Bundesministerium für Bildung und Forschung

technische universität dortmund

LHCb

$b \to c\ell\nu$ global Wilson coefficent fit with LHCb and Belle II

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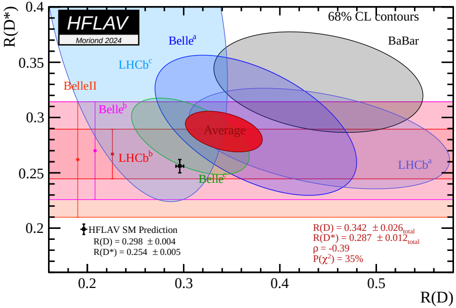
Outline

Introduction

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

$$R(D^*) = \frac{BR(B^0 \to D^*\tau\nu)}{BR(B^0 \to D^*\mu\nu)}$$

- Measurements from LHCb, Belle and Babar avaialable
- R(D*) measurements from LHCb use $\tau \to \mu\nu\nu$ or $\tau \to \pi^+\pi^-\pi^+\nu$



The goal:

Measure potential New Physics scenarios contributions

LFU tests in semileptonic B decays at LHCb

Muonic τ decay

$R(D^{*+})$ Run I (2015)

$0.336 \pm 0.027(\mathrm{stat}) \pm 0.030(\mathrm{syst})$

▸ PRL 115 111803

$R(D^0)$ vs $R(D^*)$ Run I (2023)

$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.024(syst)$

$R(D^0) = 0.441 \pm 0.060(stat) \pm 0.066(syst)$

▸ PRL 131 111802

$R(D^+)$ vs $R(D^{*+})$ Run II (2024)

$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$

$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$

▸ arXiv:2406.03387

$R(J/\psi)$ Run I (2018)

$0.71 \pm 0.17(stat) \pm 0.18(syst)$

▸ PRL 120 121801

Hadronic τ decay

$R(D^{*+})$ Run I (2018)

$0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(ext)$

▸ PRL 120 171802

$R(D^{*+})$ part Run II (2023)

$0.247 \pm 0.015(stat) \pm 0.015(syst) \pm 0.012(ext)$ ▸ PRD 108 012018

$R(\Lambda_c^+)$ Run I (2022)

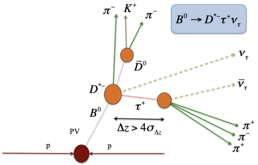
$0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$ ▸ PRL 128 191803

D^* polarisation (2023)

$0.242 \pm 0.026(stat) \pm 0.040(syst) \pm 0.059(ext)$ ▸ LHCb-PAPER-2023-020

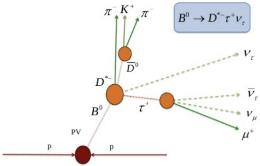
Muonic vs hadronic tau decays at LHCb

Muonic τ decay



- High statistics sample
- $R(D^*)$ directly measured
- Multiple missing neutrinos
- Precise background modelling

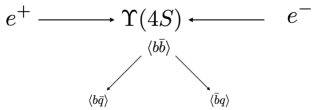
Hadronic τ decay



- High purity sample: allowed by being able to fully reconstruct the τ vertex
- $R(D^*)$ needs external input
- Low statistics

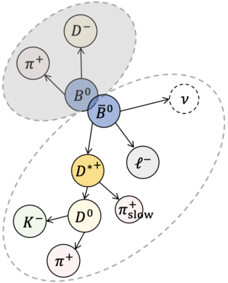
Complementary analyses that provide independent result

LFU tests in semileptonic B decays at Belle II



Untagged

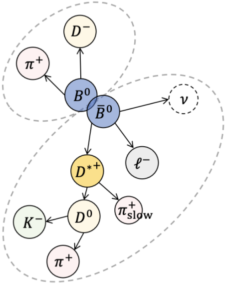
Partner B is not reconstructed explicitly



✓ 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: $R(D)$ vs $R(D^*)$ (2015)

$R(D)=0.375\pm0.064(stat)\pm0.026(syst)$

$R(D^*)=0.293\pm0.038(stat)\pm0.015(syst)$

▸ PRD 92 072014

Had tag: P_τ and $R(D^*)$ (2018)

$P_\tau(D^*)=-0.38\pm0.51(stat)\pm^{0.21}_{0.16}(syst)$

$R(D^*)=0.270\pm0.035(stat)\pm^{0.028}_{0.025}(syst)$

▸ PRD 97 012004

SL tag: $R(D)$ vs $R(D^*)$ (2020)

$R(D)=0.307\pm0.037(stat)\pm0.016(syst)$

$R(D^*)=0.283\pm0.018(stat)\pm0.014(syst)$

▸ PRD 92 072014

Belle II

Had tag: $R(X)$ (2024)

$R(X)=0.228\pm0.016(stat)\pm0.036(syst)$

▸ PRL 132 211804

Had tag: $R(D^*)$ (2024)

$R(D^*)=0.262\pm^{0.041}_{0.039}(stat)\pm^{0.035}_{0.032}(syst)$

▸ arXiv:2401.02840

$R(D^*)$ measurement strategy

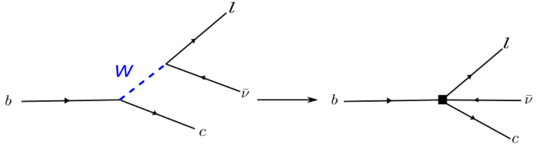
$$R(D^*) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{signal}}$$

- 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 τ decay different backgrounds to model

New Physics

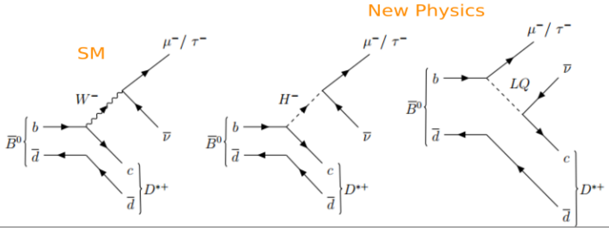
- We can use operators with unknown coupling constants and write them in an effective Hamiltonian

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum C_i O_i$$



$$C_i = C_i^{SM} + C_i^{NP}$$

- C_i^{NP} are the Wilson coefficients that describe the NP effects
- O_i 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 ▸ talk by L.Grillo 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

HAMMER - Helicity Amplitude Module for Matrix Element Reweightingt

- Tool that weights a MC sample from the generation amplitude to a new desired one ▸ Hammer ▸ arXiv:2002.00020v2

Theoretical approach

The decay rate ($B \to X l \nu_l$):

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{(2\pi)^3} V_{ij}^2 \frac{(q^2 - m_l^2)^2 p_X}{12 m_B^2 q^2} (H_+^2(q^2) + H_-^2(q^2) + H_0^2(q^2)(1 + \frac{m_l^2}{2q^2}) + \frac{3}{2} \frac{m_l^2}{2q^2} H_s^2(q^2))$$

where $H_i(q^2)$ are the helicity amplitudes.
Reweighting to New Physics scenarios, e.g. by adding extra scalar, vector or tensor couplings can be done with the weight vector for each event calculated as:

$$\omega_i = \frac{\Gamma_{old}}{\Gamma_{new}} \frac{d^n\Gamma_{new}/dx}{d^n\Gamma_{old}/dx}$$

where Γ_{old} is the decay rate for the model implemented in the Monte Carlo and Γ_{new} is the the decay rate for updated model

Wilson coefficient fit strategy

- Use Hammer to directly fit the Wilson coefficients
- Model the signal and background(where possible) template with Hammer
- Allows for floating the Wilson coefficients and as well the form factor parameters in the fit
- Produce multidimensional templates with a choice of kinematic variables
- Easy to fit for specific New Physics model
- Provide sensitivity of each NP operator
- BLPR form factor parameterisation in use (calculations by Bernlochner et al. arXiv:1703.05330v4, using both the leading and $O(\Lambda_{QCD}/m_b)$ and subleading Isgur-Wise function)

Combine several analyses to measure WCs?

Project proposal

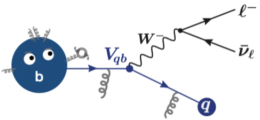
- Combine statistical power of several channels and observables from LHCb and Belle II
- Similar measurements available within LHCb and Belle II
- A starting point for this could be already published analyses

Leveraging LHCb and Belle II

+

Belle II

$\mathcal{R}(D^{(*)})$	$\mathcal{R}(X_{(c)})$	$\mathcal{R}(\pi/\rho/\omega)$
had. Tagging leptonic τ	had. Tagging leptonic τ	had. Tagging all τ
had. Tagging hadronic τ		
SL Tagging leptonic τ		
incl. Tagging leptonic τ		



LHCb

$\mathcal{R}(D^{(*)})$	$\mathcal{R}(J/\psi)$	$\mathcal{R}(\Lambda_c)$	$\mathcal{R}(D_s^{(*)})$
leptonic τ	leptonic τ	leptonic τ	leptonic τ
hadronic τ	hadronic τ	hadronic τ	hadronic τ

- Global $b \to c\ell\nu$ fit that avoids biases and SM assumptions
- Share WCs between templates of different measurements and (where possible) background models and systematics

Combined WCs analysis strategy

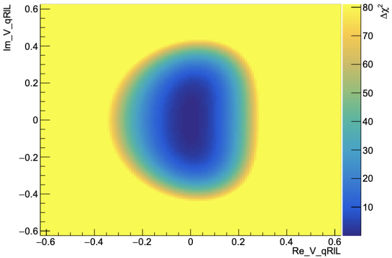
- A scan over the WCs is performed: combined multiple fits in different phase space regions

Profile likelihood method

$\chi^2(\alpha)$ = -2 ln $L(\alpha)$
where α is the phase space.

With the confidence interval as

$1 - CL = \frac{1}{\sqrt{2}\Gamma(1/2)} \int_{\delta\chi^2}^{\infty} e^{-1/2} t^{-1/2} dt$

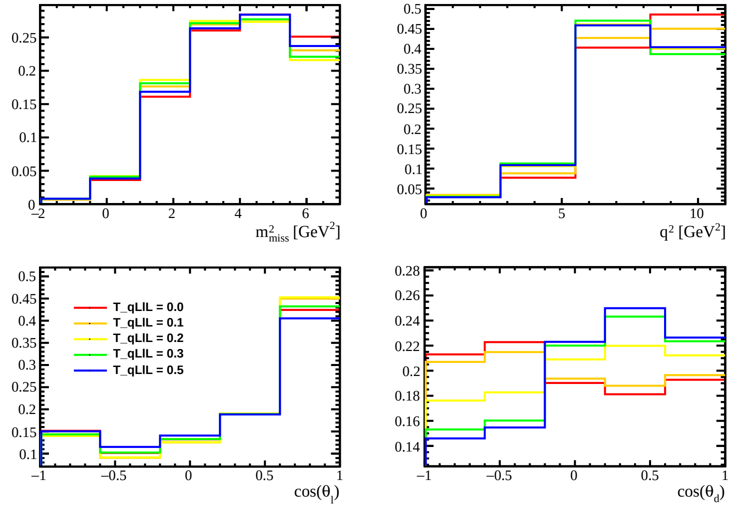


- Different regions of phase space can be scanned separately to paralelize the scan

WC template shapes at LHCb

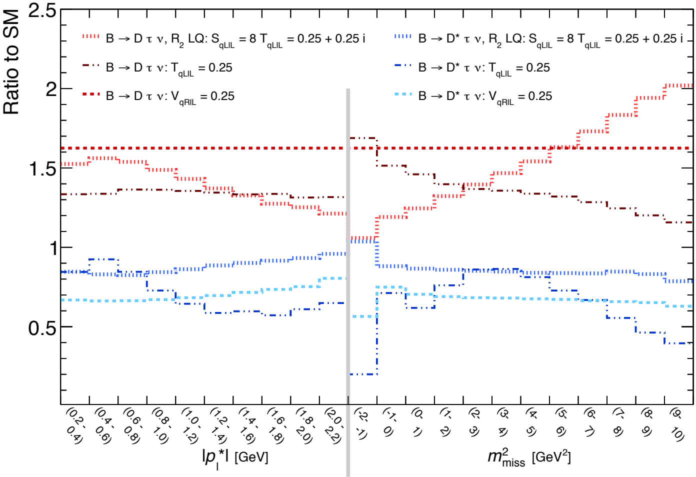
$TqLlL$ - $[\bar{c}\chi_L^T \gamma^\mu P_L b][\bar{l}\lambda_L^V \gamma_\mu P_L \nu]$: plots for $B^0 \to D^* \tau\nu$ from HAMMER

arXiv:1602.03030v2 arXiv:1610.02045v2 arXiv:1203.2654v2



WC template shapes at Belle II

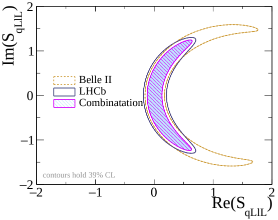
Shape change for selected New Physics in p_ℓ^* and m^2_{miss}

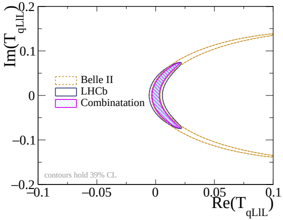


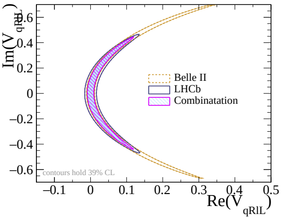
▸ arXiv:2002.00020v2

First proof of principle

- LHCb input: Toy MC with $B^0 \to D^* \tau \nu$ (with $\tau \to \mu \nu \nu$)
- Belle II input: Toy MC with $B^0 \to D^* \tau \nu$ (with $\tau \to \pi/\rho \nu$)



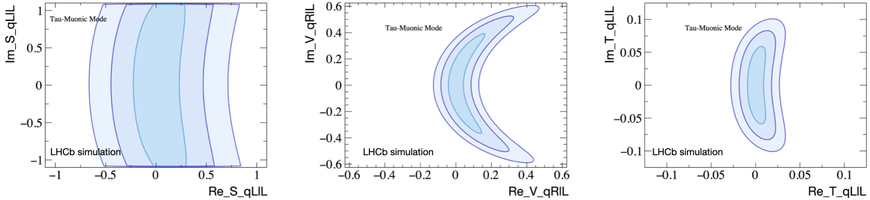




- The combination (dashed pink contour) demonstrates improvement in sensitivity
- No backgrounds or systematic uncertainties considered in the plots

LHCb toy studies: WC with $\tau \to \mu\nu\nu$

- **Asimov** scan is applied in signal+control configuration to study the sensitivity
- Each scan considers one of the WCs floating in the fit (the Re and Im part)
- The SM contribution is shared to parametrize the yields

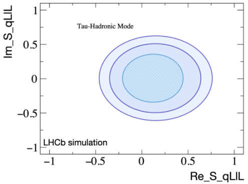


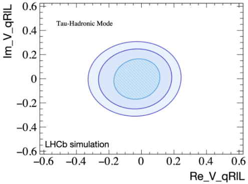
- Less sensitive to the scalar WC as compared to vector and tensor
- Im part results with small sensitivity in all WCs

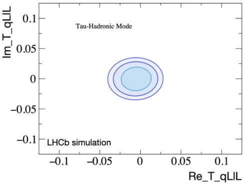
Other background contributions have been excluded in these preliminary studies

LHCb toy studies: WC with $\tau \to 3\pi\nu$

- **Asimov** scan is applied to study the sensitivity
- Each scan considers one of the WCs floating in the fit (the Re and Im part)
- A background (non-Hammer reweighted) is added $\to$ yield not shared parameter





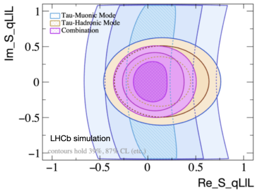


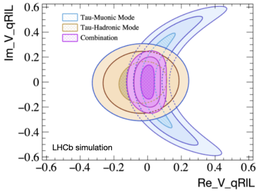
- Less sensitive in scalar WC as compared with vector and tensor
- Similar Im and Re WC sensitivity

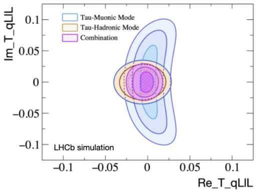
NOTE: Difference in Hammer reweighting between muonic and hadronic τ: here we reweight the τ vertex with RCT FF parameterization

LHCb toy studies: LHCb combination

- **Complementary** measurements from $\tau \to 3\pi\nu$ and $\tau \to \mu\nu\nu$
- NP and SM Wilson Coefficients shared among the two modes
- The **muonic mode** constraints the Re part of the WCs (higher statistics)
- The **hadronic** mode constraints the Im part of the WCs (τ vertex weight)







Not a final sensitivity:
- Hammer reweighting to be aligned between samples
- Full background model to be added

What we want to provide

- If there is NP the global WC fit could provide consistent picture among observables
- Not possible to interpret consistently our current $R(D^{(*)})$ measurements: they contain SM templates that could result with biases

How will this proposal evolve

1. Each experiment should **continue to perform SM measurements** and pursue their own physics programme
2. Concentrate at the LHCb or Belle combination only at the moment
3. Combine the Belle II and LHCb results

Summary and next steps

- We are working on a **combined WCs** fit in $b \to c\tau\nu$ decays using several LHCb + Belle II analyses
- Currently setting up the framework and **studying sensitivity of the WCs**
- The framework allows to **combine** multiple analysis
- Preliminary sensitivity studies here done with hadronic and muonic τ modes from LHCb

Next steps:

- Full description of the background in the toy studies needs to be added
- Carry on working with simulation to perform a full sensitivity study
- The framework can be used to setup a combined measurement with Belle once all the inputs are confirmed

BACKUP

BGL and CLN form factor parameterisation

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2}=\frac{G_F^2|V_{cb}^2||\eta_{EW}|^2|\vec{p}|^2q^2}{96\pi^3 m_{B^0}^2}\left(1-\frac{m_\ell^2}{q^2}\right)\times\left[\,(|H_+|^2+|H_-|^2+|H_0|^2)\left(1-\frac{m_\ell}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

Helicity amplitudes in BGL ‣ PRL 74 4603 (1995)

$$r=\frac{m_B}{m_{D^*}}$$

$$\omega(q^2)=\frac{m_B^2+m_{D^*}^2-q^2}{2m_{D^*}m_B}$$

$$H_\pm(\omega)=f(\omega)\mp m_B m_{D^*}\sqrt{\omega^2-1}\,g(\omega)$$

$$H_0(\omega)=\frac{F_1(\omega)}{\sqrt{q^2}}$$

$$H_t(\omega)=m_B\left(\frac{r\omega^2-1}{1+r^2-2r\omega}F_2(\omega)\right)$$

$$f(z)=\frac{1}{P_{1+}(z)\phi_f(z)}\sum_{n=0}^{N}b_n z^n$$

$$F_1(z)=\frac{1}{P_{1+}(z)\phi_{F_1}(z)}\sum_{n=0}^{N}c_n z^n$$

$$g(z)=\frac{1}{P_{1-}(z)\phi_g(z)}\sum_{n=0}^{N}a_n z^n$$

$$F_1(z)=\frac{1}{P_{0-}(z)\phi_{F_2}(z)}\sum_{n=0}^{N}d_n z^n$$

Helicity amplitudes in CLN ‣ Nucl. Phys. B 530 1 (1998)

$$H_\pm(\omega)=m_B\sqrt(r)(\omega+1)h_{A_1}(\omega)\left[1\mp\sqrt{\frac{\omega-1}{\omega+1}}R_1(\omega)\right]$$

$$H_0(\omega)=m_B\sqrt(r)(\omega+1)\frac{1-r}{\sqrt(q^2)}h_{A_1}(\omega)\left[1+\frac{\omega-1}{1-r}(1-R_2(\omega))\right]$$

$$h_{A_1}(\omega)=h_{A_1}(1)[1-8\rho_{D^*}^2 z(\omega)+(53\rho_{D^*}^2-15)z^2(\omega)-(231\rho_{D^*}^2-91)z^3(\omega)]$$

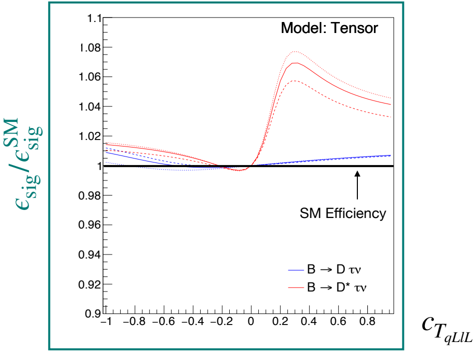
$$R_1(\omega)=R_1(1)-0.12(\omega-1)+0.05(\omega-1)^2$$

$$R_2(\omega)=R_2(1)+0.11(\omega-1)+0.06(\omega-1)^2$$

$$R_0(\omega)=R_0(1)-0.11(\omega-1)+0.01(\omega-1)^2$$

WC template shapes at Belle II

Change of selection efficiency of $B \to D^{*}\tau\nu$ vs New Physics contribution



▸ arXiv:2002.00020v2