Long distance weak annihilation contribution to $B^{\pm} \to (\pi/K)^{\pm}\, l^{+}\, l^{-}$

Pablo Roig

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Phys.Rev. D92 (2015) 5, 054035 (arXiv:1503.06890/hep-ph) and work in progress

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CONTENTS

- **Motivation**

- **Weak effective Hamiltonian for FCNC transitions involving heavy flavors**

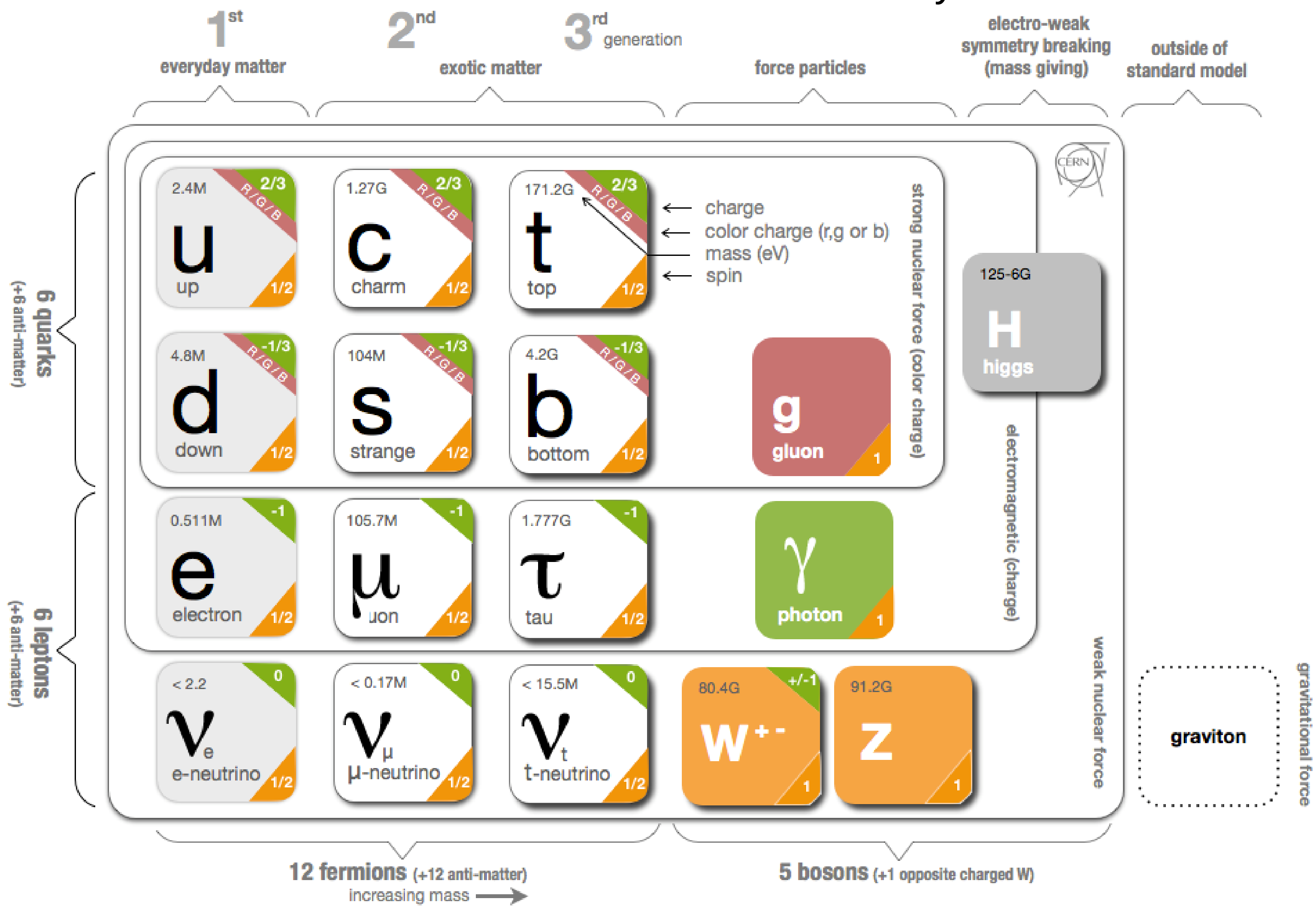
- **'New' long distance contribution: recalling $K^{\pm} \to \pi^{\pm} l^{+} l^{-}$**

- **Application to $(B_{(c)}/D_{(s)})^{\pm} \to (\pi/K^{\pm}) l^{+} l^{-}$ decays**

- **Conclusions**

Motivation

The Standard Model of Particle Physics



Two paths towards New Physics (in addition to searches at the Cosmic Frontier):

Energy & Intensity Frontiers

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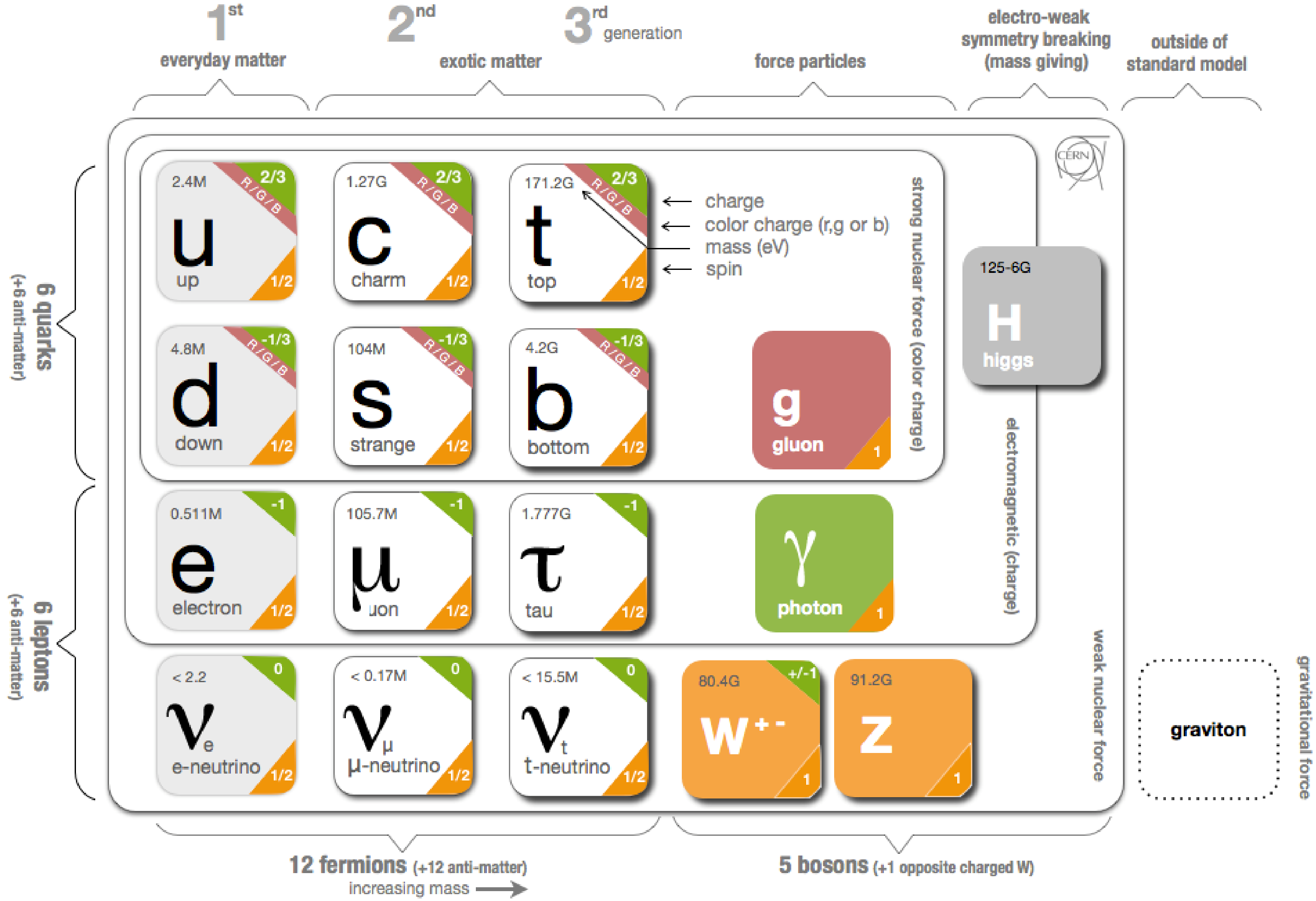

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Energy & Intensity Frontiers

Flavour changing charged currents

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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(Cabibbo ’63. Kobayashi & Maskawa ’73)

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$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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(Wolfenstein ’83)

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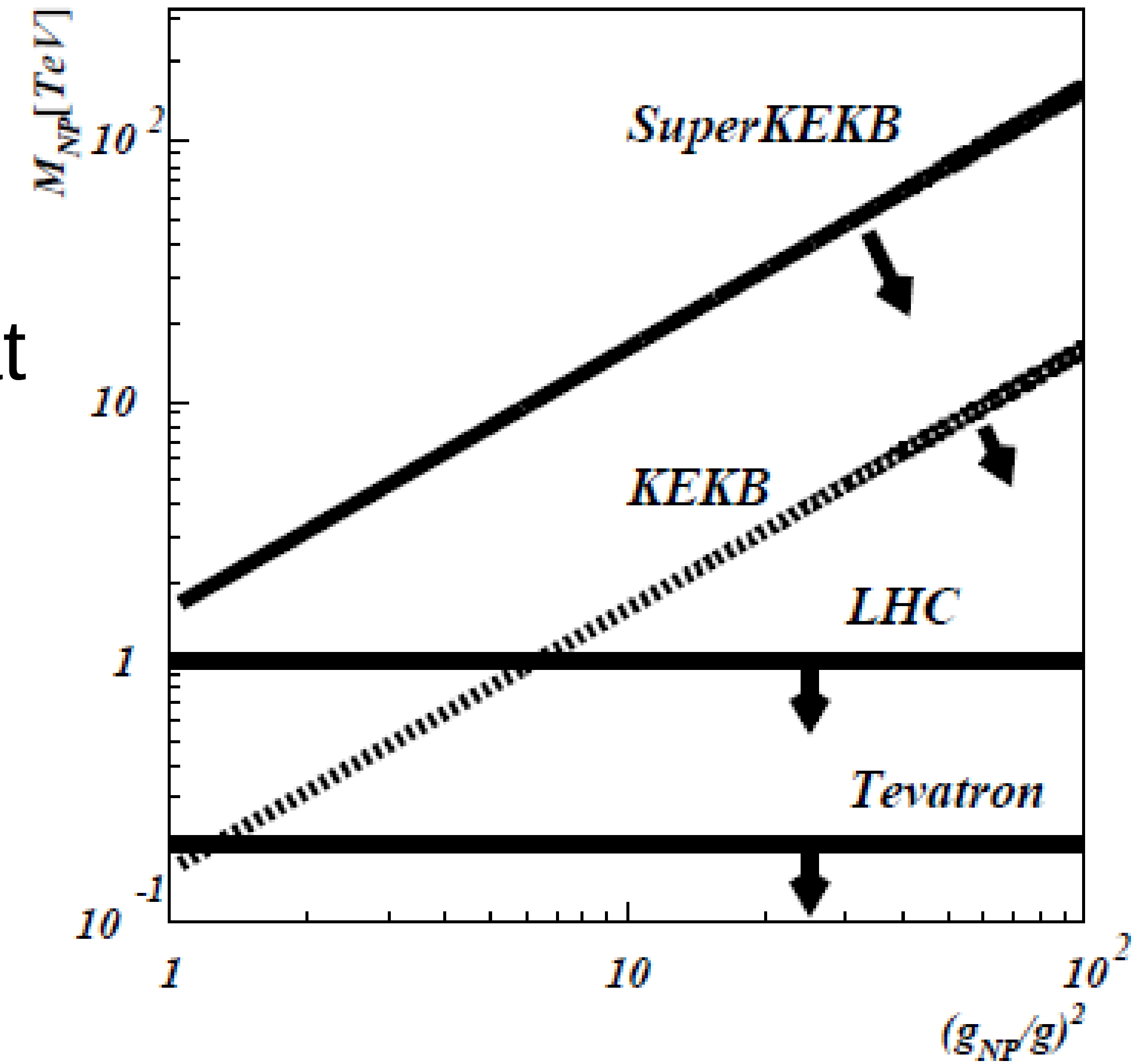
Idea: Searching for forbidden processes in the SM + accurate measurements of allowed rare decays confronted to precise calculations as signs of New Physics.

Motivation

Detailed characterization of NP through measurements that overconstrain it in different related observables of Flavor Physics.



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Caveat: In ad-hoc models one can have sizable LUV in B decays and respect the bounds from $BR(\pi\to e\nu_e(\gamma))/(\pi\to\mu\nu_\mu(\gamma))$ [PIENU PRL’15], (although some effects in K decays should be seen).

Weak effective Hamiltonian for FCNC transitions involving heavy flavors

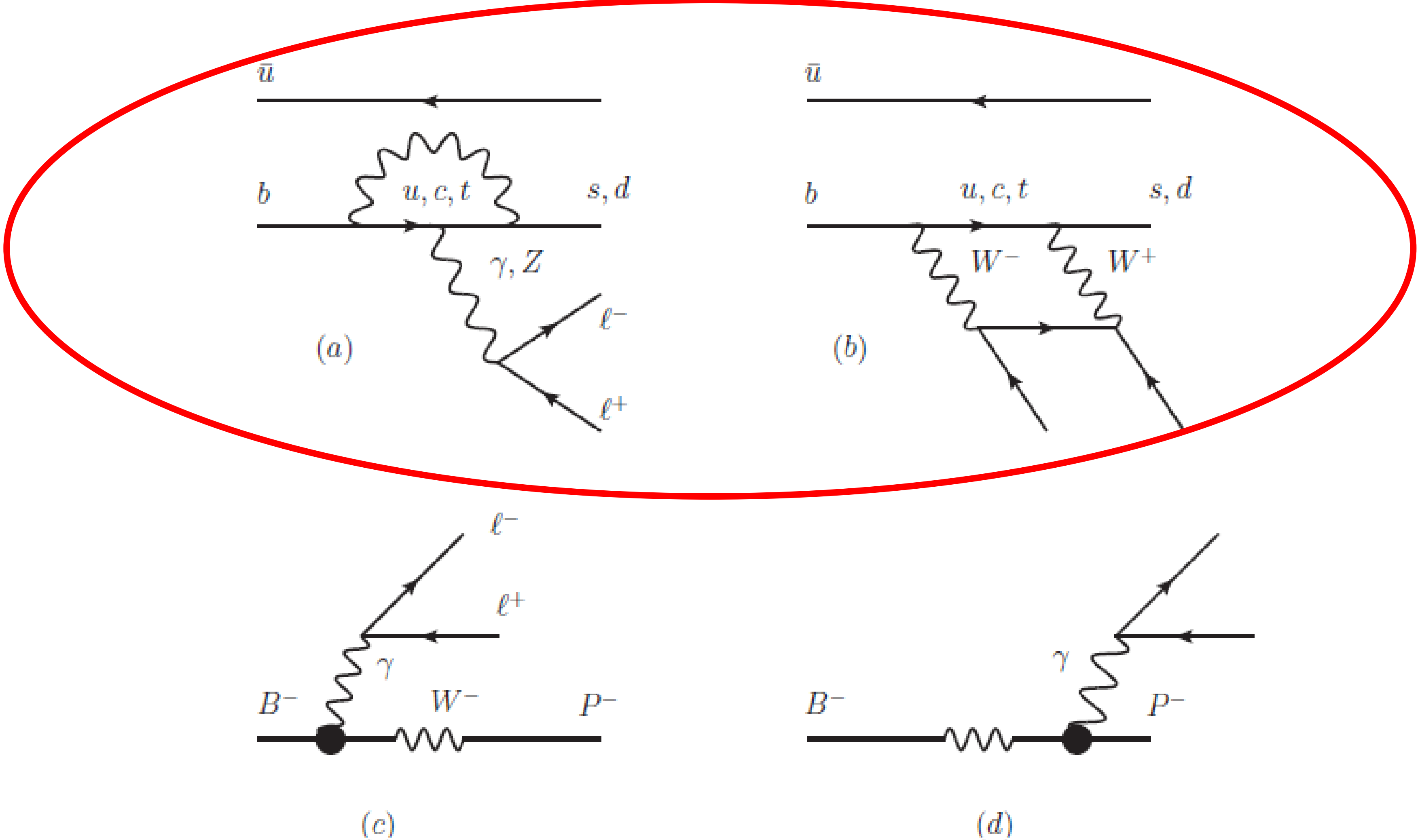

FIG. 1. Short-distance contributions to $B^- \to P^- \ell^+ \ell^-$ decays are shown in (a) (penguin) and (b) (W box) diagrams. The one-photon, LD, contributions are shown in (c) and (d). The full circle denotes the electromagnetic form factor of the charged pseudoscalar mesons. Other long-distance structure-dependent vector and axial-vector terms do not contribute due to gauge invariance [18].

(Ecker, Pich & de Rafael '87)

Weak effective Hamiltonian approach for the |ΔB|=1 transitions

(Chetyrkin, Misiak, Munz '97; Beneke, Feldmann & Seidel '01, '05)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} \underbrace{V_{tb}V_{ts}^*}_{\mathcal{O}(\lambda^2)} \sum_i C_i(\mu)\mathcal{O}_i(\mu) \qquad \mu_f \sim \sqrt{\Lambda_{\rm QCD} m_b}$$

Dipole Operators

$$\mathcal{O}_7 = \frac{e}{(4\pi)^2}\overline{m}_b[\bar{s}\sigma^{\mu\nu}P_R b]F_{\mu\nu},$$

$$\mathcal{O}_8 = \frac{g_s}{(4\pi)^2}\overline{m}_b[\bar{s}\sigma^{\mu\nu}P_R T^a b]G^a_{\mu\nu},$$

Semileptonic Operators

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}[\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu l],$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}[\bar{s}\gamma_\mu P_L b][\bar{l}\gamma^\mu \gamma_5 l]$$

$\mathcal{O}_{1..6}$ are four-fermion operators (Weak-annihilation contributions)

$$\mathcal{O}_1 = \left(\bar{d}_L\gamma_\mu T^A c_L\right)\left(\bar{c}_L\gamma^\mu T^A b_L\right), \quad \mathcal{O}_2 = \left(\bar{d}_L\gamma_\mu c_L\right)\left(\bar{c}_L\gamma^\mu b_L\right)$$

$$\mathcal{O}_1^{(u)} = \left(\bar{d}_L\gamma_\mu T^A u_L\right)\left(\bar{u}_L\gamma^\mu T^A b_L\right), \quad \mathcal{O}_2^{(u)} = \left(\bar{d}_L\gamma_\mu u_L\right)\left(\bar{u}_L\gamma^\mu b_L\right)$$

There can also be BSM type of contributions

(for instance)

$$\mathcal{O}_S^l = \frac{e^2}{(4\pi)^2}[\bar{s}P_R b][\bar{l}l], \qquad \mathcal{O}_S^{\prime l} = \frac{e^2}{(4\pi)^2}[\bar{s}P_L b][\bar{l}l]$$

$$\mathcal{M}[\bar{B} \to K\bar{l}l] = \langle l(p_-)\bar{l}(p_+)K(p_K)|\mathcal{H}_{\rm eff}|\bar{B}(p_B)\rangle \qquad q^2 = (p_- + p_+)^2$$

In the large recoil region: $E_K \gg \Lambda_{QCD}$, $q^2 \ll M_B^2$

↓

Expansion of γ^*-exchange in 1/ E_K using QCDF, SCET (Bauer, Fleming, Pirjol & Stewart '01)

In the $m_b \to \infty$ limit, only one soft form factor is relevant (Charles et. al. '99, Beneke & Feldmann '01)

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$$\langle K(p_K)|\bar{s}\gamma_\mu b|\bar{B}(p_B)\rangle = (2p_B - q)_\mu f_+(q^2) + \frac{M_B^2 - M_K^2}{q^2} q_\mu [f_0(q^2) - f_+(q^2)],$$

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$$f_+(q^2) \equiv \xi_P(q^2)$$

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$$+ (F_S + \cos\theta F_T)\,[\bar{l}l] + (F_P + \cos\theta F_{T5})\,[\bar{l}\gamma_5 l] \Big)$$

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To a very good approximation, with

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$$F_A = C_{10} \quad F_V = C_9 + \frac{2 m_b}{M_B} \frac{\mathcal{T}_P(q^2)}{\xi_P(q^2)}$$ in the SM

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$$\mathcal{T}_P^{(0)}(q^2) = \xi_P(q^2) \left[C_7^{\mathrm{eff}(0)} + \frac{M_B}{2m_b} Y^{(0)}(q^2) \right]$$

$\mathcal{O}_{1,\ldots,6}$ (Weak-annihilation contributions)

$C_9 \to C_9^{\mathrm{eff}}$ (Buras, Munz '95)

F_A, F_V (C_{10}, C_9): NNLL

$\mathcal{T}_P^{(0)}$: NLO

(Beneke, Feldmann & Seidel '01)

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- The leading contribution comes from the O_9 and O_{10},

$$O_9^q = [\bar{q}\gamma_\mu b_L][\bar{\ell}\gamma^\mu \ell], \qquad O_{10}^q = [\bar{q}\gamma_\mu b_L][\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

- The q^2 dependence of the form factors ξ_P, F_V, and F_A may be computed using HQET, QCDF and LCSM (Bobeth et. al.'07. Khodjamiriam et. al.'13, Ball & Zwicky '05)

$$\xi_\pi(q^2) = \frac{0.918}{1 - q^2/(5.32 \text{ GeV})^2} - \frac{0.675}{1 - q^2/(6.18 \text{ GeV})^2} + \mathcal{P}_\pi(q^2)$$

$$\xi_K(q^2) = \frac{0.0541}{1 - q^2/(5.41 \text{ GeV})^2} + \frac{0.2166}{[1 - q^2/(5.41 \text{ GeV})^2]^2} + \mathcal{P}_K(q^2)$$

$$F_A = C_{10} = -4.312 \qquad F_V \approx C_9 = 4.214$$

(Beneke et. al. '01)

- Where $\mathcal{P}_P(q^2)$ is a q^2 polynomial; C_9 and C_{10} are taken at NNLL

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$$F_A = C_{10} \quad F_V = C_9 + \frac{2 m_b}{M_B} \frac{\mathcal{T}_P(q^2)}{\xi_P(q^2)}$$ in the SM

$$\Gamma_l{}^{\text{SM}} = \frac{\Gamma_0}{3} \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \xi_P^2(q^2) \sqrt{\lambda}^3 (|F_A|^2 + |F_V|^2) \times \left\{ 1 + \mathcal{O}\left(\frac{m_l^4}{q^4} \right) + \frac{m_l^2}{M_B^2} \times \mathcal{O}\left(\alpha_s, \frac{q^2}{M_B^2} \sqrt{\frac{\Lambda_{\text{QCD}}}{E}} \right) \right\}$$

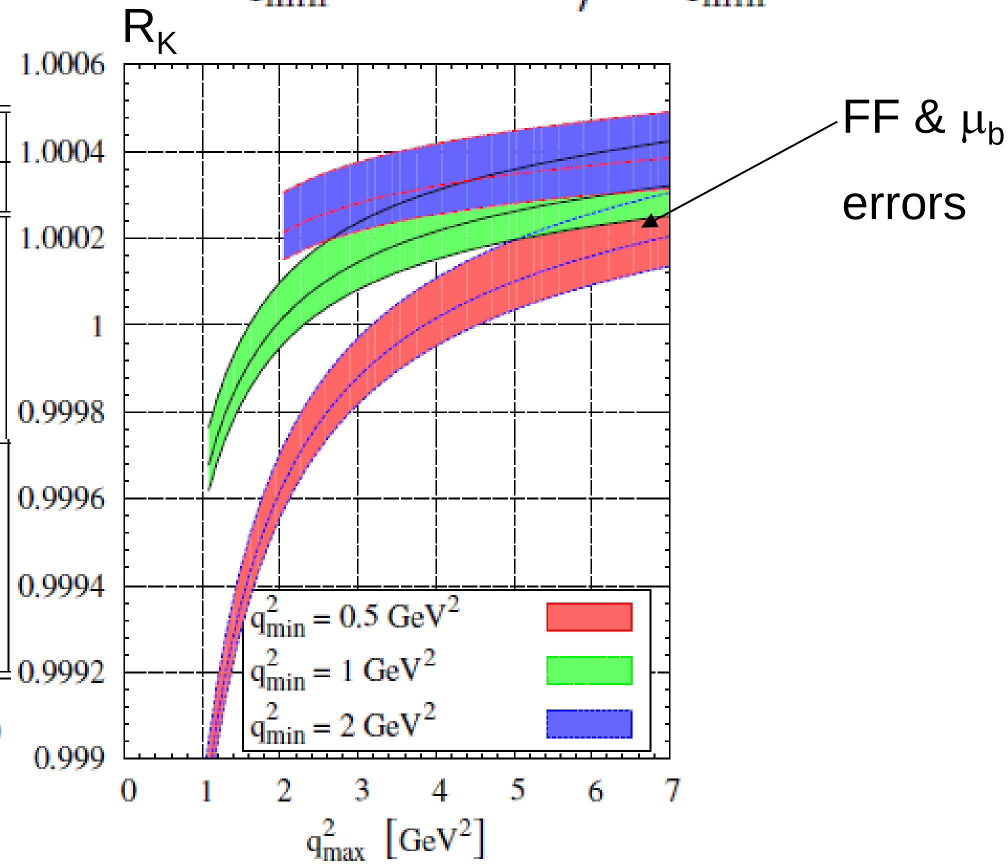
$$\Gamma_0 = \frac{G_F^2 \alpha_e^2 |V_{tb} V_{ts}^*|^2}{512 \pi^5 M_B^3} \qquad \lambda = M_B^4 + M_K^4 + q^4 - 2(M_B^2 M_K^2 + M_B^2 q^2 + M_K^2 q^2)$$

Interesting observable → $R_K \equiv \frac{\Gamma_\mu}{\Gamma_e} = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \frac{d\Gamma_\mu}{dq^2} \Bigg/ \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \frac{d\Gamma_e}{dq^2}$

Interesting observable → $R_K \equiv \frac{\Gamma_\mu}{\Gamma_e} = \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma_\mu}{dq^2} \Big/ \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma_e}{dq^2}$

	$B^- \to K^- \bar{l}l$		
	SM value	$\xi_P[\%]$	$\mu_b[\%]$
$\mathcal{B}_\mu$ $[10^{-7}]$	$1.60^{+0.51}_{-0.46}$	$^{+29.9}_{-27.0}$	$^{+2.0}_{-1.8}$
	$1.27^{+0.40}_{-0.36}$	$^{+29.4}_{-26.6}$	$^{+2.2}_{-2.1}$
	$1.91^{+0.59}_{-0.54}$	$^{+29.2}_{-26.6}$	$^{+2.2}_{-2.2}$
	$1.59^{+0.48}_{-0.44}$	$^{+28.7}_{-26.0}$	$^{+2.4}_{-2.4}$
R_K	$1.00030^{+0.00010}_{-0.00007}$	$^{+0.004}_{-0.003}$	$^{+0.010}_{-0.006}$
	$1.00037^{+0.00010}_{-0.00007}$	$^{+0.004}_{-0.003}$	$^{+0.010}_{-0.006}$
	$1.00032^{+0.00010}_{-0.00007}$	$^{+0.004}_{-0.003}$	$^{+0.010}_{-0.006}$
	$1.00039^{+0.00011}_{-0.00007}$	$^{+0.004}_{-0.003}$	$^{+0.010}_{-0.006}$

$(q^2_{\min}, q^2_{\max}) = (1,6), (2,6), (1,7), (2,7)$ GeV^2 (from top to bottom)



(Bobeth, Hiller & Piranishvili ’07) (Khodjamirian, ‘07)

Then it comes the LHCb result:

Interesting observable $\longrightarrow$ $$R_K \equiv \frac{\Gamma_\mu}{\Gamma_e} = \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma_\mu}{dq^2} \Bigg/ \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma_e}{dq^2}$$

	$B^- \to K^- \bar{l}l$		
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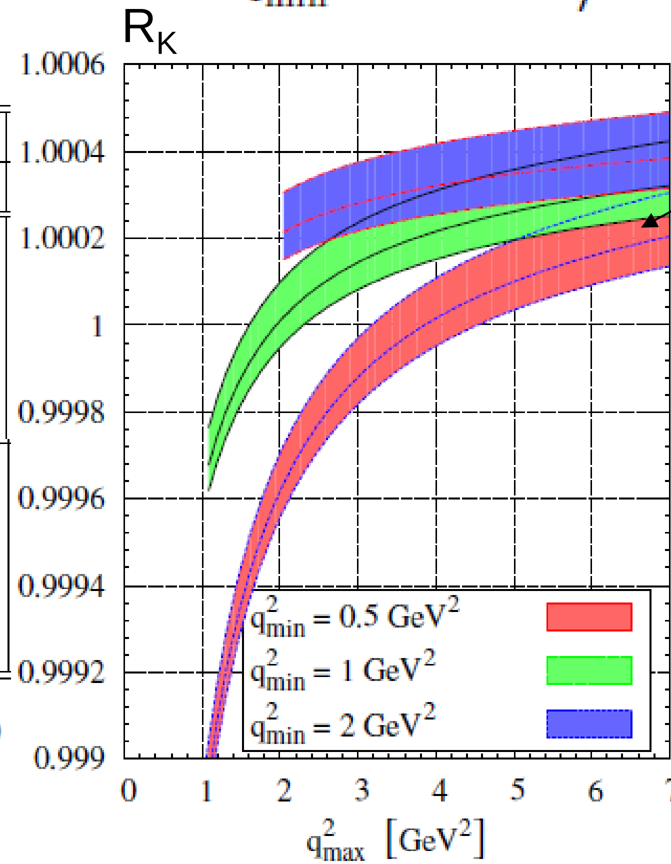
$(q^2_{\rm min}, q^2_{\rm max}) = (1,6), (2,6), (1,7), (2,7)$ GeV^2 (from top to bottom)



(Bobeth, Hiller & Piranishvili ’07) (Khodjamirian, ‘07)

$$1 \leq q^2 \leq 6 \text{ GeV}^2$$

Then it comes the LHCb result: $R_K^{\rm LHCb} = 0.745^{+0.090}_{-0.074} \pm 0.036$ $\quad 2.6\sigma$

Effective Weak $b \to d$ Hamiltonian

$$H_{\rm eff}^{(b\to d)} = -\frac{4G_F}{\sqrt{2}}\Big[V_{tb}^*V_{td}\sum_{i=1}^{10}C_i(\mu)\mathcal{O}_i(\mu)$$
$$+V_{ub}^*V_{ud}\sum_{i=1}^{2}C_i(\mu)\Big(\mathcal{O}_i(\mu)-\mathcal{O}_i^{(u)}(\mu)\Big)\Big] + \text{h.c.}$$

- G_F (Fermi constant), $C_i(\mu)$ (Wilson coefficients), and $\mathcal{O}_i(\mu)$ (dimension-six operators) are the same (modulo $s \to d$) as in $H_{\rm eff}^{(b\to s)}$
- However, the CKM structure of the matrix elements more interesting in $H_{\rm eff}^{(b\to d)}$, as $V_{tb}^*V_{td} \sim V_{ub}^*V_{ud} \sim \lambda^3$ are of the same order in $\lambda = \sin\theta_{12}$
- Anticipate sizable CP-violating asymmetries in $b \to d$ transitions compared to $b \to s$

‘New’ long distance contribution: recalling $K^{\pm} \to \pi^{\pm} l^{+} l^{-}$

(Ecker, Pich & de Rafael ’87)

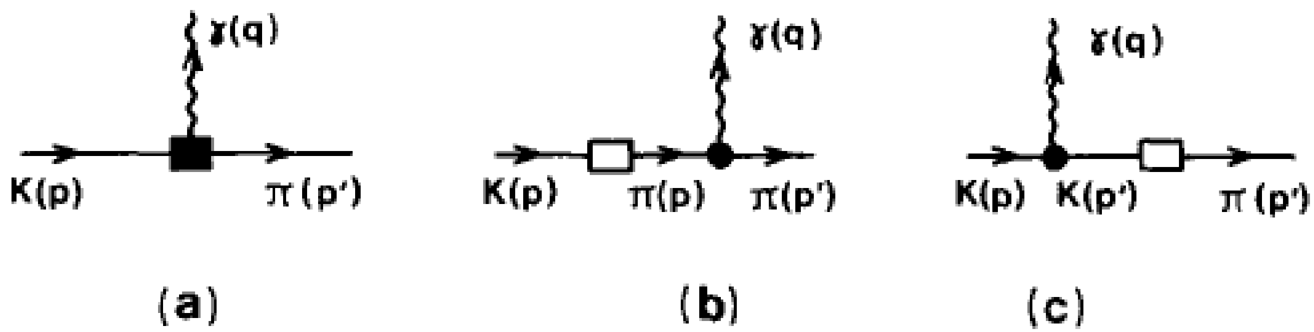
‘Everything’ is long-distance

It is immediately obvious that the amplitude for $K^0 \to \pi^0$'γ' vanishes at the tree level. What is probably not so obvious is that the same is true for the $K^+ \to \pi^+$'γ' amplitude. The three diagrams of fig. 1 lead to the following tree level amplitude

$$G_8 f_\pi^2 (p+p')_\mu \left\{ \underset{(a)}{2ie} + \underset{(b)}{2ip^2 \frac{i}{p^2 - m_\pi^2} ie} + \underset{(c)}{ie \frac{i}{p'^2 - M_K^2} 2ip'^2} \right\}, \tag{3.1}$$

which is exactly zero for all q^2 as long as $p^2 = M_K^2$, $p'^2 = m_\pi^2$ (on-shell mesons).

Fig. 1. Tree level diagrams for $K \to \pi$'γ'.



This holds trivially the same in our cases of interest: **$(B_{(c)}/D_{(s)})^{\pm} \to (\pi/K^{\pm})\, l^+ l^-$**

Lorentz + em gauge invariance imply

$$K(p) \to \pi(p') + \text{`}\gamma\text{'}(q), \qquad p^2 = M_K^2, \qquad p'^2 = m_\pi^2, \qquad q^2 \neq 0$$

has the form

$V_{ud}V_{us}$ $\quad \Delta I = \frac{1}{2}$ $\qquad$ dynamics

$$A = \sqrt{\tfrac{1}{2}}\, G_F s_1 c_1 c_3 g_8 e F^{\mu\nu}(q)(p'_\mu p_\nu - p_\mu p'_\nu)\phi(q^2/M_K^2, m_\pi^2/M_K^2),$$

where $F^{\mu\nu}(q) = \varepsilon^\mu q^\nu - \varepsilon^\nu q^\mu$ and ε^μ denotes the photon polarization vector.

With A ~ $\varepsilon^\mu V_\mu(p,q)$ $\quad V_\mu(p,q) = \left[q^2(p+p')_\mu - (M_K^2 - m_\pi^2)q_\mu\right]\phi(q^2/M_K^2, m_\pi^2/M_K^2)$

$$\to \quad A(K \to \pi \ell^+ \ell^-) = G_8 e V_\mu(p,q)\frac{(-i)g^{\mu\nu}}{q^2 + i\varepsilon}(-ie)\bar{u}(k)\gamma_\nu v(k')$$

This part does not contribute to the amplitude because of gauge invariance

$$\to \quad V_\mu(p,q) \sim q^2(p+p')_\mu\, \phi(q^2/M_K^2, m_\pi^2/M_K^2)$$

Penguin type (when quark structure is resolved)

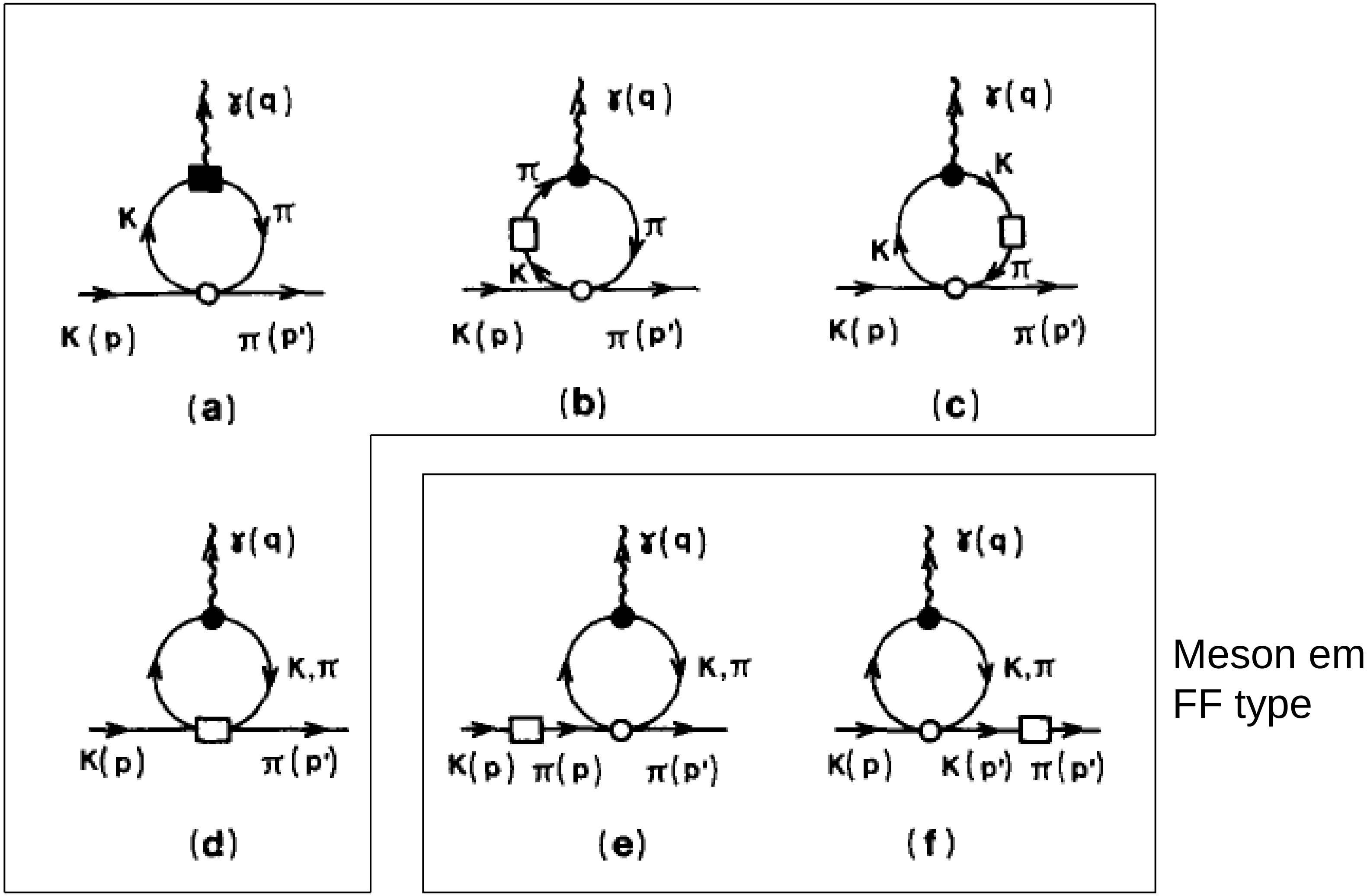
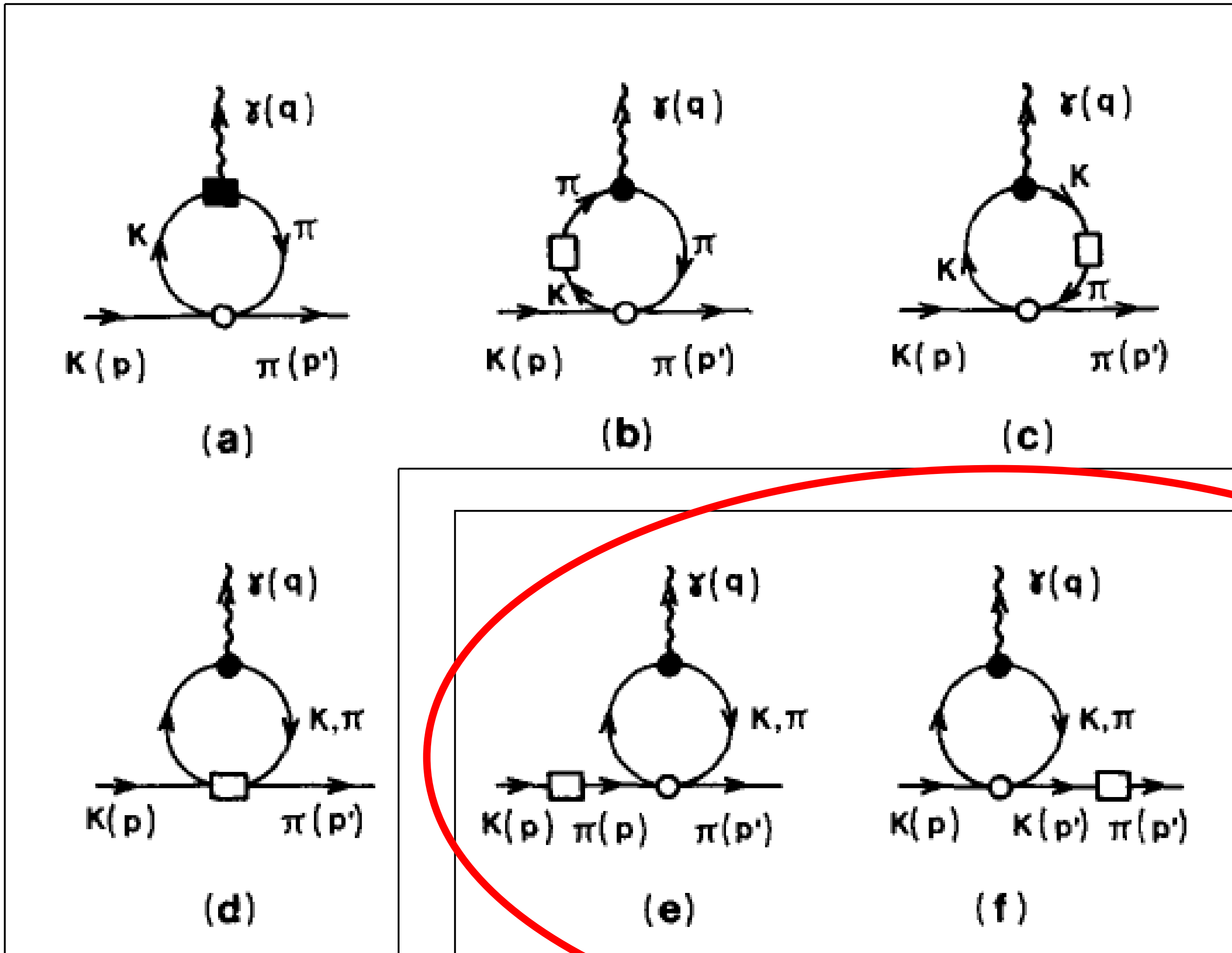


Fig. 2. One-loop diagrams for $K \to \pi$‘γ’ which can lead to terms in the amplitude proportional to $q^2(p+p')_\mu$. The notation for vertices is as in fig. 1.

Penguin type (when quark structure is resolved)



Meson em FF type

Fig. 2. One-loop diagrams for $K \to \pi$'γ' which can lead to terms in the amplitude proportional to $q^2(p+p')_\mu$. The notation for vertices is as in fig. 1.

This is the 'new' contribution we consider in $(B_{(c)}/D_{(s)})^{\pm} \to (\pi/K^{\pm})\, l^+ l^-$ decays

Application to $(B_{(c)}/D_{(s)})^{\pm} \to (\pi/K^{\pm})\, l^+ l^-$ decays

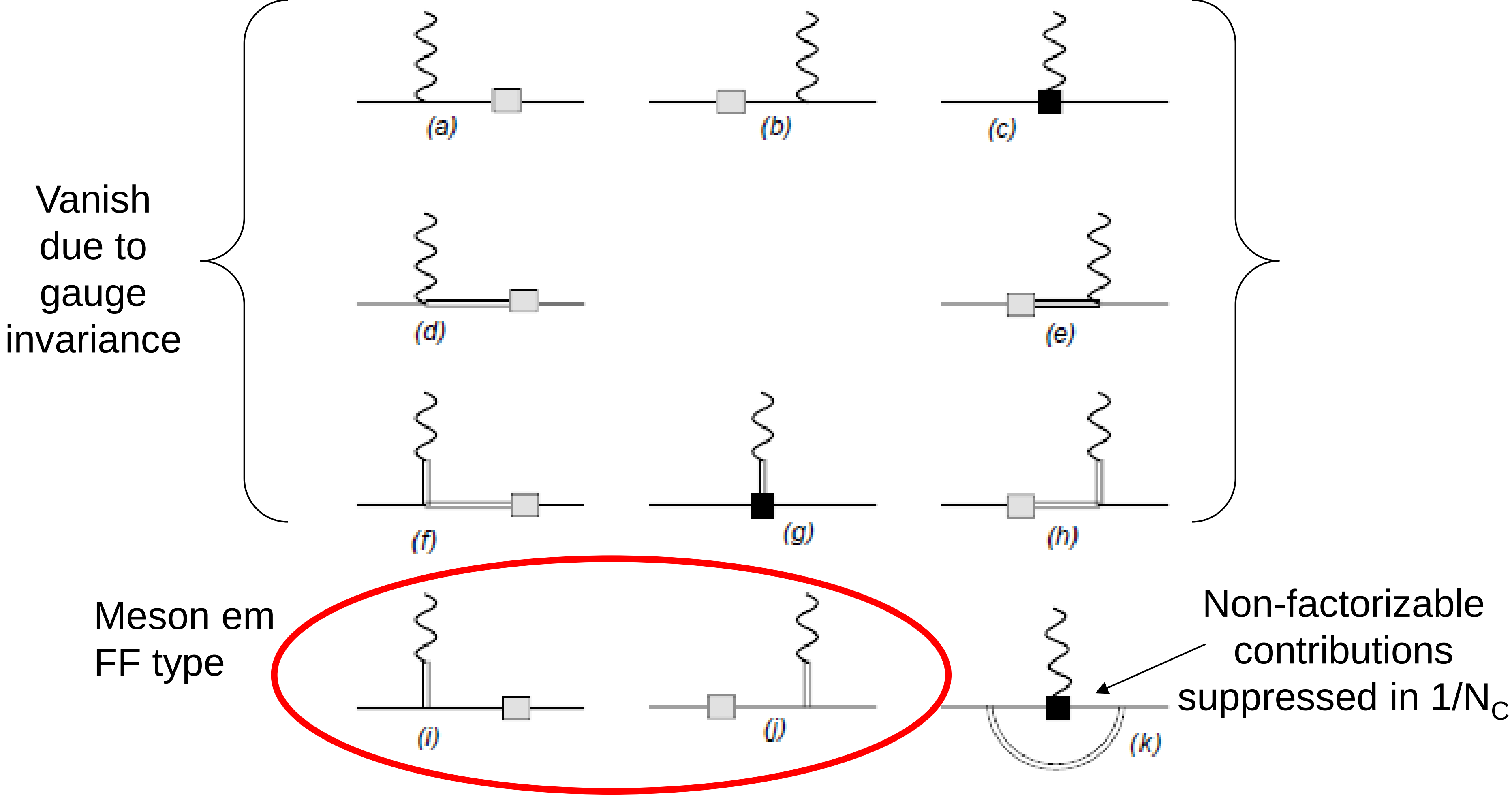
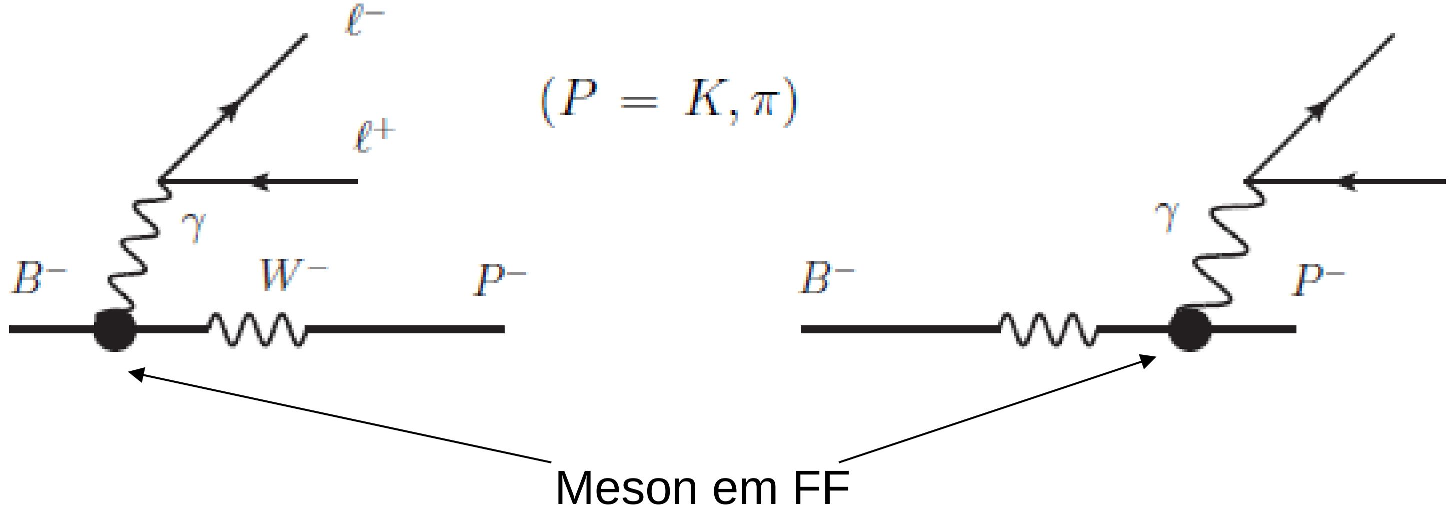
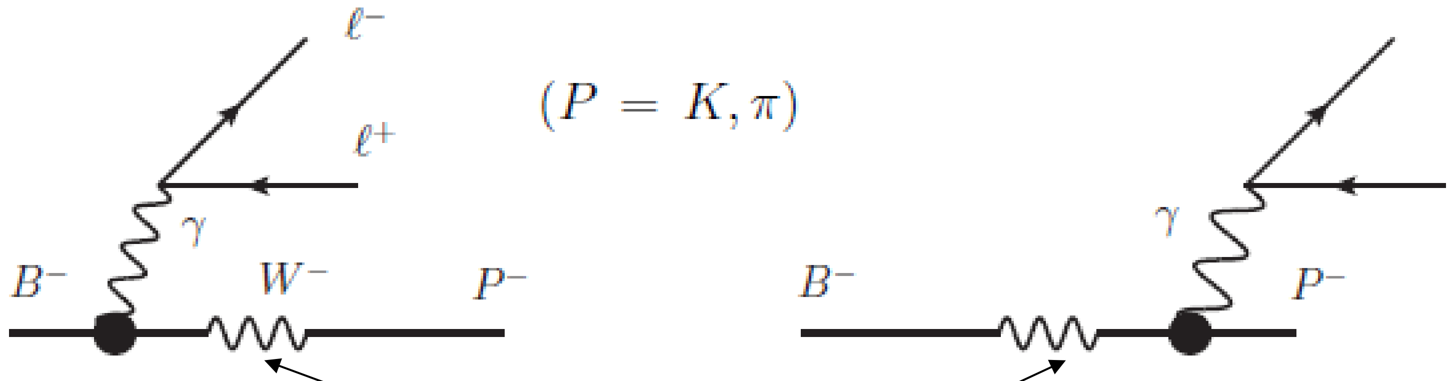


FIG. 2. Some of the Feynman diagrams contributing to the effective hadronic electromagnetic $B^\pm \to P^\pm \gamma^*$ vertex. Single lines stand for pseudoscalar mesons, double lines for (axial-)vector resonances and wavy lines for the virtual photon (due to the spin-one nature of the weak current, spin-zero resonance contributions are suppressed). Filled squares denote the weak/electromagnetic vertex, while the empty rectangles denote the WA Hamiltonian. All contributions to the $B^\pm \to P^\pm \ell^+ \ell^-$ decays (including the pointlike interactions in the first line) vanish due to gauge invariance [21] or are suppressed, except diagrams (i) and (j) which contribute to the electromagnetic form factors of pseudoscalar mesons. Odd-intrinsic parity violating vertices are also considered in the



$\langle B^-(P_P)|j^\mu{}_{em}|B^-(P_B)\rangle = F_V{}^B(q^2)(P_B+P_P)^\mu \sim F_V{}^B(q^2)\ 2\ P_B{}^\mu$

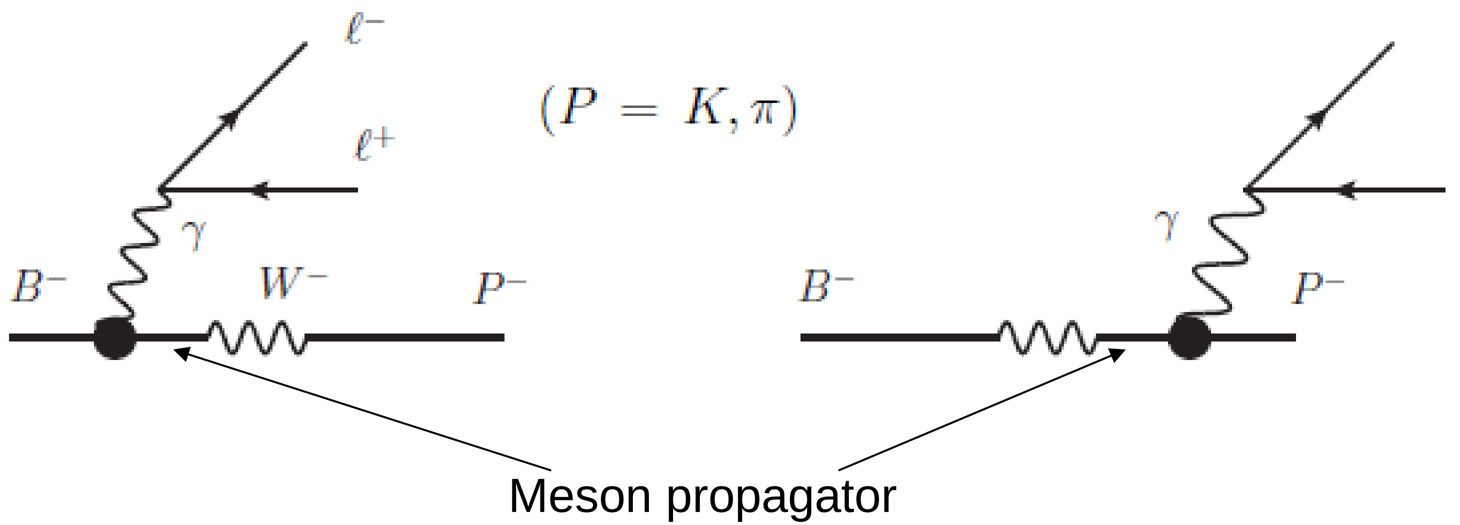
$\langle P^-(P_P)|j^\mu{}_{em}|P^-(P_B)\rangle = F_V{}^P(q^2)(P_B+P_P)^\mu \sim F_V{}^P(q^2)\ 2\ P_B{}^\mu$



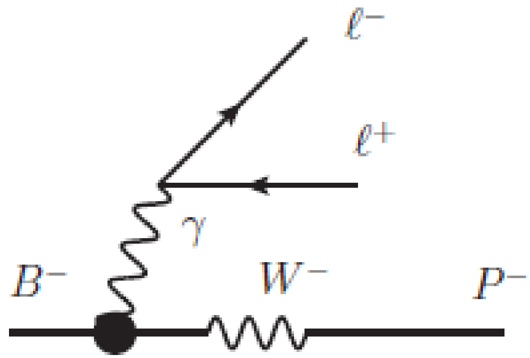
Weak annihilation

$$\langle P^-(P_P)|j^\mu{}_w|0\rangle\langle 0|j_{\mu w}|B^-(P_P)\rangle = G_F/\sqrt{2}\ F_P\ F_B\ M_P^2$$

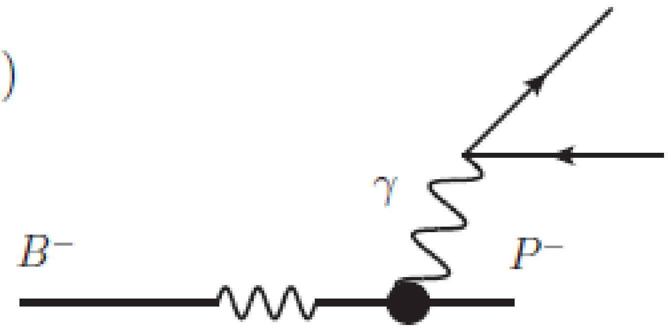
$$\langle P^-(P_B)|j^\mu{}_w|0\rangle\langle 0|j_{\mu w}|B^-(P_B)\rangle = G_F/\sqrt{2}\ F_P\ F_B\ M_B^2$$



$i/(P^2-M_B^2)=i/(M_P^2-M_B^2)$ ← Relative sign → $i/(P^2-M_P^2)=i/(M_B^2-M_P^2)$



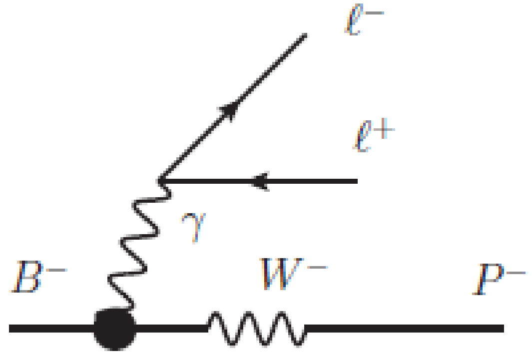
$(P = K, \pi)$



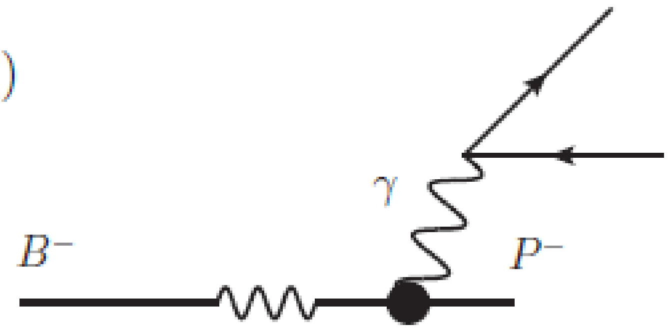
$$\mathcal{M}_{LD} = \sqrt{2} G_F (4\pi\alpha) V_{ub} V^*_{uD} f_B f_P \frac{1}{q^2(m_B^2 - m_P^2)} \left[M_B^2 \left(F_P(q^2) - 1\right) - m_P^2 \left(F_B(q^2) - 1\right)\right] p_B^\mu \bar{\ell} \gamma_\mu \ell$$

Pure scalar QED (point meson) vanishes as well as other V and A SD LD contributions

As dictated by gauge invariance



$(P = K, \pi)$



Kinematical & dynamical suppression

$$\mathcal{M}_{LD} = \sqrt{2} G_F (4\pi\alpha) V_{ub} V^*_{uD} f_B f_P \frac{1}{q^2 (m_B^2 - m_P^2)} \left[M_B^2 \left(F_P(q^2) - 1 \right) - m_P^2 \left(F_B(q^2) - 1 \right) \right] p_B^\mu \bar{\ell} \gamma_\mu \ell$$

SD: $$\mathcal{M}[\bar{B} \to K \bar{l} l] = i \frac{G_F \alpha_e}{\sqrt{2}\pi} V_{tb} V^*_{ts}\, \xi_P(q^2) \left(F_V\, p_B^\mu\, [\bar{l} \gamma_\mu l] + F_A\, p_B^\mu\, [\bar{l} \gamma_\mu \gamma_5 l] \right)$$

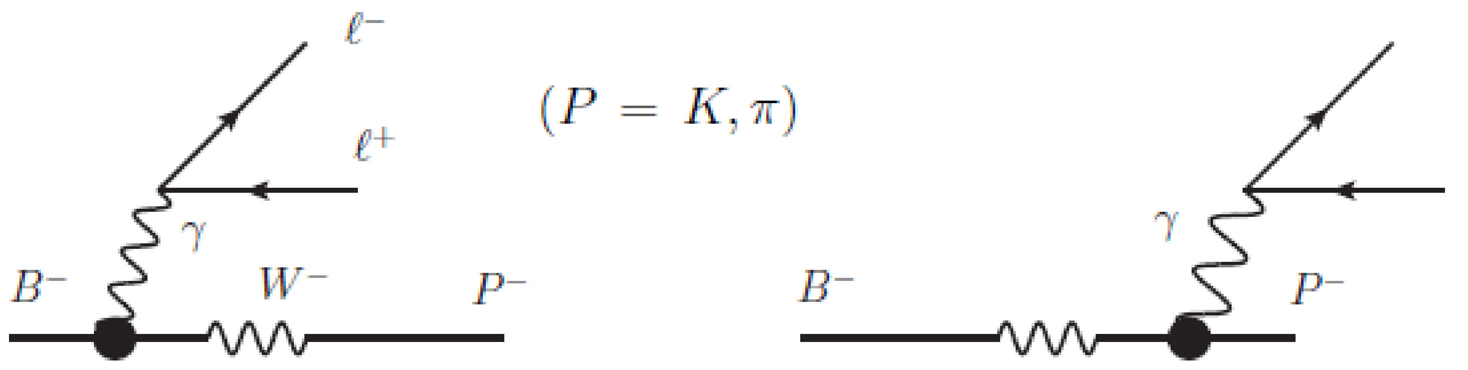
$$\xi_P(q^2) F_V \longrightarrow \xi_P(q^2) F_V + \kappa_P m_B^2 \left[\frac{F_P(q^2) - 1}{q^2} \right]$$

$$\kappa_P = -8\pi^2 \frac{V_{ub} V^*_{uD}}{V_{tb} V^*_{tD}} \frac{f_B f_P}{m_B^2 - m_P^2} \qquad \kappa_P \sim \mathcal{O}(10^{-2}) \times \frac{V_{ub} V^*_{uD}}{V_{tb} V^*_{tD}}$$

$\sim \mathcal{O}(\lambda^2)$ for $P = K$

$\sim \mathcal{O}(\lambda^0)$ for $P = \pi$

$\lambda = V_{us} \sim 0.2255$



$(P = K, \pi)$

Kinematical & dynamical suppression

$$\mathcal{M}_{LD} = \sqrt{2} G_F (4\pi\alpha) V_{ub} V_{uD}^* f_B f_P \frac{1}{q^2(m_B^2 - m_P^2)} \left[M_B^2 \left(F_P(q^2) - 1 \right) - m_P^2 \left(F_B(q^2) - 1 \right) \right] p_B^\mu \bar{\ell} \gamma_\mu \ell$$

Two different approaches are used for these FFs:

- Resonance Chiral Theory (Ecker et. al. ’88 & ‘89)
- Gounaris-Sakurai parametrizations (‘’68)

They are important in the 1 GeV region, where theory is better controlled

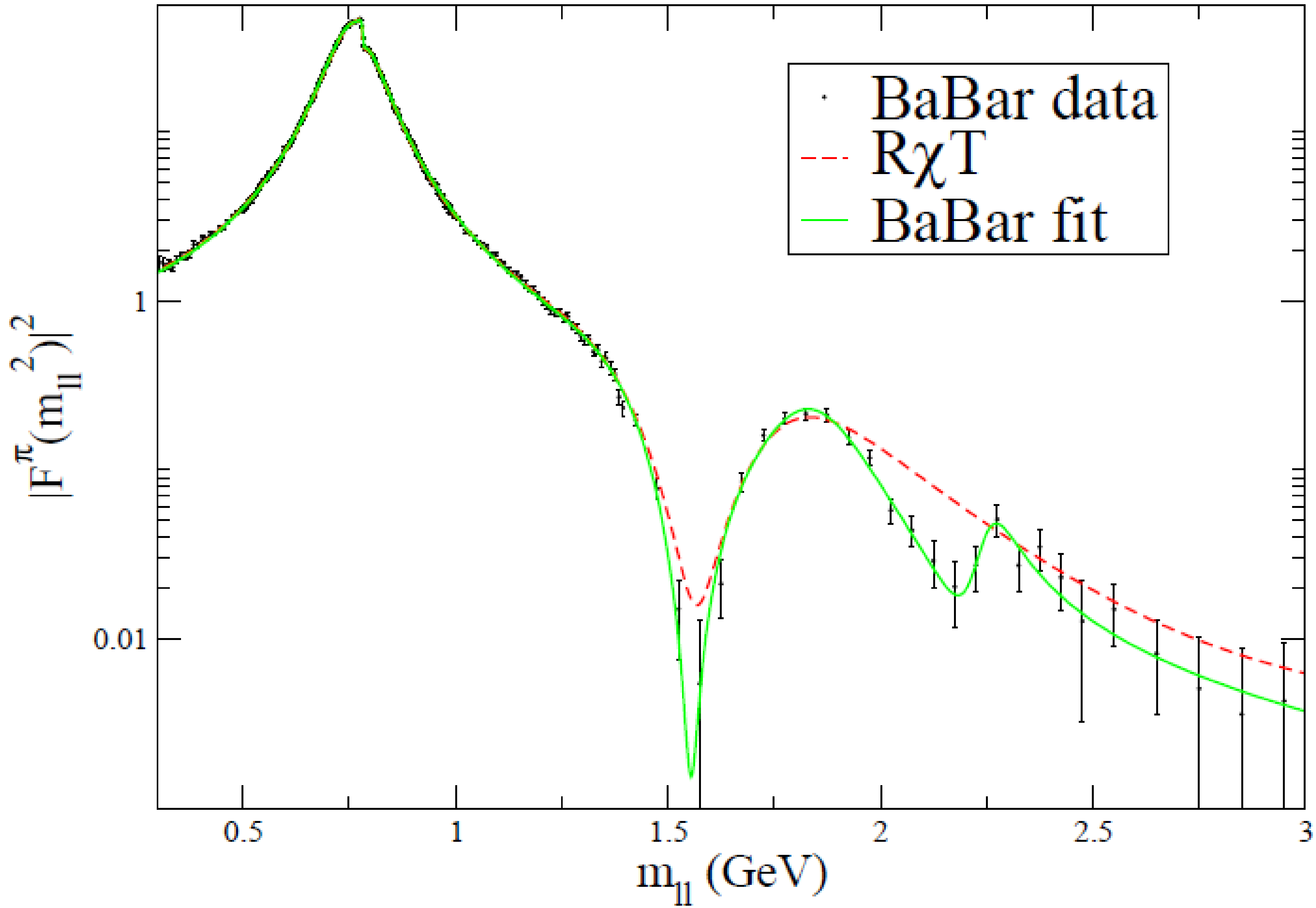


FIG. 2. RχT and GS parametrization (BaBar fit) of the electromagnetic pion form factor as a function of $m_{ll} = \sqrt{q^2}$ are compared to experimental data from BABAR [31].

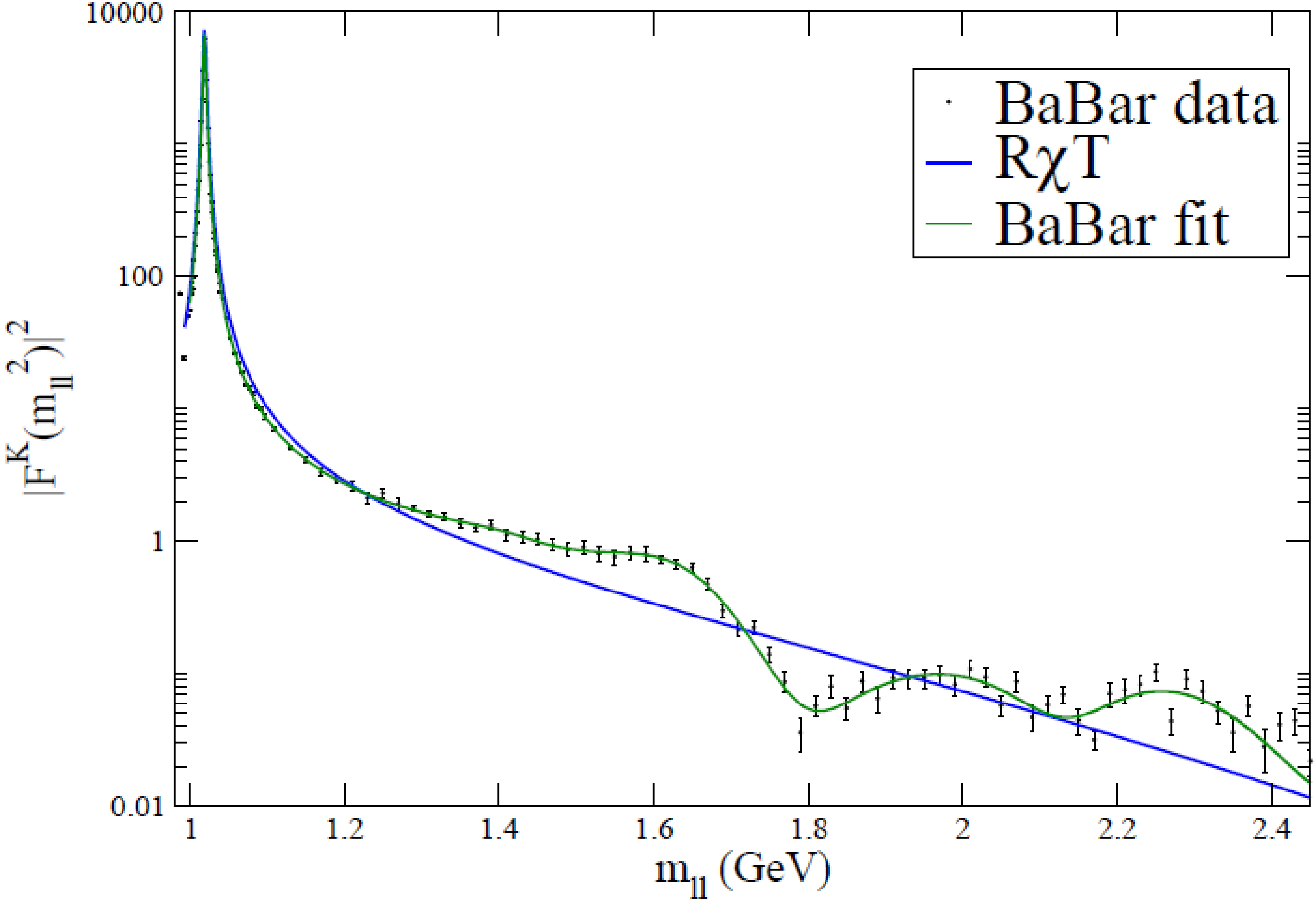
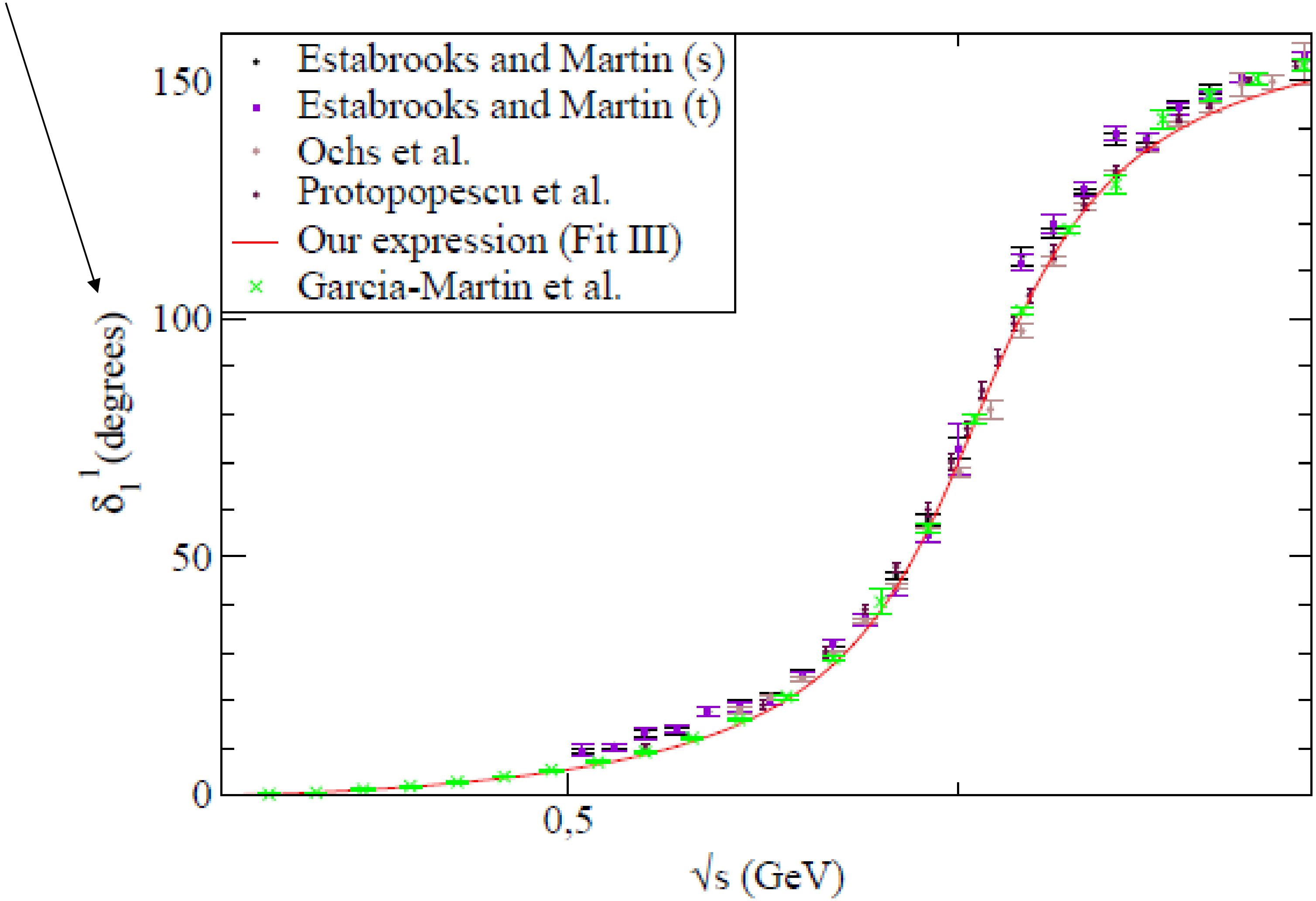


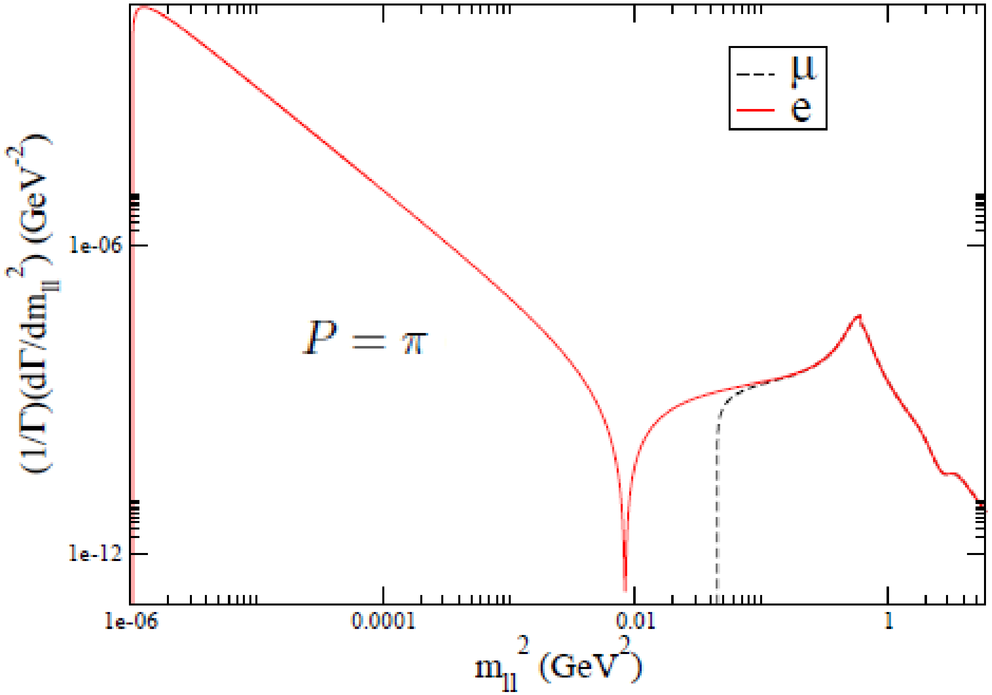
FIG. 3. RχT and GS parametrization (BaBar fit) of the electromagnetic kaon form factor as a function of $m_{ll} = \sqrt{q^2}$ are compared to experimental data from BABAR [33].

From Gómez-Dumm & Roig '12 (See also TAUOLA papers)

$\tan^{-1}[\mathrm{Im}(F_V^{\pi}(s))/\mathrm{Re}(F_V^{\pi}(s))]$

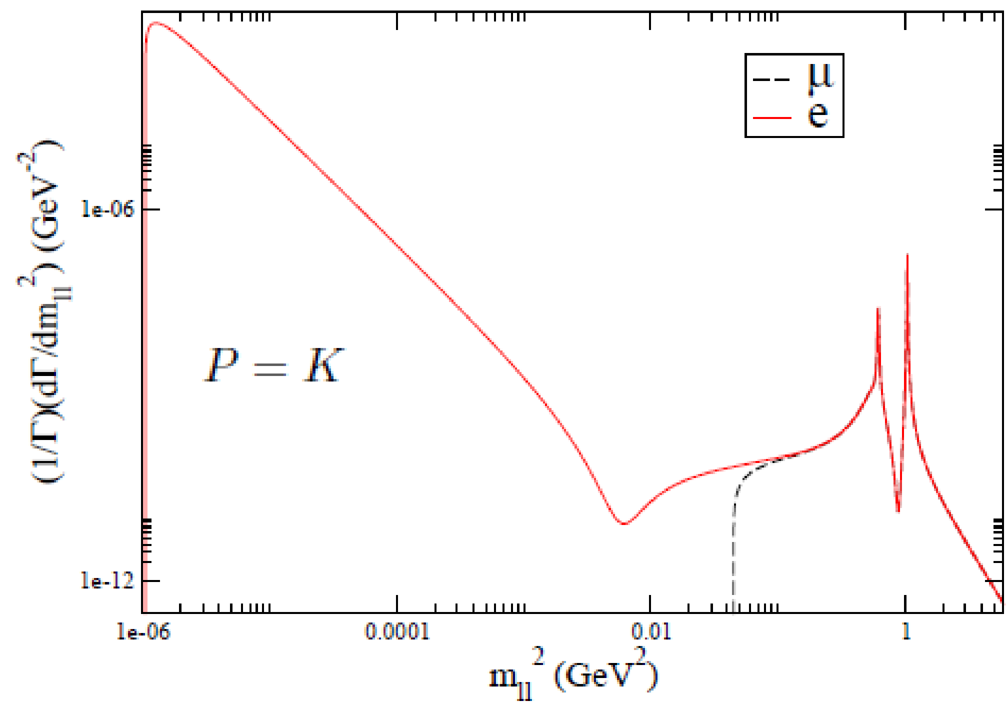


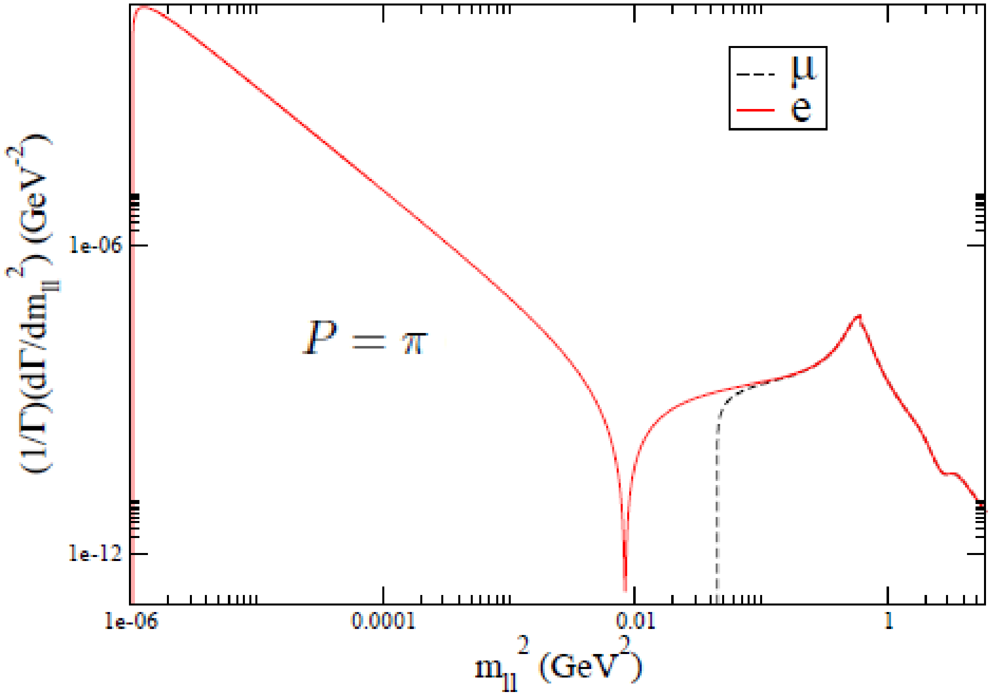
Similarly for $\tan^{-1}[\mathrm{Im}(F_V^{K}(s))/\mathrm{Re}(F_V^{K}(s))]$



There is a huge breaking

of Lepton Universality



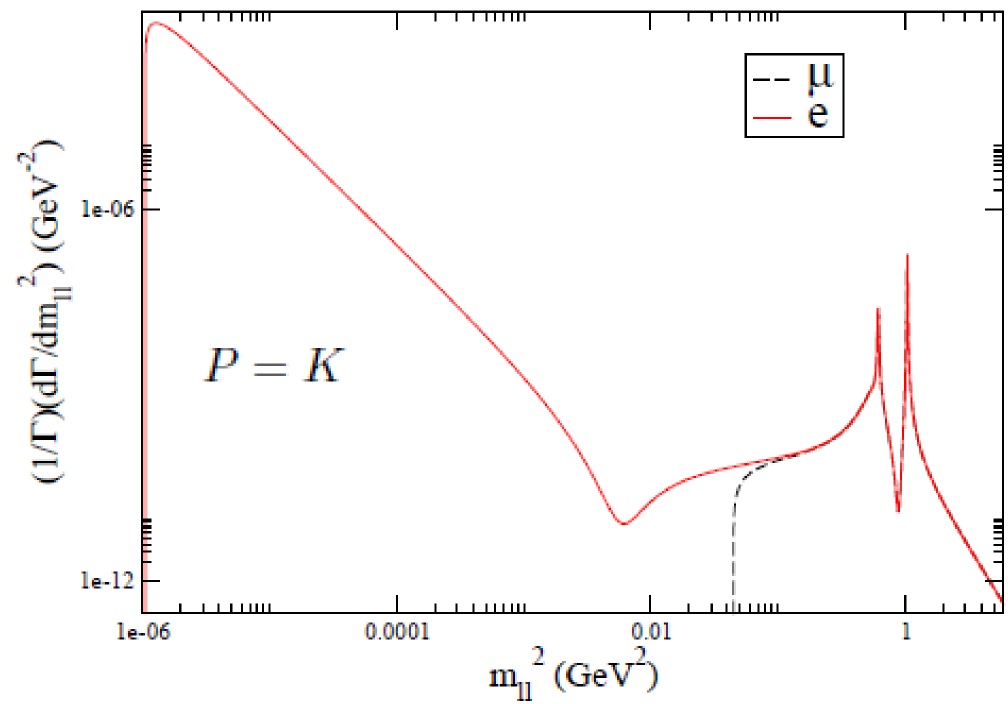


There is a huge breaking of Lepton Universality

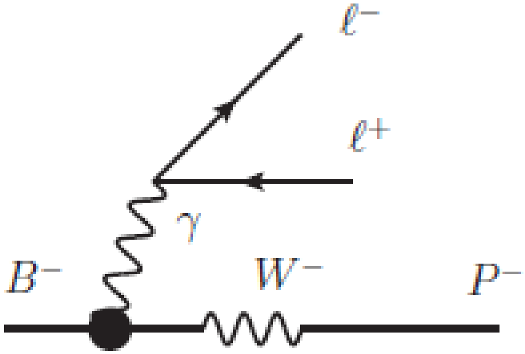
It is important only for q^2<0.3 GeV^2 and its effect is always smaller than the SD contribution

$$R_K^{SM} = 1 + (3.0^{+1.0}_{-0.7}) \times 10^{-4}$$

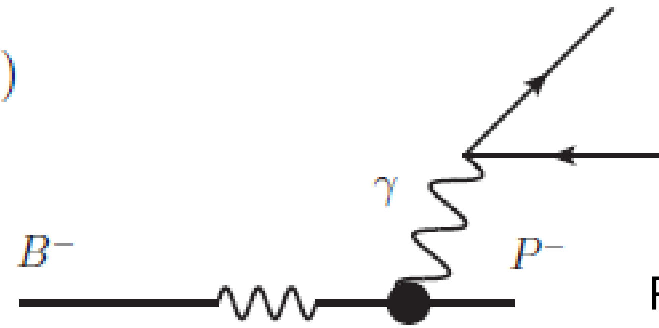
$$R_P(LD) - 1 = \mathcal{O}(10^{-5}) \text{ for } P = K \text{ or } \pi$$



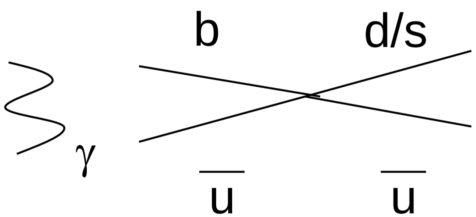
Matching of the LD & SD Weak Annihilation contributions



$(P = K, \pi)$

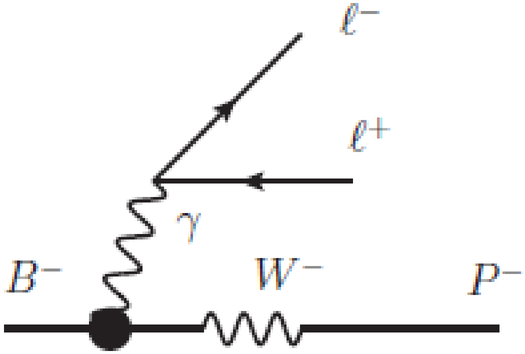


For $q^2 < q^2_{matching}$

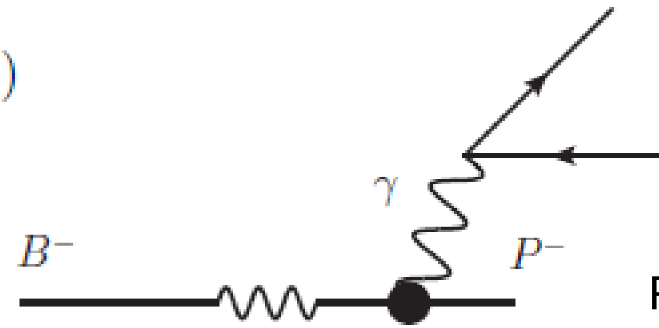


For $q^2 > q^2_{matching}$ (γ goes wherever possible)

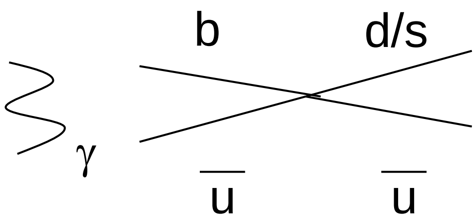
Matching of the LD & SD Weak Annihilation contributions



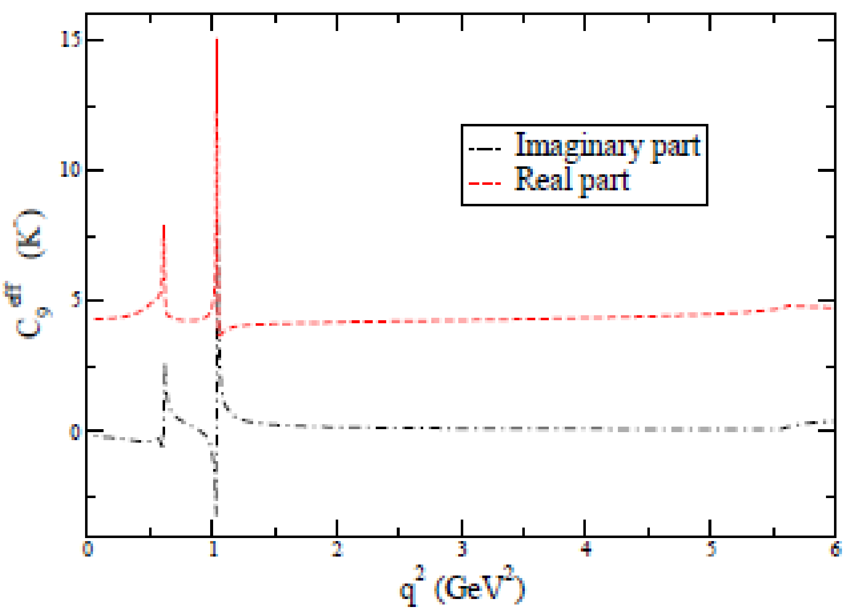
$(P = K, \pi)$



For $q^2 < q^2_{matching}$



For $q^2 > q^2_{matching}$



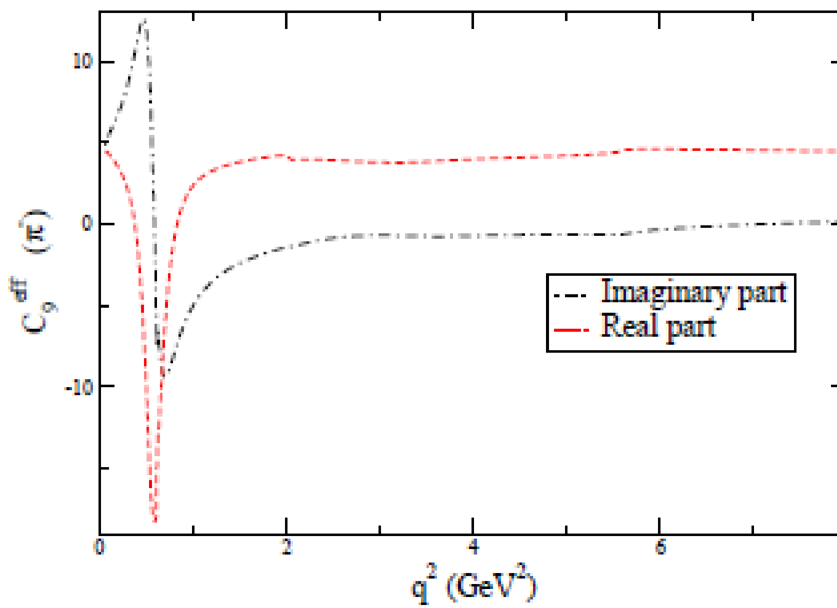


TABLE I. Integrated branching ratios of $B^- \to P^- \ell^+ \ell^-$ decays for $P = \pi$ (left hand side) and $P = K$ (right hand side) for different q^2 ranges. We tabulate separately the QCDf , long-distance WA (LD) and their interference contributions for the kinematical ranges of interest.

	$B^- \to \pi^- \ell^+ \ell^-$		$B^- \to K^- \ell^+ \ell^-$
	$0.05 \leq q^2 \leq 8$ GeV^2	$1 \leq q^2 \leq 8$ GeV^2	$1 \leq q^2 \leq 6$ GeV^2
LD	$(9.06 \pm 0.15) \cdot 10^{-9}$	$(4.74 \pm 0.05) \cdot 10^{-10}$	$(1.70 \pm 0.21) \cdot 10^{-9}$
interf.	$(-2.57 \pm 0.13) \cdot 10^{-9}$	$(-2^{+2}_{-1}) \cdot 10^{-10}$	$(-6 \pm 2) \cdot 10^{-11}$
QCDf	$(9.57^{+1.45}_{-1.01}) \cdot 10^{-9}$	$(8.43^{+1.31}_{-0.87}) \cdot 10^{-9}$	$(1.90^{+0.69}_{-0.41}) \times 10^{-7}$
Total	$(1.61^{+0.15}_{-0.11}) \cdot 10^{-8}$	$(8.69^{+1.31}_{-0.87}) \cdot 10^{-9}$	$(1.92^{+0.69}_{-0.41}) \times 10^{-7}$

It is a 1% correction, current accuracy is insensitive to it! Still ideal place to look for NP!

TABLE I. Integrated branching ratios of $B^- \to P^- \ell^+ \ell^-$ decays for $P = \pi$ (left hand side) and $P = K$ (right hand side) for different q^2 ranges. We tabulate separately the QCDf, long-distance WA (LD) and their interference contributions for the kinematical ranges of interest.

	$B^- \to \pi^- \ell^+ \ell^-$		$B^- \to K^- \ell^+ \ell^-$
	$0.05 \le q^2 \le 8$ GeV^2	$1 \le q^2 \le 8$ GeV^2	$1 \le q^2 \le 6$ GeV^2
LD	$(9.06 \pm 0.15) \cdot 10^{-9}$	$(4.74 \pm 0.05) \cdot 10^{-10}$	$(1.70 \pm 0.21) \cdot 10^{-9}$
interf.	$(-2.57 \pm 0.13) \cdot 10^{-9}$	$(-2^{+2}_{-1}) \cdot 10^{-10}$	$(-6 \pm 2) \cdot 10^{-11}$
QCDf	$(9.57^{+1.45}_{-1.01}) \cdot 10^{-9}$	$(8.43^{+1.31}_{-0.87}) \cdot 10^{-9}$	$(1.90^{+0.69}_{-0.41}) \times 10^{-7}$
Total	$(1.61^{+0.15}_{-0.11}) \cdot 10^{-8}$	$(8.69^{+1.31}_{-0.87}) \cdot 10^{-9}$	$(1.92^{+0.69}_{-0.41}) \times 10^{-7}$

This is a 3% correction. It can be controlled, so it is a good place to search for NP!

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This is a 68% correction. It is better to take $q^2>1$ GeV^2 to probe short-distance physics!

Our prediction is closer to current LHCb data than other analyses (Ali et. al. '13)

$$B(B^- \to \pi^- \mu^+ \mu^-) = (2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$$

$$B(B^- \to \pi^- \ell^+ \ell^-) = (2.6^{+0.4}_{-0.3}) \times 10^{-8}$$

(fully integrated rates)

+ LD

$$BR^{\mathrm{SM}}(SD) = (1.88^{+0.32}_{-0.21}) \times 10^{-8}$$

LHCb'15: $(1.83 \pm 0.25) \times 10^{-8}$

CP VIOLATION

$$A_{CP}(P) = \frac{\Gamma(B^+ \to P^+\ell^+\ell^-) - \Gamma(B^- \to P^-\ell^+\ell^-)}{\Gamma(B^+ \to P^+\ell^+\ell^-) + \Gamma(B^- \to P^-\ell^+\ell^-)}$$

$$\begin{aligned}\Delta_{CP} &= [\Gamma(B^+ \to P^+\ell^+\ell^-) - \Gamma(B^- \to P^-\ell^+\ell^-)] \\ &= -32\alpha^2 G_F^2 f_P f_B \Im m\{V_{tb}V_{tD}^* V_{ub}^* V_{uD}\} \\ &\quad\times \int dq^2 \int ds_{12} \frac{1}{q^2(M_B^2 - m_P^2)} \left[2(P_B \cdot P_+)(P_B \cdot P_-) - \frac{M_B^2 q^2}{2}\right] \\ &\quad\times \Im m\{\xi_P(q^2)F_V(q^2)\left[M_B^2\left(F_P(q^2)-1\right) - m_P^2\left(F_B(q^2)-1\right)\right]\}\end{aligned}$$

$$A_{CP}(P) = \begin{cases} (16.1 \pm 1.9)\%, & \text{for } P = \pi,\ 0.05 \le q^2 \le 8\ \text{GeV}^2, \\ (7.8 \pm 2.9)\%, & \text{for } P = \pi,\ 1 \le q^2 \le 8\ \text{GeV}^2, \\ (-1.0 \pm 0.3)\%, & \text{for } P = K,\ 1 \le q^2 \le 6\ \text{GeV}^2. \end{cases}$$

Hou et. al. '14

$P = \pi$

(q^2_{min}, q^2_{max})	Ref. [24]	Our results
(1, 8) GeV^2	13 ± 2	7.8 ± 2.9
(1, 6) GeV^2	16 ± 2	9.2 ± 1.7
(2, 6) GeV^2	13^{+2}_{-3}	7.7 ± 0.5

$(14.3^{+3.5}_{-2.9})\%$ Khodjamirian et. al.'15

CP VIOLATION

$$A_{CP}(P) = \frac{\Gamma(B^+ \to P^+\ell^+\ell^-) - \Gamma(B^- \to P^-\ell^+\ell^-)}{\Gamma(B^+ \to P^+\ell^+\ell^-) + \Gamma(B^- \to P^-\ell^+\ell^-)}$$

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$$A_{CP}(P) = \begin{cases} (16.1 \pm 1.9)\%, & \text{for } P = \pi,\ 0.05 \le q^2 \le 8 \text{ GeV}^2, \\ (7.8 \pm 2.9)\%, & \text{for } P = \pi,\ 1 \le q^2 \le 8 \text{ GeV}^2, \\ (-1.0 \pm 0.3)\%, & \text{for } P = K,\ 1 \le q^2 \le 6 \text{ GeV}^2. \end{cases}$$

Hou et. al. '14

LHCb'15

$A_{CP} = 0.11 \pm 0.12 \pm 0.01$ $P = \pi$

(q^2_{min}, q^2_{max})	Ref. [24]	Our results
(1, 8) GeV^2	13 ± 2	7.8 ± 2.9
(1, 6) GeV^2	16 ± 2	9.2 ± 1.7
(2, 6) GeV^2	13^{+2}_{-3}	7.7 ± 0.5

$(14.3^{+3.5}_{-2.9})\%$ Khodjamirian et. al.'15

$(B_c/D_{(s)})^{\pm} \to (\pi/K)^{\pm}\, l^+ l^-$

In progress…

Long-distance dynamics is basically unchanged, however SD contributions are heavily suppressed in some of the channels because:

- there is no spectator quark: $(B_c, D_s)^{\pm} \to \pi^{\pm}$, $(B_c, D)^{\pm} \to K^{\pm}$

And just suppressed in some others because:

- the CKMs are tiny: $D^{\pm} \to \pi^{\pm}$, $D_s^{\pm} \to K^{\pm}$

$c \to u\,\gamma$ transitions $\to V_{cb} V_{ub} f(m_b) + V_{cs} V_{us} f(m_s) + V_{cd} V_{ud} f(m_d)$

$V_{cb} V_{ub}$: $O(\lambda^5)$

$f(m_b)$: Sizeable

$V_{cs} V_{us}$, $V_{cd} V_{ud}$: $O(\lambda)$

$f(m_s)$, $f(m_d)$: Small

We give definite prediction for these decays BRs:

$(2.67 \pm 0.04)10^{-6}$, $(1.26 \pm 0.02)10^{-5}$, $(3.08 \pm 0.19)10^{-7}$ & $(1.06 \pm 0.10)10^{-7}$

Only the non-resonant component has been studied by LHCb

$(B_c/D_{(s)})^{\pm} \to (\pi/K)^{\pm}\, l^+\, l^-$

In progress…

Long-distance dynamics is basically unchanged, however SD contributions are heavily suppressed in some of the channels because:

• there is no spectator quark: $(B_c,D_s)^{\pm} \to \pi^{\pm}$, $(B_c,D)^{\pm} \to K^{\pm}$

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$c \to u\,\gamma$ transitions $\to V_{cb}\, V_{ub}\, f(m_b) + \underbrace{V_{cs}\, V_{us}\, f(m_s) + V_{cd}\, V_{ud}\, f(m_d)}$

↓

Main contribution through excitation of a light resonance in the d/s quark loops

Lim, Morozumi & Sanda '89

↓

In these decays our LD mechanism and the SD(LD) contribution interfere!

$D^{\pm} \to \pi^{\pm}\, l^+\, l^-$ dominated by SD(LD), $D_s^{\pm} \to K^{\pm}\, l^+\, l^-$ dominated by our LD contribution

Phenomenological analysis in progress

Conclusions

$B \to \pi \ell^+ \ell^-$

- Our analysis shows that new physics studies should be restricted to the [1,8] GeV^2 range.
- The new contribution is important to understand the current LHCb measurement.
- LHCb could be able to measure this LD effect on the next run in the [1,8] GeV^2 range.

$B \to K \ell^+ \ell^-$

- LHCb might be sensitive to our contribution, but not in the next run.
- This Long Distance contribution will not affect the search for new physics in the $[1, 6]$ GeV^2 region.
- There is a significant CP asymmetry for π and K that has to be taken into account in the search for new physics.

$\longrightarrow$ Sharp predictions for $(B_c/D_{(s)})^{\pm} \to (\pi/K^{\pm})\, l^+ l^-$ to be tested at LHCb & Belle-II

SKIPPED

SLIDES

MOTIVACIÓN

Experimentos precisos a bajas energías pueden ser sondas precisas de física a energías inaccesibles directamente. Ejemplos históricos:

IDEA: Búsqueda de procesos prohibidos o de pequeñas desviaciones al SM en procesos muy raros como signos de **Nueva Física**.

HERRAMIENTAS: Medidas y cálculos ultraprecisos. FACTOR LIMITANTE: QCD no perturbativa

La **Física de Sabor** puede probar **E > E(LHC)**. Efectos virtuales de nuevas partículas modifican ligeramente las predicciones del SM.

- Si LHC encuentra Nueva Física, las factorías de sabor la caracterizarán.
- Si LHC no la encuentra, las factorías de sabor pueden ser sensibles a **E > E(LHC)** utilizando haces muy intensos.

MOTIVACIÓN

Isidori, Nir, Pérez '10

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$$

$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2} (\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$$

FORMALISMO DE TEORÍAS EFECTIVAS: Más general posible, sistemática, control de los errores, …

Expansión en potencias inversas de la escala de Nueva Física.

Coeficientes calculables perturbativamente. En principio con tanta precisión como uno quiera.

Operadores con los g.d.l. relevantes cuyos elementos de matriz deben calcularse no perturbativamente: constantes de desintegración, factores de forma, … *Su precisión debería ser comparable a la del experimento!* ***Si no, se pierde la sensibilidad a Nueva Física!***

CPV & OSCILACIONES EN Ks, Bs & Ds: EJEMPLO CLARO DONDE SON IMPORTANTES TANTO EL INPUT PERTURBATIVO ELECTRODÉBIL (CORTAS DISTANCIAS) COMO EL DE QCD NO PERTURBATIVA (BAJAS ENERGÍAS)

MOTIVACIÓN

Isidori, Nir, Pérez '10

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$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2} (\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$$

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

TABLE I: Bounds on representative dimension-six $\Delta F = 2$ operators. Bounds on Λ are quoted assuming an effective coupling $1/\Lambda^2$, or, alternatively, the bounds on the respective c_{ij}'s assuming $\Lambda = 1$ TeV. Observables related to CPV are separated from the CP conserving ones with semicolons.

MOTIVACIÓN

Isidori, Nir, Pérez '10

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$$

Tensión con escalas requeridas para estabilizar **EWSB (M_H)**

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)(\overline{E}_R\gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)(\overline{L}_L\gamma_\mu L_L)$	1.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)(eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

TABLE II: Bounds on the scale of new physics (at 95% C.L.) for some representative $\Delta F = 1$ [27] and $\Delta F = 2$ [12] MFV operators (assuming effective coupling $\pm 1/\Lambda^2$), and corresponding observables used to set the bounds.

La Nueva Física o se da a muy altas energías, o es muy débilmente acoplada o se parece muchísimo al SM (en la estructura de sabor).