



Prospects and results using HAMMER at LHCb

Biljana Mitreska

Flavour Physics with b Baryons and B_c mesons: Opportunities for discoveries
29.05.2026

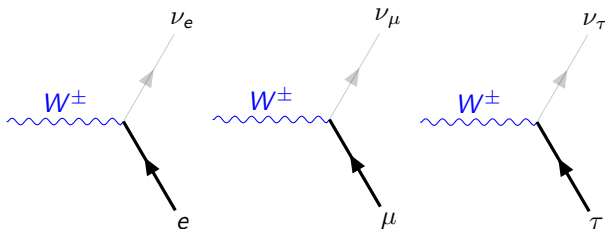
Outline

- 1 Introduction
- 2 $b \rightarrow cl\nu$ at LHCb
- 3 HAMMER
- 4 Analyses at LHCb
- 5 Prospects and summary

Introduction

Semileptonic b-hadron decays provide powerful probes for testing the Standard Model (SM) and search for BSM effects

Lepton Flavour Universality (LFU) hypothesis: equal gauge boson couplings to leptons



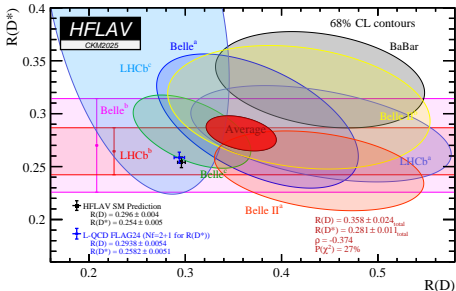
- Plethora of measurements that can be done:
 - CKM elements: V_{cb} , V_{ub}
 - Form factor measurements and angular observables
 - Lepton flavour universality tests: $\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \rightarrow H_c \tau \nu)}{\mathcal{B}(H_b \rightarrow H_c \mu \nu)}$

► more in talk by Ricardo

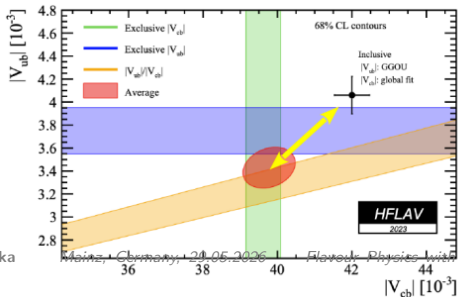
$b \rightarrow cl\nu$ transitions

Currently intriguing discrepancies exist:

- 3.8σ in $R(D^{(*)})$ measurements



- Inclusive vs exclusive V_{cb} and V_{ub}

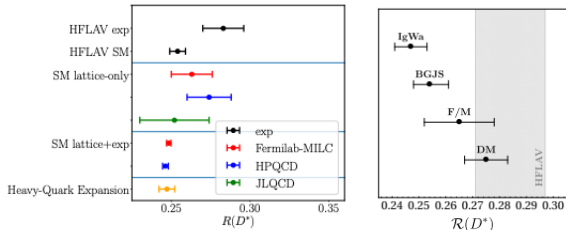


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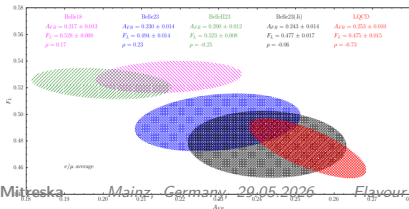
Mainz, Germany, 24.05.2026 Flavour Physics with b Baryons and B_c

$b \rightarrow cl\nu$ transitions

- Discrepancies when including lattice input
- Different form factor predictions shift variables of interest: how to solve this? ▶ talk by J.Harrison , ▶ talk by M.Blanke

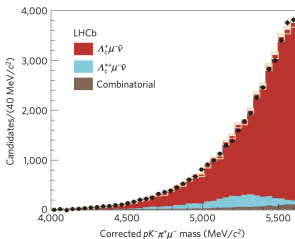


- Discrepancies when including lattice input in angular observables

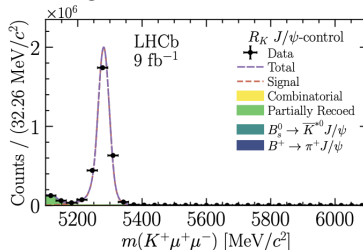


$b \rightarrow c l \nu$ at LHCb: challenges

- Neutrinos not detected at LHCb: approximation needed to reconstruct the B momentum \rightarrow Broad resolutions
- No mass peaks, harder to search for signatures



► Nature 11 (2015) 743-747

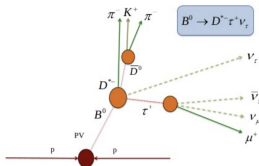


► PRD 108 (2023) 032002

- Heavily background polluted: precise modelling needed
- Different τ decay modes give rise to different background treatment: $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$ and $\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau$

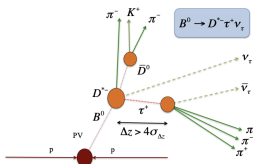
Muonic vs hadronic tau decays at LHCb

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

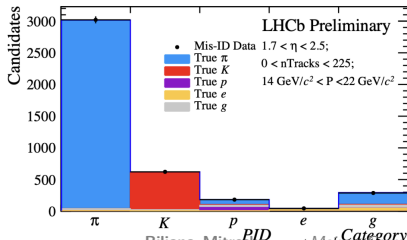
$b \rightarrow cl\nu$ LHCb: backgrounds

Usually modelled with simulation

- Semileptonic decays to heavier charmed hadrons
 $D^{**} \rightarrow D^{*+} \pi \pi$
- $B \rightarrow D^{*+} H_c X$

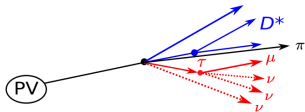
Data derived

- Misidentified hadrons (π , K , p)
- Combinatorial backgrounds



Biljana Mitreska reconstructed, Mainz, Germany, 29.05.2026

- Use of charged and neutral isolation to reject backgrounds

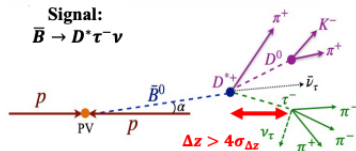


► arXiv:2302.02886

► PRL 120,121801

► PRL 128, 191803

- Residual prompt background rejected knowing the τ vertex



Flavour Physics with b Baryons and B_c

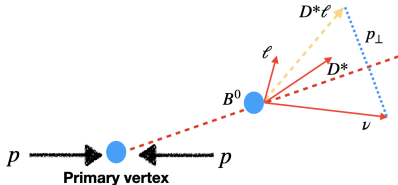
Neutrino reconstruction

Approximate B rest frame

$$p_z^B = \frac{m_B}{m_{D^{*l}}} p_z^Y \quad |p_B| = \frac{m_B}{m_{D^{*l}}} p_z^{D^{*l}} \sqrt{1 + \tan^2(\alpha_z)}$$

Quadratic equation

$$p_{D^{*l}}^\perp, p_{D^{*l}}^\parallel$$



$$a = \frac{p_{D^{*l}}^\parallel (m^2 - m_{D^{*l}}^2 - 2(p_{D^{*l}}^\perp)^2)}{2((p_{D^{*l}}^\perp)^2 - E_{vis}^2)}$$

$$r = \frac{E_{D^{*l}}^\parallel (m^2 - m_{D^{*l}}^2 - 2(p_{D^{*l}}^\perp)^2)}{4((p_{D^{*l}}^\perp)^2 - E_{vis}^2)^2} + \frac{(E_{D^{*l}} p_{D^{*l}}^\perp)^2}{(p_{D^{*l}}^\perp)^2 - E_{vis}^2}$$

$$p^+ = p_{D^{*l}}^\parallel - a + \sqrt{r}$$

$$p^- = p_{D^{*l}}^\parallel - a - \sqrt{r}$$

- Choose a random solution
- Linear regression algorithm: [arXiv:1611.08522v2](https://arxiv.org/abs/1611.08522v2)

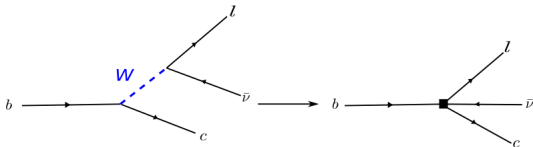
New Physics

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

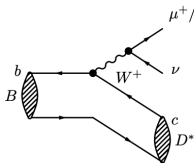
$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \sum C_i O_i$$

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

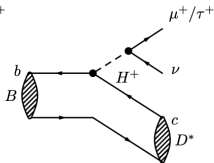
- C_i^{NP} are the Wilson coefficients that describe the New Physics effects
- O_i are effective operators that can be a vector, scalar or tensor type



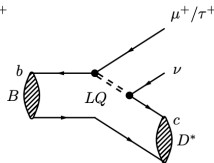
Any discrepancy could be a clear sign of New Physics (NP)



Biljana Mitreska



Mainz, Germany, 29.05.2026



Flavour Physics with b Baryons and B_C

HAMMER

- Tool that weights a MC sample from the generation amplitude to a new desired one

▶ Hammer

▶ arXiv:2002.00020v2

Theoretical approach

The decay rate ($B \rightarrow Xl\nu_l$):

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

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 simulation and Γ_{new} is the the decay rate for updated model

HAMMER: overview of functionalities

- Fast reweighting and no need to simulate new data
- Choose hadronic form factor parameterisation of your choice:

Decay	Form factor parameterisation
$B \rightarrow D/D^*$	BGL/CLN/BLPRXP
$B_c \rightarrow J/\psi$	EFG, BGL, Kiselev
$B_s \rightarrow K$	BCL
$B \rightarrow D^{**}$	BLR/BLRS/BLRSXP/ISGW2/LLSW
$B \rightarrow \rho$	BSZ
$B \rightarrow \pi$	BCL, GkVD
$\Lambda_b \rightarrow \Lambda_c^*$	LCPR, PCR
$D^{**} \rightarrow D^*\pi$	PW
$\tau \rightarrow 3\pi$	RCT

HAMMER: overview of functionalities

- Access to New Physics Wilson coefficients: all possible vector, scalar and tensor operators

$$\begin{aligned}
 H_{eff} &= \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i O_i \\
 &= \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + C_{V_{LL}}) O_{C_{V_{LL}}} + C_{V_{RL}} O_{C_{V_{RL}}} \\
 &\quad + C_{V_{LR}} O_{C_{V_{LR}}} + C_{V_{RR}} O_{C_{V_{RR}}} + C_{S_{LL}} O_{C_{S_{LL}}} \\
 &\quad + C_{S_{RL}} O_{C_{S_{RL}}} + C_{S_{LR}} O_{C_{S_{LR}}} + C_{S_{RR}} O_{C_{S_{RR}}} \\
 &\quad + C_{T_{LL}} O_{C_{T_{LL}}} + C_{T_{RR}} O_{C_{T_{RR}}}] + h.c.,
 \end{aligned}$$

Current	WC Tag	WC	4-Fermi/(i2√2 V _{cb} G _F)
SM	SM	1	$[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu]$
Vector	V-qL1L	$\chi_L^V \lambda_L^V$	$[\bar{c}\chi_L^V \gamma^\mu P_L b][\bar{\ell}\lambda_L^V \gamma_\mu P_L \nu]$
	V-qR1L	$\chi_R^V \lambda_L^V$	$[\bar{c}\chi_R^V \gamma^\mu P_R b][\bar{\ell}\lambda_L^V \gamma_\mu P_L \nu]$
	V-qL1R	$\chi_L^V \lambda_R^V$	$[\bar{c}\chi_L^V \gamma^\mu P_L b][\bar{\ell}\lambda_R^V \gamma_\mu P_R \nu]$
	V-qR1R	$\chi_R^V \lambda_R^V$	$[\bar{c}\chi_R^V \gamma^\mu P_R b][\bar{\ell}\lambda_R^V \gamma_\mu P_R \nu]$
Scalar	S-qL1L	$\chi_L^S \lambda_L^S$	$[\bar{c}\chi_L^S P_L b][\bar{\ell}\lambda_L^S P_L \nu]$
	S-qR1L	$\chi_R^S \lambda_L^S$	$[\bar{c}\chi_R^S P_R b][\bar{\ell}\lambda_L^S P_L \nu]$
	S-qL1R	$\chi_L^S \lambda_R^S$	$[\bar{c}\chi_L^S P_L b][\bar{\ell}\lambda_R^S P_R \nu]$
	S-qR1R	$\chi_R^S \lambda_R^S$	$[\bar{c}\chi_R^S P_R b][\bar{\ell}\lambda_R^S P_R \nu]$
Tensor	T-qL1L	$\chi_L^T \lambda_L^T$	$[\bar{c}\chi_L^T \sigma^{\mu\nu} P_L b][\bar{\ell}\lambda_L^T \sigma_{\mu\nu} P_L \nu]$
	T-qR1R	$\chi_R^T \lambda_R^T$	$[\bar{c}\chi_R^T \sigma^{\mu\nu} P_R b][\bar{\ell}\lambda_R^T \sigma_{\mu\nu} P_R \nu]$

- Reweighting to combinations of Wilson coefficients possible
- Only available for $B \rightarrow D^*$ with BLPR form factor parameterisation

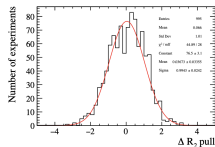
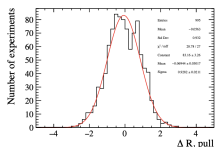
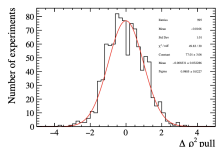
Fitting interfaces at LHCb

- Analyses usually perform binned likelihood fits using **HistFactory** or **pyhf**
- Developed fitting interfaces that embed HAMMER-weighted templates in the HistFactory/pyhf likelihood

$$\mathcal{L}(\mathbf{n}, \mathbf{a} | \boldsymbol{\eta}, \boldsymbol{\chi}) = \prod_c \prod_b \text{Pois}(n_{cb} | \nu_{cb}(\boldsymbol{\eta}, \boldsymbol{\chi})) \times \prod_k f_k(\mathbf{a}_k | \chi_k)$$

n = events, \mathbf{a} = auxiliary data, $\boldsymbol{\eta}$ = unconstrained params, $\boldsymbol{\chi}$ = constrained params

- Fitting interface of RooFit/pyhf with HAMMER allows for likelihood dependent on WCs and FFs [▶ RooFit-Hammer](#) [▶ pyhf-Hammer](#)



- For pyhf: [▶ pyhf-Hammer](#) introduces custom modifiers of the likelihood varying the shapes of the templates
- Dynamic template reweighting during minimization of FFs or WCs

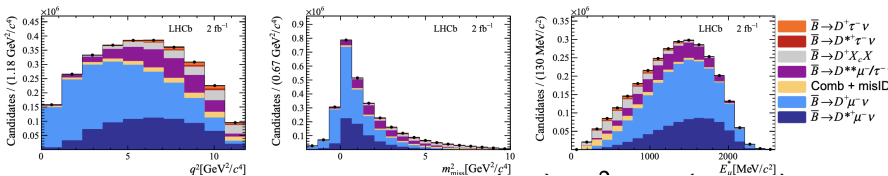
Hammer usage: $R(D^+)$ and $R(D^{*+})$

$R(D^+)$ and $R(D^{*+})$ [▶ PRL 134 \(2025\) 061801](#)

Simulation derived templates

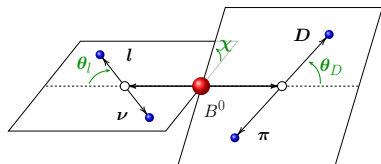
Form factor parameters varied during fitting via a RooFit-HAMMER interface

- $B^0 \rightarrow D^+$ and $B^0 \rightarrow D^* \rightarrow$ **BGL** [▶ PRL 74 4603 \(1995\)](#)
- $B^0 \rightarrow D^{**} \rightarrow$ **BLR** [▶ PRD 97 075011 \(2018\)](#)
- 3D binned template fit in q^2 , E_ℓ and m_{miss}^2



$$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$$
$$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$$

Hammer usage: $B^0 \rightarrow D^* \mu \nu$ angular analysis



- θ_l angle between the direction of the lepton and the direction opposite the B meson in the virtual W rest frame

- θ_d angle between the direction of the D meson and the direction opposite the B meson in the D^* rest frame

- χ angle between the plane by the D^* and the plane formed by the W decay, defined in the B rest frame

$$B^0 \rightarrow D^* \mu \nu$$

$$D^* \rightarrow D^0 \pi_s$$

$$D^0 \rightarrow K \pi$$

- 5D templates (three angles, q^2 and m_{miss}^2) **Main background contributions:**

- $B^0 \rightarrow D^* \tau \nu$ - using the same FF parameterisation as the signal
- $B \rightarrow D^{**} \mu \nu$ - modelled with the BLR FF parameterisation

► PRD 97 075011 (2018)

- Form factors and Wilson coefficients are floated in the fit

BGL fit - BGL truncation estimate

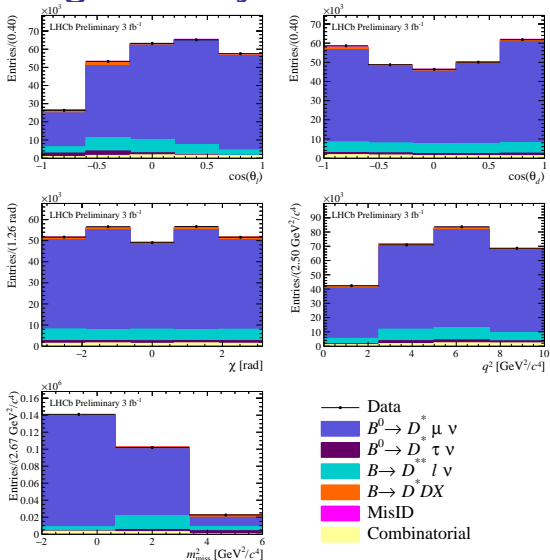
- Use the Bayesian Information Criterion (BIC) to choose between alternative models = choose the order of fitting parameters

$$\text{BIC} = \chi^2 + k \ln(n)$$

k is the number of model parameters
 n is the sample size (number of bins)

- Comparing models involves calculating BIC for each model
- Make all the combinations of fitting parameters: a_i , b_i (b_0 fixed), c_i and shared between $B^0 \rightarrow D^* \mu \nu$ and $B^0 \rightarrow D^* \tau \nu$
- The model with lowest BIC is considered as the nominal model measuring: a_0 , a_1 , b_1 , c_1 and c_2
- To estimate truncation systematic uncertainty one order higher is taken in the a , b and c series
- d_i parameters are fixed from prediction in [JHEP11 \(2017\) 061](#)

$B^0 \rightarrow D^* \mu \nu$ angular analysis



► LHCb-CONF-2026-001

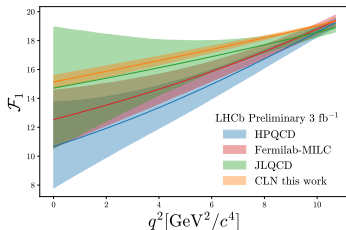
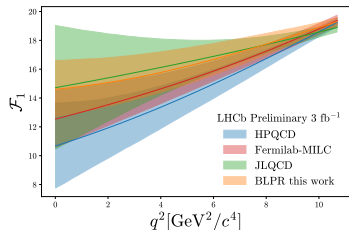
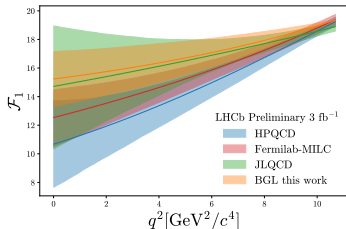
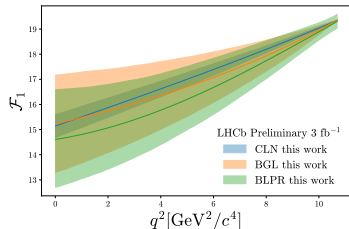
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Mainz, Germany, 29.05.2026

Flavour Physics with b Baryons and B_C

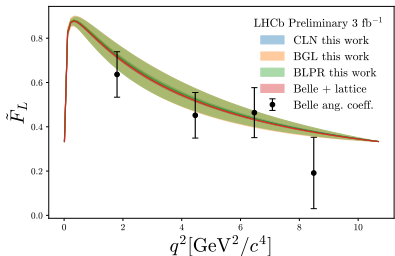
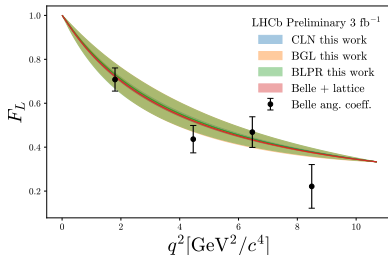
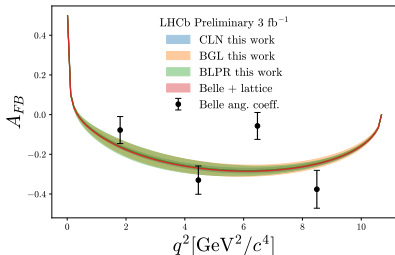
$B^0 \rightarrow D^{*\mu\nu}$ angular analysis

Form factor results:



- Compatible with lattice determinations and achieving improved precision

Example LHCb analyses that use Hammer

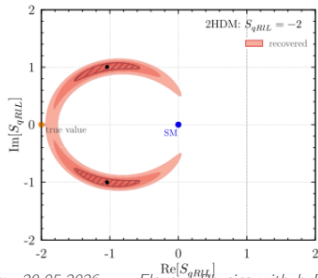
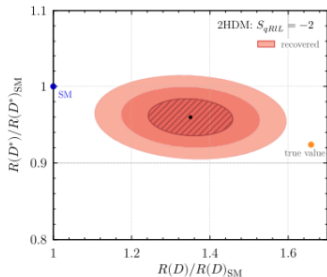


- In agreement with:
 - Belle angular coefficient measurement (black markers)
 - ▶ PRL 133 (2024) 131801
 - BLPR prediction containing lattice and Belle data
 - ▶ PRD 95 (2018) 115008

New physics and connections with $R(H_c)$

Bias due to model dependence

- $R(D)$ and $R(D^*)$ rely on SM templates
- Potential bias when fitting NP-sensitive data with SM shapes
- Discussed in [EPJC 80 883 \(2020\)](#) via fitting a NP pseudo dataset with a SM fit model
- Preferred strategy is to have a model independent ratio measurements

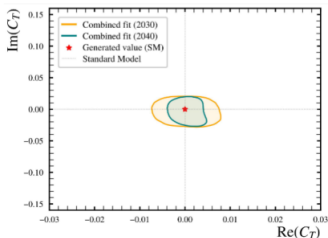
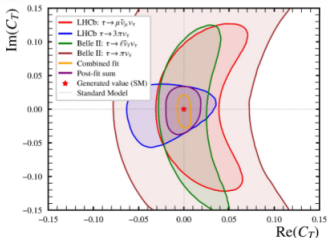


Model independent data reinterpretation

Proof of concept for agnostic reinterpretation of $R(D^*)$

▶ arXiv:2604.00735

- Using set of Belle II and LHCb-like toy samples
- Various signal and background components produced to emulate the 'real' experimental templates in muonic and hadronic $R(D^*)$ templates
- Test sensitivity enhancements in Wilson coefficients from combination of LHCb and Belle II datasets

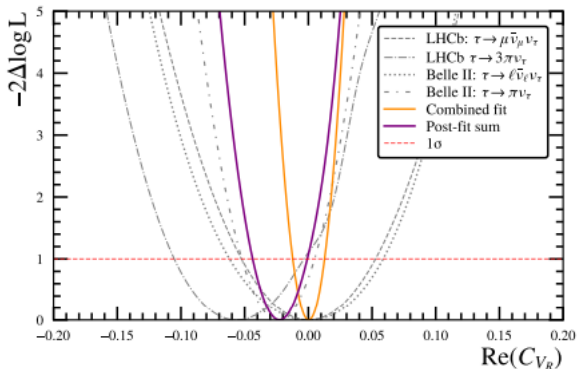


Model independent data reinterpretation

Proof of concept for agnostic reinterpretation of $R(D^*)$

▶ arXiv:2604.00735

- Working with New Physics templates
- Quantify biases due to SM templates
- Plot below: scan of the vector Wilson coefficient



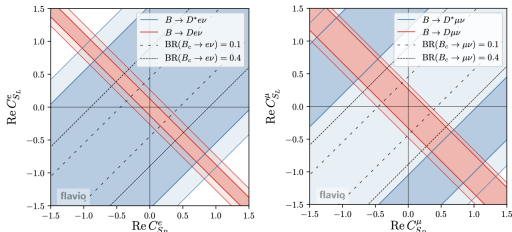
$B^0 \rightarrow D^{*\mu\nu}$ angular analysis: WCs + FFs

WCs fit with BLPR

- Plan to report several configurations:
 - Fitting one NP operator at a time (vector, scalar or tensor)
 - Fit combination of real only parts (scalar, vector or tensor)
 - Reparameterise the multi WC case into

$$C_V^I = C_{V_R}^I + C_{V_L}^I, \quad C_A^I = C_{V_R}^I - C_{V_L}^I, \quad C_P^I = C_{S_R}^I - C_{S_L}^I, \quad C_T^I,$$

- Fix one imaginary part since the overall phase is not observable



► Eur. Phys. J. C (2021) 81:984

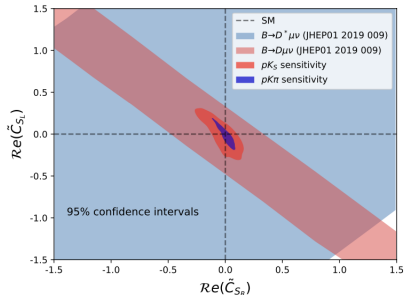
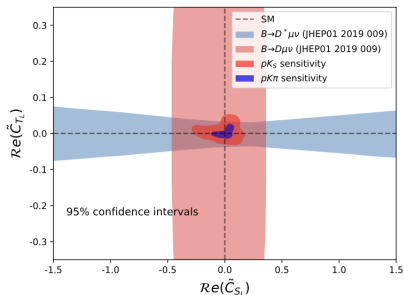
► arXiv:1801.01112

$$\Lambda_b \rightarrow \Lambda_c \tau / \mu \nu$$

- Ratios $R(\Lambda_c)$ already measured and can be related to $R(D^*)$

$$\frac{\mathcal{R}_{\Lambda_c}^{\text{expt}}}{\mathcal{R}_{\Lambda_c}^{\text{SM}}} = \alpha \frac{\mathcal{R}_D^{\text{expt}}}{\mathcal{R}_D^{\text{NP}}} + \beta \frac{\mathcal{R}_{D^*}^{\text{expt}}}{\mathcal{R}_{D^*}^{\text{NP}}} + \delta$$

- Beyond ratios angular observables to be explored at LHCb with $\Lambda_b \rightarrow \Lambda_c \tau \nu$
- Sensitivity study for NP Wilson coefficients
 - C_{VR} , C_{TL} , C_{SR} and C_{SL}



► JHEP 12 148(2019)

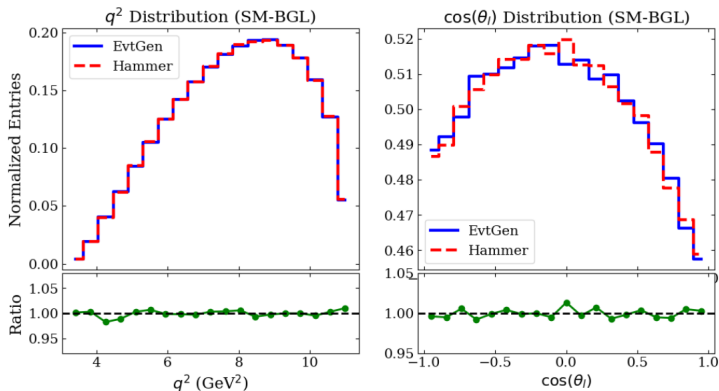
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Flavour Physics with b Baryons and B_C

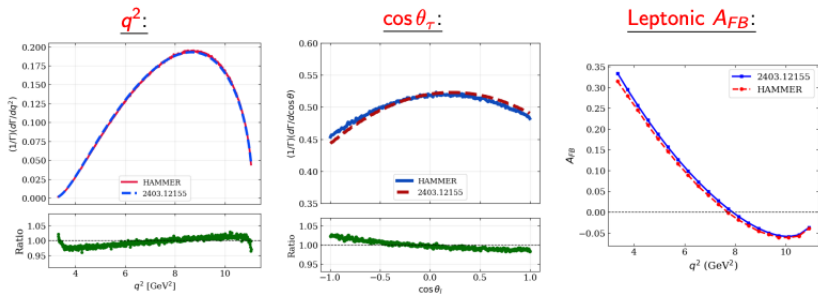
$$\Lambda_b \rightarrow \Lambda_c \tau \nu$$

- Prospects for angular studies: ▶ slides by B.Dey
- Check of BGL in Hammer and EvtGen (plots by Samad M.):
good agreement



$$\Lambda_b \rightarrow \Lambda_c \tau \nu$$

- Prospects for angular studies: [slides by B.Dey](#)
- Check of BGL in Hammer and lattice QCD from [arXiv:2403.12155](#), form factor parameter values fully aligned



- Small differences observed, to be understood before using directly in analysis

HAMMER: new developments and additions v1.5

See latest LHCb&Theory talk by Hammer developers:

▶ talk and recording

- New API for Wilson coefficient partial specialization (simplified model subspaces)
- $\mathcal{O}(10)$ speed and memory improvements for NP+FF fitting

We are organising a half day workshop on Hammer in July where wish list and hands-on session will be given by developers

<https://indico.cern.ch/event/1691444/>

The screenshot shows the Indico event page for 'HFLAVTech - Form Factors'. The event is scheduled for 8 July 2026 in Europe/Zurich timezone. The page includes a search bar and a navigation menu with 'Overview', 'Registration', and 'Inputs from participants for discussion'. The main image features a circular diagram with various physics symbols and the text 'HFLAV^{XX}-tech Form Factors'.

Biljana Mitreska, Milica Garčinović, 09/05/2026
The workshop will bring together theorists and experimentalists from the LHC and non-LHC collaborations to discuss recent results, analysis techniques, new strategies and theoretical aspects for a description of the hadronic matrix elements. In more details, the workshop is focused on:

Flavour Physics with b Baryons and B_c

Summary

- Persistent tensions exist in semileptonic decays
- Already collected large datasets however efficient tools are needed for analysis and reinterpretation
- HAMMER developments allows to constrain or reweight to FFs and Wilson coefficients or fit directly these parameters
- Many analyses at LHCb have validated its usage
- The tool starting to become the default in many ongoing analyses

BACKUP

Form factor results

CLN parametrisation

		Statistical correlations		
		R_1	R_2	ρ^2
R_1	1.303 ± 0.032 (stat) ± 0.049 (syst)	R_1 1.000	0.66	-0.61
R_2	0.859 ± 0.014 (stat) ± 0.031 (syst)	R_2	1.000	-0.77
ρ^2	1.211 ± 0.020 (stat) ± 0.030 (syst)	ρ^2		1.000

BGL parametrisation

		Statistical correlations				
		a_0	a_1	b_1	c_1	c_2
a_0	0.026 ± 0.001 (stat) ± 0.002 (syst)	a_0 1.000	-0.91	0.50	0.35	-0.27
a_1	-0.039 ± 0.022 (stat) ± 0.031 (syst)	a_1	1.000	-0.56	-0.23	0.15
b_1	-0.008 ± 0.004 (stat) ± 0.031 (syst)	b_1		1.000	0.58	-0.48
c_1	-0.001 ± 0.001 (stat) ± 0.007 (syst)	c_1			1.000	-0.97
c_2	0.019 ± 0.026 (stat) ± 0.026 (syst)	c_2				1.000

BLPR parametrisation

		Statistical correlations				
		$\bar{\rho}_*^2$	$\chi_2(1)$	$\chi_2'(1)$	$\eta(1)$	$\eta(1)'$
$\bar{\rho}_*^2$	1.28 ± 0.03 (stat) ± 0.04 (syst)	$\bar{\rho}_*^2$ 1.000	-0.28	-0.68	-0.27	0.83
$\chi_2(1)$	-0.11 ± 0.12 (stat) ± 0.29 (syst)	$\chi_2(1)$	1.000	0.11	-0.68	-0.33
$\chi_2'(1)$	0.38 ± 0.18 (stat) ± 0.20 (syst)	$\chi_2'(1)$		1.000	0.32	-0.85
$\eta(1)$	0.43 ± 0.14 (stat) ± 0.36 (syst)	$\eta(1)$			1.000	-0.38
$\eta(1)'$	-0.52 ± 0.52 (stat) ± 0.47 (syst)	$\eta(1)'$				1.000

Largest systematic uncertainties: template statistics, simulation corrections and BGL truncation