Rare heavy mesons decays to leptons

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in collaboration with

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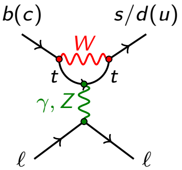
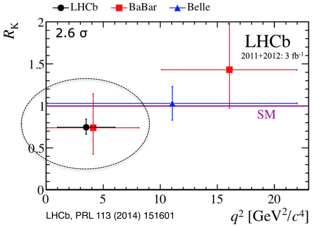
Introduction

- Flavor Changing Neutral Current (FCNC) meson decays are only at loop level in Standard Model (SM) $\Rightarrow$ Rare but very sensitive to new physics (NP) !





- Many deviations from SM seen in FCNC ($b \to s\ell\ell$) : $R_{K^{0(*)}} = \frac{\mathcal{B}(B^0 \to K^{0(*)}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{0(*)}e^+e^-)}$, P'_5
- But also at tree level $R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{+(*)}\tau^-\nu)}{\mathcal{B}(B^0 \to D^{+(*)}\mu^-\nu)}$, NP scenario with lepton flavor dependence ?

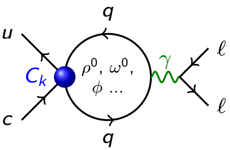
Need to pursue all possible ways to constrain NP. In this light, working on 2 projects :

Experimental

- CPPM, LHCb
- Purely leptonic $b \to s\ell\ell$ transition
- ▶ **Pursue the search for $B^0_{(s)} \to \tau^+\tau^-$**

Phenomenology

- CPT and D. Boito (São Paulo University)
- Semi-leptonic $c \to u\ell\ell$ transition
- ▶ **Improve predictions for $D \to \pi\ell\ell$**



$$q^2 = m^2_{\ell\ell}$$

GOAL : Improve predictions around $D \to \pi\ell\ell$

- FCNC decay of type $c \to u\ell\ell$
- Should be sensitive to the same NP as FCNC B decay like $b \to s\ell\ell$

- So why it's not a golden channel yet ?

Because of resonances entering the quark loop in one of the leading order diagram.

▶ For B decay, predictions not done when resonances stands in the q^2-phase space

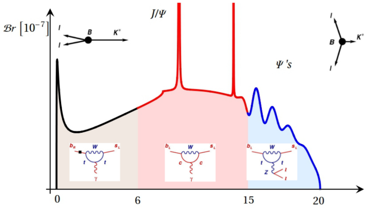
▶ For D decay, we cannot do this because it's equivalent to throw away most of the phase space

$\Rightarrow$ We need to model these resonances.

Predictions done in the framework of Effective Field Theory :

In blue, effective operators with as "coupling" the Wilson coefficient C_k.

(all which is not relevant at the scale $\mathrm{m_c}$)



☞ [Grinstein]

Phenomenology project on $D \to \pi\ell\ell$: References

The framework to treat D meson decays is inspired from the one for B meson nicely summarised in :
☞ arXiv 0106067, Beneke, Feldmann, Seidel

The main references on the $D \to \pi\ell\ell$ are :
☞ arXiv 1705.05891, Feldmann, Muller, Seidel (mainly on $D \to \rho\ell\ell$)
☞ arXiv 1510.00311, Boer, Hiller
☞ arXiv 1510.00965, Fajfer, Kosnik

The main difference between the Boer-Hiller reference and our work are :
• the treatement of resonances (inspired from ☞ arXiv 1406.0566).
• the implementation of non factorizable (n.f.) correction via the QCD factorization approach (inspired from ☞ arXiv 1705.05891).

Phenomenology project on $D \to \pi\ell\ell$: Framework

The effective hamiltonian :

$$\mathcal{H}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} \sum_{q=b,d} V_{cq}^* V_{uq} \sum_i \cdot C_i \cdot \mathcal{O}_i$$

In our case $\mathcal{O}_1$, $\mathcal{O}_2$ and $\mathcal{O}_9$ are the dominant operators.

The amplitude can schematically be written :

$$\langle \ell\ell\pi^+ \mid \mathcal{H}_{\text{eff}} \mid D^+ \rangle = C \cdot ff + \Phi_{D^+} \otimes T \otimes \Phi_{\pi^+}$$

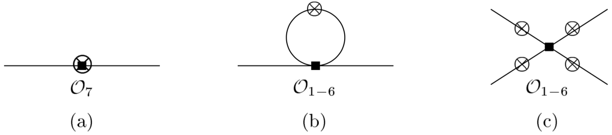
where *ff* stands for form factors, the Φ are the light-cone distribution amplitudes.

The C and T factors are caculables in renormalization-group improved perturbation theory and can be further decomposed into :

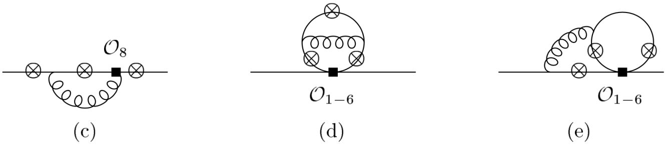
$$C = C^{(0)} + a_s \cdot C^{(1)} \text{ and } T = T^{(0)} + a_s \cdot T^{(1)} \text{ with } a_s = C_F \frac{\alpha_s}{4\pi}$$

Phenomenology project on $D \to \pi\ell\ell$: Leading Order (LO) and Next-to-Leading Order (NLO) contributions

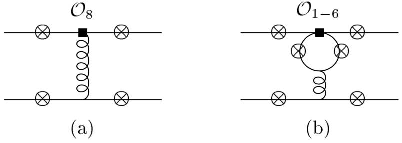
LO : (a) and (b) included in $C = C^{(0)}$, weak annihilation diagram (c) included in $T^{(0)}$ (not taken into account in the Boer-Hiller reference.)



NLO form factor correction : inlcuded in $C = C^{(1)}$, partly taken into account in the Boer-Hiller reference.



NLO hard spectator scattering correction : inlcuded in $C = T^{(1)}$, not taken into account in the Boer-Hiller reference

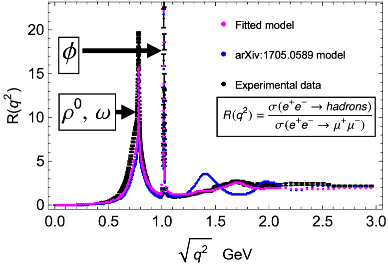


Phenomenology project on $D \to \pi\ell\ell$: Treatment of resonances

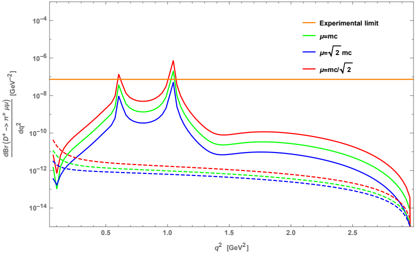
In the Boer-Hiller reference, resonances are treated by simple Breit-Wigner peaks.

Our strategy : improve resonances modelization by using the Shifman parametrisation and by extracting these parameters from a fit to e^+e^- experimental data R by virtue of the optical theorem :

$$\frac{\pi}{3}R(q^2) = \mathrm{Im}[L](q^2) \overset{\text{dispersion relation}}{\rightarrow} L(q^2) \text{ (function describing the resonances entering into } C_9\text{)}$$



$\Rightarrow$



Shifman parametrisation : ☞ hep-0009131

Resonances modelled by an infinite tower of equidistant vector resonances

Phenomenology project on $D \to \pi\ell\ell$: Conclusion

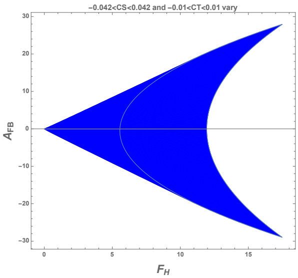
$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ depends on C_7, C_9 and NP : $C_{10}, C_S, C_P, C_T, C_{T5}$

Experimental measurements :
- $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \cdot 10^{-8}$ at 90% C.L. ☞ LHCB-PAPER-2012-051
- $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \cdot 10^{-9}$ at 90% C.L. ☞ LHCB-PAPER-2013-013

Take-home messsage :
The work is still ongoing !
Thanks to a **more accurate estimation of the hadronic contribution** as well as the non factorizable contribution, we aim at giving **more accurate bounds on NP Wilson coefficients.**

This will help us to estimate the room left for other observables like the angular observables (A_{FB}, F_H), the CP assymetries, lepton flavor universality ratio...

Eye candy example :
If C_T and C_S real and the other NP C_i null, we get :
⚠Preliminary plot (doesn't include either n.f. corrections or hadronic contributions)



Experimental project on $B^0_{(s)} \to \tau^+\tau^-$: Introduction

- $B^0_{(s)} \to \ell\ell$ are golden channels, theoretically clean and with clear experimental signature.
- $\mathcal{B}(B^0_s \to \mu\mu) = (3.0 \pm 0.6 \pm^{+0.3}_{-0.2}) \times 10^{-9}$ in agreement with SM ☞LHCB-PAPER-2017-001
- Nevertheless, several models predict BR higher than SM ☞ arXiv 1505.05164 , 1609.09078
- But the τ channel is more challenging :

	$B^0_s \to \tau^+\tau^-$	$B^0 \to \tau^+\tau^-$
SM	7.7×10^{-7}	2.2×10^{-8}
Limit at 95% C.L.	$< 6.8 \times 10^{-3}$	$< 2.1 \times 10^{-3}$

Best world limit set with LHCb Run 1 data (Lumi $\simeq 3fb^{-1}$) ☞ LHCB-PAPER-2017-003

2 axes to improve these limits :

(1) Explore another channel with Run 1 data : $B^0_{(s)} \to \tau(3\pi^\pm)\tau(\mu)$

(2) Run 2 data (Lumi $\simeq 7fb^{-1}$, energy $\times$ 2)

Motivations for the $(3\pi, \mu)$ channel :

☺ Higher effective branching ratio : $\simeq 17.4\%$ for $\tau \to \mu\nu\nu$ vs $\simeq 9.3\%$ for $\tau \to 3\pi\nu$
☺ Only 4 tracks required in the detector acceptance.
☺ μ trigger more efficient than the hadronic trigger.
☹ Plus one ν / only 1 τ vertex, less handle to discriminate signal and background.
☹ Substantial semi-leptonic B and D decays as background.

Regions :
3 ν in the final state $\Rightarrow$ no narrow mass peak to fit !
Idea : Exploit the ρ^0 resonances of the $\tau \to 3\pi$ decay

$$\tau^- \to a1(1260)^- \nu_\tau$$
$$\hookrightarrow \pi_1^- \rho(770)^0$$
$$\hookrightarrow \pi_2^+ \pi_3-$$

Region	$(3\pi, \mu)$	$(3\pi, 3\pi)$
Signal	τ in 5	τ^+ and τ^- in 5
Bkg.	τ in 1/3/7/9	τ^+ (or τ^-) in 1/3/7/9
Control	τ in 4/8	τ^+ in 4/5/8 and τ^- in 4/8

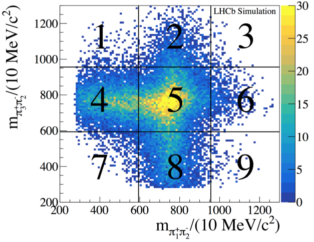


FIGURE – MC simulation of $B_s^0 \to \tau^+\tau^-$

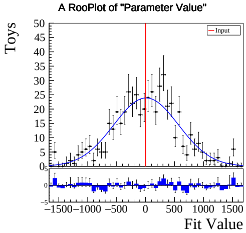
Experimental project on $B^0_{(s)} \to \tau^+\tau^-$: Axe ① : $(3\pi, \mu)$ Run1, Workflow

Workflow (inspired from the $(3\pi, 3\pi)$ Run 1 analysis) :

1. **Selection :** Loose cut-based + BDT-based
   Based on kinematical, geometric variables and custom-made variables, mainly isolation variables.

2. **1D binned Maximum Likelihood fit :**
   - Fit a new BDT output for data in the signal region.
   - Fit error for zero signal events estimated via a toys study.

3. **Normalisation :** channel : $B^0 \to D^+(K^-\pi^+\pi^+)\pi^-$
   $\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-) = \frac{N^{\text{obs}}_{\tau\tau}}{\epsilon^{\text{tot}}_{\tau\tau} N_{B^0}} \equiv \alpha \cdot N^{\text{obs}}_{\tau\tau}$



Experimental project on $B^0_{(s)} \to \tau^+\tau^-$: Axe ① : $(3\pi, \mu)$ Run1, Results

B^0_s	$(3\pi, \mu)$	$(3\pi, 3\pi)$
$\epsilon^{\text{tot}}(10^{-5})$	1.42	2.4
$\alpha(10^{-5})$	3.5	4.1
signal yield error	444	38
$\mathcal{UL}$ at 95 % C.L. $\mathcal{B}(B^0_s \to \tau^+\tau^-)$	3.1×10^{-2} ⚠	6.8×10^{-3}

⚠ Toy estimate obtained by : $\mathcal{UL} = 2 \cdot \alpha \cdot$ signal-yield-error
(no systematics, no efficiency correction, no template correction)

Axe ① explored : $\frac{\mathcal{UL}(3\pi,\mu)}{\mathcal{UL}(3\pi,3\pi)}$ for $B^0_{(s)}$: 3.7(4.5)

- Appeared to be difficult to fight the B and D substantial background.
- Internal note delivered on June 2018 ☞ LHCb-INT-2018-021

Axe ② : $(3\pi, 3\pi)$ analysis workflow and results

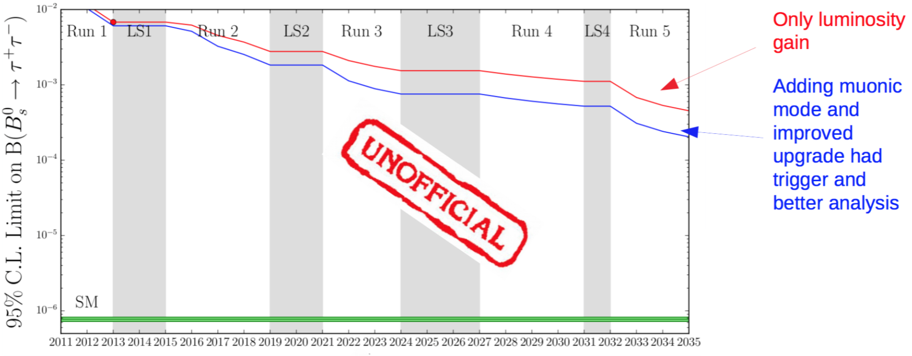
The signal yield obtained for Run 1 data $s = -15^{+67}_{-56}(\text{stat})^{+44}_{-42}(\text{syst})$
Uncertainty mainly statistical, hence adding Run 2 data is highly motivated.

Axe ② started 2 month ago, two strategy explored in parallel :
- Apply the exact same selection than for Run 1.
- Re-optimize the selection, the used regions, etc...

What is done :
- Normalization channel (except systematics)
- A possible re-selection has been designed (performance estimation ongoing).
- Apply the Run 1 selection (ongoing).

Prospects :
- Deliver soon an estimate of the limit we could reach for both strategy

Experimental project on $B^0_{(s)} \to \tau^+\tau^-$: Conclusion



[Courtesy of Kristof De Bruyn]

- If not for LHC, $B^0_{(s)} \to \tau^+\tau^-$ will be a golden mode for the future collider (like FCC).
  - Comparison with sister processes with e or μ $\to$ test of LFU.
  - Richer phenomenelogy (angular observables)
- Definitively worthwhile to work on it and to prepare the future of this channel ! !

Back-Up

Phenomenology project on $D \to \pi\ell\ell$: Angular observables

The decay rate can be expressed like :

$$\frac{d\Gamma}{d\cos\theta} = A + B\cos\theta + C\cos^2\theta \qquad \Rightarrow \Gamma = 2\left(A + \frac{C}{3}\right)$$

with θ angle between the D and ℓ^- direction of motion in the dipleton center of mass frame.

Two clean null-tests can be defined (more deltails in ☞ arXiv:0709.4174)

- **Forward-backward asymmetry :**

$$A_{FB} = \frac{B}{\Gamma} \quad \text{, depends on } (C_S \cdot C_T, C_P \cdot C_{T5})$$

- **Flat term :**

$$F_H = 2\frac{A+C}{\Gamma} \quad \text{, depends on } (C_S, C_P, C_T, C_{T5})$$

If C_T and C_S real and the other NP C_i null, we get :
⚠Preliminary plot (doesn't include either n.f. corrections or hadronic contributions)