$K_L \to \pi\ell\ell$ and radiative K decays

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in collaboration with
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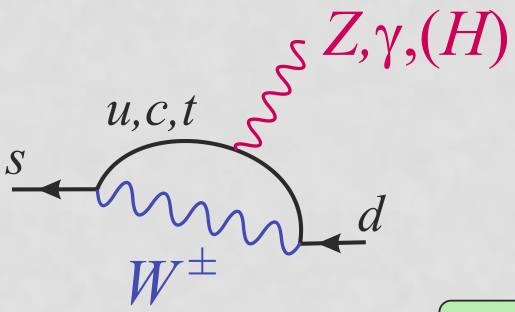
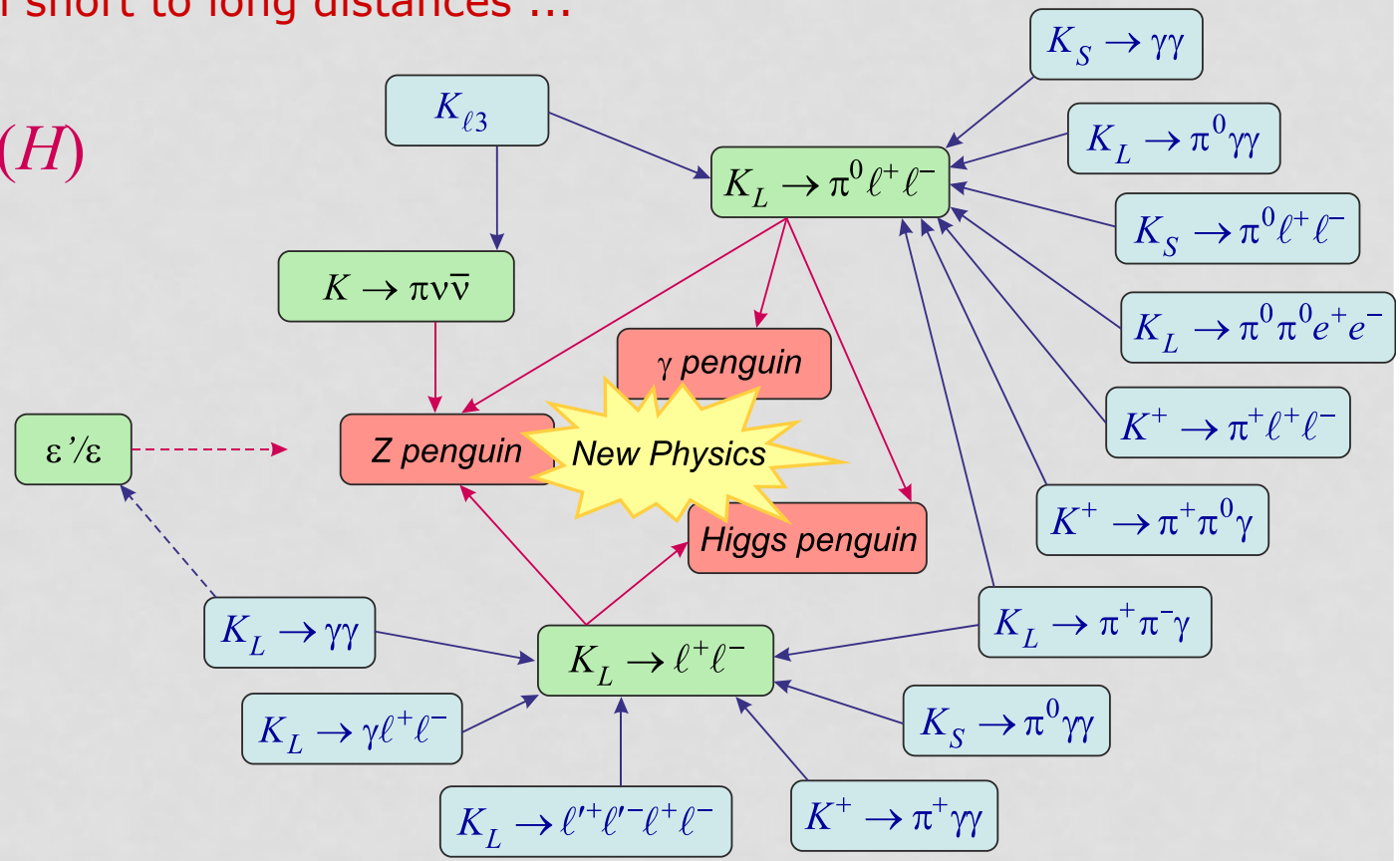
2012 Project X Physics Study, Kaon Working Group
Fermi National Accelerator Laboratory

A. Round-trip from short to long distances ...





$\approx 1000\,\mathrm{GeV}$

New Physics

$\approx 100\,\mathrm{GeV}$

Electroweak windows

$\approx 0.5\,\mathrm{GeV}$

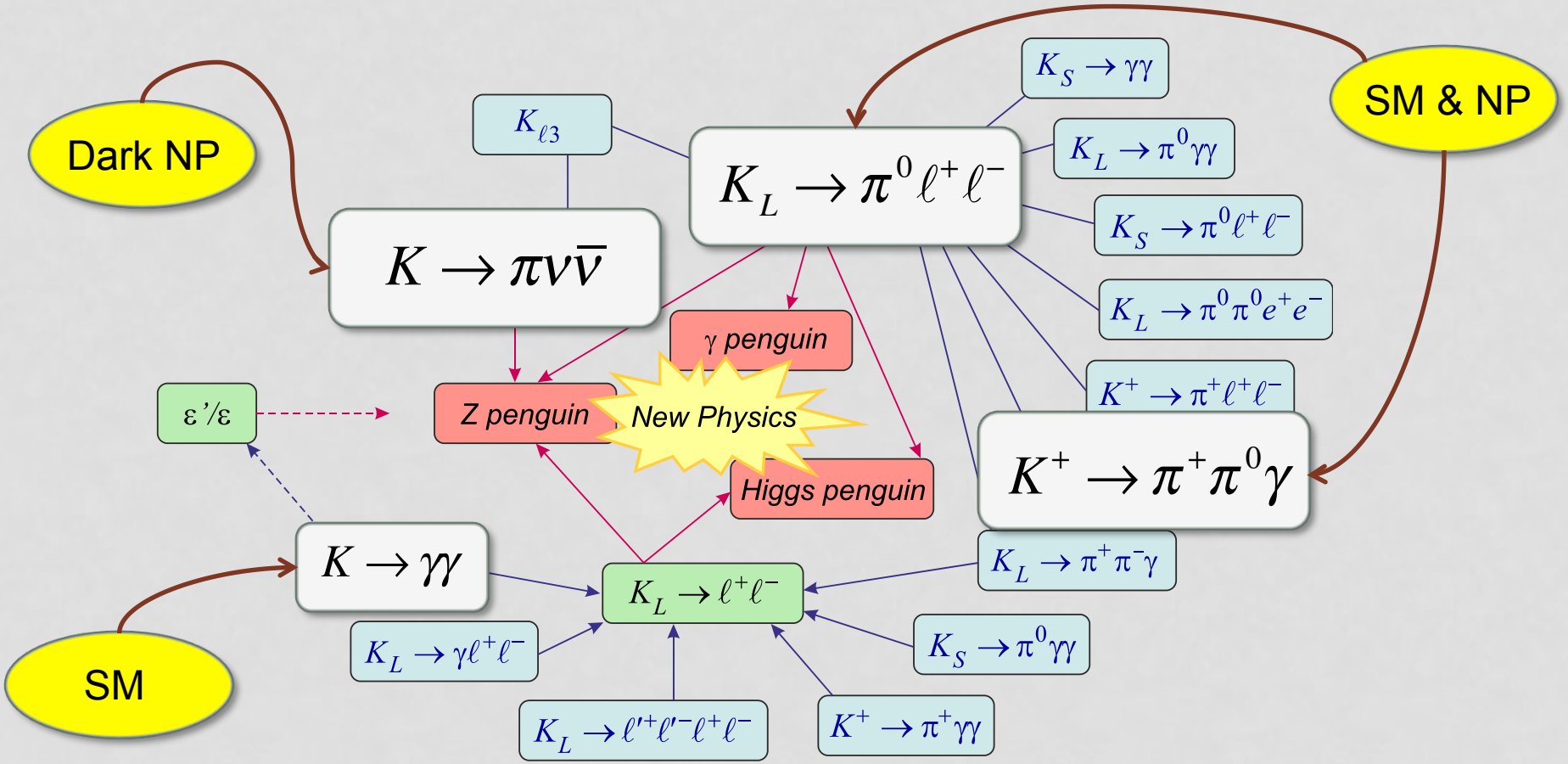
Golden modes:
Rare decays

Chiral Theory

$\approx 0.5\,\mathrm{GeV}$

Radiative modes provides :
Control on Hadronic effects

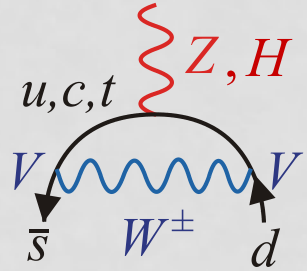
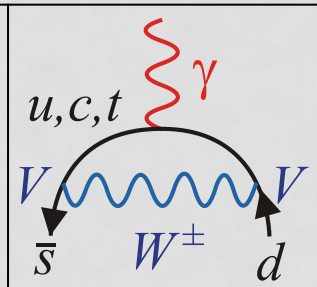
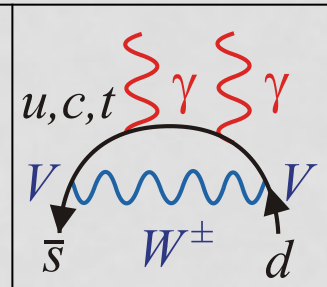
B. The « connections and complementarity » picture :



TH : Ulrich's, Joachim's, Stephania's and Wolfgang's talk.

EXP : Patrizia's, David's, Elizabeth's, Yau's and Laurence's talk.

C. Disentangling FCNC :

				
Rare	$K \to \pi\nu\bar{\nu}$	SD (no H)	-	-
	$K_L \to \pi^0 \ell^+ \ell^-$	SD	SD+ ε_K LD	α_{QED} LD
	$K_{L,S} \to \ell^+ \ell^-$	SD	-	α_{QED} LD
Radiative	$K_S, K^+ \to \pi^{0,+} \ell^+ \ell^-$	Negligible, except for CP-asymmetries.	LD	(α_{QED}-suppr.)
	$K \to (n\pi)\gamma\gamma$		-	LD
	$K \to (n\pi)\gamma$		LD	-

The dark side of $K \to \pi \nu \bar{\nu}$

A. Are there only SM particles at low-energy?

Experimentally:

- Even very light states could be missed if very weakly interacting,
- There is dark matter in the Universe; it could be relatively light.

Theoretically: Plenty of models predict new light particles.

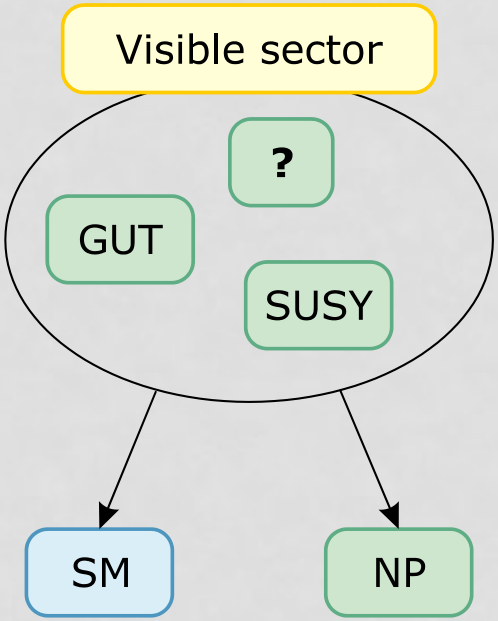
- Pseudo-Goldstone scalars (axion, familon,...),
- U(1) vectors (string, ED,...),
- Hidden sectors & messengers (SUSY, mirror worlds,...)
- Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...

Phenomenologically, the dark state can be assumed

- Unstable → No DM constraints,
- Long-lived → Escape as missing energy,
- Weakly coupled → SM processes unaffected.

} Main impact is to open new decay channels.

B. How to systematically investigate the low-energy particle content?

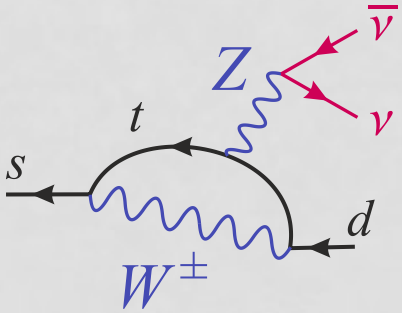


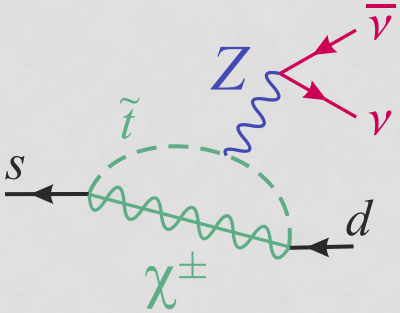
Dark matter

$$\mathrm{L}_{SM} + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

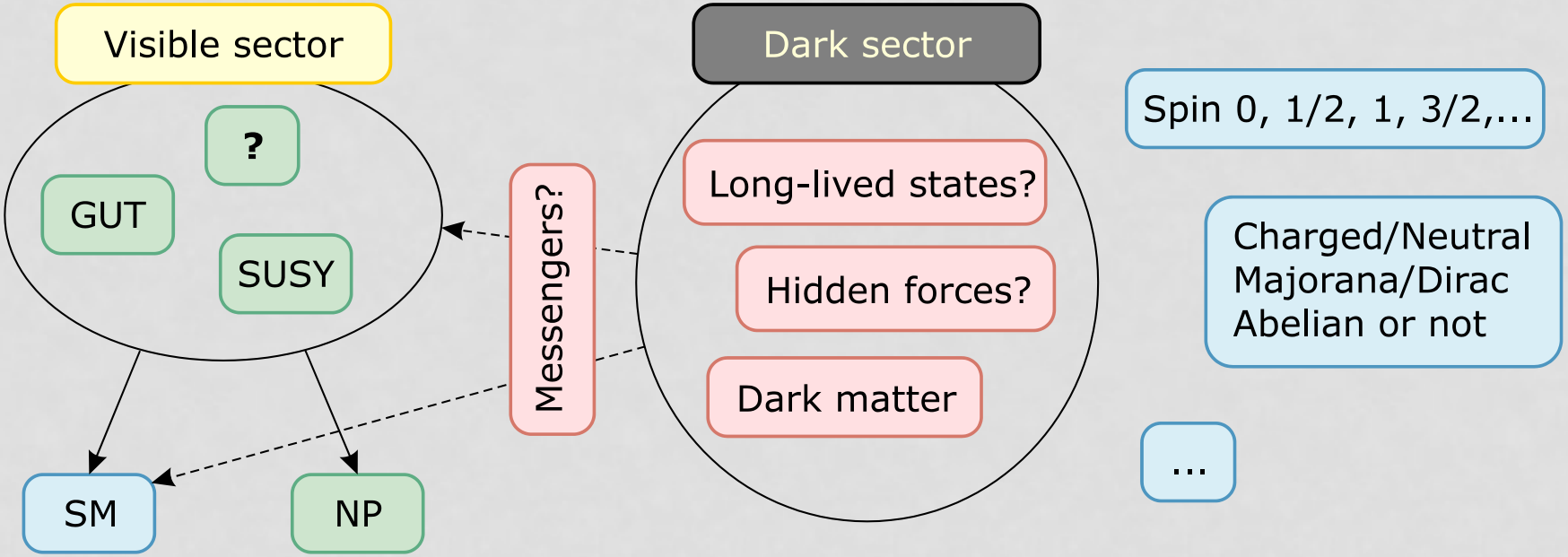
Buchmüller, Wyler '86

Weinberg '79



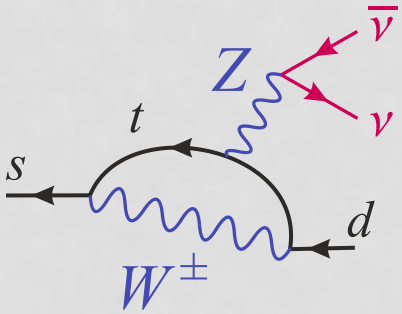


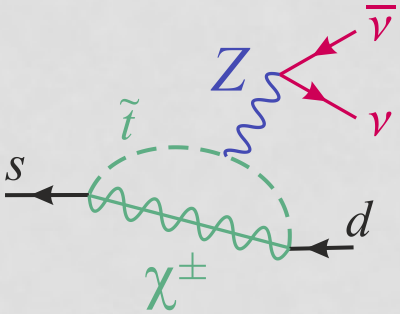
B. How to systematically investigate the low-energy particle content?

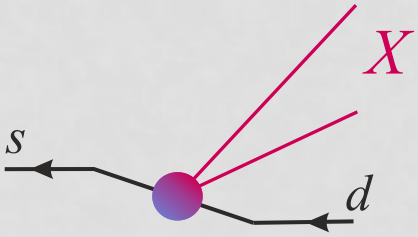


$$\mathrm{L}_{SM} + \frac{c_i}{\Lambda^2} Q_i + \ldots + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

Kamenik, Smith '11

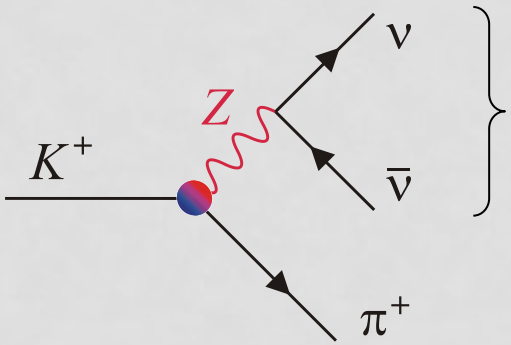






C. What rare K decays could tell?

Only the pion is seen, whose energy is not fixed (three-body decay).



Missing "energy": $z = (p_\nu + p_{\bar{\nu}})^2 / m_K^2$

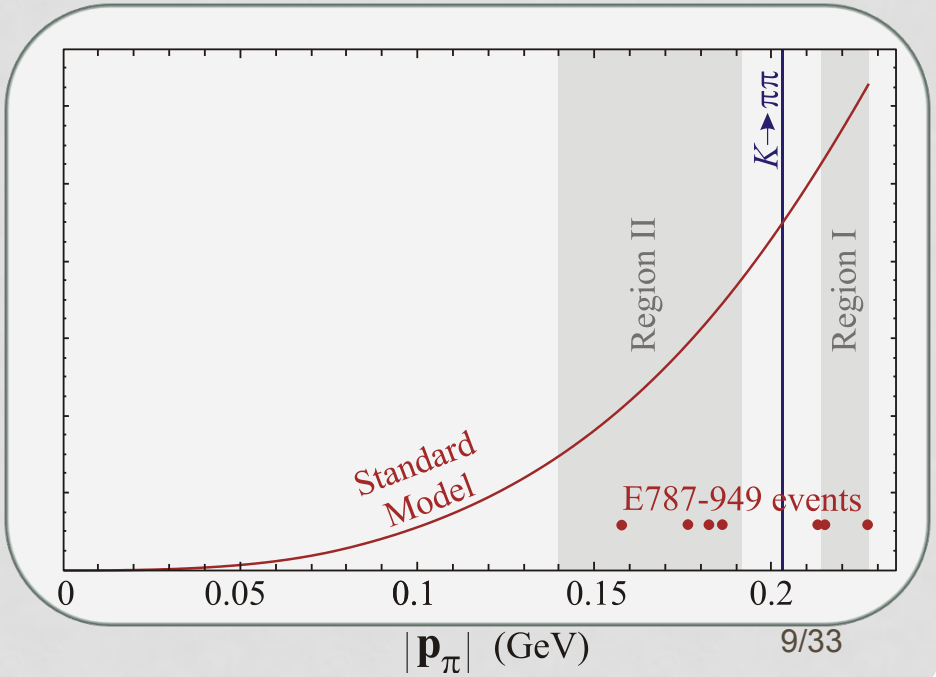
Pion momentum: $|\mathbf{p}_\pi| = \frac{m_K}{2}\lambda(1, z, r_\pi^2)$

The V-A interaction of the SM predicts:

$$\frac{\partial \ln \Gamma}{dz} \sim \frac{|\mathbf{p}_\pi|^3}{m_K^3} |f(z)|^2$$

with $\langle \pi | \bar{s}\gamma^\mu d | K \rangle \approx f(z)(p_K + p_\pi)^\mu$.

Crucial tool for background rejection!



C. What rare K decays could tell? Five messages:

1- For $K \to \pi\nu\bar{\nu}$, use the correct SM spectrum:

Mescia & Smith '06

- Fixed from $K_{\ell 3}$ slopes → $f(z)$ will evolve!

2- For $K \to \pi + \not{E}$ with $\not{E}$ = dark state(s), the spectrum may not be V-A.

- It could even be a two-body decay (e.g. axion-like scalars).
- So, keep open the possibility to alter the spectrum,
- Measure $\Gamma_{\text{Region I}} / \Gamma_{\text{Region II}}$ as model-independently as possible.

3- Dark particles may be more massive than neutrinos.

- Important to probe the region between $\pi\pi\pi$ and the $\pi\pi$ peak.

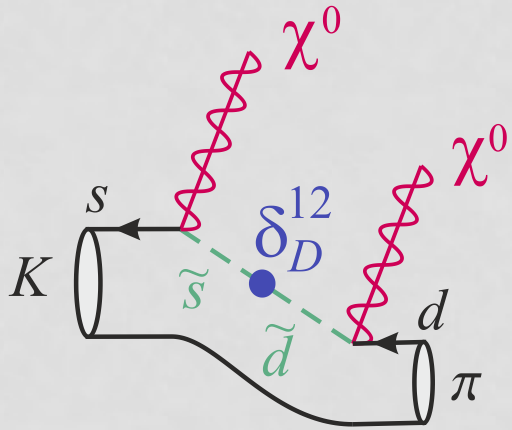
4- $K_L \to \gamma + \not{E}$ is also very sensitive to dark states.

- Neutrino mode not a background since $\mathrm{B}(K_L \to \gamma\nu\bar{\nu})^{SM} \approx 3 \cdot 10^{-13}$.

5- $K_L \to \not{E}$ is best but inaccessible (?); $K \to \pi\pi + \not{E}$ are not competitive.

Example 1: Very light neutralinos in the generic MSSM

Dreiner et al. '09
Kamenik, Smith '11

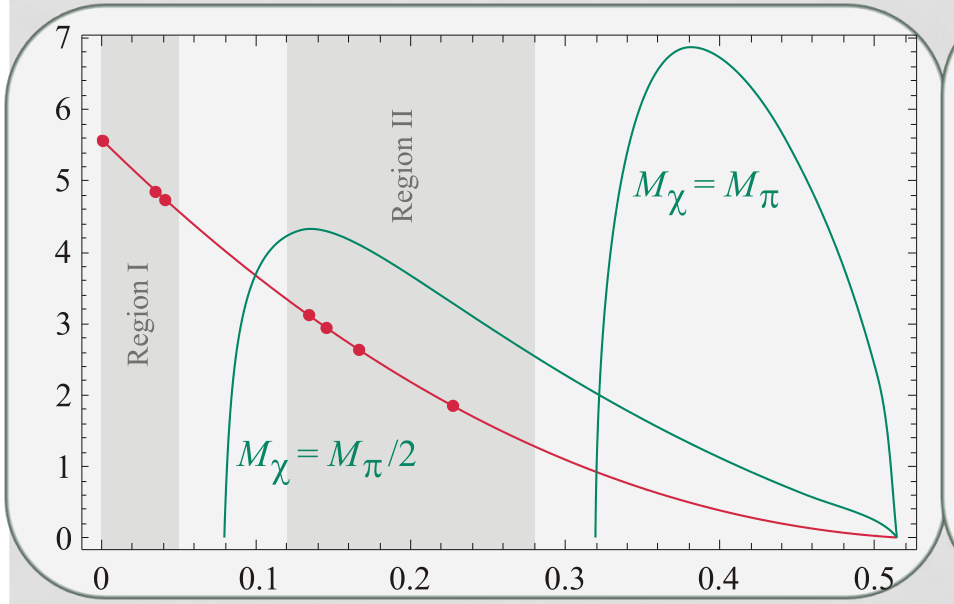


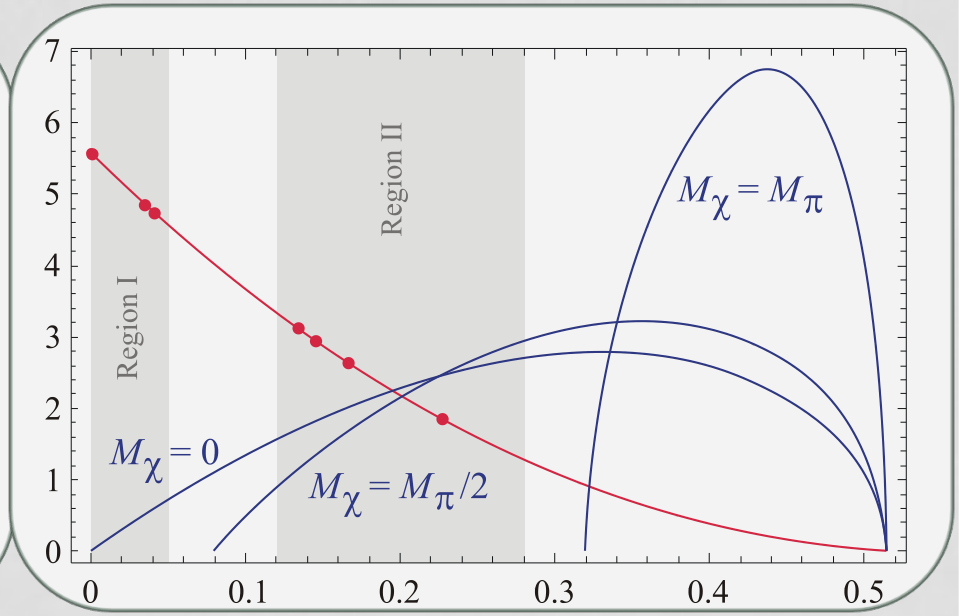
(Axial-)vector :

$\bar{s}\gamma^\mu(1\pm\gamma_5)d \otimes \bar{\chi}\gamma_\mu\gamma_5\chi$

(Pseudo)scalar:

$\bar{s}(1\pm\gamma_5)d \otimes \bar{\chi}(1\pm\gamma_5)\chi$





Example 2: Kinetically-mixed light vector boson

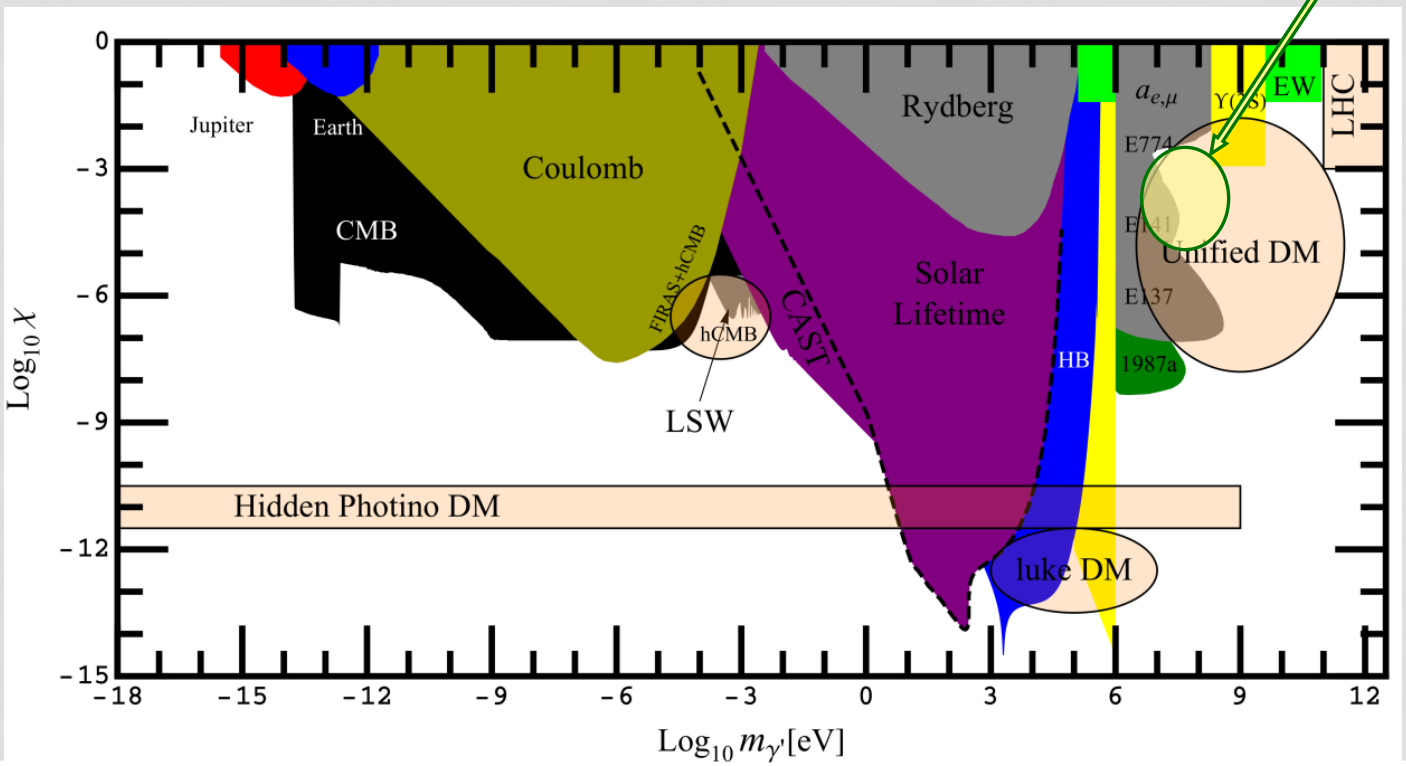
Holdom '86
Arkani-Hamed et al. '08
Kamenik, Smith '11

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} \to e\chi V_\mu \left(\tfrac{2}{3}\bar{u}\gamma^\mu u - \tfrac{1}{3}\bar{d}\gamma^\mu d - \tfrac{1}{3}\bar{s}\gamma^\mu s \right)$$

Up to $m_V \neq 0$, rates proportional to those of radiative decays.

$K \to \pi V$: Very suppressed because $K \to \pi\gamma$ is forbidden.

$K \to \gamma V$: A bound in the 10^{-12} range probes down to χ : $4 \cdot 10^{-5}$.

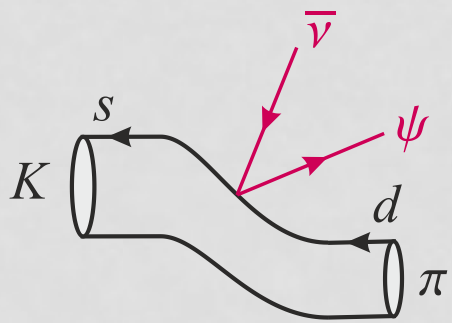


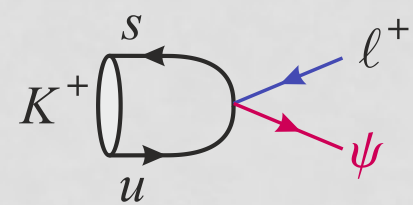
Jaeckel, Ringwald, 1002.0329

Example 3: Leptonic dark state (sterile neutrino,...)

Correlated neutral and charged current interactions:

$$\mathcal{H}_{eff} = \frac{1}{\Lambda^2}(\bar{d}_L s_R \otimes \bar{\nu}_L \psi + \bar{u}_L s_R \otimes \bar{\ell}_L \psi)$$





Rare FCNC modes like $K \to \pi + \not{E}$ probe scales up to $\Lambda:\ 100\ \mathrm{TeV}$.

Current universality test,

$$\mathcal{R}_K^{\exp} = \frac{\Gamma(K_{e2})^{SM} + \Gamma(K \to e\psi)}{\Gamma(K_{\mu 2})^{SM} + \Gamma(K \to \mu\psi)}$$

reaches a similar scale $\Lambda:\ 80\ \mathrm{TeV}$.

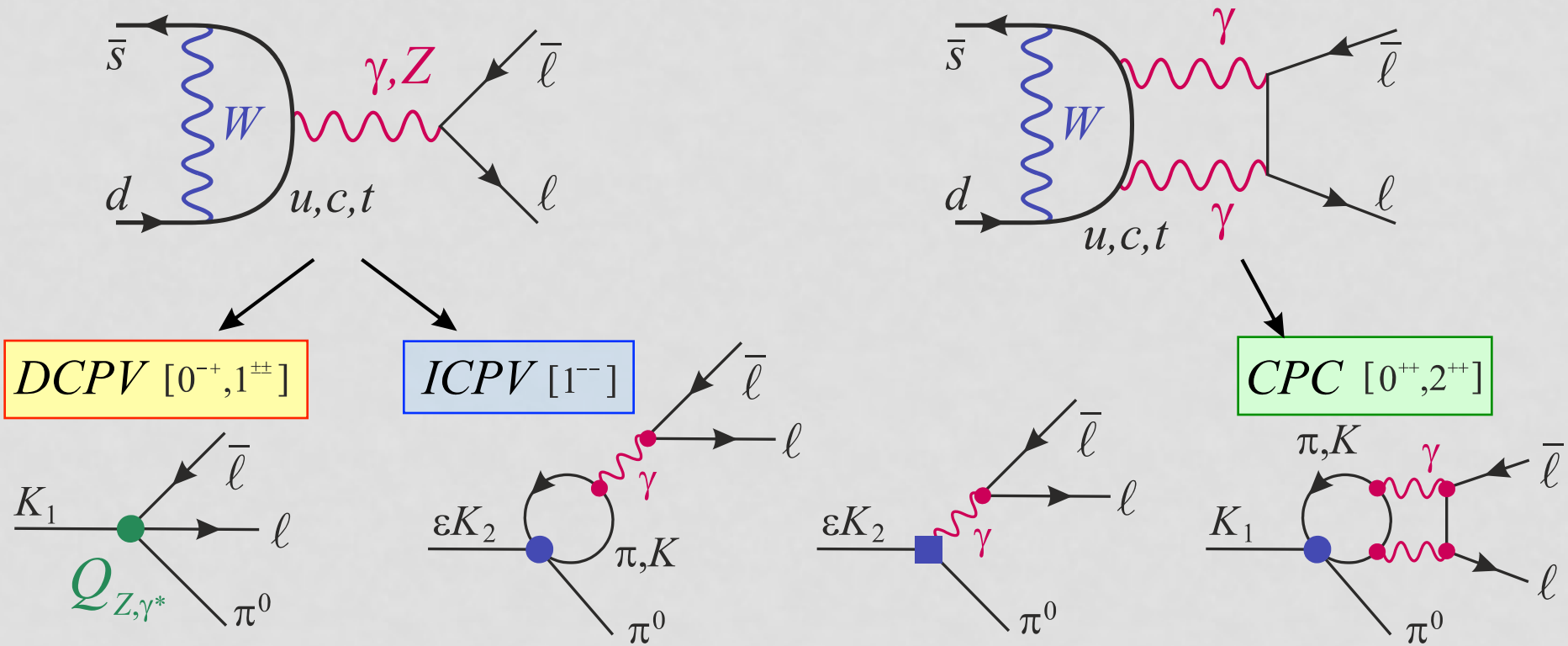
($\delta R_\pi^{\exp}:\ 10^{-3}$ would probe $\Lambda:\ 70\ \mathrm{TeV}$)

Shrock '81; Gorbunov, Shaposhnikov '07; Kamenik, Smith '11

$$K_L \to \pi^0 \ell^+ \ell^-$$

A. Various contributions :

$$K_L \sim K_2 + \varepsilon K_1 \to \pi^0 \ell^+ \ell^-$$



Direct CPV (Short-distance)

Indirect CPV (Long-distance)

CPC (Long-distance)

B. Direct CPV: Matrix elements of the dimension-six operators

Mescia, Smith '06

LD effects for the top/charm "pure" SD contribution = matrix elements

$$Q_{eff}^{V} = (\bar{s}d)_V \otimes (\bar{\ell}\ell)_V, \; Q_{eff}^{A} = (\bar{s}d)_V \otimes (\bar{\ell}\ell)_A$$

As for $K \to \pi \nu \bar{\nu}$, those are extracted from $K_{\ell 3}$ decays:

		Exp.			Th.		
		t_+	$f(0)$	*slopes*	r_K	r	Future?
$\kappa_e^{V,A}$	0.7691(64)	-	77%	12%	9%	2%	±0.0046
κ_μ^{V}	0.1805(16)	-	73%	16%	8%	2%	±0.0011
κ_μ^{A}	0.4132(51)	-	54%	38%	6%	2%	±0.0031

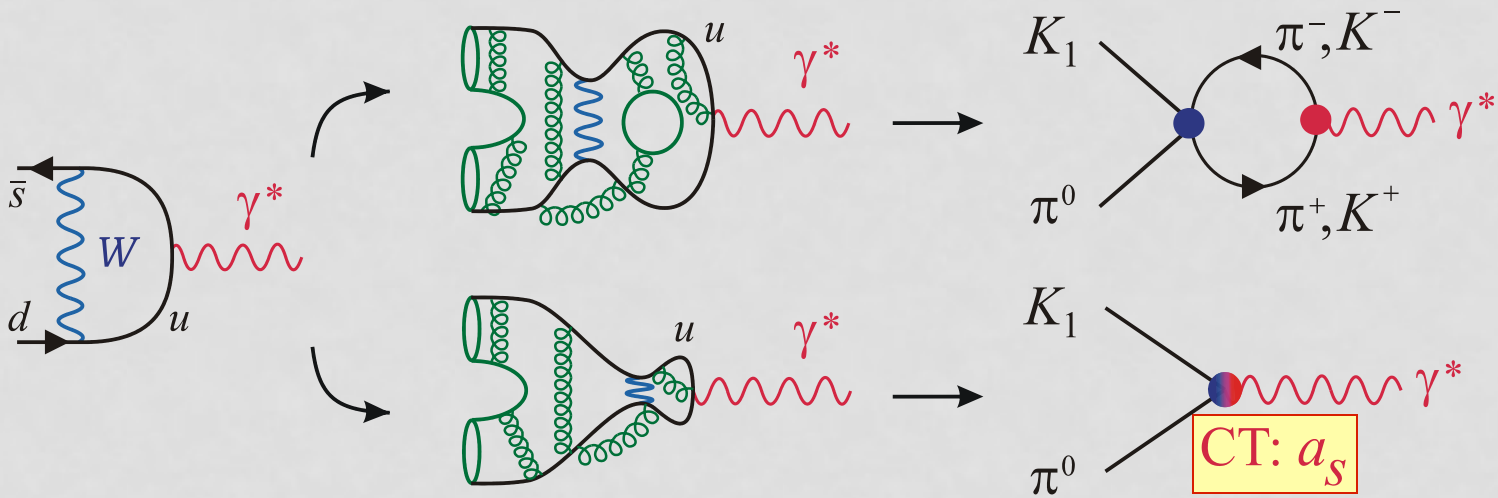
$$\kappa_\ell^{V,A} \sim \int d\Phi_3 \, |\langle \pi^0 \ell \bar{\ell} | Q_{eff}^{V,A} | K_L \rangle|^2$$

Already very precise compared the other contributions.

C. Indirect CPV: Long-distance photon penguin

D' Ambrosio et al. '98

Indirect CP-violation is $K_L \to \varepsilon K_1 \to \pi^0 \ell^+ \ell^-$, related to $K_S \to K_1 \to \pi^0 \ell^+ \ell^-$:



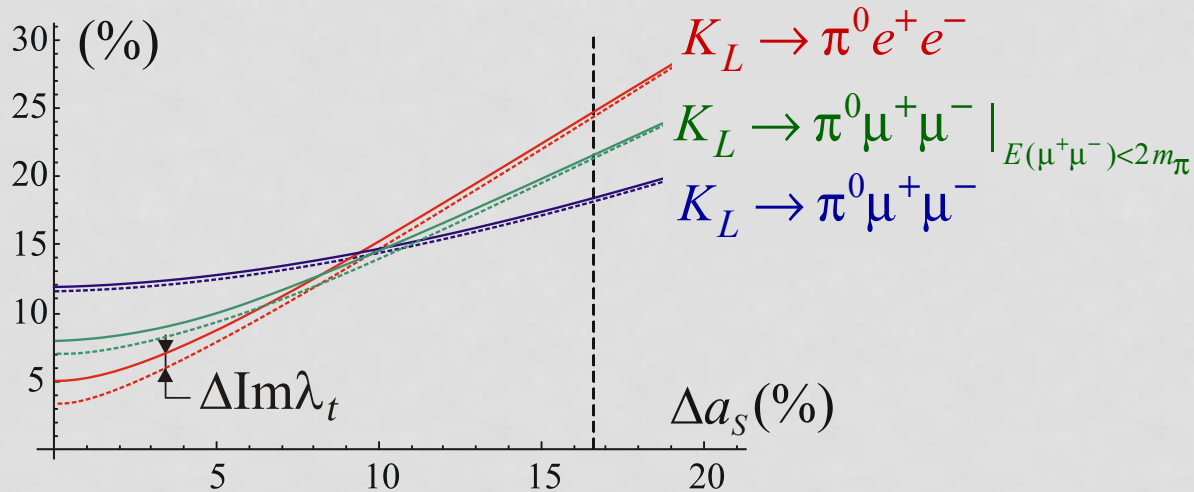
Loops are rather small, a single counterterm a_S dominates.

It is fixed from $K_S \to \pi^0 \ell^+ \ell^-$ (up to its sign) measured by NA48:

$$\left.\begin{aligned} Br(K_S \to \pi^0 e^+ e^-)_{m_{ee}>165\,\mathrm{MeV}} &= \left(3.0^{+1.5}_{-1.2} \pm 0.2\right) \times 10^{-9} \\ Br(K_S \to \pi^0 \mu^+ \mu^-) &= \left(2.9^{+1.4}_{-1.2} \pm 0.2\right) \times 10^{-9} \end{aligned}\right\} \to |a_S| = 1.2 \pm 0.2$$

C. Indirect CPV: Long-distance photon penguin

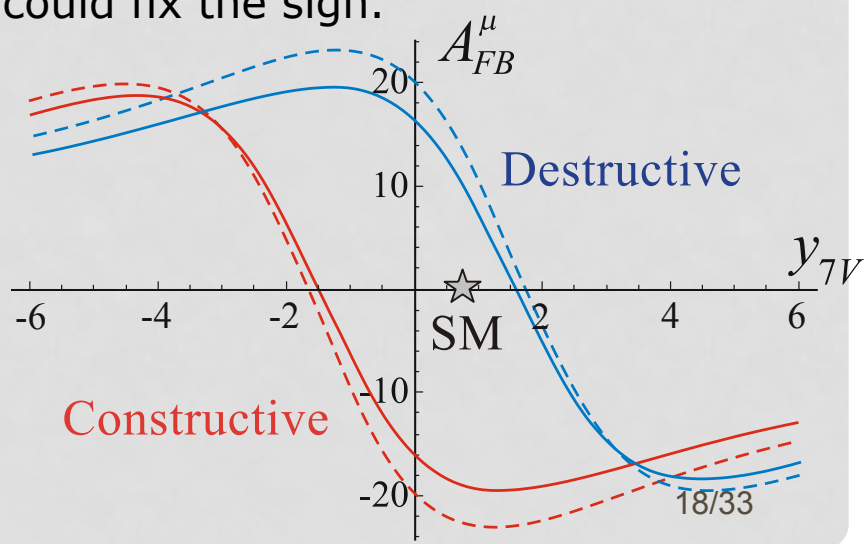
This CT is the main source of error for



Besides $K_S \to \pi^0 \ell^+ \ell^-$, the paths to constrain or measure a_S are (among other):

- FB asymmetries for $K_L \to \pi^0 \mu^+ \mu^-$ could fix the sign.

$$A_{FB}^{\ell} = \frac{N(E_- > E_+) - N(E_- < E_+)}{N(E_- > E_+) + N(E_- < E_+)}$$

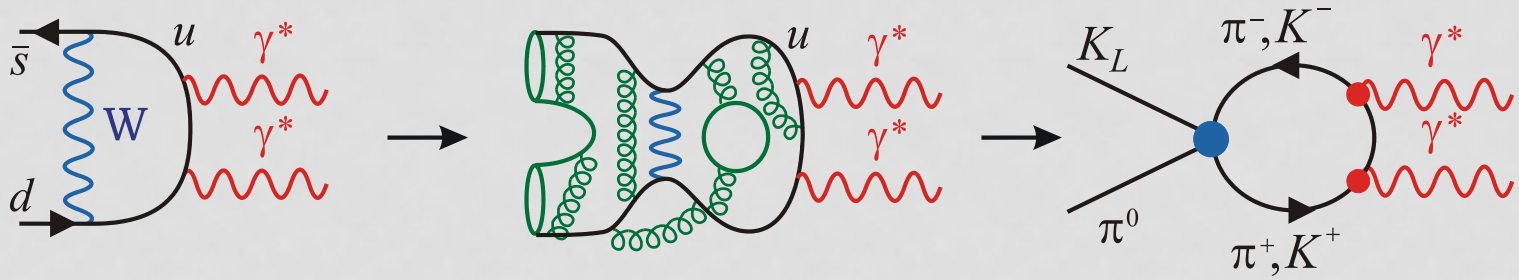


Clean enough to fix the sign of a_S

Mescia,Trine, Smith '06

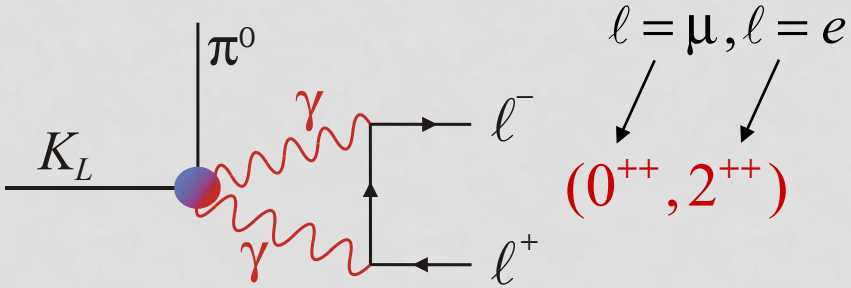
$$(y_{7V} Q_{eff}^{V} = y_{7V} (\bar{s} d)_V \otimes (\bar{\ell} \ell)_V \ )$$

D. CPC: Long-distance double photon penguin



LO (p^4) is finite, produces $\ell^+\ell^-$ in a scalar state only (helicity-suppressed),

Higher order estimated using the $K_L \to \pi^0\gamma\gamma$ rate and spectrum:



- Production of $(\mu^+\mu^-)_{0^{++}}$ under control within 30%. Isidori,Unterdorfer,Smith '04

- No signal of $(\gamma\gamma)_{2^{++}}$ implies $(e^+e^-)_{2^{++}}$ is negligible. Buchalla,D'Ambrosio, Isidori '03

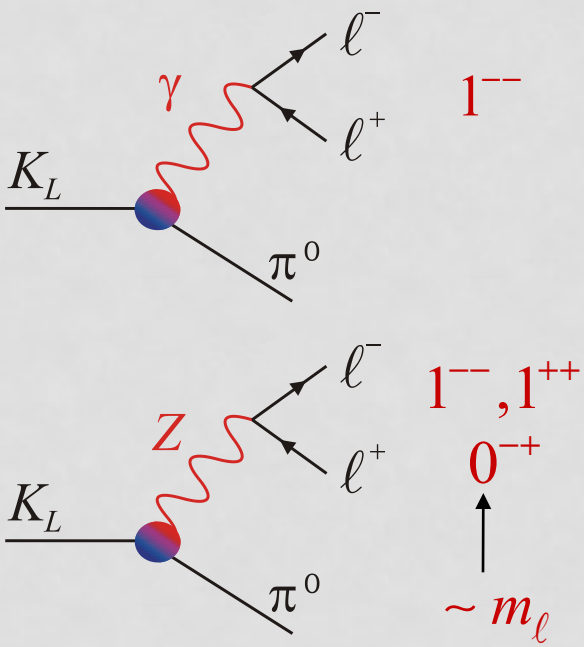
($K_S \to \gamma\gamma$ is also useful to constrain the p^6 CT structure)

In the SM :

	V, A	K^0-$\bar{K}^0$	2^{++}	0^{++}	SM ($\times 10^{-11}$)	Experiment	
$K_L \to \pi^0 \nu \bar{\nu}$	**100%**	($\approx$ 1%)	–	–	$2.43^{+0.40}_{-0.40}$	$< 2.6 \cdot 10^{-8}$	E391a
$K_L \to \pi^0 e^+ e^-$	**40%**	60%	(<3%)	–	$3.23^{+0.91}_{-0.79}$	$< 2.8 \cdot 10^{-10}$	KTeV
$K_L \to \pi^0 \mu^+ \mu^-$	**30%**	35%	–	35%	$1.29^{+0.24}_{-0.23}$	$< 3.8 \cdot 10^{-10}$	KTeV
$K^+ \to \pi^+ \nu \bar{\nu}$	**100%**	–	–	–	$7.81^{+0.80}_{-0.80}$	$1.73^{+1.15}_{-1.05} \cdot 10^{-11}$	E787 E949

And what's beyond ?

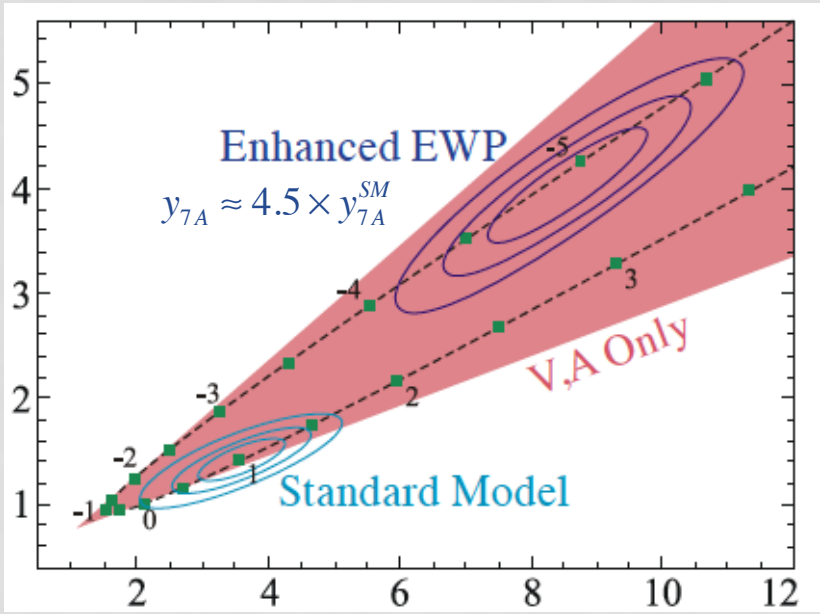
The $K_L \to \pi^0 \ell^+ \ell^-$ modes permit to isolate the γ penguin:



$\Rightarrow$ Only for muons!

Specific regions in the plane for specific correlations between γ and Z penguins.

Isidori,Unterdorfer,Smith '04

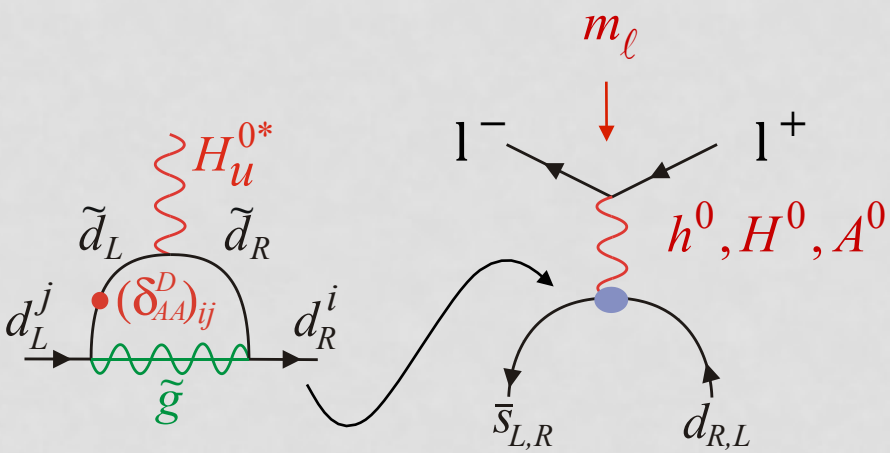


$$\Leftrightarrow 0.1 + 0.24 B_e \le B_\mu \le 0.6 + 0.58 B_e$$

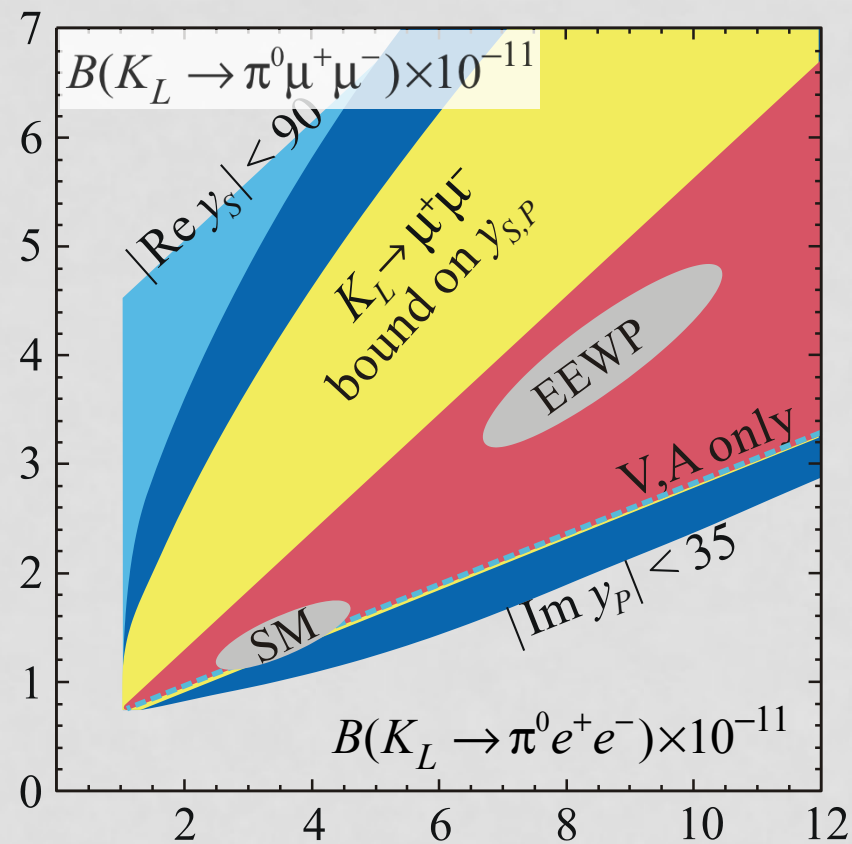
with $B_\ell \equiv B(K_L \to \pi^0 \ell^+ \ell^-) \cdot 10^{11}$

They also probe a broad class of helicity-suppressed NP effects, as those generated by neutral Higgs penguins.

Isidori,Retico '01, '02
Mescia,Trine,Smith '06



$$H_{eff} \sim y_S\,(\bar{s}d)(\bar{\ell}\ell) + y_P\,(\bar{s}d)(\bar{\ell}\gamma_5\ell)$$



Even if directly correlated with $K_L \to \mu^+\mu^-$, large effects still possible.

Looking for the unexpected?

1- $K_L \to \pi^0 \ell^+ \ell^-$ probe the (pseudo-)scalar and (pseudo-)tensor operators:

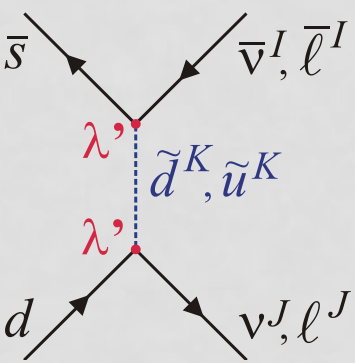
$$H_{eff} \sim y_S^{IJ}\,(\bar{s}d)(\bar{\ell}^I \ell^J) + y_P^{IJ}\,(\bar{s}d)(\bar{\ell}^I \gamma_5 \ell^J) + y_T\,(\bar{s}\sigma_{\mu\nu}d)(\bar{\ell}\sigma^{\mu\nu}\ell) + \ldots$$

Presummably killed by $K_L \to ee, e\mu$ ...but tensors still free.

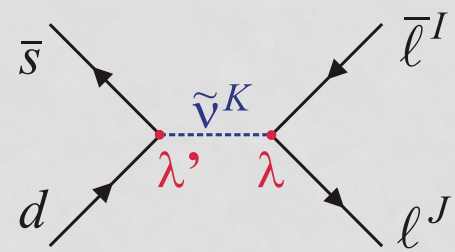
2- Similar operators for $K \to \pi\nu\bar{\nu}$ require active right-handed neutrinos.

3- The RPV couplings can induce quark & lepton flavor transitions, hence could contribute to all $P \to P'\nu^I\bar{\nu}^J$ and $P \to P'\ell^I\bar{\ell}^J$ decays :

$$W_{RPV} = \underbrace{\mu'^I L^I H_d + \lambda^{IJK} L^I L^J E^K + \lambda'^{IJK} L^I Q^J D^K}_{\Delta L = 1} + \underbrace{\lambda''^{IJK} U^I D^J D^K}_{\Delta B = 1}$$



$$\bar{s}\gamma^\mu(1 \pm \gamma_5)d \otimes \begin{cases} \bar{\nu}\gamma_\mu(1-\gamma_5)\nu \\ \bar{\ell}\gamma_\mu(1-\gamma_5)\ell \end{cases}$$



$$\bar{s}(1 \pm \gamma_5)d \otimes \bar{\ell}(1 \mp \gamma_5)\ell$$

$$s \to d\gamma$$

A. The flavor-changing electromagnetic operators

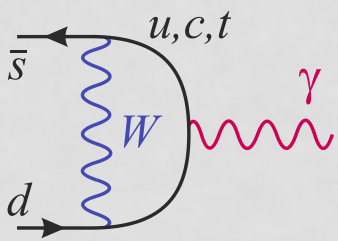
$$\mathcal{H}_{eff} = C_{\gamma}^{L,R}\, \bar{s}_{R,L} \sigma^{\mu\nu} d_{L,R}\, F_{\mu\nu} \qquad \text{Dim 5}$$

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

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

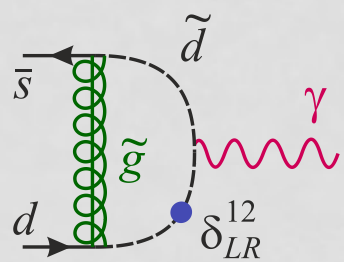
$$+ \ldots$$

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



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

Sensitive to NP: Dimension 5 & alternative chirality flips



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

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

$$K \to (n\pi)(m\gamma^{(*)}),$$

$n =$	0	1	$2,3$
$m =$	$2,3,\ldots$	$1^*,2,\ldots$	$1,2,\ldots$

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

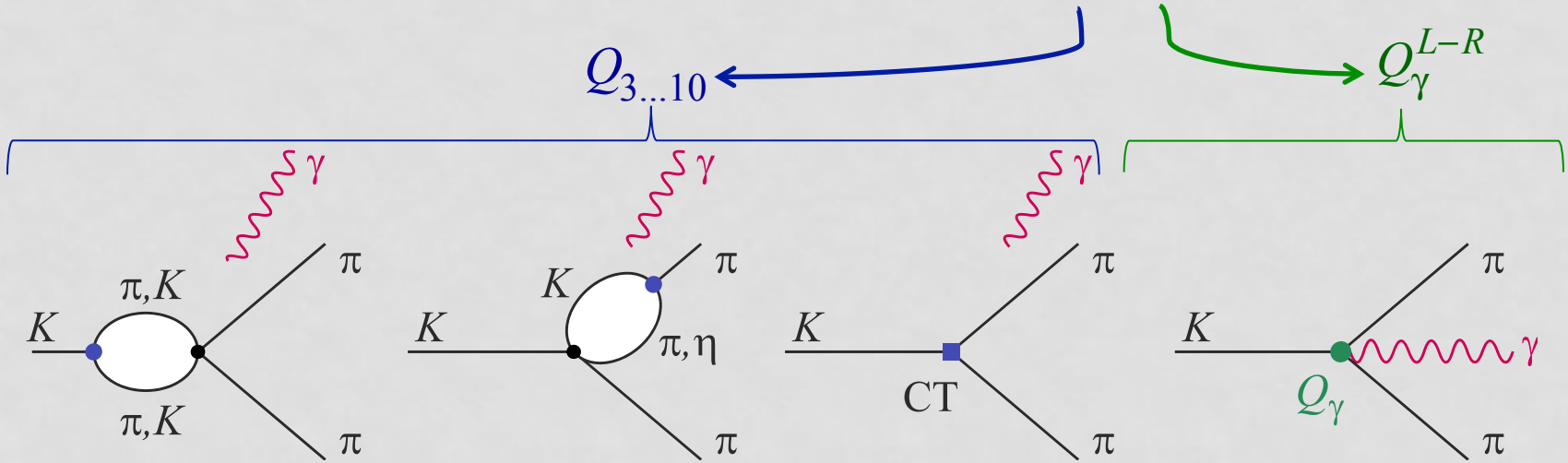
Real photon(s): $A_{CP}(K \to \gamma\gamma,\, K \to \pi\pi\gamma)$ (only magnetic)

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

B. Anatomy of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$

MP,Smith, '11

Meson processes lack the chirality flip → Automatic LD-SD factorization



- Good control over meson contributions (loops usually finite, no/small CTs)
- Non-local CP-violating effects ($Q_{3\to10}^{u,d,s}$) → To be estimated using ε'/ε
- Local CP-violating effects ($Q_{\gamma}^{L\pm R}$) → Local chiral realization of the tensor currents

We got a probe for NP in the magnetic photon operator Q_{γ}^{L-R}

B. Short reminder

Isospin decomposition:

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

$\Delta I = 1/2$ rule:

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

CP-violation: $\dfrac{\mathcal{M}(K_L \to \pi^+\pi^-)}{\mathcal{M}(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$, $\dfrac{\mathcal{M}(K_L \to \pi^0\pi^0)}{\mathcal{M}(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$

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

$\Delta S = 2$ mixing

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

C. SD sensitivity from CP asymmetry

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. SD sensitivity from CP asymmetry

The CP-violating parameter is

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

MP,Smith, '11 $\qquad -0.6(3)\times 10^{-4} \qquad +1.2(4)\times 10^{-4}$

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

- $\varepsilon'_{+0\gamma}$ is not $\Delta I = 1/2$ suppressed, but its sensitivity to Ω is !

Experimentally: $\varepsilon'_{+0\gamma} = -0.21 \pm 0.34 \quad \rightarrow \mathrm{Im}\, C_\gamma^{L-R} \leq -0.08 \pm 0.13$
(NA48/2 '10)

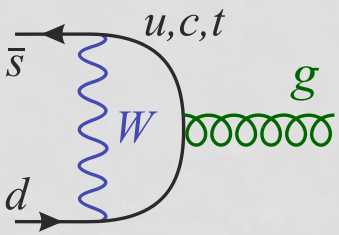
Large room for NP effects !

D. Correlation in the MSSM

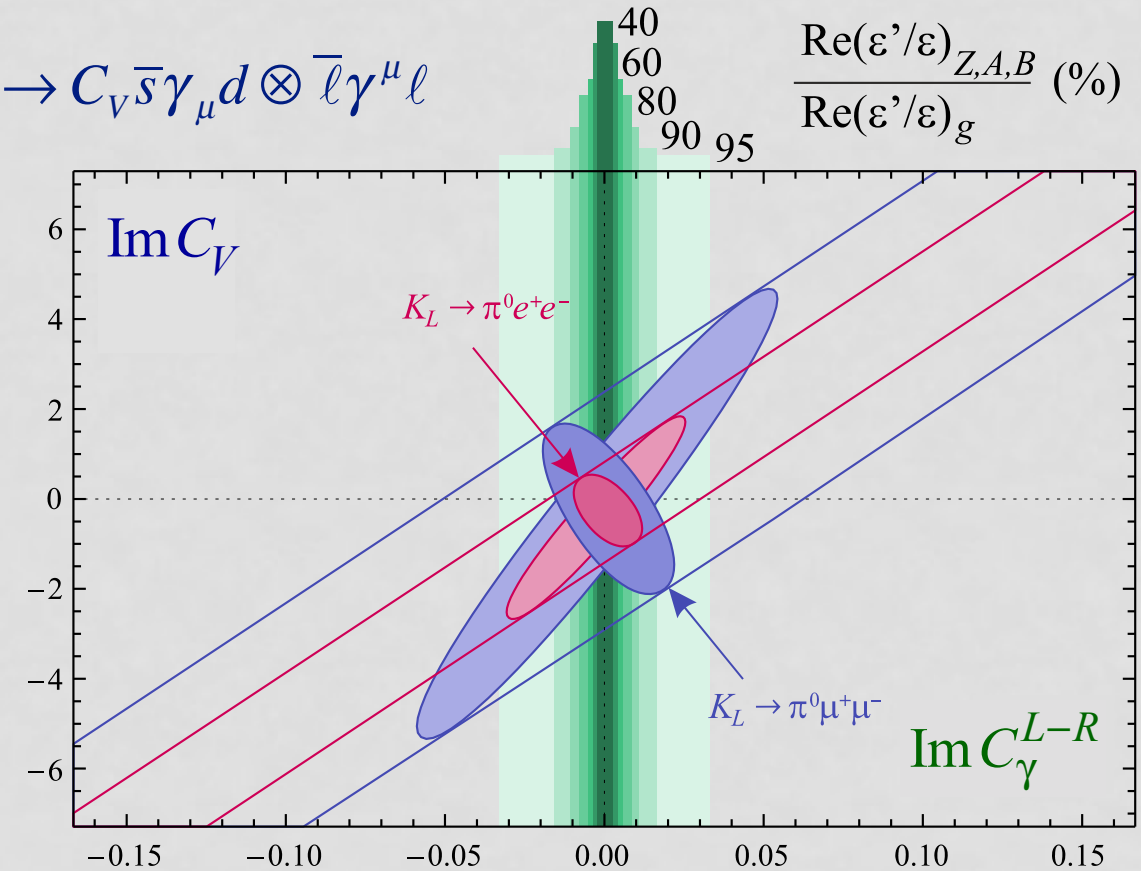
Buras,Colangelo,Isidori, Romanino,Silvestrini, '00

Loop particles colored and charged → Chromomagnetic penguins

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



Z,γ^* *penguins* $\rightarrow C_V \bar{s}\gamma_\mu d \otimes \bar{\ell}\gamma^\mu \ell$

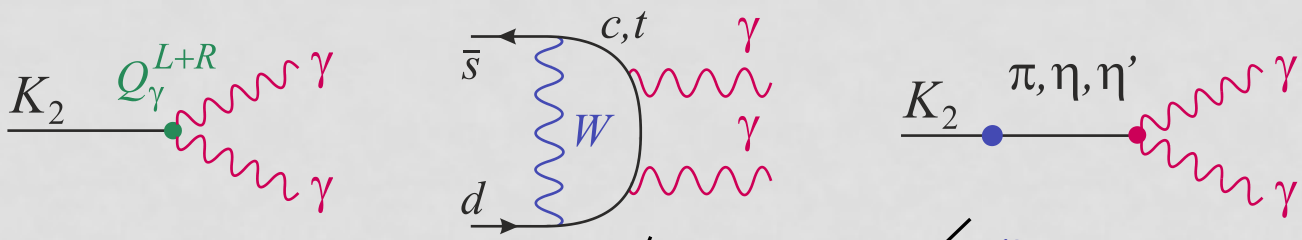


The $K^0 \to \gamma\gamma$ decays

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:



Q_1^u only!!

Gérard,Smith,Trine, '05

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

MP,Smith, '11 $\quad : \; 10^{-5} \qquad 5\times10^{-5} \to 7\times10^{-4}$

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

1- $K \to \pi\nu\bar{\nu}$ *and* $K_L \to \pi^0 \ell^+ \ell^-$ *decays are unique windows into the* $s \to d$ *sector.*

Essential to constrain (and discriminate among) New Physics models.

2- *Message to experimentalists*: Go for the $K \to \pi\nu\bar{\nu}$ modes, they are the cleanest,

But do not disregard other modes:

$K_L \to \pi^0 \ell^+ \ell^-$: Sensitive to a larger class of NP effects

$K_S \to \pi^0 \ell^+ \ell^-, K_L \to \pi^0 \gamma\gamma, K_{\ell 3}$: Theoretical control for rare K decays

$K_S \to \pi^0 \gamma\gamma, K^+ \to \pi^+ \gamma\gamma$: Theoretical control over $K_L \to \mu^+ \mu^-$

Radiative decays could hold the key to (finally) control and probe ε'/ε

- 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.