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Rare heavy mesons decays to leptons

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in collaboration with

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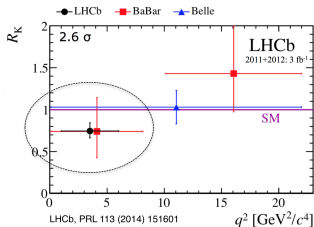
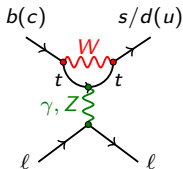
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2018 6th November



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

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

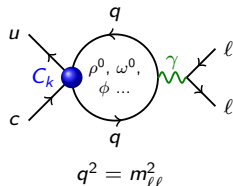
Experimental

- CPPM, LHCb
- Purely leptonic $b \rightarrow s\ell\ell$ transition
- Pursue the search for $B_{(s)}^0 \rightarrow \tau^+ \tau^-$

Phenomenology

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

Phenomenology project on $D \rightarrow \pi \ell \ell$: Introduction



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

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

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

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

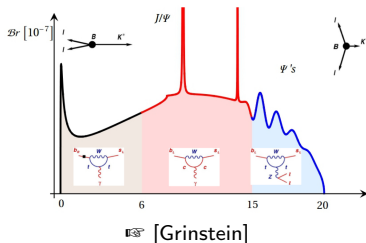
► For B decay, predictions not done when resonances stands in the q^2 -phase space

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

⇒ 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 m_c)



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 $D \rightarrow \pi \ell \ell$ are :

☞ arXiv 1705.05891, Feldmann, Muller, Seidel (mainly on $D \rightarrow \rho \ell \ell$)

☞ arXiv 1510.00311, Boer, Hiller

☞ arXiv 1510.00965, Fajfer, Kosnik

The main difference between the Boer-Hiller reference and our work are :

- the treatment 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).

The effective hamiltonian :

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

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

The amplitude can schematically be written :

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

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

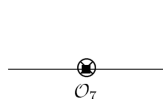
The C and T factors are calculables in renormalization-group improved perturbation theory and can be further decomposed into :

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

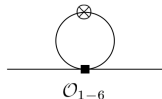
Phenomenology project on $D \rightarrow \pi ll$:

Leading Order (LO) and Next-to-Leading Order (NLO) contributions

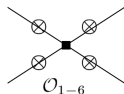
LO : (a) and (b) included in $C = C^{(0)}$, weak annihilation diagram (c) included in $T^{(0)}$ (not taken into account in the Boer-Hiller reference.)



(a)

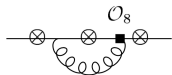


(b)

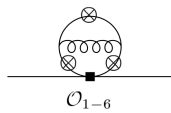


(c)

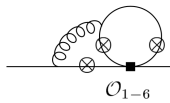
NLO form factor correction : included in $C = C^{(1)}$, partly taken into account in the Boer-Hiller reference.



(c)

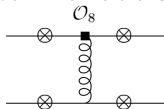


(d)

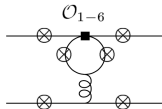


(e)

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



(a)



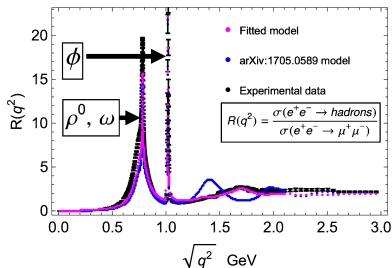
(b)

Phenomenology project on $D \rightarrow \pi ll$: Treatment of resonances

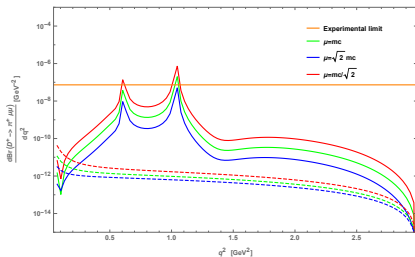
In the Boer-Hiller reference, resonances are treated by simple Breit-Wigner peaks.

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 :

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



\Rightarrow





Shifman parametrisation : [hep-0009131](https://arxiv.org/abs/hep-0009131)

Resonances modelled by an infinite tower of equidistant vector resonances

Phenomenology project on $D \rightarrow \pi ll$: Conclusion

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

Experimental measurements :

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

Take-home message :


The work is still ongoing!

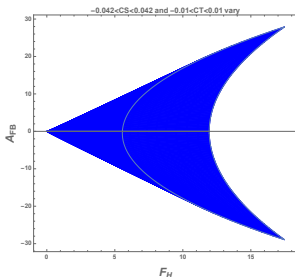
Thanks to a **more accurate estimation of the hadronic contribution** as well as the non factorizable contribution, we aim at giving **more accurate bounds on NP Wilson coefficients**.

This will help us to estimate the room left for other observables like the angular observables (A_{FB}, F_H), the CP asymmetries, 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 $B_{(s)}^0 \rightarrow \tau^+ \tau^-$: Introduction

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

| | $B_s^0 \rightarrow \tau^+ \tau^-$ | $B^0 \rightarrow \tau^+ \tau^-$ |
|-------------------|-----------------------------------|---------------------------------|
| 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 $\simeq 3fb^{-1}$) \llcorner LHCb-PAPER-2017-003

2 axes to improve these limits :

- ① Explore another channel with Run 1 data : $B_{(s)}^0 \rightarrow \tau(3\pi^\pm)\tau(\mu)$
- ② Run 2 data (Lumi $\simeq 7fb^{-1}$, energy $\times 2$)

Experimental project on $B_{(s)}^0 \rightarrow \tau^+ \tau^-$:

Axe ① : $(3\pi, \mu)$ Run 1, Motivations and regions

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

- 😊 Higher effective branching ratio : $\simeq 17.4\%$ for $\tau \rightarrow \mu\nu\nu$ vs $\simeq 9.3\%$ for $\tau \rightarrow 3\pi\nu$
- 😊 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 $\tau \rightarrow 3\pi$ decay

$$\begin{aligned}\tau^- &\rightarrow a_1(1260)^- \nu_\tau \\ &\hookrightarrow \pi_1^- \rho(770)^0 \\ &\quad \hookrightarrow \pi_2^+ \pi_3^-\end{aligned}$$

| 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 |

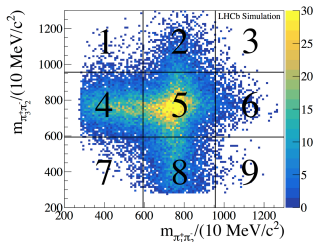


FIGURE – MC simulation of $B_s^0 \rightarrow \tau^+ \tau^-$

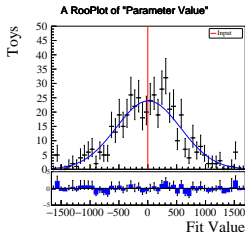
Experimental project on $B_{(s)}^0 \rightarrow \tau^+ \tau^-$:

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 : $B^0 \rightarrow D^+(K^-\pi^+\pi^+)\pi^-$

$$\mathcal{B}(B_{(s)}^0 \rightarrow \tau^+ \tau^-) = \frac{N_{\tau\tau}^{\text{obs}}}{\epsilon_{\tau\tau}^{\text{tot}} N_{B^0}} \equiv \alpha \cdot N_{\tau\tau}^{\text{obs}}$$



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

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

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

Experimental project on $B_{(s)}^0 \rightarrow \tau^+ \tau^-$:

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

The signal yield obtained for Run 1 data $s = -15_{-56}^{+67}(\text{stat})_{-42}^{+44}(\text{syst})$
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...

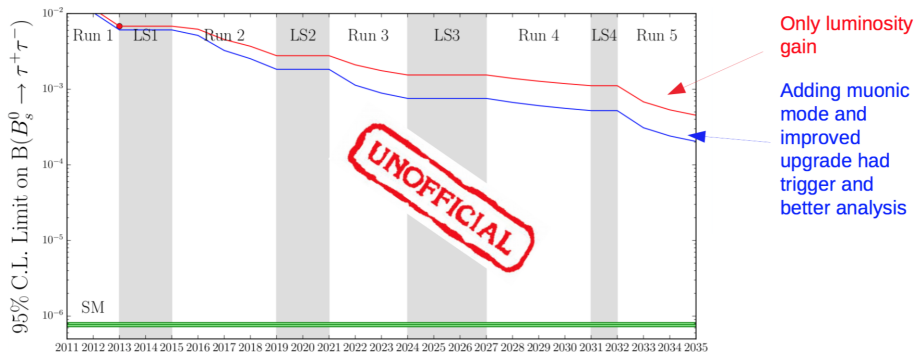
What is done :

- 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 $B_{(s)}^0 \rightarrow \tau^+ \tau^-$: Conclusion



[Courtesy of Kristof De Bruyn]

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

Back-Up

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

The decay rate can be expressed like :

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

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 details 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)

