

$b \rightarrow cl\nu$ global Wilson coefficient fit with LHCb and Belle II

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Challenges in Semileptonic B decays
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Outline

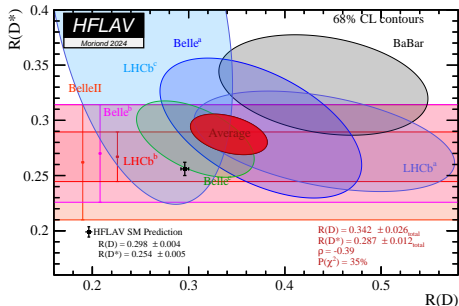
- 1 Introduction
- 2 LFU tests at LHCb and Belle II
- 3 New Physics measurements
- 4 Summary

Introduction

- Semileptonic B decays are ideal for testing Lepton Flavour Universality (LFU)
- $R(?)$ and $R(?^*)$ measurements report a 3.1 discrepancy with the Standard Model

$$R(?) = \frac{3p(3^E \rightarrow ?)}{3p(3^E \rightarrow ?)}$$

- Measurements from LHCb, Belle and Babar available
- $R(D^*)$ measurements from LHCb use \rightarrow or \rightarrow
 \rightarrow + +



The goal:

Measure potential New Physics scenarios contributions

LFU tests in semileptonic B decays at LHCb

Muonic decay

$p(\tau^+)$ Run I (2015)

$\mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

▶ [dpX ccl cccDCf](#)

$p(\tau^+)$ vs $p(\tau^0)$ Run I (2023)

$p(\tau^0) = \mathcal{B}(B \rightarrow \tau^0 \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$p(\tau^+) = \mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

▶ [dpX c\(c cccDCf](#)

$p(\tau^+)$ vs $p(\tau^+)$ Run II (2024)

$p(\tau^+) = \mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$p(\tau^+) = \mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

▶ [-of S+JCE/CE{Du](#)

$p(T=)$ Run I (2018)

$\mathcal{B}(B \rightarrow T^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

▶ [dpX c|CE|cDCf](#)

Hadronic decay

$p(\tau^+)$ Run I (2018)

$\mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$\mathcal{B}(B \rightarrow \tau^+ \mu^-)$

▶ [dpX c|CEucDCf](#)

$p(\tau^+)$ part Run II (2023)

$\mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$\mathcal{B}(B \rightarrow \tau^+ \mu^-)$ ▶ [dp? cCB CE|CE](#)

$p(\tau^+)$ Run I (2022)

$\mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$\mathcal{B}(B \rightarrow \tau^+ \mu^-)$ ▶ [dpX c|Dc_cDCf](#)

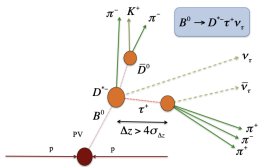
? polarisation (2023)

$\mathcal{B}(B \rightarrow \tau^+ \mu^-) = 0.030(\text{stat}) \pm 0.003(\text{syst})$

$\mathcal{B}(B \rightarrow \tau^+ \mu^-)$ ▶ [XO: 4Ql, dBpQCE{CECE](#)

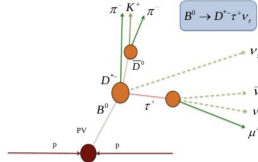
Muonic vs hadronic tau decays at LHCb

Muonic decay



- High statistics sample
- $p(\tau)$ directly measured
- Multiple missing neutrinos
- Precise background modelling

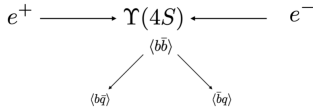
Hadronic decay



- High purity sample: allowed by being able to fully reconstruct the vertex
- $p(\tau)$ needs external input
- Low statistics

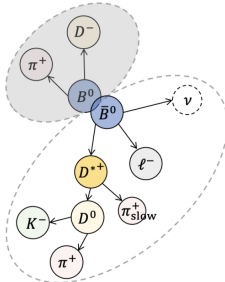
Complementary analyses that provide independent result

LFU tests in semileptonic B decays at Belle II



Untagged

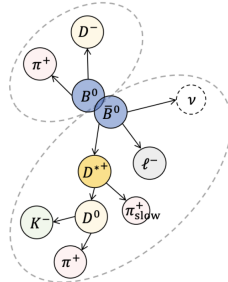
Partner B is not reconstructed explicitly



- ✓ Higher efficiency
- △ Approximate B kinematics information

Tagged

Partner B is fully reconstructed with hadronic decays to tag $B\bar{B}$ events



- △ Lower efficiency
- ✓ More precise B kinematics from the partner B
- ↪ Partner B identification is unique to B -factories

LFU tests in semileptonic B decays at Belle (II)

Belle

Had tag: $p(?)$ vs $p(?)$ (2015)

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

▶ $\mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$

Had tag: d and $p(?)$ (2018)

$$d(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

▶ $\mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$

SL tag: $p(?)$ vs $p(?)$ (2020)

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

▶ $\mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$

Belle II

Had tag: $p(t)$ (2024)

$$p(t) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

▶ $\mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$

Had tag: $p(?)$ (2024)

$$p(?) = \mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$$

▶ $\mathcal{B}(b \rightarrow c \ell \bar{\nu}_\ell) \mathcal{B}(c \rightarrow s \ell \bar{\nu}_\ell)$

$R(D^*)$ measurement strategy

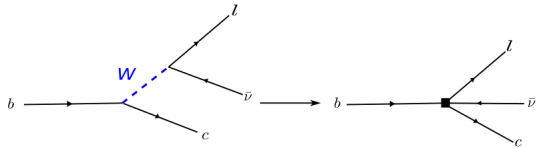
$$p(?) = \frac{\int_{\text{sig}} \text{sig}}{\int_{\text{bck}} \text{bck}}$$

- Signal/norm **yield ratio** determined from fit to data
- Signal/norm **efficiency ratio** determined from simulation: assuming SM scenarios
- Form factors varying in the templates or a systematic uncertainty assigned (depending on analysis setup)
- Largest systematic uncertainties coming from the form factor parameterisation, background modelling and simulation sample size
- Depending on the choice of decay different backgrounds to model

New Physics

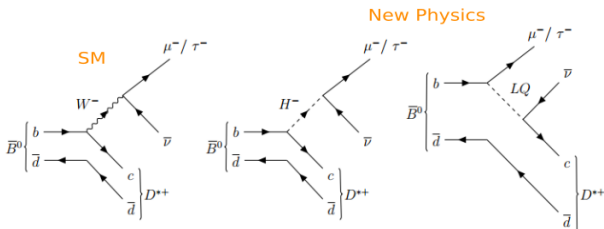
- We can use operators with unknown coupling constants and write them in an effective Hamiltonian

$$O_{\alpha H} = \frac{K_G}{\sqrt{2}}, \quad \times \quad ; \quad a_S$$



$$; S = ; S^l + ; S^d$$

- $; S^d$ are the Wilson coefficients that describe the NP effects
- a_S are effective operators that can be of a vector, scalar or tensor type



New Physics measurement strategies

- Model the New Physics effects in the fitting template
 - Hammer usage crucial
- More sensitivity to NP using the shape of the angles as fitting variables: see [▶ z- WW4%XiK cPb](#) at this workshop
- Measure **directly Wilson coefficients** : flexible to use NP model or be model independent
- Measure **angular coefficients**
- Currently no published analyses, several in progress at LHCb

> JJ1_ @ > 2HB+Biv KTHBim/2 JQ/m
 1H2K2Mi _2r2B;?iBM;i

hQQH i? i r2B;?ib J* b KTH2 7`QK i?2 ;2M
 KTHBim/2 iQ M2r > KK2` sBp.kyykXy

h?2Q`2iB+ H TT`Q +?

h?2 /2+ v `!i2 sUHV,

$$\frac{1}{[k]} = \frac{6}{(k)} o_{BD}^{k([k]} \frac{K_H^k K_T^k}{R K^k [k]} (>_+^k([k]) + >^k([k]) + >_y^k([k]) (R \frac{K_H^k}{K^k}) + j_k \frac{K_H^k}{K^k} >_b^k([k]))$$

r?2`2B([k]) `2 i?2 ?2HB+Biv KTHBim/2 bX
 _2r2B;?iBM;iQ L2r S?vbB+b b+2M `BQb- 2X;X #v
 Q` i2MbQ` +QmTHBM;b + M #2 /QM2 rBi? i?2 r2B;
 + H+mH i2/ b,

$$! B = \frac{Q_H / M \quad M_{2T} / t}{M_{2r} / M \quad Q_H / t}$$

r?2`2QH/Bb i?2 /2+ v ` i2 7Q` i?2 KQ/2H BKTH2K2M
 * `HQ M2r/Bb i?2 i?2 /2+ v ` i2 7Q` mT/ i2/ KQ/2H

qBHbQM + Q2{+B2Mi }i bi` i2;v

Ib2 > KK2` iQ /B`2+iHv }i i?2 qBHbQM + Q2
JQ/2H i?2 bB;M H M/ # +F;` QmM/Ur?2` 2`
rBi? > KK2`

HHQrb 7Q` ~Q iBM; i?2 qBHbQM + Q2{+B2
7 +iQ` T ` K2i2`b BM i?2 }i

S`Q/m+2 KmHiB/BK2MbBQM H i2KTH i2b
FBM2K iB+ p `B #H2b

1 bv iQ }i 7Q` bT2+B}+ L2r S?vbB+b KQ/2H
S`QpB/2 b2MbBiBpBiv Q7 2 +? LS QT2` iQ

"GS_ 7Q`K 7 +iQ` T ` K2i2`Bb iBQM BM m

"2`MHQ+?M` sBp,RdyjXy{- mbBM; #Qi? i?2 H2 /
P(z*. =K#V M/ bm#H2 /BM; Ab;m` @qBb2 7m

* QK#BM2 b2p2` H M Hvb2b iQ K2 b

S`QD2+i T`QTQb H

*QK#BM2 bi iBbiB+ H TQr2` Q7 b2p2` H +
7`QK G>*# M/ "2HH2 AA

aBKBH `K2 bm`2K2Mib p BH #H2 rBi?BM
bi `iBM; TQB Mi 7Q` i?Bb +QmH/ #2 H`2

G 2 p 2 ` ; B M ; G > * # M / " 2 H H 2 A A

: H Q # ! H ÷ } i i ? i p Q B / b # B b 2 b M / a J b b m K T
a ? ` 2 q * b # 2 i r 2 2 M i 2 K T H i 2 b Q 7 / B z 2 ` 2 M i K 2 b
U r ? 2 ` 2 T Q b b B # H 2 V # + F ; ` Q m M / K Q / 2 H b M / b

" B H D M J B i ` 2 b a f 2 T i 2 K # 2 ` k 9 - k y k 9 * ? H H 2 M ; 2 b B M a G " / 2 + R 1 9

* QK#BM2/ q* b M HvbBb bi` i2;v

b+ M Qp2` i?2 q* b Bb T2`7Q`K2/, +QK#B
/Bz2`2Mi T? b2 bT +2 `2;BQMb

S`Q}H2 HBF2HB?QQ/ K2i?Q/

k() 4 @k GIM

r?2`2Bb i?2 T? b2 bT +2X

qBi? i?2 +QM}/2M+2 BMi2`p H b

R * G= p $\frac{R}{k(\mathbb{R}k)}$ R_1 k^2 $\mathbb{R}k_j$ $\mathbb{R}k/i$

.Bz2`2Mi `2;BQMb Q7 T? b2 bT +2 + M #2
T ` H2HBx2 i?2 b+ M

q* i2KTH i2 b? T2b i G>* #

h[G H G (h S G #) H G S G), THQ i " b ! 7 Q ` 7 ` Q K > J J 1 _

▶ `sBp,ReykXy ▶ `sBp,ReRyX ▶ `sBp,RkyjX

q* i2KTH i2 b? T2b i "2HH2 AA

a? T2 +? M;2 7Q` b2H2+i2TL M/S? yb B+b BM

▶ `sBp,kykXy

"BHD M JBi`2baF2Ti2K#2` k9- kyk9 *? HH2M;2b BM aG " /2+ Rtd

6 B ` b i T ` Q Q 7 Q 7 T ` B M + B T H 2

G > * # B M T Q v J * r B Y ? . U r B i ? V
" 2 H H 2 A , A h Q W T m i r B Y ? . U r B i ? = V

h ? 2 + Q K # B M i B Q M U / b ? 2 / 7
+ Q M i Q m ` V / 2 K Q M b i ` i 2 b B K
b 2 M b B i B p B i v
L Q # + F ; ` Q m M / b Q ` b v b i 2 K
m M + 2 ` i B M i B 2 b + Q M b B / 2 ` 2

G > * # i Q v b i m / B 2 b , q ! * r B i ?

b B K O p M B b T T H B 2 / B M b B ; M H Y + Q M i ` C
b i m / v i ? 2 b 2 M b B i B p B i v
1 + ? b + M + Q M b B / 2 ` b Q M 2 Q 7 i ? 2 q * b ~ Q i B M ;
A K T ` i v
h ? 2 a J + Q M i ` B # m i B Q M B b b ? ` 2 / i Q T ` K 2 i ` B x

G 2 b b b 2 M b B i B p 2 i Q i ? 2 b + H ` q * b + Q K T ` 2 /
A K T ` i ` 2 b m H i b r B i ? b K H H b 2 M b B i B p B i v B M
P i ? 2 ` # + F ; ` Q m M / + Q M i ` B # m i B Q M b ? p 2 # 2 2 M 2 t
b i m / B 2 b

G > * # i Q v b i m / B 2 b , q ! * r j B i ?

b B K O p M B b T T H B 2 / i Q b i m / v i ? 2 b 2 M b B
1 + ? b + M + Q M b B / 2 ` b Q M 2 Q 7 i ? 2 q * b ~ Q i B M ;
A K T ` i V
+ F ; ` Q m M / U M Q M @ > K K 2 ` ` 2 r 2 B ; 2 H 2 // M B i b
b ? ` 2 / T ` K 2 i 2 `

G 2 b b b 2 M b B i B p 2 B M b + H ` q * b + Q K T ` 2 / r B i
a B K B H ` A K M / _ 2 q * b 2 M b B i B p B i v

L P h 1 , . B z 2 ` 2 M + 2 B M > K K 2 ` ` 2 r 2 B ; ? i B M ; # 2 i r 2 2 M
, ? 2 ` 2 r 2 ` 2 r 2 B ; p 2 i ? 2 t r B i ? _ * h 6 6 T ` K 2 i 2 ` B x i B

G > * # i Q v b i m / B 2 b , G > * # + Q K # B M i B

* Q K T H 2 K 2 M i 2 ` b m ` 2 K 2 M i b 7 ` Q K M / !

L S M / a J q B H b Q M * Q 2 { + B 2 M i b b ? ` 2 / K Q M ; i

h ? 2 K m Q M B + K Q M 2 b i ` B M i b i ? 2 _ 2 T ` i Q 7 i ? 2 q *

b i i B b i B + b V

h ? 2 / ` Q M K B / 2 + Q M b i ` B M i b i ? 2 A K T p 2 Q 2 t i ? 2

r 2 B ; ? i V

L Q i } M H b 2 M b B i B p B i v ,

@ > K K 2 ` ` 2 r 2 B ; ? i B M ; i Q # 2 H B ; M 2 / # 2 i r 2 2 M b K

@ 6 m H H # + F ; ` Q m M / K Q / 2 H i Q # 2 // 2 /

q? i r2 r Mi iQ T` QpB/2

A7 i?2`2 Bb LS i?2 ;HQ# H q* }i +QmH/ T` QpB/
KQM; Q#b2`p #H2b

LQi TQbbB#H2 iQ BMi2`T`2i +Q(Mb)bi2MiHv Q
K2 bm`2K2Mib, i?2v +QMi BM aJ i2KTH i2b i?
#B b2b

>Qr rBHH i?Bb T`QTQb H 2pQH p2

RX +? 2tT2`BK2M iQp iBmH/2 iQ T2`7Q`K aJ K2 b
M/ Tm`bm2 i?2B` QrM T?vbB+b T`Q;` KK2

kX*QM+2Mi` i2 i i?2 G> *# Q` "2HH2 +QK#BM iB
jX*QK#BM2 i?2 "2HH2 AA M/ G> *# `2bmHib

amKK `v M/ M2ti bi2Tb

q2 `2 rQ`FBM; QM#BM2/}q*BM + /2+ vb
mbBM; b2p2` H G>*# Y "2HH2 AA M Hvb2
*m``2MiHv b2iiBM; mT i? Bi7m/KB2MQ`b2MMb/Bi
Q7 i?2 q*b
h?2 7` K2rQ`F H G Q#BMQ2 HiBTH2 M HvbBb
S`2HBKBM `v b2MbBiBpBiv bim/B2b ?2`2
KmQM B Q/2b 7`QK G>*#

L2ti bi2Tb,

6mHH /2b+`BTiBQM Q7 i?2 # +F;`QmM/ BM
#2 //2/
* ``v QM rQ`FBM; rBi? bBKmH iBQM iQ T2
bim/v
h?2 7` K2rQ`F + M #2 mb2/ iQ b2imT +QK
K2 bm`2K2Mi rBi? "2HH2 QM+2 HH i?2 BM

" * E I S

" : G M / * G L 7 Q ` K 7 + i Q ` T ` K 2 i 2 ` B b

$$\frac{f(i, j)}{f(k)} = \frac{\sum_{j=0}^k \binom{k}{j} \binom{k-j}{i} \binom{k-i}{j}}{\sum_{j=0}^k \binom{k}{j} \binom{k-j}{i} \binom{k-i}{j}} R \frac{K}{L^k} U \frac{j}{k} > j > j^k + j > j^k R \frac{K}{L^k} + \frac{j}{k} \frac{K^k}{L^k} > j^k$$

> 2HB + Biv KTHB [S_G d9 9eyj U](#) " : G

> 2HB + Biv KTHB [Lm+HX S?vbX " 8jy L](#)

