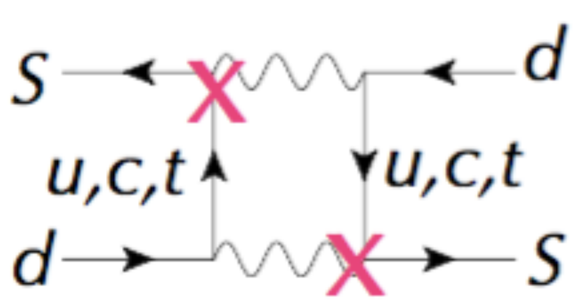
$\epsilon \sim \mathcal{O}(10^{-3})$ Christenson et al 64

$\epsilon' \sim \mathcal{O}(10^{-6})$ CERN NA31, Fermilab KTeV

$H_{\Delta S=2}$

Indirect CP violation

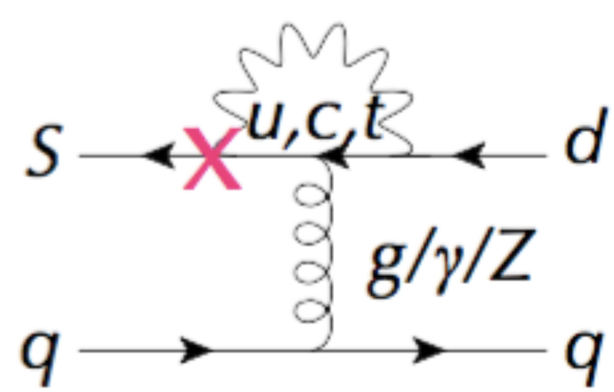
Kaon oscillation



$H_{\Delta S=1}$

Direct CP Violation

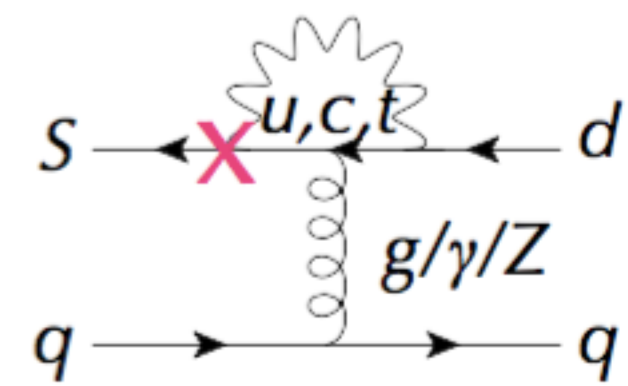
Penguin



$$\frac{\epsilon'_K}{\epsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|_{\exp}} \frac{\omega_{\exp}}{(\mathrm{Re}A_0)_{\exp}} \left(-\mathrm{Im}A_0 + \frac{1}{\omega_{\exp}} \mathrm{Im}A_2 \right) \quad \text{where} \quad \frac{1}{\omega} \equiv \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.46 \text{ (exp.)}$$

gluon penguin Q_6

EW penguin Q_8



<O6> and <O8> have chiral enhancement factor

$$\langle Q_6(\mu)\rangle_0 = -4 \left[\frac{m_K^2}{m_s(\mu) + m_d(\mu)} \right]^2 (F_K - F_\pi) B_6^{(1/2)}$$

$$\langle Q_8(\mu)\rangle_2 = \sqrt{2} \left[\frac{m_K^2}{m_s(\mu) + m_d(\mu)} \right]^2 F_\pi B_8^{(3/2)}.$$

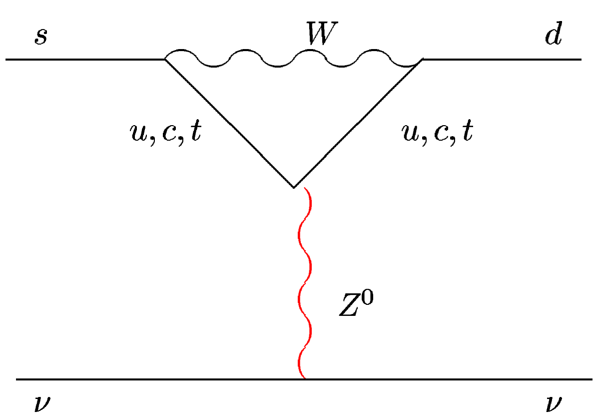
New lattice result 2015

Kei Yamamoto

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

Why we need to the experiments 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 $\underbrace{V-A\otimes V-A}$ 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

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

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

- κ_+ from K_{l3}
- P_c: SD charm quark contribution (30%±2.5% to BR)
  LD $\delta P_{c,u} \sim 4 \pm 2\%$
- $B(K^{\pm}) = (8.82 \pm 0.8 \pm 0.3) \times 10^{-11}$ first error parametric (V_{cb}), second non-pert. QCD
- E949 $B(K^{\pm}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

K_L

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

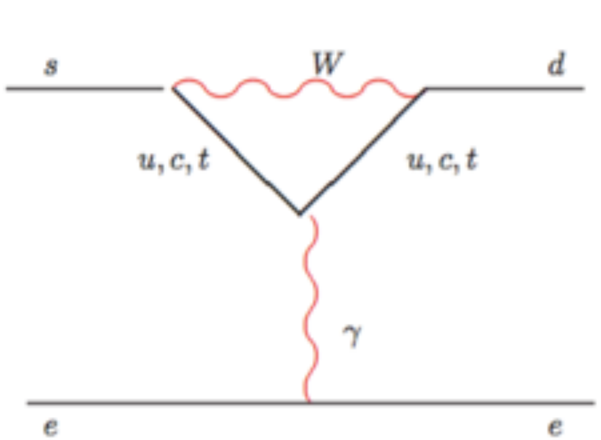
E391a $B(K_L) < 2.6 \times 10^{-8}$ at 90% C.L.

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

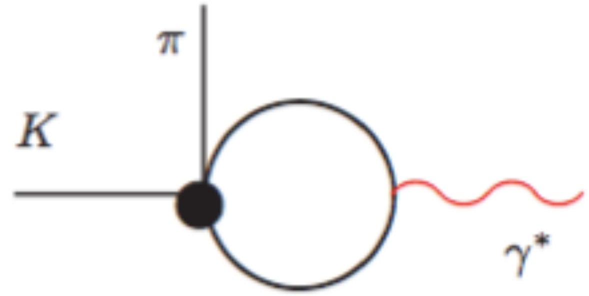
$$B(K_L) \leq \frac{\tau_L}{\tau_+} \times B(K^{\pm})_{\mathrm{E949}} \leq 1.4 \times 10^{-9} \quad \text{at } 90\% C.L.$$

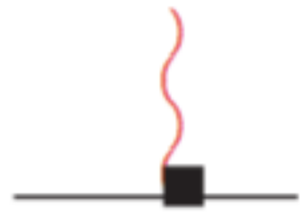
	PDG	Prospects
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	(LD)$(5.0 \pm 1.5) \cdot 10^{-12}$ NP $< 10^{-11}$
$K_L \to \mu\mu$	$(6.84 \pm 0.11) \times 10^{-9}$	difficult : SD << LD
$K_S \to \mu\mu\mu\mu$	$-$	SM LD $\sim 2 \times 10^{-14}$
$K_S \to ee\mu\mu$	$-$	$\sim 10^{-11}$
$K_S \to eeee$	$-$	$\sim 10^{-10}$
$K_S \to \pi^+\pi^-\mu^+\mu^-$	$-$	SM LD $\sim 10^{-14}$

$K^+ \to \pi^+ e^+ e^-$ $K_S \to \pi^0 e^+ e^-$



Short distance

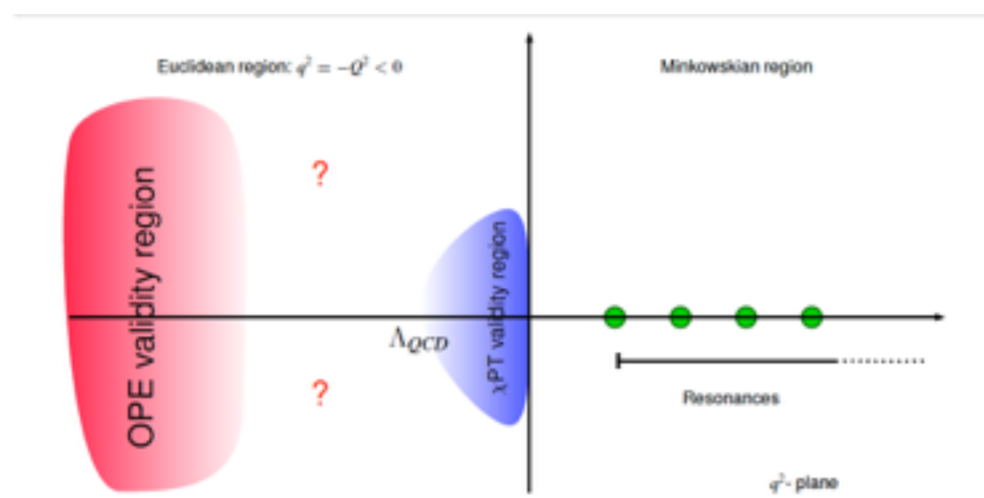




$O(p^4)$ ChPT

electrons and μ's in the final state

constant+ loop Ecker, Pich, de Rafael



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

$K^+ \to \pi^+ e^+ e^-$ $K_S \to \pi^0 e^+ e^-$

- gauge+Lorentz inv. =>1 ff

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

$$W^i = G_F m_K^2 (a_i + b_i z) + W^i_{\pi\pi}(z)$$

$$i = \pm, S$$

$$a_i, b_i \sim O(1), \qquad z = \frac{q^2}{m_K^2}$$

- Observables $\Gamma(K^+ \to \pi^+ e^+ e^-)$, $\Gamma(K^+ \to \pi^+ \mu \bar{\mu})$, slopes
- a_i $O(p^4)$ $a_+ \sim N_{14} - N_{15}$, $a_S \sim 2N_{14} + N_{15}$ Ecker, Pich, de Rafael
- b_i $O(p^6)$ G.D., Ecker, Isidori, Portoles
- $a_+, \; b_+$ in general not related to $a_S, \; b_S$ Recent lattice determinations Christ et al.

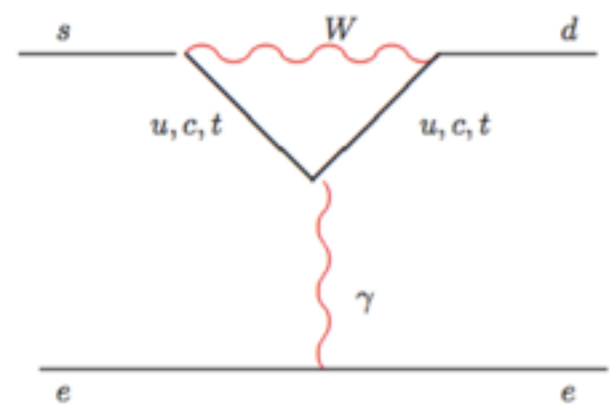
averaging flavour

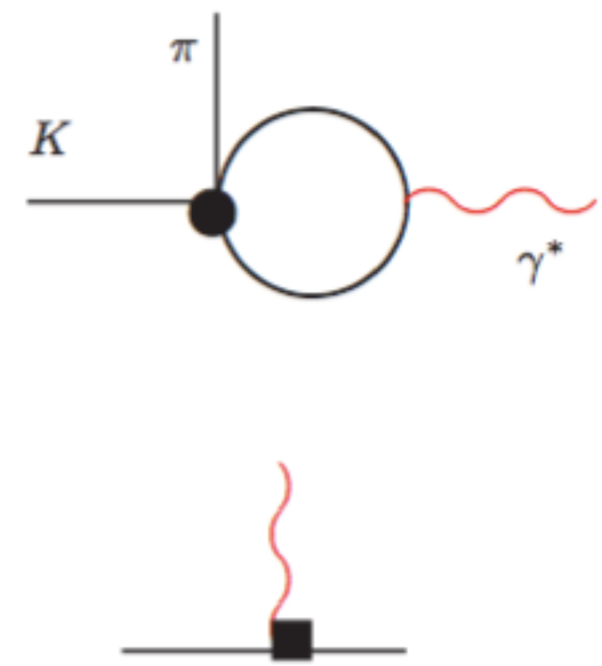
$$a_+^{\rm exp.} = -0.578 \pm 0.016$$
$$b_+^{\rm exp.} = -0.779 \pm 0.066$$

LFUV: Kaons

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

SM





$$W^i = G_F m_K^2 (a_i + b_i z) + W^i_{\pi\pi}(z)$$

$$i = \pm, S$$

$$a_i, b_i \sim O(1), \qquad z = \frac{q^2}{m_K^2}$$

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

LFUV: Kaons

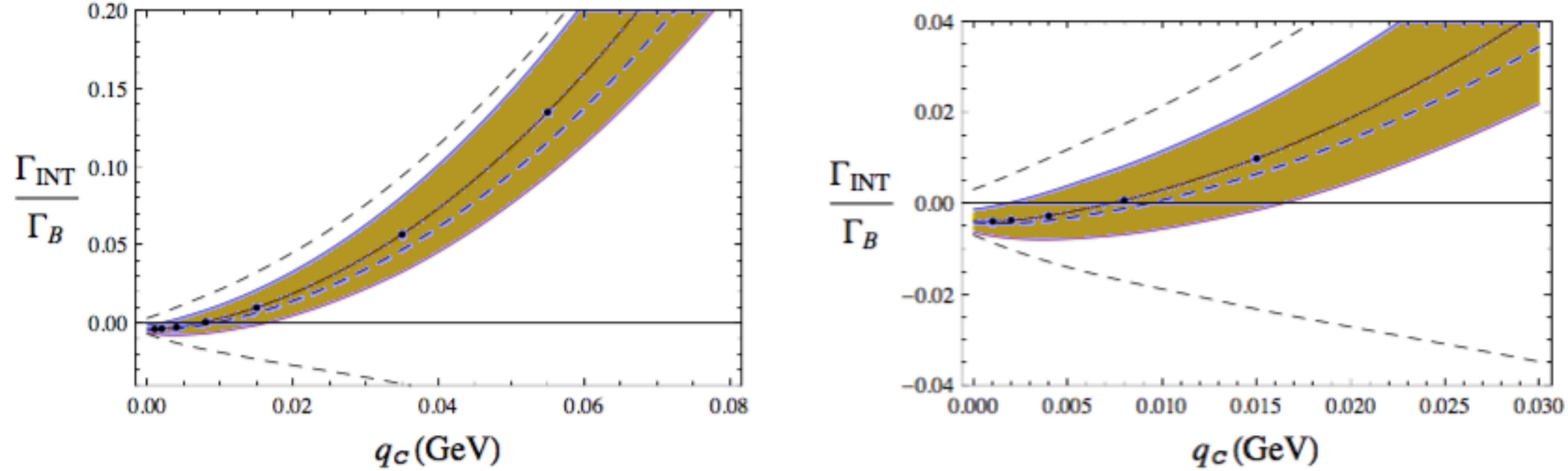
Channel	a_+	b_+	Reference
ee	-0.587 ± 0.010	-0.655 ± 0.044	E865
ee	-0.578 ± 0.016	-0.779 ± 0.066	NA48/2
$\mu\mu$	-0.575 ± 0.039	-0.813 ± 0.145	NA48/2

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

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

NA62 PLEASE!!

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



q cut in minimum dilepton

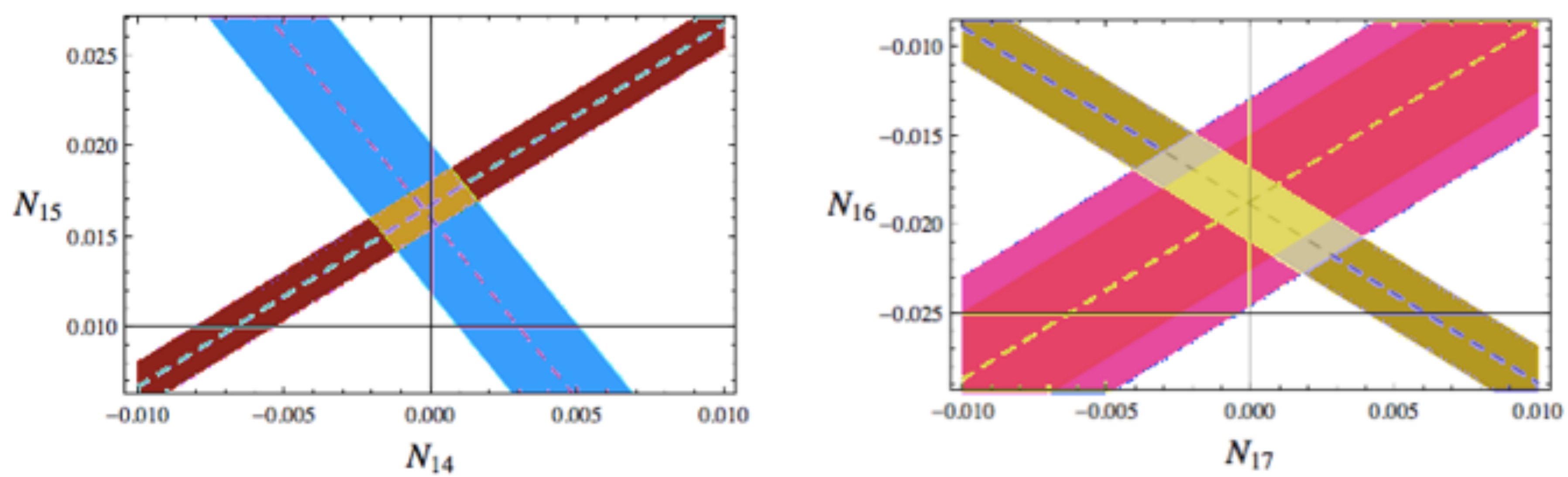


Figure 4: *Left panel: values of* N_{14} *and* N_{15} *as given by* $K^{\pm} \to \pi^{\pm}\gamma^{*}$ *(blue band) and* $K_S \to \pi^0\gamma^*$ *(violet band). Right panel: values for* N_{16} *and* N_{17} *extracted from* $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ *(blue band) and* $K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-$ *(yellow band) measurements. The latter is an educated estimate (see main text).*

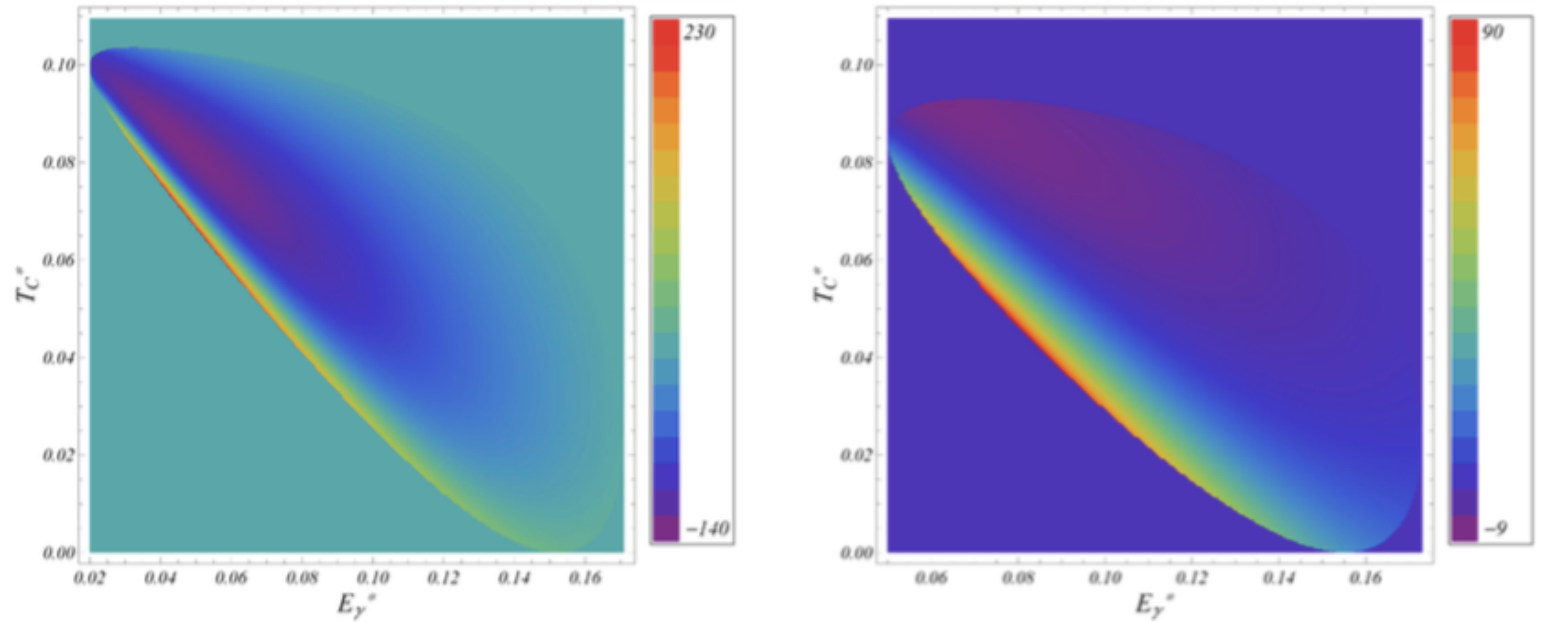


Figure 1: *Dalitz plots for the interference differential decay rate in the* (E_γ, T_c) *plane for* $q = 20$ *MeV (left panel) and* $q = 50$ *MeV (right panel). Numbers are given in units of* 10^{-20} GeV^{-1}*. The contour plot is 'spikier' the lower the q values are, a pattern mostly dictated by the structure of the Bremsstrahlung term.*

$$BR(K_S \to \pi^+\pi^-e^+e^-) = \underbrace{4.74 \cdot 10^{-5}}_{\text{Brems.}} + \underbrace{4.39 \cdot 10^{-8}}_{\text{Int.}} + \underbrace{1.33 \cdot 10^{-10}}_{\text{DE}}$$

q_c (MeV)	$10^8 \times \Gamma_{\mathcal{B}}$	$\left[\frac{\Gamma_{\mathcal{E}}}{\Gamma_{\mathcal{B}}}\right]^{-1}$	$\left[\frac{\Gamma_{\text{INT}}}{\Gamma_{\mathcal{B}}}\right]^{-1}_{(1,1,1)}$	$\left[\frac{\Gamma_{\text{INT}}}{\Gamma_{\mathcal{B}}}\right]^{-1}_{(1,0,1)}$	$\left[\frac{\Gamma_{\text{INT}}}{\Gamma_{\mathcal{B}}}\right]^{-1}_{(1,1,0)}$	$\left[\frac{\Gamma_{\text{INT}}}{\Gamma_{\mathcal{B}}}\right]^{-1}_{(0,1,1)}$
$2m_l$	418.27	1100	-253	-225	-115	216
2	307.96	821	-265	-226	-98	159
4	194.74	529	-363	-264	-78	101
8	109.60	304	1587	-850	-59	58
15	56.12	161	102	156	-43	31
35	15.50	50	18	21	-26	11
55	5.62	22	7	9	-18	5
85	1.37	8	3	4	-13	3
100	0.67	5	2	3	-11	2
120	0.24	3	1.6	2	-10	1.4
140	0.04	2	1.0	1.1	-8	0.9
180	0.003	1	0.7	0.8	-7	0.7

Table 2: *Branching ratios for the Bremsstrahlung and the relative weight of the electric and electric interference terms for different cuts in q, starting at q_{min} (first row) and ending at 180 MeV. To highlight the role of the different counterterms, the last columns show how the interference term changes when they are switched off one at a time.*

QCD at work: Short Distance expansion for weak interaction

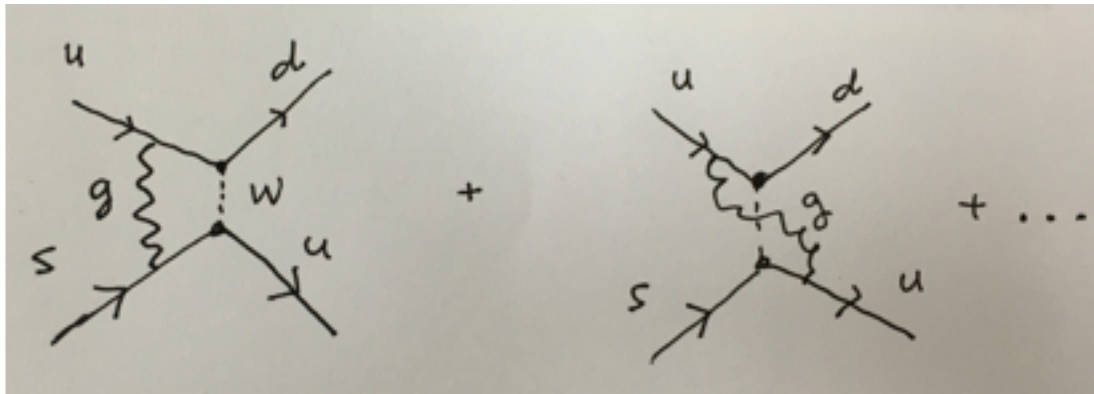
- Fermi lagrangian: description of the ΔS=1 weak lagrangian, in particular the explanation of ΔI =1/2 rule

$$\frac{A(K^+ \to \pi^+\pi^0)}{A(K_S \to \pi^+\pi^-)} \sim \frac{1}{22}$$

- Wilson suggestion (Feynman) , short distance expansion

$$-\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* C_- (\overline{s}_L \gamma^\mu u_L)(\overline{u}_L \gamma_\mu d_L)$$

- Gaillard Lee, Altarelli Maiani: right direction but not fully understood (Long distance?)



QCD at work, theoretical tools

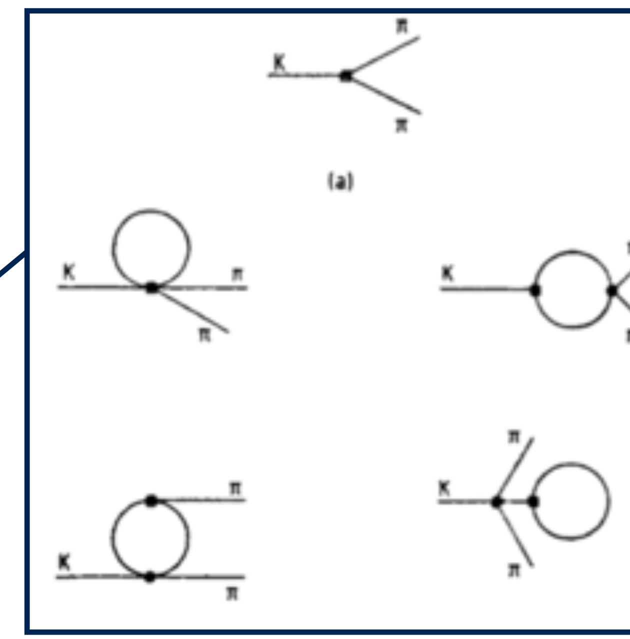
- analytic calculation 't Hooft, large Nc (it explains basic phenomenological facts of QCD, i.e. Zweig's rule) many implications: Skyrme model, VMD, Maldacena
- G. Parisi, `80s lattice: can we predict from QCD the proton mass at 10% level?
- Precise calculation of low energy QCD?

Bardeen Buras Gerard approach to K->ππ

Also evaluated ΔS=2 transitions, epsilon′ (Buras) and $\pi^+ - \pi^0$ mass diff.

Main idea: phys. amplitudes scale independent

Match SD with LD with a precise prescription for CT



CHPT+Large Nc

$$H_{\rm eff} = \sum_i C_i(\mu)\, Q_i(\mu)$$

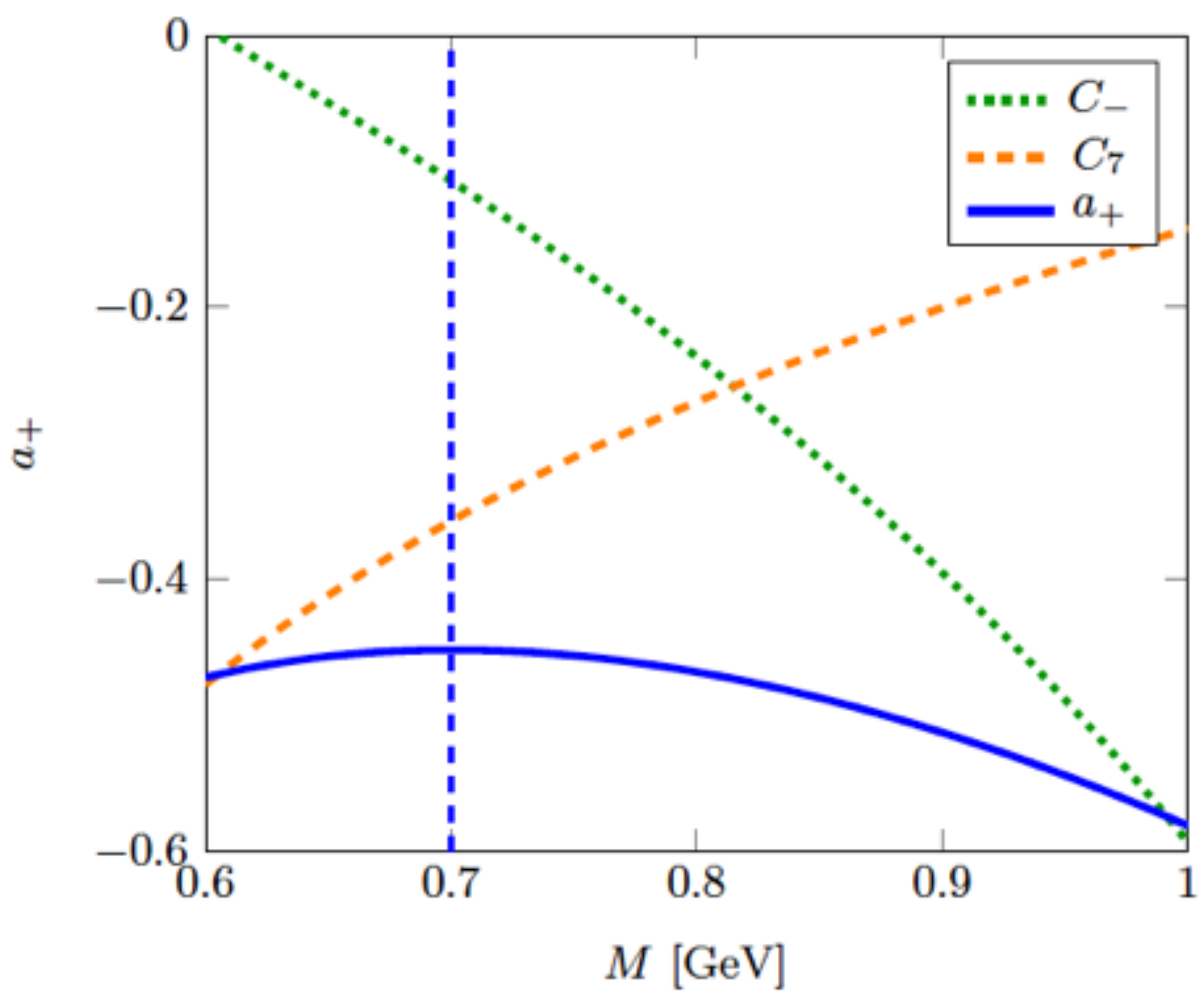
SD

Can we test somewhereelse the Bardeen Buras Gerard (BBG) approach?

Coluccio-Leskow, Estefania, GD, Greynat,David and Nath,Atanu

Matching a la BBG for $K^+ \to \pi^+ e^+ e^-$

Coluccio-Leskow,E. G.D ,Greynat, D and Nath, A



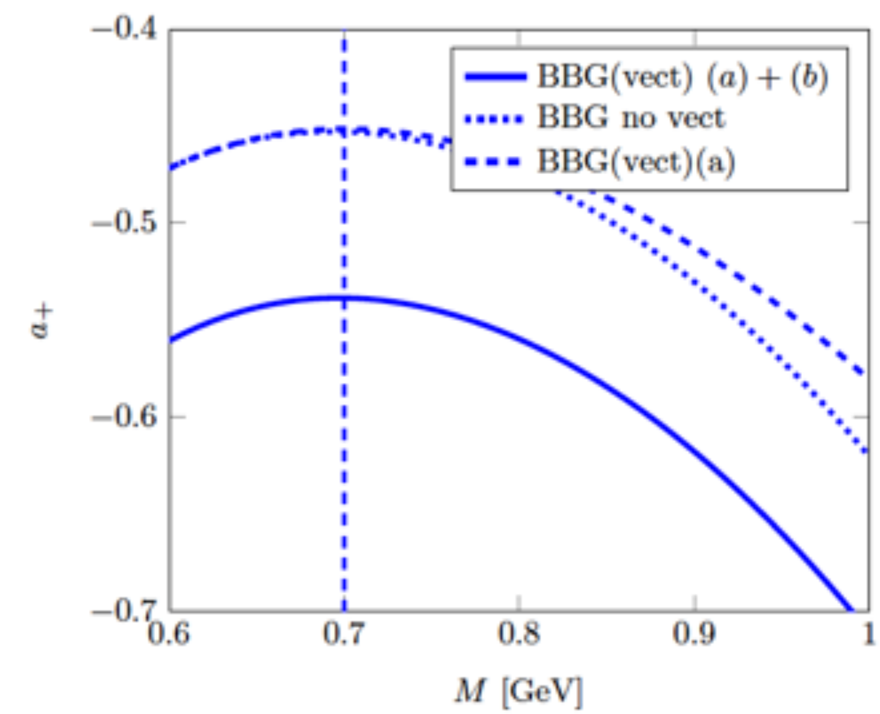
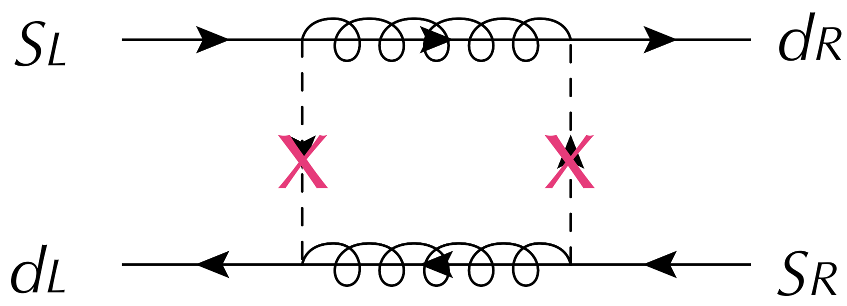


FIG. 5. a_+ as a function of M in the three different frameworks:'BBG no vect.' where vectors are not included, 'BBG(vect)(a)' represents the contribution coming only from diagrams (a) in Fig. 4 and 'BBG(vect) $(a) + (b)$' is the case where both (a) and (b) diagrams were included. The vertical line indicates the value $M = 0.7$ GeV.

Main Constraint: ϵ_K (ΔS=2, ID-CPV) cont.

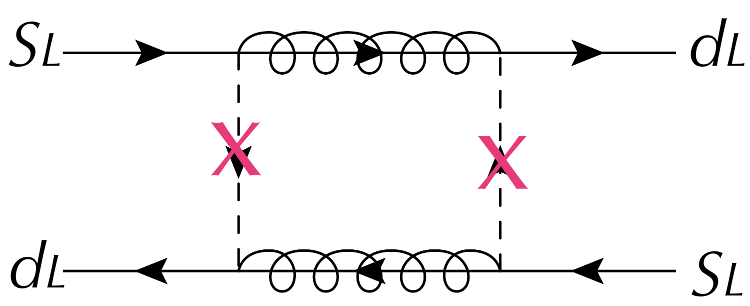
- The leading contribution is given by $\overline{d_L} s_L \overline{d_R} s_R$

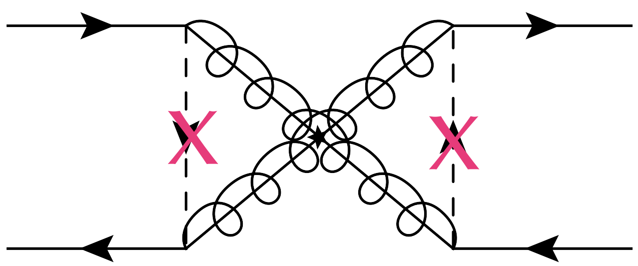


$\propto \left(\frac{m_K}{m_s + m_d} \right)^2$

this contribution is suppressed when $\Delta_{\bar{D},12} \simeq 0$

- The next contribution is given by $\overline{d_L} s_L \overline{d_L} s_L$





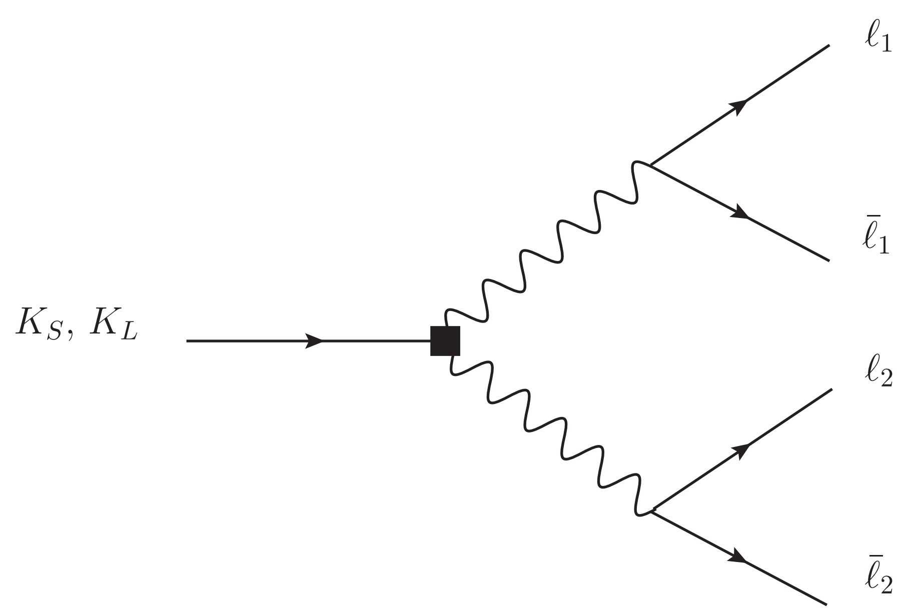
Crossed diagram gives **relatively negative** contributions

$m_{\tilde{g}} \simeq 1.5 m_{\tilde{q}}$: these contributions almost cancel out [Crivellin, Davidkov '10]

$m_{\tilde{g}} \gtrsim 1.5\ m_{\tilde{q}}$: suppressed by heavy gluing mass

Other interesting channels

$$K_S \to \mu\mu\mu\mu \quad - \quad \text{SM LD} \;\sim 2\times 10^{-14}$$
$$K_S \to ee\mu\mu \quad - \quad \sim 10^{-11}$$
$$K_S \to eeee \quad - \quad \sim 10^{-10}$$



GD,Greynat, Vulvert