UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II - DIPARTIMENTO DI FISICA "ETTORE PANCINI"

INFN NAPOLI

RFK 2019 2nd Forum on rare Kaon decays

29-31 May 2019

Opening

Giancarlo D'Ambrosio

INFN Sezione di Napoli

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

Rare n Strange 2017: strange physics at LHCb
GD, Lewis Tunstall, Diego Martinez Santos,Veronika Chobanova, Xabier Cid Vidal, Francesco Dettori, Marc-Olivier Bettler

Closing in on the radiative weak chiral couplings
Luigi Cappiello, Oscar Cata, Giancarlo D'Ambrosio.
arXiv:1712.10270,,EPJC

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

Flavour issues in warped custodial models: B anomalies and rare K decays
GD, Abhishek M. Iyer. Dec 21, 2017. 22 pp.
arXiv:1712.08122

Collaboration with Teppei Kitahara arXiv: 1707.06999 PRL

Collaboration with M.Knecht ,L. E. Greynat,D.

Edinburgh 2018

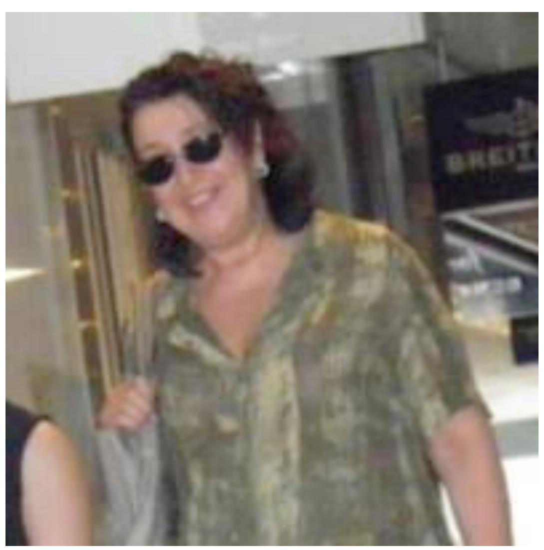
Flavour Changing Neutral Current (FCNC) decays are extremely rare processes in particle physics which are forbidden at the classical level in the Standard Model. Therefore, they constitute attractive channels to try to observe new physics beyond the Standard Model. A particular family of such decays are the kaon decays where the final state is composed by a pion plus a lepton or neutrino pair. It is crucial that both theorists and experimentalists join forces to try to provide the most precise test possible of the Standard Model though rare decays.

The aim of this workshop is to bring together both communities to exchange ideas and shape future research activities on rare kaon decays. All the afternoons of the workshop are focused on thematic discussions, aiming at creating fruitful collaborations between the two communities. We wish to make this event a recurrent one, determining the frequency and location of future editions will be discussed during this first meeting.

The experimental research on rare kaon decays will be led by the ambitious NA62 experiment at CERN for the years to come (NA62 will take data until at least 2023). As this experiment started taking data last summer, it is a particularly important moment for theory and experiment to connect and understand how to maximise our chances to discover new physics through this program. On the other hand, the lattice QCD group at the Higgs Centre is working on starting this year the first physical simulations of rare kaon decays. Lattice calculations open the way to predict unknown Standard Model amplitudes which are dominated by non-perturbative hadronic phenomena. These calculations are more complex than most lattice computations and will only be possible thanks to the £4.5M DiRAC Extreme Scaling supercomputer that will be acquired by the University of Edinburgh this year.

LFUV B-decays/K-decays interplay
Analytic vs Lattice
experimental limits vs TH wishful th

Patrizia Cenci
Director



RFK Napoli

Paolo Massarotti

Marco Mirra

Fabio Ambrosino

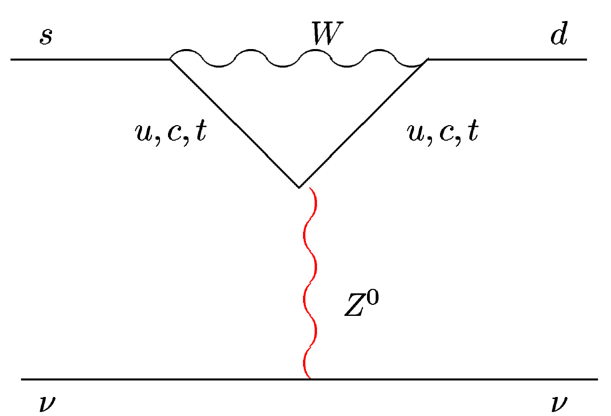
Outline

- $K\to\pi\nu\nu$
- K-anomalies, NP in ε'
- $K_{S,L}\to\mu\mu$
- QCD, weak counterterms

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

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

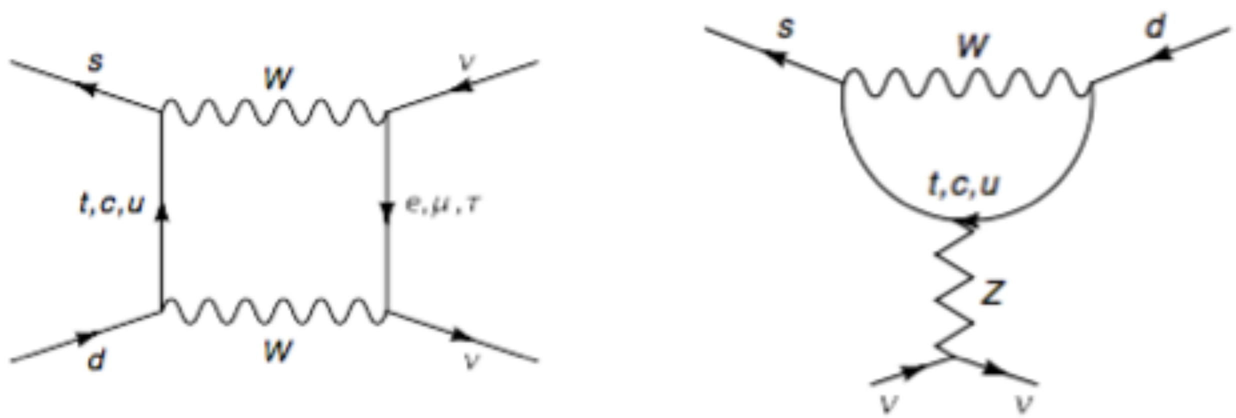
$$\Downarrow$$

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

SM

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

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



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

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

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

$\kappa_+ \downarrow K_{l3}$

$30\% \pm 2.5\%$

LD

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

V_{cb} nonpert QCD

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

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

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

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

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

UV sensitivity

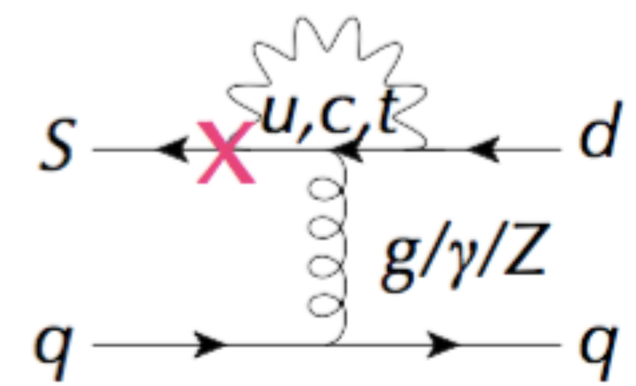
$$\mathcal{L} \sim \frac{1 - 0.3\ i}{(180\ \text{TeV})^2} (\overline{s}_L \gamma_\mu d_L \overline{\nu}_L \gamma^\mu \nu_L)$$

News: anomalies in Kaons?

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

gluon penguin Q_6

EW penguin Q_8



<O6> and <O8> have chiral enhancement factor

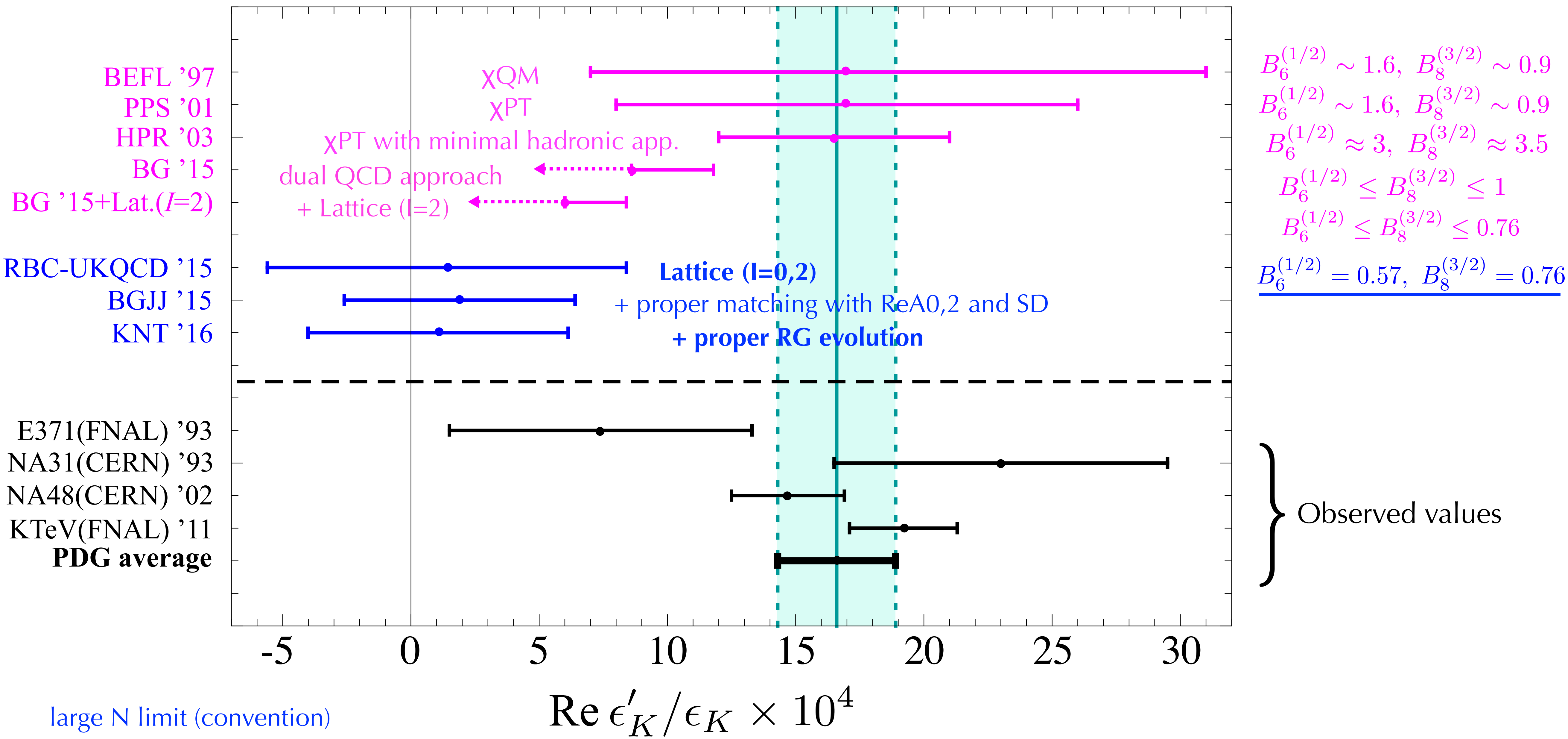
Kei Yamamoto

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

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

New lattice result 2015

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

Kei Yamamoto, FPCP2017

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

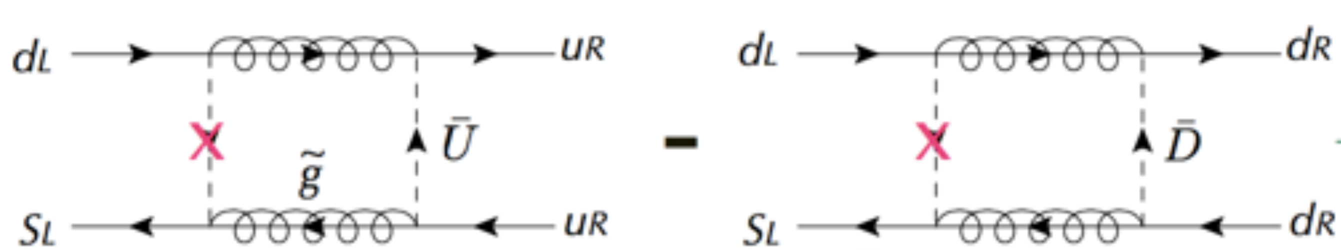
Kitahara,Nierste, Tremper PRL 16

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 ${\rm Im}A_2$

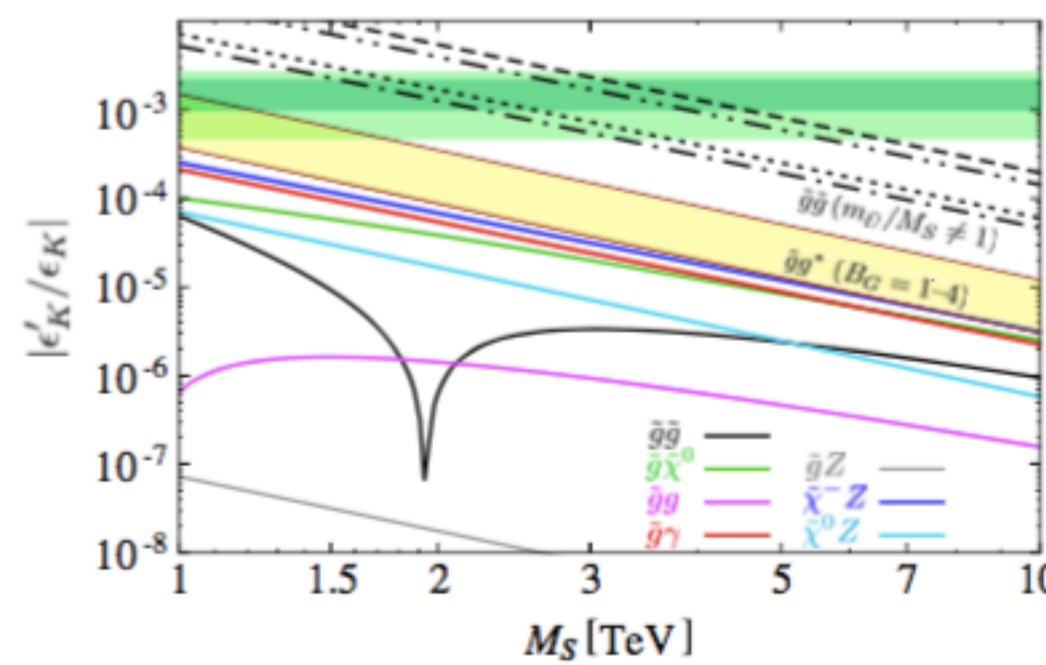
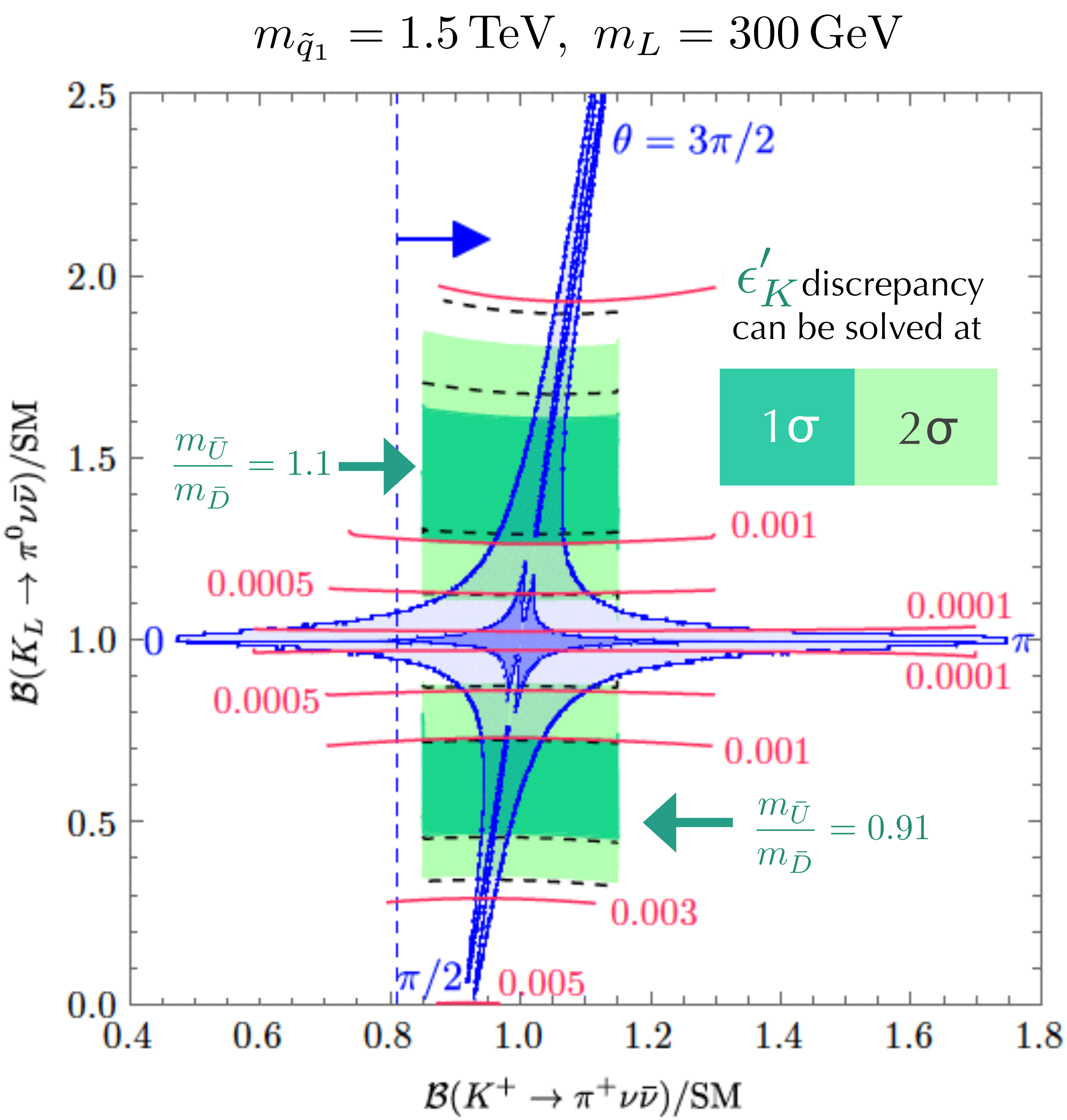


FIG. 3. Individual supersymmetric contributions to $|\epsilon'_K/\epsilon_K|$

B(K→πνν)

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



- (dark blue) 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
- (light blue) 1-10 % mass shift of the gluino mass is possible

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})/\text{SM} \lesssim 2\,(1.2)$$
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})/\text{SM} \lesssim 1.4\,(1.1)$$

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

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

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

$$\downarrow$$

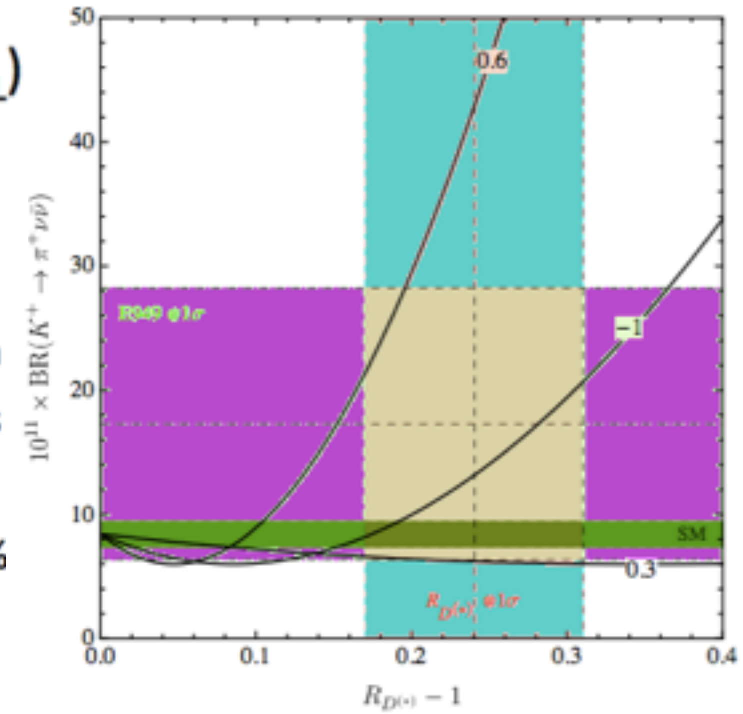
$$\text{sgn}\left[\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) - \mathcal{B}^{\text{SM}}(K_L \to \pi^0 \nu\bar{\nu})\right]$$

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})

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

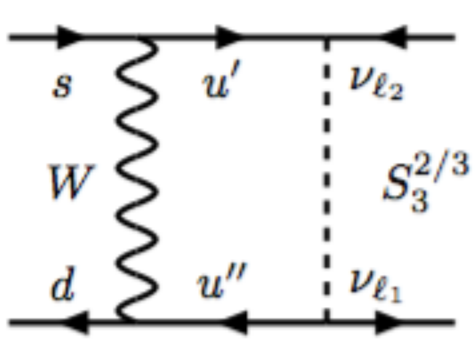


The interference of NP (weak interaction triplets) with the SM amplitude is always destructive.

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

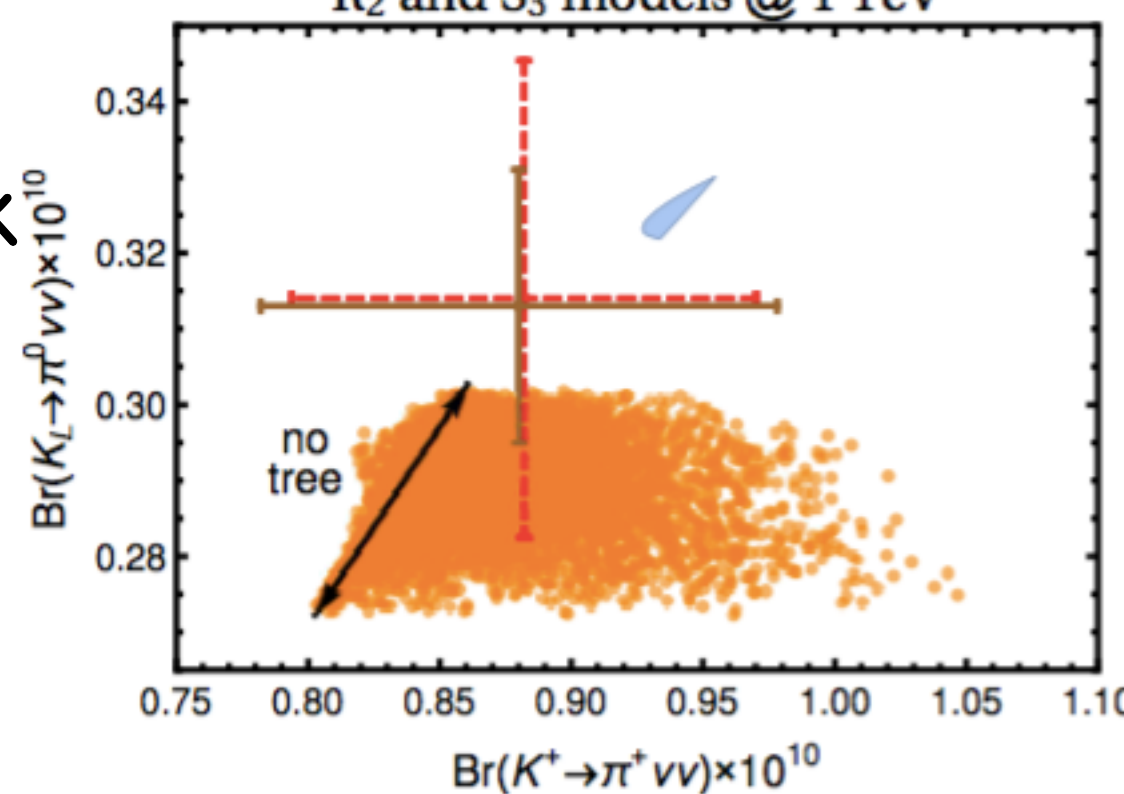
S. Fajfer N. Koˇsnik, L. Vale Silva

Scalar/triplet leptoquark

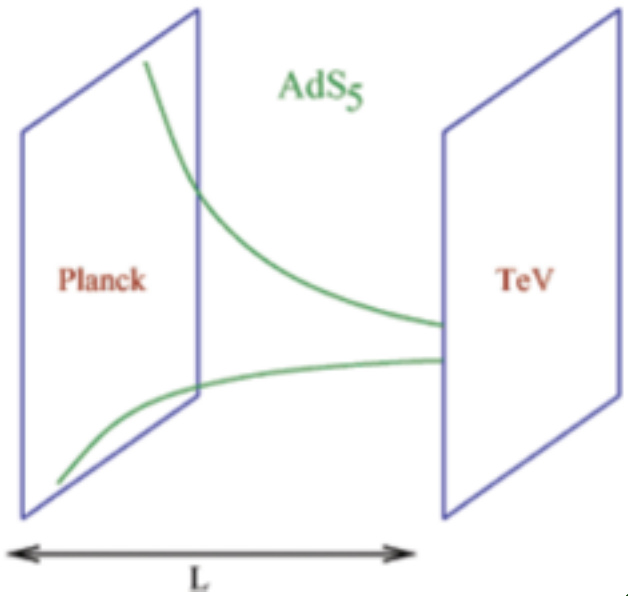


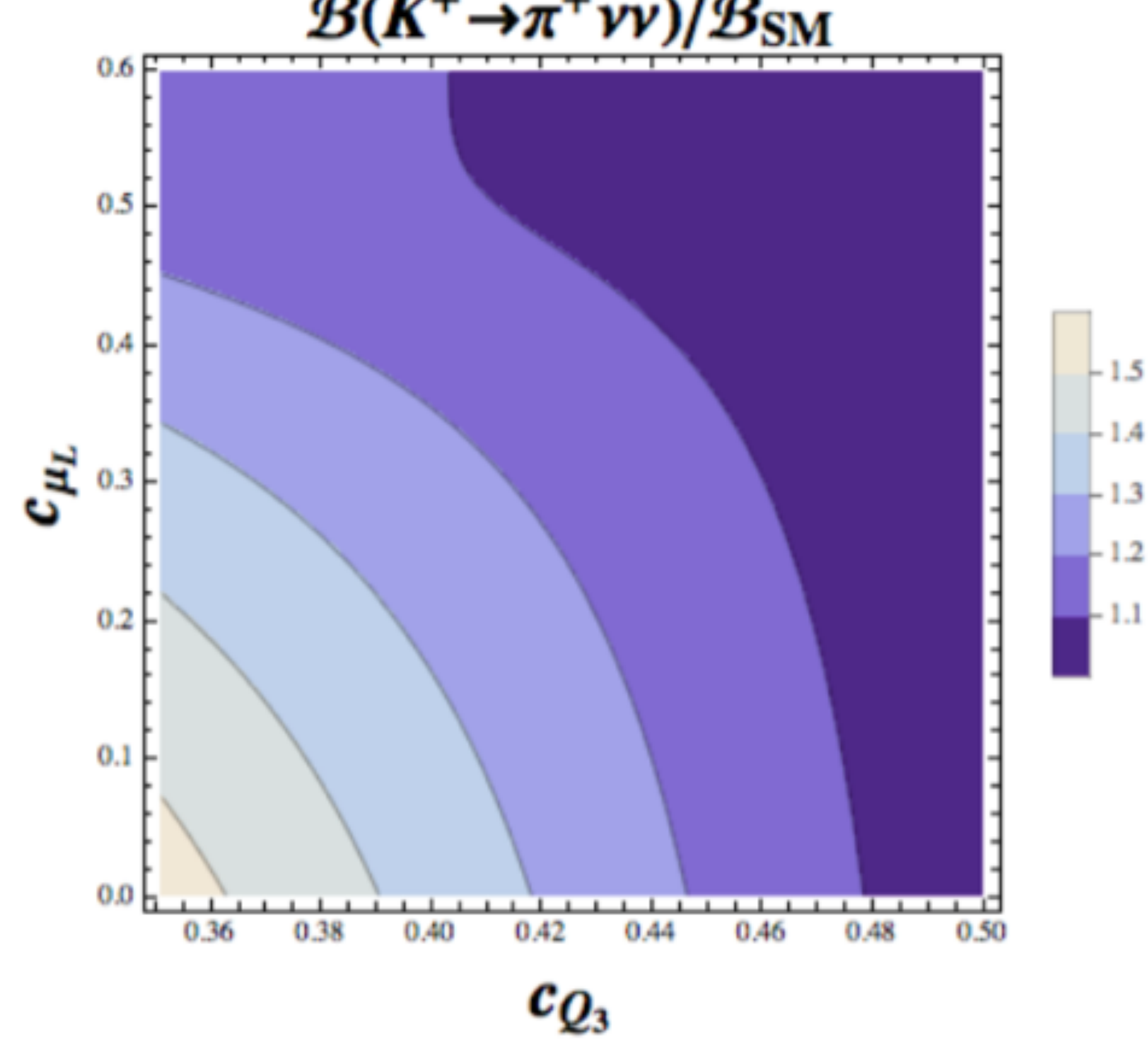
(a) *Box diagram (Box).*

R$_2$ and S$_3$ models @ 1 TeV



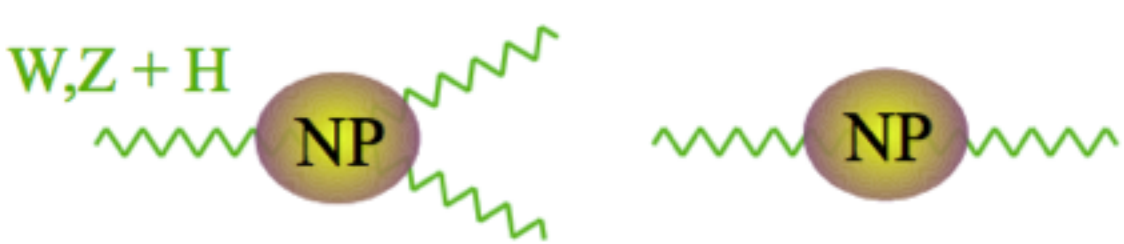
EW vs flavor scale

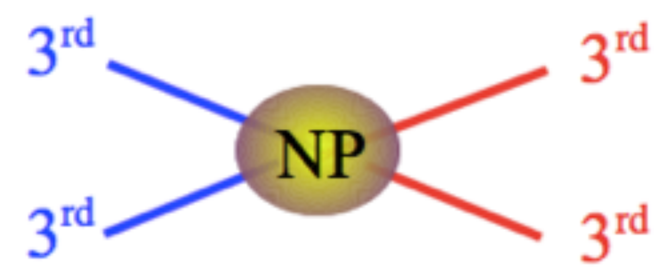




GD,Iyer

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





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

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

Javier Fuentes-Martín

M. Bordone, C. Cornella and **G. Isidori**

Further NA62 K Physics Program

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h\rightarrow\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

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

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

$K_L \to \mu\mu$

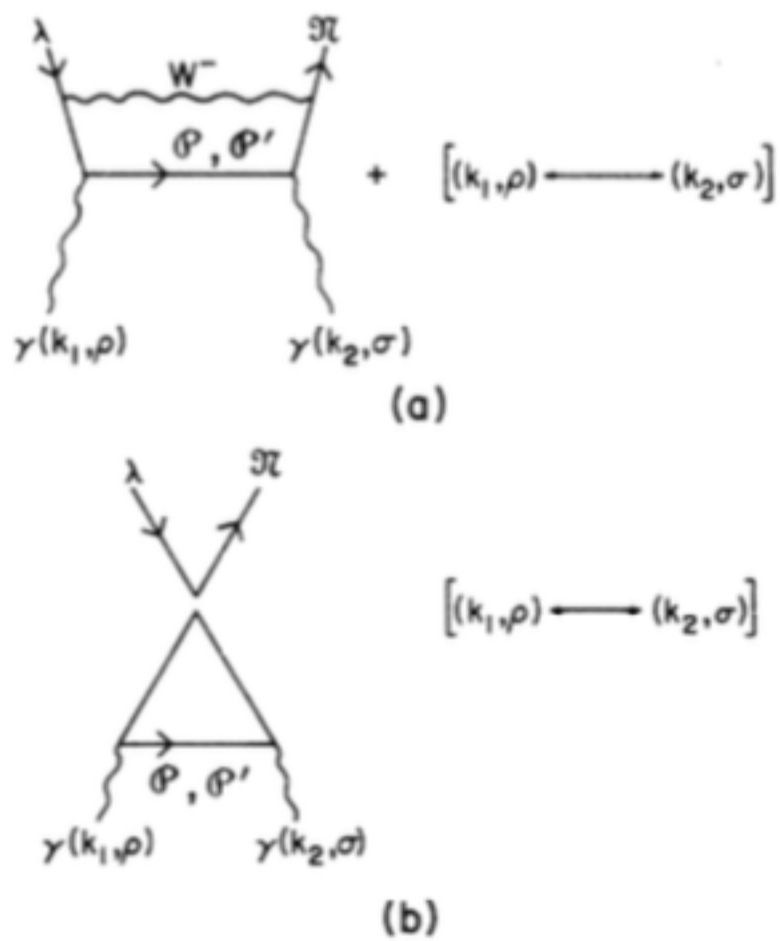


FIG. 7. Leading contributions to $\lambda + \bar{\mathfrak{N}} \to \gamma + \gamma$. To leading order in M_W^{-2}, the diagrams in (a) reduce to those of (b).

Gaillard Lee

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

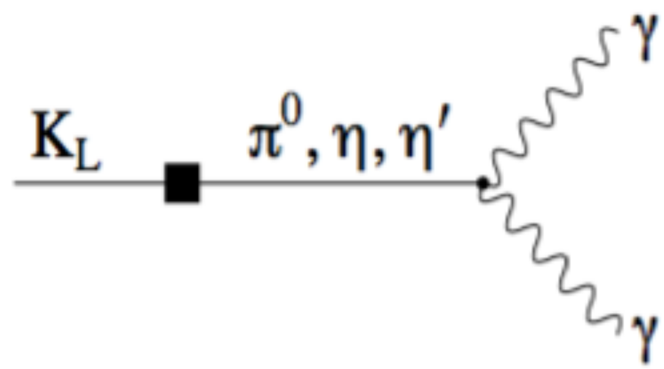
VALUE (10^{-6})	EVTS	DOCUMENT ID		TECN	CO
3.48 ± 0.05	**OUR AVERAGE**				
3.474 ±0.057	6210	AMBROSE	2000	B871	
3.87 ±0.30	179	[1] AKAGI	1995	SPEC	
3.38 ±0.17	707	HEINSON	1995	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	1991B	SPEC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

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

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

Dispersive calculation: Re A, Im A

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

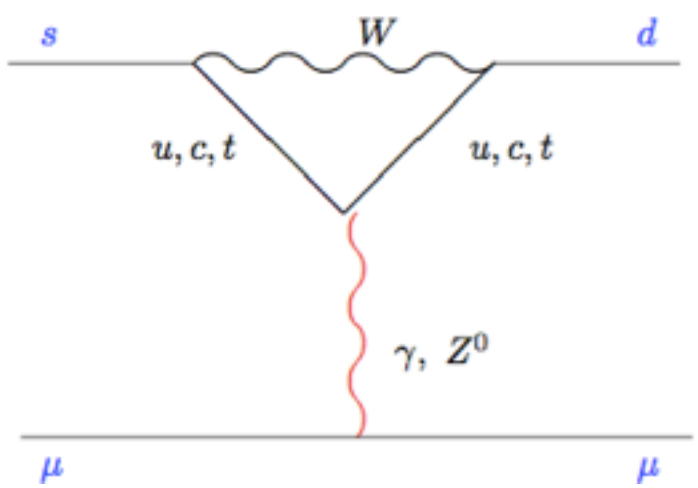


$$A(K_L \to 2\gamma_\perp)_{O(p^4)} = A(K_L \to \pi^0 \to 2\gamma_\perp) + A(K_L \to \eta_8 \to 2\gamma_\perp)$$

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

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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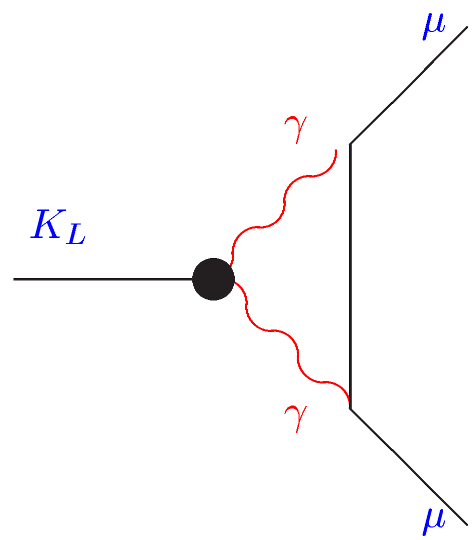


$$\frac{\Gamma(K_L \to \mu\bar{\mu})}{\Gamma(K_L \to \gamma\gamma)} \sim \quad |ReA|^2 + |ImA|^2$$

Absorptive calculation model independent

$$27.14$$

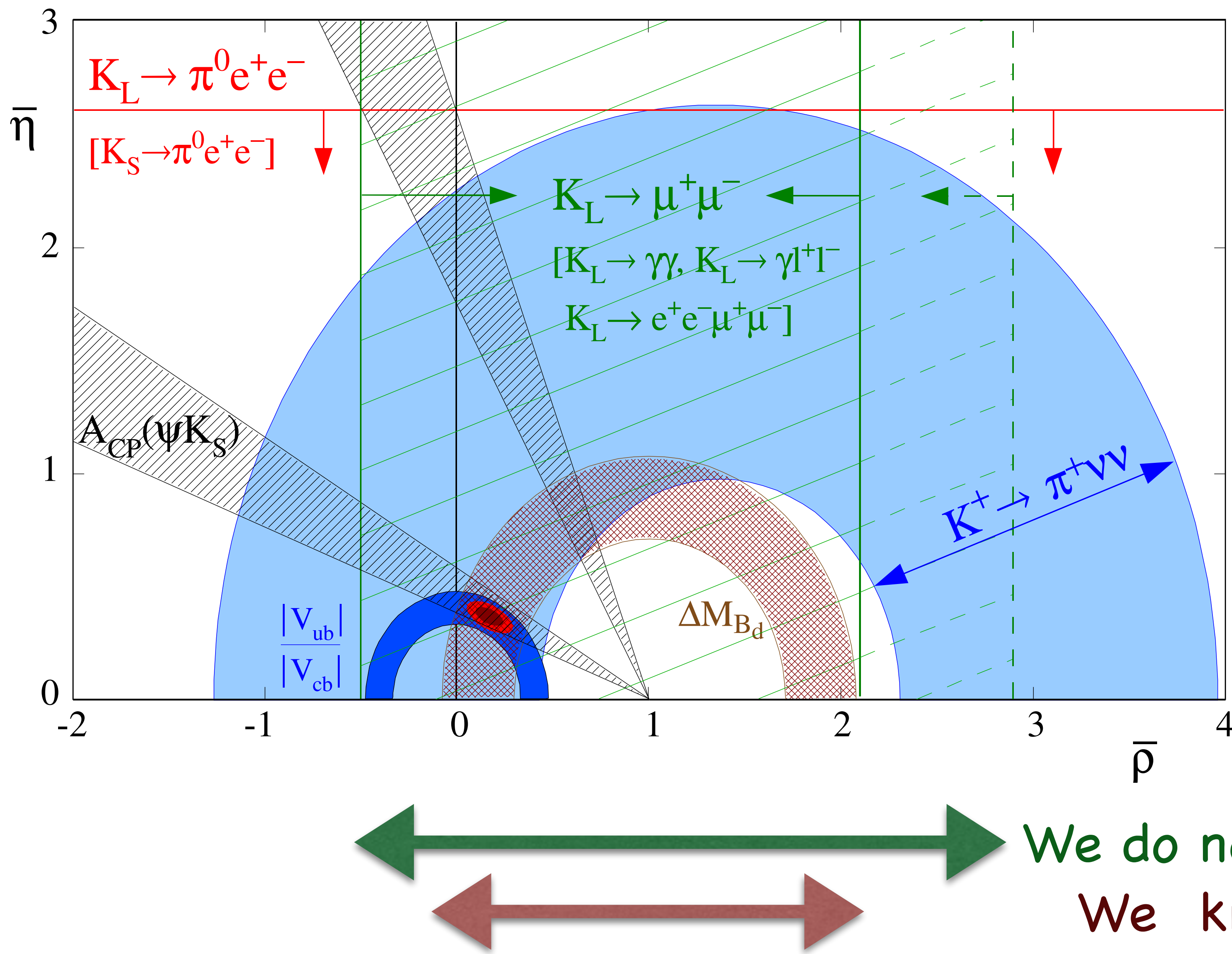
Subtracting from expt. the Absorptive contribution

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

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

Isidori Unterdorfer

K_L->$\mu\mu$: our sign ignorance



We do not know the sign

We know the sign

$K_S \to \mu\mu$

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 $\lambda + \mathfrak{N} \to l + \bar{l}$ 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 $m_{\varphi}/m_{\varphi'} \ll 1$, where m_{φ} is the mass of the proton quark and $m_{\varphi'}$ the mass of the charmed quark, and $m_{\varphi'} < 5$ 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

Run1 data (3 fb^{-1})

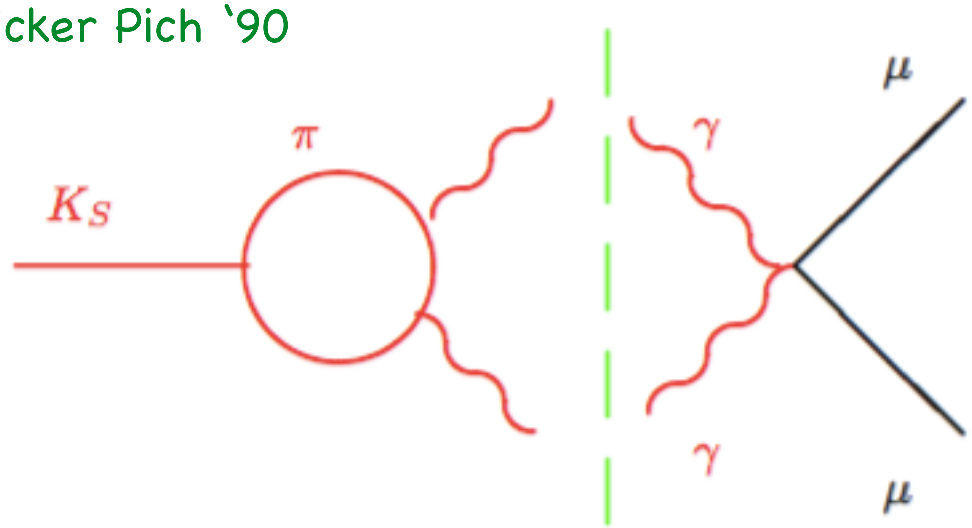
$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$
90%, 95% CL
factor 11 improvement

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. • • •					
$< 0.032 \times 10^4$	90		GJESDAL	1973	ASPK
$< 0.7 \times 10^4$	90		HYAMS	1969B	OSPK

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

$K_S \to \mu\mu$

Ecker Pich '90



No CP conserving Short Distance due to Furry Theorem

Gaillard Lee

LD 5×10^{-12} 30% TH err

Short Distance

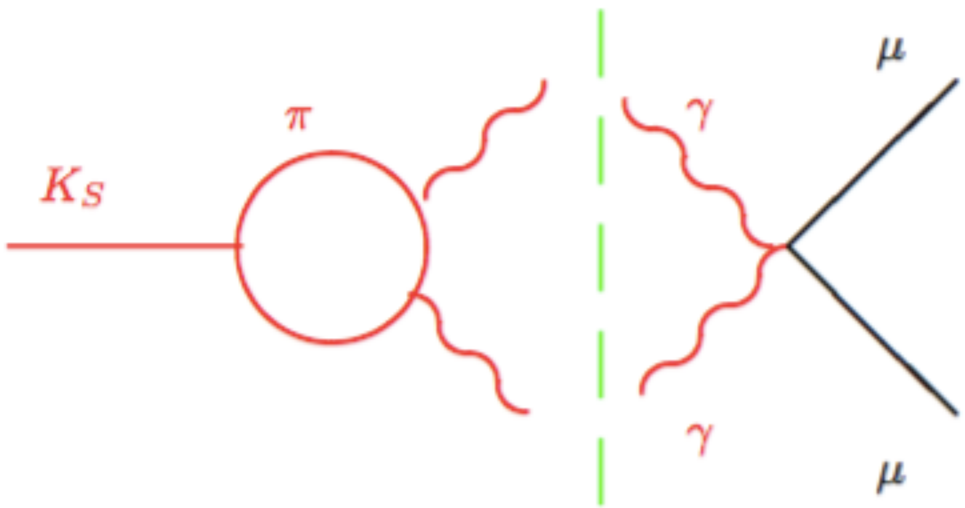
SM $10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$

NP few 10^{-11} allowed

LHCB

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

$K_S \to \mu\mu$: 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

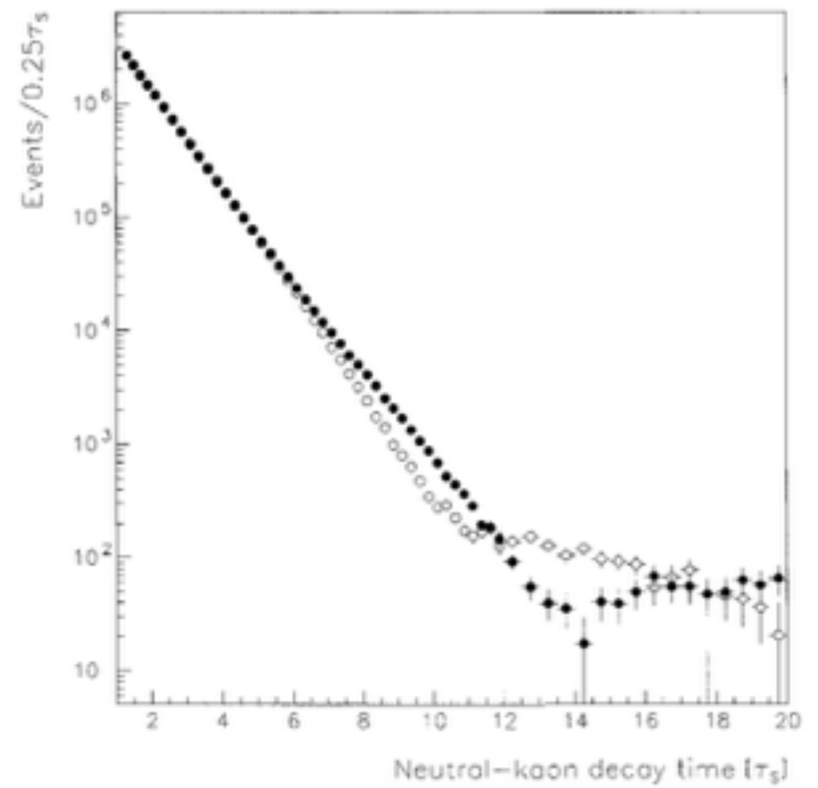
$$K_S \to \gamma\mu\mu$$
$$K_S \to \mu\mu\mu\mu$$
$$K_S \to ee\mu\mu$$
$$K_S \to \gamma\gamma$$

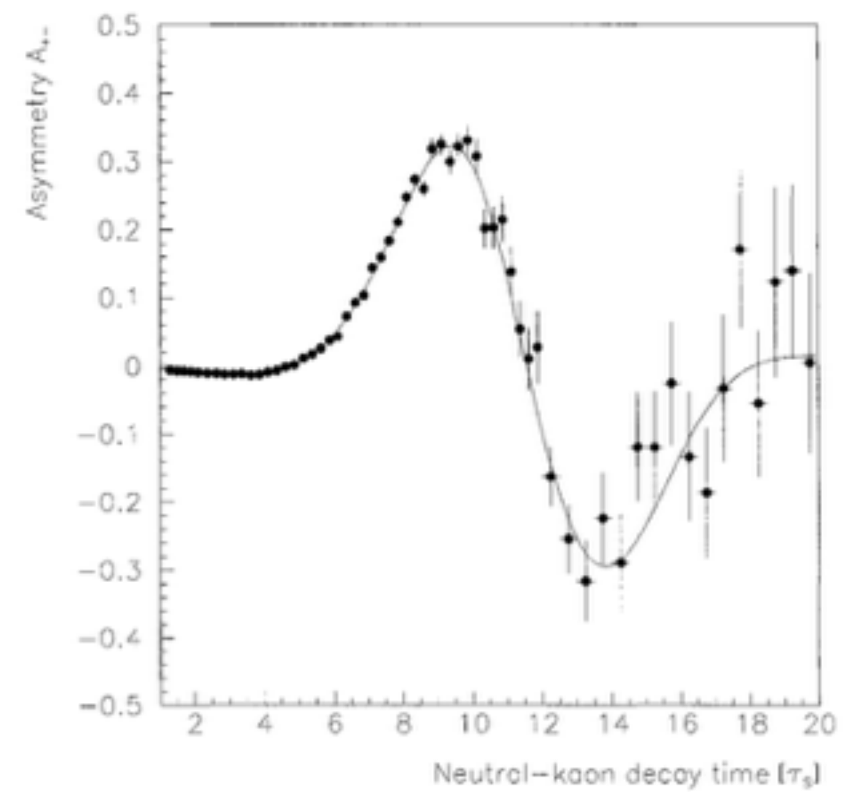
{

CPLEAR Flavor tagging

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

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





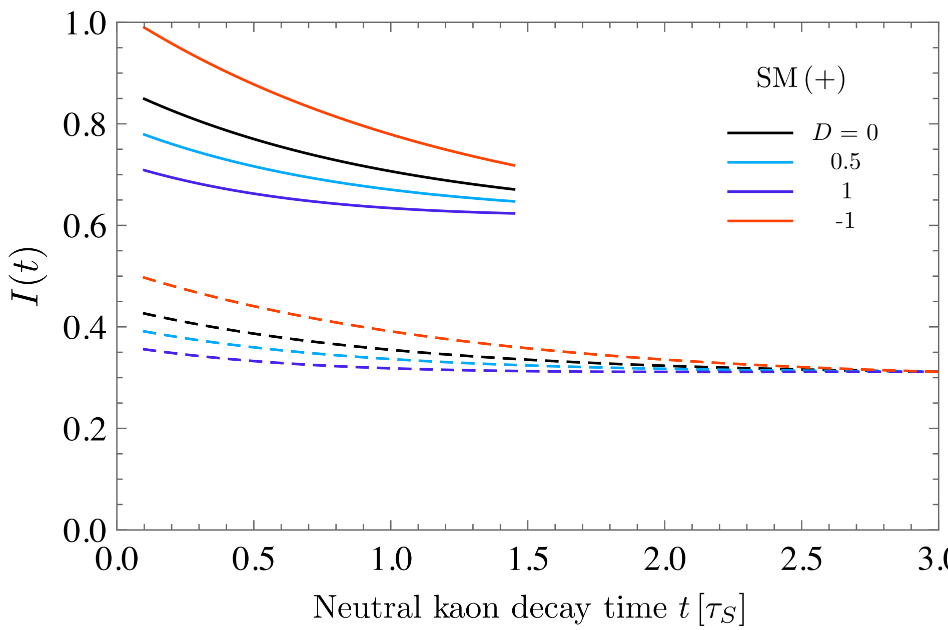
}

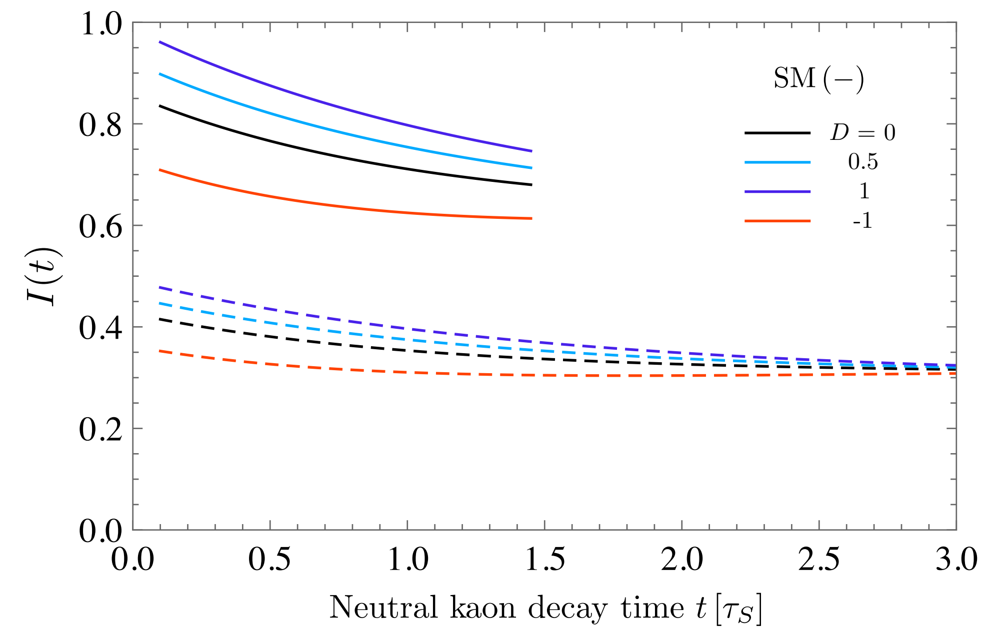
Can we study $K^0(t)$?

GD , Kitahara
1707.06999 PRL

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

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





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

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

- Short distance interfering with Large CP conserving LD contribution !

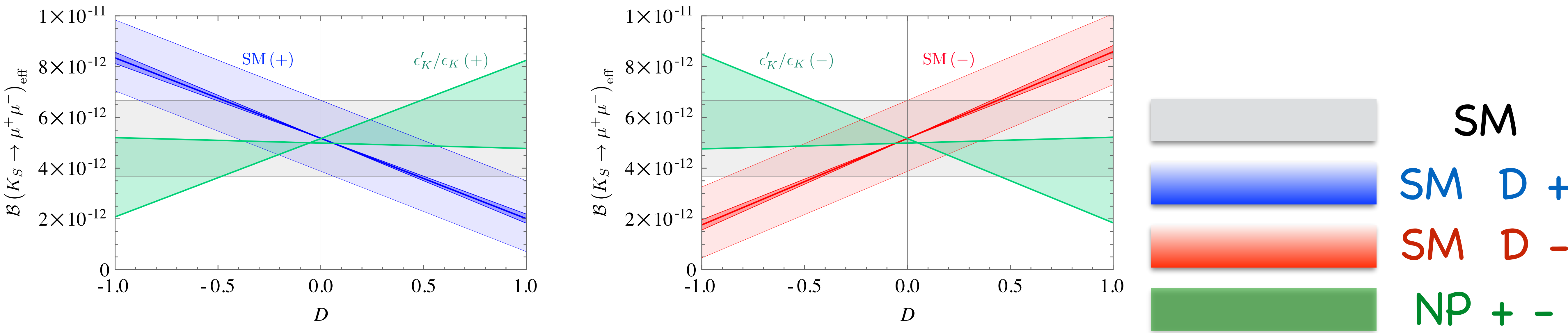
- We may be able to study the time evolution of K^0 by tracking the associated particles (K^-)

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

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

Short distance window

GD , Kitahara
1707.06999 PRL

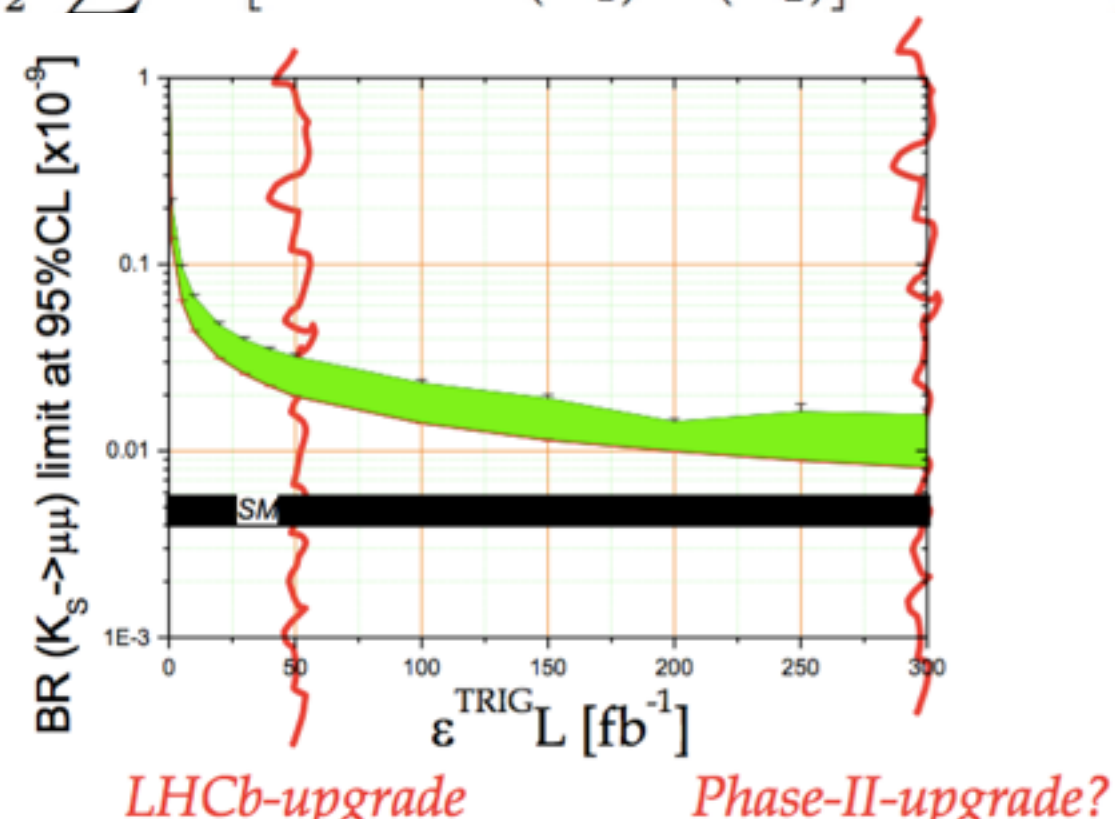


modified Z-coupling model. ϵ'_K/ϵ

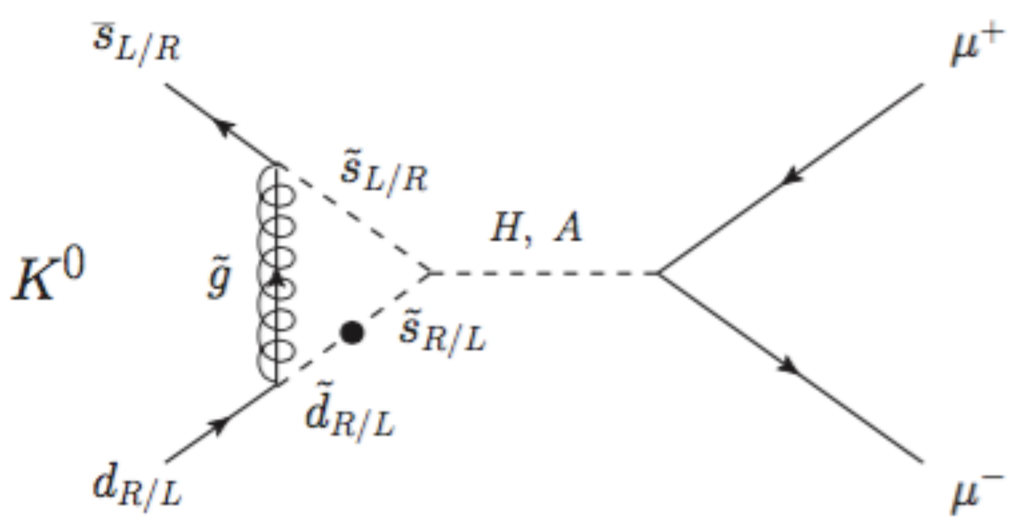
$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm eff}$$

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

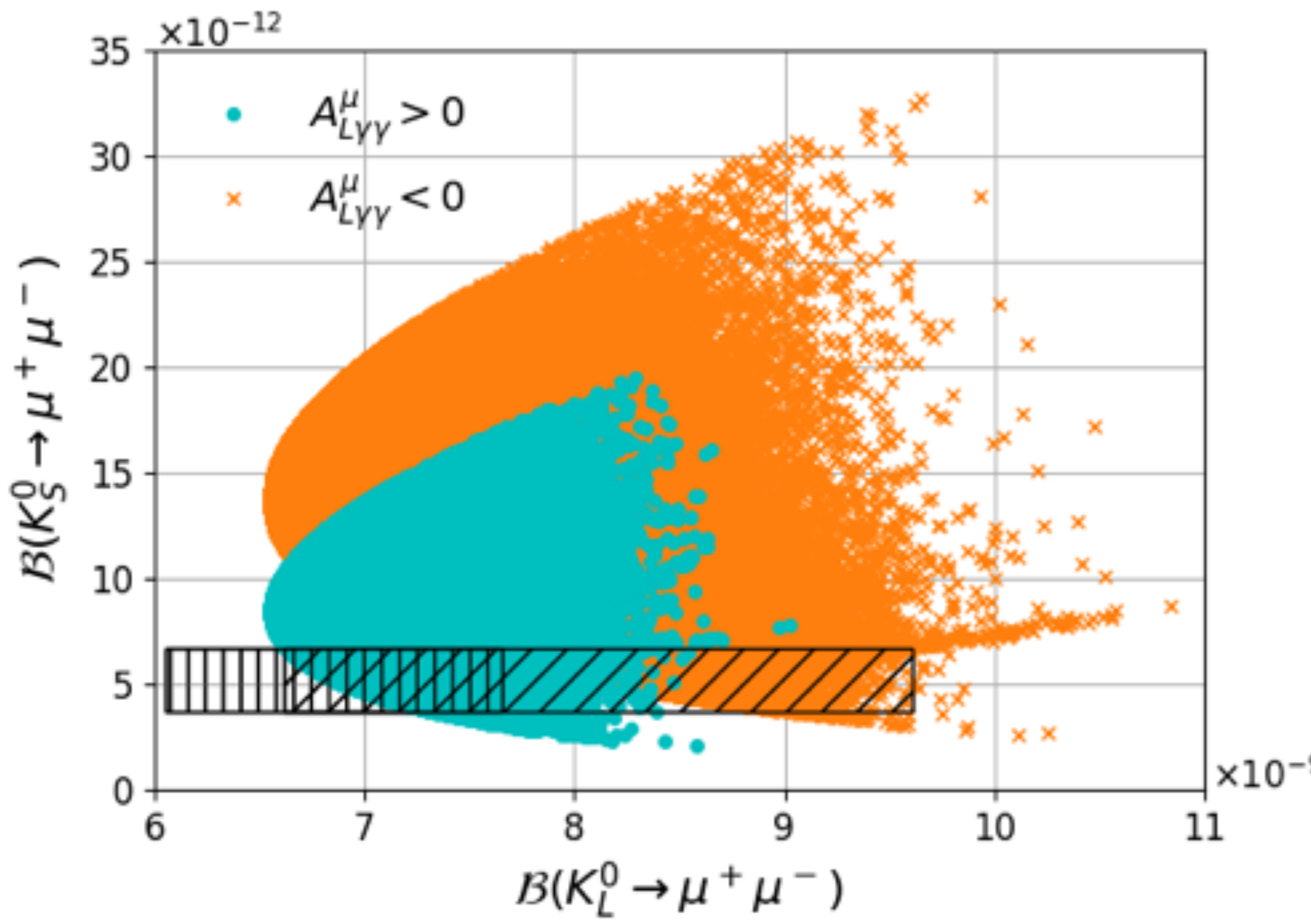
$$\times \left(\int_{t_{min}}^{t_{max}} dt \, e^{-\Gamma_S t} \varepsilon(t) \right)^{-1},$$



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



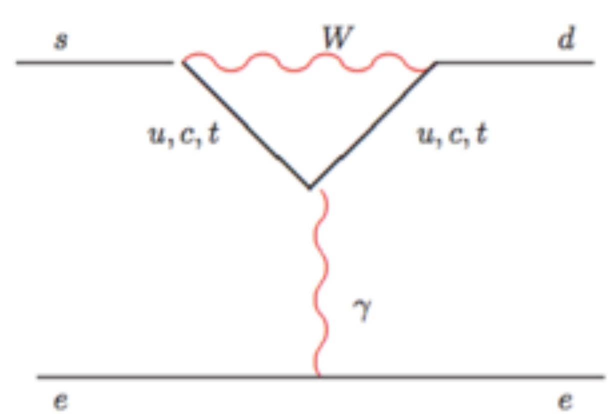
Miriam Lucio

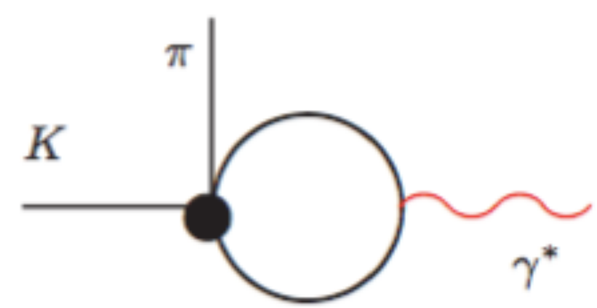


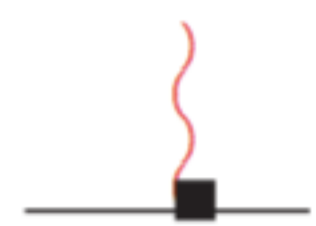
LFUV in Kaons

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

SD << LD







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

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

averaging flavour

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

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

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 $\langle 0|J_{5\mu}|\pi\rangle$, $\langle 0|q_L q_R|0\rangle$

$F_\pi \approx 93$ 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

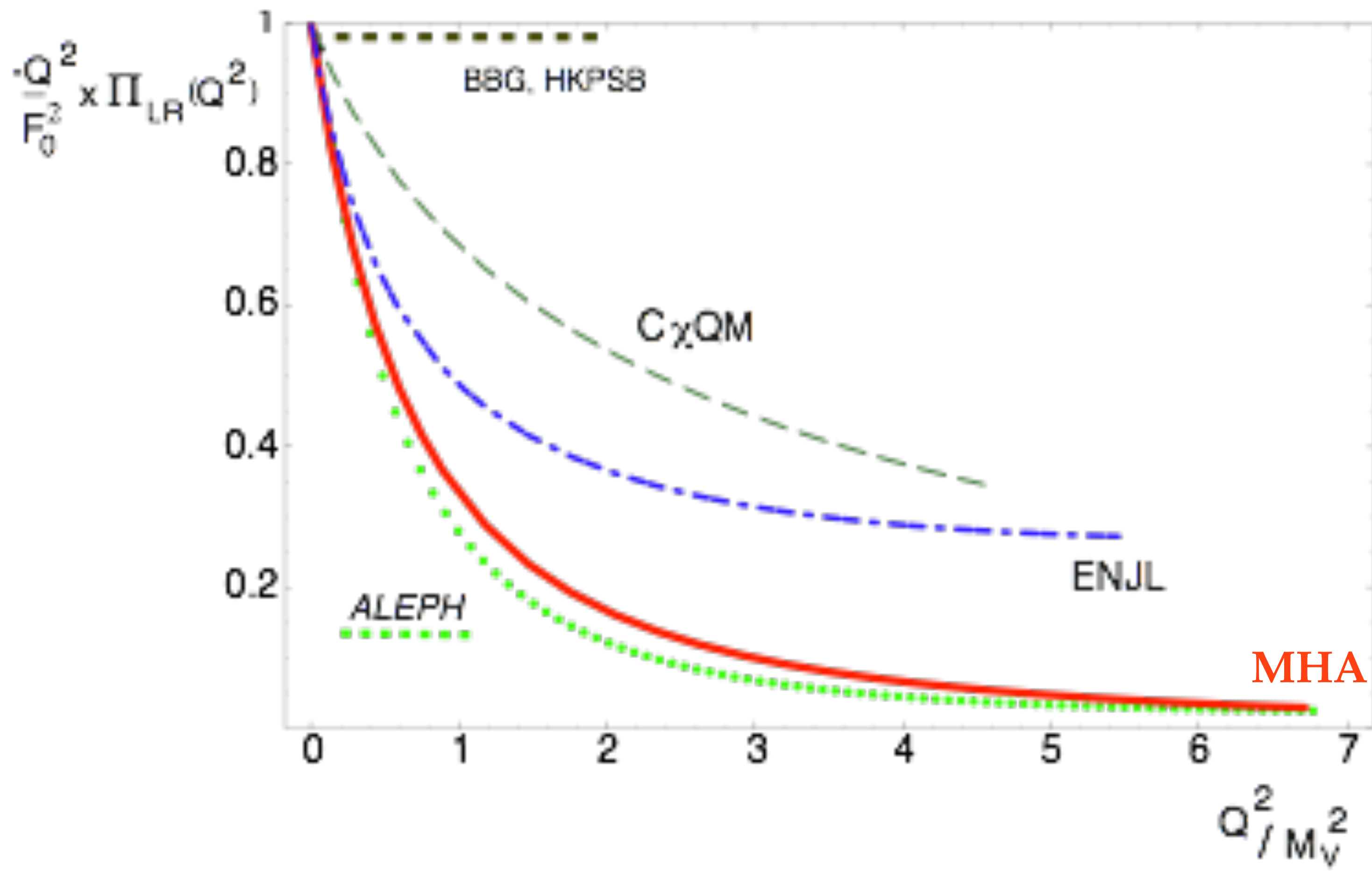
$$L_1^V = \frac{L_2^V}{2} = -\frac{L_3^V}{6} = \frac{G_V^2}{8M_V^2}, \qquad L_9^V = \frac{F_V G_V}{2M_V^2}, \qquad L_{10}^{V+A} = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2}$$

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)	$6N_{28} + 3N_{29} - 5N_{30}$

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

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

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

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

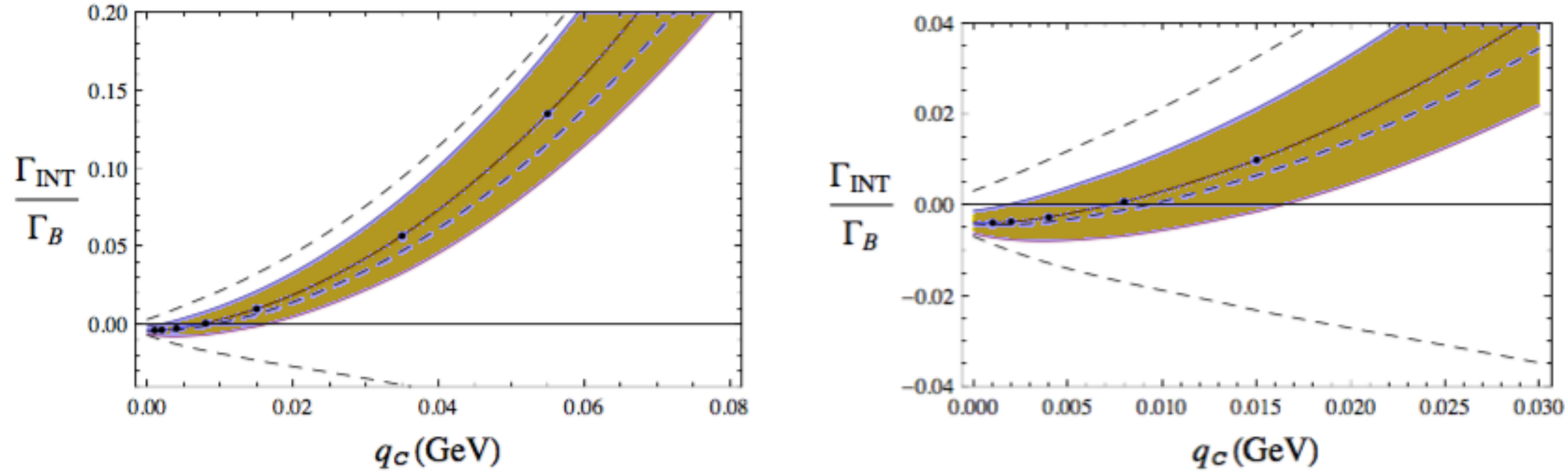
$$\mathcal{N}_E^{(1)} \equiv N_{14}^r - N_{15}^r = \frac{3}{64\pi^2}\left(\frac{1}{3} - \frac{G_F}{G_8}a_{+} - \frac{1}{3}\log\frac{\mu^2}{m_K m_\pi}\right) - 3L_9^r ;$$

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

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

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

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)



q cut in minimum dilepton

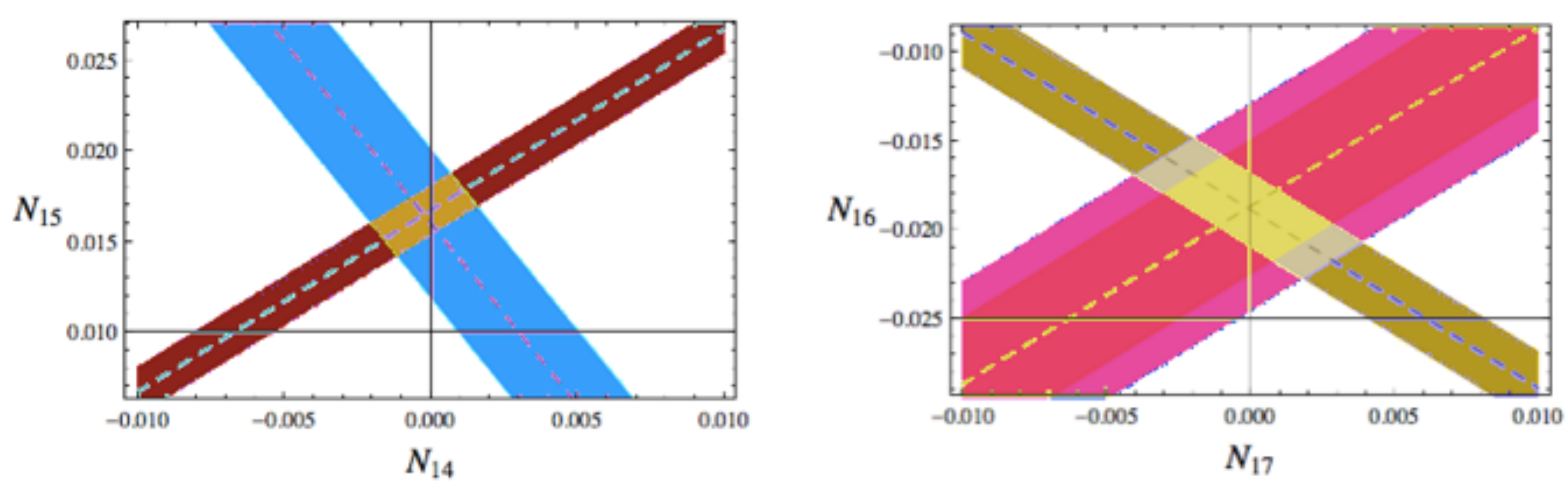
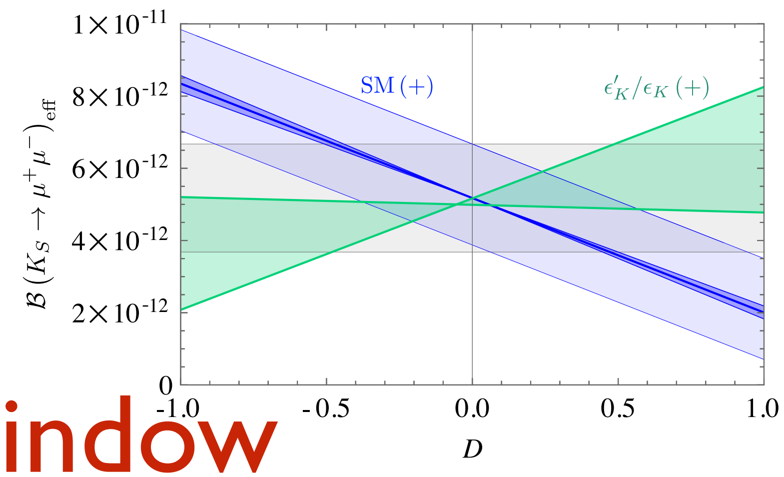


Figure 4: *Left panel: values of N_{14} and N_{15} as given by $K^{\pm} \to \pi^{\pm}\gamma^{*}$ (blue band) and $K_S \to \pi^0\gamma^*$ (violet band). Right panel: values for N_{16} and N_{17} extracted from $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ (blue band) and $K^{\pm} \to \pi^{\pm}\pi^0 e^+e^-$ (yellow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

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

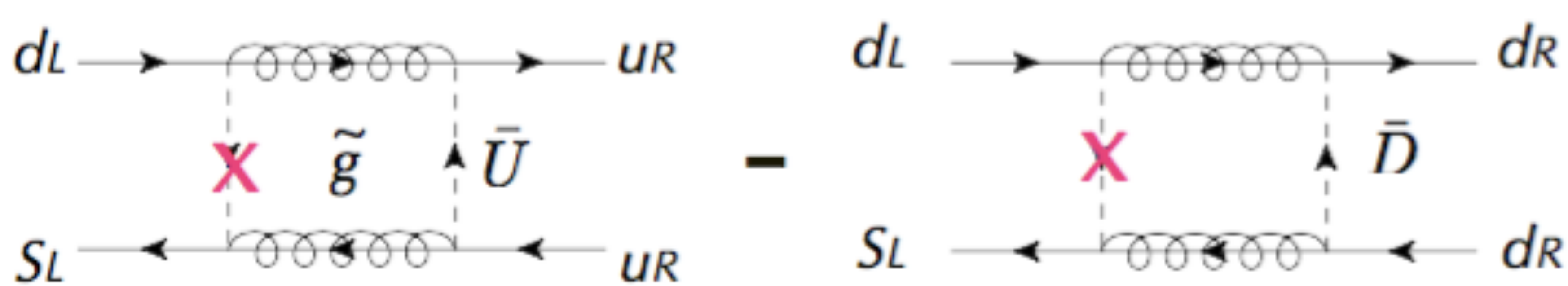
- LFUV in Kaons very useful

- Rich rare kaon program

Gluino contribution to ϵ'_K/ϵ_K

[Kagan, Neubert, PRL '99, Grossman, Kagan, Neubert, JHEP '99]

- The main contribution to ϵ'_K/ϵ_K comes from gluino box loop
- In spite of QCD correction, gluino box diagrams **can** break strong isospin symmetry through mass difference between right-handed up and down squark masses, and they can contribute **ImA2**, which is enhanced by small **ReA2,exp** value



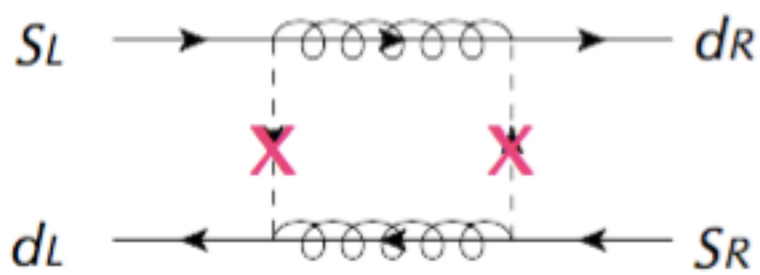
$m_{\bar{U}} \neq m_{\bar{D}}$ $\xrightarrow{\text{RGE}}$ EW penguin operators are generated at the low energy scale

$\xrightarrow{\text{with HMEs}}$ contribute to **ImA2** ⟶ **ϵ'_K can be solved**

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

Main Constraint: ϵ_K (Δ*S*=2, ID-CPV) cont.

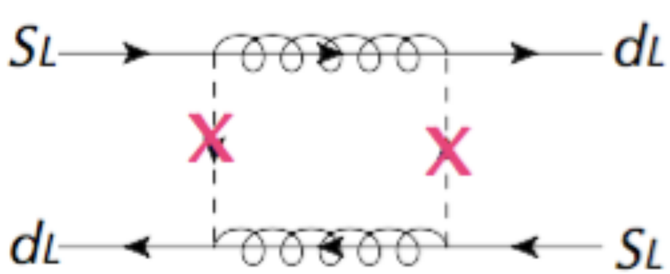
- The leading contribution is given by $\overline{d_L} s_L \overline{d_R} s_R$

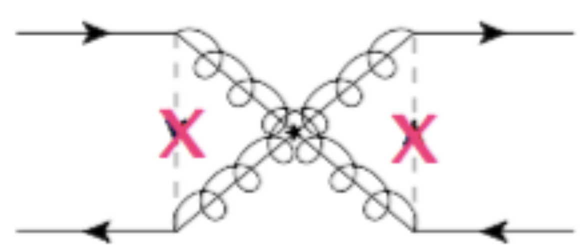


$\propto \left(\frac{m_K}{m_s + m_d} \right)^2$

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

- 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

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.*

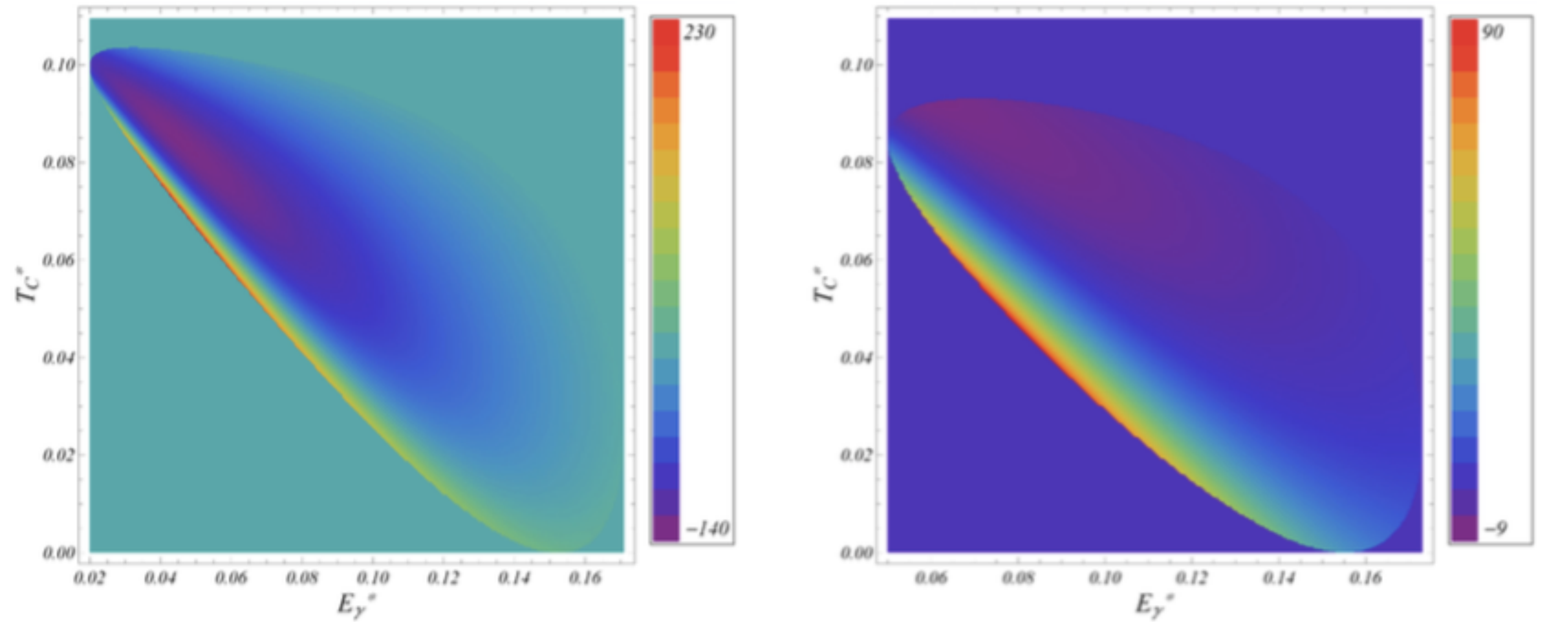
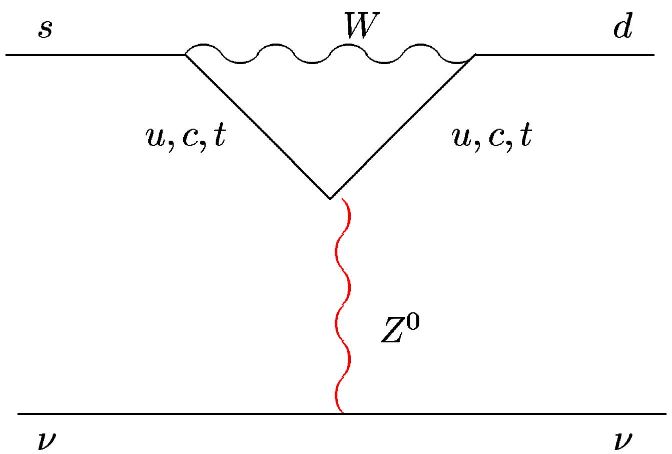


Figure 1: *Dalitz plots for the interference differential decay rate in the* (E_γ, T_c) *plane for* $q = 20$ *MeV (left panel) and* $q = 50$ *MeV (right panel). Numbers are given in units of* 10^{-20} GeV^{-1}*. The contour plot is 'spikier' the lower the q values are, a pattern mostly dictated by the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

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

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	5.9×10^{-11} $m_{X^0} = 0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h, \nu_h \to \nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350\ MeV$	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$



s
W
d
u, c, t
u, c, t
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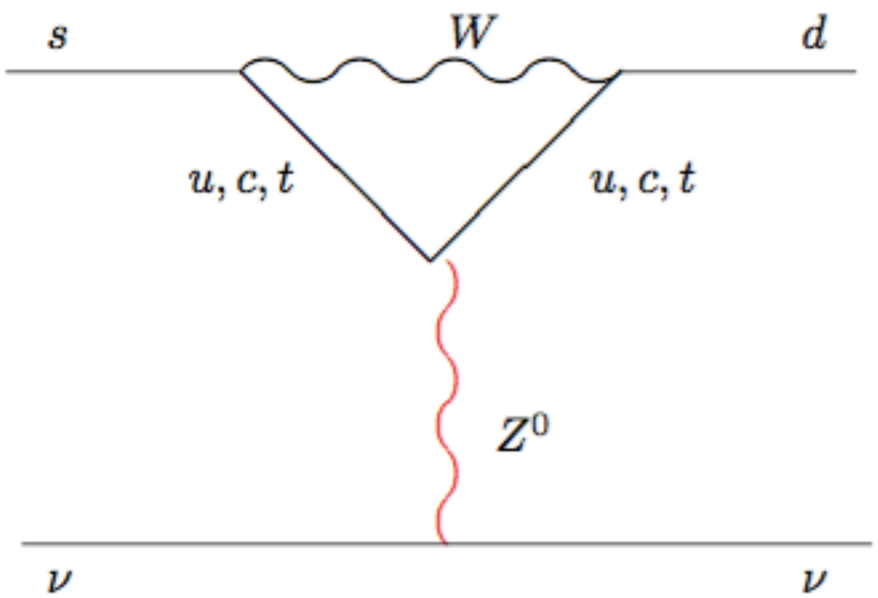

s
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u, c, t
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ν
ν

Back up

CP violation in $K \to 2\pi$

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

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

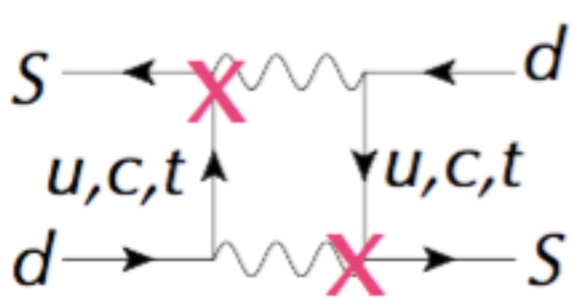
$\epsilon \sim \mathcal{O}(10^{-3})$ Christenson et al 64

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

$H_{\Delta S=2}$

Indirect CP violation

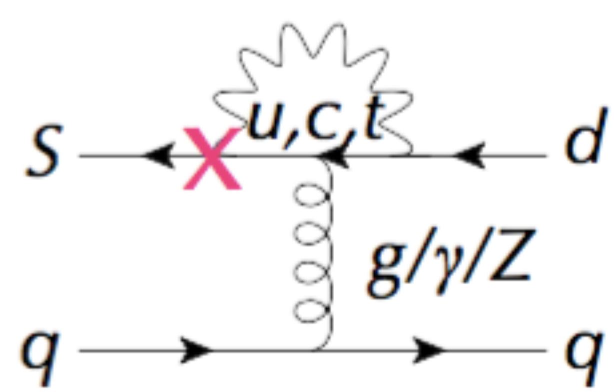
Kaon oscillation



$H_{\Delta S=1}$

Direct CP Violation

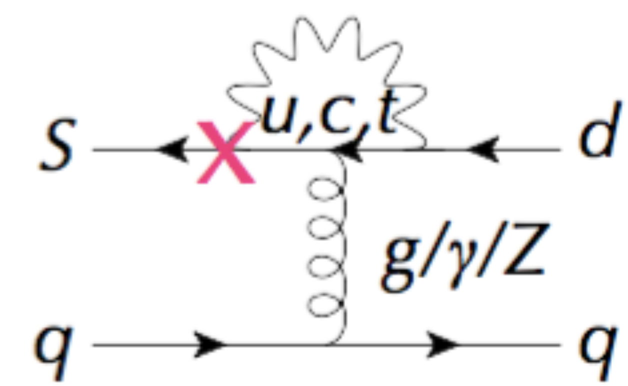
Penguin



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

gluon penguin Q_6

EW penguin Q_8



<O6> and <O8> have chiral enhancement factor

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

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

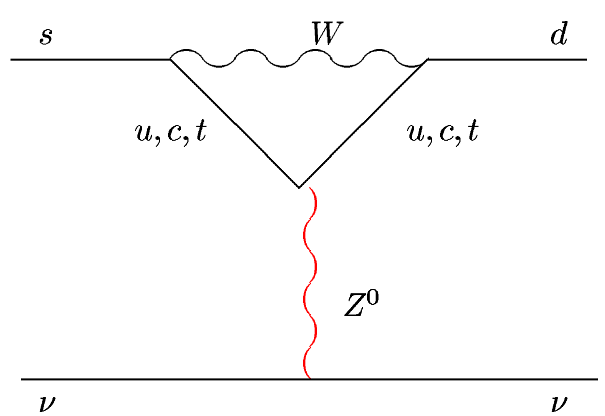
New lattice result 2015

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 $\quad \underbrace{V-A\otimes V-A}$ 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

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

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

- 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

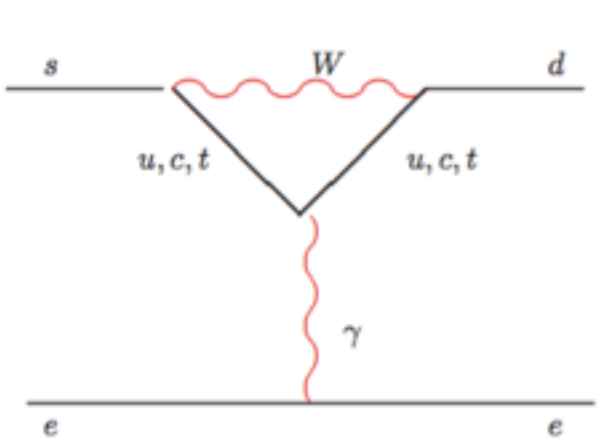
$B(K_L) = (3.14 \pm 0.17 \pm 0.06) \times 10^{-11}$ vs

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

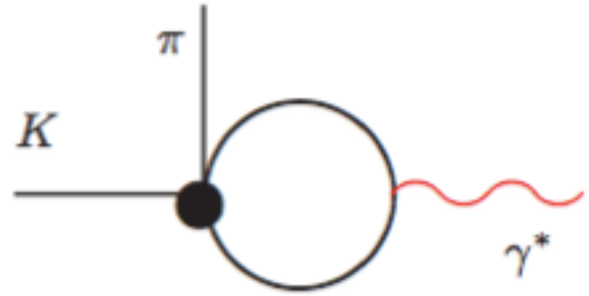
K_L Model-independent bound, based on $SU(2)$ properties dim-6 operators for $\bar{s}d\bar{\nu}\nu$ Grossman-Nir

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

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

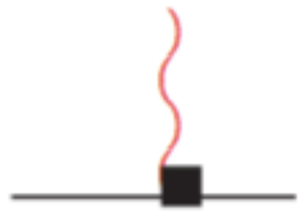


Short distance

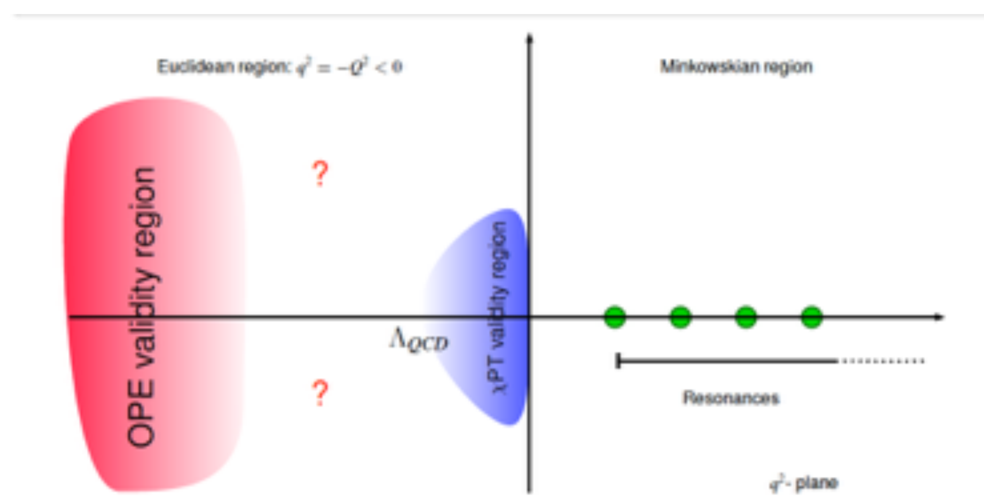


$O(p^4)$ ChPT

electrons and μ's in the final state



constant+ loop Ecker, Pich, de Rafael



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

Collaboration with LHCB

	PDG	Prospects
$K_S \to \mu\mu$	$< 9 \times 10^{-9}$ at 90% CL	$(\text{LD})(5.0 \pm 1.5) \cdot 10^{-12}$ $\quad$ $\text{NP} < 10^{-11}$
$K_S \to \mu\mu\mu\mu$	–	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

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

- gauge+Lorentz inv. =>1 ff

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

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

$$i = \pm, S$$

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

- 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.

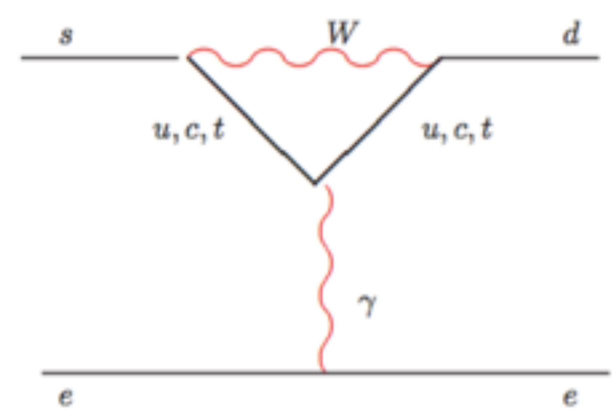
averaging flavour

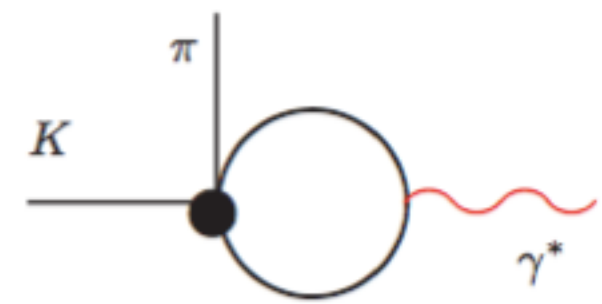
$$a_+^{\rm exp.} = -0.578 \pm 0.016$$
$$b_+^{\rm exp.} = -0.779 \pm 0.066$$

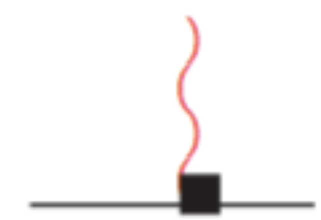
LFUV: Kaons

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

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

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

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

NA62 PLEASE!!

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

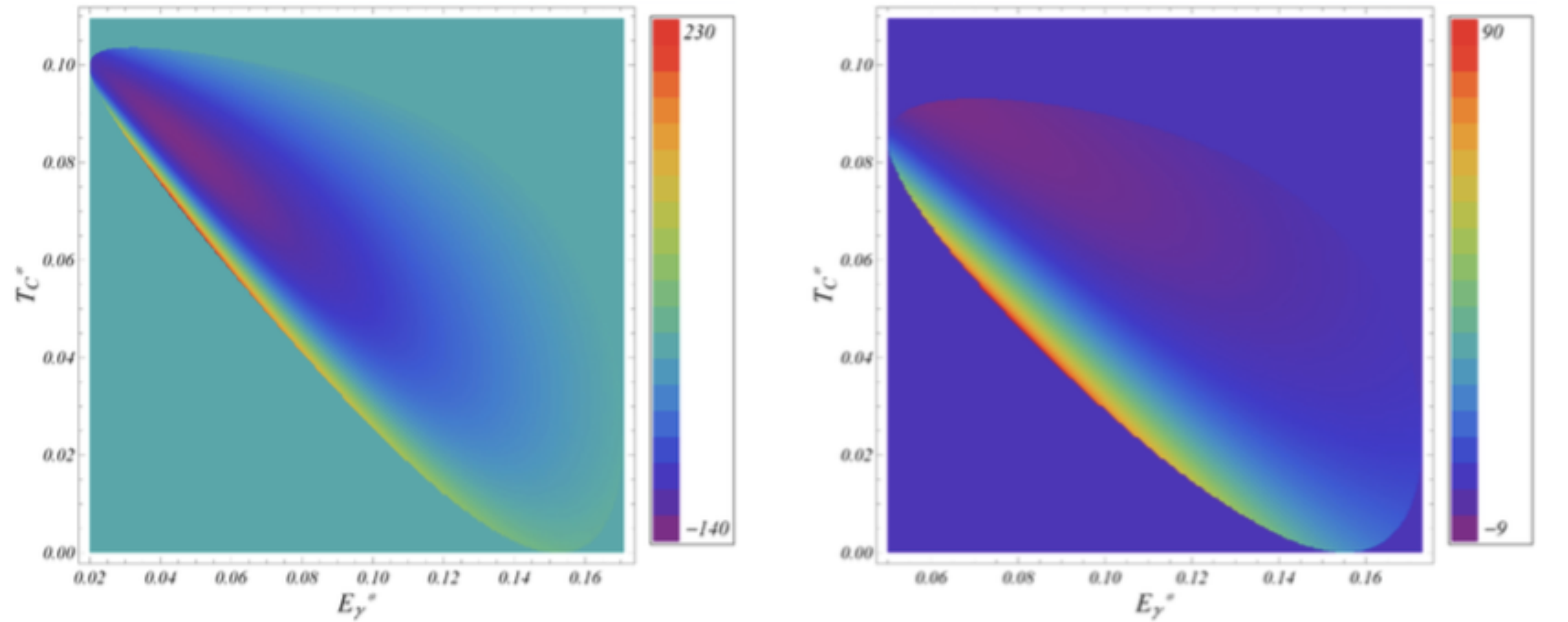


Figure 1: *Dalitz plots for the interference differential decay rate in the* (E_γ, T_c) *plane for* $q = 20$ *MeV (left panel) and* $q = 50$ *MeV (right panel). Numbers are given in units of* 10^{-20} GeV^{-1}. *The contour plot is 'spikier' the lower the q values are, a pattern mostly dictated by the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

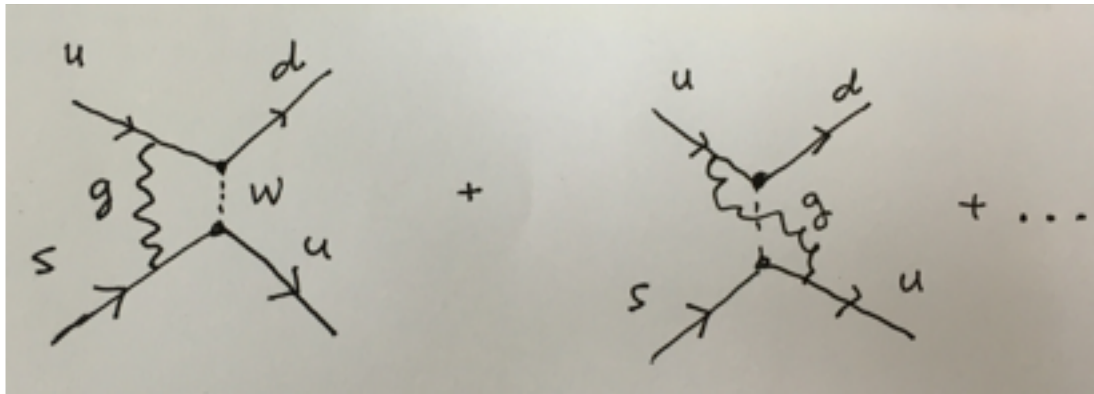
- Fermi lagrangian: description of the ΔS=1 weak lagrangian, in particular the explanation of ΔI =1/2 rule

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

- 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.

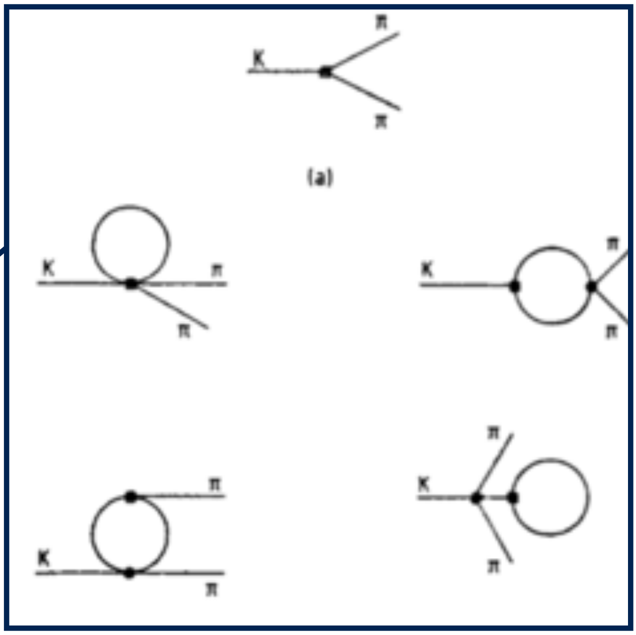
Main idea: phys. amplitudes scale independent

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

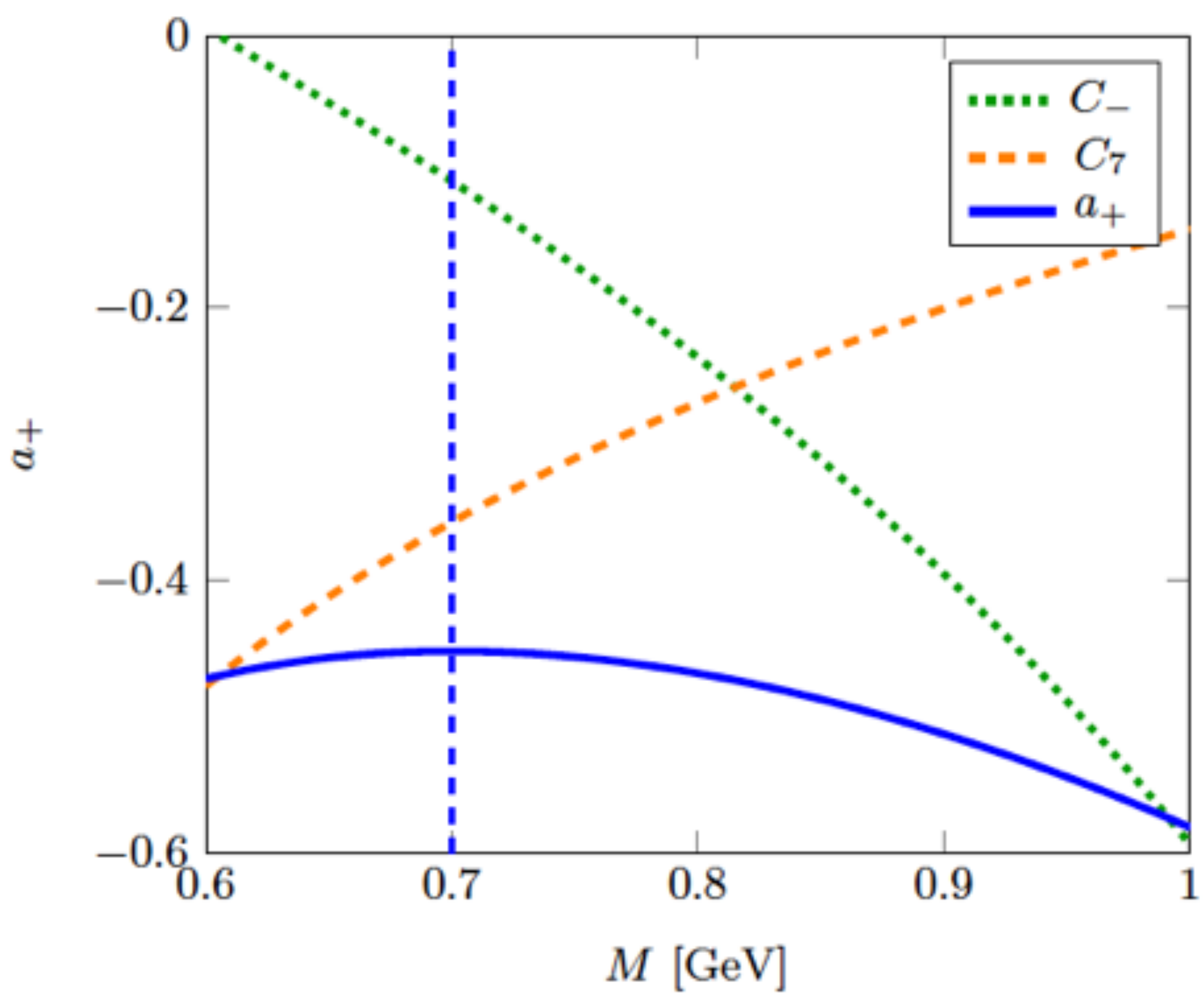


Can we test somewhereelse the Bardeen Buras Gerard (BBG) approach?

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



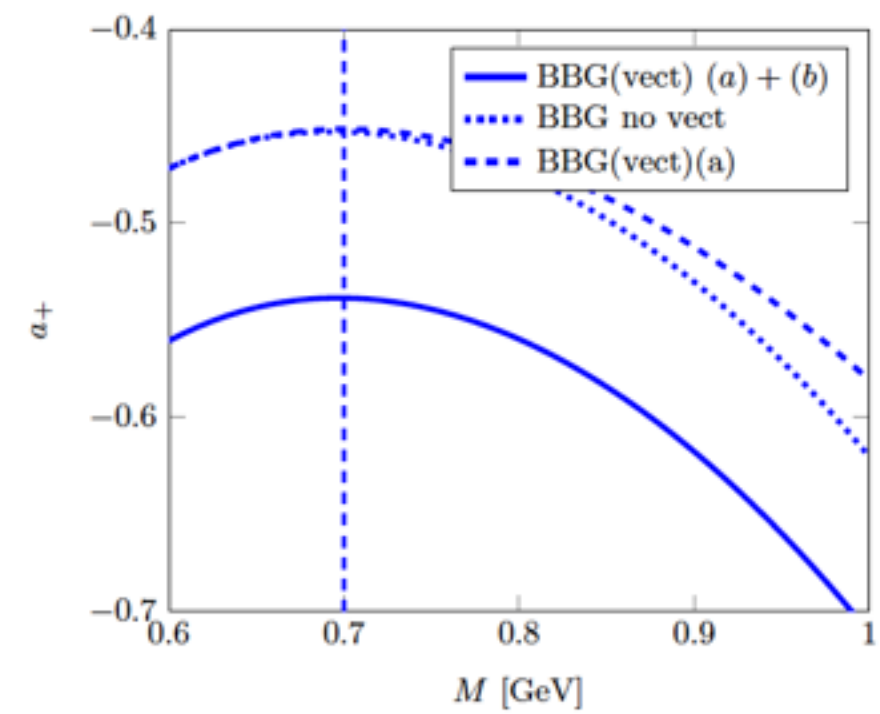
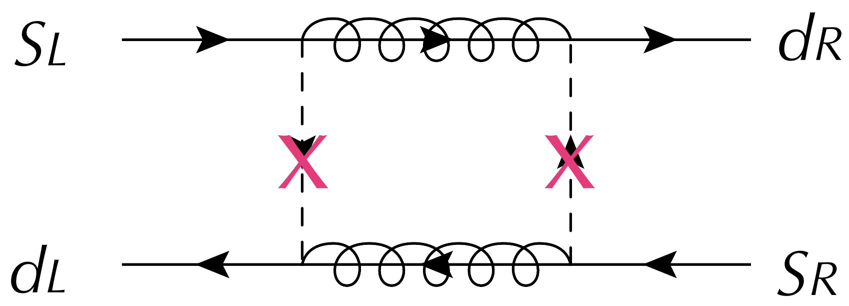


FIG. 5. a_+ as a function of M in the three different frameworks:'BBG no vect.' where vectors are not included, 'BBG(vect)(a)' represents the contribution coming only from diagrams (a) in Fig. 4 and 'BBG(vect) $(a)+(b)$' is the case where both (a) and (b) diagrams were included. The vertical line indicates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

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

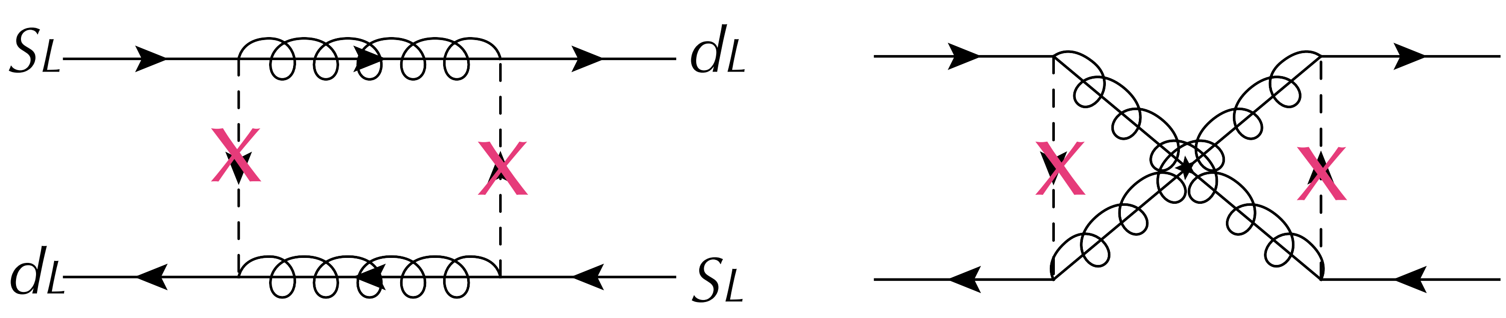
- The leading contribution is given by $\overline{d_L} s_L \overline{d_R} s_R$



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

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

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



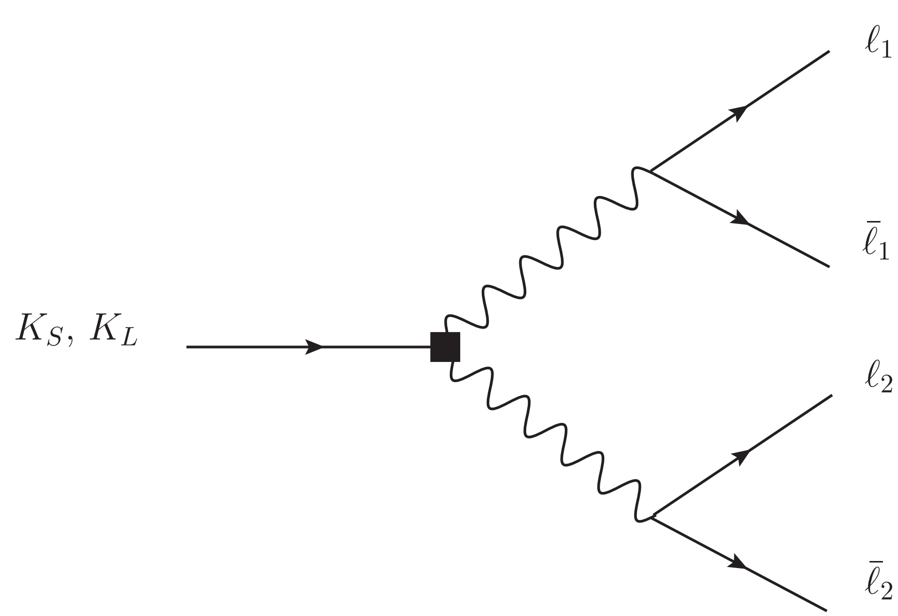
Crossed diagram gives **relatively negative** contributions

$m_{\tilde{g}} \simeq 1.5 m_{\tilde{q}}$: 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

$$
\begin{array}{llll}
K_S \to \mu\mu\mu\mu & - & \text{SM LD} & \sim 2\times 10^{-14} \\
K_S \to ee\mu\mu & - & & \sim 10^{-11} \\
K_S \to eeee & - & & \sim 10^{-10}
\end{array}
$$



GD,Greynat, Vulvert