”Rare heavy mesons decays to leptons”

Cédric Méaux, Giampiero Mancinelli, Justine Serrano, Aoife Bharucha, Diogo Boito

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

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in collaboration with

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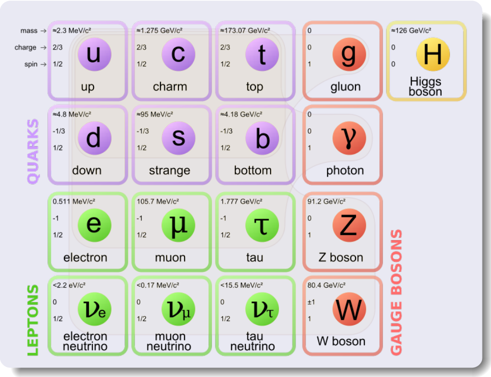
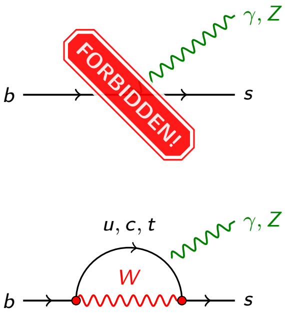
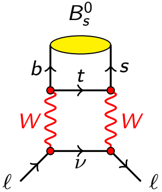
Introduction : Standard Model and Flavor Changing Neutral Current transitions

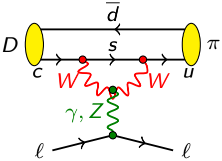


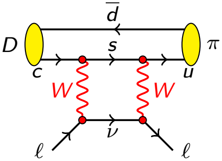


In the Standard Model (SM), Flavour Changing Neutral Current (FCNC) processes are forbidden at tree level ⇒ They can proceed only via loops.

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







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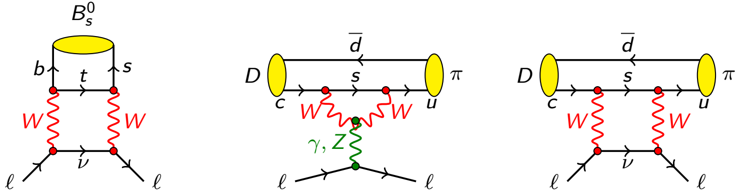
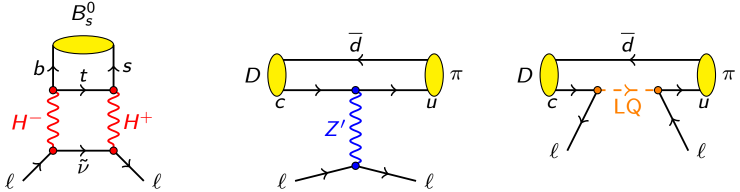


- In new physics (NP) beyond the SM, new particles can enter into the loop diagram or generate new diagrams.

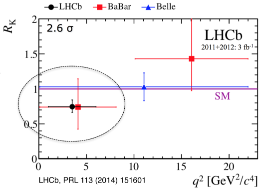


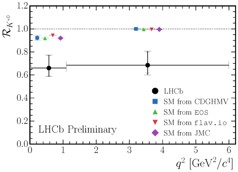
- FCNC meson decays can be sensitive probes of NP and allows us to test **scales potentially beyond the direct searches at LHC**

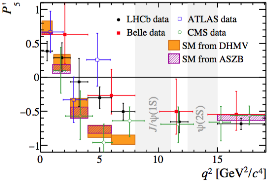
- The three most significant $b \to s\ell\ell$ deviations from SM :

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

Angular observable P_5' in $B^* \to K^*\mu\mu$







In this light, I am working on 2 projects :

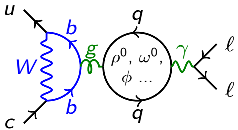
Experimental :

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

Phenomenology :

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

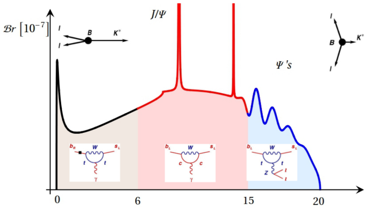
Predictions of $c \to u\ell\ell$ meson decay are more challenging than for $b \to s\ell\ell$ decays :



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

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 diagram.
$\Rightarrow$ **For D decay, we need to model these resonances.**

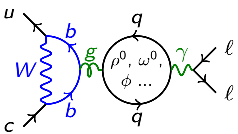


☞ [Grinstein]

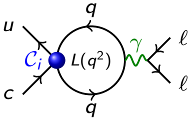
We are focusing on the mode $D^+ \to \pi^+\ell\ell$

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

• Multiscale problem (μ_W, μ_b, μ_c, Λ_{QCD}) $\Rightarrow$ **Weak Effective Field Theory (EFT)** :
Integrate out heavy fields (b, W, NP particles...) wrt the scale of interest $\mu \sim m_c$



EFT
$\Rightarrow$



This leads to an effective hamiltonian :

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

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

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

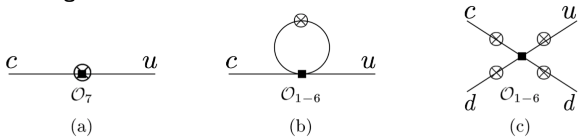
ff stands for form factors (parametrize the role of quarks within hadrons)
Φ are the light-cone distribution amplitudes

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

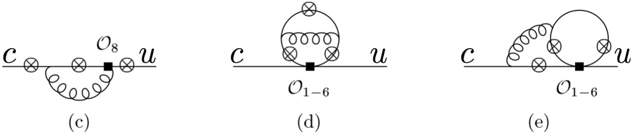
Used first time for D decays in [Feldmann, Muller, Seidel, arXiv 1705.05891]

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 :

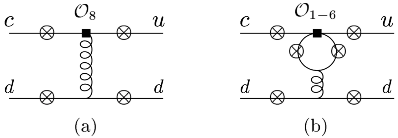


Next-to-Leading Order form factor correction :



$\otimes$ marks the possible insertions of the virtual photon line.

Next-to-Leading Order hard spectator scattering correction :



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

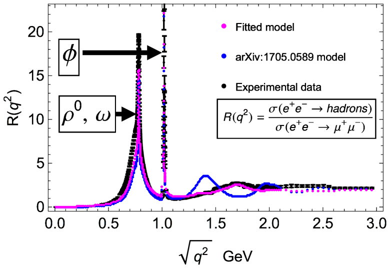
In [De Boer, Hiller, arXiv 1510.00311] and [Fajfer, Kosnik, arXiv 1510.00965], resonances are treated by simple Breit-Wigner peaks.

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

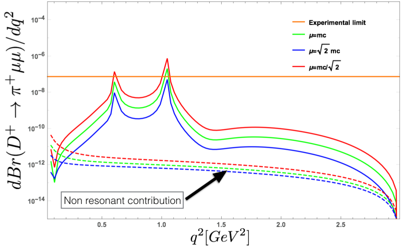
▶ Resonances modelled by an infinite tower of equidistant vector resonances [Shifman, hep-0009131]

▶ 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]

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



$\Rightarrow$



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

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]

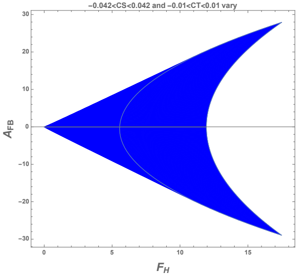
Angular observables :

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

Two clean null tests :

$A_{FB} = \frac{B}{\Gamma}$ and $F_H = 2\frac{A+C}{\Gamma}$ 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 uncertanties from our predictions (and compare it to previous work).

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 for τ lepton [arXiv 1505.05164 , 1609.09078]

- But the τ lepton final state 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 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 : $B^0_{(s)} \to \tau(3\pi^\pm)\tau(\mu)$

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

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

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

$\frac{\mathcal{UL}(3\pi,\mu)}{\mathcal{UL}(3\pi,3\pi)}$ 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) : $(3\pi, 3\pi)$ final state, Run 2 data

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

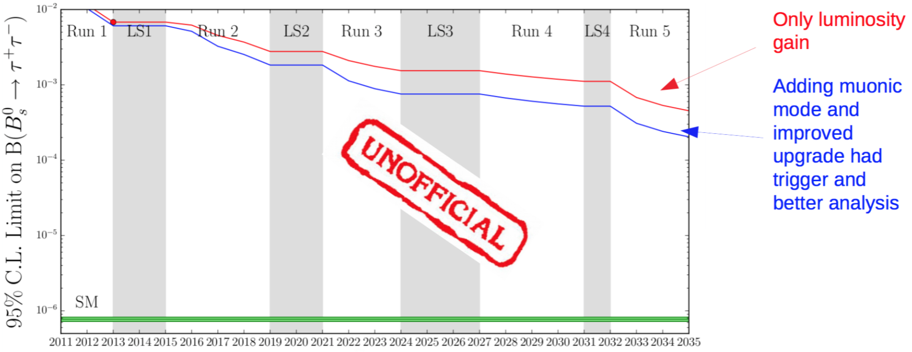
What has been done :

- 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 $B^0_{(s)} \to \tau^+\tau^-$: Future



[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

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 $\tau \to \mu\nu\nu$ 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

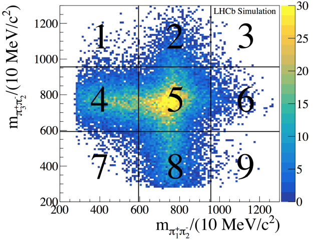


FIGURE – MC simulation of $B^0_s \to \tau^+\tau^-$

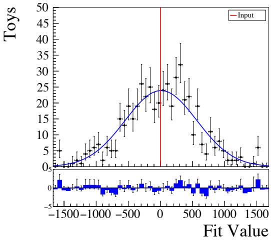
Experimental project on $B^0_{(s)} \to \tau^+\tau^-$: Axe ① : $(3\pi, \mu)$ Run1, Workflow

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



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

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)