Heavy Fermions in Fundamental Physics

Portoroz, April 2011

The $s \to d\gamma$ decay in and beyond the SM

Christopher Smith

CNRS IN2P3 Les deux infinis

dépasser les frontières

IPNL

Introduction

Electromagnetic current can be flavor changing in the SM, but this requires a delicate interplay (GIM breaking) at the loop level

→ *Very sensitive to NP effects*

	In the SM	*Hadronic effects*	*Experiment*
$\mu \to e\gamma$	Extremely suppressed ($\sim m_\nu$)	*None*	$< 1.2\times10^{-11}$ (MEG)
$b \to s\gamma$	Not so suppressed: $3.15(23)\times10^{-4}$	*Under control (NNLO*)* - Hard photon - Inclusive analysis	Well-measured: $3.55(26)\times10^{-4}$
$s \to d\gamma$	Suppressed: $\frac{V_{ts}^* V_{td}}{V_{ts}^* V_{tb}} \sim 1\%$	*Very large:* - (Very) soft photon(s) - Exclusive (→ K decays)	Many modes, but → *Sensitivity to SD?* → *SM predictions?*

* *Misiak et al.'06*

- Outline

  I. *Anatomy of the* $s \to d\gamma$ *process*

  II. *Observables and SM predictions*

  III. *Sensitivity to New Physics*

P. Mertens, CS, ArXiv:1103.5992

Anatomy of the $s \to d\gamma$ process

A. *The flavor-changing electromagnetic operators*

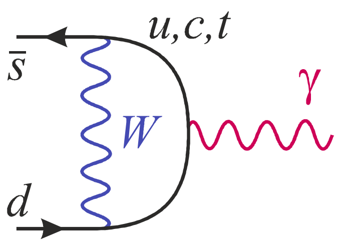
$$\mathcal{H}_{eff} = C_{\gamma}^{L,R}\,\bar{s}_{R,L}\sigma^{\mu\nu}d_{L,R}\,F_{\mu\nu} \qquad \text{Dim 5}$$

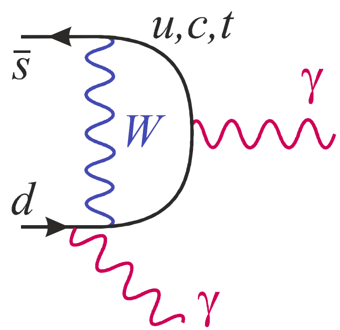
$$+\,C_{\gamma^*}^{L,R}\,\bar{s}_{L,R}\gamma^{\nu}d_{L,R}\,\partial^{\mu}F_{\mu\nu} \qquad \text{Dim 6}$$

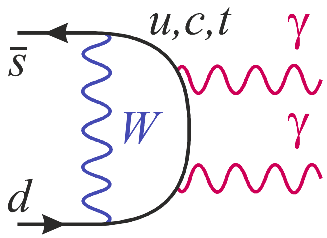
$$+\,C_{\gamma\gamma}^{L,R}\,\bar{s}_{R,L}d_{L,R}\,F_{\mu\nu}F^{\mu\nu} + \tilde{C}_{\gamma\gamma}^{L,R}\,\bar{s}_{R,L}d_{L,R}\,F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \text{Dim 7}$$

$$+\ldots$$

Induced at one loop in the SM:







$+\ldots$

A. *The flavor-changing electromagnetic operators*

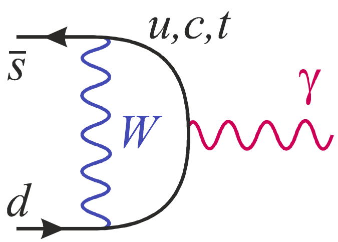
$$\mathcal{H}_{eff} = C_\gamma^{L,R}\, \bar{s}_{R,L}\sigma^{\mu\nu} d_{L,R}\, F_{\mu\nu}$$ Dim 5

$$+ C_{\gamma^*}^{L,R}\, \bar{s}_{L,R}\gamma^\nu d_{L,R}\, \partial^\mu F_{\mu\nu}$$ Dim 6

$$+ C_{\gamma\gamma}^{L,R}\, \bar{s}_{R,L} d_{L,R}\, F_{\mu\nu}F^{\mu\nu} + \tilde{C}_{\gamma\gamma}^{L,R}\, \bar{s}_{R,L} d_{L,R}\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$ Dim 7

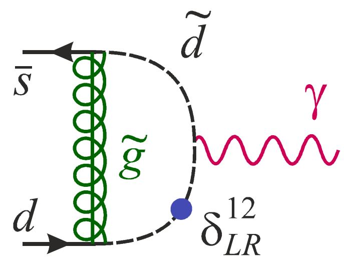
$$+ \dots$$

Induced at one loop in the SM ($x_q \equiv m_q^2 / M_W^2$):



Magnetic: $C_\gamma^{L,R} \sim m_{s,d} \sum_{q=u,c,t} V_{qs}^* V_{qd} D'(x_q)$

Sensitive to NP: Dimension 5 & alternative chirality flips



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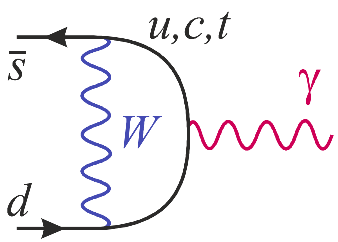
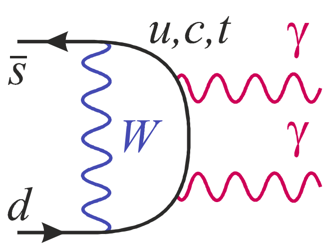
$$+\ldots$$

Induced at one loop in the SM $(x_q \equiv m_q^2 / M_W^2)$:



Magnetic: $C_{\gamma}^{L,R} \sim m_{s,d} \sum_{q=u,c,t} V_{qs}^{*}V_{qd}D'(x_q)$

Electric: $C_{\gamma^*}^{L} \sim \sum_{q=u,c,t} V_{qs}^{*}V_{qd}D(x_q)\ ,\ C_{\gamma^*}^{R} \sim 0$



Double photon: $C_{\gamma\gamma}^{L,R} \sim \sum_{q=u,c,t} V_{qs}^{*}V_{qd}D''(x_q)$

A. *The flavor-changing electromagnetic operators*

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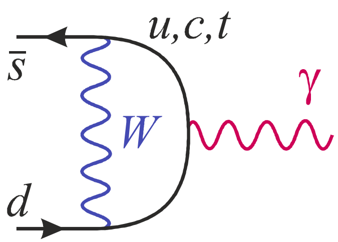
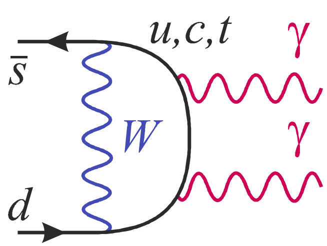
$$+\ldots$$

Induced at one loop in the SM $(x_q \equiv m_q^2 / M_W^2)$: *Long-distance:*



Magnetic: $C_{\gamma}^{L,R} \sim m_{s,d} \sum_{q=u,c,t} V_{qs}^* V_{qd}\, x_q$ *Small???*

Electric: $C_{\gamma^*}^{L} \sim \sum_{q=u,c,t} V_{qs}^* V_{qd} \log(x_q)$ *Large*



Double photon: $C_{\gamma\gamma}^{L,R} \sim \sum_{q=u,c,t} V_{qs}^* V_{qd} \frac{1}{x_q}$ *Dominant*

A. *The flavor-changing electromagnetic operators*

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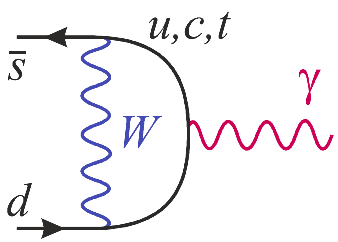
$$+\ldots$$

Induced at one loop in the SM $(x_q \equiv m_q^2 / M_W^2)$:

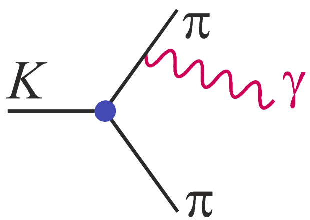
Long-distance:



Magnetic: $C_\gamma^{L,R} \sim m_{s,d} \sum_{q=u,c,t} V_{qs}^* V_{qd}\, x_q$

Small???

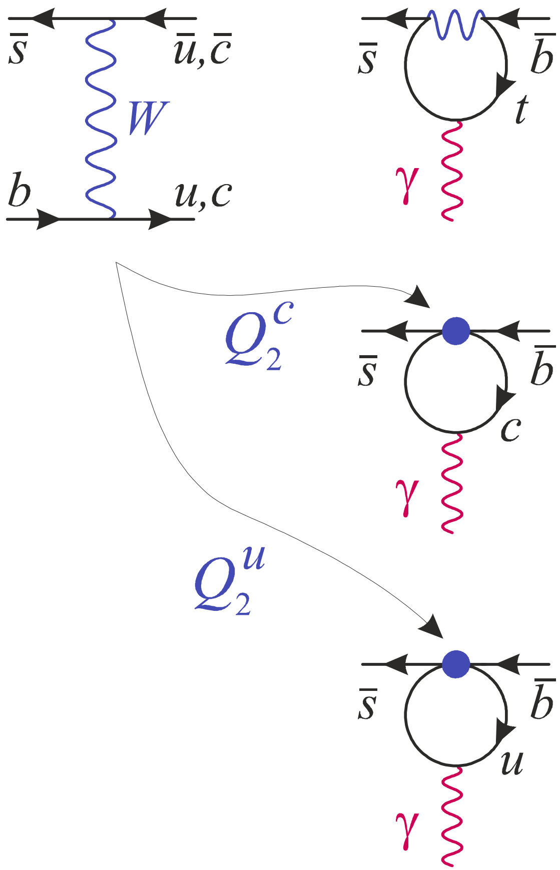
...but this cannot be true, e.g.



is huge!

So, *long-distance QCD corrections are very large*.

B. *QCD corrections and theoretical strategy*



$V_{ts}^* V_{tb}$

$V_{cs}^* V_{cb} \approx -V_{ts}^* V_{tb}$

$V_{us}^* V_{ub} \ll 1$

At M_W: $D'(x_t) \approx +0.40$

$D'(x_c) \approx +0.0001$

↓ + QCD

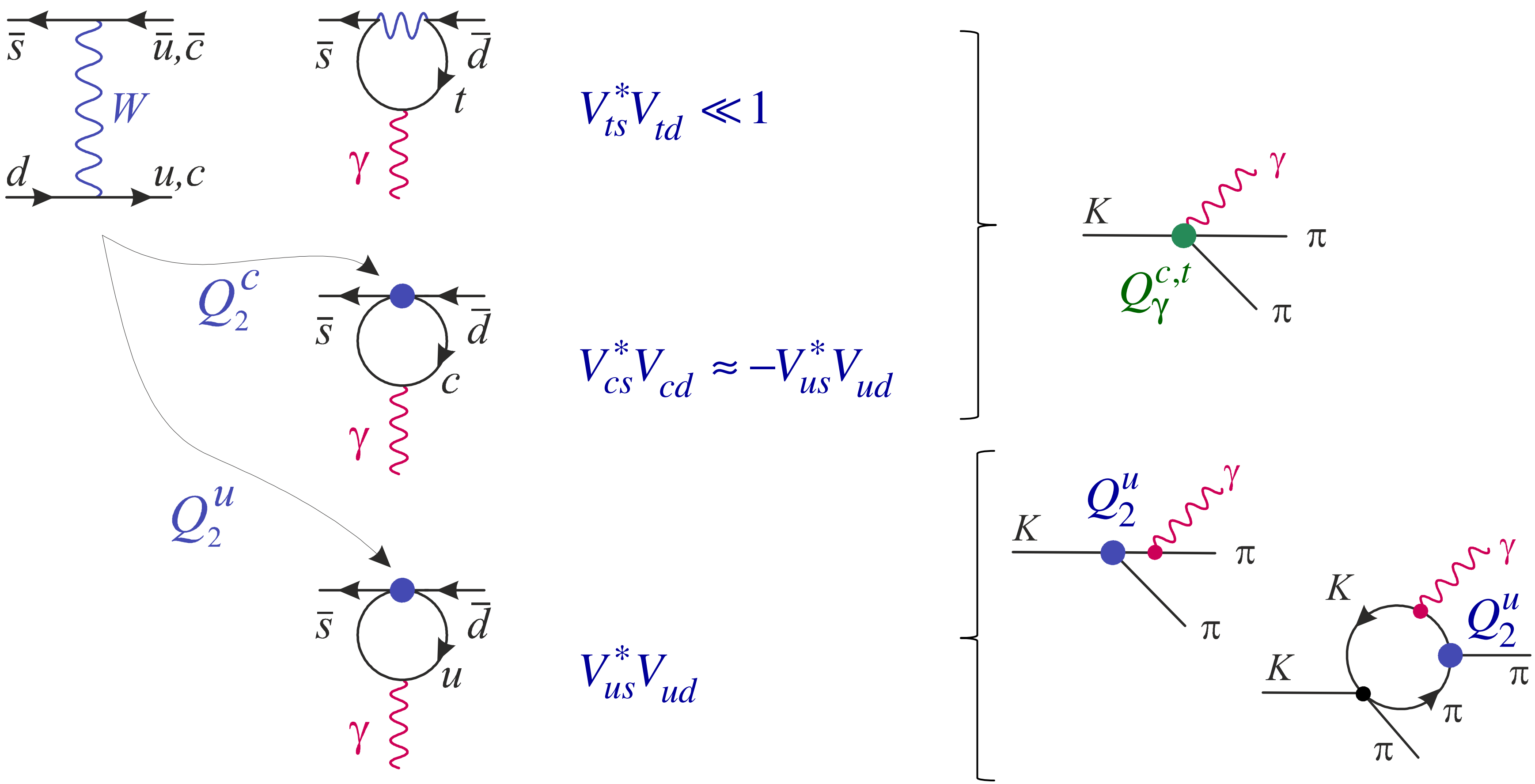
At m_b : $D'(x_t) \approx +0.27$

$D'(x_c) \approx +0.32$

The *c-quark* contribution is large but manageable for $b \to s\gamma$.

See e.g. Shifman,Vainshtein, Zakharov ’78
Buchalla,Buras,Lautenbacher ‘95

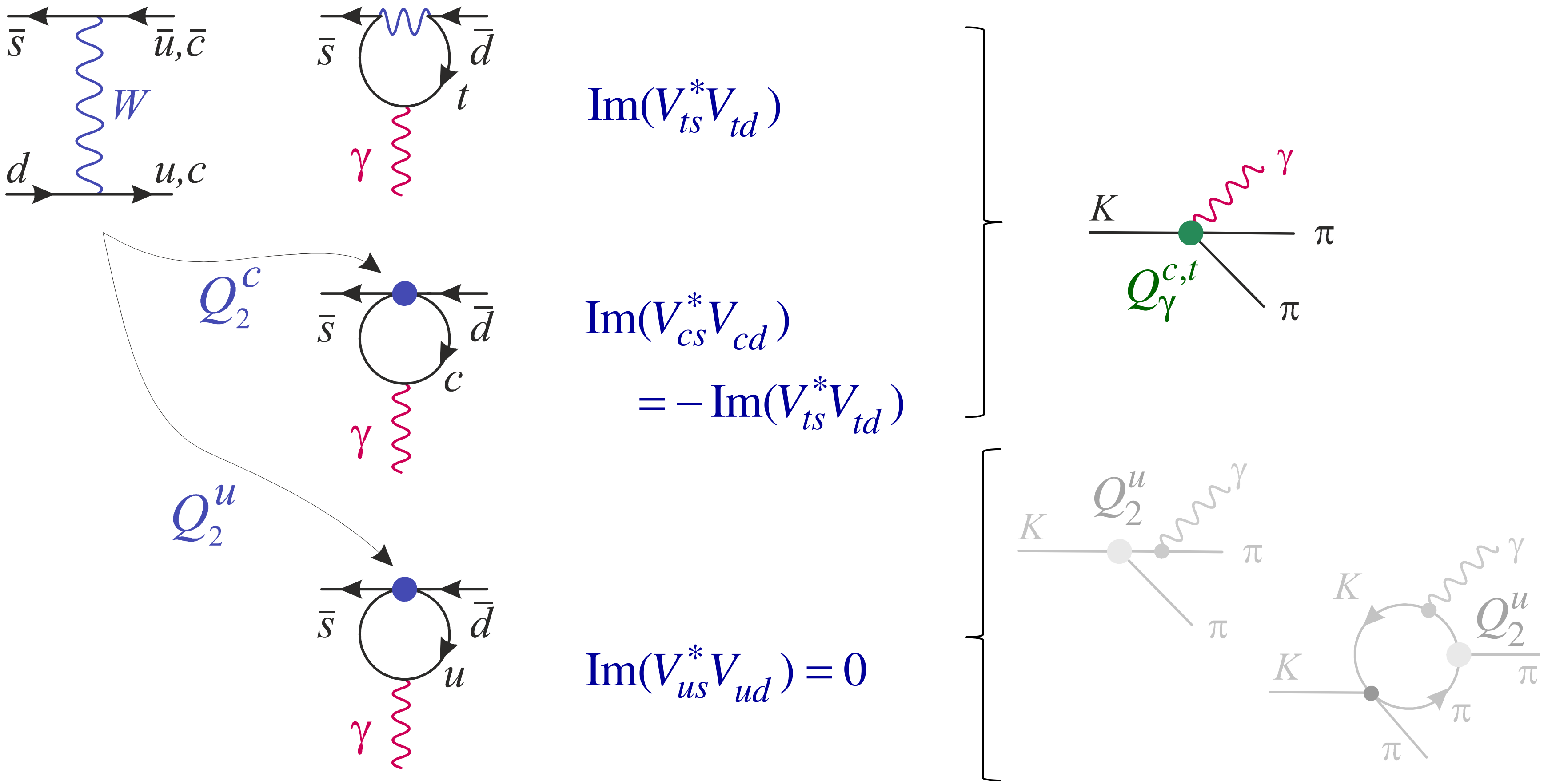
B. *QCD corrections and theoretical strategy*



For $s \to d\gamma$, the *c-quark* is CKM-enhanced, and non-local *u-quark* even larger

→ *Is the sensitivity to SD completely lost?*

B. *QCD corrections and theoretical strategy*

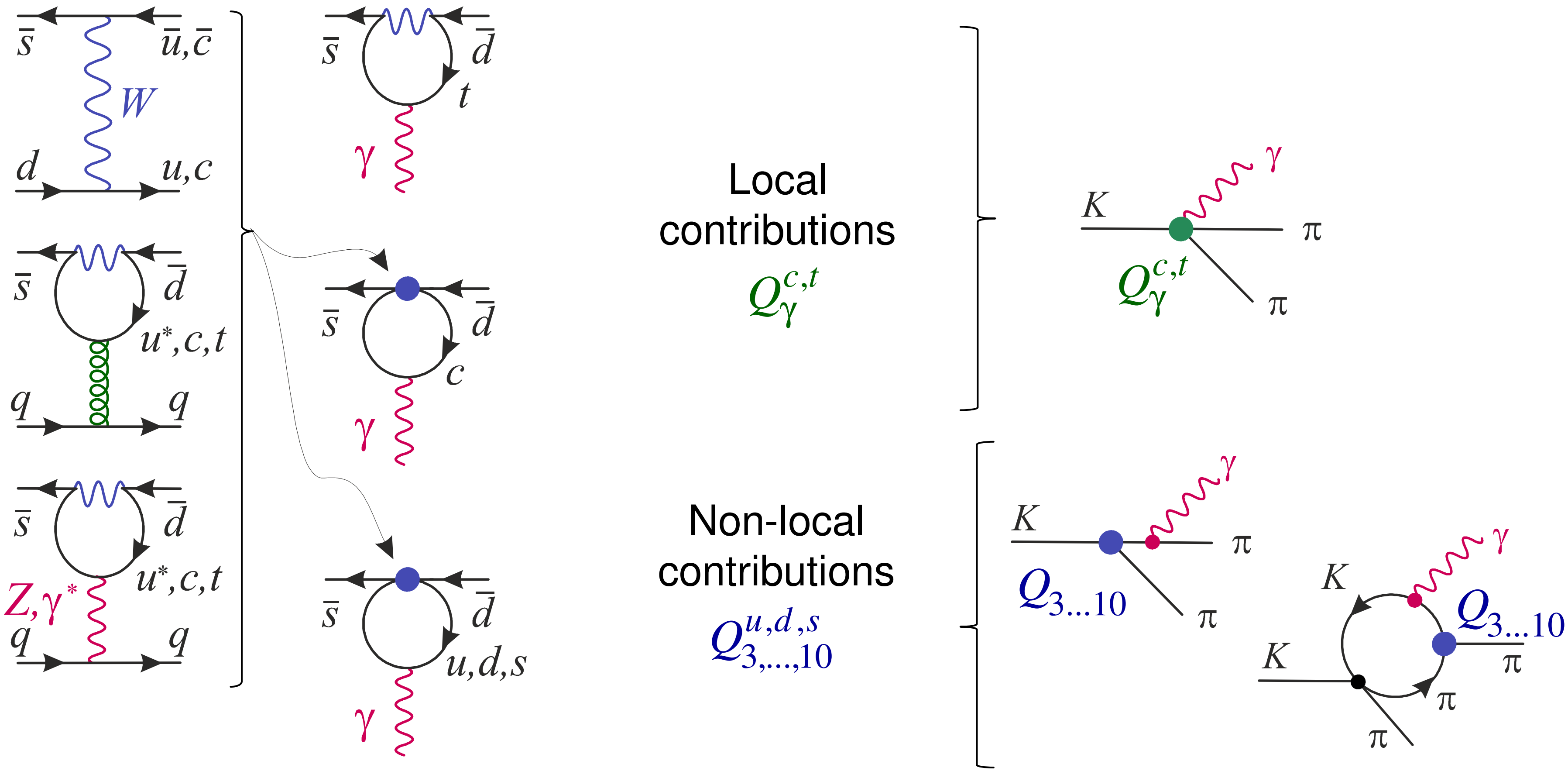


Bypass 1: LD effects are dominantly CP-conserving

→ Look at *CP-violating observables* (CKM scaling as for $b \to s\gamma$)

Anatomy 4/5

B. *QCD corrections and theoretical strategy*

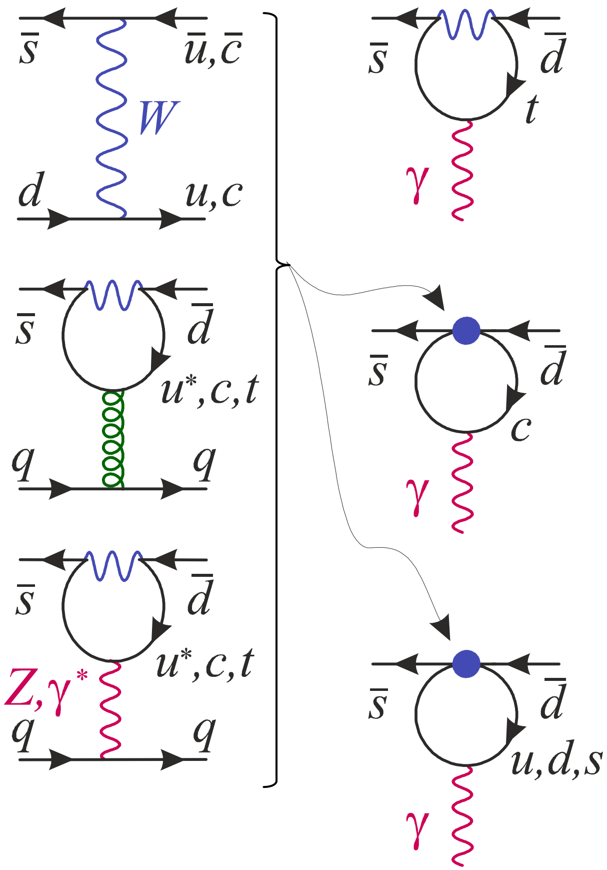


Bypass 1: LD effects are dominantly CP-conserving

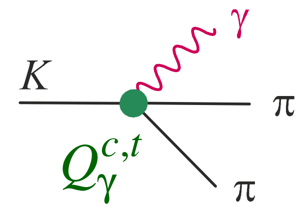
→ Look at *CP-violating observables* (CKM scaling as for $b \to s\gamma$)

→ But still residual long-distance *hadronic penguin* contributions.

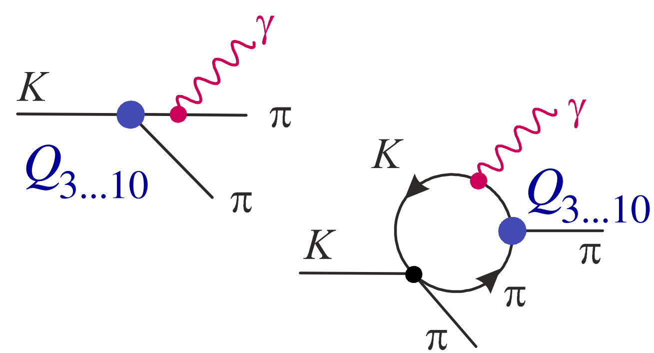
B. *QCD corrections and theoretical strategy*



Local contributions
$Q_\gamma^{c,t}$



Non-local contributions
$Q_{3,\ldots,10}^{u,d,s}$



Bypass 2: Meson processes lack the chirality flip → *Automatic LD–SD factorization*

→ *Good control over meson contributions*
(loops usually finite, no/small CTs).

Observables and SM predictions

A. *Best windows for* $s \to d\gamma$

The magnetic operators $Q_\gamma^{L\pm R}$ contribute to all the *radiative modes*:

$$K \to (n\pi)(m\gamma^{(*)}), \quad \begin{array}{llll} n = & 0 & 1 & 2,3 \\ m = & 2,3,\ldots & 1^*,2,\ldots & 1,2,\ldots \end{array}$$

Dominantly CP-violating observables, with minimal n and m (largest rates):

Real photon(s): $A_{CP}(K \to \gamma\gamma,\ K \to \pi\pi\gamma)$ (only magnetic)

Virtual photon: $Br(K_L \to \pi^0\gamma^*[\to \ell^+\ell^-])$ (electric and magnetic)

Local CP-violating effects ($Q_\gamma^{L\pm R}$) → Local chiral realization of the tensor currents,

Non-local CP-violating effects ($Q_{3\to 10}^{u,d,s}$) → To be estimated using ε'/ε.

B. *Short reminder*

Isospin decomposition:

$$\mathcal{M}(K_1 \to \pi^+\pi^-) = \sqrt{2}A_0 + A_2$$
$$\mathcal{M}(K_1 \to \pi^0\pi^0) = \sqrt{2}A_0 - 2A_2$$
$$\mathcal{M}(K^+ \to \pi^+\pi^0) = 3/2A_2$$

$\Delta I = 1/2$ *rule*:

$$\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2} = 22.4 \equiv \omega^{-1}$$

CP-violation:

$$\frac{\mathcal{M}(K_L \to \pi^+\pi^-)}{\mathcal{M}(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon' \,,\quad \frac{\mathcal{M}(K_L \to \pi^0\pi^0)}{\mathcal{M}(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\varepsilon = \varepsilon_{box} + i\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0} \sim 10^{-3} \,,\quad \varepsilon' = i\frac{e^{i(\delta_2^0-\delta_0^0)}}{\sqrt{2}}\omega\left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right] \sim 10^{-6}$$

$\Delta S = 2$ mixing

$$\frac{\text{EW penguins } (Q_8)}{\text{QCD penguins } (Q_6)} = \frac{\mathrm{Im}\,A_2}{\mathrm{Im}\,A_0} \equiv \Omega\omega \overset{SM\,?}{=} 0.35(15)\omega$$

C. *The* $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ *decay*

Ecker, Neufeld, Pich, '94

Direct charge asymmetry: interfering amplitudes + different weak & strong phases.

$$\mathcal{M} = \varepsilon_{\mu}^{*}(k)\left[E(p_{+,0}) \frac{p_0^{\mu} p_+ \cdot k - p_+^{\mu} p_0 \cdot k}{m_K^3} + M(p_{+,0}) \frac{i\varepsilon^{\mu\nu\rho\sigma} p_{+,\nu} p_{0,\rho} k_{\sigma}}{m_K^3} \right]$$

$$E(p_{+,0}) = E_{IB}(p_{+,0}) + E_{DE}(p_{+,0})$$

Low theorem:

$$E_{IB}(p_{+,0}) \sim \frac{\mathcal{M}(K^{+} \to \pi^{+}\pi^{0})}{k \cdot p_{+}\, k \cdot p_{K}}$$

Strong phase: $I = 2, L = 0$

Weak phase: $Q_{7\to 10}$

Multipole expansion:

$$E_{DE}(p_{+,0}) = E_1(k) + E_2(k)(p_{+} - p_{0}) \cdot k + \ldots$$

Strong phase: $I = 1, L = 1$

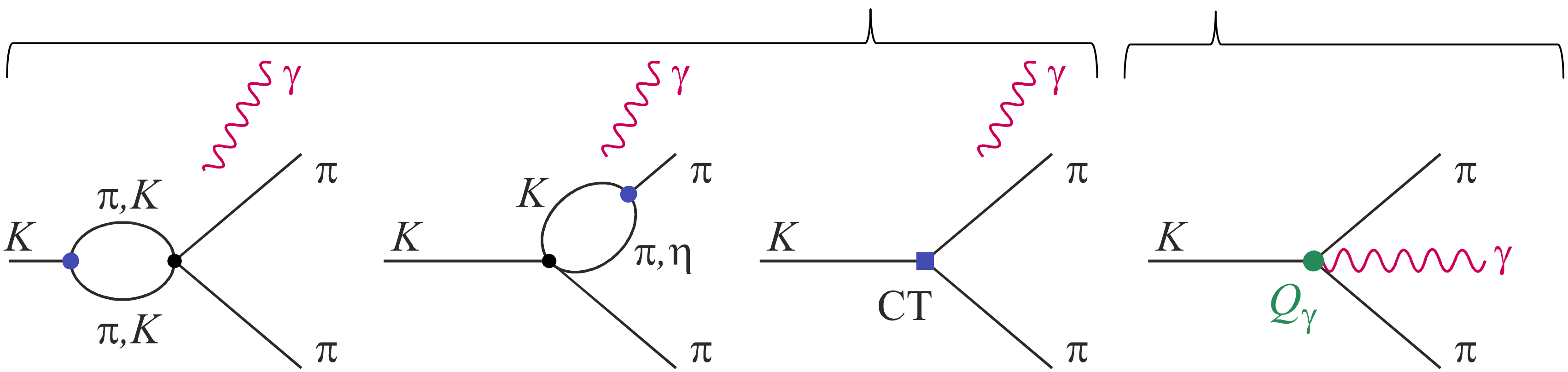
Weak phase: $Q_{3\to 10}$, Q_{γ}^{L-R}

C. *The* $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ *decay*

The CP-violating parameter is

$$\varepsilon'_{+0\gamma} = \frac{\mathrm{Im}\, E_{DE}}{\mathrm{Re}\, E_{DE}} - \frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} \approx -\frac{2}{3}\frac{\sqrt{2}\,|\varepsilon'|}{\omega}\left[1+\frac{\Omega}{1-\Omega}\omega\right] + 3\,\mathrm{Im}\, C_{\gamma}^{L-R}$$

$$-0.6(3)\times 10^{-4} \qquad +1.2(4)\times 10^{-4}$$



The $\Delta I = 1/2$ suppressed loops are enhanced by the ππ contribution

$\varepsilon'_{+0\gamma}$ is $\Delta I = 1/2$ enhanced, but its sensitivity to Ω is $\Delta I = 1/2$ suppressed.

C. *The* $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ *decay*

The CP-violating parameter is

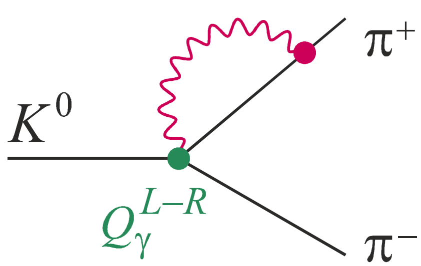
$$\varepsilon'_{+0\gamma} = \frac{\mathrm{Im}\, E_{DE}}{\mathrm{Re}\, E_{DE}} - \frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} \approx -\frac{2}{3}\frac{\sqrt{2}\,|\varepsilon'|}{\omega}\left[1+\frac{\Omega}{1-\Omega}\omega\right] + 3\,\mathrm{Im}\, C_\gamma^{L-R}$$

$$-0.6(3)\times 10^{-4} \qquad\qquad +1.2(4)\times 10^{-4}$$

Experimentally: $\varepsilon'_{+0\gamma} = -0.21 \pm 0.34 \quad \to \mathrm{Im}\, C_\gamma^{L-R} \leq -0.08 \pm 0.13$

(NA48/2 '10)

- Large room for NP effects!
- Sufficient to control a missing contribution to ε'/ε :



$$\frac{\mathrm{Re}(\varepsilon'/\varepsilon)_\gamma}{\mathrm{Re}(\varepsilon'/\varepsilon)^{\exp}} \approx \frac{2}{3}\varepsilon'_{+0\gamma} = 16(26)\%$$

C. *The* $K^0 \to \pi^+\pi^-\gamma$ *decay*

The CP-violating parameter is

D'Ambrosio,Isidori, '95,'98
Tandean,Valencia, '00

$$\varepsilon'_{+-\gamma} \sim \frac{\mathcal{M}(K_L \to \pi^+\pi^-\gamma)_{IB+DE_1}}{\mathcal{M}(K_S \to \pi^+\pi^-\gamma)_{IB+DE_1}} - \frac{\mathcal{M}(K_L \to \pi^+\pi^-)}{\mathcal{M}(K_S \to \pi^+\pi^-)}$$

The $IB + DE_1$ amplitude is CP-violating (conserving) for $K_{L(S)} \to \pi^+\pi^-\gamma$.

$$\varepsilon'_{+-\gamma} \sim -0.4 |\varepsilon'| e^{i\phi_{\varepsilon'}} + 0.2\,\mathrm{Im}\, C_\gamma^{L-R}\; e^{i\phi_\gamma}$$

$$-2\times 10^{-6} \qquad\qquad +8\times 10^{-6}$$

Totally insensitive to Ω (non-trivial cancellation!), and $\Delta I = 1/2$ suppressed.

Experimentally: $\varepsilon'_{+-\gamma} < 0.06 \quad \to \mathrm{Im}\, C_\gamma^{L-R} \leq 0.3$
(Matthews et al.'95)

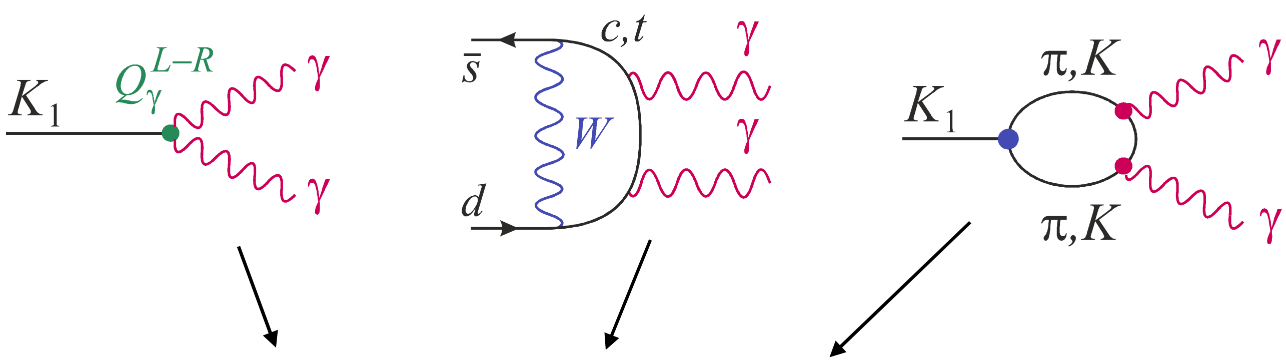
D. *The* $K^0 \to \gamma\gamma$ *decays*

Sehgal,Wolfenstein, '67
Martin,De Rafael, '68
Decker,Pavlopoulos,Zoupanos, '85

The CP-violating parameters are

$$\frac{\mathcal{M}(K_L \to \gamma\gamma_{\parallel})}{\mathcal{M}(K_S \to \gamma\gamma_{\parallel})} = \varepsilon + \varepsilon'_{\parallel}\,, \quad \frac{\mathcal{M}(K_S \to \gamma\gamma_{\perp})}{\mathcal{M}(K_L \to \gamma\gamma_{\perp})} = \varepsilon + \varepsilon'_{\perp}$$

For the parallel polarization:



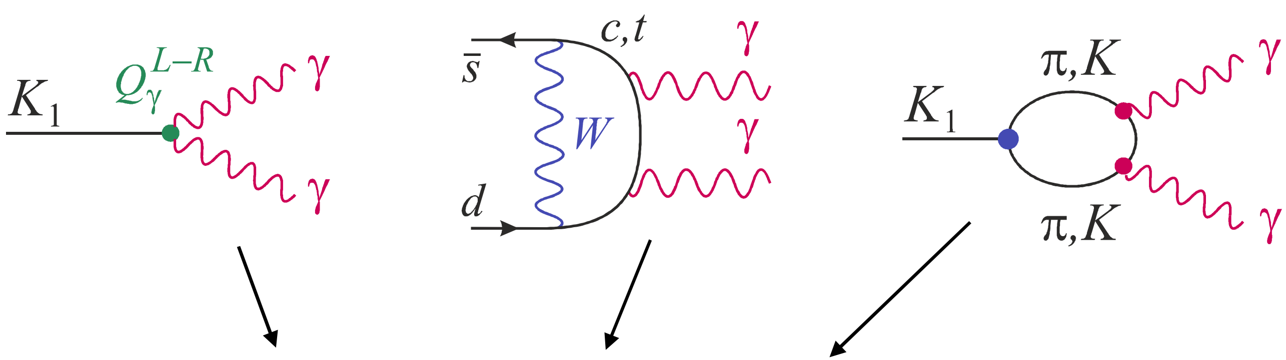
$$\varepsilon'_{\parallel} = i\left[\frac{\text{Im}\, A_{\gamma}^{L-R}}{\text{Re}\, A_{\gamma}^{L-R}} + \frac{\text{Im}\, A_{SD}^{\parallel}}{\text{Re}\, A_{SD}^{\parallel}} + \frac{\text{Im}\, A_{LD}^{\parallel}}{\text{Re}\, A_{LD}^{\parallel}} - \frac{\text{Im}\, A_0}{\text{Re}\, A_0}\right]$$

D. *The* $K^0 \to \gamma\gamma$ *decays*

The CP-violating parameters are

$$\frac{\mathcal{M}(K_L \to \gamma\gamma_{\parallel})}{\mathcal{M}(K_S \to \gamma\gamma_{\parallel})} = \varepsilon + \varepsilon'_{\parallel}\,, \quad \frac{\mathcal{M}(K_S \to \gamma\gamma_{\perp})}{\mathcal{M}(K_L \to \gamma\gamma_{\perp})} = \varepsilon + \varepsilon'_{\perp}$$

For the parallel polarization:



$$\varepsilon'_{\parallel} = i\left[\frac{\mathrm{Im}\, C_{\gamma}^{L-R}}{3} + \; < 10^{-7} \; + \frac{|\varepsilon'|\, e^{-i(\delta_2^0-\delta_0^0)}}{1+\omega/\sqrt{2}}\right]$$

$\sim 10^{-5}$ $\qquad\qquad$ $\sim 10^{-6}$ (*)

(*)Buccella, D'Ambrosio, Miragliuolo, '91

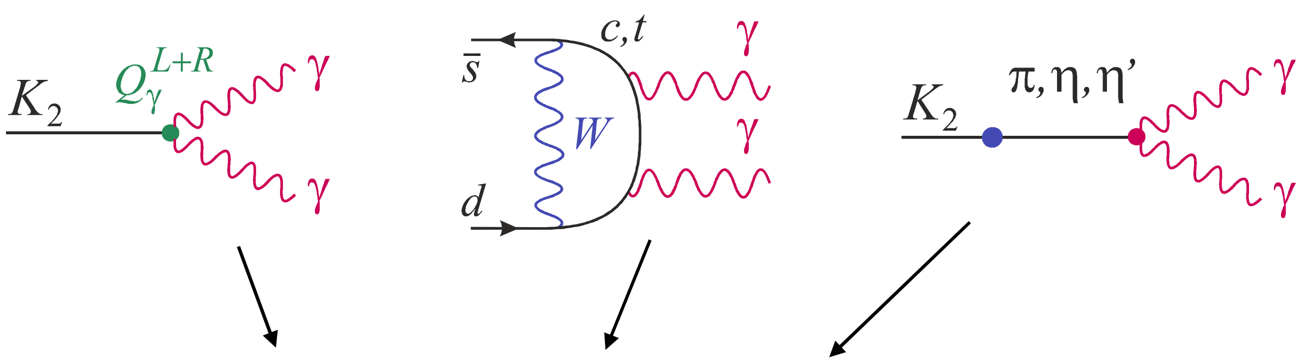
Totally insensitive to Ω and $\Delta I = 1/2$ suppressed.

D. *The* $K^0 \to \gamma\gamma$ *decays*

The CP-violating parameters are

$$\frac{\mathcal{M}(K_L \to \gamma\gamma_{\parallel})}{\mathcal{M}(K_S \to \gamma\gamma_{\parallel})} = \varepsilon + \varepsilon'_{\parallel}\,, \quad \frac{\mathcal{M}(K_S \to \gamma\gamma_{\perp})}{\mathcal{M}(K_L \to \gamma\gamma_{\perp})} = \varepsilon + \varepsilon'_{\perp}$$

For the orthogonal polarization:



$$\varepsilon'_{\perp} = i\left[\frac{\mathrm{Im}\,A_{\gamma}^{L+R}}{\mathrm{Re}\,A_{\gamma}^{L+R}} + \frac{\mathrm{Im}\,A_{SD}^{\perp}}{\mathrm{Re}\,A_{SD}^{\perp}} + \frac{\mathrm{Im}\,A_{LD}^{\perp}}{\mathrm{Re}\,A_{LD}^{\perp}} - \frac{\mathrm{Im}\,A_{0}}{\mathrm{Re}\,A_{0}}\right]$$

D. *The* $K^0 \to \gamma\gamma$ *decays*

The CP-violating parameters are

$$\frac{\mathcal{M}(K_L \to \gamma\gamma_{\parallel})}{\mathcal{M}(K_S \to \gamma\gamma_{\parallel})} = \varepsilon + \varepsilon'_{\parallel}\,, \quad \frac{\mathcal{M}(K_S \to \gamma\gamma_{\perp})}{\mathcal{M}(K_L \to \gamma\gamma_{\perp})} = \varepsilon + \varepsilon'_{\perp}$$

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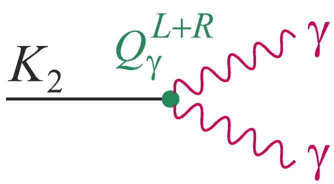
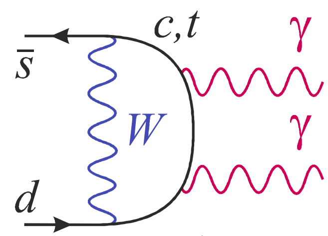
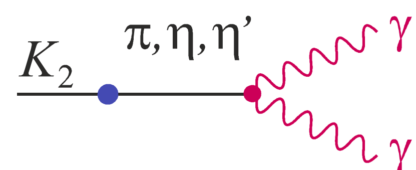






Q_1^u only!!

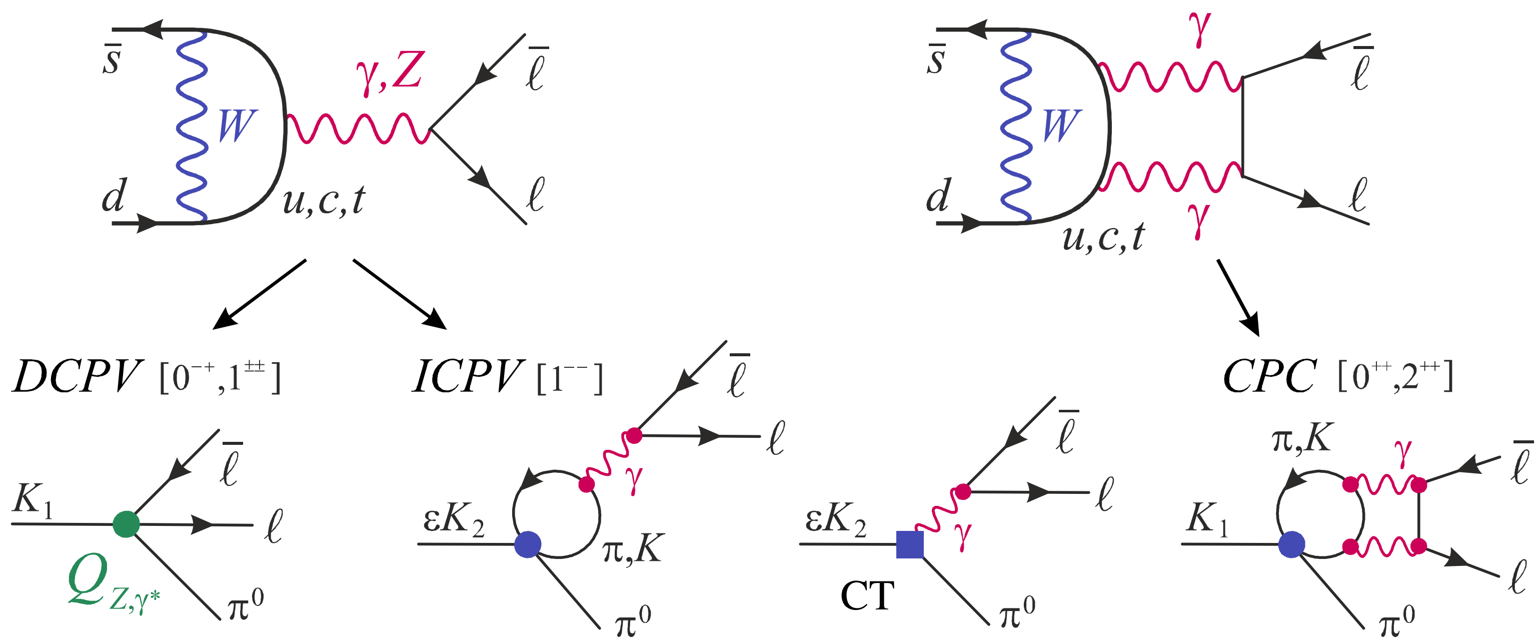
Gérard,Smith,Trine, '05

$$\varepsilon'_{\perp} = i\left[\frac{\operatorname{Im} C_\gamma^{L+R}}{2} + <10^{-7} + \sim 0 \quad - \frac{\operatorname{Im} A_0}{\operatorname{Re} A_0}\right] \approx i\,\frac{\sqrt{2}\,|\varepsilon'|}{\omega(1-\Omega)}$$

$\sim 10^{-5}$ $\qquad 5\times10^{-5} \to 7\times10^{-4}$

Directly measures the *QCD penguins* (hence Ω) and is $\Delta I = 1/2$ enhanced.

E. *The* $K_L \to \pi^0 \ell^+ \ell^-$ *decays*



With NP only in $Q_\gamma^{L\pm R}$, the current experimental bounds imply: (KTeV '00,'04)

$$B(K_L \to \pi^0 e^+ e^-) < 2.8\times 10^{-10} \quad \to -0.018 \le \mathrm{Im}\, C_\gamma^{L+R} \le 0.030$$

$$B(K_L \to \pi^0 \mu^+ \mu^-) < 3.8\times 10^{-10} \quad \to -0.050 \le \mathrm{Im}\, C_\gamma^{L+R} \le 0.063$$

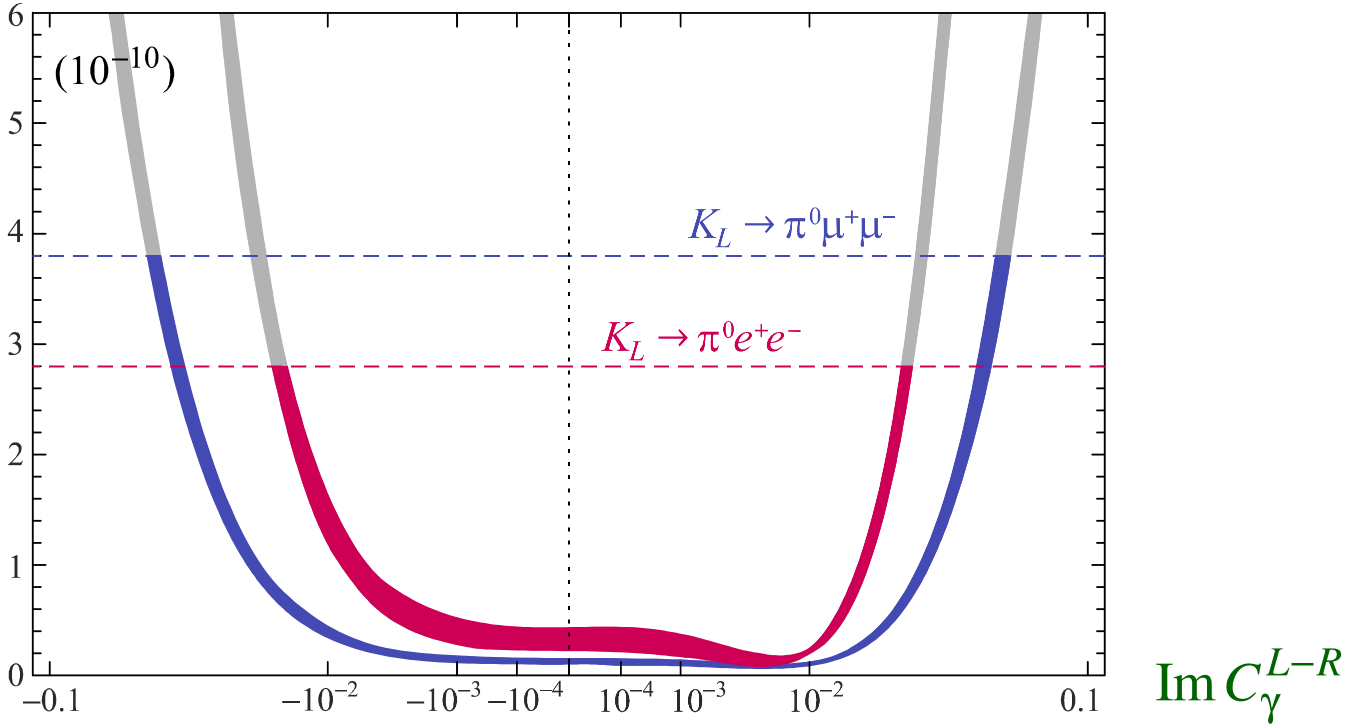
New Physics effects

A. *How large could the asymmetries be?*

With large NP in $Q_\gamma^{L\pm R}$, the asymmetries satisfy

$$\frac{1}{3}\left|\varepsilon'_{+0\gamma}\right| \approx 5\left|\varepsilon'_{+-\gamma}\right| \approx 3\left|\varepsilon'_{||}\right| \approx \mathrm{Im}\, C_\gamma^{L-R}$$

Experimental information is still scarce, so use $K_L \to \pi^0 \ell^+ \ell^-$

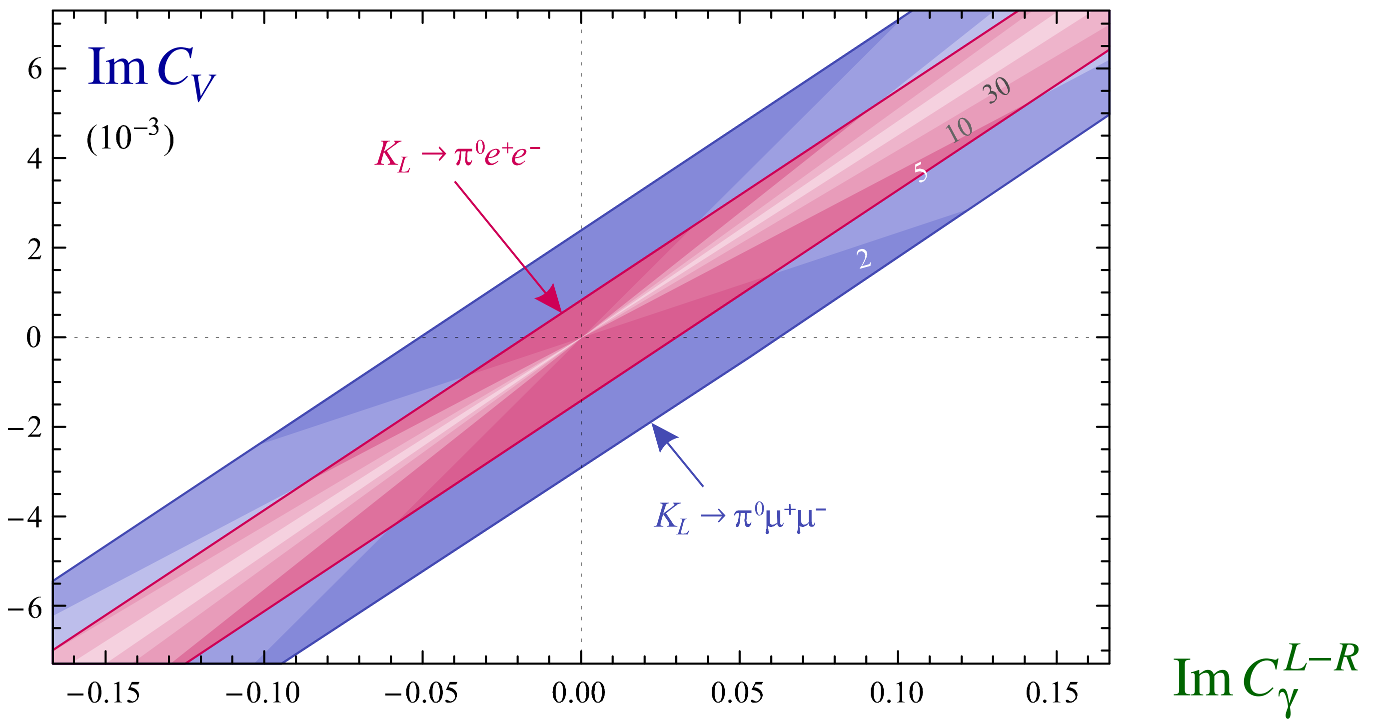


B. *The model-independent basis*

Magnetic penguin can interfere with semi-leptonic operators:

$$\mathcal{H}_{eff}^{sl} = \bar{s}\gamma^{\mu} d \otimes [C_V \bar{\ell}\gamma_{\mu}\ell + C_A \bar{\ell}\gamma_{\mu}\gamma_5\ell + C_{\nu}\bar{\nu}_L\gamma_{\mu}\nu_L]$$

A large (but not extreme) 80% cancellation: $\varepsilon'_{+0\gamma}$ reaches the $K^+ \to \pi^+\pi^0\gamma$ bound.
$(\mathrm{Im}\, C_{\gamma}^{L-R} \leq -8(13)\%)$



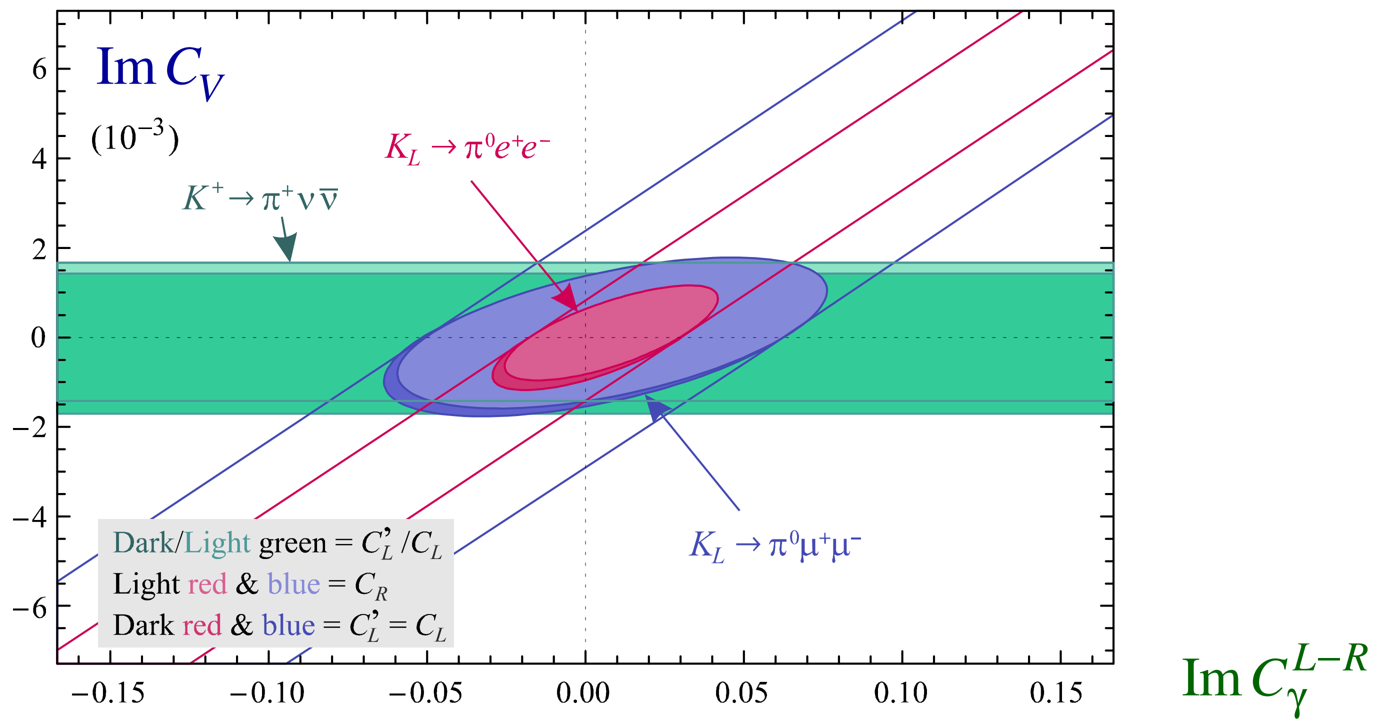
C. *The gauge basis*

Buchmuller,Wyler, '86

If NP is gauge-invariant & tree-level (LQ, RPV,...):

$$\mathcal{H}_{eff}^{sl} = \bar{s}\gamma^{\mu}d \otimes \left[C_L \bar{L}\gamma_{\mu}L + C_L' \bar{L}\gamma_{\mu}\sigma_3 L + C_R \bar{E}\gamma_{\mu}E\right]$$

All the operators contribute either to $K \to \pi\nu\bar{\nu}$ or $K_L \to \pi^0(\ell^+\ell^-)^{1++,0-+}$.



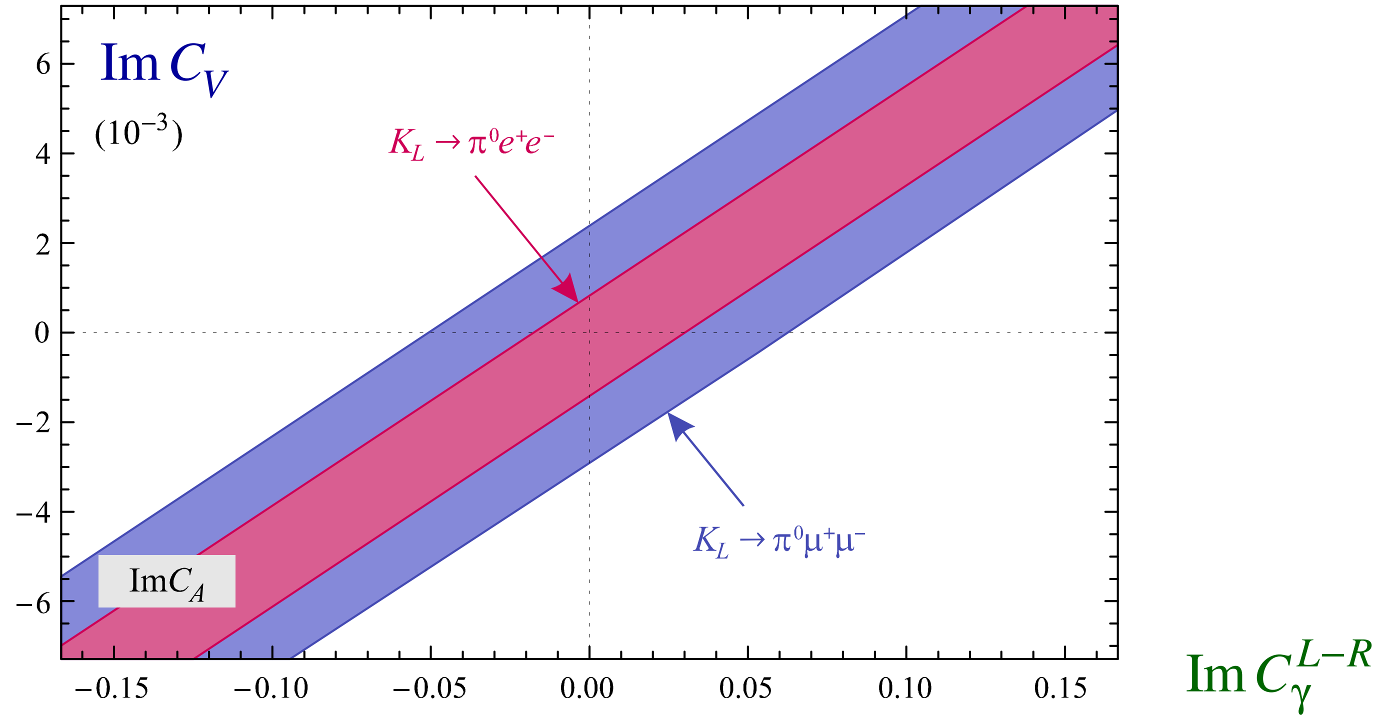
D. *The "penguin-box" basis – Electroweak version*

Buchalla,Buras,Harlander, '91

If NP arises from the same FCNC as in the SM (MSSM, 4th, LHT,...):

$$\mathcal{H}_{eff}^{sl} = \bar{s}\gamma^{\mu}d \otimes \left[\frac{s_W^2(4C_Z + C_A)}{4}\bar{\ell}\gamma_{\mu}\ell + \frac{C_Z - C_B}{2}\bar{\ell}_L\gamma_{\mu}\ell_L + \frac{C_Z - 4C_B}{2}\bar{\nu}_L\gamma_{\mu}\nu_L \right]$$

Electromagnetic penguins are entangled in $K_L \to \pi^0(\ell^+\ell^-)^{1--}$.



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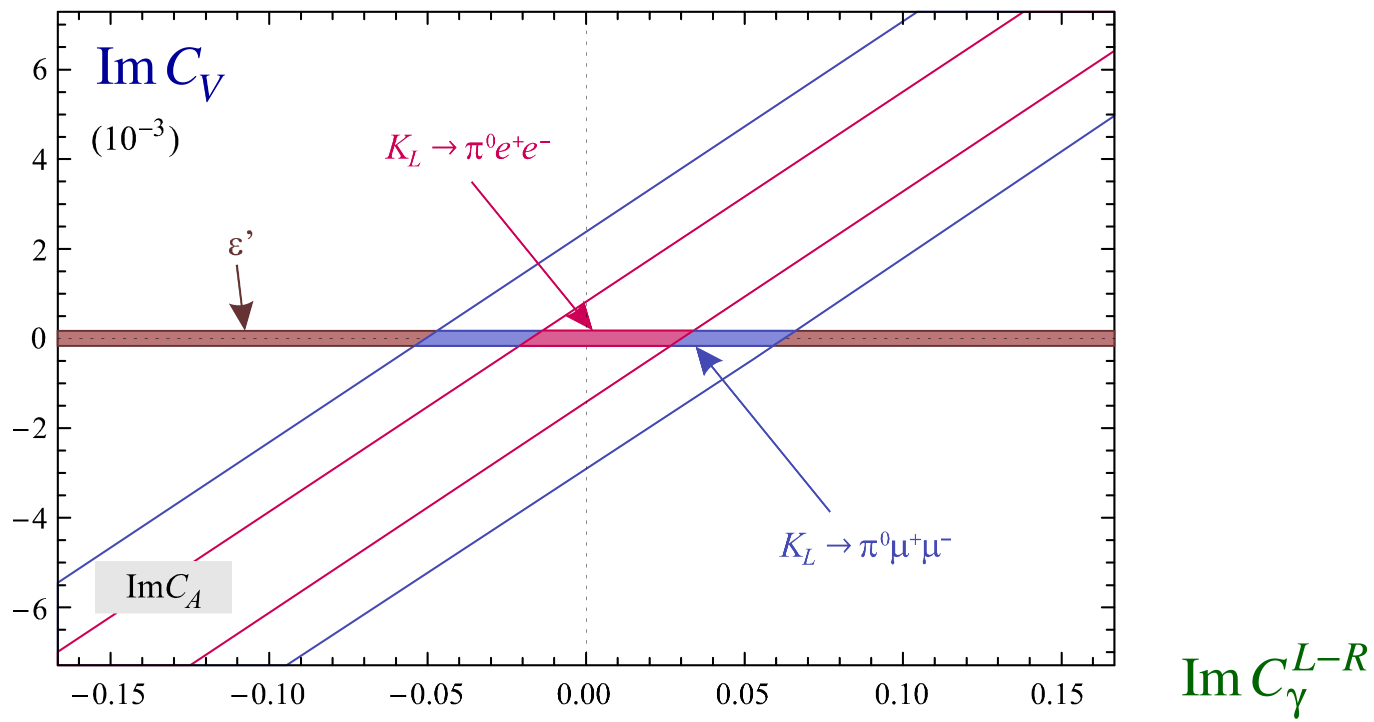
But the photon penguin may contributes to $\mathrm{Re}(\varepsilon'/\varepsilon) \approx 2\,\mathrm{Im}(4C_Z + C_A) + \ldots$



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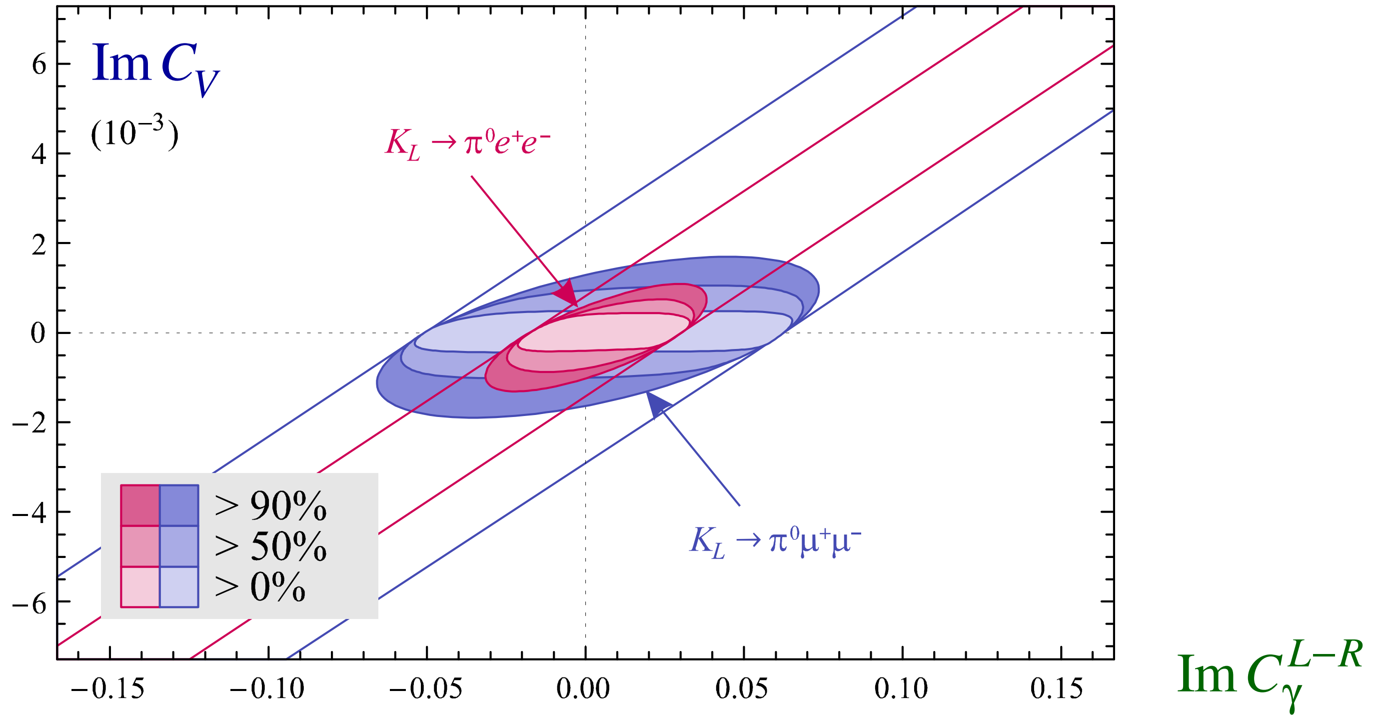
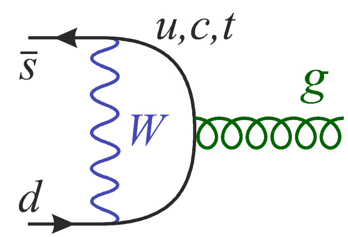


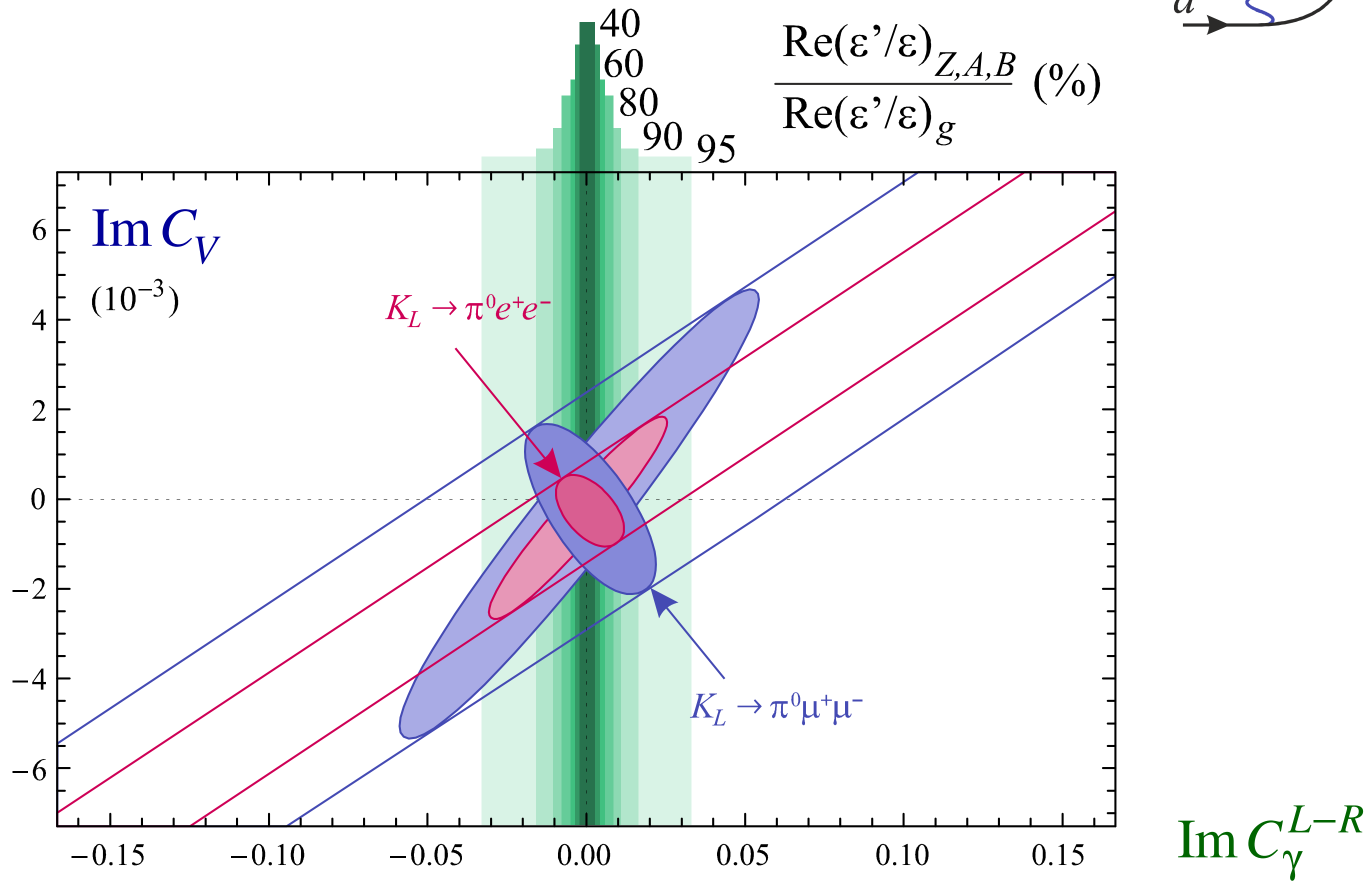
E. *The "penguin-box" basis – Gluonic (or MSSM) version*

Buras,Colangelo,Isidori,
Romanino,Silvestrini, '00

Loop particles colored and charged → *Chromomagnetic penguins*



Let us fix $\mathrm{Im}\, C_\gamma^{L+R} = \pm 3/2\, \mathrm{Im}\, C_g^{L-R}$



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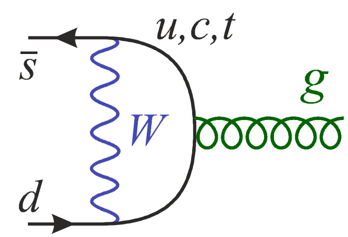
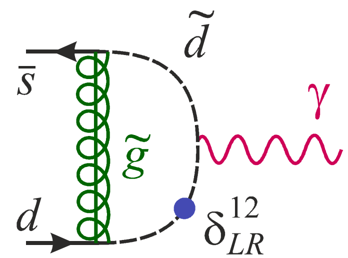


Let us fix $\mathrm{Im}\, C_\gamma^{L+R} = \pm 3/2\, \mathrm{Im}\, C_g^{L-R}$

A large (but not impossible) 80% cancellation in ε' allows for



$$\mathrm{Im}\, C_\gamma^{L+R} \approx 10^{-2}$$

- Close to $K_L \to \pi^0 e^+ e^- \to \left|\mathrm{Im}\, C_\gamma^{L+R}\right| \leq 0.03$
- Much larger than $\left|\mathrm{Im}\, C_\gamma^{L+R}\right| \leq 7\times 10^{-4}$ without cancellations.
- Corresponds to the maximum allowed for $\mathrm{Im}\, \delta_{LR}^{D,12}$ from ε.

Definitive test: $|\varepsilon'_\perp|_g = \dfrac{\sqrt{2}\,|\varepsilon|}{\omega}\mathrm{Re}(\varepsilon'/\varepsilon)_g \approx 65\% \times |\varepsilon|$

$$|\varepsilon'_\perp|_\gamma = \frac{1}{4}\mathrm{Re}(\varepsilon'/\varepsilon)_g \approx 220\% \times |\varepsilon| \approx \frac{1}{6}\left|\varepsilon'_{+0\gamma}\right| \approx \frac{5}{2}\left|\varepsilon'_{+-\gamma}\right| \approx \frac{3}{2}\left|\varepsilon'_{||}\right|$$

Conclusion

The $s \to d\gamma$ transition is now under good control theoretically.

- Several observables are identified

- Their sensitivity to NP is quantified → *Often large* (even few tens of %)

Radiative decays could hold the key to (finally) control and probe $\varepsilon' / \varepsilon$

- Magnetic contribution under control thanks to $K^+ \to \pi^+ \pi^0 \gamma$.

- The $K_{L,S} \to \gamma\gamma_\perp$ asymmetry could directly measure QCD penguins.

→ The full set of radiative asymmetries can signal cancellations between NP in the EW and the QCD penguins.

Radiative decays should complement the physics program of NA62/K0TO.

With $K \to \pi\nu\bar{\nu}$ sensitive only to the *Z penguin*,
and $K_L \to \pi^0 \ell^+ \ell^-$ sensitive also to *Higgs penguins*,
the *radiative decays* offer pure probes of the *photon penguins*.