Istituto Nazionale di Fisica Nucleare
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Flavor anomalies and possible manifestations in kaon decays

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Collaboration with Crivellin, A Hoferichter, M and Tunstall, L

Phys.Rev. D 2016

Collaboration with Coluccio-Leskow, E. Greynat,D. and Nath,A.
Phys.Rev. D 2016

Collaboration with Cappiello,Luigi Cata, Oscar and Gao, Droneng
EPJ . C72 (2012) 1872

Outline

- LFUV from B decays to Kaon decays
- BBG approach: can we test it in rare decays? I like to understand the method!
- $K^+ \to \pi^+ l^+ l^-$ / $K_S \to \pi^0 l^+ l^-$ form factors
- L9 in progress
- $K^+ \to \pi^+ \pi^0 l^+ l^-$ and other decays channels
- Conclusions

Why testing Lepton Flavor Universality Violation (LFUV) in Kaon decays?

- Several anomalies in B-physics

[Bobeth, Hiller, Piranishvili (07)]

- LFUV from LHCb $$R(K) = \frac{\mathrm{Br}[B \to K\mu^+\mu^-]}{\mathrm{Br}[B \to Ke^+e^-]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- P'$_5$ angular observable in $B \to K^*\mu^+\mu^-$

[Descotes-Genon et al. (13 & 14); Altmannshofer & Straub (15); Jäger & Martin Camalich (16)]

- Also in semi-leptonic B-decays $B \to D(D^*)\tau\nu$ see FLAG

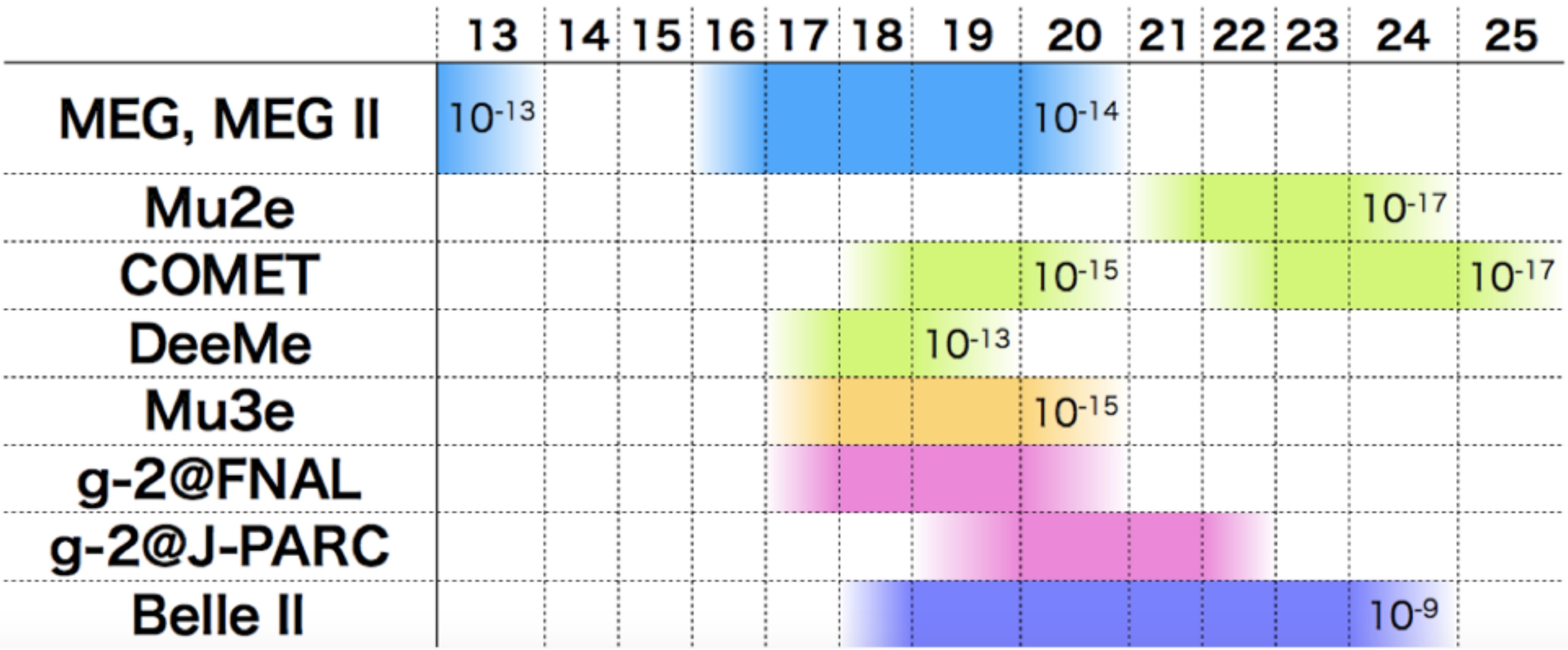
- maybe a global 3 sigma effect

[Altmannshofer & Straub (15); Descotes-Genon et al. (15)]

KAON2016

Aoki

Timelines



Work in collaboration with A. Crivellin, L.Tunstull and M. Hoferichter

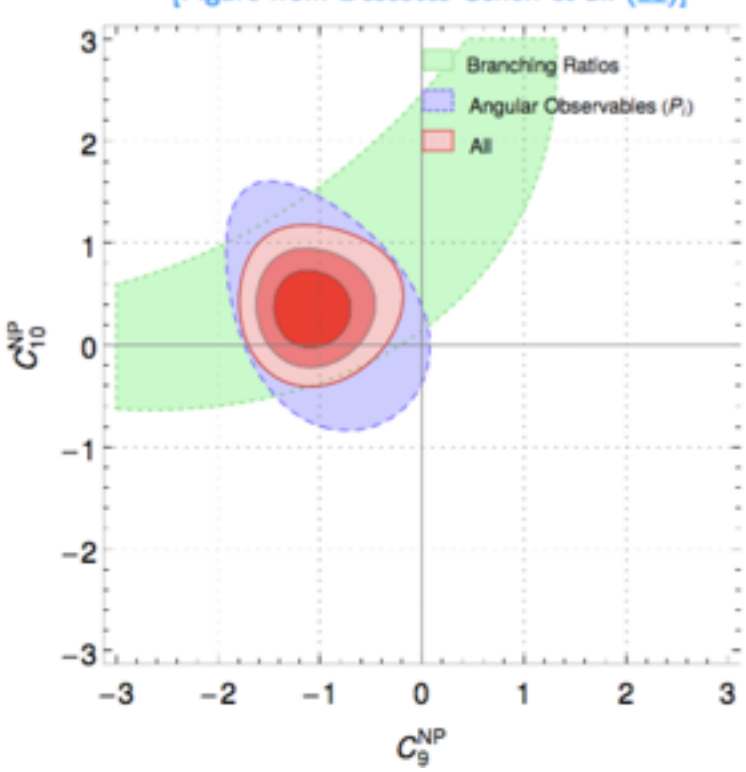
Addressing LFUV in kaon decays

$$\mathcal{H}_{\rm eff}^{|\Delta B|=1} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i^B(\mu) Q_i^B(\mu)$$

$$Q_9^B = \frac{e^2}{32\pi^2}[\bar{s}\gamma^\mu(1-\gamma_5)b] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \ell] \,,$$

$$Q_{10}^B = \frac{e^2}{32\pi^2}[\bar{s}\gamma^\mu(1-\gamma_5)b] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \gamma_5 \ell] \,.$$

[Figure from Descotes-Genon et al. (15)]



$C_{9,10}^{NP}$ ~O(1)

Assuming MFV: what we expect in kaon decays ?

$$\mathcal{L}_{\rm eff}^{|\Delta S|=1} = -\frac{G_F}{\sqrt{2}} V_{ud}V_{us}^* \sum_{i=1}^{13} C_i(\mu) Q_i(\mu)$$

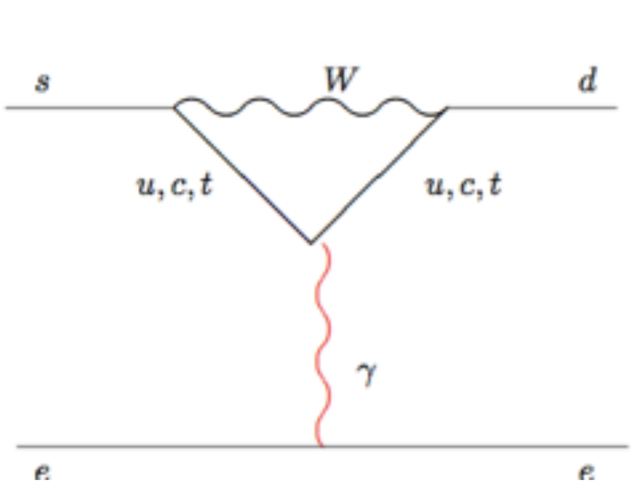
$$Q_{11} \equiv Q_{7V} = [\bar{s}\gamma^\mu(1-\gamma_5)d] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \ell] \,,$$

$$Q_{12} \equiv Q_{7A} = [\bar{s}\gamma^\mu(1-\gamma_5)d] \sum_{\ell=e,\mu} [\bar{\ell}\gamma_\mu \gamma_5 \ell] \,.$$

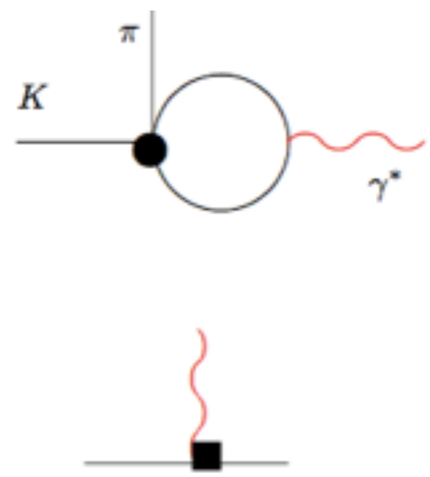
$K^+ \to \pi^+ e^+ e^-$ $K_S \to \pi^0 e^+ e^-$

- gauge+Lorentz inv. =>1 ff $W^{+/-,S}$

CHPT



SD



CHPT

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

$$i = \pm, S$$

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

- Observables $\Gamma(K^+ \to \pi^+ e^+ e^-)$, $\Gamma(K^+ \to \pi^+ \mu \overline{\mu})$, slopes
- a_i $O(p^4)$ $a_+ \sim N_{14} - N_{15}$, $a_S \sim 2N_{14} + N_{15}$ Ecker, Pich, de Rafa
- b_i $O(p^6)$ G.D., Ecker, Isidori, Portole

- a_+, b_+ in general not related to a_S, b_S

Recent lattice determinations Christ et al.

averaging flavour

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

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

Also analyzed LFV Kaon decays and $K_L \to \mu\mu \quad (C_{10}^{NP})$

$K^+ \to \pi^+ e^+ e^-$ $K_S \to \pi^0 e^+ e^-$ form factor calculation

- Bardeen Buras Gerard
- Recent lattice determinations Christ et al.
- epsilon′ ?

QCD at work: Short Distance expansion for weak interaction

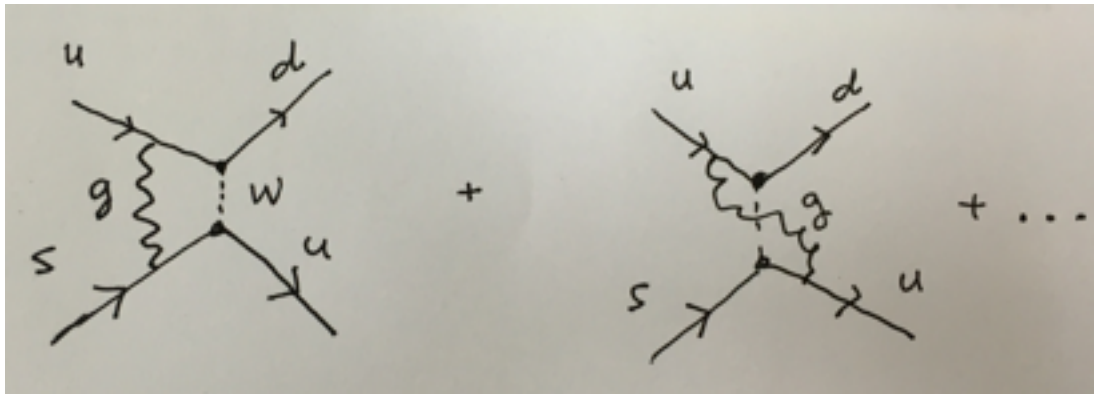
- Fermi lagrangian: description of the ΔS=1 weak lagrangian, in particular the explanation of ΔI =1/2 rule

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

- 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

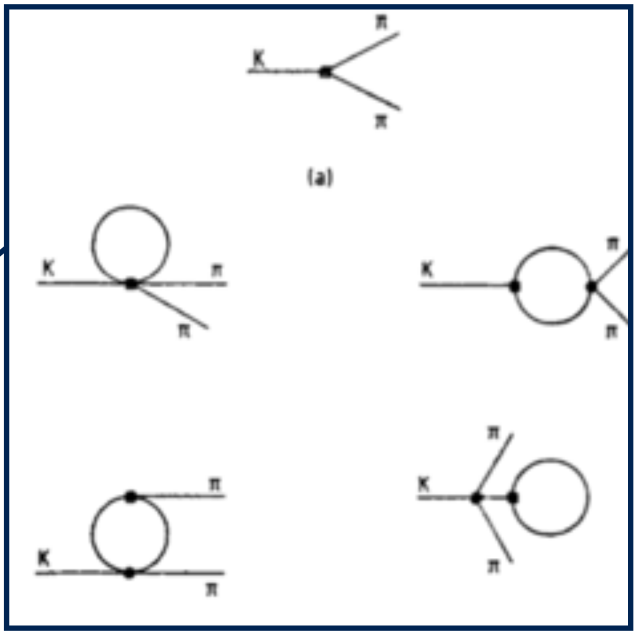
- analytic calculation 't Hooft, large Nc (it explains basic phenomenological facts of QCD, i.e. Zweig's rule) many implications: Skyrme model, VMD, Maldacena
- G. Parisi, `80s lattice: can we predict from QCD the proton mass at 10% level?
- Precise calculation of low energy QCD?

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

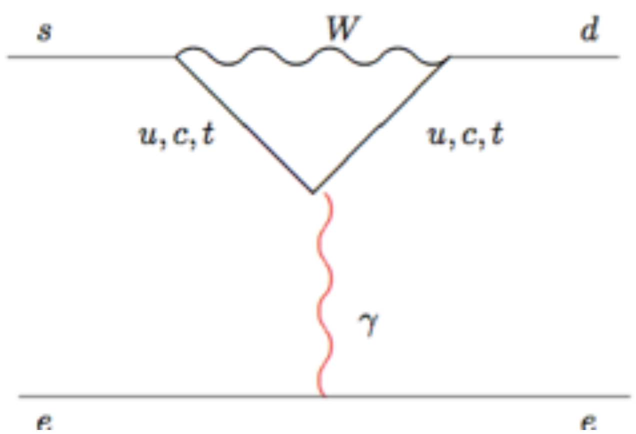
Can we test somewhereelse the Bardeen Buras Gerard (BBG) approach?

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

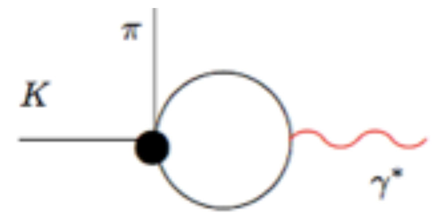
$K^+ \to \pi^+ e^+ e^-$ $\quad$ $K_S \to \pi^0 e^+ e^-$

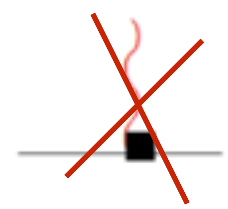
Coluccio-Leskow,E. G.D ,Greynat, D and Nath, A

BBG approach



SD





NO CT IN BBG

CHPT

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

$$i = \pm, S$$

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

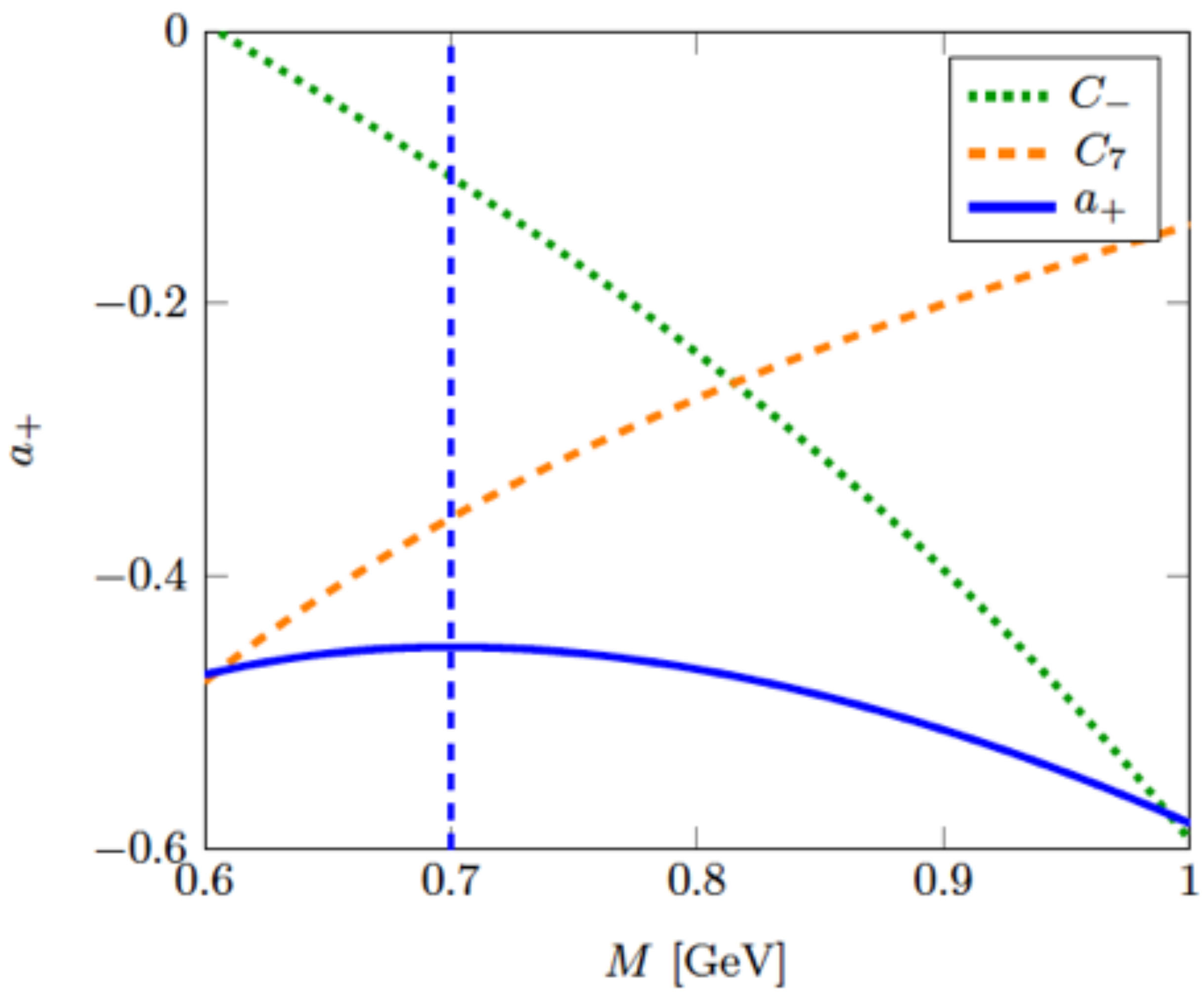
Quadratic divergences in K->3π interaction matched to the subleading log in $C_7(\mu)$

$$Q_{7V} = \bar{s}\gamma^\mu(1-\gamma_5)d\,\bar{\ell}\gamma_\mu\ell$$

$$\mathcal{H}_{eff}^{|\Delta S|=1} = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \Big[\sum_{i=1}^{6,7V} (z_i(\mu) + \tau y_i(\mu)) Q_i(\mu) \; + \; \tau y_{7A}(M_W) Q_{7A}(M_W) \Big]$$

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

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



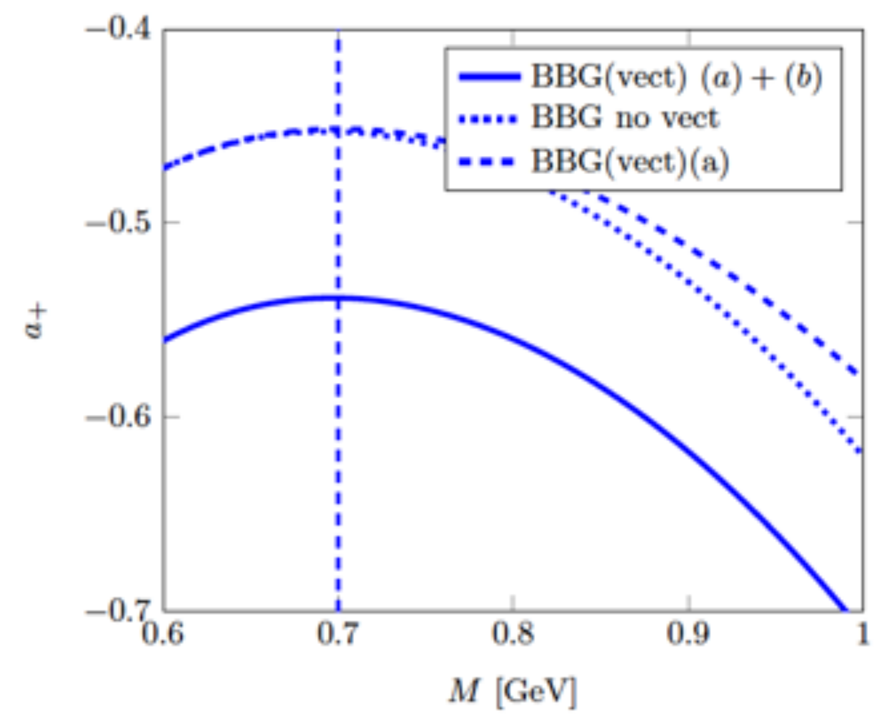


FIG. 5. a_+ as a function of M in the three different frameworks:'BBG no vect.' where vectors are not included, 'BBG(vect)(a)' represents the contribution coming only from diagrams (a) in Fig. 4 and 'BBG(vect) $(a)+(b)$' is the case where both (a) and (b) diagrams were included. The vertical line indicates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

L9

Collaboration with Greynat,David and Nath,Atanu

in progress

$$\mathcal{L} \sim -i \; L_9 \; F_{\mu\nu} \;\; < Q \; D^{\mu}U \; D^{\nu}U >$$

- No OPE: DIFFERENT from the weak decays!!
- However it must appear at O(p4) to improve matching with QCD

VMD '88: DEGLP, Donoghue et al

Matching the BBG form factor, M-dependent with phenomenology

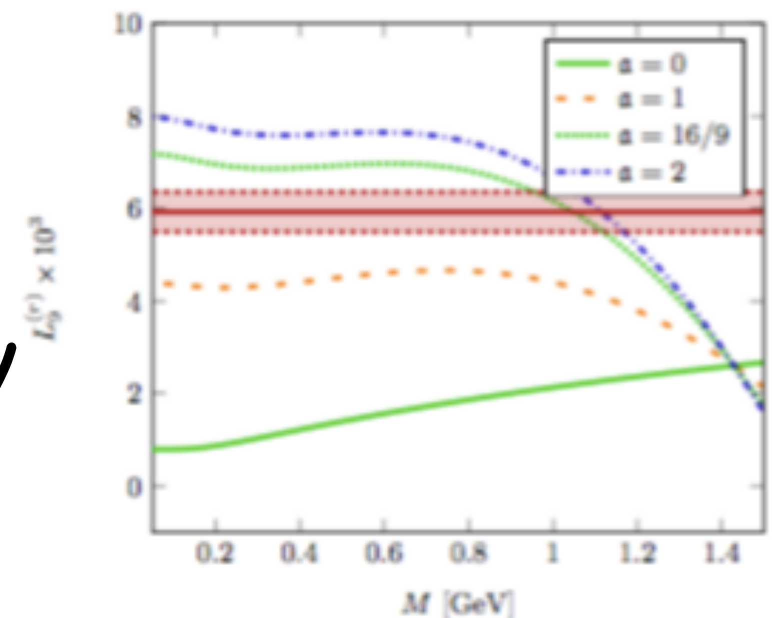


FIG. 9. Variation of $L_9^{(r)+Vec}(M)$ with scale M (in GeV) (calculated in BBG scheme including vectors through hidden local symmetry) given by Eq. (17). Area shaded in pink represents the uncertainty of $\pm 0.43 \times 10^{-3}$ around the phenomenological value 5.93×10^{-3} measured [28] at $m_\rho = 0.77$ GeV.

$$K(p_K) \to \pi(p_1)\pi(p_2)\gamma(q)$$

- Lorentz + gauge invariance $\Rightarrow$ Electric (E) and Magnetic(M) amplitude

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K\partial_\nu\pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K\partial^\sigma\pi\right]$$

- Unpolarizated photons

$$\frac{d^2\Gamma}{dz_1 dz_2} \sim |E|^2 + |M|^2$$

$$|E^2| = |E_{IB}|^2 + 2Re(E^*_{IB}E_D) + |E_D|^2$$

$$\downarrow$$

Low Theorem $\Rightarrow E_{IB} \sim \frac{1}{E^*_\gamma} + \mathrm{c}$ $\qquad E_D$, M chiral tests

We need FIGHT DE/IB$\sim 10^{-3}$

	IB	DE_{exp}	
$K_S \to \pi^+\pi^-\gamma$	10^{-3}	$< 9 \cdot 10^{-5}$	$E1$
$K^+ \to \pi^+\pi^0\gamma$	10^{-4} $(\Delta I = \frac{3}{2})$	$(0.44 \pm 0.07)10^{-5}$ PDG	$M1$,$E1$
$K_L \to \pi^+\pi^-\gamma$	10^{-5} (CPV)	$(2.92 \pm 0.07)10^{-5}$ KTeVnew	$M1$, VMD

CPV is only from IB K_L (also measured in $K_L \to \pi^+\pi^-e^+e^-$)

BUT IB suppressed in K^+ and K_L.

$$K^+ \to \pi^+\pi^0\gamma$$

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K\partial_\nu\pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K\partial^\sigma\pi\right]$$

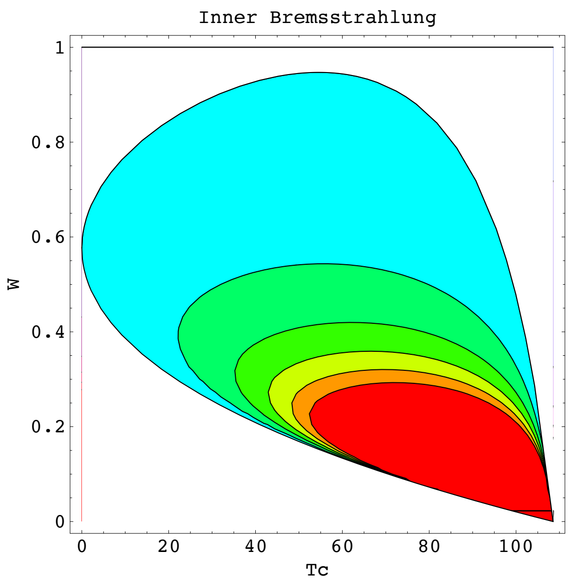
$E1$ and $M1$ are measured with Dalitz plot

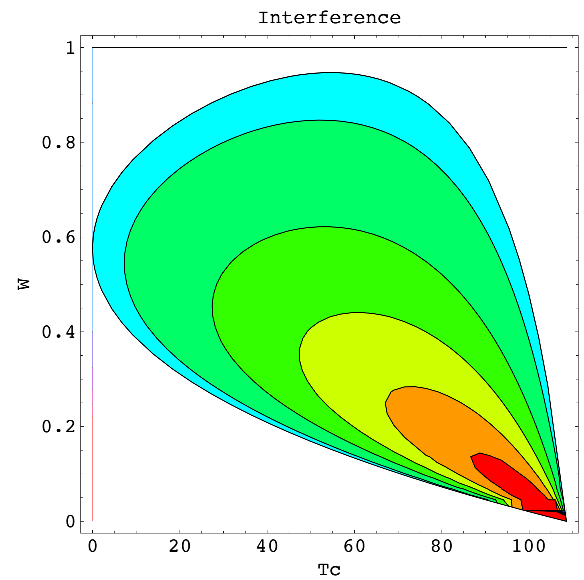
$$\frac{\partial^2\Gamma}{\partial T_c^*\partial W^2} = \frac{\partial^2\Gamma_{IB}}{\partial T_c^*\partial W^2}\left[1 + \frac{m_{\pi^+}^2}{m_K}2Re\left(\frac{E1}{eA}\right)W^2 + \frac{m_{\pi^+}^4}{m_K^2}\left(\left|\frac{E1}{eA}\right|^2 + \left|\frac{M1}{eA}\right|^2\right)W^4\right]$$

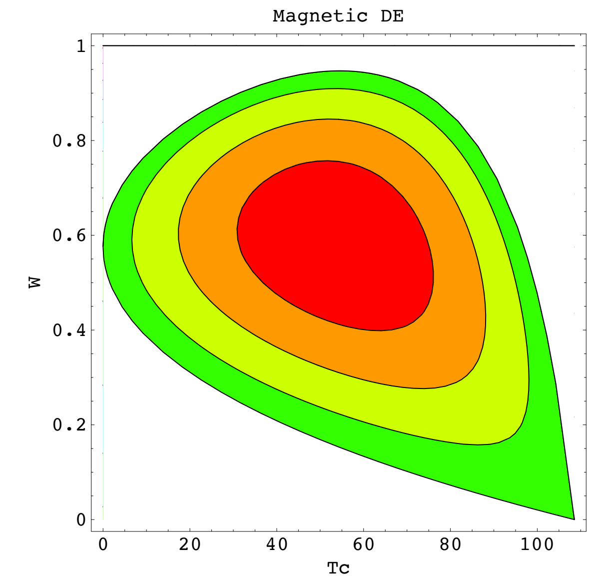
$$W^2 = (q \cdot p_K)(q \cdot p_+)/(m_\pi^2 m_K^2)$$

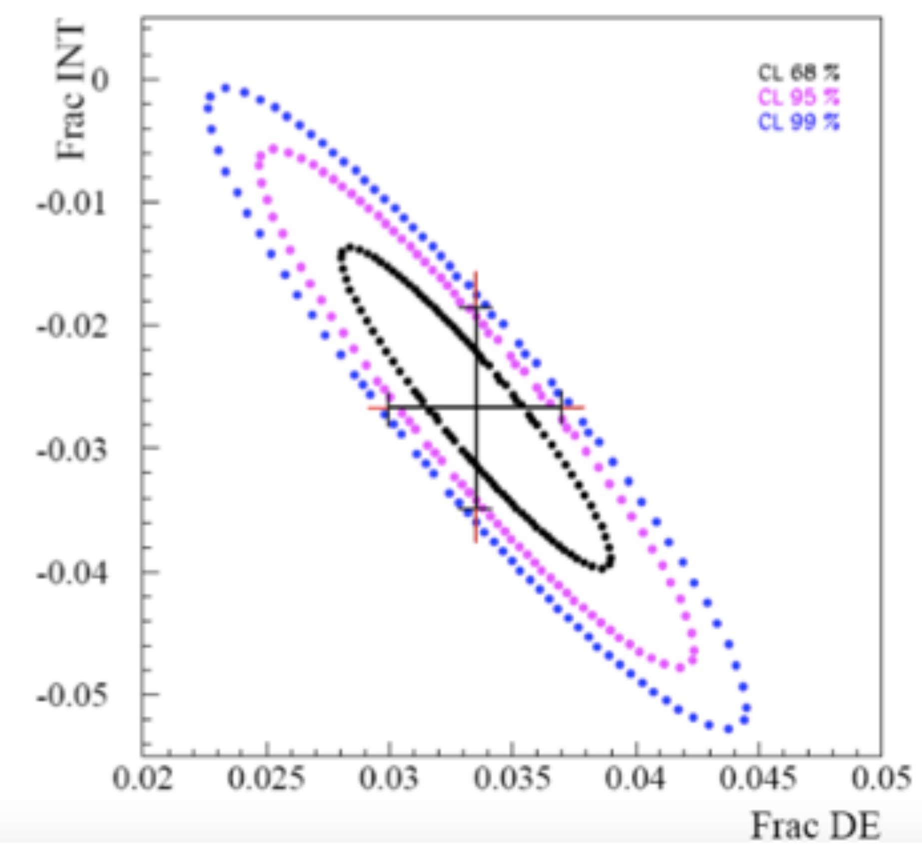
$$A = A(K^+ \to \pi^+\pi^0)$$

Dalitz plot NA48/2

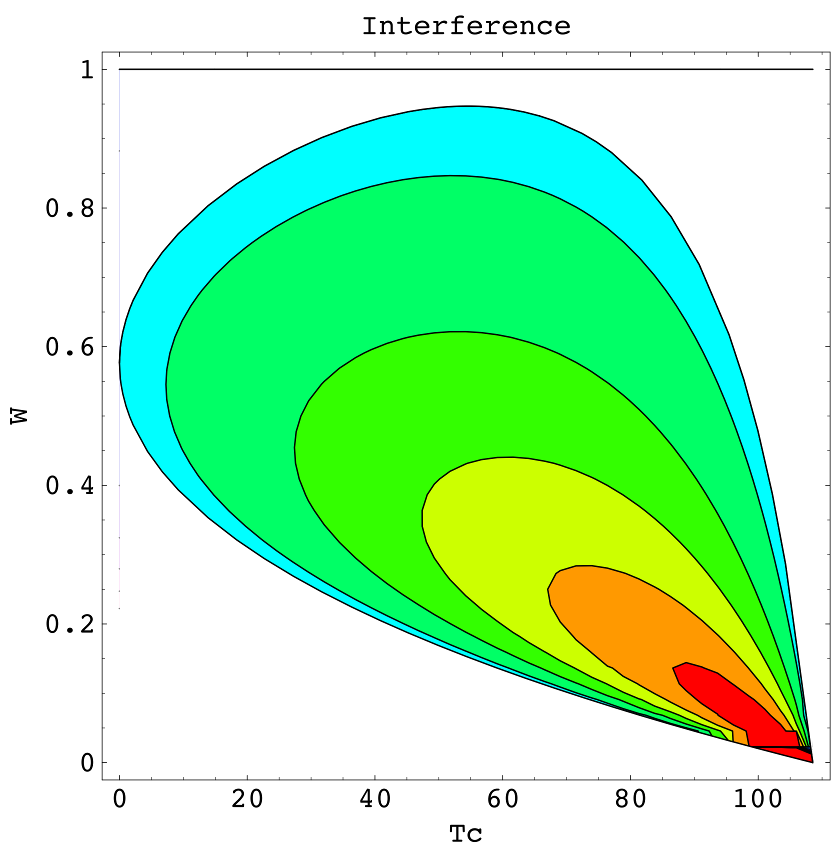








NA48/2 CP violation



Dalitz plot analysis crucial

SM $\leq \mathcal{O}(10^{-5})$ Paver et al.

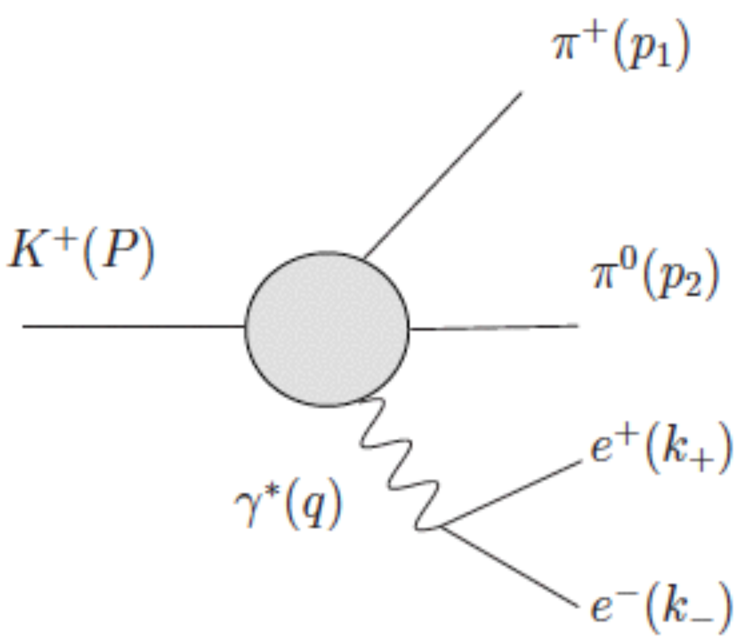
NP $\leq \mathcal{O}(10^{-4})$ Colangelo et al.

NA48/2 $< 1.5 \cdot 10^{-3}$ at 90% CL

BUT NOT in the interesting interf. kin. region (statistics)

$K_L \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$

Sehgal et al; Savage,Wise et al



- $\mathcal{M}_{LD} = \frac{e}{q^2}\, \bar{e}\gamma^\mu(1-\gamma^5)\; e\; H_\mu$
- $H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3\; \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta$
- $F_{1,2} \sim E \quad F_3 \sim M$

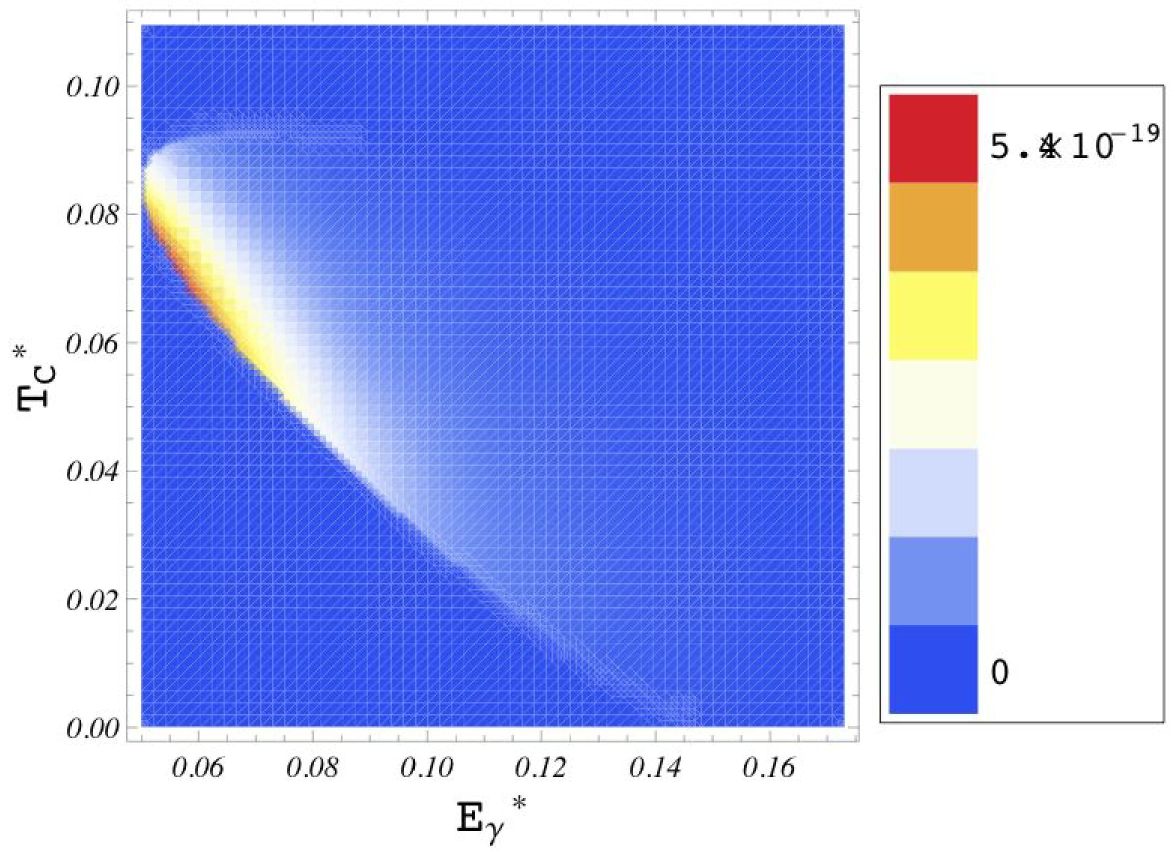
- Interference $E \quad M$ novel compared to $K_L \to \pi^+\pi^-\gamma$
- $E \quad M$ known from $K_L \to \pi^+\pi^-\gamma$ (IB and DE)

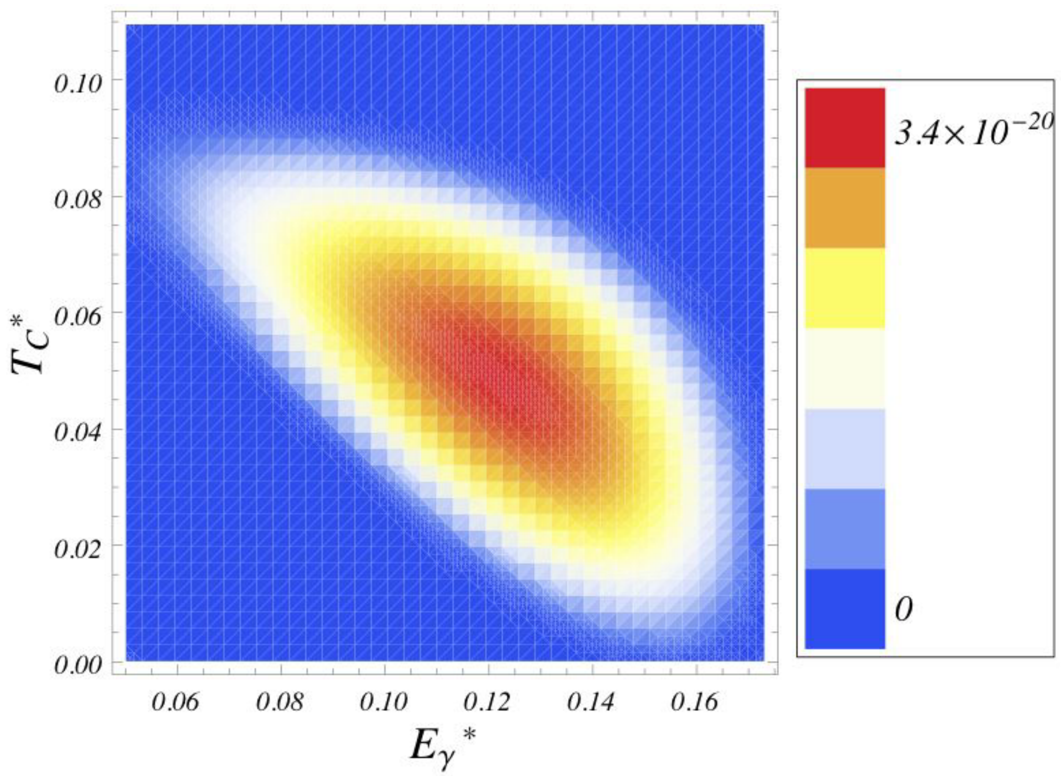
$K^+ \to \pi^+\pi^0\gamma^* \to \pi^+\pi^0 e^+ e^-$ Cappiello, Cata,G.D. and Gao,

- the asymm. , $\dfrac{\Re(E_B\ M^*)}{|E_B|^2 + |M|^2}$, not as lucky $E_B >> M$:
- $B(K^+)_{IB} \sim 3.3 \times 10^{-6}\ \sim\ 50\ B(K^+)_M$
- Short distance info without having simultaneously K^+ and K^-, asymm. in phase space, (P-violation) interesting! No ϵ-contamination
- interesting Dalitz plots (at fixed q^2) to disentangle M from E_B
- at $q^2 = 50\mathrm{MeV}$ IB only 10 times larger than DE

Starting from CP conserving IB, DE

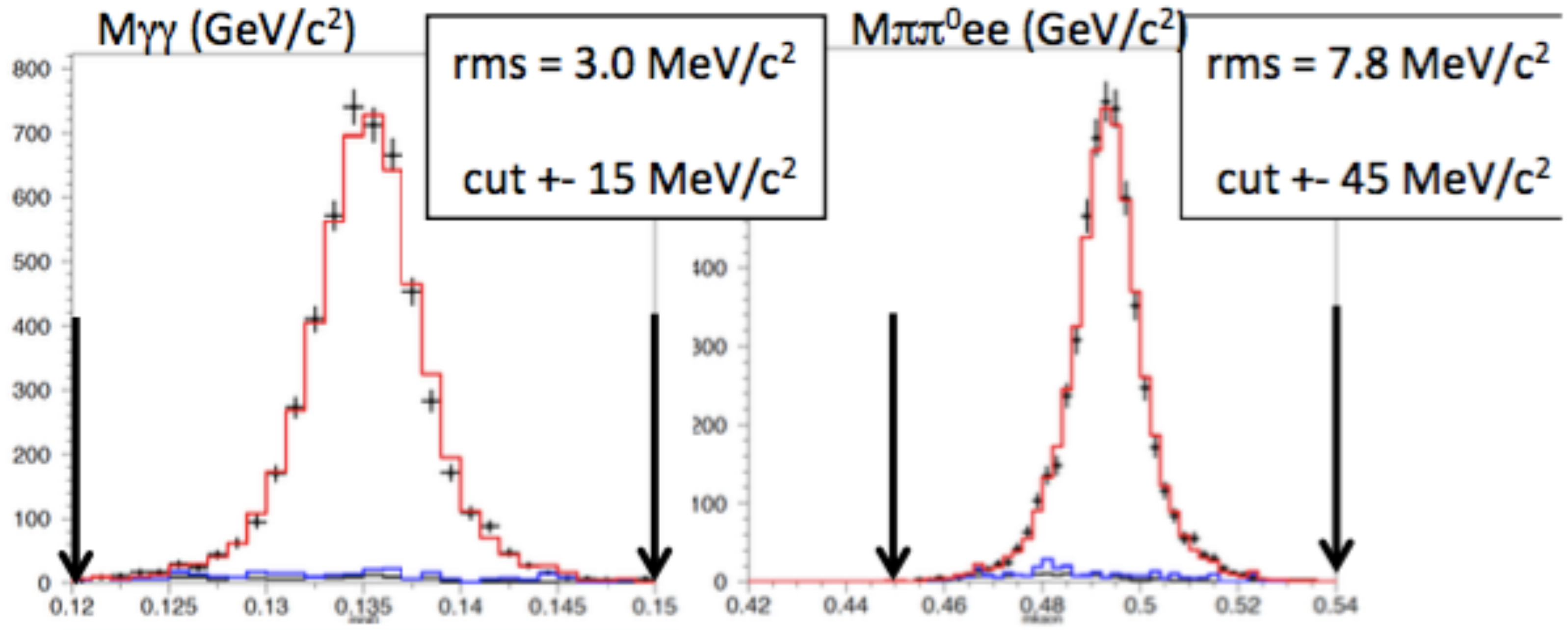
q_c (MeV)	B $[10^{-8}]$	B/M	B/E	B/BE	B/BM
$2m_l$	418.27	71	4405	128	208
55	5.62	12	118	38	44
100	0.67	8	30	71	36
180	0.003	12	5	-19	44

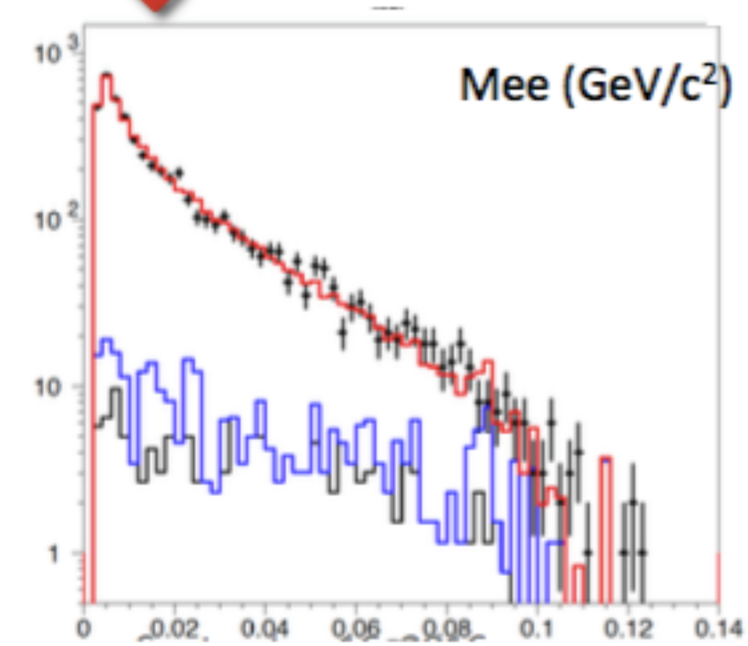




NA48/2: $K^{+/-} \rightarrow \pi^{+/-} \pi^0 e^+ e^-$

Bloch-Devaux





New Result!

BR = $(4.22 \pm 0.06_{stat} \pm 0.04_{syst} \pm 0.13_{ext})\ 10^{-6}$

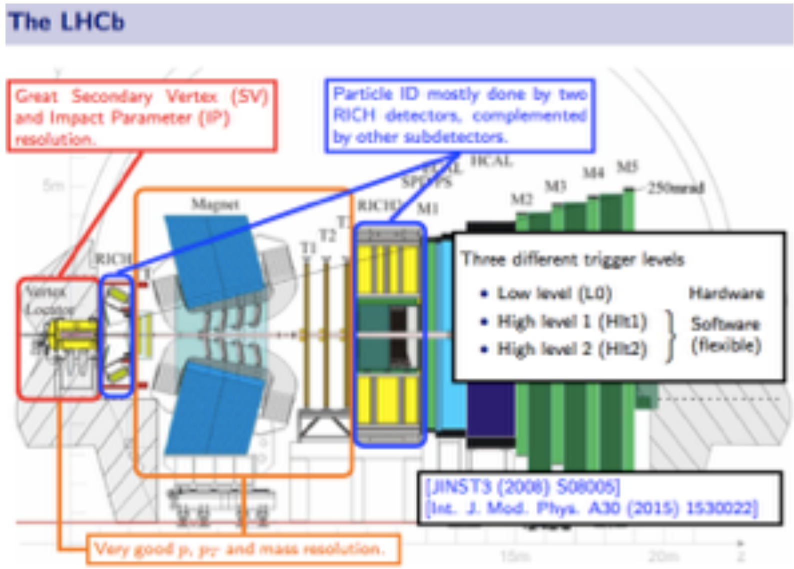
dominated by external error on BR(π0D)

In perfect agreement with

Theory : ChPT calculations EPJ C72 (2012) IB +DE + INT

BR (IB) = 4.19 10^{-6} no Rad Cor, No Isospin breaking Cor Total 4.29 10^{-6}
BR (IB) = 4.10 10^{-6} no Rad Cor, with Isospin breaking Cor** Total 4.19 10^{-6}

$K_S \to \mu\overline{\mu}$ LHCB

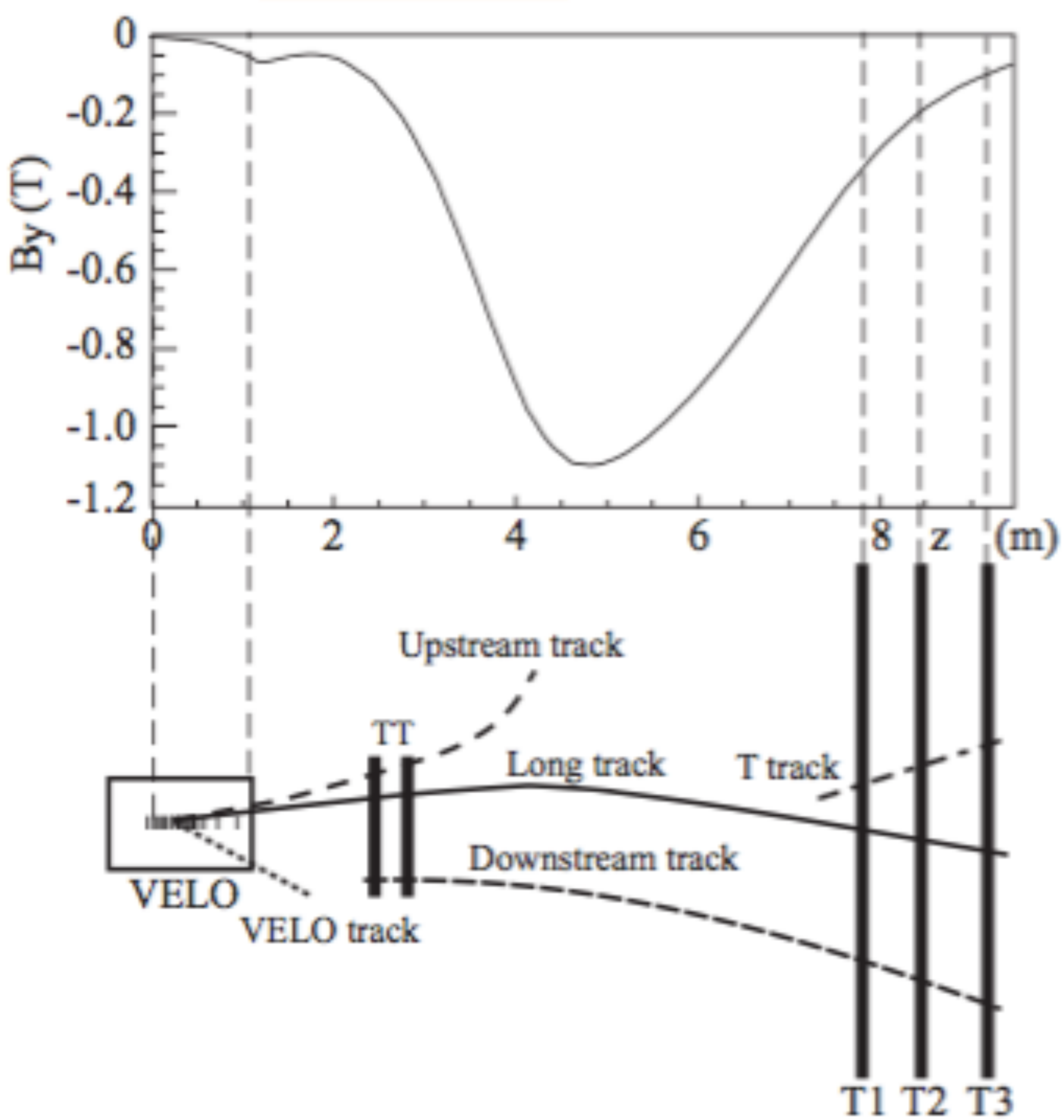


CERN SPS

After 40 years $B(K_S \to \mu^+\mu^-) < 3.1 \times 10^{-7}$ at 90%CL

improvement by 3 orders of magnitudes from LHCB

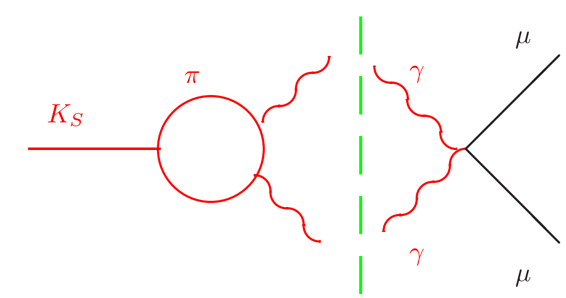
$$B(K_S \to \mu^+\mu^-) < 6.9(5.8) \times 10^{-9} \text{at } 95(90)\%\text{CL}$$



[Int. J. Mod. Phys. A30 (2015) 1530022]

SM

$$\sim 5 \times 10^{-12}$$



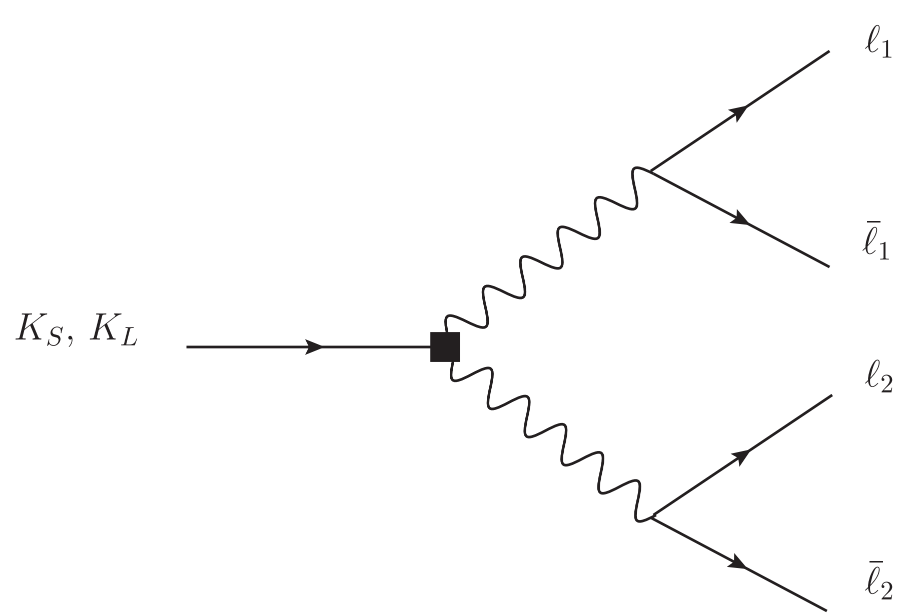
SD 1.5 10^-12

NP 1.5 10^-11 Allowed

NP Limits from CPviol in $K_L \to \mu\mu$

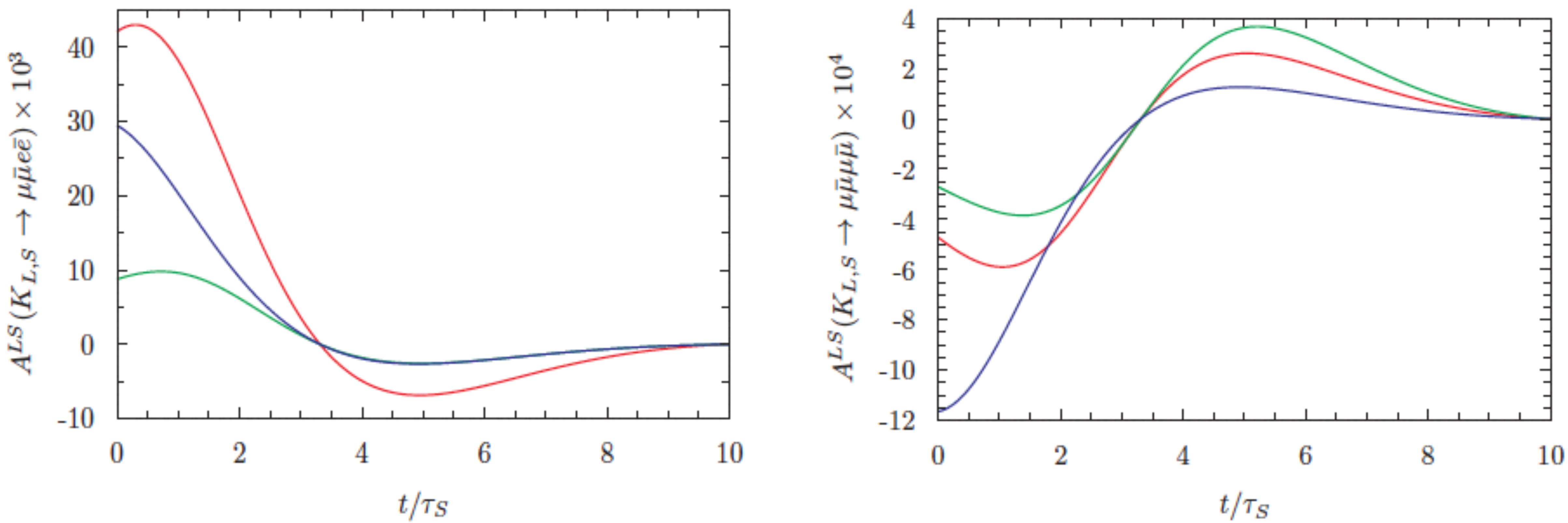
Other interesting channels

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



GD, Greynat, Vulvert

Time interference effects



Interferences between K_L and $K_S \to \ell_1\bar{\ell}_1\ell_2\bar{\ell}_2$. The red line corresponds to the case $\alpha_S = 0$, the green line is $\alpha_S = -3$ while the blue line is $\alpha_S = 3$. As explained in the text we assume the sign $K_L \to \gamma\gamma$. For 4μ's 10^{14} K_S needed , $ee\mu\mu$ 10^{12}

Conclusion

- LFUV interesting
- BBG interesting and positive news from our calculations
- $K^+ \to \pi^+ \pi^0 l^+ l^-$ hard fight but good perspectives, more CP violating observables
- $K_S \to \pi^+ \pi^- \mu^+ \mu^-$ Br ~ 10^{-14}


SM
NP
TuristadiMestiere.com

	$K_L \to \mu^\pm e^\mp$	$K^+ \to \pi^+ \mu^\pm e^\mp$	$K_L \to \pi^0 \mu^\pm e^\mp$	$K^+ \to \pi^+ \mu^\pm e^\mp$ (NA62 projection)
$\left(\lvert C_{7V}^{\mu e}\rvert^2 + \lvert C_{7A}^{\mu e}\rvert^2\right)^{1/2}$	$< 1.3 \times 10^{-6}$	$< 2.2 \times 10^{-5}$		$< 5.1 \times 10^{-6}$
$\left(\lvert y_{7V}^{\mu e}\rvert^2 + \lvert y_{7A}^{\mu e}\rvert^2\right)^{1/2}$			< 0.040	
$\left(\lvert C_9^{B,\mu e}\rvert^2 + \lvert C_{10}^{B,\mu e}\rvert^2\right)^{1/2}$	< 0.71	< 12	< 35	< 2.7

Kaon physics

Tests of CPV already among most stringent (ε_K, ε')

Near future improvements mostly due to theory (Lattice)

More progress foreseen in rare decays

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

⇒ rare K decays at HL-LHCb?

d'Ambrosio, PoS(FPCP2015)018

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