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”Rare heavy mesons decays to leptons”

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"Lepton flavour in b to s transitions: prospects at the LHC and beyond"
or rather
"Rare heavy mesons decays to leptons"

Cédric Méaux¹²

in collaboration with

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²Aix Marseille Univ, Univ Toulon, CNRS, CPT, Marseille, France

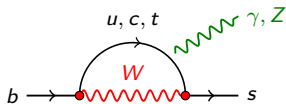
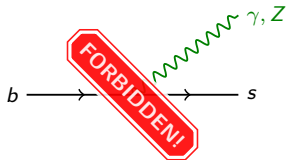
³São Paulo Univ, Instituto de Física de São Carlos, Brazil

2018 15th November



Introduction : Standard Model and Flavor Changing Neutral Current transitions

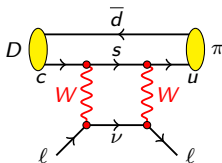
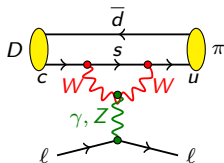
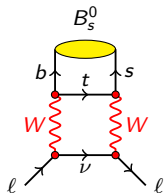
	mass → charge → spin →	$\approx 2.3 \text{ MeV}/c^2$ 2/3 1/2 u up	$\approx 1.275 \text{ GeV}/c^2$ 2/3 1/2 c charm	$\approx 173.07 \text{ GeV}/c^2$ 2/3 1/2 t top	0 1 g gluon	$\approx 126 \text{ GeV}/c^2$ 0 0 H Higgs boson
QUARKS		$\approx 4.8 \text{ MeV}/c^2$ -1/3 1/2 d down	$\approx 95 \text{ MeV}/c^2$ -1/3 1/2 s strange	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2 b bottom	0 0 1 γ photon	
		$0.511 \text{ MeV}/c^2$ -1 1/2 e electron	$105.7 \text{ MeV}/c^2$ -1 1/2 μ muon	$1.777 \text{ GeV}/c^2$ -1 1/2 τ tau	0 0 1 Z Z boson	GAUGE BOSONS
	LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 1/2 ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 1/2 ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 1/2 ν_τ tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson	



In the Standard Model (SM), Flavour Changing Neutral Current (FCNC) processes are forbidden at tree level \Rightarrow They can proceed only via loops.

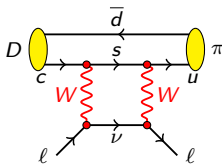
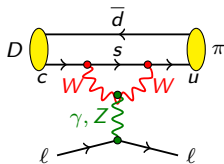
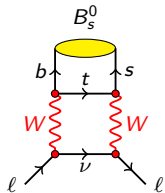
Introduction : A probe of New Physics

- The rare ($B \sim 10^{-6}$) decays $b \rightarrow s\ell^+\ell^-$ ($\ell = e, \mu, \tau$) and $c \rightarrow u\ell^+\ell^-$ ($B \sim 10^{-9}$) are FCNC processes that proceed via box and penguin diagrams in SM :

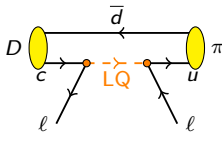
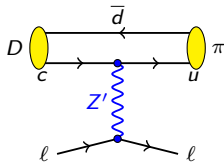
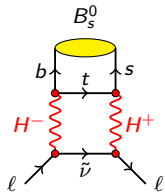


Introduction : A probe of New Physics

- The rare ($B \sim 10^{-6}$) decays $b \rightarrow s\ell^+\ell^-$ ($\ell = e, \mu, \tau$) and $c \rightarrow u\ell^+\ell^-$ ($B \sim 10^{-9}$) are FCNC processes that proceed via box and penguin diagrams in SM :



- In new physics (NP) beyond the SM, new particles can enter into the loop diagram or generate new diagrams.



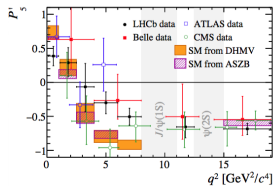
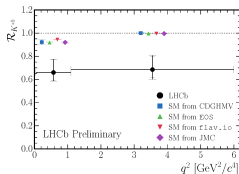
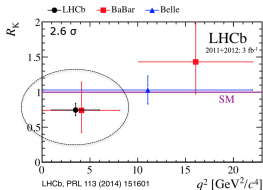
- FCNC meson decays can be sensitive probes of NP and allows us to test **scales potentially beyond the direct searches at LHC**

Motivation : The FCNC anomalies

- The three most significant $b \rightarrow sll$ deviations from SM :

$$R_{K^{0(*)}} = \frac{\mathcal{B}(B^0 \rightarrow K^{0(*)} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{0(*)} e^+ e^-)}$$

Angular observable P'_5 in $B^* \rightarrow K^* \mu \mu$



In this light, I am working on 2 projects :

Experimental :

- **Search for $B_{(s)}^0 \rightarrow \tau^+ \tau^-$**
- Purely leptonic $b \rightarrow sll$ transition
- CPPM, LHCb

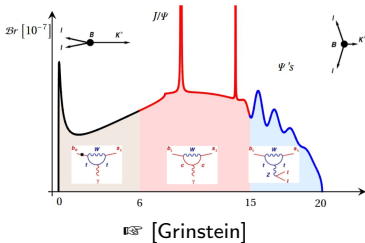
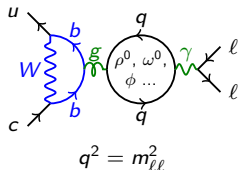
Phenomenology :

- **Improve predictions for $D \rightarrow \pi ll$**
- Rare $c \rightarrow ull$ transition
- CPT and D. Boito (São Paulo University)

Predictions of $c \rightarrow ull$ meson decay are more challenging than for $b \rightarrow sll$ decays :

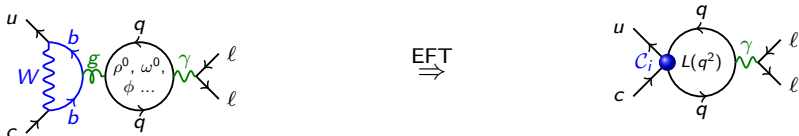
- 1) Factorization doesn't work as well as for B decays.
 - 2) Because of resonances entering the quark loop in one of the leading order diagrams.
- \Rightarrow **For D decay, we need to model these resonances.**

We are focusing on the mode $D^+ \rightarrow \pi^+ ll$



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

- Multiscale problem ($\mu_W, \mu_b, \mu_c, \Lambda_{\text{QCD}}$) \Rightarrow **Weak Effective Field Theory (EFT)** :
Integrate out heavy fields (b, W, NP particles...) wrt the scale of interest $\mu \sim m_c$



This leads to an effective hamiltonian :

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{q=b,d} \underbrace{V_{cq}^* V_{uq}}_{\text{CKM elements}} \left[\sum_i \underbrace{C_i}_{\text{Wilson coefficients}} \overbrace{\mathcal{O}_i}^{\text{Operators}} + C_i' \mathcal{O}_i' \right]$$

whose amplitude can schematically be written (**QCD factorization approach**) :

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

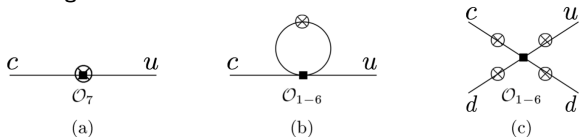
ff stands for form factors (parametrize the role of quarks within hadrons)
 Φ are the light-cone distribution amplitudes

- QCD factorization inspired from B decay [[Beneke, Feldmann, Seidel, arXiv 0106067](#)]

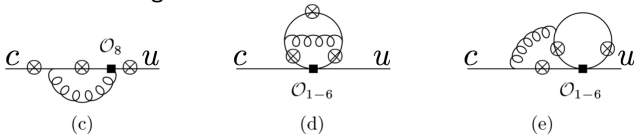
Used first time for D decays in [[Feldmann, Muller, Seidel, arXiv 1705.05891](#)]

But doesn't work as well as for B decays since expansion in $\frac{\Lambda_{QCD}}{m_c}$ instead of $\frac{\Lambda_{QCD}}{m_b}$

Leading Order :

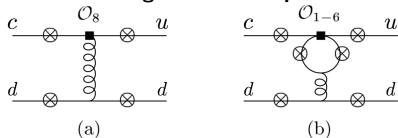


Next-to-Leading Order form factor correction :



⊗ marks the possible insertions of the virtual photon line.

Next-to-Leading Order hard spectator scattering correction :



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

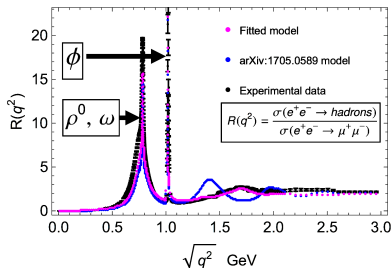
In [De Boer, Hiller, arXiv 1510.00311] and [Fajfer, Kosnik, arXiv 1510.00965], resonances are treated by simple Breit-Wigner peaks.

Our strategy : Improve resonances modelization by using a Shifman model, inspired from [Feldmann, Muller, Seidel, arXiv 1705.05891]

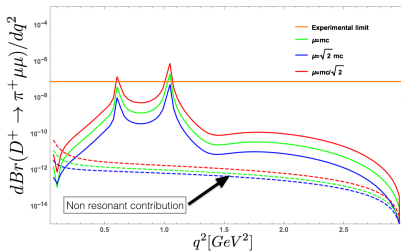
► Resonances modelled by an infinite tower of equidistant vector resonances [Shifman, hep-0009131]

► Parameters of the model extracted from a fit to e^+e^- experimental data R by virtue of the optical theorem, inspired from [Lyon, Zwicky, arXiv 1406.0566]

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



⇒



$$\frac{d^2\Gamma}{dq^2 d\cos\theta}(D^+ \rightarrow \pi^+ \mu\mu) = a(q^2) + b(q^2) \cos\theta + c(q^2) \cos^2\theta$$

depends on C_7, C_9 and NP : $C_{10}, C_S, C_P, C_T, C_{T5}$

The branching ratio spectrum :

Integrated branching ratio measured by LHCb [[LHCb-PAPER-2012-051](#)]

Angular observables :

$$\frac{d\Gamma}{d\cos\theta}(D^+ \rightarrow \pi^+ \mu\mu) = A + B \cos\theta + C \cos^2\theta$$

Two clean null tests :

$$A_{FB} = \frac{B}{\Gamma} \text{ and } F_H = 2 \frac{A+C}{\Gamma} \text{ with } \Gamma = 2 \left(A + \frac{C}{3} \right)$$

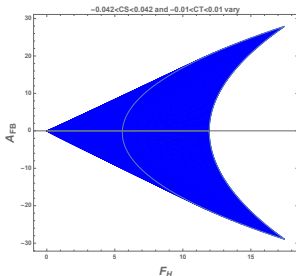
If C_T and C_S real and the other NP C_i null, we get :

⚠ Preliminary plot (doesn't include either n.f. corrections or hadronic contributions)

Lepton Flavor Universality Ratio

Prospects :

- ▶ Define observables sensitive to NP that could be improved by our work thanks to :
 - QCD factorization approach
 - Resonances modelling technique
- ▶ Estimate the uncertainties from our predictions (and compare it to previous work).



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 [LHCB-PAPER-2017-001]
- Nevertheless, several models predict BR higher than SM for τ lepton [arXiv 1505.05164 , 1609.09078]
- But the τ lepton final state 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 on $(3\pi, 3\pi)$ final state 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 : $B_{(s)}^0 \rightarrow \tau(3\pi^\pm)\tau(\mu)$
- ② Run 2 data (Lumi $\simeq 7fb^{-1}$, energy $\times 2$)

Axe ① : $(3\pi, \mu)$ final state, Run 1 data

$$\frac{\mathcal{UL}(3\pi, \mu)}{\mathcal{UL}(3\pi, 3\pi)} \text{ for } B_{(s)}^0 : 3.7(4.5)$$

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

Axe ② : $(3\pi, 3\pi)$ final state, Run 2 data

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

Two strategy explored in parallel :

- Apply the exact same selection than for Run 1.
- Re-optimize the selection, the regions, etc...

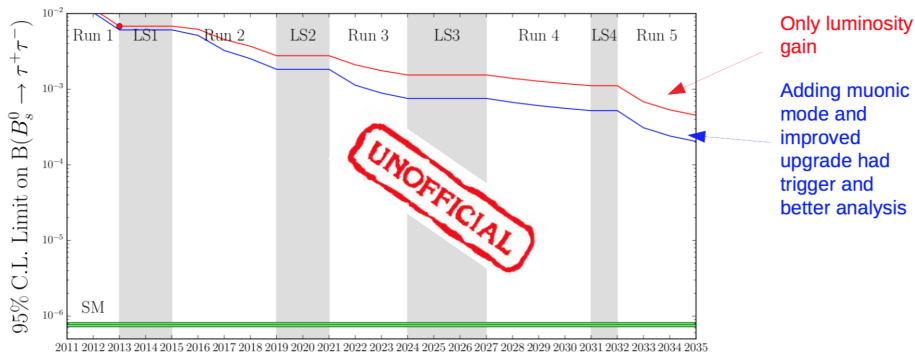
What has been done :

- Normalisation channel (except systematics)
- Data-MC comparison.
- Apply the Run 1 selection (ongoing).
- A possible re-selection has been designed (performance estimation ongoing).

Prospects :

- **Deliver soon an estimate of the limit that we could reach for both strategy**

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



[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

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

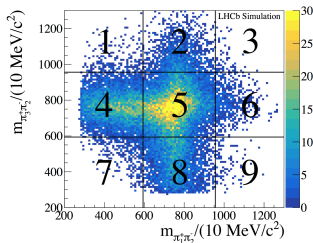


FIGURE – MC simulation of $B_s^0 \rightarrow \tau^+ \tau^-$

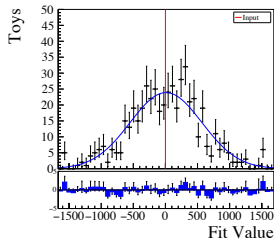
Experimental project on $B_{(s)}^0 \rightarrow \tau^+ \tau^-$:

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**

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 diplectron 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)

